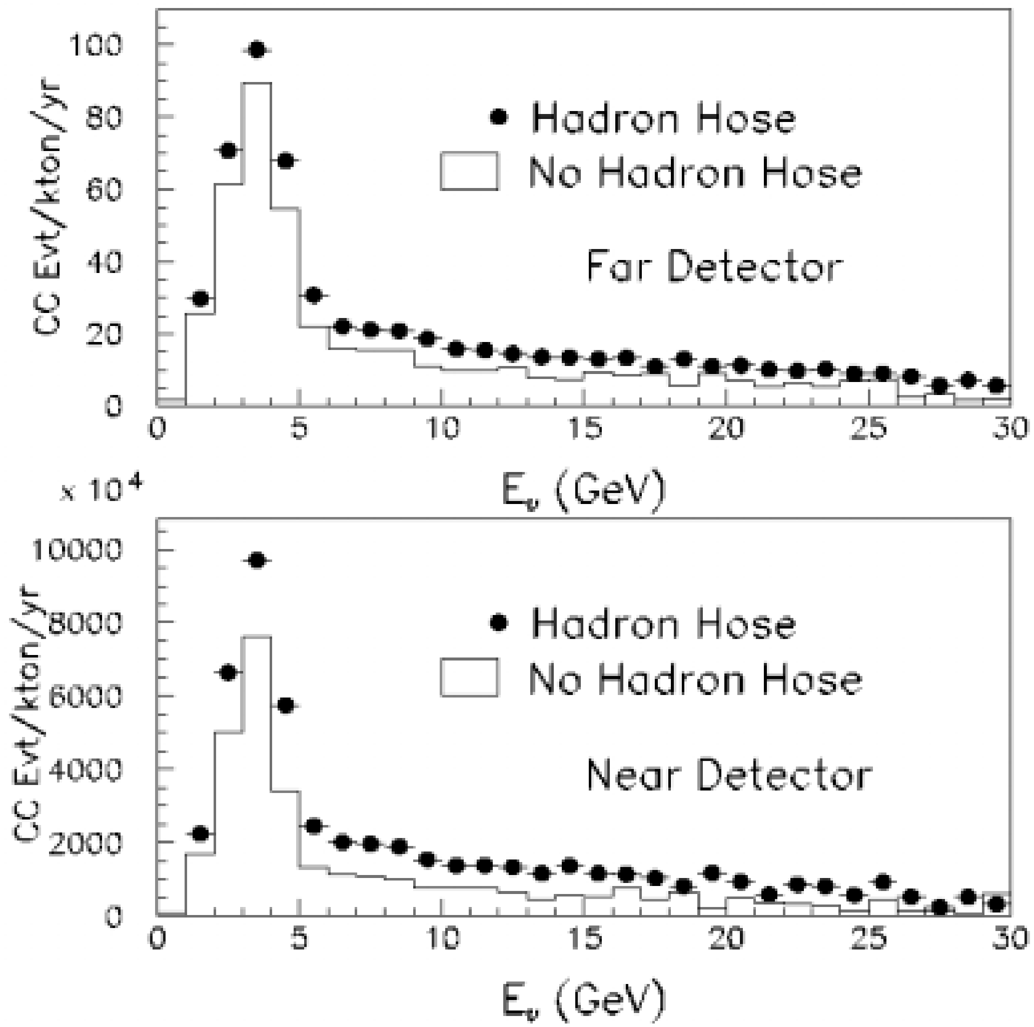
Impact of the Hadron Hose on MINOS Physics

Sacha E. Kopp,
University of Texas – Austin

Neutrino Energy Spectra

- Hose produces spectra at near and far detectors that are
  - »“More similar”
  - »Broader and smoother
- 25% more events in the peak region E_{υ}<6 GeV.
- Plots here are after resolutions, reconstruction efficiencies (makes it a 30% increase!)



Uncertainties from the Beam

- Because we have two detectors, beam uncertainties are "second order:"

$$N_{\mathrm{far}} = R_{FN}\, N_{\mathrm{near}}$$

where

R_{FN} is extrapolation factor

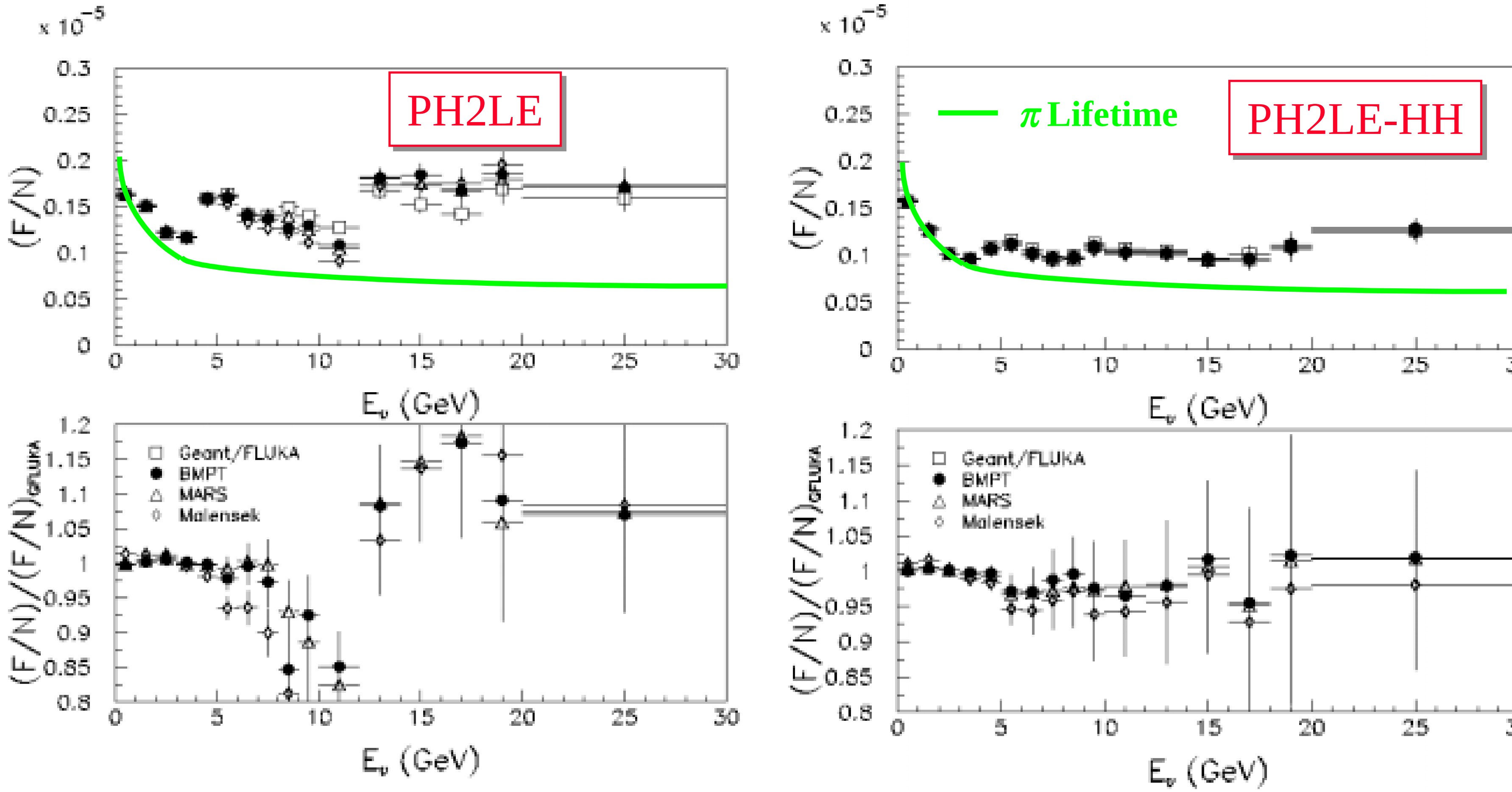
N_{near} is measured flux in near detector.

- Two ways of handling beam uncertainties:
  - »Input distortions in R_{FN}, see what happens ("blindsided" experiment)
  - »Uncertainties added as systematics in R_{FN}.

Look at Many "Experiments"

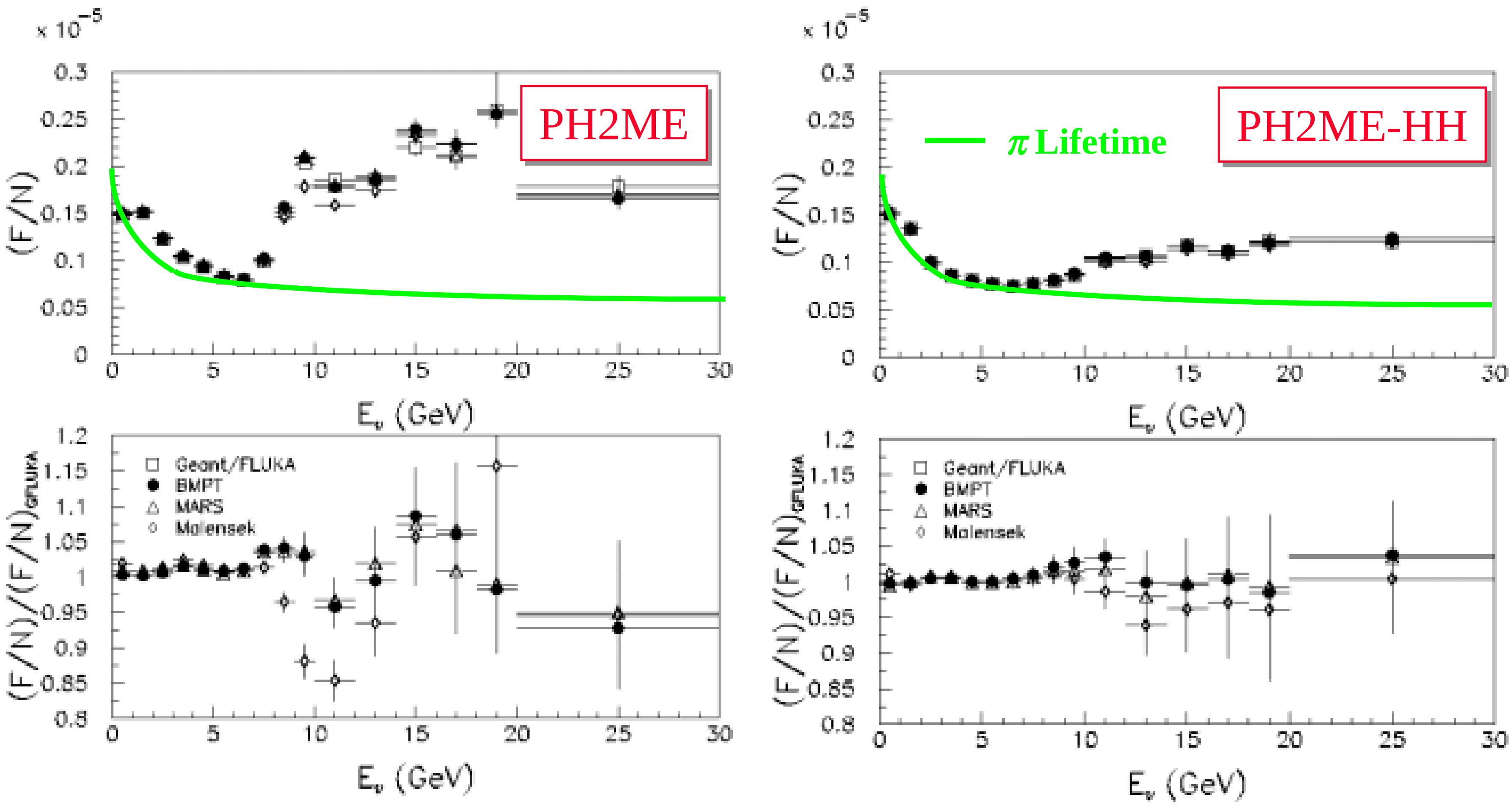
- A MINOS "experiment" consists of 3 parts:
  1) Spectrum measured in near detector
  2) Spectrum measured in far detector
  3) Monte Carlo extrapolation R_{FN} to predict far spectrum
- Far spectrum compared to prediction ⇒ oscillations?
- Simulate MINOS experiments with 10 kt-yr. exposure.
  » Generate using different hadron production models.
- Always extrapolate near→far using R_{FN} calculated with Geant/FLUKA.

