New Perspectives 2016

A Search for Large Extra Dimensions in MINOS and MINOS+

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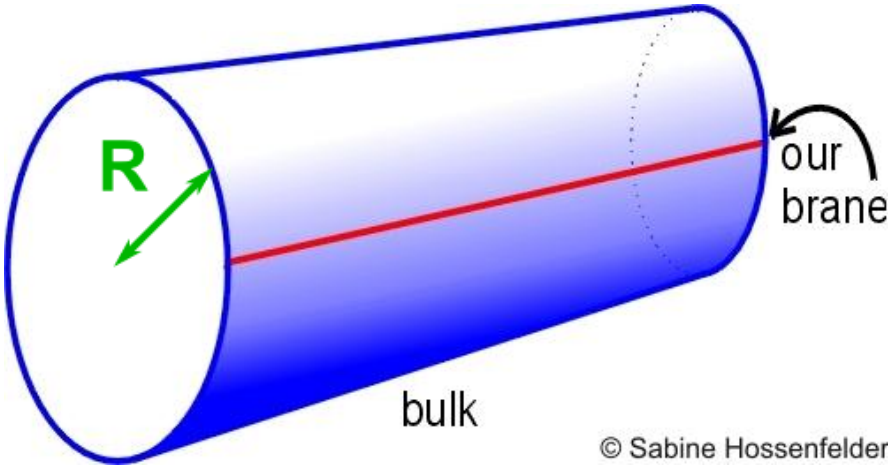
June 14, 2016

Large Extra Dimensions



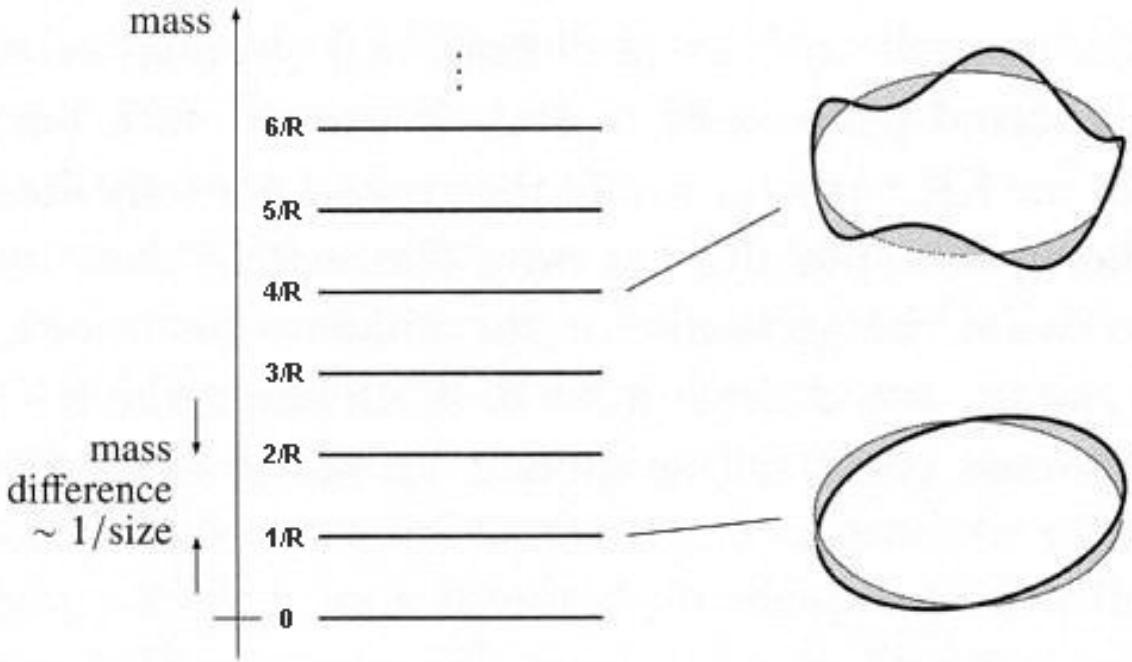
Hierarchy problem

- $M_{\rm Pl} \gg m_{\rm EW} \Rightarrow \overline{M}_{\rm Pl} \sim m_{\rm EW}$
- d extra dimensions scale up $\overline{M}_{\rm Pl}$ [1]

Neutrino masses

- Add 3 singlet fermion fields in bulk [2]

$$m_\nu = \kappa v \frac{\overline{M}_{\rm Pl}}{M_{\rm Pl}} \text{ (Dirac)}$$

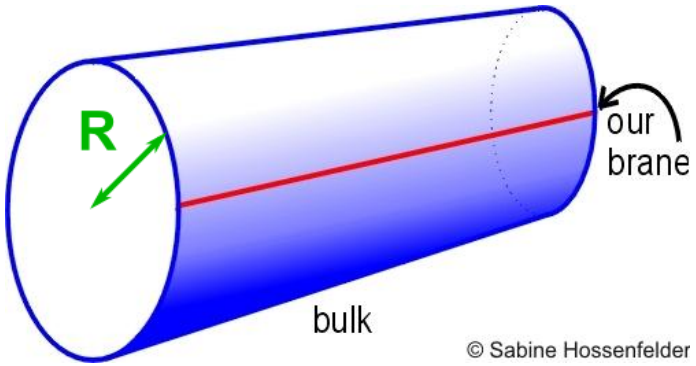


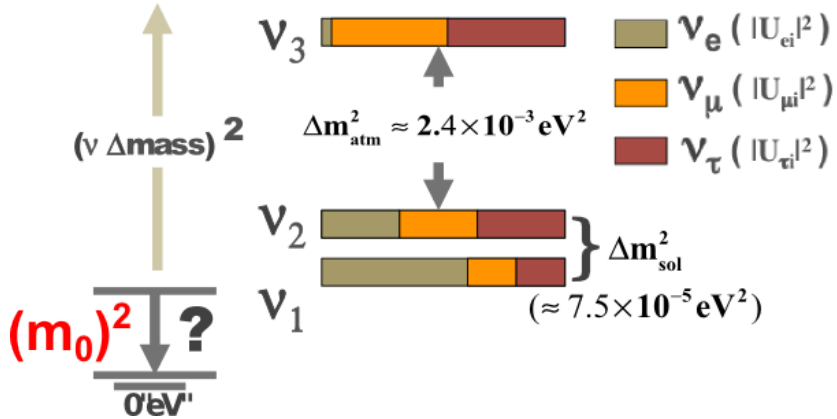
Neutrino oscillation

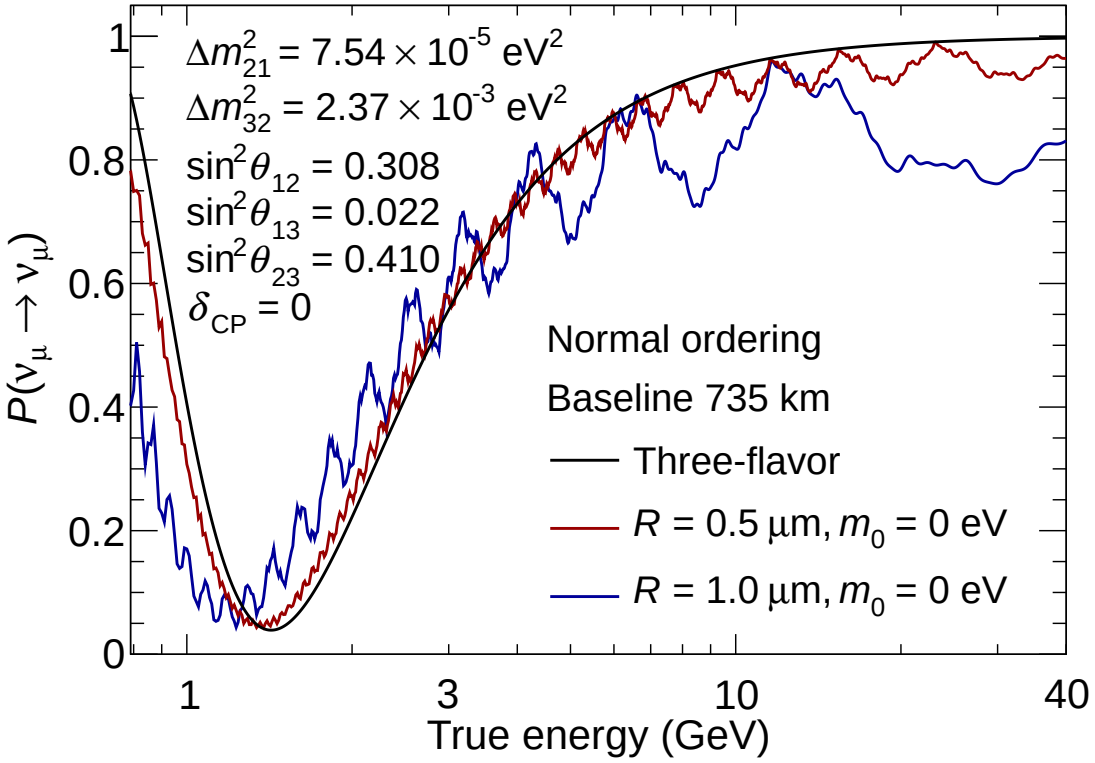
- Active $\leftrightarrow$ sterile [3]

