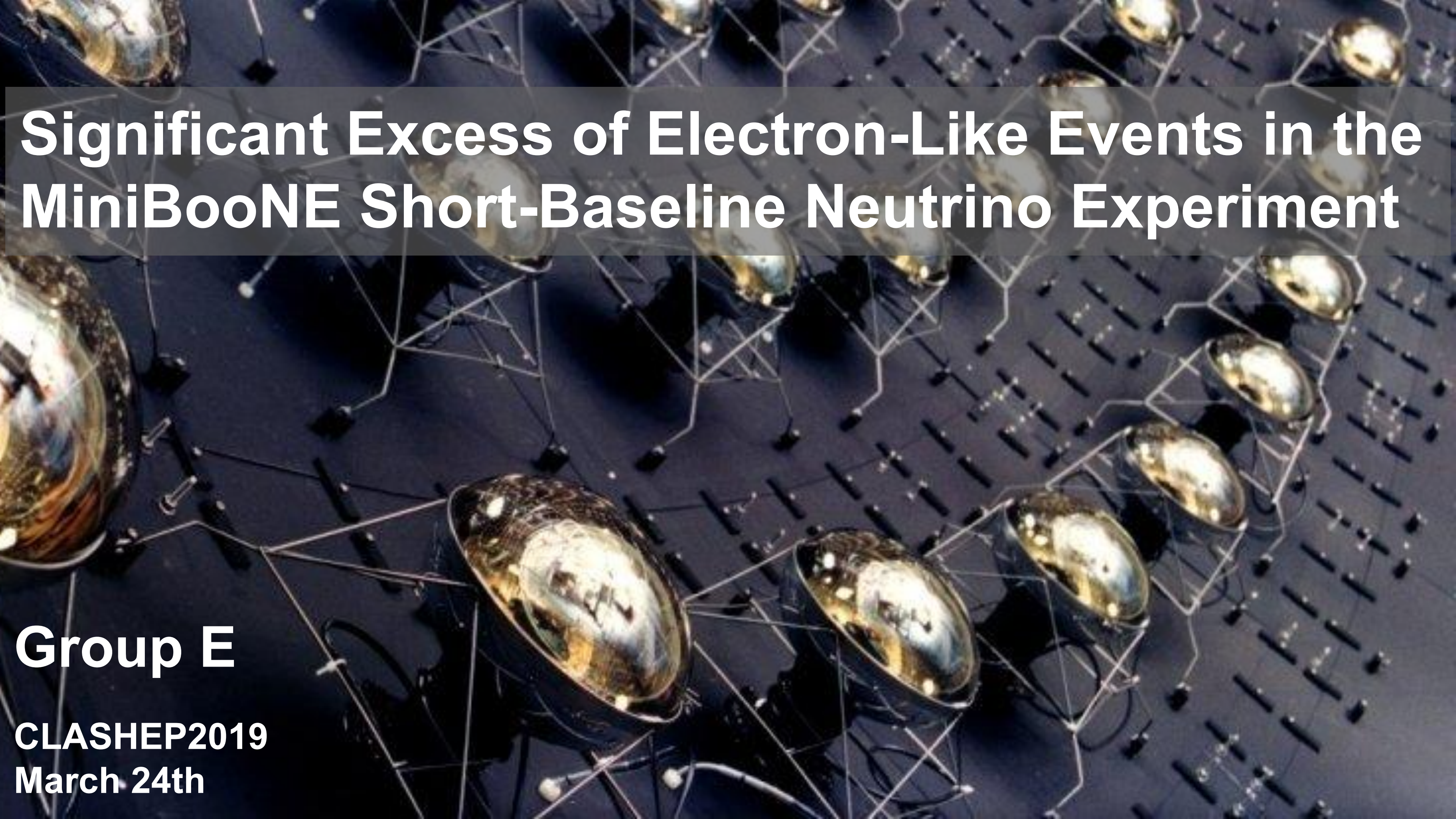
Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

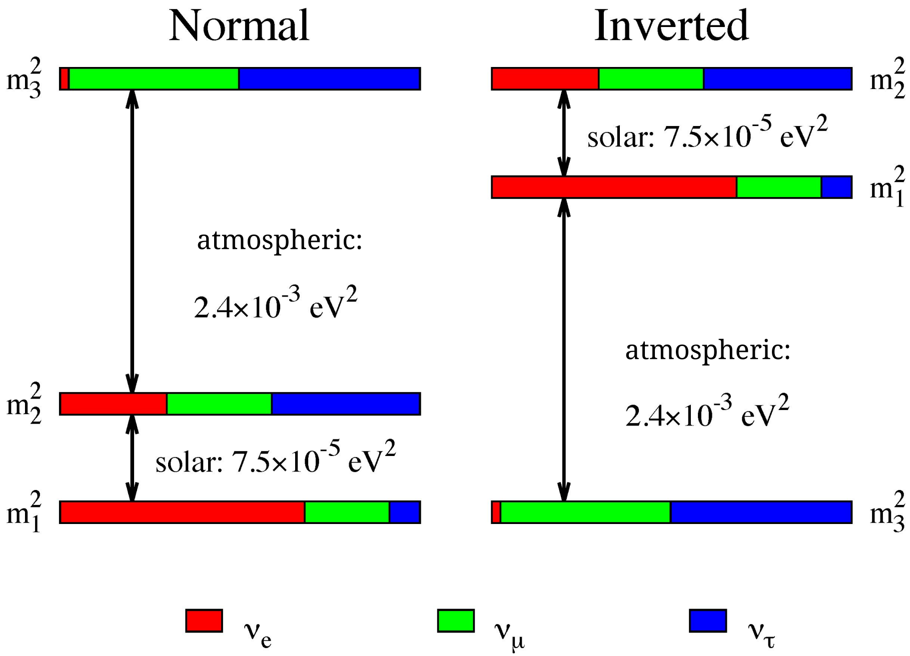


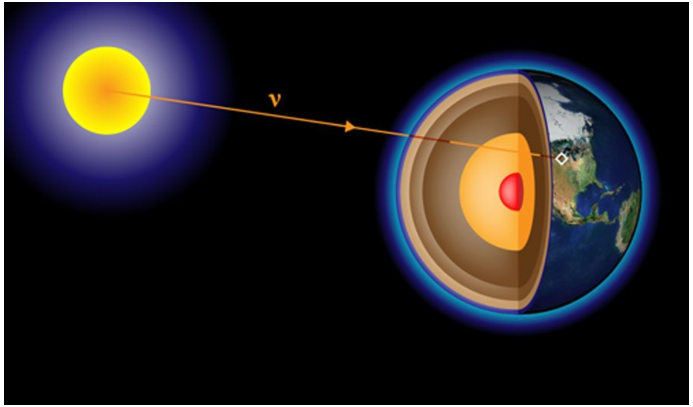
Group E

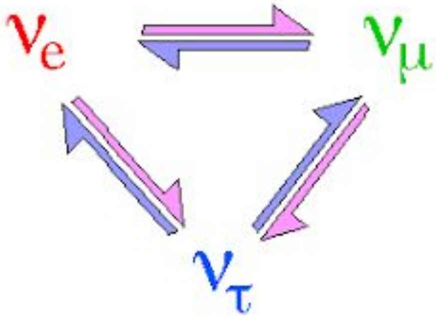
CLASHEP2019
March 24th

Current status - 3 neutrino generations

2 mass differences + 3 mixing angles

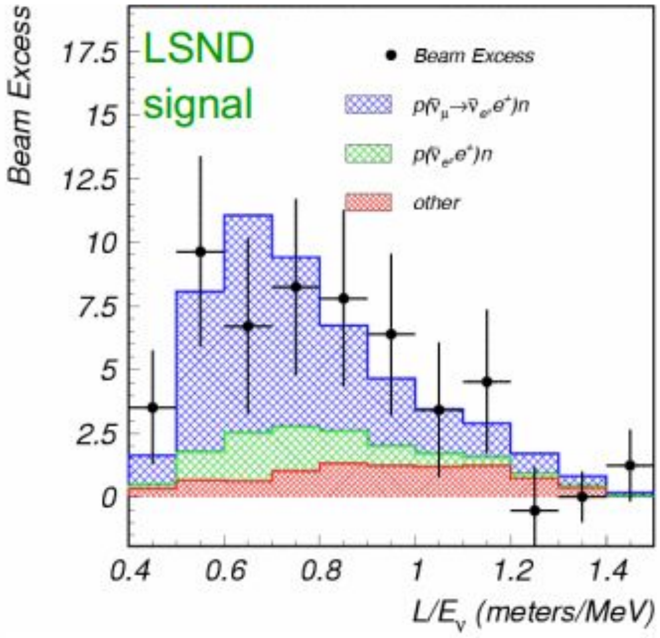






An elephant in the room

$$\overline{\nu}_\mu \xrightarrow{oscillation} \overline{\nu}_e$$



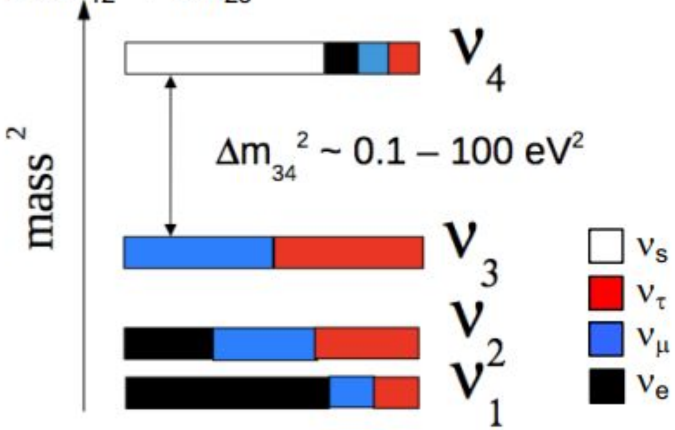
Excess of ν_e: 87.9 ± 22.4 ± 6.0 (3.8σ)

