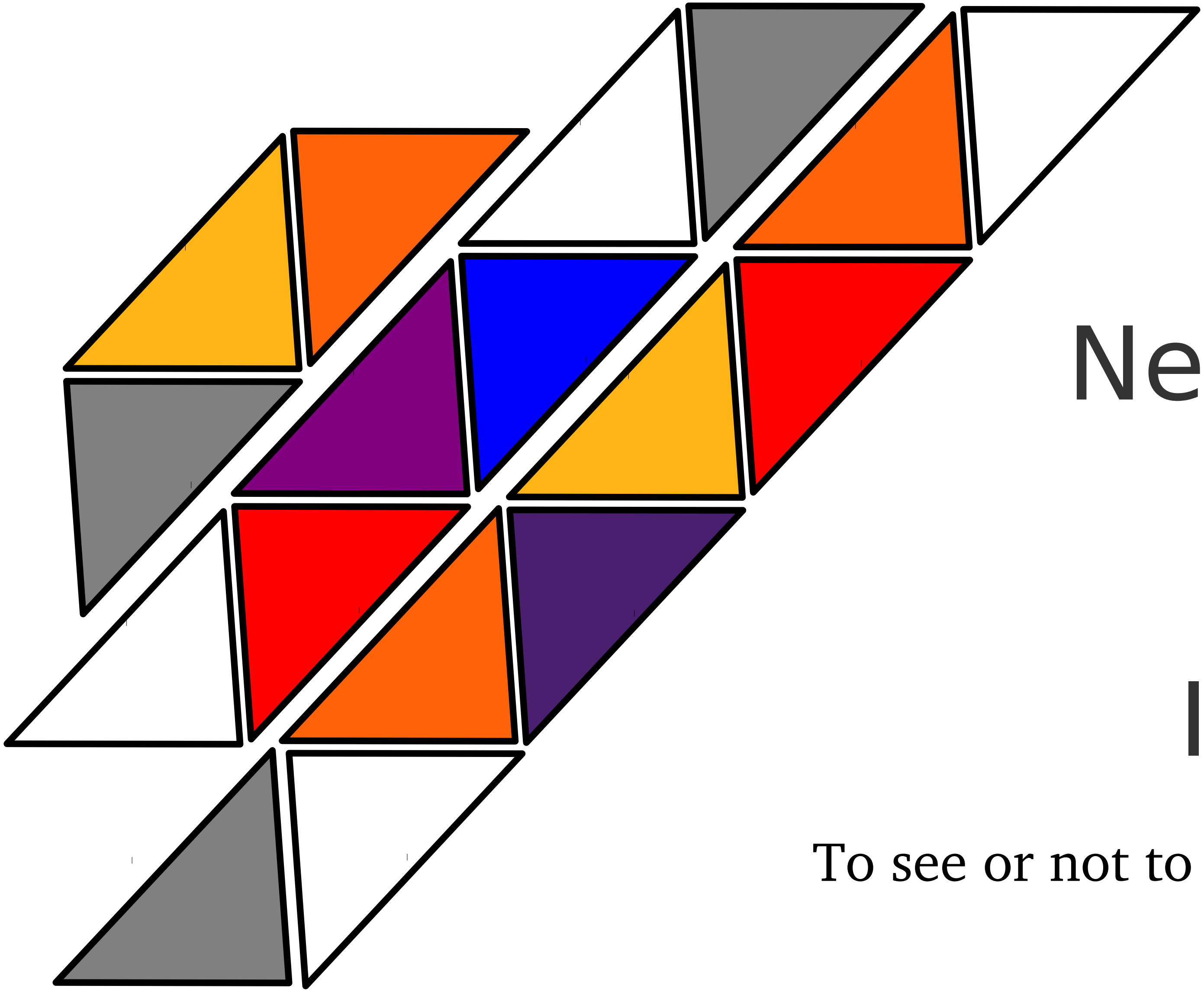


Sterile Neutrinos and Neutrino Interactions

To see or not to see, that is the question

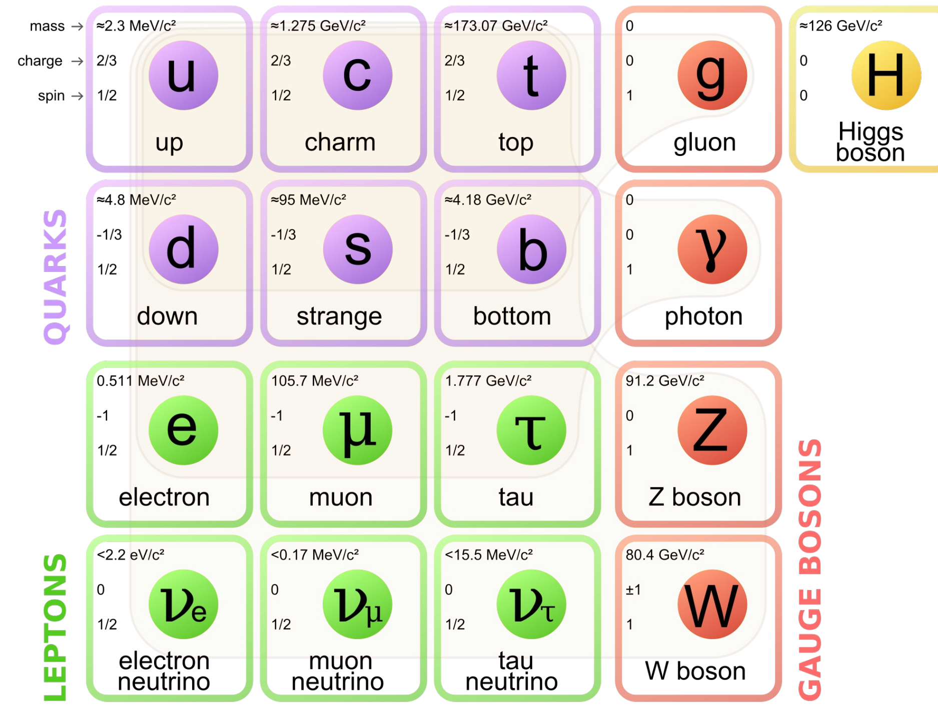
Mike Kordosky

William & Mary

UVa HEP Seminar
February 4, 2015

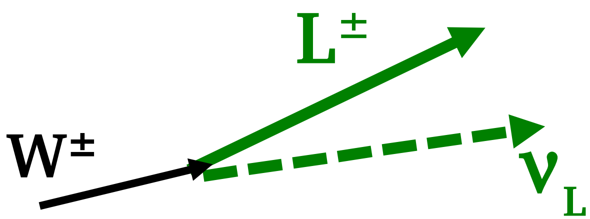
Neutrinos: not just MET!

- Vital but mysterious part of the SM
    - Why $SU(2)_L$?
- Massive, but very light.
    - How do they get their masses?
    - Different from other fermions?
- Flavor mixing is large,
  in contrast to quarks



- May violate CP, perhaps even maximally
- Could be their own anti-particle
- Interesting/complementary probe of nucleons/nuclei

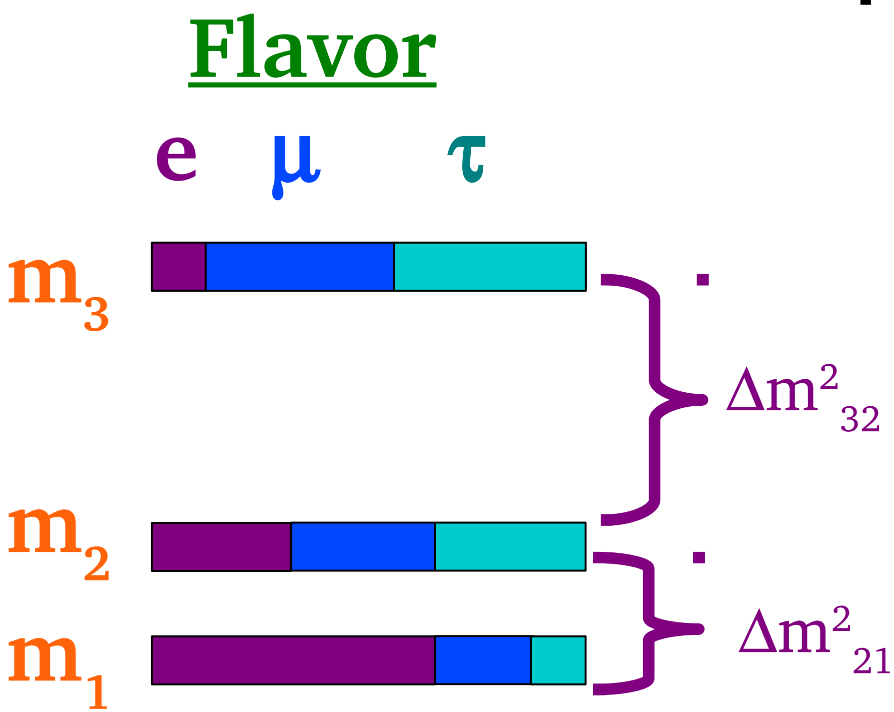
Oscillation Formalism



Mass

$\nu_i \rightarrow \nu_i$

$E^2=p^2+m_i^2$



PMNS
Mixing Matrix

$$U=\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Propagation (vacuum)

flavor mass states

$$|\nu_\alpha(L)\rangle=\sum_j U^*_{\alpha j}|\nu_j\rangle \exp(-i L m_j^2/2p)$$

(L=distance)

Flavor change

$\nu_\mu \rightarrow \nu_e$

E_ν=few GeV

L= few 100 km

Three flavor mixing matrix

PMNS Mixing Matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Muon neutrino disappearance

PMNS Mixing Matrix

$$U=\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Propagation (vacuum)

flavor mass states

$$|\nu_\alpha(L)\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle \exp(-i L m_j^2/2p)$$

(L=distance)

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4|U_{\mu 3}|^2|U_{\mu 1}|^2 \sin^2\Delta_{31} - 4|U_{\mu 3}|^2|U_{\mu 2}|^2 \sin^2\Delta_{32} - 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2\Delta_{21}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Characteristic oscillatory behavior depends on Δm^2 and L/E

"Survival Probability"
For a neutrino of energy E a distance L from the source

Muon neutrino disappearance

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

"Atmospheric oscillations"
L/E~500 km/GeV

Limiting Case

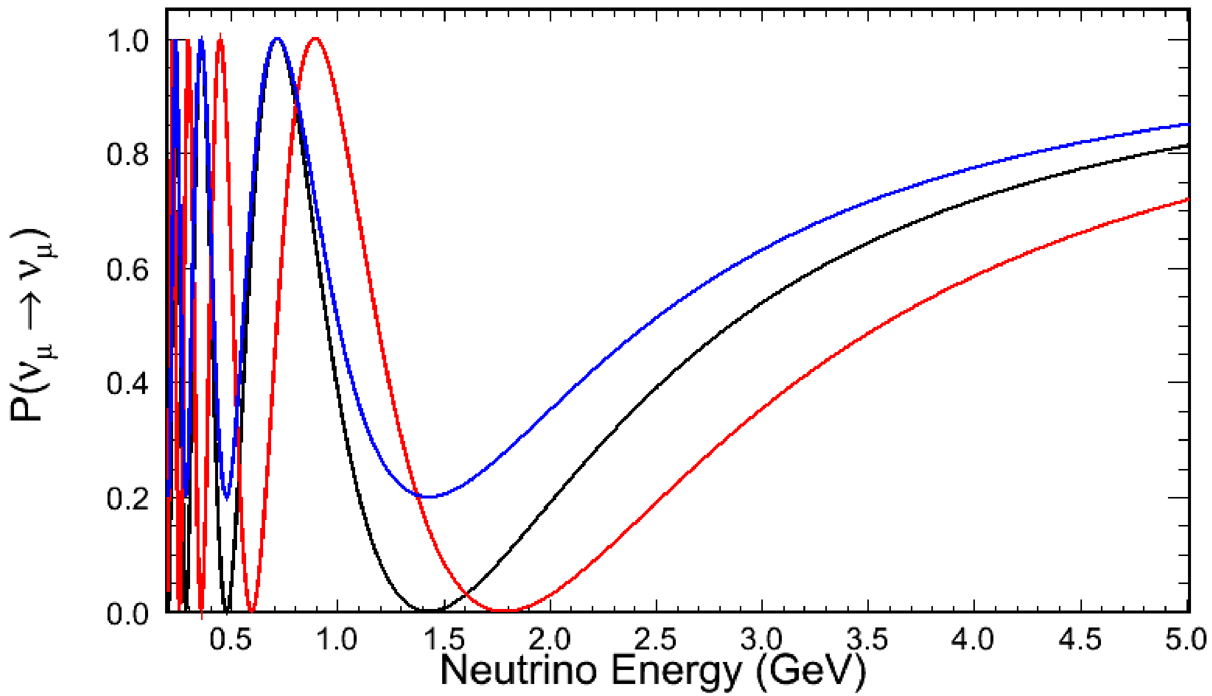
$\theta_{13} = 0$

$|\Delta_{21}| << |\Delta_{31}| \approx |\Delta_{32}|$

$$\left.\begin{aligned} P(\nu_\mu \rightarrow \nu_\mu) = 1 &- 4|U_{\mu 3}|^2|U_{\mu 1}|^2 \sin^2\Delta_{31} \\ &- 4|U_{\mu 3}|^2|U_{\mu 2}|^2 \sin^2\Delta_{32} \\ &- 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2\Delta_{21} \end{aligned}\right\} \approx 1 - \sin^2 2\theta \sin^2(|\Delta m^2| L/4E)$$

$|\Delta m^2| \rightarrow \approx |\Delta m^2_{32}|$

$\theta \rightarrow \approx \theta_{23}$



$|\Delta m^2| = 2.5\times10^{-3}$ eV^2, $\sin^2 2\theta = 0.8$

$|\Delta m^2| = 2.5\times10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$

$|\Delta m^2| = 3.0\times10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E∼500 km/GeV

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

depends on Δm^2_{31} and θ_{13}

"Solar" Term

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

<1% effect for current accelerator experiments

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

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$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

depends on Δm^2_{31} and θ_{13}

L/E oscillatory behavior embedded in Δ_{ij} terms

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

"Solar" Term

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

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"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23})\sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

<1% effect for current accelerator experiments

depends on Δm^2_{31} and θ_{13}

Matter Effect

Additional term in Hamiltonian introduced by ν_e+e and ν_e+e CC scattering modifies oscillations

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Positive for neutrinos
Negative for anti-neutrinos

$$a = \frac{\pm G_F N_e}{\sqrt{2}} \approx \frac{1}{4000\,km}$$

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

"Solar" Term

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

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"Atmospheric" Term

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<1% effect for current accelerator experiments

depends on Δm^2_{31} and θ_{13}

CP Violating Phase

$+\delta$ for neutrinos

$-\delta$ for anti-neutrinos

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

"Solar" Term

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

$<1\%$ effect for current accelerator experiments

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

depends on Δm^2_{31} and θ_{13}

Mass Hierarchy

Unknown sign of Δm^2_{31} & Δm^2_{32} modifies probabilities

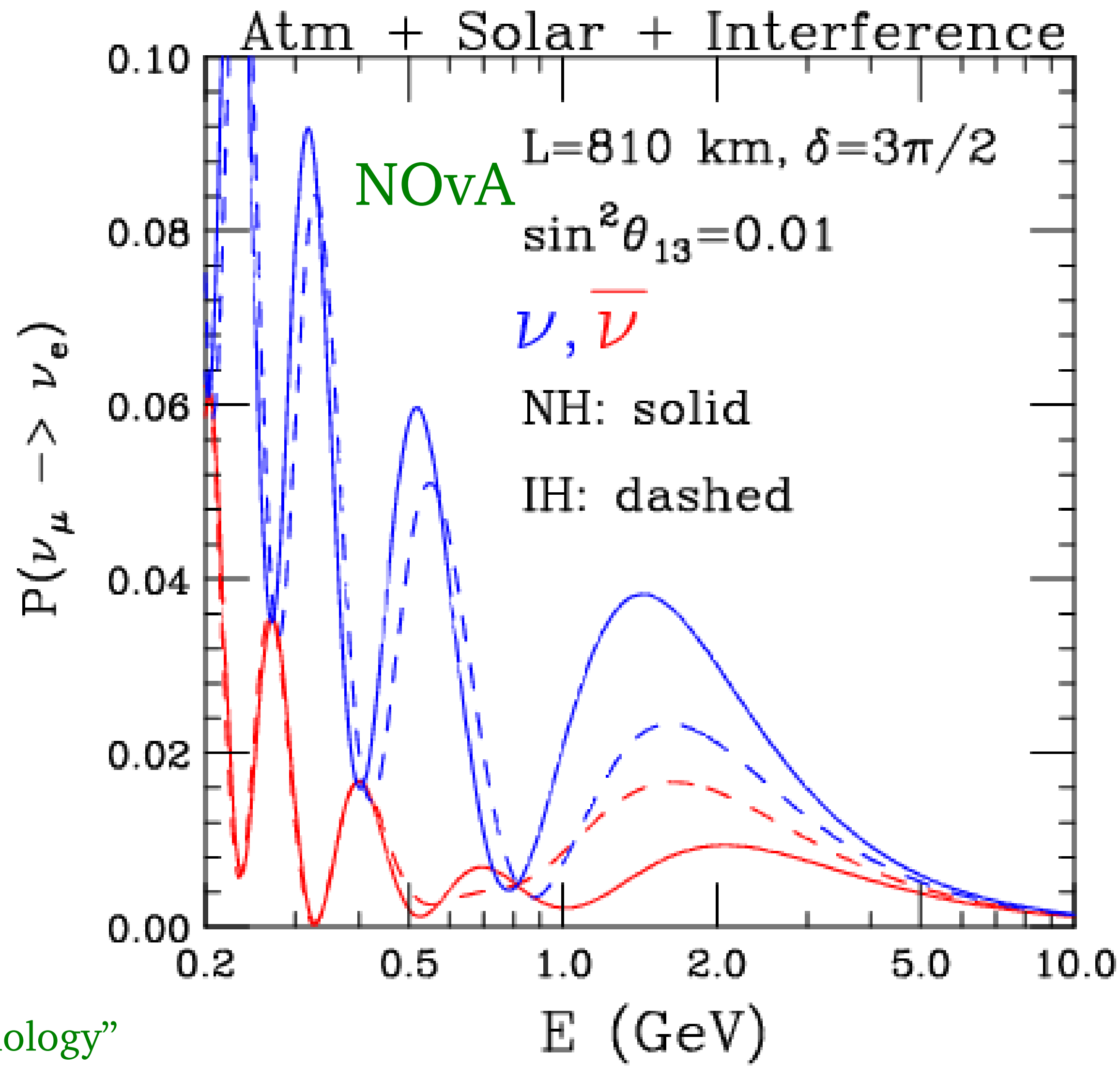
Electron Neutrino Appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} \mathrm{e}^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

$$a = \frac{\pm G_F N_e}{\sqrt{2}} \approx \frac{1}{4000\,km}$$



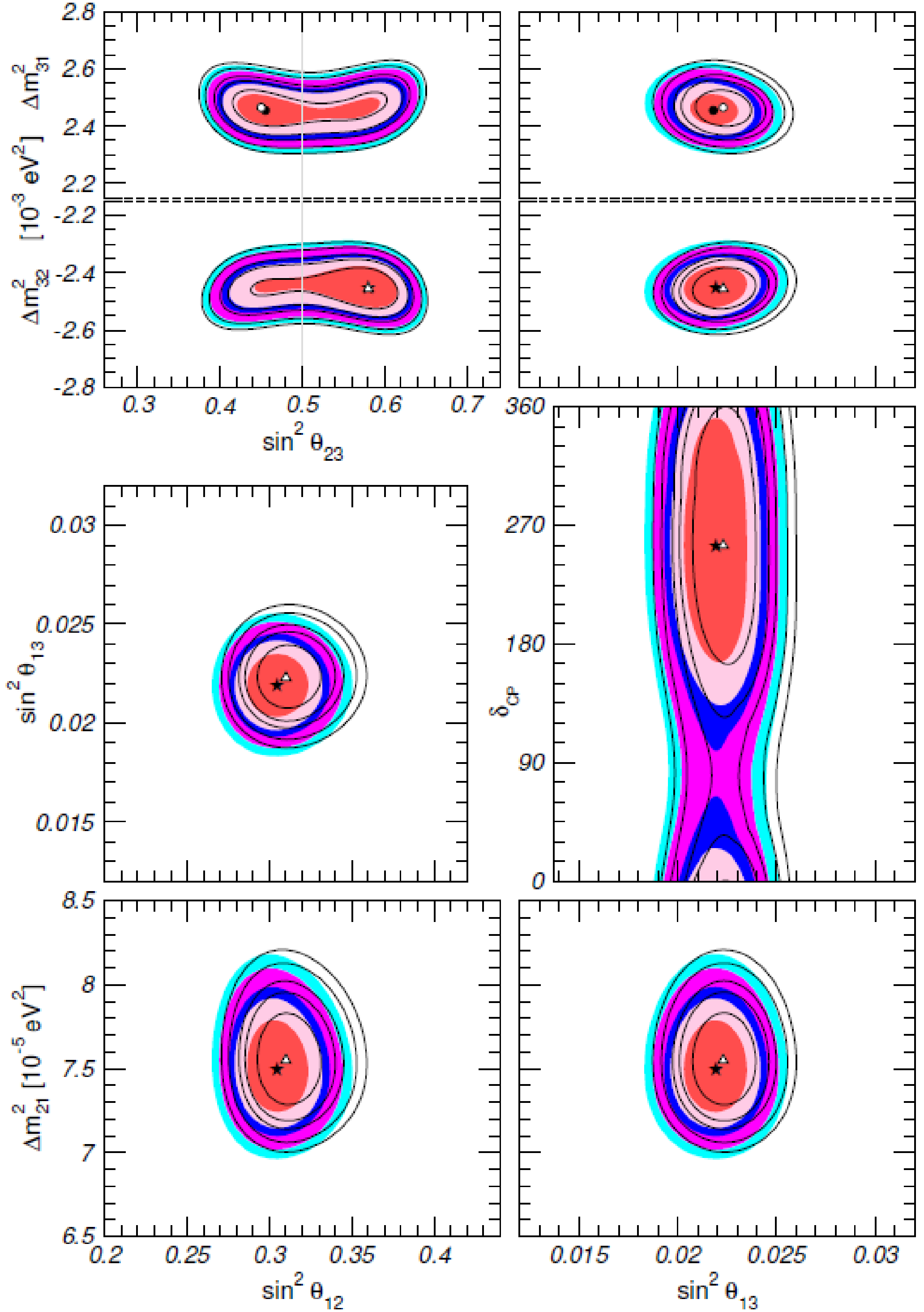
S. Parke, "Neutrino Oscillation Phenomenology" in *Neutrino Oscillations: Present Status and Future Plans*, Ed. J. Thomas, P. Vahle

What do we know?

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Three active flavors (LEP $Z \rightarrow l\bar{l}, q\bar{q}$)
- $\sin^2\theta_{12}$ and Δm^2_{21} from $\nu_e \rightarrow \nu_\mu$ in the Sun and from $\bar{\nu}_e \rightarrow \bar{\nu}_e$ at reactors (SuperK/SNO/KAMLAND)
- $\sin^2\theta_{23}$ and $|\Delta m^2_{31}| \approx |\Delta m^2_{32}|$ from $\nu_\mu \rightarrow \nu_\mu$ in the atmosphere and long baseline accelerators (SuperK, MINOS, T2K)
- $\sin^2\theta_{13}$ from $\bar{\nu}_e \rightarrow \bar{\nu}_e$ at reactors (Daya Bay, RENO, D-CHOOZ)

What do we know?

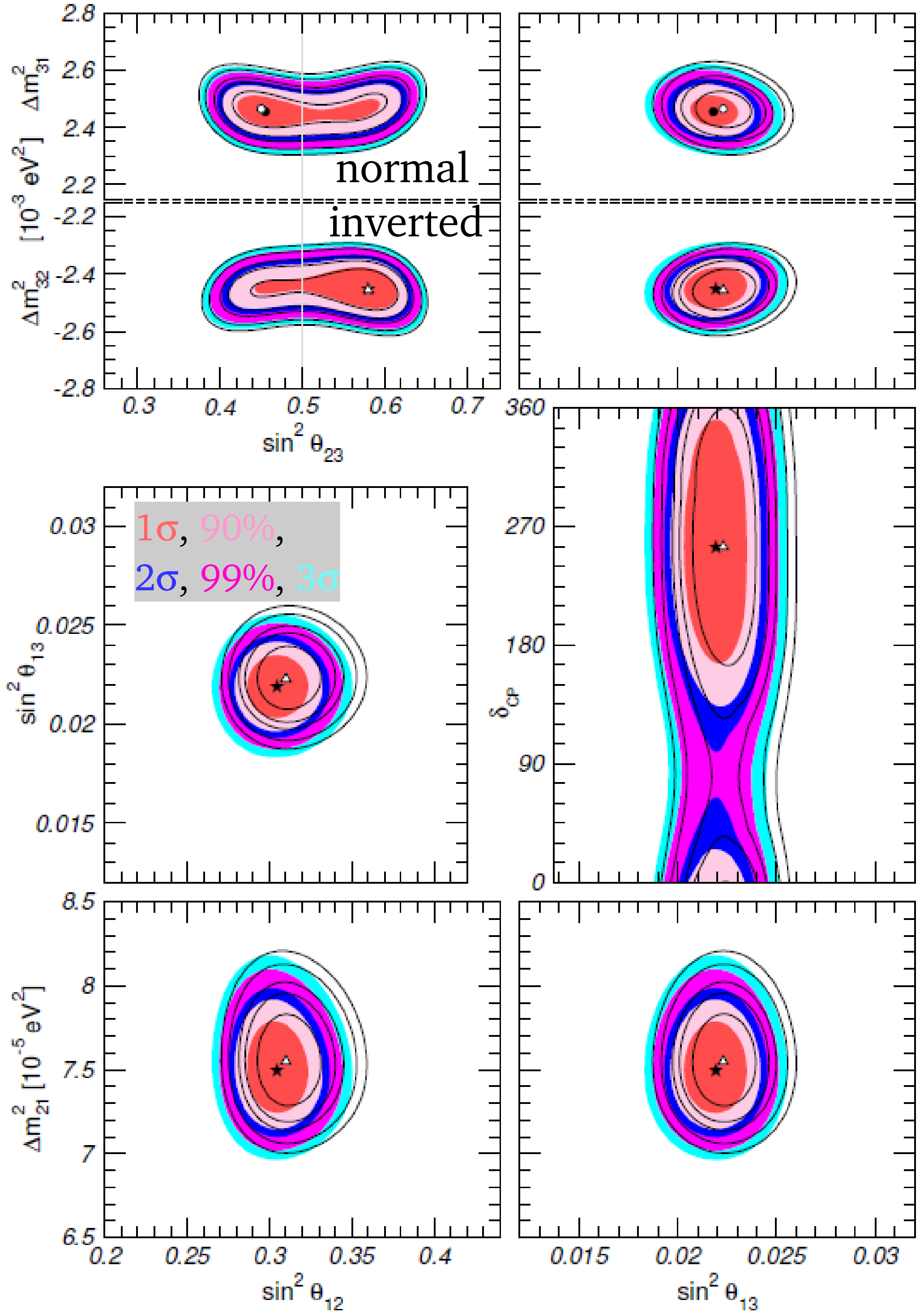


Updated fit to three neutrino mixing: status of leptonic CP violation

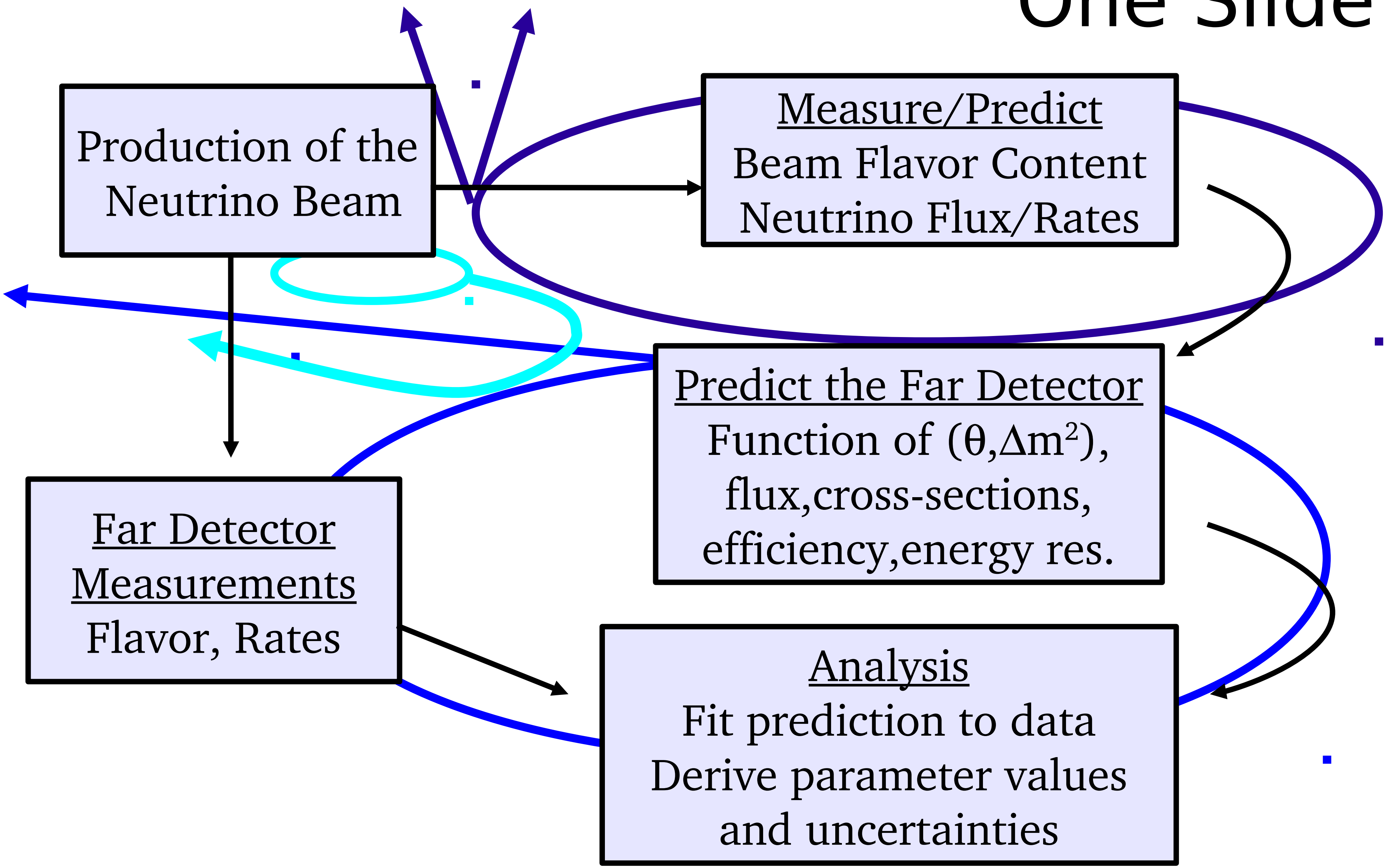
Gonzalez-Garicia, Maltoni, Schwetz arXiv-1409.5439

What we can learn?

- δ_{CP} from $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  (NOvA, LBNF)
- Mass ordering
  $m_3 > m_2, m_1$ "normal"
  $m_3 < m_2, m_1$ "inverted"
  (NOvA, JUNO, PINGU)
- Octant of θ_{23}
- **Are there sterile neutrinos?**

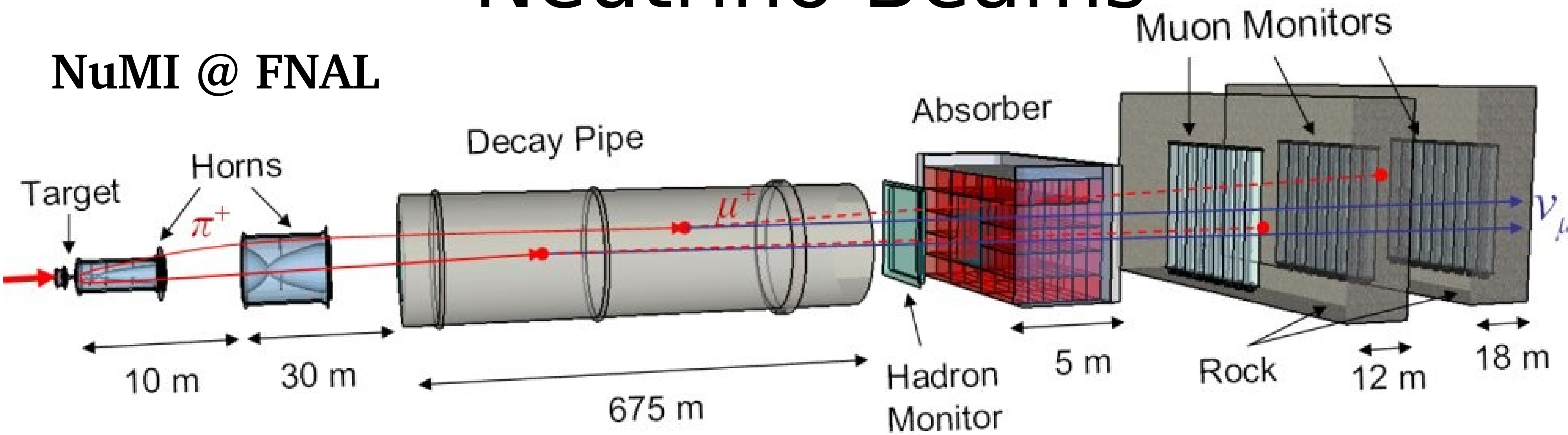


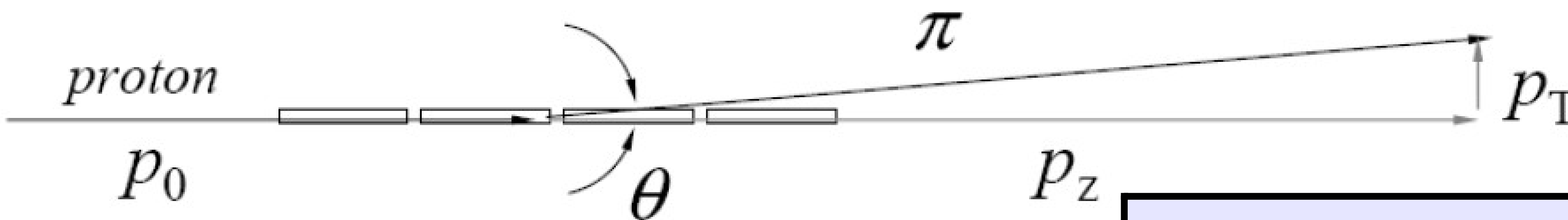
An Oscillation Experiment In One Slide



Neutrino Beams

NuMI @ FNAL





- π,K production off a solid target
- Wide range of pt, pz
- Cross-sections not well known

<u>Important decay modes</u>

$\pi^+, K^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$, $\pi^0 e^+ \nu_e$

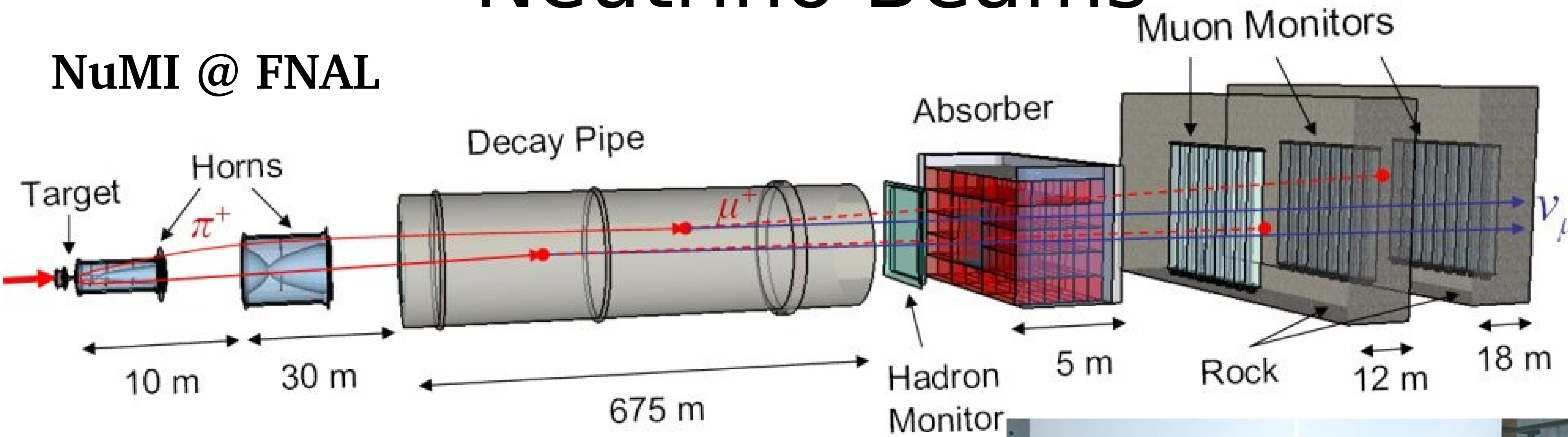
$K^0_L \rightarrow \pi^- e^+ \nu_e$ + CC

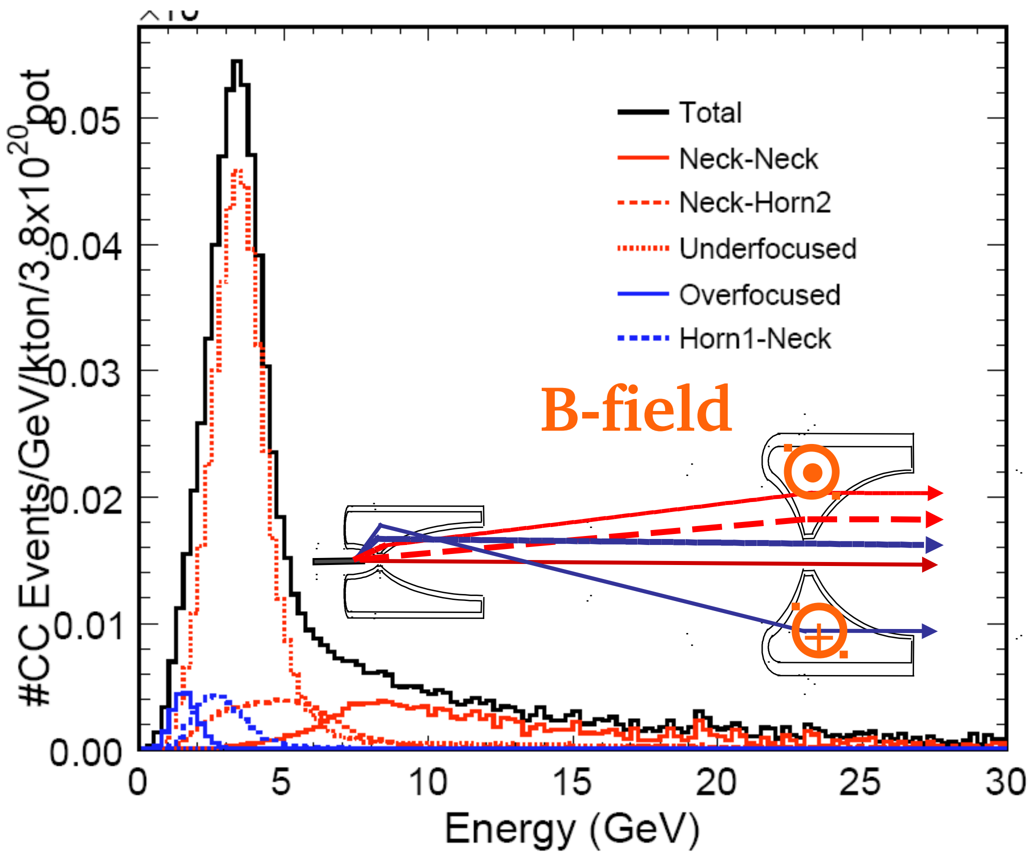
$\rightarrow \pi^- \mu^+ \nu_\mu$ +CC

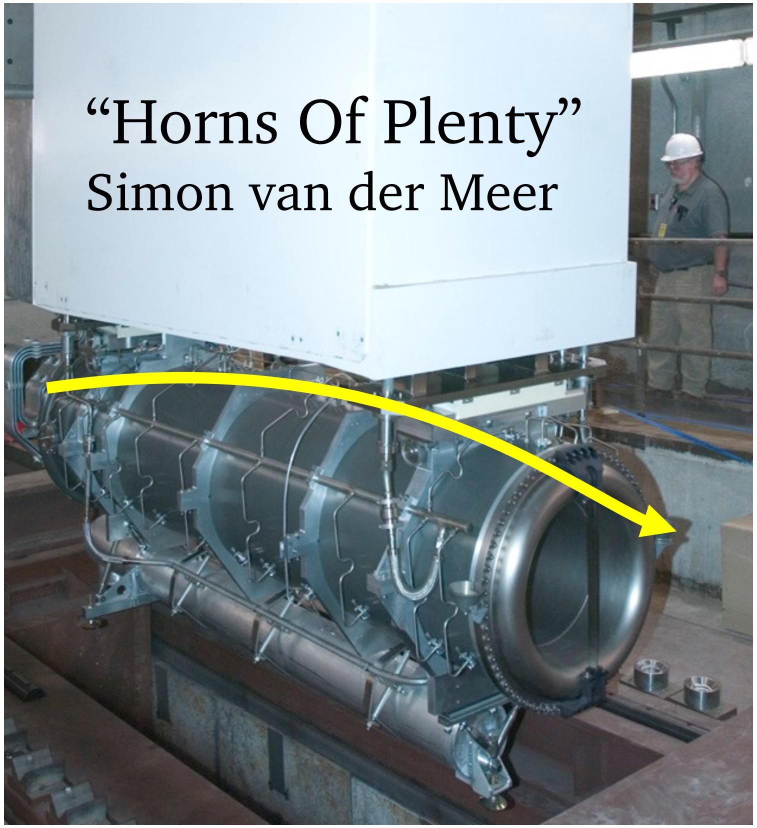
$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

Neutrino Beams

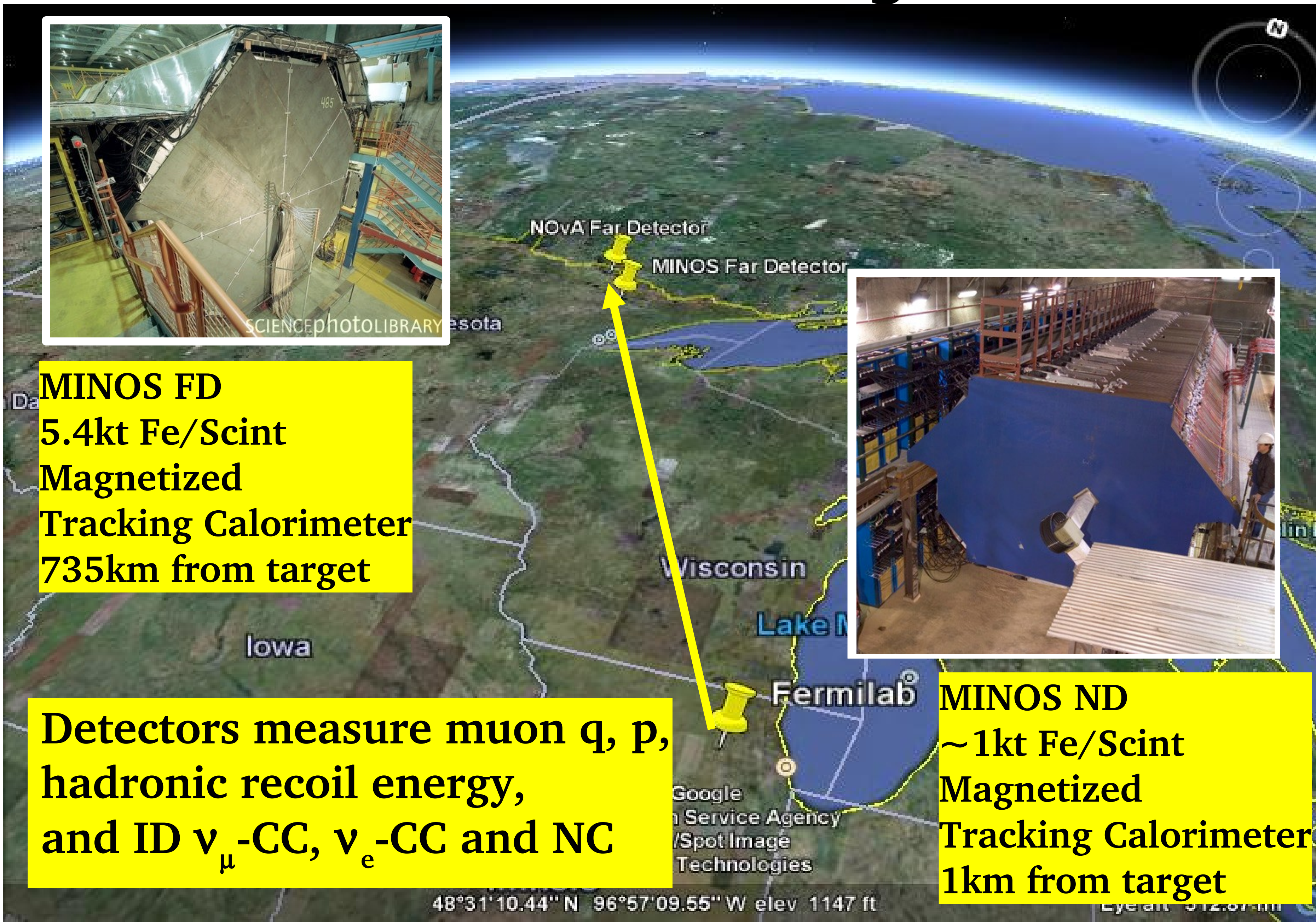
NuMI @ FNAL







Weak interaction = Big Detectors

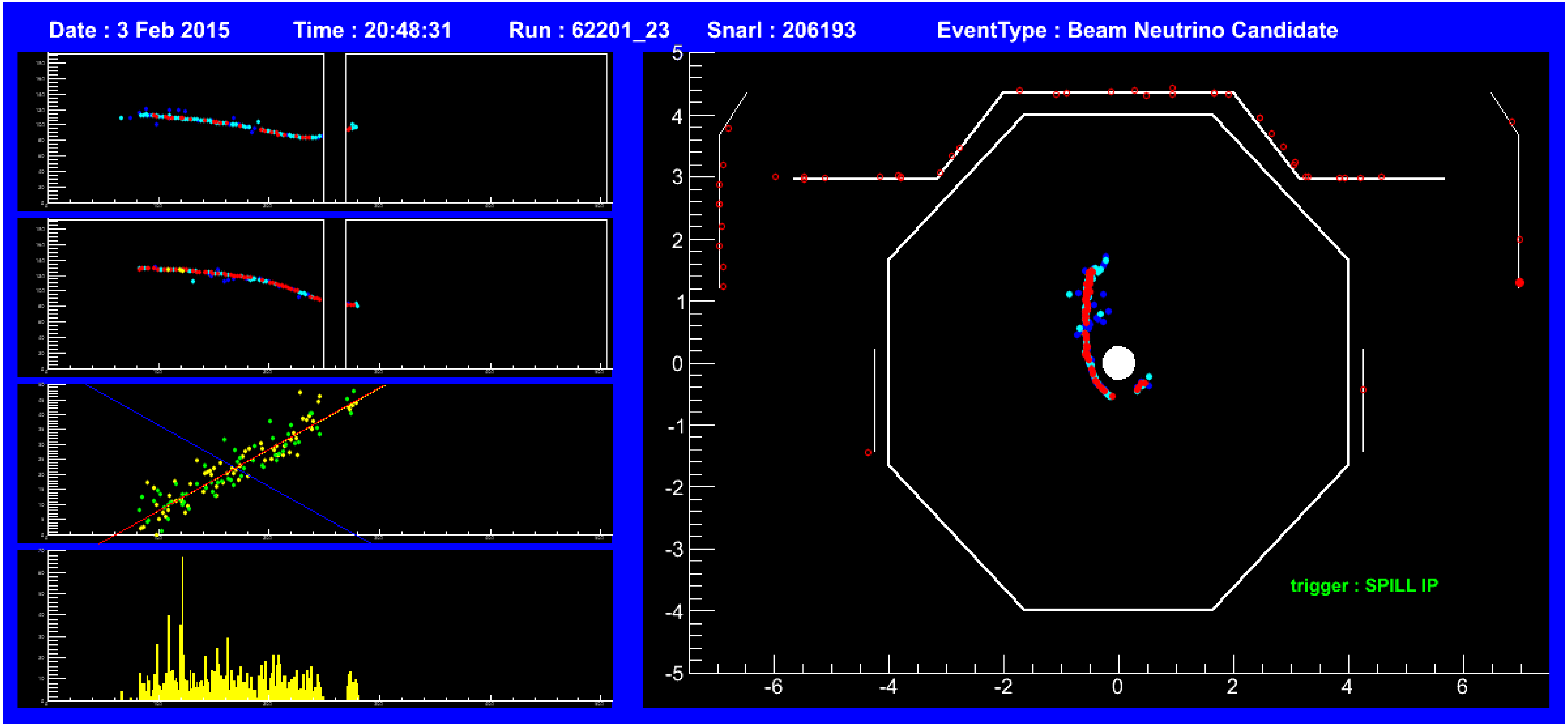


MINOS FD
5.4kt Fe/Scint
Magnetized
Tracking Calorimeter
735km from target

MINOS ND
~1kt Fe/Scint
Magnetized
Tracking Calorimeter
1km from target

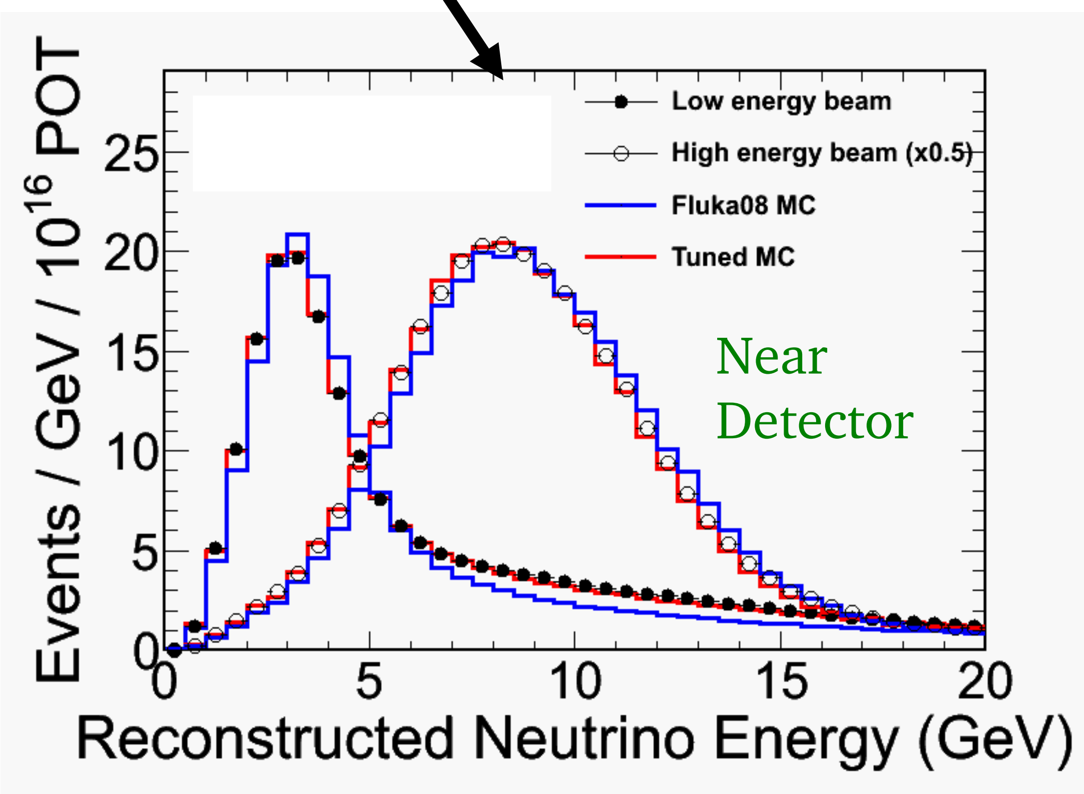
Detectors measure muon q, p,
hadronic recoil energy,
and ID ν_μ-CC, ν_e-CC and NC