Oscillation Probabilities

Two extra parameters on top of three-flavor case: R and m_0

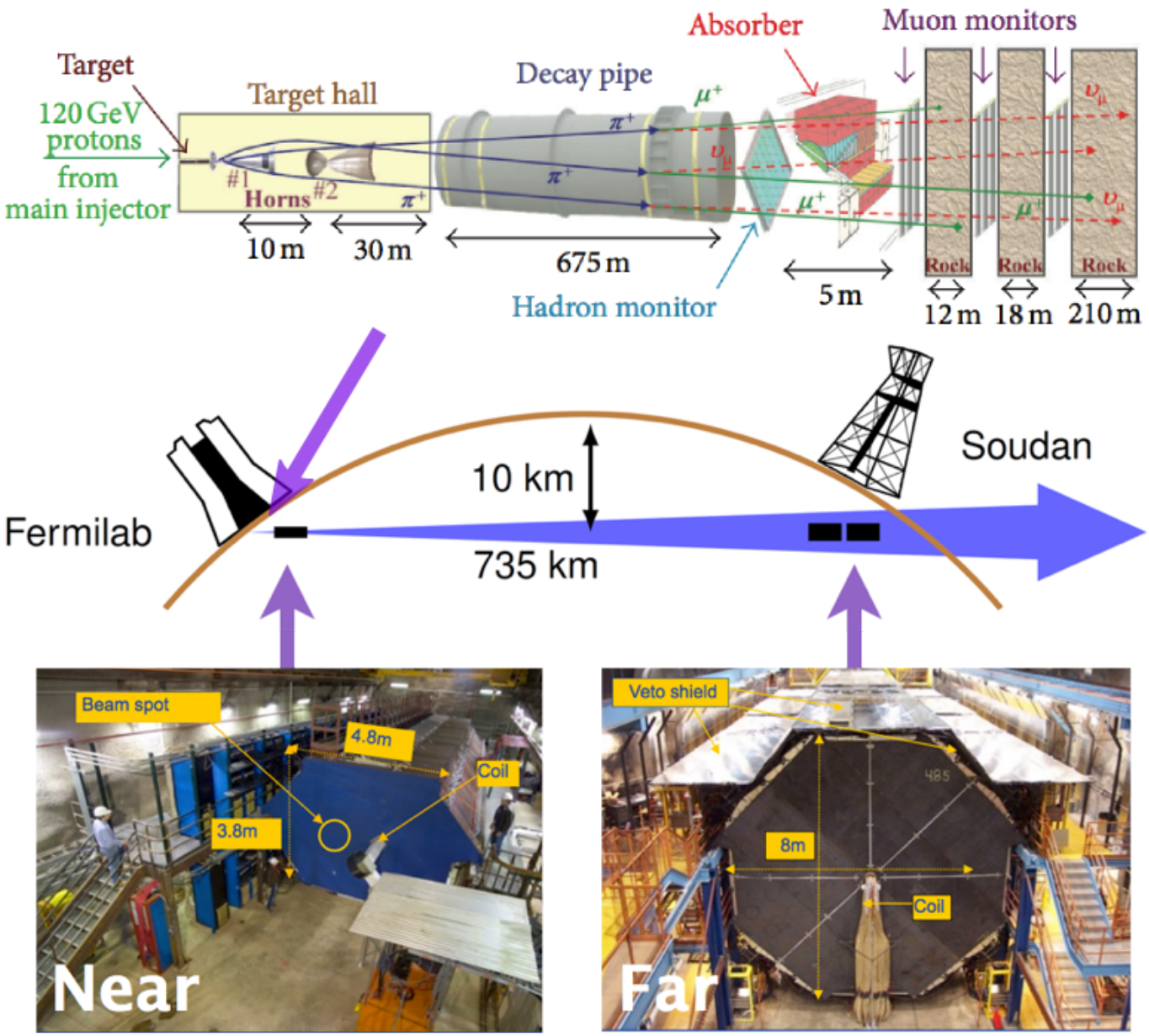






MINOS/MINOS+ Experiment

Two NuMI **on-axis** magnetized steel-scintillator tracking calorimeters



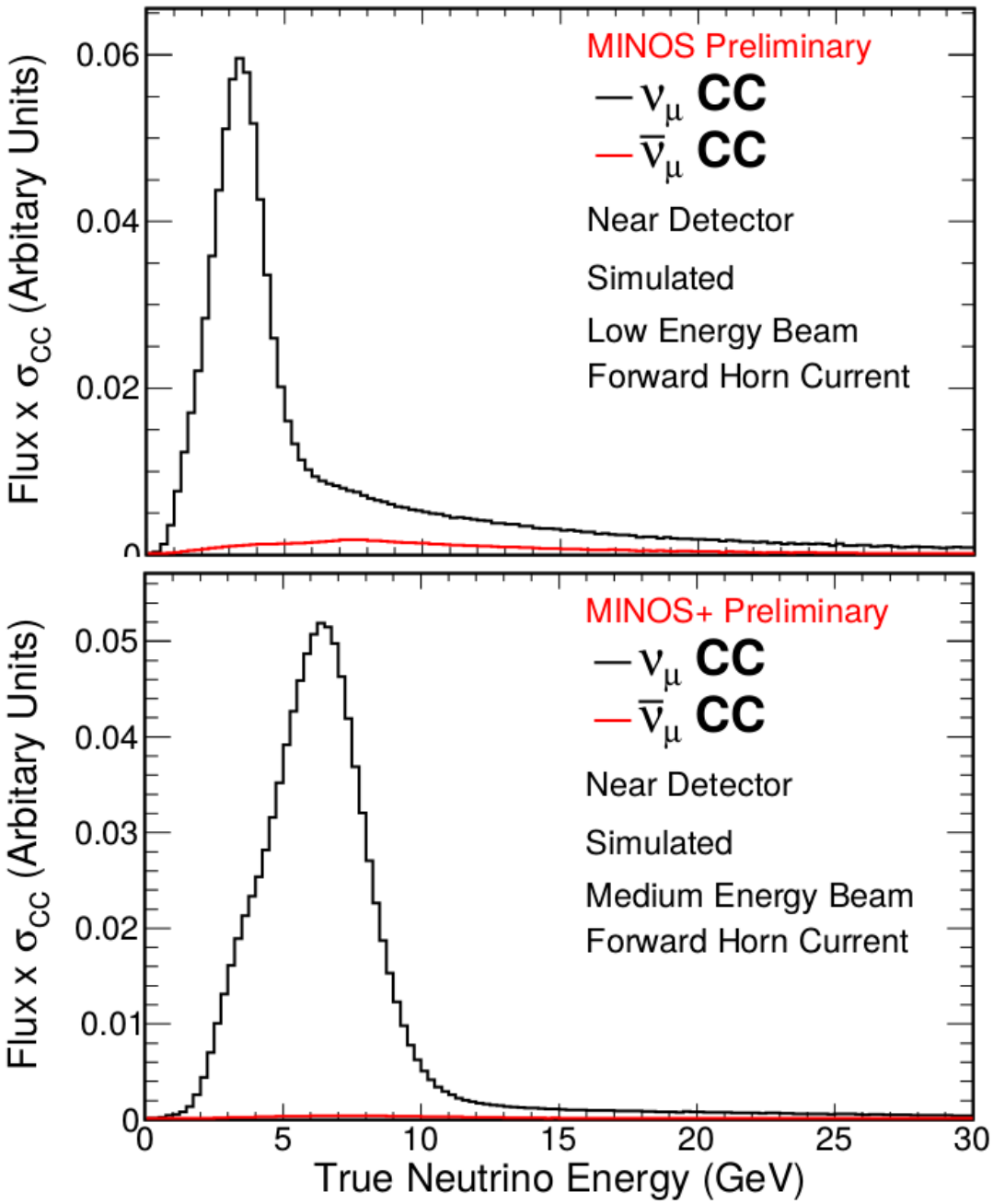
Near Detector Spectra

MINOS

→ This talk

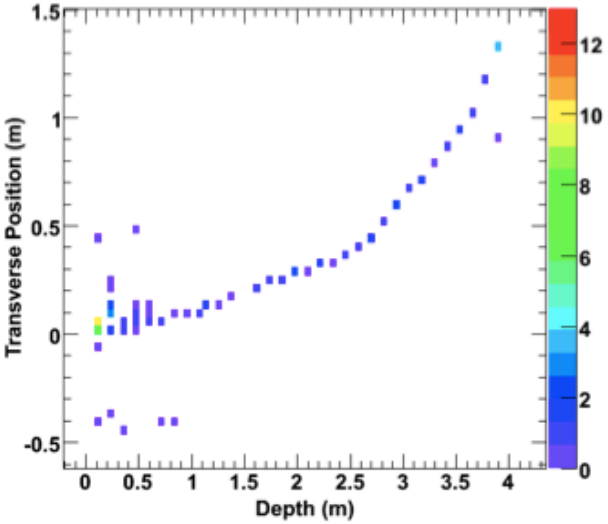
MINOS+

→ Neutrino 2016

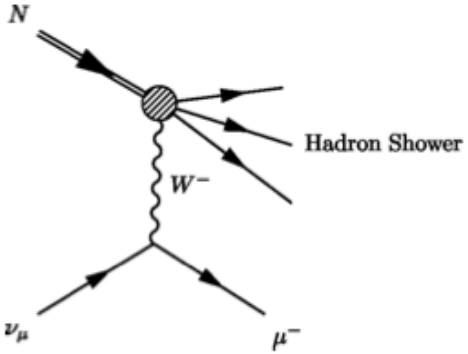


Event Topologies

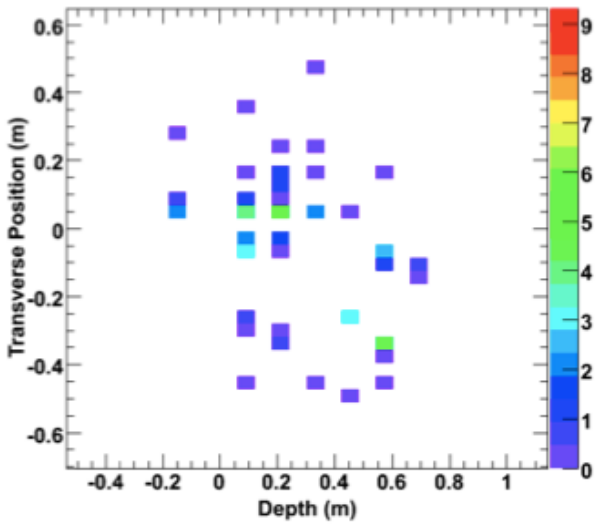
ν_μ Charged Current (CC)



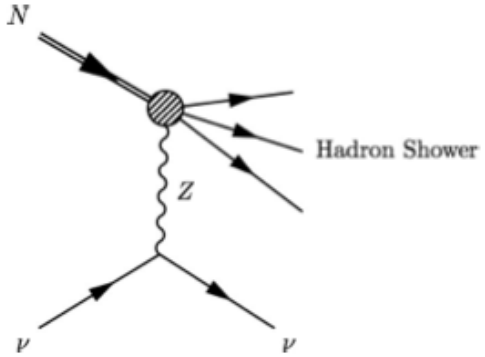
$$\nu_\mu + N \rightarrow \mu^- + X$$



Neutral Current (NC)



$$\nu + N \rightarrow \nu + X$$



CC energy =

track + kNN shower energy

15% mean energy resolution

NC energy =

calorimetric energy

40% mean energy resolution

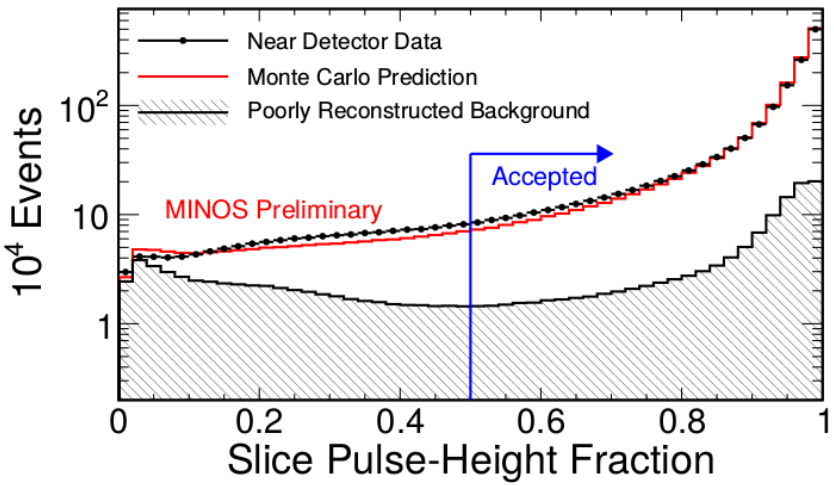
Event Selection

NC

Fiducial volume cuts

Poor reconstruction

- $\frac{\text{reco energy}}{\text{true energy}} < 0.3$
- Consecutive planes in event > 3



