

フェルミ研ブースター
ニュートリノビームを用いた
短基線ニュートリノ振動の探索

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ICEPPシンポジウム

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- ニュートリノ振動解析

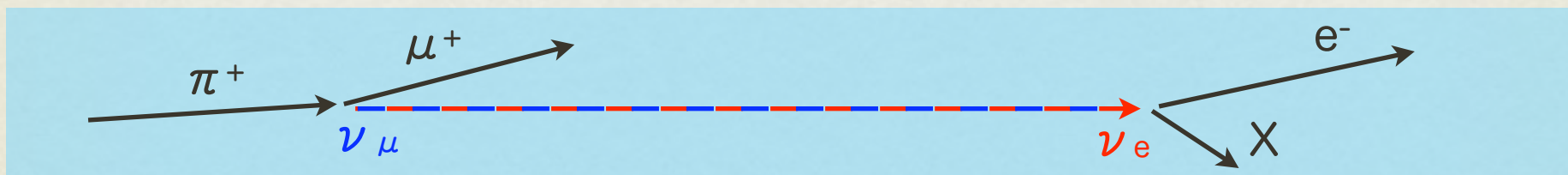
Introduction

Neutrino Oscillation

- ニュートリノ振動：
- ニュートリノのフレーバー固有状態と質量固有状態が混合しているため、時間(飛行距離)とともにフレーバーが変化する現象。

$$|\nu_\alpha(t=0)\rangle = \sum_i U_{\alpha i} |\nu_i\rangle. \quad \begin{array}{l} \alpha = e, \mu, \tau \text{ (フレーバー固有状態)} \\ i = 1, 2, 3 \text{ (質量固有状態)} \end{array}$$

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & s_{13}e^{-i\delta} & \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \quad \begin{array}{l} \text{MNS行列} \\ s_{ij} = \sin \theta_{ij}, c_{ij} = \cos \theta_{ij} \end{array}$$



$$P_{\alpha \rightarrow \beta} = \left| \langle \nu_\beta(t) | \nu_\alpha(0) \rangle \right|^2 \quad \text{振動確率}$$

$$= \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right)$$

θ : 混合の大きさ
 Δm^2 : ニュートリノ質量二乗差
 L : 飛行距離
 E : ニュートリノエネルギー

Neutrino Oscillations

- Atmospheric region: $\Delta m^2 \sim 10^{-3} \text{ eV}^2$

- Super-K, K2K, MINOS, etc

- Solar region: $\Delta m^2 \sim 10^{-5} \text{ eV}^2$

- SNO, Super-K, KamLAND, etc.

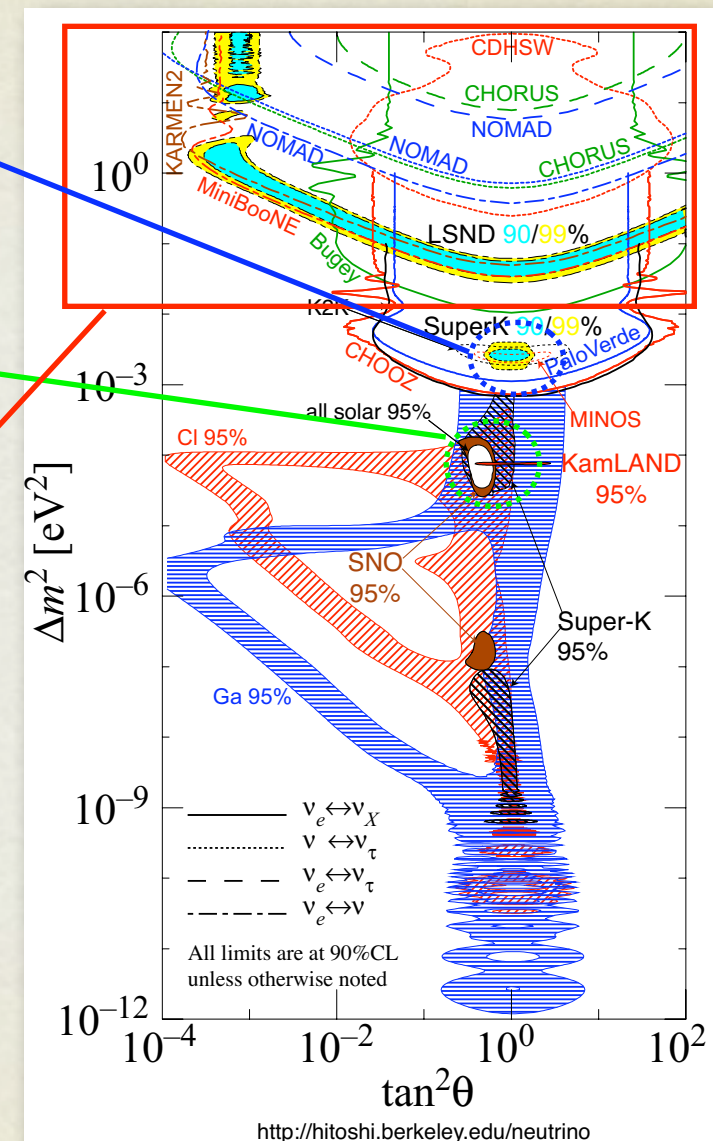
Only 2 Δm^2 regions are allowed in the current

SM with 3 neutrino generations

- High Δm^2 region: $\Delta m^2 \sim 1 \text{ eV}^2$

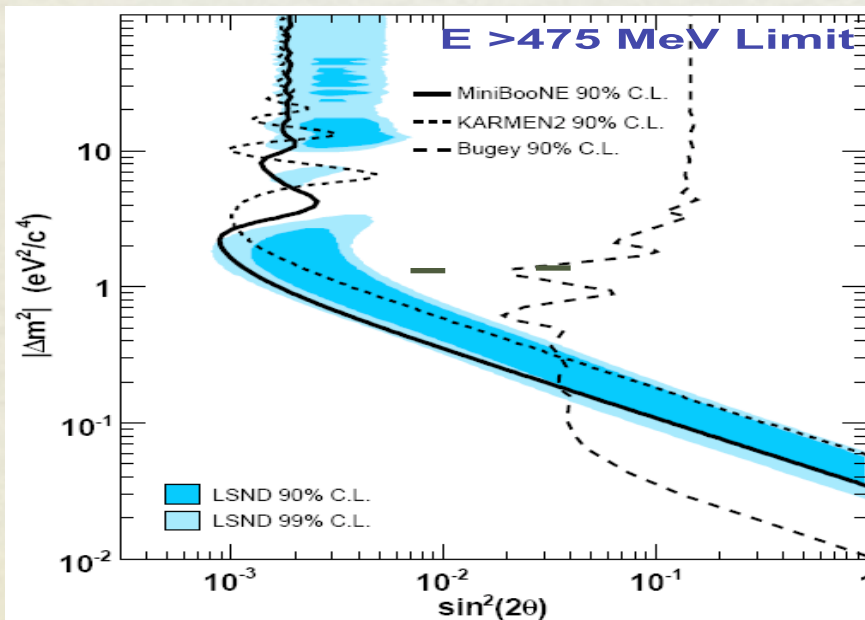
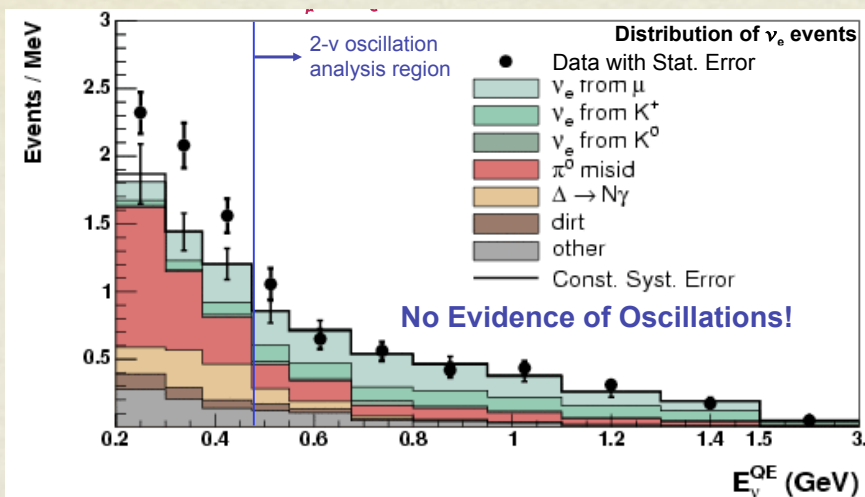
- Observed at LSND ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

- Ruled out by MiniBooNE
if $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

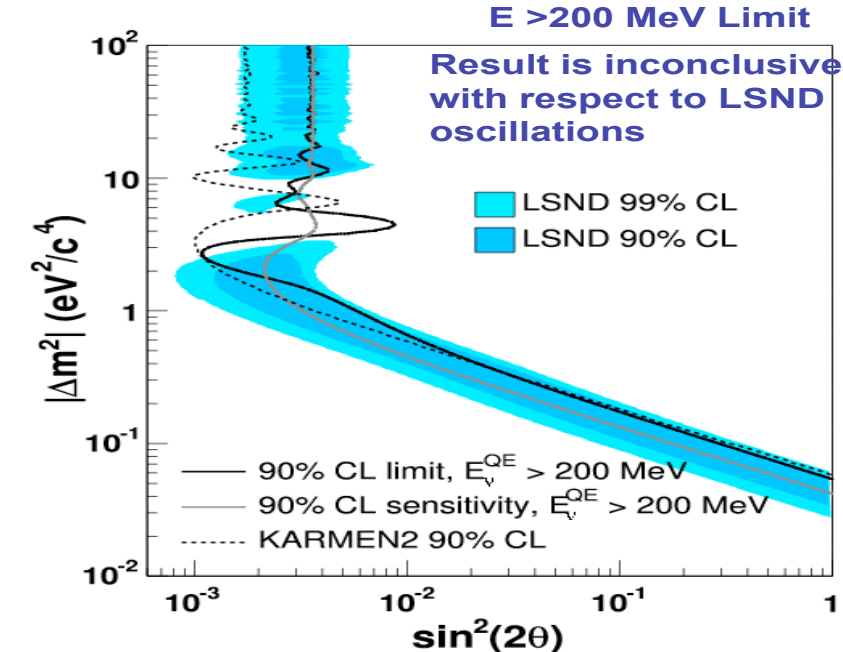
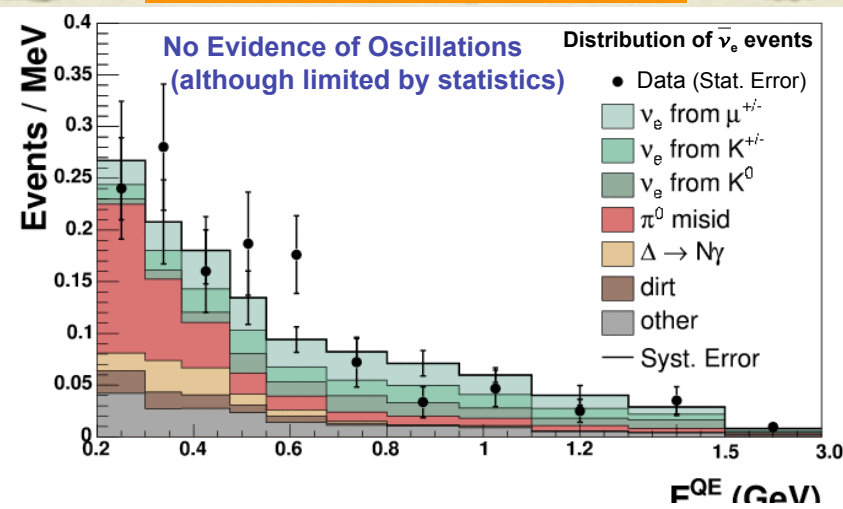


MiniBooNE ν_e results

$\nu_\mu \rightarrow \nu_e$ 探索

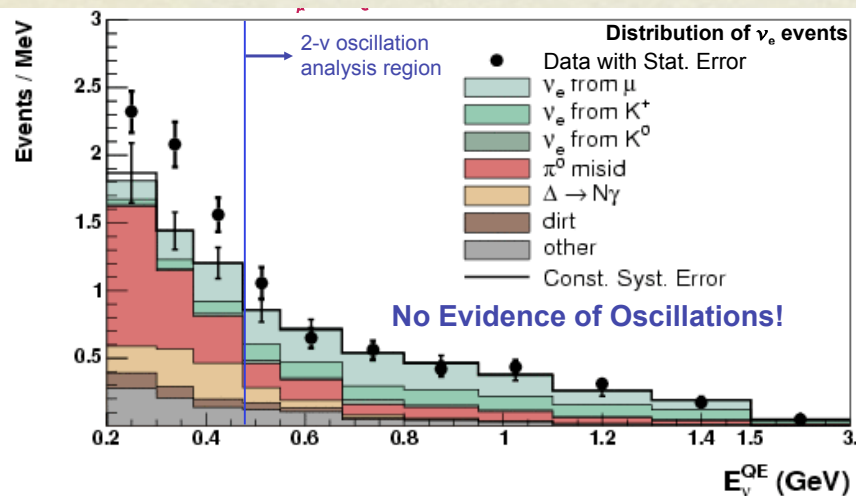


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 探索

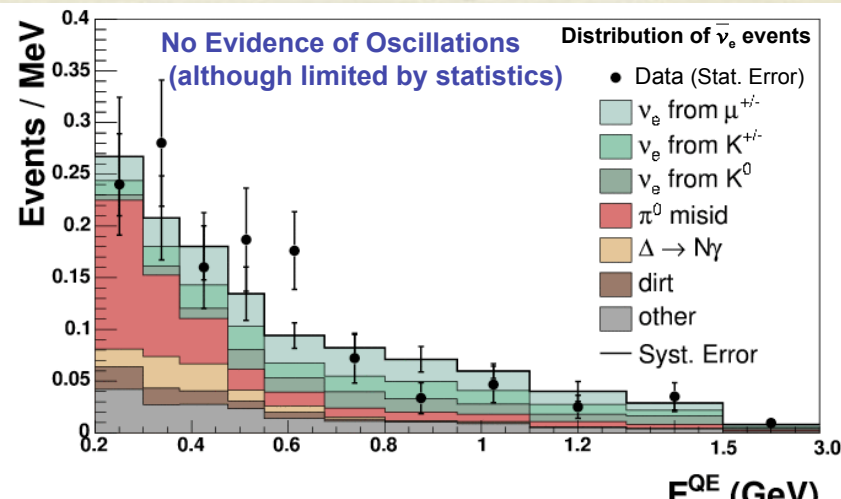


MiniBooNE ν_e results

$\nu_\mu \rightarrow \nu_e$ 探索

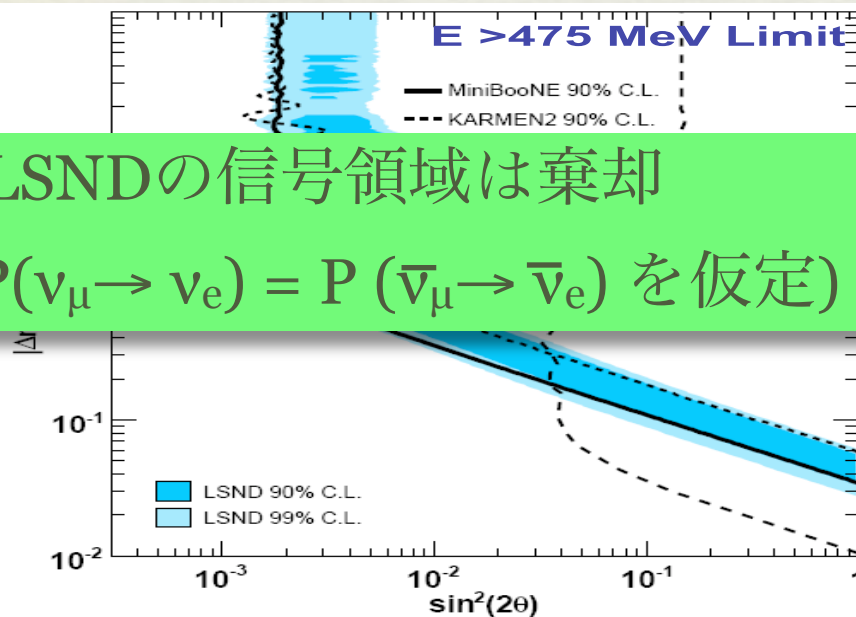


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 探索

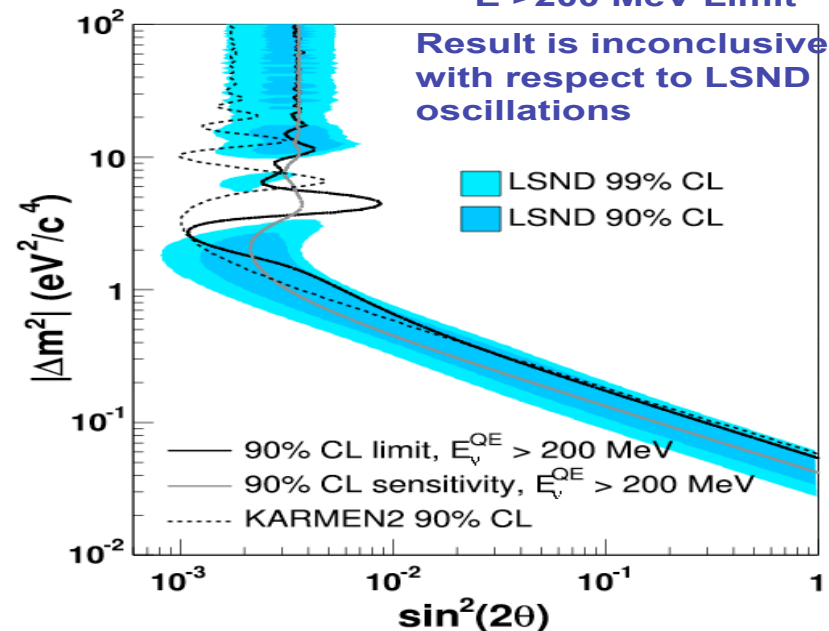


LSNDの信号領域は棄却

($P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ を仮定)