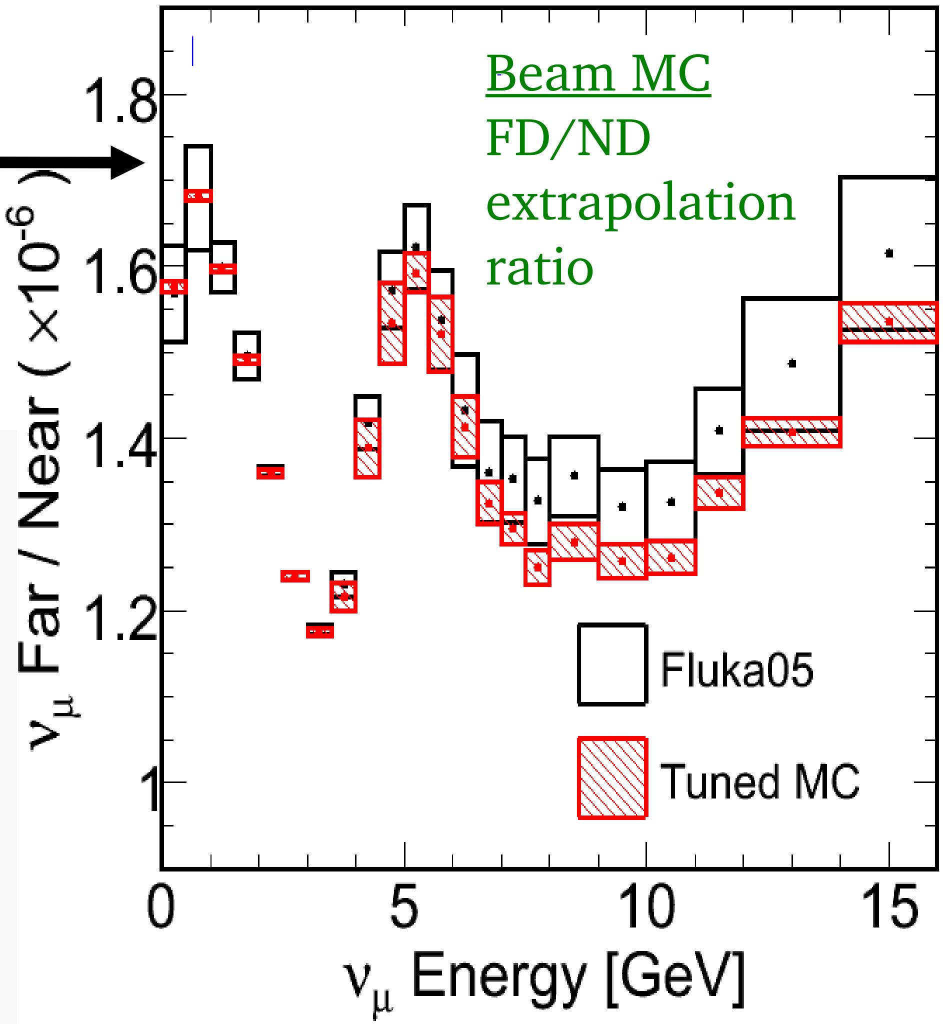
One event at the FD



Predicting the FD $\nu_\mu \rightarrow \nu_\mu$

- Extrapolation improved by tuning beam MC to data in multiple focusing configurations

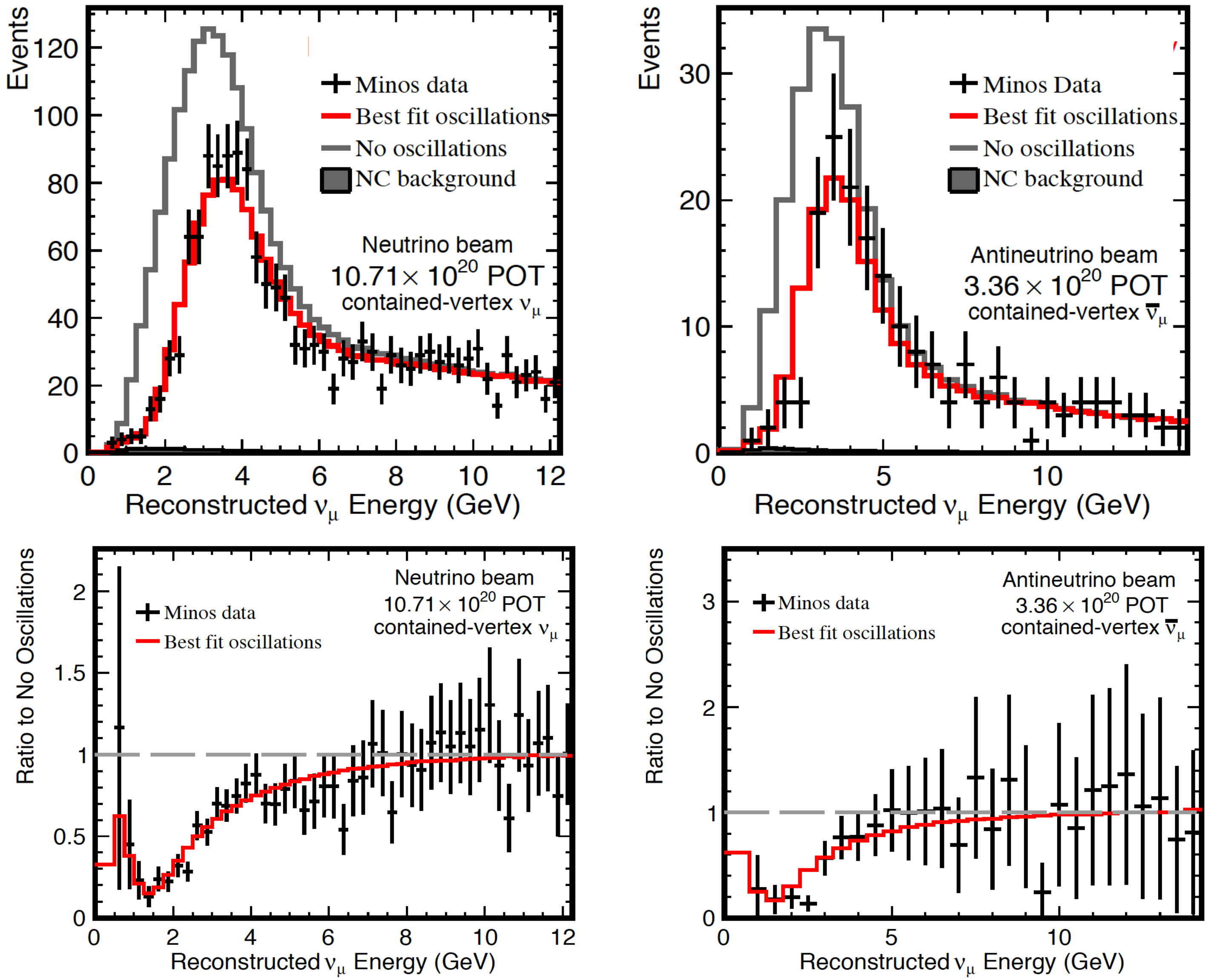




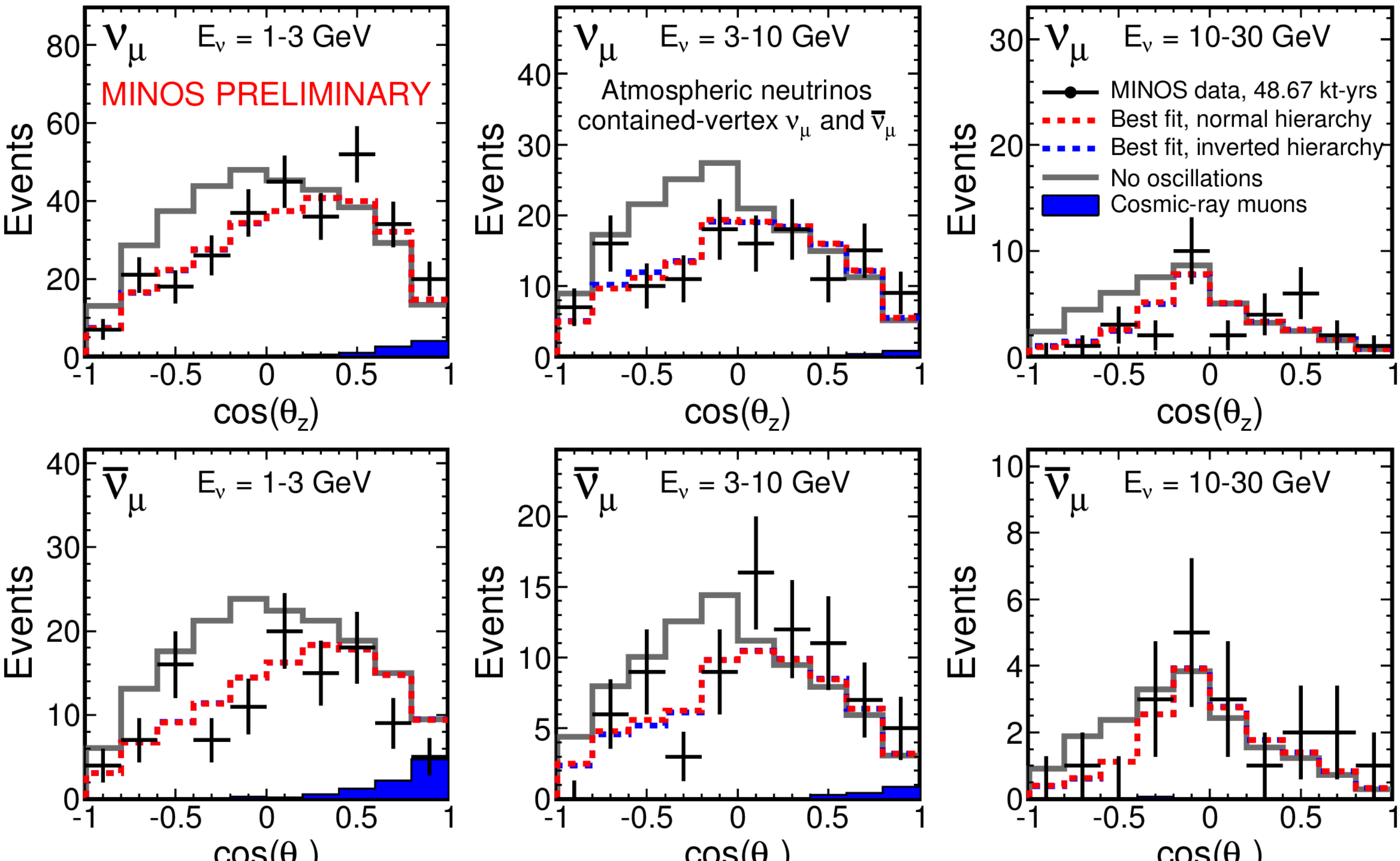
Full 3 flavor oscillation analysis

- Multi-parameter likelihood fit, with systematics handled as nuisance parameters
- Beam ν_μ- and $\bar{\nu}_\mu$-CC events from the entire "low energy" dataset
  - 10.7e20 + 3.4e20 protons on target
  - constrain $\sin^2 2\theta_{23}$, Δm^2_{32}
- Atmospheric ν_μ- and $\bar{\nu}_\mu$ -47.6 kiloton-years
  - mass ordering (a.k.a. hierarchy), θ_{23} octant
- Beam ν_e-CC:
  - θ_{13}, δ_{CP}, mass ordering
  - θ_{13} fit with penalty term using measurements from reactor experiments.

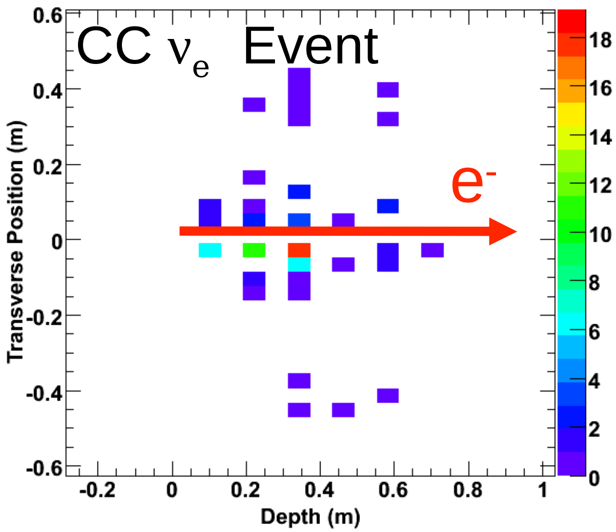
Beam ν_μ at the FD



Atmospheric neutrinos

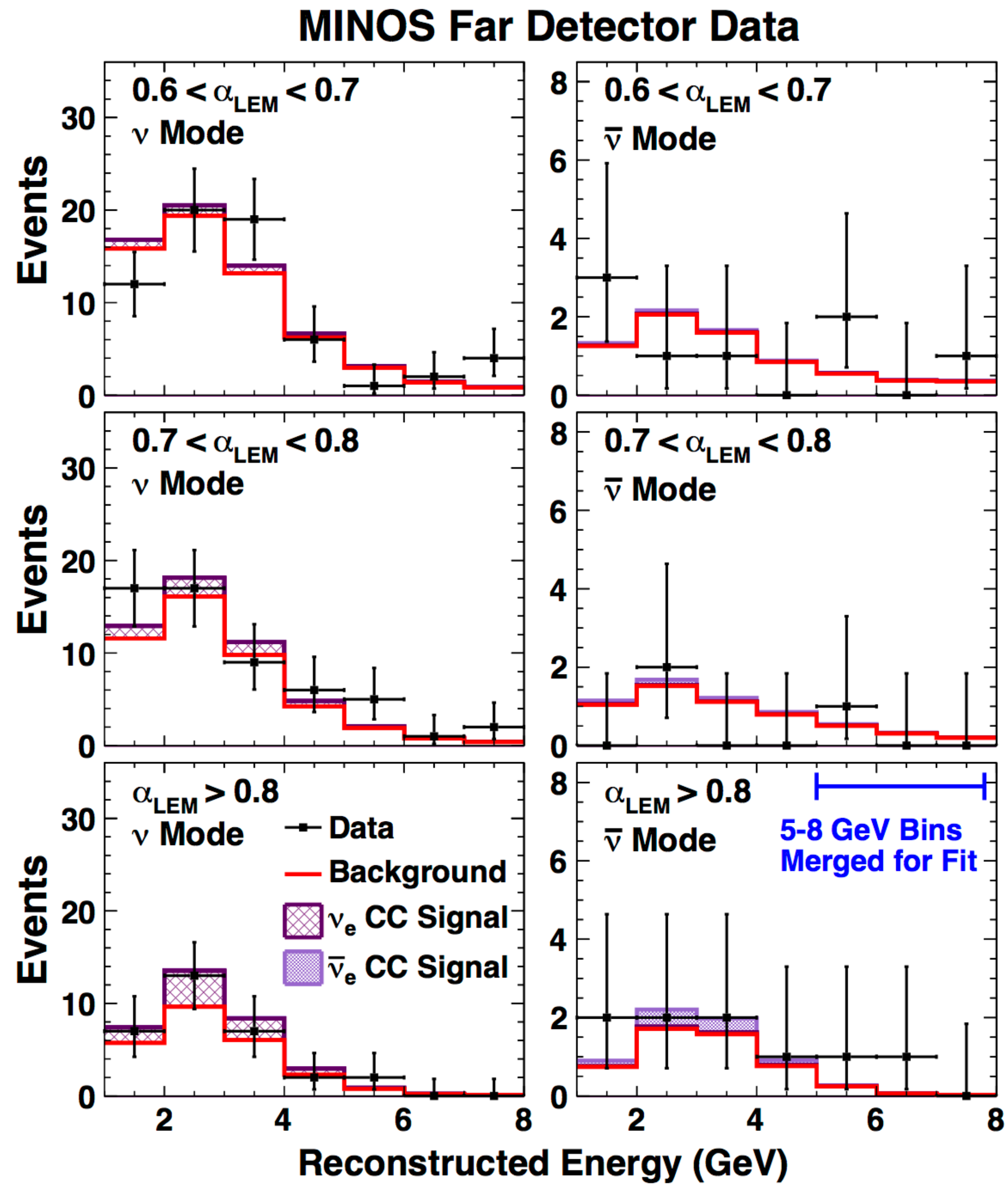


$\nu_\mu \rightarrow \nu_e$

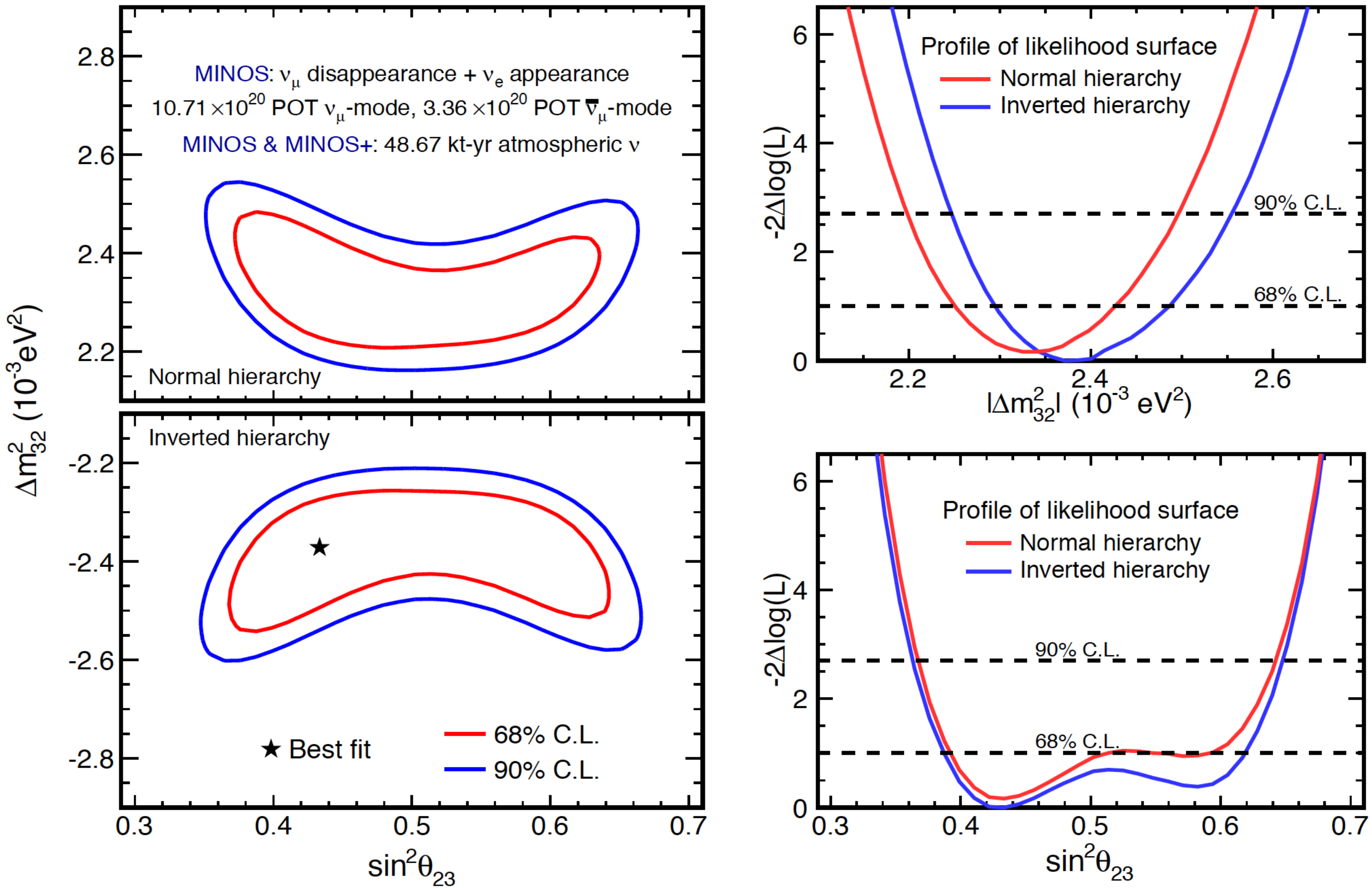


FD event yields for normal mass hierarchy, $\delta_{CP}=0$, $\theta_{23}=\pi/4$

	ν-beam	$\bar{\nu}$-beam
$\theta_{13}=0$	69.1	10.5
$\theta_{13}=0.1$	+26.0	+3.1
Obs.	88	12



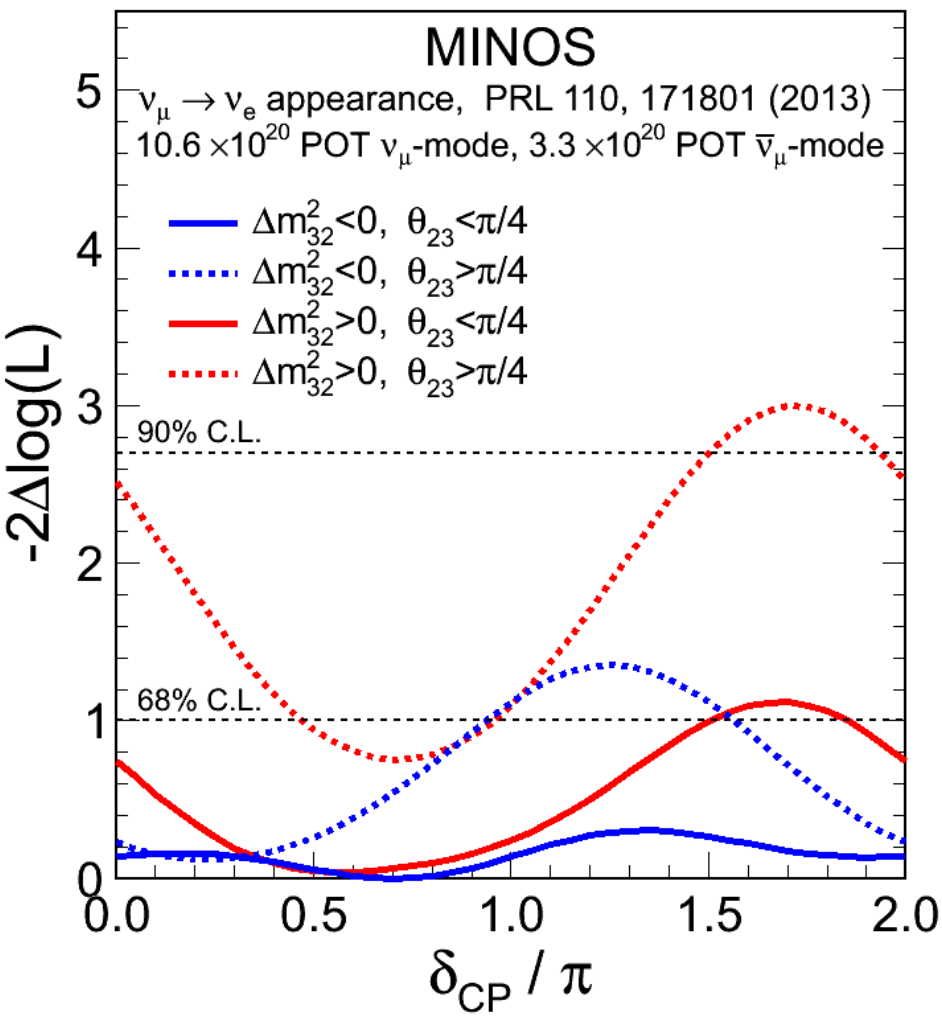
Three Flavor Results



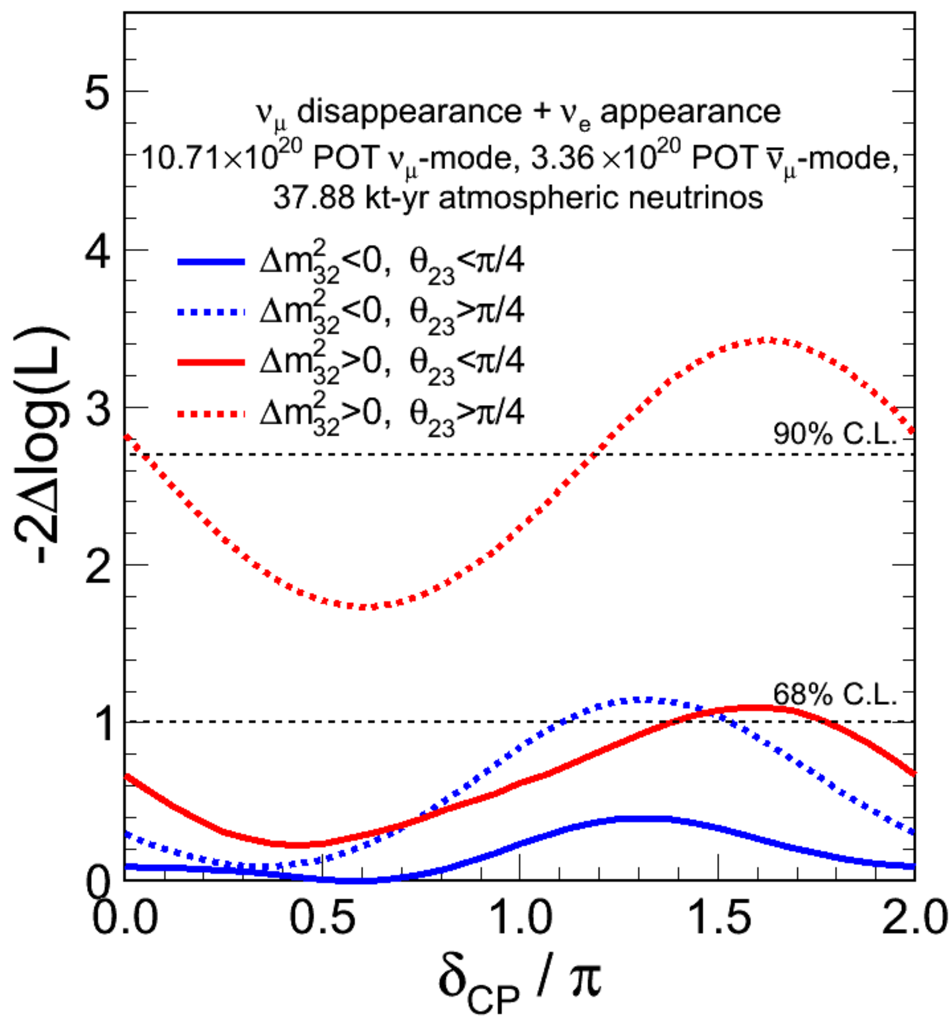
- Solar mixing parameters fixed to $\Delta m^2_{21} = 7.54\times10^{-5}\,eV^2$ and $\sin^2\theta_{12} = 0.307$ *Fogli et al., PRD **86**, 013012 (2012)*
- θ_{13} fit as nuisance parameter, constrained by reactor results: $\sin^2\theta_{13} = 0.0242 \pm 0.0025$ (θ_{13}=8.95°)
- δ_{CP} , θ_{23}, Δm^2_{32} unconstrained
- 19 systematic uncertainties (4 for beam+15 for atmospherics) included as nuisance parameters

Three flavor results

Appearance only



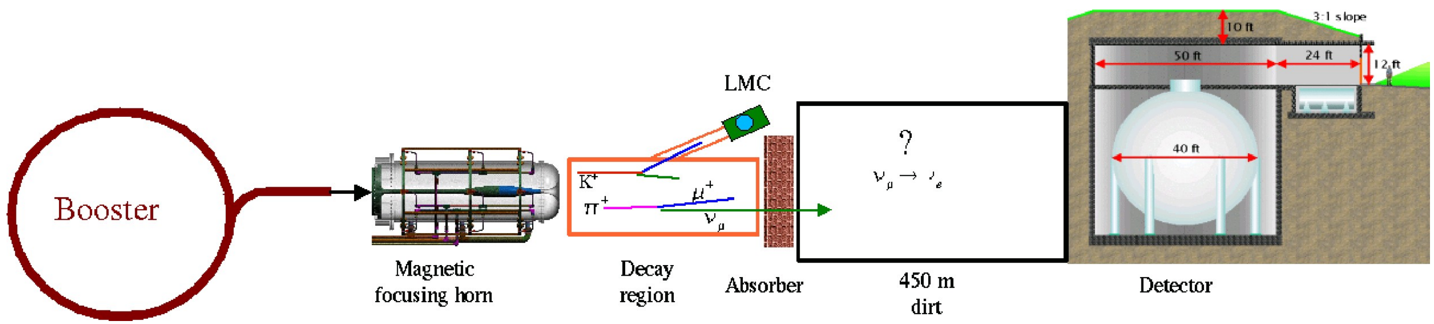
Disappearance + Appearance



Phys. Rev. Lett. ***112****, 191801 (2014)*

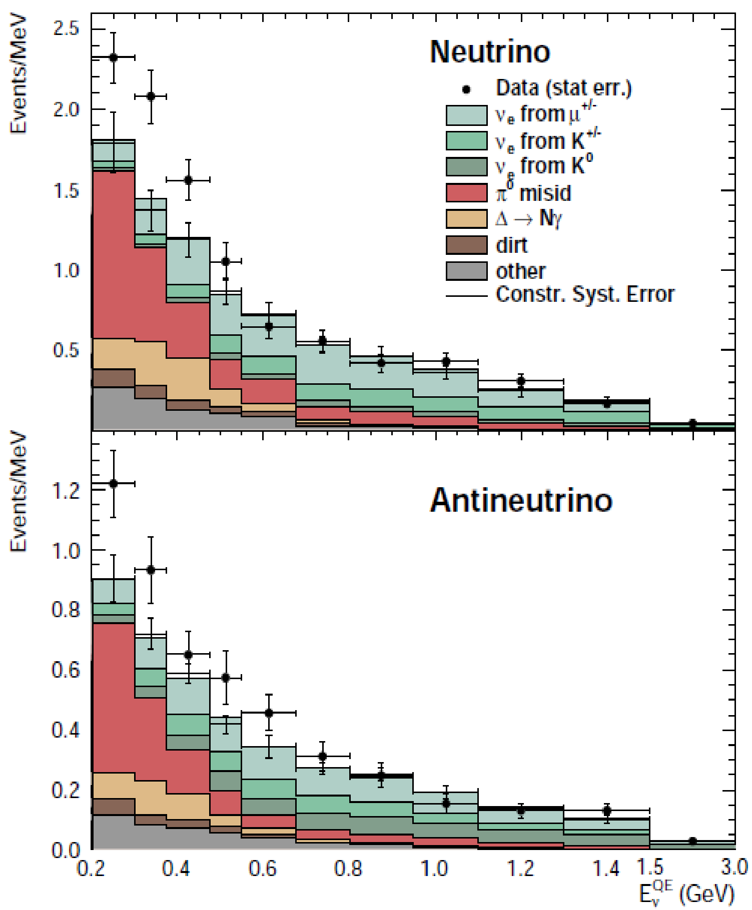
A fourth neutrino?

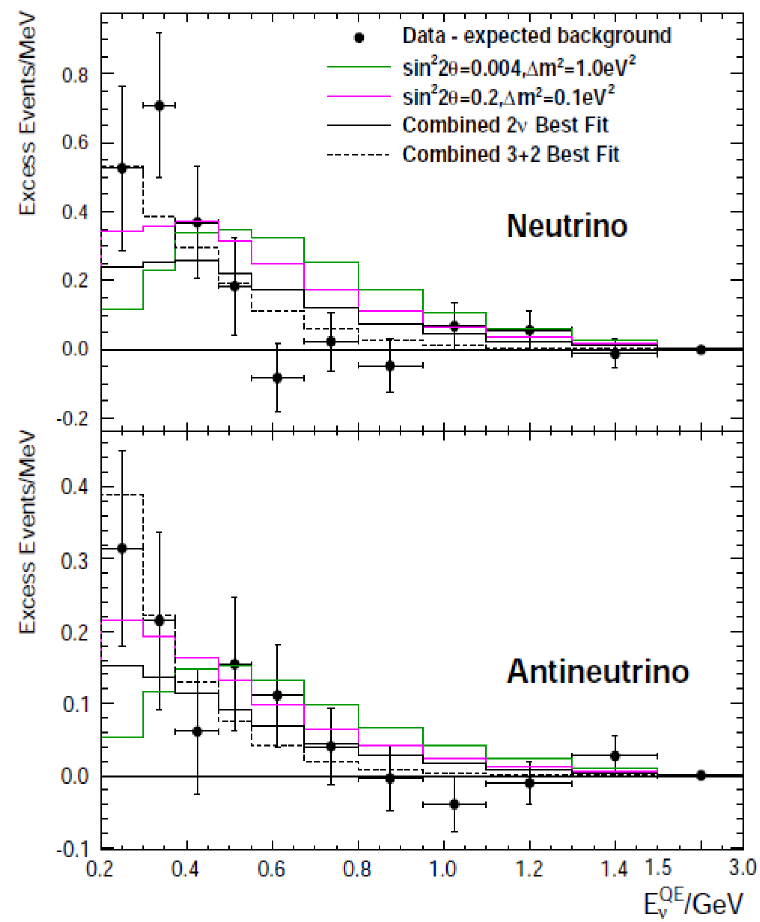
A fourth neutrino?



Anomalies in:

accelerator $\nu_\mu \to \nu_e$



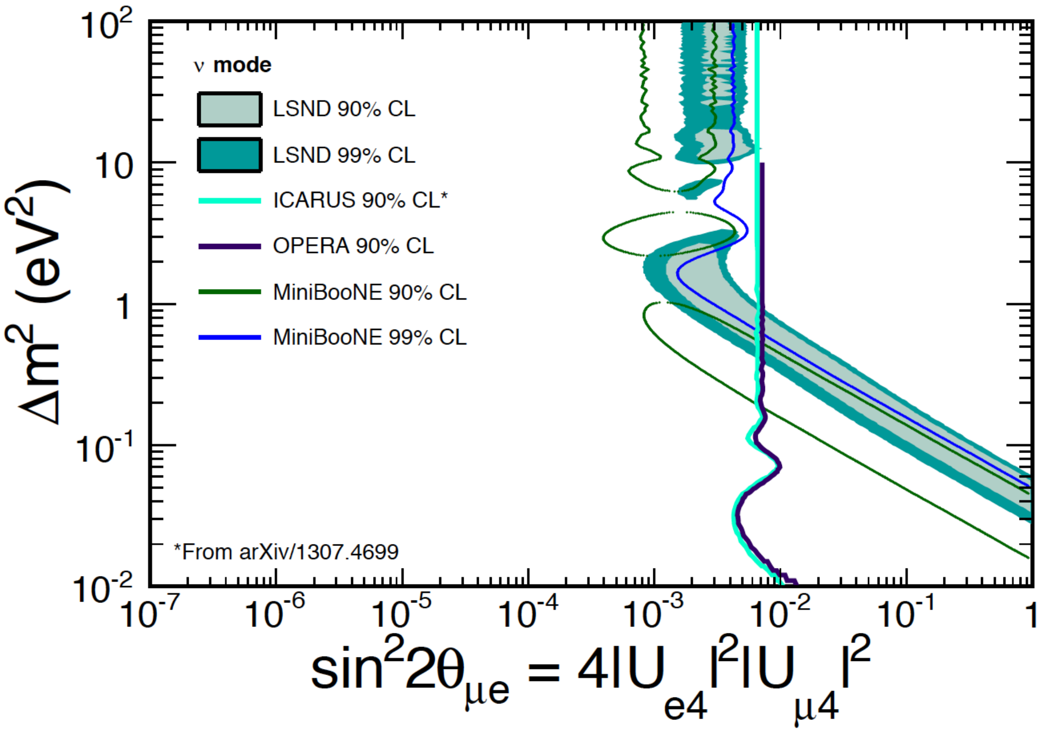


MiniBooNE, PRL 110, 161801(2013)

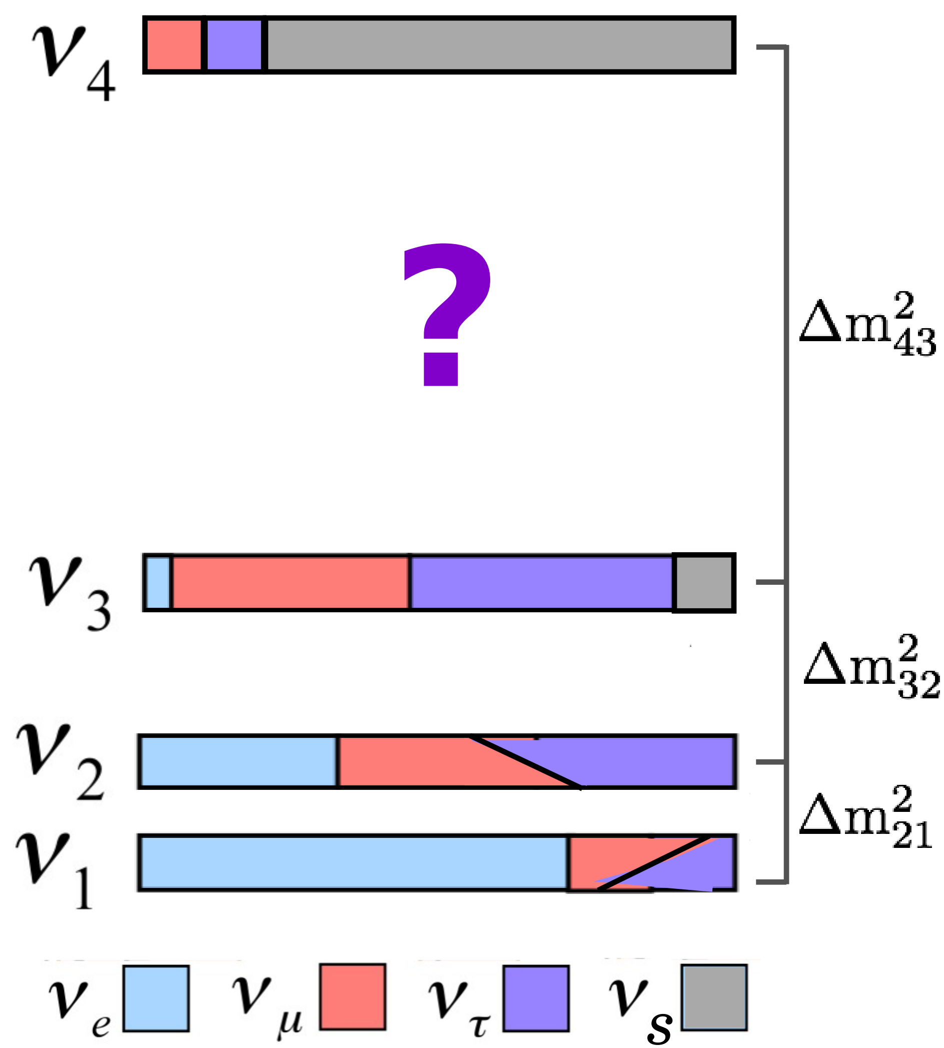
A fourth neutrino state?

Anomalies in: accelerator $\nu_\mu \rightarrow \nu_e$ and reactor $\nu_e \rightarrow \nu_e$

If oscillations, requires $\Delta m^2 \gg \Delta m^2_{32}$

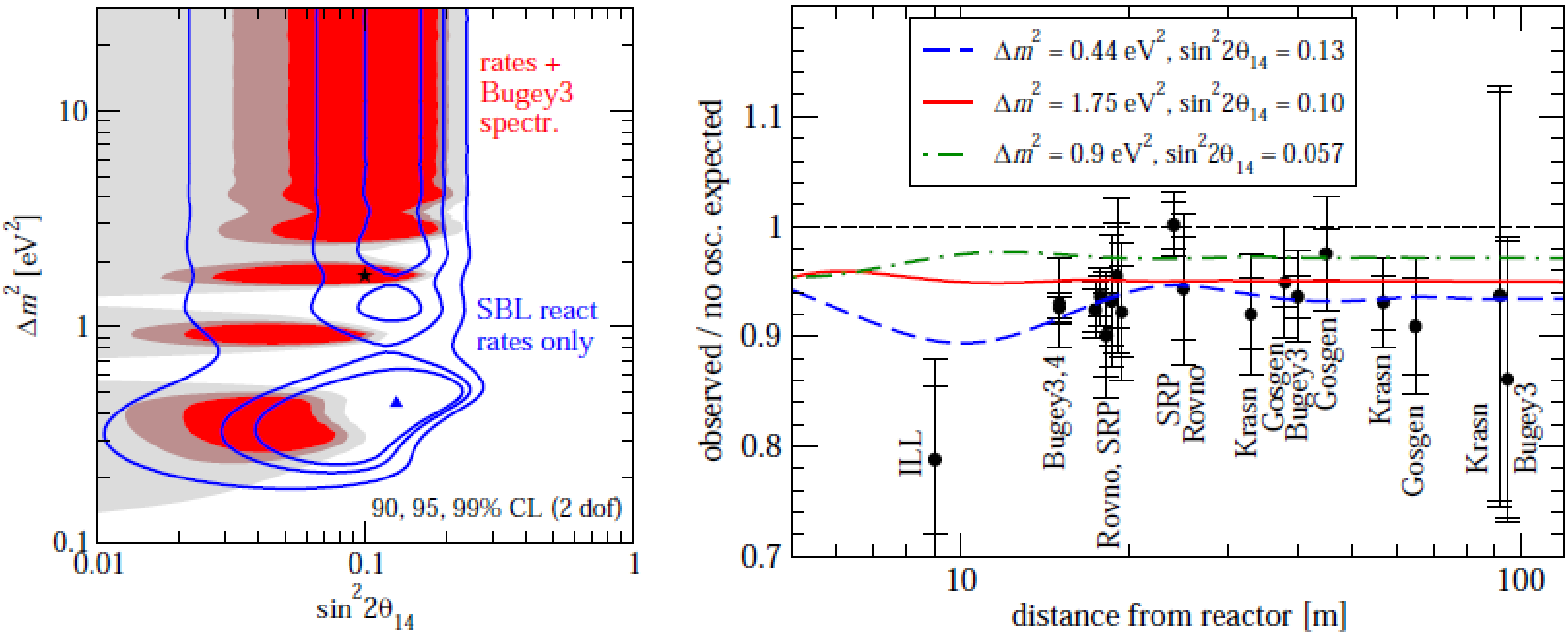


MiniBooNE, PRL 110, 161801(2013)



A fourth neutrino state?

Anomalies in: reactor $\nu_e \rightarrow \nu_e$



MiniBooNE, PRL 110, 161801(2013)

Adding a 4th neutrino

$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

Example:

$$U_{\mu 4} = \cos\theta_{14}\sin\theta_{24}$$
$$= c_{14}s_{24}$$

Three new mixing angles

$$\theta_{14}, \theta_{24}, \theta_{34}$$

Two new phases

$$\delta_{14}, \delta_{24}$$

Phases come packaged with angles $\sin\theta_{24}e^{i\delta_{24}}$

Phenomenology: $\nu_\mu \rightarrow \nu_\mu$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

General form for survival probability

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4 \sum_{i=1}^{4} \sum_{j<i} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \Delta_{ji}$$

Look at ν_μ disappearance for the case $\Delta m^2_{43} \gg \Delta m^2_{31}$ and expand to second order in s_{13} s_{14} and s_{24}:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \Delta_{32} - \sin^2 2\theta_{24} \sin^2 \Delta_{43}$$

Therefore, θ_{24} controls disappearance driven by the sterile state

Phenomenology: $\nu_\mu \rightarrow \nu_s$

Disappearance of NC events = sterile appearance

$$P(\nu_\mu \to \nu_s) \approx c_{14}^4 c_{34}^2 \sin^2 2\theta_{24} \sin^2 \Delta_{43} + A \sin^2 \Delta_{32} + B \sin 2\Delta_{32}$$

A and B are a big mess, but to first order:

$$A = s_{34}^2 \sin^2 2\theta_{23}$$

$$B = \frac{1}{2} \sin \delta_{24} s_{24} \sin 2\theta_{34} \sin 2\theta_{23}$$

The oscillation probability also gets modified at the L/E where standard 3 flavor oscillations occur

Oscillation Regimes

A) $10^{-3} < \Delta m^2_{43} < 10^{-1}$ eV^2

i) Energy dependent depletion at high energy in FD but ND unaffected

ii) Use ND to predict FD as usual

B) $10^{-1} < \Delta m^2_{43} < 1$ eV^2

i) Fast oscillations at the FD. Energy independent depletion.

ii) No effect at the ND

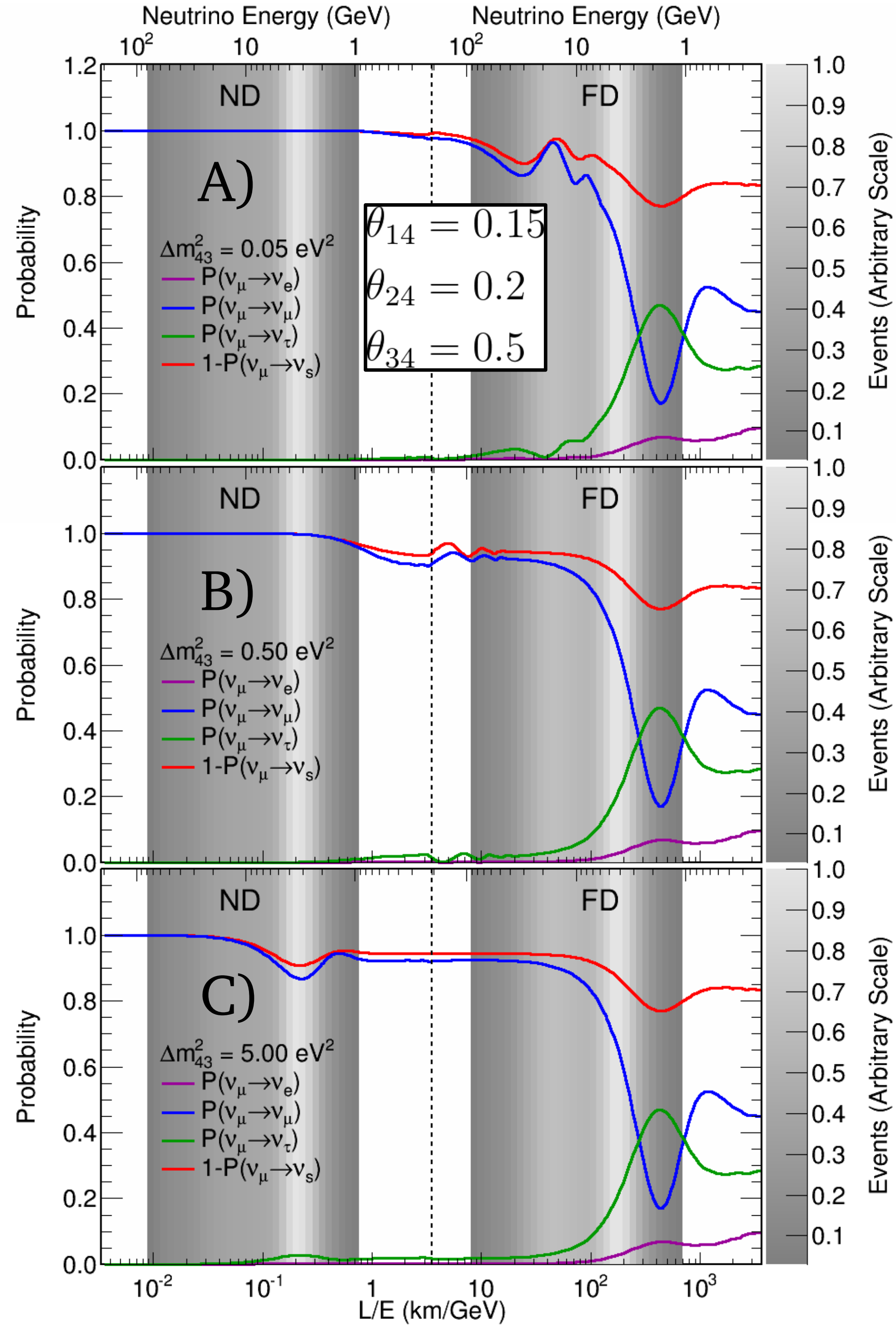
iii) "counting experiment"

C) $\Delta m^2_{43} > 1$ eV^2

i) Oscillations begin to occur at the ND

ii) Fast oscillations at the FD.

iii) Cannot use ND to predict FD.