Extrapolating to the Far Detector



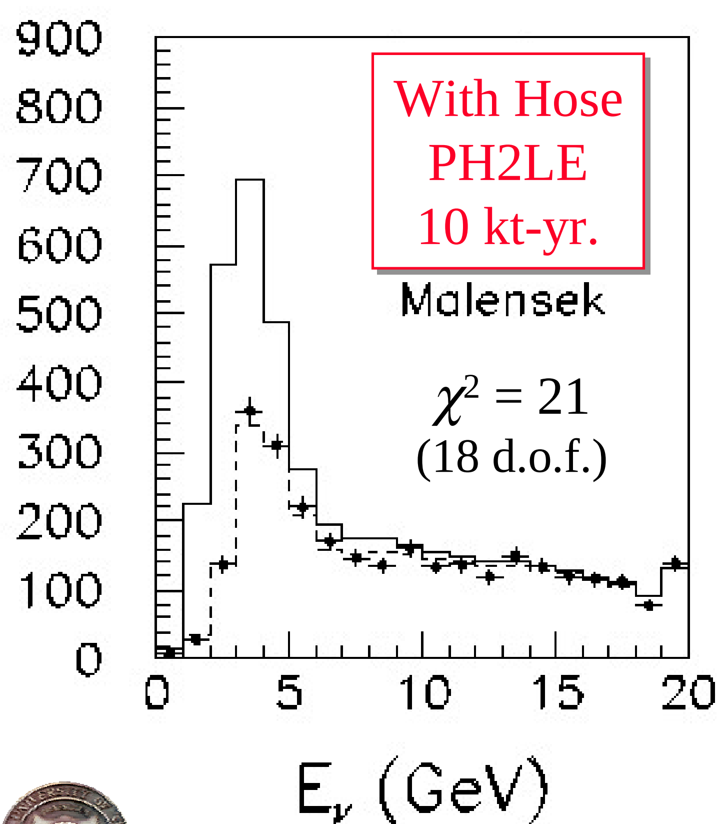
- Largest variations in high energy tail.
- Still ~2% variations for E_υ < 6 GeV! (no hose)

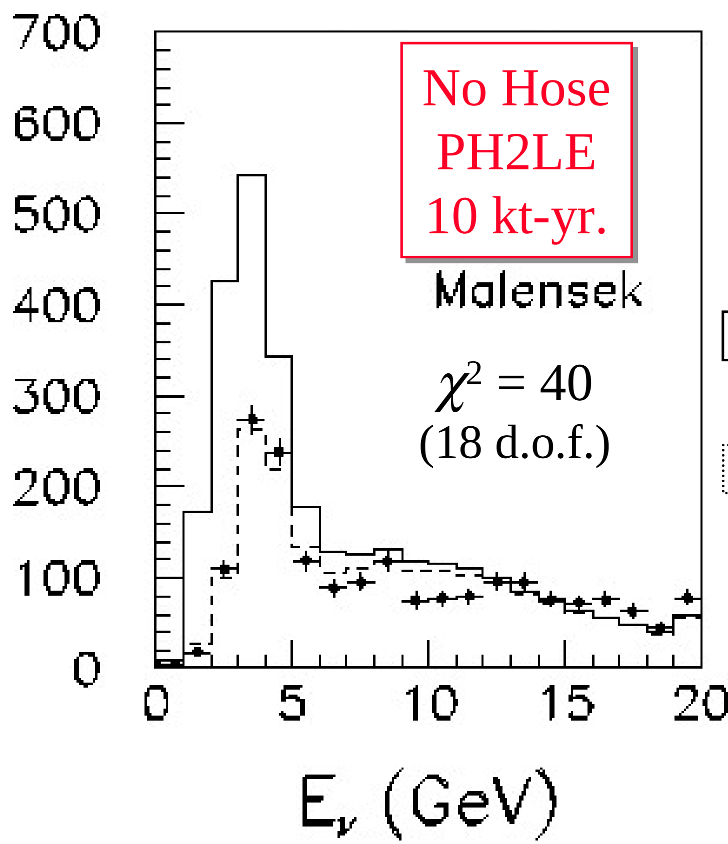
Medium Energy Beam



How Bad Could it Be?

- For most Δm^2, distortions won't produce oscillation-like signals.
- Accurate spectrum prediction for best parameter determination.





- Agreement across entire E_υ important for credibility of measurement in oscillation region.

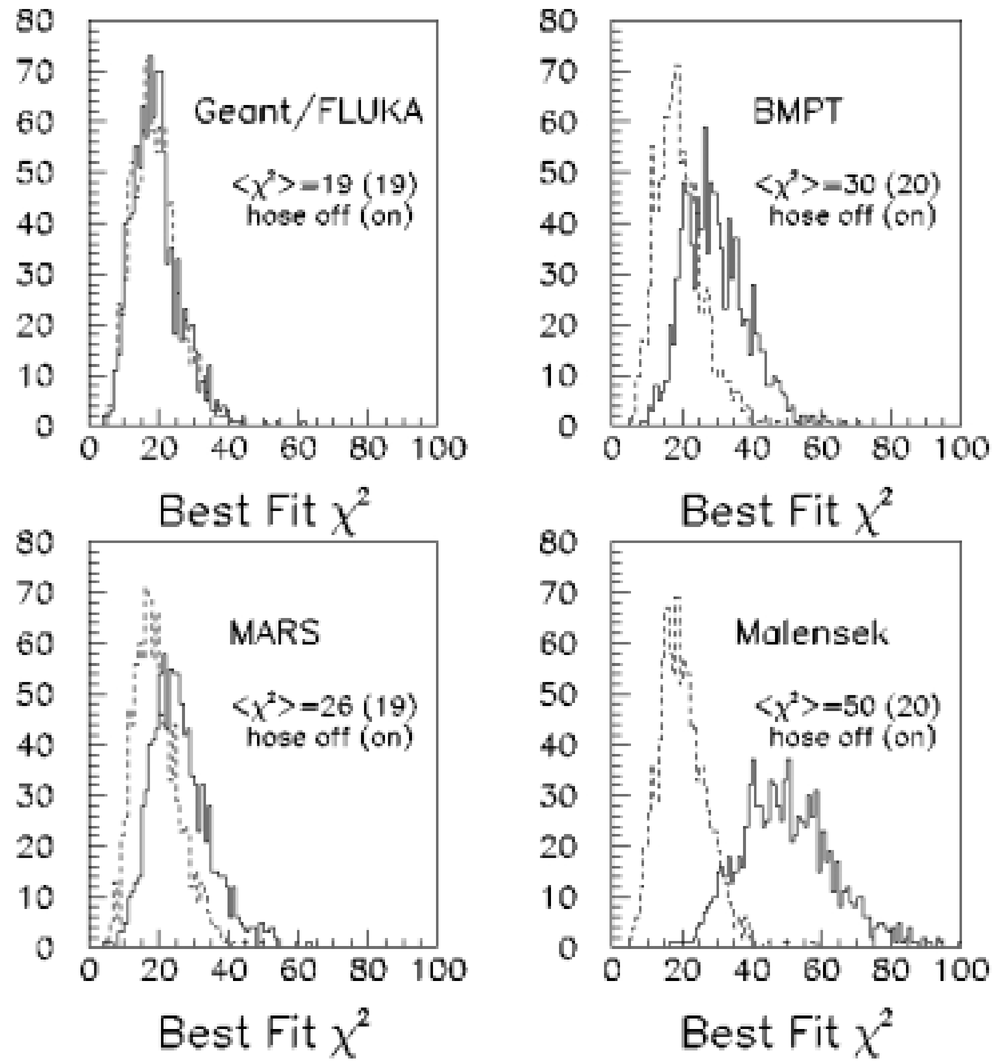
Expectation (no oscillations)

Expectation (Δm^2=0.002 eV^2)

Far Detector Observed Events

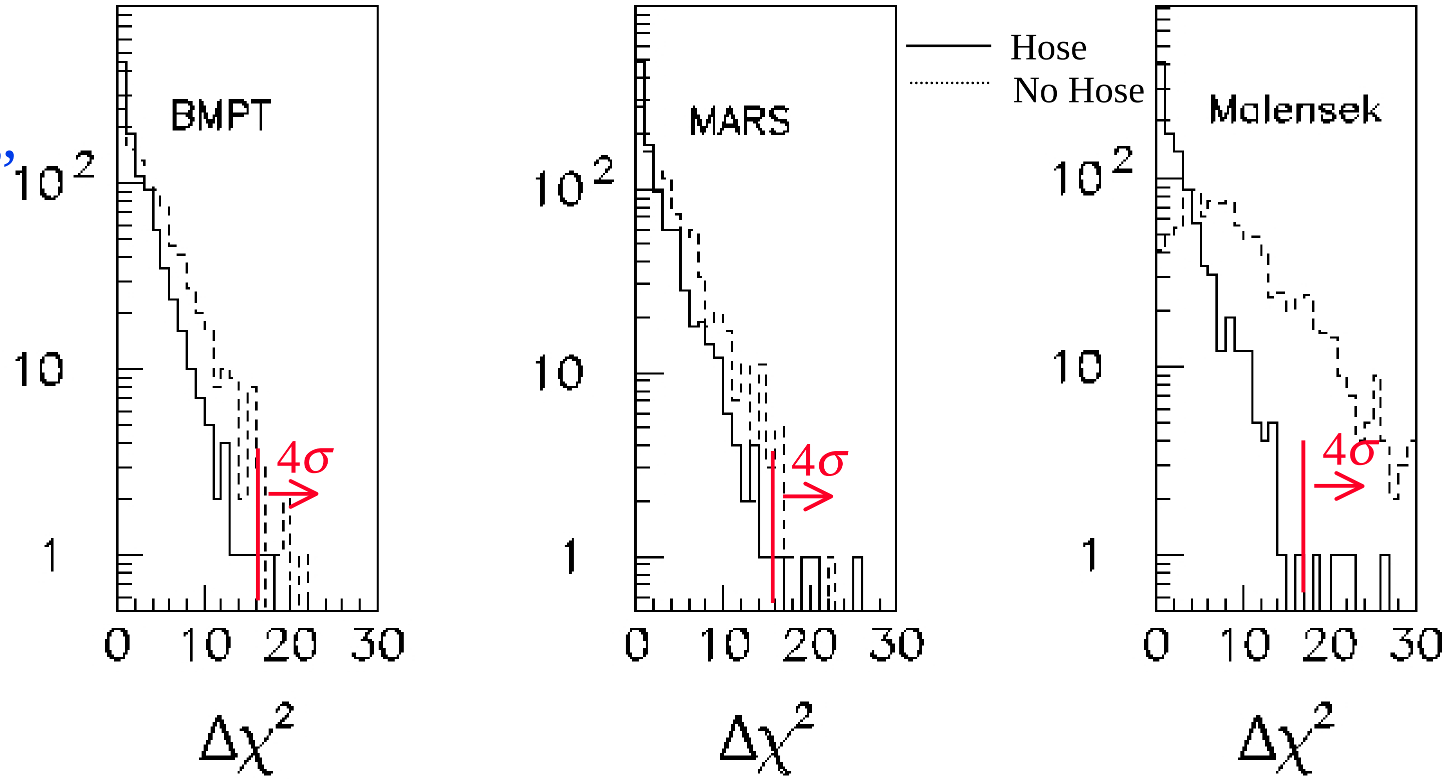
Comparing with Extrapolation

- Probability of getting $P(\chi^2)<10\%$ is 10, 54, 43, or 97% for different models (no hose).
- With hose on, it's always 10 - 11% of experiments.
- Clearly systematic distortions larger than statistical errors (even for PH2LE!).



Get False Signals?