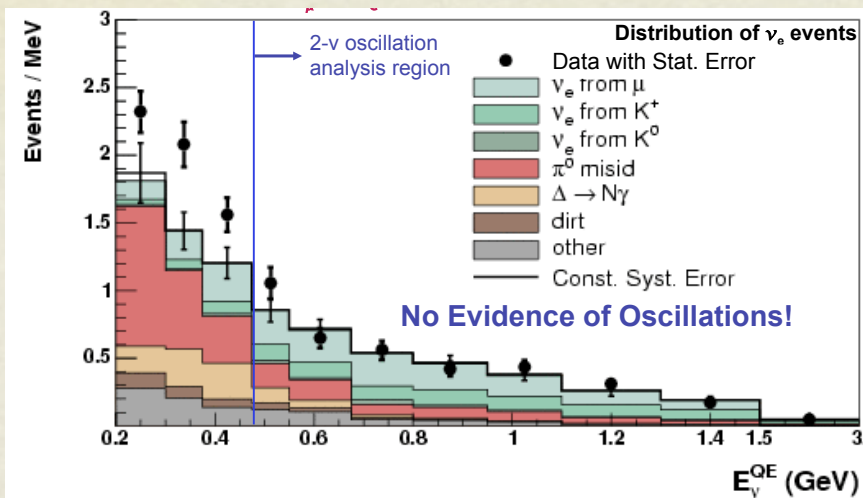


E > 200 MeV Limit

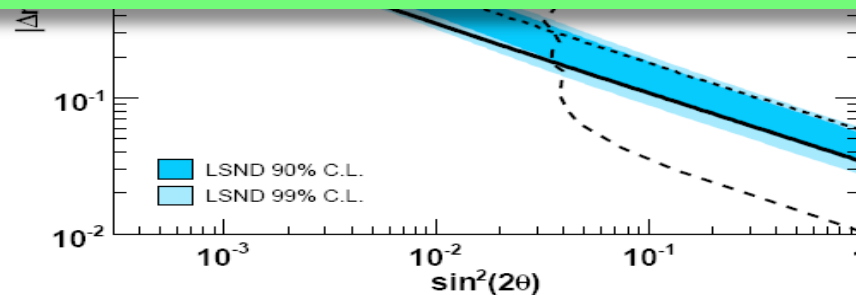


MiniBooNE ν_e results

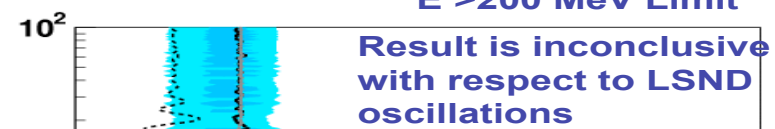
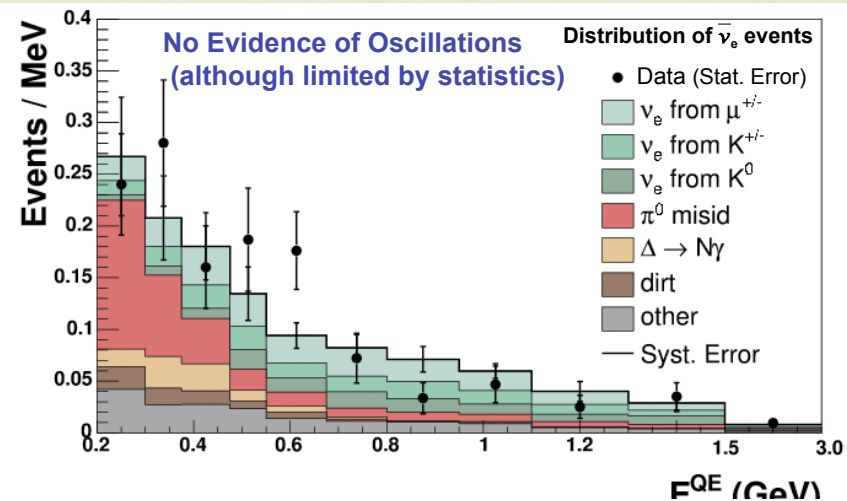
$\nu_\mu \rightarrow \nu_e$ 探索



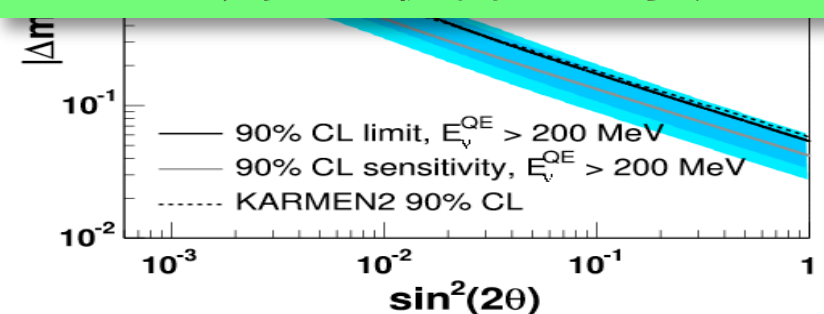
LSNDの信号領域は棄却
($P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ を仮定)



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 探索



LSND領域をテストするには
もう少し統計が必要



Possible Scenarios

(ニュートリノ振動の枠組みの中では)

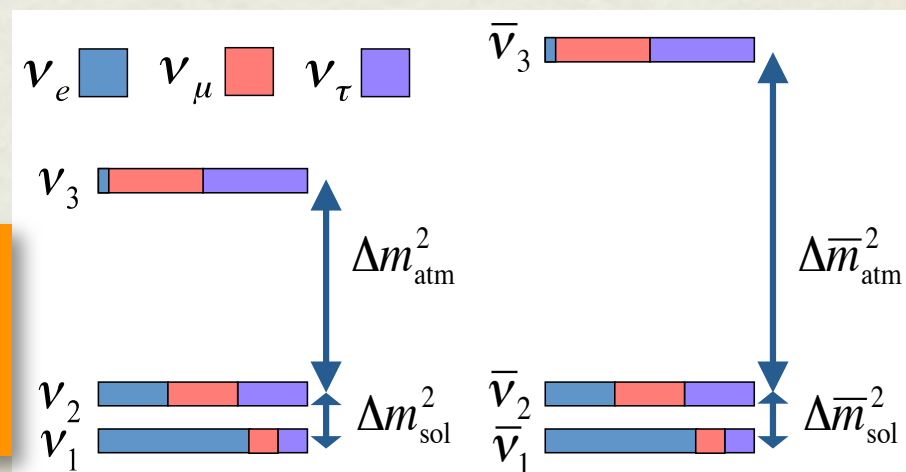
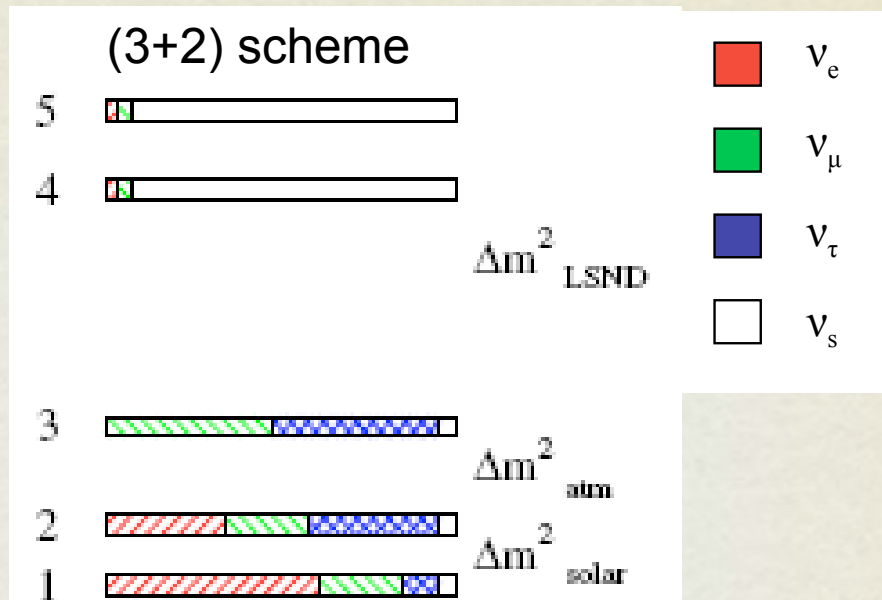
- “Sterile” ニュートリノ との振動 + CP-violation

- CPの破れは混合行列の複素位相

- (Effective) CPT-violation

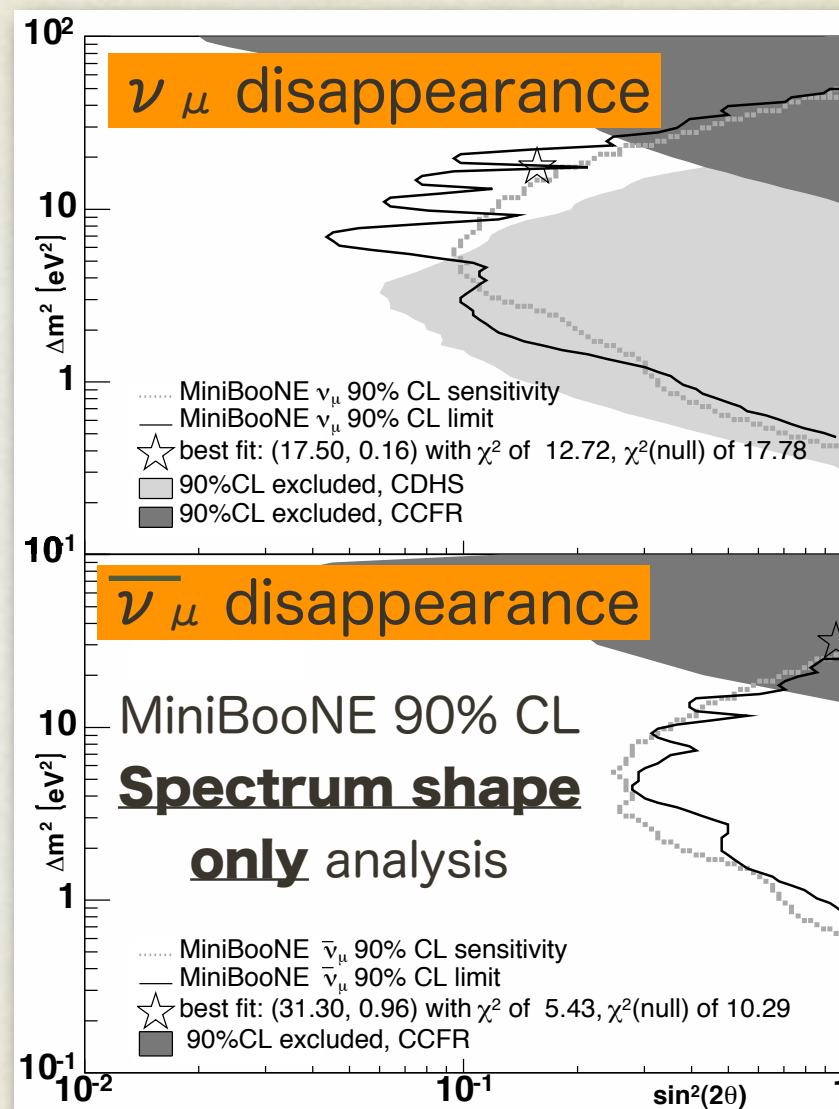
- Δm^2 が ν と anti- ν で違う

ν_μ /anti- ν_μ 消失を測定することによって
 これらのモデルを検証可能



Search for Muon Neutrino Disappearance at high Δm^2

- MiniBooNEのデータのみを用いた解析
- スペクトラムの「形」のみを用いた解析
- フラックスと断面積の不定性大
- 前置検出器(SciBooNE)を用いればより高い感度での探索が可能！



Phys. Rev. Lett. 103, 061802 (2009)



SciBooNE Detector Installation April, 2007

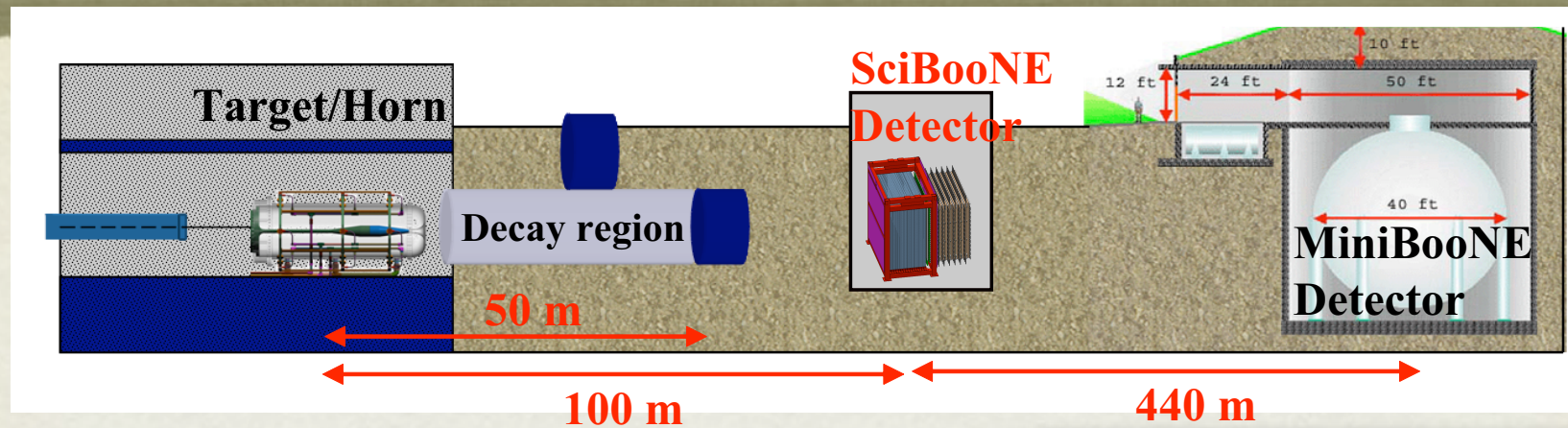
Experimental Setup

Sci-/Mini-BooNE Sites

Fermilab



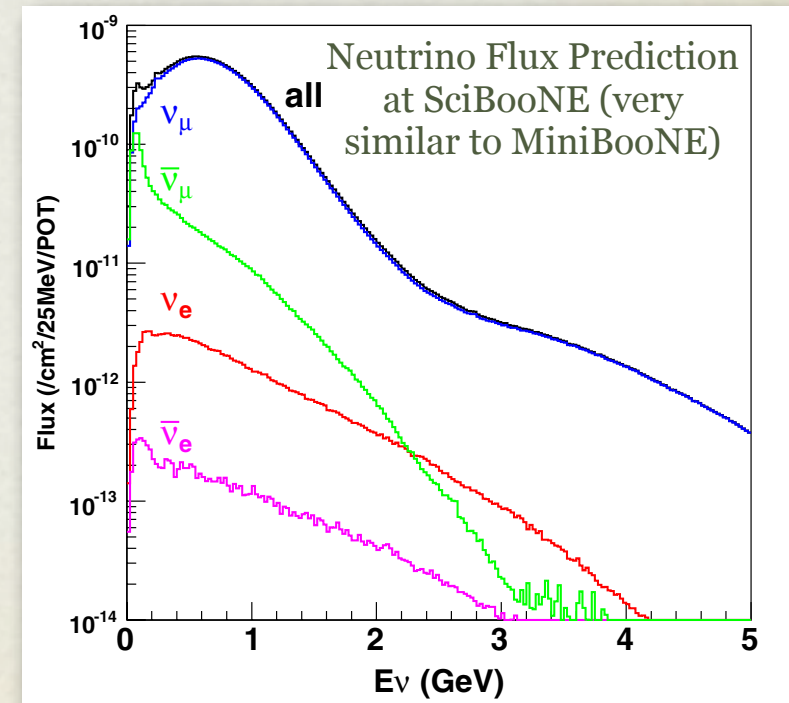
Fermilab Booster Neutrino Beamline



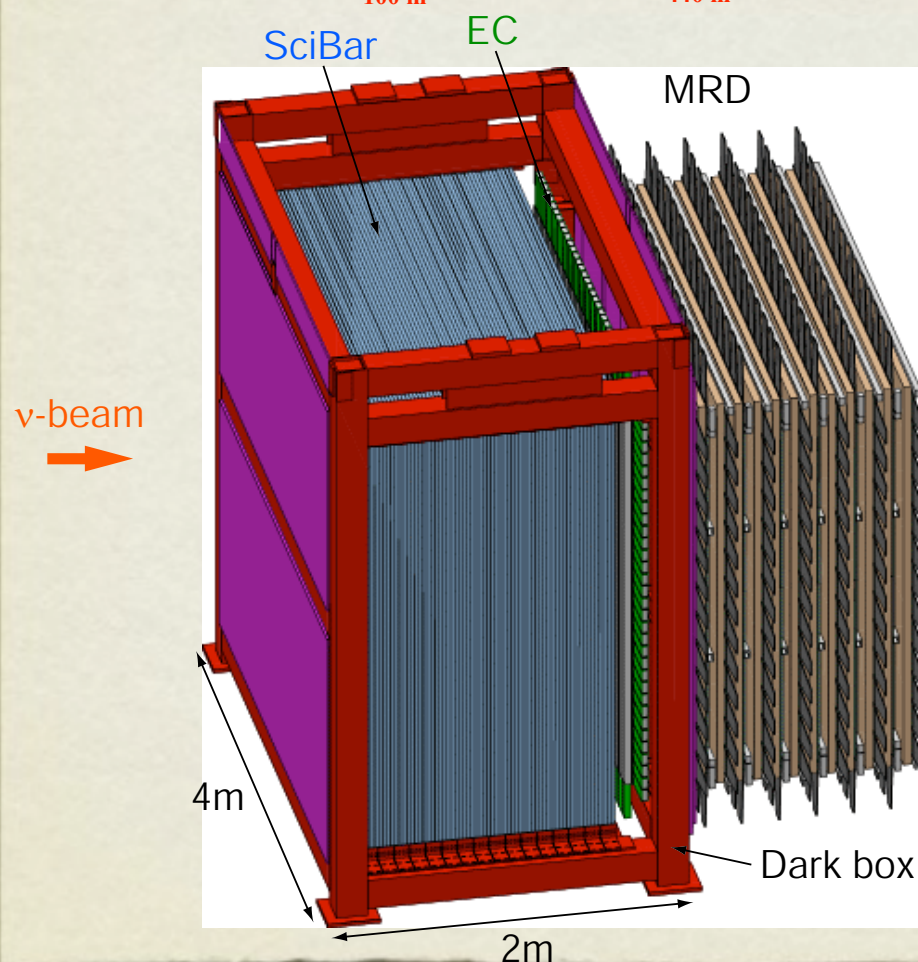
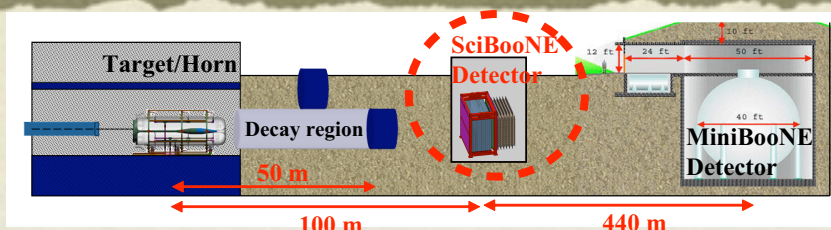
- High intensity Neutrino and Anti-Neutrino beam
 - $E_\nu \sim 1 \text{ GeV}$
- Neutrino Fluxes are measured at 2 detectors: SciBooNE and MiniBooNE
 - $L \sim 500 \text{ m}$

