

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

PRL121(2018)221801

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
Physics Colloquium
DESY, Zeuthen, Germany, April 24, 2019

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

Thursday, May 31, 2018

New results confirm old anomaly in neutrino data

The collaboration of a neutrino experiment called MiniBooNE just published their new results.

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 Laboratory in Chicago has detected far more electron neutrinos than expected, a possible harbinger of a revolutionary new element called the sterile neutrino, though many physicists

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

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Has US physics lab found a new particle?

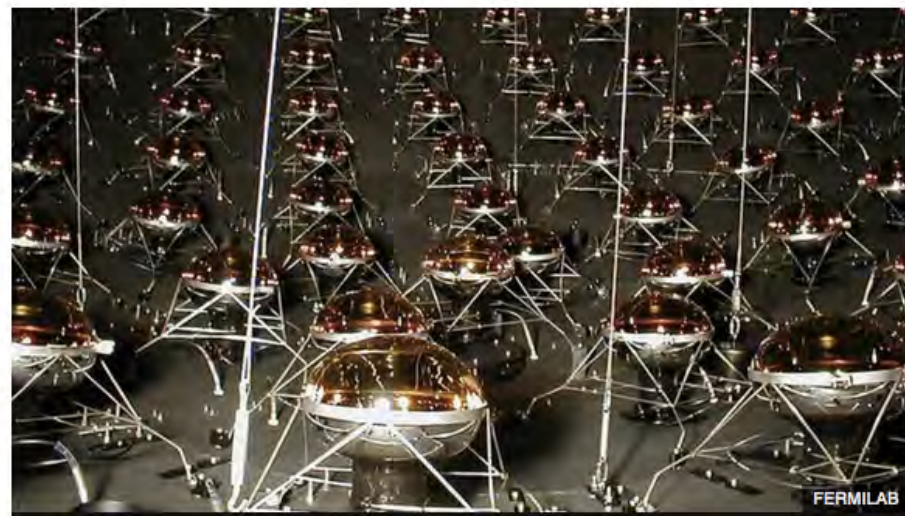
By Paul Rincon

Science editor, BBC News website

© 6 June 2018



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Featured in Physics

Editors' Suggestion

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

A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration)
Phys. Rev. Lett. **121**, 221801 – Published 26 November 2018

Physics See Viewpoint: [The Plot Thickens for a Fourth Neutrino](#)

The most visible particle physics result of the year 2018



Physics ABOUT BROWSE PRESS COLLECTIONS CELEBRATING 10 YEARS

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#7,064

of 12,363,617 outputs

OUTPUTS FROM
PHYSICAL REVIEW
LETTERS

#13

of 25,606 outputs

OUTPUTS OF SIMILAR
AGE

#448

of 270,805 outputs

OUTPUTS OF SIMILAR AGE
FROM PHYSICAL REVIEW
LETTERS

#1

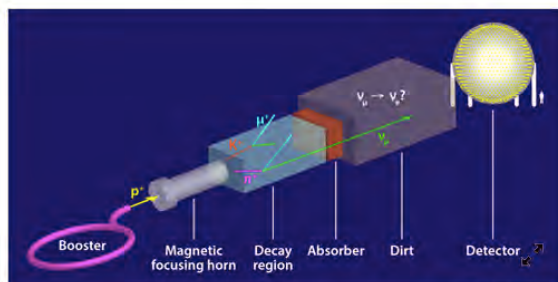
of 520 outputs

Viewpoint: The Plot Thickens for a Fourth Neutrino

Joachim Kopp, Theoretical Physics Department, CERN, Geneva, Switzerland, and PRISMA Cluster of Excellence, Mainz, Germany

November 26, 2018 • Physics 11, 122

Confirming previous controversial results, the MiniBooNE experiment detects a signal that is incompatible with neutrino oscillations involving just the three known flavors of neutrinos.



Teppei Ka

<https://physics.aps.org/articles/v11/122>

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Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **120**, 231801 – Published 4 June 2018

Physics See Viewpoint: [Sizing Up the Top Quark's Interaction with the Higgs](#)



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Observation of Higgs Boson Decay to Bottom Quarks

A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **121**, 121801 – Published 17 September 2018

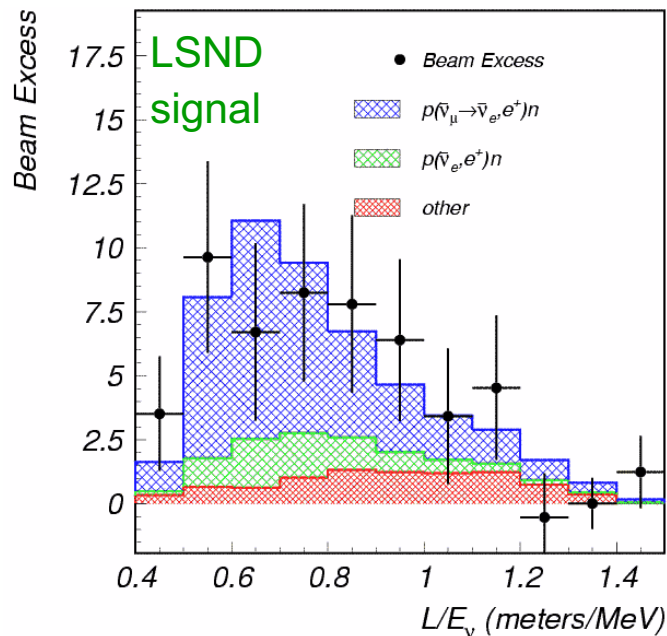
Physics See Viewpoint: [Higgs Decay into Bottom Quarks Seen at Last](#)



1. LSND experiment

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

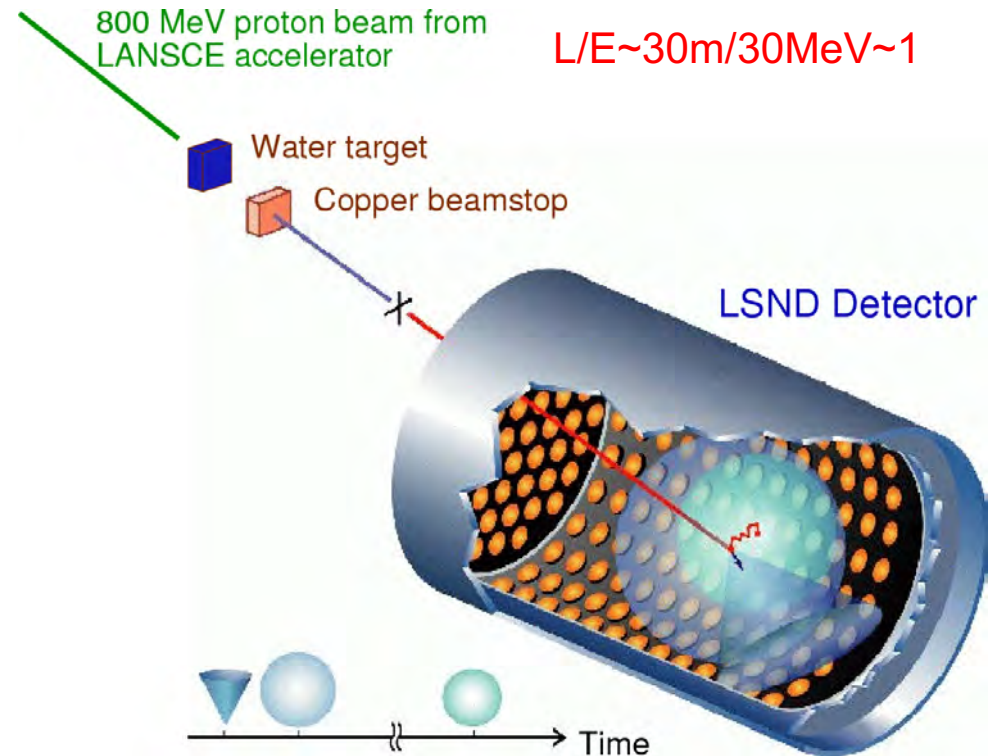
$$87.9 \pm 22.4 \pm 6.0 \text{ (3.8.}\sigma\text{)}$$



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

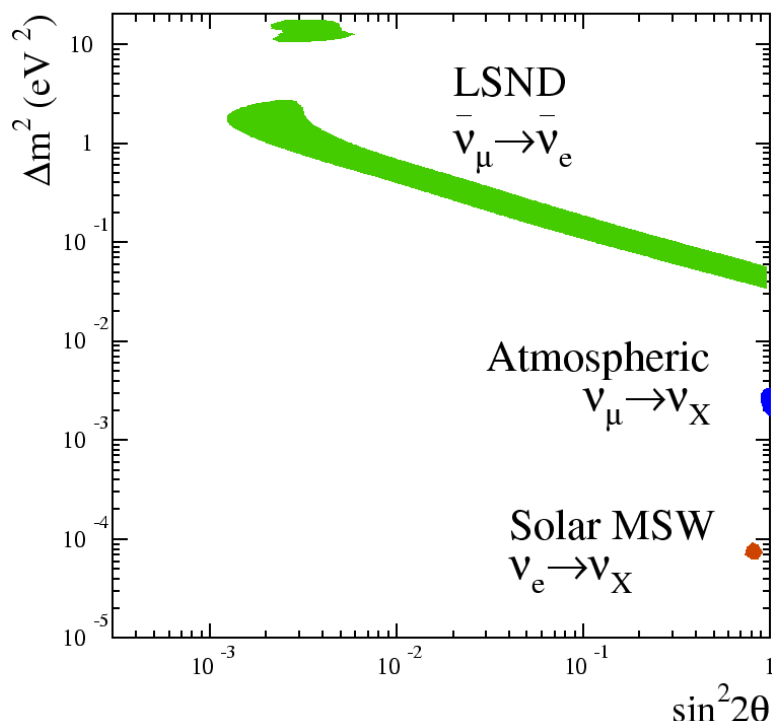
$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow e^+ + n$$

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



1. LSND experiment

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

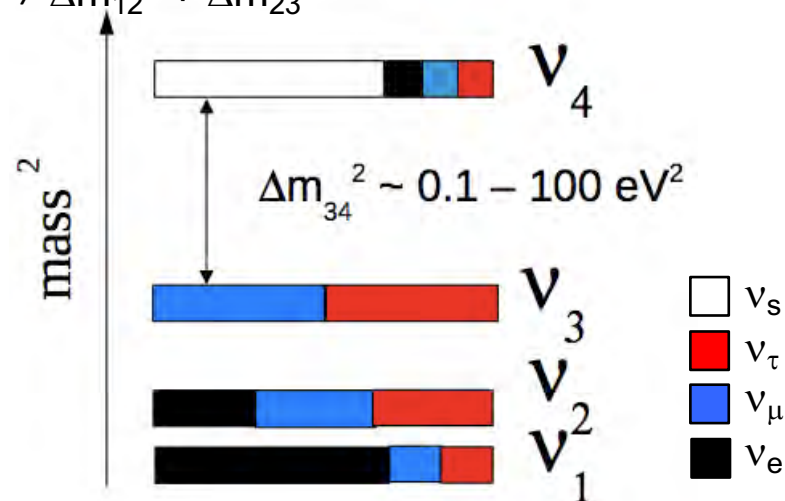


3 types of neutrino oscillations are found:

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

But we cannot have so many Δm^2 !

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



LSND signal indicates 4th generation neutrino, but we know there is no additional flavour from Z-boson decay, so it must be **sterile neutrino**

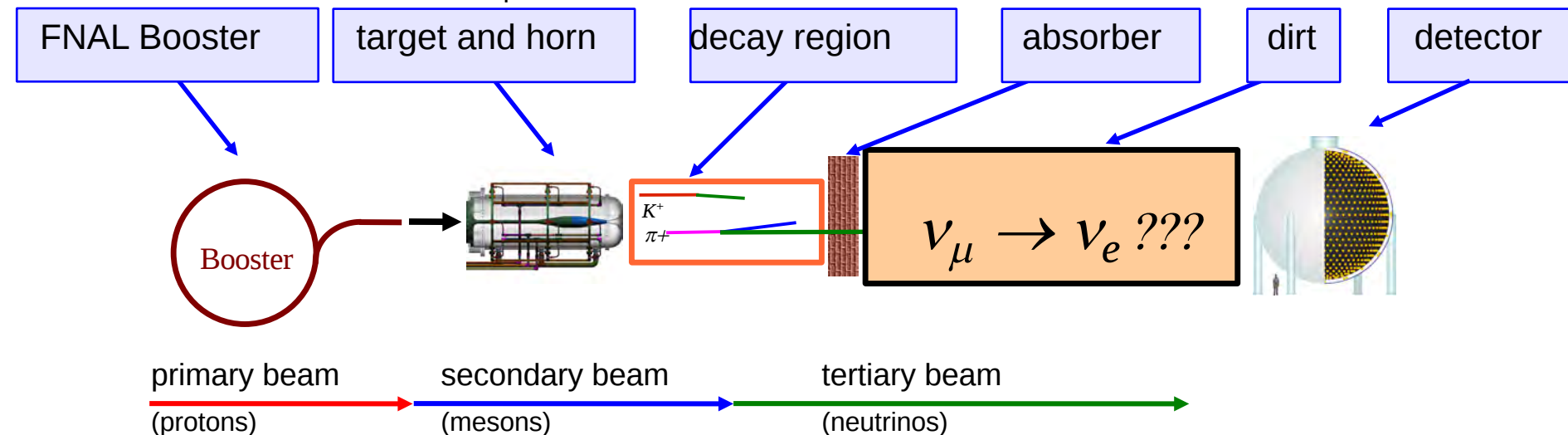
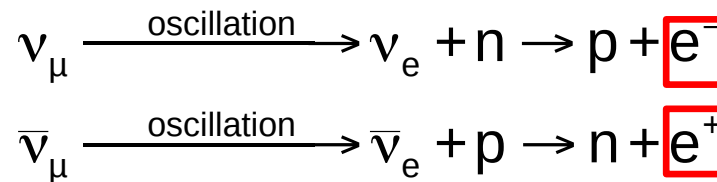
MiniBooNE is designed to have same $L/E \sim 500 \text{m}/500 \text{MeV} \sim 1$ to test LSND $\Delta m^2 \sim 1 \text{eV}^2$

