# A Combined BNL and FNAL Long Baseline Experiment

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# Outline:

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- Baselines Considered.
- NuMI and AGS Beams.
- Detector and Run Time Assumptions.
- Oscillation Probabilities and,
- Expected Event Rate Distributions.
- Conclusions and Future Work.

# Baselines

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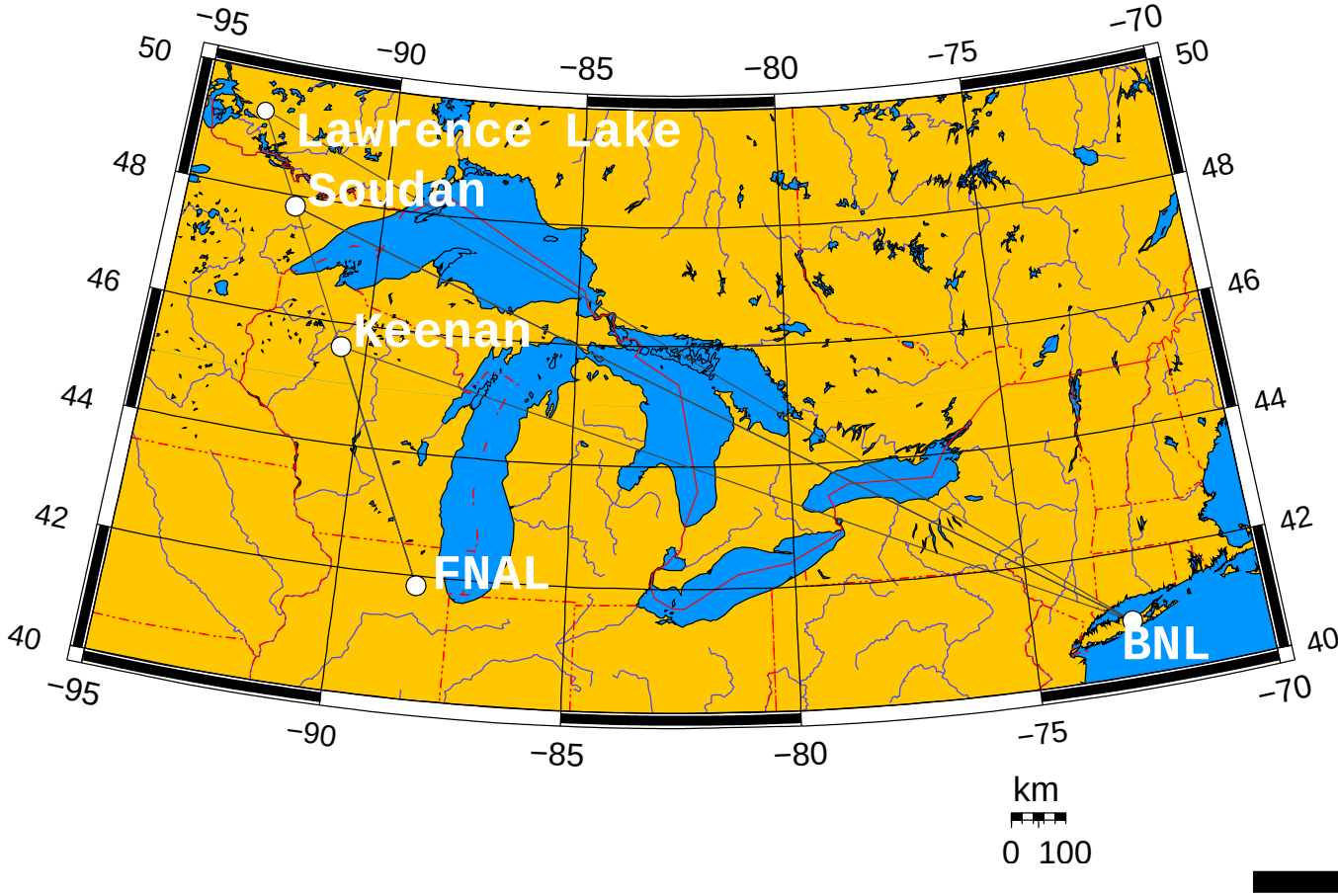
| | Keenan, WI | Soudan, MN | Lawrence Lake, ON |
|---|---|---|---|
| FNAL | 458 km | 735 km | 911 km |
| BNL | 1522 km | 1711 km | 1840 km |



# FNAL NuMI Beam

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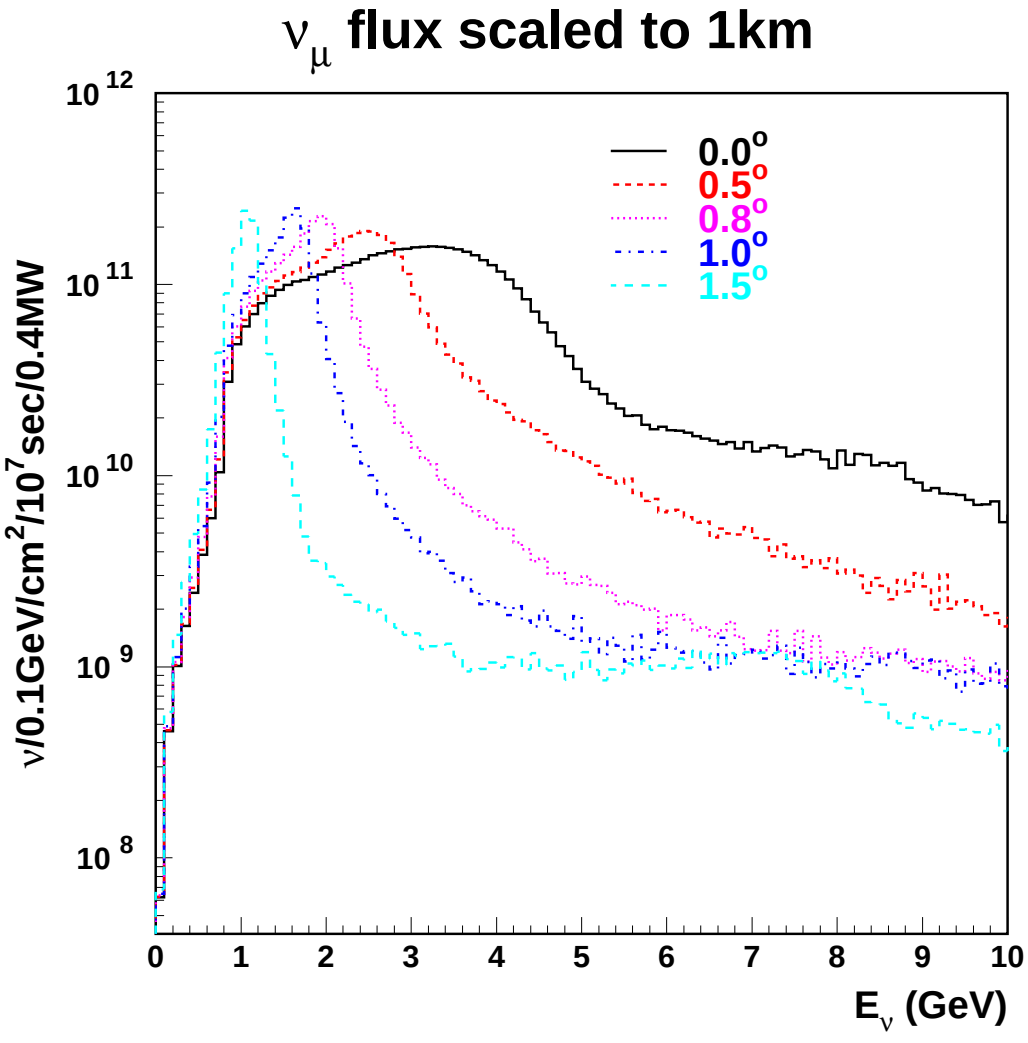