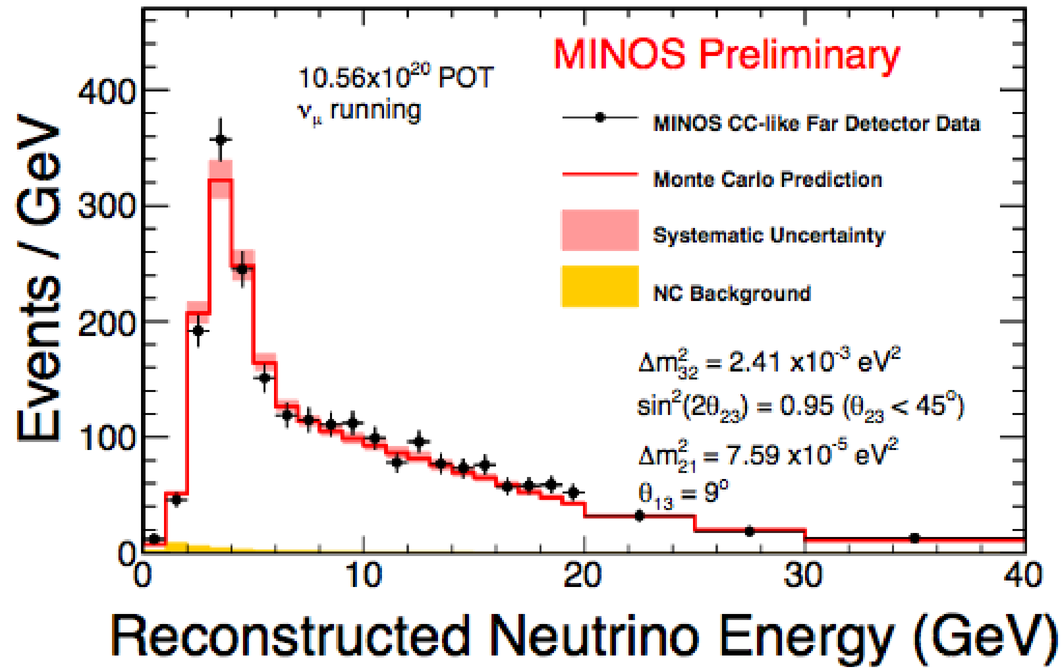
FD energy spectra

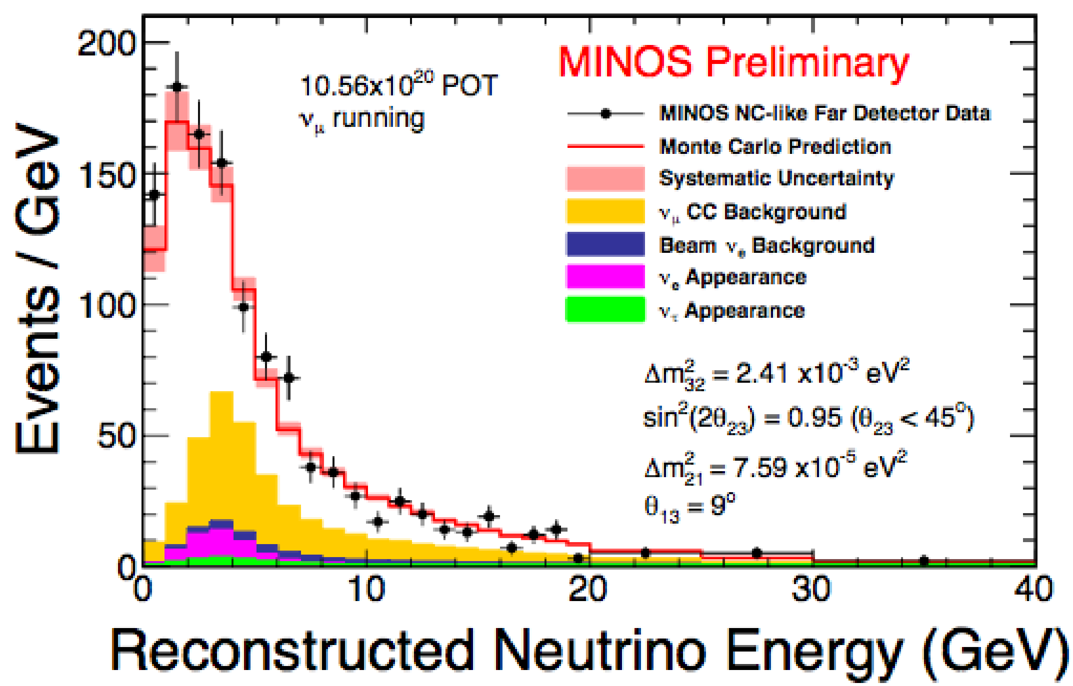
Comparison with the null hypothesis: 3 flavors only

2721 CC events
1221 NC events

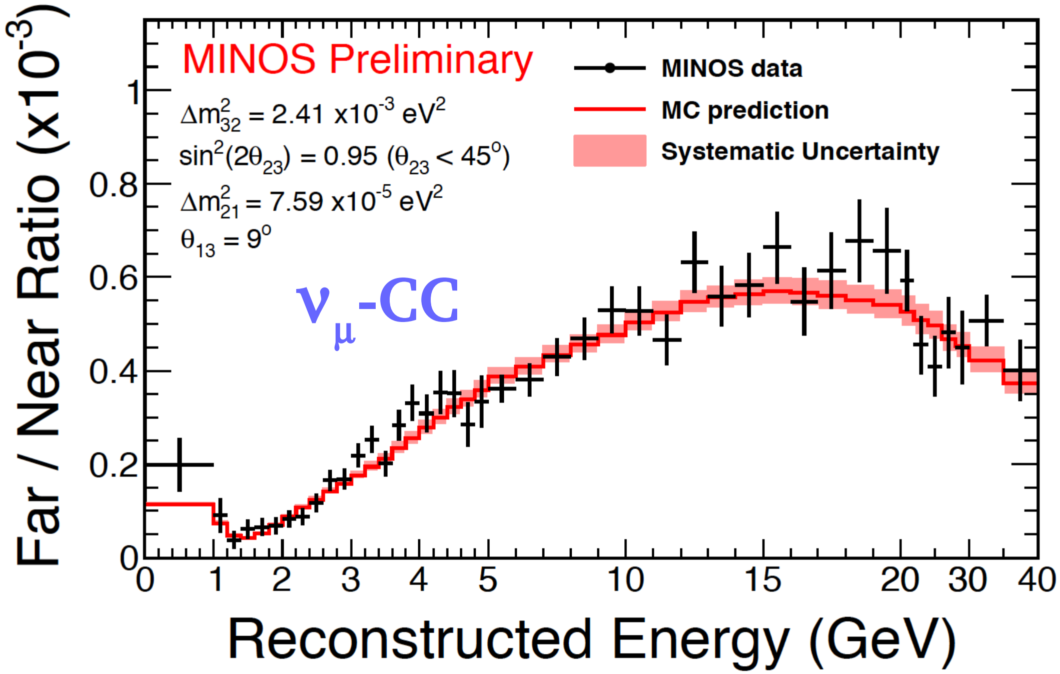
Slight excess of NC in the FD.

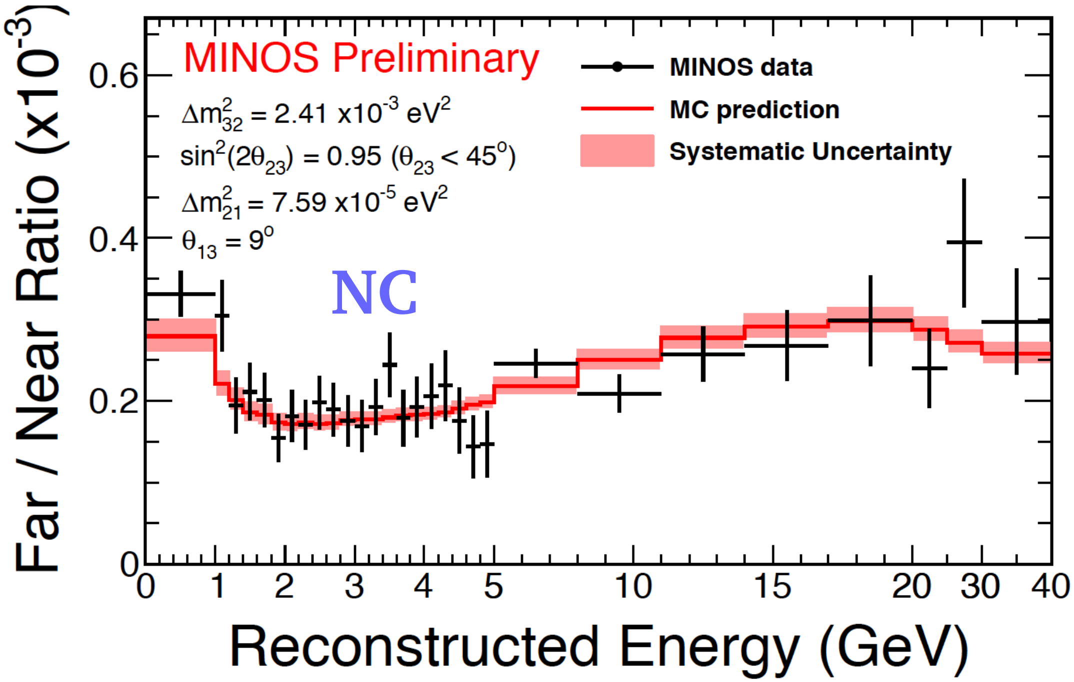
Important: FD prediction tuned to ND here.





Analysis Strategy





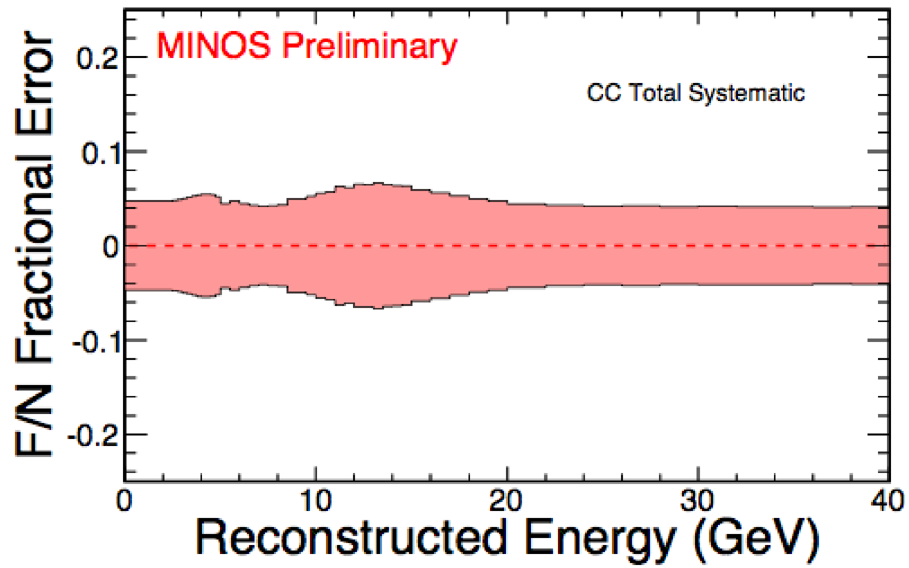
- Key observable is the ratio Far/Near
  - Sensitive to wiggles in either detector
  - Insensitive to fast oscillations in both detectors
- Strategy:
  - fit Far/Near for CC and NC samples to extract θ_{24} and Δm^2_{43} as well as θ_{23}, Δm^2_{32}, and θ_{34}
  - Penalty terms for θ_{13}, θ_{12} and Δm^2_{21} informed by global fits
  - Set θ_{14} and CP phases to zero
- Assign an uncertainty of 40% to the overall rate in the ND

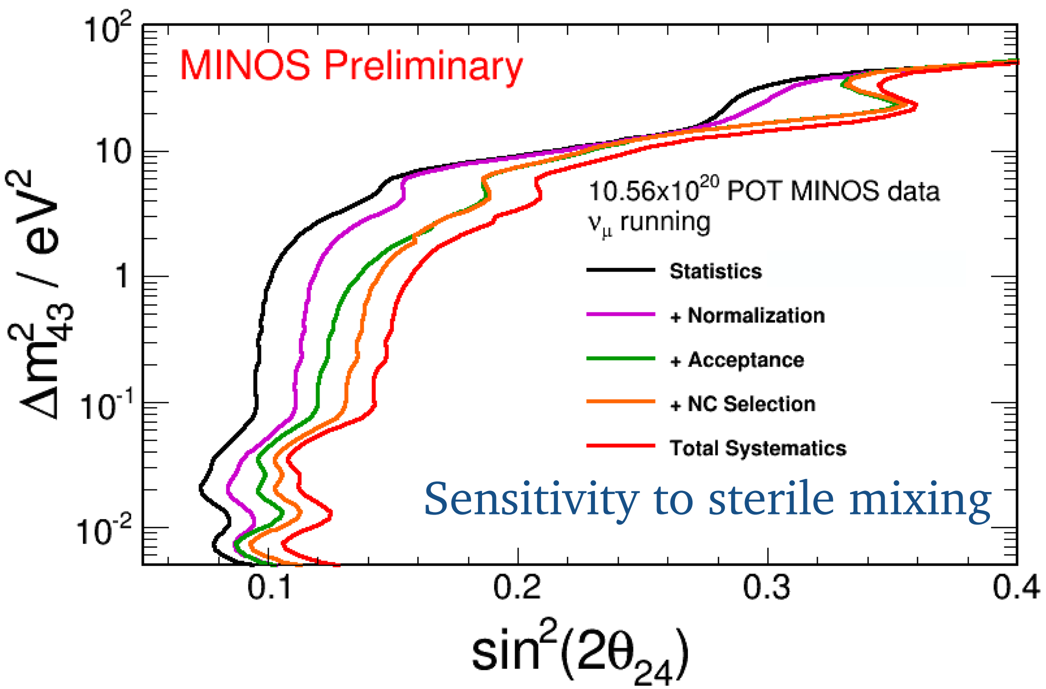
Systematics

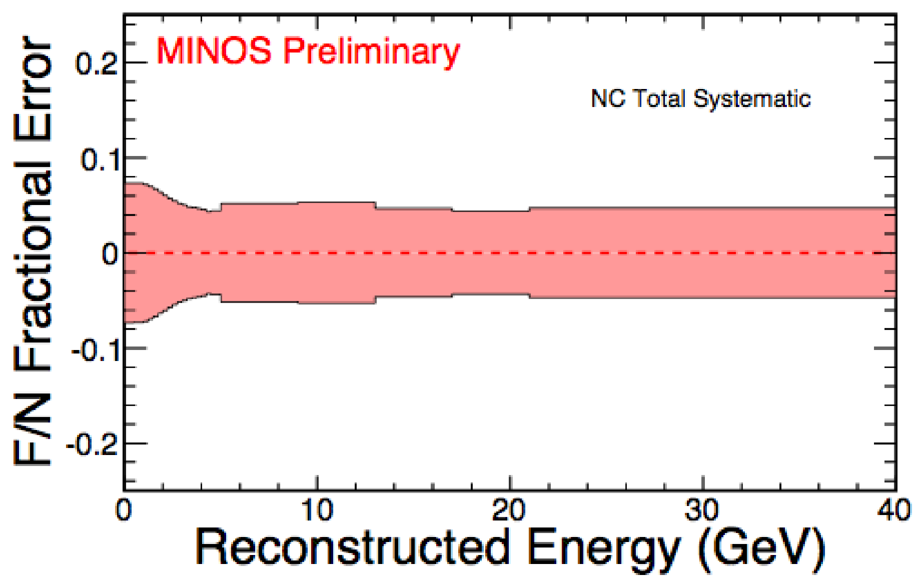
Worries:

1) anything that causes a "wiggle" in E
2) overall normalization effects

Assessed 26 different systematics.

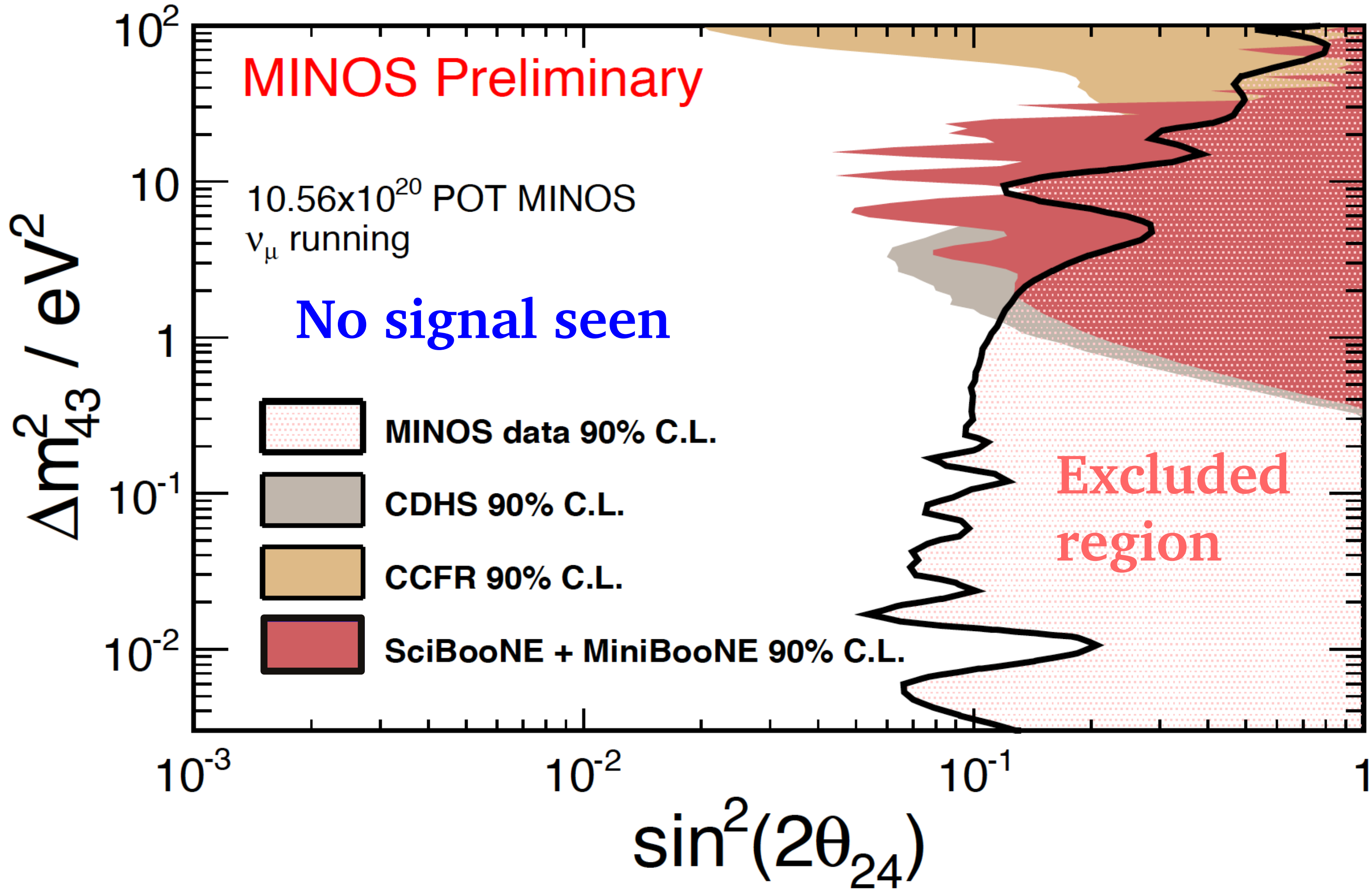






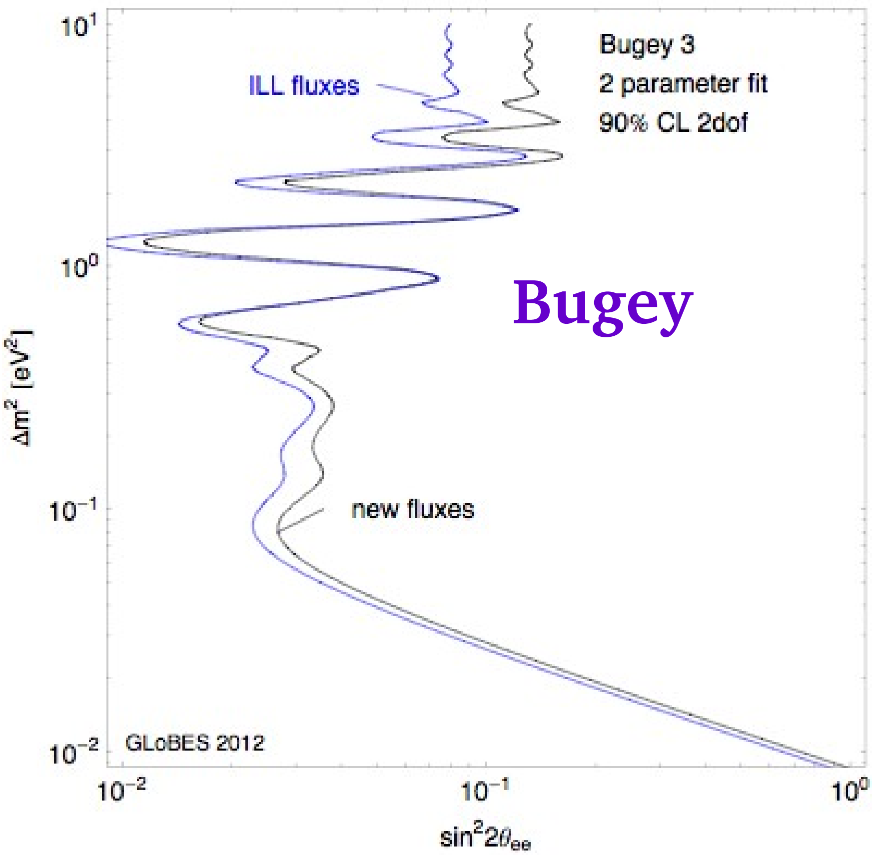
Results

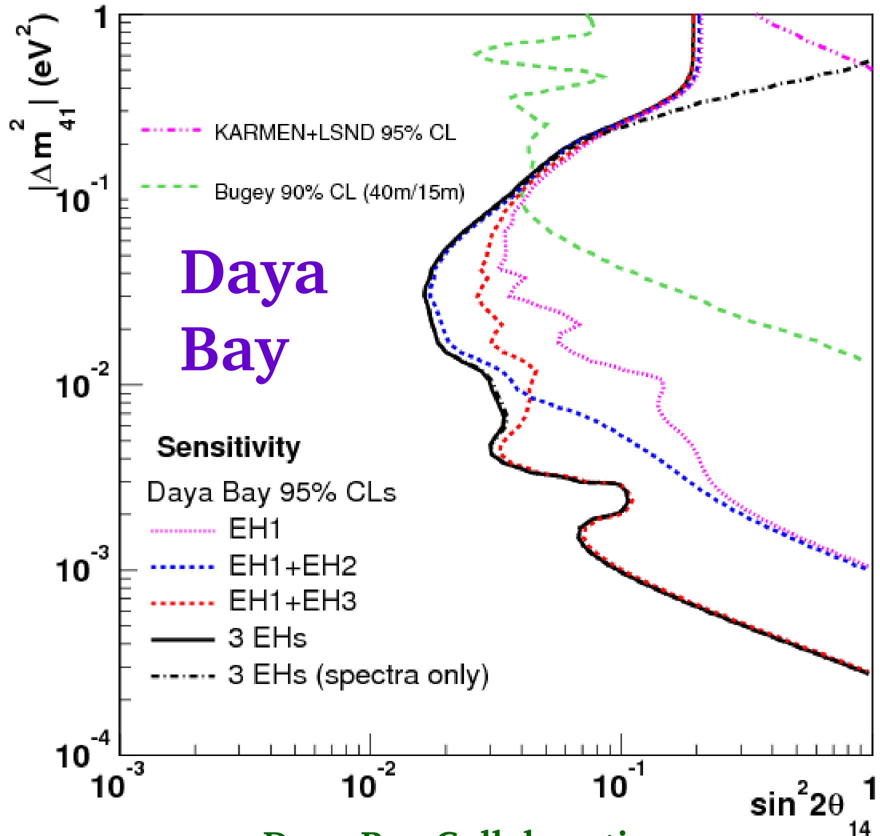
Fit with a bin-by-bin stats + systematics covariance matrix.
Fit is "global" with confidence intervals set by pseudo experiments (Feldman-Cousins "modified frequentist procedure").



Reactor neutrino constraints

Reactor ν_e disappearance is similar to accelerator ν_μ disappearance, but constrains θ_{14} instead of θ_{24}





Daya Bay Collaboration

Phys.Rev.Lett. 113 (2014) 141802

Combining $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$

Major takeaway

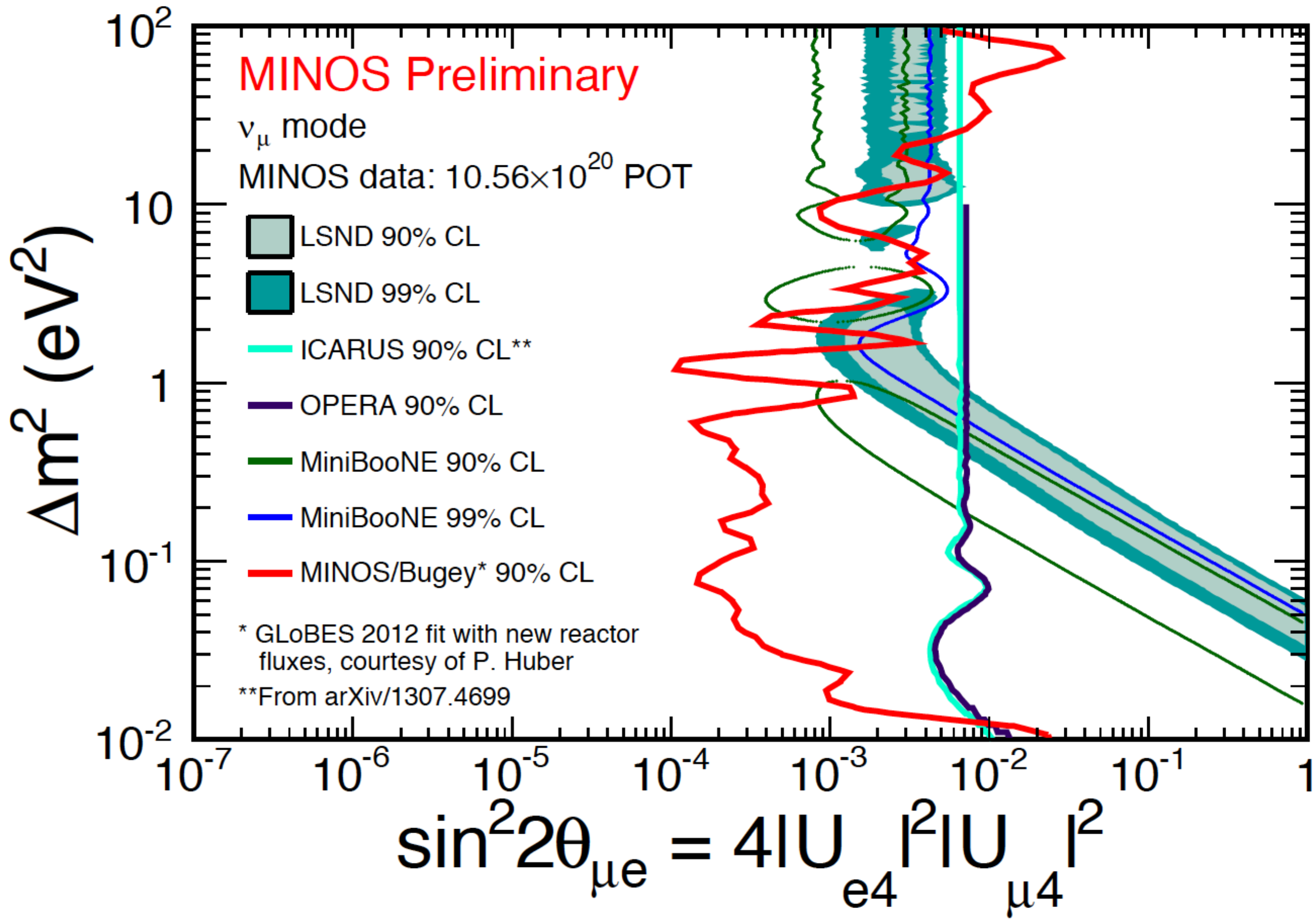
$\nu_\mu \to \nu_e$ requires both

$\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_e$

Oscillation probability for MiniBooNE and LSND

$$P(\nu_\mu \to \nu_e) \approx 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 \Delta_{41}$$
$$= 4s_{14}^2 c_{14}^2 s_{24}^2 \sin^2 \Delta_{41}$$

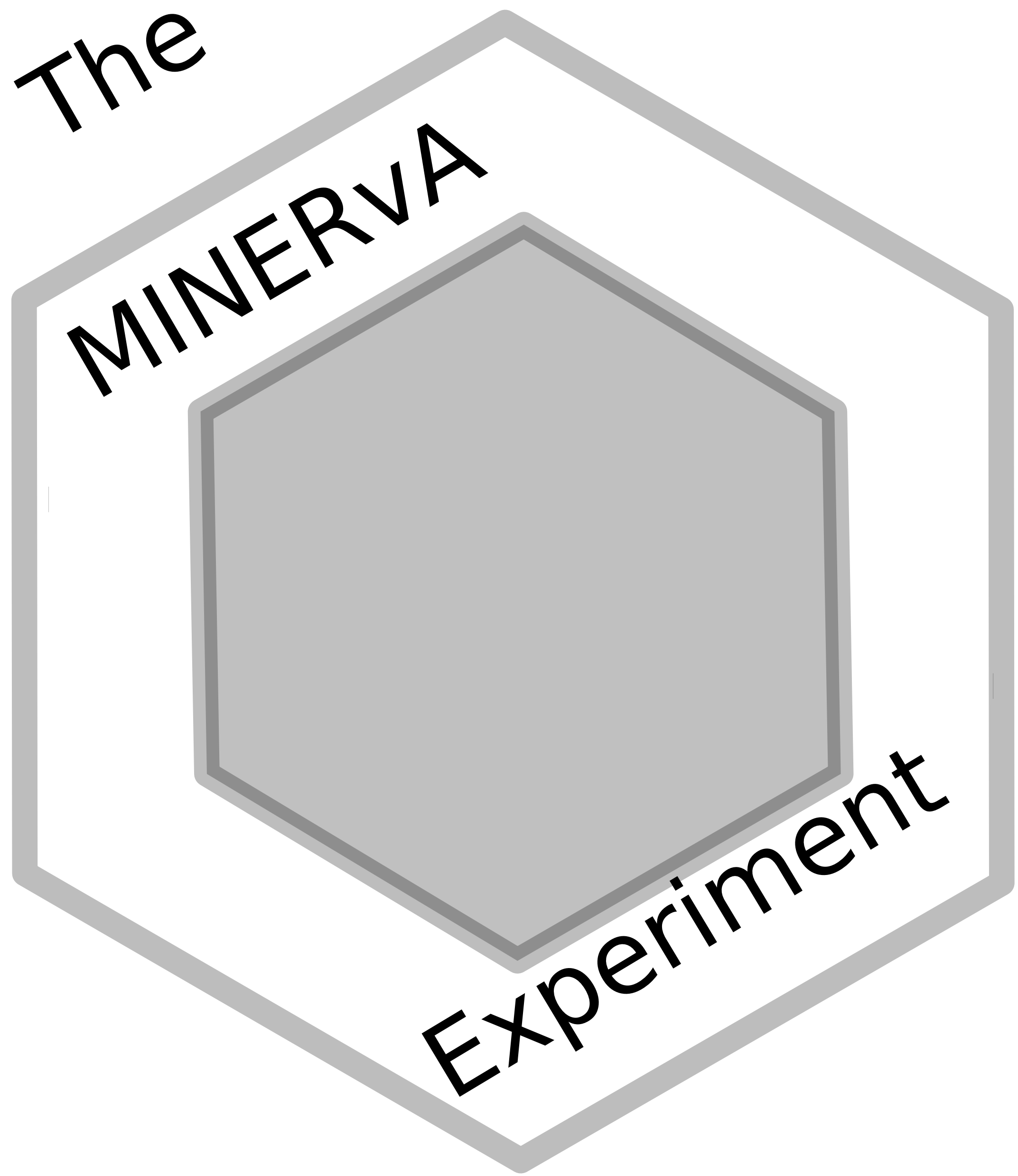
- Combine MINOS and Bugey results to constrain MiniBooNE and LSND
- MINOS + Daya Bay combination in the works



Oscillations Summary

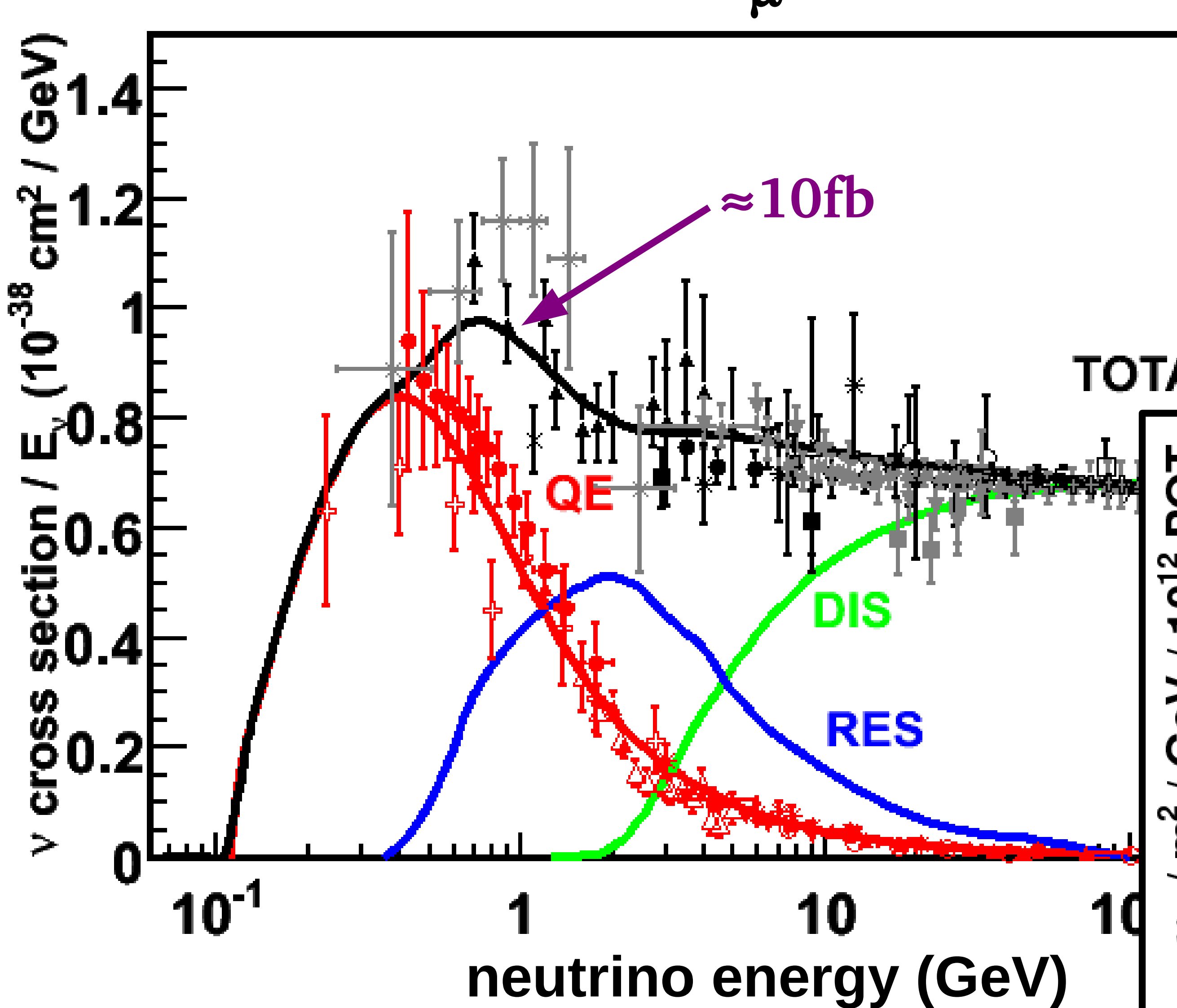
- Three flavor oscillations appear to describe world's data very well.
  - Entering era of precision tests, exploration of mass ordering and CP violation.
- Disappearance measurements combine to exclude much of the MiniBooNE / LSND allowed region.
  - In general, sterile driven $\nu_\mu \rightarrow \nu_e$ requires ν_μ and ν_e disappearance.
  - Robust two detector experiments set limits that will be hard to beat, even in the next generation of experiments at FNAL.
  - Possible x2 factor on sensitivity with additional datataking by MINOS +

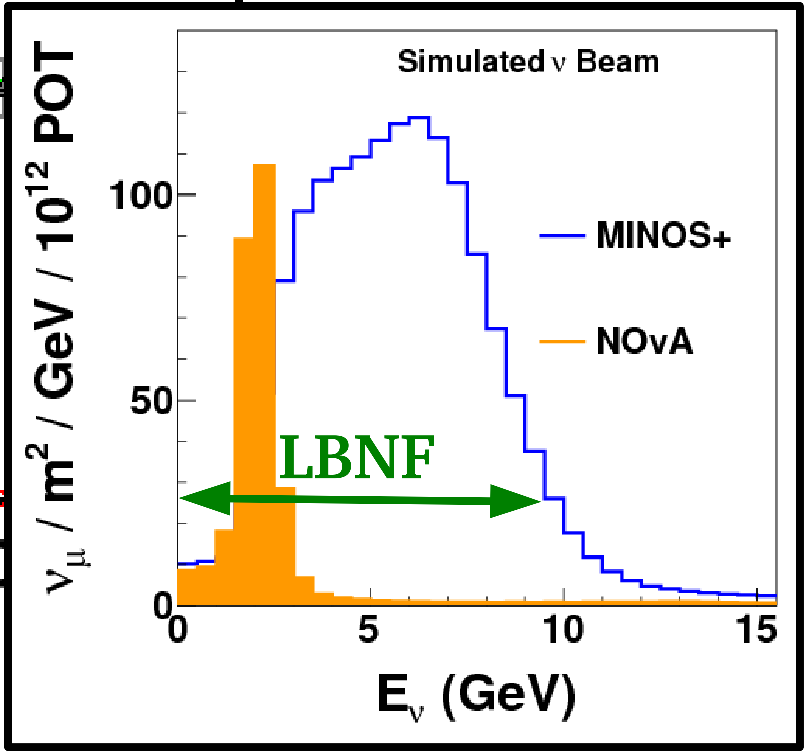
Cross-sections and



Why are we interested?

World ν_μ cross-section





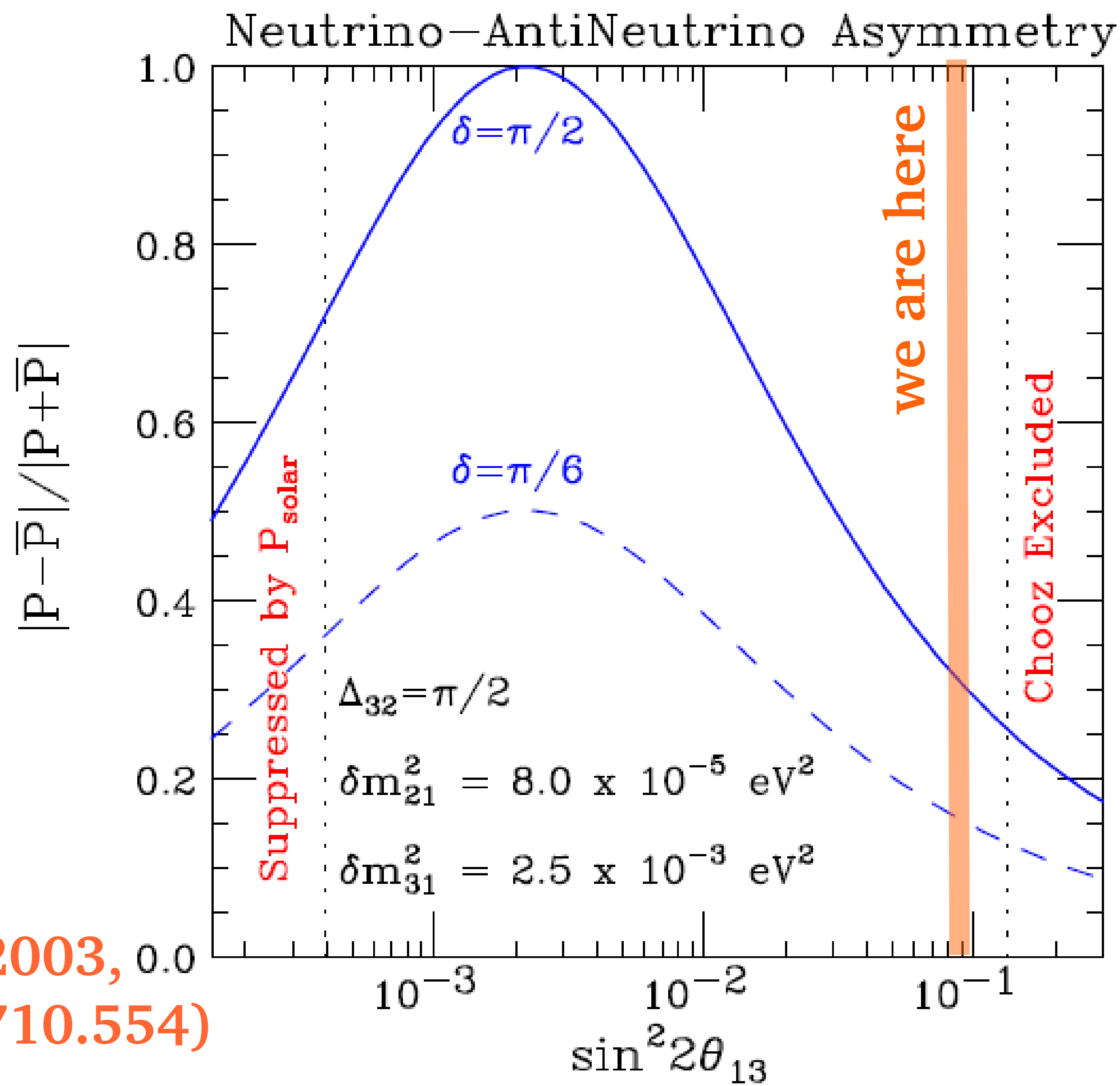
J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", Rev. Mod. Phys. 2012

Why are we interested?

implications of large θ_{13}

Rate of $\nu_\mu \rightarrow \nu_e$ increases

but ν - $\bar{\nu}$ asymmetry decreases



(Parke 2003, arXiv:0710.554)

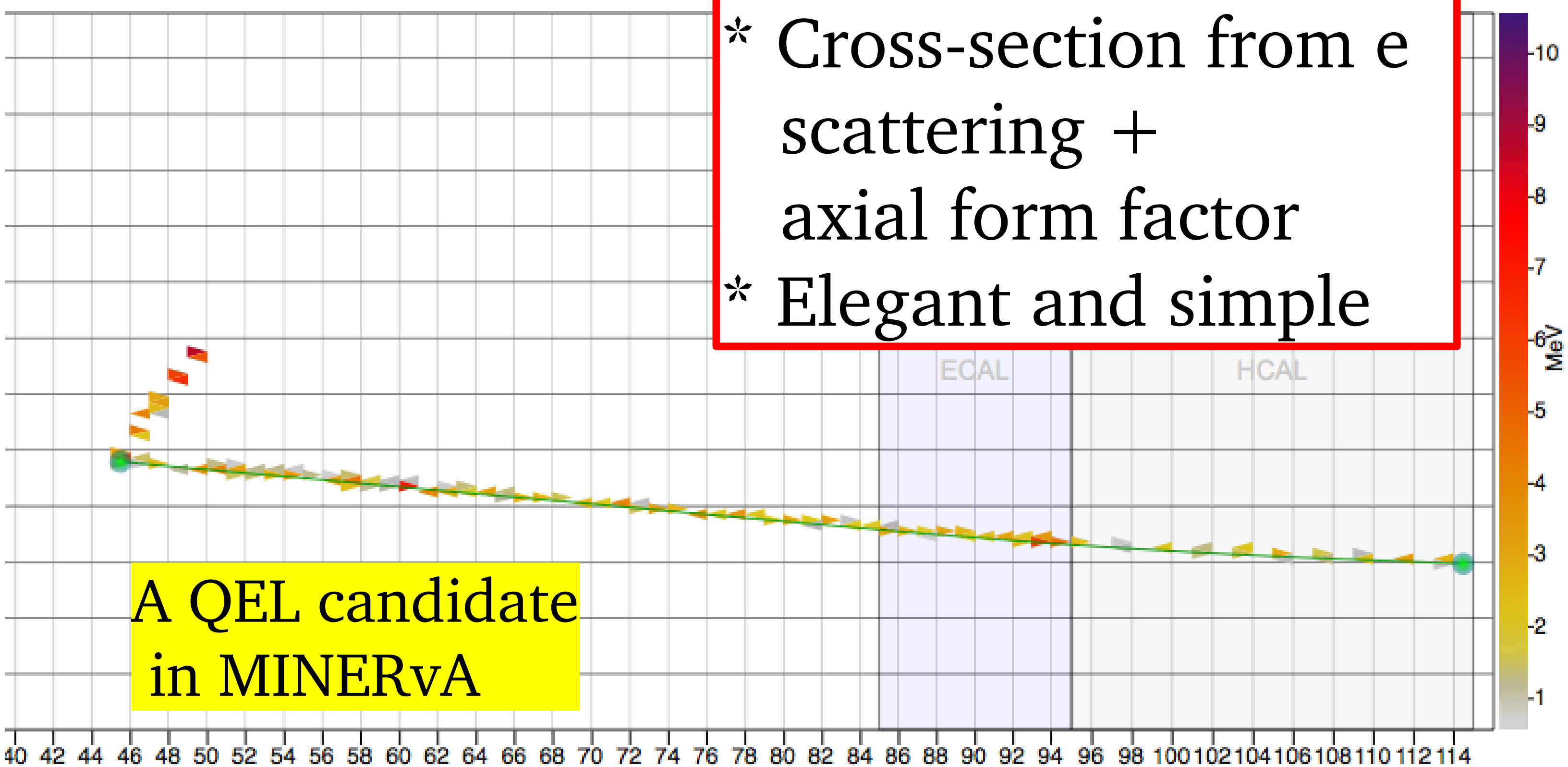
In search of a standard candle

Quasi-elastic scattering

$\nu\, n \rightarrow p\, \mu^-$

Pros:

- Low energy threshold
- No messy pions
- Energy from 2 of 3 p_μ , θ_μ or p_{proton}
- Cross-section from e scattering + axial form factor
- Elegant and simple



A QEL candidate in MINERvA

Why are we interested?

