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

outline

1. MiniBooNE neutrino experiment
2. Booster Neutrino Beamline (BNB)
3. MiniBooNE detector
4. Oscillation candidate search
5. Discussion

Teppei Katori for the MiniBooNE collaboration
Queen Mary University of London
HEP seminar, Rutherford Appleton Lab, UK, Nov. 23, 2018

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

| Home | Talk To A Scientist | Comment Rules | About |

Thursday, May 31, 2018

New results confirm old anomaly in neutrino data

The collaboration of a neutrino experiment called MiniBooNe just published their new result

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment
MiniBooNE Collaboration
arXiv:1805.12028 [hep-ex]

It's a rather unassuming paper, but it deserves a signal boost because for once we have an anomaly that did not vanish with further examination. Indeed, it actually increased in significance, now standing at a whopping 6.1σ.

Quanta magazine

ABSTRACTIONS BLOG

Evidence Found for a New Fundamental Particle

💬 10

An experiment at the Fermi National Accelerator
Chicago has detected far more electron neutrinos
a possible harbinger of a revolutionary new elem
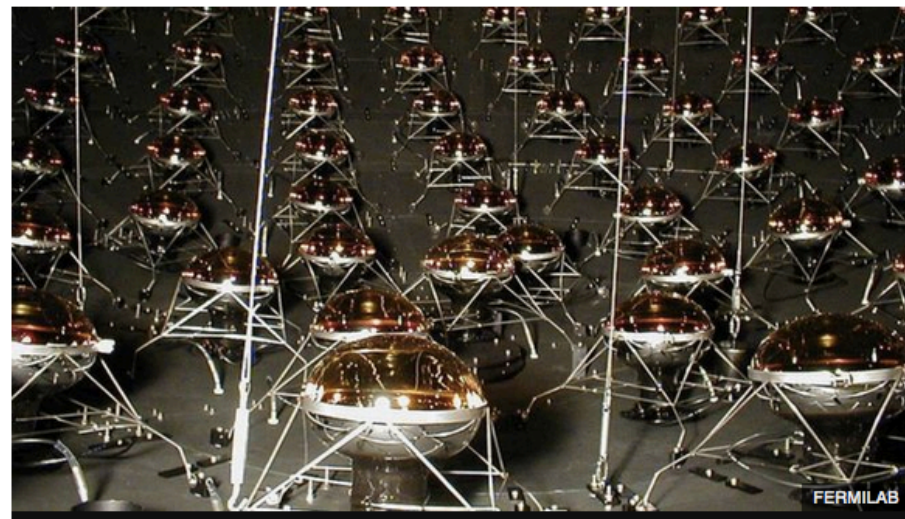*called the sterile neutrino, though many physicis*

PHYSICS

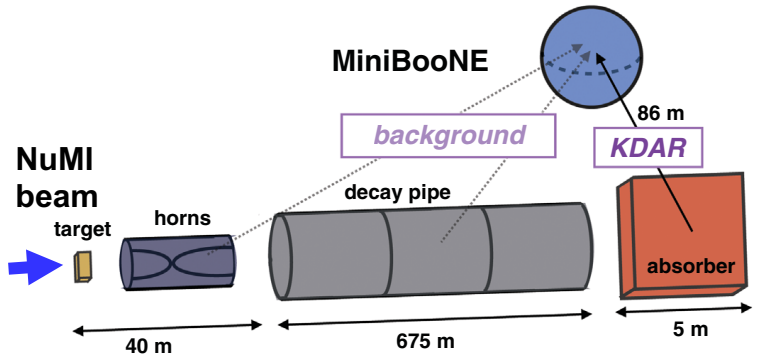## Physicists Are Excited About Fresh Evidence for a New 'Sterile' Fundamental Particle

Ryan F. Mandelbaum
6/04/18 3:20pm · Filed to: NEUTRINOS

19.4K   5   9

Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

🕐 6 June 2018

f   🐦   💬   ✉   ≪ Share

FERMILAB

MiniBooNE

NuMI beam
target
horns
decay pipe
background
86 m
KDAR
absorber
40 m
675 m
5 m

Blast from the past—First measurement of mono-energetic neutrinos

June 5, 2018 by Savannah Mitchem, Argonne National Laboratory
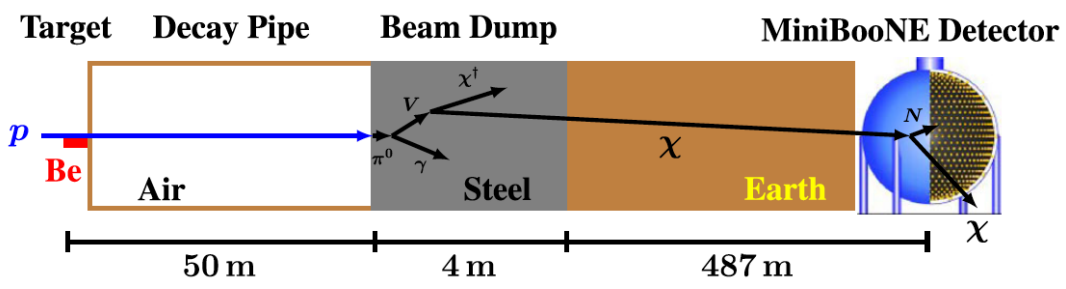
PHYSICAL REVIEW LETTERS **120**, 141802 (2018)

Editors' Suggestion   Featured in Physics

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions

A. A. Aguilar-Arevalo,[13] B. C. Brown,[6] L. Bugel,[12] G. Cheng,[5] E. D. Church,[20] J. M. Conrad,[12] R. L. Cooper,[10,16] R. Dharmapalan,[1] Z. Djurcic,[2] D. A. Finley,[6] R. S. Fitzpatrick,[14,*] R. Ford,[6] F. G. Garcia,[6] G. T. Garvey,[10] J. Grange,[2,†] W. Huelsnitz,[10] C. Ignarra,[12] R. Imlay,[11] R. A. Johnson,[3] J. R. Jordan,[14,‡] G. Karagiorgi,[5] T. Katori,[17] T. Kobilarcik,[6] W. C. Louis,[10] K. Mahn,[5,15] C. Mariani,[19] W. Marsh,[6] G. B. Mills,[10] J. Mirabal,[10] C. D. Moore,[6] J. Mousseau,[14] P. Nienaber,[18] B. Osmanov,[7] Z. Pavlovic,[10] D. Perevalov,[6] H. Ray,[7] B. P. Roe,[14] A. D. Russell,[6] M. H. Shaevitz,[5] J. Spitz,[14,§] I. Stancu,[1] R. Tayloe,[9] R. T. Thornton,[10] R. G. Van de Water,[10] M. O. Wascko,[8] D. H. White,[10] D. A. Wickremasinghe,[3] G. P. Zeller,[6] and E. D. Zimmerman[4]

PRL120(2018)141802   (MiniBooNE Collaboration)

Researchers ask A... does God look like? 27

Speculative wormho... revolutionize astrop... 2018 💬 19

Choice matters: The

News at work

Target   Decay Pipe   Beam Dump   MiniBooNE Detector

p
Be
Air
$\chi^\dagger$
V
π^0 γ
Steel
χ
Earth
N
χ

50 m   4 m   487 m

MiniBooNE keep providing high impact results!

The MiniBooNE search for dark matter

July 18, 2017 | Ranjan Dharmapalan and Tyler Thornton

PHYSICAL REVIEW LETTERS

week ending
2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

A. A. Aguilar-Arevalo,[1] M. Backfish,[2] A. Bashyal,[3] B. Batell,[4] B. C. Brown,[2] R. Carr,[5] A. Chatterjee,[3] R. L. Cooper,[6,7] P. deNiverville,[8] R. Dharmapalan,[9] Z. Djurcic,[9] R. Ford,[2] F. G. Garcia,[2] G. T. Garvey,[10] J. Grange,[9,11] J. A. Green,[10] W. Huelsnitz,[10] I. L. de Icaza Astiz,[1] G. Karagiorgi,[5] T. Katori,[12] W. Ketchum,[10] T. Kobilarcik,[2] Q. Liu,[10] W. C. Louis,[10] W. Marsh,[2] C. D. Moore,[2] G. B. Mills,[10] J. Mirabal,[10] P. Nienaber,[13] Z. Pavlovic,[10] D. Perevalov,[2] H. Ray,[11] B. P. Roe,[14] M. H. Shaevitz,[5] S. Shahsavarani,[3] I. Stancu,[15] R. Tayloe,[6] C. Taylor,[10] R. T. Thornton,[6] R. Van de Water,[10] W. Wester,[2] D. H. White,[10] and J. Yu[3]
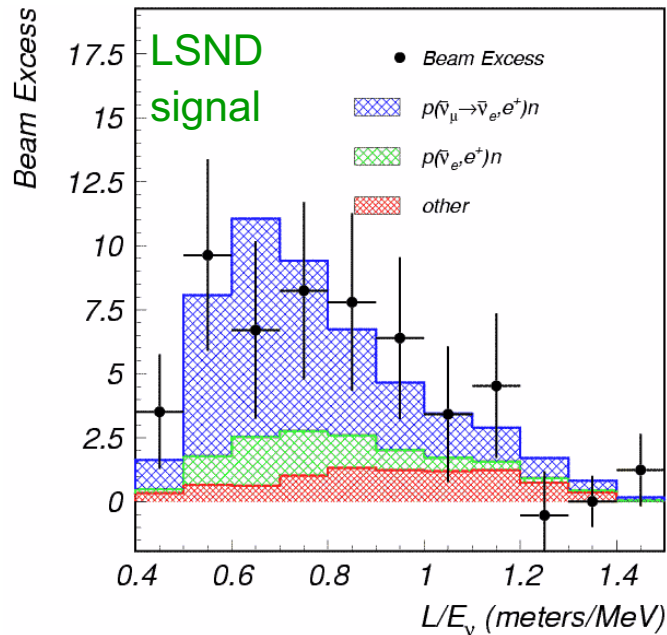
MiniBooNE-DM Collaboration

PRL118(2017)221803

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1. LSND experiment

$$P(v_\mu \rightarrow v_e) = sin^2 2\theta sin^2 \left(1.27 \Delta m^2 \frac{L}{E}\right)$$

LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

$$\overline{v}_\mu \xrightarrow{\text{oscillation}} \overline{v}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

87.9 ± 22.4 ± 6.0 (3.8.σ)

LSND signal

Beam Excess

● Beam Excess

$p(\bar{v}_\mu \rightarrow \bar{v}_e, e^+)n$

$p(\bar{v}_e, e^+)n$

other

L/E_v (meters/MeV)

800 MeV proton beam from LANSCE accelerator

L/E~30m/30MeV~1

Water target

Copper beamstop

LSND Detector

Time

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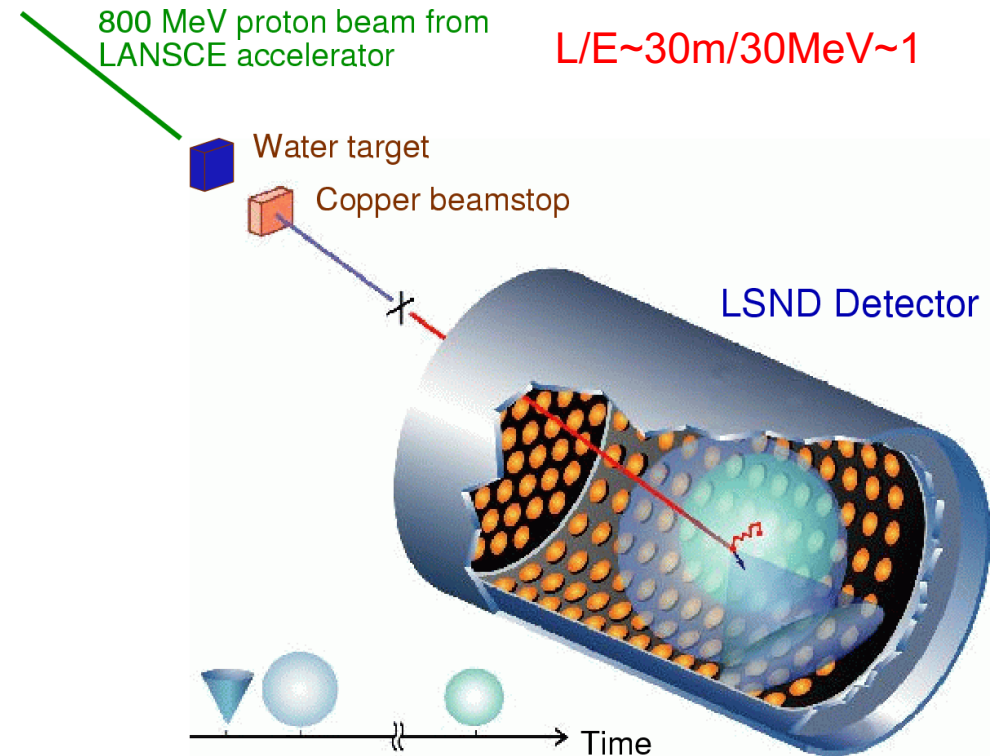
1. LSND experiment
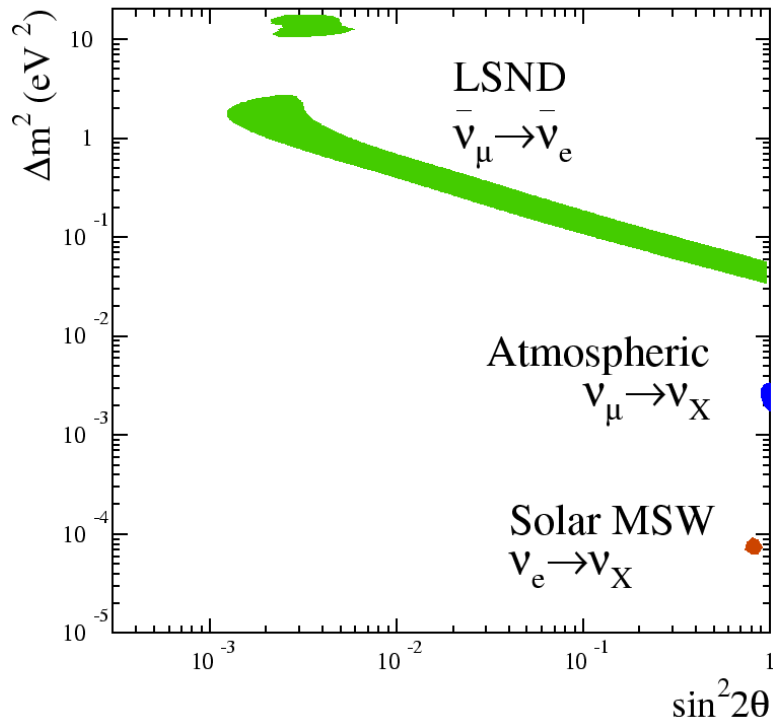
3 types of neutrino oscillations are found:

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

But we cannot have so many $\Delta m2$!

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

$\Delta m_{34}^2 \sim 0.1 - 100 \ eV^2$
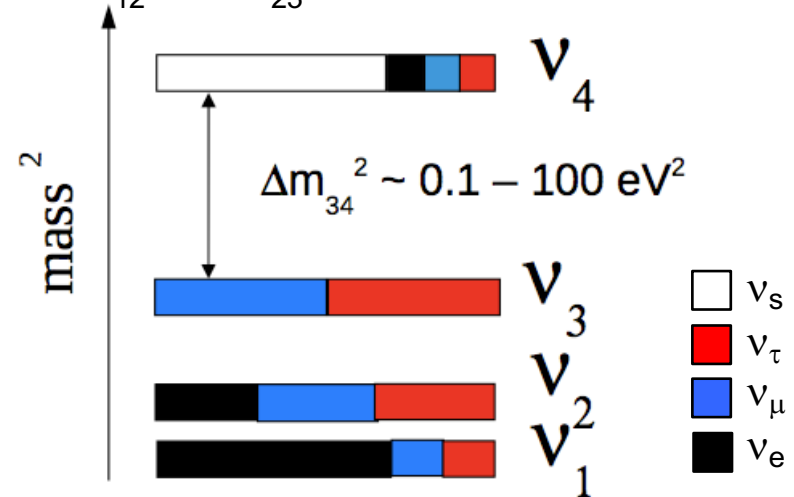
LSND signal indicates 4th generation neutrino, but we know there is no additional flavour from Z-boson decay, so it must be sterile neutrino
MiniBooNE is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment $P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27 \Delta m^2 \dfrac{L}{E}\right)$
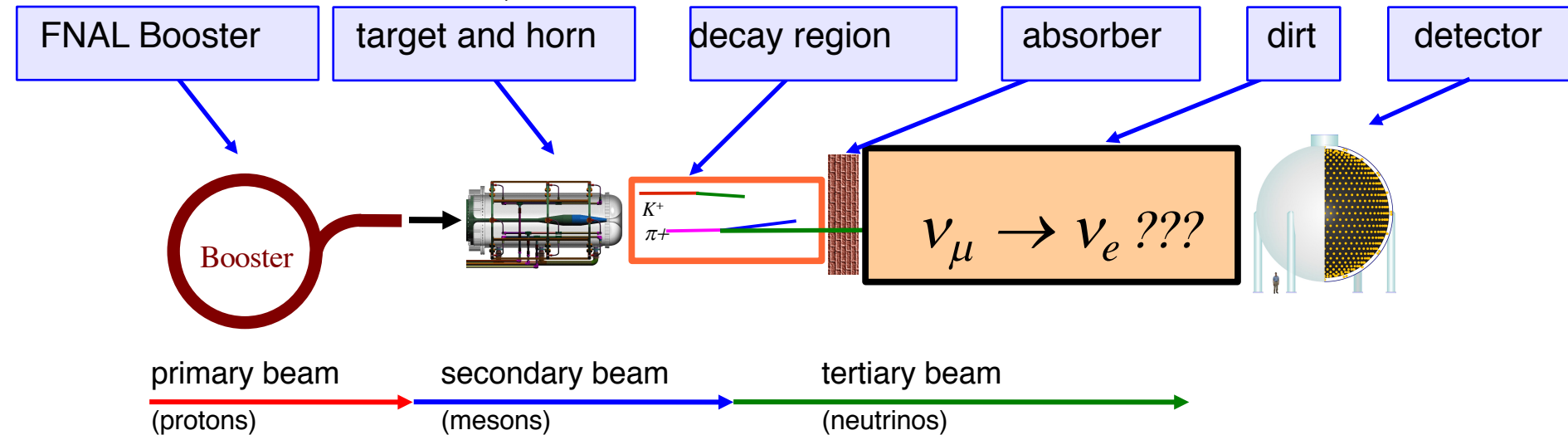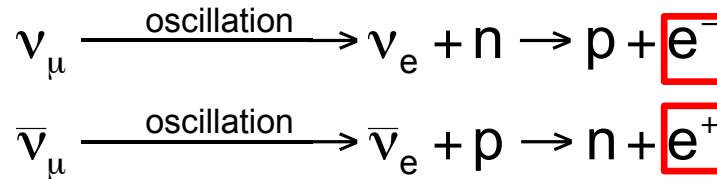
Keep L/E same with LSND, while changing systematics, energy & event signature;

MiniBooNE is looking for the single isolated electron like events, which is the signature of ν_e events

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + \boxed{e^-}$$

$$\overline{\nu}_\mu \xrightarrow{\text{oscillation}} \overline{\nu}_e + p \rightarrow n + \boxed{e^+}$$

| FNAL Booster | target and horn | decay region | absorber | dirt | detector |

$$\nu_\mu \rightarrow \nu_e \; ???$$

Booster

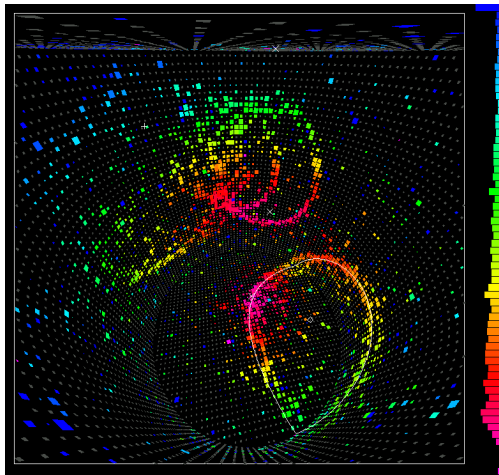K^+
$\pi+$

primary beam (protons)
secondary beam (mesons)
tertiary beam (neutrinos)

MiniBooNE has;
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

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1. MiniBooNE is extremely influential! – Tools

fitQun: MiniBooNE: NIMA608(2009)206

Likelihood-based Cherenkov ring fitter, the main reconstruction used by Super-Kamiokande (LSND→MiniBooNE→SuperK).

Flux systematic error: MiniBooNE: PRD79(2009)072002
 - Errors are derived directly from hadron production data (spline fit), not any flux model.
 - Event weighted with multiverse simulation to make a smooth covariance matrix with taking account all correlations correctly.
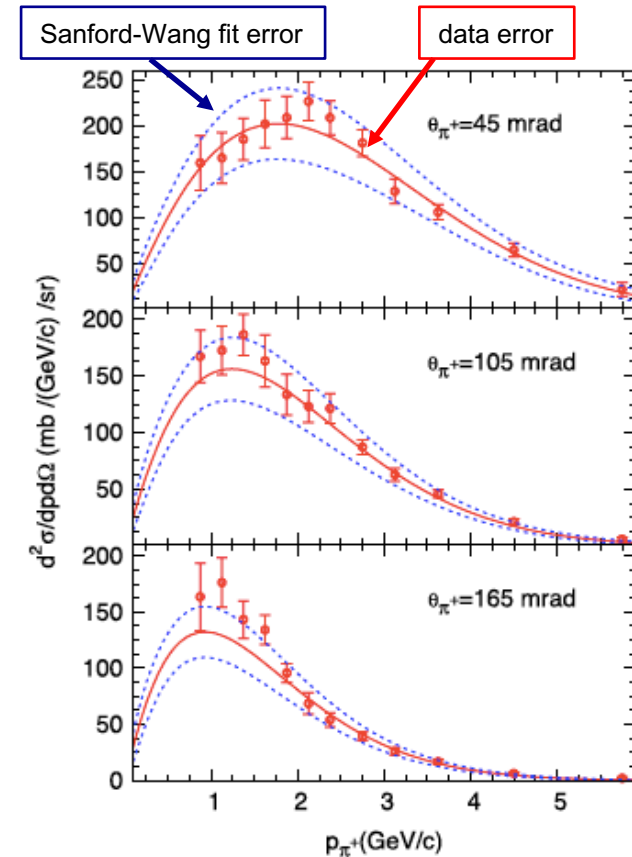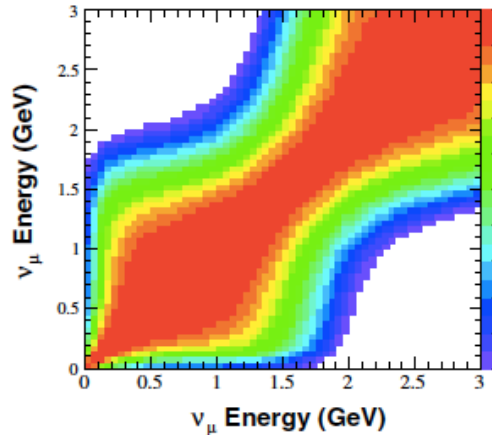

Online remote shift:
 - <1 event per minute
 - Even ACNET became web interface after this!
 - Almost all neutrino experiments at Fermilab adapted online remote shift, including NOvA, MicroBooNE, MINERvA, etc

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1. MiniBooNE is extremely influential! – Offspring

Argonne: Zelimir Djurcic (PD)

MSU: Kendall Mahn (PhD)

Lancaster: Jarek Nowak (PD)

Fermilab:
Jen Raaf (PhD)
Fernanda Garcia (PD)
Zarko Pavlovic (PD)
Chris Polly (PD)
Sam Zeller (PD)

Chicago: Dave Schmitz (PhD)

Yale: Bonnie Fleming (PD)

Royal Holloway: Jocelyn Monroe (PhD)

Queen Mary: Teppei Katori (PhD)

Columbia: Georgia Karagiorgi (PhD)

IHEP: Jun Cao (PD)

SLAC: Hiro Tanaka (PD)

Stony Brook: Mike Wilking (PhD)

Imperial: Morgan Wascko (PD)

Caltech: Ryan Patterson (PhD)

Pittsburgh: Brian Batell (PD)

IFIC: Michel Sorel (PhD)

NMSU: Robert Cooper (PD)

Virginia Tech: Jon Link (PD)

Colorado: Eric Zimmerman (PD)

LSU: Martin Tzanov (PD)

Florida: Heather Ray (PD)

UNAM: Alexis Aguilar Arevalo (PhD)

…and more are coming!

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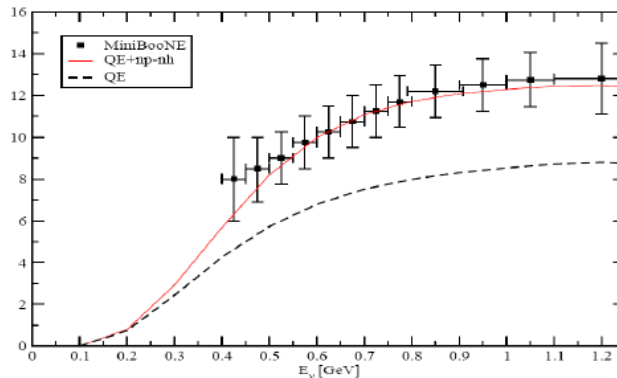# 1. MiniBooNE is extremely influential! – Cross Sections

Flux-integrated differential cross section:
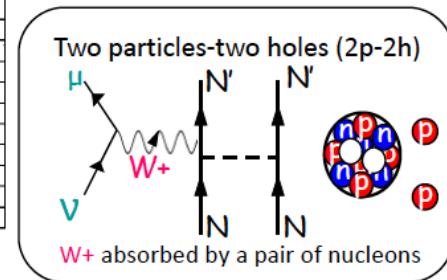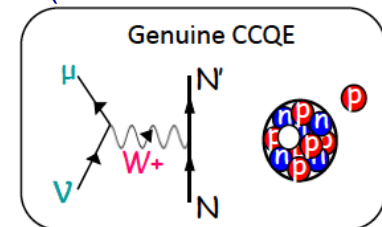A new concept to measure, and report neutrino cross section data, now the standard of the community.