3 types of neutrino oscillations are found:

LSND neutrino oscillation: $\Delta m^2 \sim 1 eV^2$
Atmospheric neutrino oscillation: $\Delta m^2 \sim$10-3eV^2
Solar neutrino oscillation : $\Delta m^2 \sim$10-5eV^2

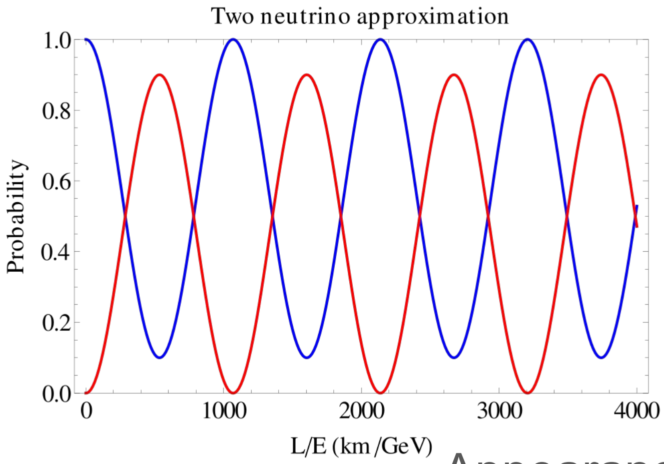
But we cannot have so many Δm^2!

$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$



Theoretical model: Neutrino Oscillations

Weak eigenstates of neutrinos are a combination of mass eigenstates



Two neutrino vacuum approximation:

$$\begin{vmatrix} \nu_e \\ \nu_\mu \end{vmatrix} = \begin{vmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{vmatrix} \cdot \begin{vmatrix} \nu_1 \\ \nu_2 \end{vmatrix}$$

$$|\,\nu_\mu(0) >= -sin\theta\,|\,\nu_1 > \; + \, cos\theta\,|\,\nu_2 >$$

$$|\,\nu_\mu(t) >= -sin\theta\; e^{-iE_1 t}\;|\,\nu_1 > \; + \, cos\theta\; e^{-iE_2 t}\;|\,\nu_2 >$$

Appearance probability

E and L fixed experimentally

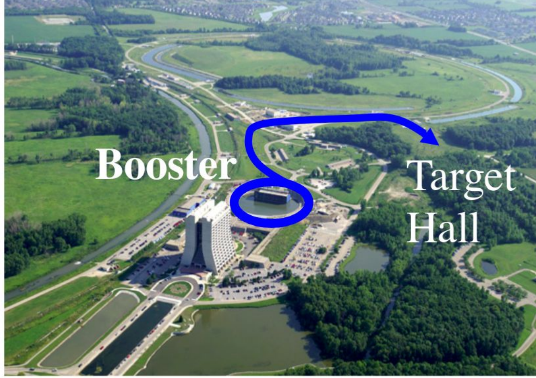
2 parameters: mass difference

Δm^2, mixing angle θ

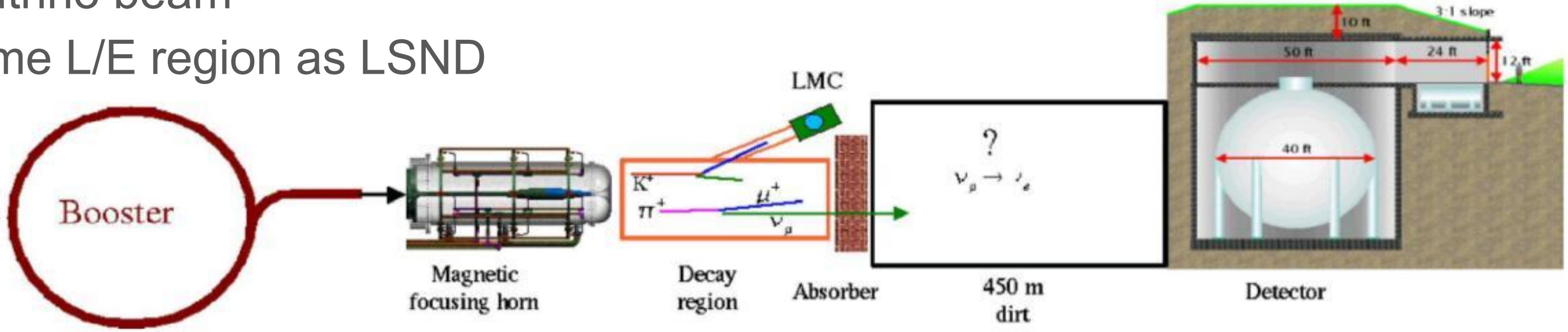
$$P_{osc} = |< \nu_e \,|\, \nu_\mu(t) >|^2$$

$$P_{osc} = sin^2(2\theta) \cdot \sin^2(\frac{1.27 \cdot \Delta m^2 \cdot L}{E})$$

The experiment: MiniBooNE



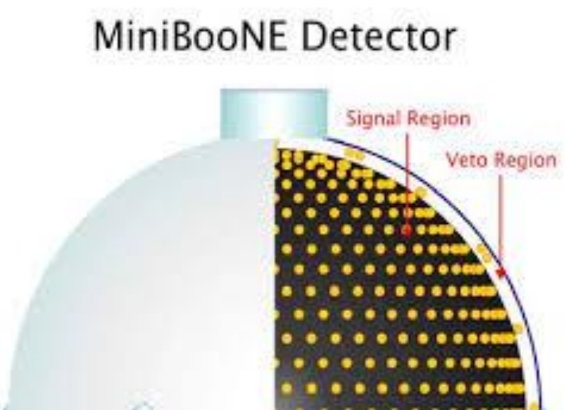
- 8 GeV proton beam from Booster strikes a beryllium target inside a magnetic focusing horn
- Beam of charged mesons generated, decay into neutrino beam
- Same L/E region as LSND



- Changes in the polarity of the horn to select neutrino or anti-neutrino beam

MiniBooNE Detector

- 541m downstream of target
- 12m diameter sphere (fiducial volume 10m)
- Filled with 800t of pure mineral oil (CH_2)
  (Fiducial volume: 450t)
- 1280 inner photo-multiplier tubes
- 240 veto photo-multiplier tubes



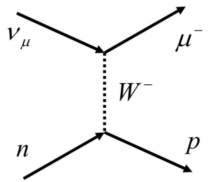
Neutrino interactions in the detector

- **Quasi-elastic CC**

$\nu_e + n \rightarrow p + e^-$

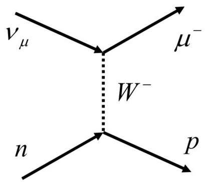
$\nu_\mu + n \rightarrow p + \mu^-$

$$\nu_\mu + n \rightarrow \mu^- + p$$



Neutrino interactions in the detector

$\nu_\mu + n \to \mu^- + p$



- **Quasi-elastic CC**

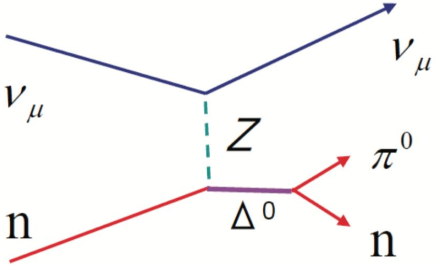
ν_e + n → p+ e$^-$

ν_μ + n → p + μ$^-$

Pion production
(Neutral current)

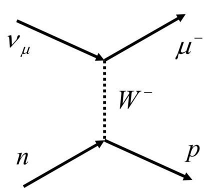
- **Resonant**

ν_μ + p → Δ$^+$ + ν_μ → p + ν_μ+ π^0
n Δ^0 n



Neutrino interactions in the detector

$$\nu_\mu + n \rightarrow \mu^- + p$$



- **Quasi-elastic CC**

  ν_e + n → p+ e^-

  ν_μ + n → p + μ^-

Pion production (Neutral current)

