Constraining Large Extra Dimensions with MINOS+

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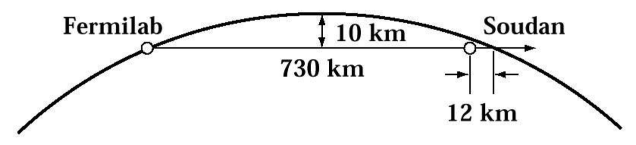
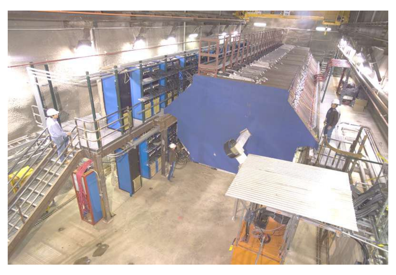
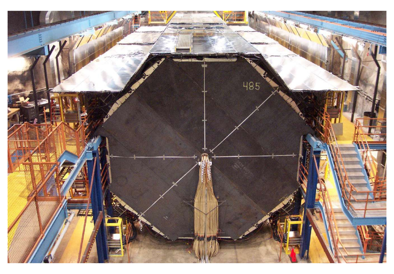
On behalf of the MINOS+ Collaboration

MINOS/MINOS+ Experiment







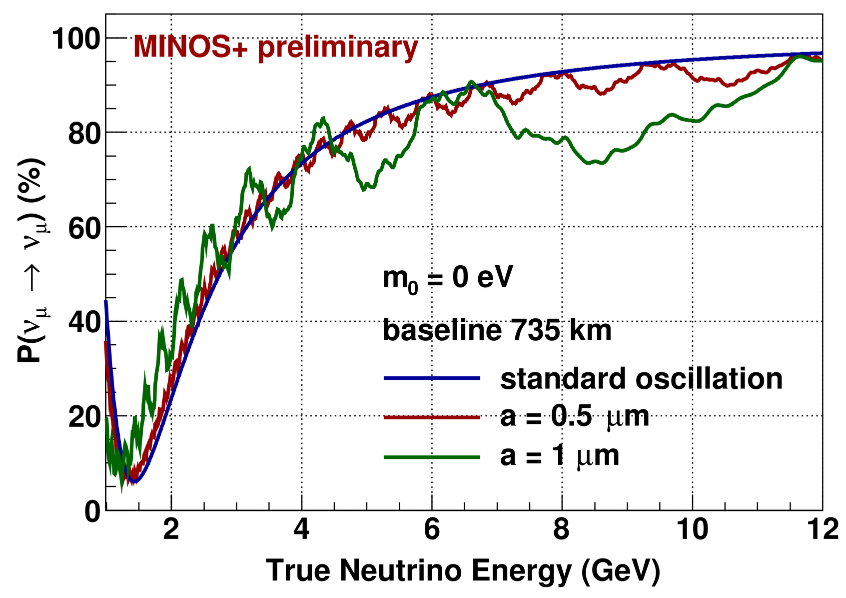
- MINOS (Main Injector Neutrino Oscillation Search)
  - precision measurement of neutrino oscillations via ν_μ disappearance
  - Near and Far Detectors (ND and FD) are located 1.04 and 735 km downstream of the neutrino production target
  - low energy beam setting, peaks around 3 GeV
- MINOS+
  - started in 2013, continuation of MINOS using medium energy beam optimized for NOνA
  - opportunities to probe new physics at higher energies (4 - 10 GeV)

Large Extra Dimension (LED) Model

- proposed by Arkani-Hamed *et al.* for gauge hierarchy problem [1]
- used in ν physics to explain small yet non-vanishing ν masses
  - left-handed neutrinos are confined to 4-dimensional subspace
  - sterile neutrinos can propagate in more than 4 dimensions, Kaluza-Klein (KK) states
- assumption [1, 2]
  - one of the extra dimensions is much larger than the rest
  - perturbations to the standard oscillation scenario
- oscillation amplitude among active neutrino states $\nu_{e,\ \mu,\ \tau}$