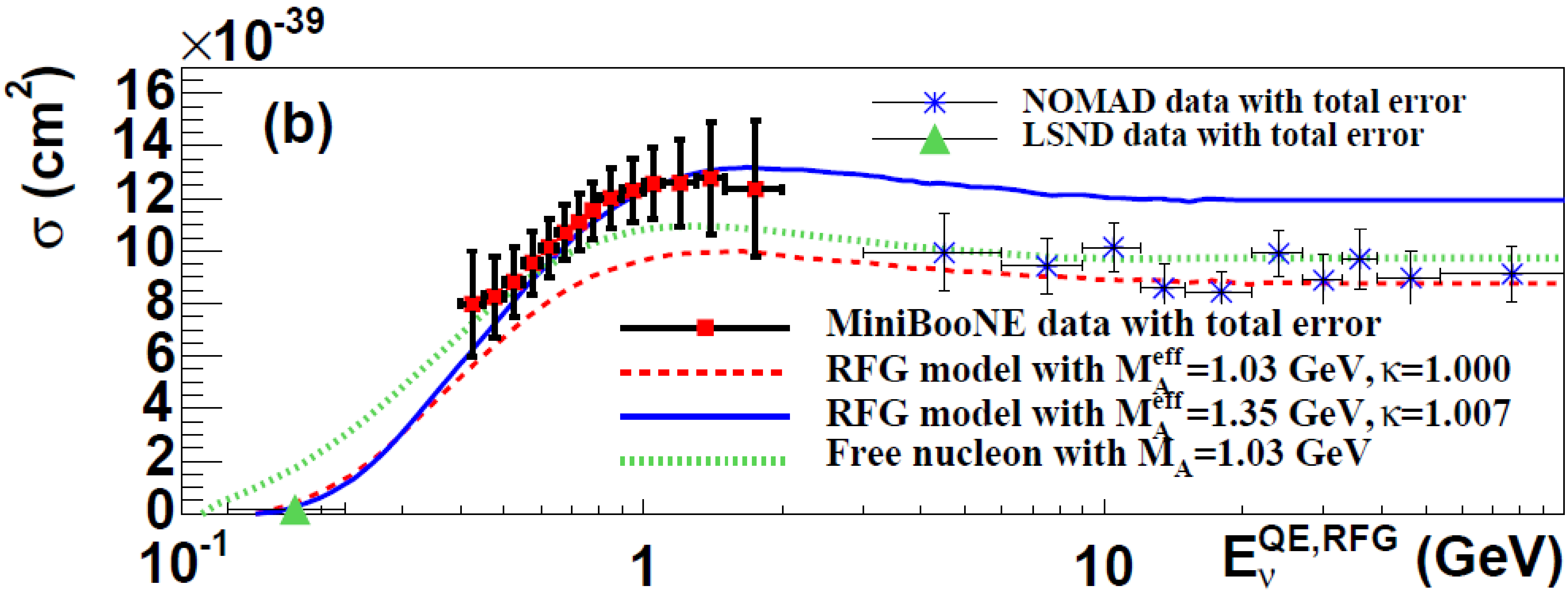
In search of a standard candle

Quasi-elastic scattering

$\nu\ (A,Z) \rightarrow (A\text{-}1,Z)\ p\ \mu^-$

<u>Cons:</u>

* We don't fully understand the energy dependence

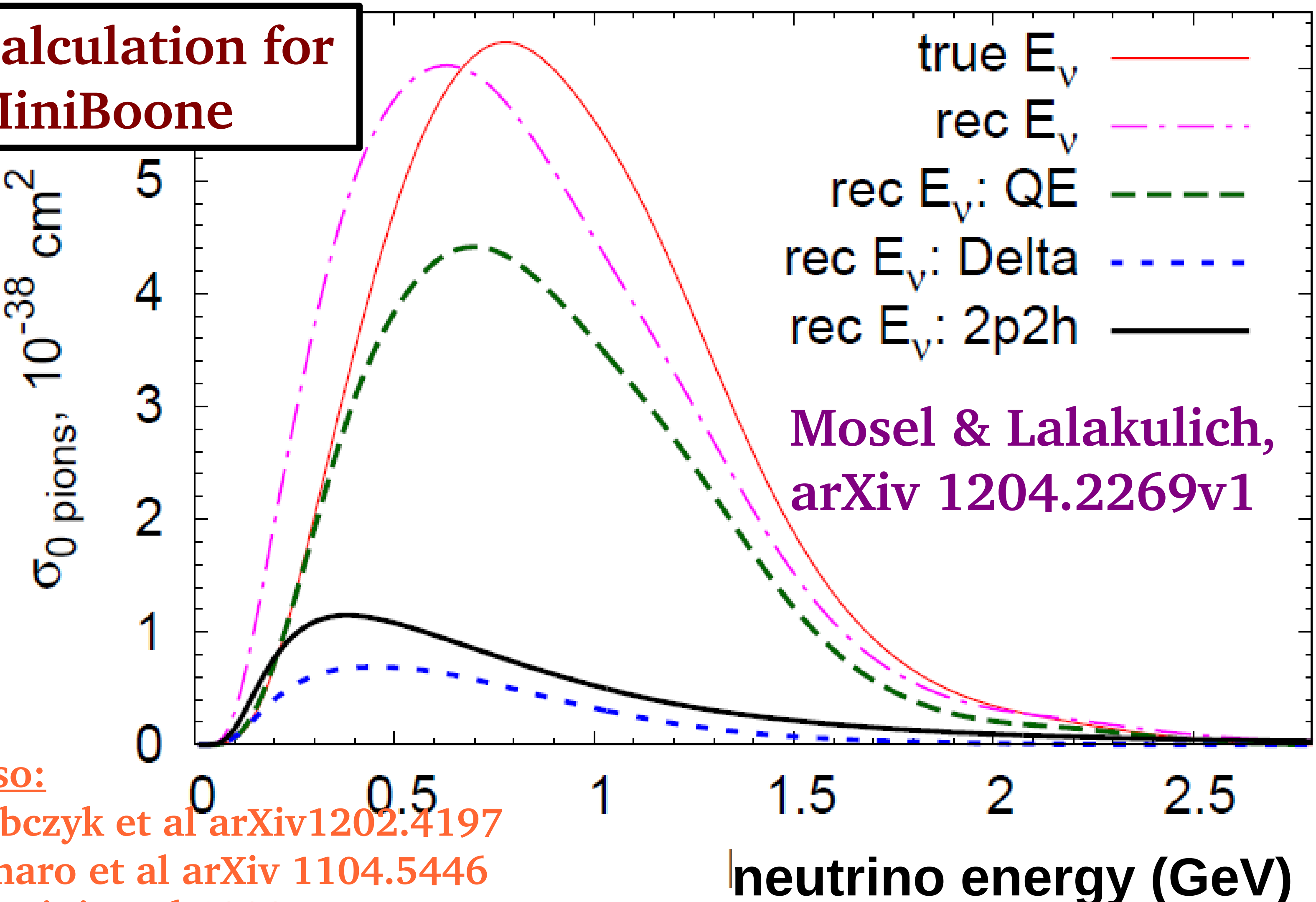


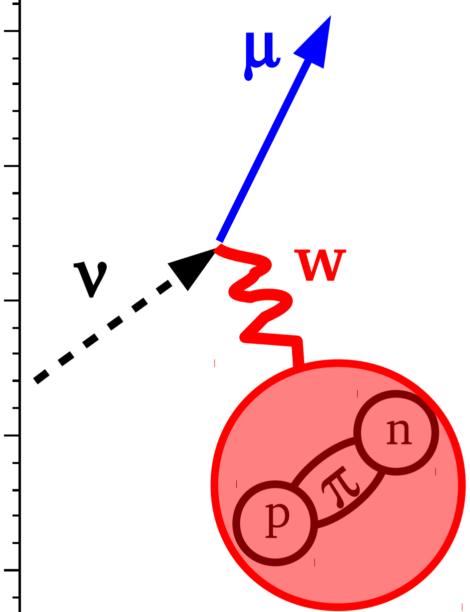
Why are we interested?

In search of a standard candle

Cons: We don't fully understand energy reconstruction

Calculation for MiniBoone





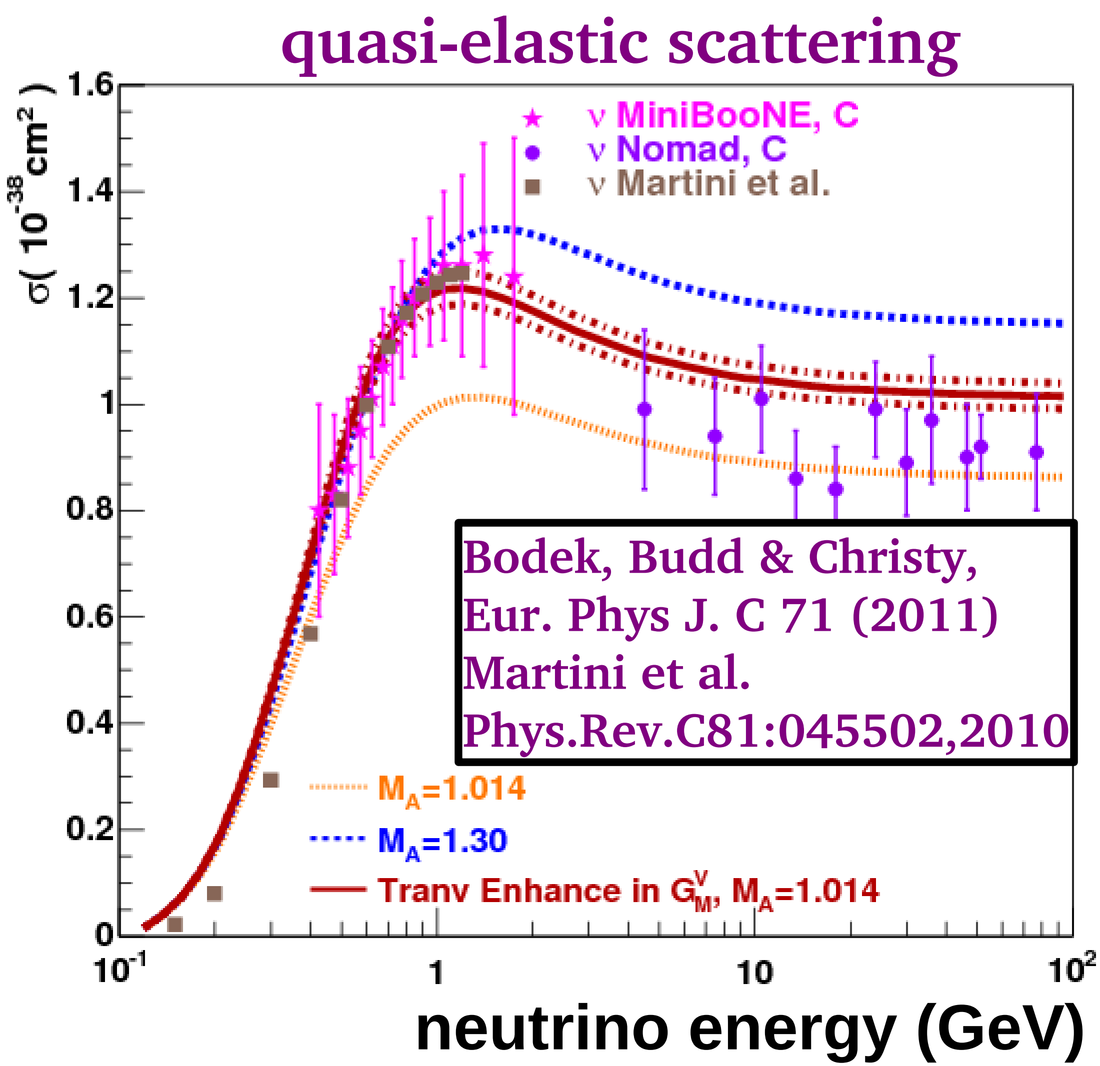
"meson exchange currents" also "short range correlations" "2p2h"

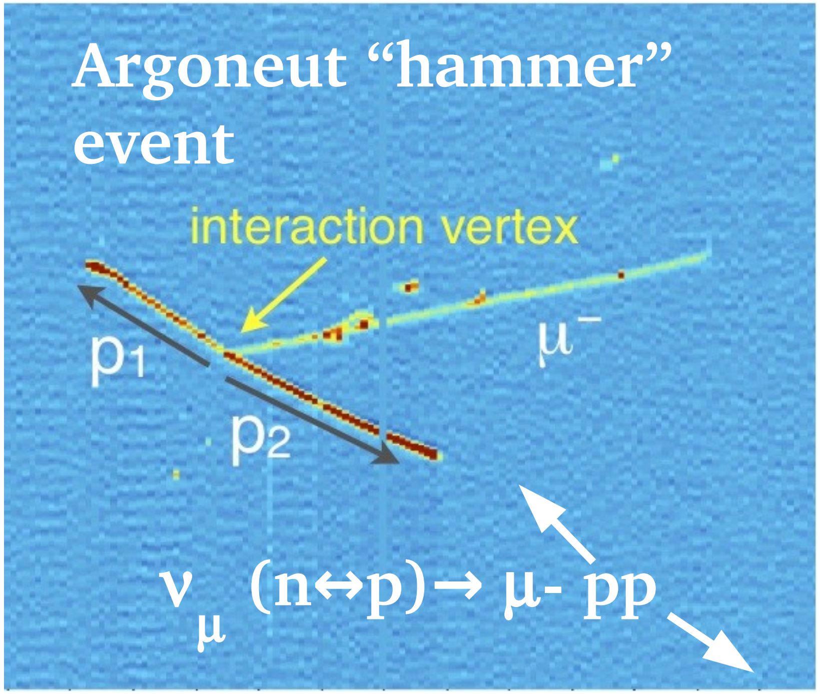
Also:
Sobczyk et al arXiv1202.4197
Amaro et al arXiv 1104.5446
Martini et al 1202.4745
Mosel et al arXiv 1402.0297

Why are we interested?

In search of a standard candle

Cons: initial nuclear state, multi-body dynamics matter





No pions!
Looks like QEL if you can't see the protons.

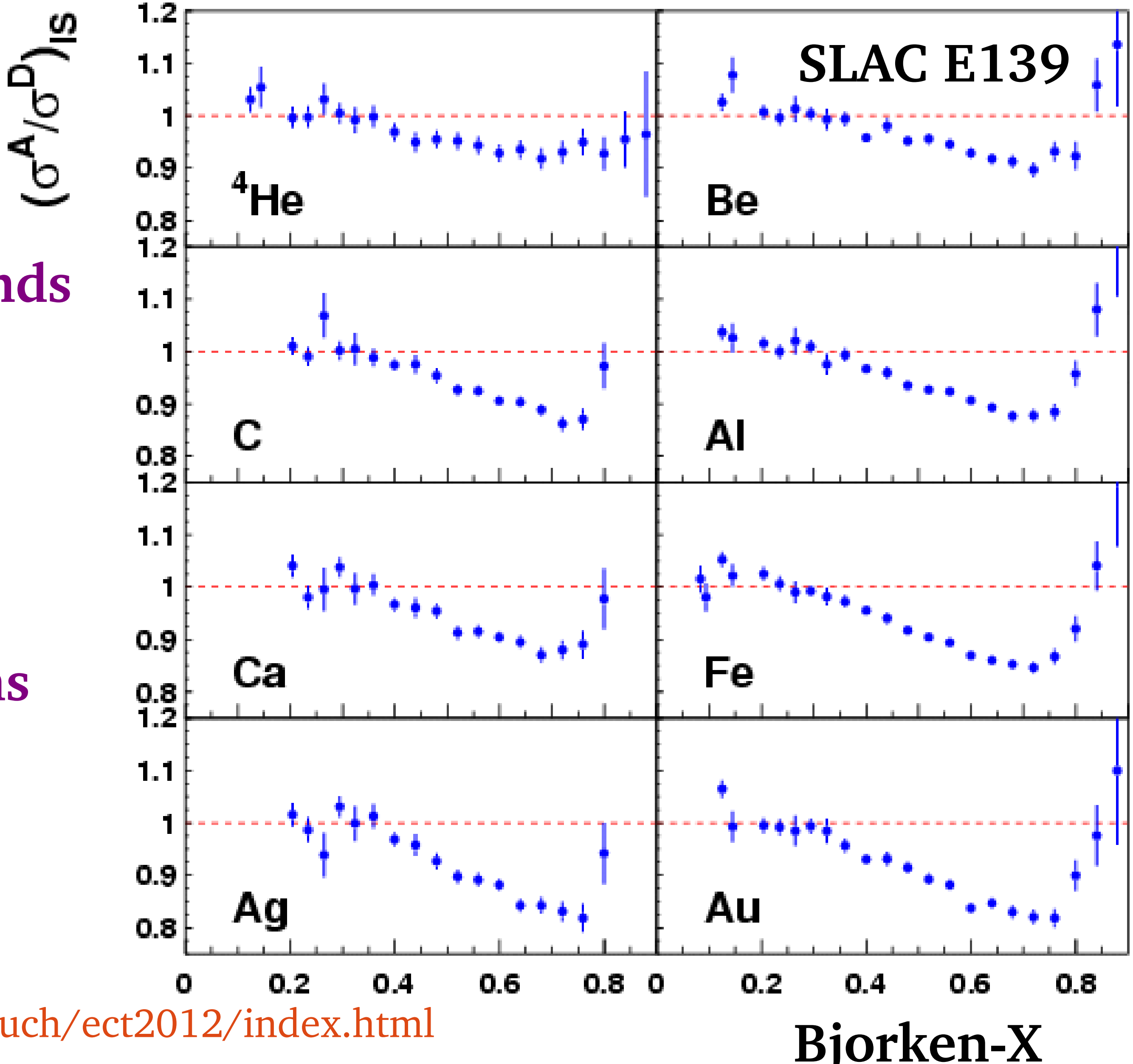
An old mystery

"EMC Effect"

x dependence of eA DIS cross-section depends on A → why?

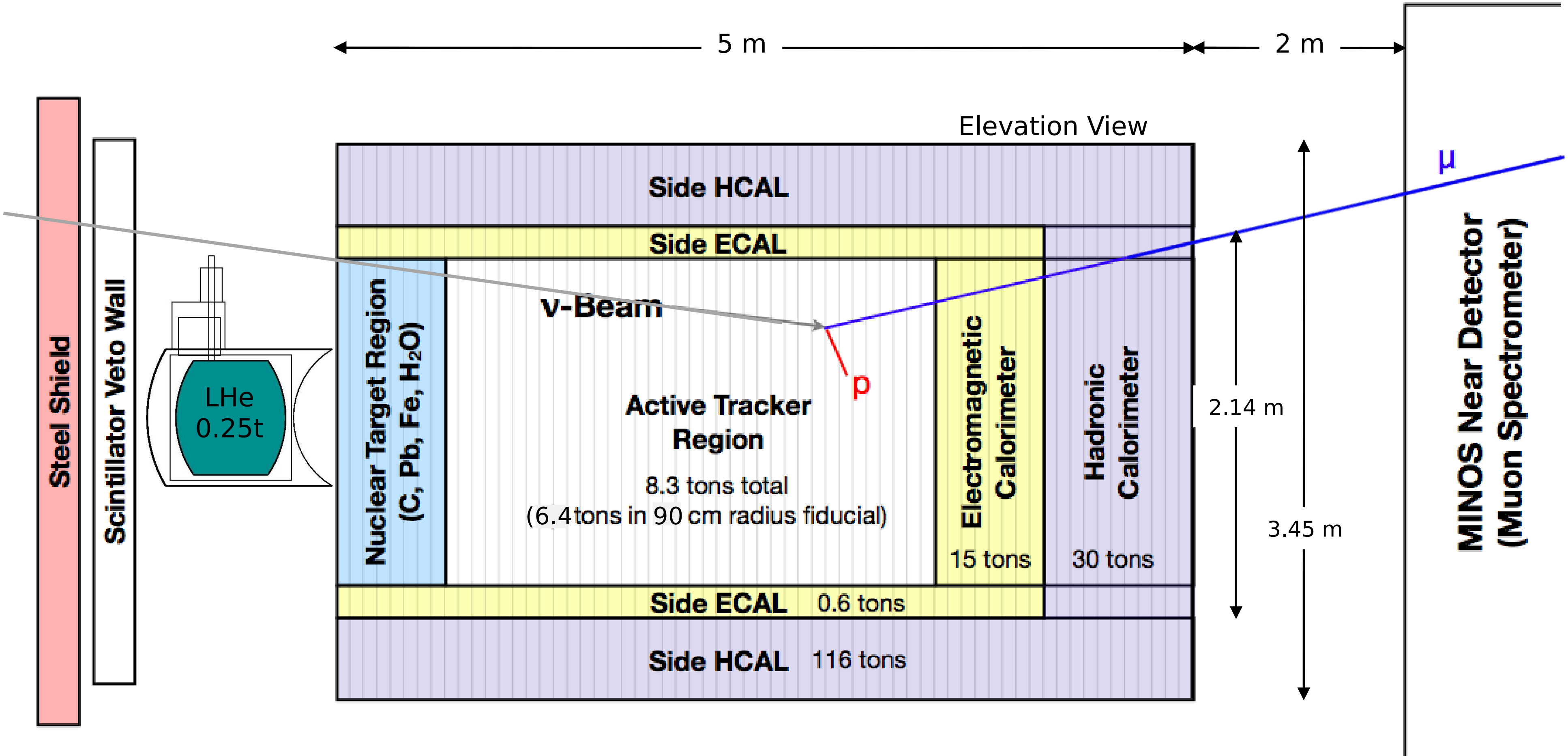
Some evidence that νA has different behavior

Short range correlations / multi-body dynamics ↔ EMC ?

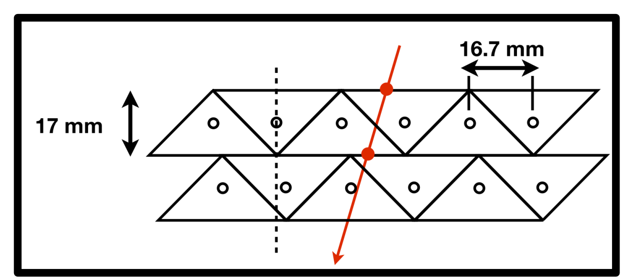


Nice review talk
D. Gaskell ECT*, Trento 2012
http://www.physics.sc.edu/~strauch/ect2012/index.html

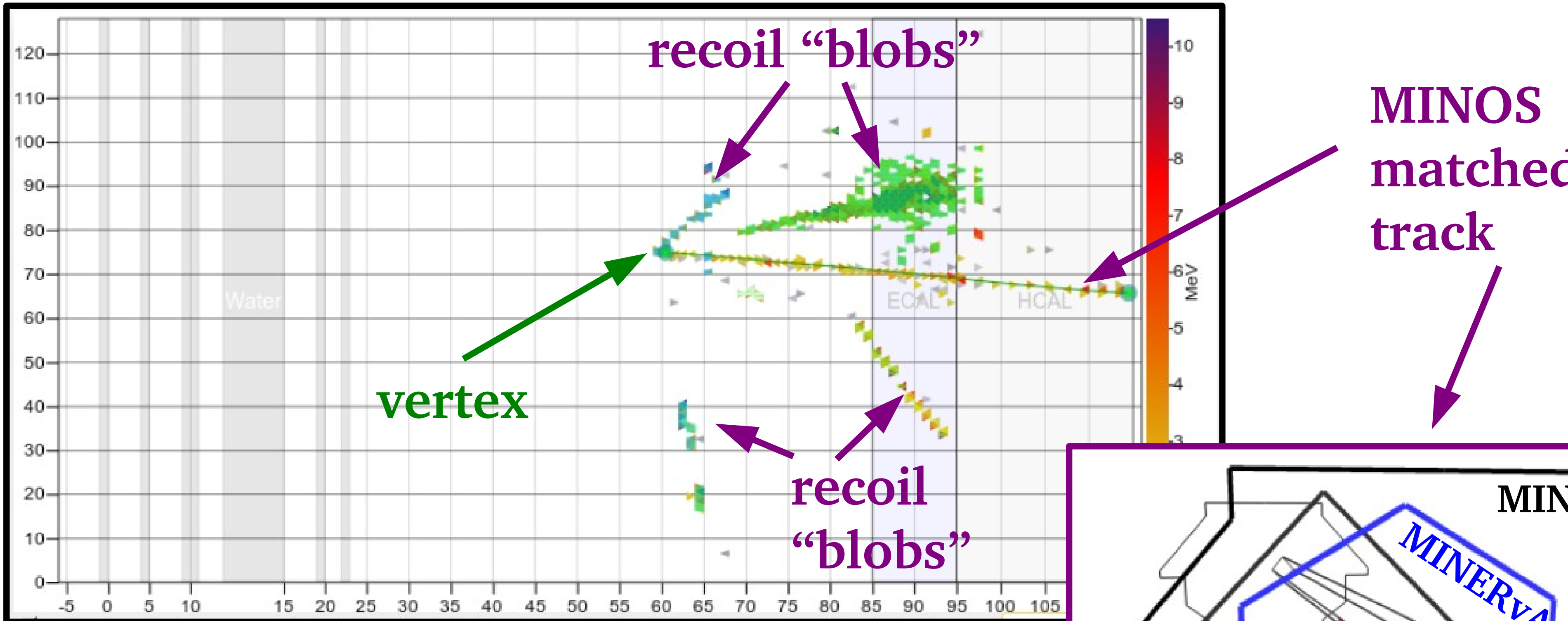
The MINERvA detector

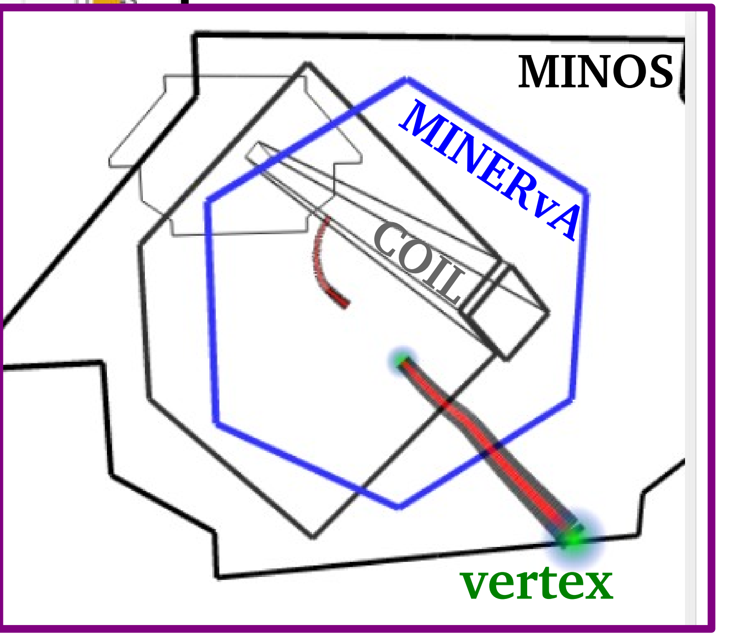


* 200 finely segmented scintillator planes (CH) in 3 views
* <u>Calib</u>: FEB bench tests, source mapper, LI, rock μ, Michel electrons, test-beam
* 4% channel to channel variations after calibration



Event reconstruction

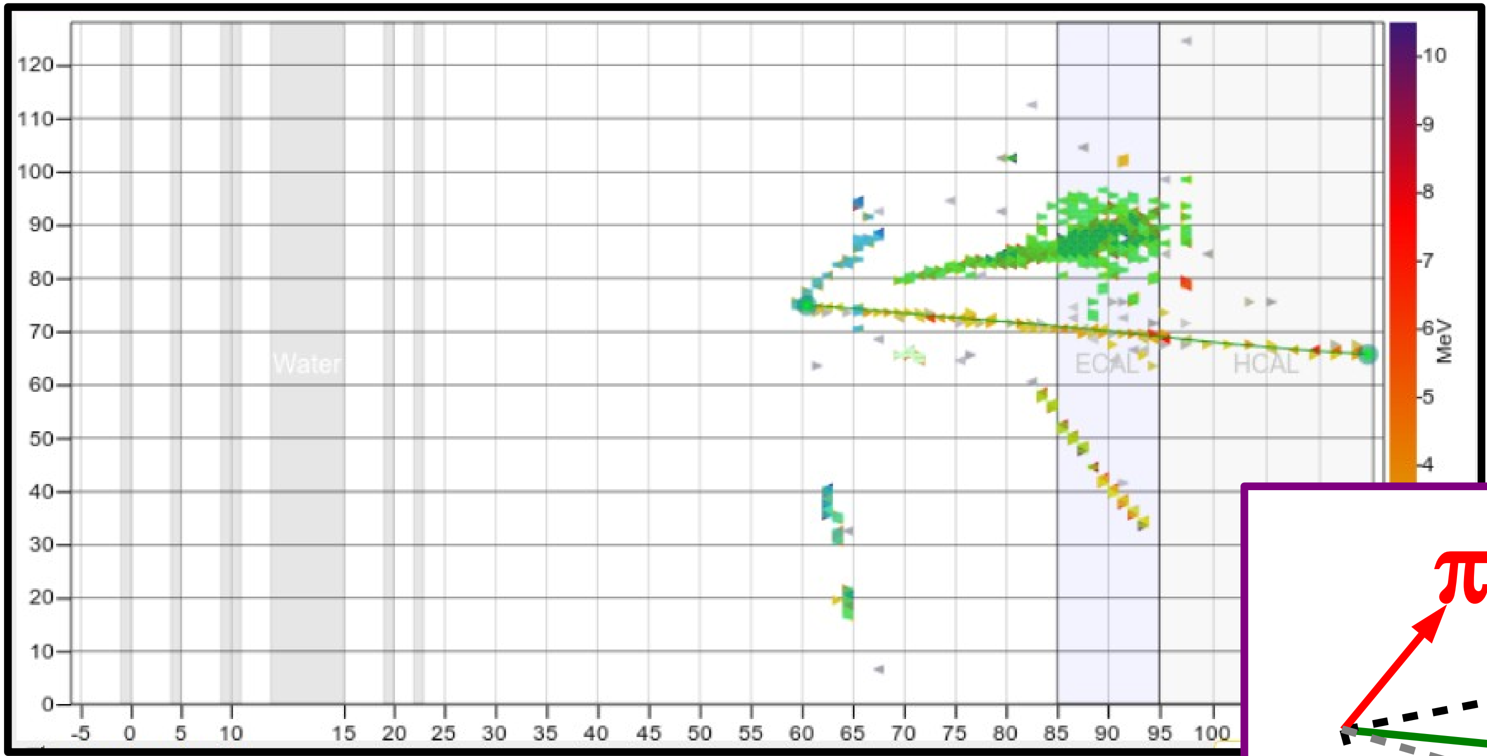




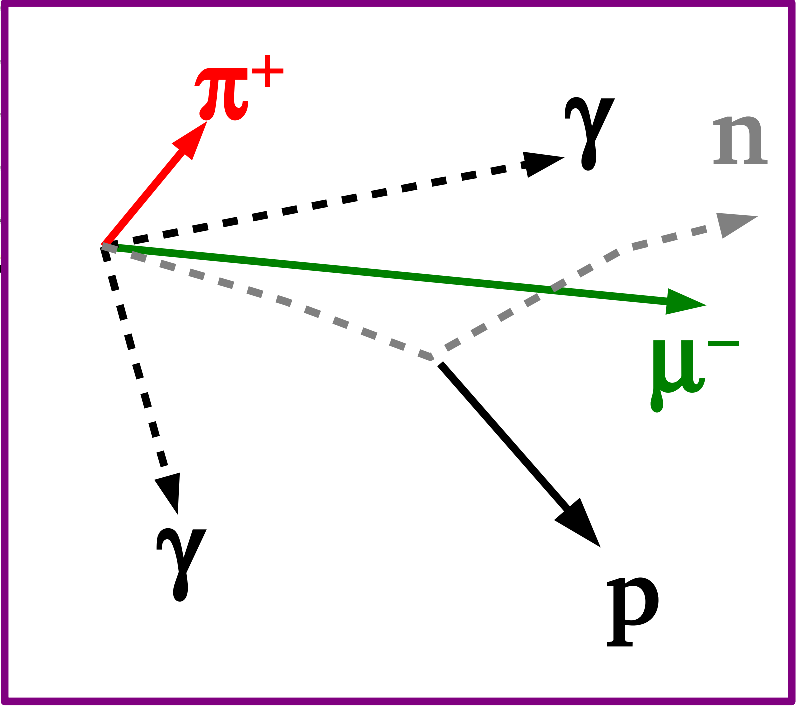
Reconstructed objects

MINOS tracks, other tracks, vertices, endpoints, blobs

Event reconstruction



My guess, just for fun

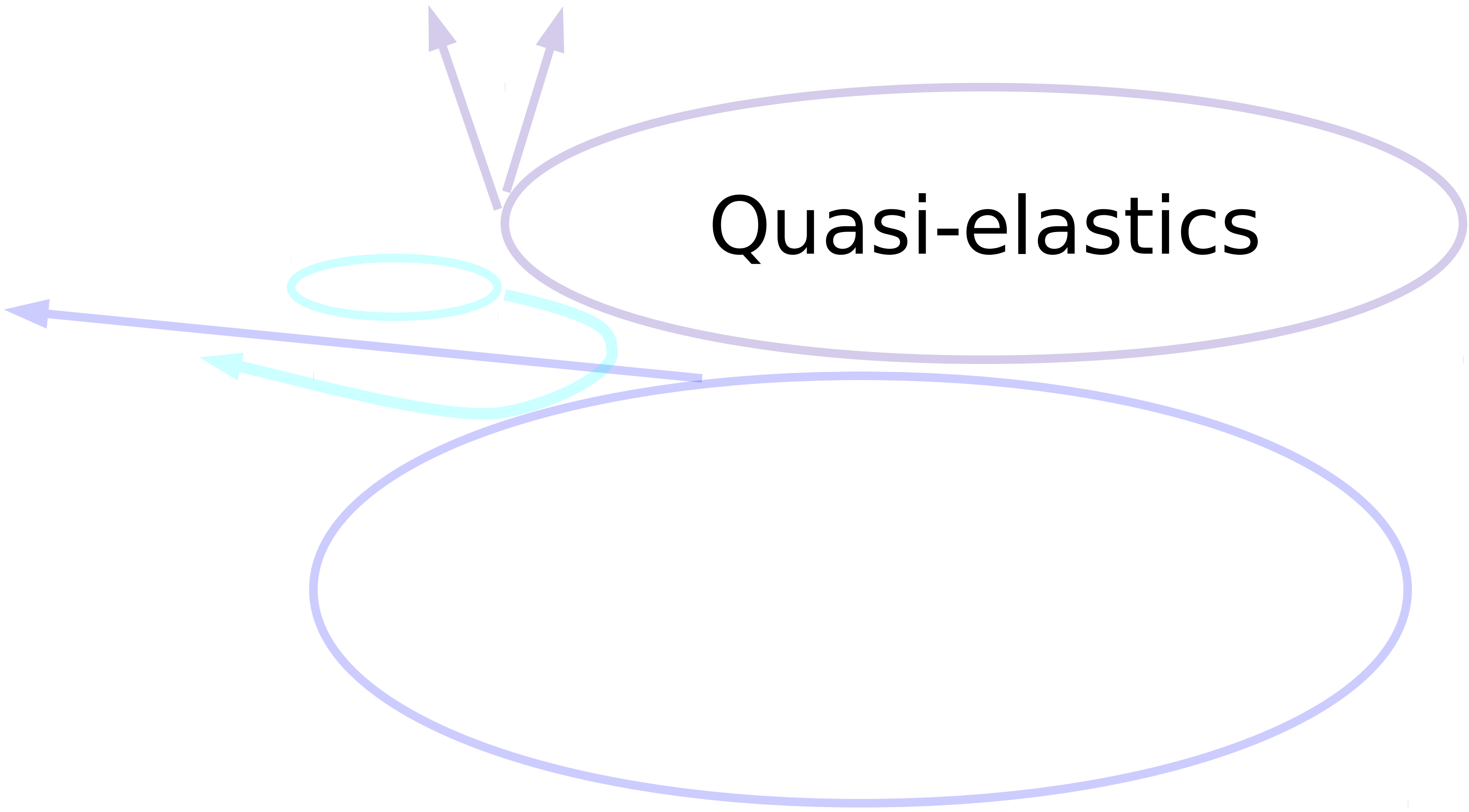


Most important quantities:

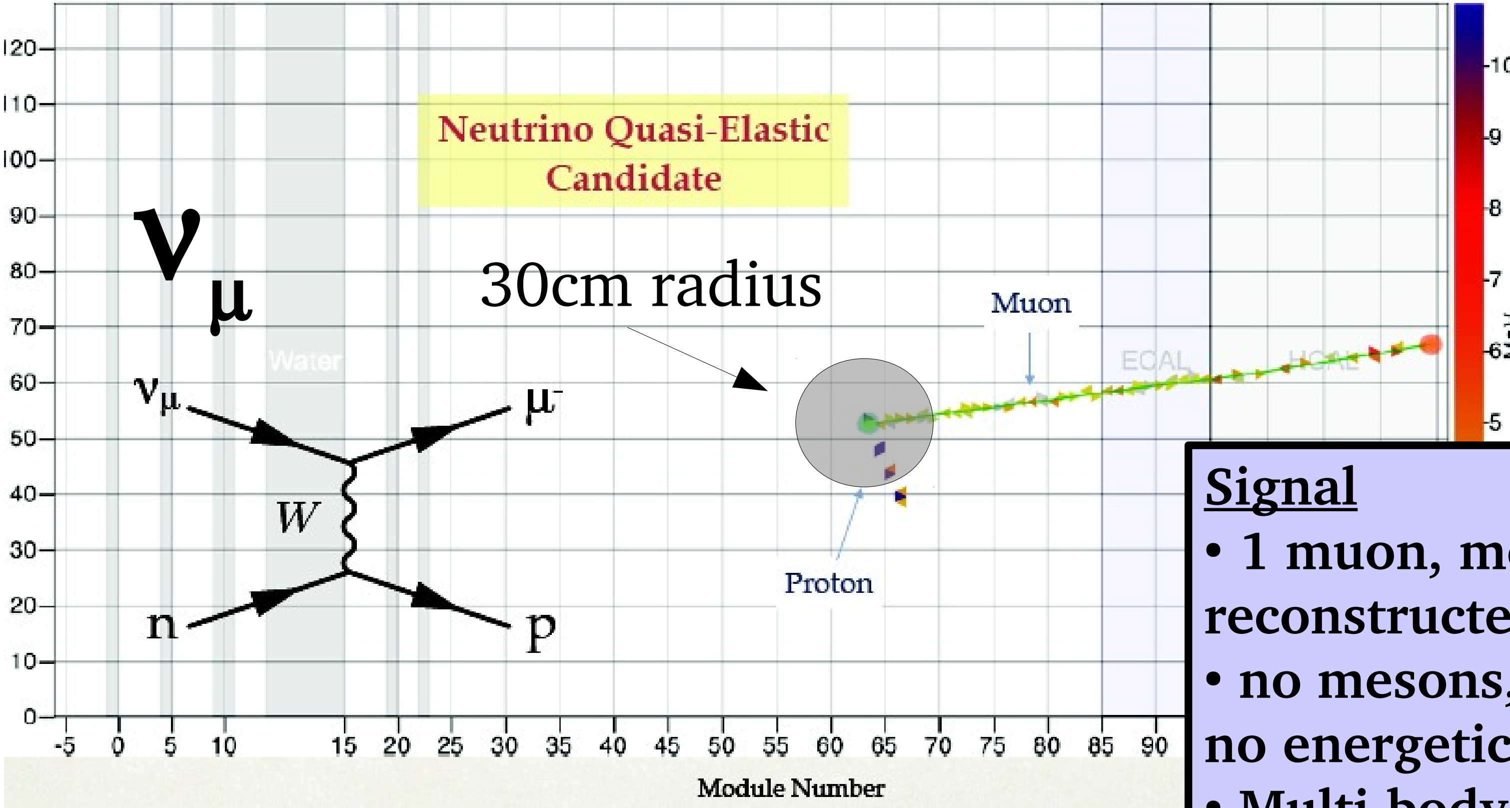
muon energy and angle

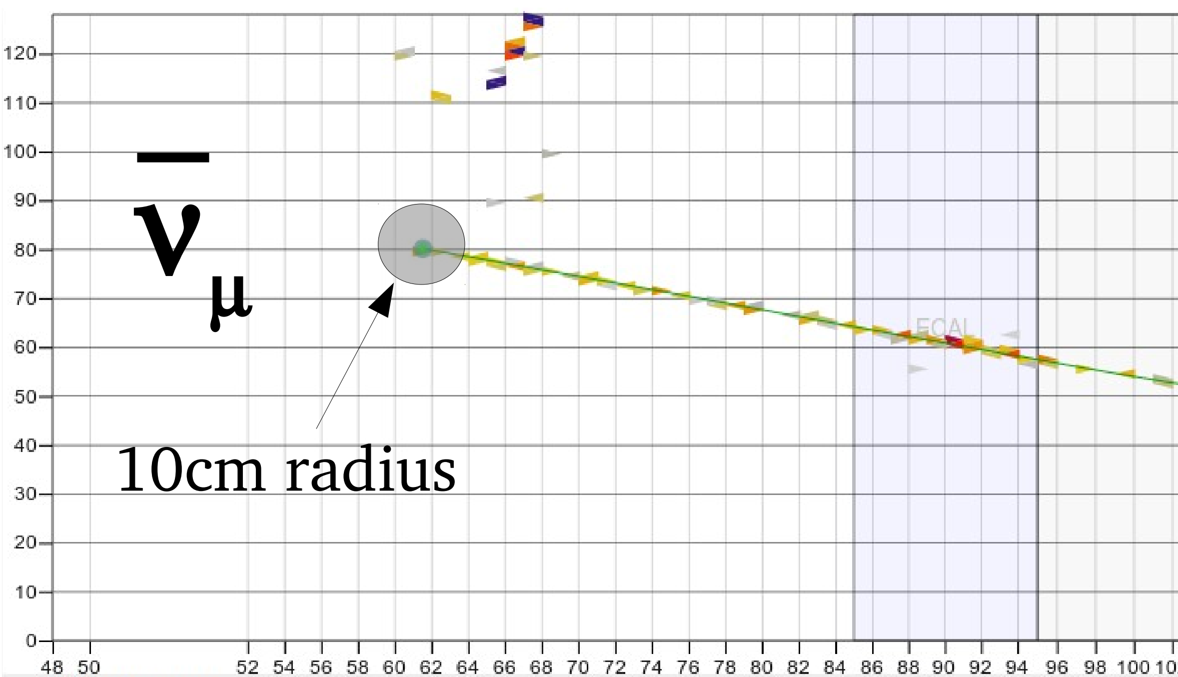
recoil energy

secondary tracks/blobs


Quasi-elastics

QEL event selection





Signal

- **1 muon, momentum and charge reconstructed in MINOS**
- **no mesons, no heavy baryons, no energetic photons**
- **Multi-body effects may result in multiple nucleons – allow those**

Background

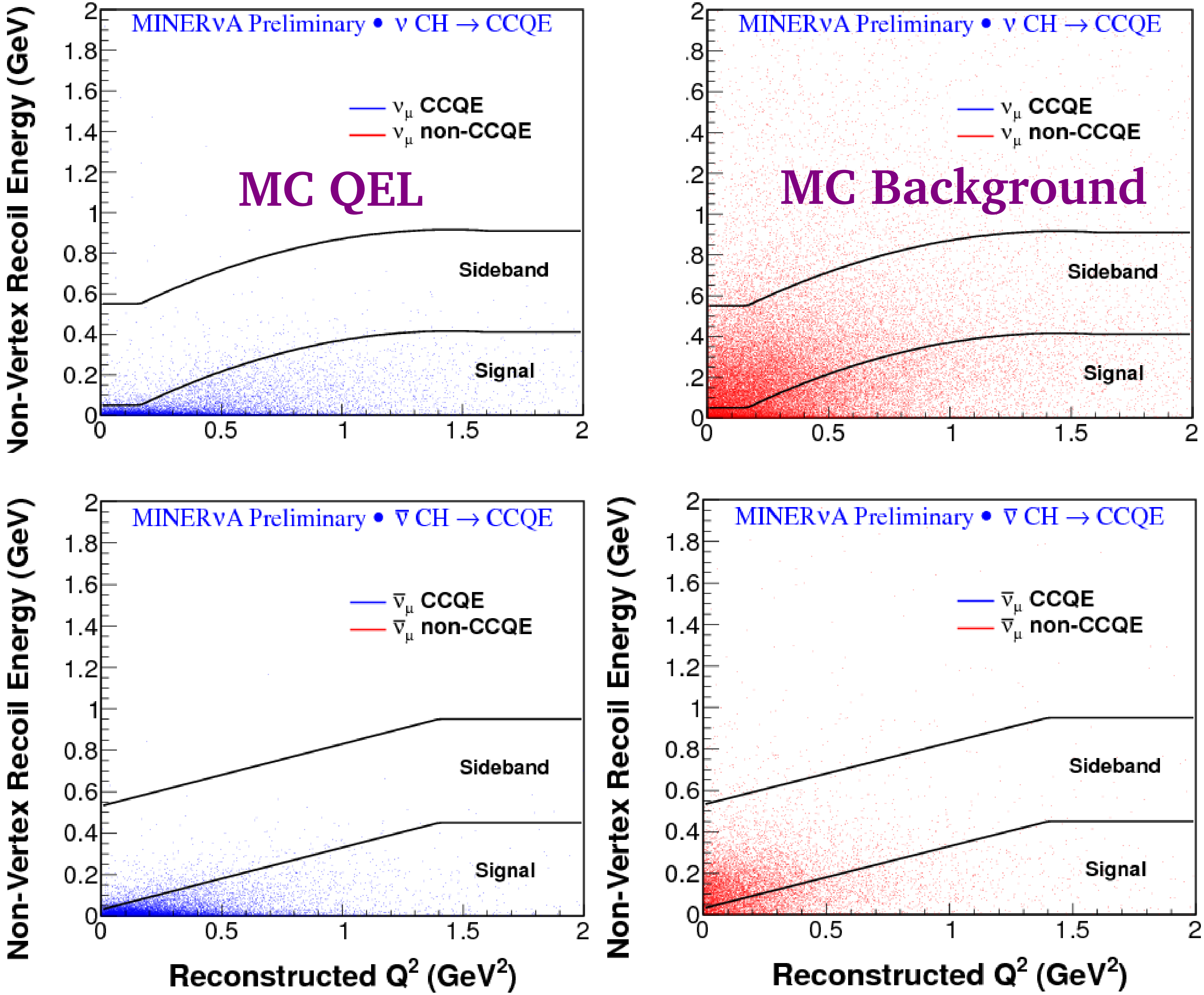
- **Pions deposit energy away from the vertex → use calorimetry**
- **"Black out" region around the vertex**
  - **poorly modeled in MC**
  - **sensitive to multi-nucleon effects**

Recoil vs. Q^2

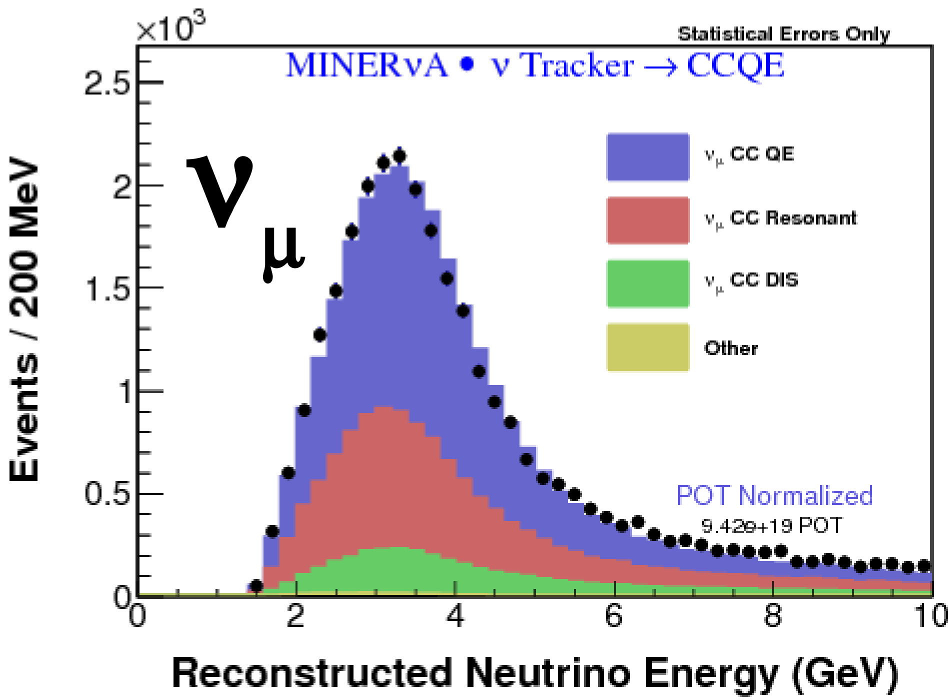
For $x_{Bj}=1$ expect $E_{recoil} = Q^2/2M_N$