- Deliberately fit to "wrong" models.
- Input no osc. into exp'ts.
- Ask how many experiments have

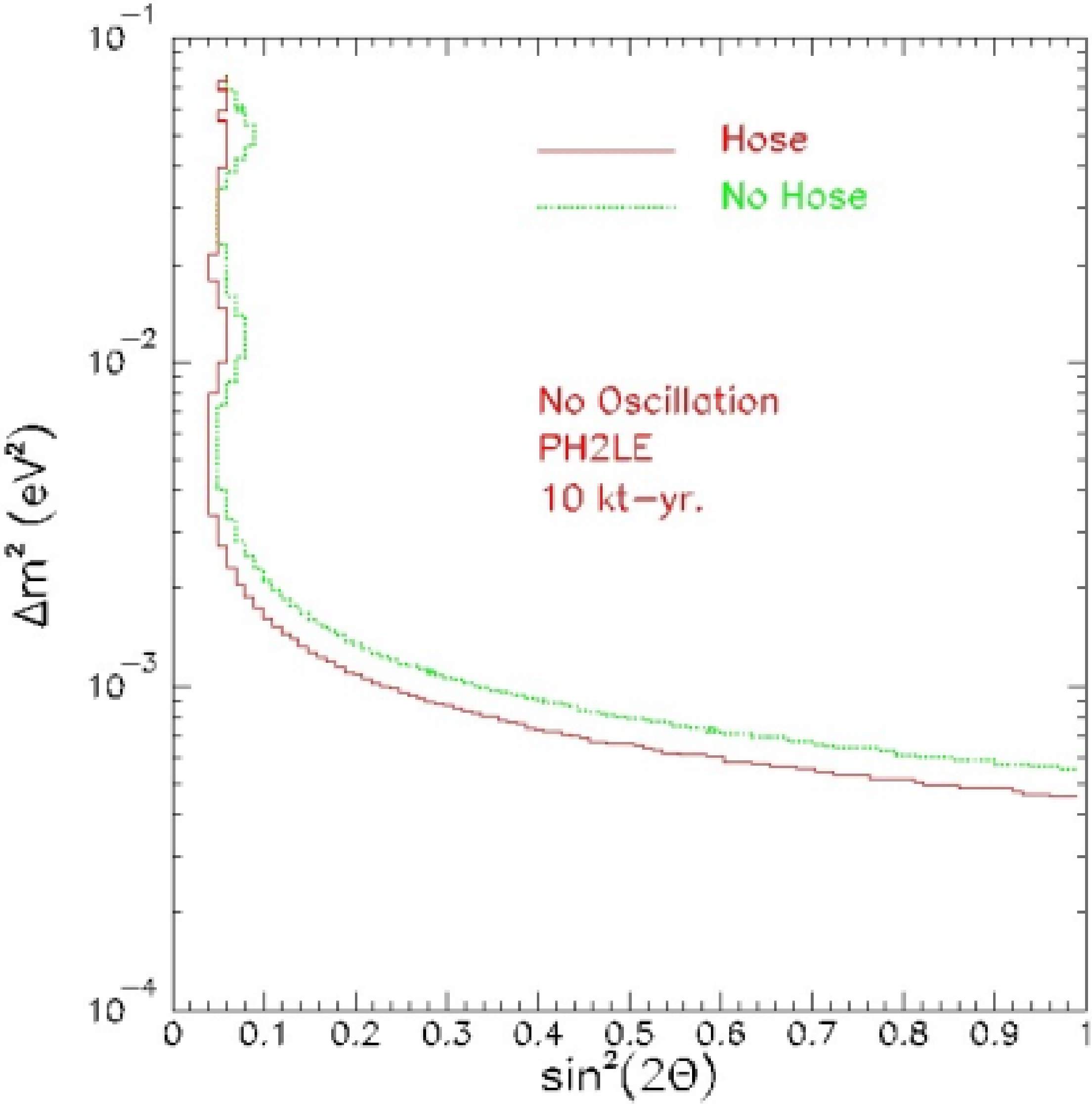


$\Delta\,\chi^2 \equiv \chi^2$(no osc. fit) - χ^2(best osc. fit) > 16

For BMPT, MARS, Malensek it's 3%, 2%,13% (no hose)
<0.5% (with hose).

Sensitivity Curves

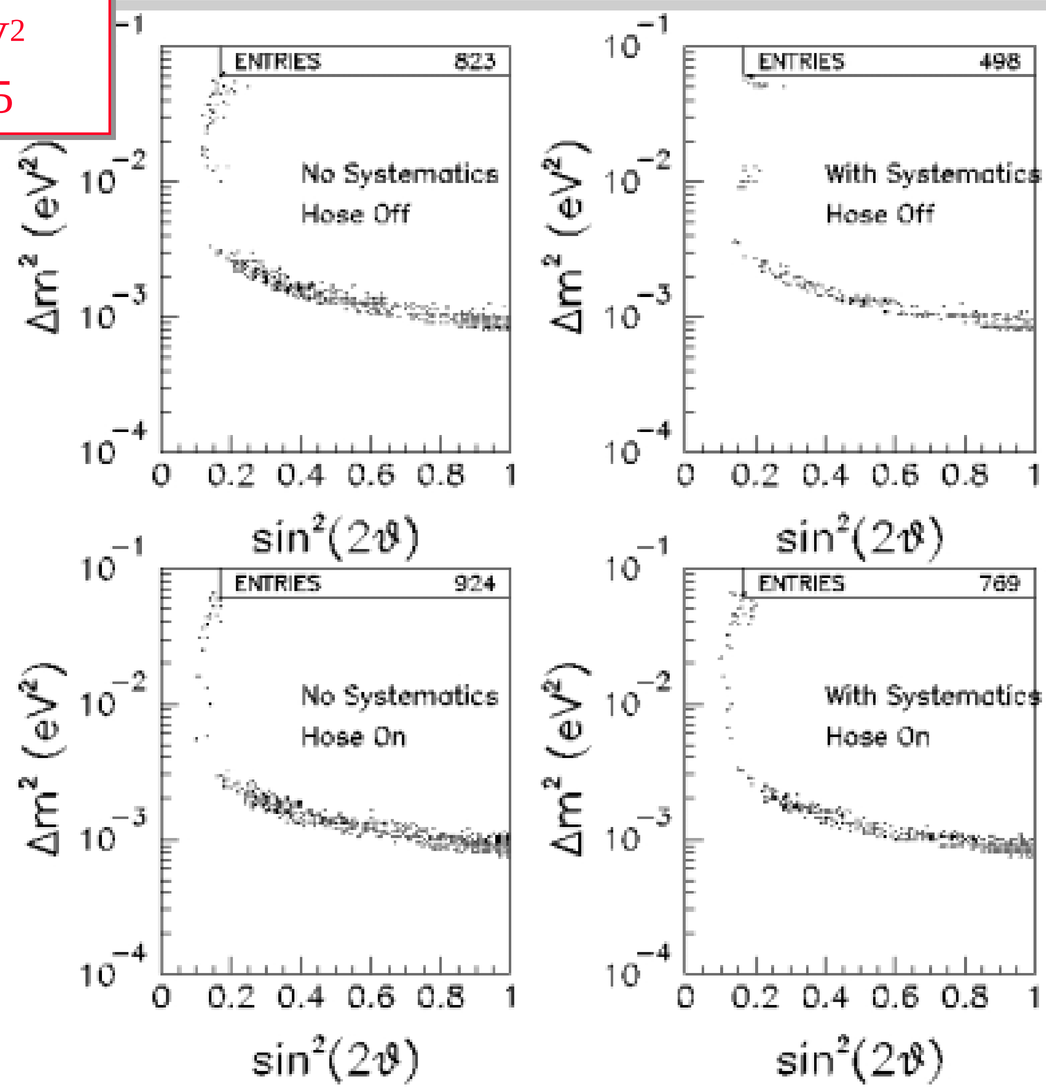
- Assumed spread of hadron production models as $\sigma_{syst.}$
- Excluded Malensek from "model spread" since it is not expected to be realistic at low E_{υ}.
- At low Δm^2, benefit from improved systematic uncertainties of hose



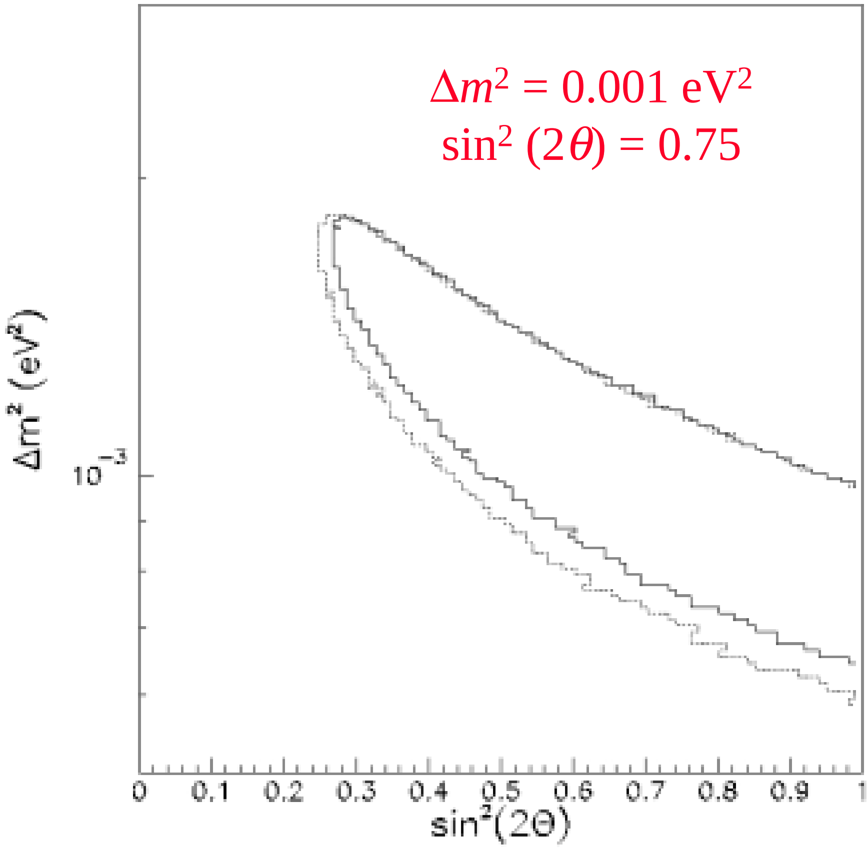
A Quick Look

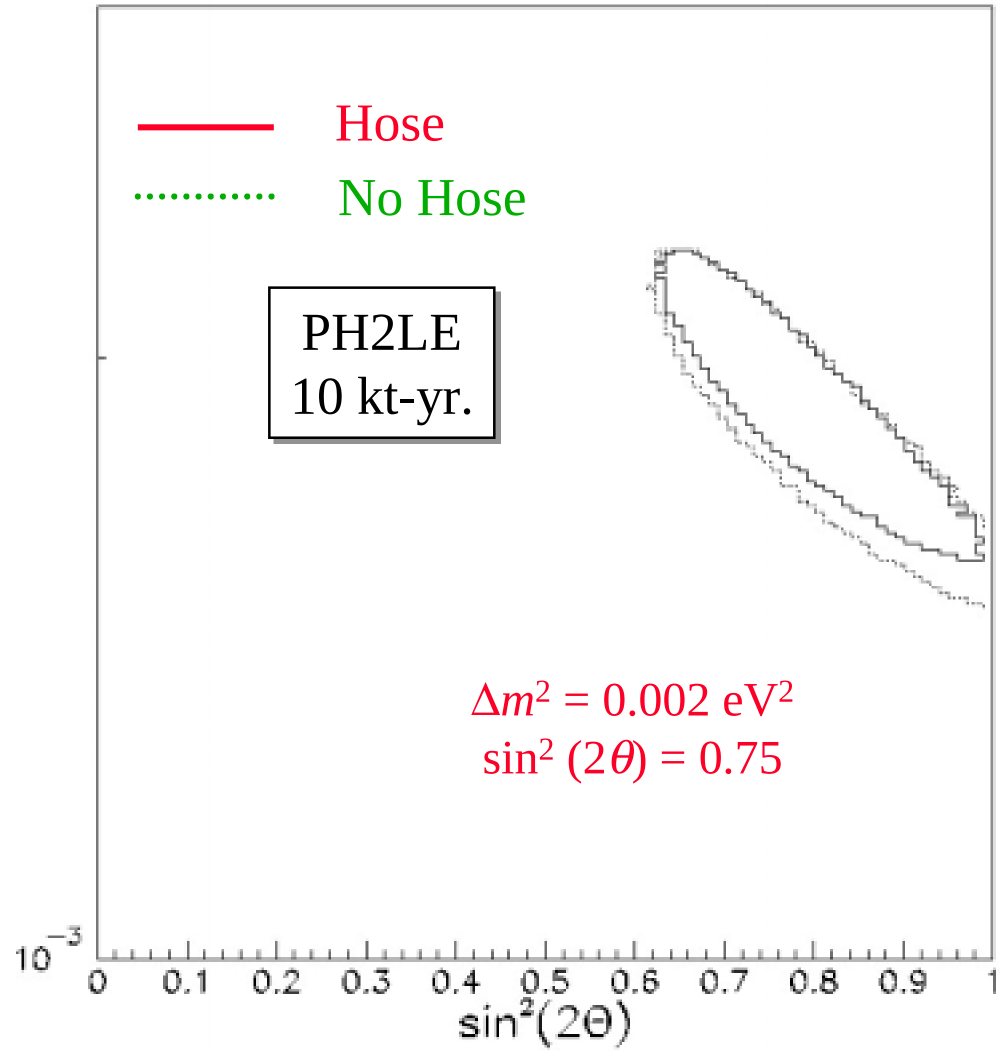
$\Delta m^2 = 0.001\ \text{eV}^2$
$\sin^2(2\theta) = 0.75$

- Increase in # of exp'ts with "4σ effect" with hose shows 25% more statistics important.
- Smaller drop in "4σ exp'ts" when systematics included shows systematics are important.