Sensitive to Oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right)$$



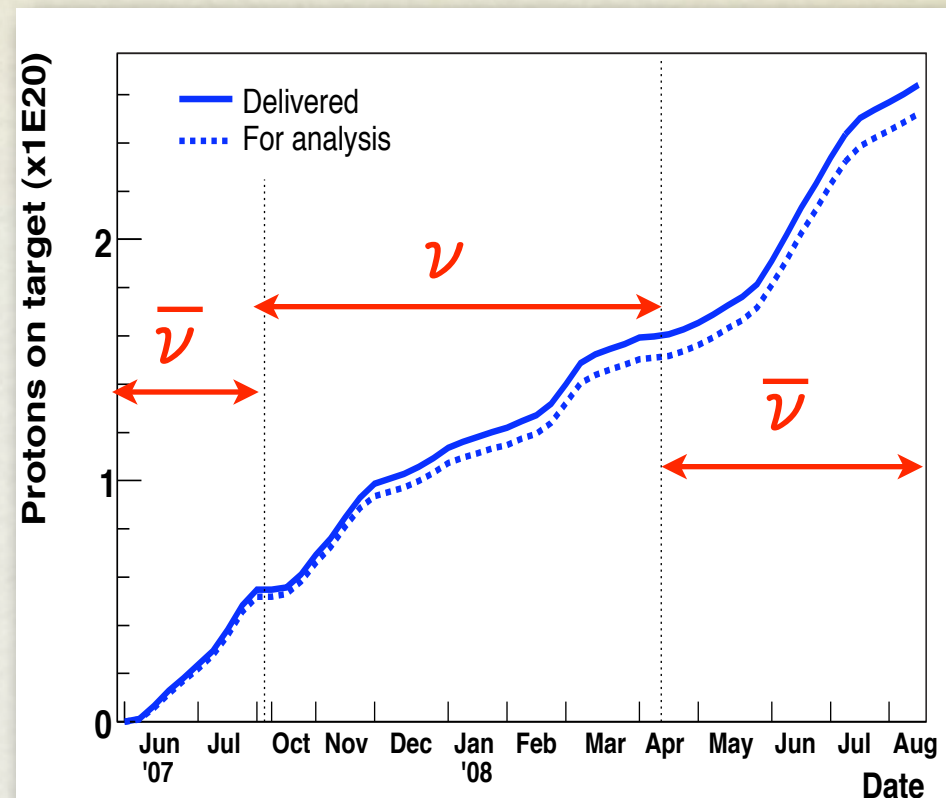
SciBooNE Detector



- SciBar:
 - Full active scintillator tracker (~14000 strips)
 - Neutrino Target
 - Fiducial volume: ~10 tons
 - Main component: CH
- Electron Catcher (EC)
 - “Spaghetti” type calorimeter
- Muon Range Detector (MRD)
 - Steel and scintillator sandwich
 - Measure muon momentum from its range

SciBooNE Data Taking

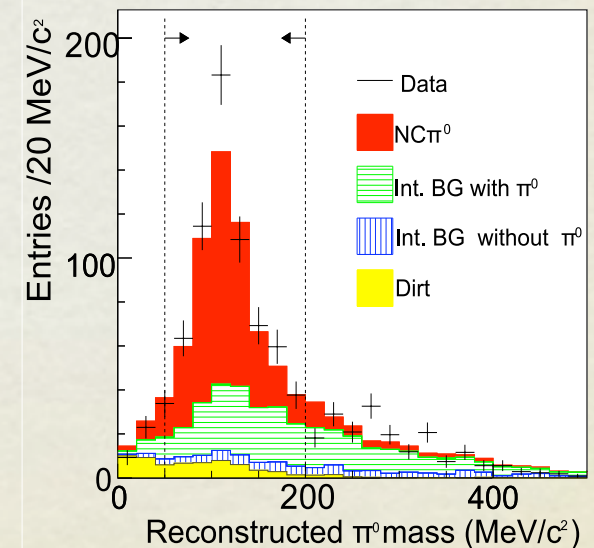
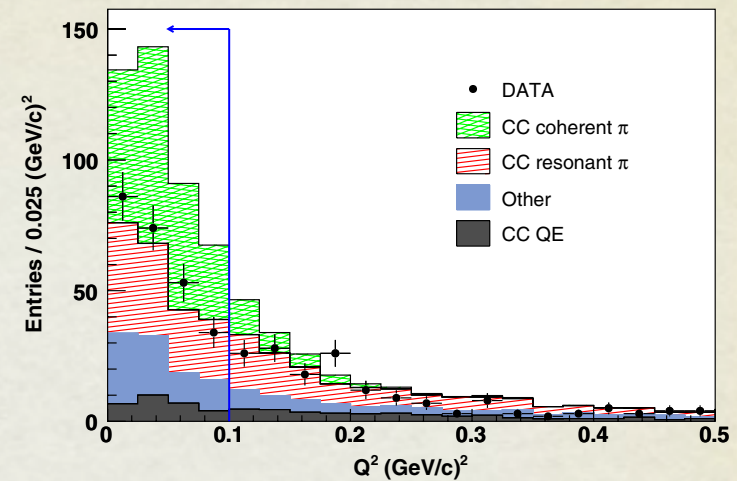
- Started beam data taking on July 2007
- Data taking completed in August 2008
- Stable data taking
- Total 2.52×10^{20} POT for analysis (95% of delivered)
 - Neutrino: 0.99×10^{20} POT
 - Anti-Neutrino: 1.53×10^{20} POT



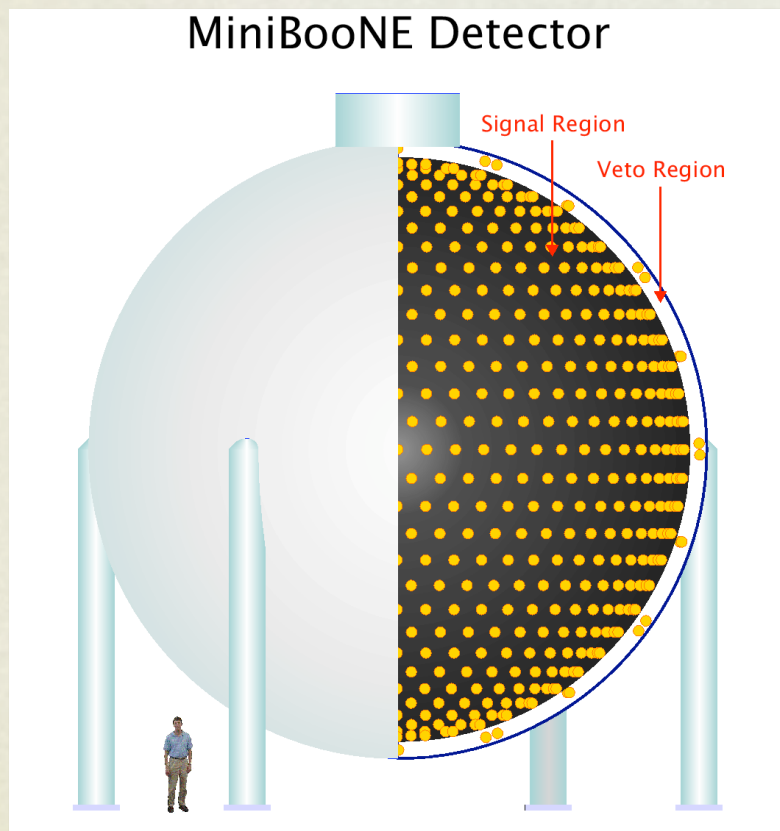
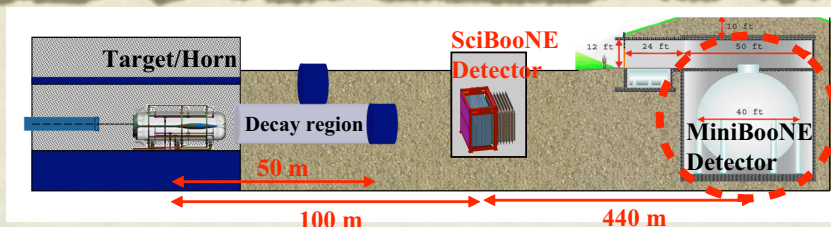
今日は主にニュートリノモード
の解析について話します。

SciBooNE Cross-Section Results

- SciBooNE実験の（もう一つの）主目的は、将来のニュートリノ振動実験のための、反応断面積精密測定。
- 荷電カレントコヒーレント π 生成反応
 - この反応が理論予想に比べて有意に少ないことを発見
- Phys. Rev. D78, 112004 (2008)
- 中性カレント π^0 生成反応
 - Phys. Rev. D81, 033004 (2010)

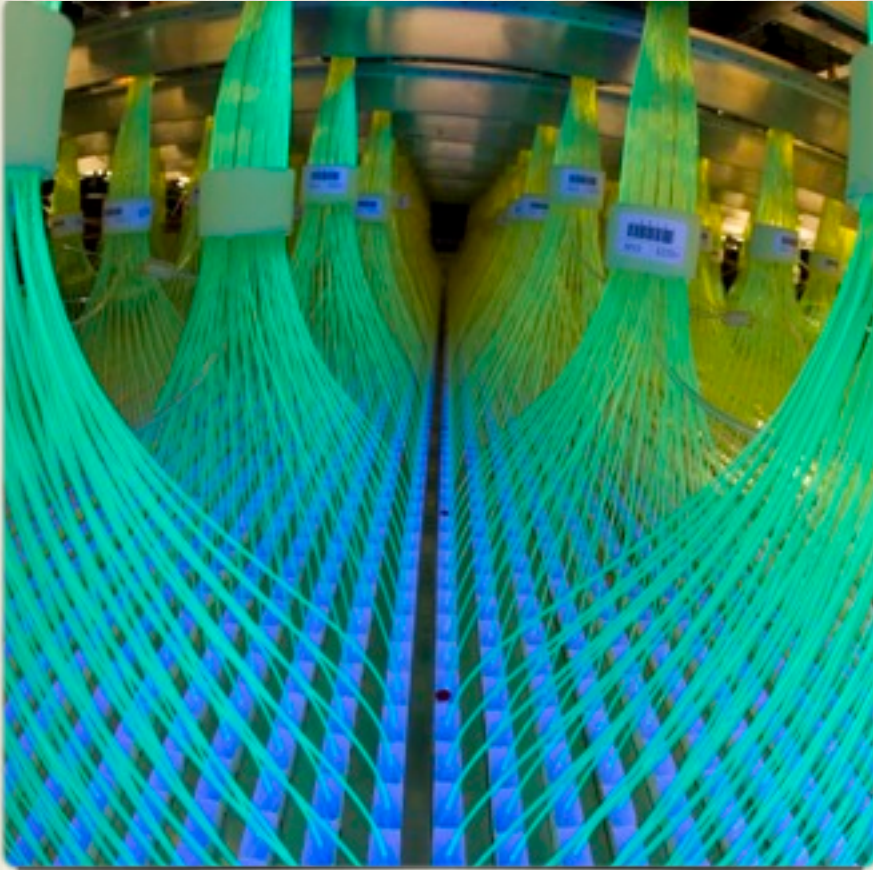


MiniBooNE Detector

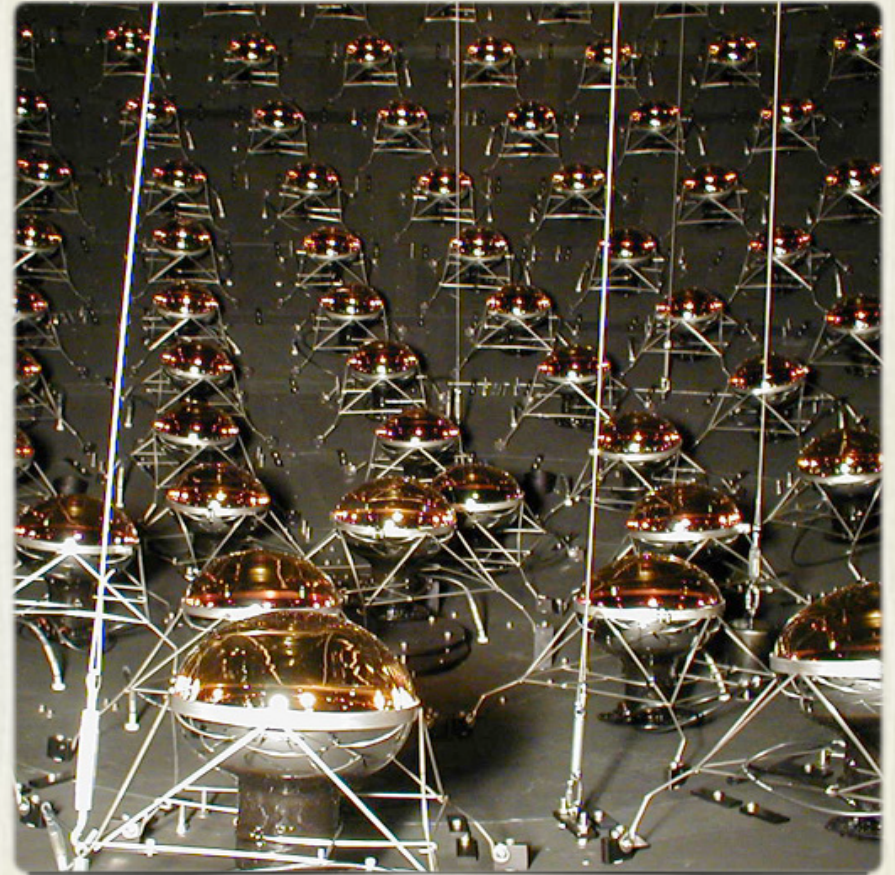


- Mineral oil Cherenkov detector
 - Select ν_μ by single muon and its decay-electron signal.
 - Total mass: ~1k ton
 - Main component: CH_2
 - Taking beam data since 2002
 - 5.58×10^{20} POT (neutrino mode) + SB-MB overlap
- 2 detectors share the beam and the target material (both carbon)