An explanation of this puzzle

(Slide from Marco Martini)

Inclusion of the multinucleon emission channel (np-nh)

PHYSICAL REVIEW D 81, 092005 (2010)

$\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$ (cm^2/GeV)
×10^{-39}

MiniBooNE data (δN_T=10.7%)

MiniBooNE data with shape error

Genuine CCQE

Two particles-two holes (2p-2h)

W+ absorbed by a pair of nucleons

Discovery of nucleon correlation in neutrino scattering:
- Significant enhancement of cross section (10-30%)
- modify lepton kinematics and final state hadrons
- the hottest topic for T2K, MINERvA, MicroBooNE, etc

Particle Data Group
- Section 42, "Monte Carlo Neutrino Generators" (Hugh Gallagher, Yoshinari Hayato)
- Section 50, "Neutrino Cross-Section Measurements" (Sam Zeller)

On going effort from MiniBooE initiative!

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The first textbook of neutrino interaction physics!
"Foundation of Nuclear and Particle Physics"
- Cambridge University Press (2017), ISBN:0521765110
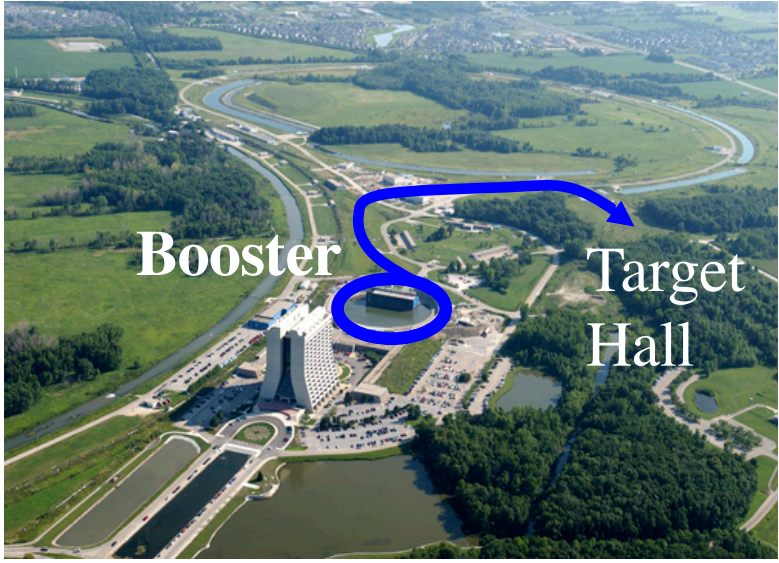- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow

FOUNDATIONS OF NUCLEAR AND PARTICLE PHYSICS

10

T. W. Donnelly J. A. Formaggio
B. R. Holstein R. G. Milner B. Surrow

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)
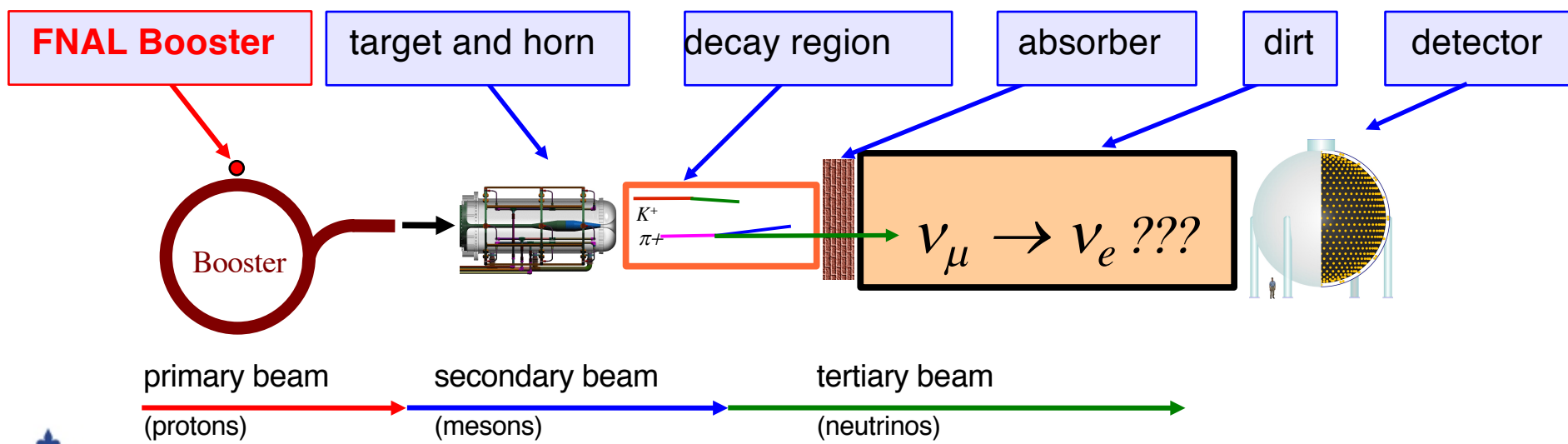
3. MiniBooNE detector
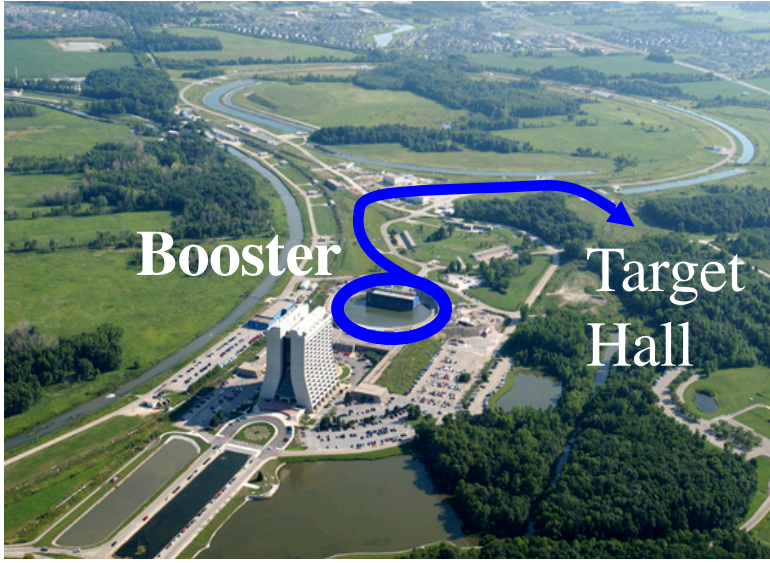
4. Oscillation candidate search

5. Discussion

MiniBooNE, PRD79(2009)072002

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

2. Neutrino beam

Booster

Target Hall

MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster

| FNAL Booster | target and horn | decay region | absorber | dirt | detector |

Booster

K^+
$\pi+$

$$\nu_\mu \rightarrow \nu_e \ ???$$

primary beam (protons)   secondary beam (mesons)   tertiary beam (neutrinos)

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MiniBooNE, PRD79(2009)072002

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Target Hall

MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster

FNAL Booster

target and horn

decay region

Booster

K^+
π^+

primary beam
(protons)

secondary beam
(mesons)

tertiary
(neutrino)

1.5ns

x82

19ns

......

Beam bunch structure

1.6μs

x5 /1sec

20μs (trigger)

Beam spill structure

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MiniBooNE, PRD79(2009)072002
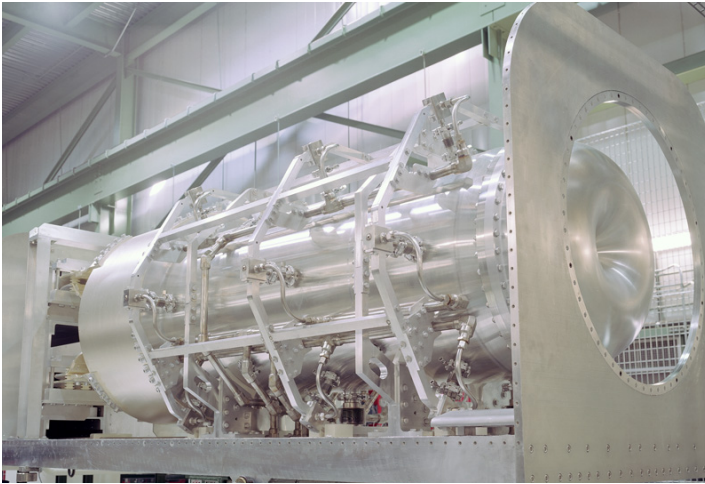
1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
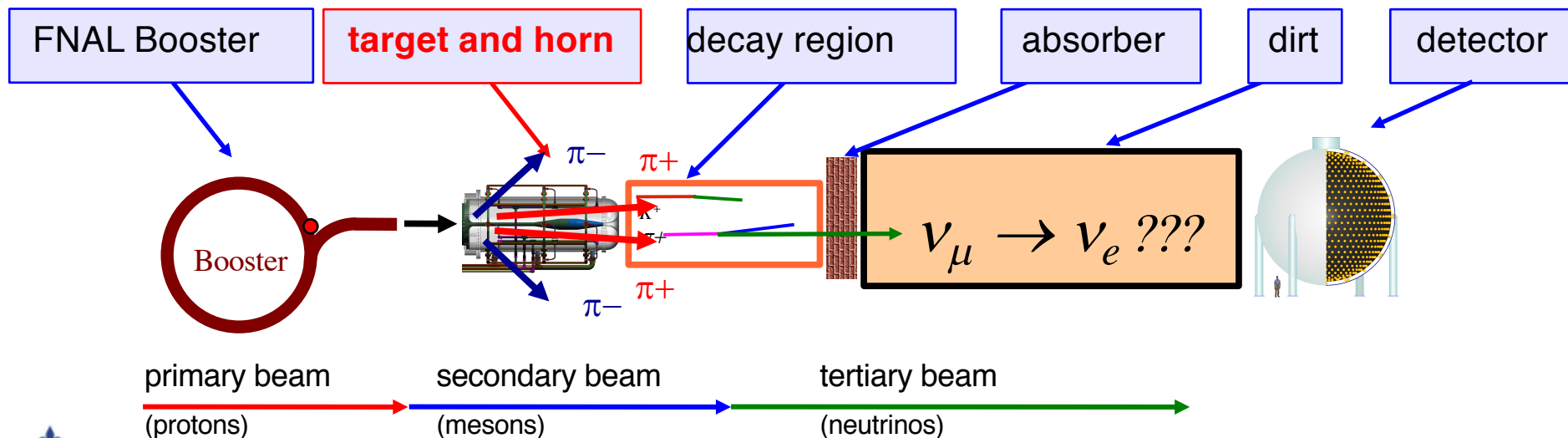5. Discussion

2. Neutrino beam

Magnetic focusing horn

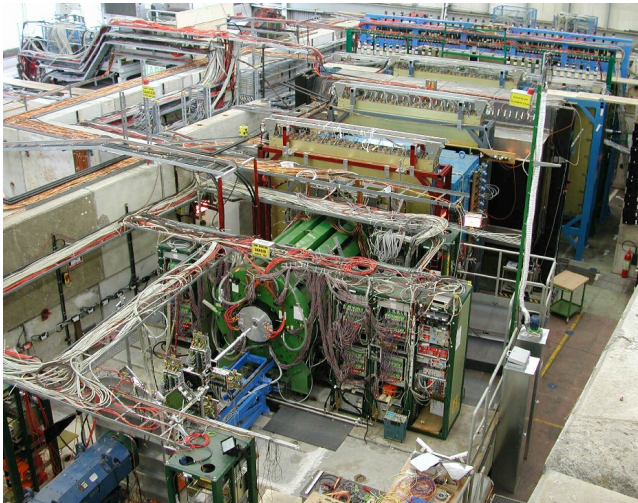8GeV protons are delivered to a 1.7 λ Be target

within a magnetic horn (2.5 kV, 174 kA) that increases the flux by $\times$ 6

By switching the current direction, the horn can focus either positive (neutrino mode) or negative (antineutrino mode) mesons.
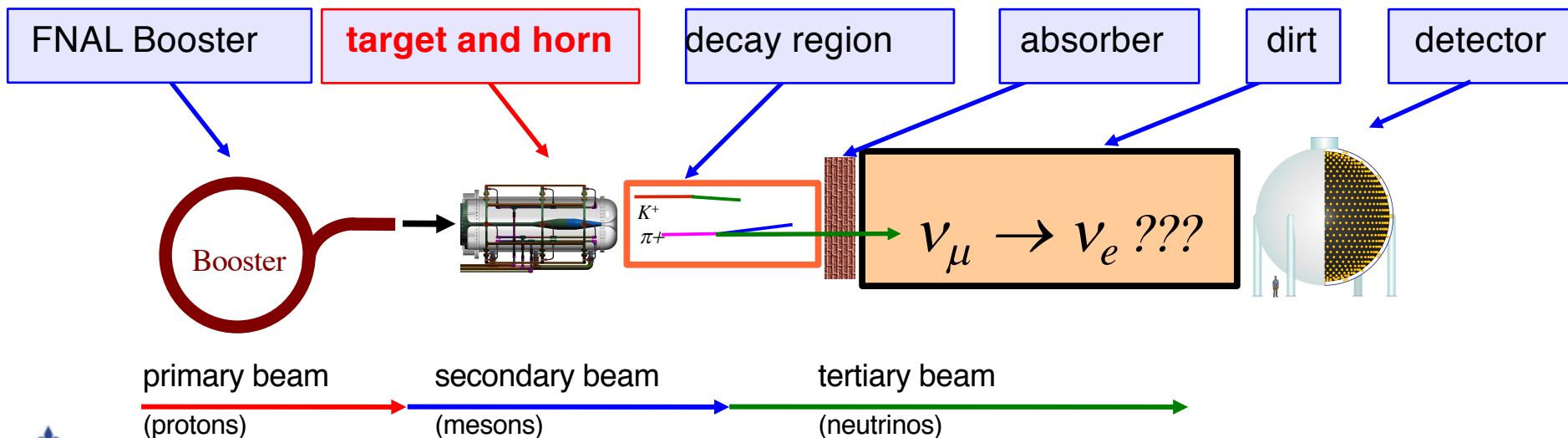
| FNAL Booster | **target and horn** | decay region | absorber | dirt | detector |

$\pi-$ $\pi+$

$\pi-$ $\pi+$

Booster

$$\nu_\mu \rightarrow \nu_e \; ???$$

primary beam (protons)

secondary beam (mesons)

tertiary beam (neutrinos)

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MiniBooNE, PRD79(2009)072002
HARP, Eur.Phys.J.C52(2007)29

1. MiniBooNE
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5. Discussion

2. Neutrino beam

HARP experiment (CERN)

Modeling of meson production is based on the measurement done by HARP collaboration.
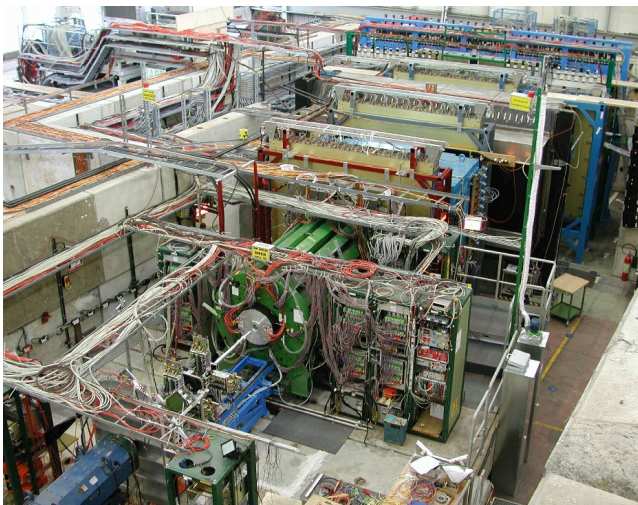 - Identical, but 5% λ Beryllium target
 - 8.9 GeV/c proton beam momentum
 - >80% coverage for $\pi+$

| FNAL Booster | **target and horn** | decay region | absorber | dirt | detector |

$$\nu_\mu \rightarrow \nu_e \; ???$$

K^+
$\pi+$

primary beam
(protons)

secondary beam
(mesons)

tertiary beam
(neutrinos)

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23/11/18   15

MiniBooNE, PRD79(2009)072002
HARP, Eur.Phys.J.C52(2007)29

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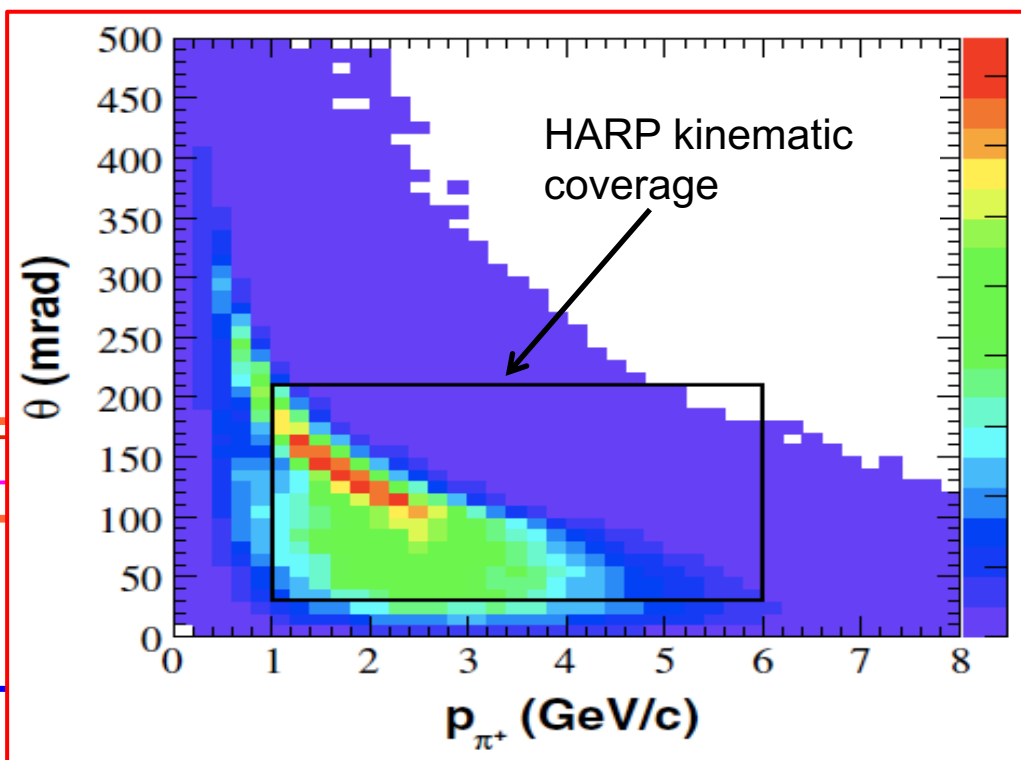 - >80% coverage for π+

FNAL Booster

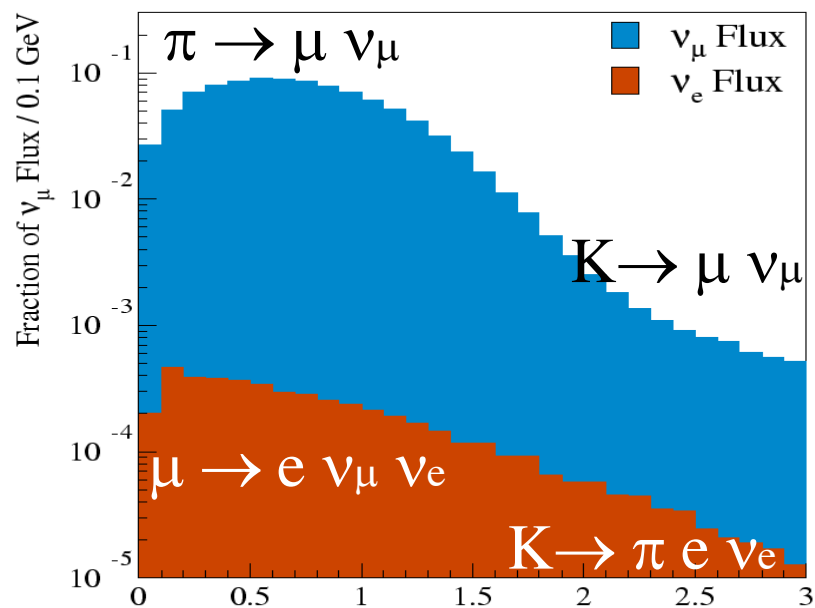**target and horn**

Booster

K^+
$\pi+$

primary beam
(protons)

secondary beam
(mesons)

HARP kinematic coverage

θ (mrad)

p_{π^+} (GeV/c)

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MiniBooNE, PRD79(2009)072002

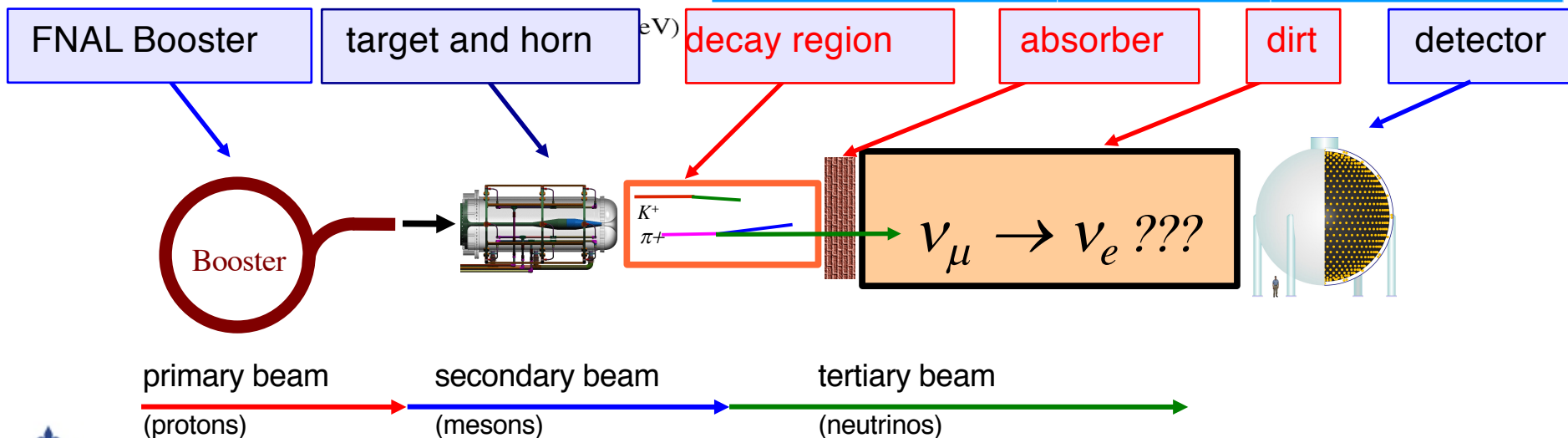1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

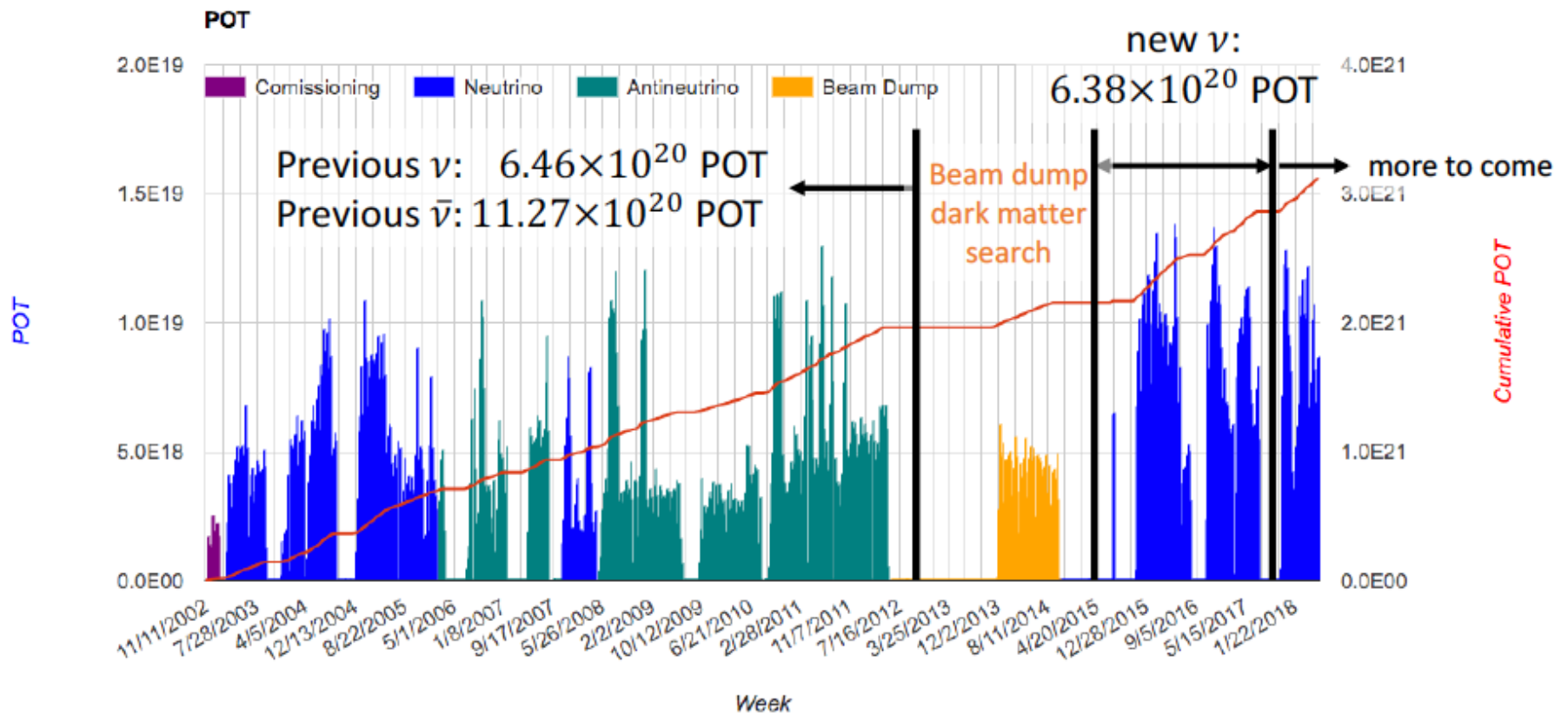# 2. Neutrino beam

Neutrino flux from simulation by GEANT4

MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%

FNAL Booster   target and horn   decay region   absorber   dirt   detector

$\nu_\mu \rightarrow \nu_e$???

primary beam
(protons)

secondary beam
(mesons)

tertiary beam
(neutrinos)

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23/11/18

17

Huang, Neutrino 2018

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

3. Data taking

- 15+ years of running in neutrino, antineutrino, and beam dump mode. More than 30×10^{20} POT to date.