CC background

- Event < 47 planes
- Track $\leq$ shower $+ 5$ planes

CC

After NC selection

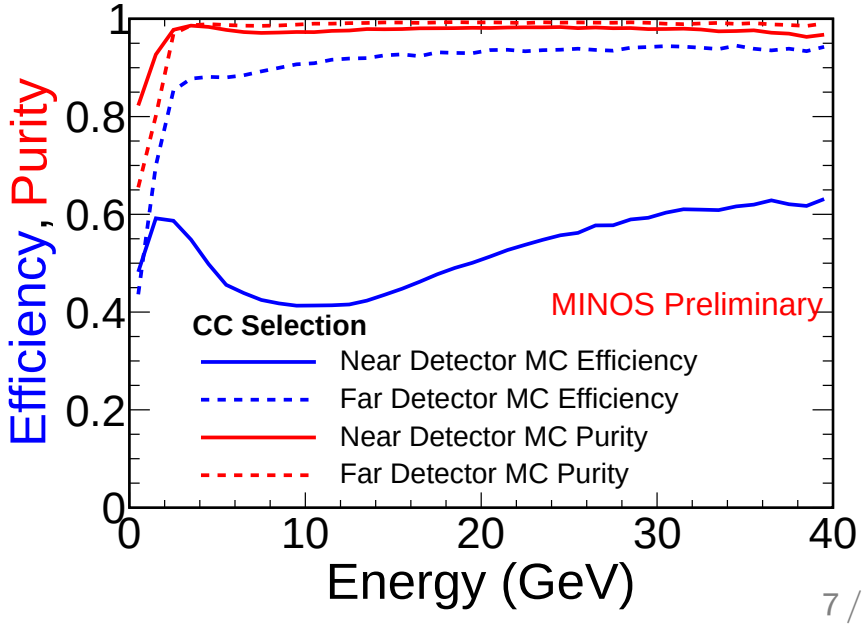
Fiducial volume cuts

No charge separation

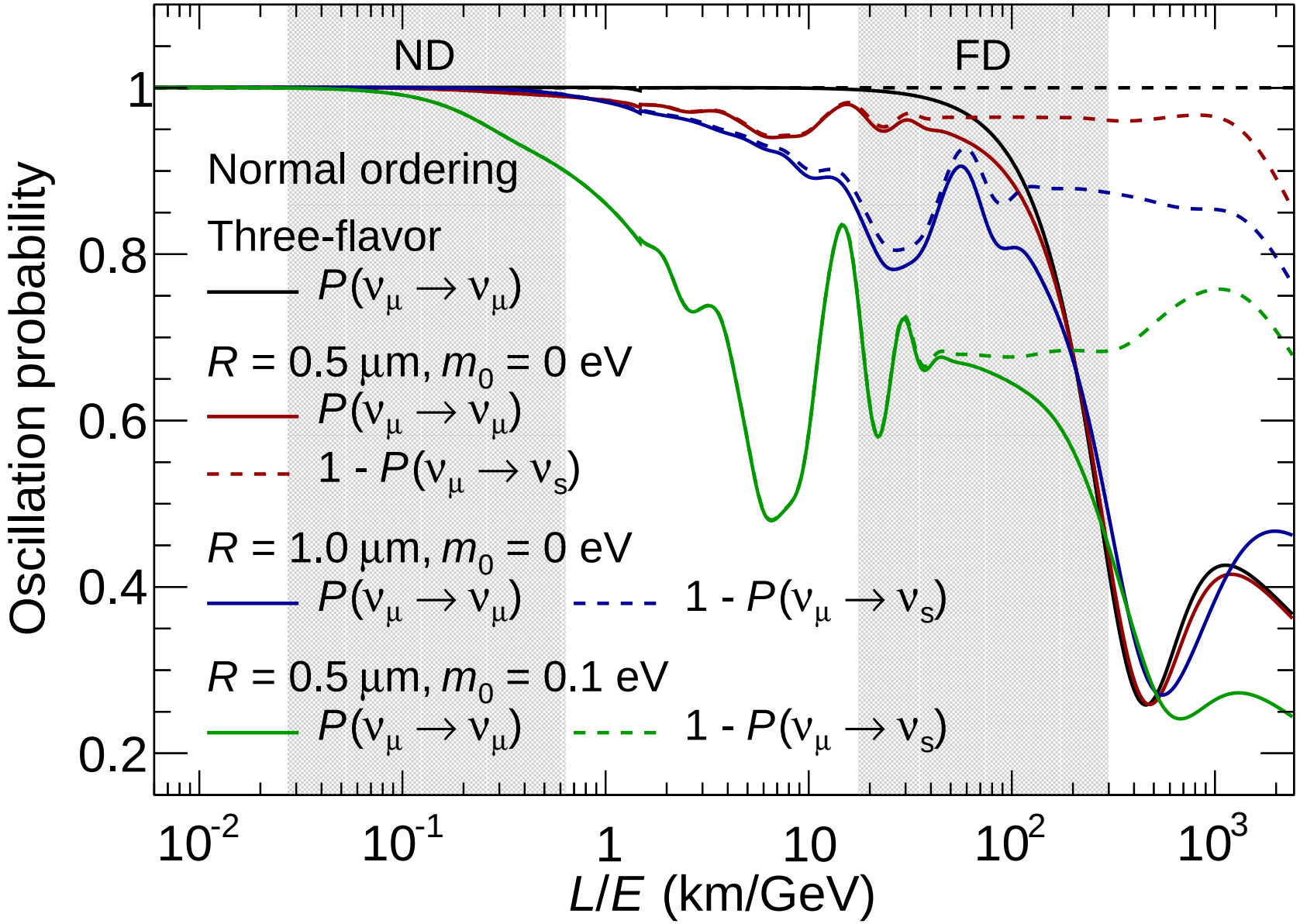
NC background

- kNN PID

Efficiency/purity



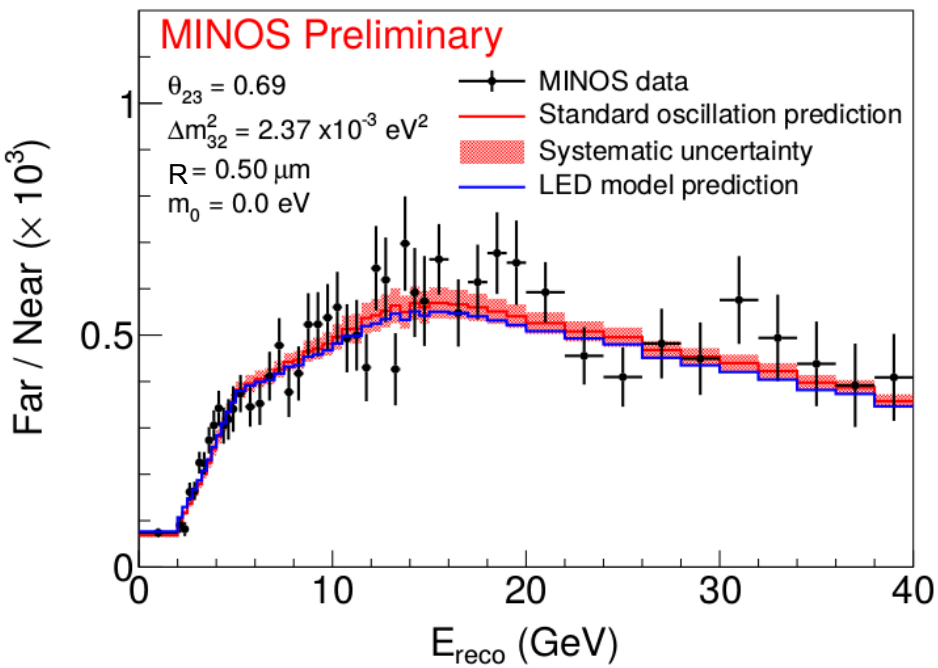
Near Detector Oscillation



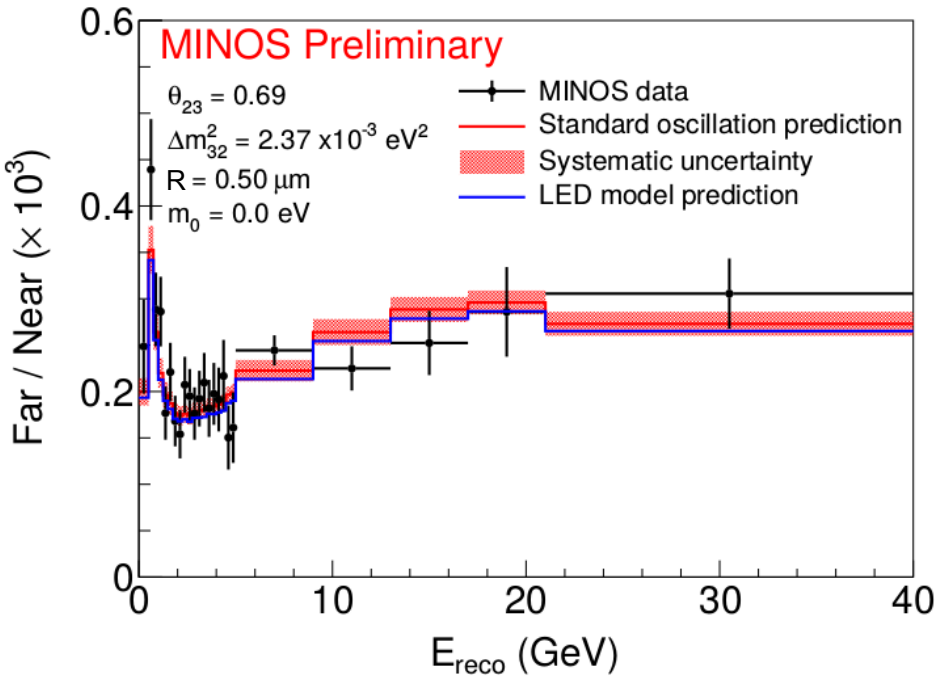
Far-Over-Near Ratio

- Accounts for oscillation along Near Detector baseline
- Many systematics reduced significantly