1. MiniBooNE experiment

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

Keep L/E same with LSND, while changing systematics, energy & event signature;

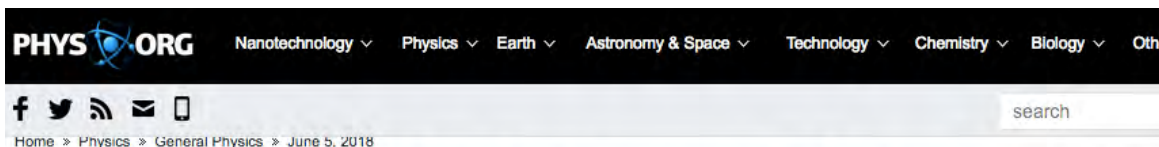
MiniBooNE is looking for **the single isolated electron like events**, which is the signature of ν_e events



MiniBooNE has;

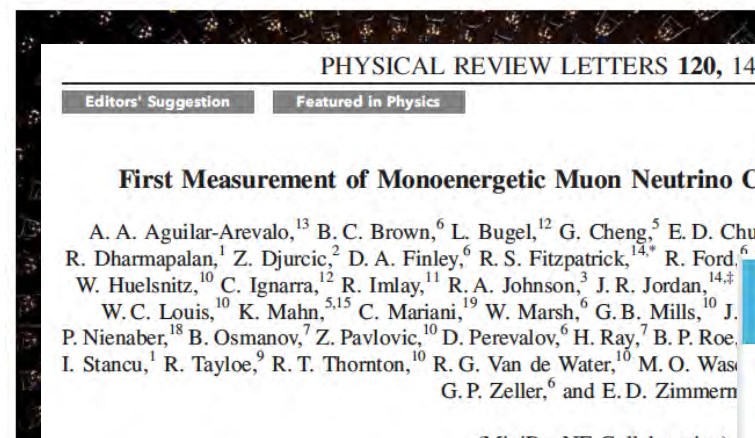
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

1. Easter Eggs of MiniBooNE 1 – Recent publications



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

June 5, 2018 by Savannah Mitchem, Argonne National Laboratory



PRL 118, 221803 (2017)

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 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. Yu³

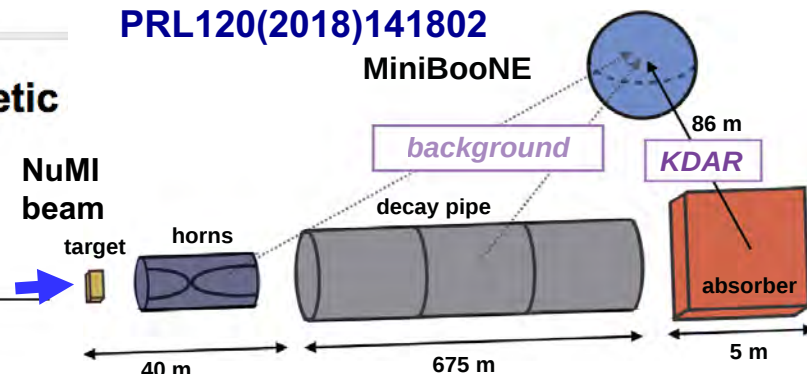
MiniBooNE-DM Collaboration



23
Tue
Wilson Hall 2nd fl South West
© 11:00 am

Teppei Katori, katori@fnal.gov

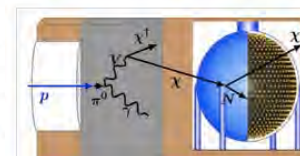
PRL120(2018)141802



News at work

The MiniBooNE search for dark matter

July 18, 2017 | Ranjan Dharmapalan and Tyler Thornton



This schematic shows the experimental setup for the dark matter search. Protons (blue arrow on the left) generated by the Fermilab accelerator chain strike a thick steel block. This interaction produces secondary particles, some of which are absorbed by the block. Others, including photons and perhaps dark-sector photons, symbolized by χ , are unaffected. These dark photons decay into dark matter, shown as χ , and travel to the MiniBooNE detector, depicted as the sphere on the right.

Particle physicists are in a quandary. On one hand, the Standard Model accurately describes most of the known particles and forces of interaction between them. On the other, we know that the Standard Model accounts for less than 5 percent of the universe. About 26 percent of the universe is composed of mysterious dark matter, and the remaining 68 percent of even more mysterious dark energy.

Some theorists speculate that dark matter particles could belong to a "hidden sector" and that there may be portals to this hidden sector from the Standard Model. The portals allow hidden-sector particles to trickle into Standard Model interactions. A large sensitive particle detector, placed in an intense particle beam and equipped with a mechanism to suppress the Standard Model interactions, could unveil these new particles.

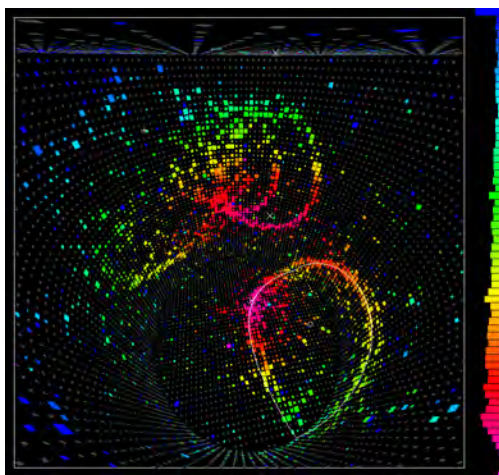
Fermilab is home to a number of neutron beams and large, extremely sensitive detectors, MiniBooNE

PRL118(2017)221803
PRD98(2018)112004

1. Easter Eggs of MiniBooNE 2 – Tools

fitQun: MiniBooNE: NIMA608(2009)206

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

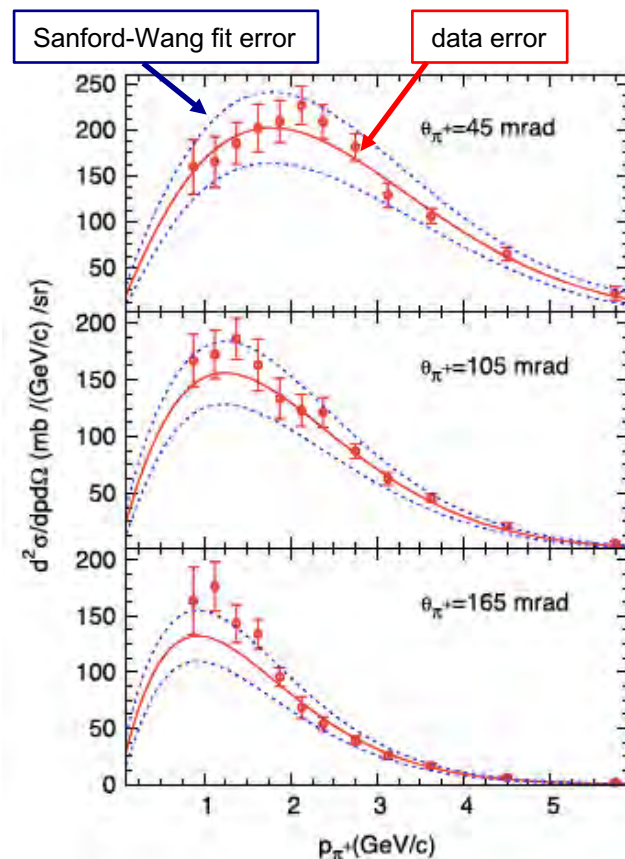
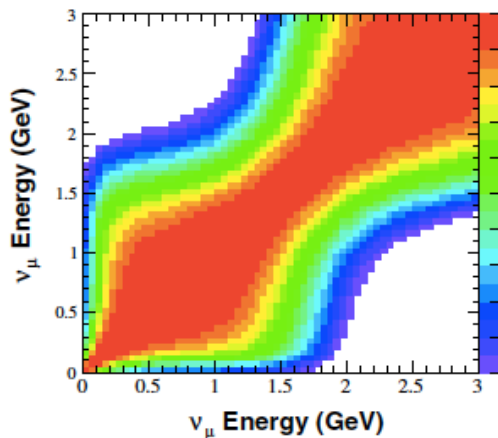


Online remote shift:

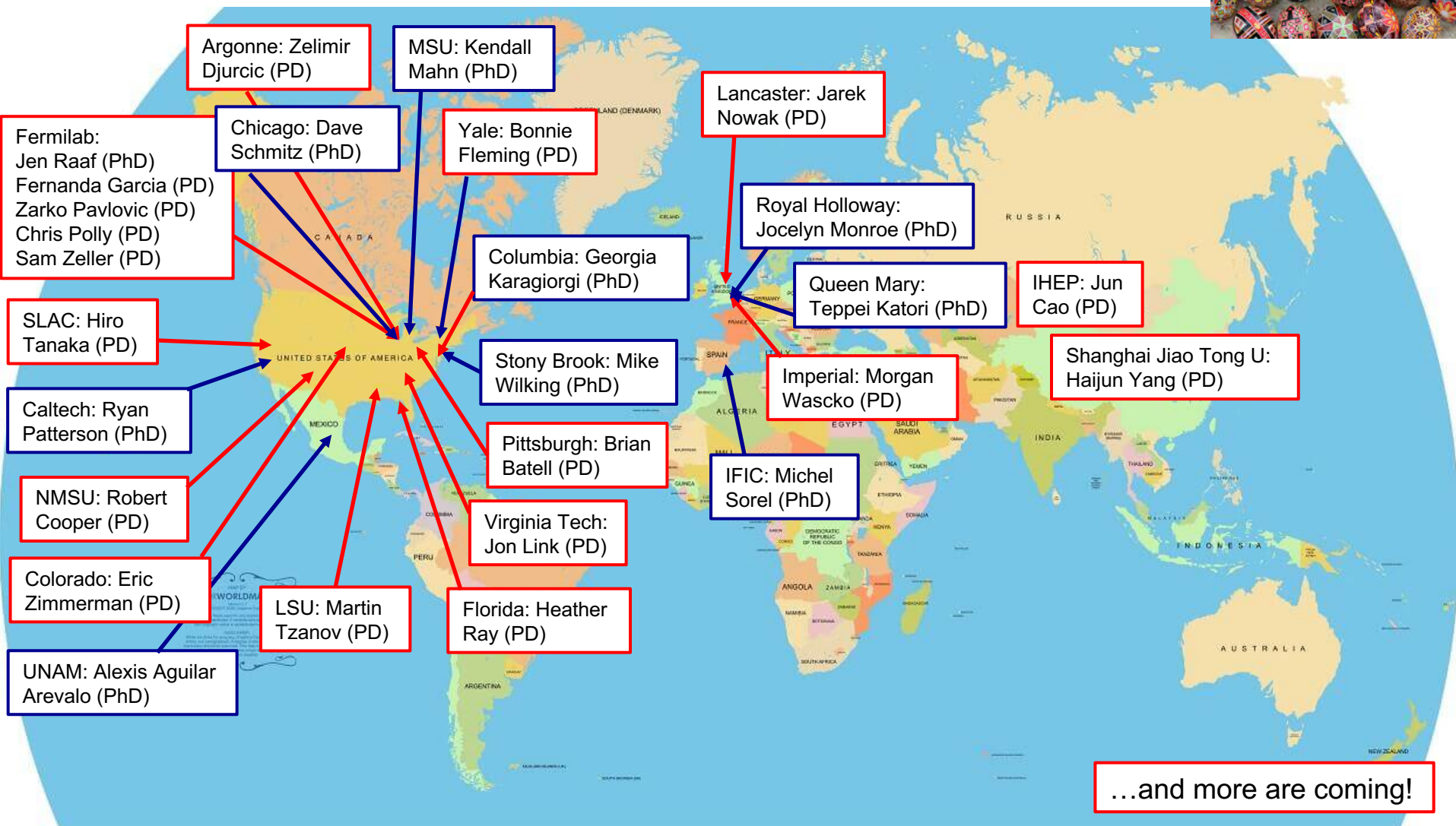
- <1 event per minute
- MiniBooNE is the first remote shift experiment at Fermilab
- All neutrino experiments at Fermilab adapted online remote shift, including NOvA, MicroBooNE, MINERvA, etc