Most of the systematic error cancels



SciBar detector at SciBooNE



MiniBooNE Detector

Oscillation Analysis

Analysis Overview

2 Independent Analyses

Step-by-step

SciBooNE Data

↓ Spectrum fit

SciBooNE True E_ν

↓ Far/Near ratio

MiniBooNE True E_ν



MiniBooNE Rec. E_ν Prediction

↕ Oscillation Fit

MiniBooNE Rec. E_ν Data

Advantage: Can see what physically happening and error size at each step

Simultaneous fit

SB + MB Rec. E_ν Data

↕ Oscillation Fit

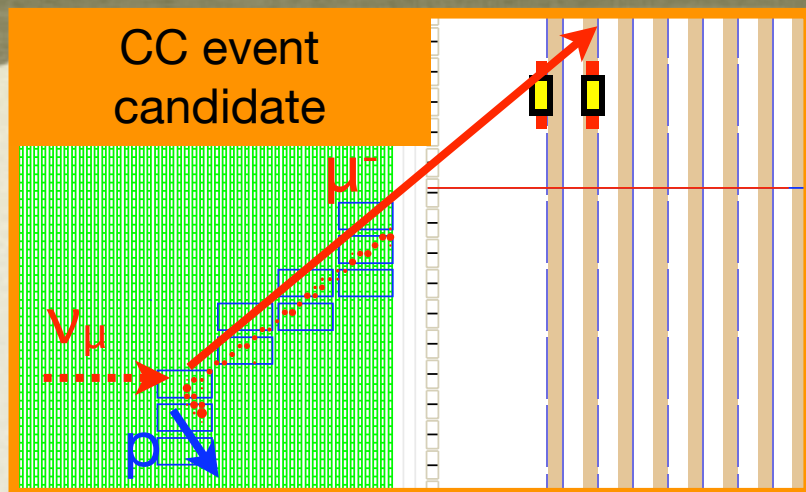
SB + MB Rec. E_ν Prediction

Advantage: Can include all correlation and minimize the systematic error

今回は、私が行っている
“Step-by-step”解析を話します

SciBooNE ν_μ Selection

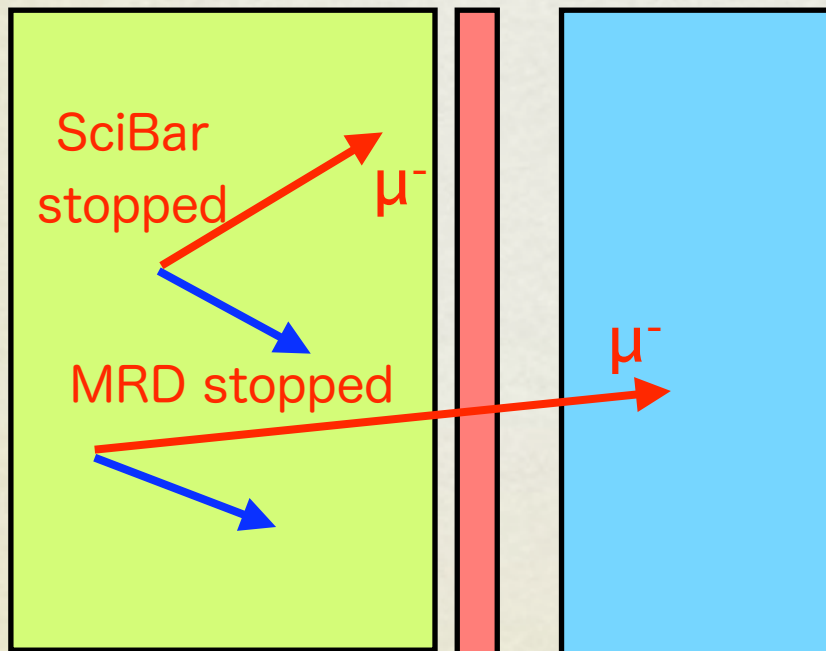
SciBooNE



SciBar

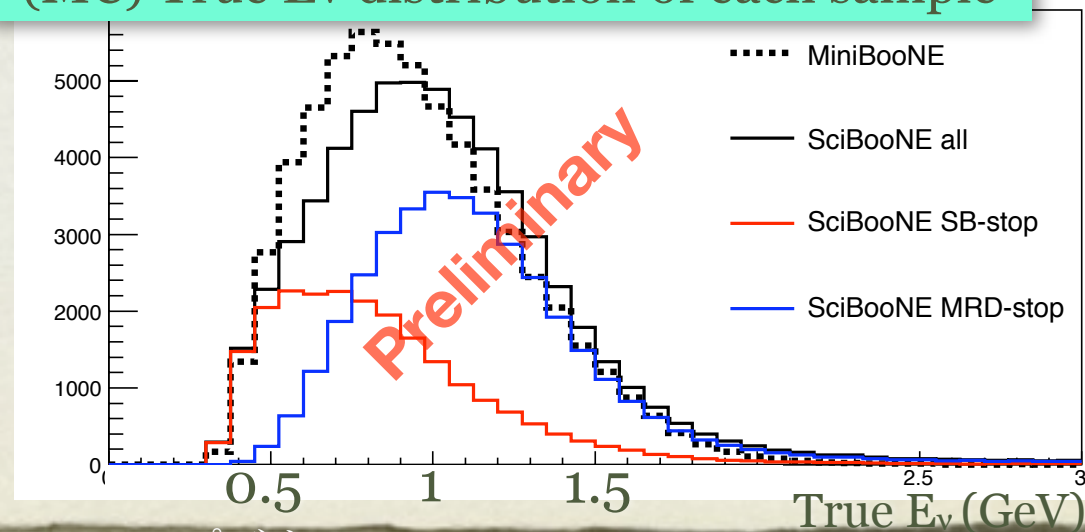
EC

MRD



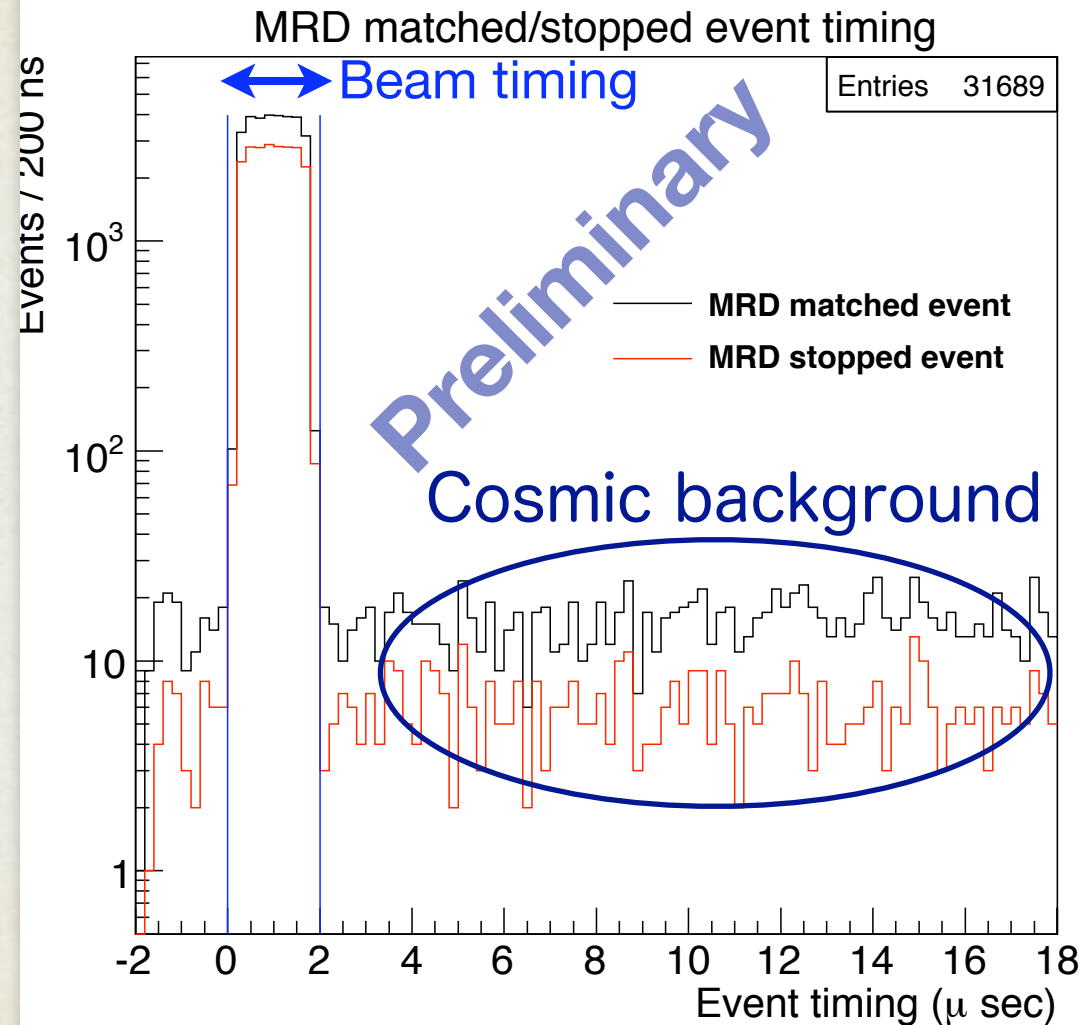
- Select events with muon track (Charged current inclusive sample)
- Muon selection
 - Muon-like energy deposit in SciBar
 - Require tracks stopped in the detectors
 - Require momentum > 0.25 GeV

(MC) True E_ν distribution of each sample



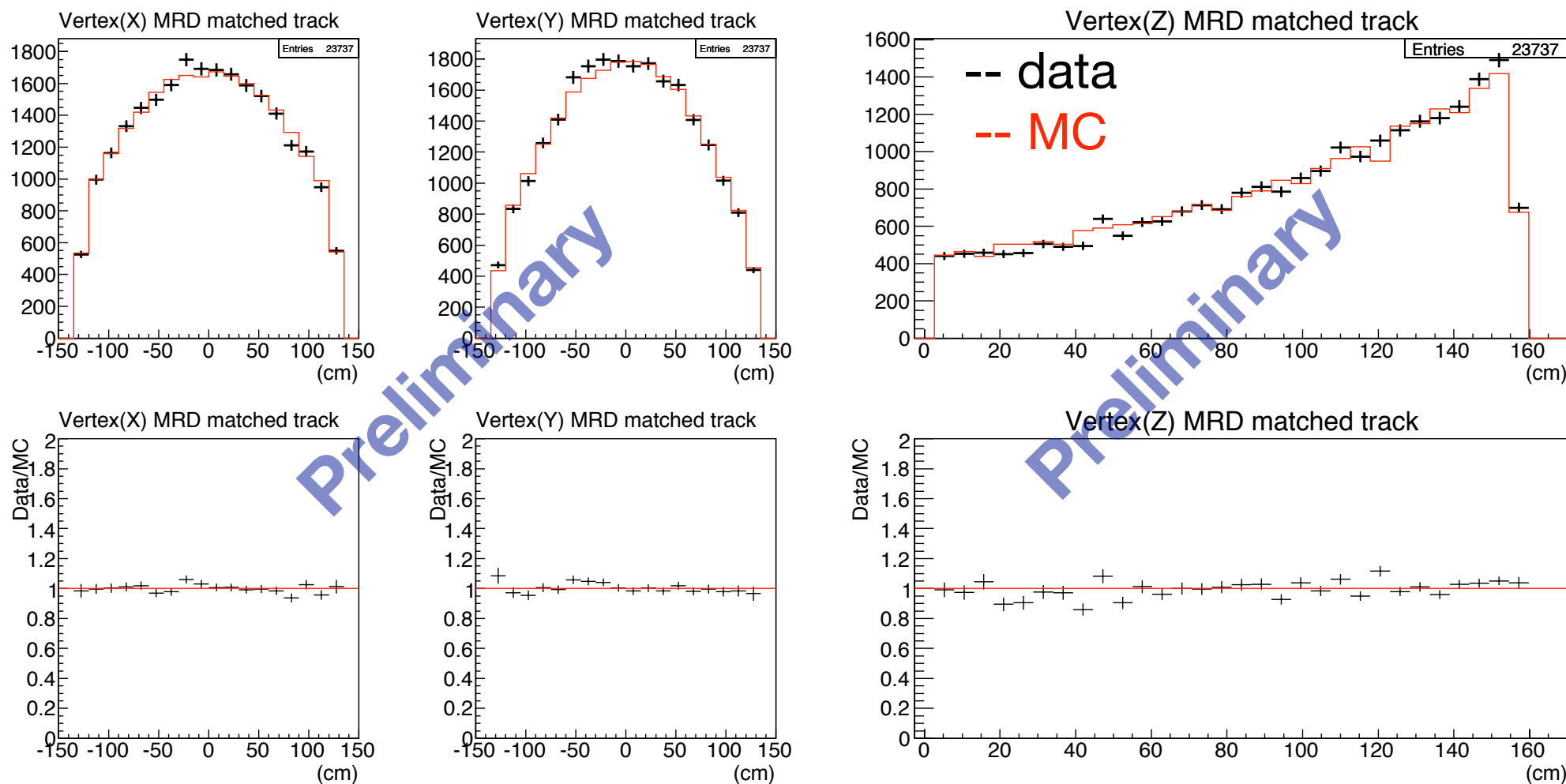
Event Selection (Timing)

- 2 μsec beam timing window.
- Less than 0.5% cosmic background contamination.
- ~14K SciBar-stopped events.
- ~20K MRD-stopped events.

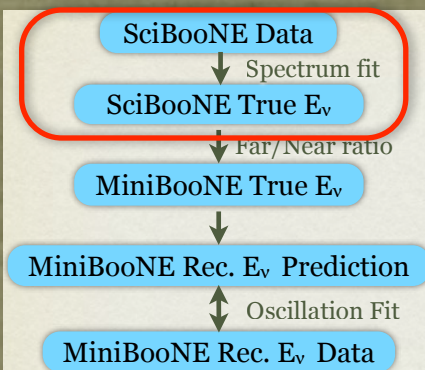


Reconstructed Interaction Vertices

MRD matched muon (relatively normalized)



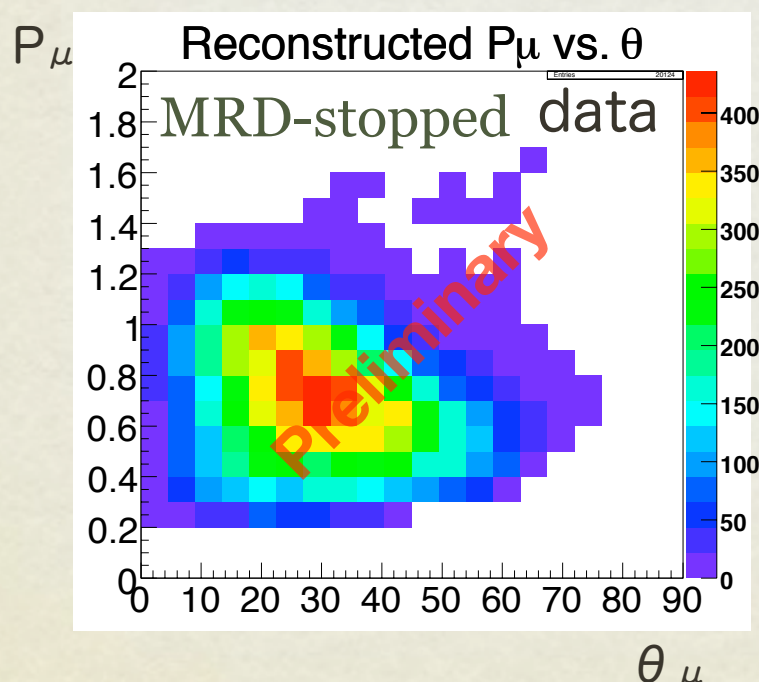
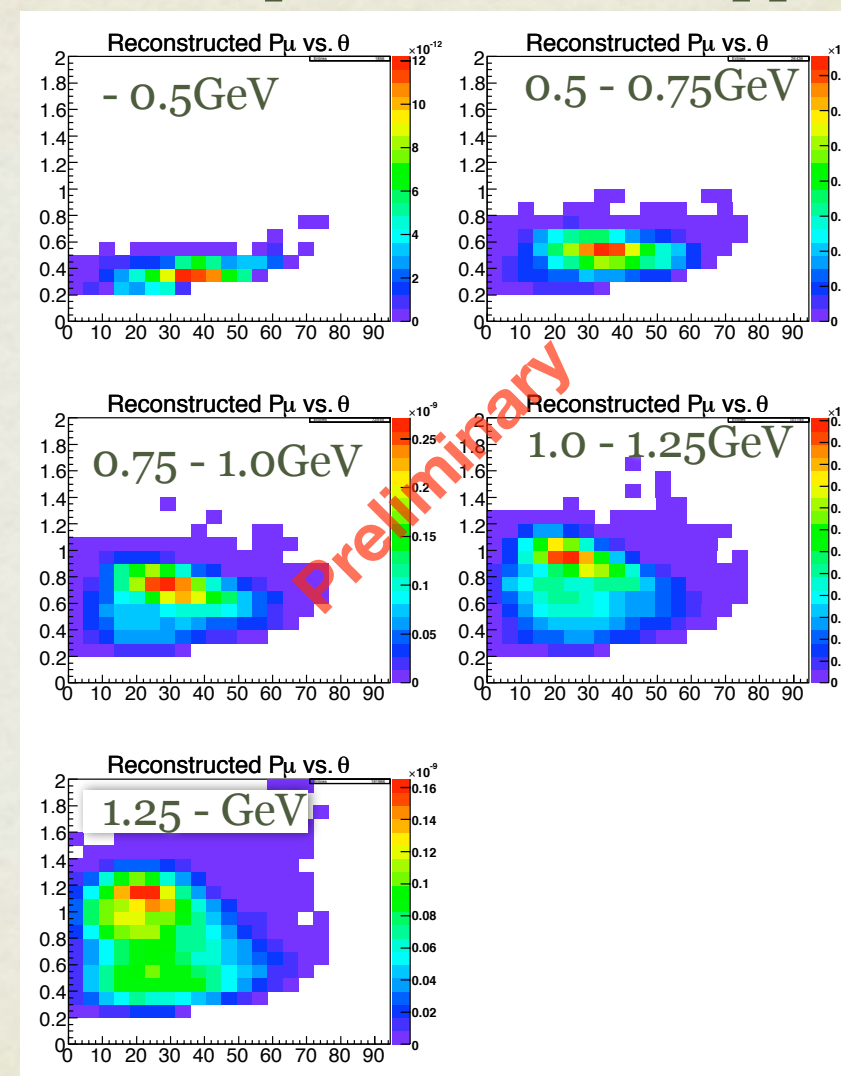
SciBooNE Spectrum Fitting (1)



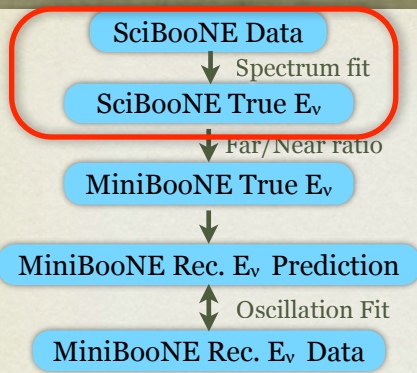
P_μ : Muon momentum
 reconstructed by its path-length
 θ_μ : Muon angle w.r.t. beam axis

- Fit P_μ vs. θ_μ distributions.
- Determine MC scale factor for each true E_ν bins.