- 0.4 MW, 120 GeV protons
- GNUMI simulation
- Must target $\Delta m^2$:

@ $\Delta m^2_{atm} = 2.5 \times 10^{-3}$

| Angle (deg) | $E_{peak}$ (GeV) | $L_{osc}$ (km) | Location |
|---|---|---|---|
| 0.0 | 3.0 | 1500 | |
| 0.5 | 2.5 | 1250 | |
| 0.8 | 2.0 | 1000 | (L. Lake) |
| 1.0 | 1.5 | 750 | (Soudan) |
| 1.5 | 1.0 | 500 | (Keenan) |
| 2.0 | 0.7 | 350 | |

# BNL AGS Beam

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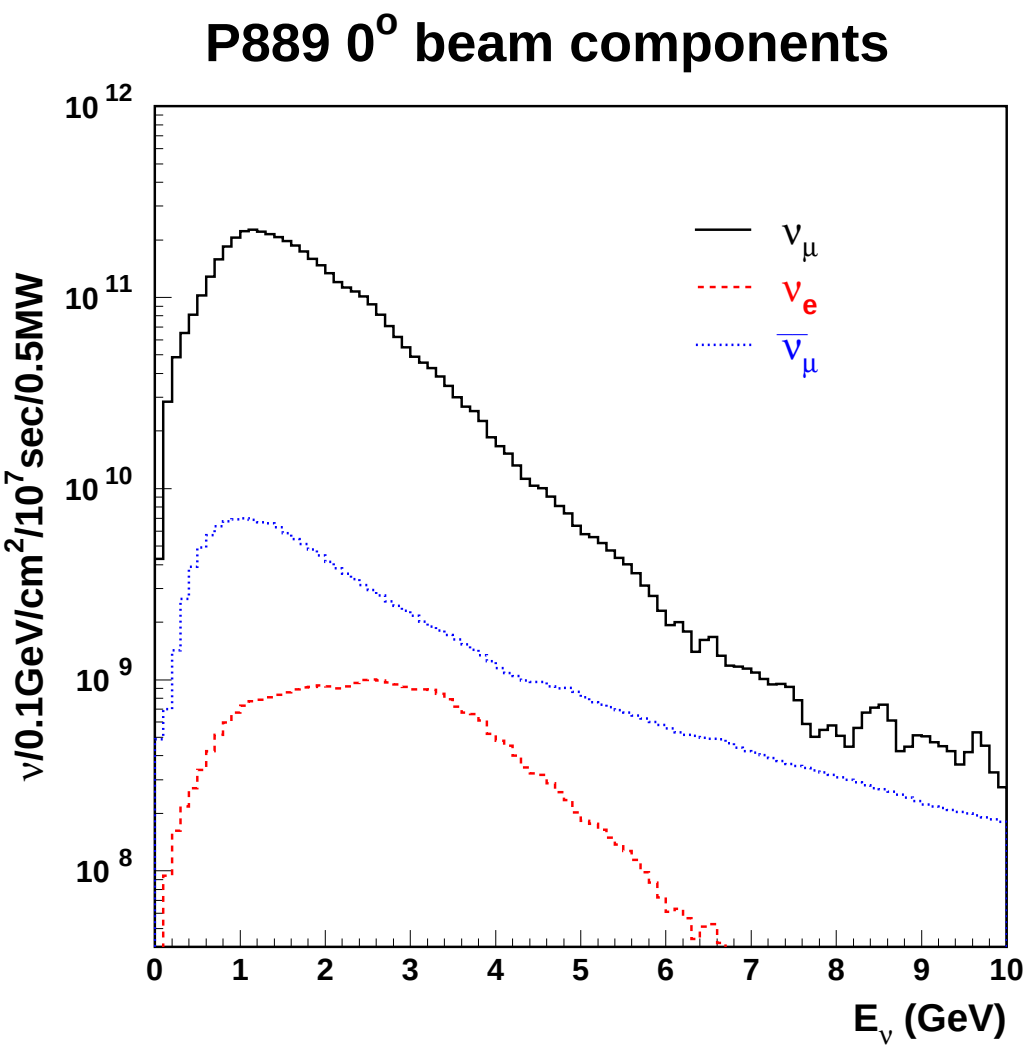


- On-axis P889 beam
- Wide $\Rightarrow$ covers range of $\Delta m^2$
- Harder spectrum, low tail.
- These spectra:
  0.5 MW, 28 GeV protons
- Upgrade AGS to **1.5 MW** $\longrightarrow$

# AGS Upgrade to 0.5 and 1.3 MW

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AGS upgrade costs, (Bill Weng, BNL. Letter of Intent to BNL, 2002.)

| Phase I (AGS at **1 Hz**) 538 kW $\Rightarrow 1.2 \times 10^{21}$ ppp. | $\$10^6$ |
|---|---|
| 300 MeV SRF (116 MeV to 400 MeV) | 35 |
| 2.5 GeV AGS accumulator ring | 25 |
| AGS Injection at 2.5 GeV | 5 |
| Total for Phase I | **65** |
| Phase-II (AGS at **2.5 Hz**), 1344 kW $\Rightarrow 2.9 \times 10^{21}$ ppp. | |
| AGS power supply | 32 |
| AGS RF upgrade | 8.6 |
| Booster Power Supply | 5.5 |
| AGS Collimation and Shielding | 8.0 |
| Total for Phase-II | **54.1** |

- **1.5 MW** assumed for this study.

# The BNL Hill (Mt. Palmer)

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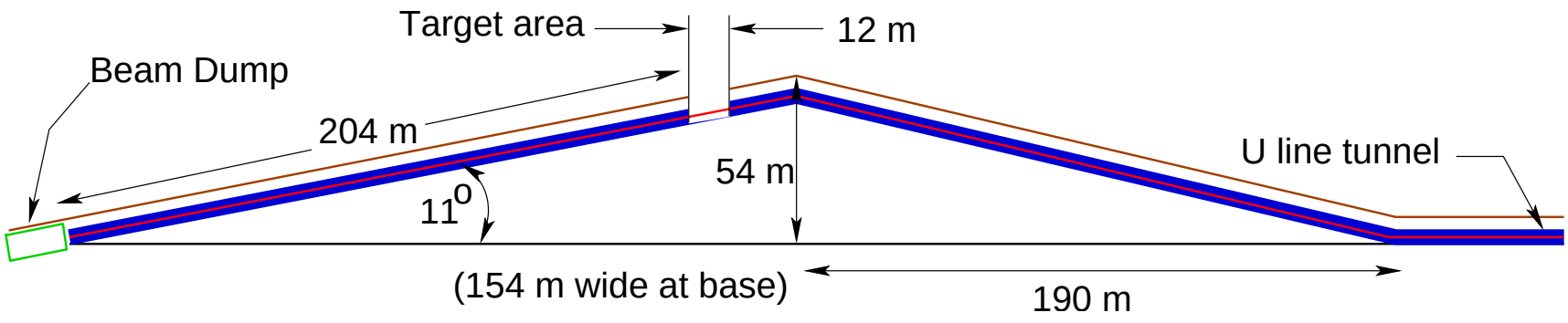
Use BNL-Homestake hill as *eg.*:




Numbers are for BNL-HS hill and $\nu$-beamline. Cheaper for lower dip angle.

| Item | Basis | 200 m ($\$10^6$) | 150 m ($\$10^6$) |
|---|---|---|---|
| Proton transport | RHIC injector | 11.85 | 11.85 |
| Target/horn | E889 | 3.0 | 3.0 |
| Installation/Beam Dump | New | 2.67 | 2.67 |
| Decay Tunnel | E889 | 0.45 | 0.45 |
| Conventional const. (hill) | New | 8.0 | 5.0 |
| Conventional const. (other) | E889 | 9.1 | 9.1 |
| Total | | 35.19 | 32.19 |

(Dana Beavis, BNL. Letter of Intent to BNL, 2002.)