- Result of a combined 12.84×10^{20} POT in ν mode + 11.27×10^{20} POT in $\bar{\nu}$ mode is presented in this talk

1. MiniBooNE neutrino experiment

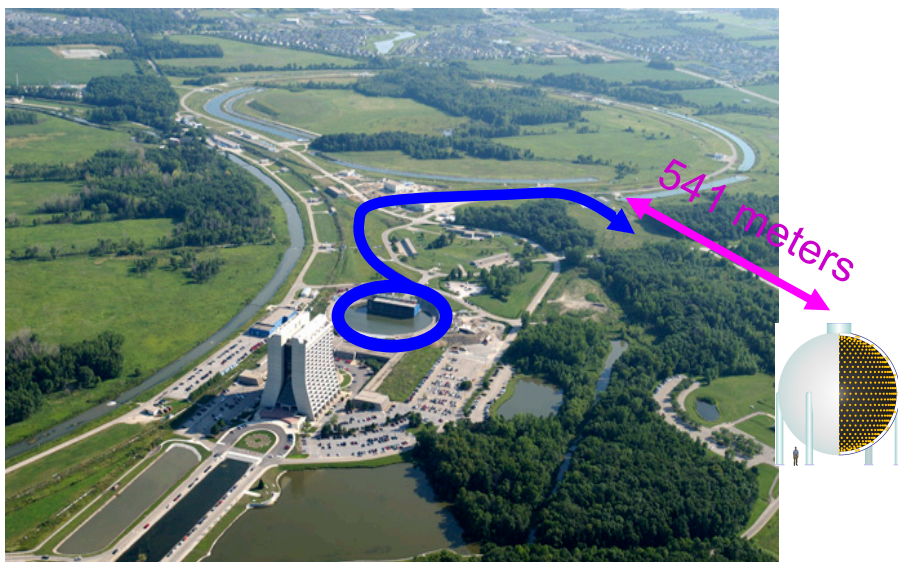# 2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

MiniBooNE,NIM.A599(2009)28

1. MiniBooNE
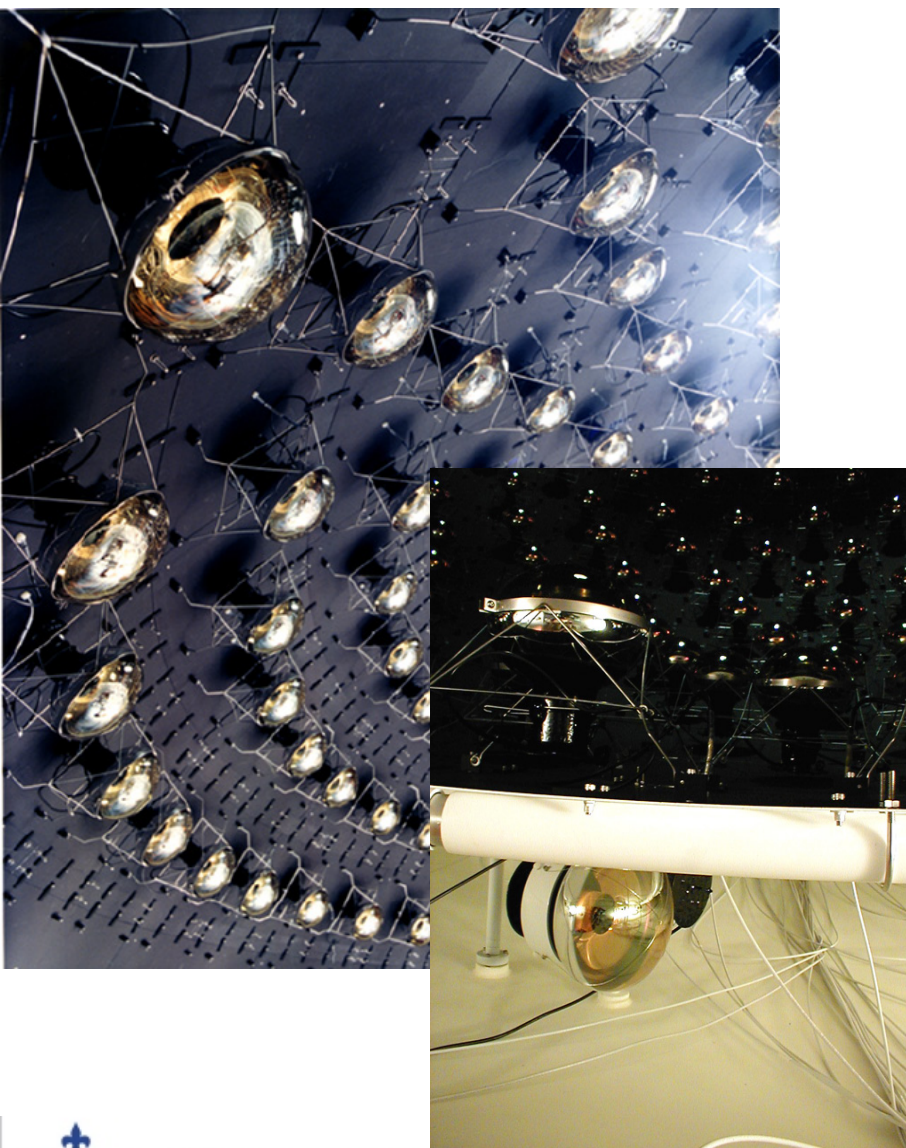2. Beam
3. Detector
4. Oscillation
5. Discussion

3. Events in the Detector

The MiniBooNE Detector

- 541 meters downstream of target

- 12 meter diameter sphere

   (10 meter "fiducial" volume)

- Filled with 800 t of pure mineral oil (CH_2)

   (Fiducial volume: 450 t)

- 1280 inner phototubes,

- 240 veto phototubes

MiniBooNE,NIM.A599(2009)28

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MiniBooNE,NIM.A599(2009)28

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3. Events in the Detector

Times of hit-clusters (subevents)

Beam spill (1.6μs) is clearly evident

  simple cuts eliminate cosmic
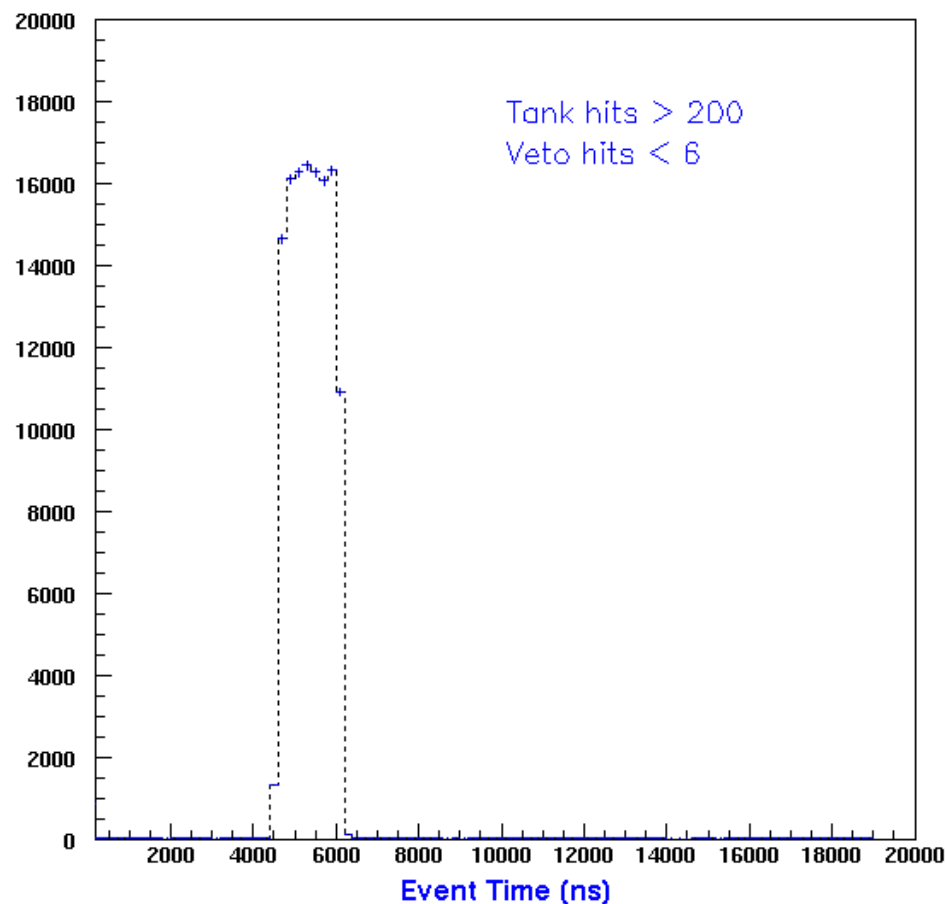   backgrounds

Neutrino Candidate Cuts

  <6 veto PMT hits

    Gets rid of muons

  >200 tank PMT hits

    Gets rid of Michels
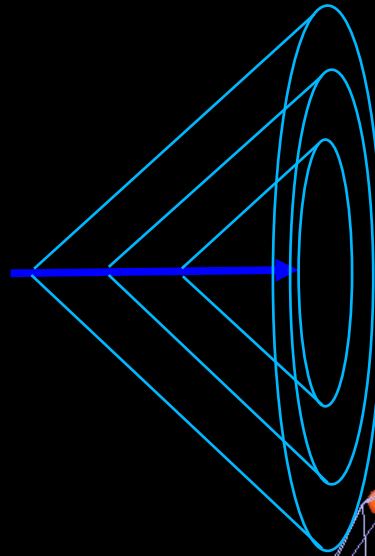
  Only neutrinos are left!

Beam and Cosmic BG
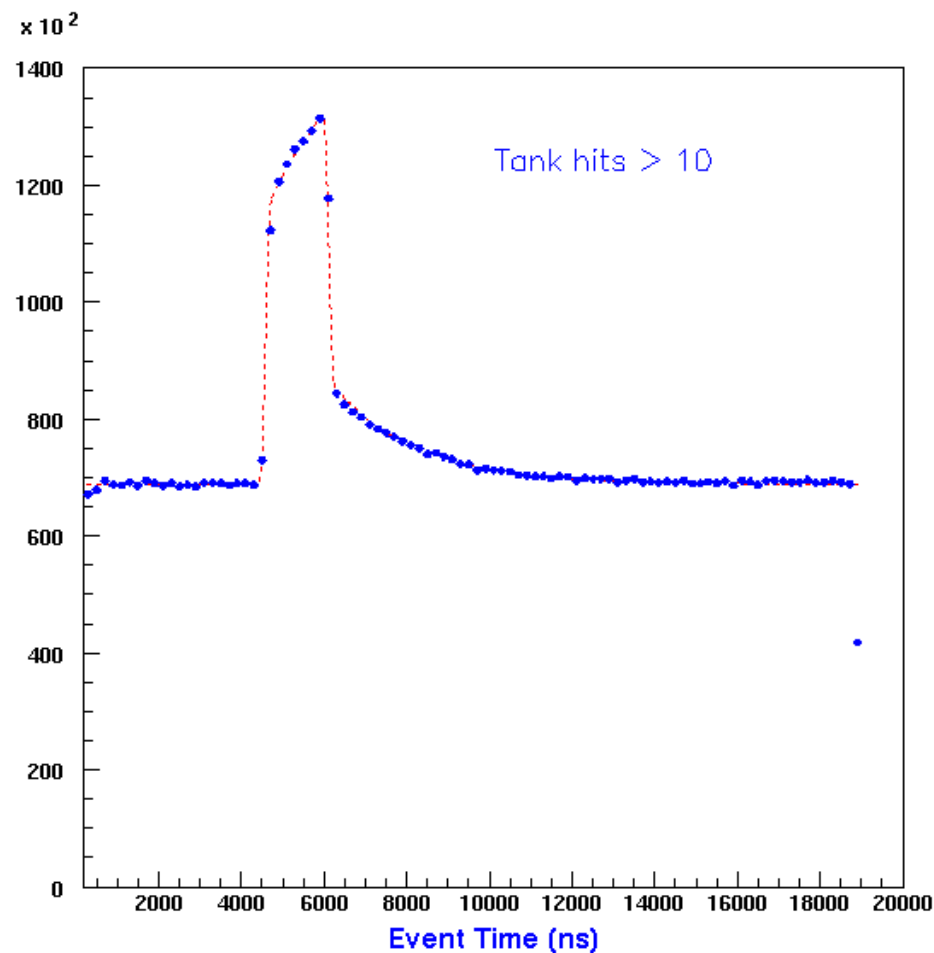
Tank hits > 10

Event Time (ns)

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MiniBooNE,NIM.A599(2009)28

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

3. Events in the Detector

Times of hit-clusters (subevents)

Beam spill (1.6μs) is clearly evident

simple cuts eliminate cosmic
backgrounds

Neutrino Candidate Cuts

<6 veto PMT hits

Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and Michels

Tank hits > 10
Veto hits < 6

Event Time (ns)

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3. Events in the Detector

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Only neutrinos are left!

Muons

- Long strait tracks

  → Sharp clear rings

Electrons

- Multiple scattering
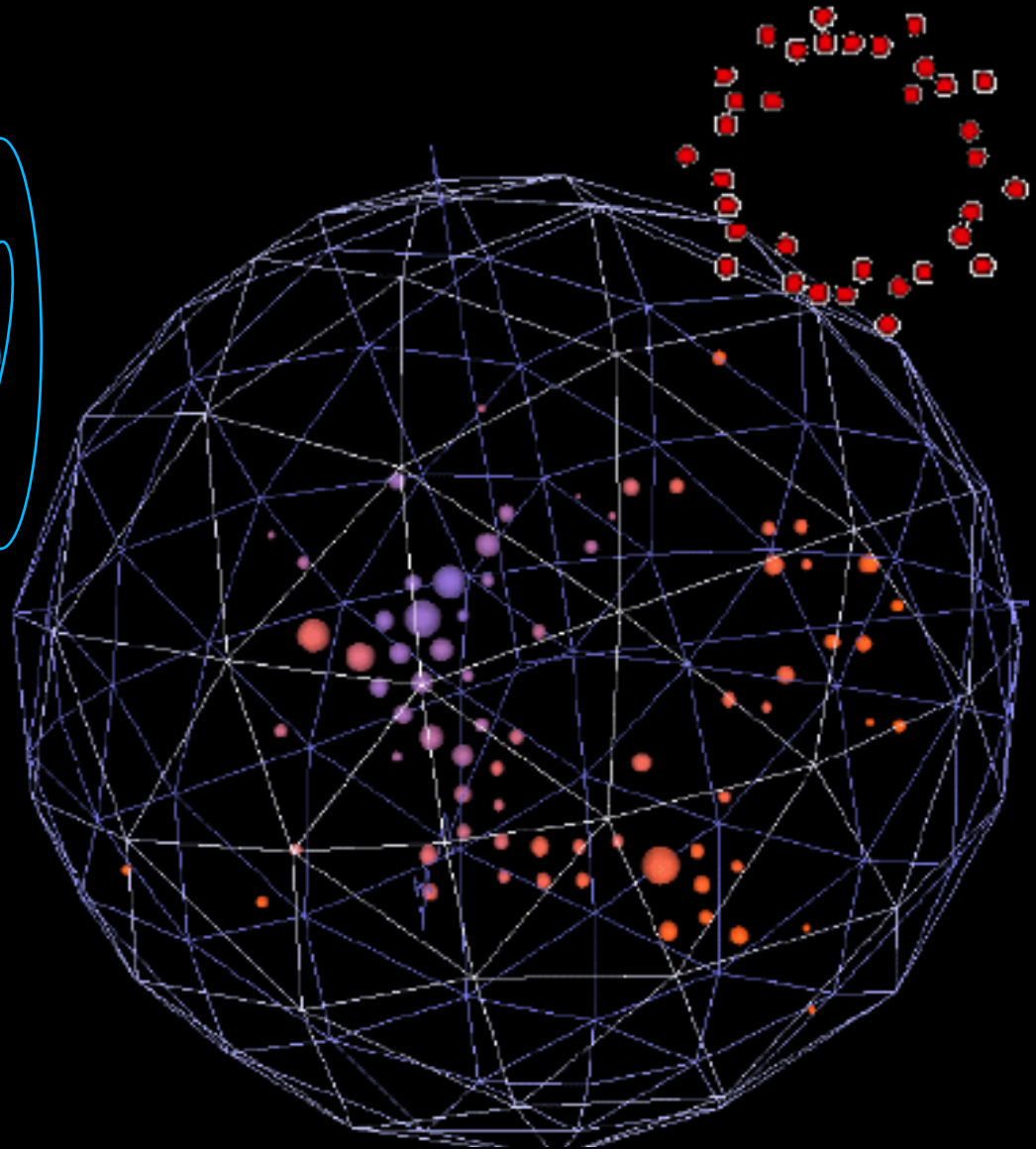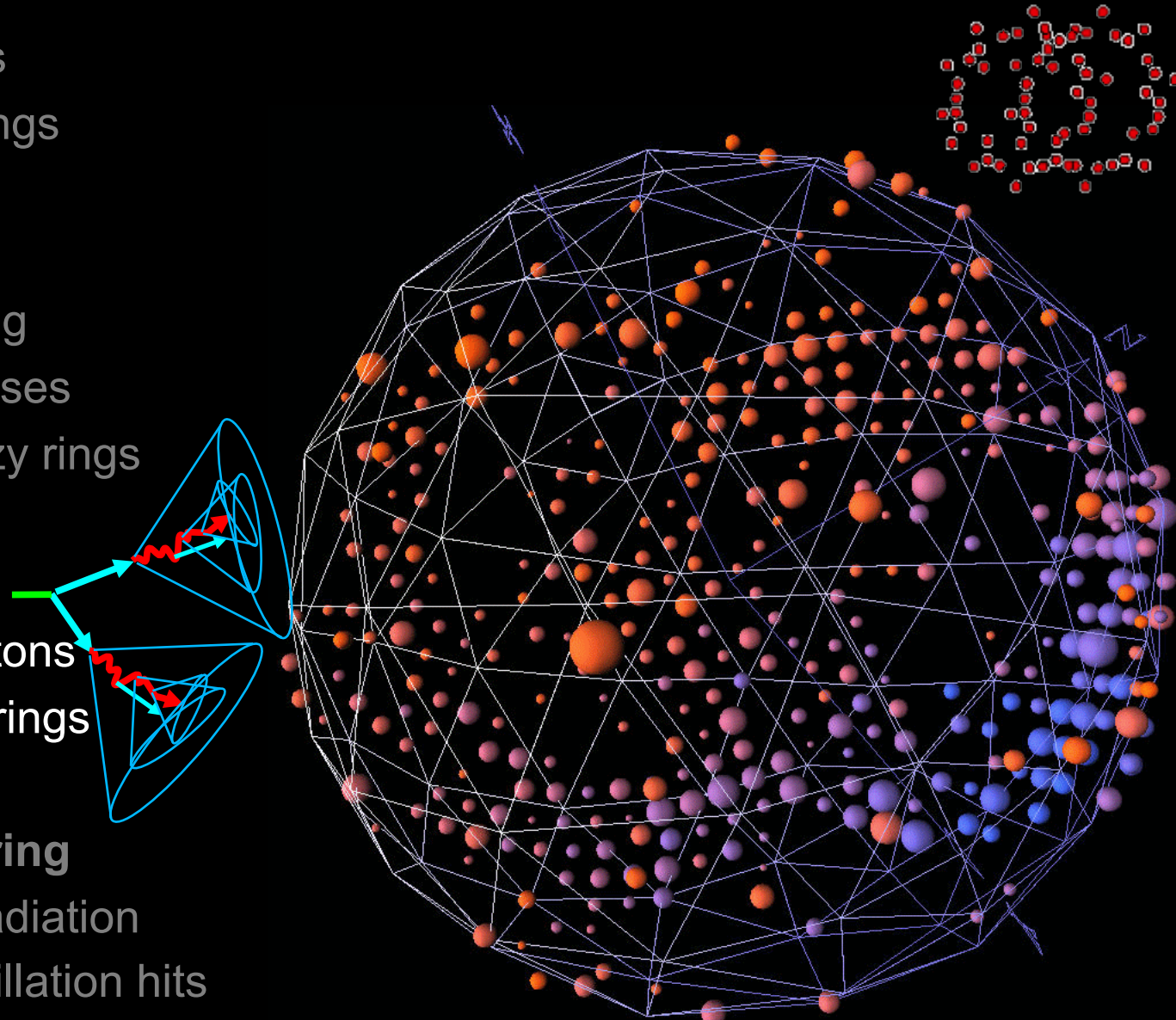
- Radiative processes

  → Scattered fuzzy rings

Neutral pions

- Decays to 2 photons

  → Double fuzzy rings

NC elastic scattering

- No Cherenkov radiation

  → Isotropic scintillation hits

Muons

- Long strait tracks

  → Sharp clear rings
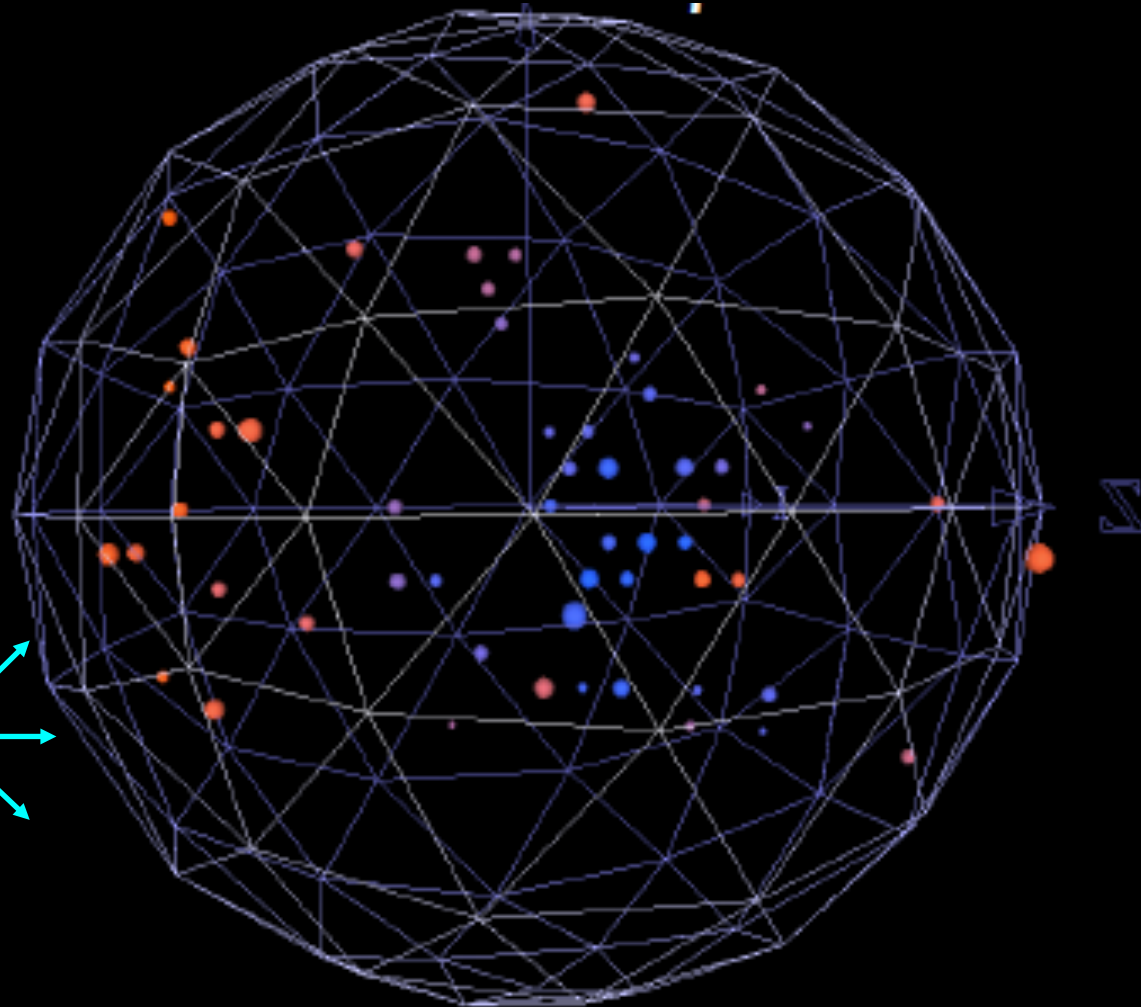
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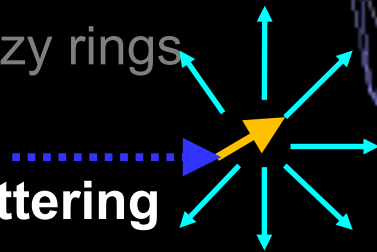
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  → Isotropic scintillation hits

MiniBooNE: PRL100(2008)032301

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

# 3. QE kinematics based energy reconstruction

Event reconstruction from Cherenkov ring profile for PID
- scattering angle θ and kinetic energy of charged lepton T are estimated