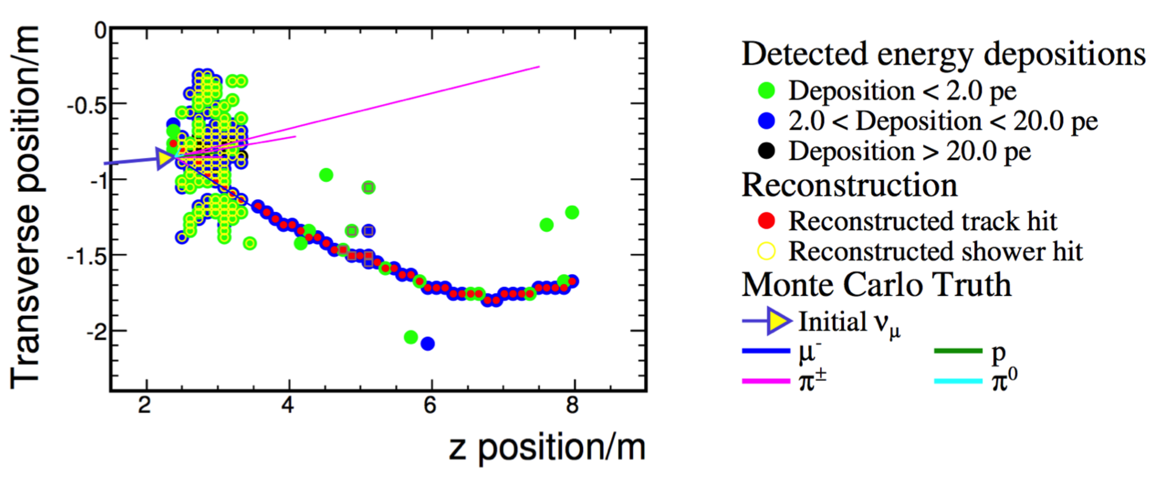
$$A\left(\nu_\alpha \to \nu_\beta\right) = \sum_{i,j,k=1}^{3} \sum_{n=0}^{+\infty} U_{\alpha i} U^*_{\beta k} W^{(0n)*}_{ij} W^{(0n)}_{kj} e^{i\frac{\left(\lambda_j^{(n)}/a\right)^2 L}{2E}}$$

- U, W are mixing matrices for active and KK states, respectively
- $\lambda_j^{(n)}/a$ is the mass for eigenstate j of the n^{th} KK mode
- parameters: lightest neutrino mass m_0, extra dimension size a



- focuses on the disappearance of ν_μ in the NuMI beam
- *left plot*: Oscillation probabilities of $\nu_\mu \to \nu_\mu$ at FD
- stronger effect for larger a
  - appearance of wiggles, more significant at higher energies
  - shift of the oscillation dip