# Detector and Run Time Assumptions

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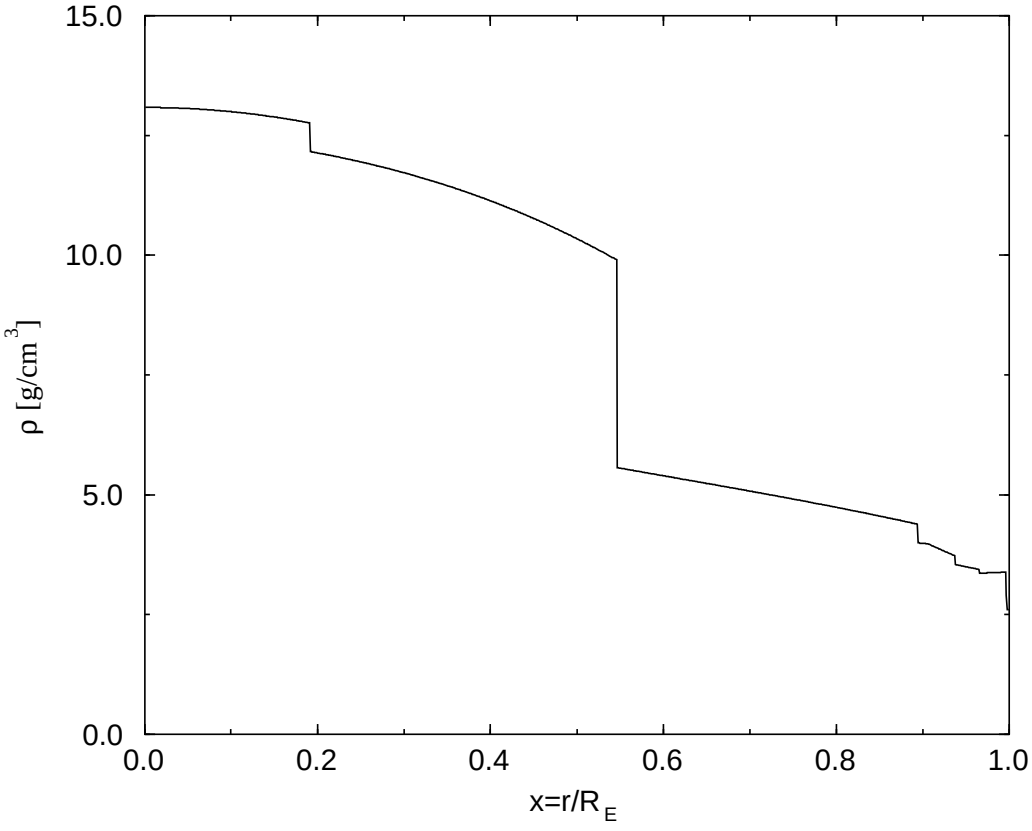
Assuming:

- 100 kTon (fiducial) water Cerenkov detector.
- SuperK-like reconstruction efficiencies and resolutions estimated from SK $\nu_{atm}$-MC:
  - $\varepsilon_{\mu,sr,cc,qe} = 80\%$. Not corrected for larger detector.
  - $\varepsilon_{e,sr,cc,qe} = 40\%$. Lower than typical due to tighter SR requirements.
  - $10\%$ energy resolution. Correct at 1 GeV, overestimate at > 1 GeV.
  - NC background to $\nu_e$ CC QE: generate matrix: $\left[E_{\nu_e,reco} \bigotimes E_{\nu_\mu,mc}\right]$, relating number of $\nu_\mu$ CC QE interactions with $E_{\nu_\mu,mc}$ to the number of $\nu_\mu$ interactions in that same energy bin which look like S.R. e-like events and reconstruct to $E_{\nu_e,reco}$. This makes use of the known $\nu$ direction.
- Running time: $5$ years, $1$ year = $10^7$ seconds.

# Oscillation probability calculation

Exact, numerical 3-$\nu$, 2-$\Delta m^2$-scale, matter effects with PREM earth density profile.




Test point:
LMA, max mix atm, medium $\theta_{13}$:

- $\sin^2 2\theta_{12} = 0.8$
- $\sin^2 2\theta_{23} = 1.0$
- $\sin^2 2\theta_{13} = 0.04$
- $\phi_{cp} = 0$
- $\Delta m^2_{sol} = 5.0 \times 10^{-5} eV^2$
- $\Delta m^2_{atm} = 2.5 \times 10^{-3} eV^2$

# $P(\nu_\mu \rightarrow \nu_\mu)$

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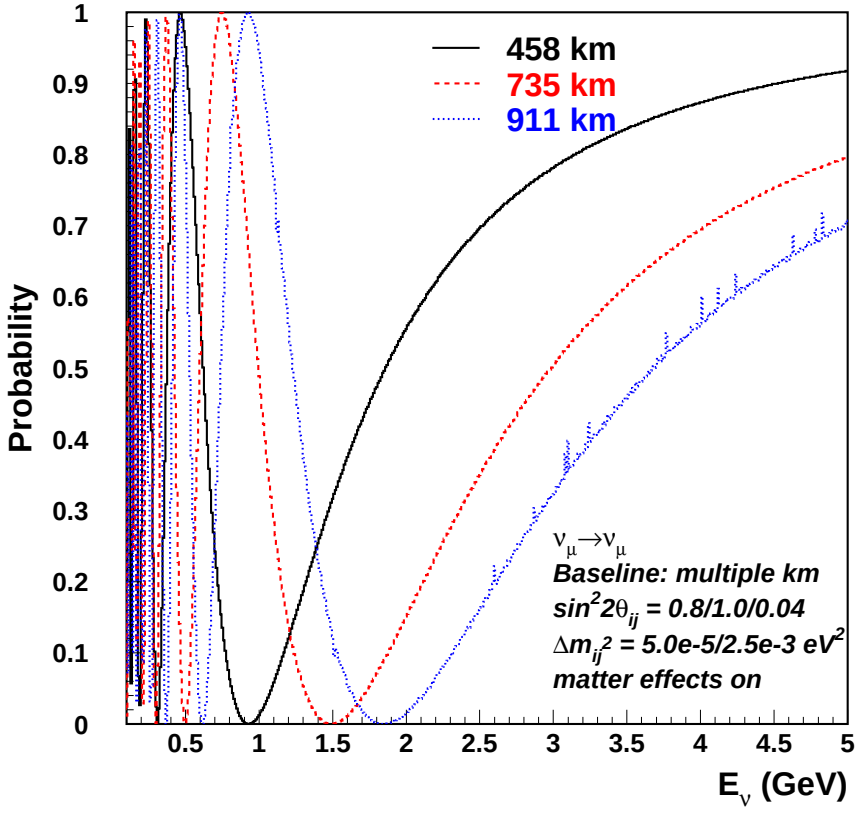
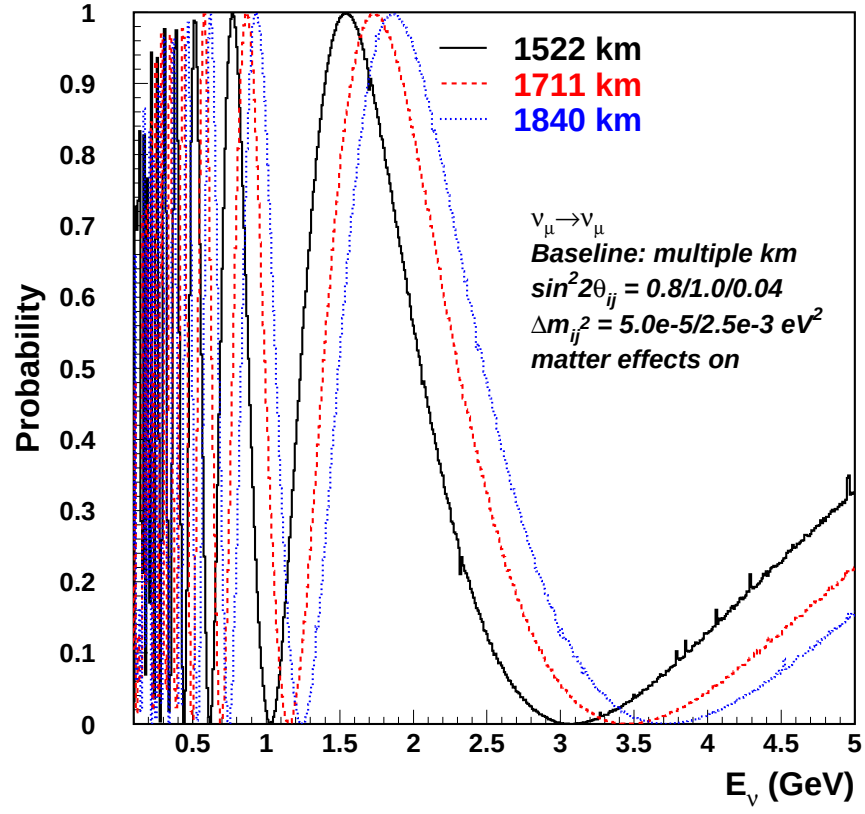
## $P(\nu_\mu \rightarrow \nu_\mu)$, FNAL baselines