Flux systematic error: MiniBooNE: PRD79(2009)072002

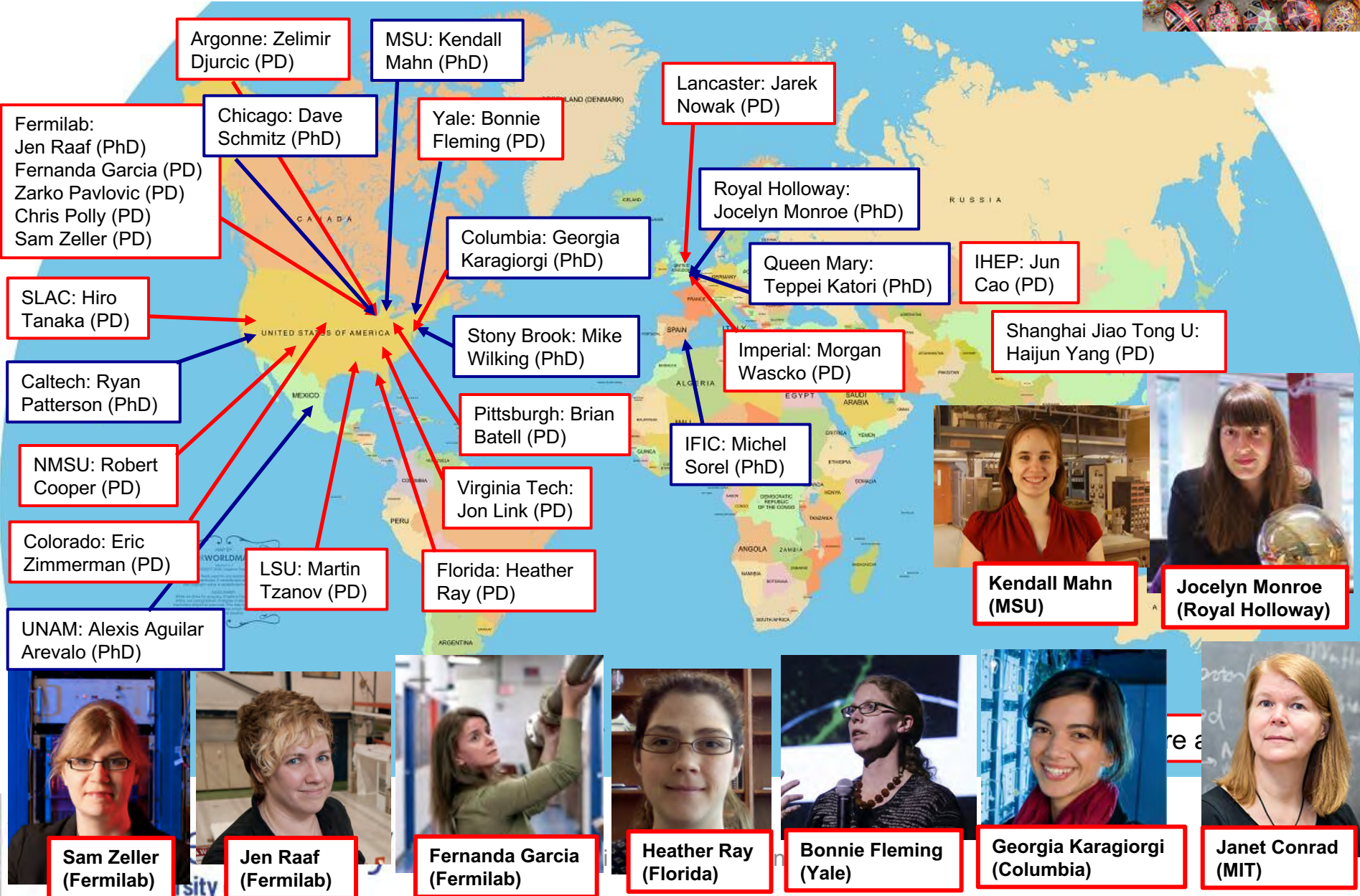
- Errors are derived directly from hadron production data (spline fit), not based on any flux model.
- Neutrino flux error = hadron production data error



1. Easter Eggs of MiniBooNE 3 – Offspring



1. Easter Eggs of MiniBooNE 4 – #WomenInSTEM



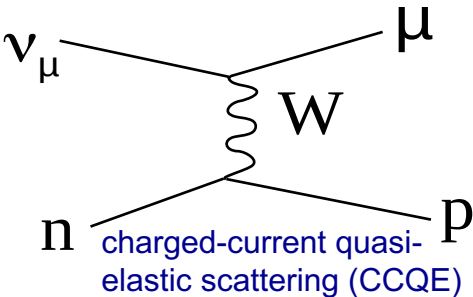


1. Easter Eggs of MiniBooNE 5 – Cross Sections

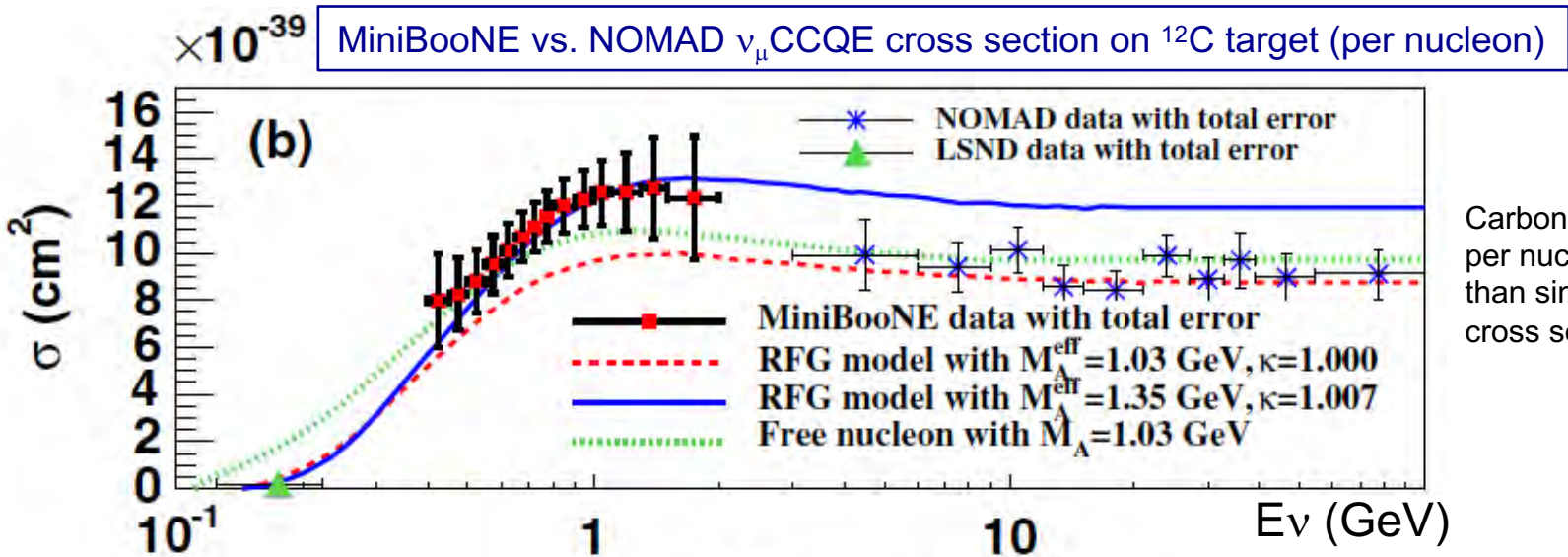
MiniBooNE made the first detailed study of neutrino-nucleus cross sections around 1 GeV.

CCQE puzzle

- 1. low Q^2 suppression $\rightarrow$ Low forward efficiency? (detector?)
- 2. high Q^2 enhancement $\rightarrow$ Axial mass > 1.0 GeV? (physics?)
- 3. large normalization $\rightarrow$ Beam simulation is wrong? (flux?)



CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality = precise prediction for neutrino CCQE cross-section...?



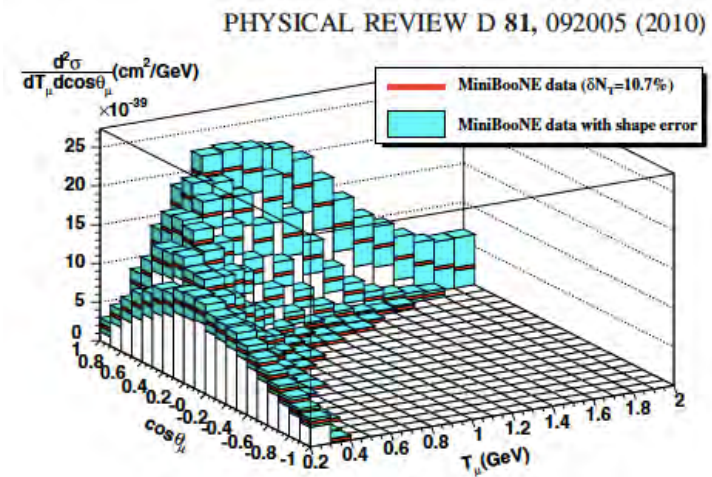
Carbon cross section per nucleon is larger than single nucleon cross section?!



1. Easter Eggs of MiniBooNE 5 – Cross Sections

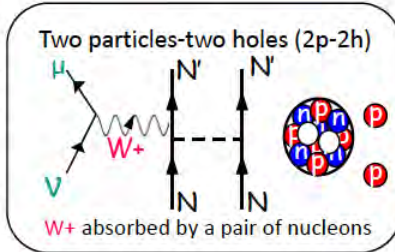
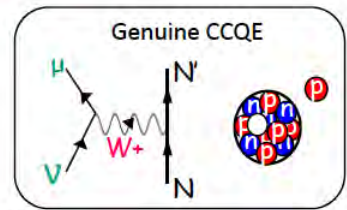
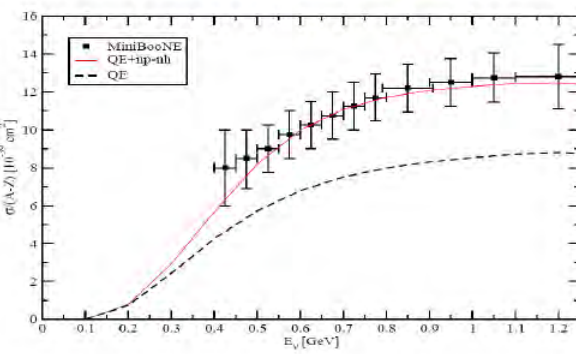
MiniBooNE made the first detailed study of neutrino-nucleus cross sections around 1 GeV.

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

Inclusion of the multinucleon
emission channel (np-nh)



Slide from
Martini

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

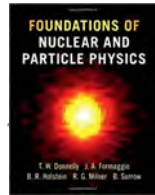
- Section 42, “Monte Carlo Neutrino Generators” (Hugh Gallagher, Yoshinari Hayato)
- Section 50, “Neutrino Cross-Section Measurements” (Sam Zeller)

On going effort from MiniBooE initiative!



Teppei K

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



1. MiniBooNE neutrino experiment

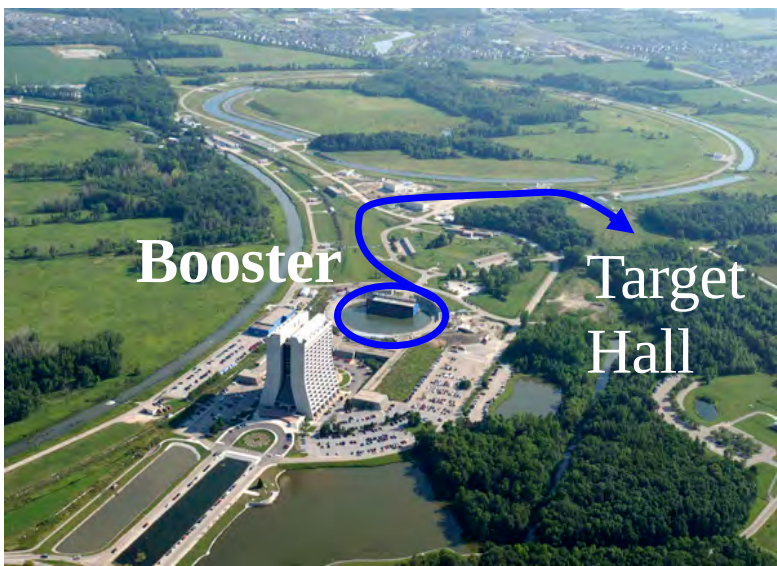
2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