$$\chi^2 = \sum_{i,j=1}^{N} (o_i - p_i)[V^{-1}]_{ij}(o_j - p_j)$$

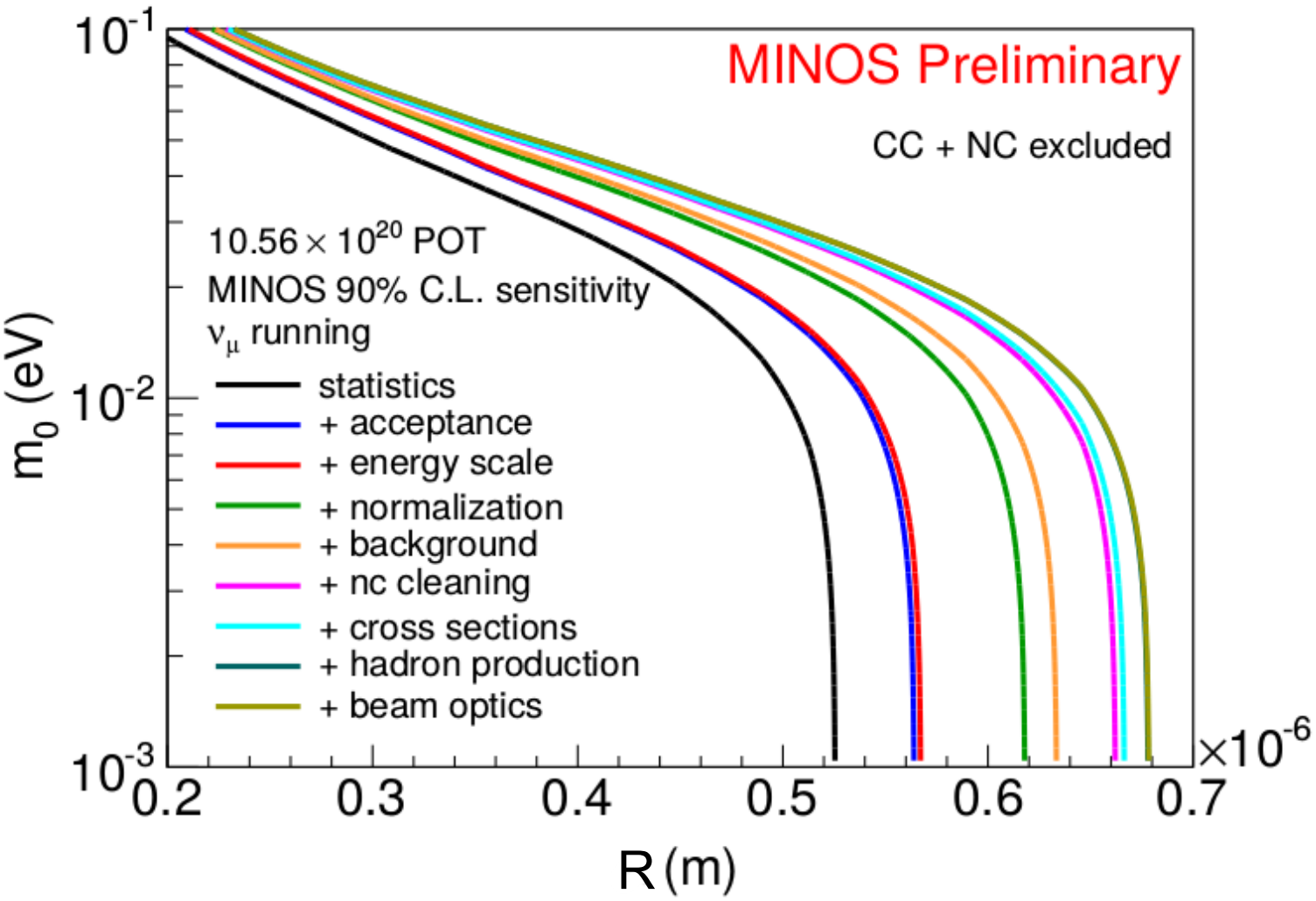


CC sample



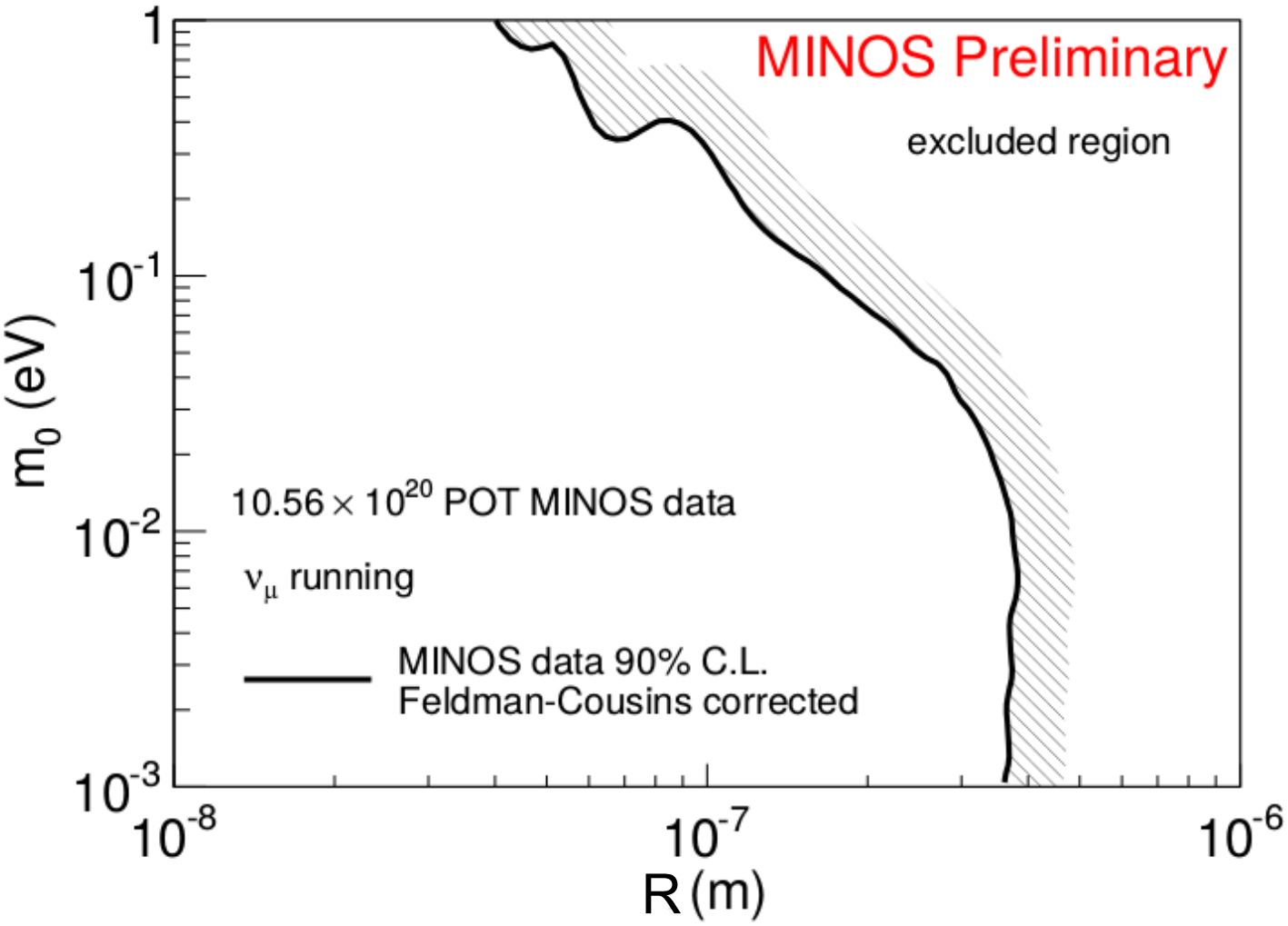
NC sample

Sensitivity and Systematics



Biggest systematics: acceptance, normalization, and NC cleaning

MINOS Feldman-Cousins Limit



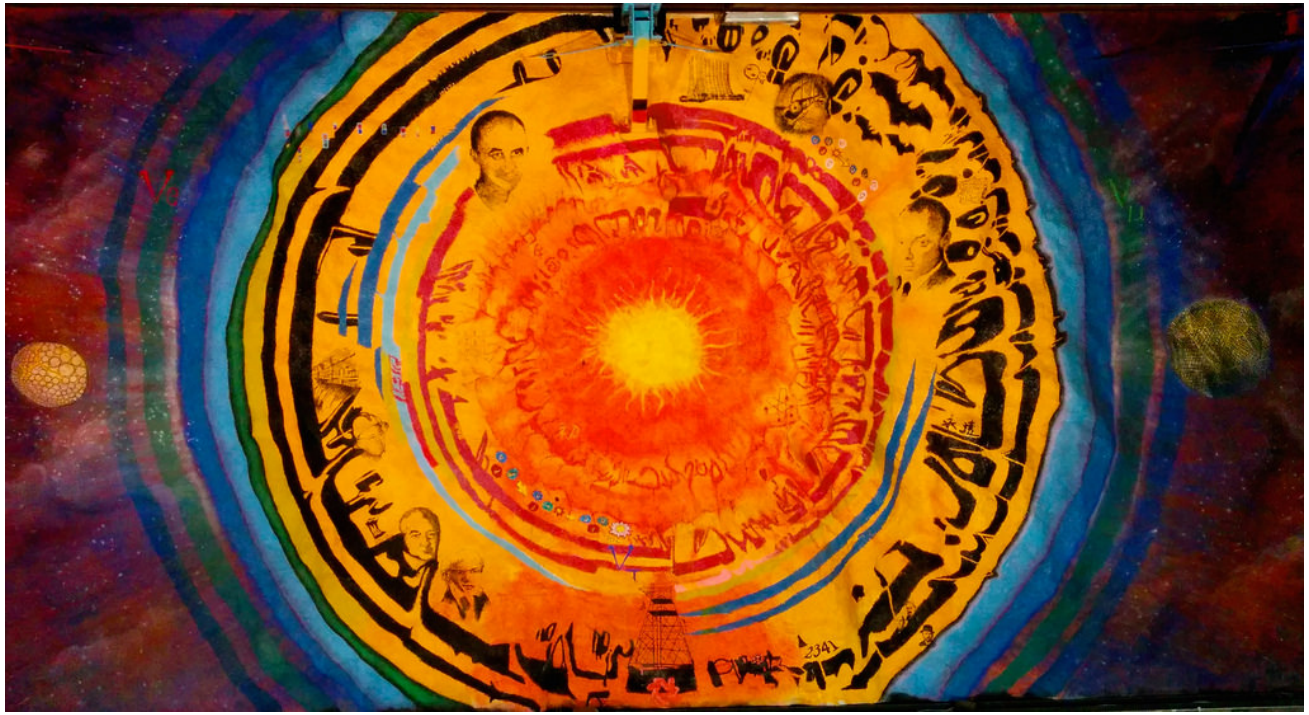
In limit of vanishing m_0, $R < 0.35\,\mu\text{m}$

Conclusions

- $R < 0.35\,\mu\text{m}$ at 90% C.L. for vanishing m_0
- Best limit on R from neutrino oscillation experiment
- Stronger limits than collider and tabletop gravitational experiments

Neutrino 2016

- Updates to MINOS analysis
- Inclusion of 5.8×10^{20} POT of MINOS+ data



References

[1] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B **429**, 263 (1998); I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. R. Divali, Phys. Lett. B **436**, 257 (1998);
N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Rev. D **59**, 086004 (1999).

[2] N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali, and J. March-Russell, Phys. Rev. D **65**, 024032 (2002)

[3] R. Barbieri, P. Creminelli, and A. Strumia, Nucl. Phys. B **585**, 28 (2000);
R. N. Mohapatra, S. Nandi, and A. Pérez-Lorenzana, Phys. Lett. B **466**, 115 (1999);
R. N. Mohapatra and A. Pérez-Lorenzana, Nucl. Phys. B **576**, 466 (2000);
R. N. Mohapatra and A. Pérez-Lorenzana, Nucl. Phys. B **593**, 451 (2001);
H. Davoudiasl, P. Langacker, and M. Perelstein, Phys. Rev. D **65**, 105015 (2002);
P. A. N. Machado, H. Nunokawa, and R. Zukanovich Funchal, Phys. Rev. D **84**, 013003 (2011).

Figures on slide 2:

- http://backreaction.blogspot.com/2006/07/extra-dimensions.html
- https://universe-review.ca/R15-17-relativity14.htm

Backup

Kaluza-Klein States

$$S = \int d^4x dy i\overline{\Psi}^\alpha \Gamma_A \partial^A \Psi^\alpha + \int d^4x \left(i\overline{\nu}_L^\alpha \gamma_\mu \partial^\mu \nu_L^\alpha + \lambda_{\alpha\beta} H \overline{\nu}_L^\alpha \psi_R^\beta(x,0) + \text{h.c.} \right)$$

Boundary conditions:

$$\Psi^\alpha(x,y) = \Psi^\alpha(x, y + 2\pi R)$$

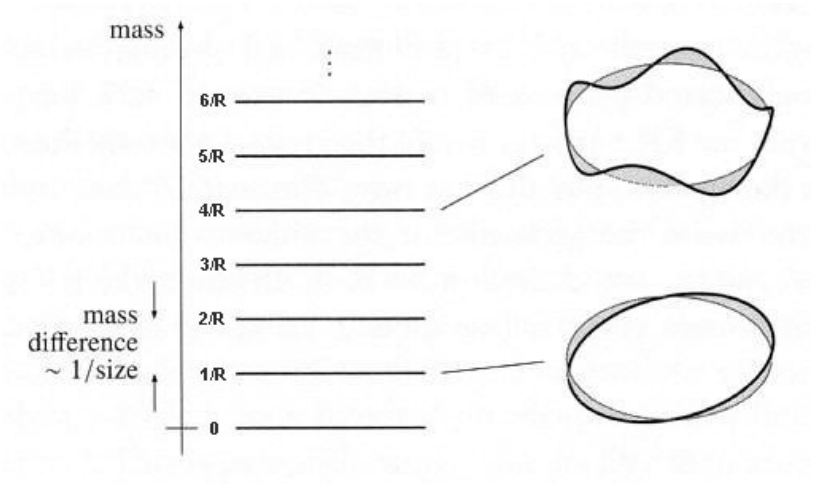
$$\psi_{L,R}^\alpha(x,y) = \sum_{n=-\infty}^{+\infty} \frac{1}{\sqrt{2\pi R}} \psi_{L,R}^{\alpha(n)} \exp\left(-i\frac{ny}{R}\right)$$

States coupling to ν_L^β:

$$\nu_R^{\alpha(0)} = \psi_R^{\alpha(0)}$$

$$\nu_R^{\alpha(n)} = \frac{1}{\sqrt{2}} \left(\psi_R^{\alpha(n)} + \psi_R^{\alpha(n)} \right)$$

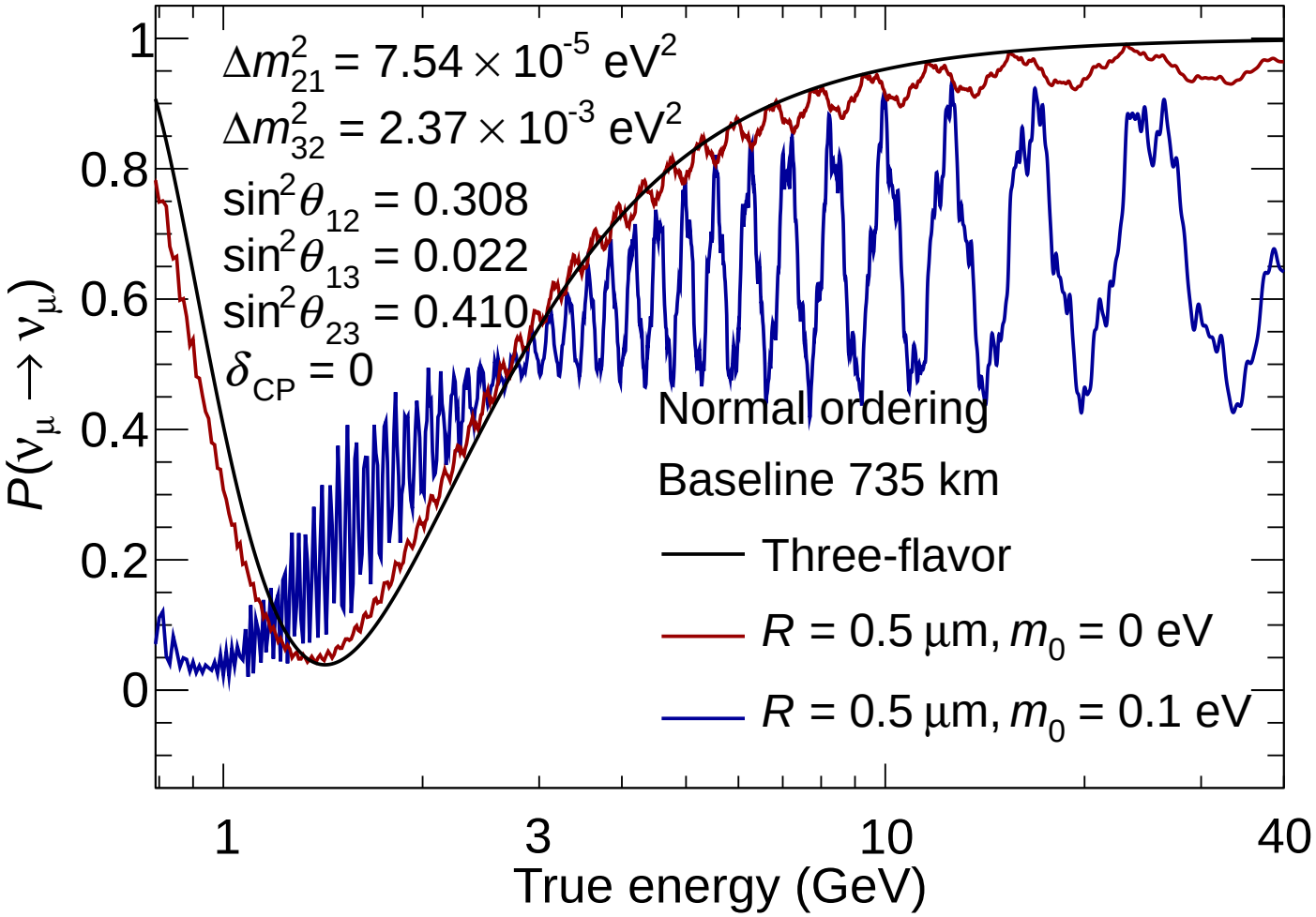
$$\nu_L^{\alpha(n)} = \frac{1}{\sqrt{2}} \left(\psi_L^{\alpha(n)} + \psi_L^{\alpha(n)} \right)$$