## $P(\nu_\mu \rightarrow \nu_\mu)$, BNL baselines




- FNAL beam targets $\Delta m^2$ (to be *a priori* well known) and sees $1^{st}$ osc. node.
- BNL beam covers $2^{nd}$, part of $1^{st}$, just gets a little of the $3^{rd}$ osc. node and covers a range of $\Delta m^2$s.

# Keenan event rates - $\nu_\mu \rightarrow \nu_\mu$ Disappearance

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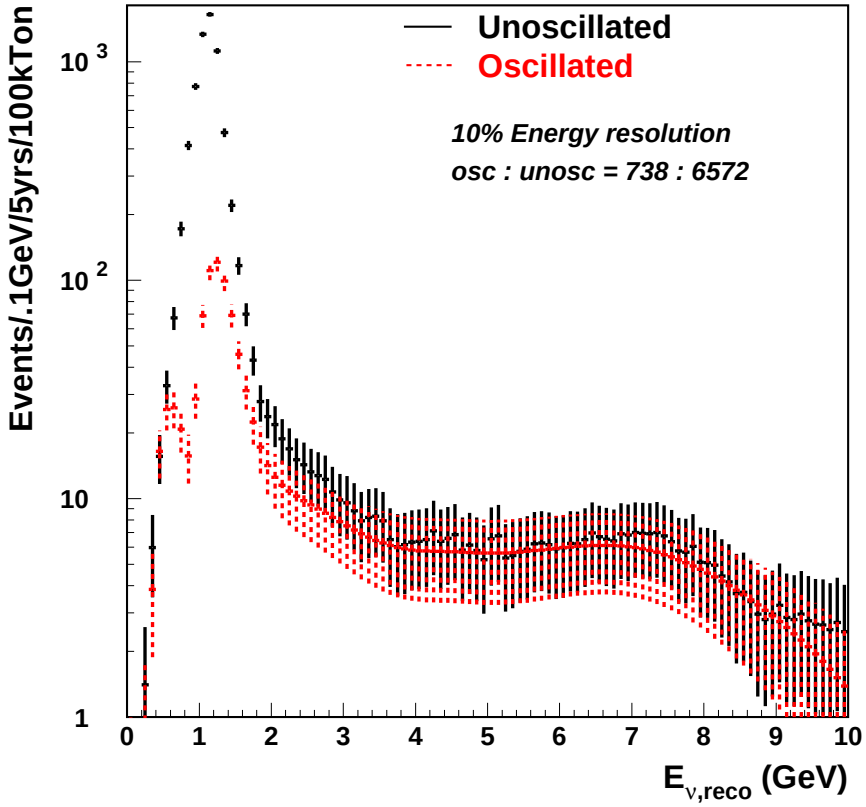
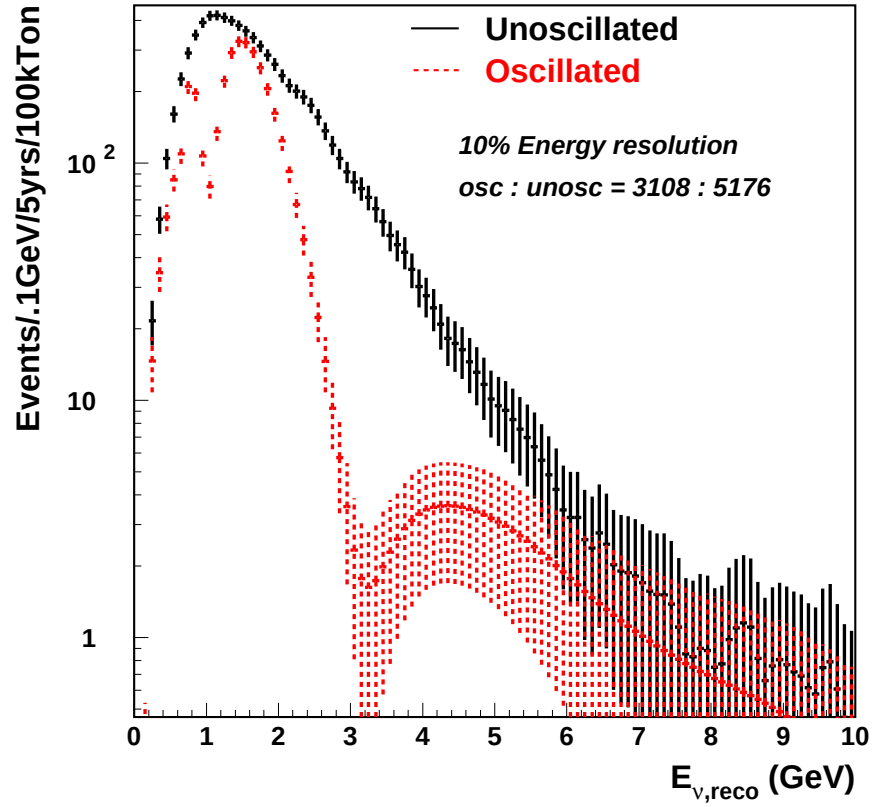
## FNAL-Keenan: 458 km