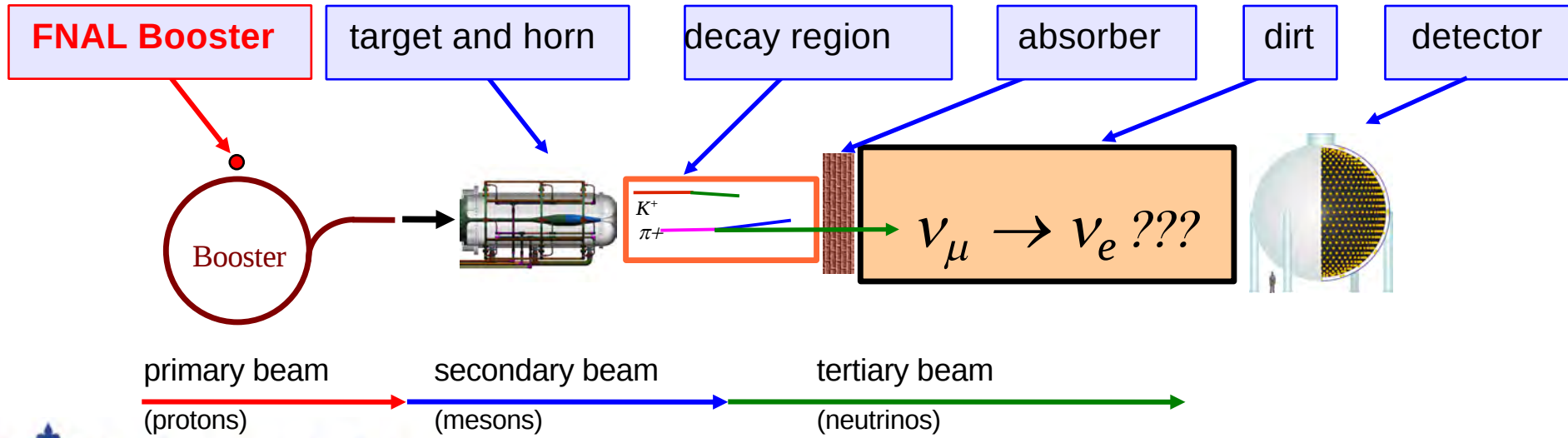
5. Discussion

2. Fermilab Booster

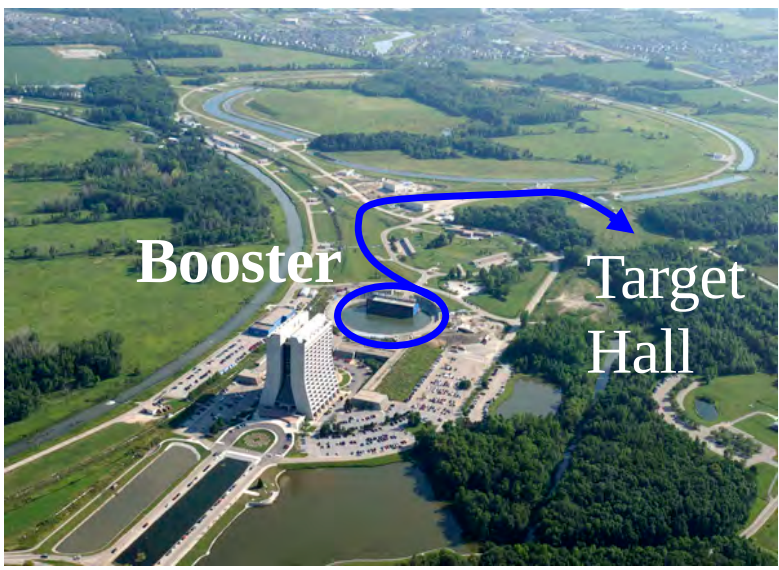


MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster

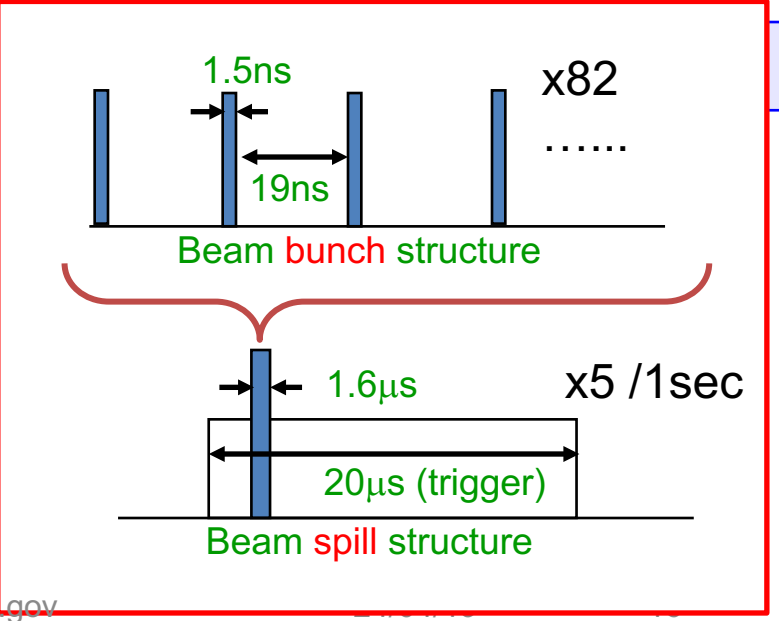
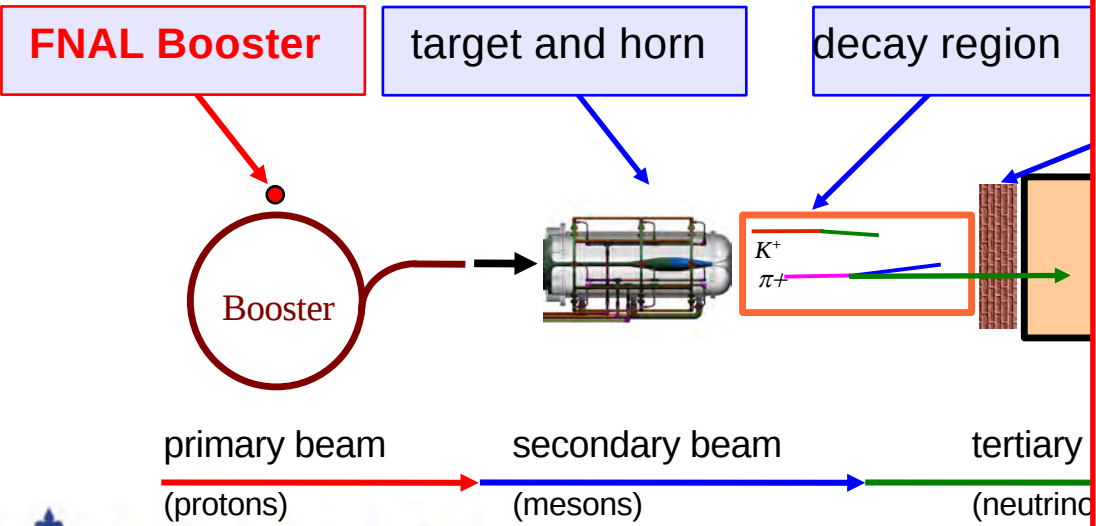


2. Fermilab Booster



MiniBooNE extracts beam from the 8 GeV Booster

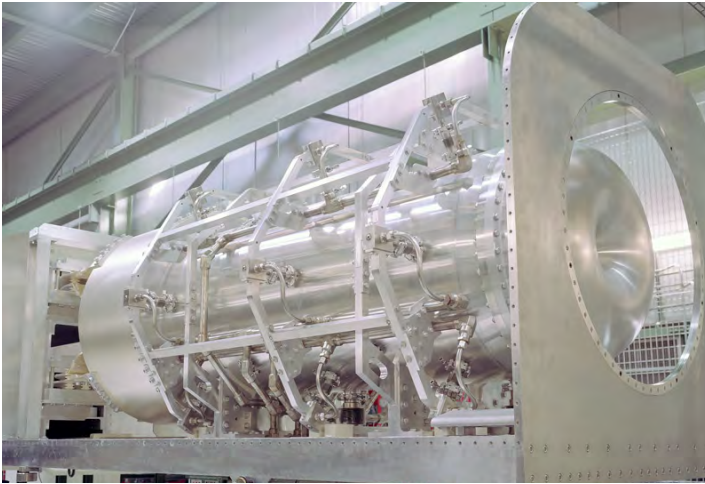
FNAL Booster





2. Magnetic Focusing Horn

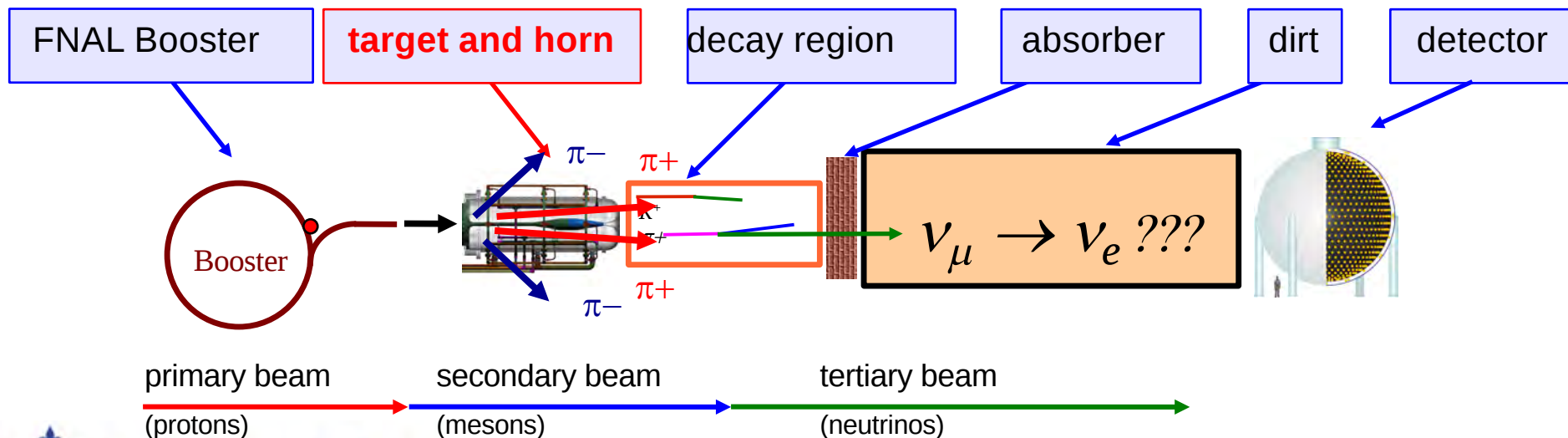
Magnetic focusing horn



8GeV protons are delivered to a 1.7λ 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.



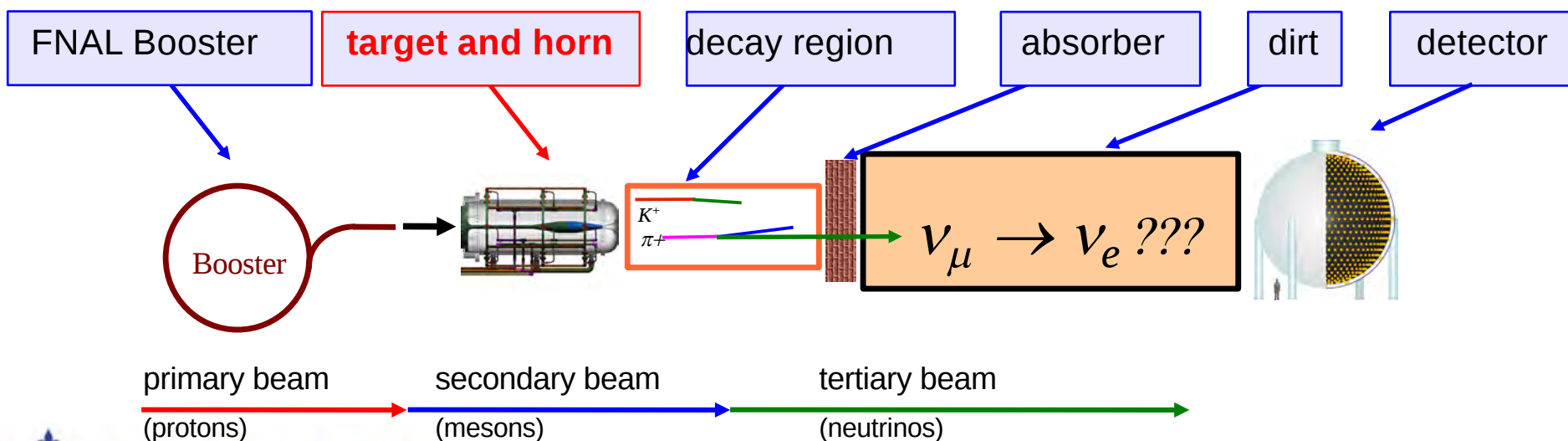
2. Hadron Production

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 π^+



2. Hadron Production

HARP experiment (CERN)



FNAL Booster

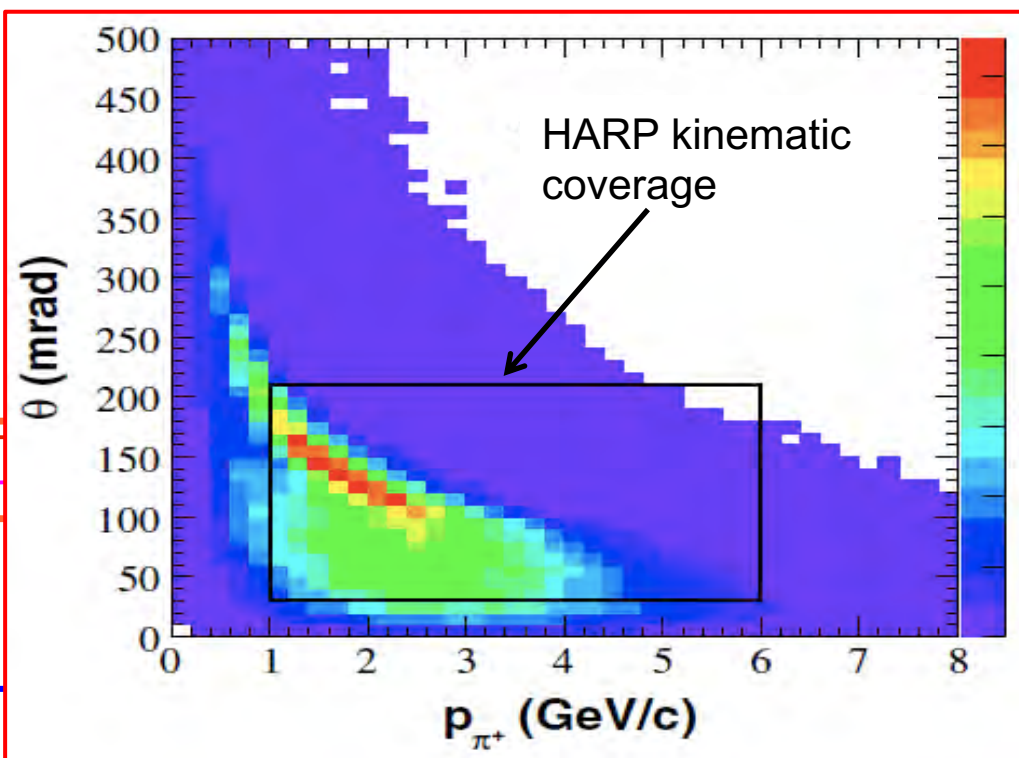
target and horn

Booster

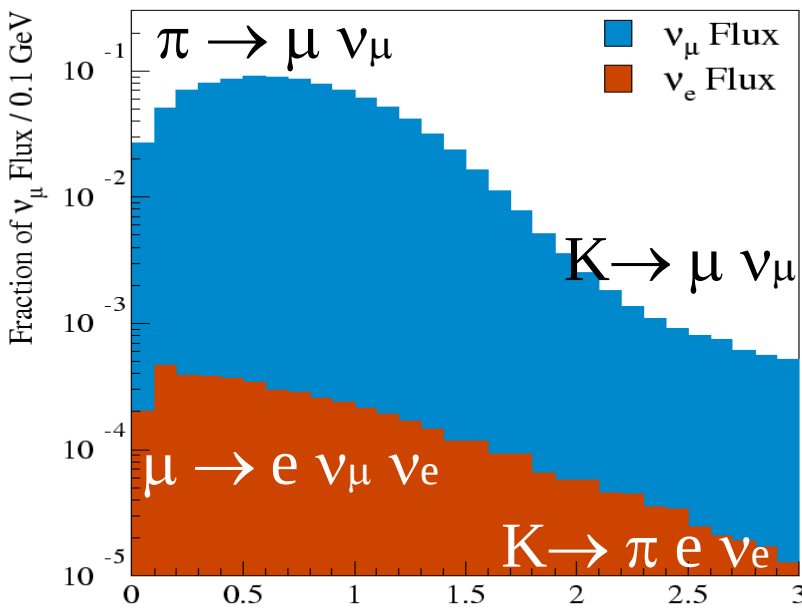
primary beam
(protons)

secondary beam
(mesons)