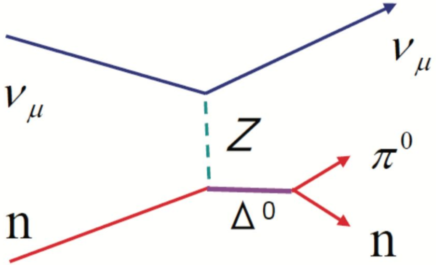
- **Resonant**

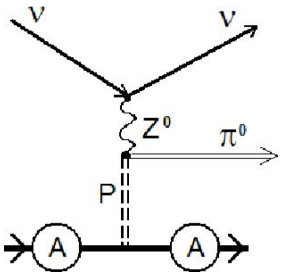
  ν_μ + p → Δ^+ + ν_μ → p + ν_μ + π^0

  n Δ^0 n

- **Coherent**

  ν_μ + A → A + ν_μ + π^0





Neutrino interactions in the detector

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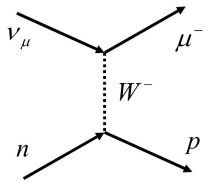
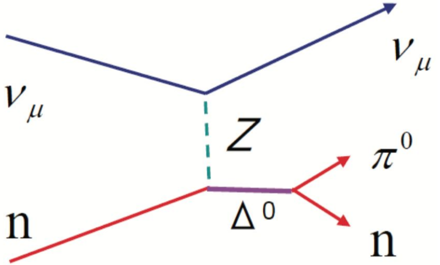
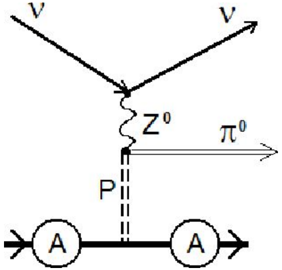


- **Quasi-elastic CC** $\nu_e + n \rightarrow p + e^-$
  $\nu_\mu + n \rightarrow p + \mu^-$

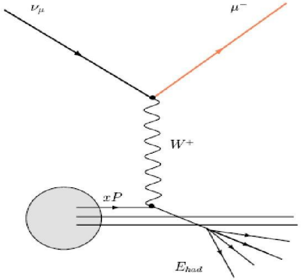
Pion production (Neutral current)

- **Resonant** $\nu_\mu + p \rightarrow \Delta^+ + \nu_\mu \rightarrow p + \nu_\mu + \pi^0$
  n Δ^0 n





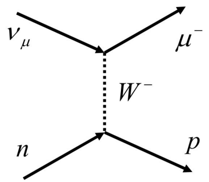
- **Coherent** $\nu_\mu + A \rightarrow A + \nu_\mu + \pi^0$



- **DIS (ν from kaons)** $\nu_e + n \rightarrow e^- + \text{hadrons}$
  $\nu_\mu + n \rightarrow \mu^- + \text{hadrons}$

Neutrino interactions in the detector

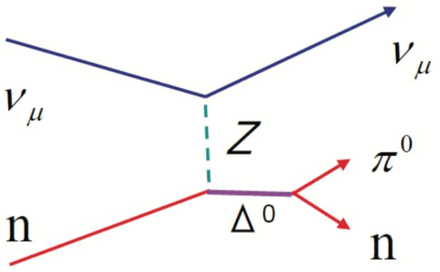
$$\nu_\mu + n \rightarrow \mu^- + p$$

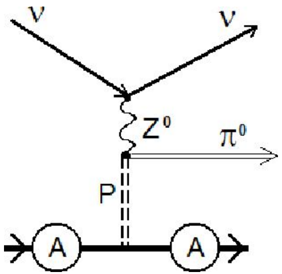


- **Quasi-elastic CC** ν_e + n → p+ e^-
  ν_μ + n → p + μ^-

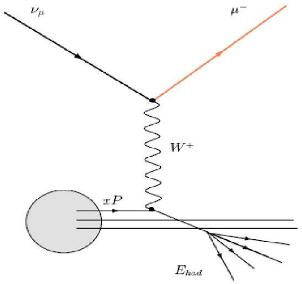
Pion production (Neutral current)

- **Resonant** ν_μ + p → Δ^+ + ν_μ → p + ν_μ+ π^0
  n Δ^0 n





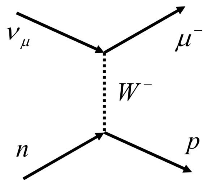
- **Coherent** ν_μ + A → A + ν_μ + π^0



- **DIS (ν from kaons)** ν_e + n → e^- + hadrons
  ν_μ + n → μ^- + hadrons

Neutrino interactions in the detector

$\nu_\mu + n \rightarrow \mu^- + p$

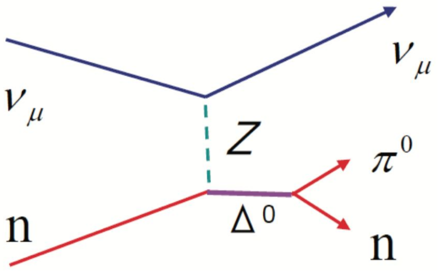


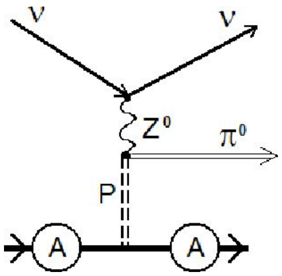
SIGNAL

- **Quasi-elastic CC** $\nu_e + n \rightarrow p + e^-$
  $\nu_\mu + n \rightarrow p + \mu^-$

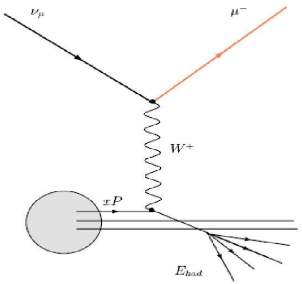
Pion production (Neutral current)

- **Resonant** $\nu_\mu + p \rightarrow \Delta^+ + \nu_\mu \rightarrow p + \nu_\mu + \pi^0$
  n Δ⁰ n





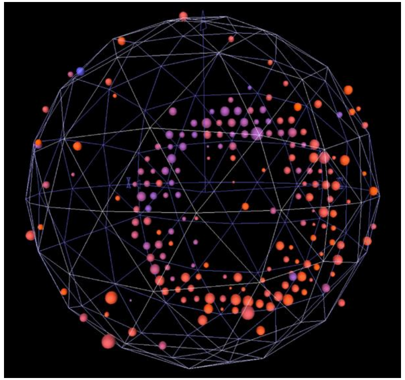
- **Coherent** $\nu_\mu + A \rightarrow A + \nu_\mu + \pi^0$



- **CC DIS (ν from kaons)** $\nu_e + n \rightarrow e^- +$ hadrons
  $\nu_\mu + n \rightarrow \mu^- +$ hadrons

Event Signatures: particle ID

- **Cherenkov light:**

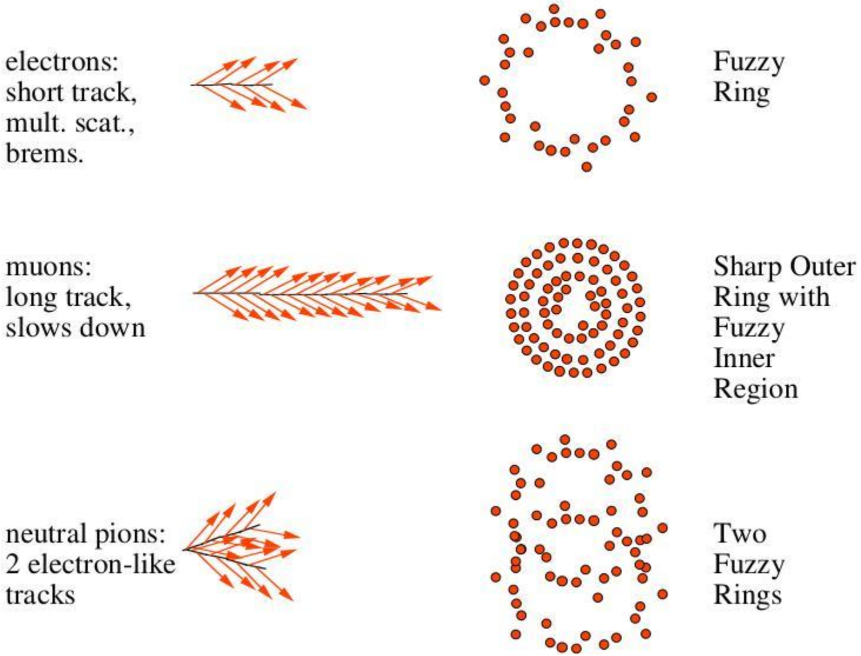


Event display of ν_e event

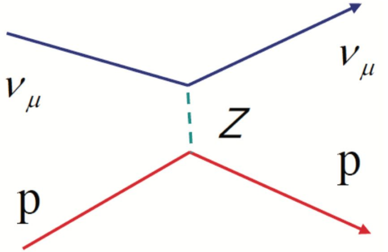
$\nu_e + n \rightarrow p + e^-$

$\nu_\mu + n \rightarrow p + \mu^-$

$\nu_\mu + p \rightarrow p + \nu_\mu + \pi^0$
$\quad\;\; n \qquad\;\; n$



- **(Isotropic) Scintillating light:** NC elastic scattering - no Черенков radiation