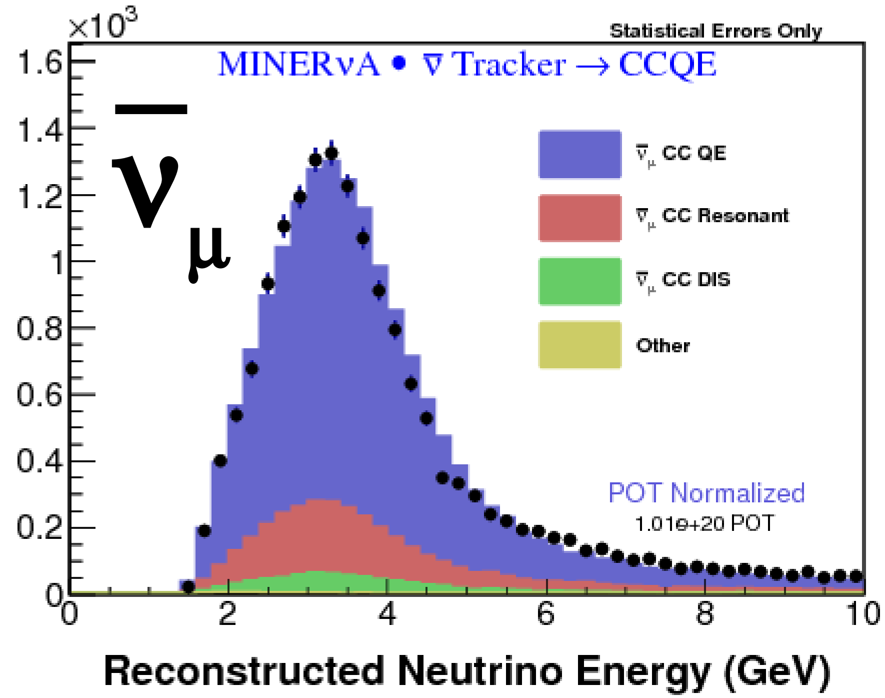
ν_μ

$\bar{\nu}_\mu$



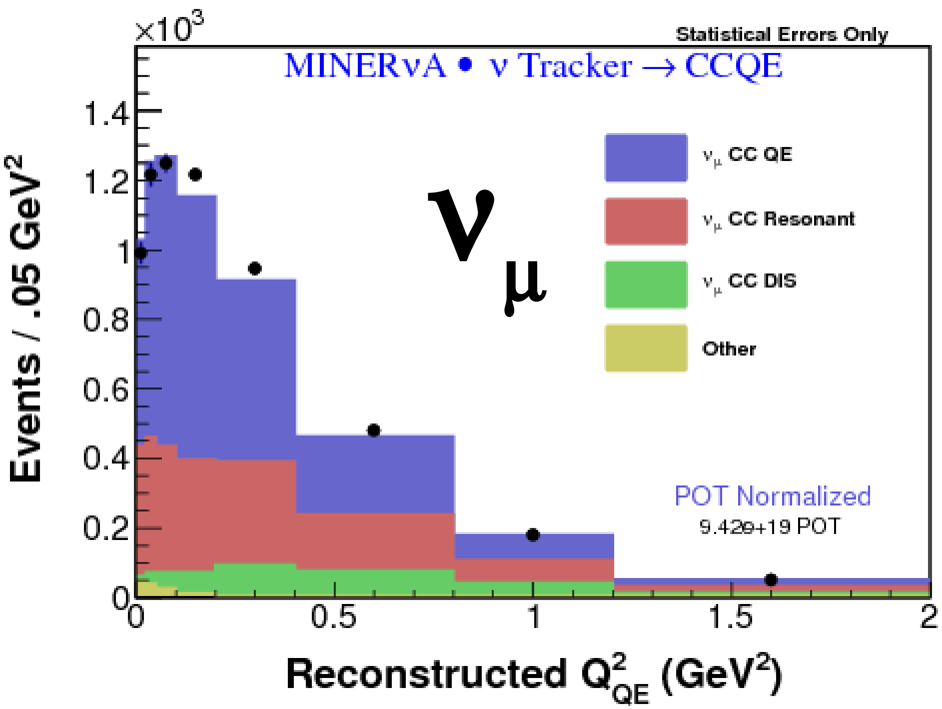
Selected samples

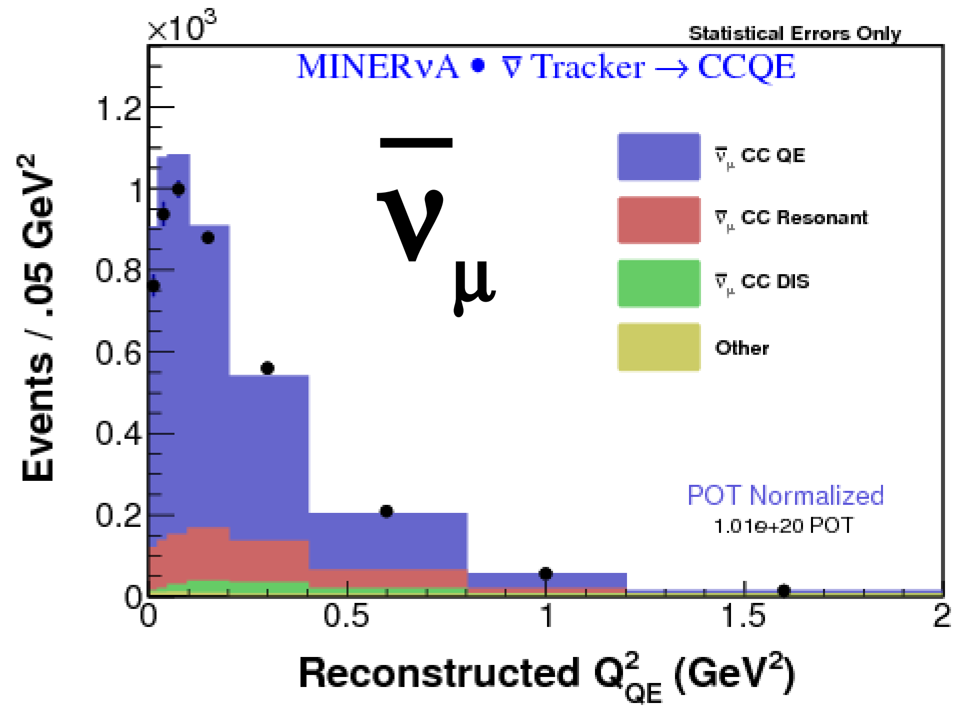




$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Selected Samples



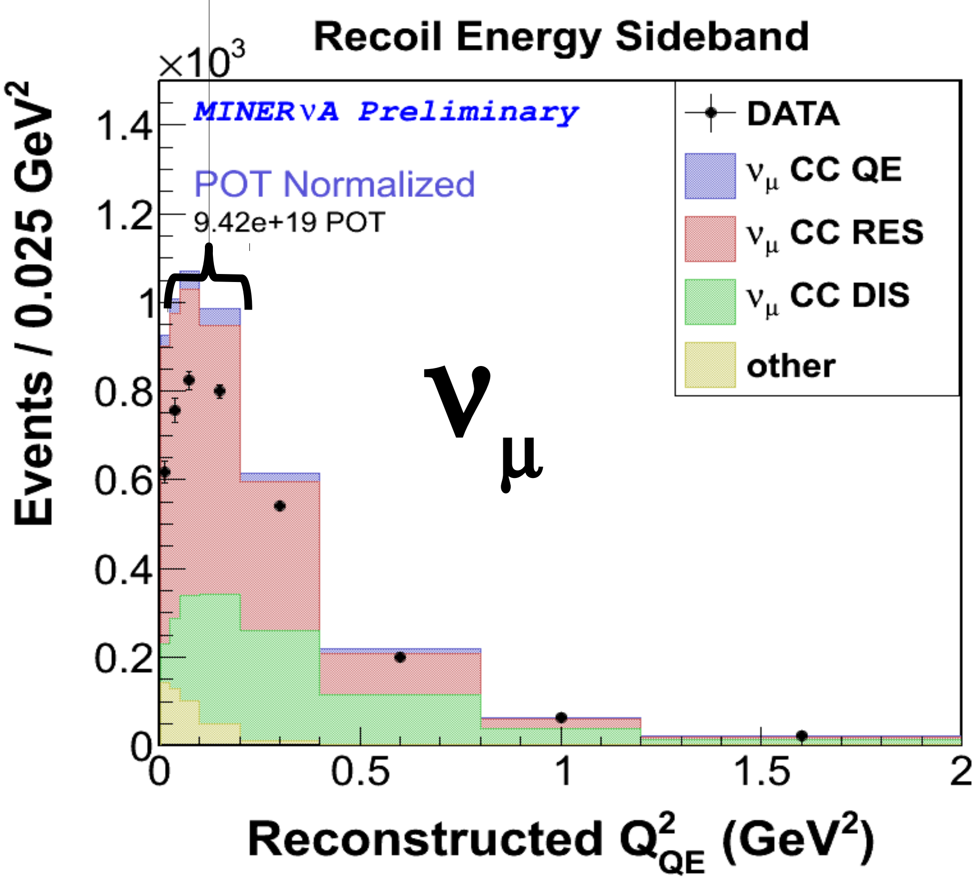


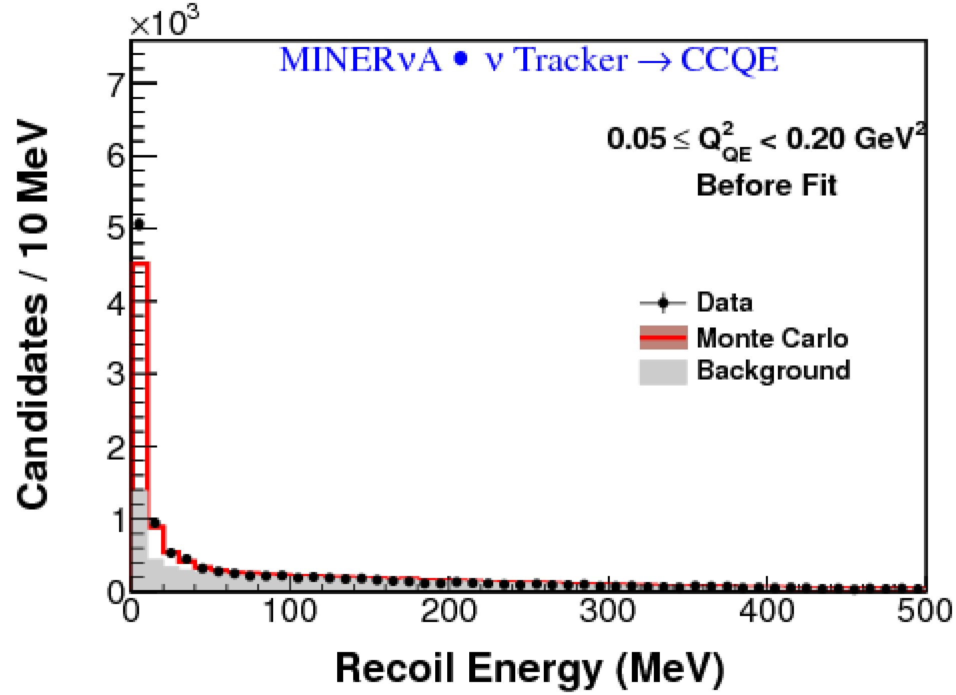
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

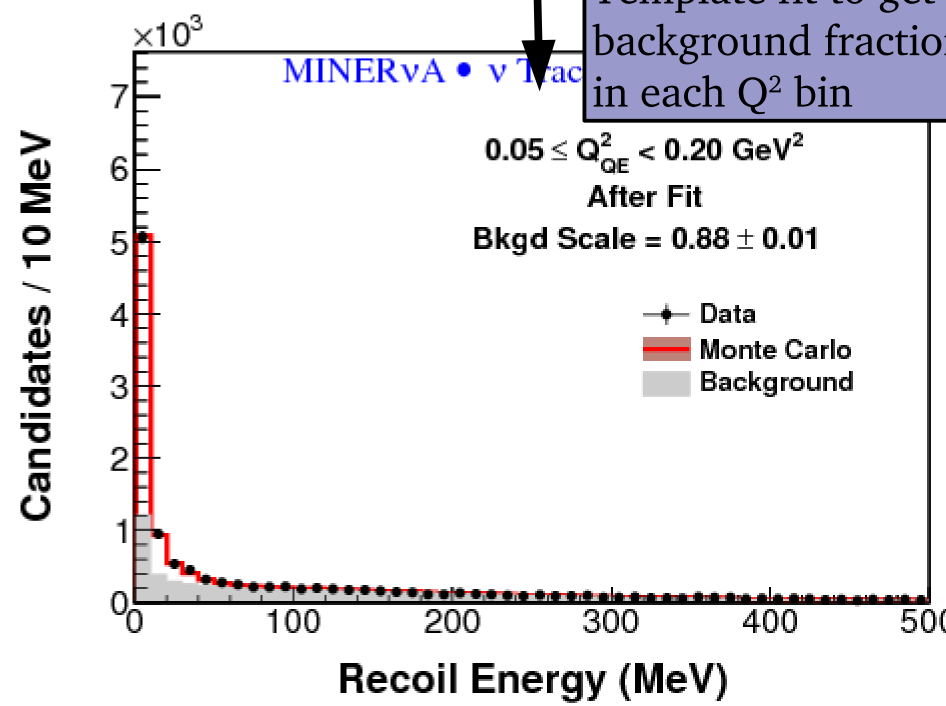
29,620 events
Efficiency: 47%
Purity: 49%

16,467 events
Efficiency: 54%
Purity: 77%

Constraining Background

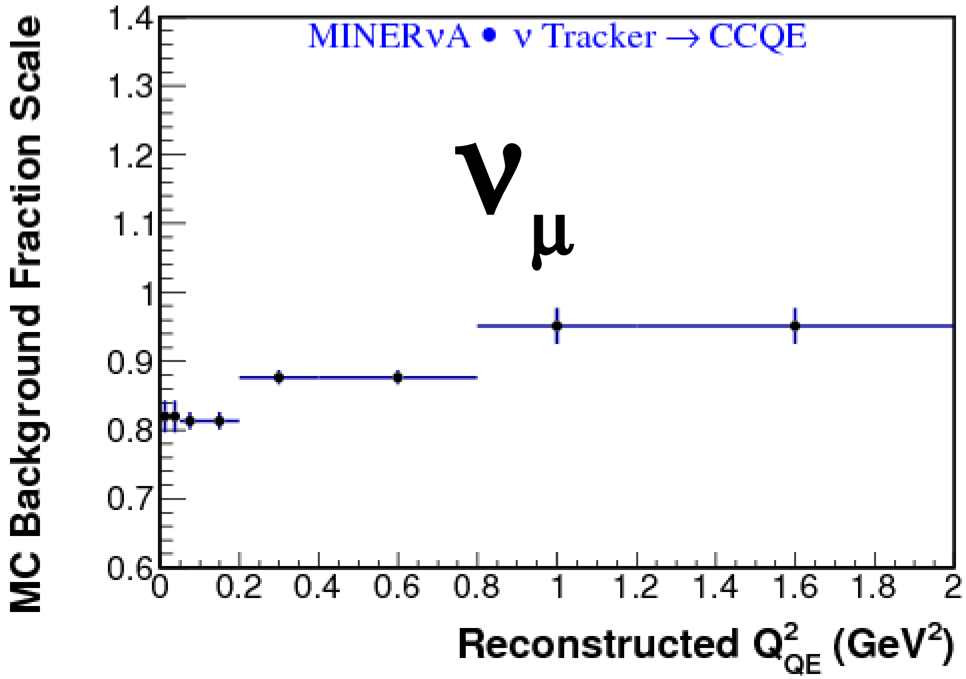


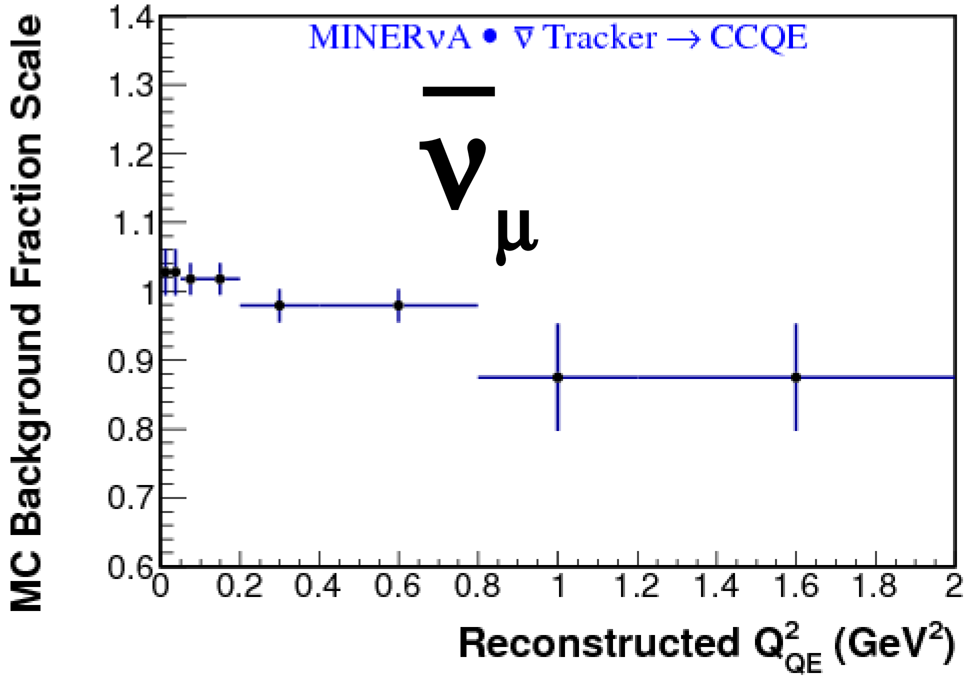




Template fit to get background fraction in each Q² bin

Background Scale Factors

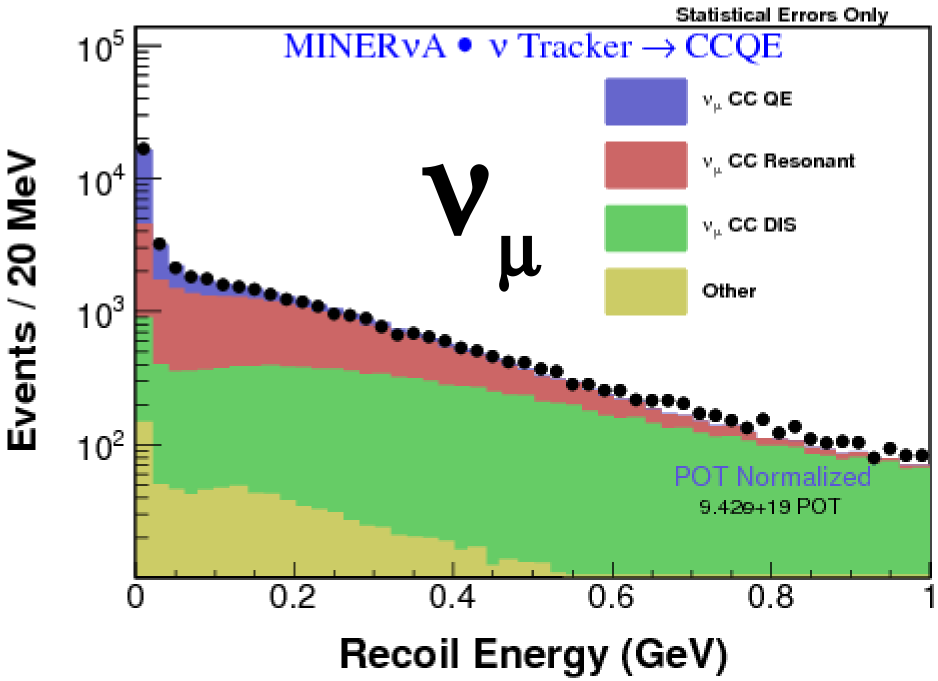


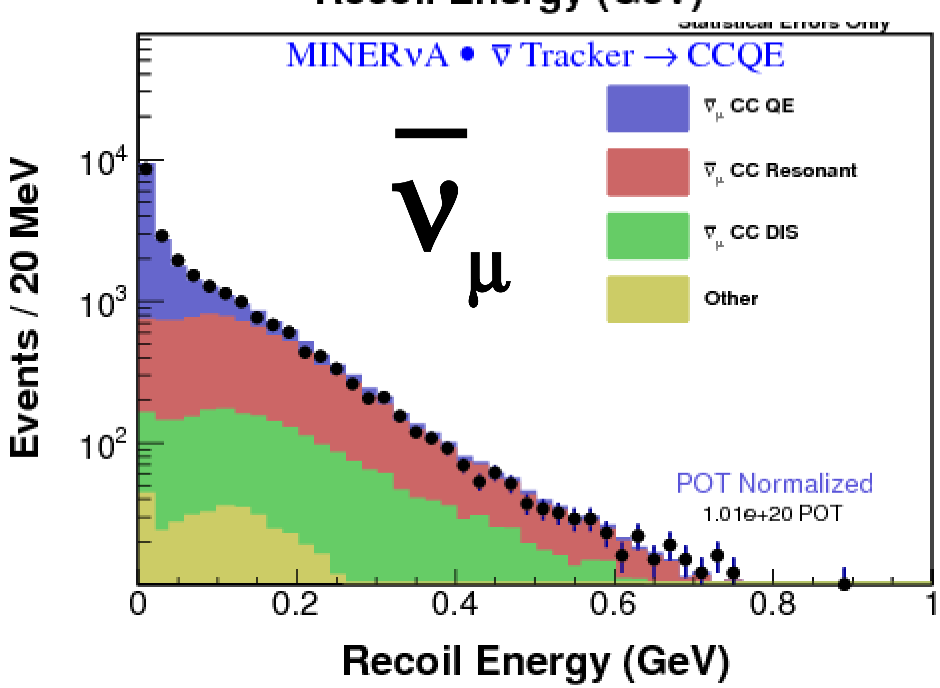


Data indicates MC background for ν_μ needs to be scaled down by 10-20% at low Q^2

More pure anti-neutrino channel needs smaller corrections

Recoil energy after the fit

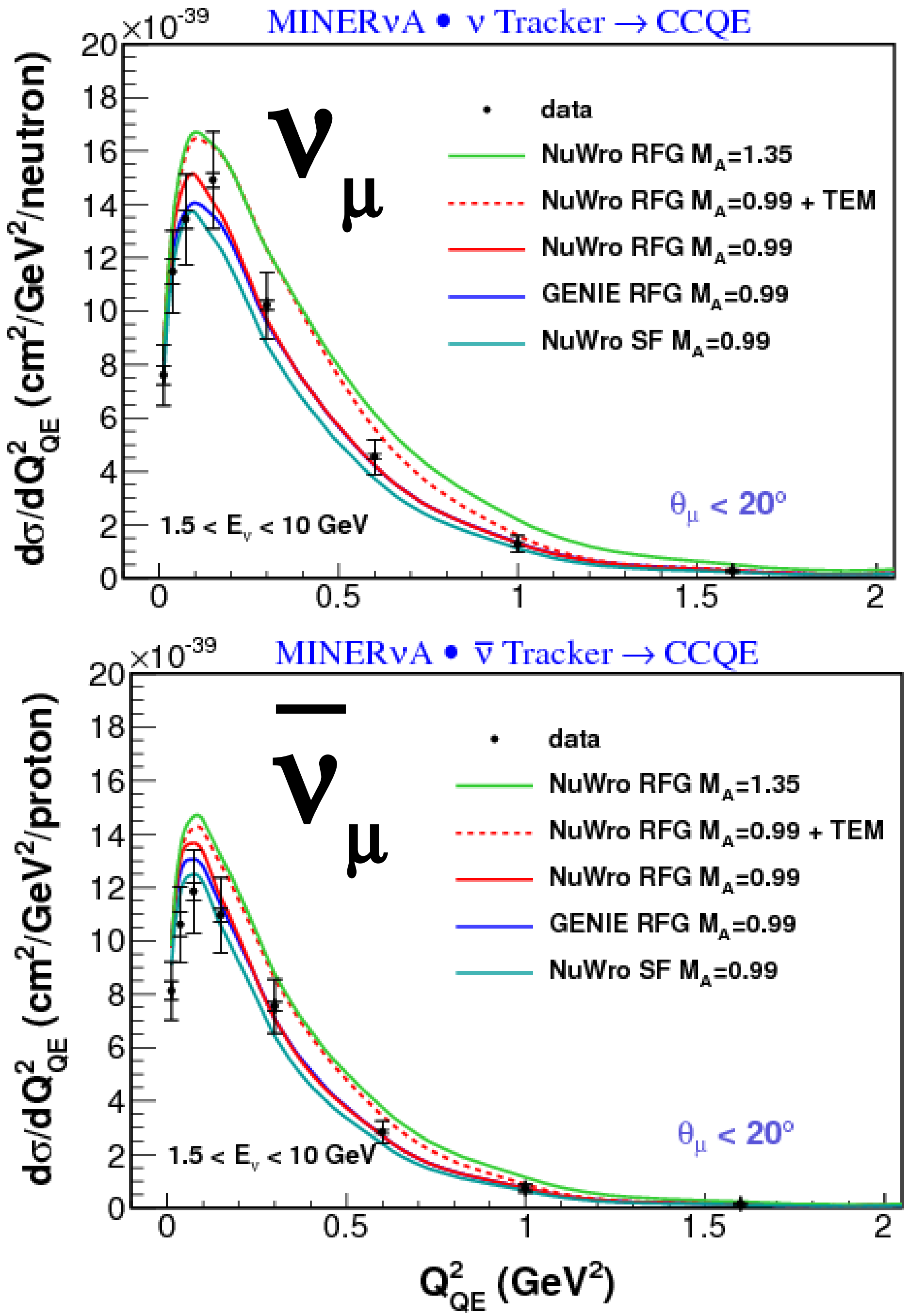




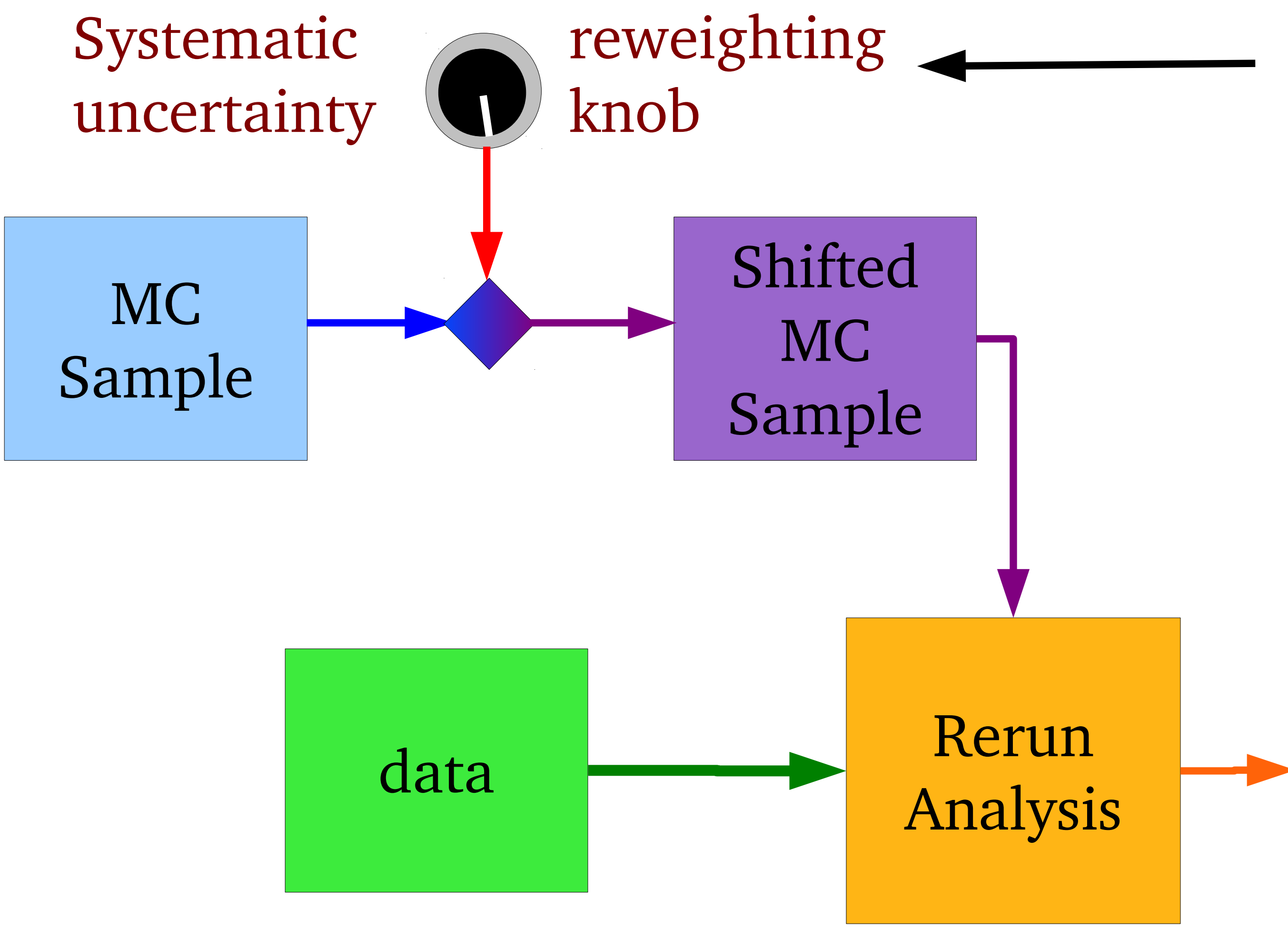
Fits successfully describe the recoil energy distribution over the whole kinematic range

Differential Cross-sections

- Background subtraction
- Iterative unfolding to true Q^2 distribution
- Efficiency correction
- Fiducial mass accounting
- Incorporation of the flux

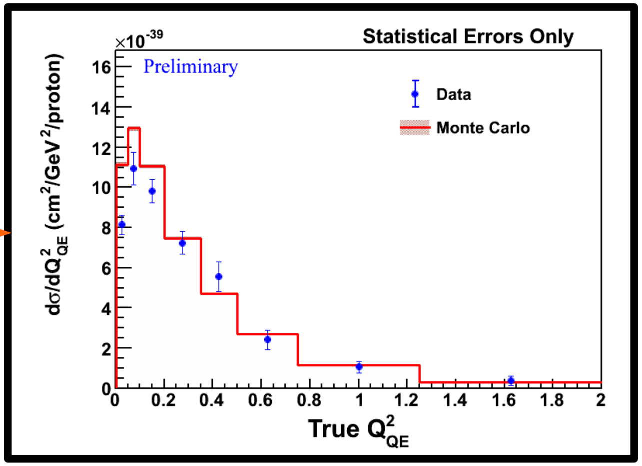


Systematic Uncertainties

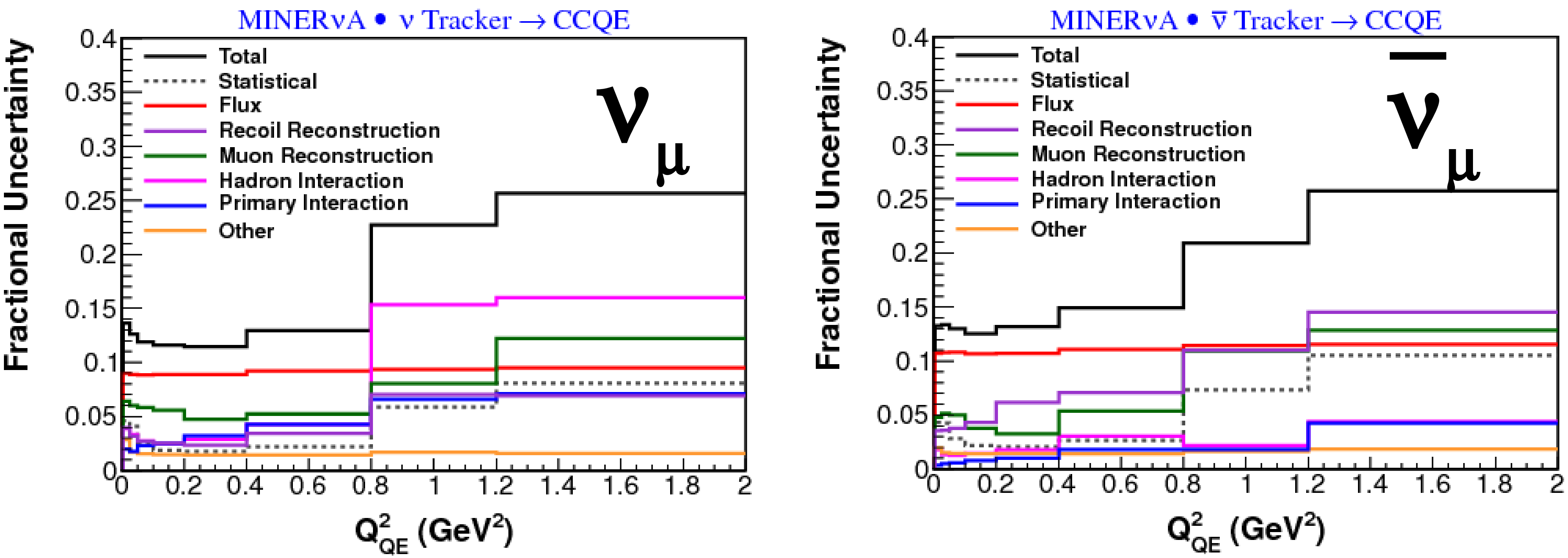


In practice we shift multiple knobs simultaneously: "many universes" "multi-sims"

Shifted Result

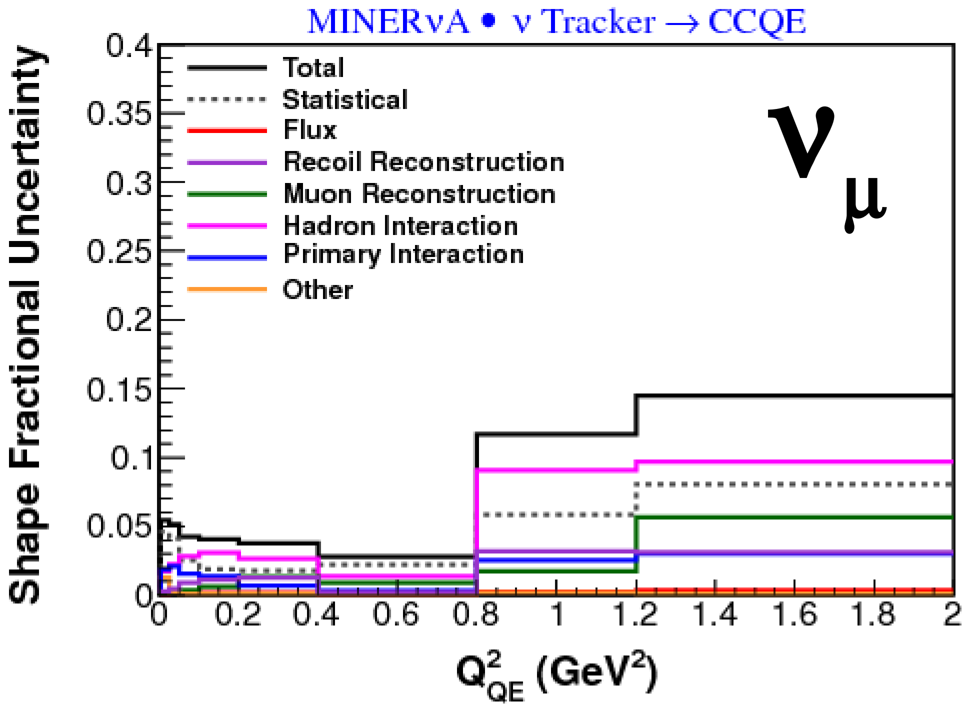


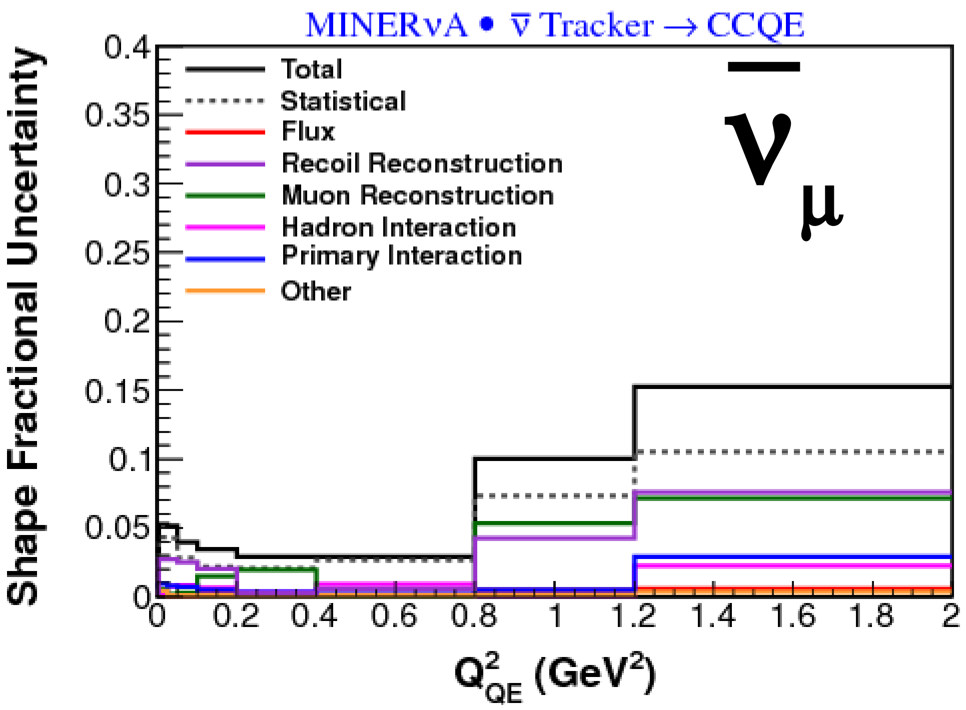
Systematic Error Bands



Most significant error: neutrino flux

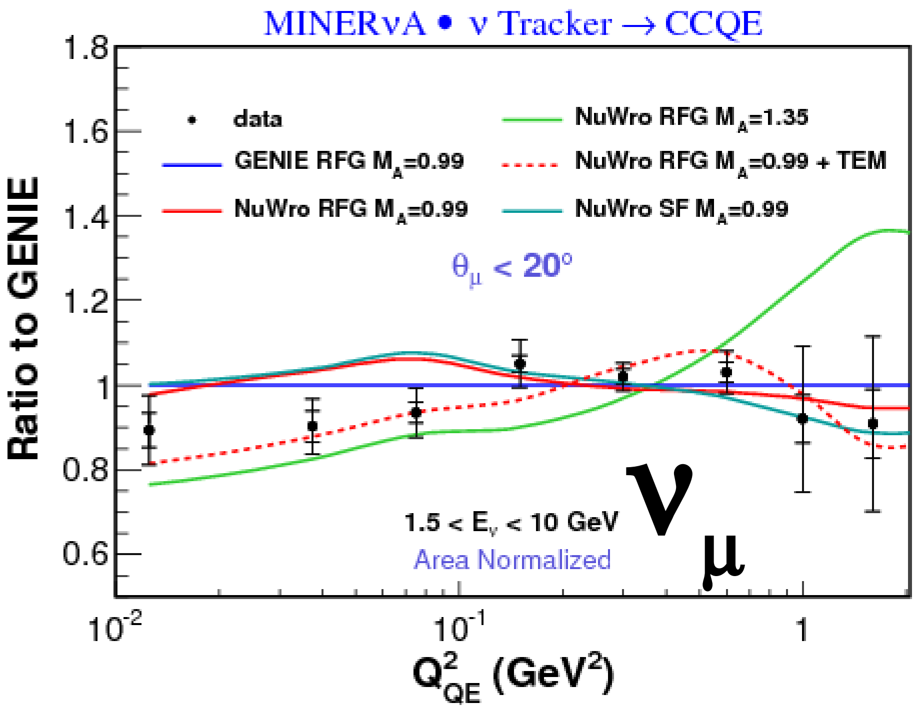
Shape uncertainties

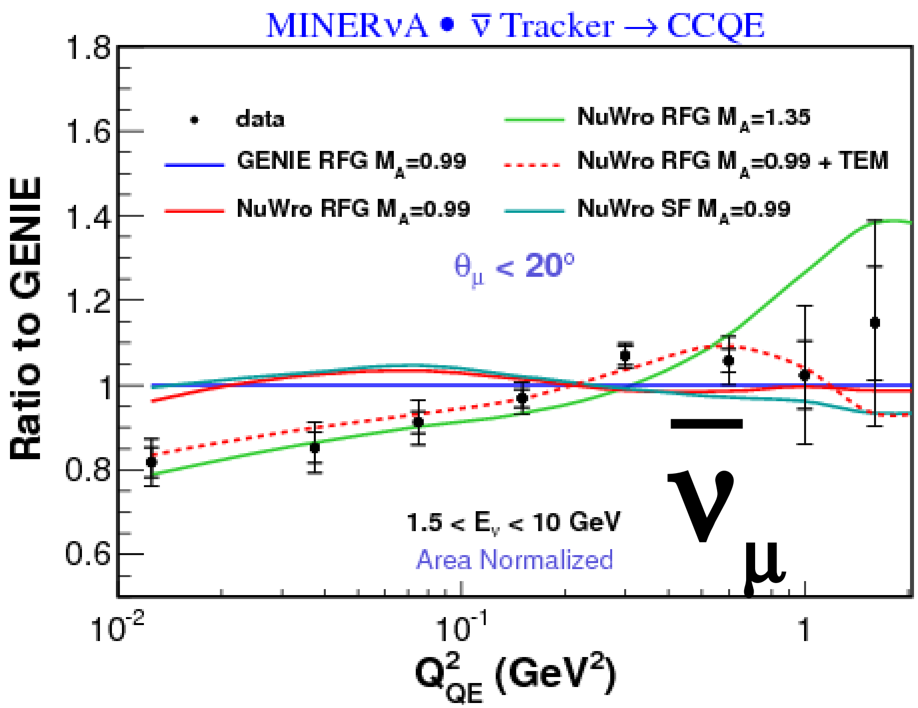




The shape of $d\sigma/dQ^2$ has smaller errors and is physics sensitive.

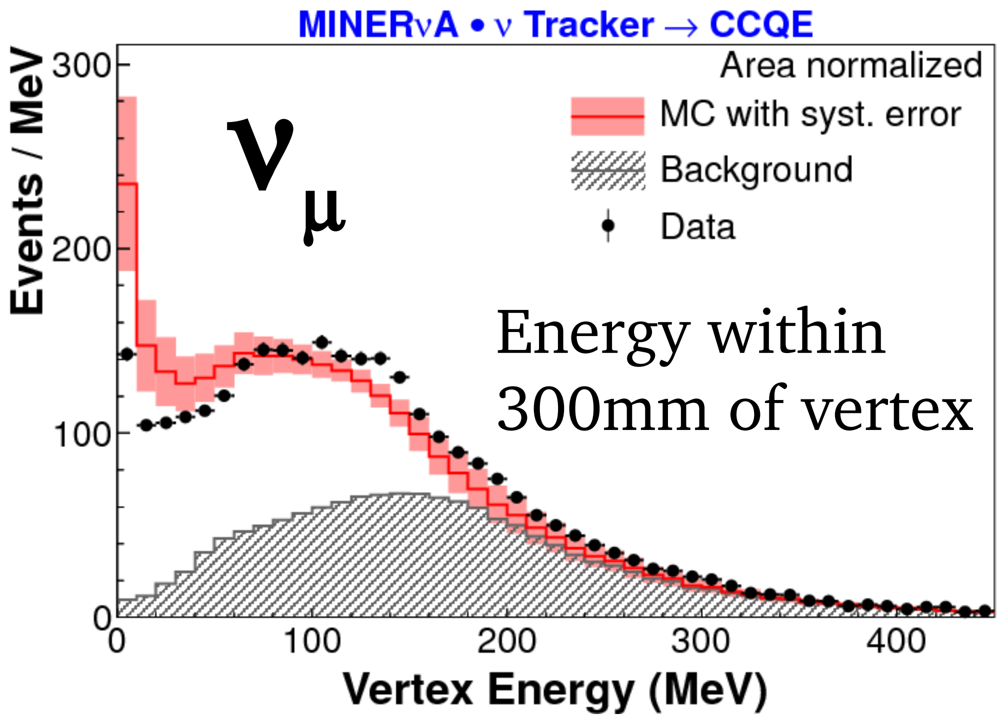
dσ/dQ² shape

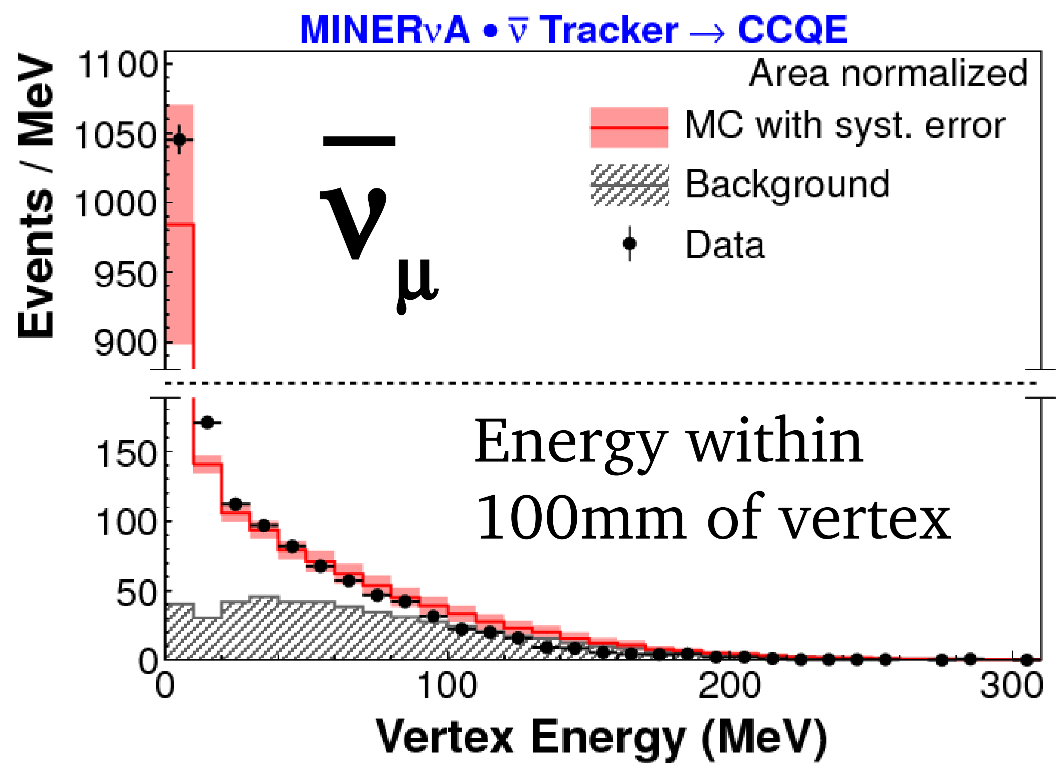




Best match is to an RFG model with M_A=0.99 GeV but with G^V_M modified in accordance with electron scattering data – "transverse enhancement" (TEM)

Vertex Energy





Excess of energy at the vertex seen in neutrino mode. Not explained by any systematic uncertainty.

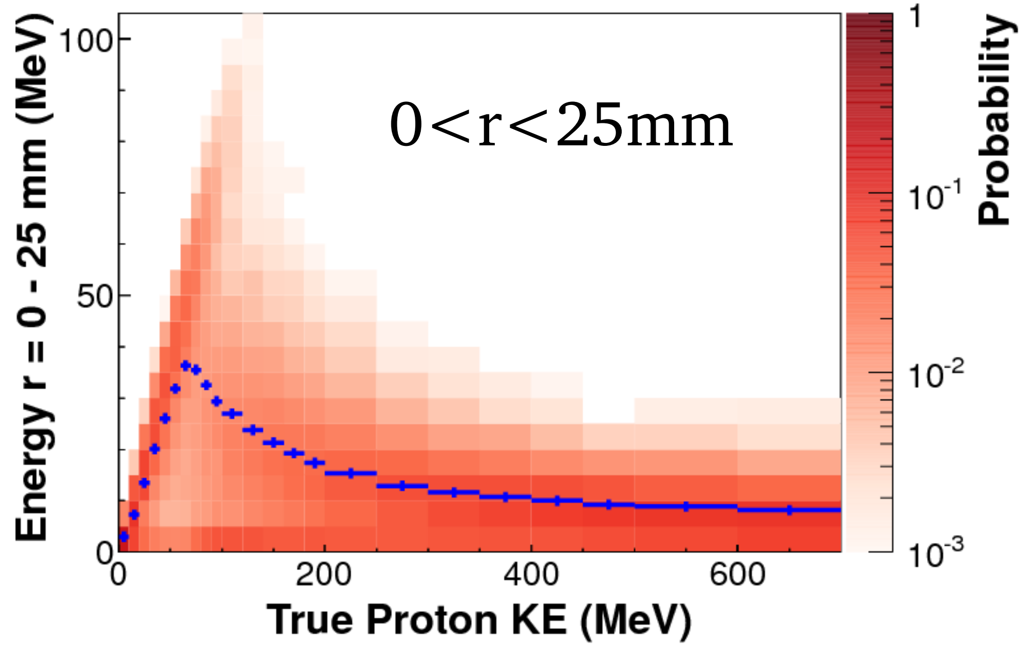
Relatively good agreement in anti-neutrino mode

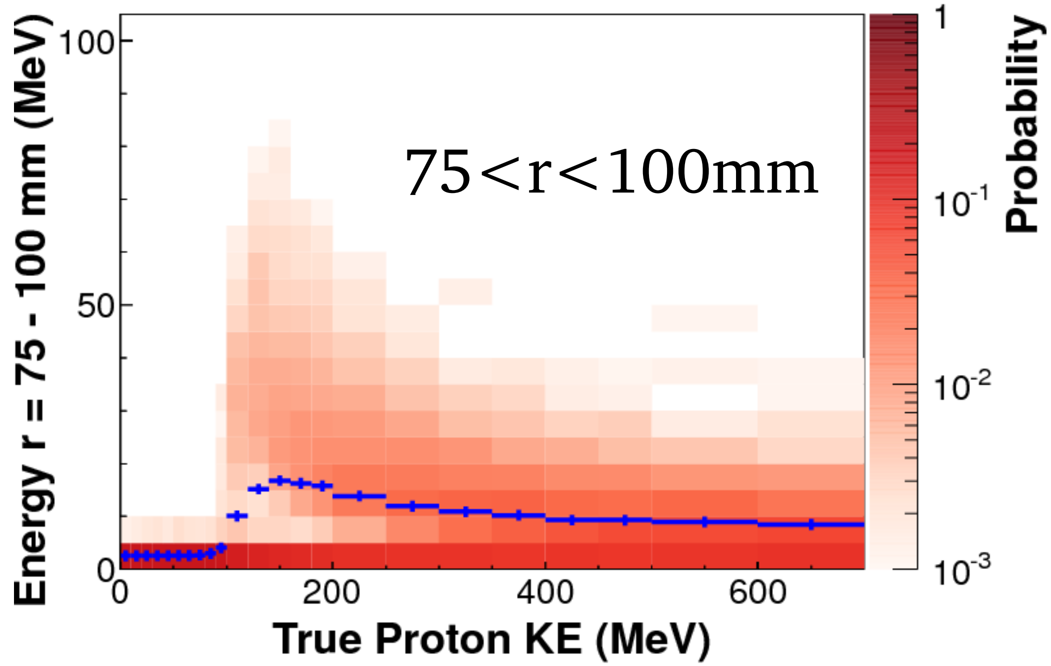
Vertex Energy Fit

<u>Hypothesis</u>: Some QEL-like events due to scattering on correlated np pairs.

Would result in an nn final state for anti-neutrinos but a pp pair for neutrinos.

Test this by adding in an additional proton to some events. Fit vertex energy in radial slices.