$$m_{\alpha\beta}^D \left(\nu_R^{\alpha(0)} \nu_L^\beta + \sqrt{2} \sum_{n=1}^{\infty} \overline{\nu}_R^{\alpha(n)} \nu_L^\beta \right) + \sum_{n=1}^{\infty} \frac{n}{R} \overline{\nu}_R^{\alpha(n)} \nu_L^{\alpha(n)}$$

Far Detector Disappearance Probability

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



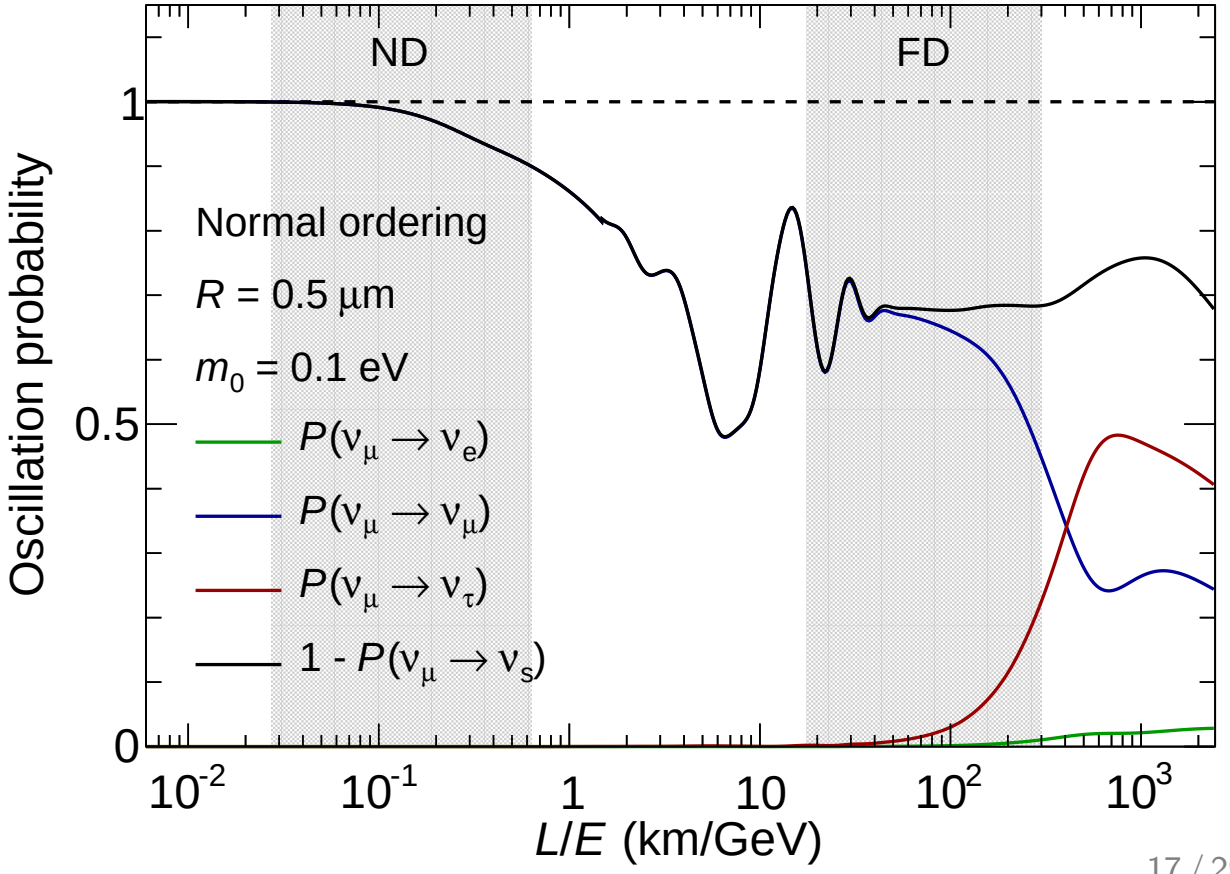
Sterile Appearance Oscillation Probability

$$\mathcal{A}\left(\nu_\alpha \to \nu_s\right) = \sum_{n=1}^{+\infty} \sum_{\beta=e,\mu,\tau} \mathcal{A}\left(\nu_L^{\alpha(0)} \to \nu_L^{\beta(n)}\right)$$

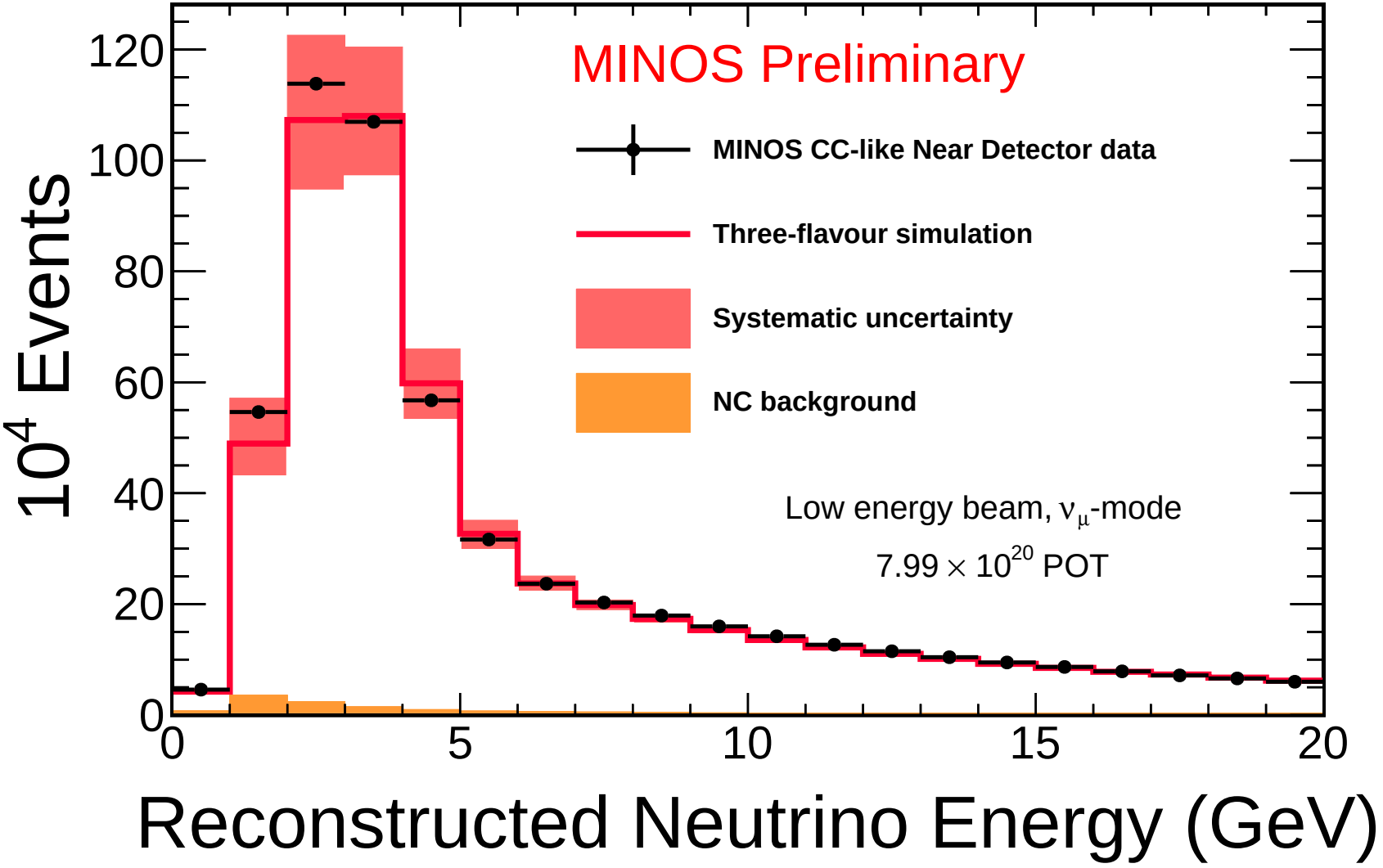
$$= \sum_{n=1}^{+\infty} \sum_{\beta=e,\mu,\tau} \sum_{i,j,k=1}^{3} \sum_{r=0}^{+\infty} U_{\alpha i} U_{\beta k}^{*} W_{ij}^{(0r)*} W_{kj}^{(nr)} \times \exp\left[i \left(\frac{\lambda_j^{(r)}}{R}\right)^2 \left(\frac{L}{2E}\right)\right]$$