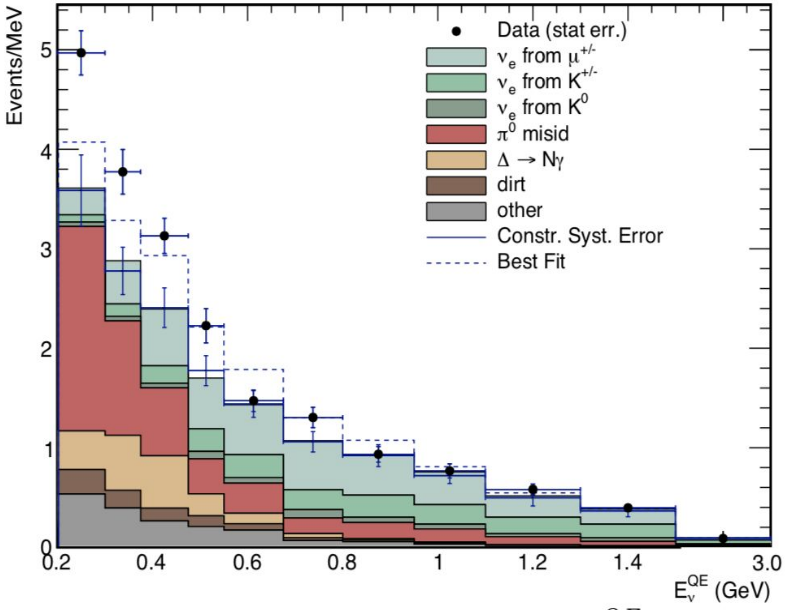


Results

misID: rows ν_μ & $\bar{\nu}_\mu$ CCQE through Other ν_μ & $\bar{\nu}_\mu$

intrinsic: rows ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay through Other ν_e & $\bar{\nu}_e$

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.6 ± 176.9	398.2 ± 49.7
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6
0.26% (LSND) $\nu_\mu \to \nu_e$	463.1	100.0



Excess of ν_e: (4.8σ)

Results

- ν_e excess wrt background (ν_e appearance) agrees with LSND
- Probability of background-only hypothesis: 0.21%
- Fit including two neutrino oscillation model has a probability of 21.1%
  - *Best fit parameter values*
    $\Delta m^2 = 0.041$ ev^2
    $\sin^2 2\theta = 0.92$

- (significance from LSND)^2 + (significance from MiniBooNE)^2 = (given result)^2

$$(3.8)^2 + (4.8)^2 = (6.1)^2$$


Thanks for Watching

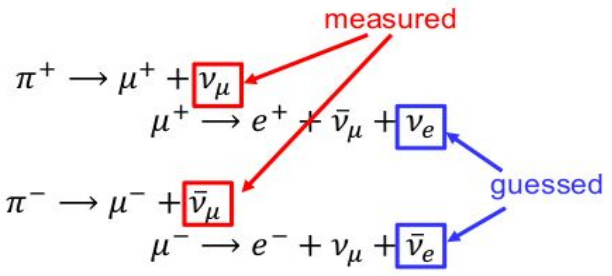

YOUR CONFERENCE PRESENTATION
HOW YOU PLANNED IT:
INTRODUCE YOURSELF
DESCRIBE OUTLINE OF TALK
MOTIVATION
METHODOLOGY AND EXPERIMENT DESIGN
RESULTS
CONCLUSIONS
APPLAUSE
ENGAGING Q&A
START
15 MINUTES
HOW IT GOES:
PREVIOUS SPEAKER RUNS LATE AND EATS INTO YOUR TIME.
TECHNICAL DIFFICULTIES CONNECTING YOUR LAPTOP.
FORGET INTRODUCING YOURSELF.
SPEND WAAAY TOO MUCH TIME DESCRIBING YOUR OUTLINE.
MOTIVA-
-TION
ANNOYING AUDIENCE MEMBER INTERRUPTS WITH SELF-AGGRANDIZING QUESTION.
REALIZE YOU ONLY HAVE 3 MINUTES LEFT.
POWER THROUGH THE REST OF YOUR 30 SLIDES.
AWKWARD SILENCE Q&A.
START
15 MINUTES

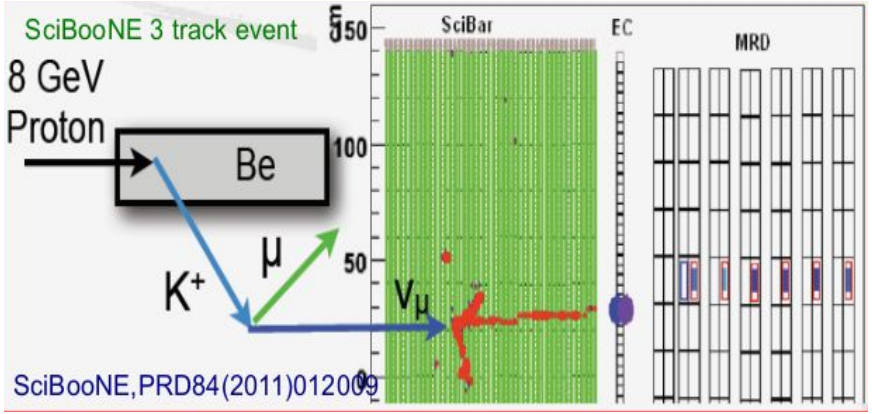
Thanks!

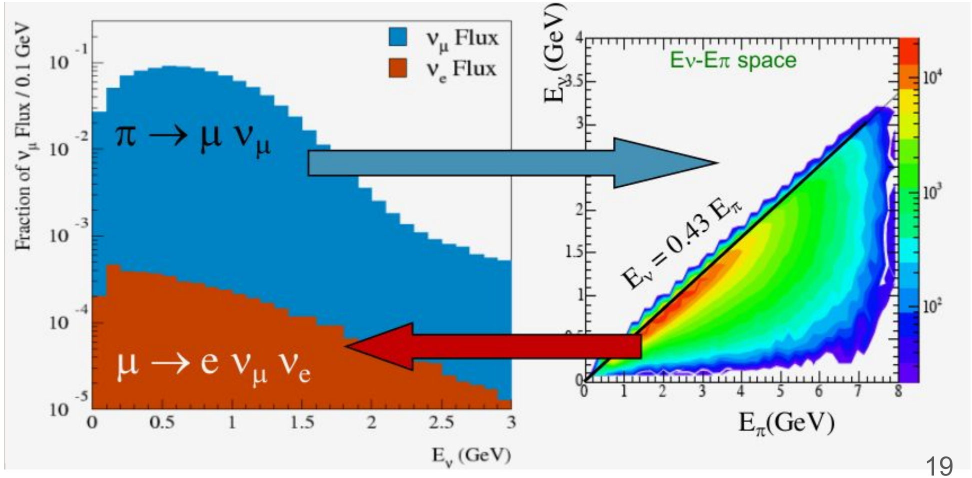
Background

All backgrounds are internally constrained:

intrinsic (beam ve) = flat







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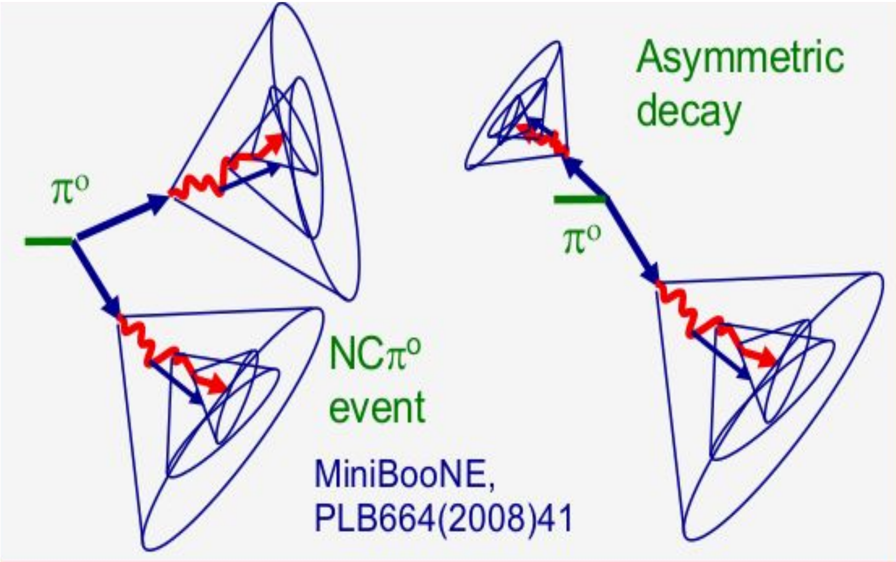
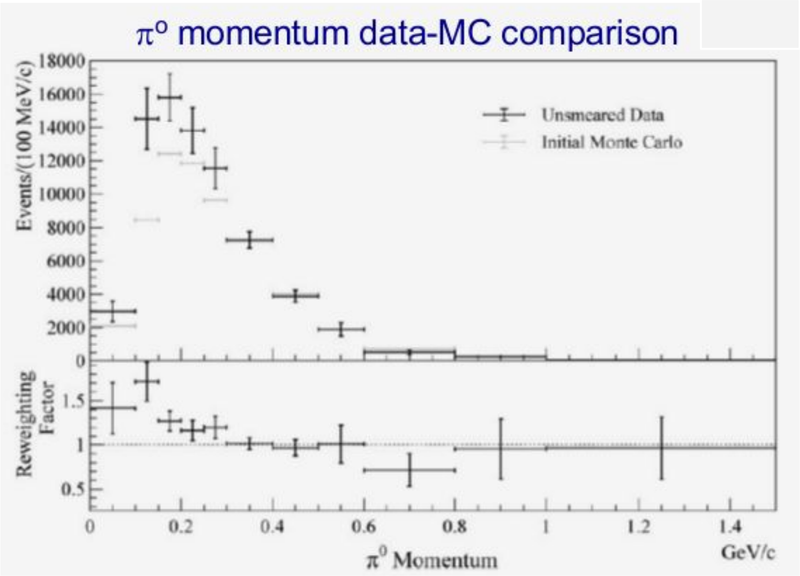




background-only

The controversy

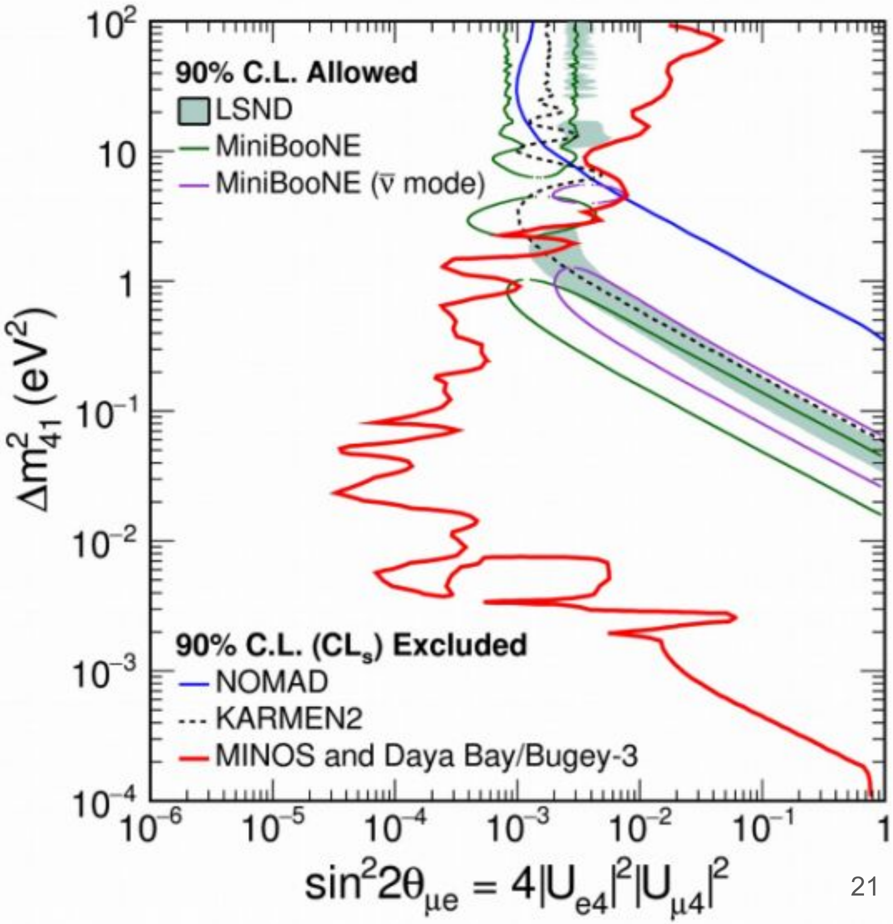
- The total significance is done by suspicious ways.

- Many members of the LSND collaboration are in the MiniBooNE collab. Possibility of **hidden bias?**

- Accusations of a **poor estimation** of neutral pions background. (also done for LSND)

- In the **Neutrino Conference 2018** (June 4-9) **MINOS** and **MINOS+** discarded the observed signal.

MINOS and MINOS+ are in significant tension with the new MiniBooNE result



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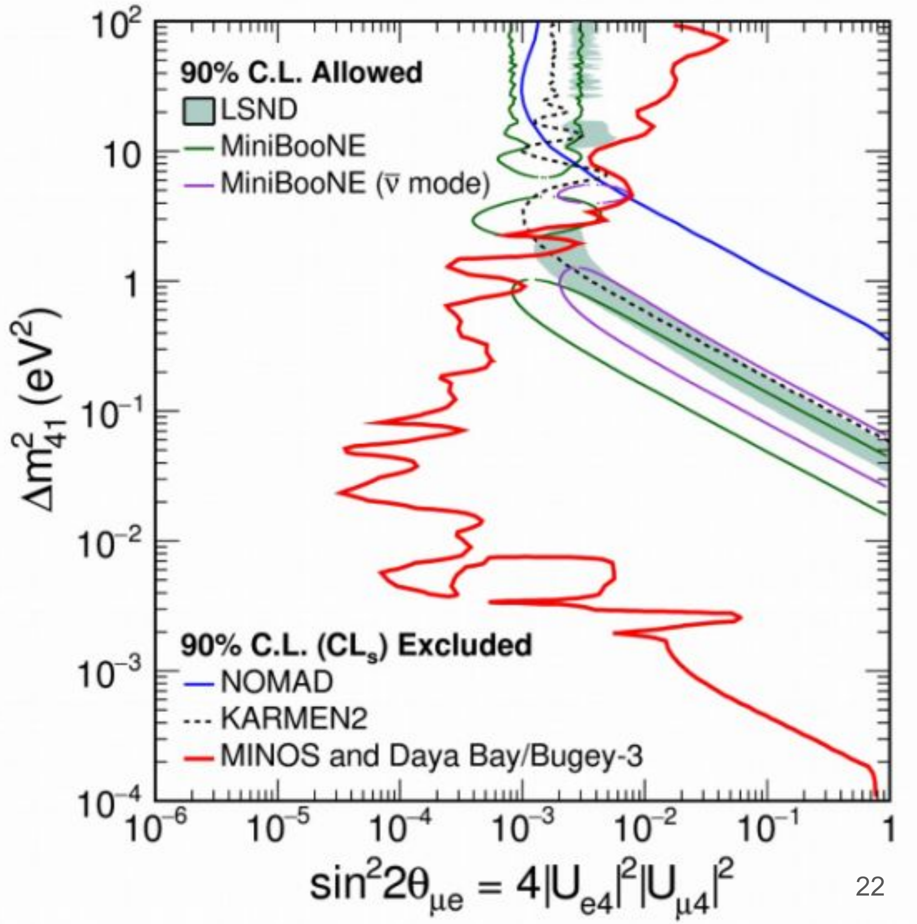
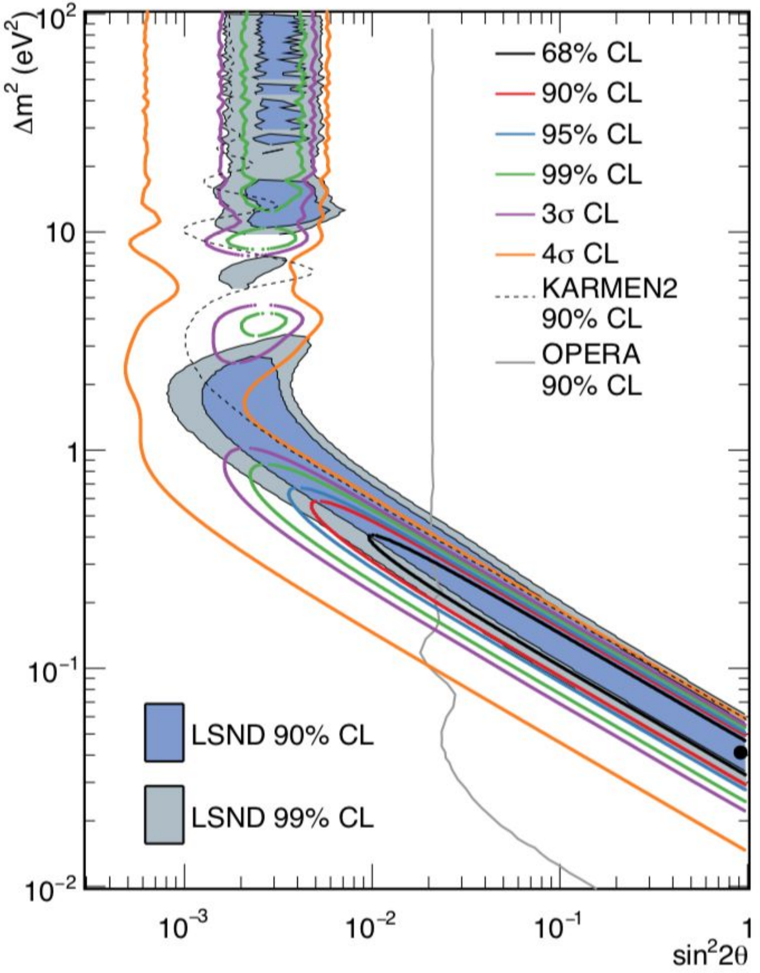
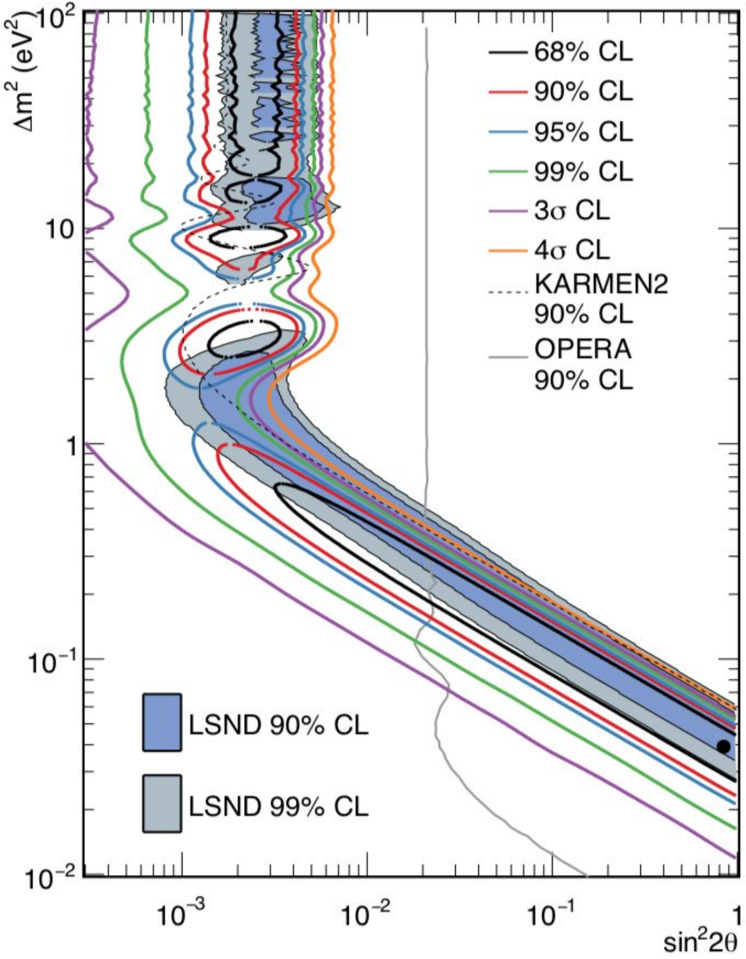