## BNL-Keenan: 1522 km



# Soudan event rates - $\nu_\mu \rightarrow \nu_\mu$ Disappearance

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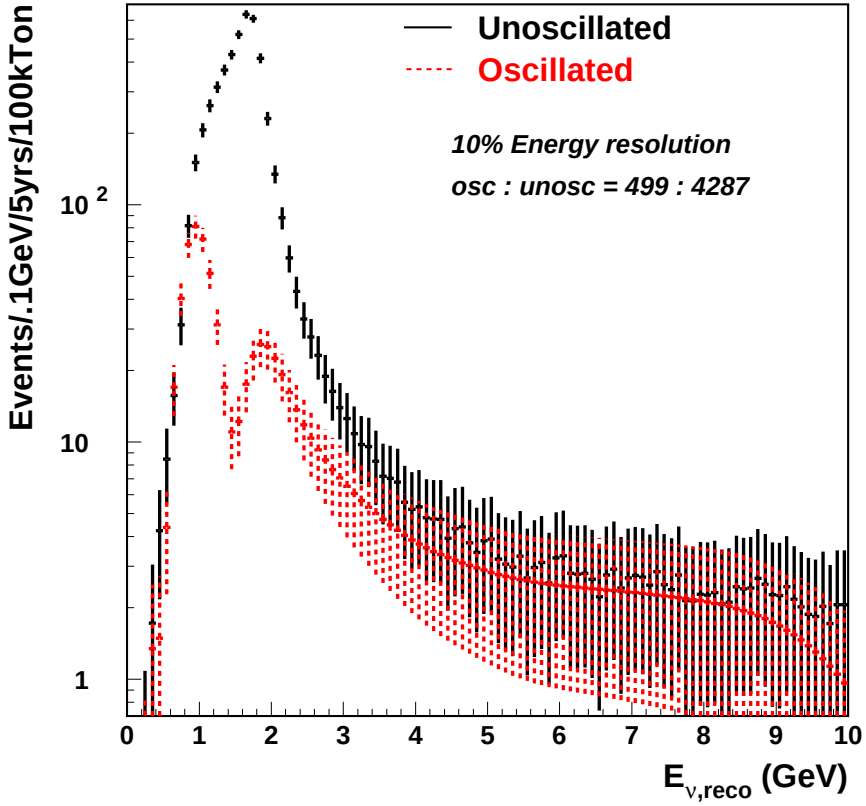
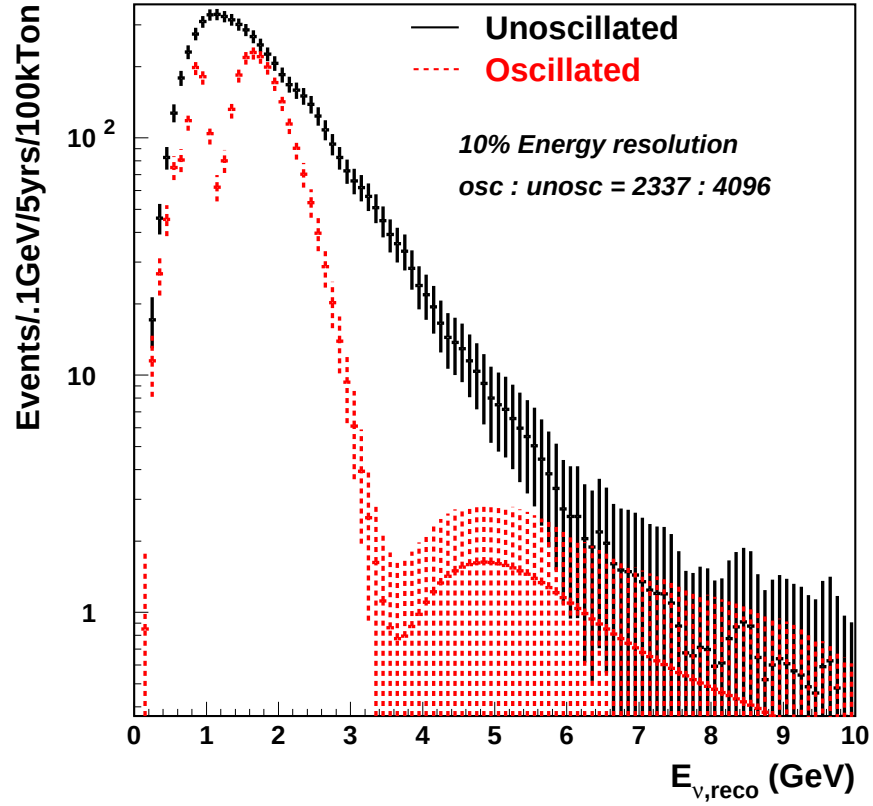
## FNAL-Soudan: 735 km




## BNL-Soudan: 1711 km



# L.Lawrence event rates - $\nu_\mu \rightarrow \nu_\mu$ Disappearance

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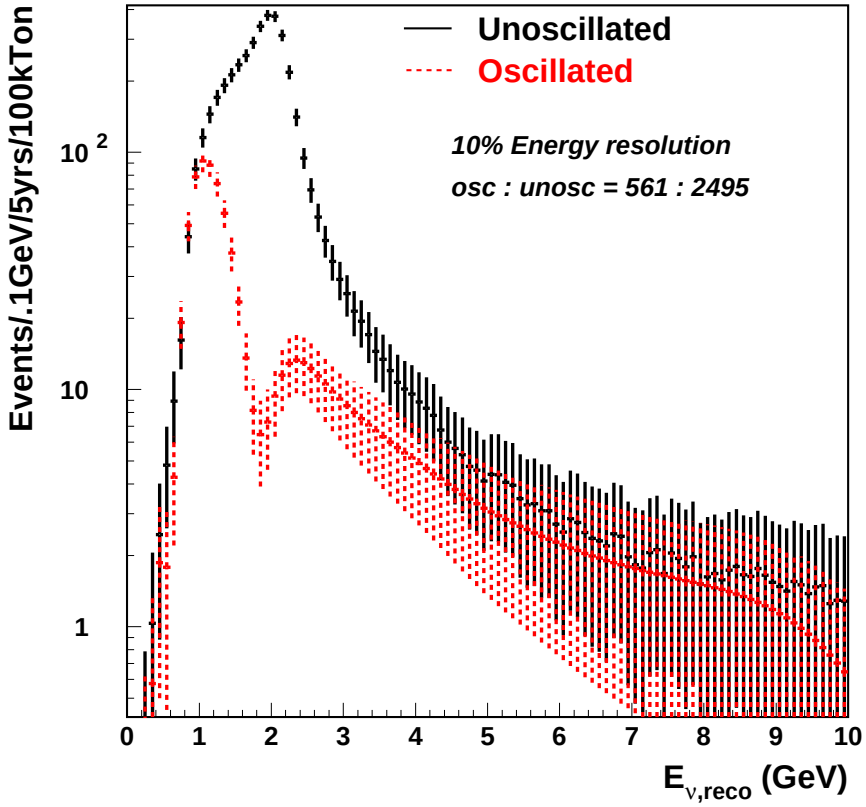
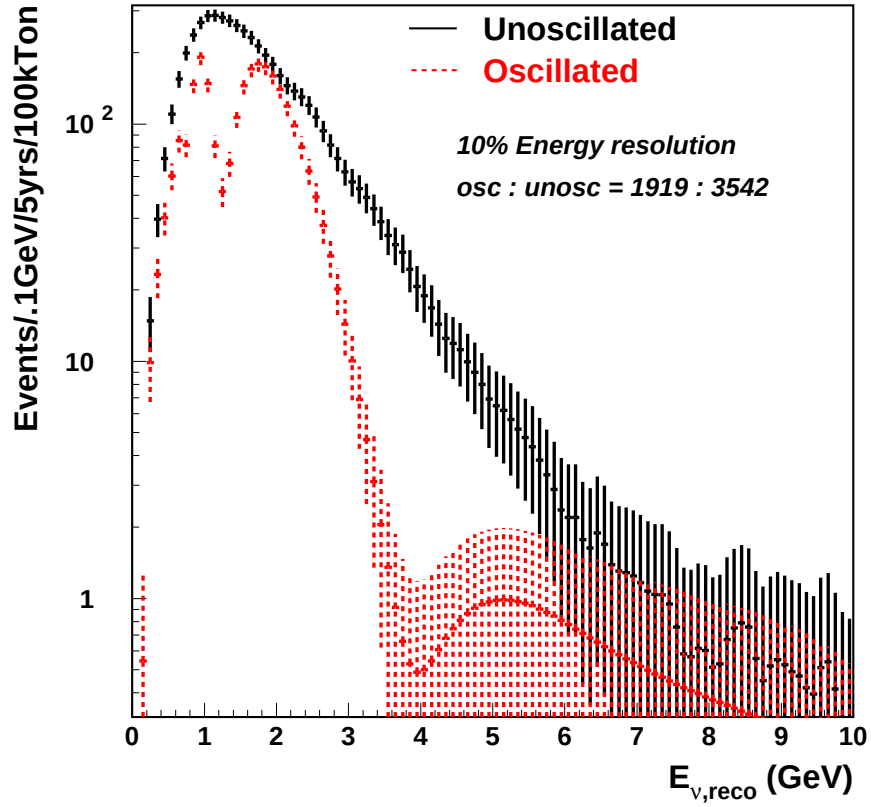
## FNAL-L.Lawrence: 911 km