K^+
 π^+



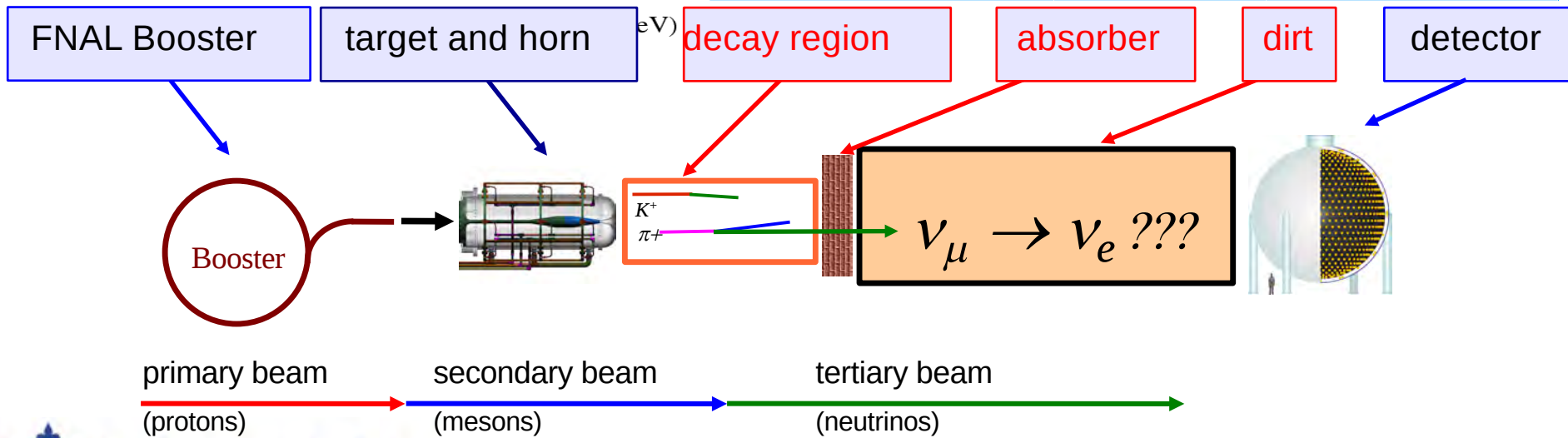
2. Booster Neutrino Beamline (BNB)



Neutrino flux from simulation by GEANT4

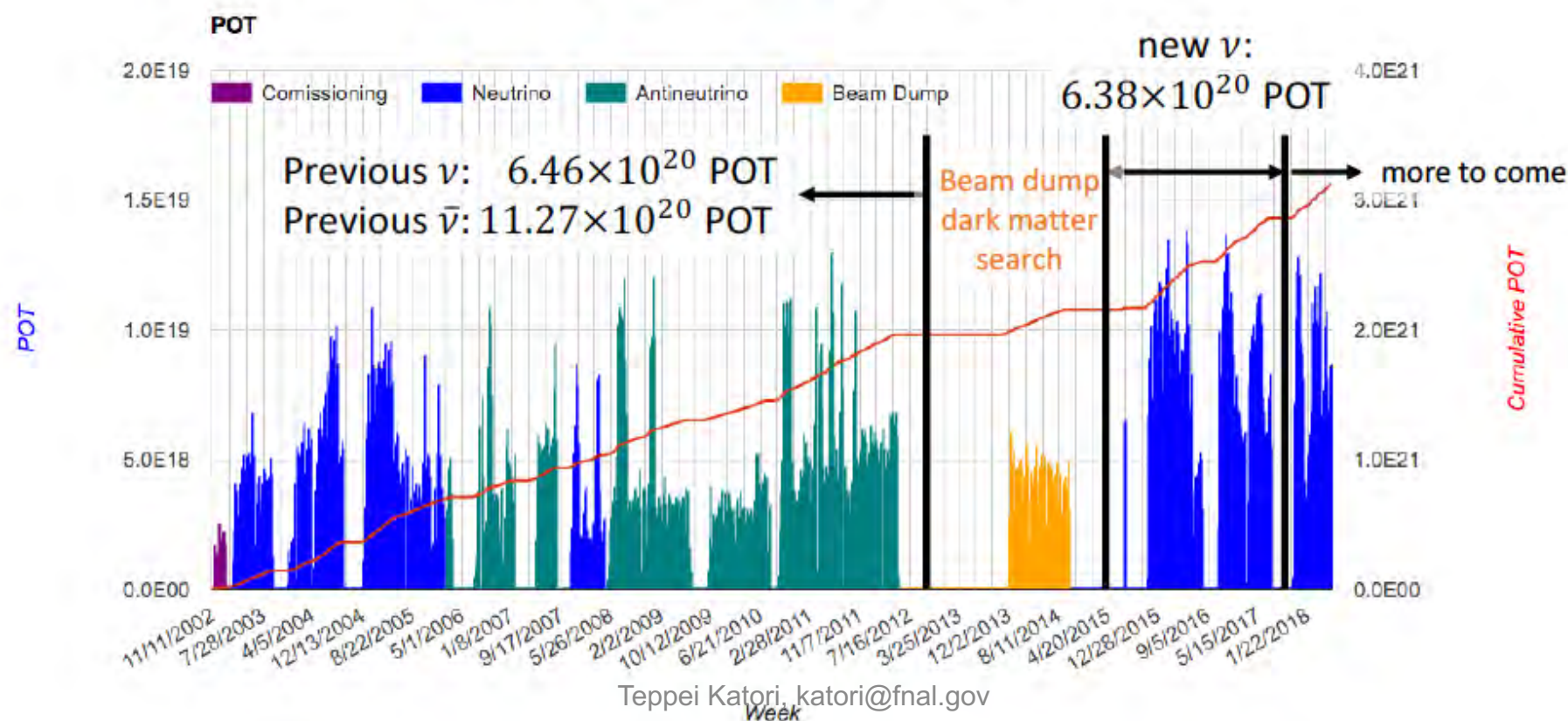
MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	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%



2. BNB status

- 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

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



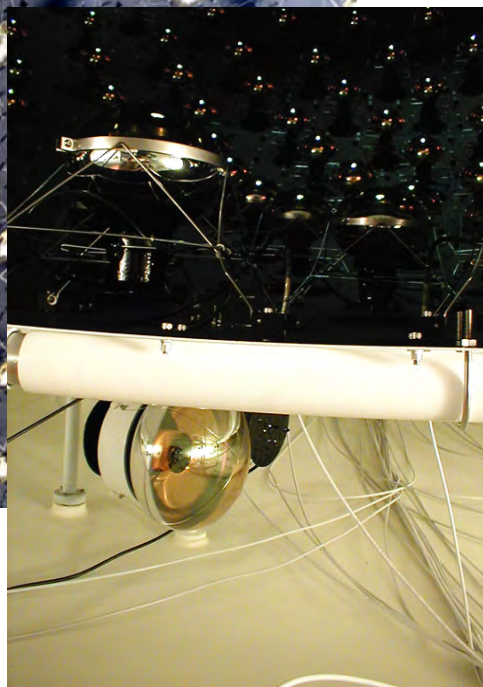
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3. Events in the Detector

Times of hit-clusters (subevents)

Beam spill ($1.6\mu\text{s}$) is clearly evident
simple cuts eliminate cosmic
backgrounds

Neutrino Candidate Cuts

<6 veto PMT hits

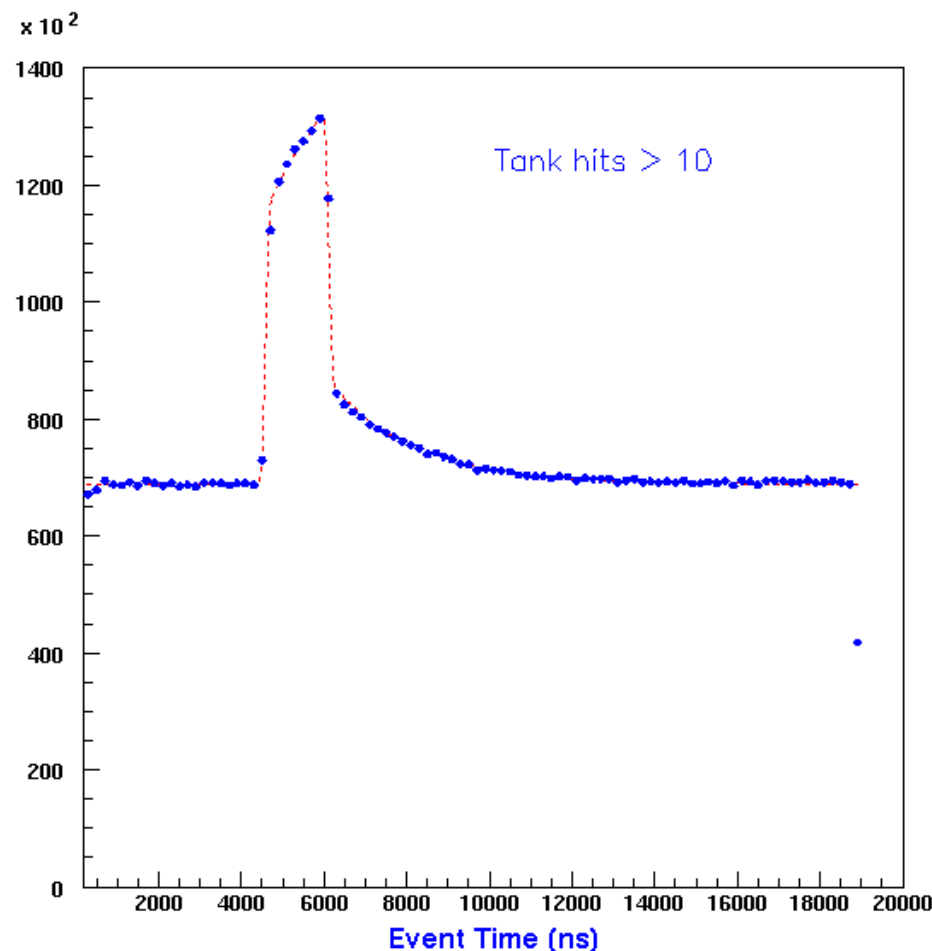
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and
Cosmic BG



3. Events in the Detector

Times of hit-clusters (subevents)

Beam spill ($1.6\mu\text{s}$) is clearly evident
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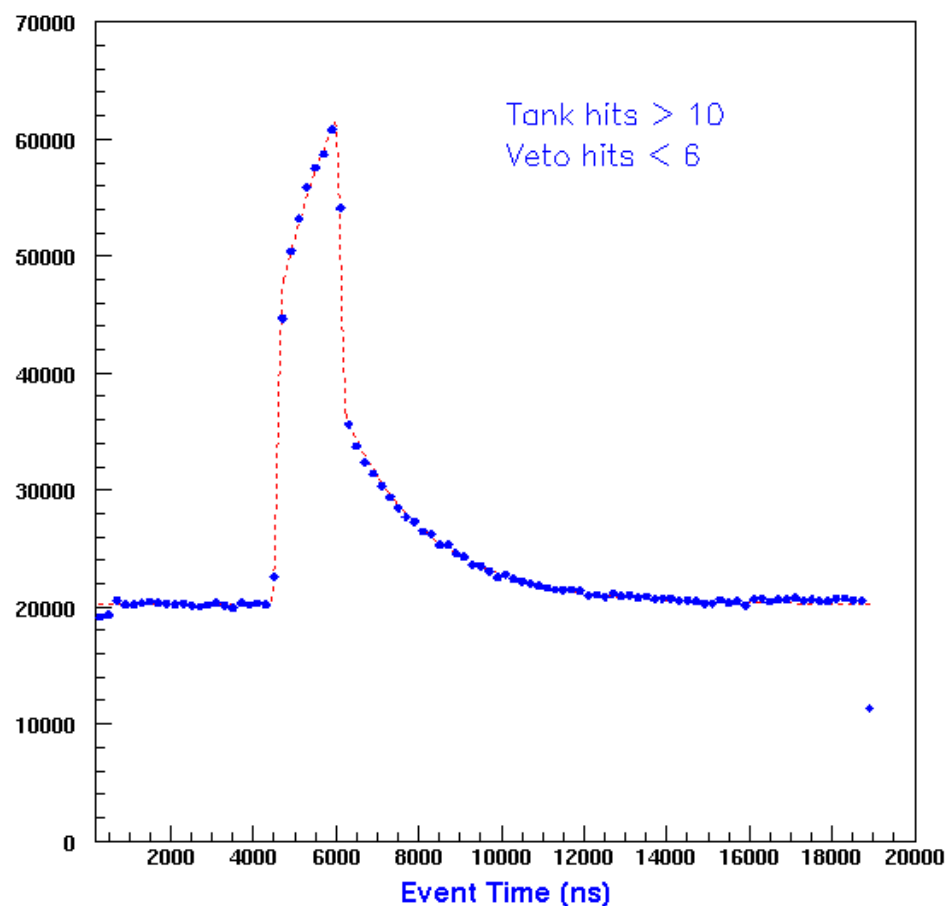
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Beam and
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3. Events in the Detector