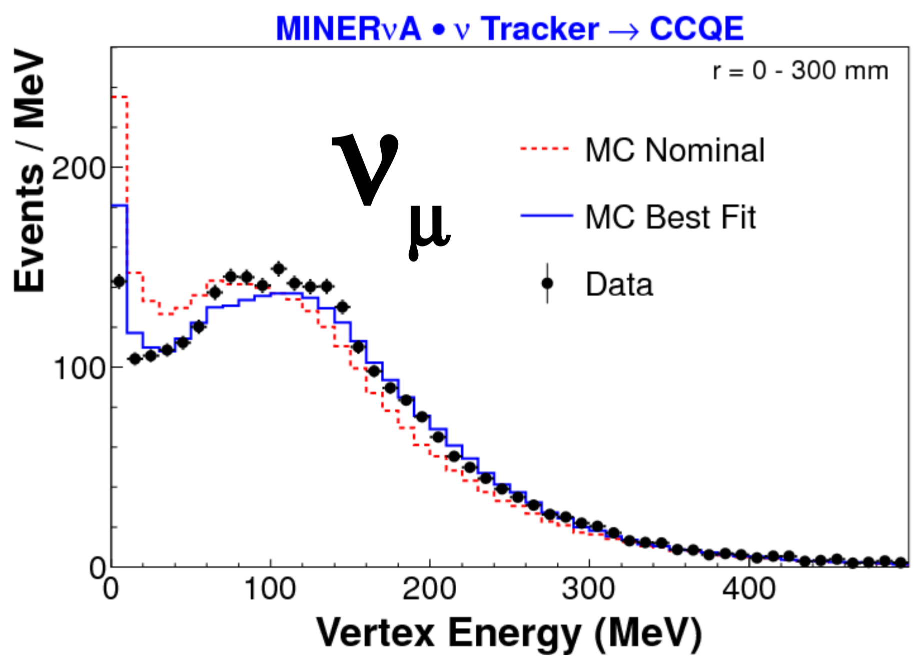


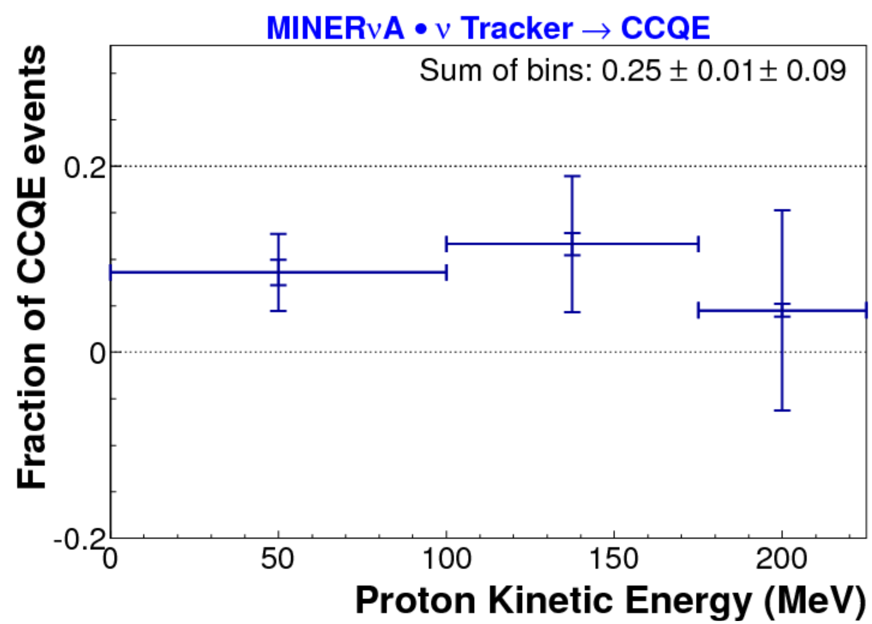
Vertex Energy Fit

Result:
Neutrinos: Best agreement if 25±9% of events have an additional proton with a flat energy distribution from $0<E_{vtx}<200$ MeV

No additional protons needed in anti-neutrino mode.

Conclusion
Neutrino cross-sections and energy reconstruction sensitive to multi-body effects. Generator tuning badly needed.





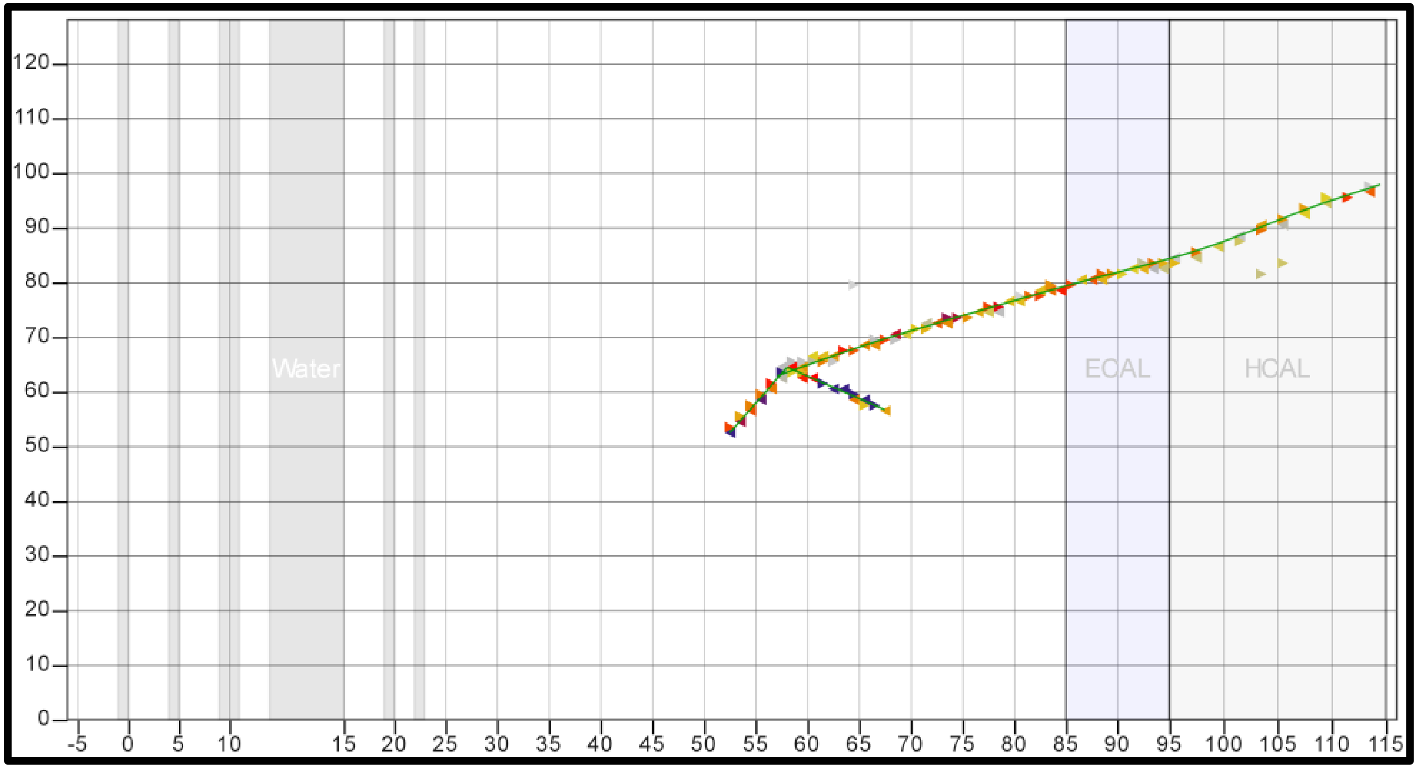
Additional Results

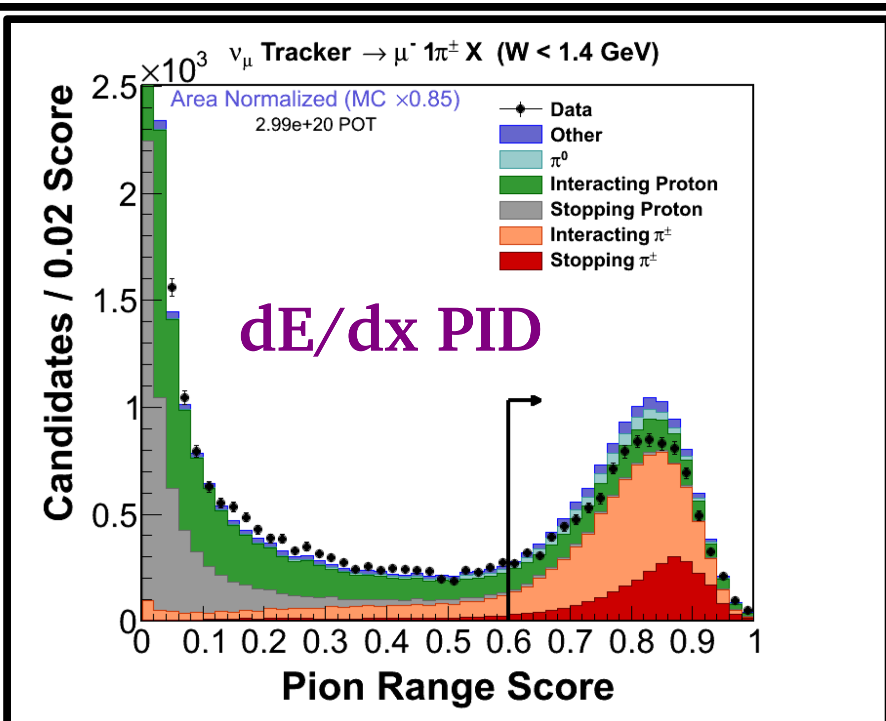
Single $\pi^{\pm}$ production

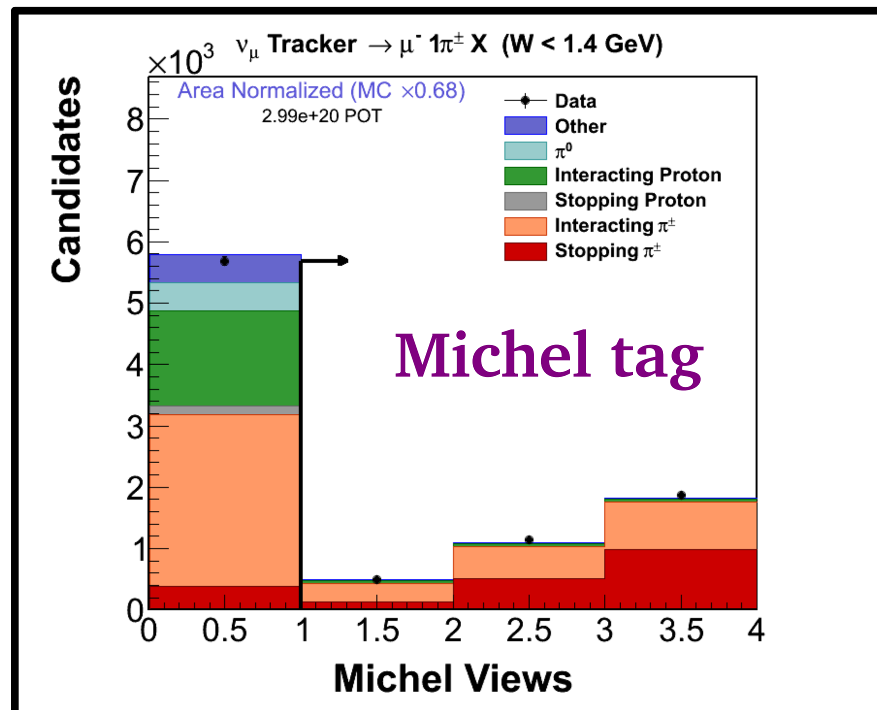
ν_μ (C,H) → π X

W<1.4 GeV

$d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$

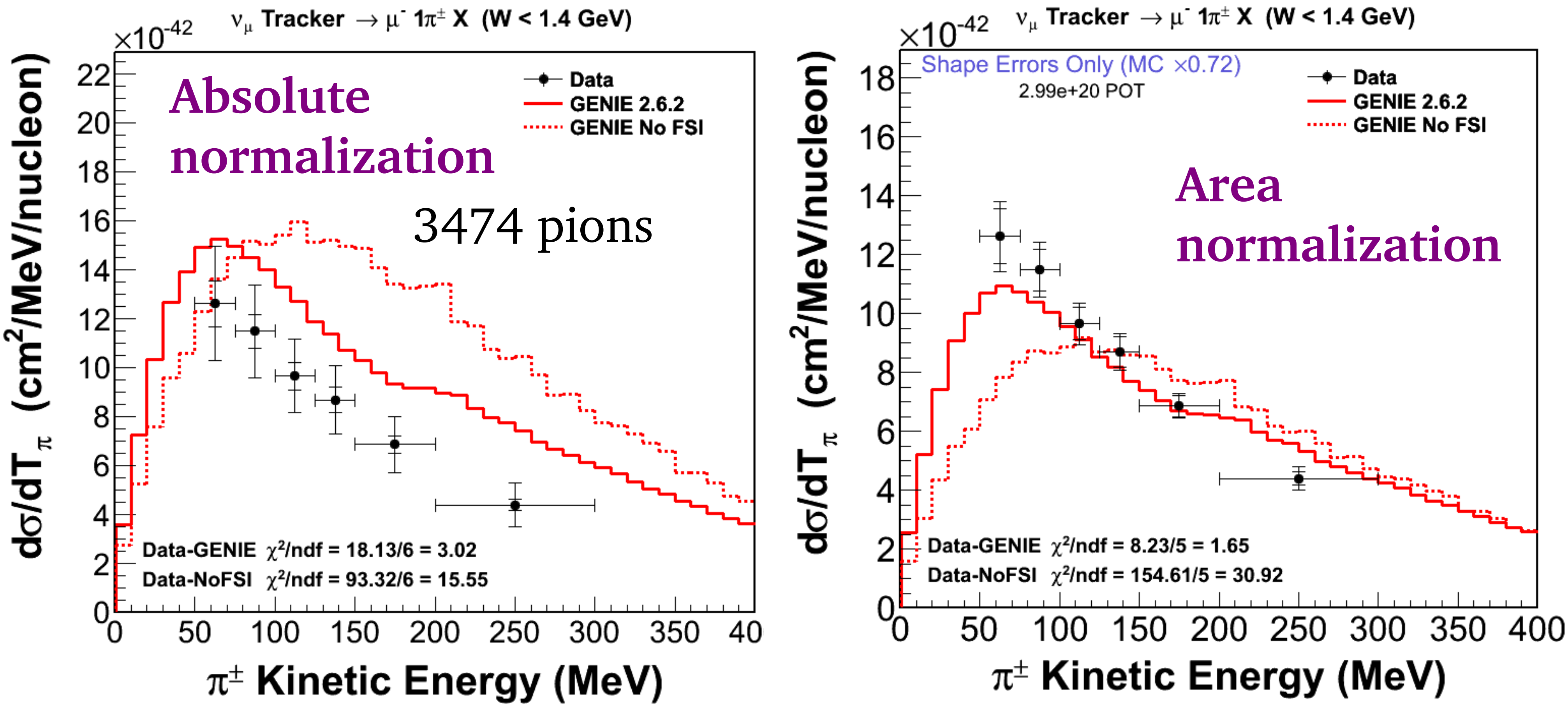






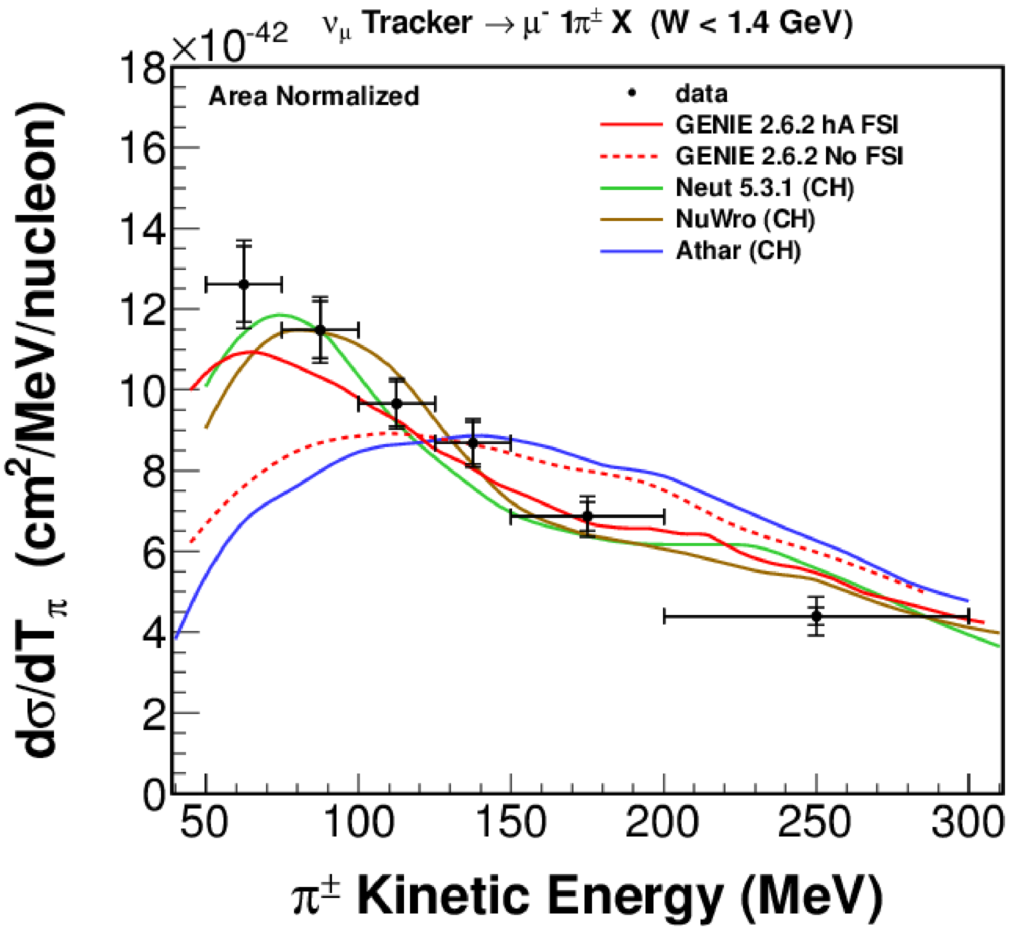
Single $\pi^{\pm}$ production

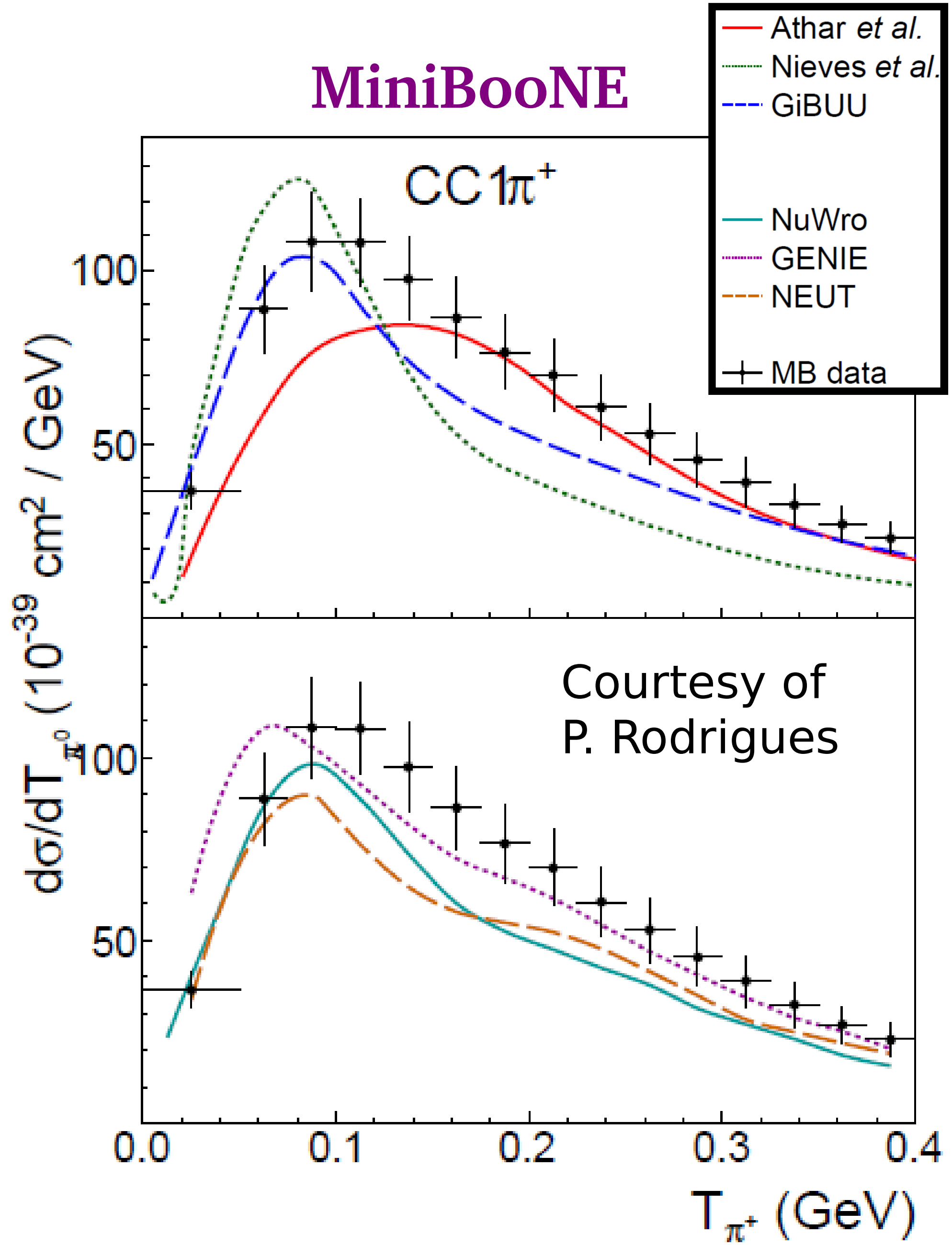
Mostly π^+



Conclusion: data are sensitive to FSI and provide model tests

Single π+ production

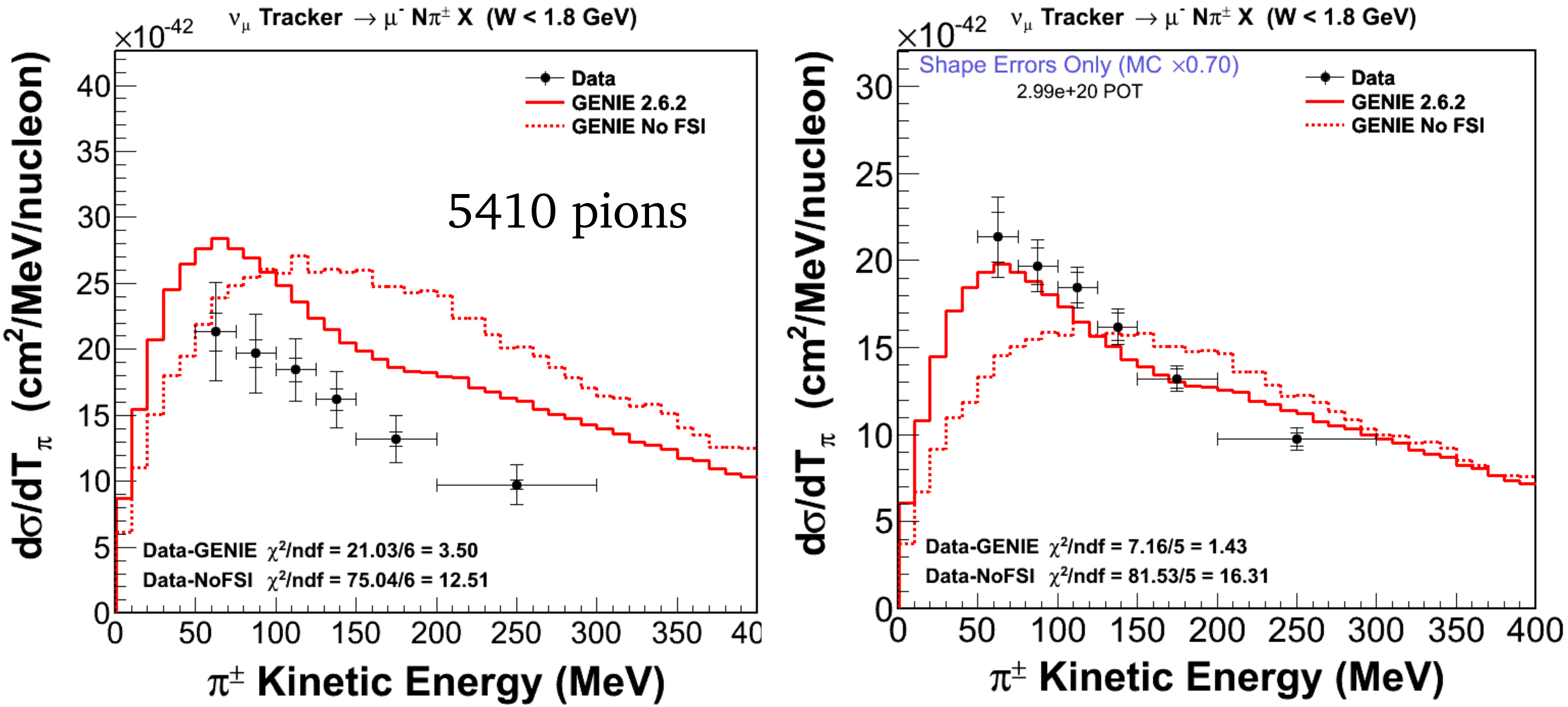




Conclusion: **MC codes tend to agree better than micro-physical calculations** *(for now…)*

Multi-$\pi^{\pm}$ production

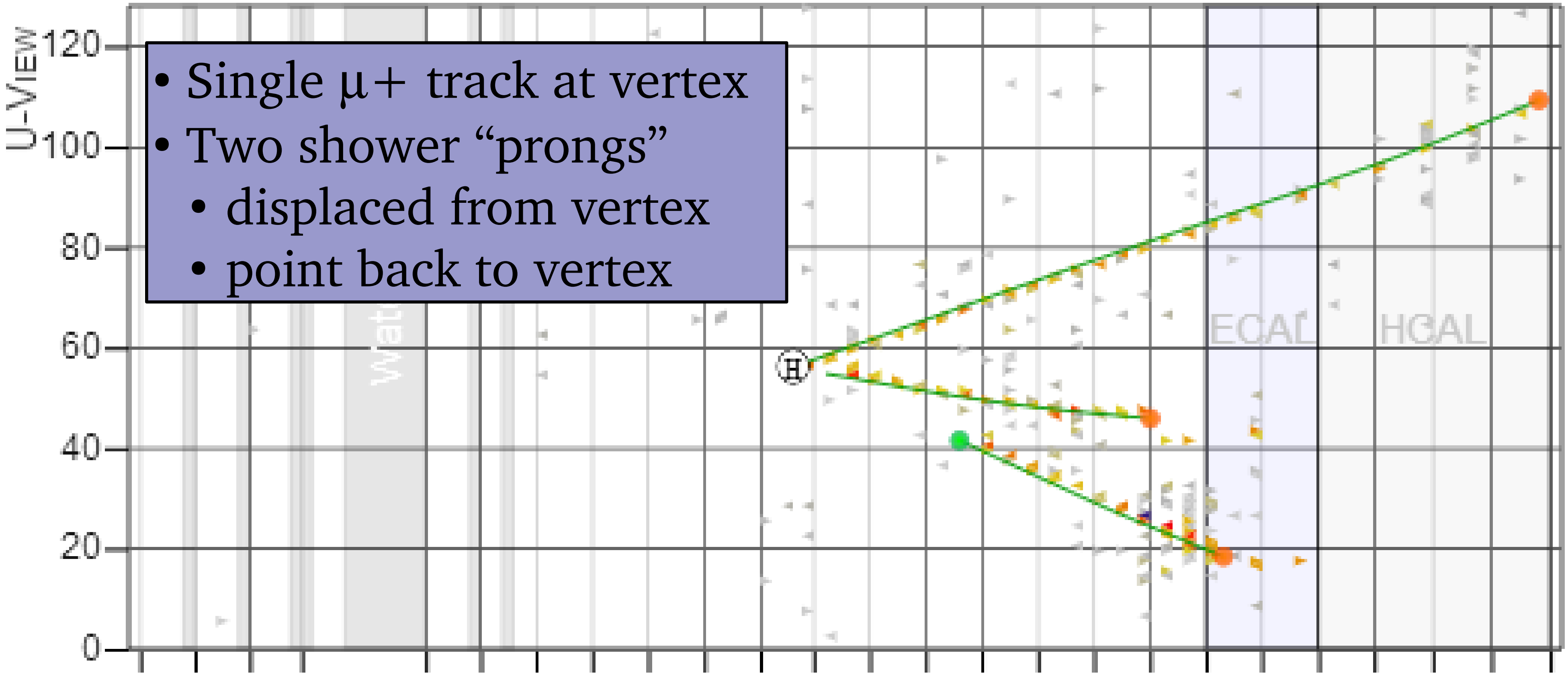
Mostly π^+



Work in progress

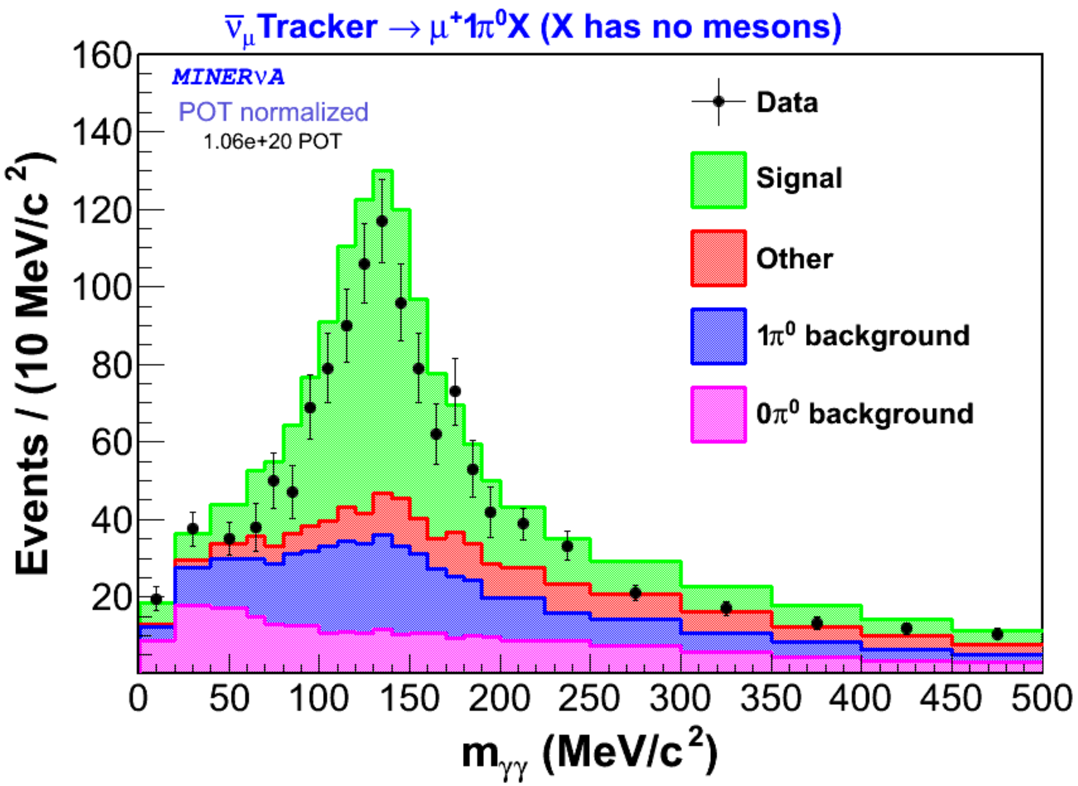
Single π^0 production

$\bar{\nu}_\mu$ (C,H) → $\mu^+ \pi^0$ + nucleons



NC mode: ν_μ (C,H) → $\nu_\mu \pi^0$ + nucleons is the main background in $\nu_\mu \to \nu_e$ searches

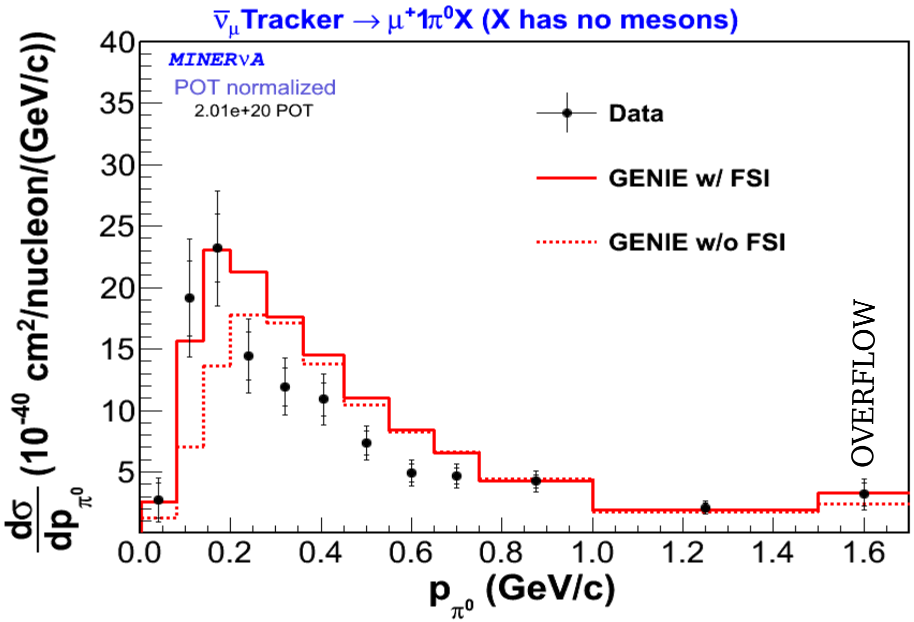
Single π^0 production

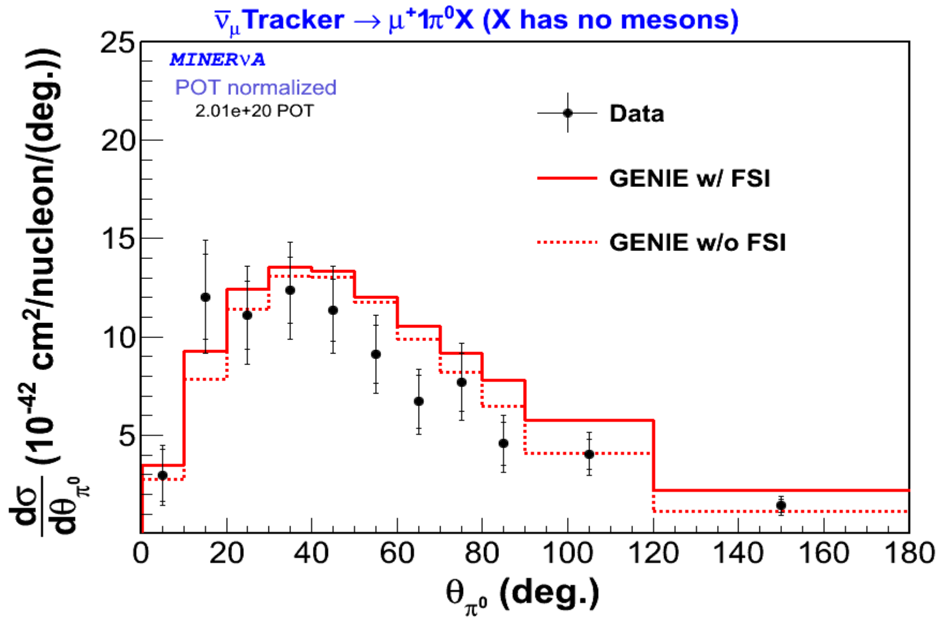


MC background breakdown:

1) Background 1: events with pi0 in the final state plus charged pion (so it's not our signal)
2) Background 2: events with no final state pi0, but there is secondary pi0s, e.g., from pi-charge exchange
3) Background 3: events with no final state nor secondary pi0s

Single π^0 Cross-sections





- Data are in better agreement with the cross section with FSI
- Cross section with FSI is above that without FSI across momentum range
- Above 0.3 GeV/c, cross sections with and without FSI are similar
- Below 0.3 GeV/c, cross sections with and without FSI are very different

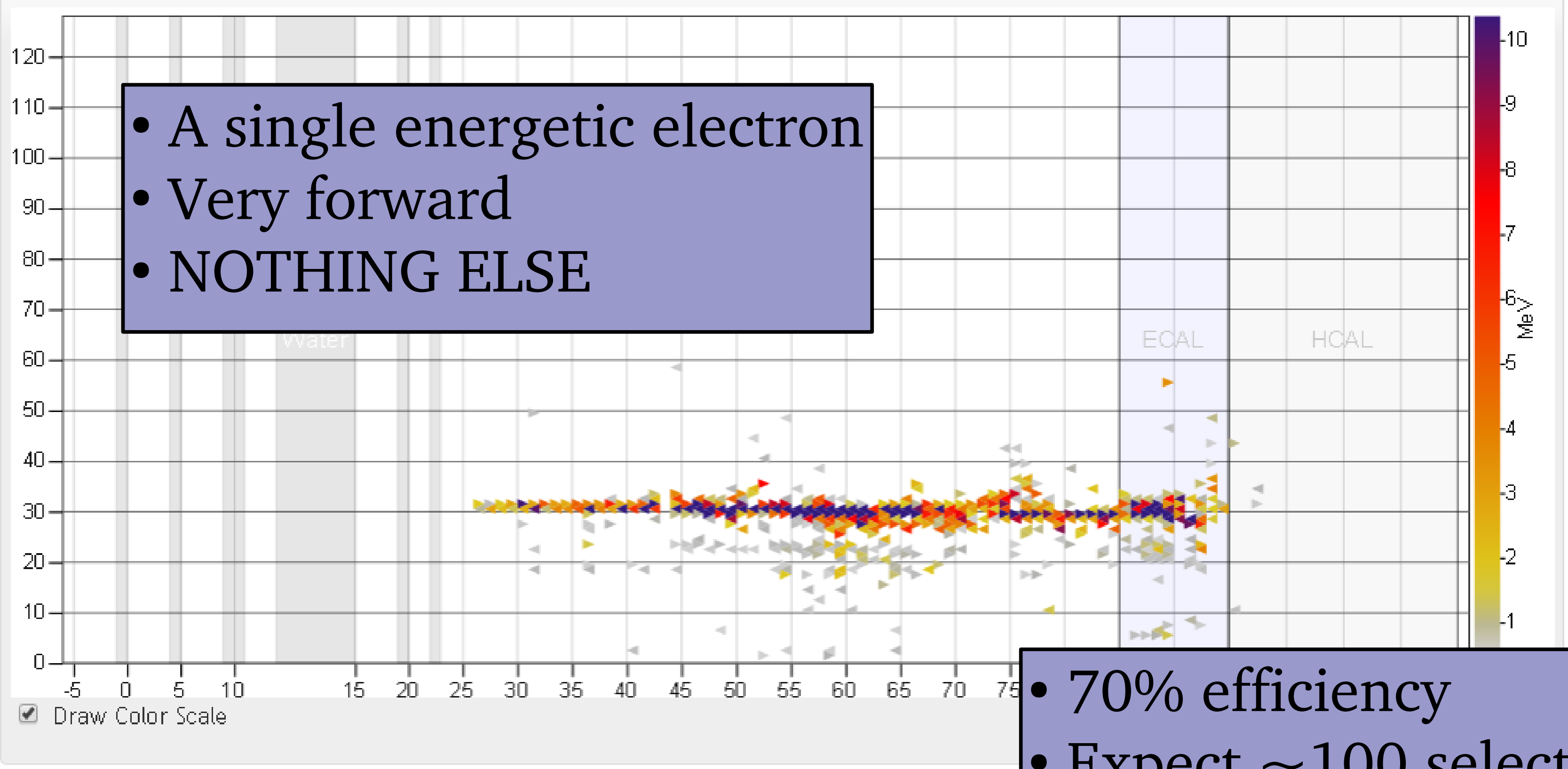
- FSI produce slightly more both forward and backward going signal

ν – electron scattering

Standard candle cross-section, precisely predicted by the SM

$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F{}^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2}-\sin^2\theta_W\right)^2 + \sin^4\theta_W(1-y)^2\right]$$

$\sim 10^{-41}\ \mathrm{cm}^2 = 0.01\mathrm{fb}$



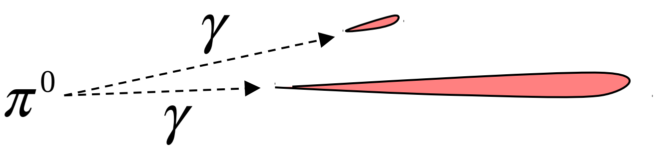
- A single energetic electron
- Very forward
- NOTHING ELSE

- 70% efficiency
- Expect ~100 selected events for 3.43e20 POT in the NuMI LE beam

ν – electron scattering

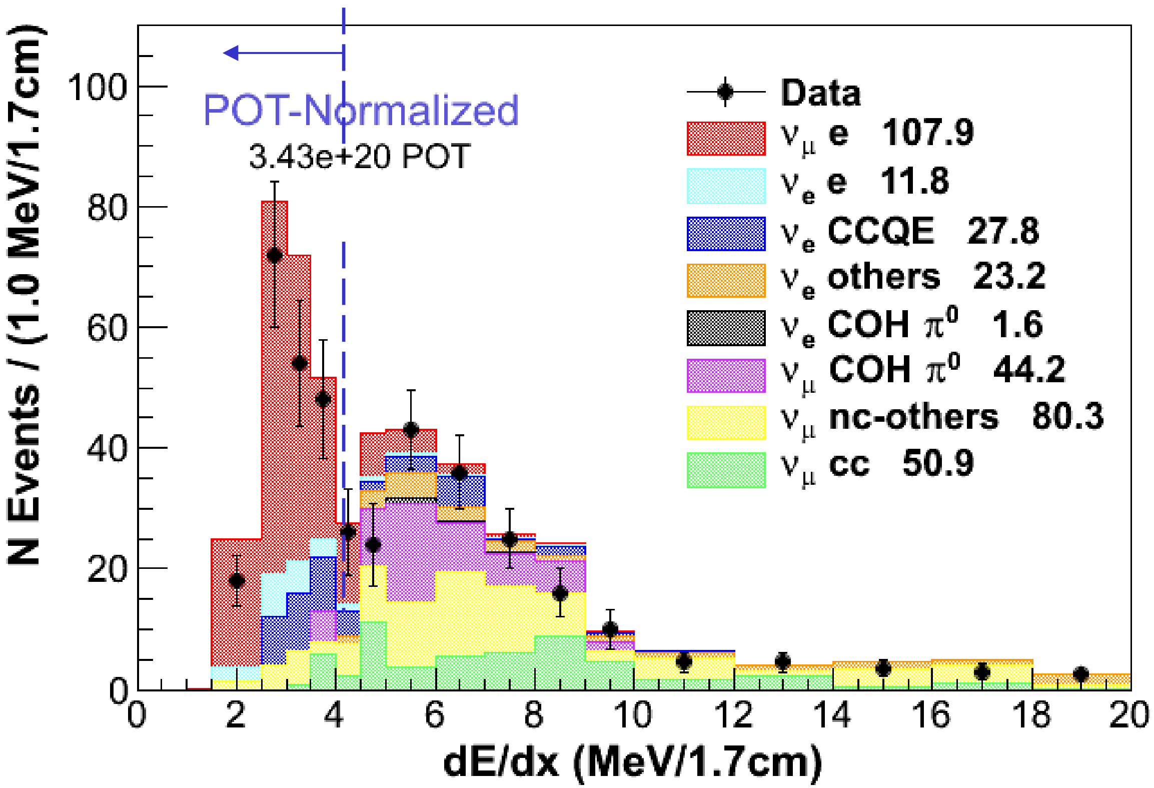
Major background from events with a π^0 where 1 γ is lost

$\nu_\mu A \rightarrow \nu_\mu A \pi^0$	NC-coherent π^0
$\nu_\mu N \rightarrow \nu_\mu N \pi^0$	NC-resonant π^0



Background rejection
Look at dE/dx near the start of the shower

electron = 1 MIP
gamma = 2 MIPs

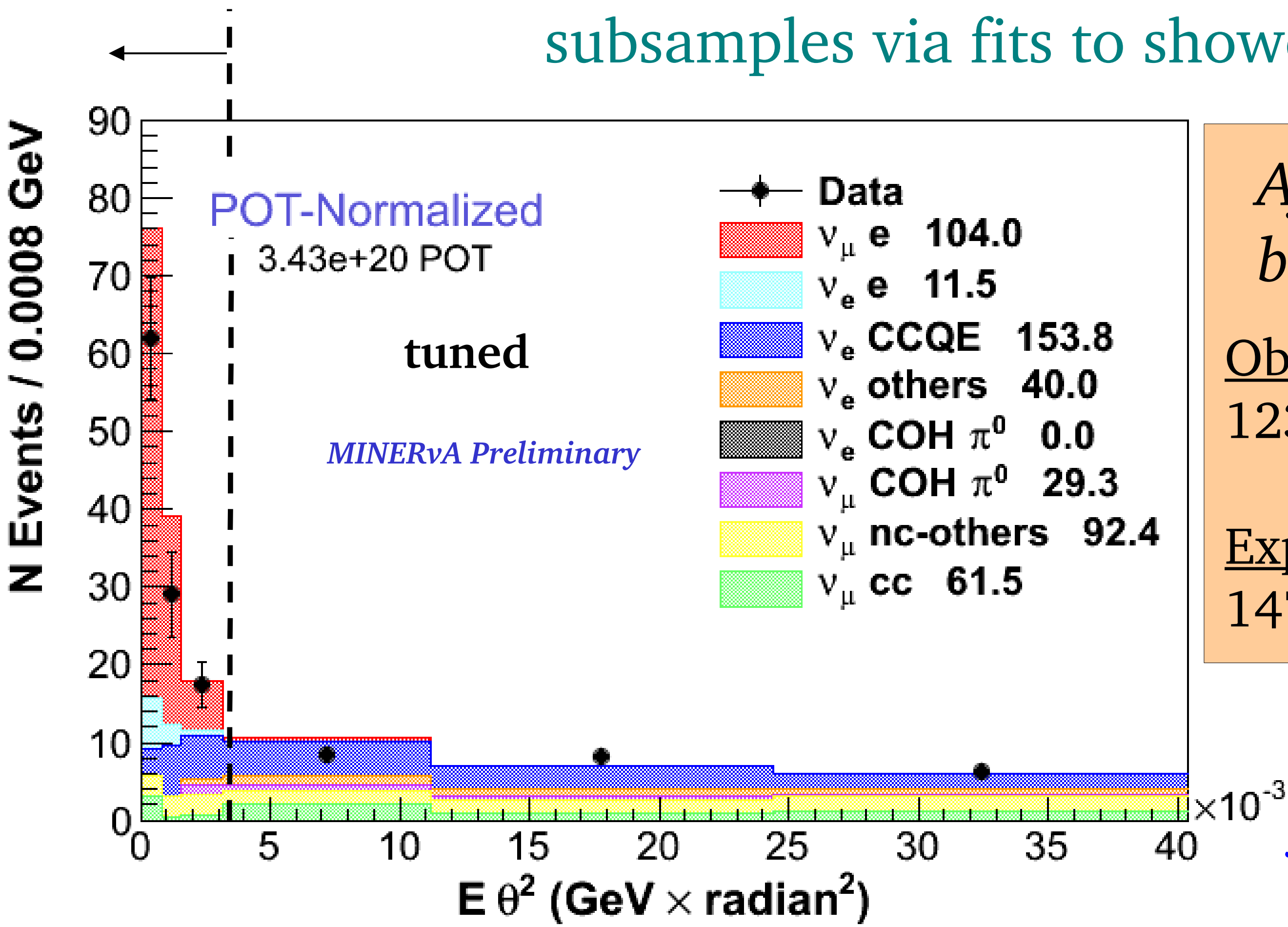


ν – electron scattering

Background from ν_e CC interactions removed via $E\theta^2$ cut

Data driven background constraint via sidebands in dE/dx, $E\theta^2$. Sensitivity to subsamples via fits to shower topological variables.

$E\theta^2 < 0.0032\,\text{GeV}\cdot\text{rad}^2$



After efficiency and background corrections

Observed

123.8 ± 17.0 (stat) ± 9.1 (syst)

Expected

147.5 ± 22.9 (flux)

Gives a constraint on the flux comparable to current uncertainty.

Other analyses in progress

- QEL:
  - two tracks. Q^2 reco with muon and proton arms compared
  - $d^2\sigma/d\theta_\mu \, dp_\mu$ for numu and numubar
  - Michel tag to remove inelastic background
  - nuclear targets
- Coherent pion production
- Inclusive scattering off of nuclear targets to explore the EMC effect
- ν_e QEL, K production, & the flux
- Many additional channels (e.g., all νA NC) and the ME beam adds kinematic reach to existing measurements.
- Also, for NOvA, T2K, LBNE I hope the community will engage in a generator tuning effort similar to that of the collider program.