MC Templates (MRD-stopped)



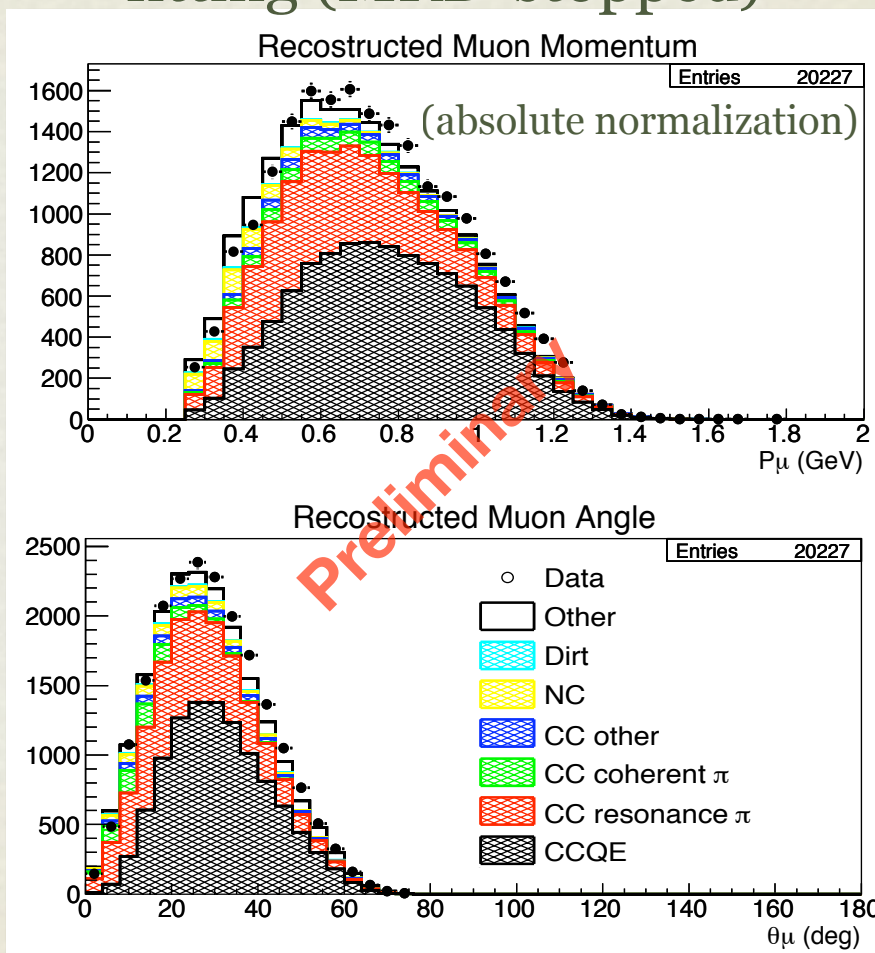
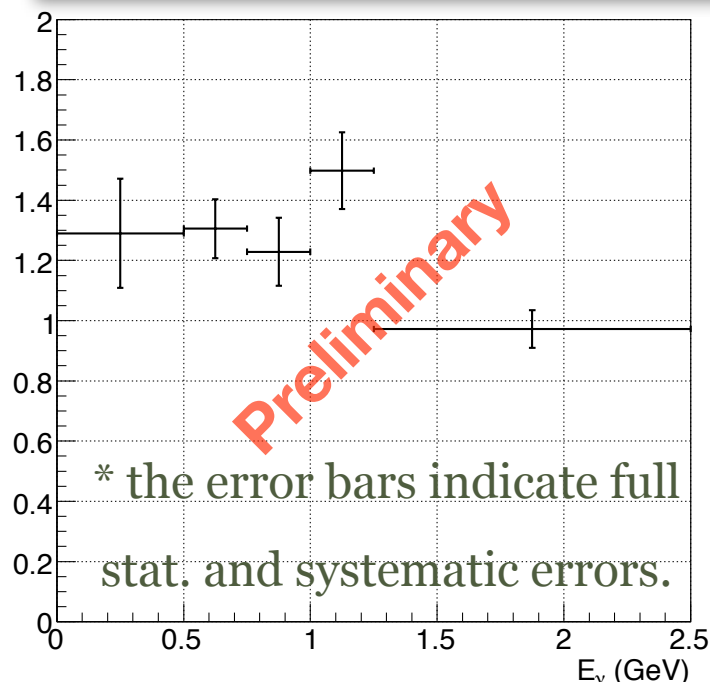
SciBooNE Spectrum Fitting (2)



P_μ and θ_μ distribution after fitting (MRD-stopped)

- 得られた E_ν scale factor を MC に適用

(Absolute) E_ν scale factor obtained by fitting

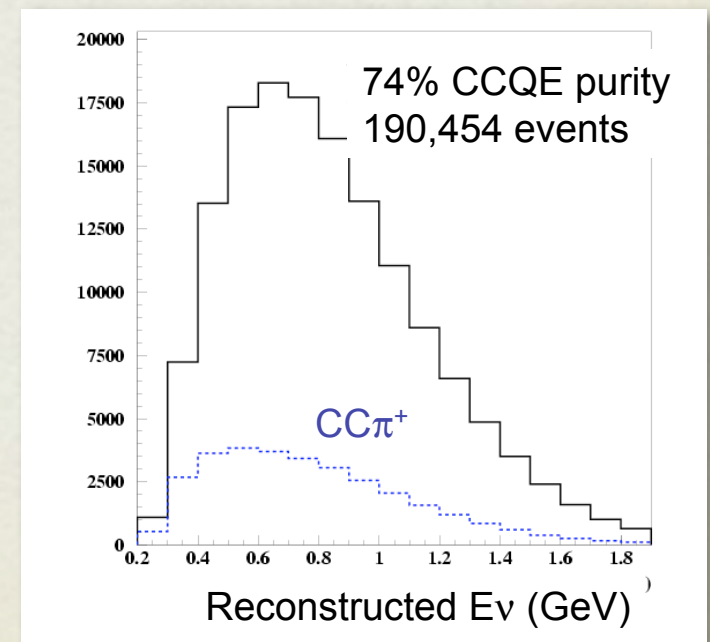
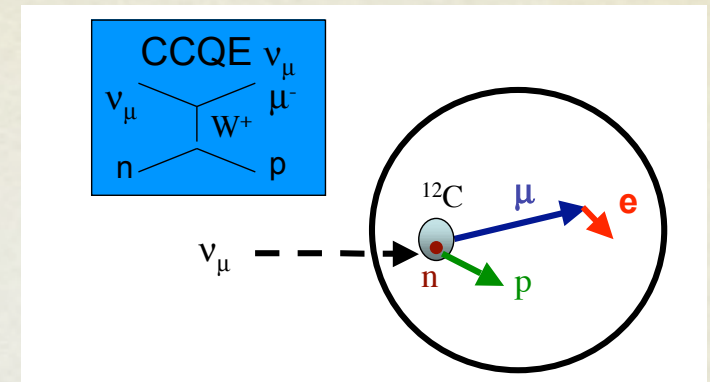


Good data and MC agreement

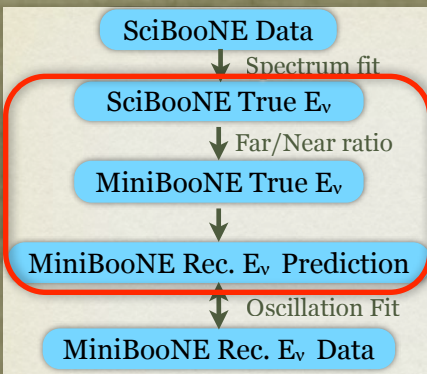
MiniBooNE Reconstruction

- 崩壊電子により μ を選択
- 荷電カレント準弾性散乱(CCQE)を
仮定し、 μ の運動量、角度から
ニュートリノエネルギーを再構成

$$E_\nu = \frac{m_p^2 - (m_n - V)^2 - m_\mu^2 + 2(m_n - V)E_\mu}{2(m_n - V - E_\mu + p_\mu \cos \theta_\mu)}$$

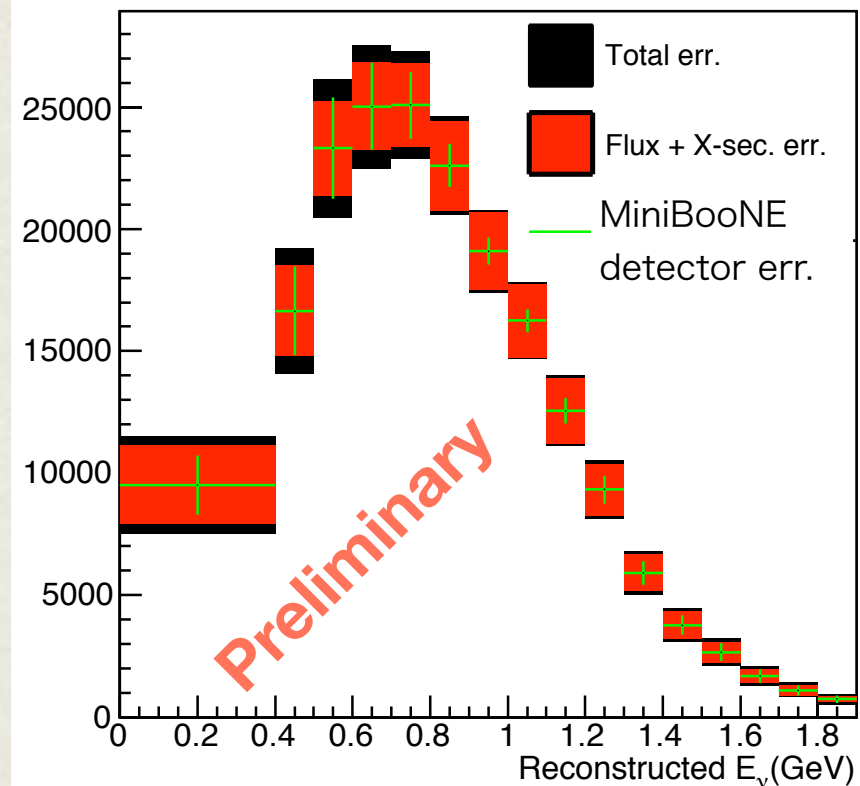


MiniBooNE Prediction

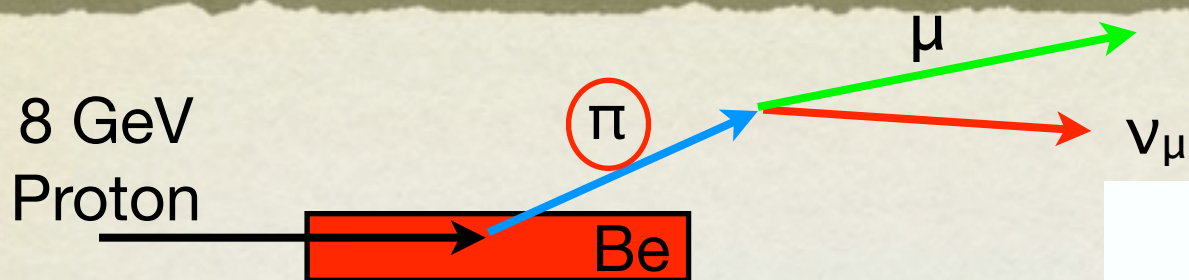


- Extrapolate measured spectrum from SciBooNE to MiniBooNE.
- Convert True $E_\nu \rightarrow$ Rec. E_ν
- Systematic Errors
 - SciBooNE spectrum measurement uncertainty
 - Beam flux model
 - Cross-section model
 - MiniBooNE detector response

MiniBooNE reconstructed E_ν and its error expectation

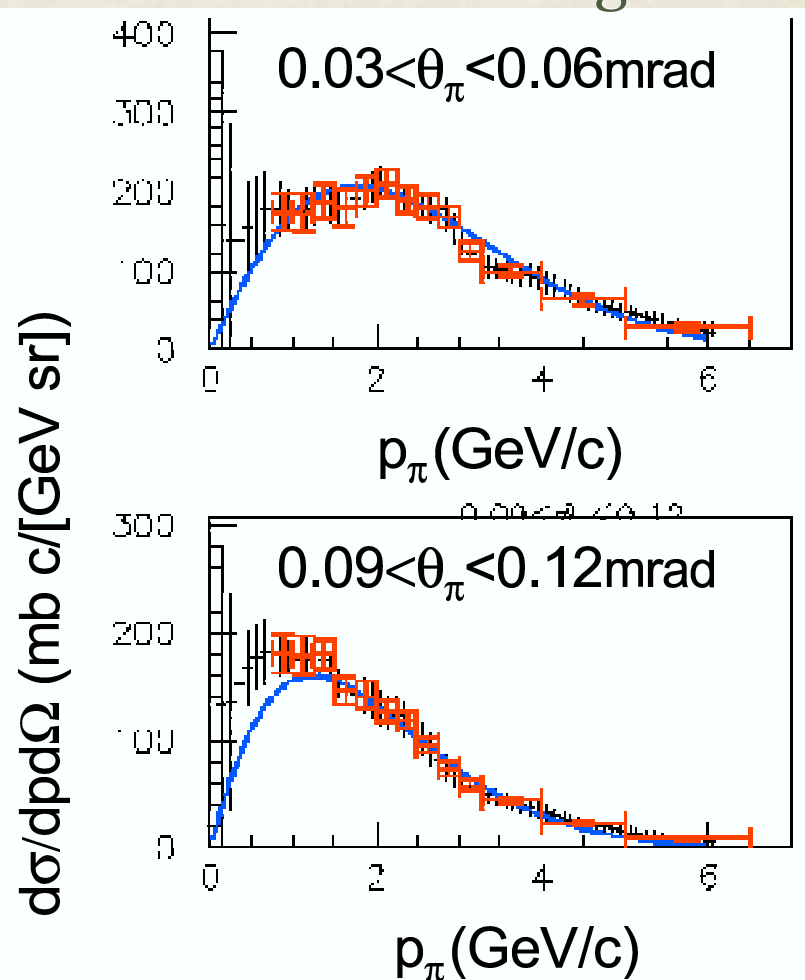


An Example of Flux Systematic Error



- フラックスの予想には、HARP実験で測定された、p-Beからのハドロン生成の断面積を使用。
- その測定誤差を系統誤差とする
- フラックスの絶対値のエラーは大きい (~10%)がSciBooNE/MiniBooNEで比をとると無視できる大きさになる (~1%)

π^+ production cross-section at the target

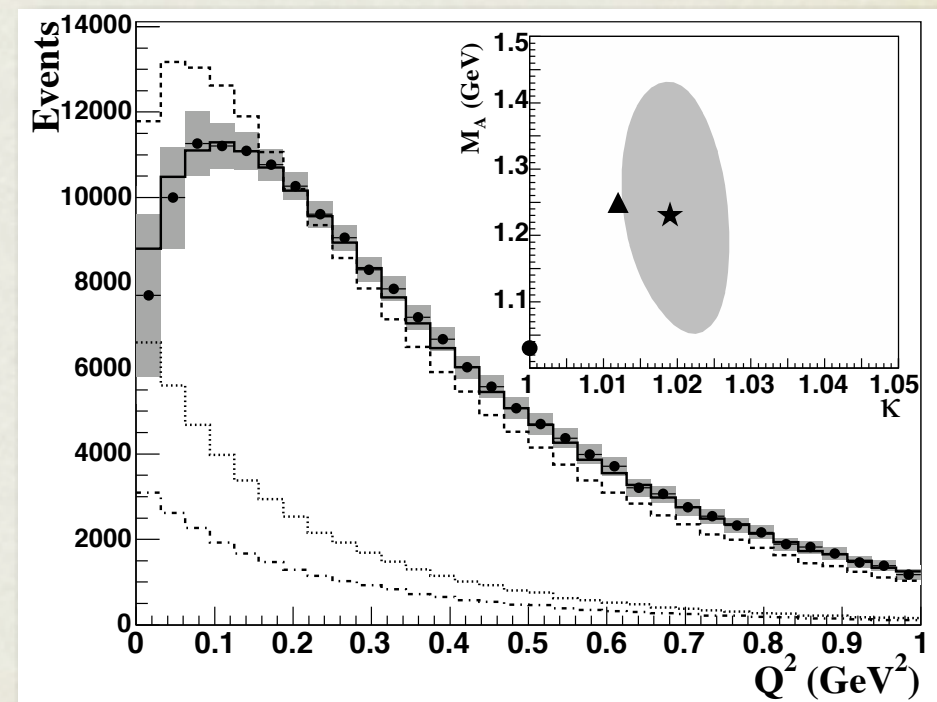


An Example of Cross-section Errors

- MiniBooNEで荷電カレント準弾性散乱を測定
 - Axial form factor (F_A), Pauli-blocking を調整
 - その誤差を系統誤差に
- 最も大きなエラーの一つ (~5%程度)
 - MiniBooNEとSciBooNEで角度アクセプタンスが大きく違うため
 - SciBooNE: 前方に集中
 - MiniBooNE: 等方的

$$F_A(Q^2) = \frac{-1.267}{1 + \frac{Q^2}{M_A^2}}$$

MiniBooNE reconstructed Q^2



ニュートリノ振動Fit

- 2-flavor間での振動を仮定し、 Δm^2 , $\sin^2(2\theta)$ のパラメーター領域をスキャン

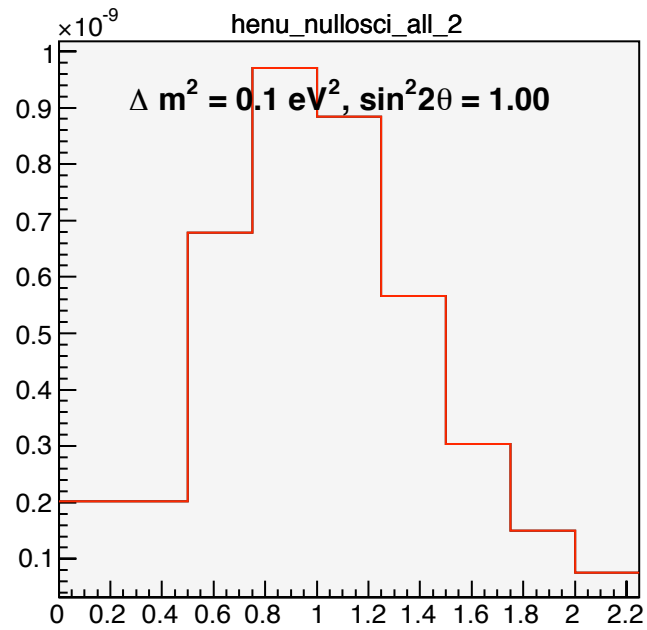
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right)$$