Δm^2 (eV^2)
68% CL
90% CL
95% CL
99% CL
3σ CL
4σ CL
KARMEN2 90% CL
OPERA 90% CL
LSND 90% CL
LSND 99% CL
$\sin^2 2\theta$



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Backgrounds

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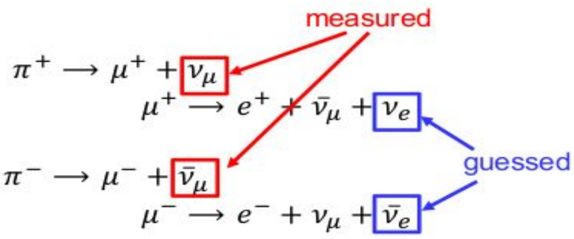
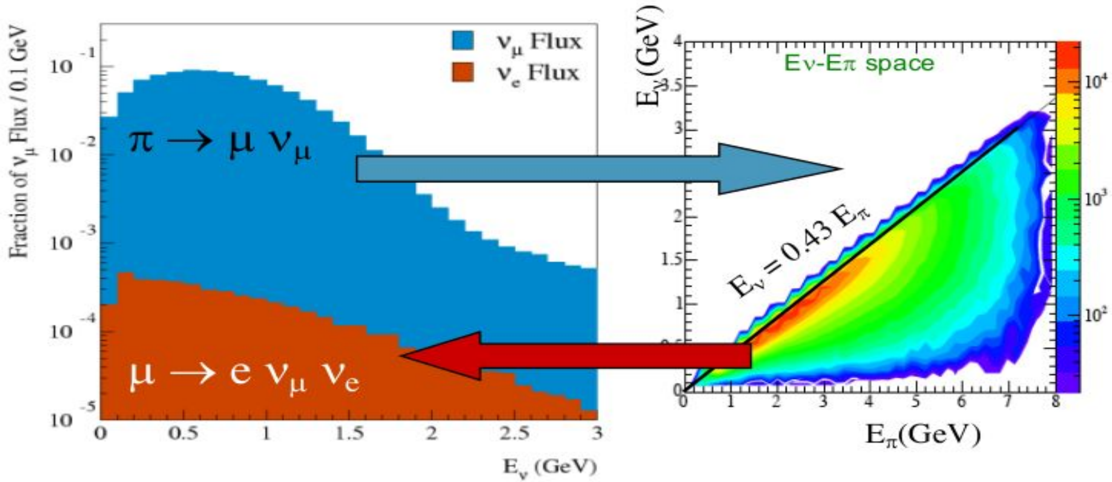
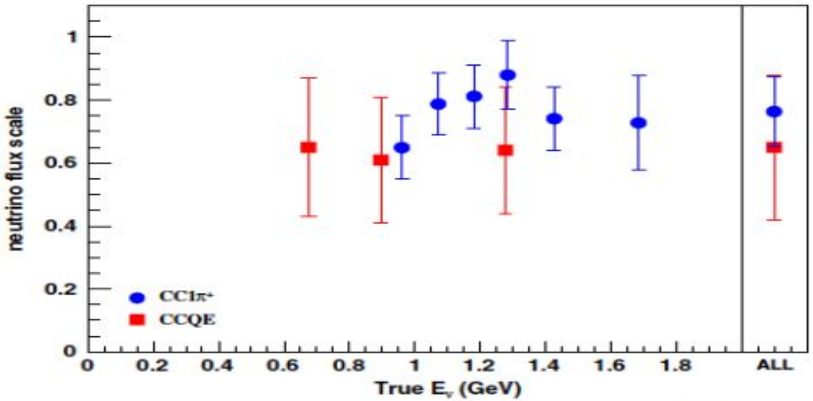


They are large background, but we have a good control of $\nu_e \& \bar{\nu}_e$ background by joint $\nu_e \& \nu_\mu (\bar{\nu}_e \& \bar{\nu}_\mu)$ fit for oscillation search.



Backgrounds

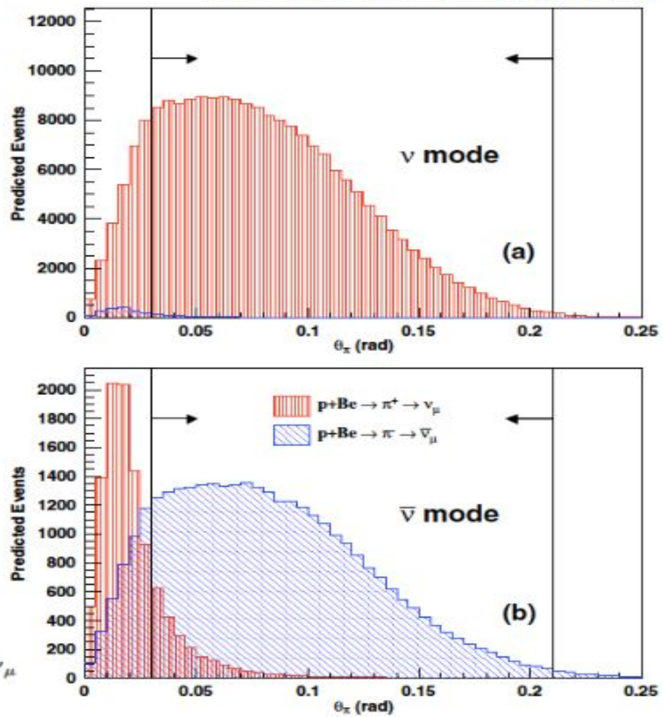
$\bar{\nu}_e \& \bar{\nu}_\mu$ flux are harder to predict due to larger wrong sign ($\nu_e \& \nu_\mu$) background, and measured lepton kinematics and π^+ production are used to tune flux
→ they consistently suggest we overestimate antineutrino flux around 20%