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Neutrino Candidate Cuts

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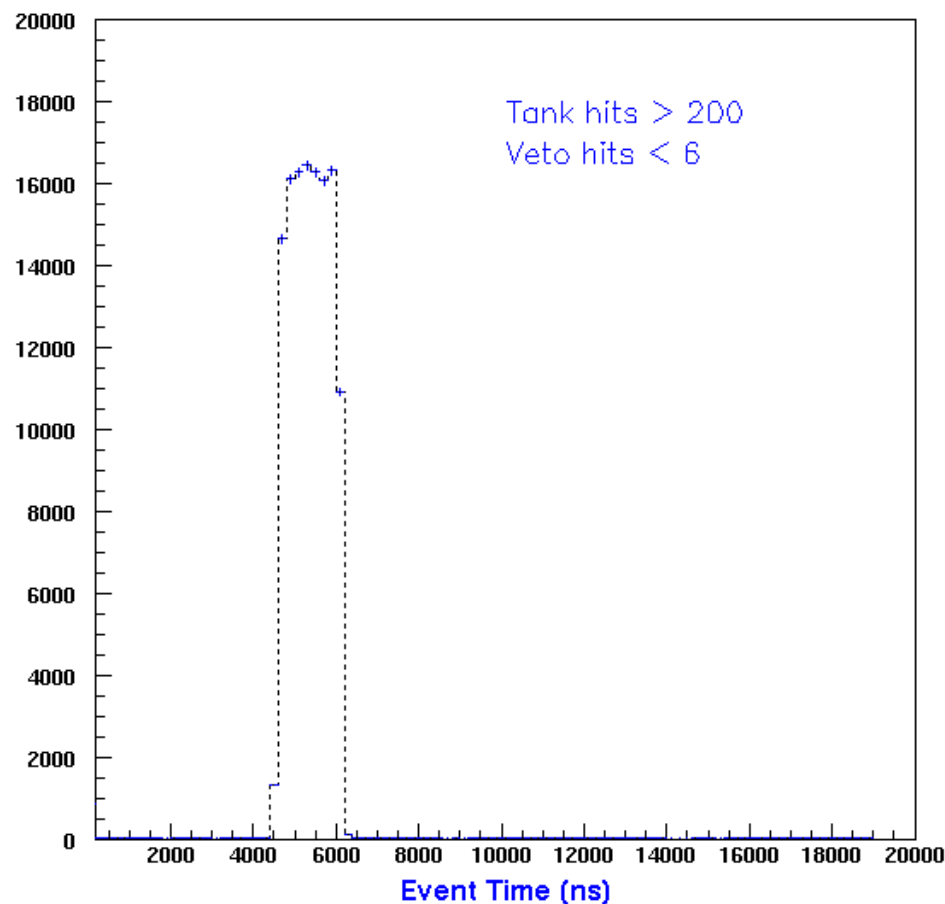
Gets rid of muons

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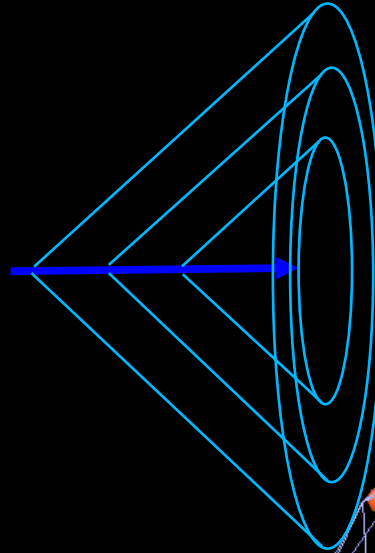
Beam
Only



3. Events in the Detector

Muons

- Long straight tracks
- Sharp clear rings



Electrons

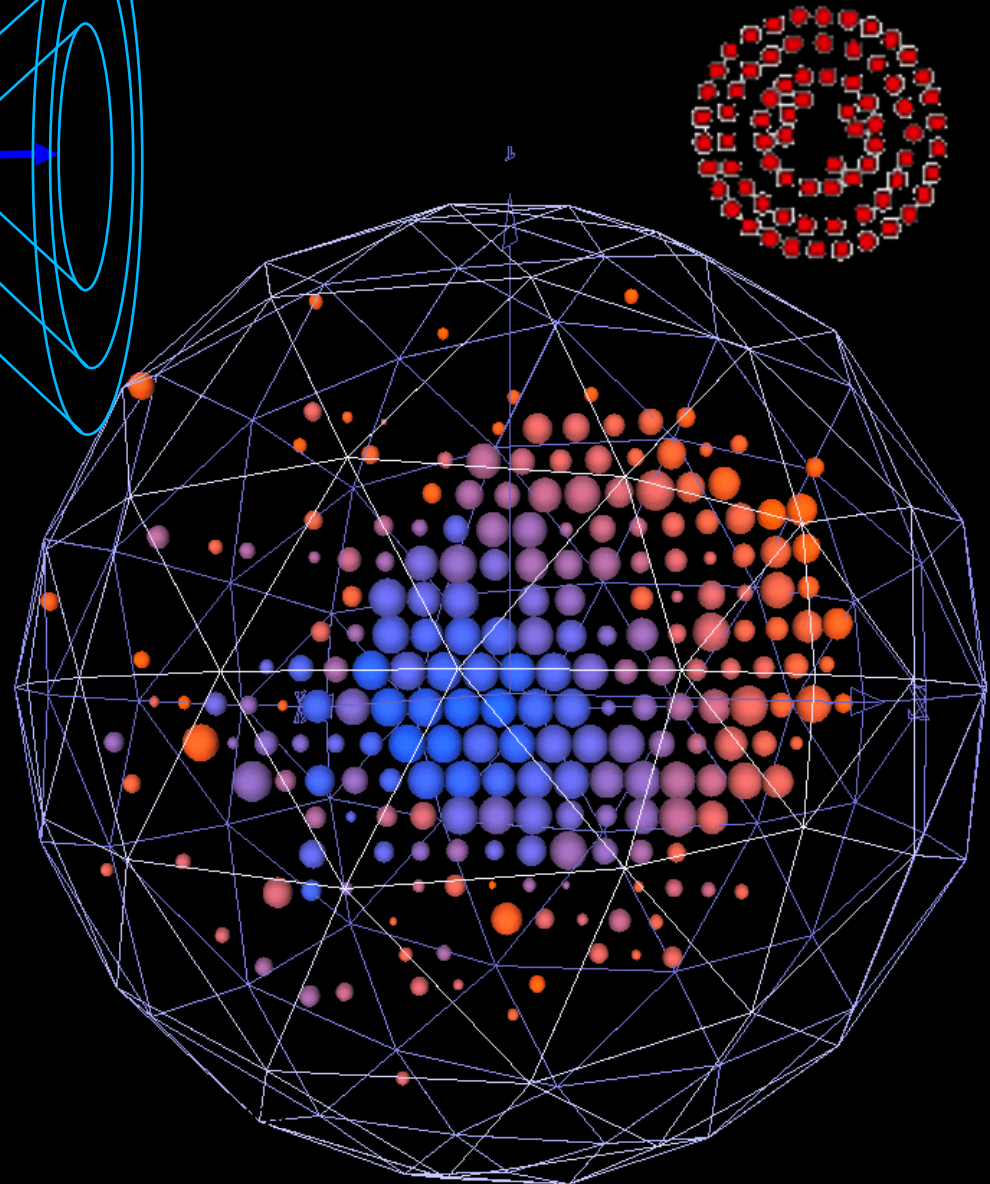
- Multiple scattering
- Radiative processes
- Scattered fuzzy rings

Neutral pions

- Decays to 2 photons
- Double fuzzy rings

NC elastic scattering

- No Cherenkov radiation
- Isotropic scintillation hits



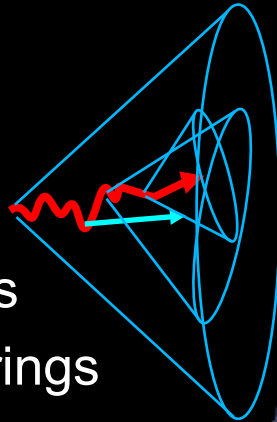
3. Events in the Detector

Muons

- Long straight tracks
- Sharp clear rings

Electrons

- Multiple scattering
- Radiative processes
- Scattered fuzzy rings

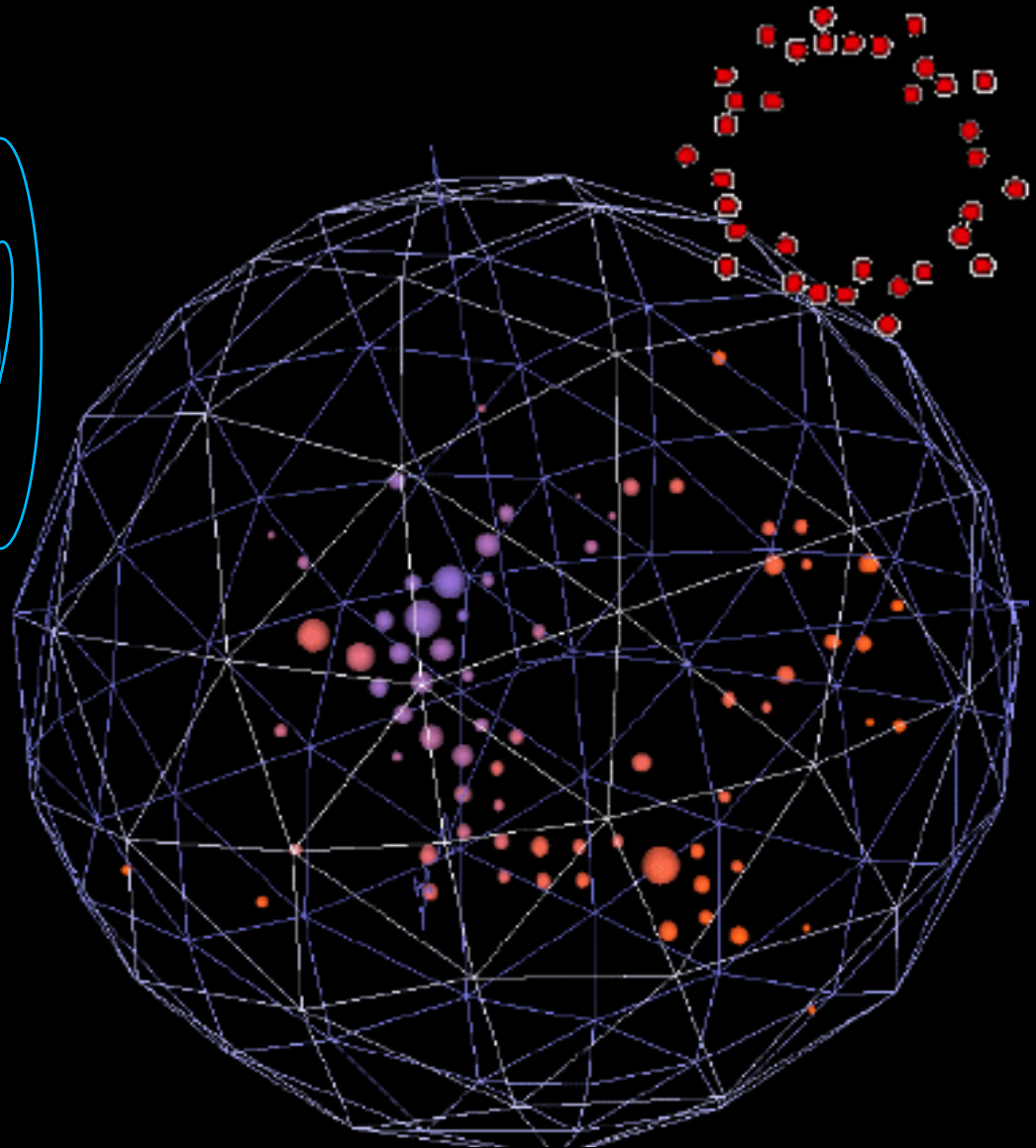


Neutral pions

- Decays to 2 photons
- Double fuzzy rings

NC elastic scattering

- No Cherenkov radiation
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3. Events in the Detector

Muons

- Long straight tracks
- Sharp clear rings

Electrons

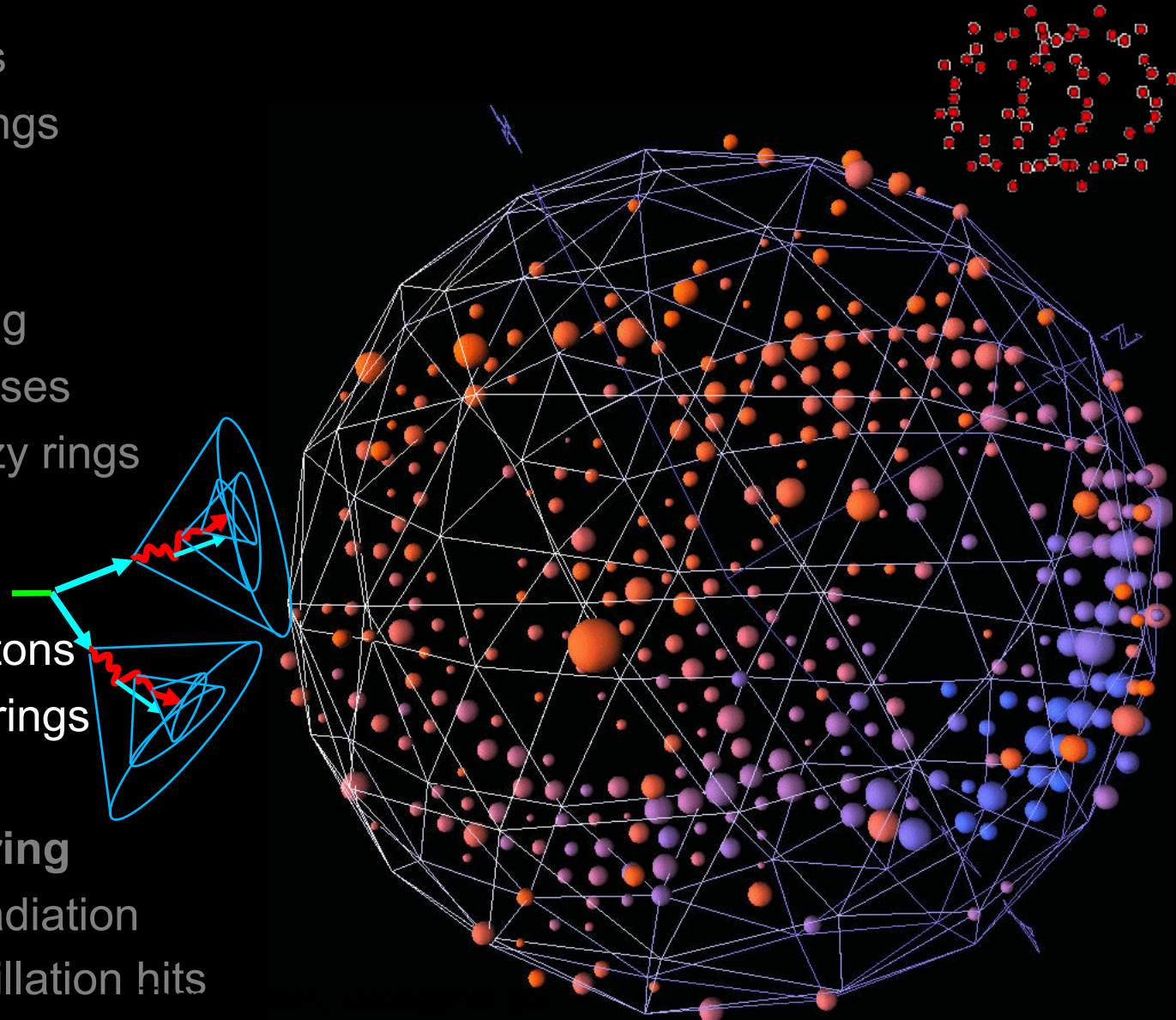
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3. Events in the Detector