- $\Delta\chi^2 = \chi^2 (\text{each point}) - \chi^2(\text{best})$ を用いて各パラメーターでの振動の可能性を評価する。

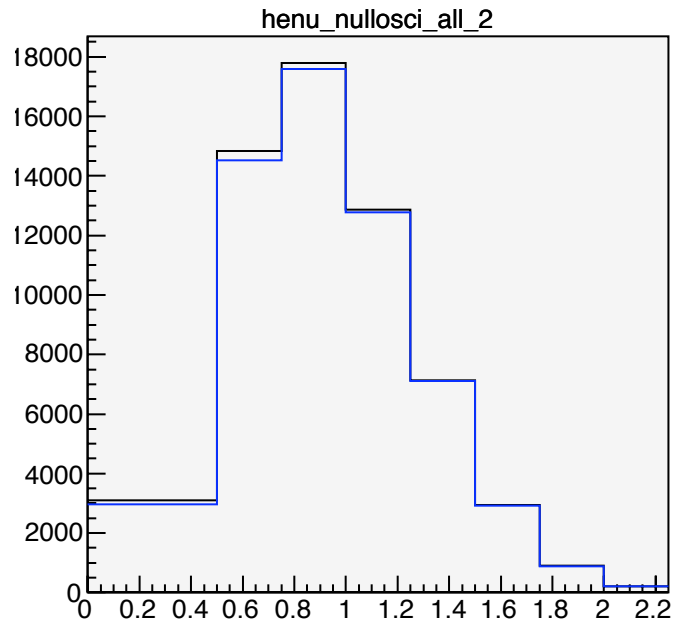
$$\chi^2 = \sum_{i,j}^{16 \text{ bins}} (N_i^{\text{data}} - N_i^p) M_{ij}^{-1} (N_j^{\text{data}} - N_j^p),$$

- 信頼度と $\Delta\chi^2$ の値の関係は、MCを用いて決定 (Feldman-Cousins method)

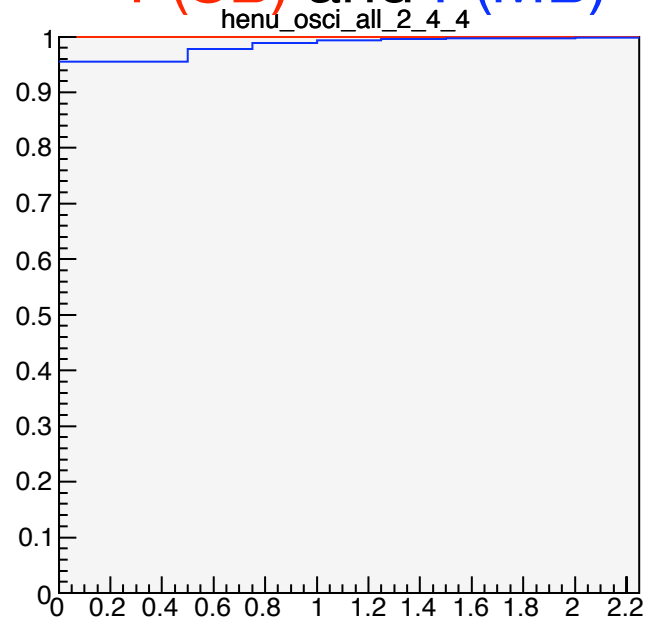
SB Enu



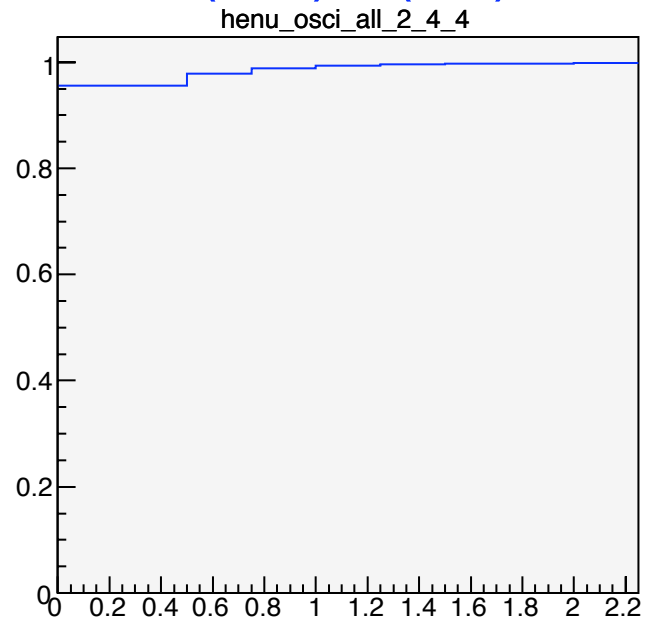
MB Enu



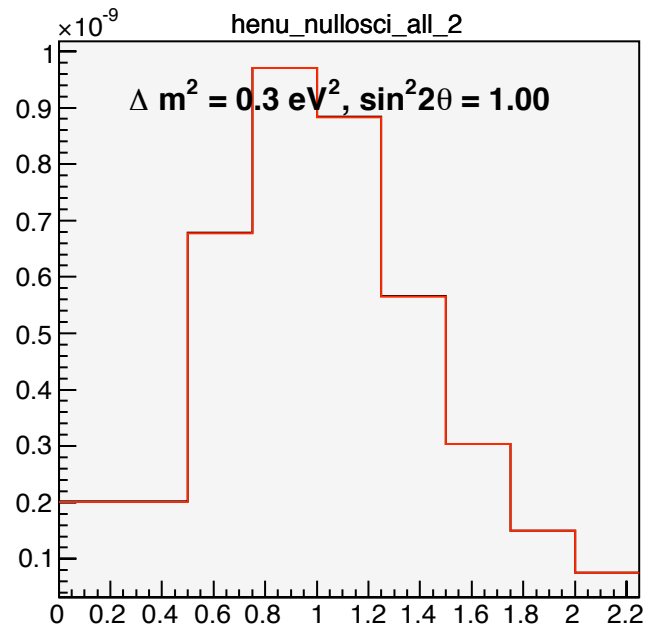
P(SB) and P(MB)



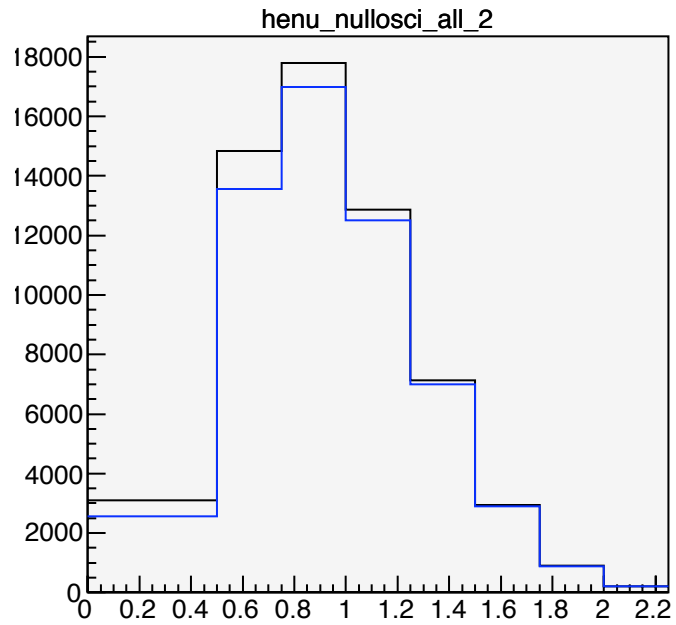
P(MB)/P(SB)



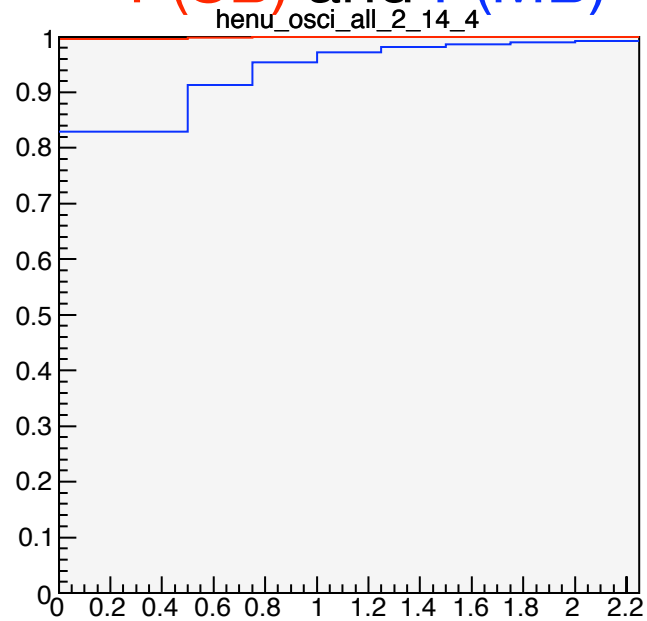
SB Enu



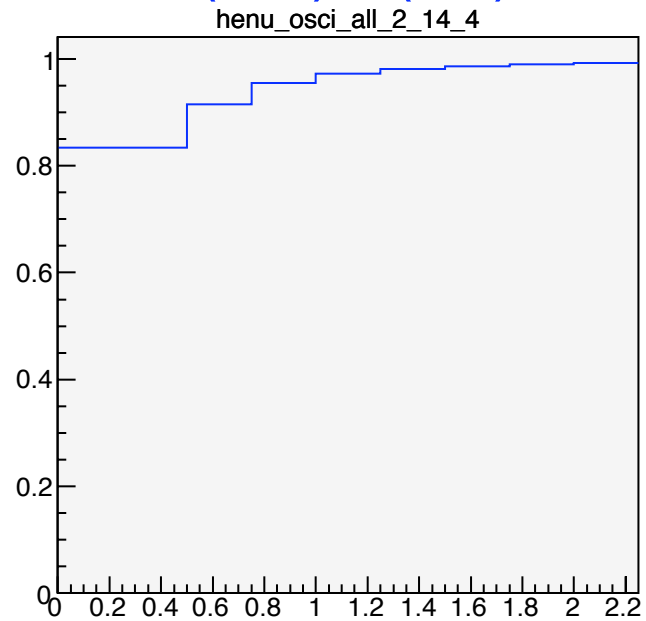
MB Enu



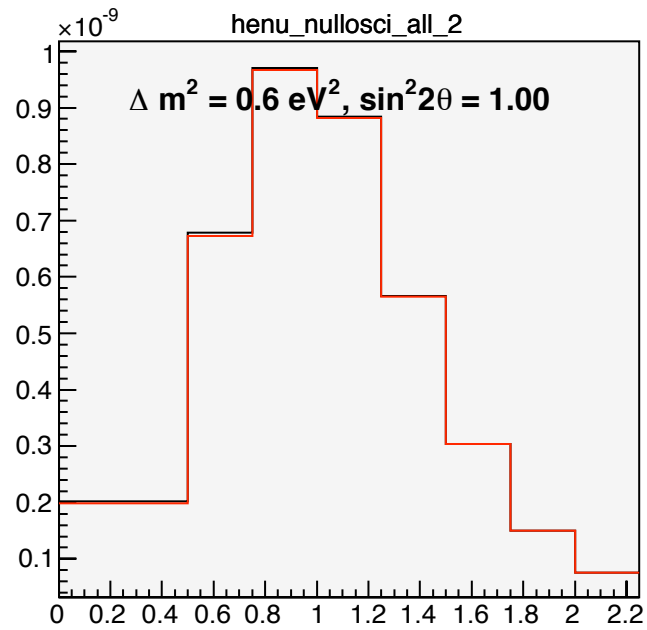
P(SB) and P(MB)



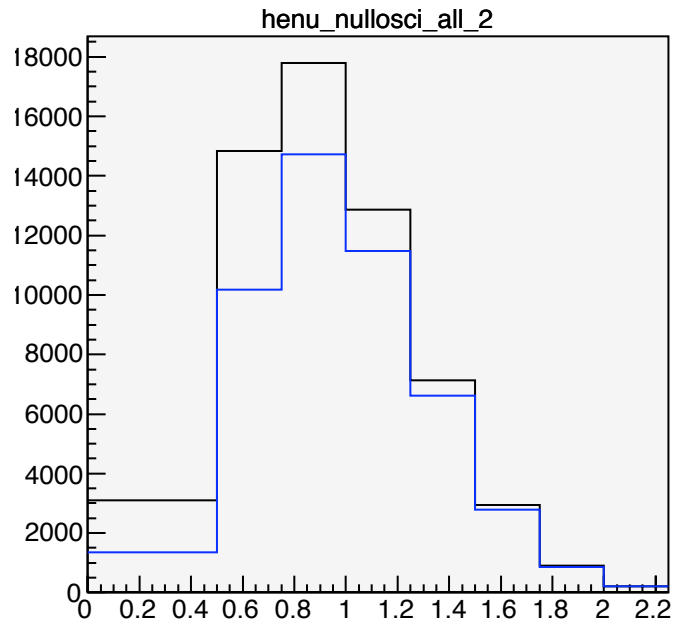
P(MB)/P(SB)



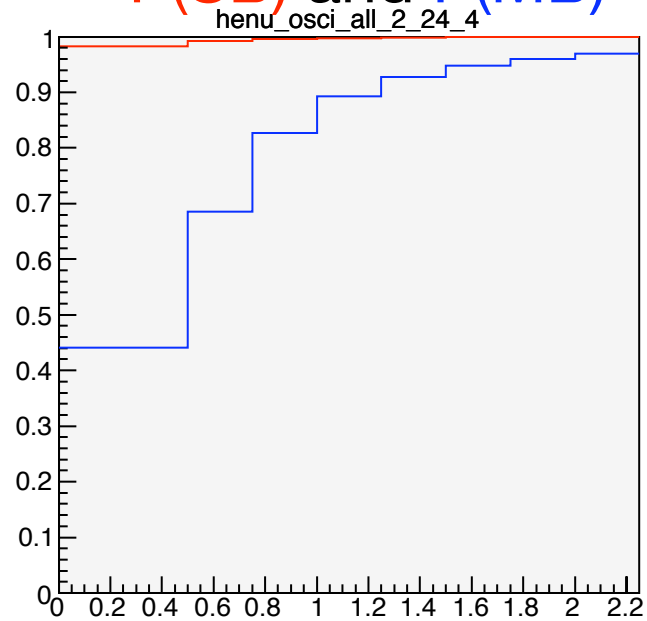
SB Enu



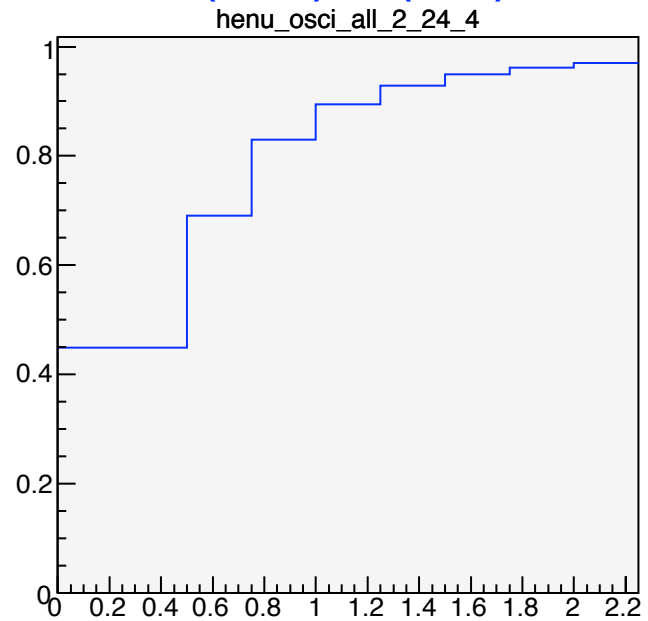
MB Enu



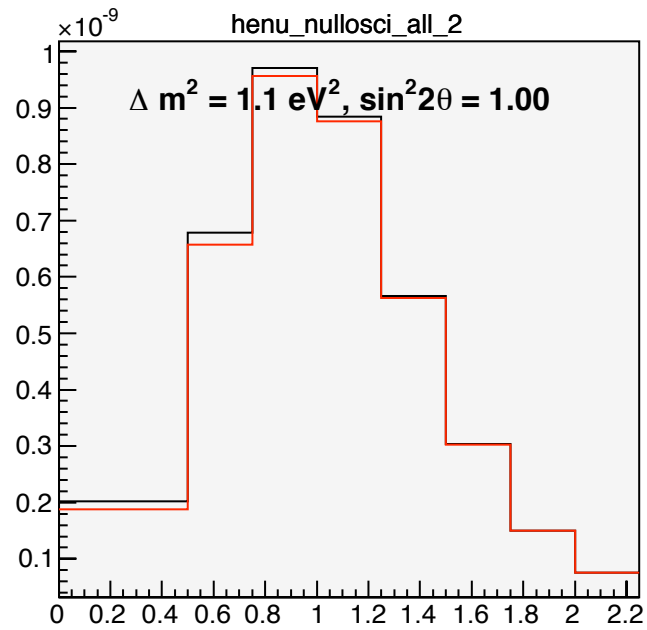
P(SB) and P(MB)