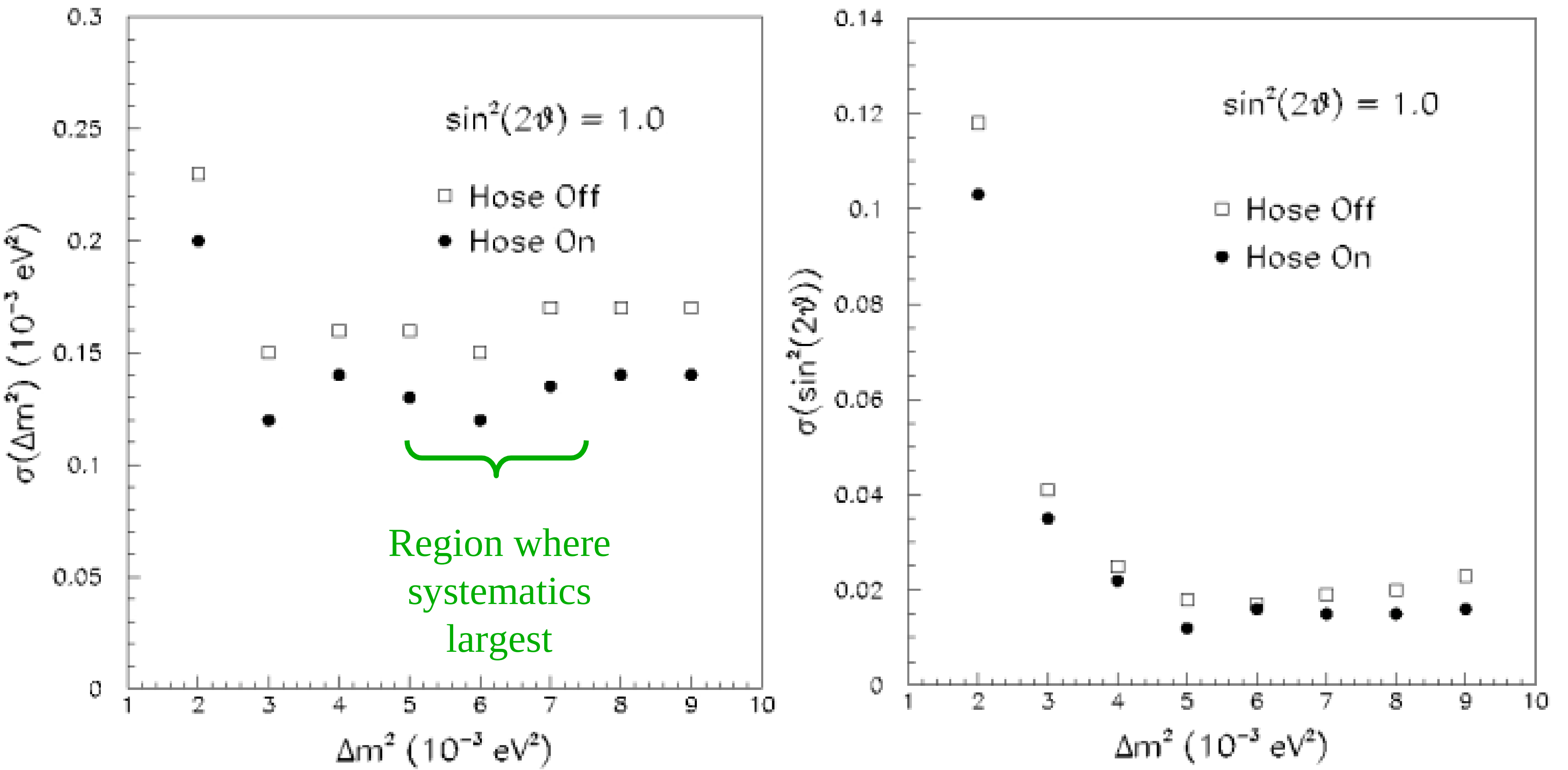


Improved Oscillation Fits

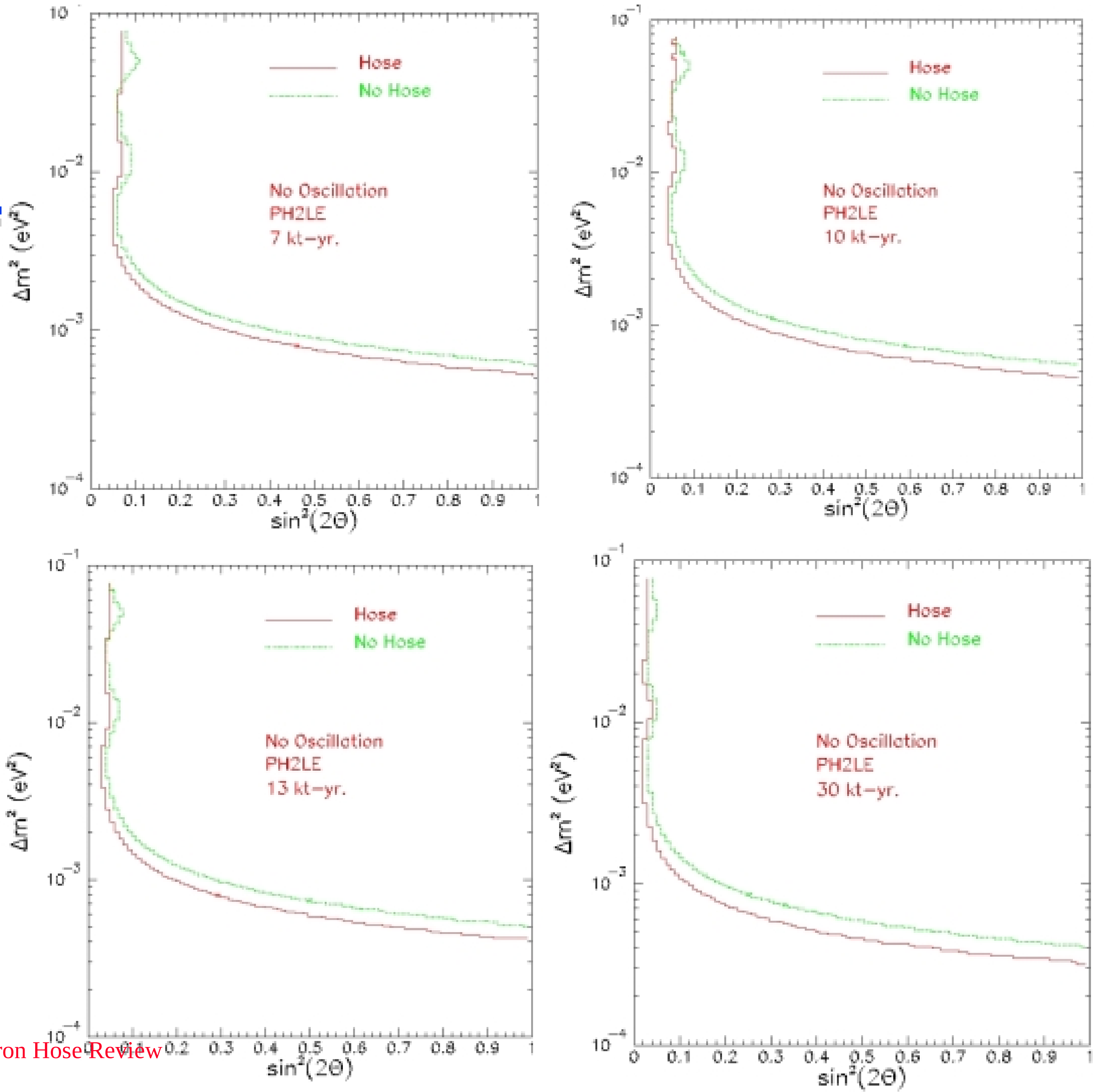




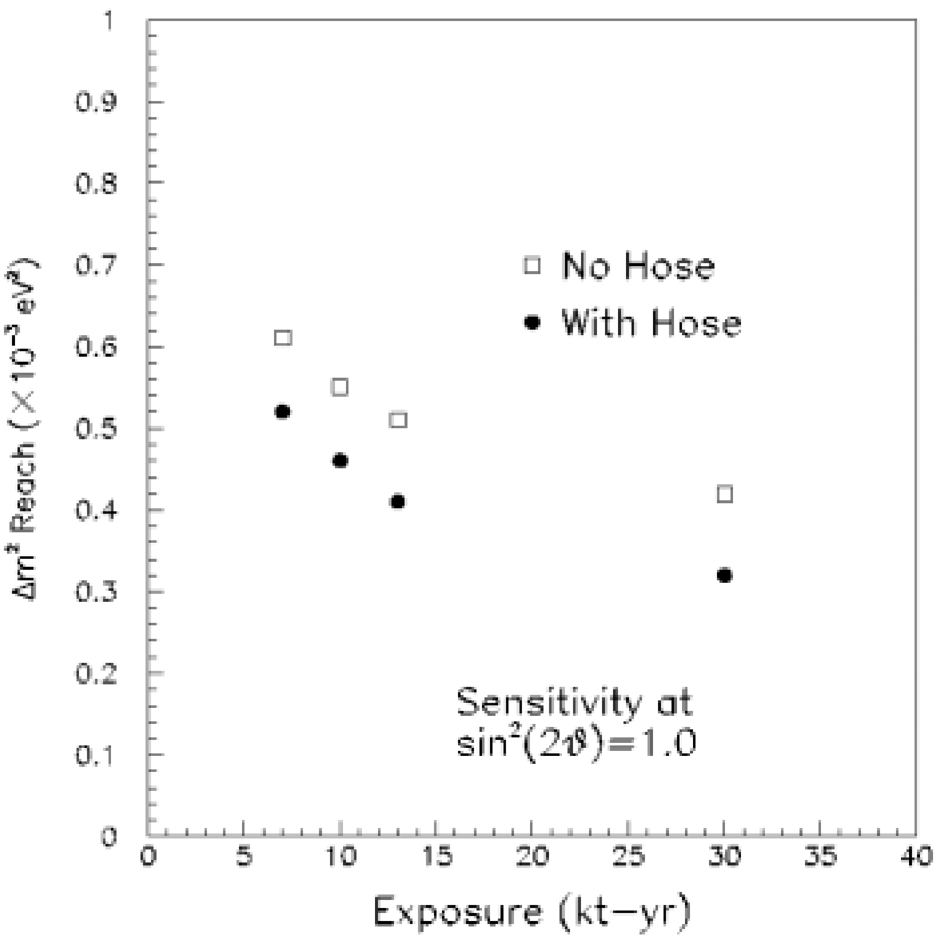
Fit Resolutions

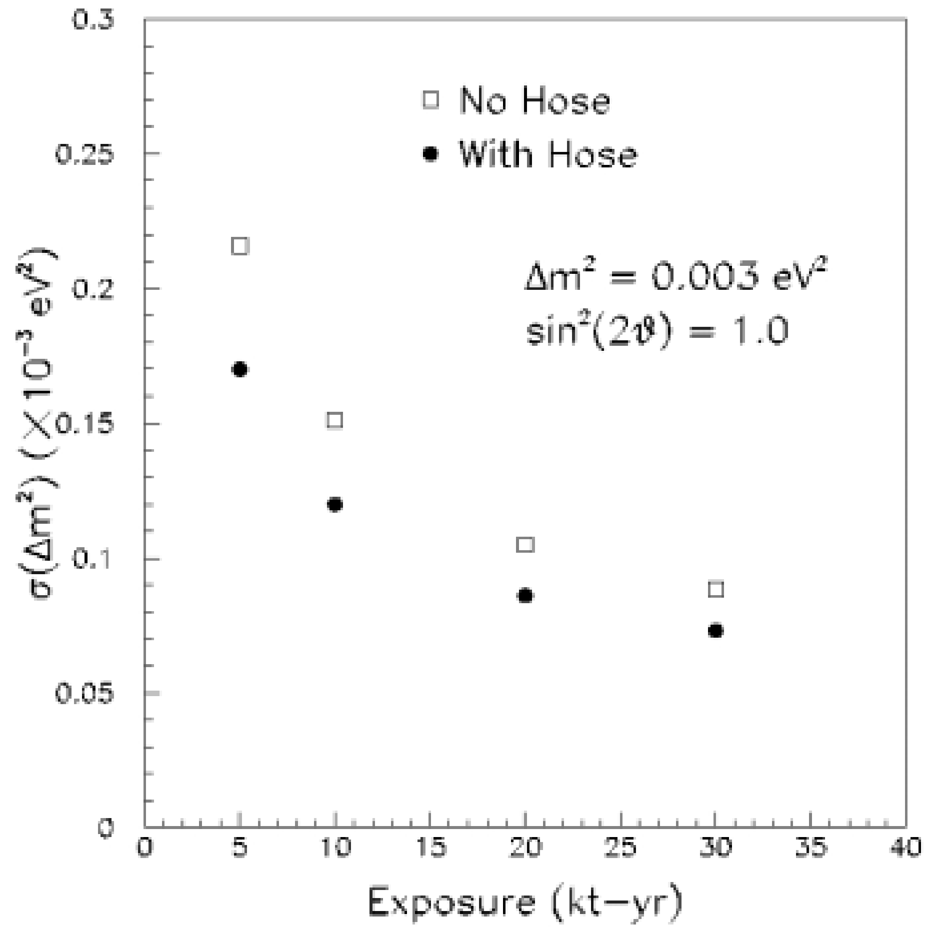


Behavior *vs.* Time



Hose Payoff *vs.* Time





Are We Sensitive to New Physics?