Centro Brasileiro de Pesquisas Físicas
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University of Florida
Universidad de Guanajuato
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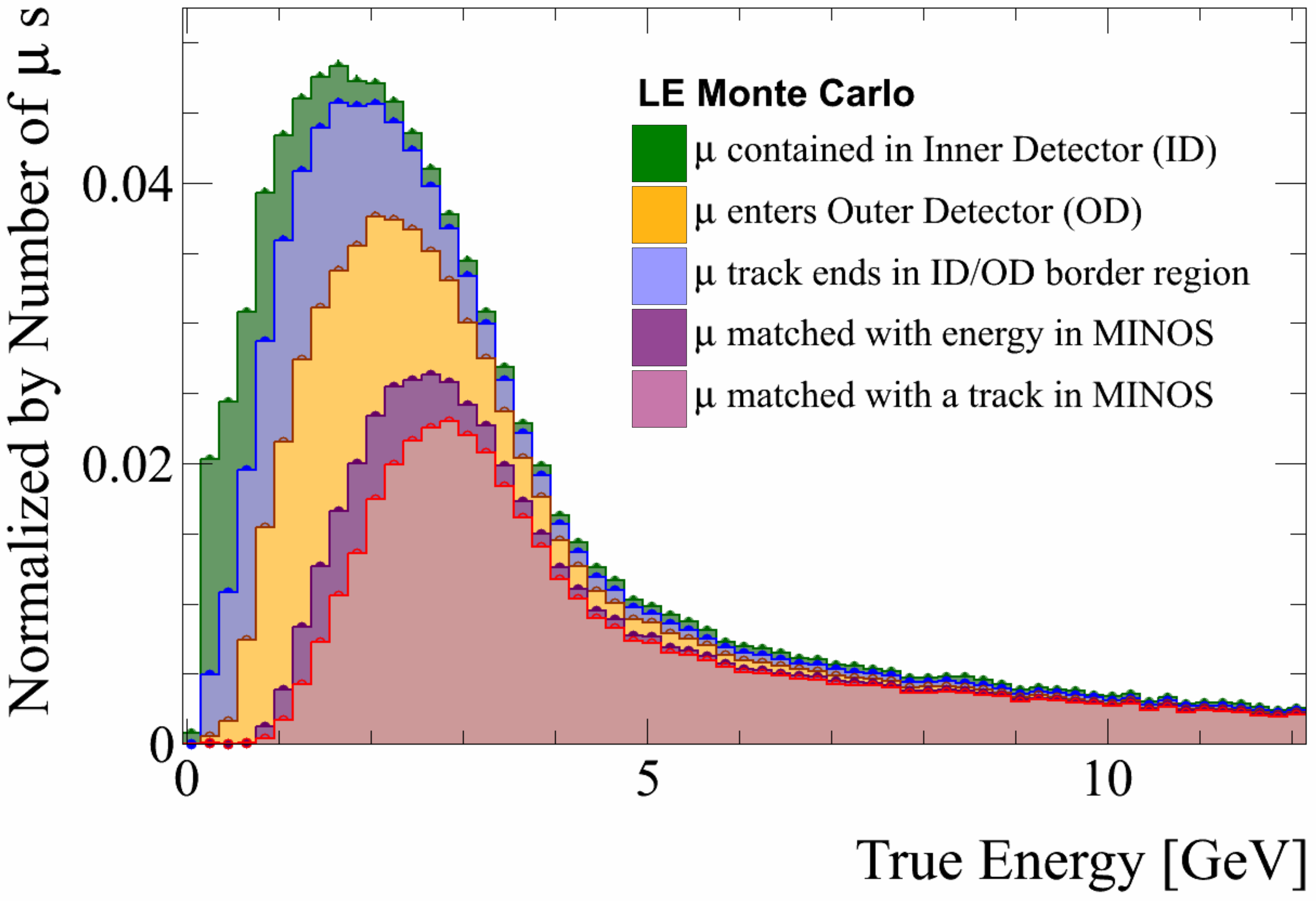
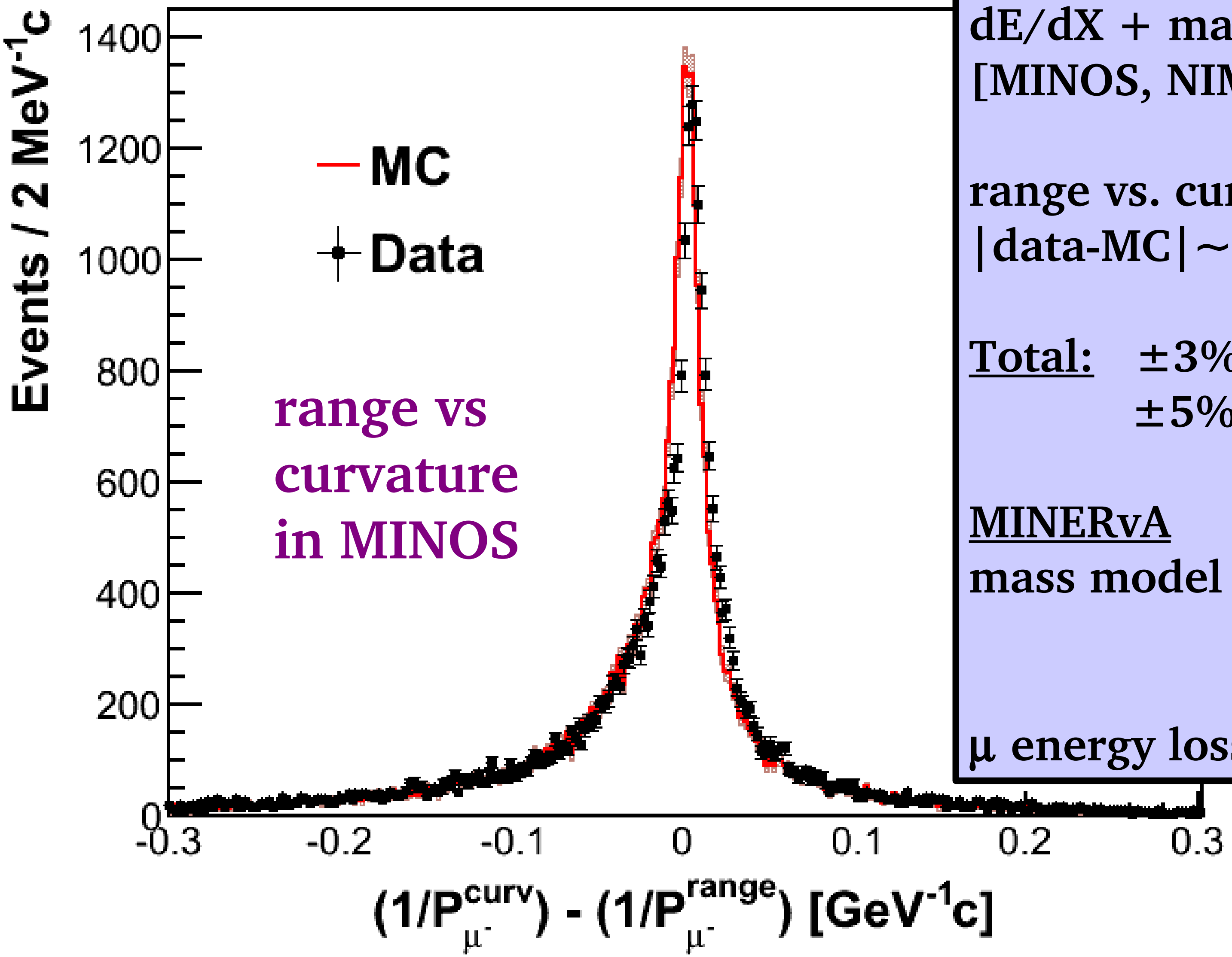
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary

Where do the muons go?

Good acceptance into MINOS for $\theta_\mu < 20°$



Muon energy uncertainty



<u>MINOS</u>
dE/dX + mass model = 2%
[MINOS, NIM A 596, 190 (2008)]

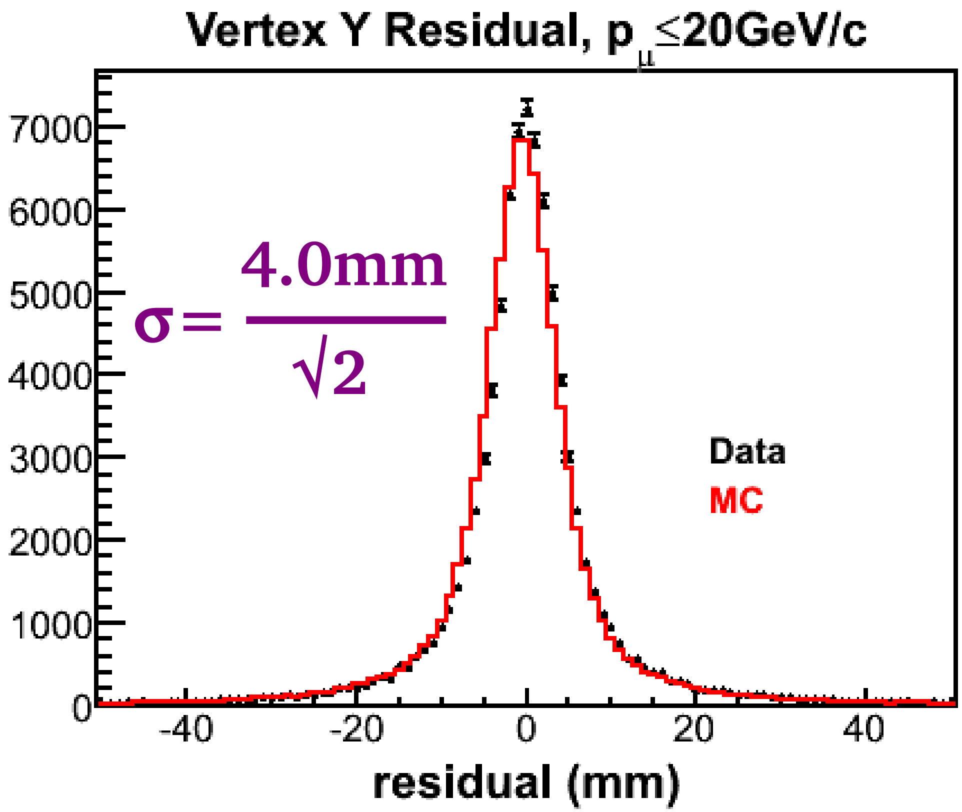
range vs. curvature
|data-MC|~25 MeV

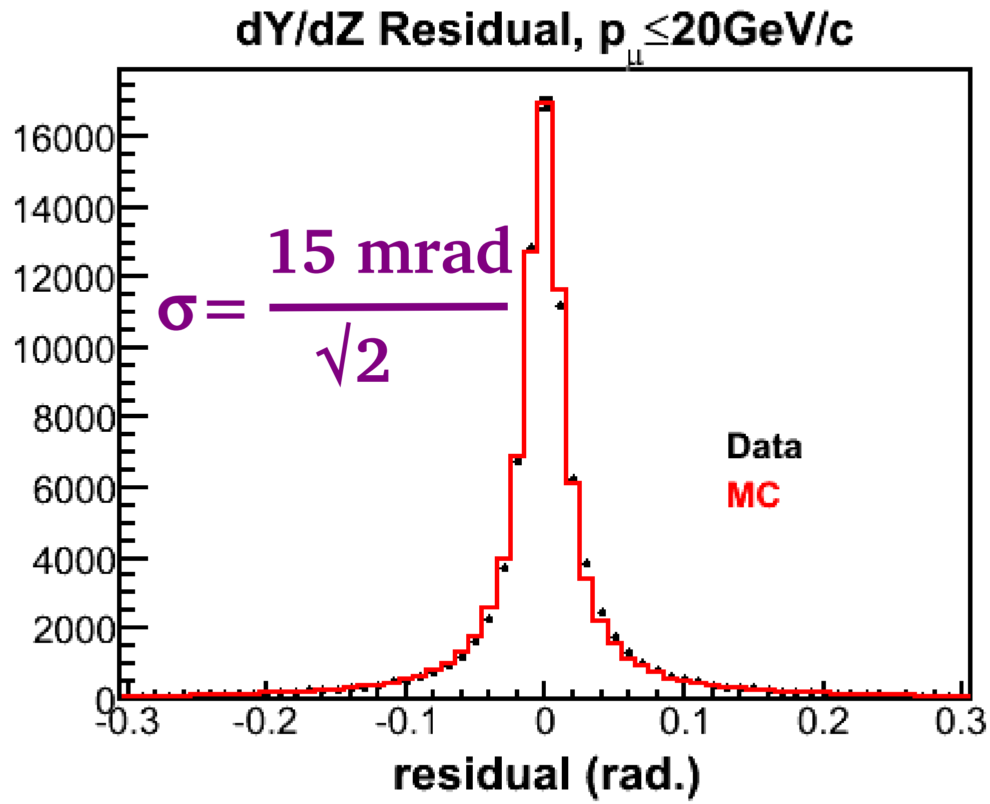
<u>Total:</u> ±3% p> 1.5 GeV
±5% P<1.5 GeV

<u>MINERvA</u>
mass model = 11 MeV tracker
= 17 MeV Nucl. Tgts.

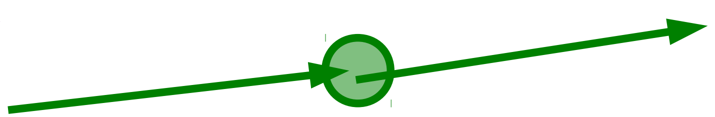
μ energy loss = 30 MeV

Tracking resolutions

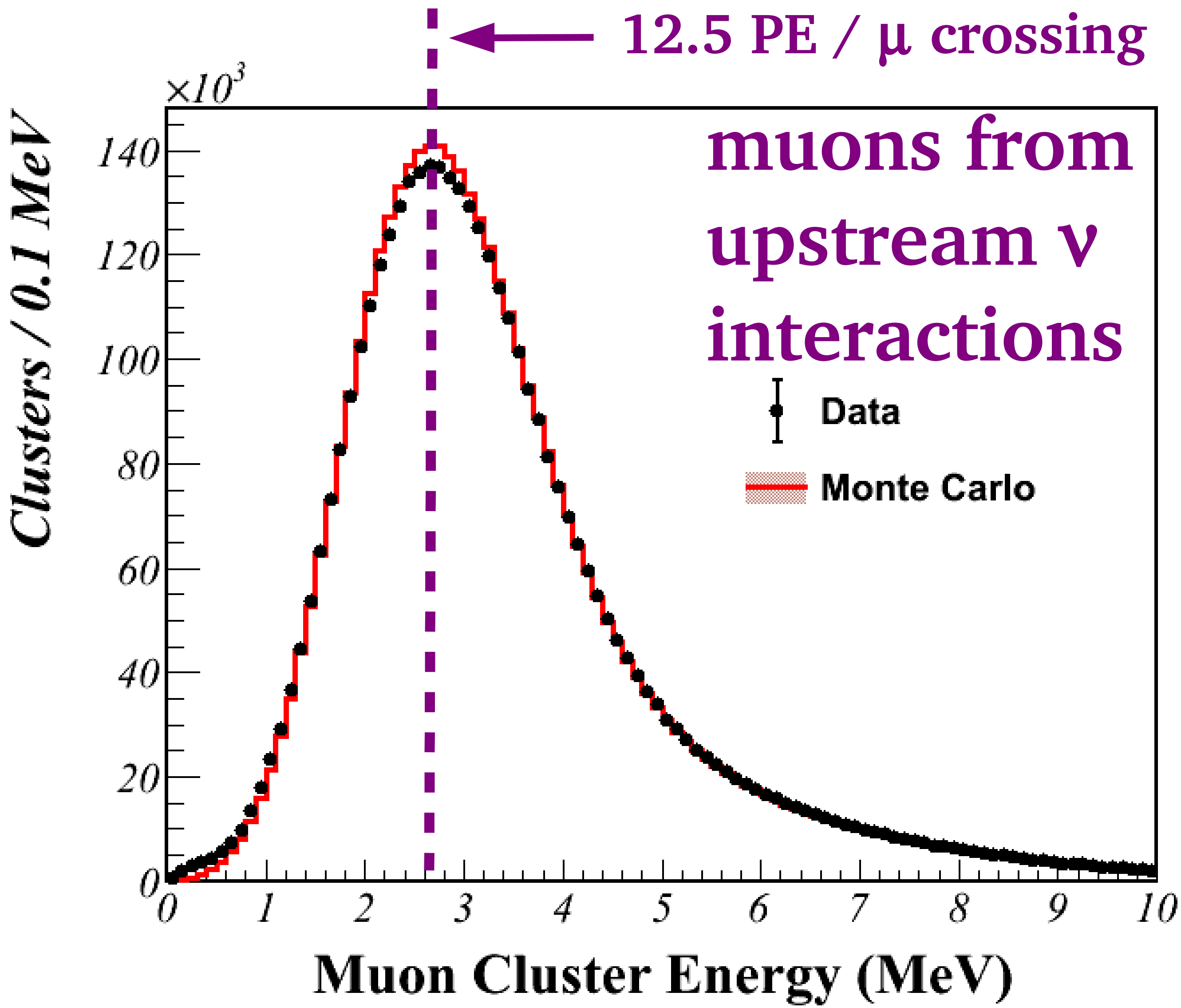




Split-track study of rock μ in tracker region

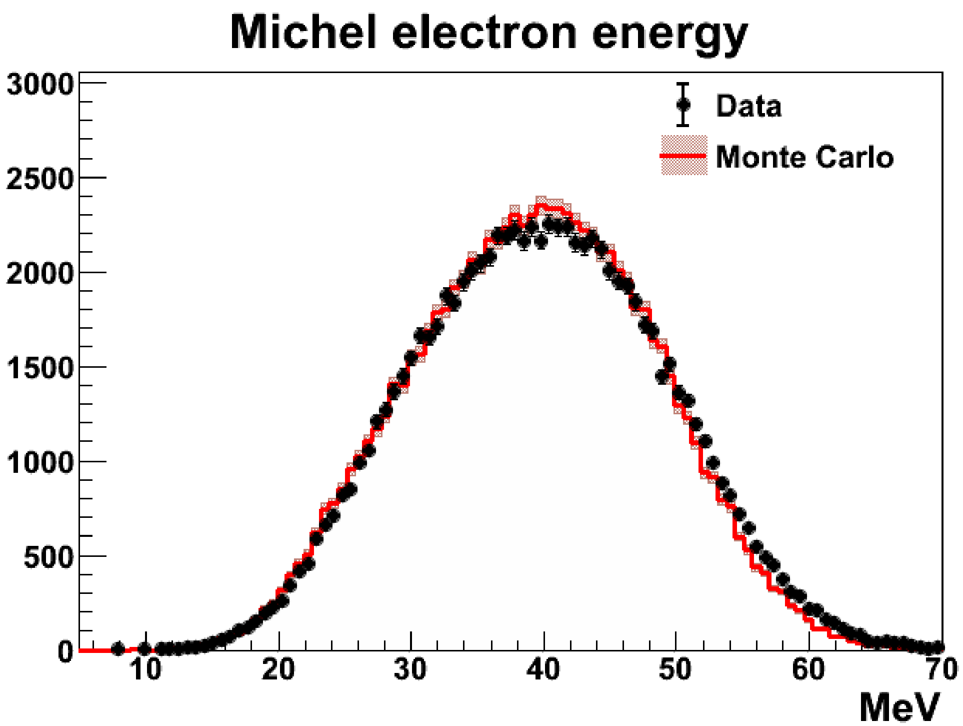


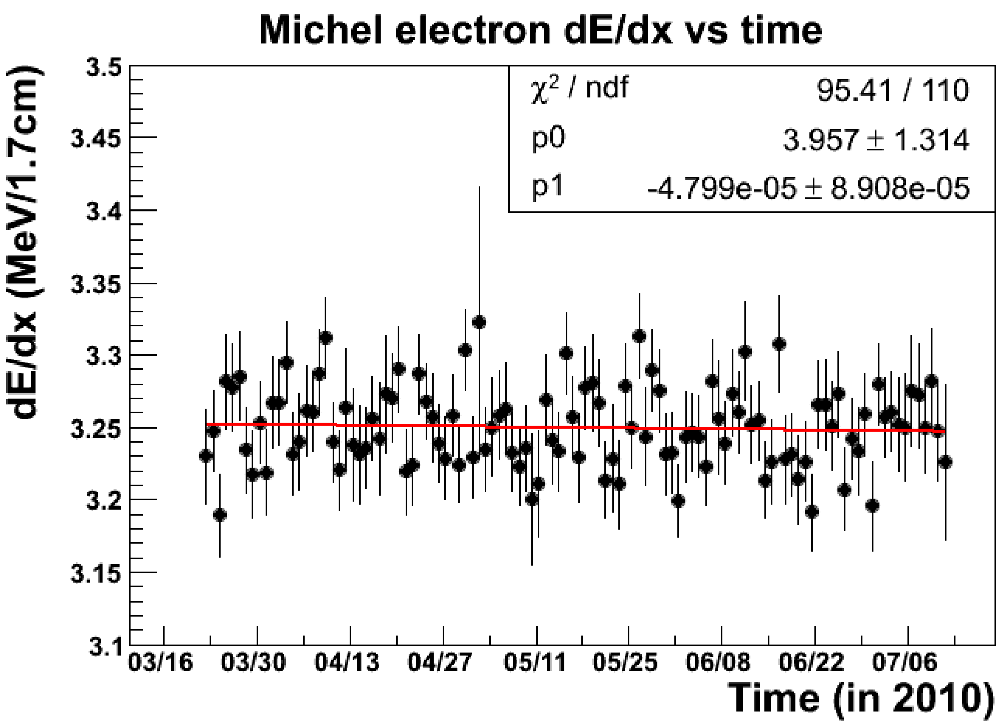
visible energy scale



Michel electrons

Michel = $\mu \rightarrow e\, \nu \bar{\nu}$



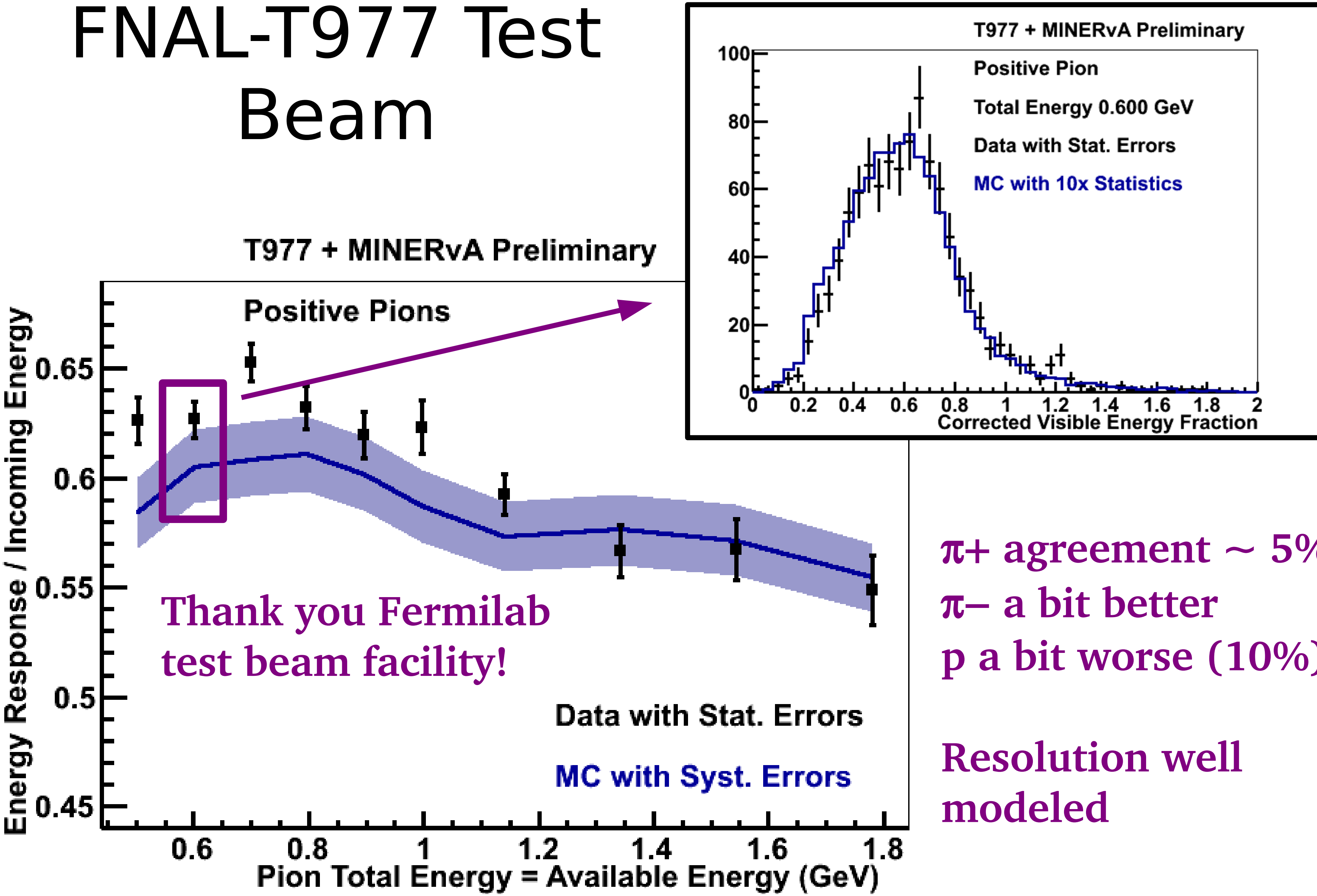


Cross-check on μ derived energy scale

EM response uncertainty = 3%

A nice stable detector!

FNAL-T977 Test Beam

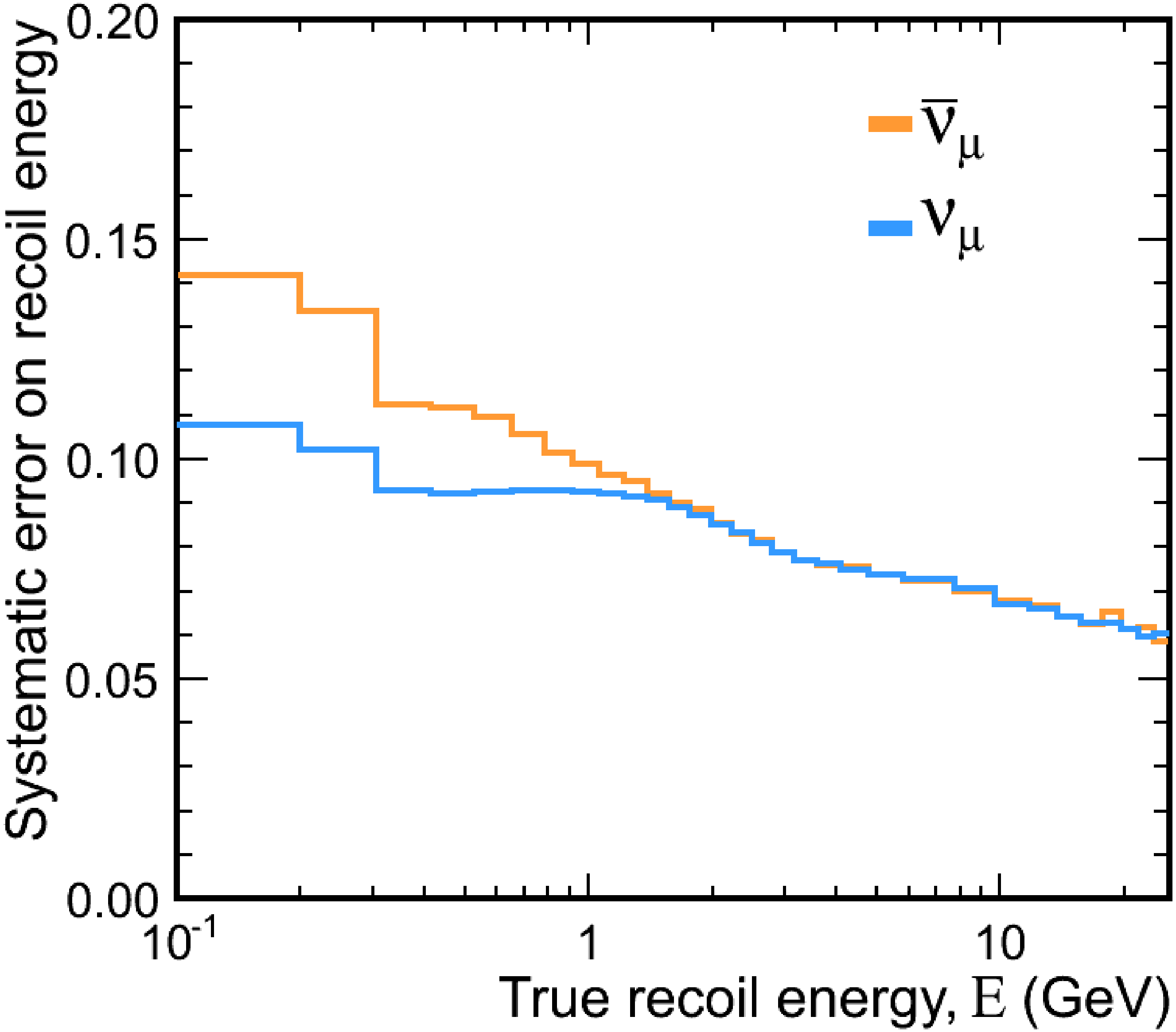


Thank you Fermilab test beam facility!

π+ agreement ~ 5%
π– a bit better
p a bit worse (10%)

Resolution well modeled

shower energy uncertainty



Convolution of single particle uncertainties

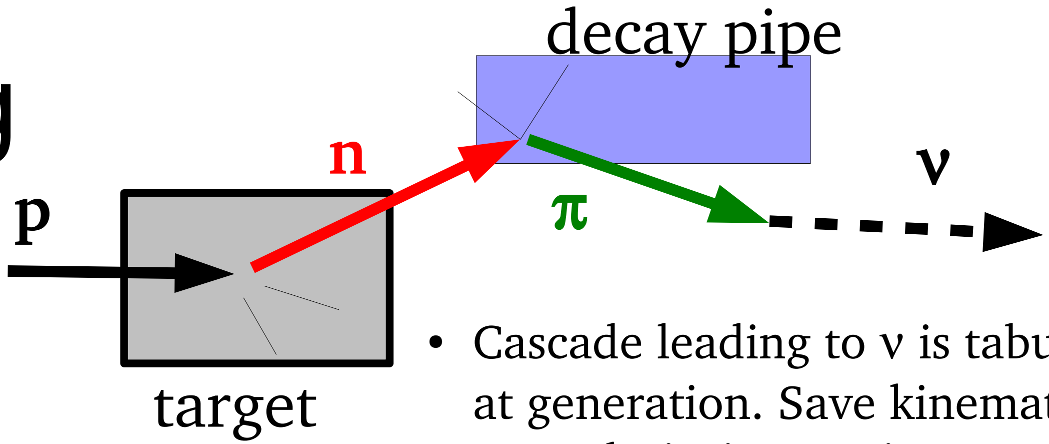
π,K = 5%

e,γ = 3%

p = 10%

n = 20%

Constraining the flux



- Cascade leading to ν is tabulated at generation. Save kinematics & material
- In analysis, interactions reweighted as σ(data)/σ(MC)
- Includes correction for beam attenuation in the target.

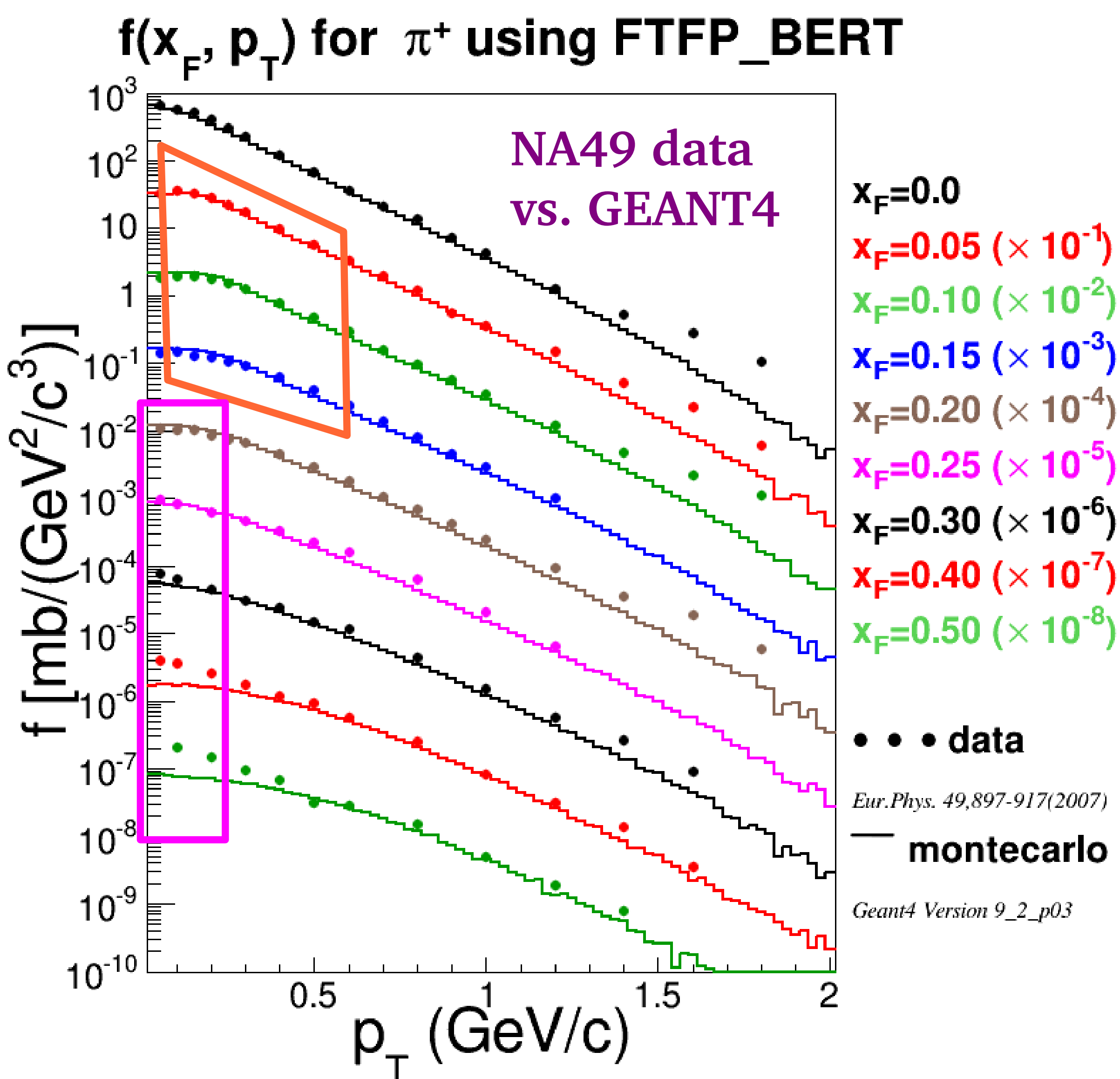
Datasets Used

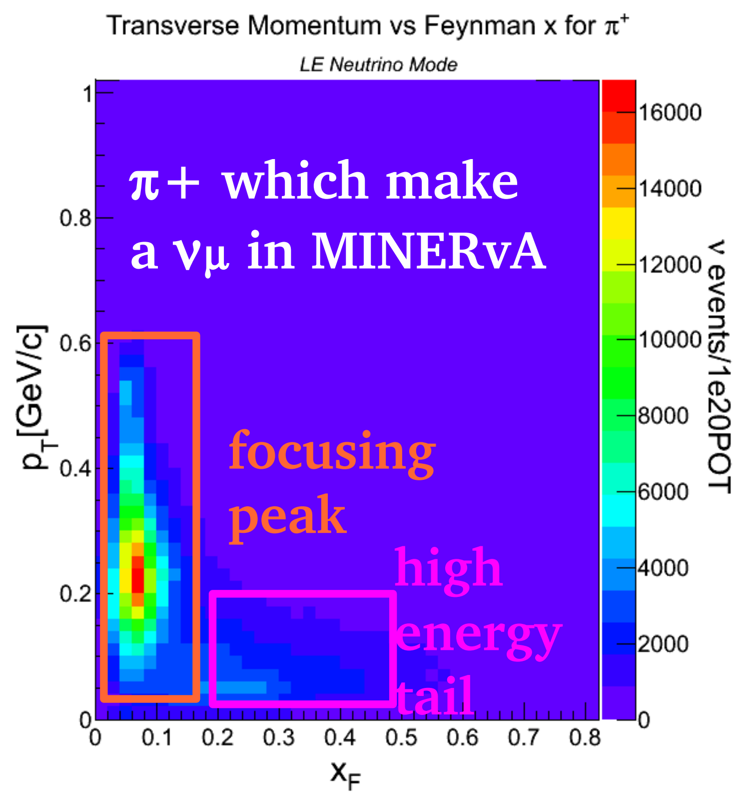
- NA49 pC @ 158 GeV
  - $\pi^{\pm}$ production for xF < 0.5 *[Eur.Phys.J. C49 (2007) 897]*
  - $K^{\pm}$ production for xF < 0.2 *[G. Tinti Ph.D. thesis]*
  - p production for xF<0.9 [*Eur.Phys.J. C73 (2013) 2364]*

  } some p_T dependence
- MIPP pC @120 GeV *[A. Lebedev Ph.D. thesis]*
  - K/π ratio + NA49 extends kaon coverage to xF<0.5
- Weights applied for 12 < $p_{incident}$ <120 GeV.
  - Data cross-section scaled using FLUKA *[www.fluka.org]*
  - Checked by comparing to NA61 pC → $\pi^{\pm}$ X at 31 GeV/c *[Phys.Rev. C84 (2011)034604]*
- Interactions on Al, Fe, He and Air treated as if on C

NA49: pC → π,K,p,n @ 158 GeV

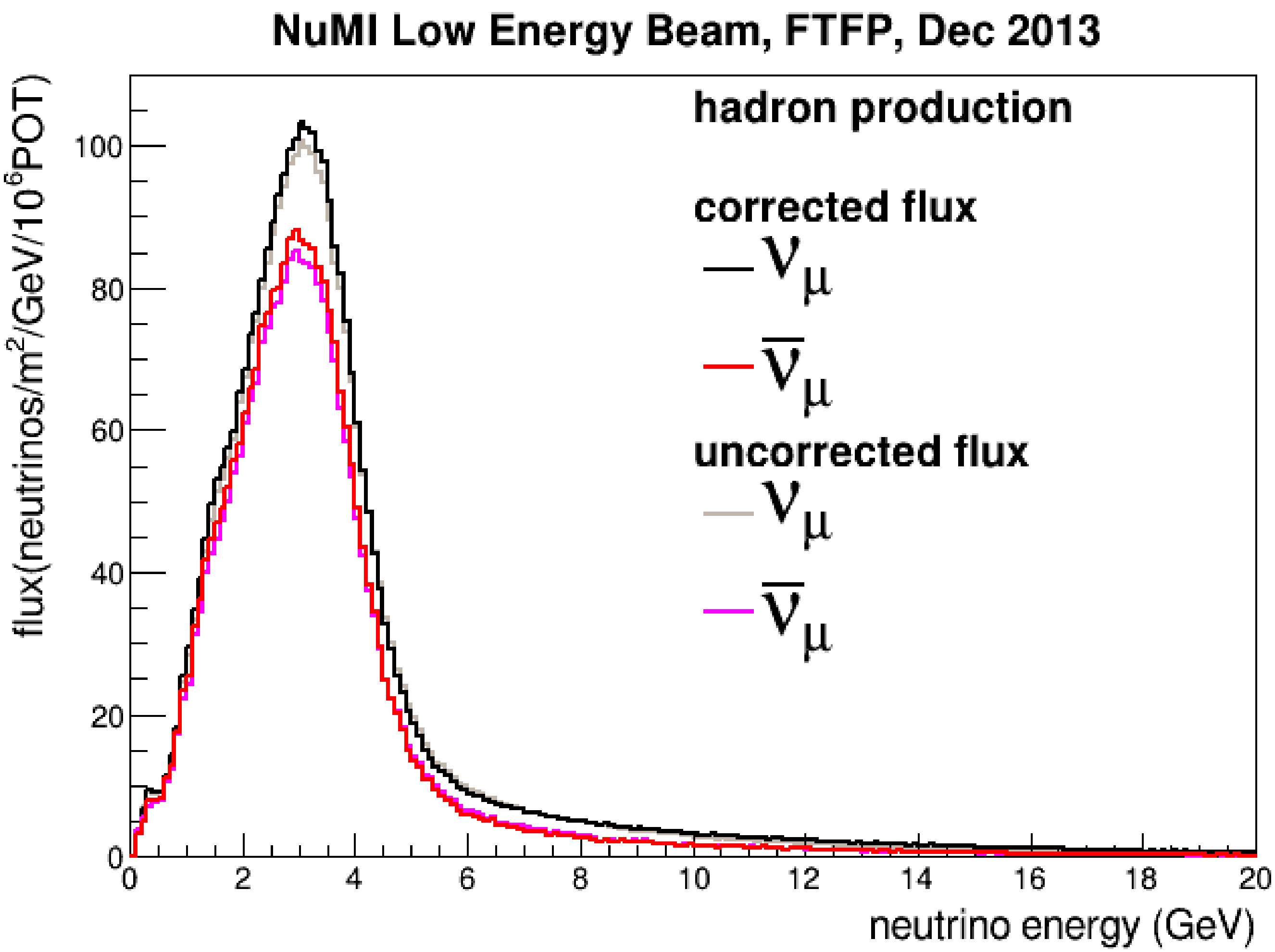
$f(x_F, p_T) = E\, d^3\sigma/dp^3$ = invariant production cross-section





Uncertainties
7.5% systematic
2-10% statistical

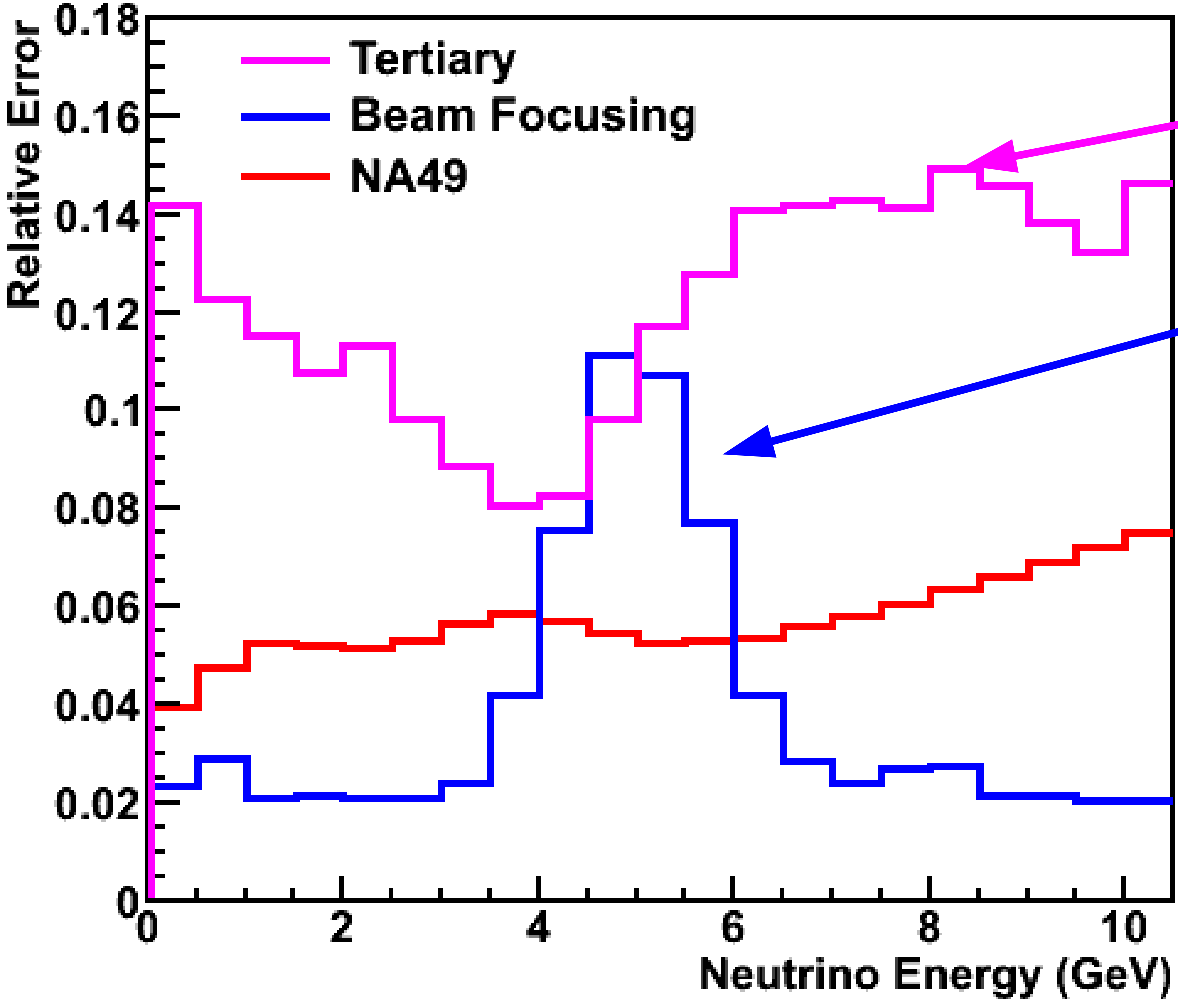
The Flux



GEANT4 based simulation of the NuMI beamline.