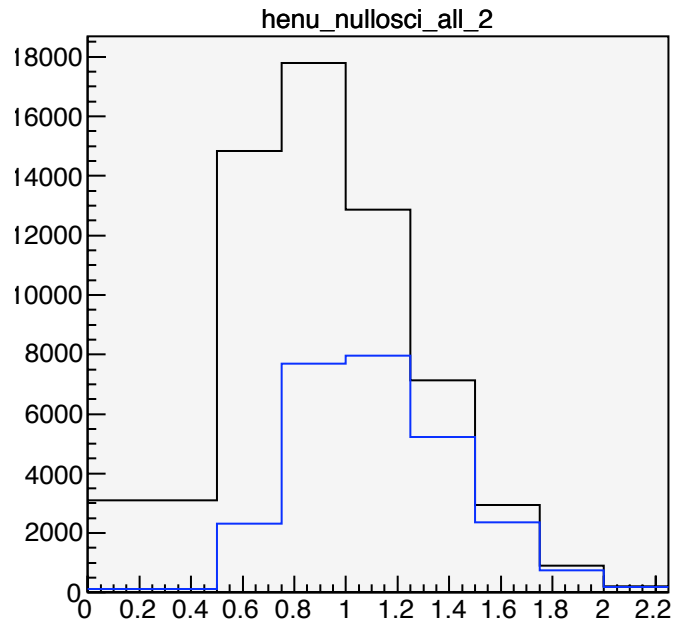
P(MB)/P(SB)



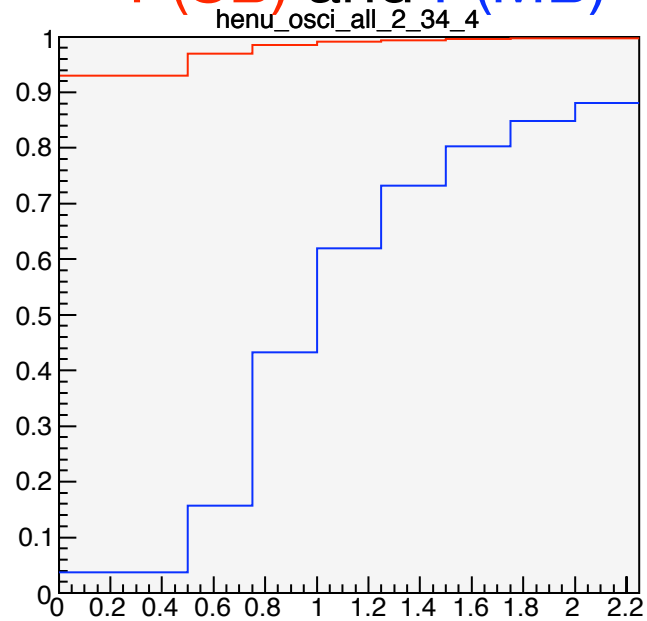
SB Enu



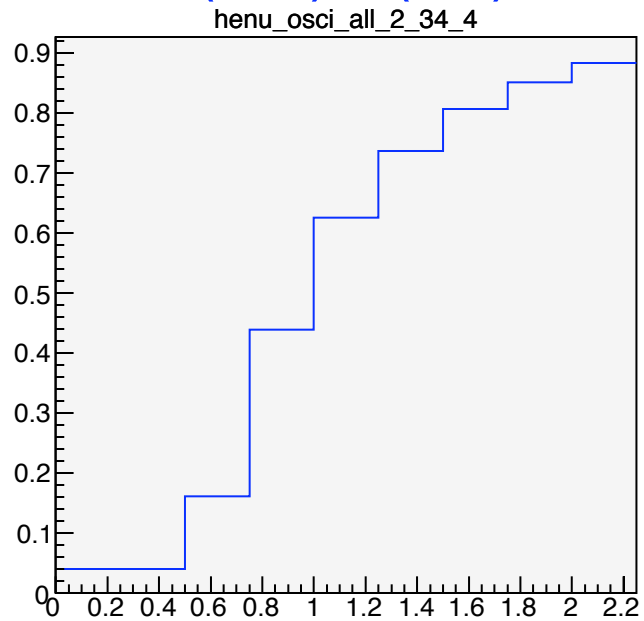
MB Enu



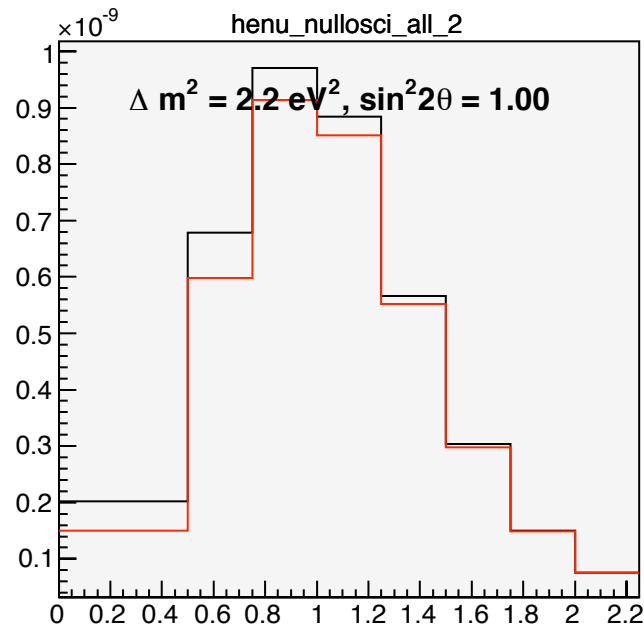
P(SB) and P(MB)



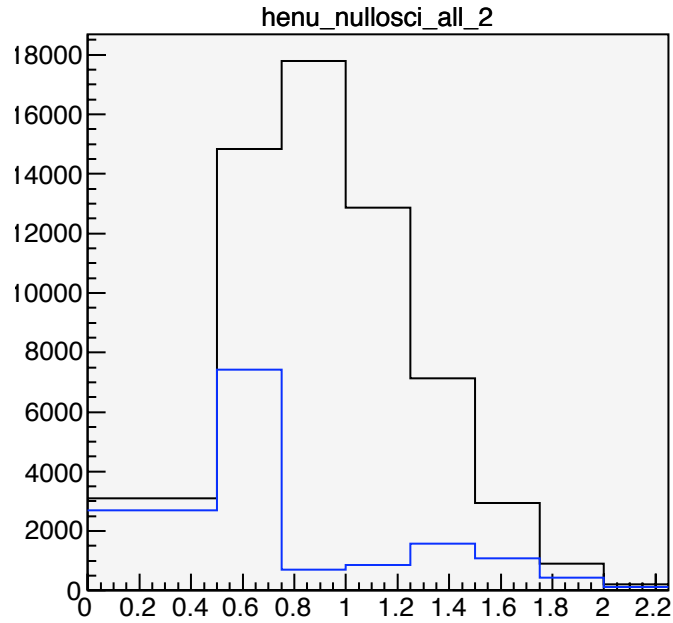
P(MB)/P(SB)



SB Enu

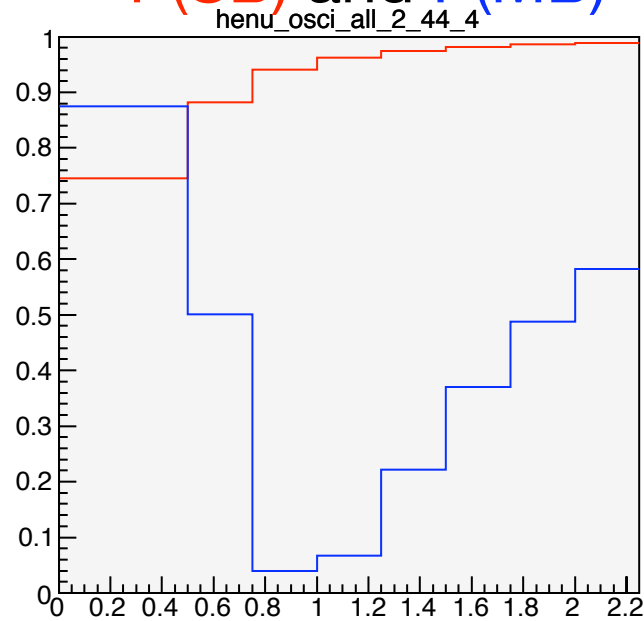


MB Enu

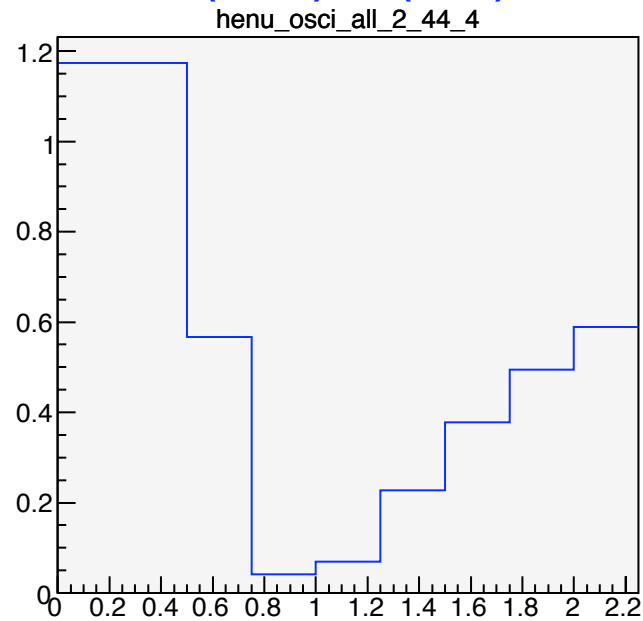


- Oscillation maximum at MiniBooNE detector at $\sim 2 \text{ eV}^2$

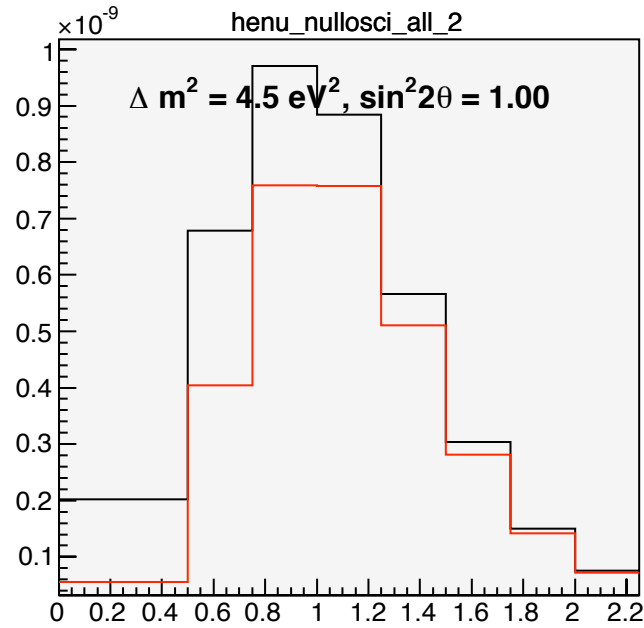
P(SB) and P(MB)



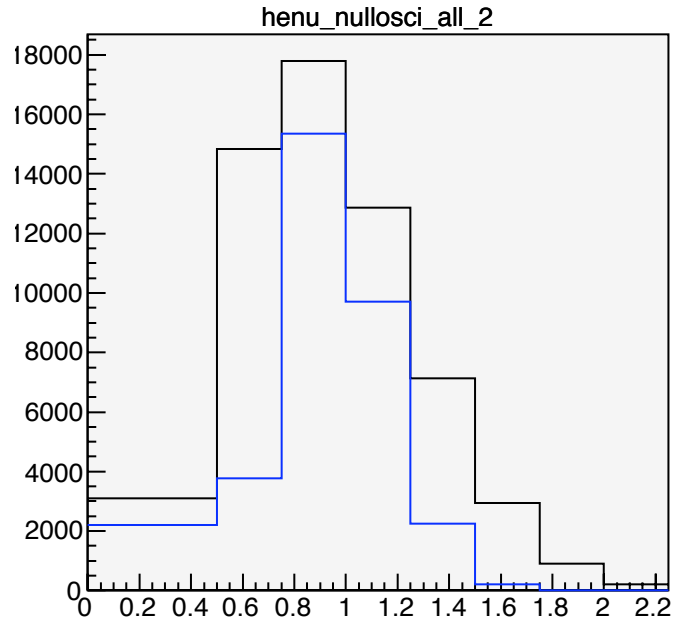
P(MB)/P(SB)



SB Enu

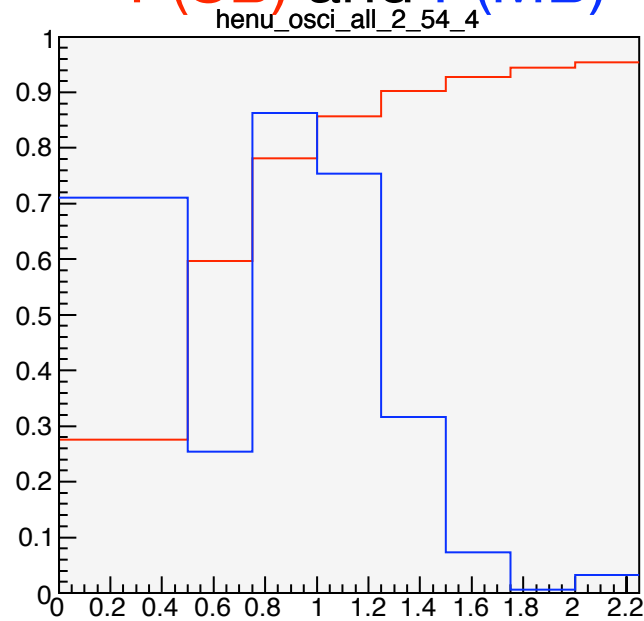


MB Enu

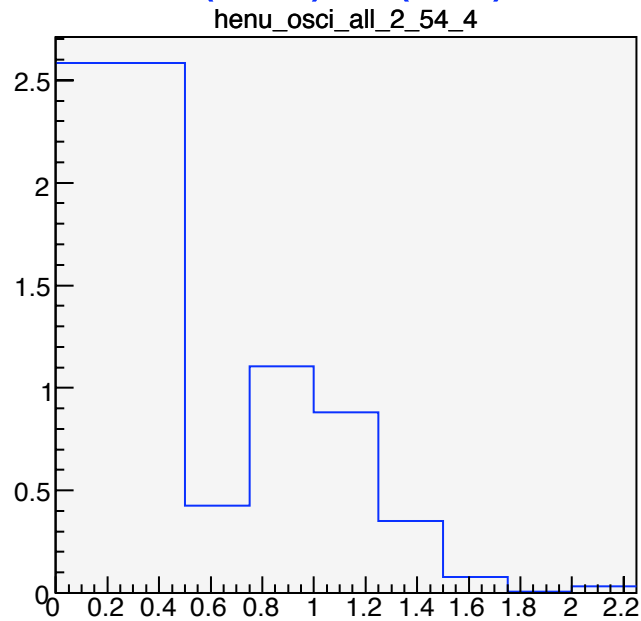


- Oscillation maximum at MiniBooNE detector at $\sim 2 \text{ eV}^2$

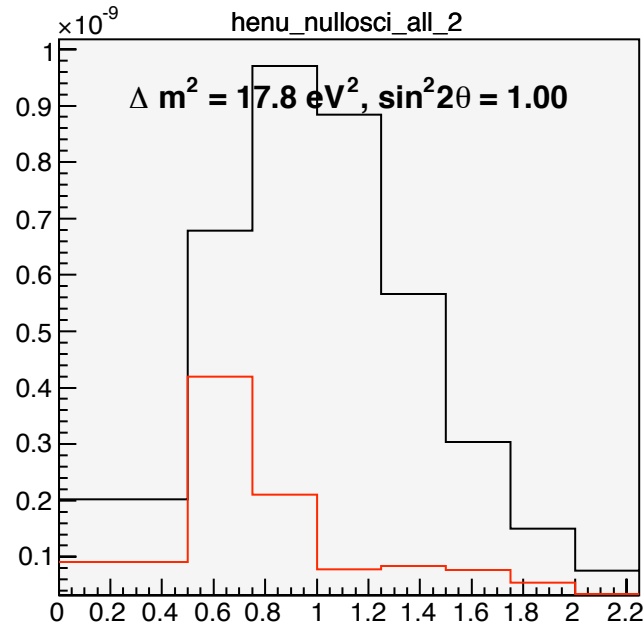
P(SB) and P(MB)



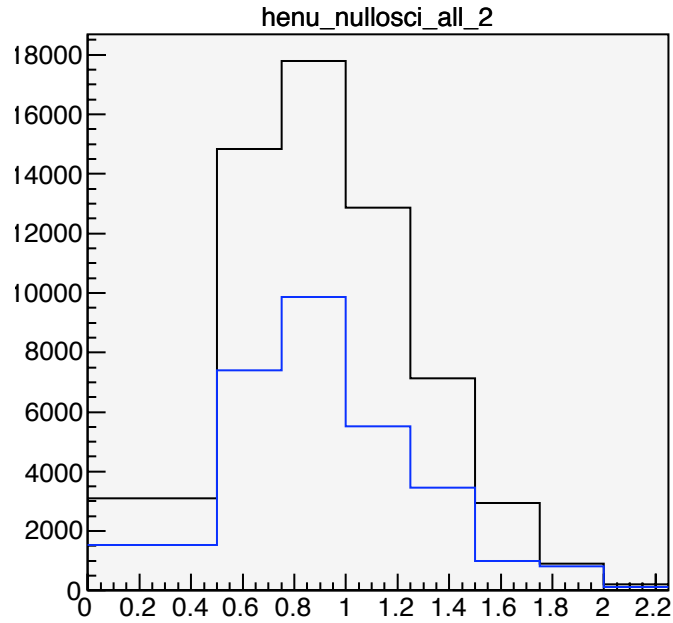
P(MB)/P(SB)