Michel electron counting is sensitive to ν_μ contamination in $\bar{\nu}_\mu$ beam

$$1: \quad \nu_\mu + p(n) \to \mu^- + p(n) + \pi^+ \hookrightarrow \mu^+ + \nu_\mu$$
$$2: \quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$3: \quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$

PHYSICAL REVIEW D 84, 072005 (2011)



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Total Data	1959	478
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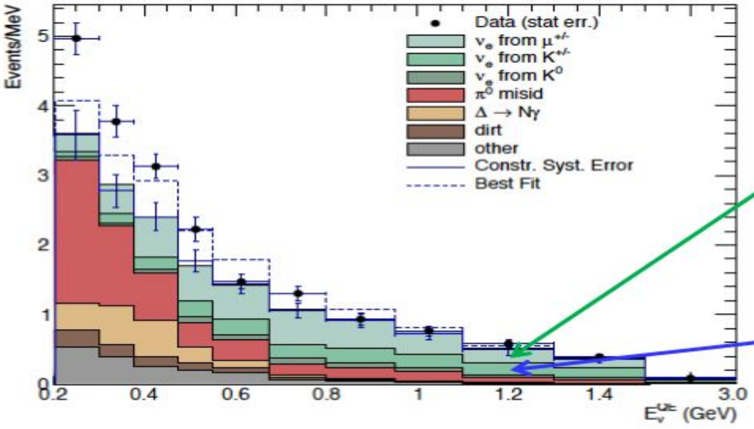
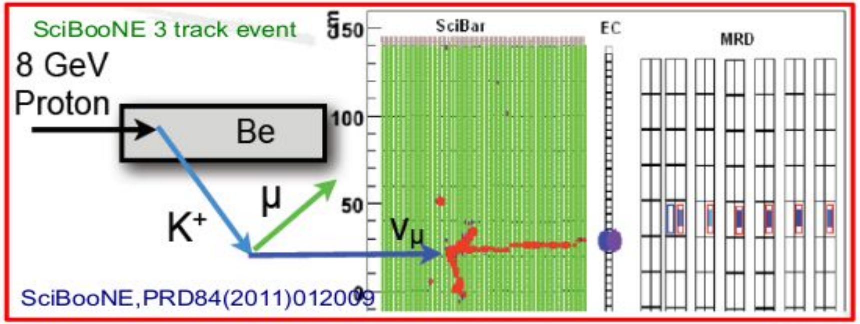


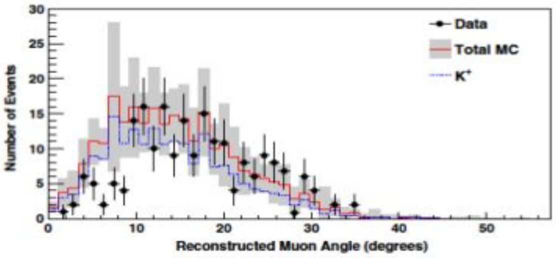
ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

MiniBooNE and SciBooNE

SciBooNE is a scintillator tracker located on BNB (detector hall is used by ANNIE now)
- neutrinos from kaon decay tend to be higher energy, and tend to make 3 tracks
- from 3 track analysis, kaon decay neutrinos are constrained (0.85±0.11, prior is 40% error)





(c) 3-Track Sample

Backgrounds

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
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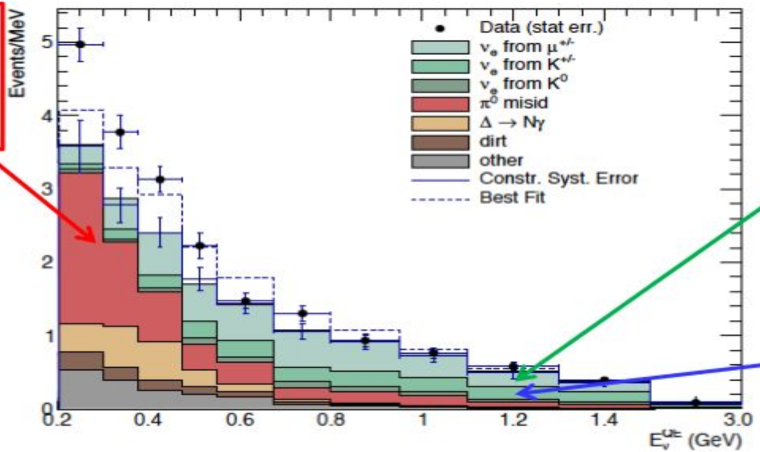
Asymmetric π^0 decay is constrained from measured $CC\pi^0$ rate ($\pi^0 \to \gamma$)



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

Backgrounds

$\pi^o \rightarrow \gamma\gamma$

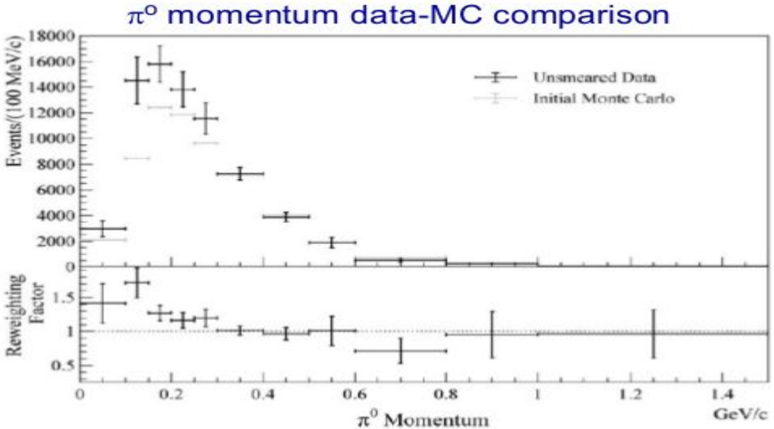
- not background, we can measure

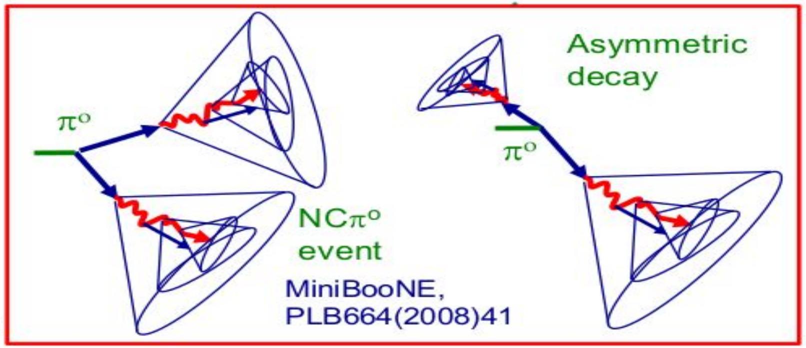
$\pi^o \rightarrow \gamma$

- misID background, we cannot measure

The biggest systematics is production rate of π^o, because once you find that, the chance to make a single gamma ray is predictable.

We measure π^o production rate, and correct simulation with function of π^o momentum





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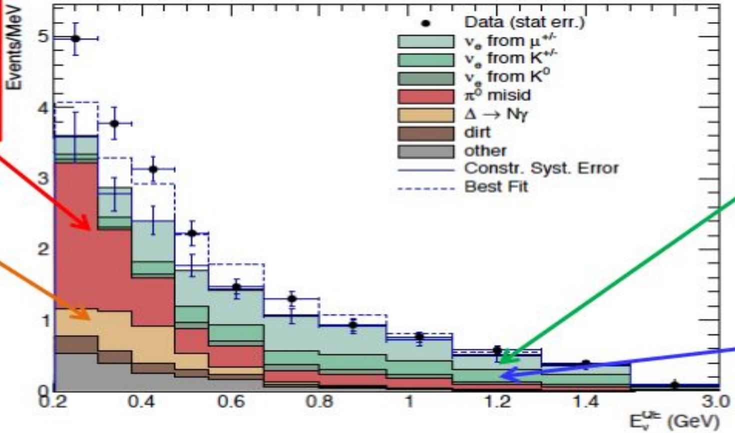
Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \to \gamma$)