Charged Current Quasi-Elastic (CCQE) interaction
The simplest and the most abundant interaction around ~1 GeV. Neutrino energy is reconstructed from the observed lepton kinematics "QE assumption"
1. assuming neutron at rest
2. assuming interaction is CCQE

$$\nu_\mu + n \longrightarrow p + \mu^- \ (\nu_\mu + X \longrightarrow X' + \mu^-)$$
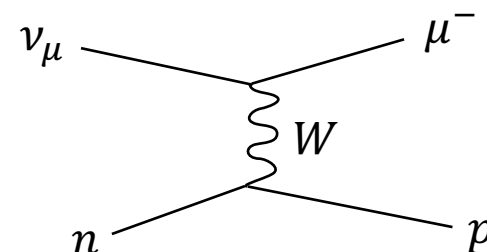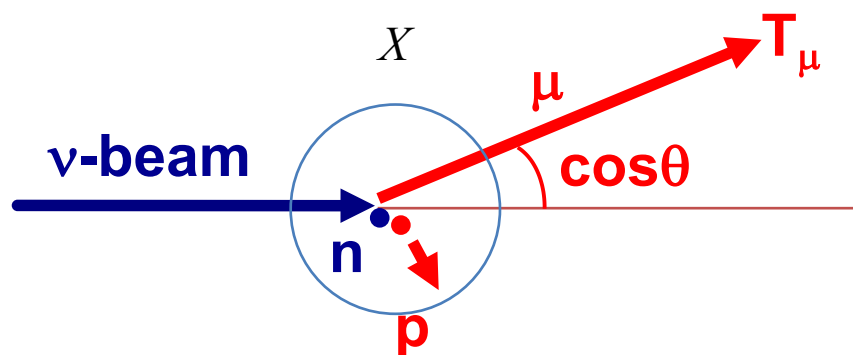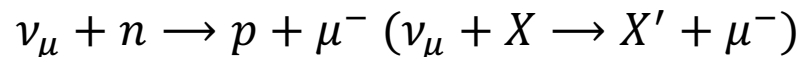
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

CCQE is the most important channel of neutrino oscillation physics for MiniBooNE, T2K, microBoonE, SBND, etc (also important for NOvA, Hyper-Kamiokande, DUNE, etc)
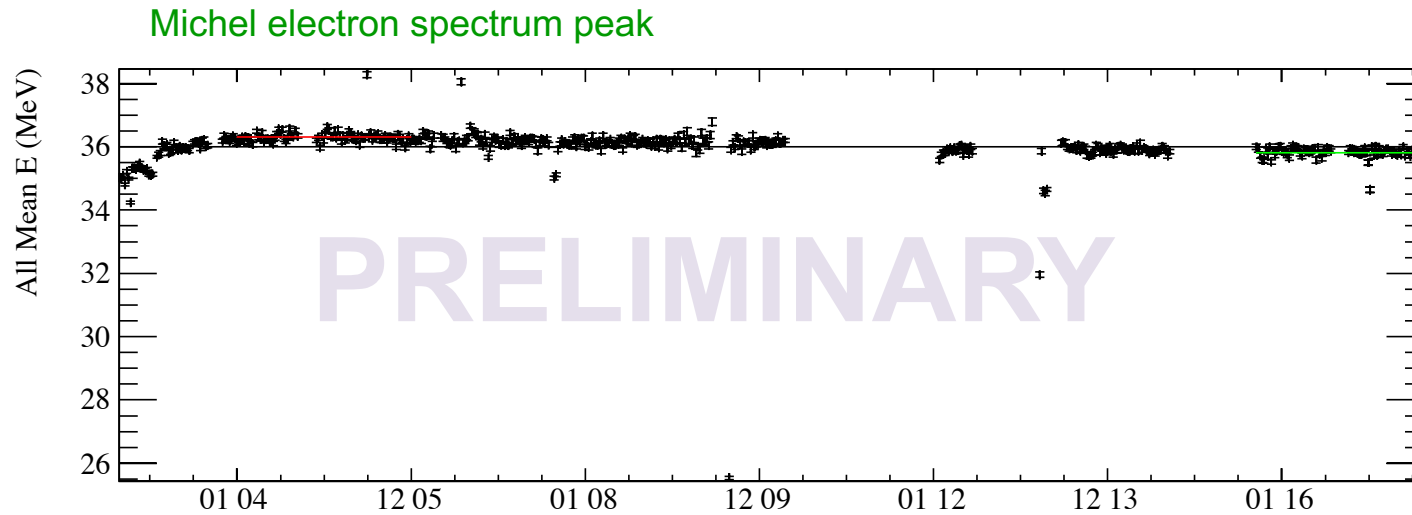
3. Detector stability

Event rate look consistent from expectations
- Antineutrino mode (factor 5 lower event rate)
  - factor ~2 lower flux
  - factor ~2-3 lower cross section
- Dark matter mode (factor 50 lower event rate) MiniBooNE, PRL118(2017)221803
  - factor ~40 lower flux
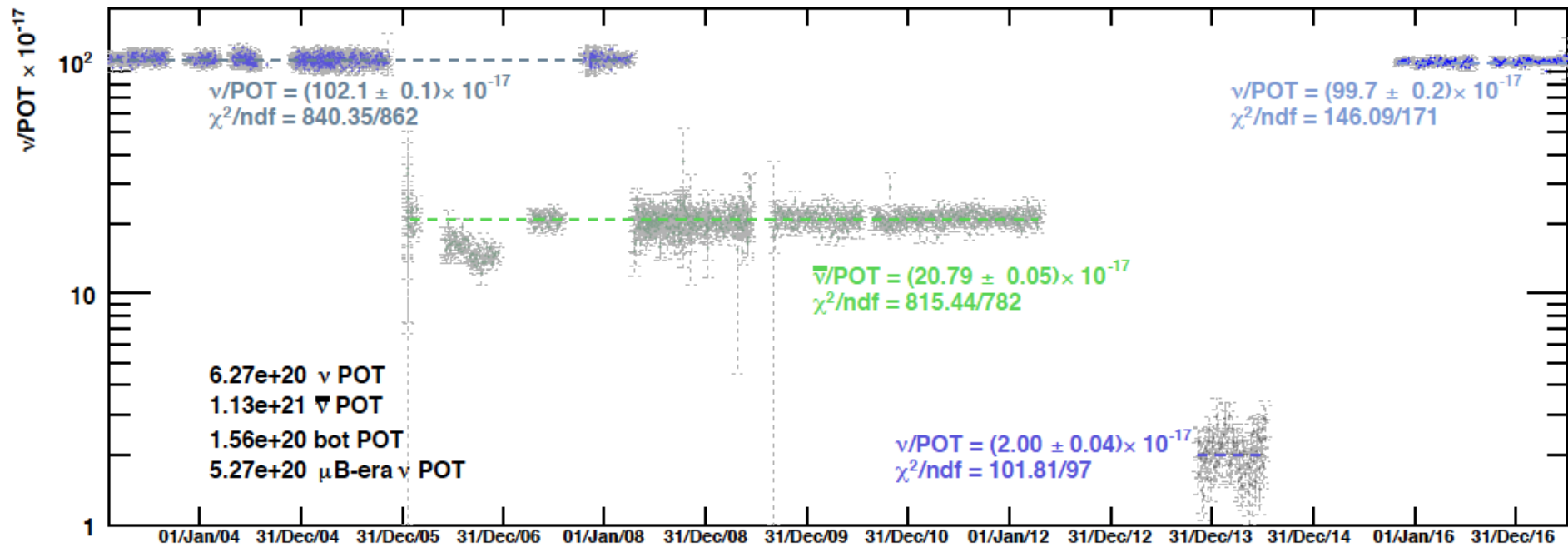
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3. Detector stability

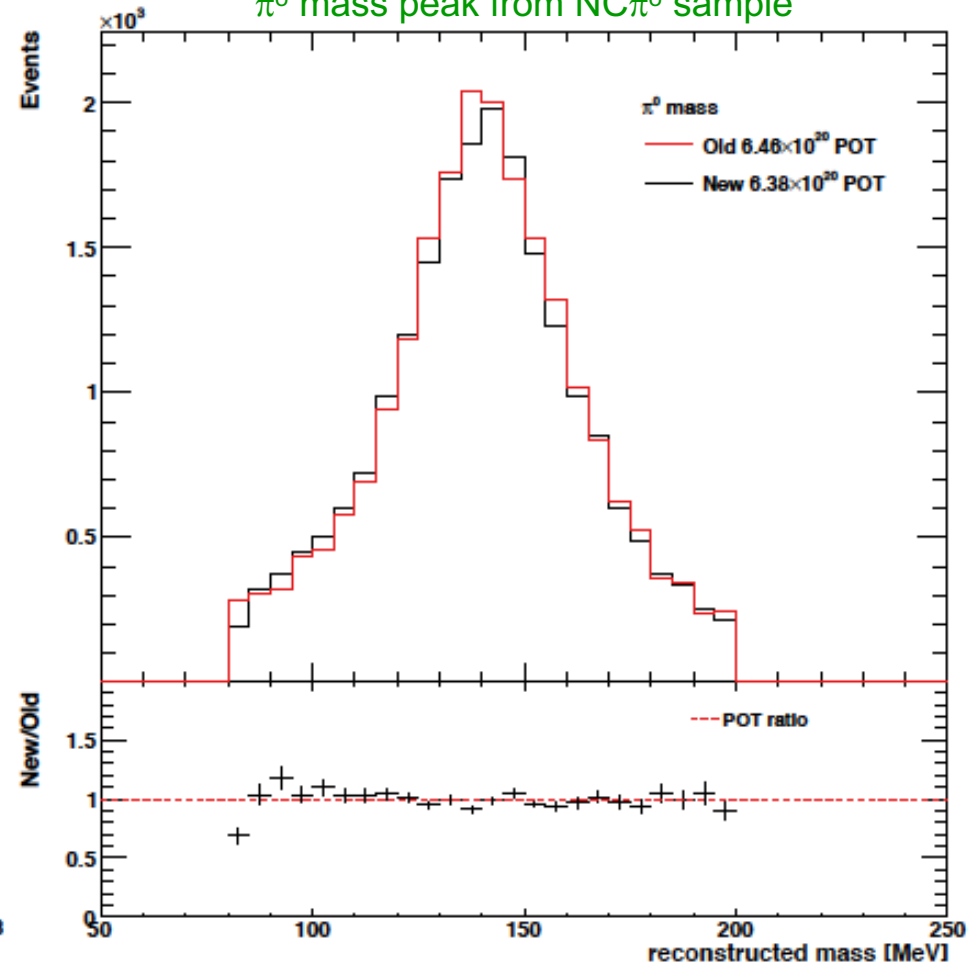Old and new data agree within 2% over 8 years separation.

Michel electron spectrum peak

3. Detector stability

Old and new data agree within 2% over 8 years separation.

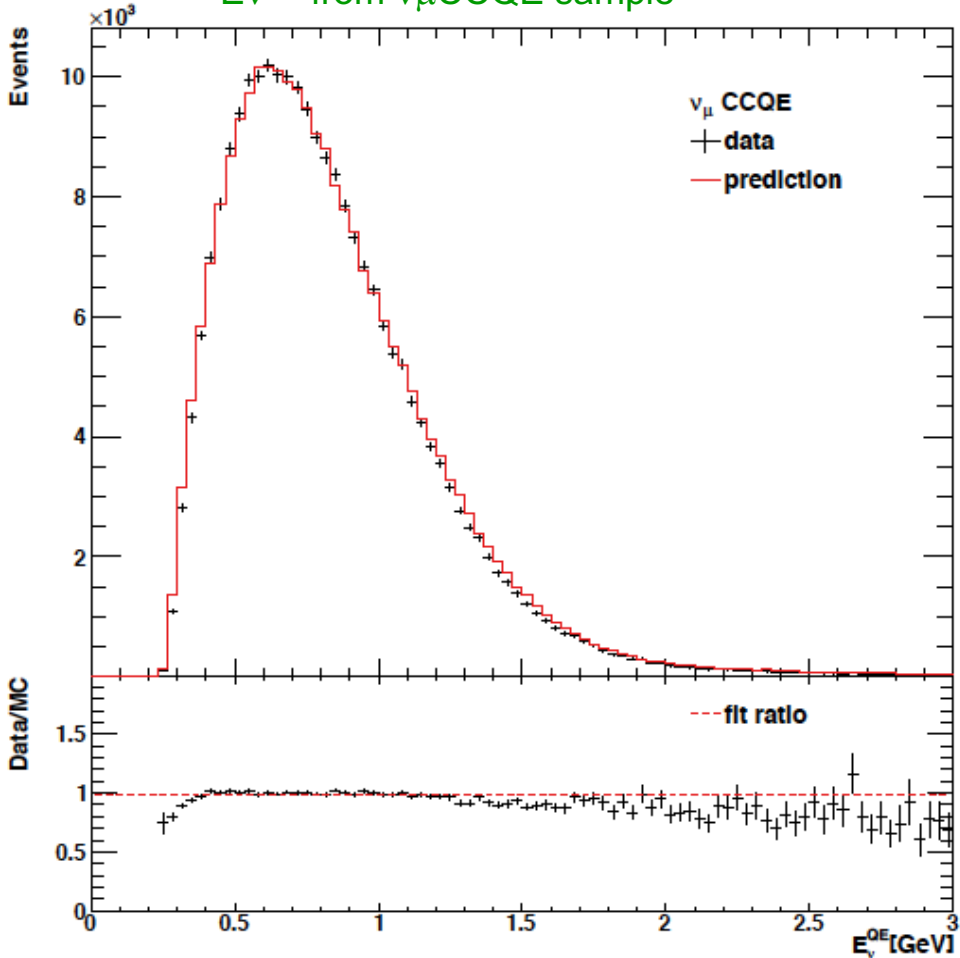Eν^{QE} from νμCCQE sample
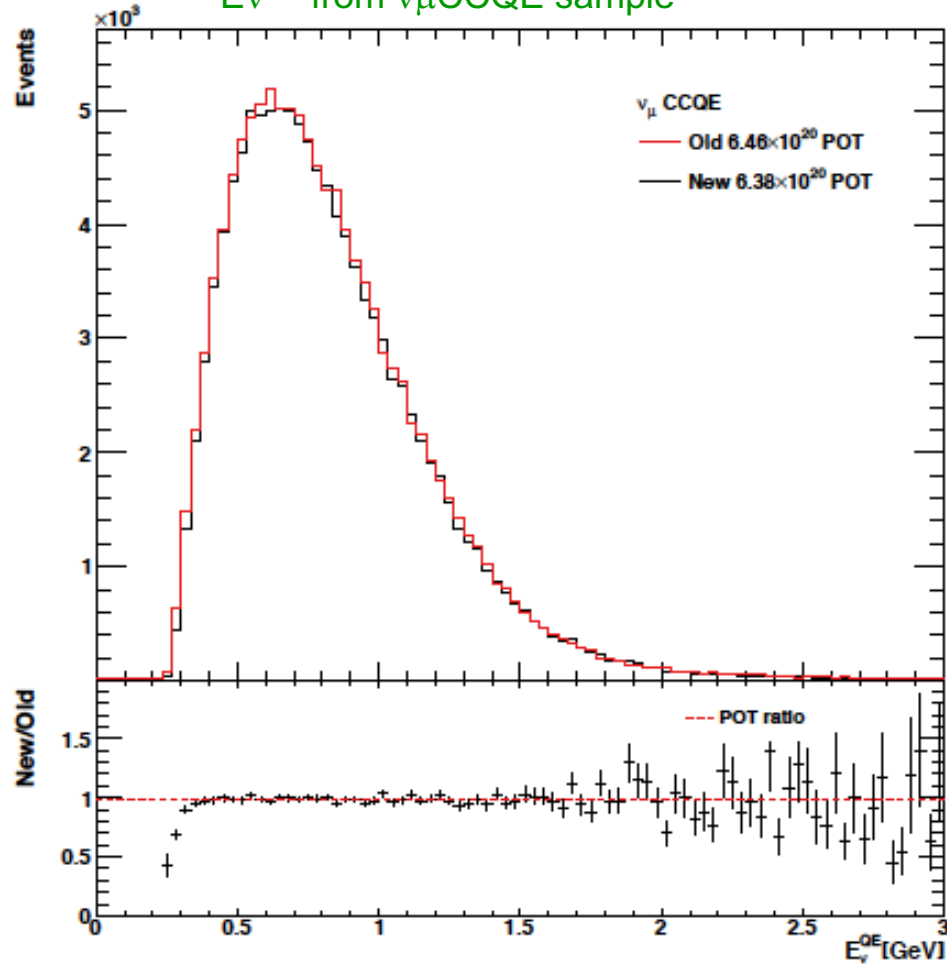
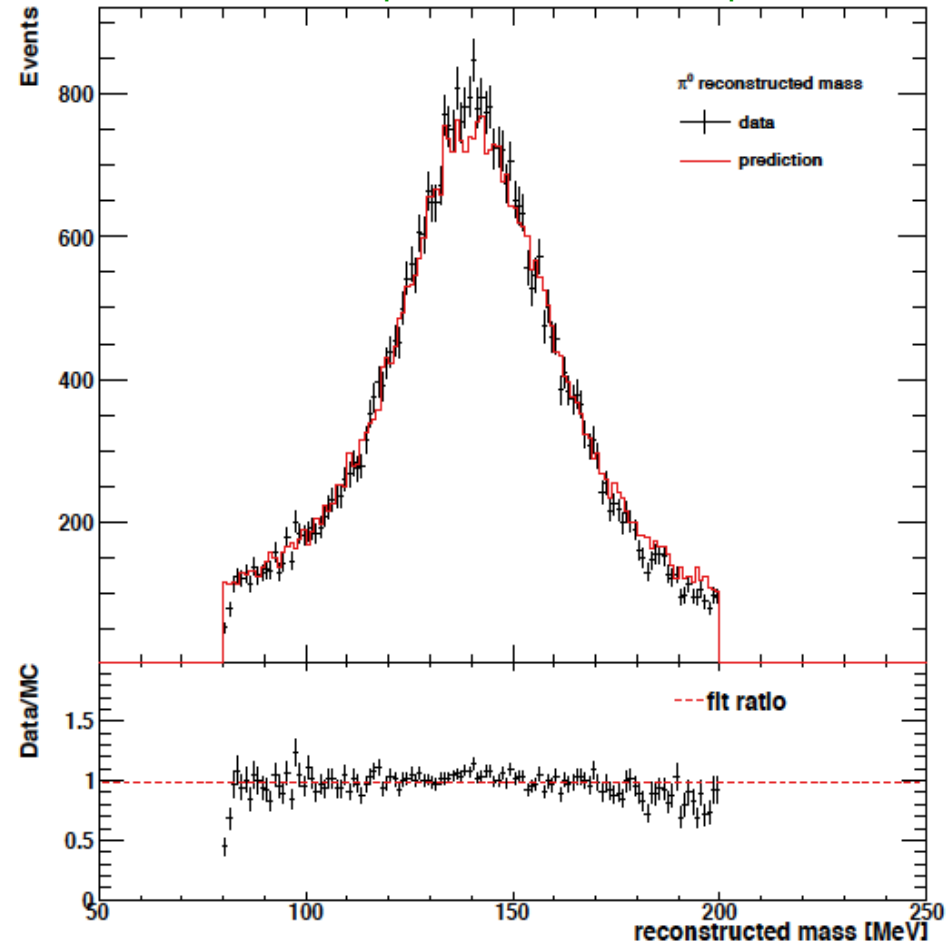π^o mass peak from NCπ^o sample

3. Data-Simulation comparison

Old and new data agree within 2% over 8 years separation.
- Excellent agreements with MC.

Eν^{QE} from $\nu\mu$CCQE sample

π^o mass peak from NCπ^o sample

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector
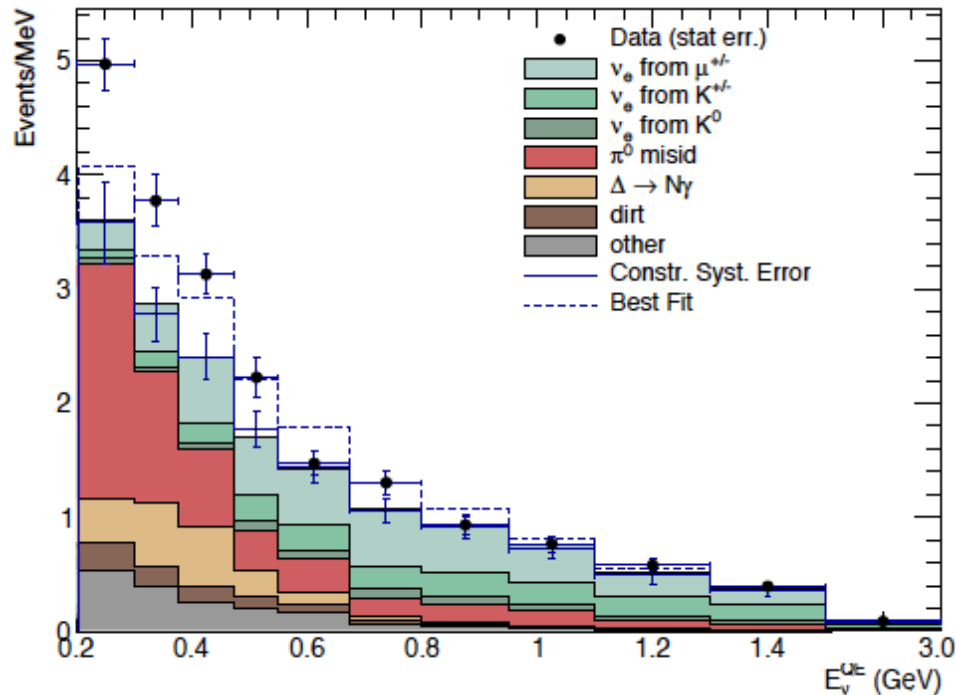
4. Oscillation candidate search

5. Discussion

4. Internal background constraints

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
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Unconstrained Bkgd.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

misID

intrinsic

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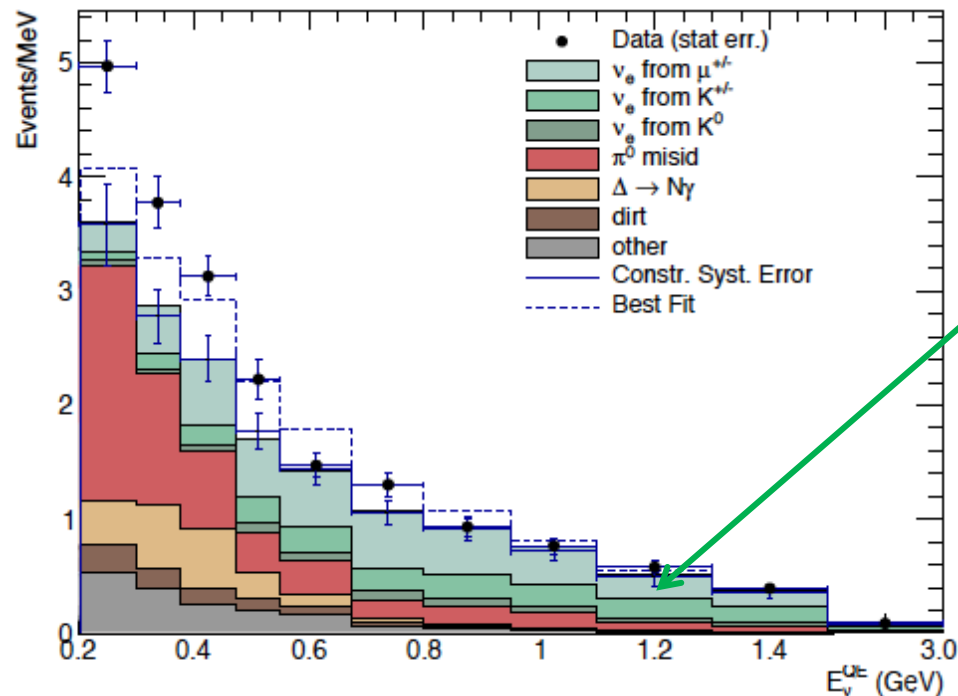→ misID (gamma) = accumulate at low E

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4. ν_e from μ-decay constraint

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ν_e from μ decay is constrained from ν_μCCQE measurement

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4. ν_e from μ-decay constraint

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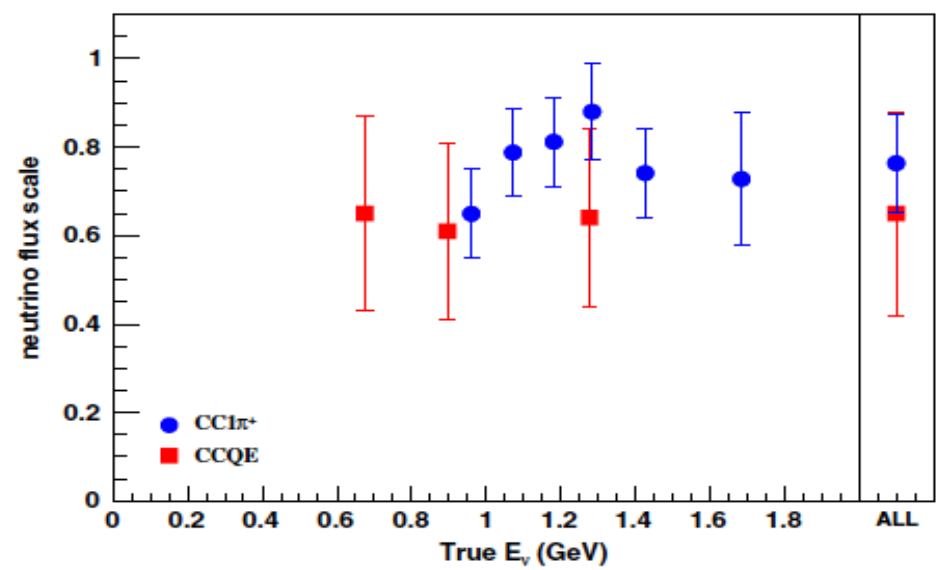→ intrinsic (beam ν_e) = flat
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$$\pi^+ \longrightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \boxed{\nu_e}$$

measured

$$\pi^- \longrightarrow \mu^- + \boxed{\bar{\nu}_\mu}$$
$$\mu^- \longrightarrow e^- + \nu_\mu + \boxed{\bar{\nu}_e}$$

guessed

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.