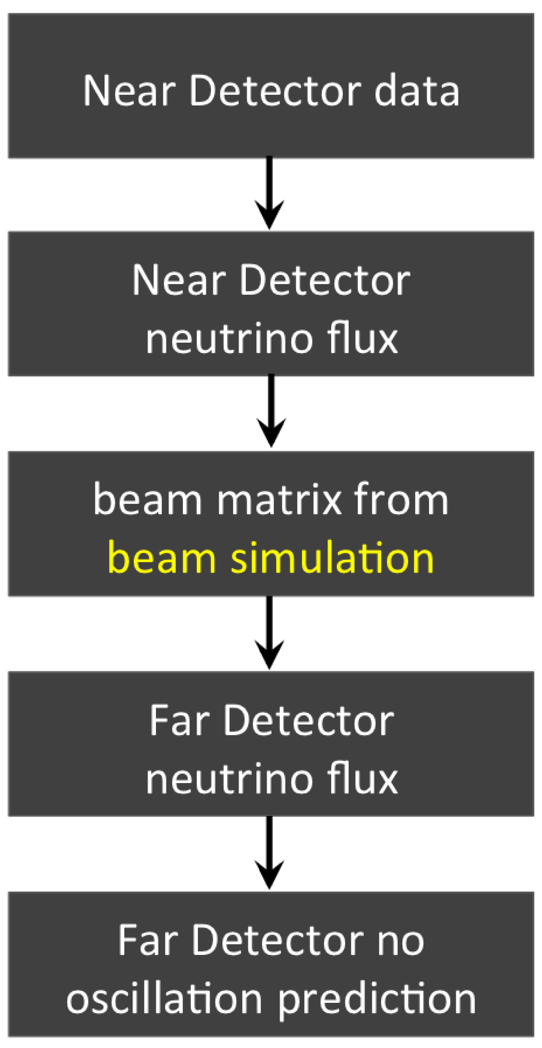
MINOS Charged Current Analysis



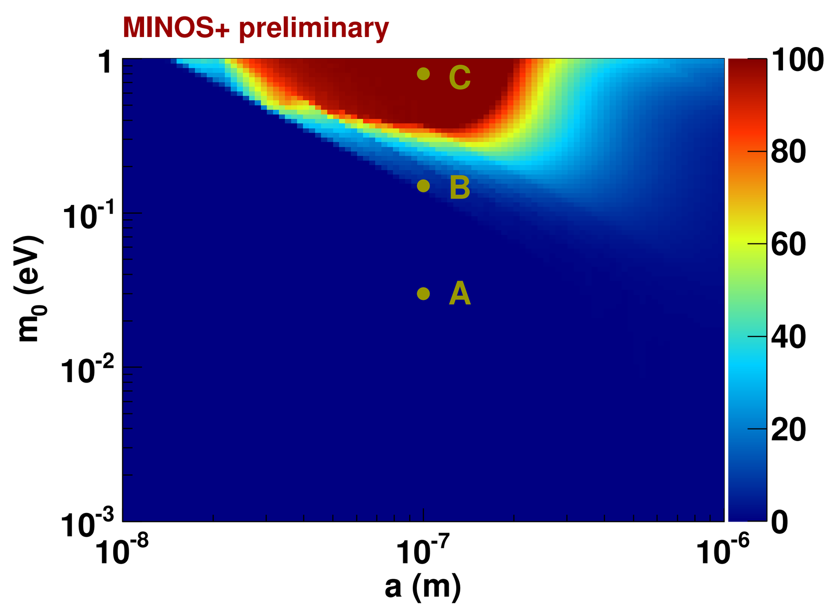
- ν_μ is identified by charged current interactions

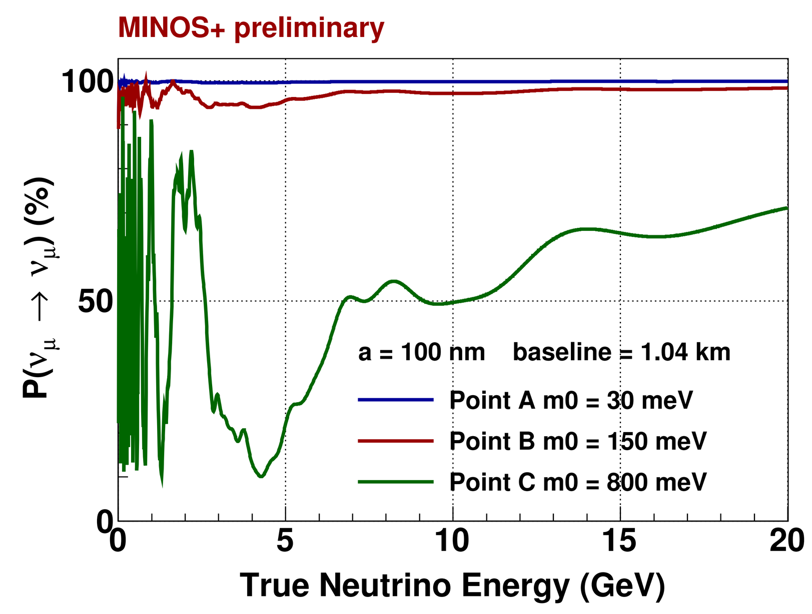
$$\nu_\mu + X \longrightarrow \mu^- + X'$$

- oscillation parameters are constrained by comparing FD predictions to data
- a beam transfer matrix is used to turn ND observation into FD predictions