In practice

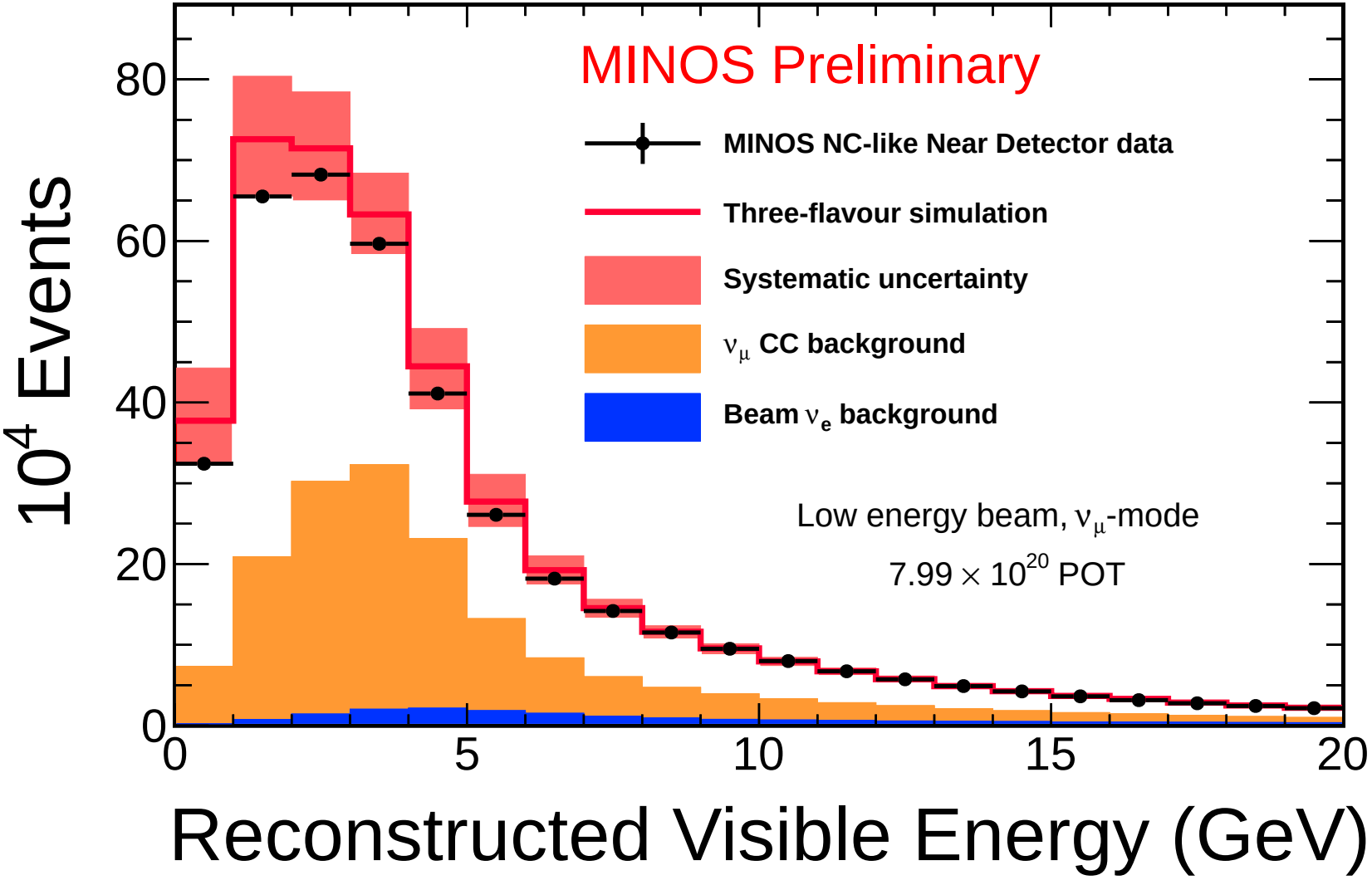
$$P\left(\nu_\alpha \to \nu_s\right) = 1 - \sum_{\beta=e,\mu,\tau} P\left(\nu_\alpha \to \nu_\beta\right)$$