- Only way to confirm ν_μ–ν_τ oscillations is to verify $\sin^2(1.27\Delta m^2 L/E_\upsilon)$ shape.
- Alternate models to explain atmospheric ν_μ?
- Barger *et al.*: neutrino decay?

$$\nu_\mu = \nu_2 \sin\theta + \nu_3 \cos\theta$$

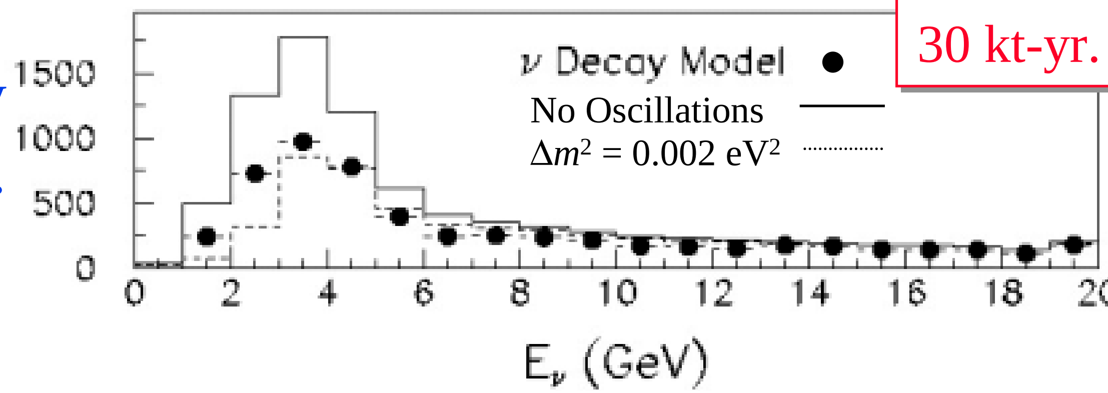
and $\nu_2 \rightarrow \nu_i X$ mass state

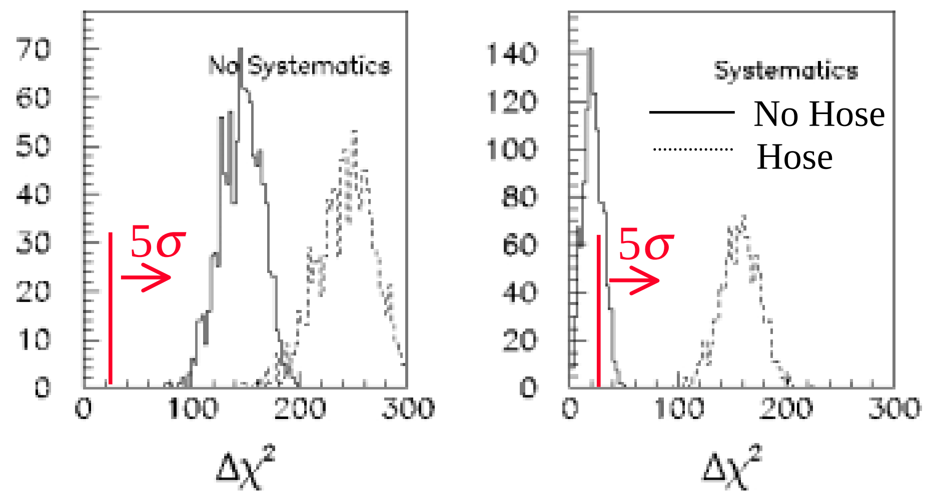
$$P(\nu_\mu \rightarrow \nu_\mu) = [\sin^2\theta + \cos^2\theta e^{-\alpha L/E}]^2$$

$$\alpha = m/\tau$$

- Fits SK if $\alpha = 1/63$ km/GeV and $\sin^2\theta = 0.3$

PH2LE
30 kt-yr.





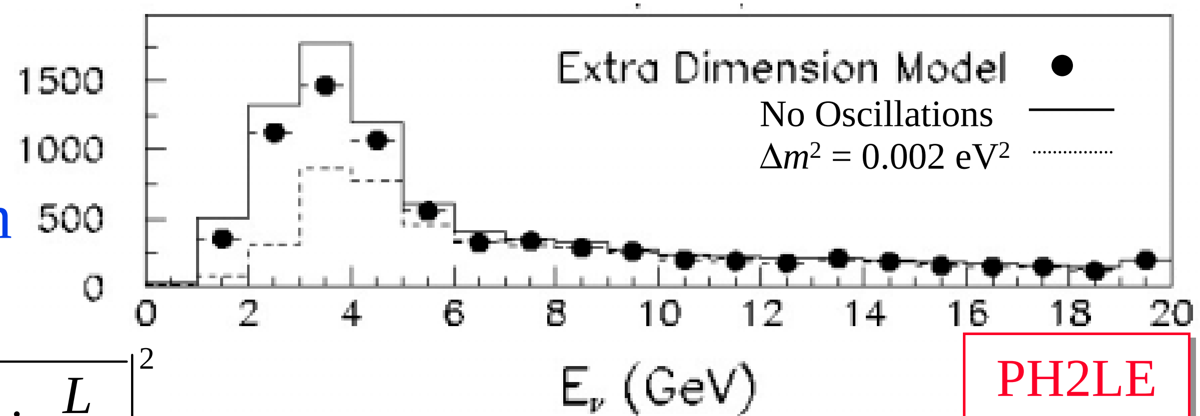
$\Delta\chi^2 \equiv \chi^2$ (osc. fit) - χ^2 (nu decay)

New Physics (II)

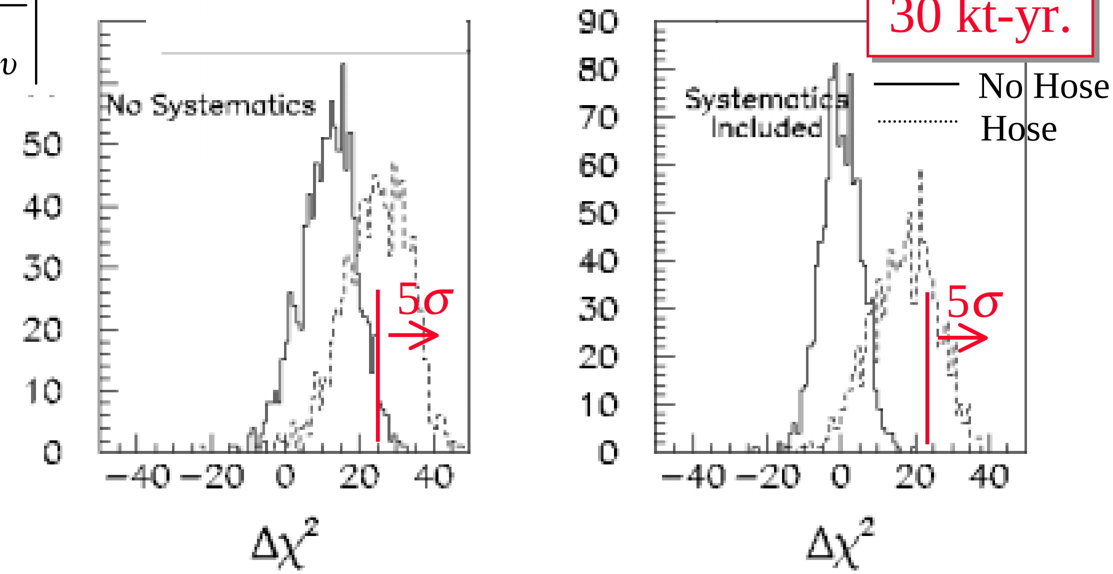
- Barbieri *et al.*, ν_μ's oscillate with Kaluza-Klein states that live in extra dimensions:

$$P(\upsilon_\mu \to \upsilon_\mu) = \left|1.0 - erf\,\frac{\pi\xi^2}{R}\sqrt{-i\frac{L}{2E_\upsilon}}\right|^2$$

- $\xi = mR$. ξ^2/R ~0.01 fits Super Kamiokande data.
- Systematics at low E_υ very important!!



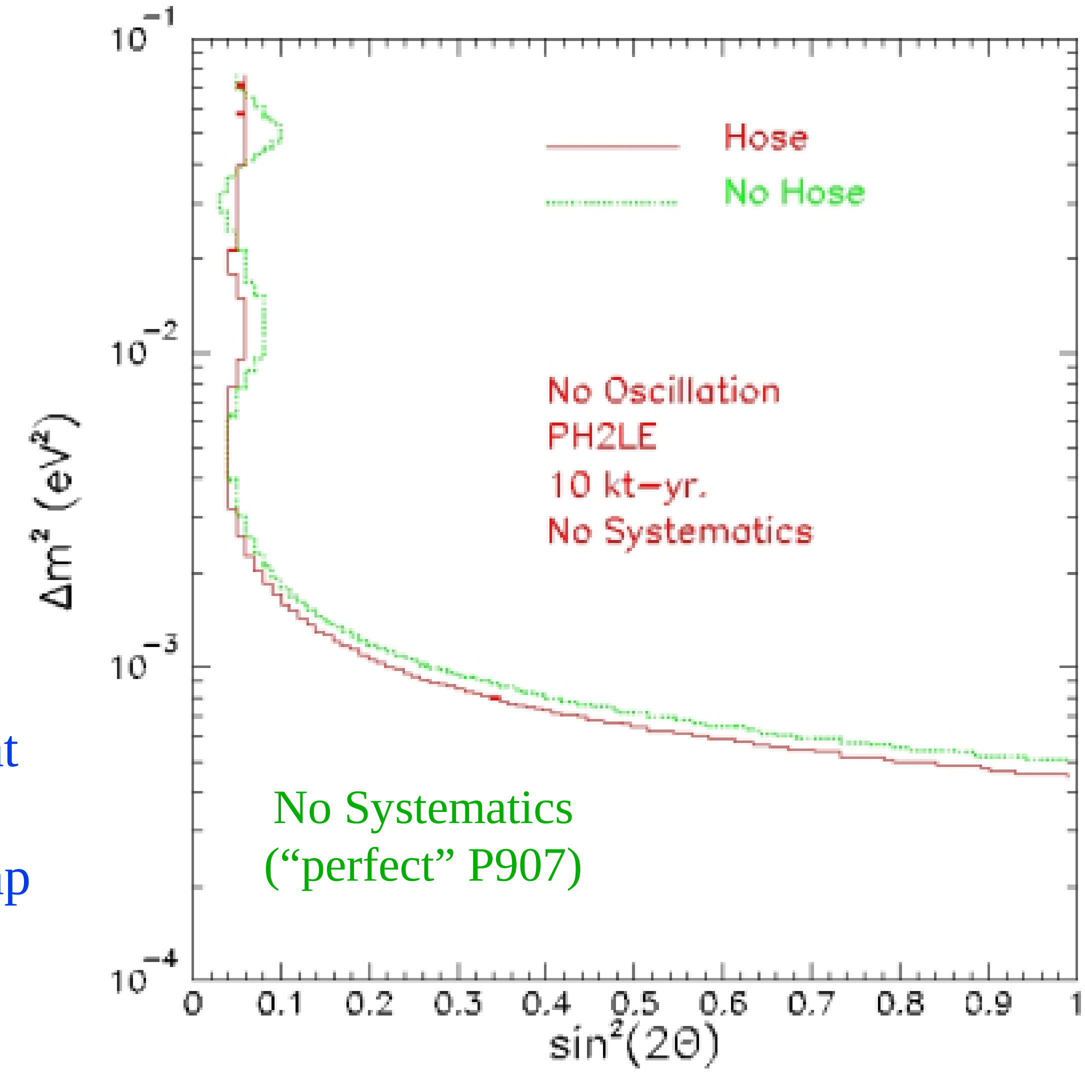
PH2LE
30 kt-yr.