## BNL-L.Lawrence: 1840 km



# $P(\nu_\mu \rightarrow \nu_e)$

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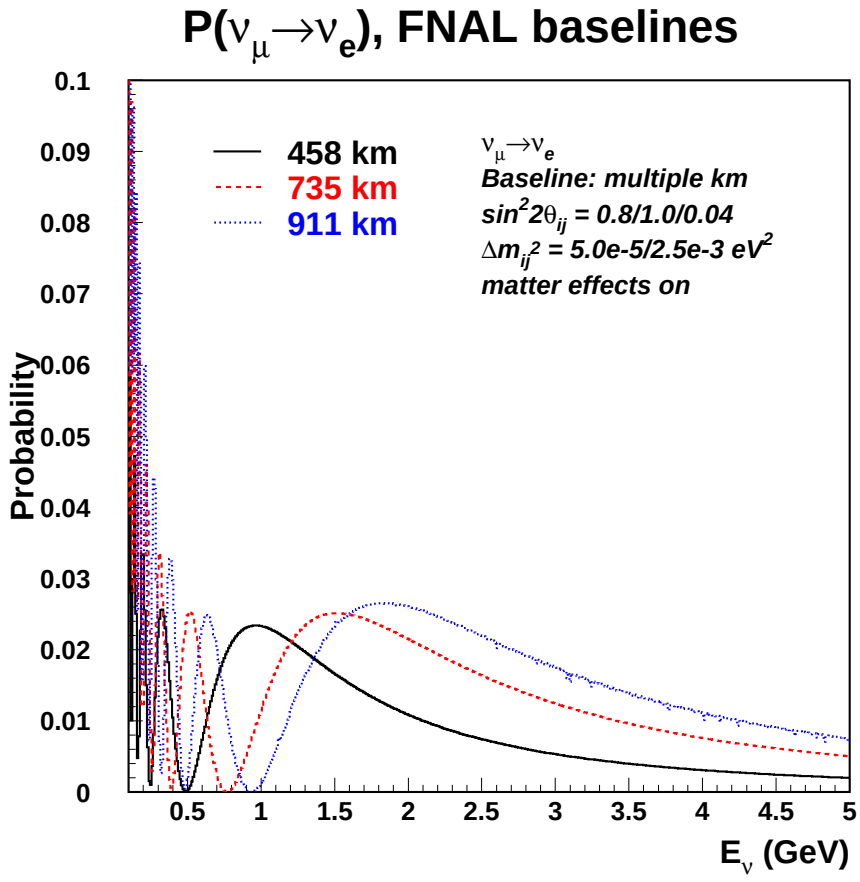


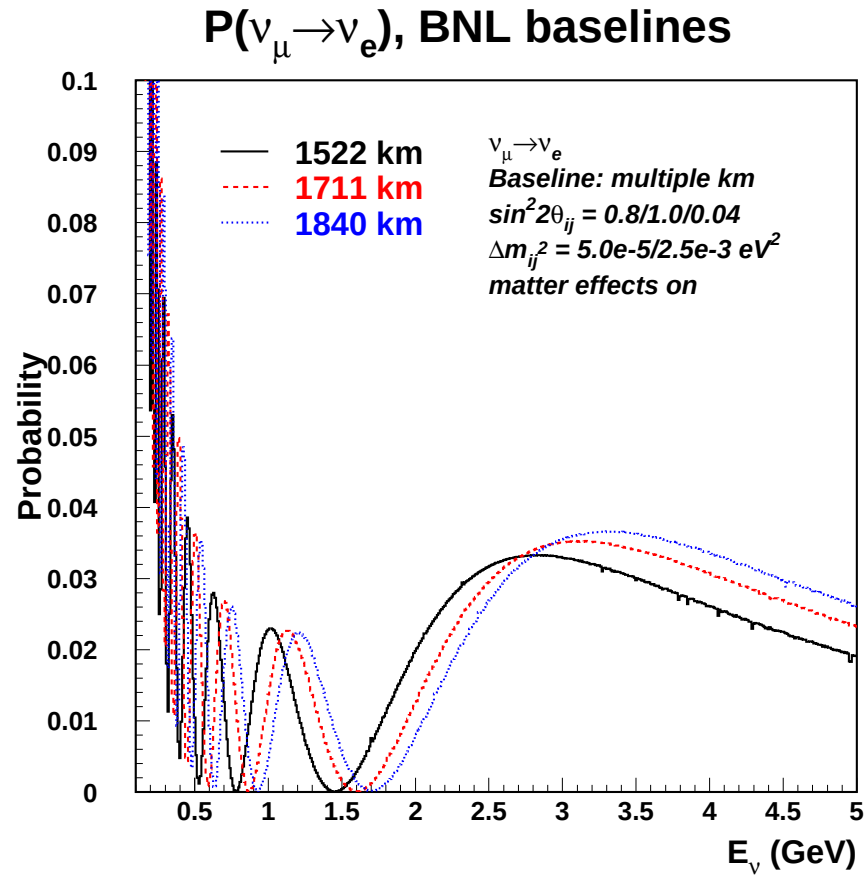


- FNAL sees $1^{st}$ oscillation, BNL $2^{nd}$ and part of $1^{st}$.
- Matter enhancement accessible at BNL and not at FNAL distances.