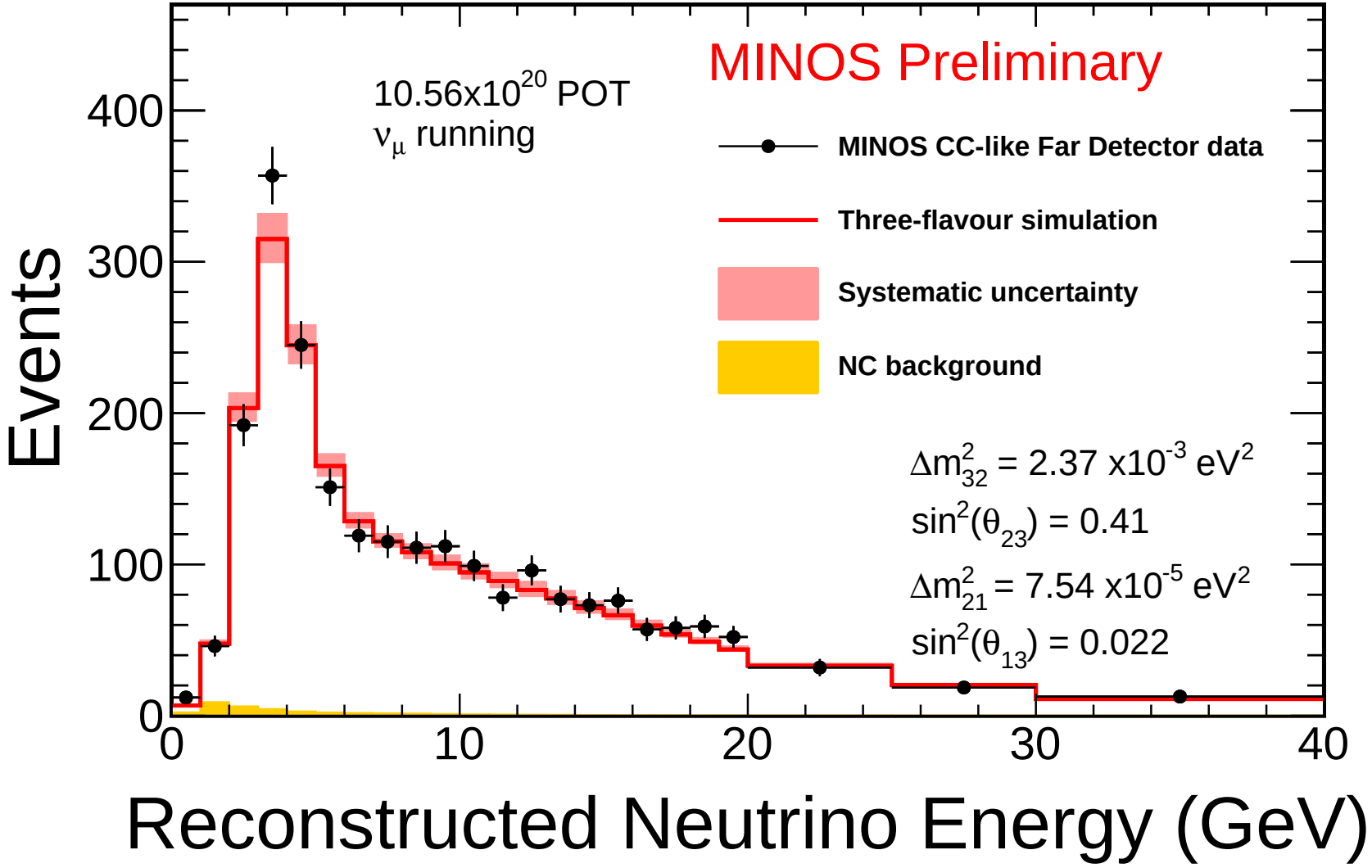
Near Detector CC Spectra



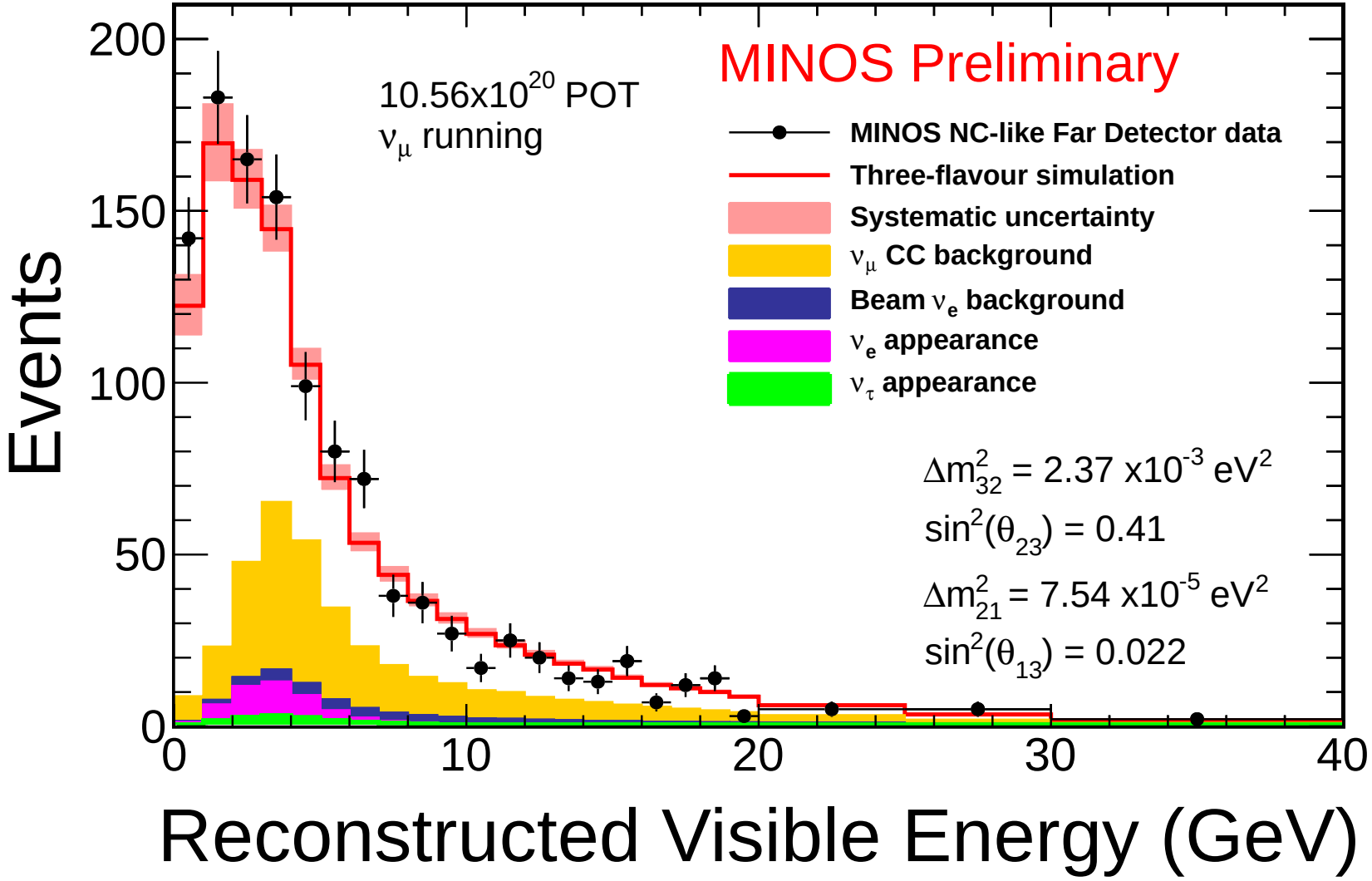
Near Detector NC Spectra



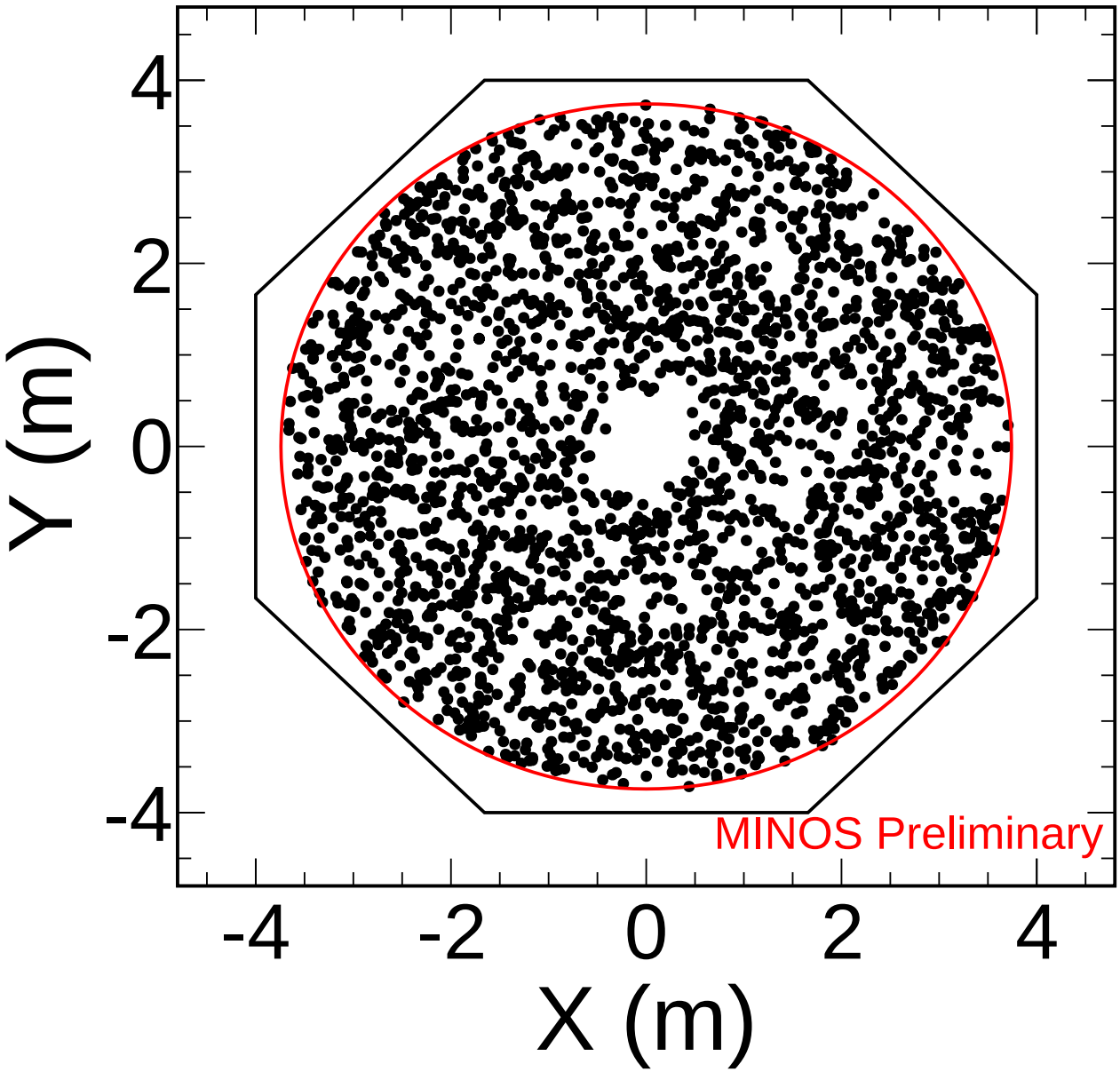
Far Detector CC Spectra



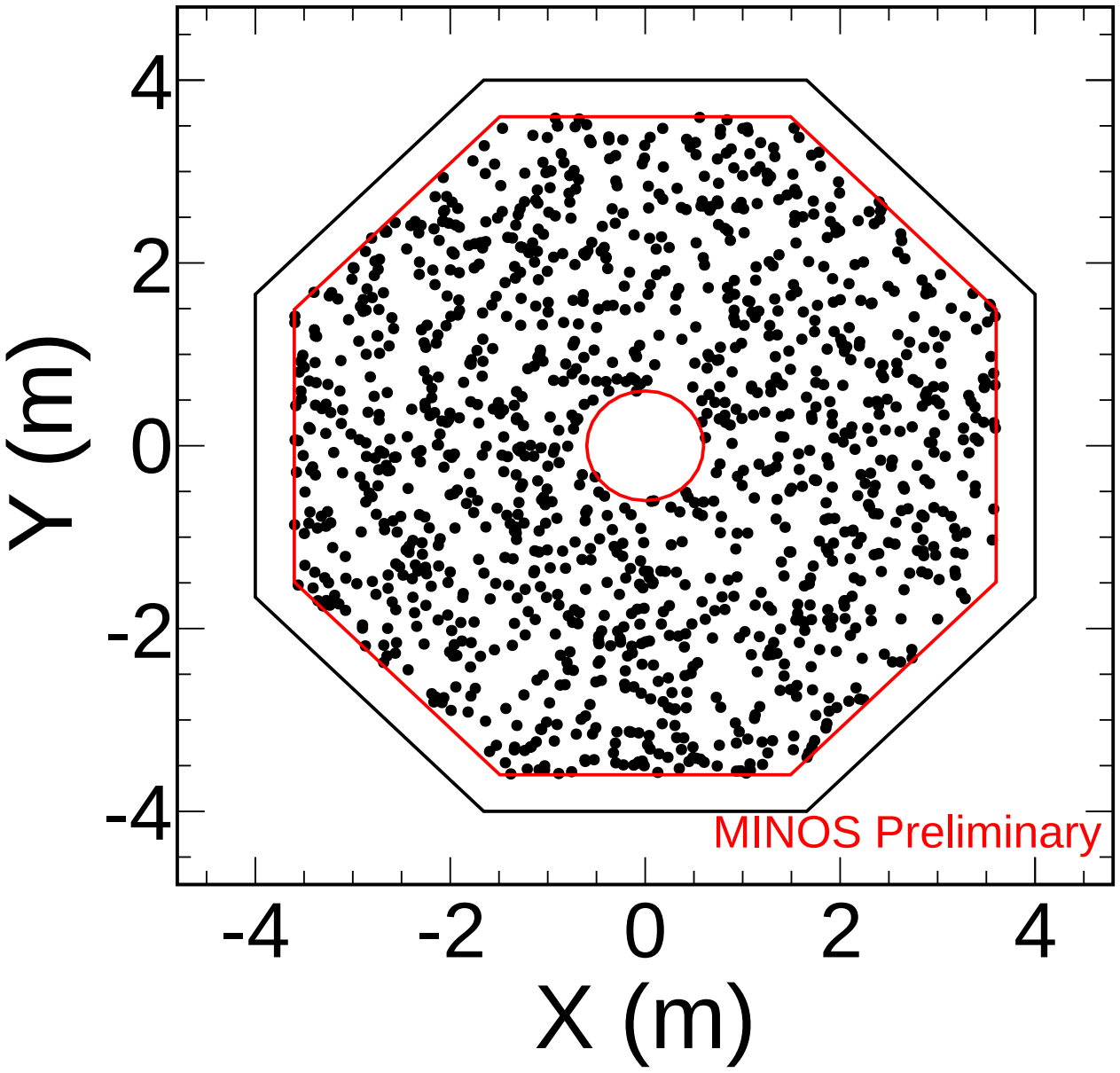
Far Detector NC Spectra



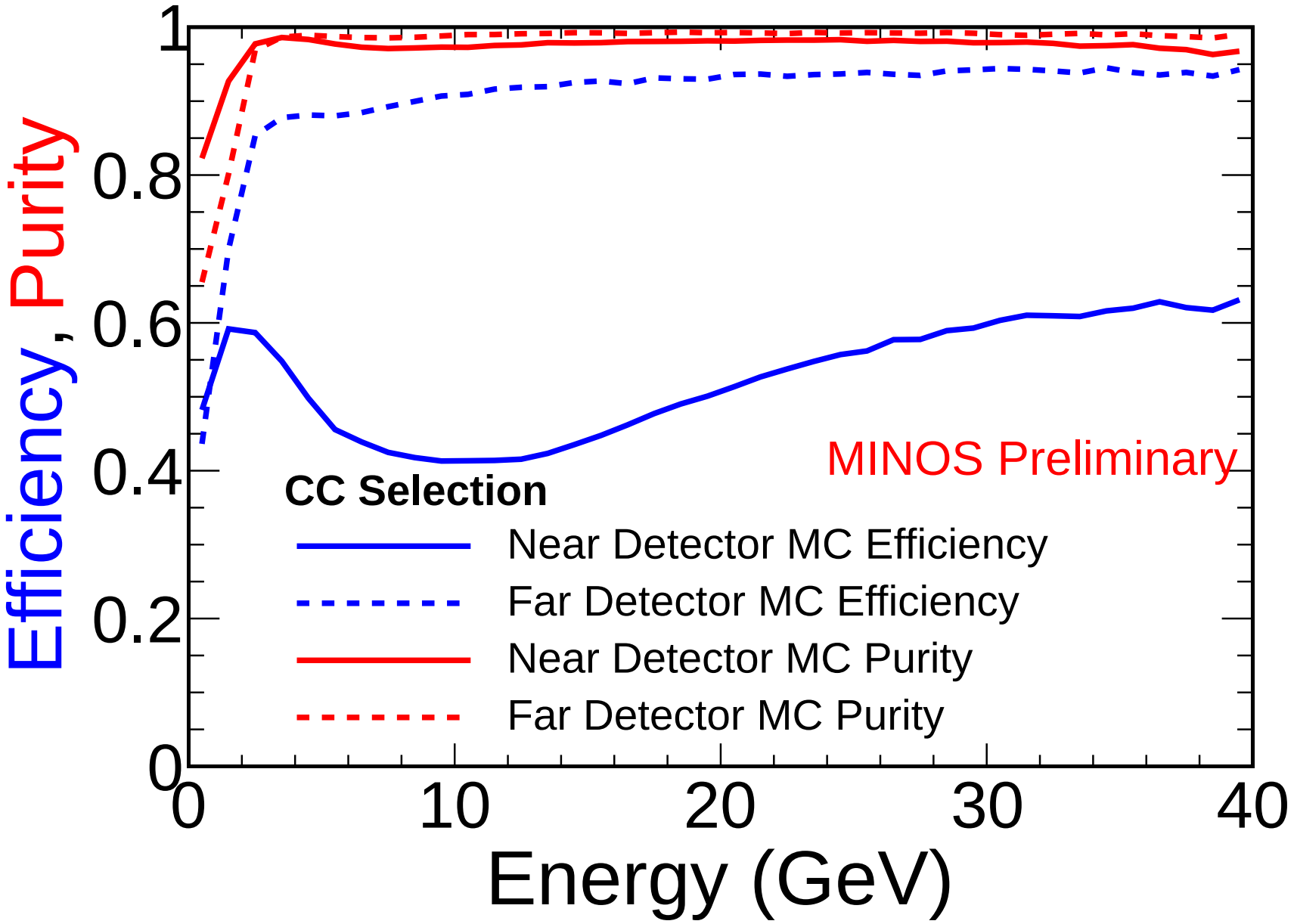
Far Detector CC Event Vertices



Far Detector NC Event Vertices



CC Efficiency and Purity