G4 9.4.p02
FTFP physics list

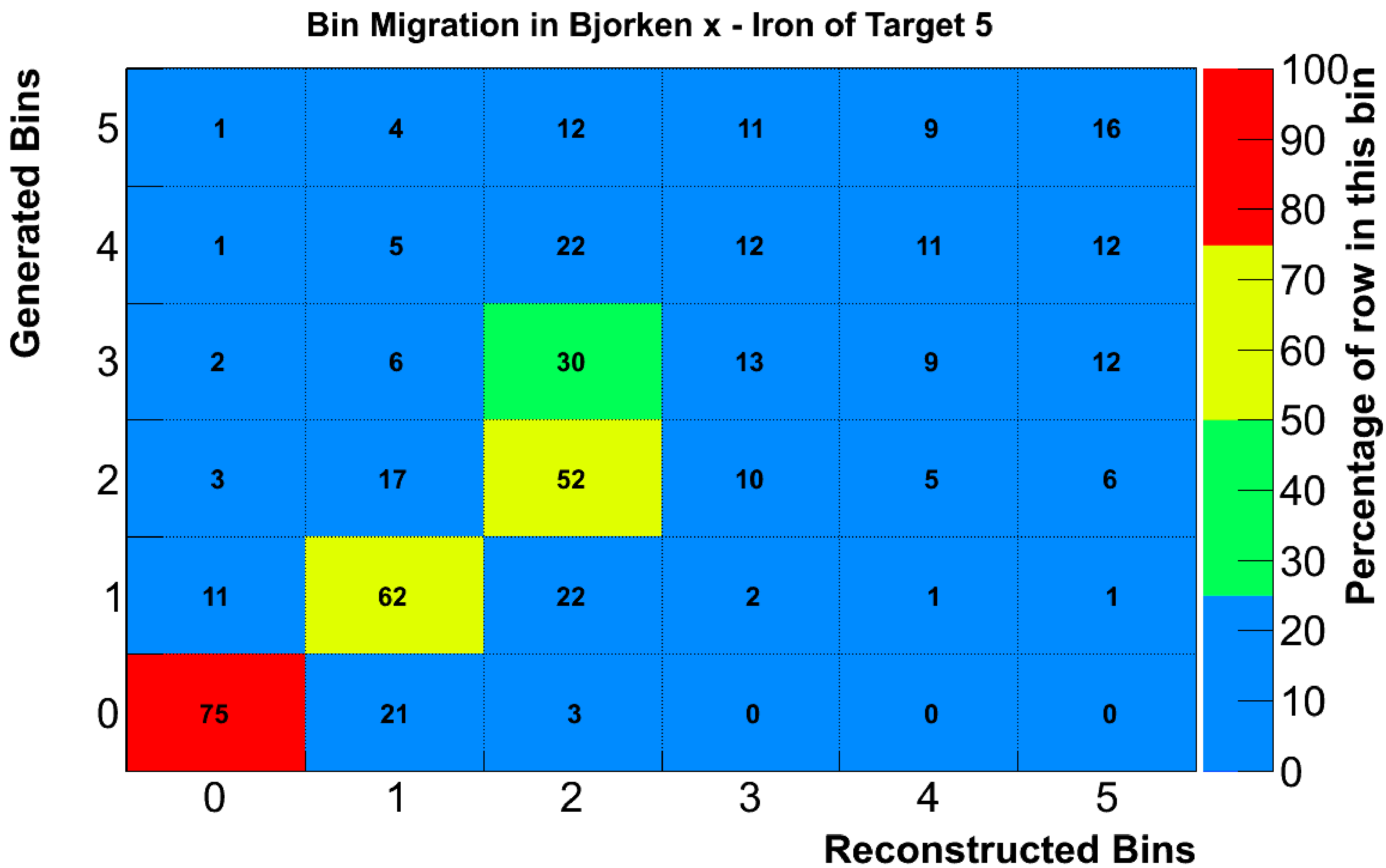
Flux Uncertainties



"Tertiary" = non-NA49 model spread

Z. Pavlovic, PhD Thesis, Texas (2008)

X_{Bj} smearing



Cross Section Model Uncertainties

Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production)	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
Modfiy Pauli blocking (CCQE) at low Q^2 (change PB momentum threshold)	± 30%

Intranuclear Rescattering Uncertainties

Uncertainty	1 σ
Pion mean free path	± 20%
Nucleon mean free path	± 20%
Pion fates – absorption	± 30%
Pion fates – charge exchange	± 50%
Pion fates – Elastic	± 10%
Pion fates – Inelastic	± 40%
Pion fates – pion production	± 20%
Nucleon fates – charge exchange	± 50%
Nucleon fates – Elastic	± 30%
Nucleon fates – Inelastic	± 40%
Nucleon fates – absorption	± 20%
Nucleon fates – pion production	± 20%
AGKY hadronization model – x_F distribution	± 20%
Delta decay angular distribution	On/off
Resonance decay branching ratio to photon	± 50%

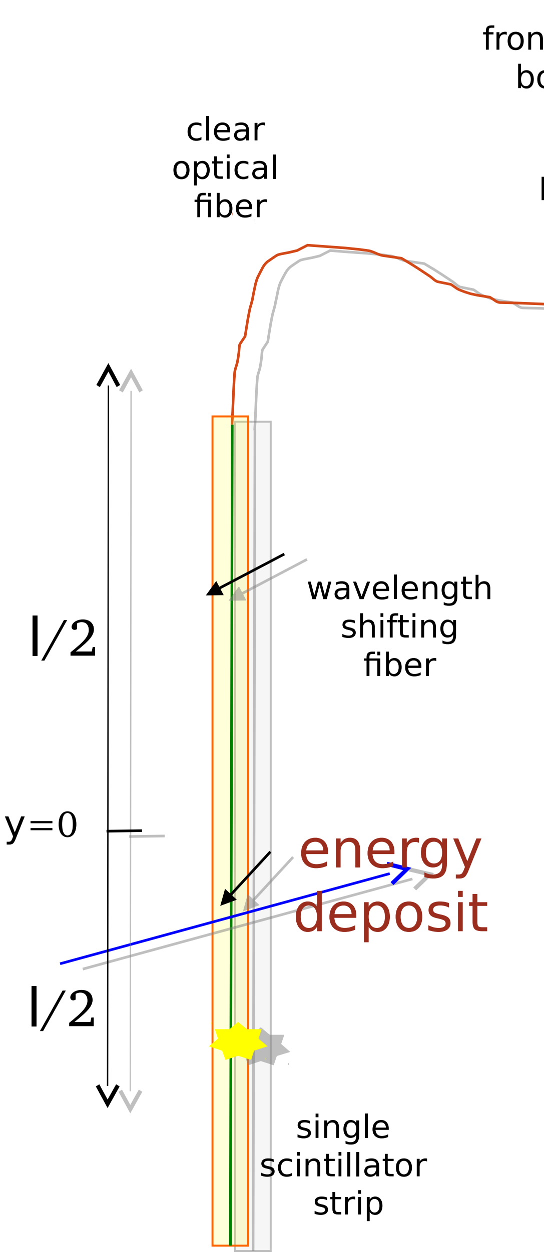
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

Nuclear Target Event Rates

Target	Fiducial Mass	ν_μ CC Events in 1.0e20 P.O.T.
Plastic	6.43 tons	340k
Helium	0.25 tons	14k
Carbon	0.17 tons	9.0k
Water	0.39 tons	20k
Iron	0.97 tons	54k
Lead	0.98 tons	57k

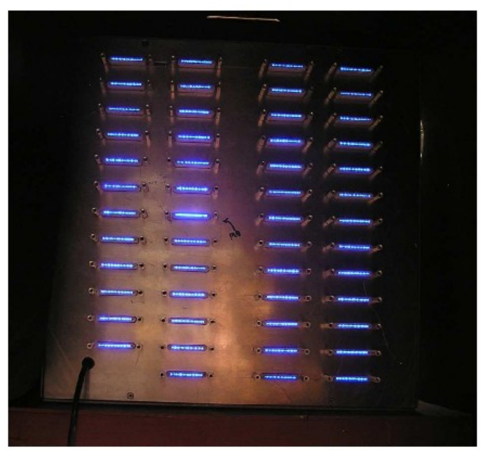
GENIE 2.6, FLUKA08, 90cm radius, 116 tracker modules

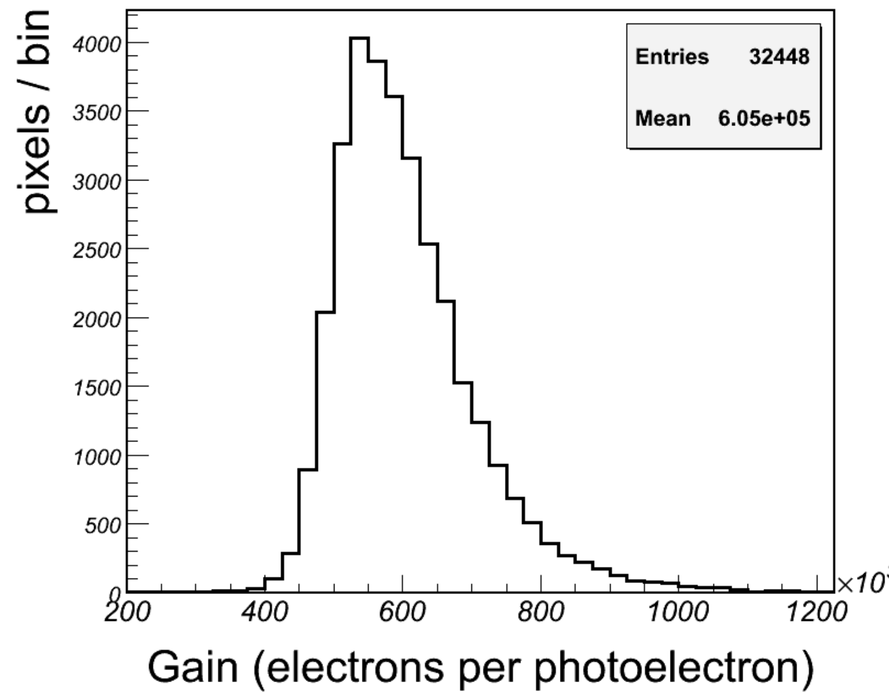
Detector Calibration



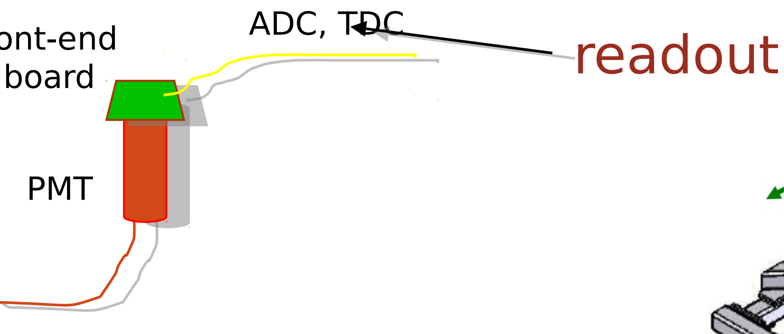
Charge to ADC conversion function measured on a test stand for every channel on every board before installation on the detector

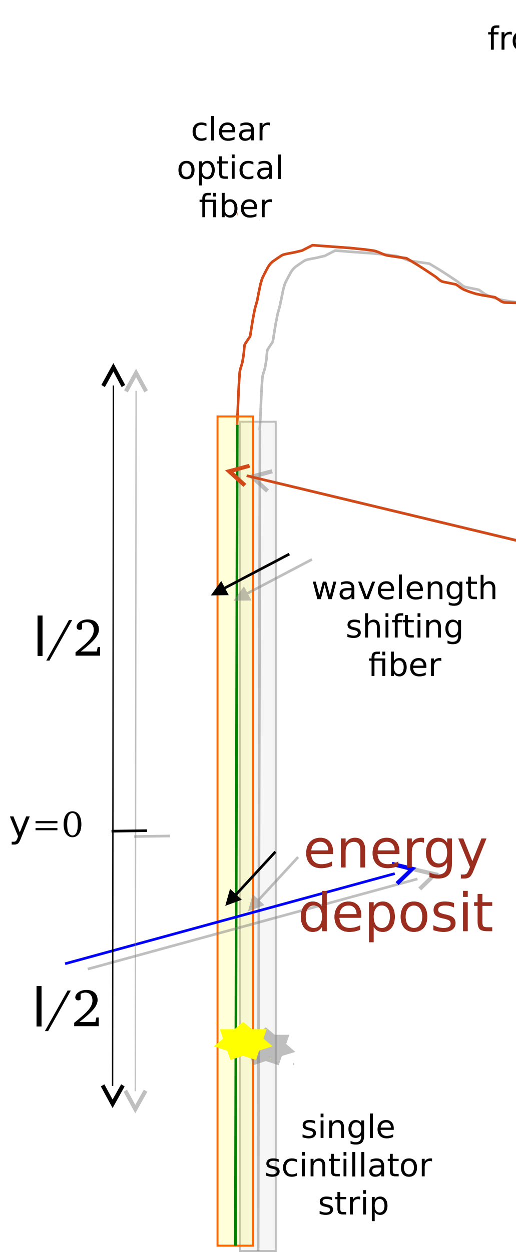
PMT gains measured continuously *in-situ* using Light Injection system

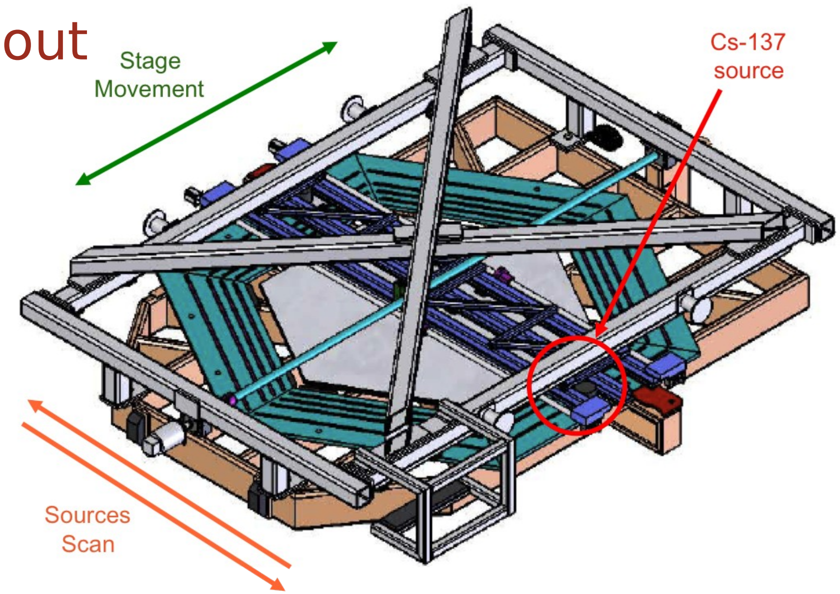




Detector Calibration



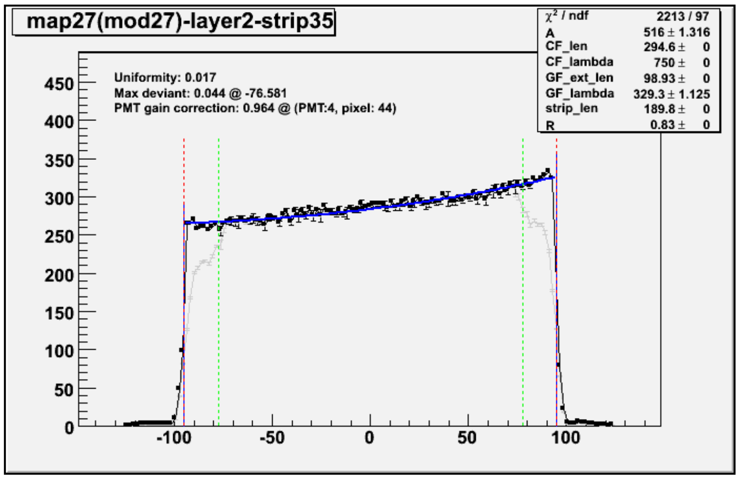


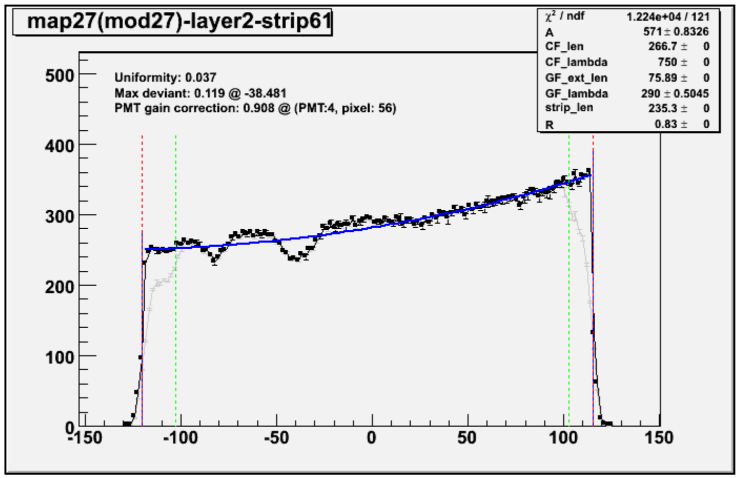


Attenuation along every strip in every plane measured using a source map before installation. We use the point-by-point map in reconstruction for every channel.

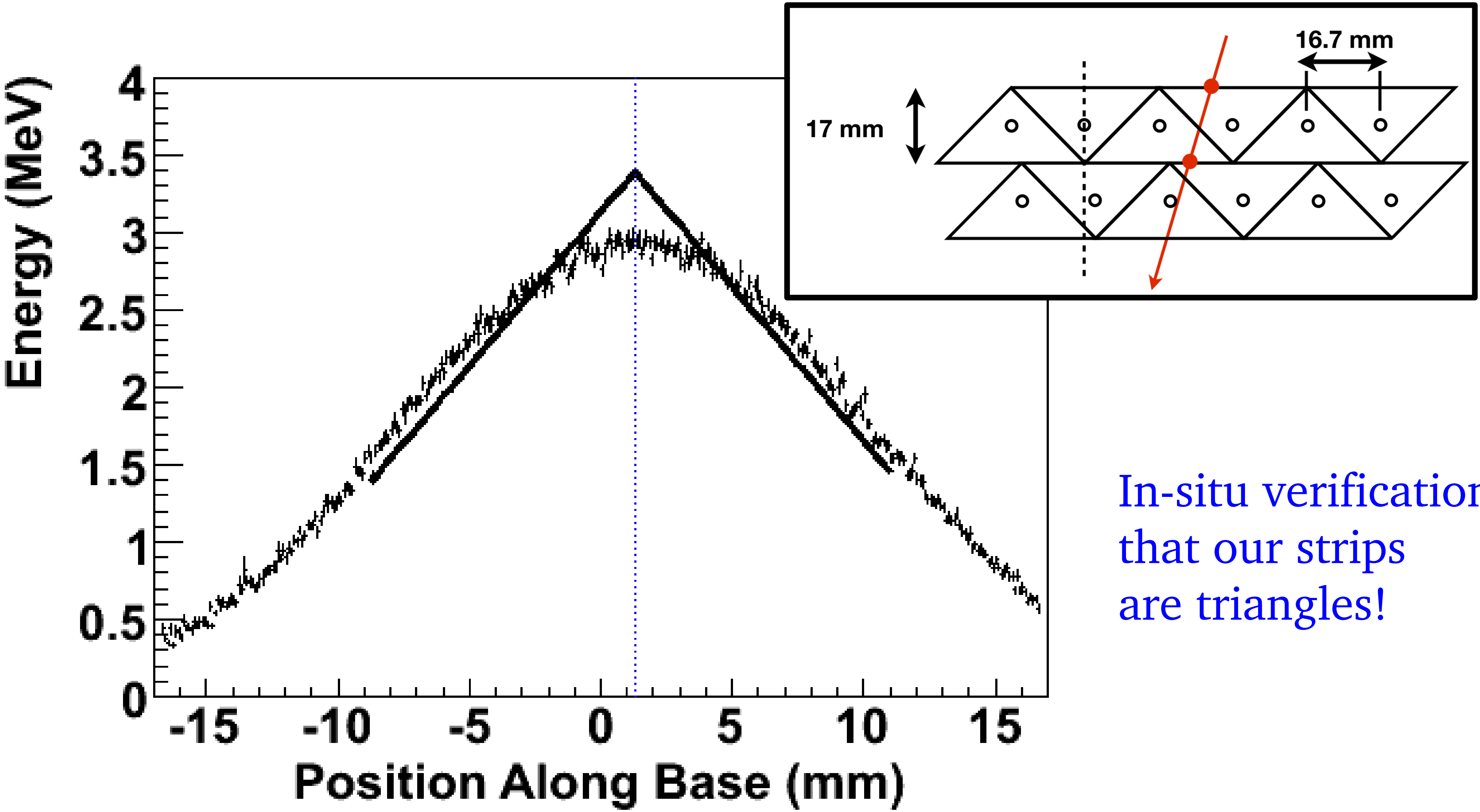
Typical attenuation length ~300 cm.

Map can find non-uniformities along the strip (e.g. air pockets in glue)





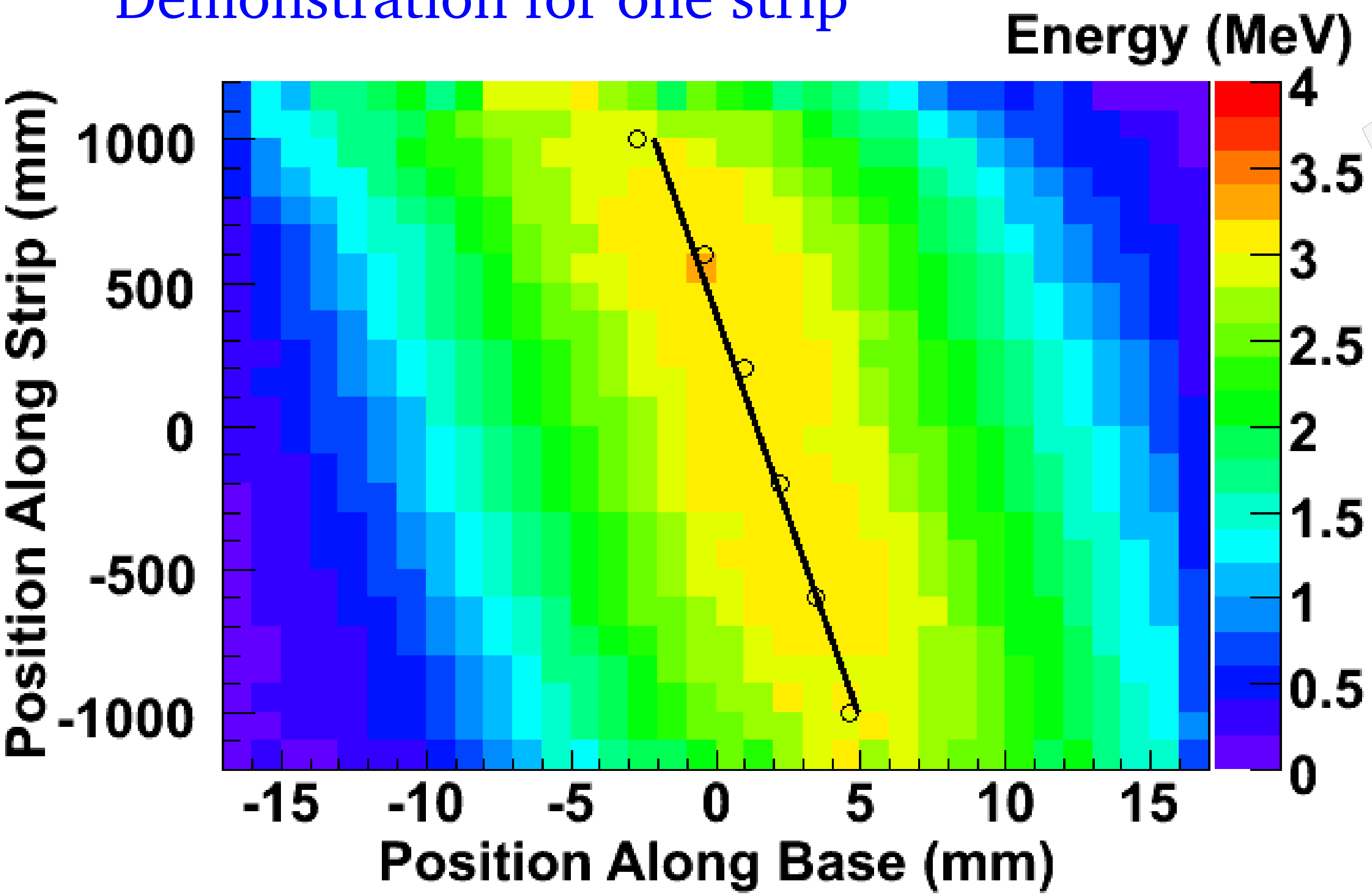
Alignment and strip response

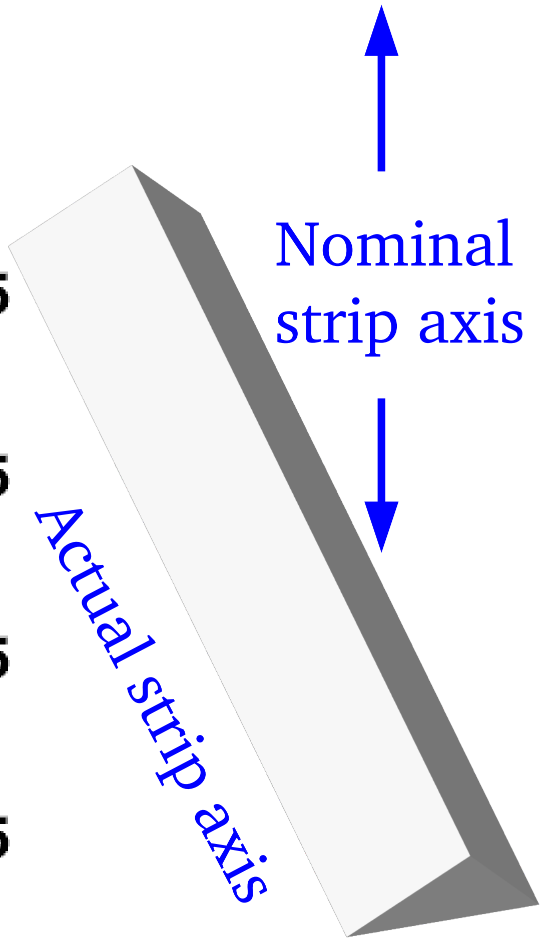


In-situ verification that our strips are triangles!

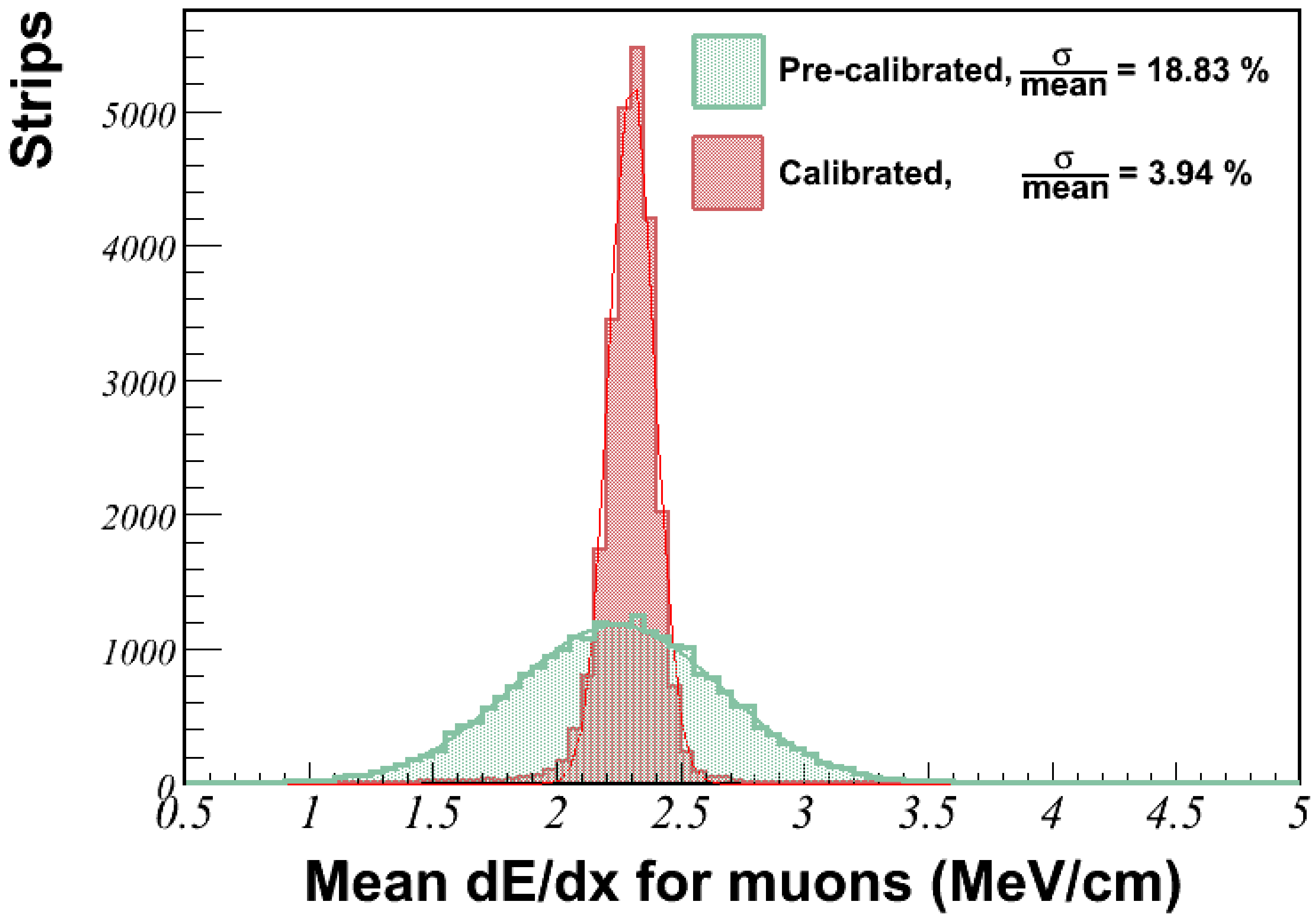
Alignment and strip response

Demonstration for one strip

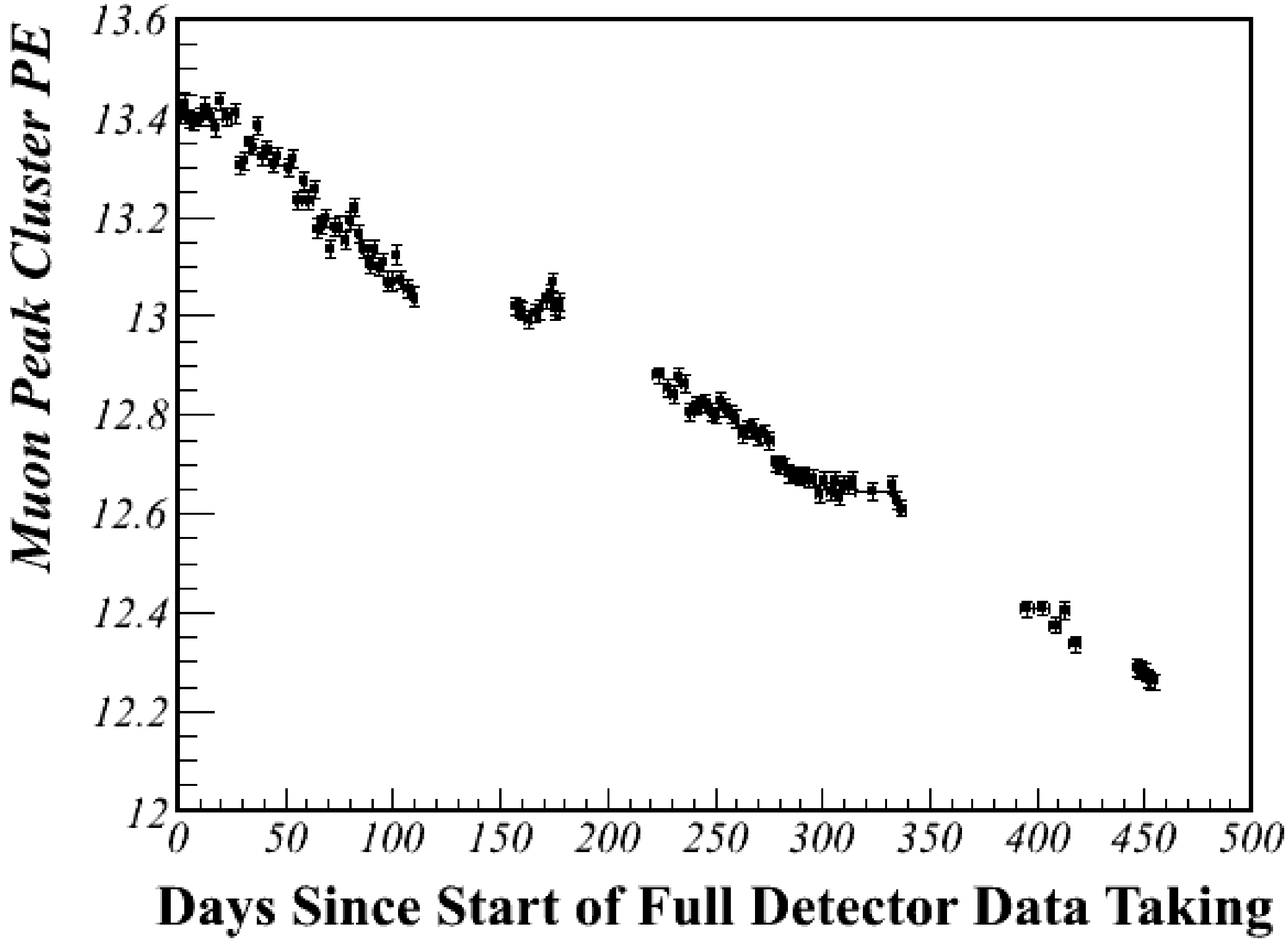




Alignment and strip response



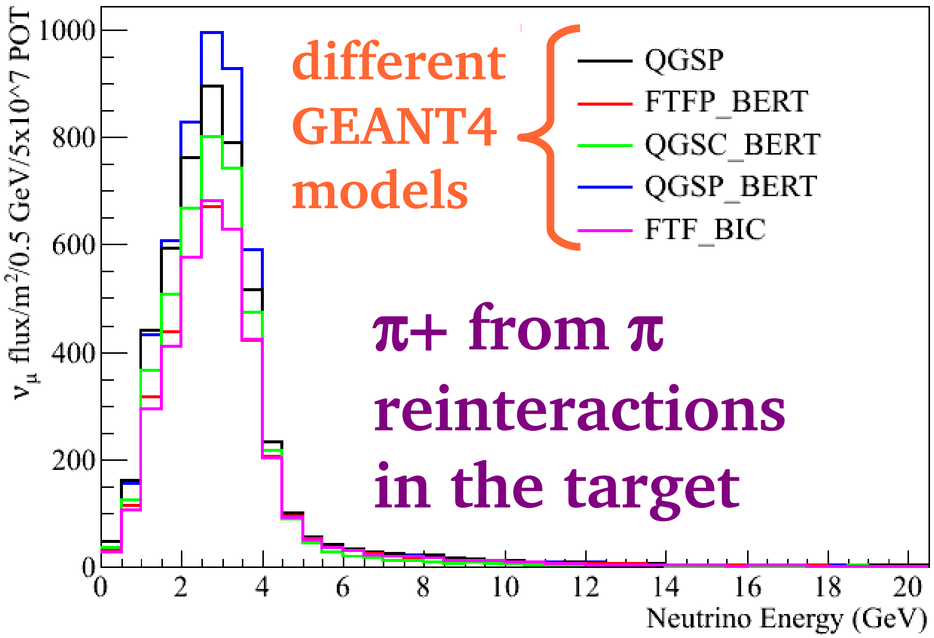
Response vs. Time

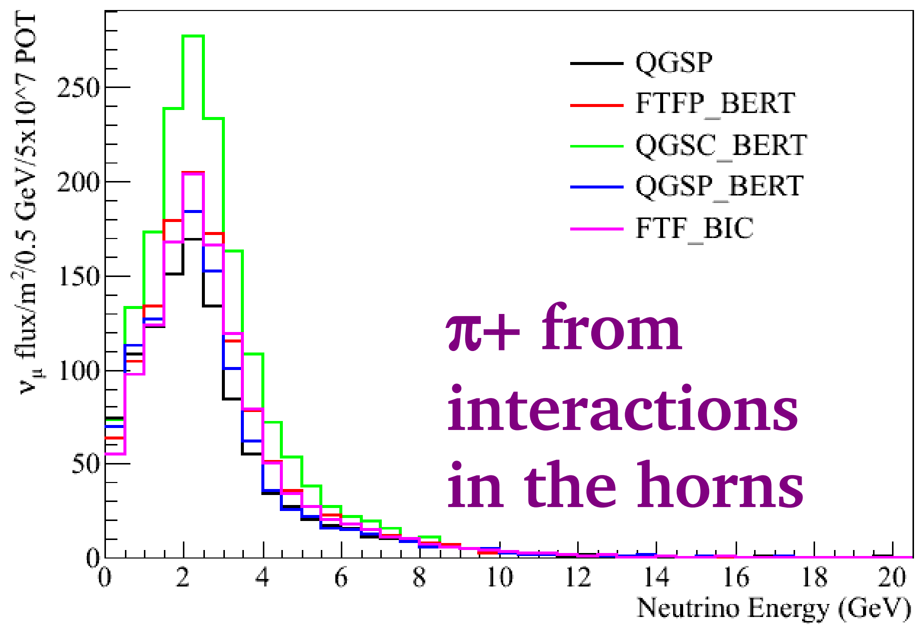


Minerva 1 (days 0-107): light loss = 10.1% per year
Minerva 5 (days 222-335): light loss = 7.1% per year

Model Spread Uncertainties

Non-NA49 uncertainties from maximum model spread





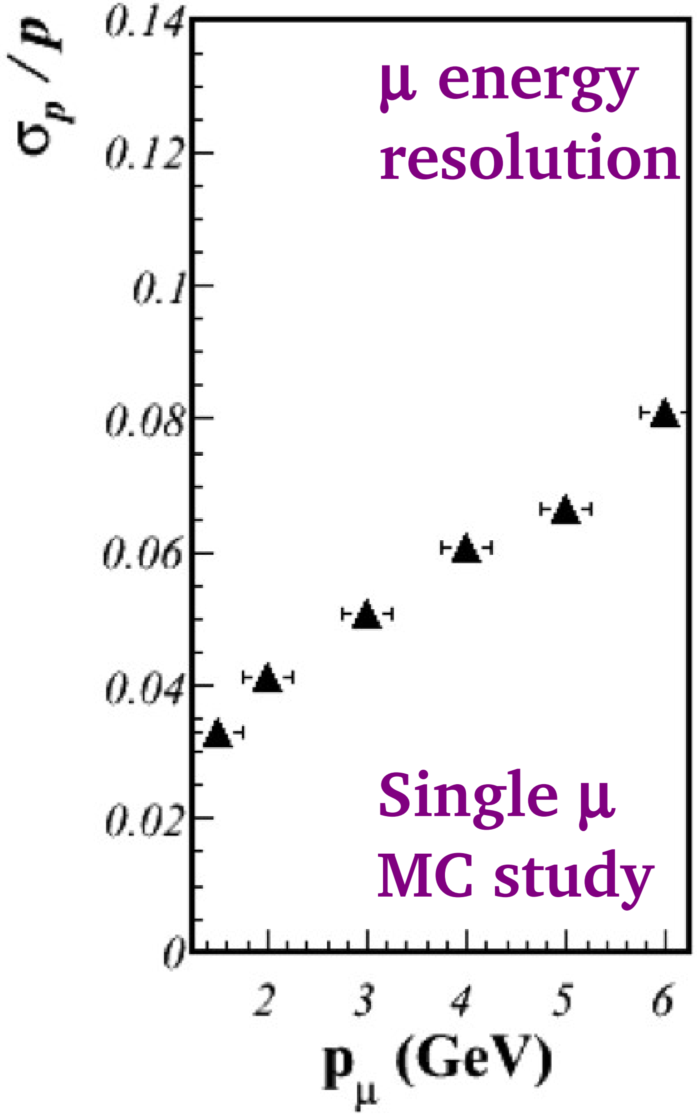
Categories

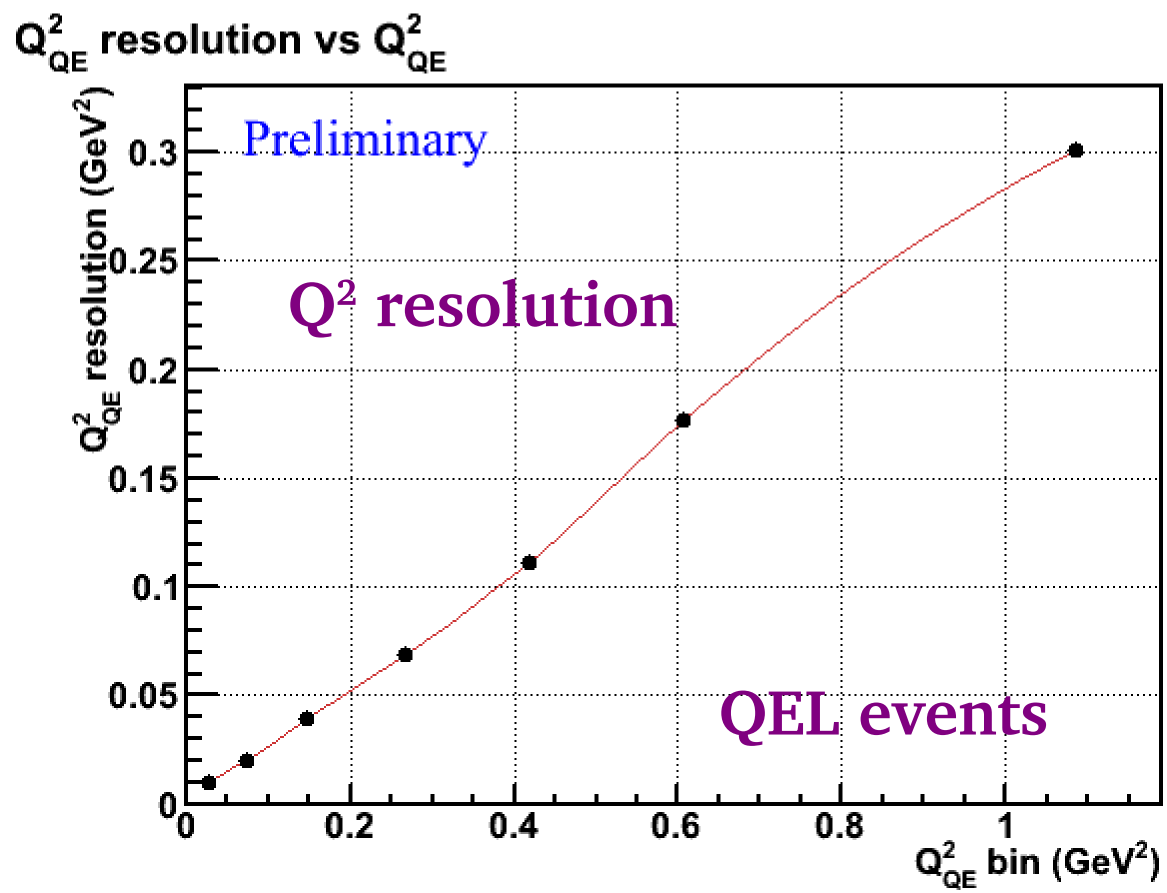
π,K,p,n,other secondary interactions in target

production in horns, decay pipe walls& He, target hall chase

Large project to
(a) add more models
(b) gradually replace model spread with existing and new data

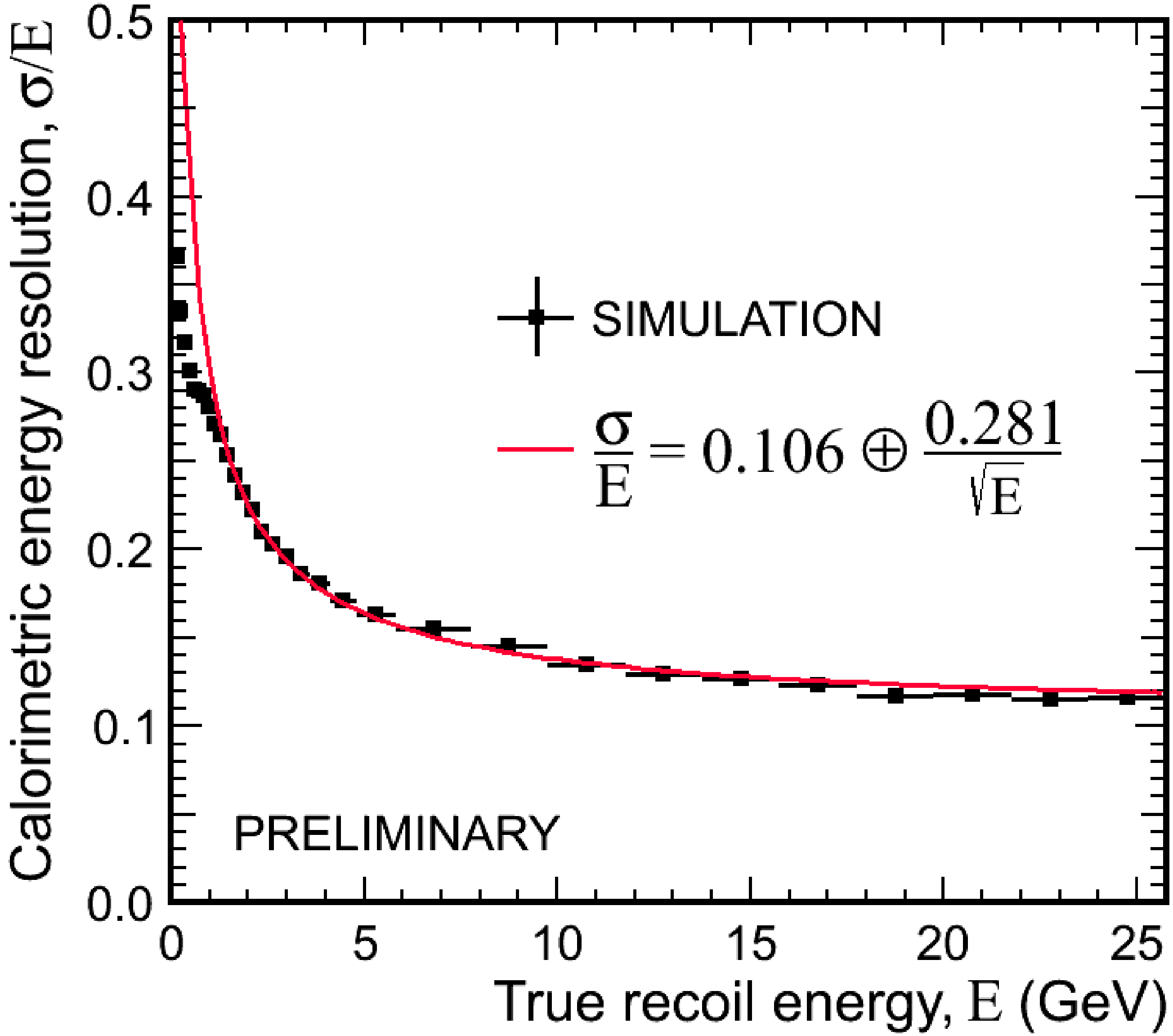
μ energy & Q^2 resolution





Q^2 = (4-momentum transfer)^2

shower energy resolution



GENIE

QEL: BBBA05 FF, M_A is 0.99 GeV/c^2

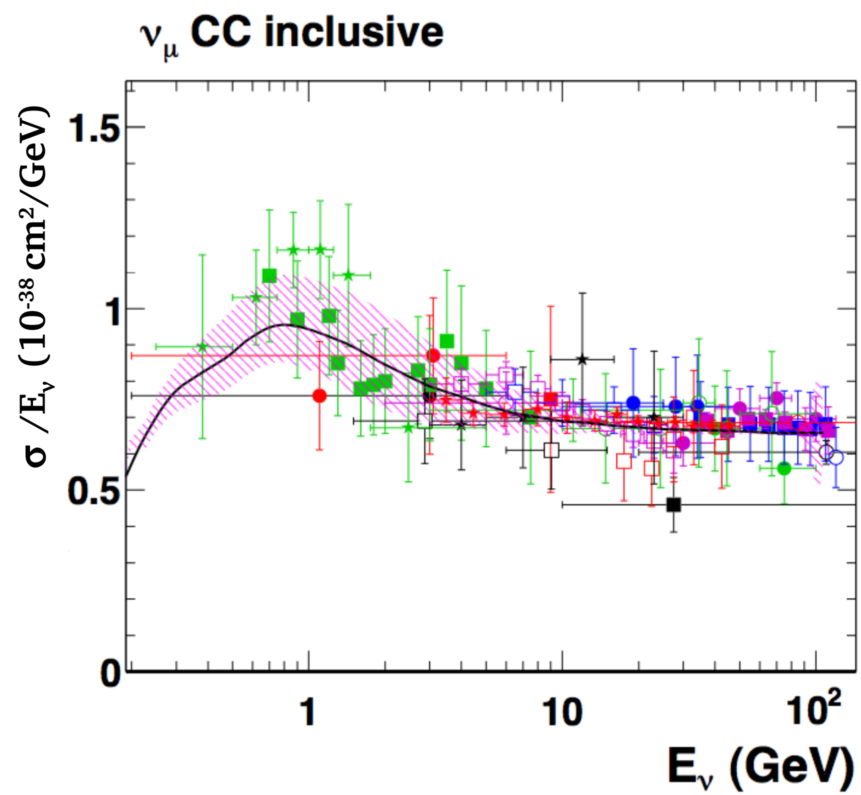
Resonance: Rein & Sehgal (K, ρ, η production, Δ-Nγ)

Coherent-π: Rein-Sehgal

DIS: GRV94/GRV98 with Bodek-Yang

DIS and QEL charm (S.G.Kovalenko, Sov.J.Nucl.Phys.52:934 (1990))

1π and 2π channels tuned in transition region to electron scattering and neutrino data.



Nuclear Model: RFGM with NN correlations

Hadronization Model: AGKY – transitions between KNO-based and JETSET

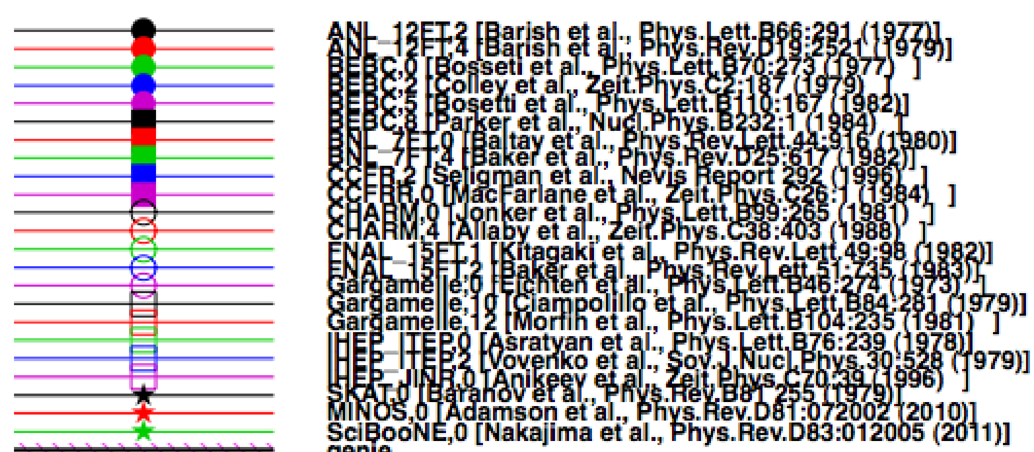
T. Yang, AIP Conf. Proc.967:269-275 (2007)

Formation zone: SKAT μ^2=0.08 GeV²

Intranuclear Rescattering: cascade model

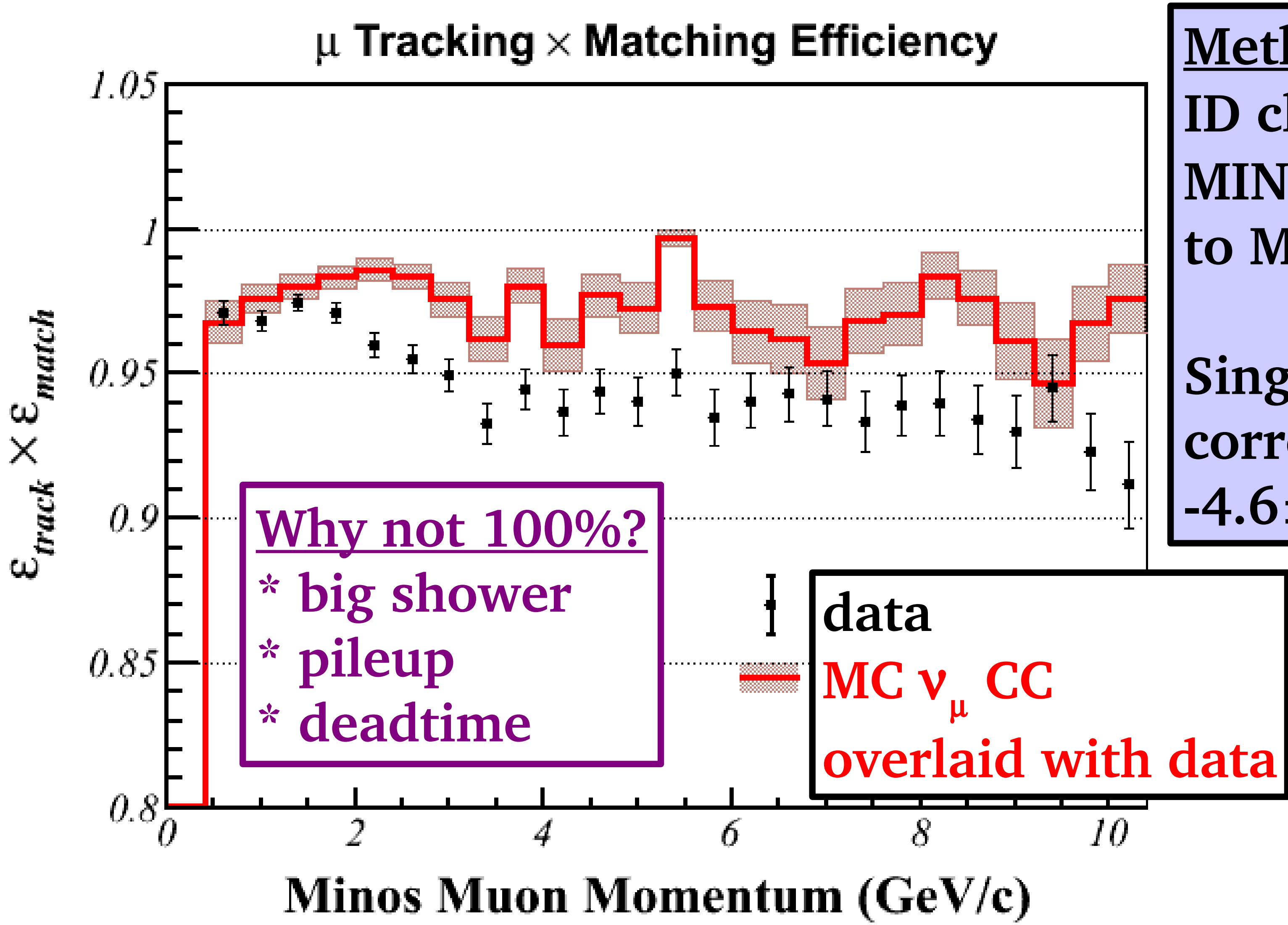
INTRANUKE-hA *(S. Dytman, AIP Conf Proc, 896, pp. 178-184 (200*

anchored to π,p/n-Fe data, scaled to all nucl



www.genie-mc.org; NIM A614 (2010) 87-104

Tracking x Matching Efficiency



Method

ID clean μ in MINOS, point back to MINERvA

Single event MC correction
-4.6±2.5%

Normalization corrections

ν_μ beam

Source	**MC scale factor**	**uncertainty**
MINERvA tracking efficiency	0.956	2.5%
MINOS μ acceptance	0.975	2.5%
MINOS pileup	0.972	0.6%
Catastrophic dead time	0.983	1.0%
Signal removed by deadtime cuts*	0.970	0.1%
Mass Model	1.000	1.4%
POT scale	1.000	2.0%
Total	f=0.865	4.0%

reco. effects on single event MC (MINERvA tracking efficiency through Signal removed by deadtime cuts)

***QEL analyses only**

other (Mass Model, POT scale)