MiniBooNE, PRD84(2011)072005

1. MiniBooNE
2. Beam
3. Detector
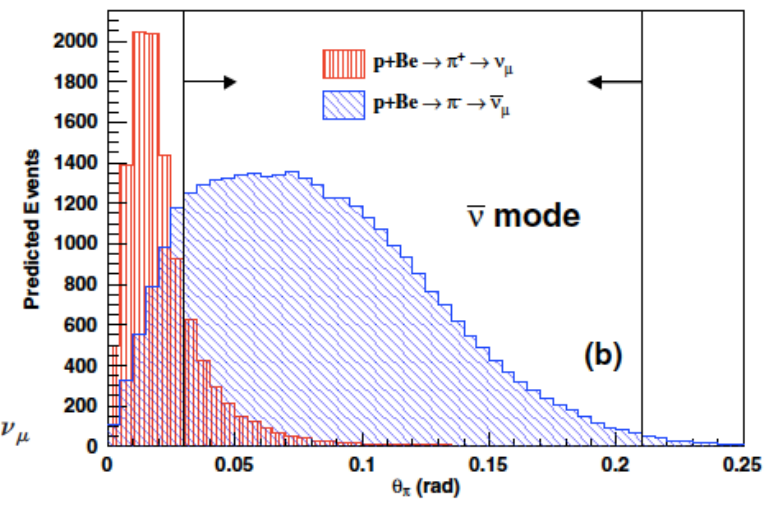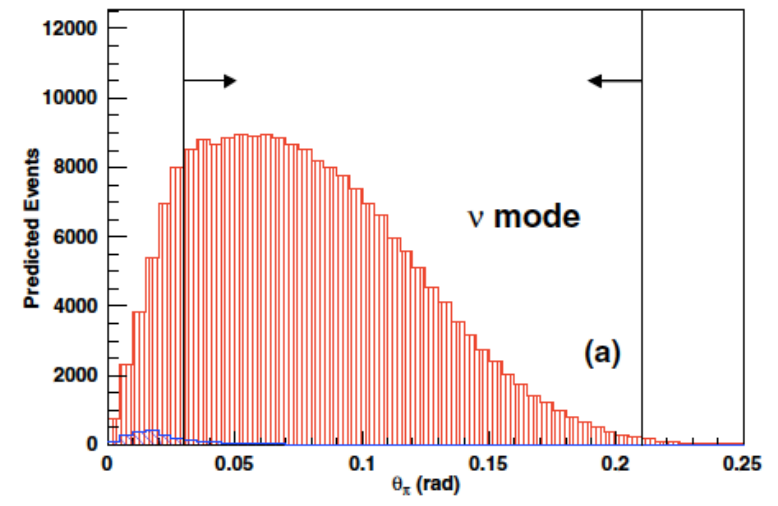4. Oscillation
5. Discussion
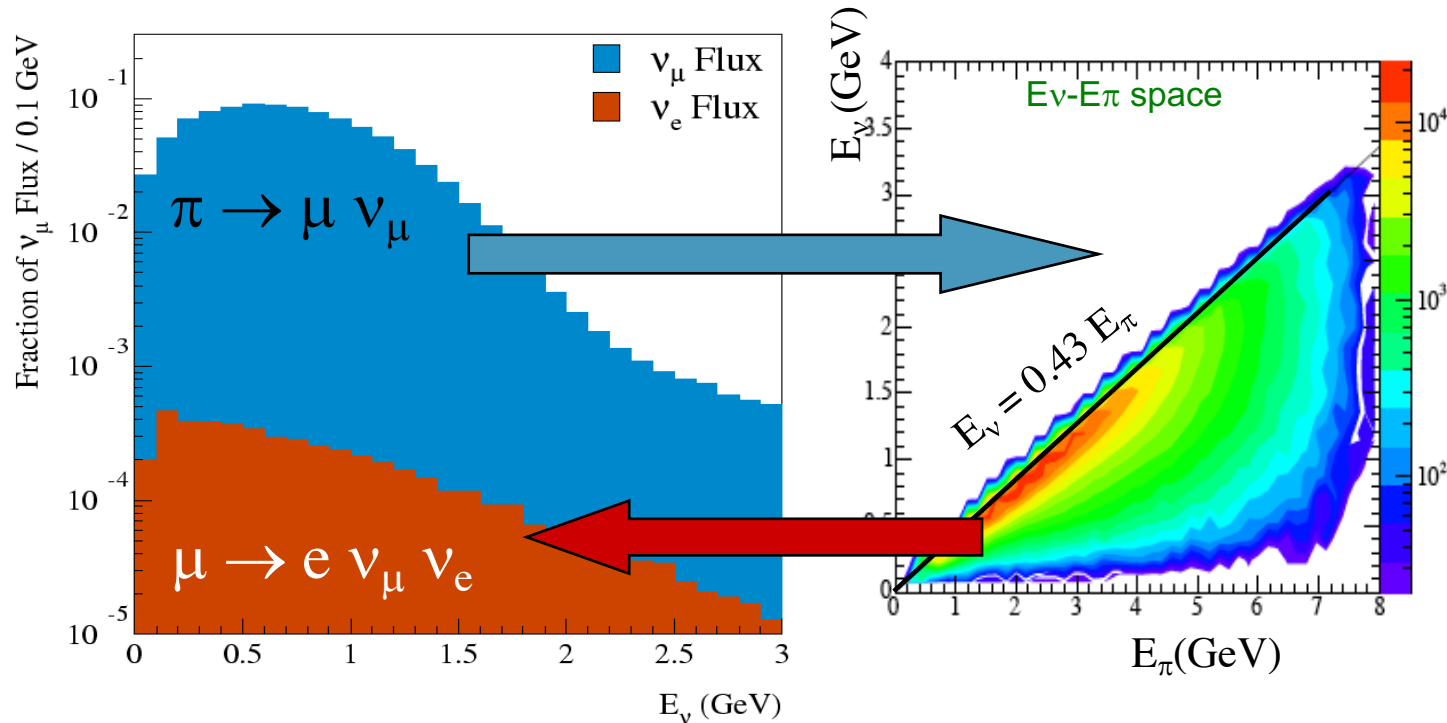
4. Anti-neutrino mode flux tuning

$\bar{\nu}_e$ & $\bar{\nu}_\mu$ flux are harder to predict due to larger wrong sign (ν_e & ν_μ) 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

$$1: \quad \nu_\mu + p(n) \rightarrow \mu^- + p(n) + \pi^+ \hookrightarrow \mu^+ + \nu_\mu$$
$$2: \quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$3: \quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$
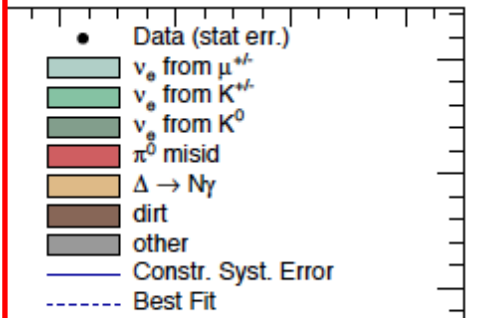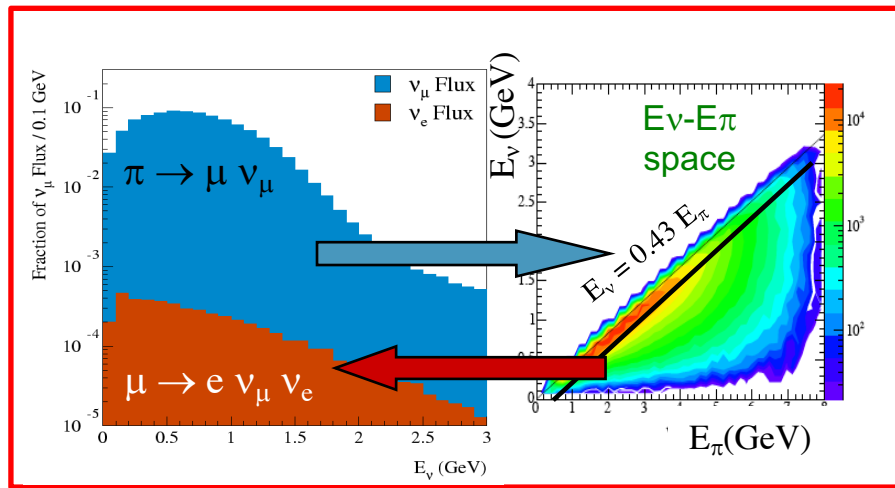
PHYSICAL REVIEW D 84, 072005 (2011)

4. ν_e from μ-decay constraint

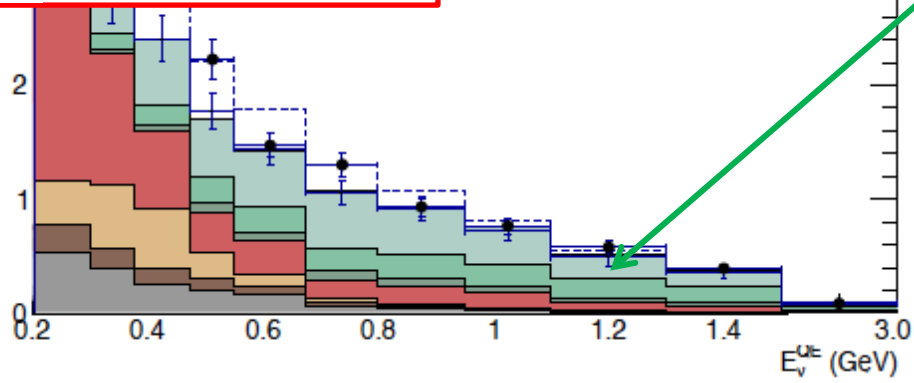All backgrounds are internally constrained
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ν_e from μ decay is constrained from ν_μ CCQE measurement
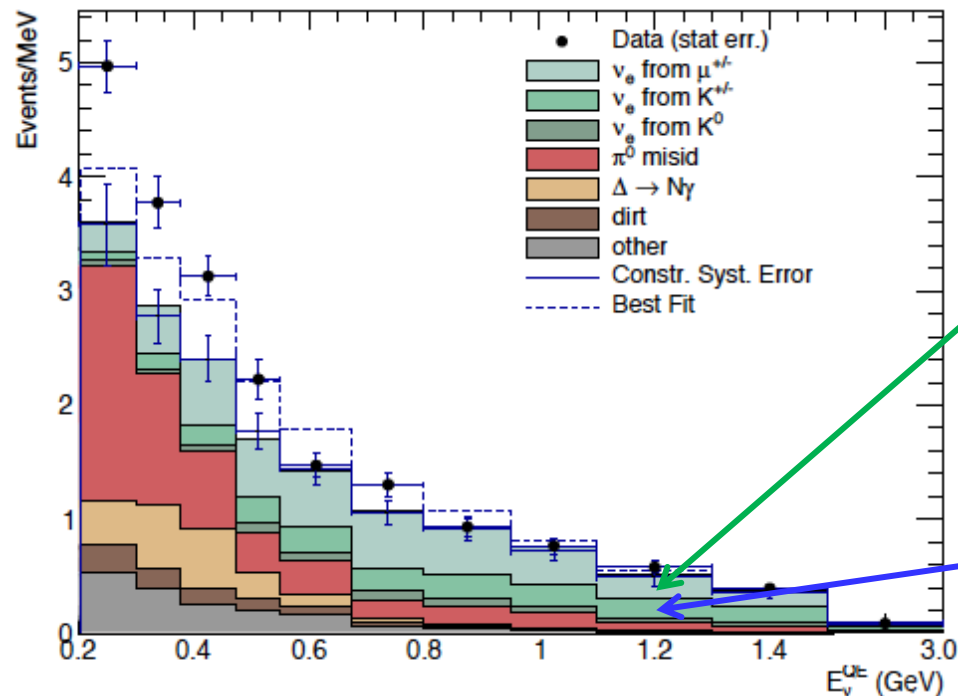
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4. ν_e from K^+-decay constraint

All backgrounds are internally constrained
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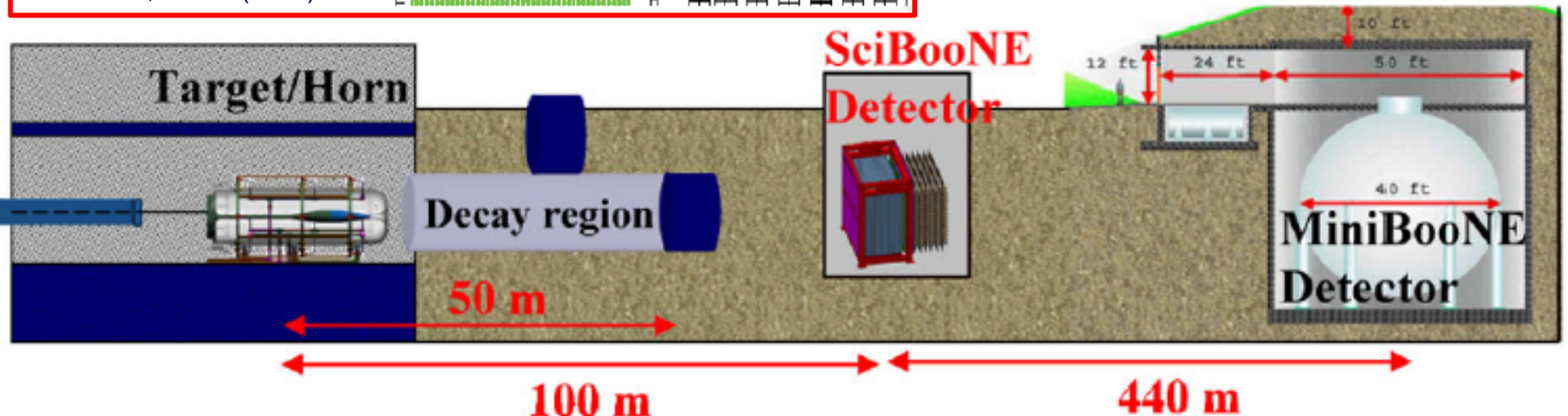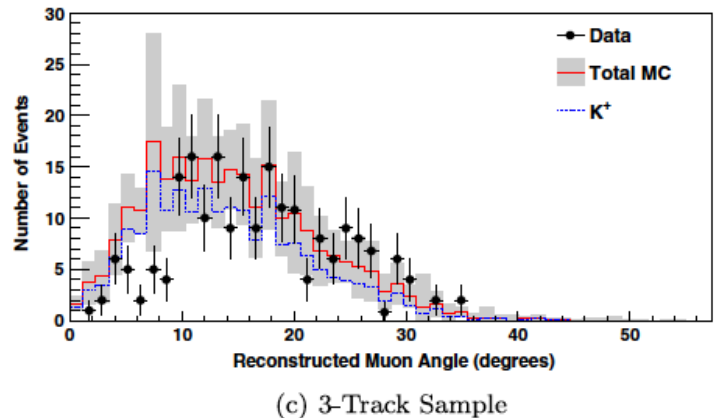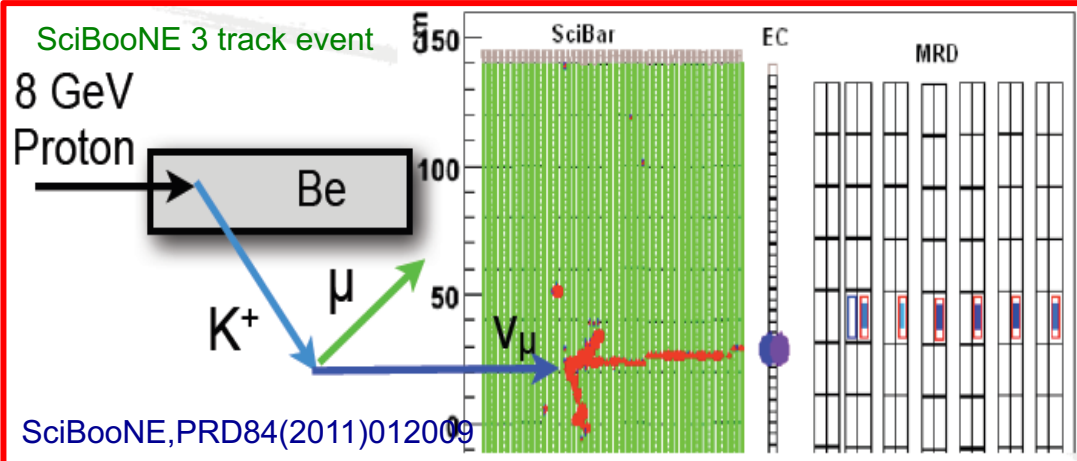| Process	Neutrino Mode	Antineutrino Mode
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ν_e from μ decay is constrained from ν_μCCQE measurement

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

SciBooNE,PRD84(2011)012009

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

4. ν_e from K$^+$-decay constraint

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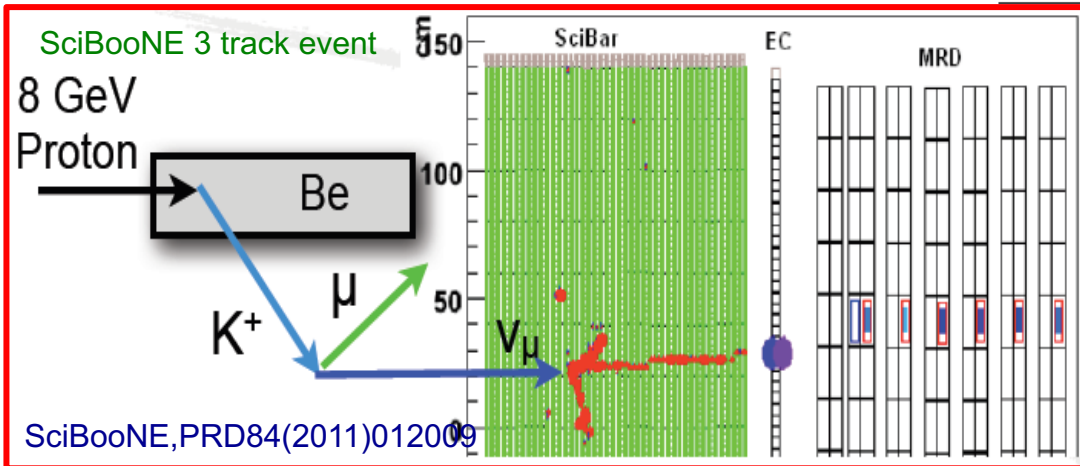

(c) 3-Track Sample

4. ν_e from K^+-decay constraint
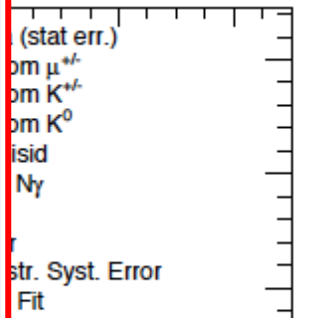
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SciBooNE 3 track event

8 GeV Proton

Be

μ

K^+

ν_μ

SciBar   EC   MRD

SciBooNE,PRD84(2011)012009

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

E_ν^{QE} (GeV)

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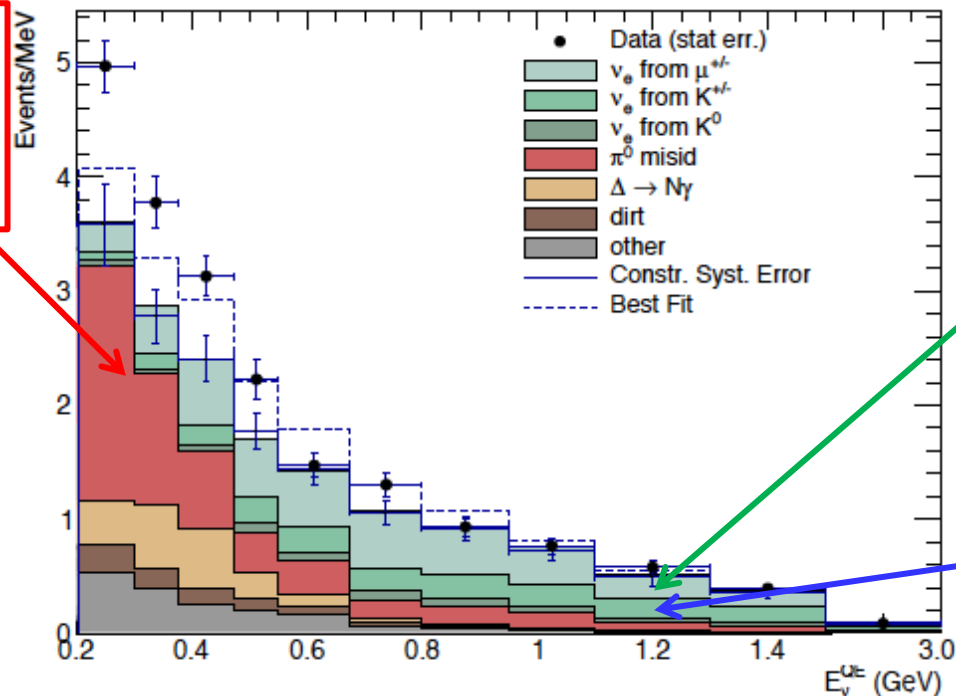# 4. ν_e from K$^+$-decay constraint

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

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

MiniBooNE, PLB664(2008)41

1. MiniBooNE
2. Beam
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4. Oscillation
5. Discussion

4. γ from π⁰ constraint

π⁰→γγ
 - not background, we can measure
π⁰→γ
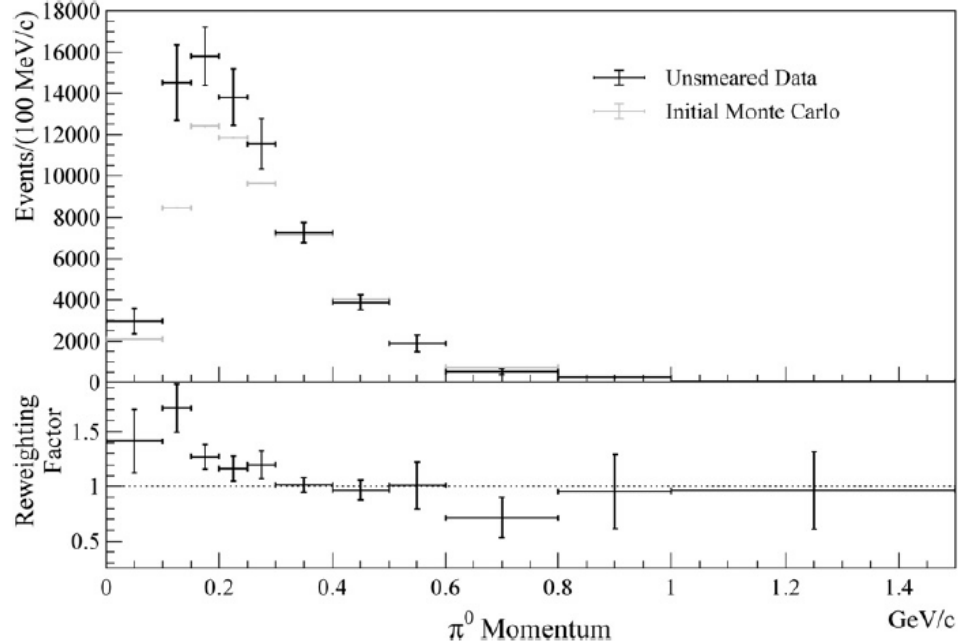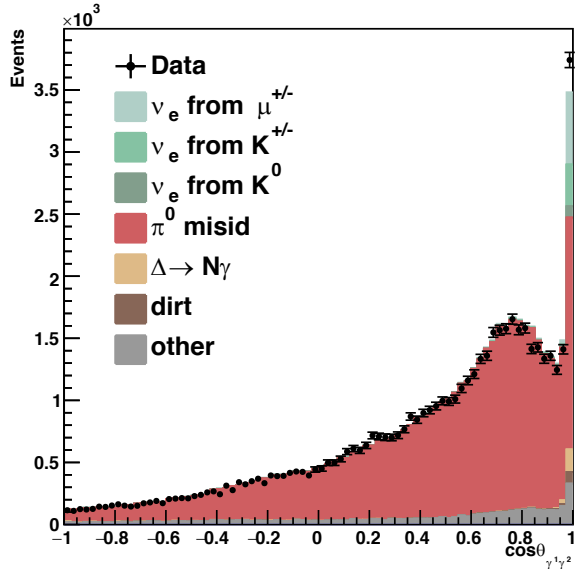 - misID background, we cannot measure

The biggest systematics is production rate of π⁰, because once you find that, the chance to make a single gamma ray is predictable.