Δ resonance rate is constrained from measured NCπ^o rate



ν_e from μ decay is constrained from ν_μCCQE measurement

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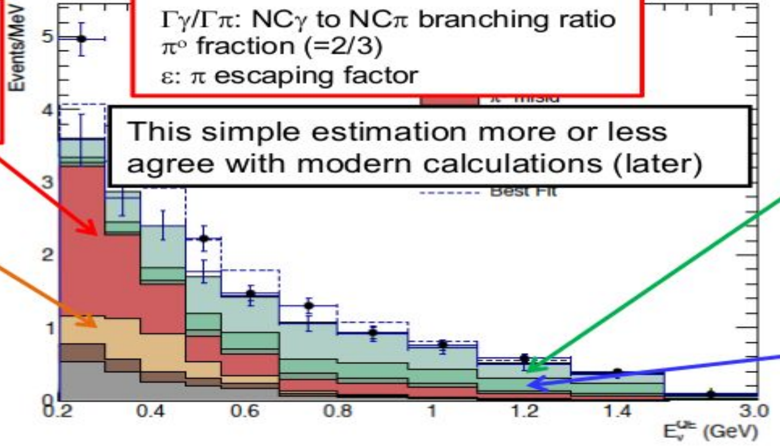
$$\frac{N(\Delta \to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

$\Gamma\gamma/\Gamma\pi$: NCγ to NCπ branching ratio
π^o fraction (=2/3)
ε: π escaping factor

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \to \gamma$)

Δ resonance rate is constrained from measured NCπ^o rate



This simple estimation more or less agree with modern calculations (later)

ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

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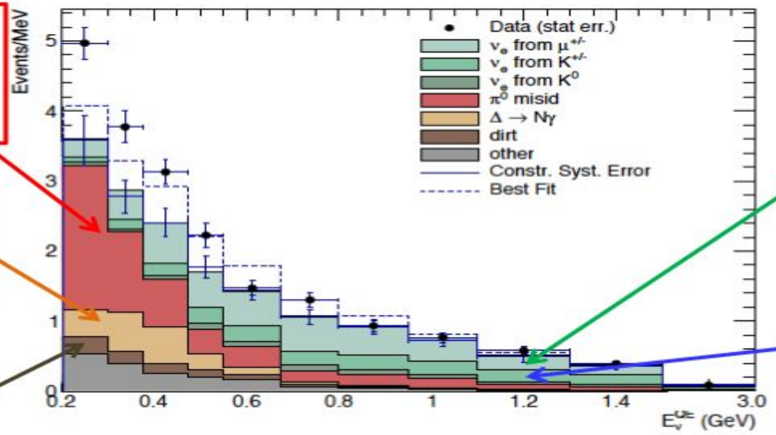
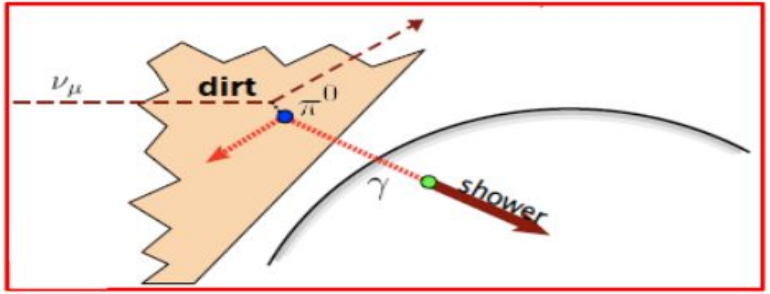


ν_e from μ decay is constrained from ν_μCCQE measurement

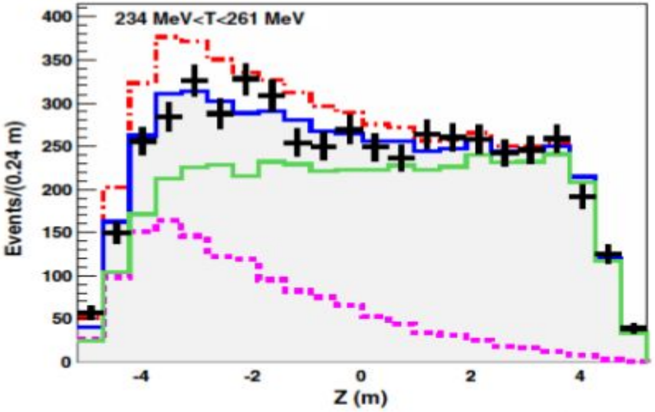
ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

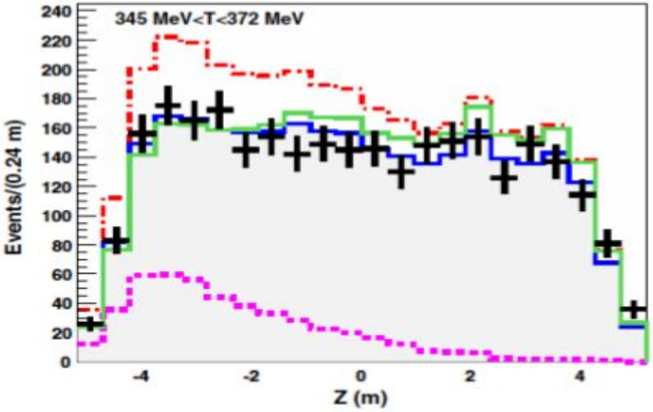
Backgrounds

MiniBooNE detector has a simple geometry
 - Spherical Cherenkov detector
 - Homogeneous, large active veto
We have number of internal measurement to understand distributions of external events.



e.g.) NC elastic candidates with function of Z
Mis-modelling of external background is visible





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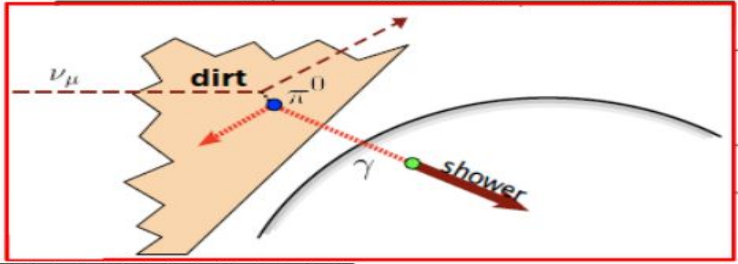

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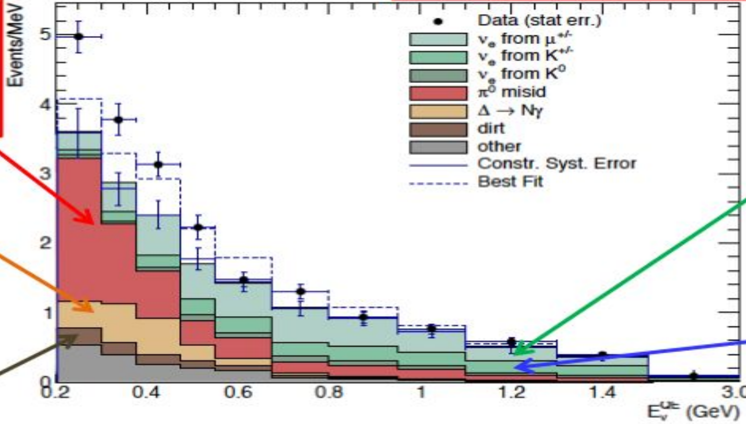

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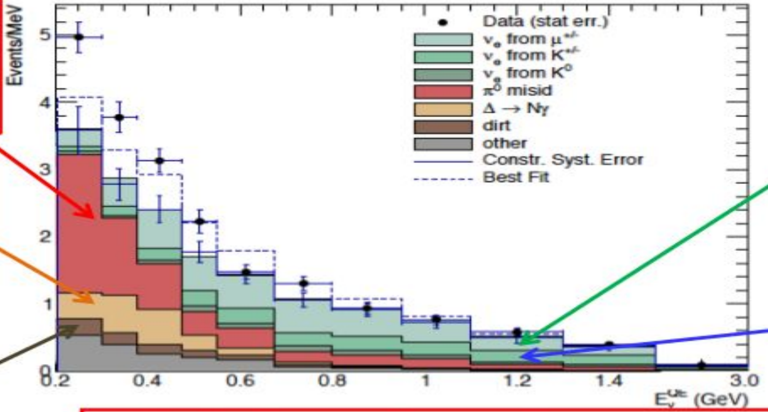

ν_e from μ decay is constrained from ν_μCCQE measurement

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Major backgrounds are all measured in other data sample and their errors are constrained!

Conclusions

MiniBooNE has observed: (with energies within 200 and 1250 MeV)

- In neutrino mode: 1959 events, from a total of 1577 events. This give us a quantity of 381 events, this would be **4.8 σ**.
- In antineutrino mode: 2437 events, from a total of 1976 events. This give us a quantity of 460 events, this would be **4.5 σ**.

After this, together with the LSND results:

$$(\text{significance from LSND})^2 + (\text{significance from MiniBooNE})^2 = (\text{given result})^2$$

$$(3.8)^2 + (4.8)^2 = (6.1)^2$$

Although the data are fit with a **two-neutrino oscillation model**, other exotic models may provide better fits to the data. e.g.: sterile neutrinos.