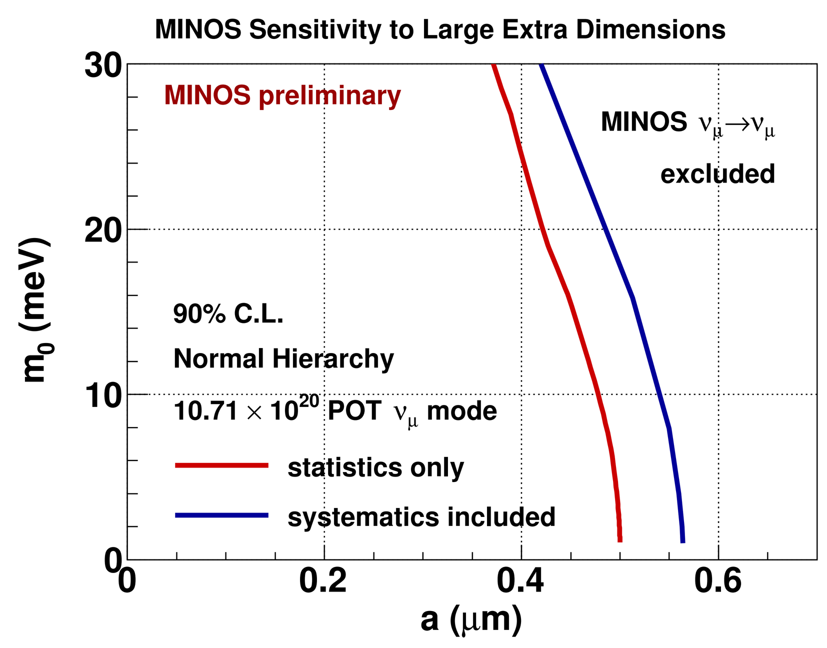
Near Detector Oscillations



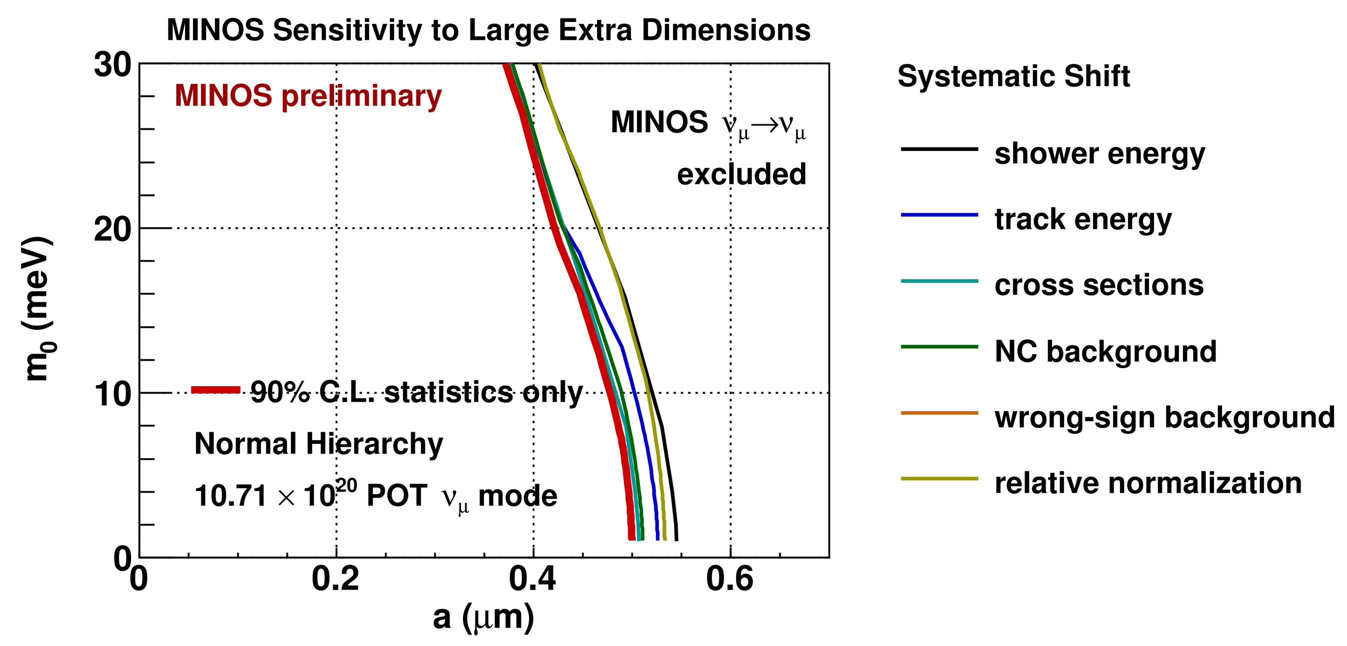


- hadron model tuned to match ND data assuming no ND oscillations
- significant ND oscillations in LED model for large m_0
  - *left plot*: percentage of energy window where the fraction of ν_μ disappearance due to oscillations is larger than 5%
  - *right plot*: examples of oscillation probability vs. ν energy
- only consider the region of parameter space where ND oscillations are negligible, limit to $m_0 < 30$ meV

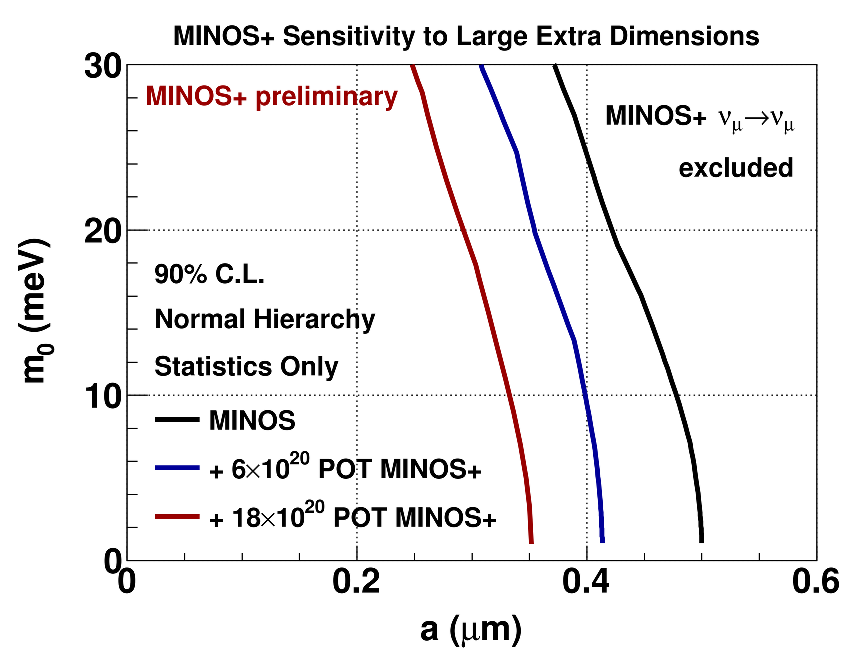
MINOS Sensitivity



- energy window is set to 1.5 GeV–50 GeV
- fake data is made with no LED assumption
- *left plot*: MINOS sensitivities with and without systematics
- *bottom plot*: effect of individual systematic shift



MINOS+ Sensitivity



- upon reaching the designed power of 750 kW, NuMI can deliver $\sim 6 \times 10^{20}$ protons on target (POT) per year
- more high energy events in the 4-10 GeV range will improve sensitivity substantially
- *left plot*: MINOS+ sensitivity for various POT

Example Limits from Other Searches

field	# extra dim n	Planck scale $< M_D$ (TeV)	extra dim size $> a$ (μm)	source
torsion balance	2	3.6	37	PDG
astrophysics	2	27	0.66	Hanhart *et al.*, 2001
colliders	2	4.17	27.6	ATLAS arXiv:1210.4491

Note: 95% C.L. for the numbers above, M_D is the Planck scale in $(4+n)$ dimensions, $M_P^2 \sim M_D^{2+n} a^n$ where $M_P = 2.4 \times 10^{18}$ GeV so a can be calculated from M_D and n (n may take integers greater than 1) [1]

References

[1] N. Arkani-Hamed, *et al.*, hep-ph/9803315, H. Davoudiasl, *et al.* hep-ph/0201128
[2] P. A. N. Machado, *et al.*, H. Nunokawa and R. Zukanovich Funchal, arXiv:1101.0003