We measure π⁰ production rate, and correct simulation with function of π⁰ momentum

π⁰ momentum data-MC comparison

2-gamma-ray opening angle

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MiniBooNE, PLB664(2008)41

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
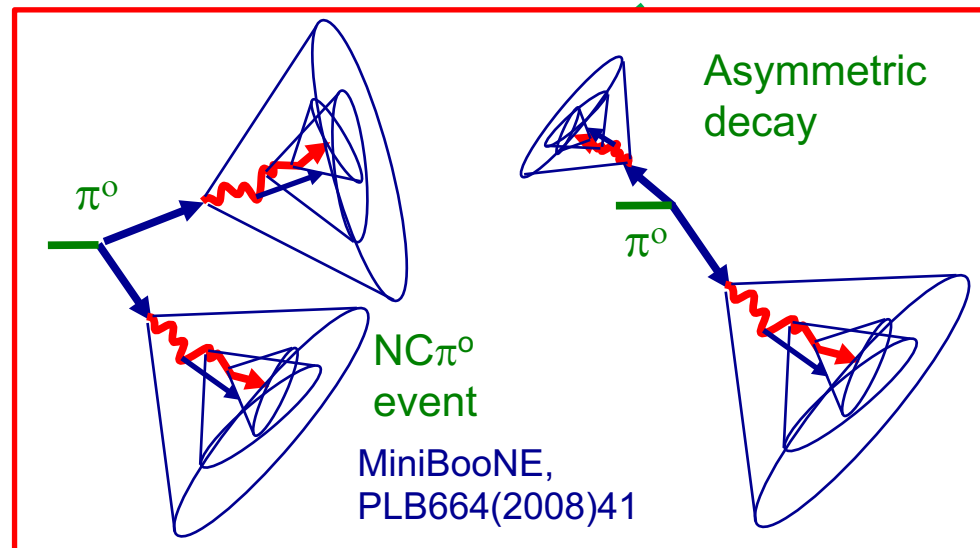5. Discussion

4. γ from π⁰ constraint

π⁰→γγ
 - not background, we can measure
π⁰→γ
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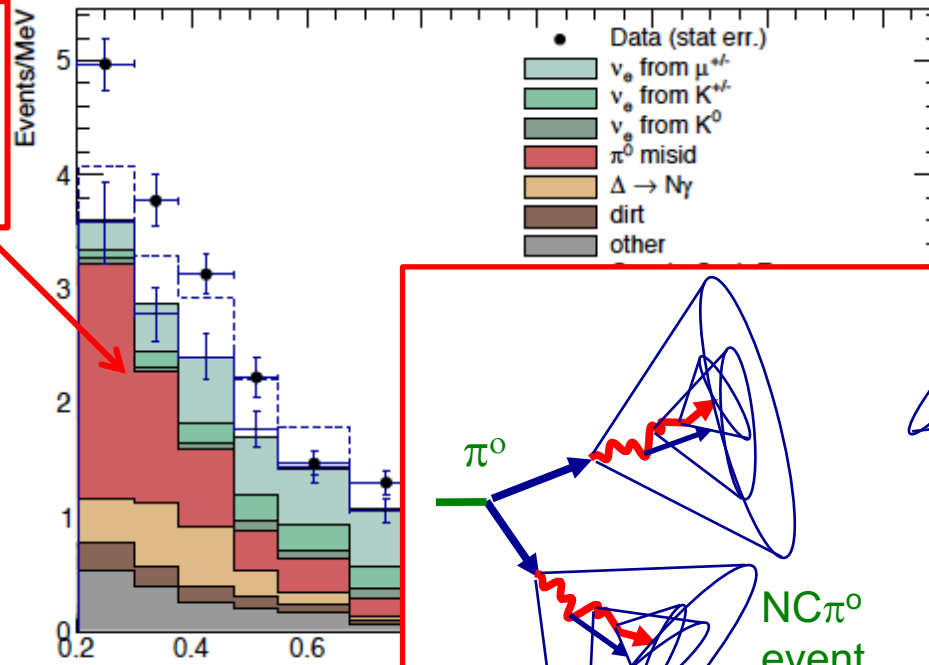
π⁰ momentum data-MC comparison

Asymmetric decay

π⁰

NCπ⁰ event

π⁰

MiniBooNE, PLB664(2008)41

![Queen Mary University of London logo]
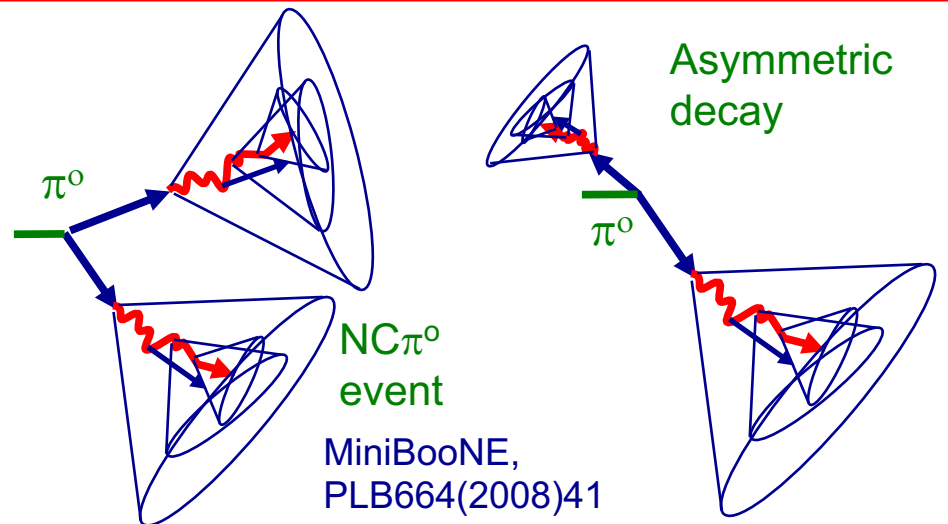
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Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

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

ν_e from μ decay is constrained from ν_μCCQE measurement

Asymmetric decay

NCπ^o event

π^o

π^o

MiniBooNE, PLB664(2008)41

Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
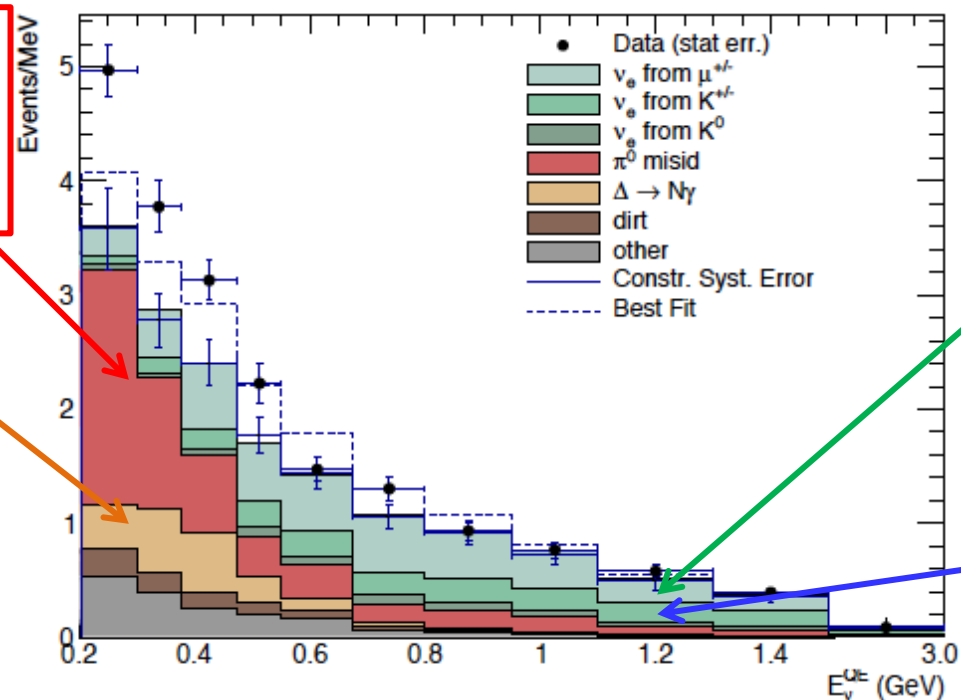$\Delta \to N\gamma$
dirt
other

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University of London

4. NCγ constraint

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
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.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
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Asymmetric π^0 decay is constrained from measured CCπ^0 rate ($\pi^0 \to \gamma$)

Δ resonance rate is constrained from measured NCπ^0 rate

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

4. NCγ constraint

All backgrounds are internally constrained
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Bkgd.	1590.5	398.2
Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
ta	1959	478
	381.2 ± 85.2	79.3 ± 28.6

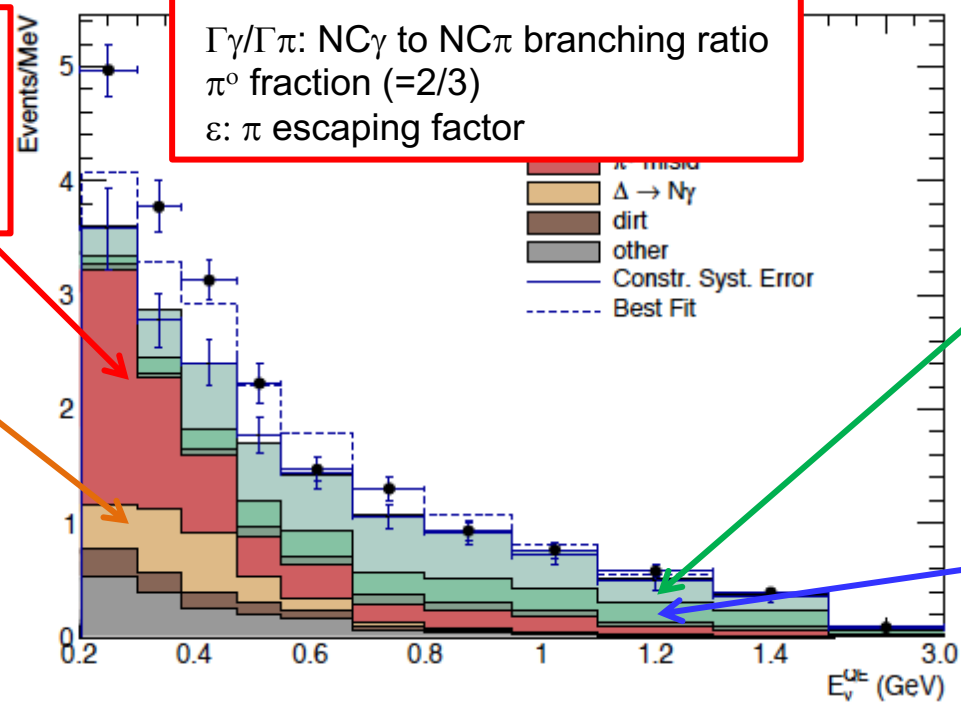$$\frac{N(\Delta \to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

$\Gamma\gamma/\Gamma\pi$: 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

ν_e from μ decay is constrained from ν_μCCQE measurement

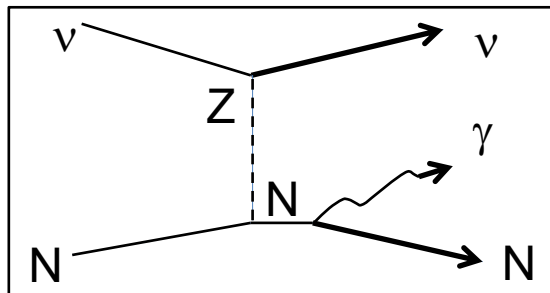ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

Queen Mary
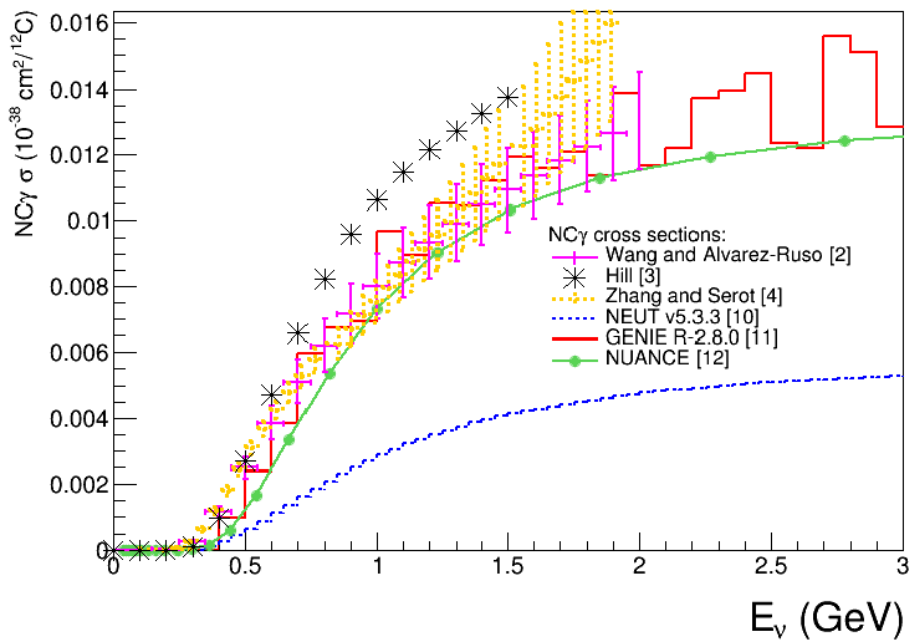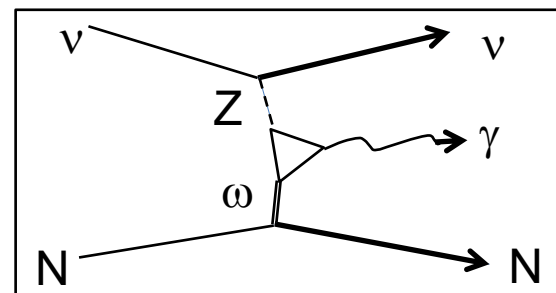University of London

4. Neutrino NC single gamma production

radiative Δ-decay
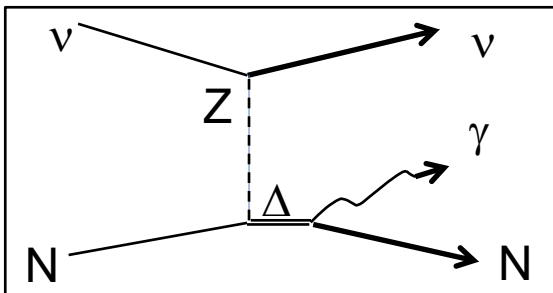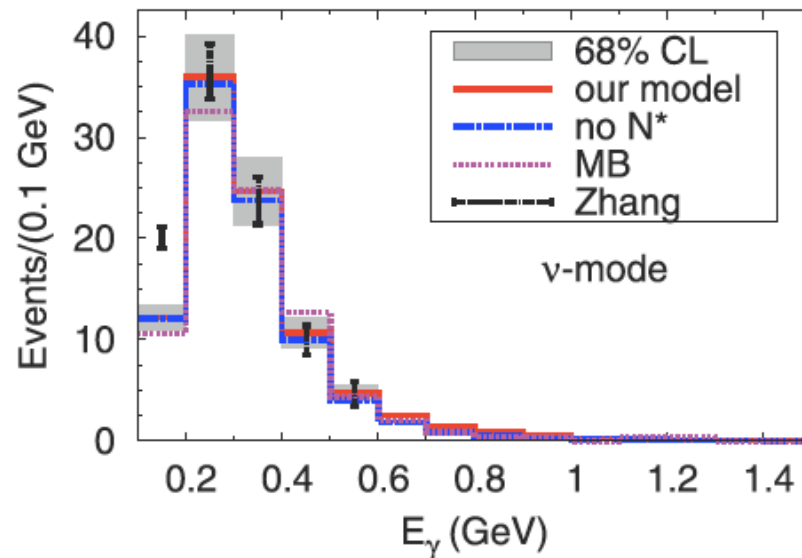
generalized Compton scattering

anomaly mediated triangle diagram

A lot of new calculations
- all theoretical models and generators more or less agree. NEUT has been fixed.
- Surprisingly, they are more or less consistent with MiniBooNE NCγ model

4. NCγ constraint

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
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ν_e & $\bar\nu_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
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ta	1959	478
	381.2 ± 85.2	79.3 ± 28.6

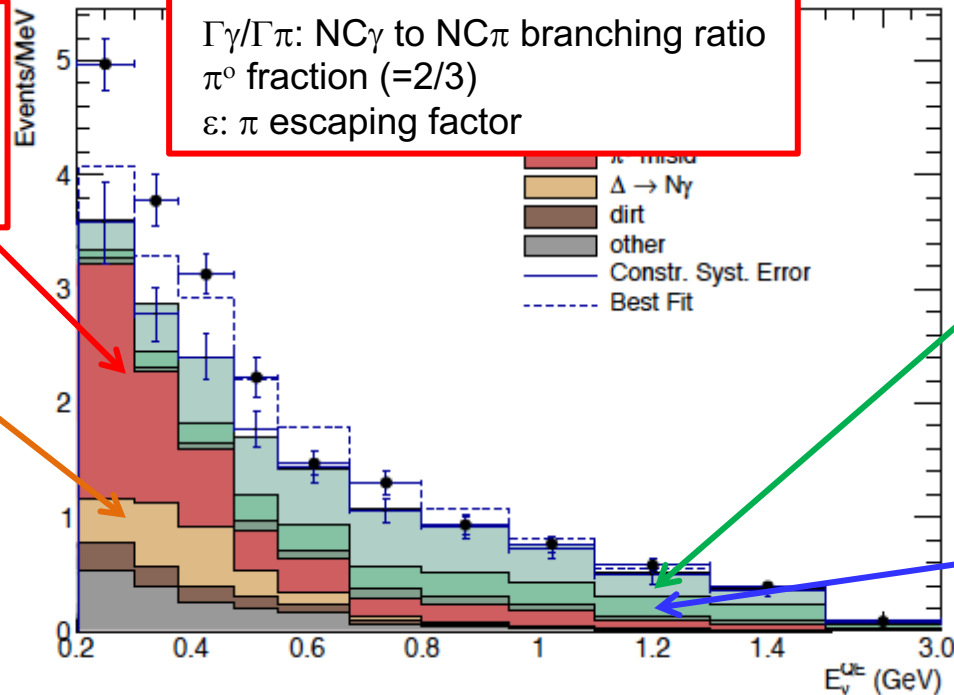$$\frac{N(\Delta \to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

$\Gamma\gamma/\Gamma\pi$: 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

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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4. External γ constraint

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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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_L^0 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.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

All backgrounds are internally constrained
 → intrinsic (beam ν_e) = flat
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Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

Δ resonance rate is constrained from measured NCπ^o rate

dirt rate is measured from dirt data sample

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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MniBooNE, PRD82(2010)092005

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
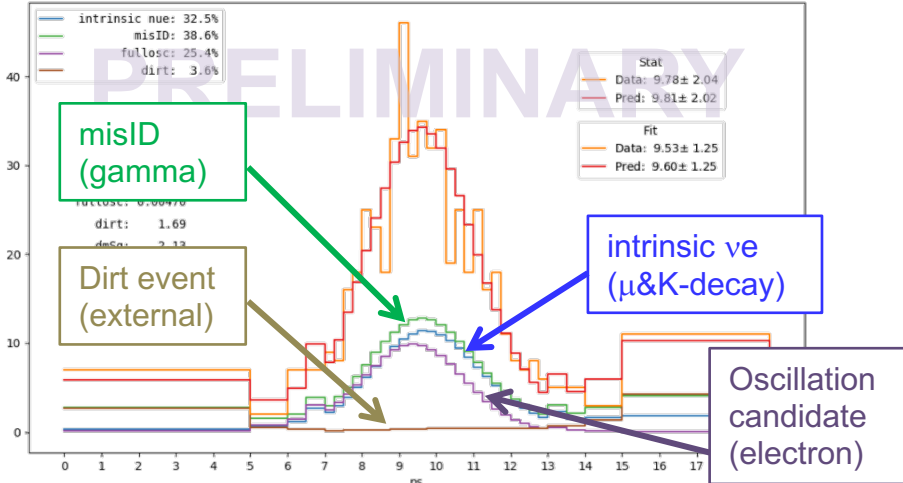5. Discussion

4. External γ constraint

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
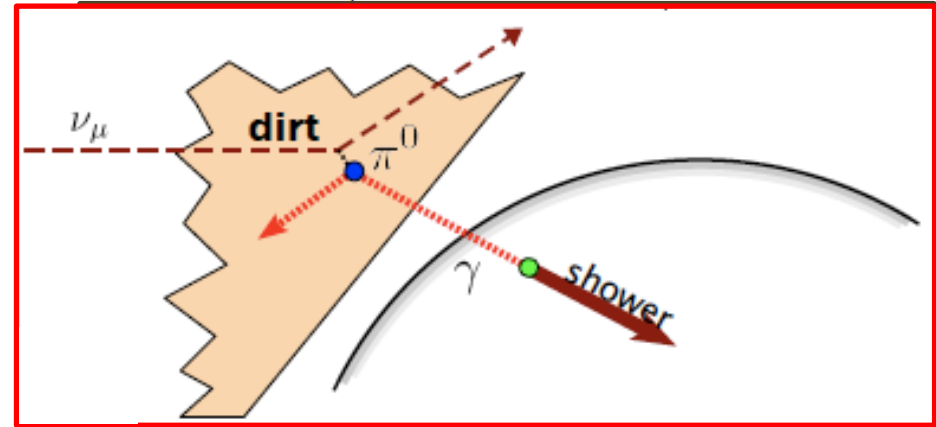Mis-modelling of external background is visible
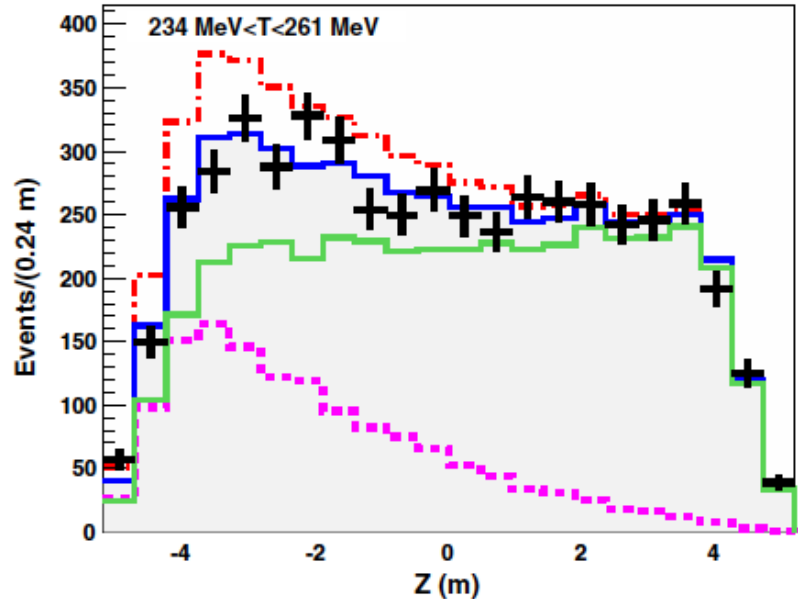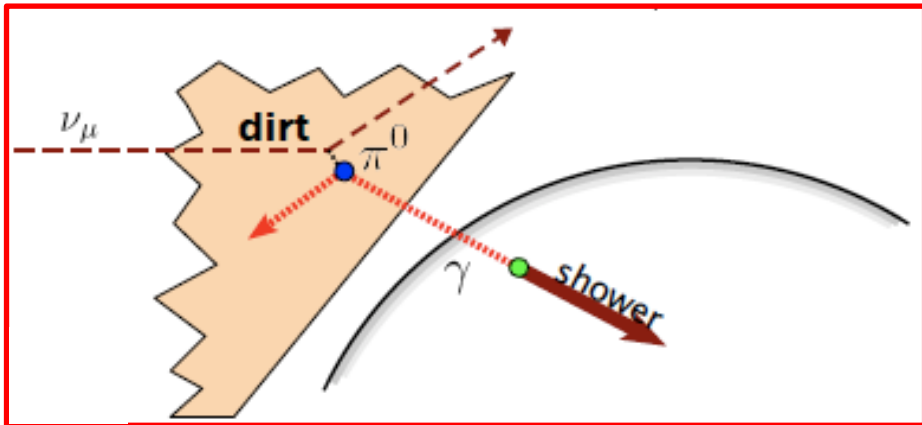
e.g.) Time of Flight
Dirt related events is consistent with ToF data including oscillation hypothesis

misID (gamma)

Dirt event (external)

intrinsic νe (μ&K-decay)

Oscillation candidate (electron)

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4. External γ constraint

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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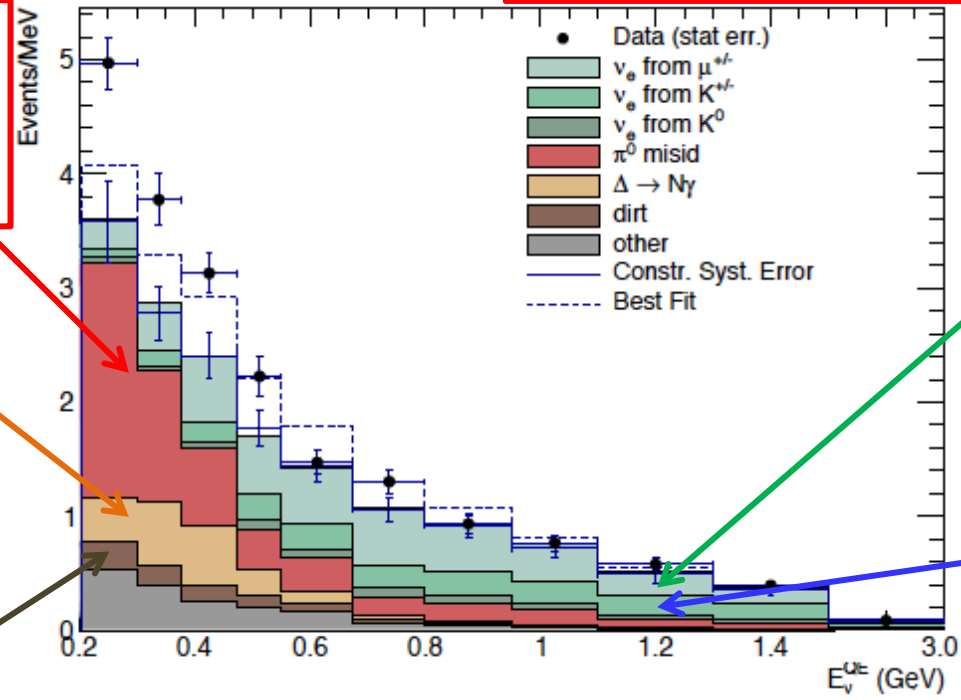 → misID (gamma) = accumulate at low E