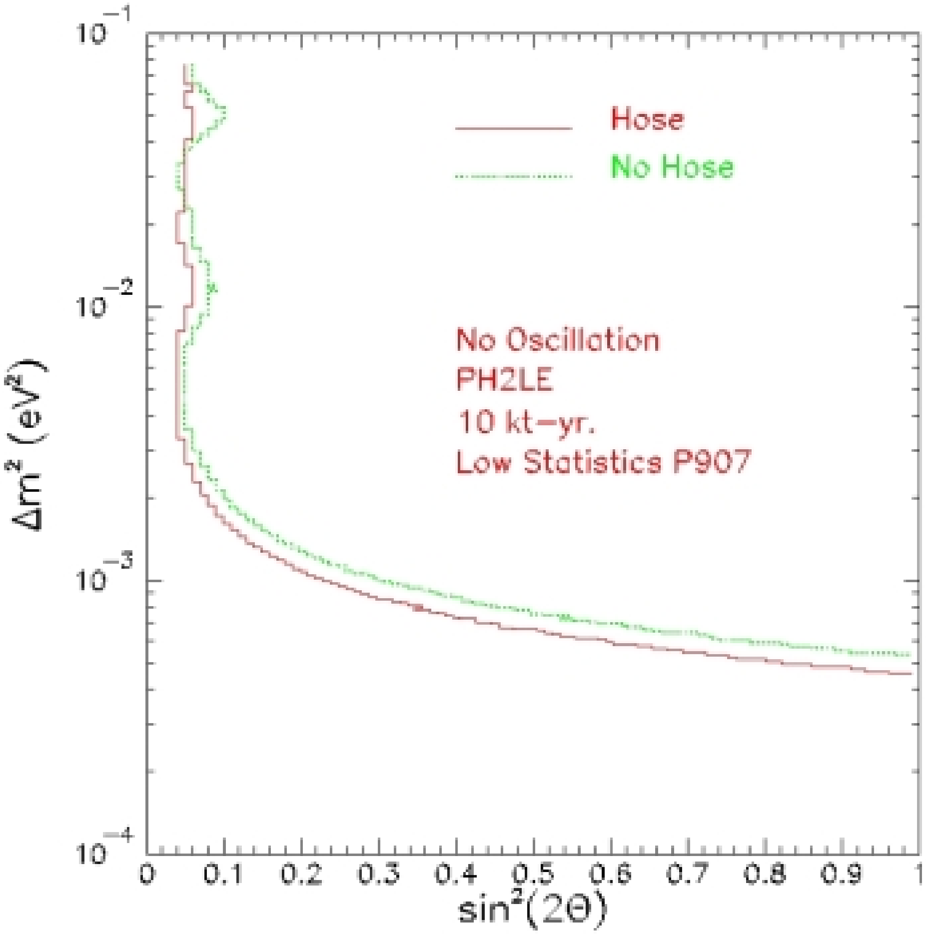
$\Delta\chi^2 \equiv \chi^2$ (osc. fit) - χ^2 (xtra dim.)

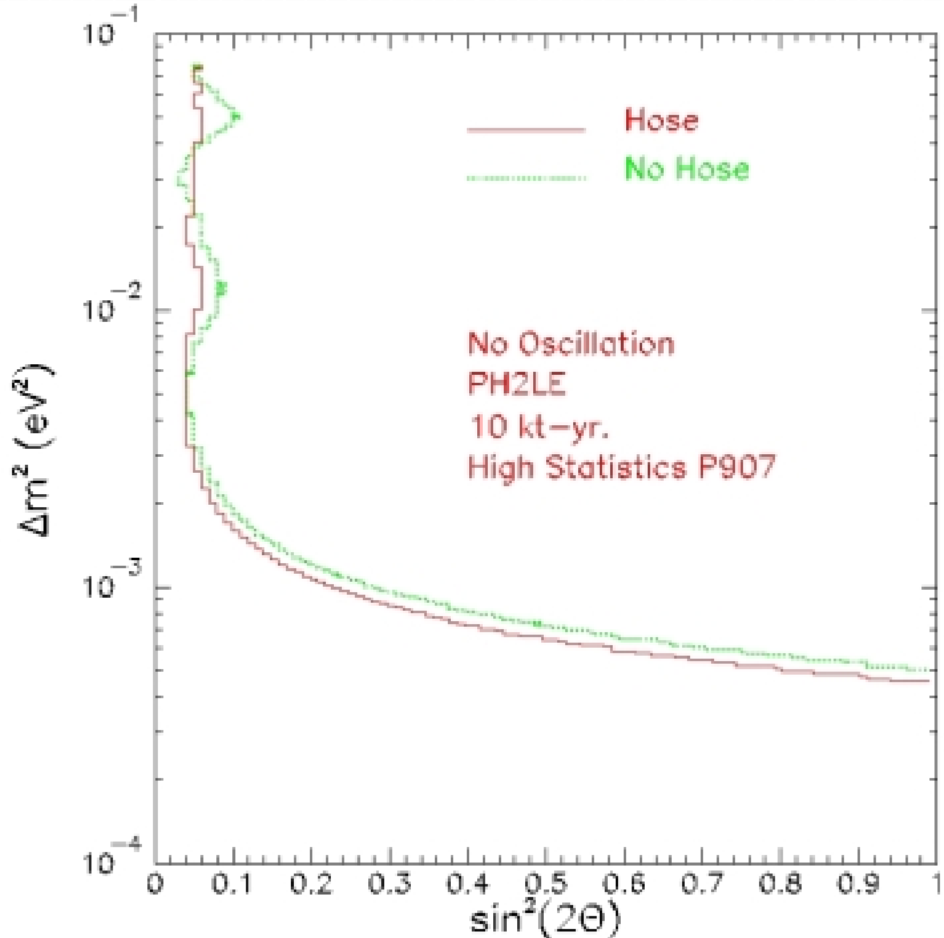
Comment on P907

- P907 would also reduce uncertainties in υ flux.
- We considered three prototypes:
  - »"perfect" P907
  - »"low statistics" (10^6 POT)
  - »"high statistics" (10^7 POT)
- Perfect case equivalent to doing fits with no systematic error incorporated in fits.
- We did analyses in a way that slightly oversells P907's performance (assume full map of p,p_T space).



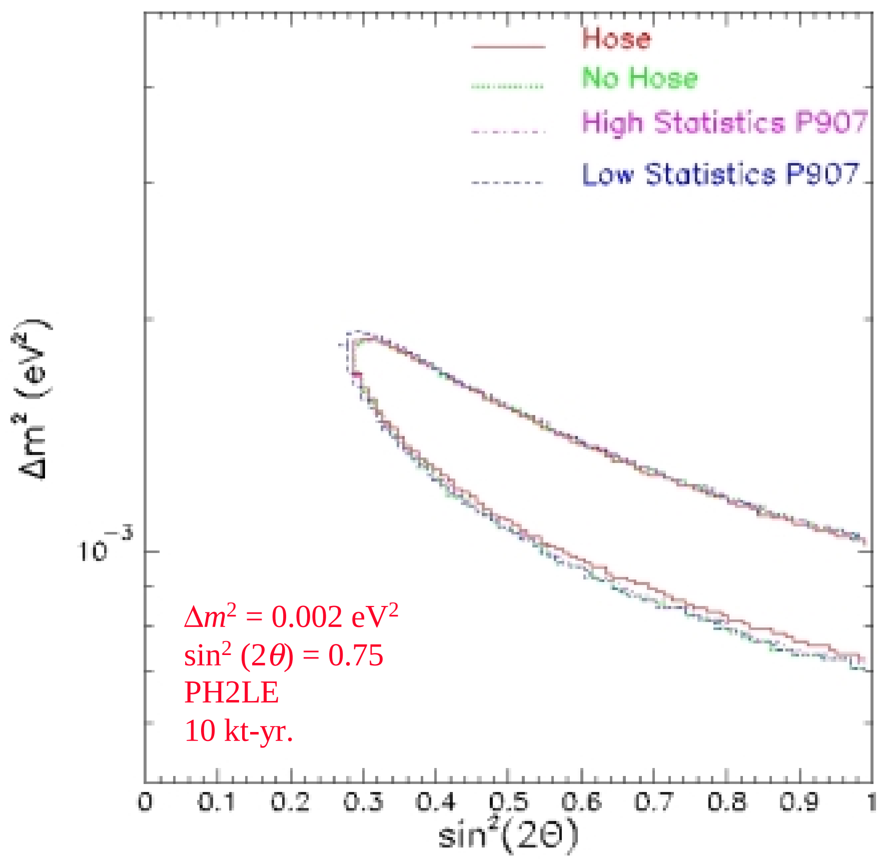
P907 Effect on Limits

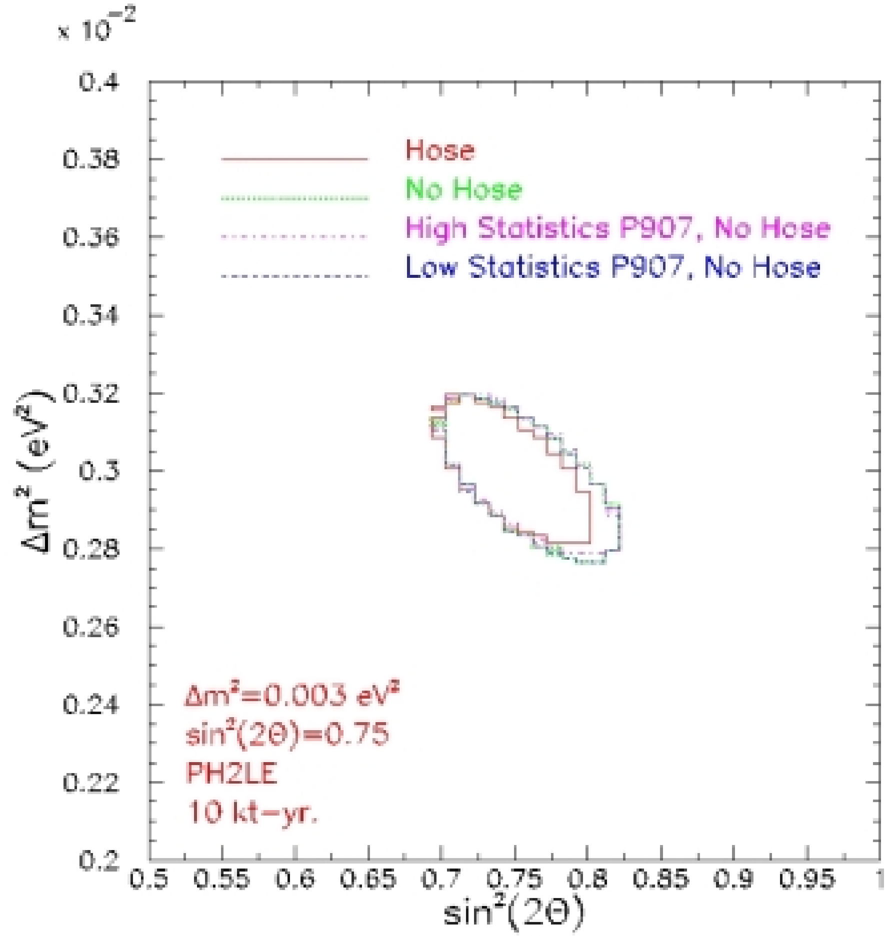




- A "P907" with 10^7 POT is essentially "perfect" (if it really mapped out all of p, p_T)

P907 Effect on Parameters

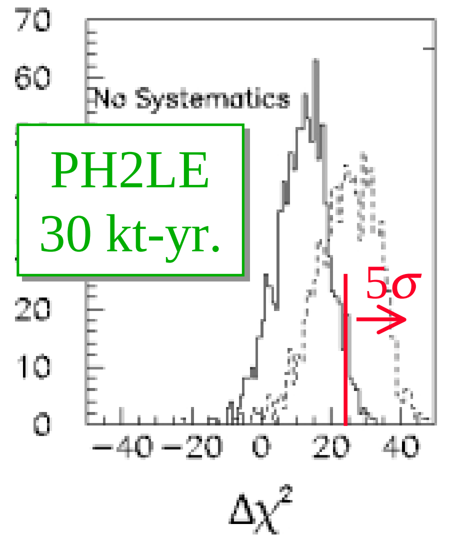




- Pretty hard to see much difference in these plots, possible residual effects of statistics with the hose.

P907 and New Physics

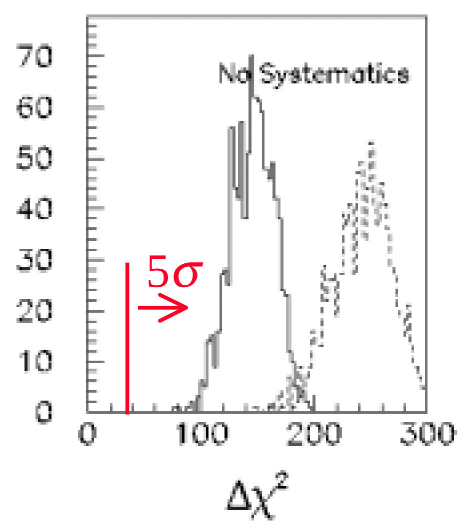
Extra Dimensions



P907 only
P907+Hose

- We considered only the "perfect P907" case here.
- Equivalent to fits with no systematic uncertainties.