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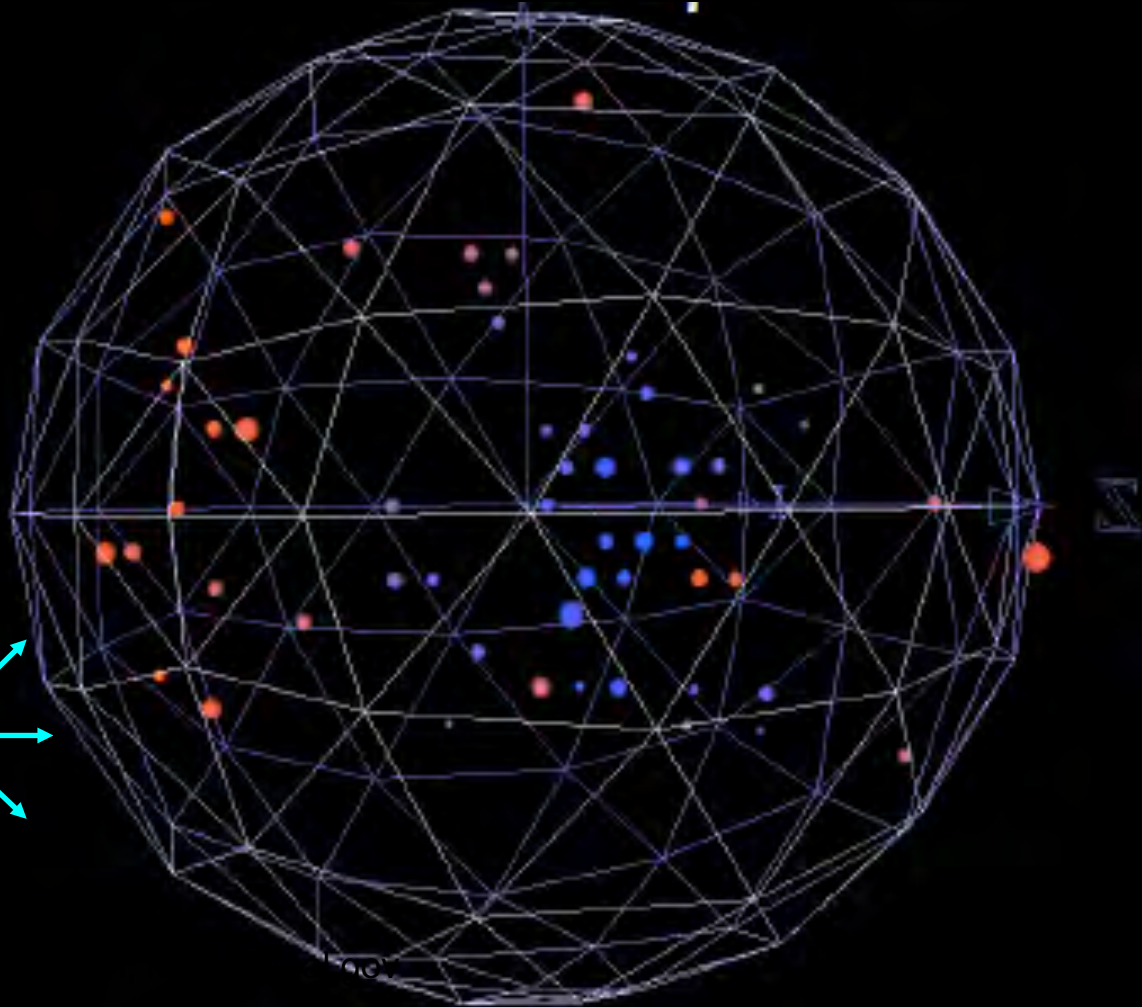
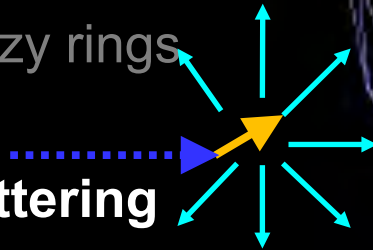
- Multiple scattering
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- Decays to 2 photons
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NC elastic scattering

- No Cherenkov radiation
- Isotropic scintillation hits



3. QE kinematics based energy reconstruction

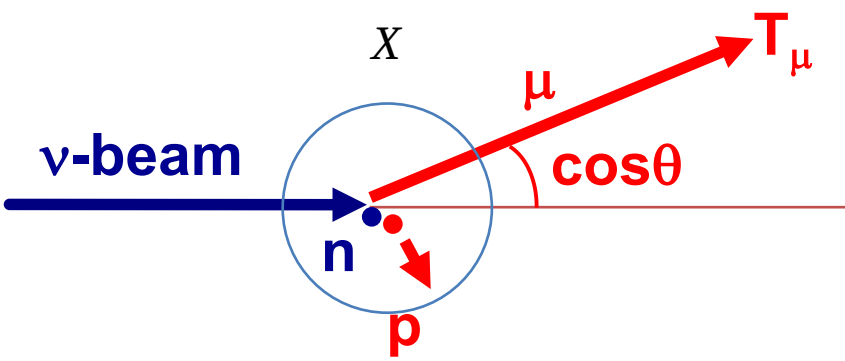
Event reconstruction from Cherenkov ring profile for PID

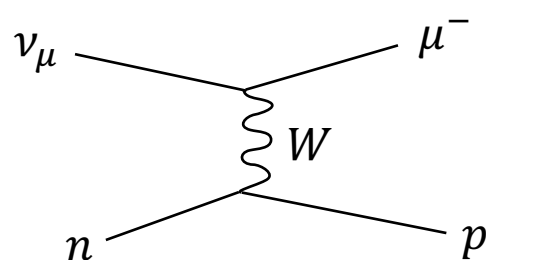
- scattering angle θ and kinetic energy of charged lepton T are measured

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

$$\nu_\mu + n \rightarrow p + \mu^- \quad (\nu_\mu + X \rightarrow X' + \mu^-)$$



$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta}$$

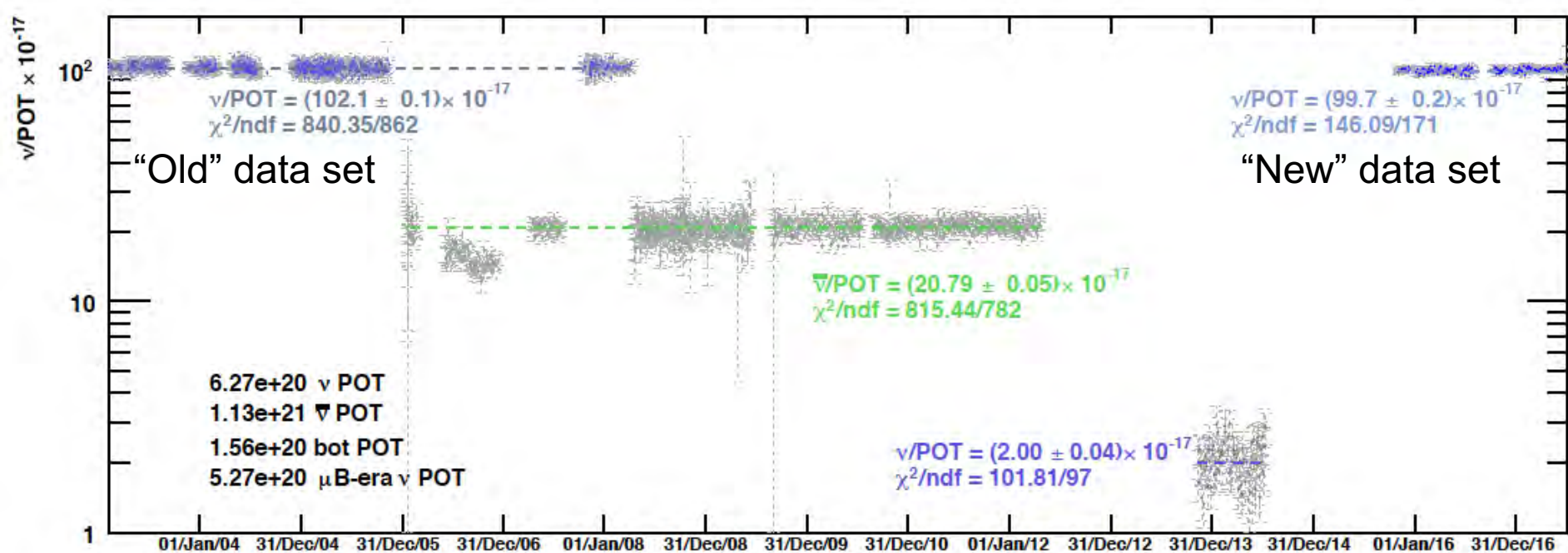
CCQE is the most important channel of neutrino oscillation physics for MiniBooNE, T2K, microBoonE, SBND, etc (also important for NOvA, Hyper-Kamiokande, DUNE, etc)

3. Detector stability

Event rate look consistent from expectations

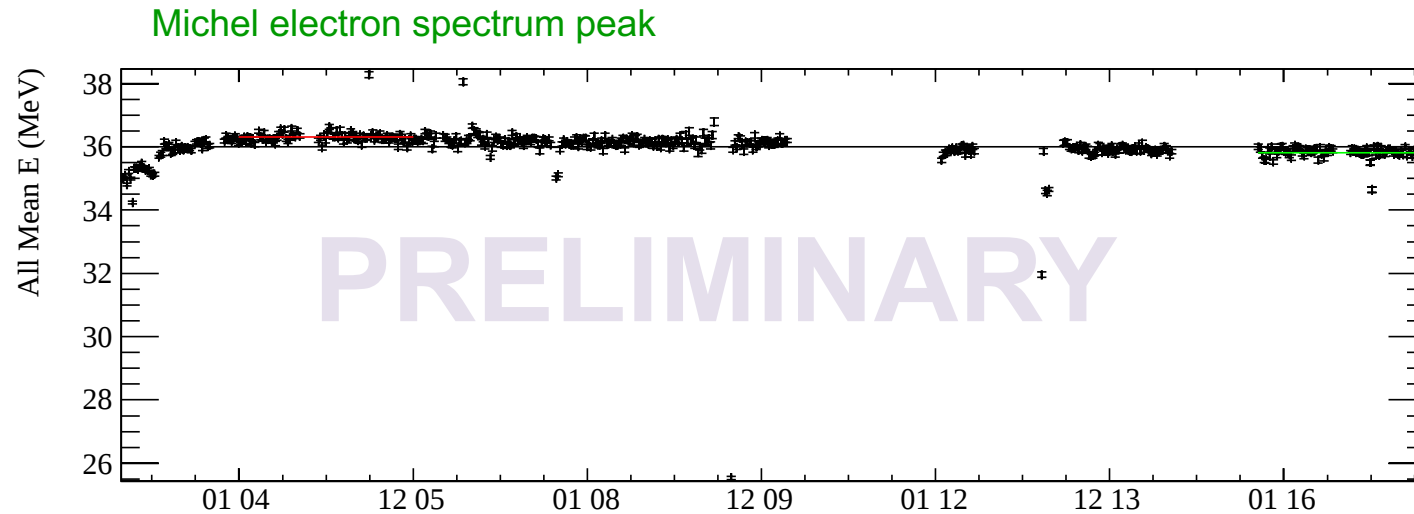
- Antineutrino mode (factor 5 lower event rate)
 - factor ~2 lower flux
 - factor ~2-3 lower cross section
- Dark matter mode (factor 50 lower event rate)
 - factor ~40 lower flux