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

dirt rate is measured from dirt data sample

ν_e from μ decay is constrained from ν_μCCQE measurement

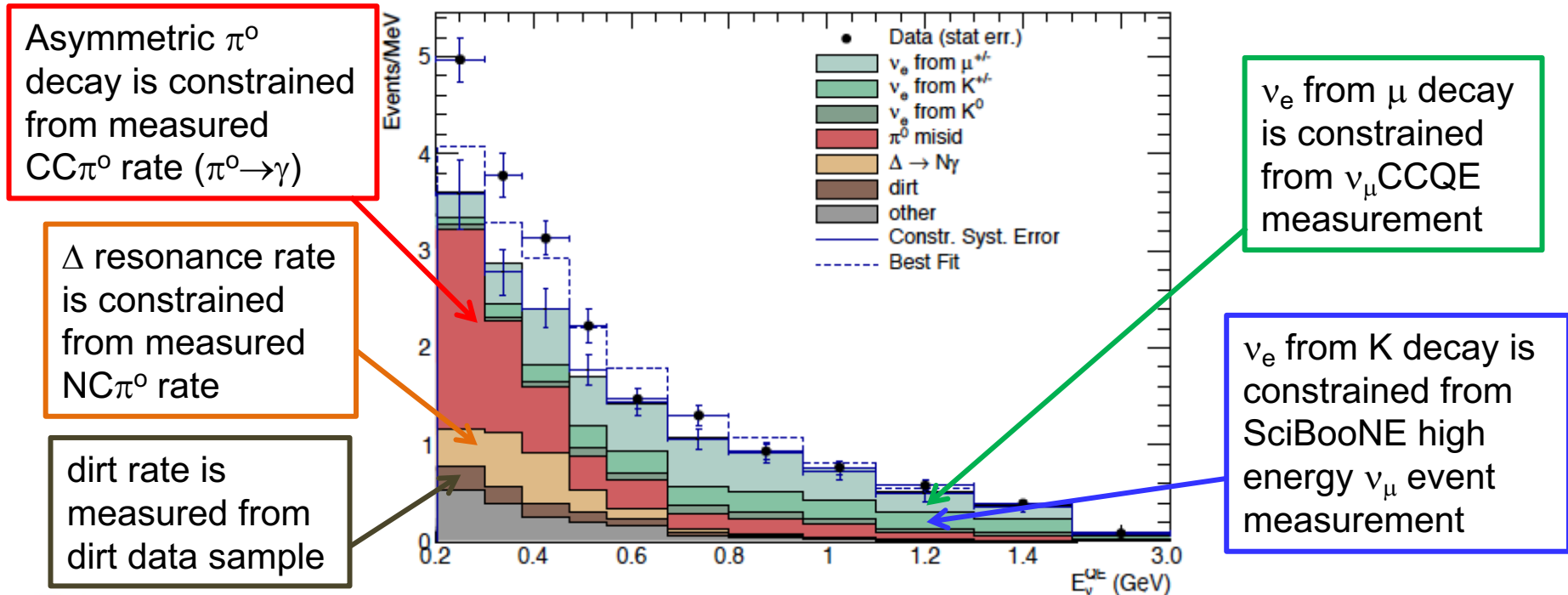ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

Legend:
- Data (stat err.)
- ν_e from $\mu^{+/-}$
- ν_e from $K^{+/-}$
- ν_e from K^0
- π^0 misid
- $\Delta \to N\gamma$
- dirt
- other
- Constr. Syst. Error
- Best Fit

Events/MeV

E_ν^{QE} (GeV)

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4. Internal background constraints

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

Δ resonance rate is constrained from measured NCπ^o rate

dirt rate is measured from dirt data sample

ν_e from μ decay is constrained from ν_μ CCQE measurement

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

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

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1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

5. Oscillation candidate event excess

200 < EνQE < 1250 MeV
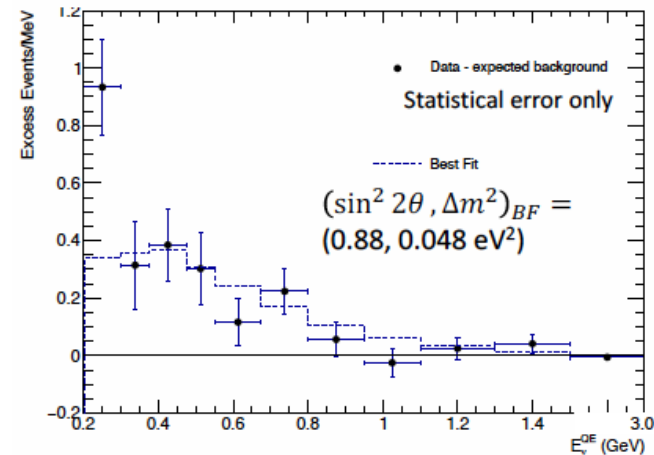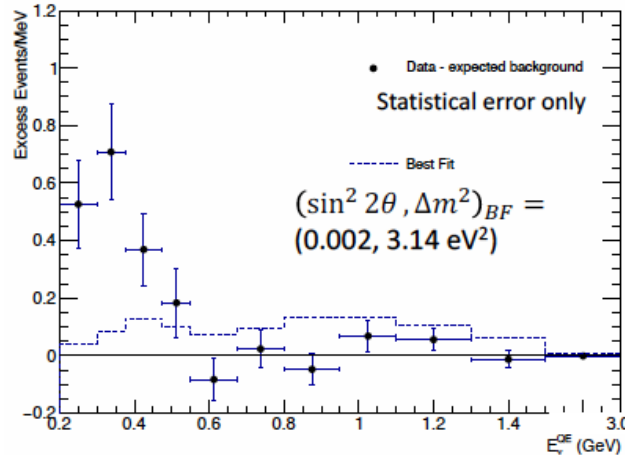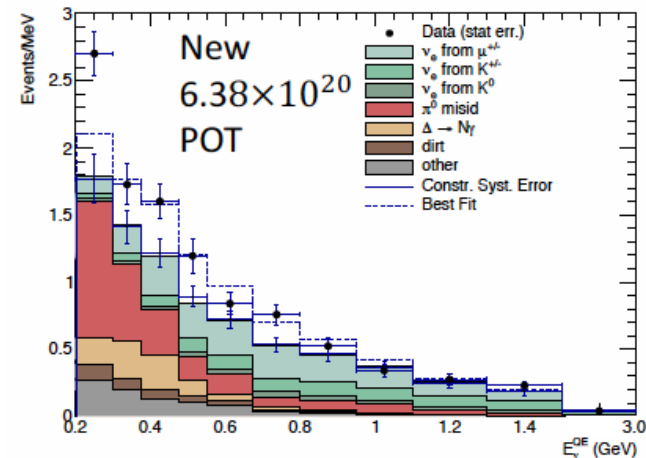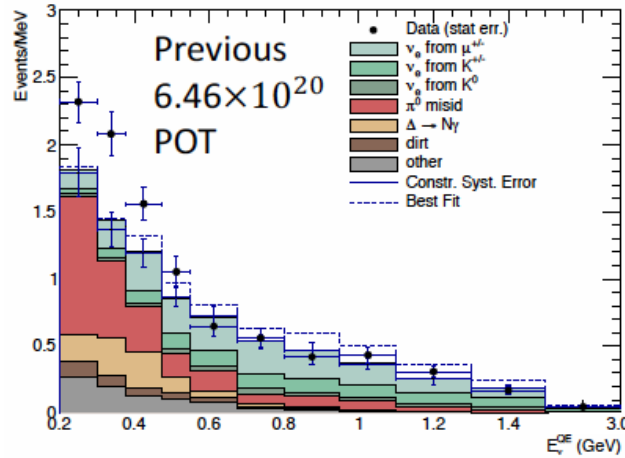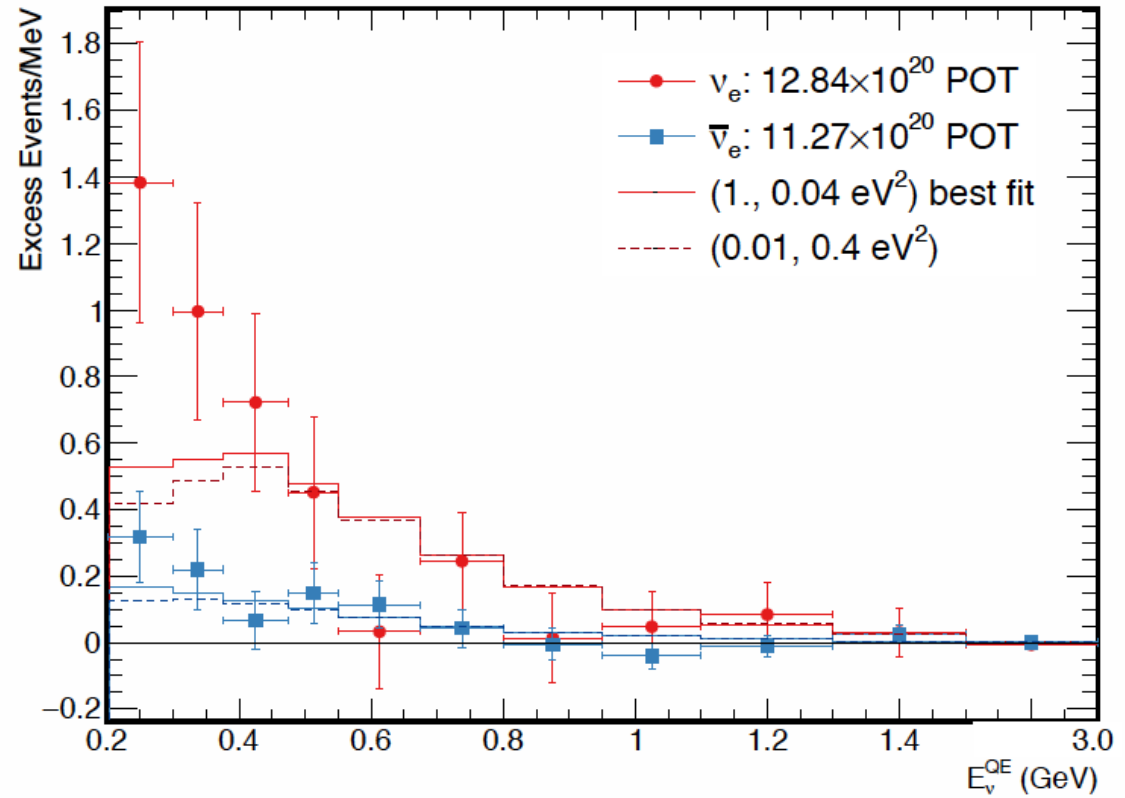 - neutrino mode: Data = 1956 events
Bkgd = 1577.8 $\pm$ 39.7(stat) $\pm$ 75.4(syst) $\rightarrow$ 381.2 $\pm$ 85.2 excess (4.5σ)

Old data (50.3%)
162.0 event excess

New data (49.7%)
219.2 event excess

KS test suggests
they are compatible
P(KS)=76%

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

5. Oscillation candidate event excess

200 < EνQE < 1250 MeV
 - neutrino mode: Data = 1959 events
Bkgd = 1577.8 $\pm$ 39.7(stat) $\pm$ 75.4(syst) $\rightarrow$ 381.2 $\pm$ 85.2 excess (4.5σ)
 - antineutrino mode: Data = 478 events
Bkgd = 398.7 $\pm$ 20.0(stat) $\pm$ 20.3(syst) $\rightarrow$ 79.3 $\pm$ 28.6 excess (2.8σ)

23/11/18

5. Oscillation candidate event excess

200 < EνQE < 1250 MeV
 - neutrino mode: Data = 1959 events
Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)
 - antineutrino mode: Data = 478 events
Bkgd = 398.7 ± 20.0(stat) ± 20.3(syst) → 79.3 ± 28.6 excess (2.8σ)

Compatible with LSND excess within 2-neutrino
oscillation hypothesis
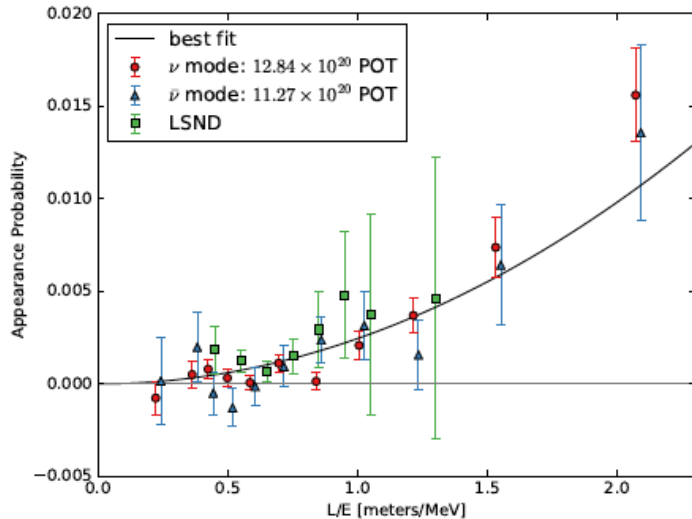
However, appearance and disappearance data
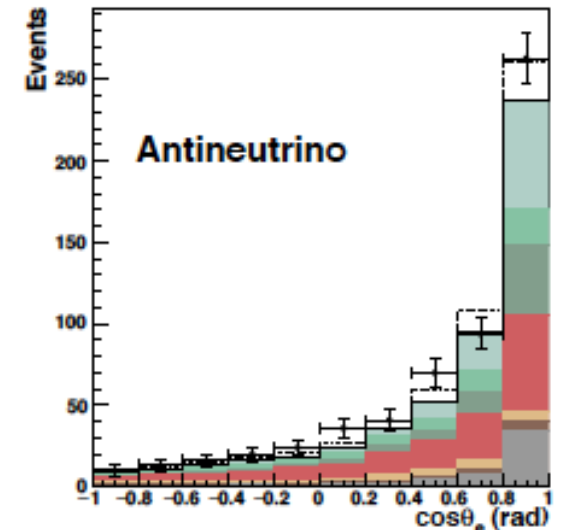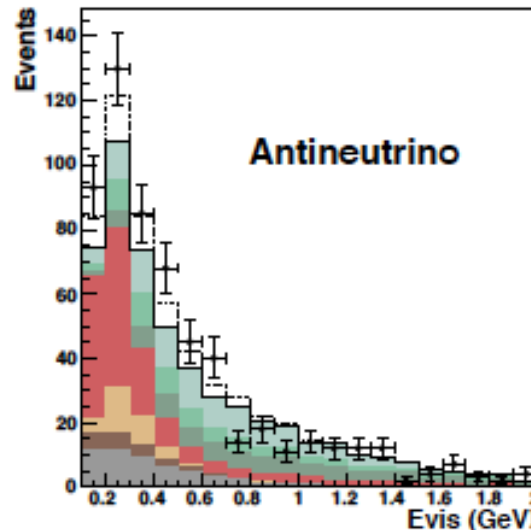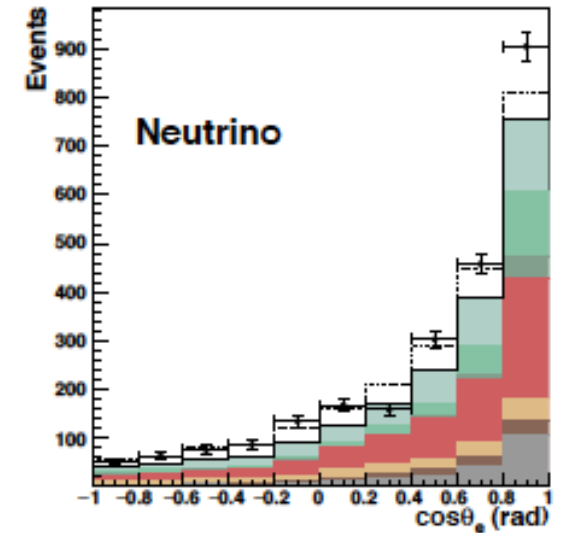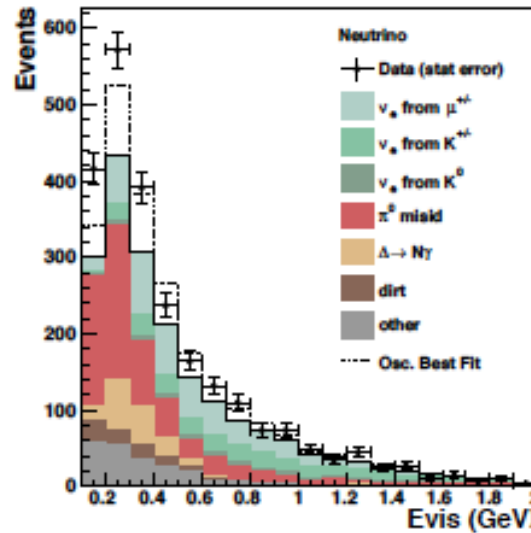have a strong tension (Maltoni, Neutrino 2018)

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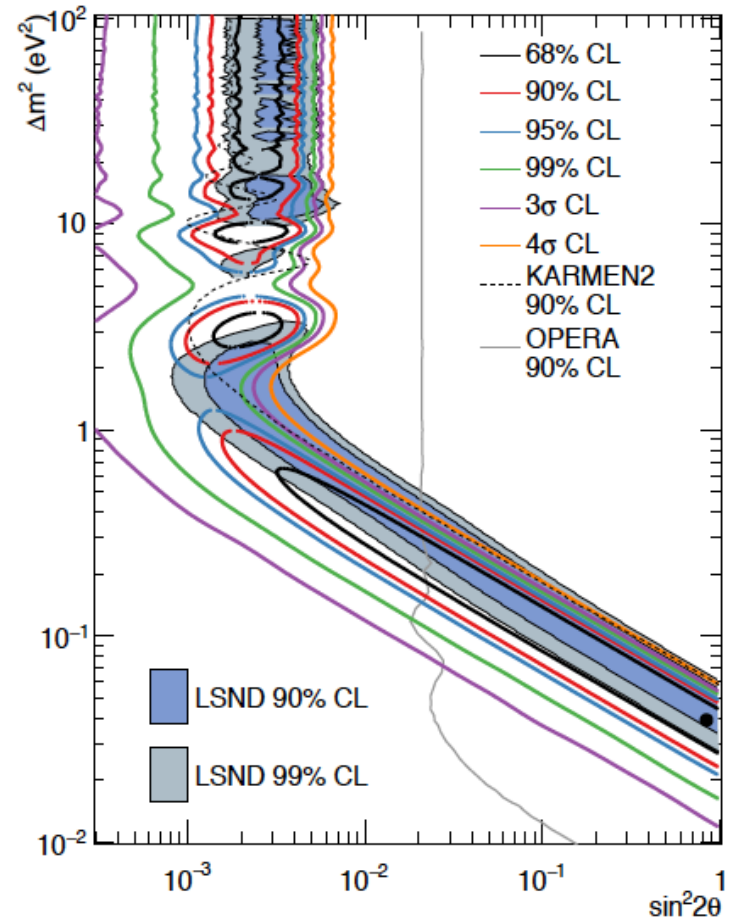
5. Alternative photon production models?

Excess look like more photons
(misID) than electrons
 - peaked forward direction
 - shape match with π^o spectrum

Any misID background missing?
 - Internal π^o?
 - external π^o?
 - New NCγ process?
 - New γ production process?

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MicroBooNE,JINST12(2017)P02017
Murrells, PhD thesis (2018)

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

5. Liquid argon time projection chamber γ production

High resolution detector with e/γ separation
- Original motivation of US LArTPC program

Collection Plane

Proton Track

Photon Shower

MicroBooNE Simulation

Wire
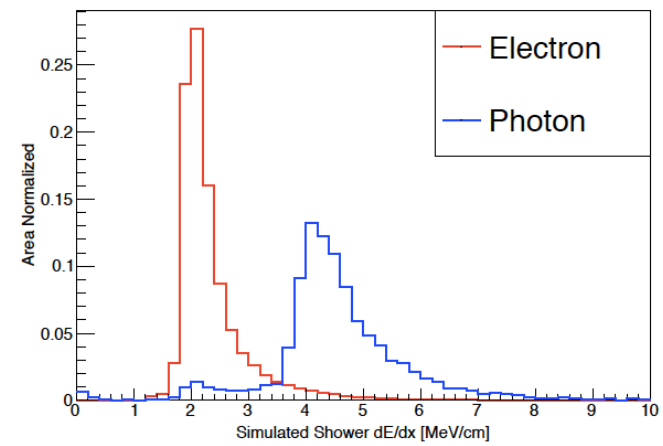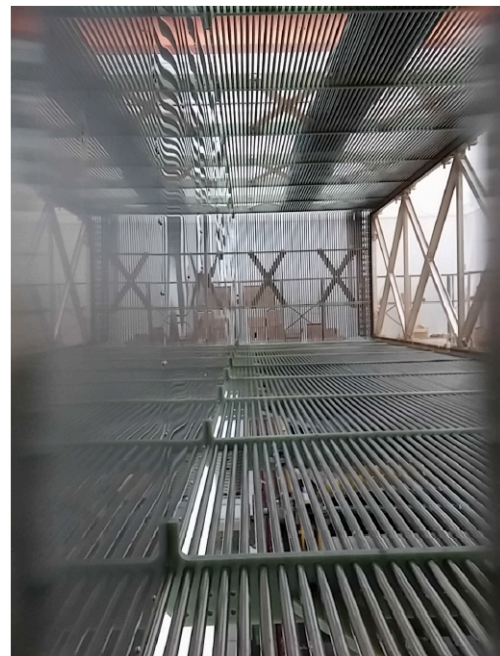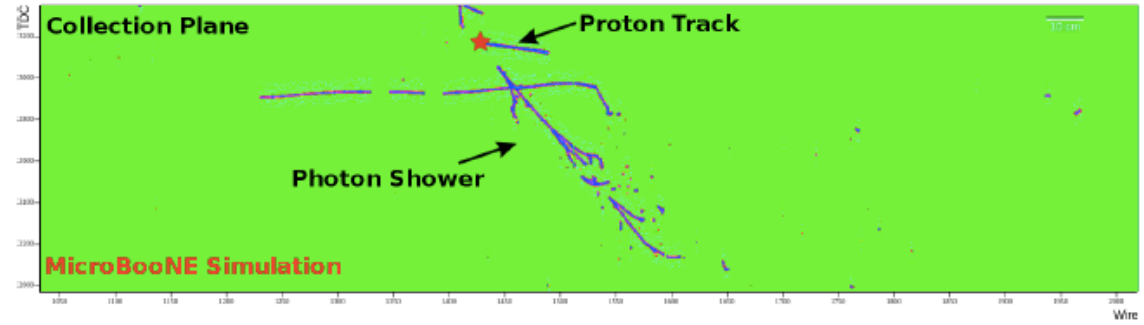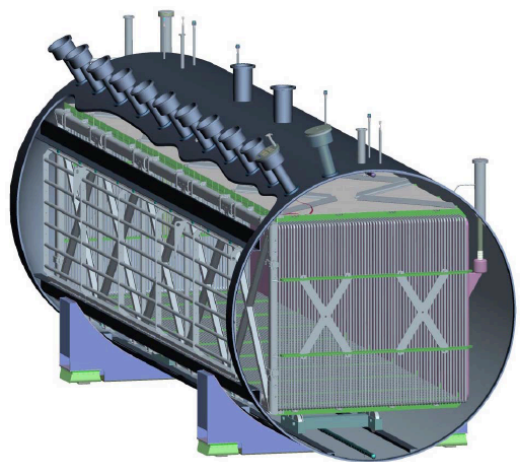
dE/dx of first 4cm track (simulation)

5. Anomaly mediated γ production

A process within SM, but not considered.

Z-boson

omega meson

N ω

Photon

γ

Particle Zoo, http://www.particlezoo.net/
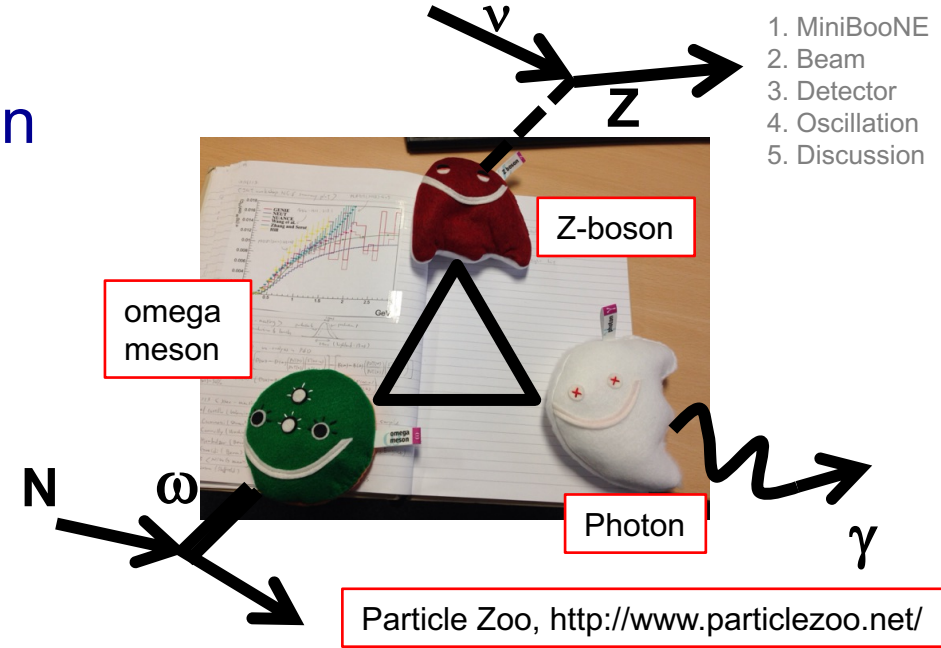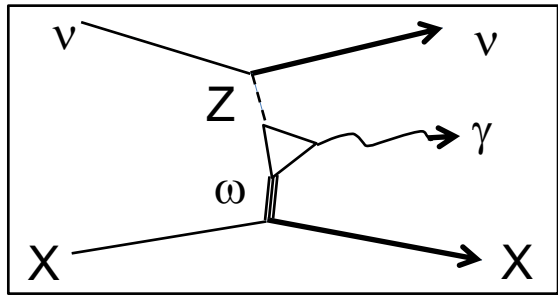
Later study found the contribution is small.