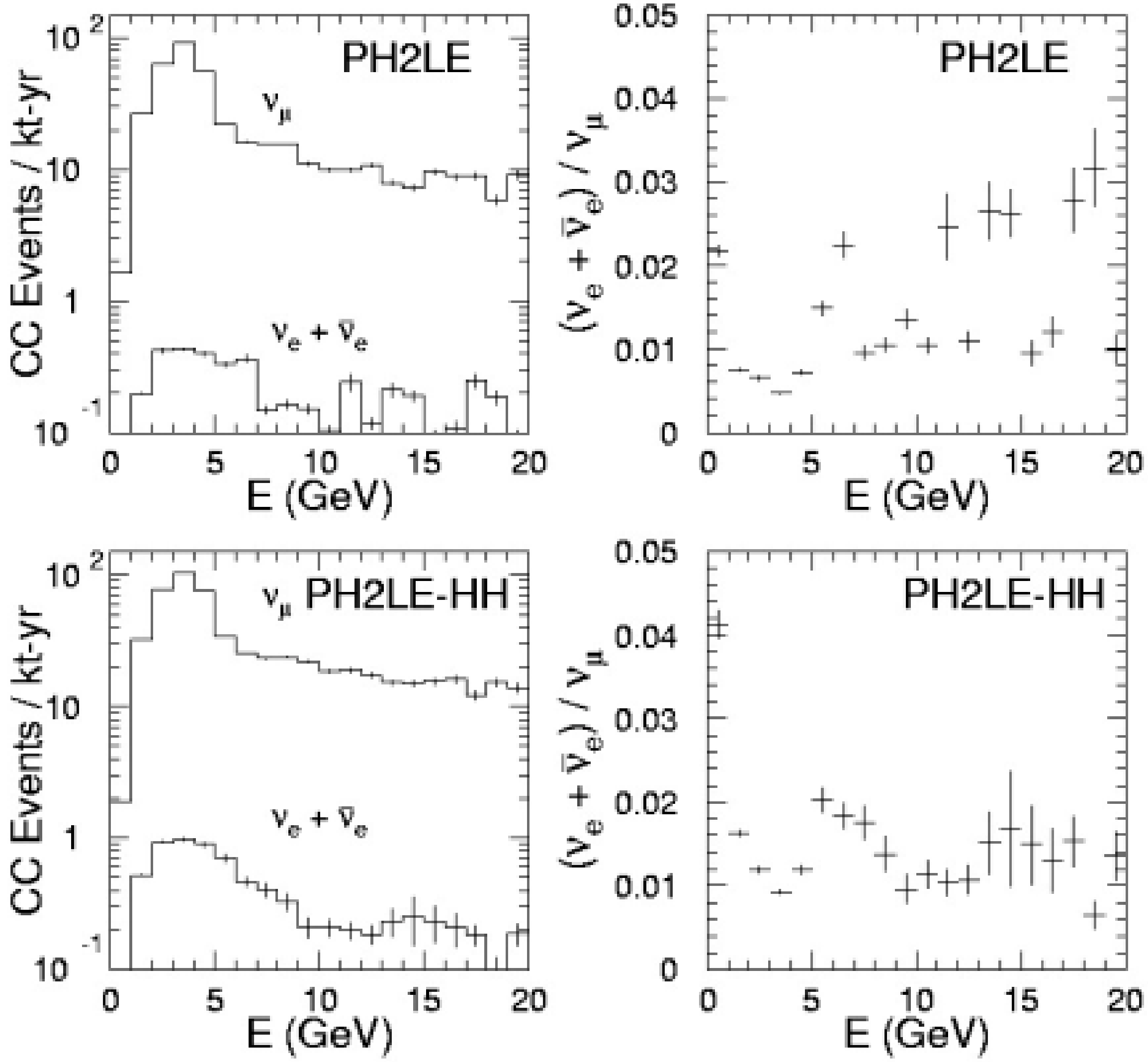
Neutrino Decay



- Hose is still better for some models.

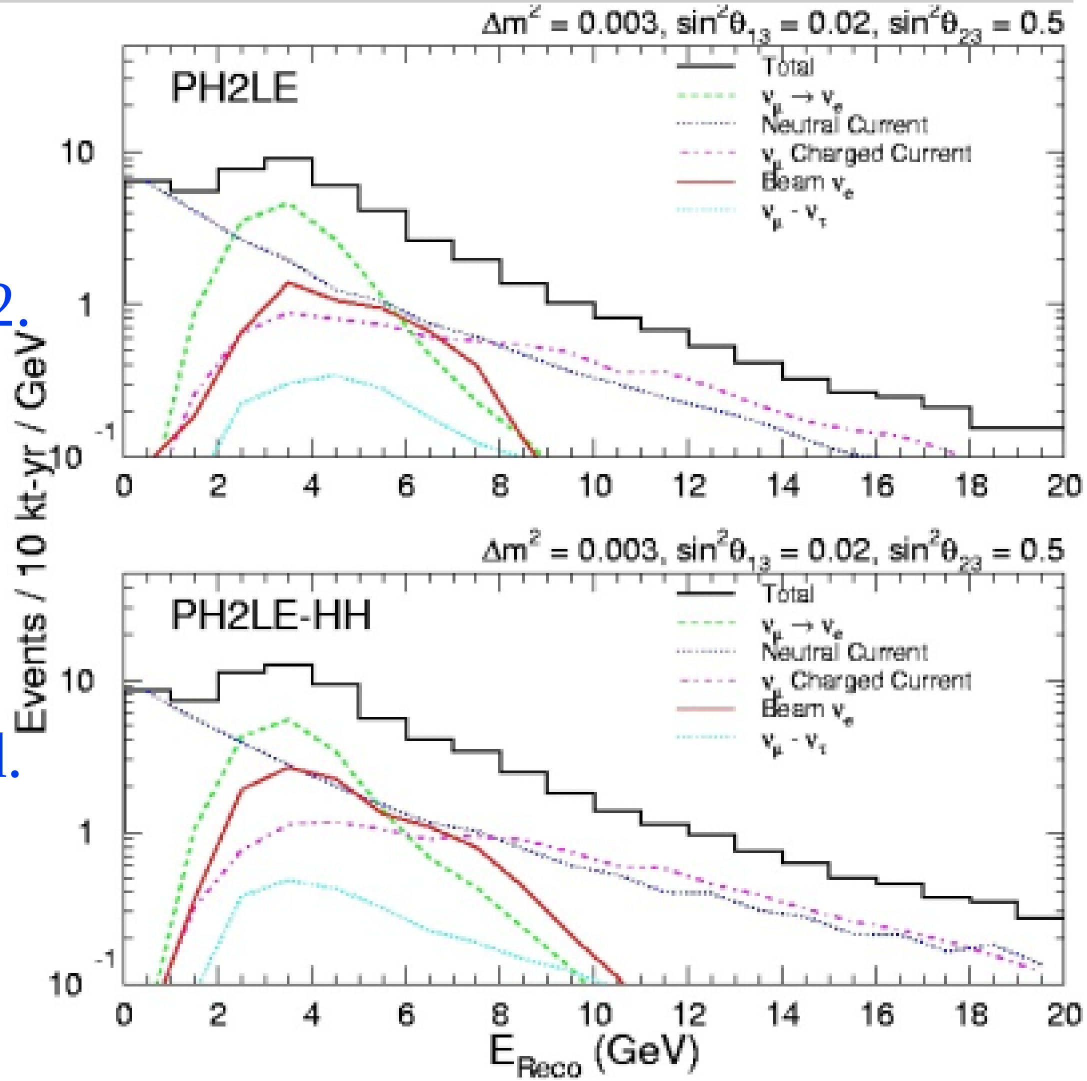
υ_μ - υ_e Oscillations

- Hose focuses muons as well as pions.
- Beam υ_e rate up by ~ $\times$2.
- Could limit sensitivity for U_{e3}?
- Note that υ_μ rate increased by 1.3 in peak.



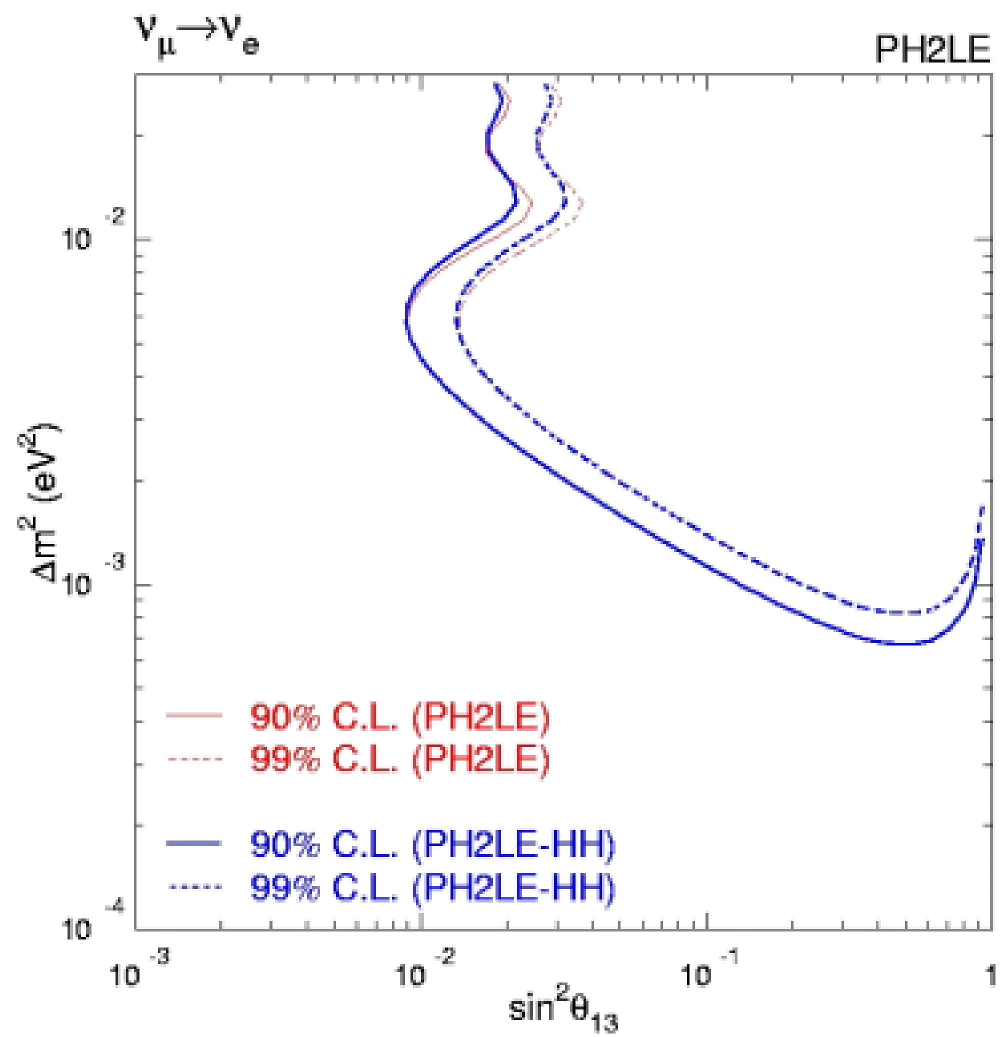
υ_e Backgrounds

- Beam υ_e contamination × 2.
- Dominant υ_e backgrounds:
  - »Neutral current events.
  - »Beam υ_e.
  - » υ_μ charged current.
- Non-trivial to model the neutral current background.