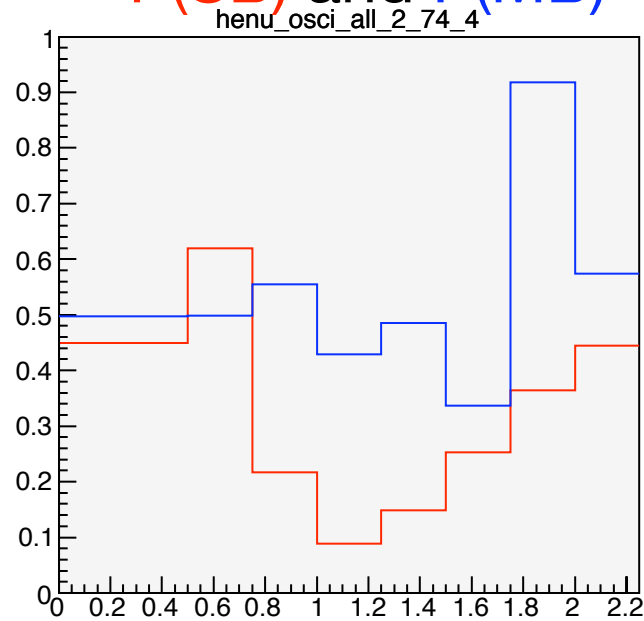
SB Enu



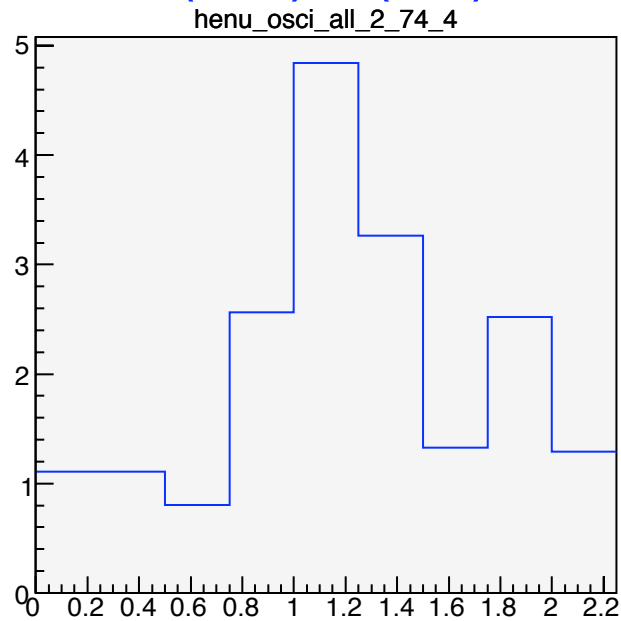
MB Enu



P(SB) and P(MB)

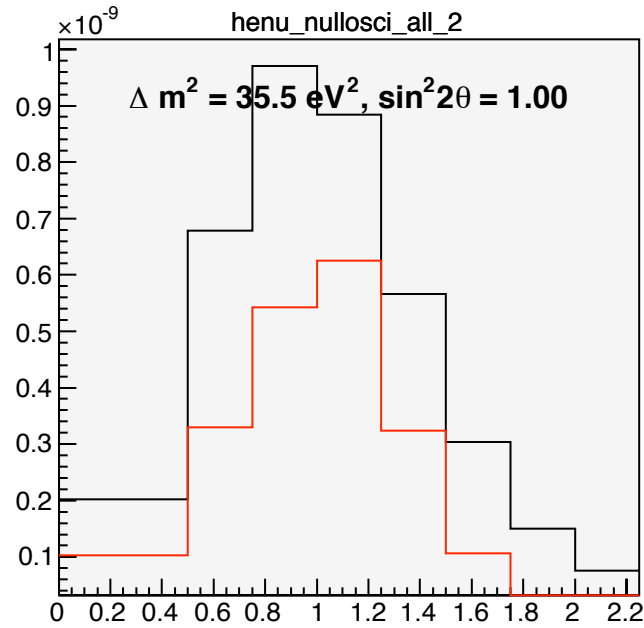


P(MB)/P(SB)

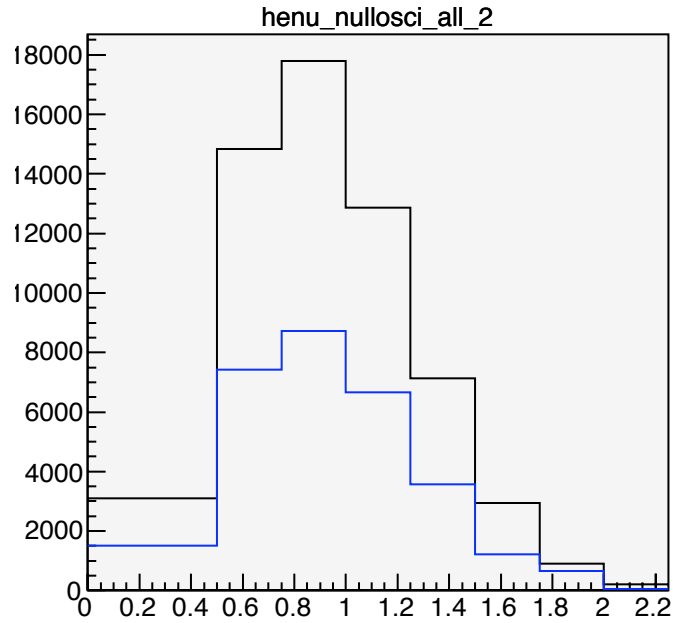


- Oscillation maximum at MiniBooNE detector at $\sim 2 \text{ eV}^2$
- Oscillation maximum at SciBooNE detector at $\sim 20 \text{ eV}^2$

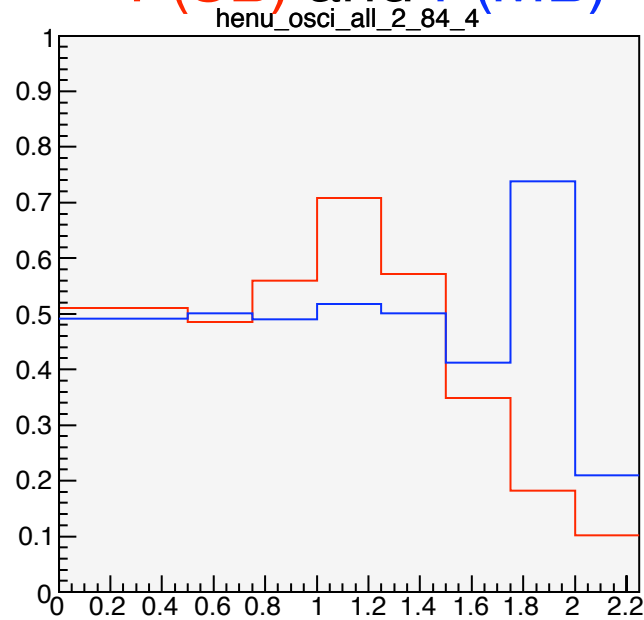
SB Enu



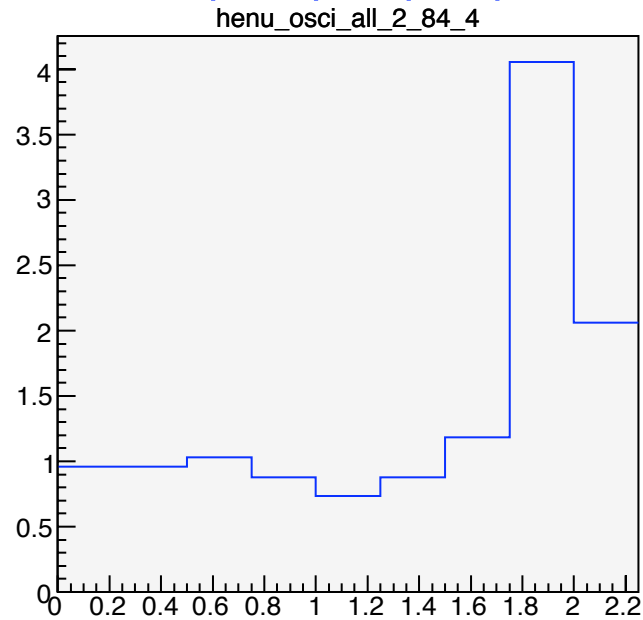
MB Enu



P(SB) and P(MB)

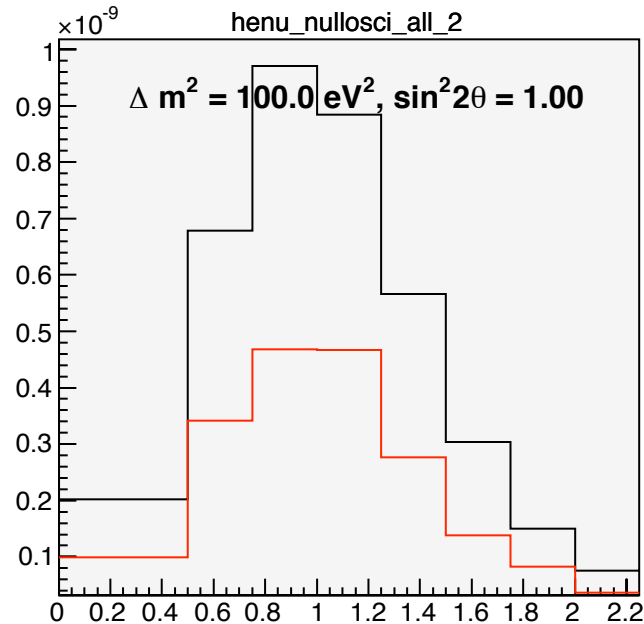


P(MB)/P(SB)

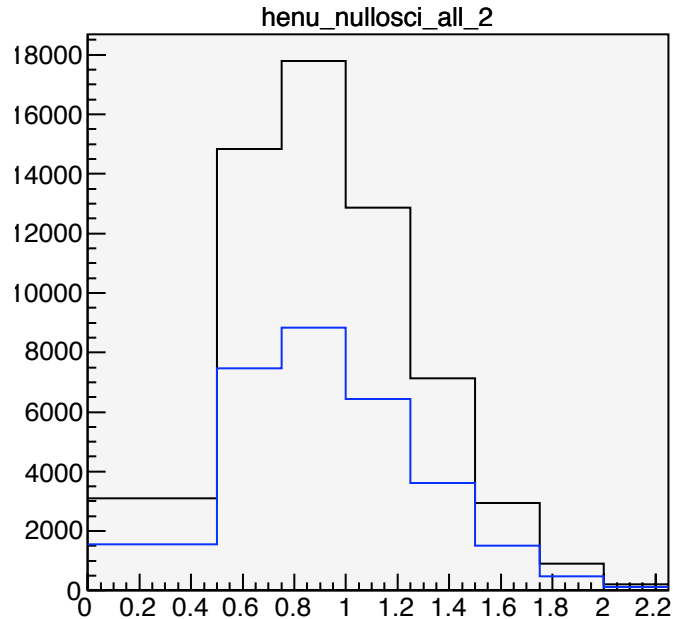


- Oscillation maximum at MiniBooNE detector at $\sim 2 \text{ eV}^2$
- Oscillation maximum at SciBooNE detector at $\sim 20 \text{ eV}^2$

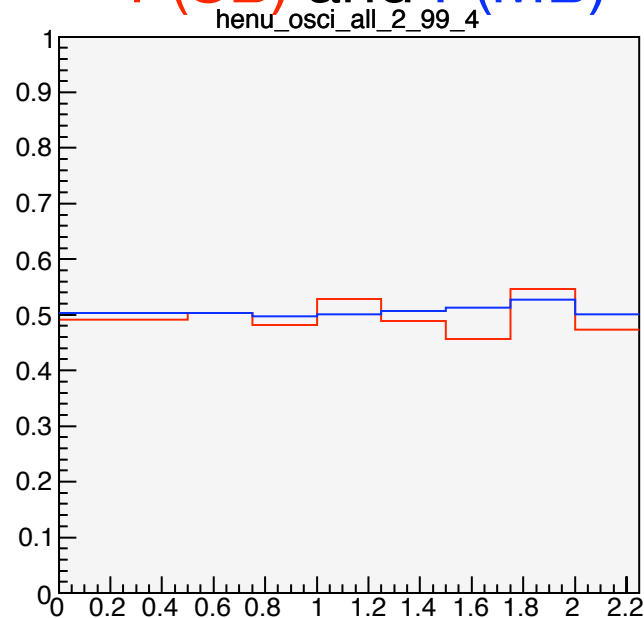
SB Enu



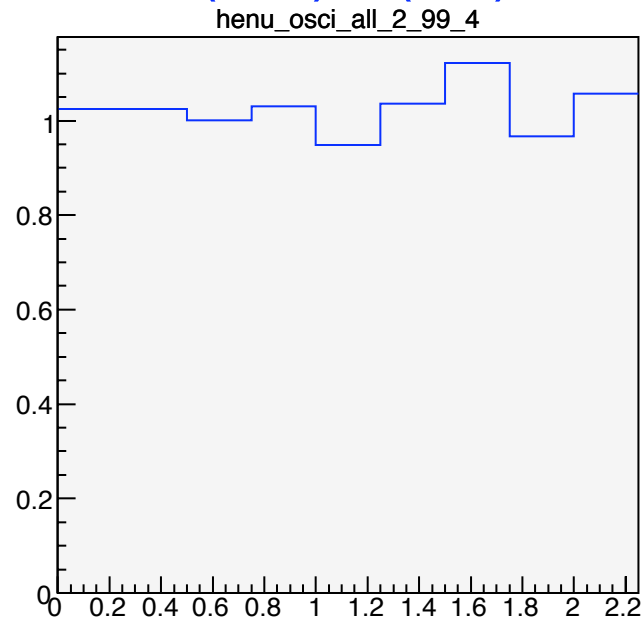
MB Enu



P(SB) and P(MB)

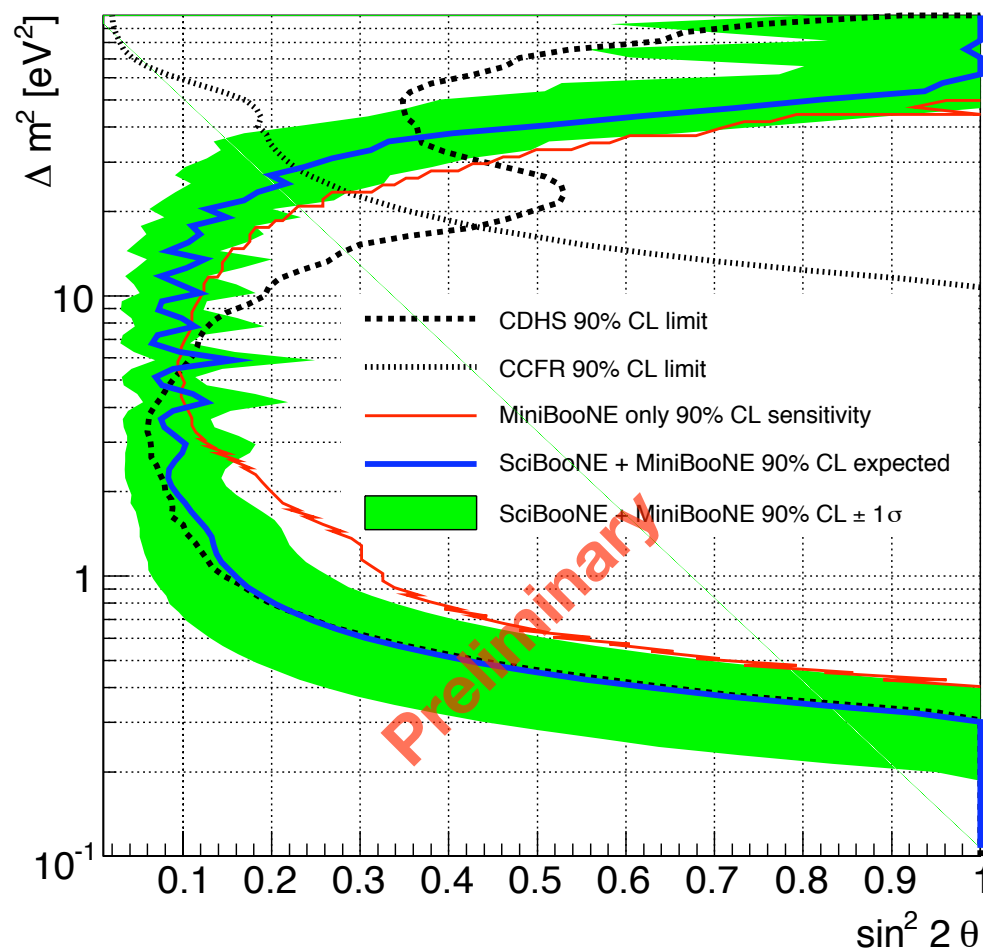
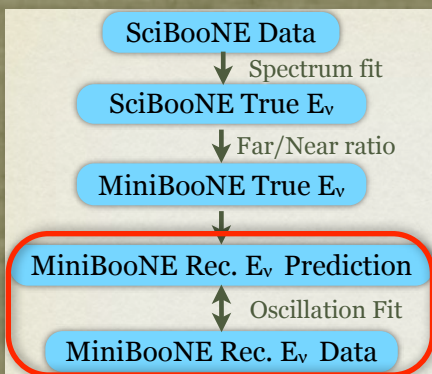


P(MB)/P(SB)



- Oscillation maximum at MiniBooNE detector at $\sim 2 \text{ eV}^2$
- Oscillation maximum at SciBooNE detector at $\sim 20 \text{ eV}^2$
- Oscillation effect completely washed out above $\sim 100 \text{ eV}^2$

Oscillation Sensitivity



- MiniBooNE単独での測定に比べ、特にlow- Δm^2 領域で感度を向上
- 近日中にdataのfit結果を発表できるはずです。

まとめ

- SciBooNEとMiniBooNE両方のデータを用いた、 $\Delta m^2 \sim 1\text{eV}^2$ 領域のニュートリノ振動の探索を行っている
- これまでに、解析手法を確立、感度の見積もりを行った
 - MiniBooNE単独に比べ感度を向上
- 近日中に結果を発表
- 反ニュートリノデータの解析も進行中