Hill, PRD84(2011)017501
Zhang and Serot, PLB719(2013)409
Wang et al, PLB740(2015)16
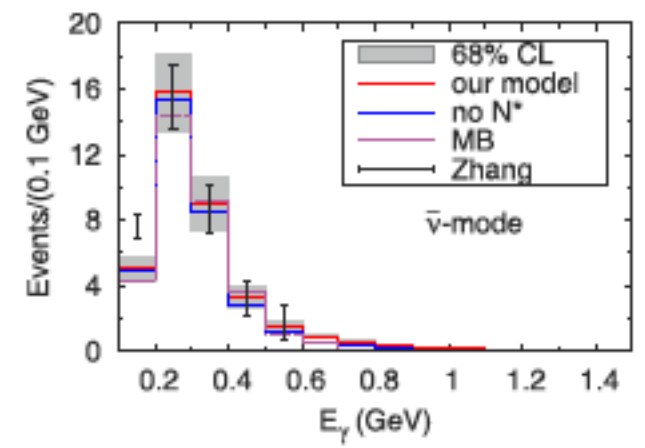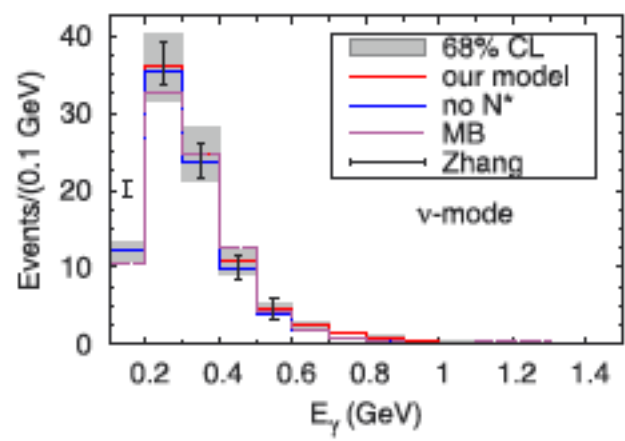
It looks it's easy to forget any processes with $\sigma \sim 10^{-41}$ cm^2
(e.g., diffractive π^o production $\sigma \sim 10^{-41}$ cm^2 was identified very recently by MINERvA)

MINERvA, PRL117(2016)111801

23/11/18

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T2K, to be published (2018)
MicroBooNE, public note 1041 (2018)

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

5. NC single photon search in T2K

T2K near detector measurement

- 95% pure photon sample (M_{inv}<50 MeV)
- Large external photon background and internal π^o production background. T2K can only set a limit.
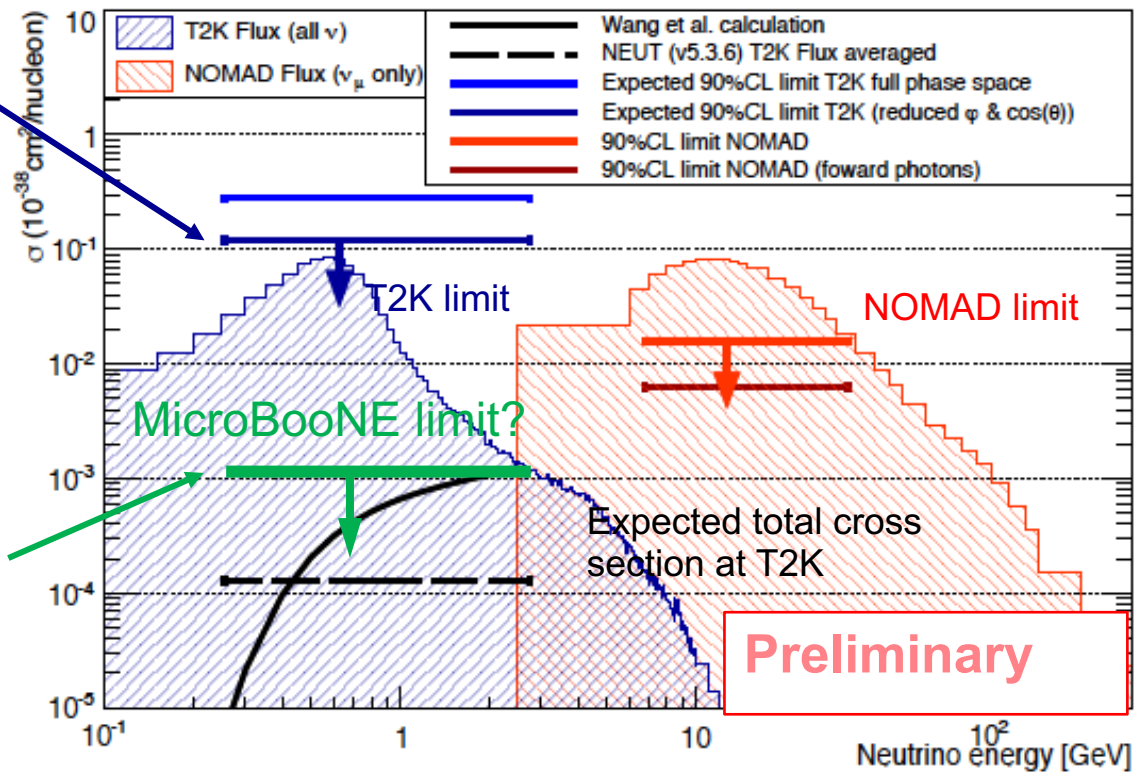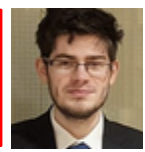
Pierre Lasorak
Queen Mary (T2K)
→ Sussex (DUNE)
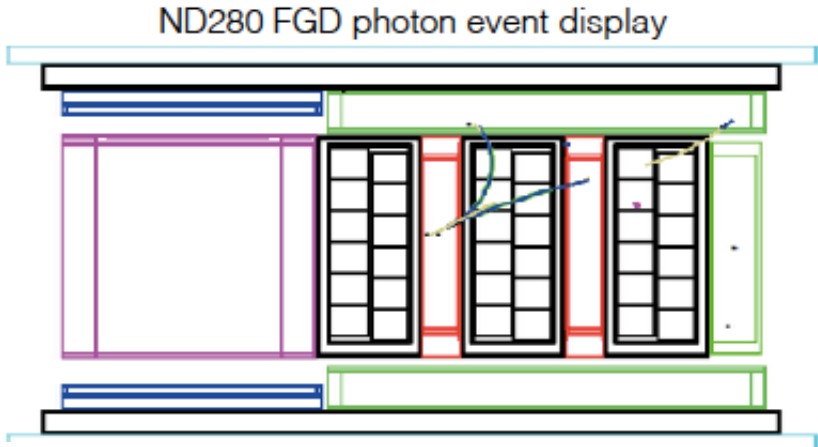
MicroBooNE

- First large LArTPC in USA
- Good e/γ PID
- Large active veto region
- Good internal π^o measurement
→ Good chance to measure the first positive signal of this channel.

Bobby Murrell
Manchester
(MicroBooNE)

ND280 FGD photon event display

Beam

T2K Flux (all ν)
NOMAD Flux (ν_μ only)
Wang et al. calculation
NEUT (v5.3.6) T2K Flux averaged
Expected 90%CL limit T2K full phase space
Expected 90%CL limit T2K (reduced φ & cos(θ))
90%CL limit NOMAD
90%CL limit NOMAD (foward photons)

T2K limit

NOMAD limit

MicroBooNE limit?

Expected total cross section at T2K

Preliminary

σ (10^{-38} cm²/nucleon)

Neutrino energy [GeV]

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Gninenko, PRL103(2009)241802;PRD83(2011)015015

1. MiniBooNE
2. Beam
3. Detector
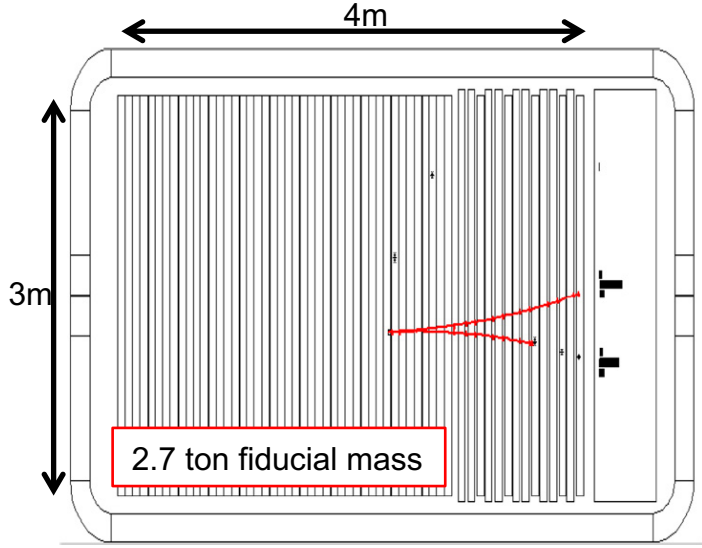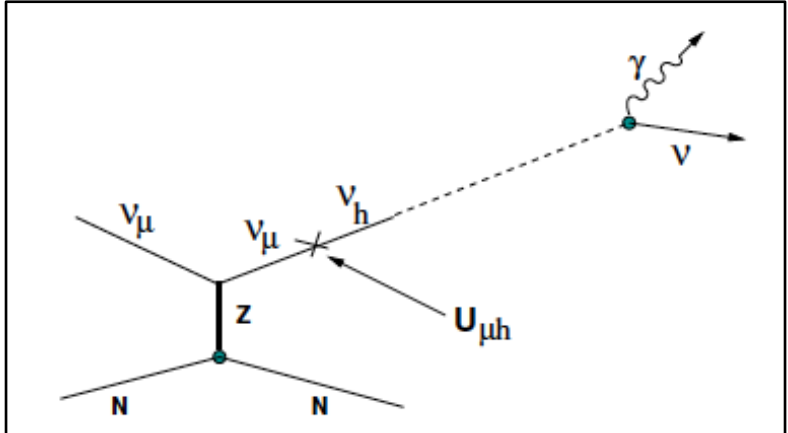4. Oscillation
5. Discussion

5. Beyond the Standard Model γ production

Heavy neutrino decay γ production
Carefully designed to avoid Karmen constraint.
 - The model works, but there are many "tricks" to avoid existing constraints, making the model bit artificial.

This model motivated NOMAD to look for such process. They didn't find it and set limit. But this limit is higher energy region and below 3 GeV is still unknown.

2.7 ton fiducial mass

NOMAD, PLB706(2012)268

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TK,Kostelecky,Tayloe,PRD74(2006)105009
Diaz and Kostelecky, PLB700(2011)25

1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

5. Lorentz violating neutrino oscillation

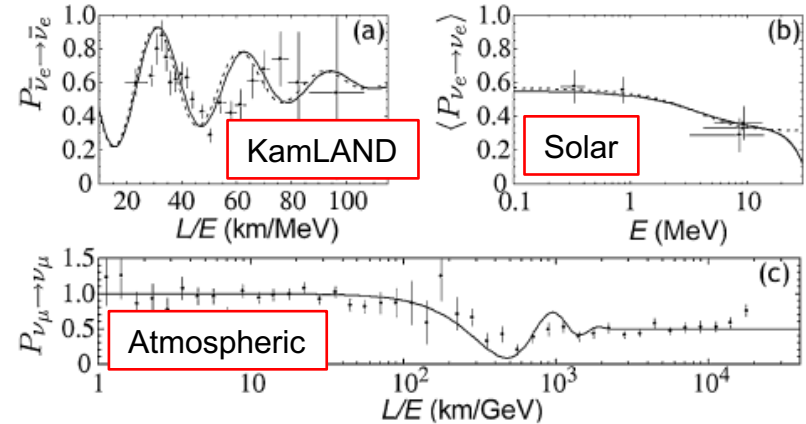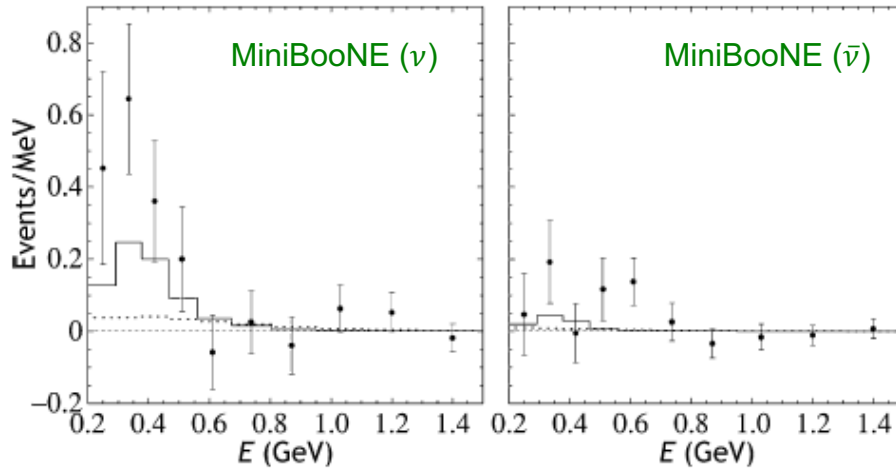Alternative oscillation explanation of LSND signal

Making a new texture in Hamiltonian to control oscillations.
 - LV-motivated model reproduce all data and LSND
 → not really reproduce details (no ν_e appearance).

puma model effective Hamiltonian

$$h_{eff}^\nu = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

where $A(E) = m^2/2E$, $B(E) = \mathring{a}E^2$, and $C(E) = \mathring{c}E^5$

MiniBooNE (ν)   MiniBooNE ($\bar{\nu}$)

KamLAND   Solar

Atmospheric

Alternative oscillation models were popular in the beginning of oscillation physics time, but after Super-K's L/E oscillatory shape measurement (2004), possible phenomenological models are extremely limited and all survived models have lots of "tricks" to avoid all constraints.

Super-Kamiokande, PRL(2004)101801

5. Lorentz violating neutrino oscillation

Search of Lorentz violation using neutrinos

Almost all neutrino experiments publish results of search of Lorentz violation.

The latest IceCube atmospheric neutrino Lorentz violation search set one of the strongest limits on anomalous space-time effect, from table top experiment to cosmology.
- highest energy (~20 TeV)
- longest baseline (~12700 km)

Neutrinos are one of the most sensitive tools to study space-time properties!

MINOS FD

MINOS ND

PRL101(2008)151601

PRL105(2010)151601

LSND

T2K ND

PRD72(2005)076004

AMANDA

Super-Kamiokande

PRD79(2009)102005

PRD91(2015)052003

PRD95(2017)111101

IceCube-40

Daya Bay

MiniBooNE

PLB718(2013)1303

Double Chooz

PRD82(2010)112003

PRD86(2013)112009

arXiv:1809.04660

IceCube

Cosmic rays

Atmospheric muon neutrinos

ν_μ

Atmosphere

Lorentz-violating field

IceCube

ν_τ

Horizontal

θ

Tau neutrino

Vertical

Nat.Phys.14(2018)961

Queen Mary
University of London

6

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Home › Physics › General Physics › July 16, 2018
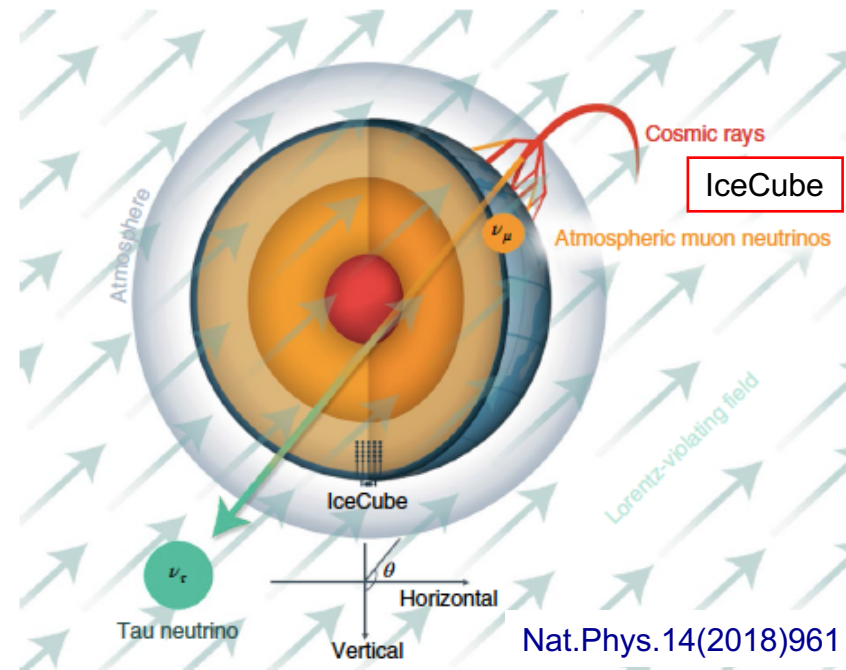
New study again proves Einstein right: Most thorough test to date finds no Lorentz violation in high-energy neutrinos

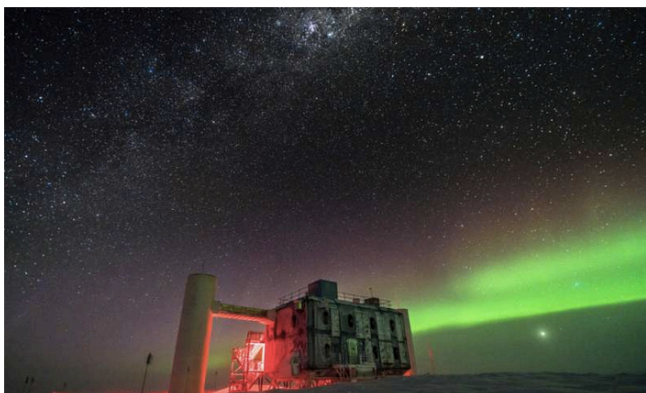July 16, 2018 by Jennifer Chu, Massachusetts Institute of Technology

The IceCube Lab at the South Pole. Credit: Martin Wolf, IceCube/NSF

SPACE.com
NEWS TECH SPACEFLIGHT SCIENCE & ASTRONOMY

Space.com › Science & Astronomy

Scientists Prove Einstein Right Using the Most Elusive Particles in the Universe

By Kimberly Hickok, Live Science Staff Writer | July 17, 2018 06:35am ET

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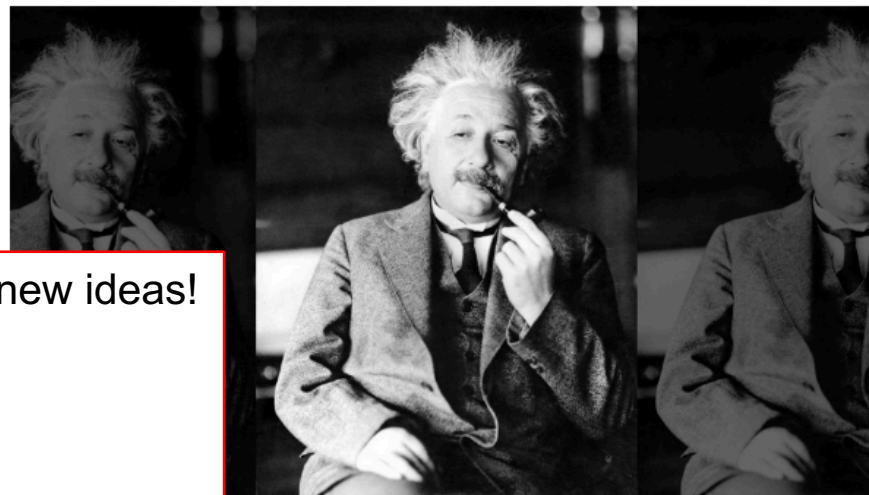
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PHYSICS · Published July 17 · Last Update July 17

Einstein's theory of special relativity works even in ghostly high-energy neutrinos

By Kimberly Hickok, Staff Writer | LiveScience

LIVESCIENCE
NEWS TECH HEALTH PLANET EARTH

Live Science › Strange News

Right Again, Einstein: Special Relativity Works Even in Ghostly High-Energy Neutrinos

By Kimberly Hickok, Staff Writer | July 16, 2018 05:21pm ET

MORE

An artist's rendition of subatomic particle movement. Neutrino physicists examined neutrinos detected by the IceCube Observatory, and found that they adhere to Albert Einstein's theory of relativity.

Credit: Shutterstock

...bellboy while traveling in Japan in 1922 fetched $1.56 million at a Jerusalem auction, The Winner auction house

Once again, scientists have shown that Albert Einstein's theory of special relativity is right — this time, thanks to a particle detector buried deep beneath Antarctica.

Trending in Scienc...
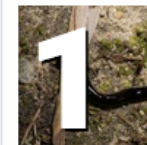
1 Florida residents warne... carrying New Guinea fl... invading part of the sta...

2 Mysterious hole shooti... Arkansas stumps offici... out' Satan

3 Lion named Mufasa ha... hacked off as four othe... poisoned in wildlife res...

MiniBooNE signal is a source of many new ideas!
 - Sterile neutrinos
 - Lorentz violating neutrino oscillation
 - new interaction models (NCγ)
 - new technology (LArTPC)
etc

Conclusion

MiniBooNE is the short-baseline neutrino oscillation experiments

After 15 years of running
 - neutrino mode: 381.2 ± 85.2 excess (4.5σ)
 - antineutrino mode: 79.3 ± 28.6 excess (2.8σ)

MiniBooNE has many legacies in this community
 - Many useful tools
 - Many useful people
 - Many new topics - Neutrino cross section measurements
                     - Test of Lorentz violation with neutrinos
                     - Production&detection Dark Matter search with neutrino detector
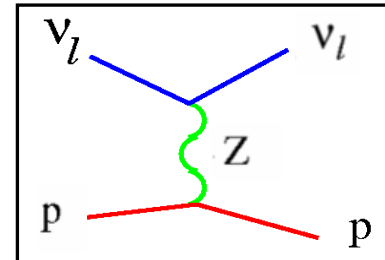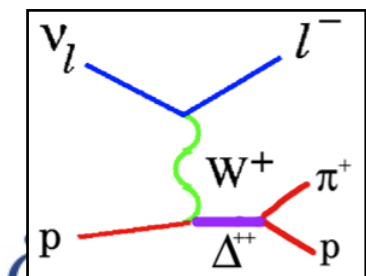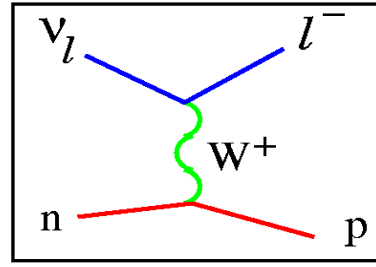
MiniBooNE, PRL118(2017)221803

But the biggest legacy is the short-baseline anomaly

Thank you for your attention!

backup

1. Cross section model
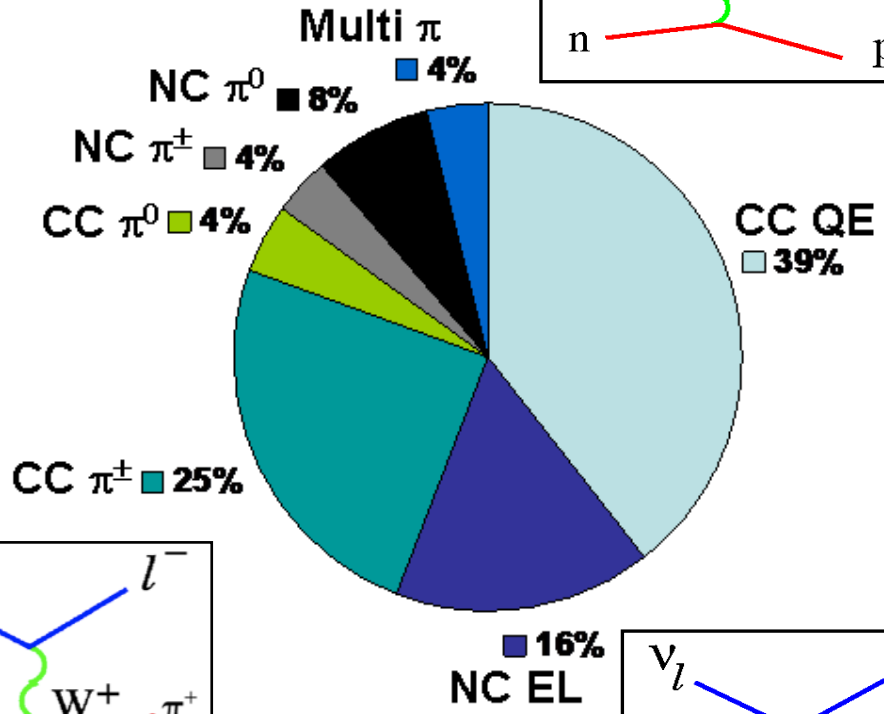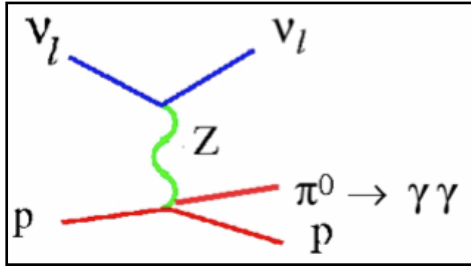
Predicted event rates before cuts
(NUANCE Monte Carlo)
Casper, Nucl.Phys.Proc.Suppl.112(2002)161

Multi π ■ 4%

NC π^0 ■ 8%

NC $\pi^\pm$ ■ 4%

CC π^0 ■ 4%

CC QE □ 39%

CC $\pi^\pm$ ■ 25%

■ 16%
NC EL
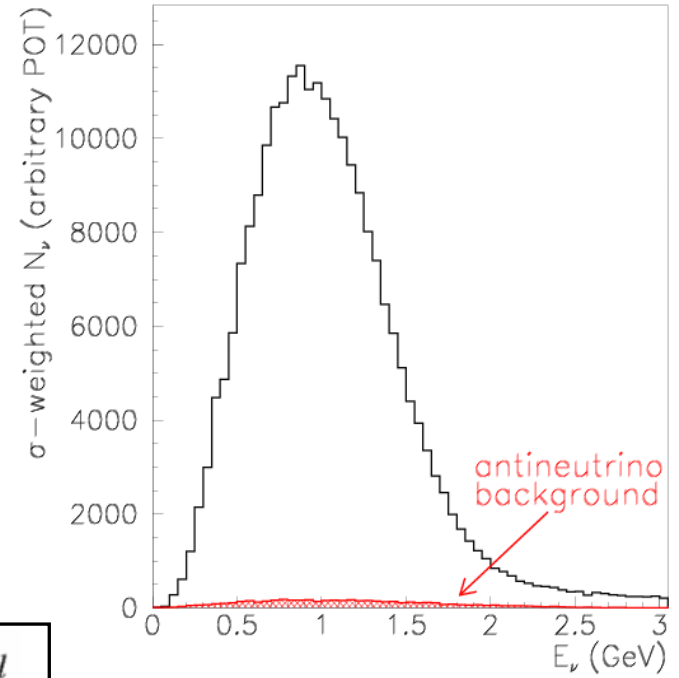
Event neutrino energy (GeV)

4. PID cuts Oscillation candidate events

4 PID cuts
(a) Before PID cuts
(b) After L(e/mu) cut
(c) After L(e/π^0) cut
(d) After m$_{\gamma\gamma}$ cut

Old and new data agree within 2% over 8 years separation.