# Keenan event rates - $\nu_\mu \rightarrow \nu_e$ Appearance

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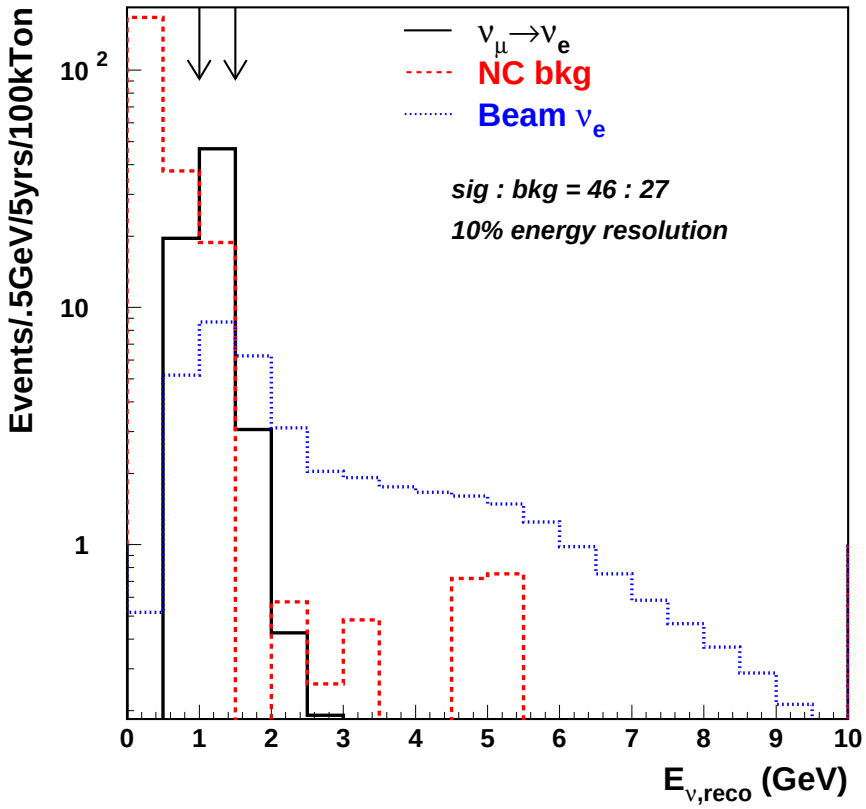
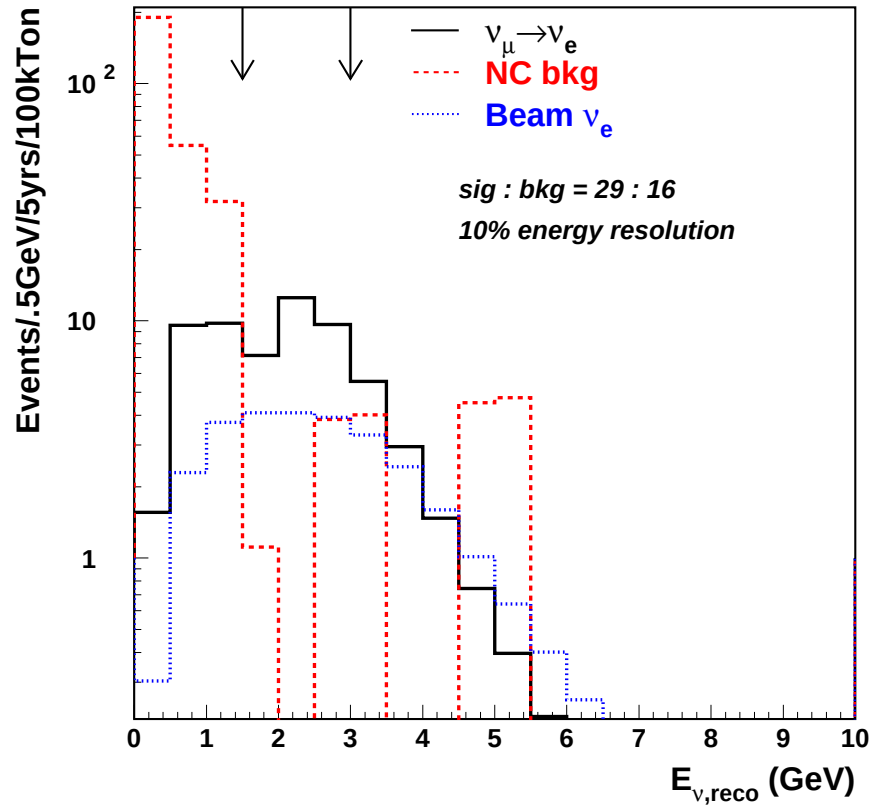
## FNAL-Keenan: 458 km




## BNL-Keenan: 1522 km



# Soudan event rates - $\nu_\mu \rightarrow \nu_e$ Appearance

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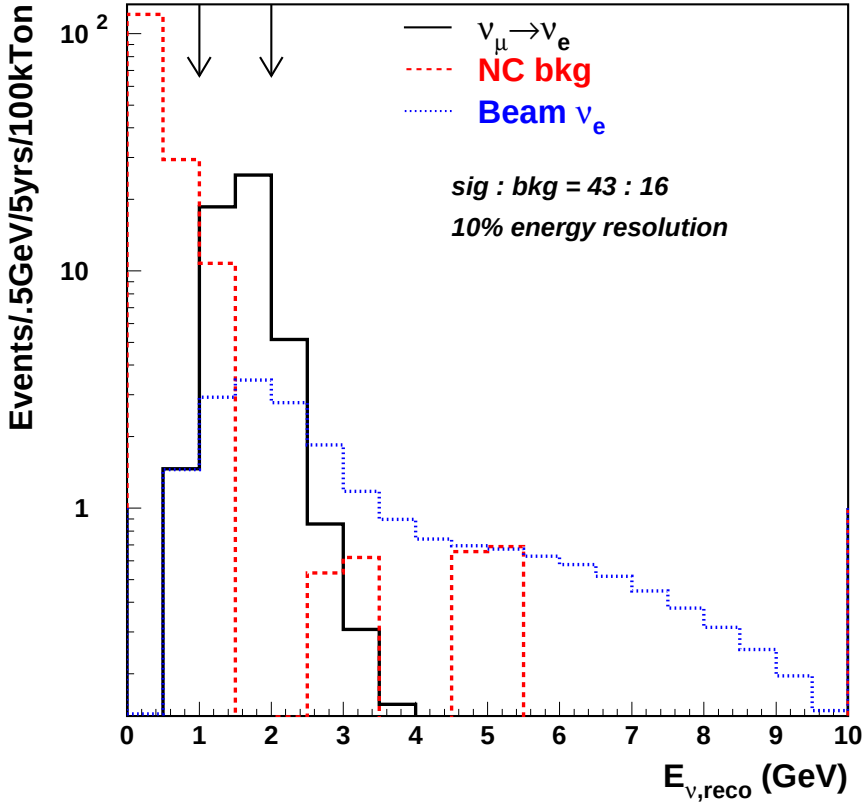
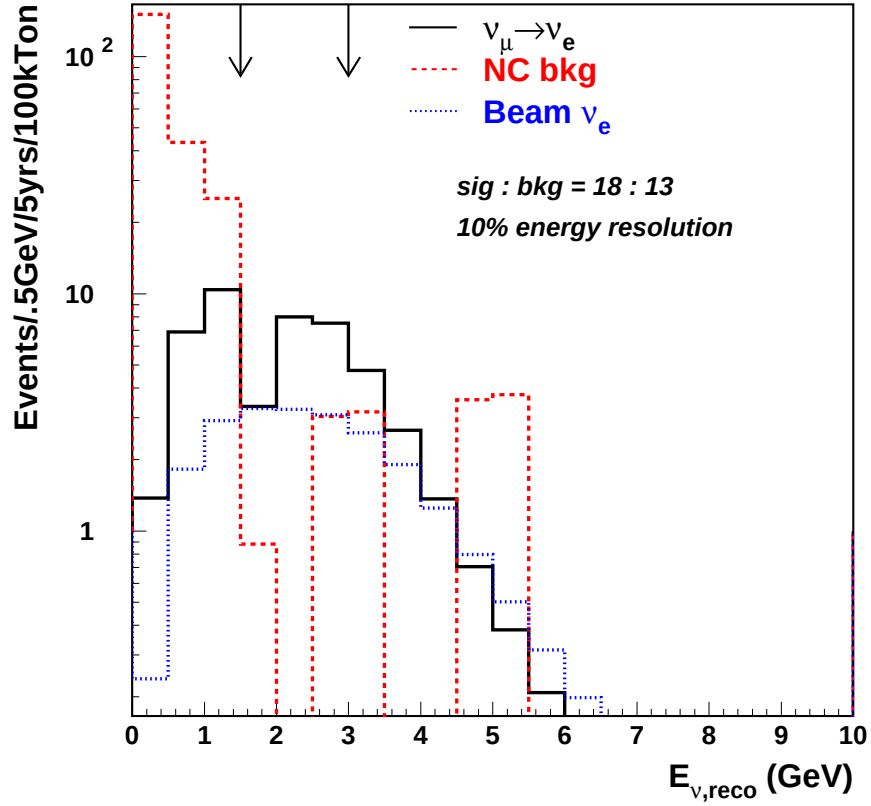
## FNAL-Soudan: 735 km