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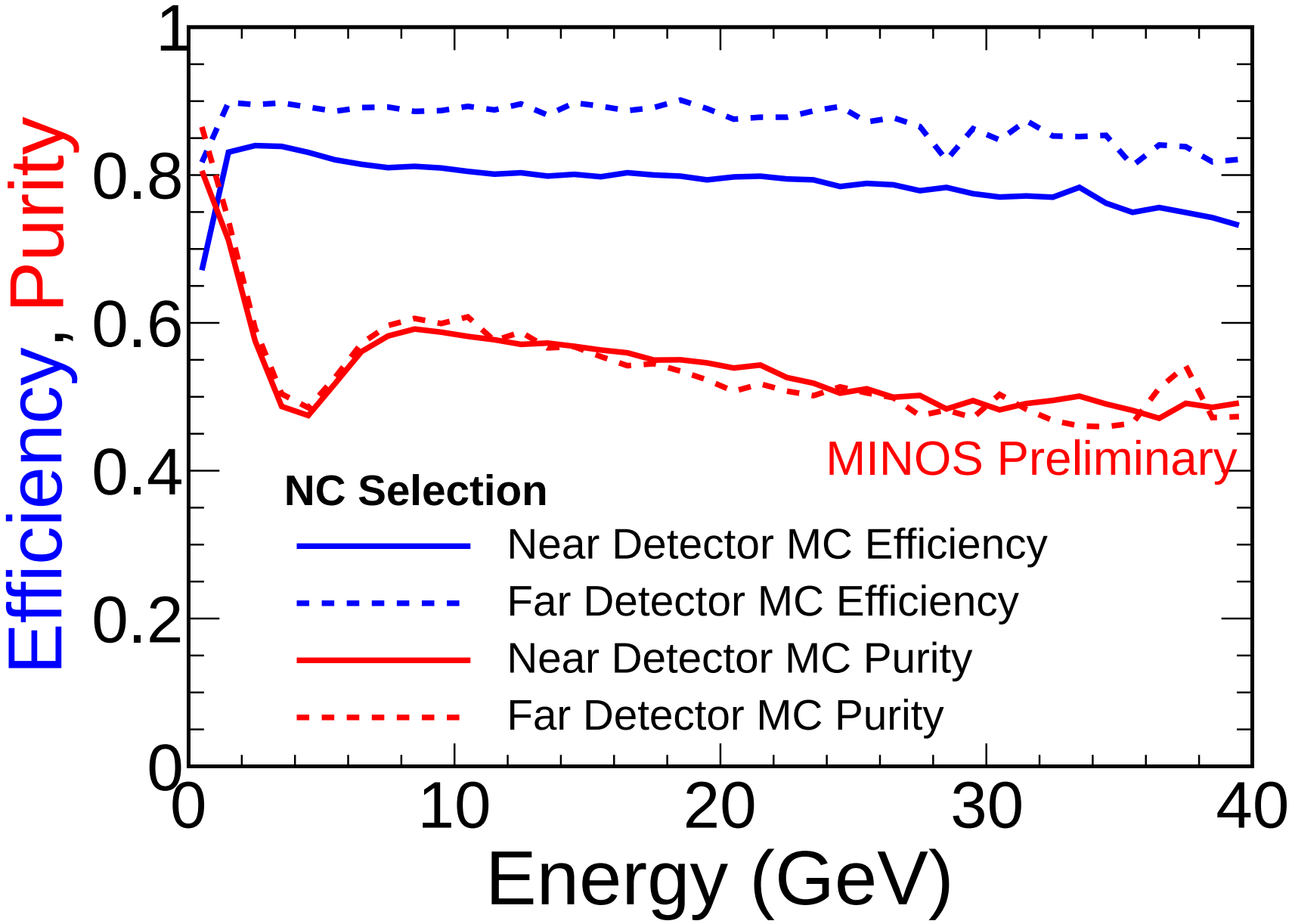
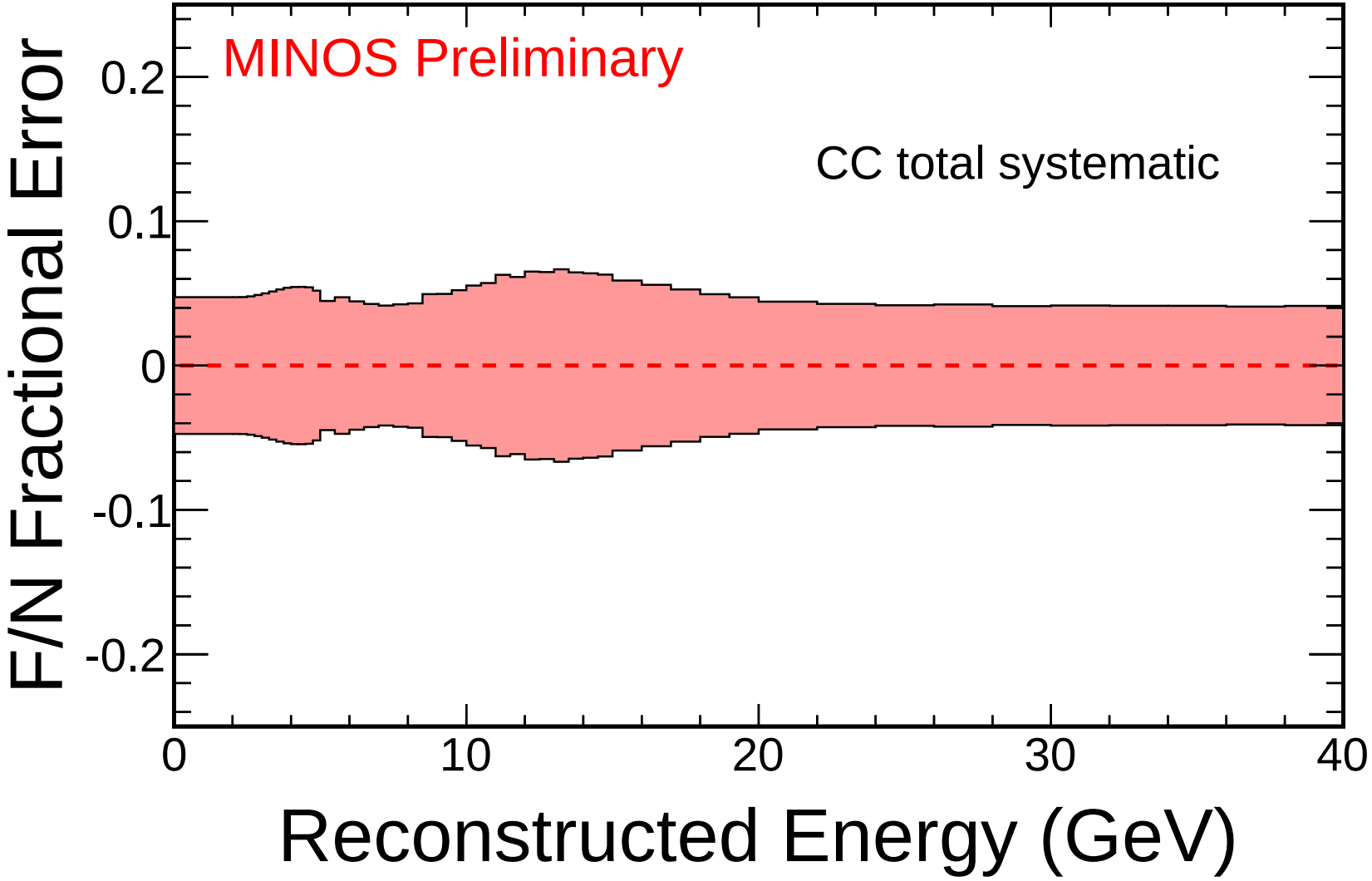
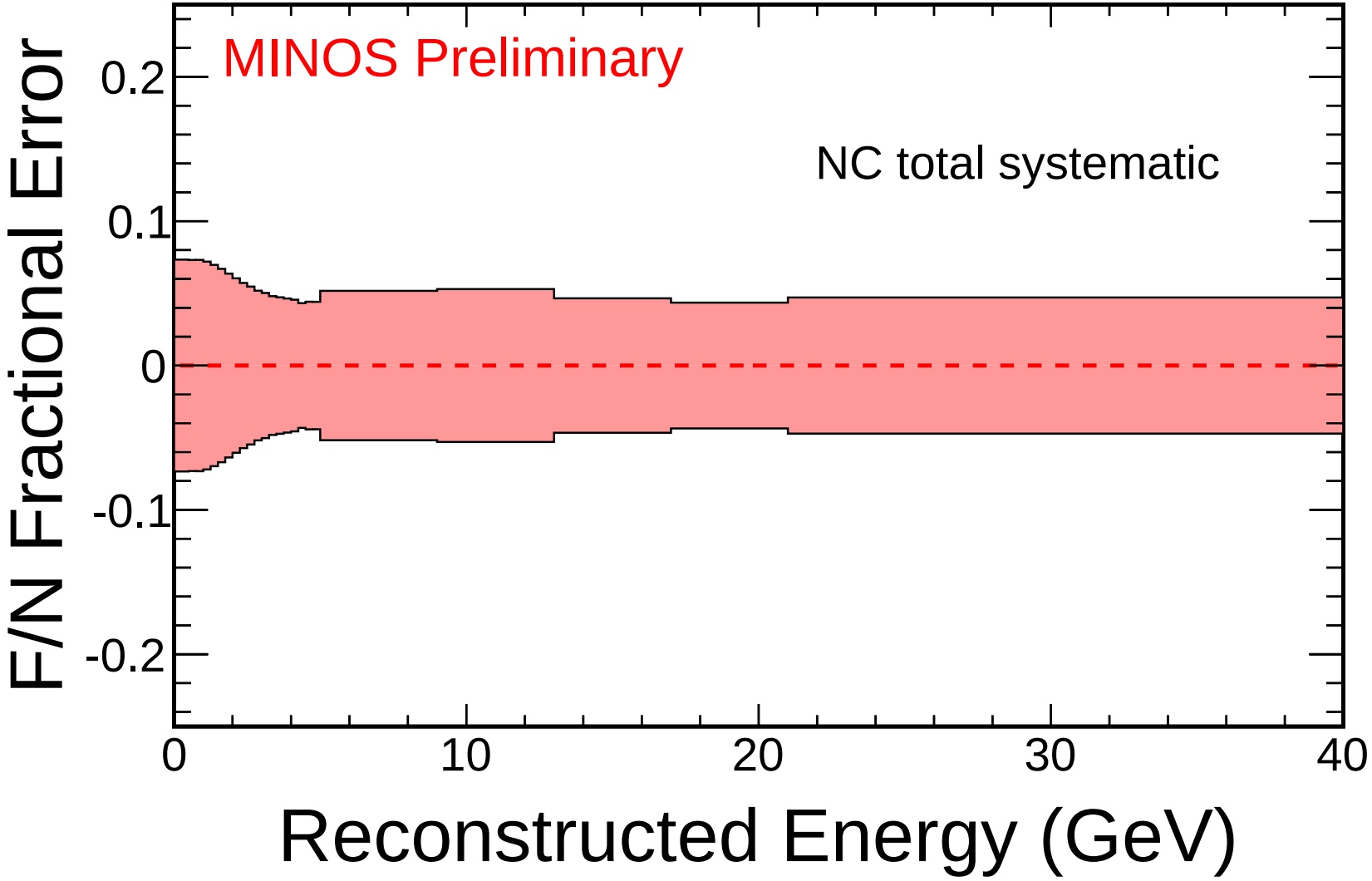


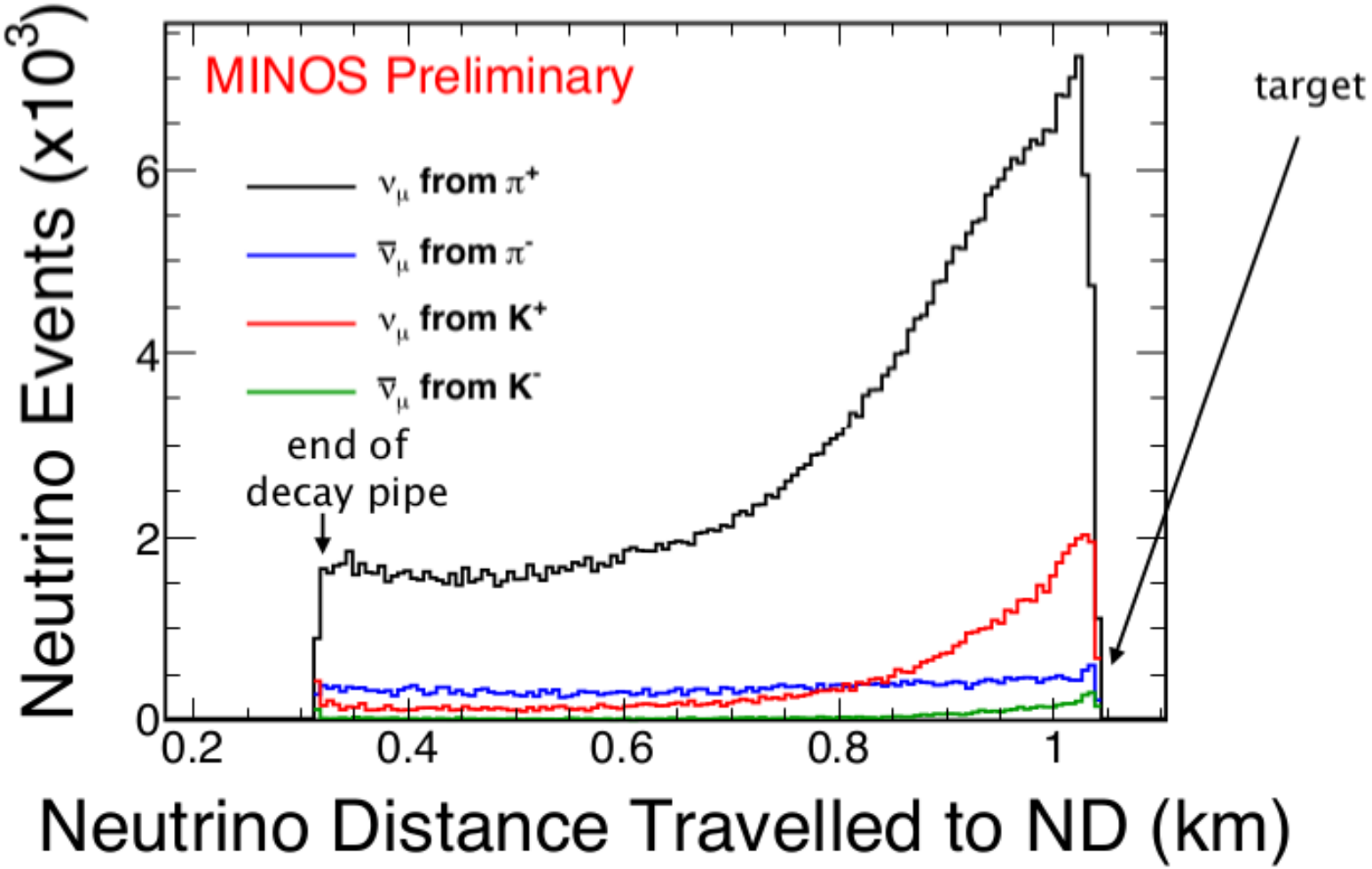
CC Total Fractional Systematic



NC Total Fractional Systematic



Near Detector Oscillation



To properly model Near Detector oscillation, it is crucial that we account for the baseline varying due to the distribution of hadron decay points within the 675 m decay pipe.