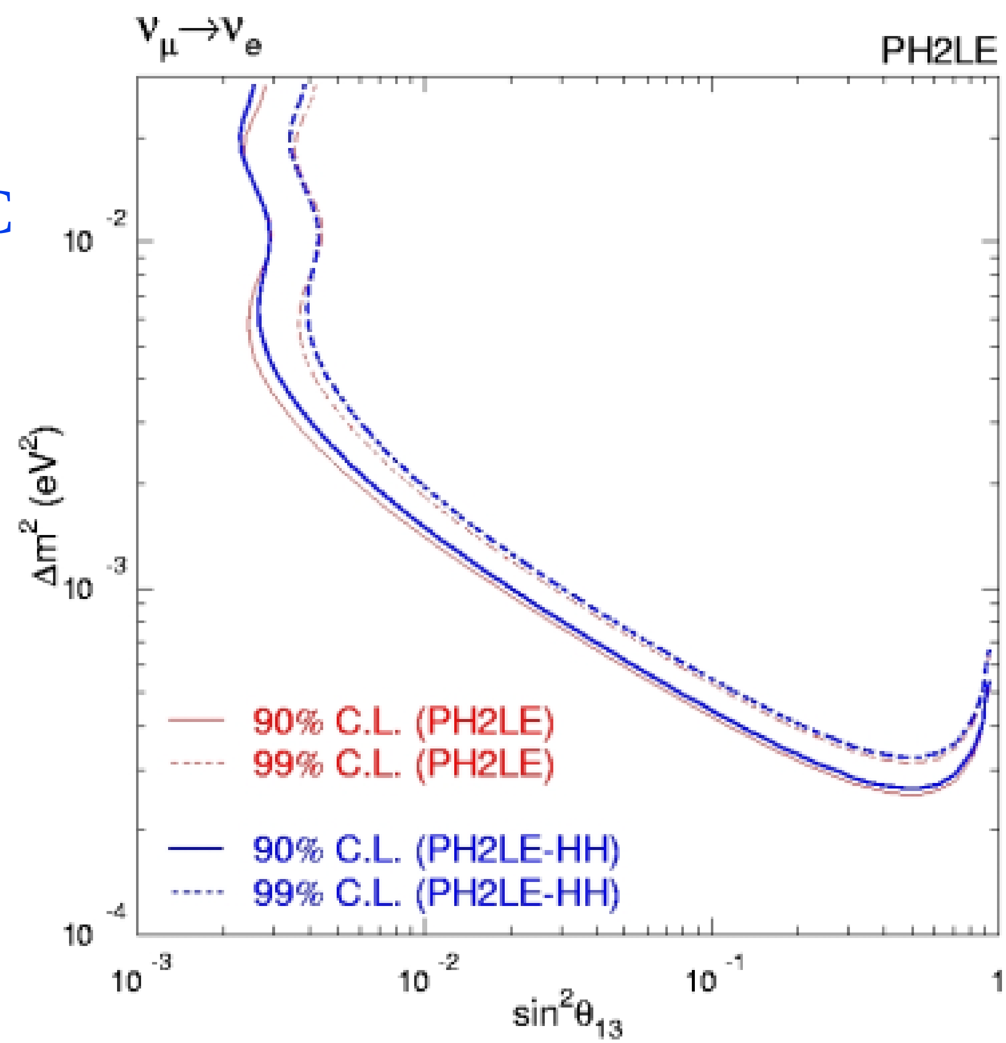
υ_μ - υ_e Oscillations (cont'd)

- Increase υ_μ flux by 1.3
- Background goes up by 1.3 - 2.0 (dep. on source)
- Our "sensitivity" signal/$\sqrt{\text{background}}$ almost unchanged
- Change in $\sin^2\theta_{13}$ reach negligible: 1.6×10^{-2} @ $\Delta m^2 = 0.003$ eV^2.

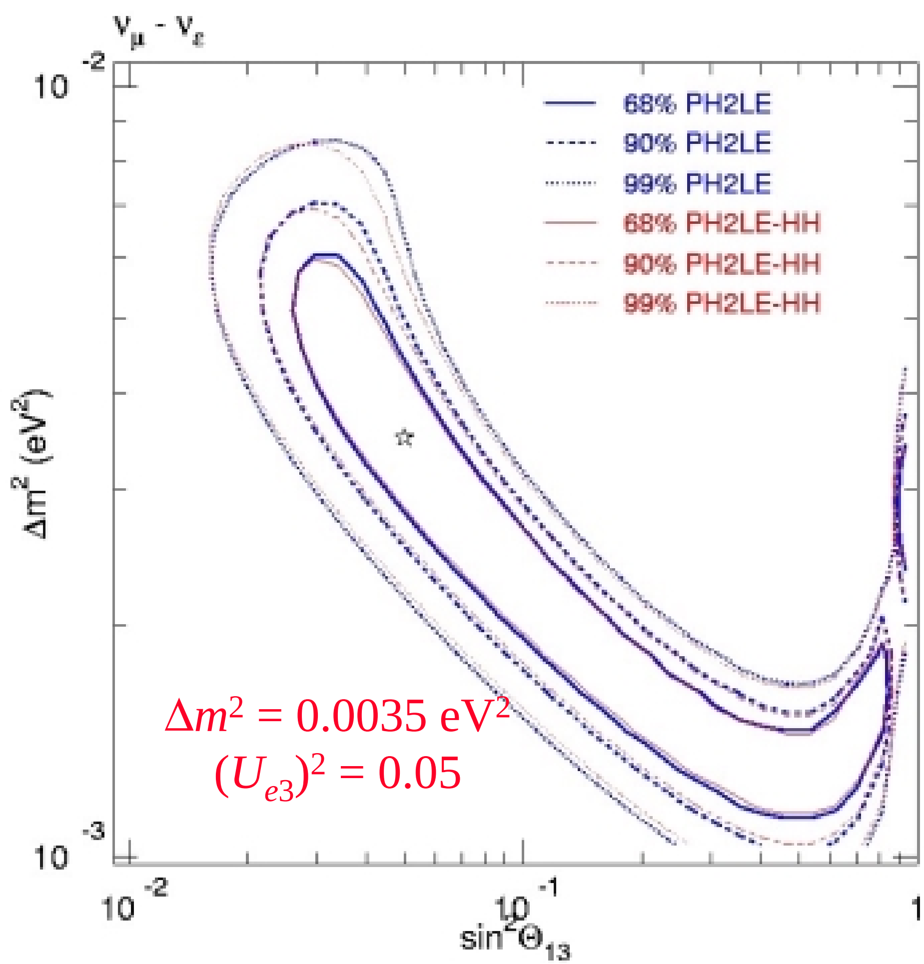


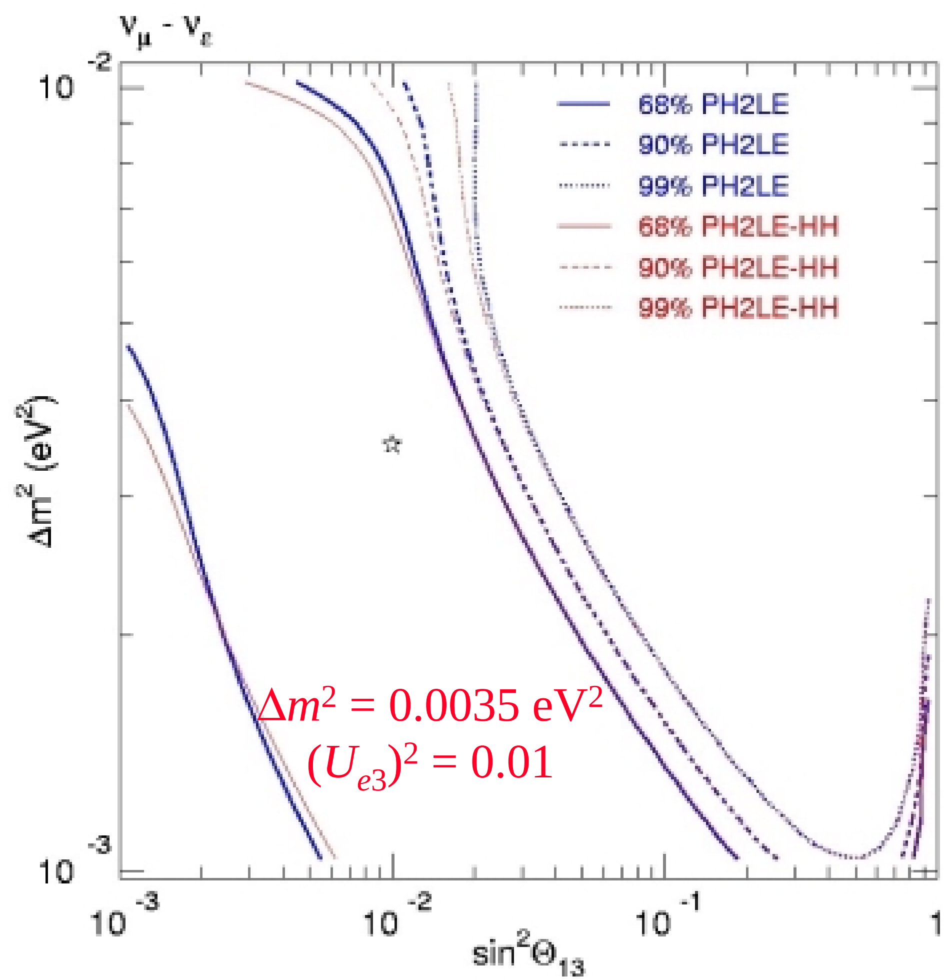
If Assume Ideal Efficiencies

- Even if suppose we were perfectly able to reject NC backgrounds, hose would not hurt too much.
- signal/$\sqrt{\text{background}}$ almost unchanged
- Change in $\sin^2\theta_{13}$ reach $3.5\times10^{-3} \rightarrow 3.0\times10^{-3}$



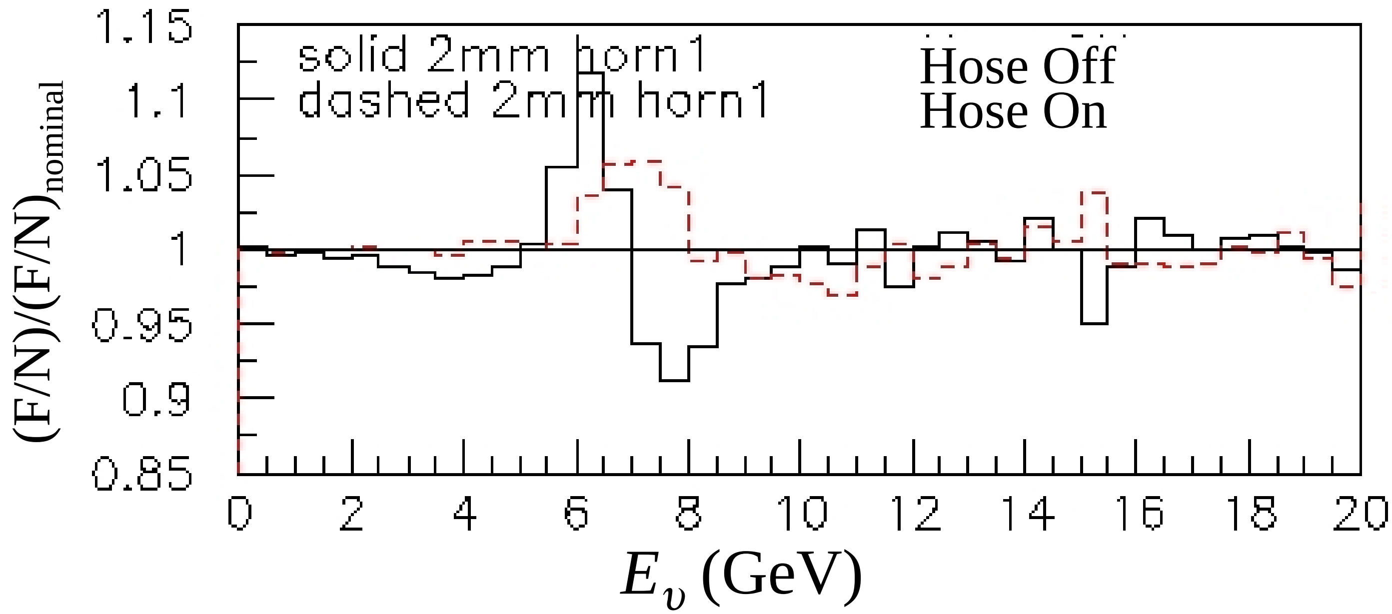
If we had a υ_e signal…





Relaxing Other Tolerances

- Increased focusing of hose means horn tolerances less stringent:



- Horn Current variation: ±1.0% → ±1.5%;

  Eccentricity Horn 1 in. conductor: 0.08 mm → 0.10 mm

Conclusions

- 25% more flux does affect ultimate sensitivity.
- Hadronic production systematics affect sensitivity, even for 10 kt-yr. exposures of MINOS.
- Systematics will be ultimate limitation to a long (~ 4-6 year) run of MINOS
  - »Limits possible observation of "new physics"
  - »Limits our ultimate "reach"
- Comparison to P907 experiment
  - »Both do a good job correcting hadronic production uncertainties.
  - »Hose increases statistics, P907 does not
    ⇒ slightly better sensitivity with hose
  - »Hose decreases sensitivity to inputs, P907 better measures inputs
    -- Good to have both.
  - »Hose important for other beam-related tolerances
- Hose only slightly decreases sensitivity of υ_e search.