## BNL-Soudan: 1711 km



# L.Lawrence event rates - $\nu_\mu \rightarrow \nu_e$ Appearance

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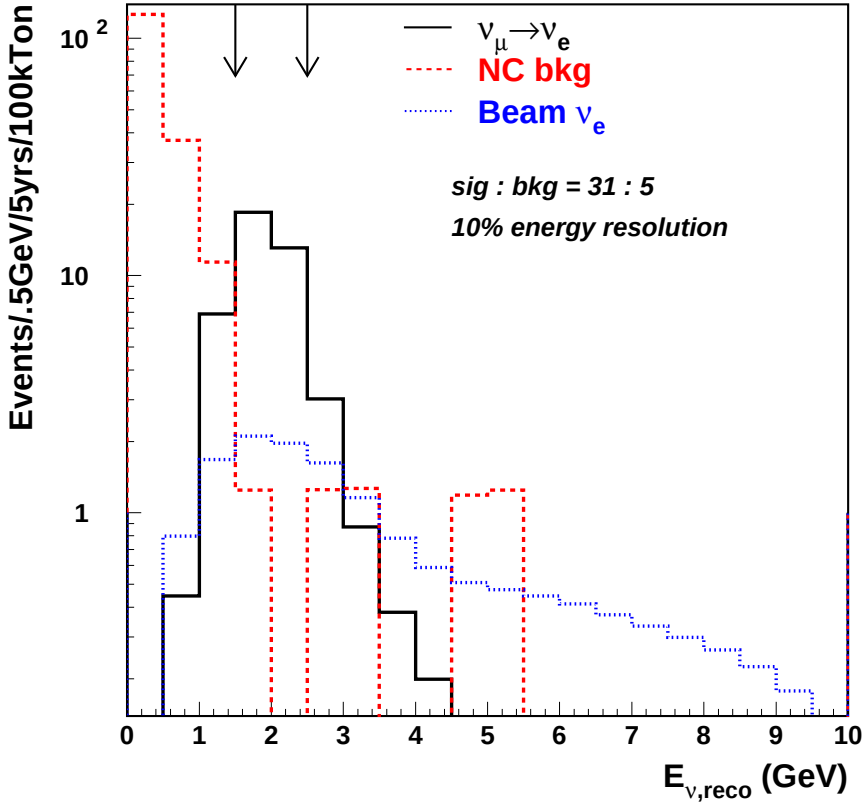
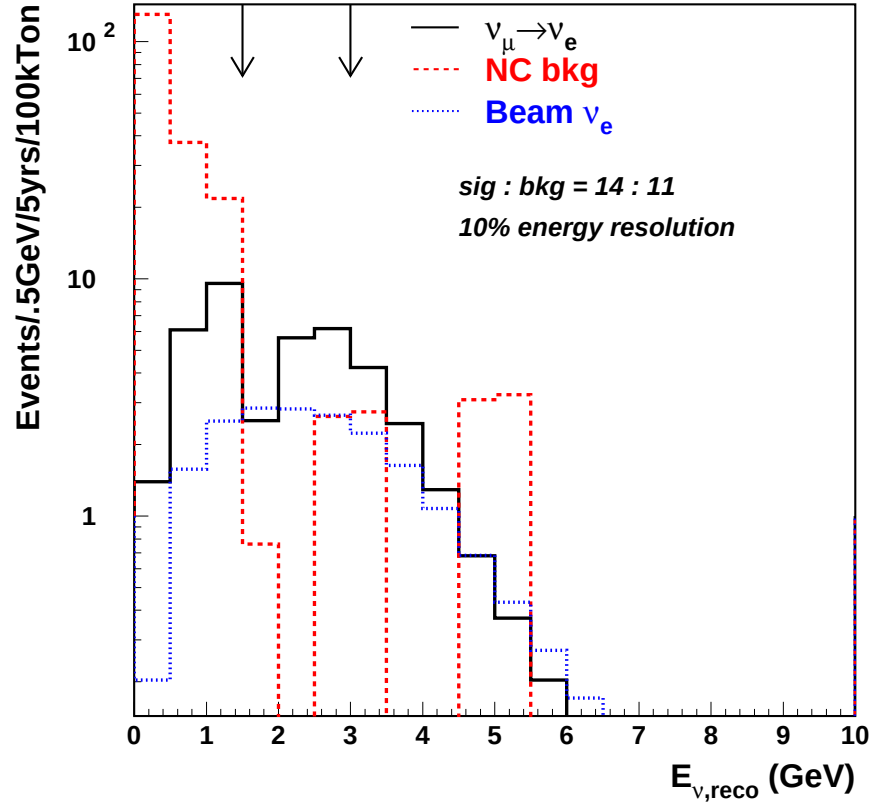
## FNAL-L.Lawrence: 911 km




## BNL-L.Lawrence: 1840 km



# Summary event rates - $\nu_\mu \rightarrow \nu_e$ Appearance

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| Baseline | $\nu_\mu \rightarrow \nu_e$ Signal | Beam $\nu_e$ oscillated | NC in cuts | Tot bkg | % tot bkg / $\overline{\nu_\mu \text{CCQE}}$ | $S/\sqrt{B}$ |
|---|---|---|---|---|---|---|
| FNAL-Keenan | 46.7 | 8.7 | 18.8 | 27.5 | 0.42% | 8.91 |
| FNAL-Soudan | 44.0 | 6.4 | 10.3 | 16.7 | 0.39% | 10.75 |
| FNAL-L.Lawrence | 31.6 | 4.1 | 1.0 | 5.1 | 0.30% | 14.03 |
| BNL-Keenan | 29.3 | 12.1 | 4.7 | 16.8 | 0.32% | 7.16 |
| BNL-Soudan | 18.8 | 9.6 | 3.7 | 13.3 | 0.32% | 5.16 |
| BNL-L.Lawrence | 14.3 | 8.3 | 3.2 | 11.5 | 0.32% | 4.22 |

Note:

- Total background remaining in cuts is 0.2%-0.4% of total $\nu_\mu$ CC QE
- Total NC background is consistent with E889 studies.
- Actual distribution of NC events is less certain:
  - Estimated with reconstructed SuperK atm-$\nu$ MC
  - Spectra reweighted, but low statistics for $E_{\nu,atm} >\sim 3$GeV.
  - FNAL on edge or under NC wall, BNL partially under.

# Conclusions

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- AGS upgrade to 1.5 MW possible, relatively affordable.
- BNL and FNAL beams are complimentary.
  - $\Delta m^2$: FNAL closer, higher rate; BNL further, sees multiple oscillations.
  - $\theta_{13}$: FNAL has higher rate; BNL has low NC and access to matter effects.
- Understanding NC background distribution is crucial for both.

# Future Work

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Short term:

- Use NUANCE + SuperK detector simulation and reconstruction chain to nail down NC and intrinsic $\nu_e$ backgrounds for these beams in an SK-like detector.
- Optimize BNL beam to lower beam $\nu_e$ and harden spectrum to better access matter enhancement effect.

Longer term:

- Is it possible to optimize reconstruction chain to knock down the NC wall?
- What changes are needed to “port” an SK-type detector to a 100+ kTon fiducial mass detector?
- Look at other detectors?