MiniBooNE, PRL118(2017)221803,
PRD98(2018)112004



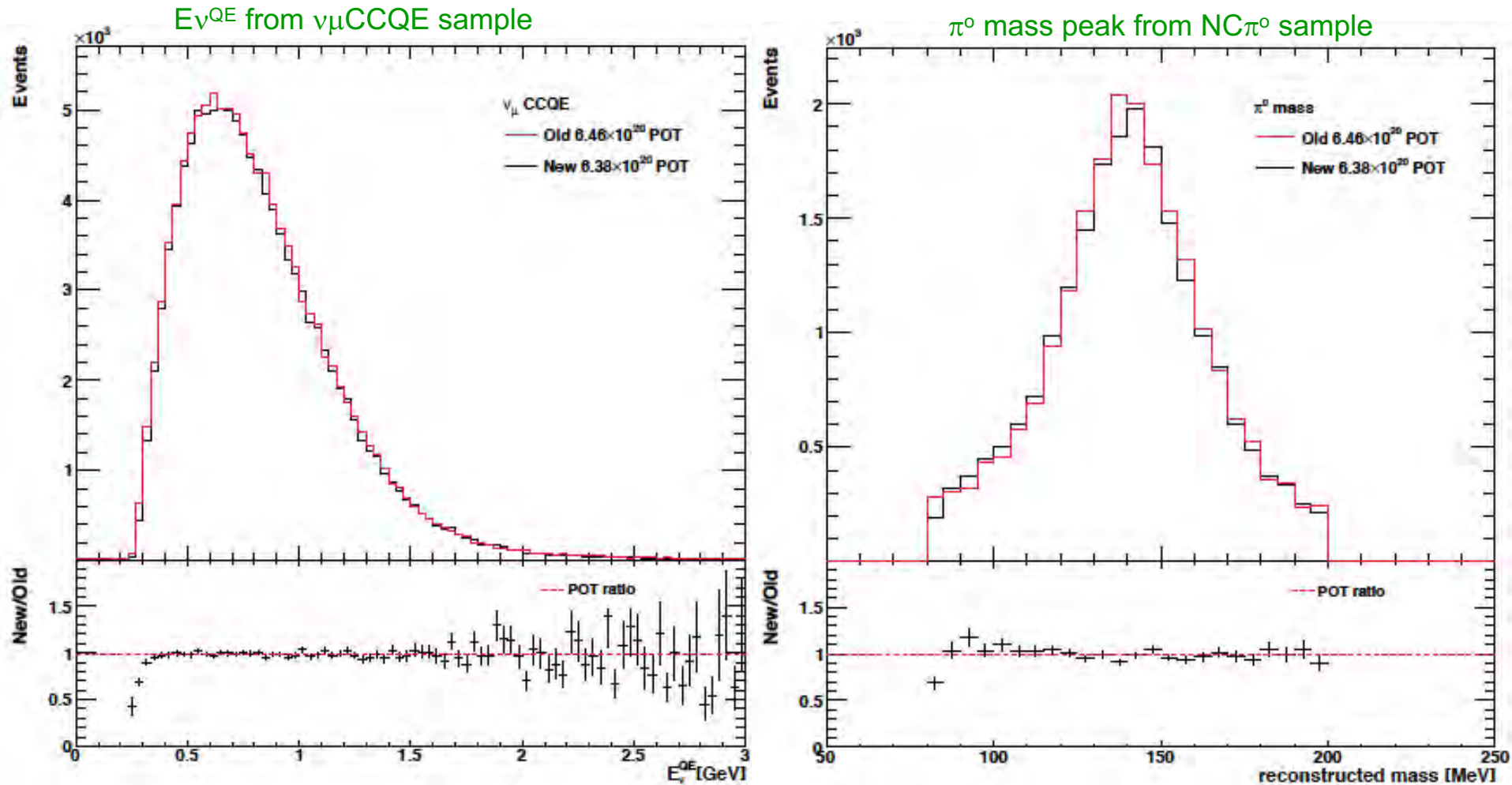
3. Detector stability

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



3. Detector stability

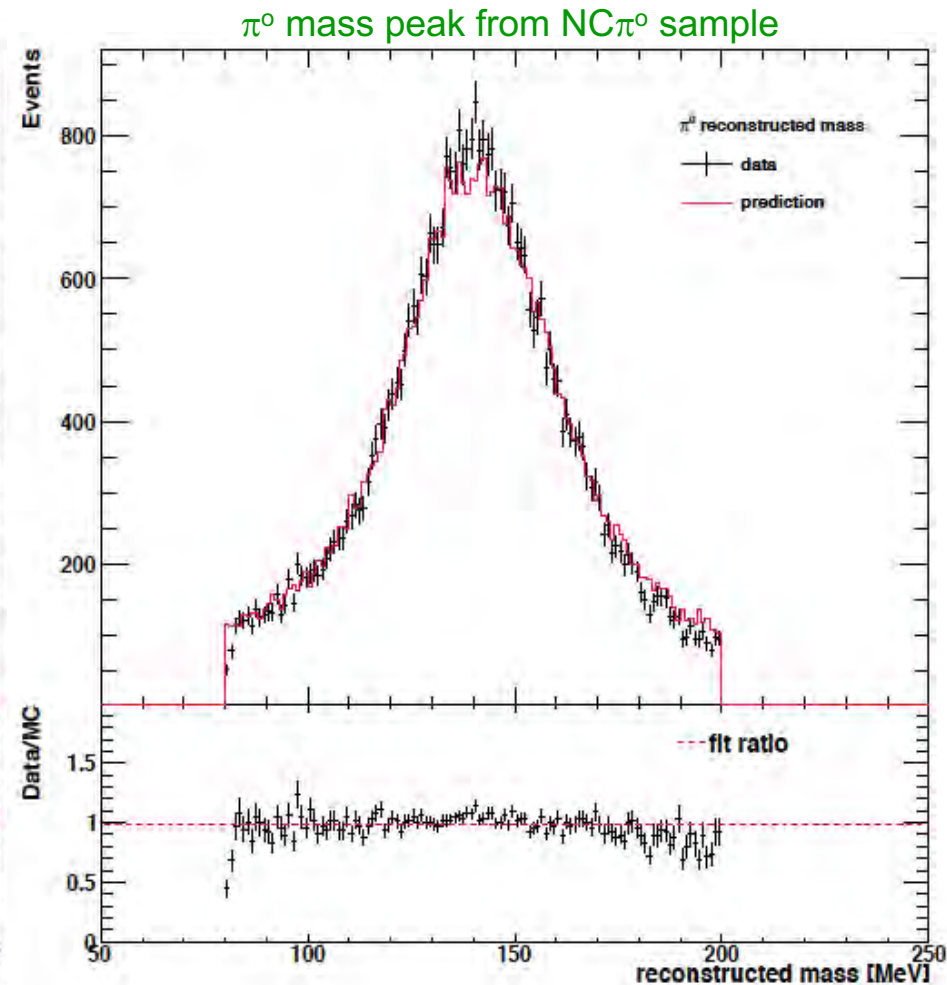
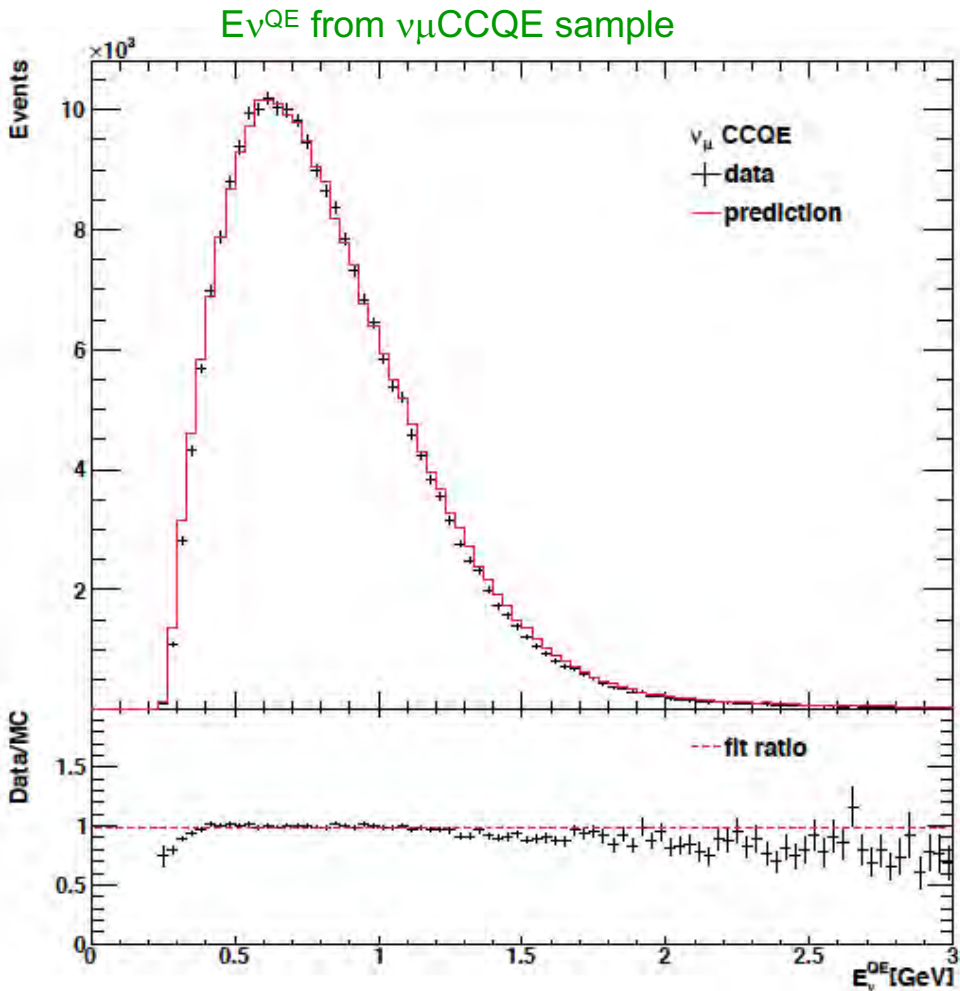
Old and new data agree within 2% over 8 years separation.



3. Data-Simulation comparison

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

- Excellent agreements with MC.



1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

4. Internal background constraints

All backgrounds are internally constrained

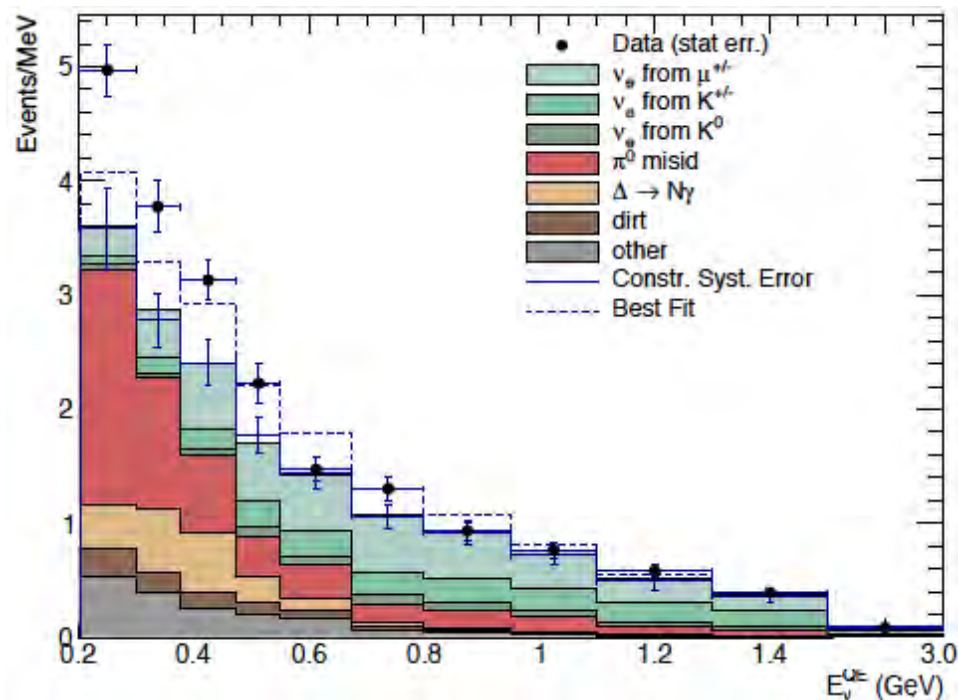
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→ misID (gamma) = accumulate at low E

misID

intrinsic

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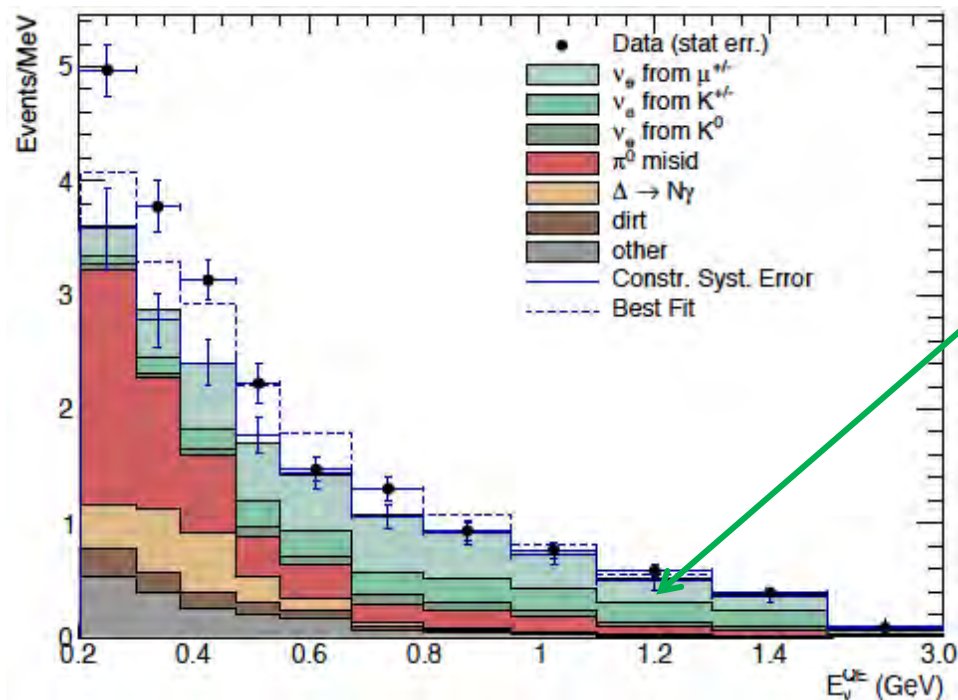
4. ν_e from μ -decay constraint

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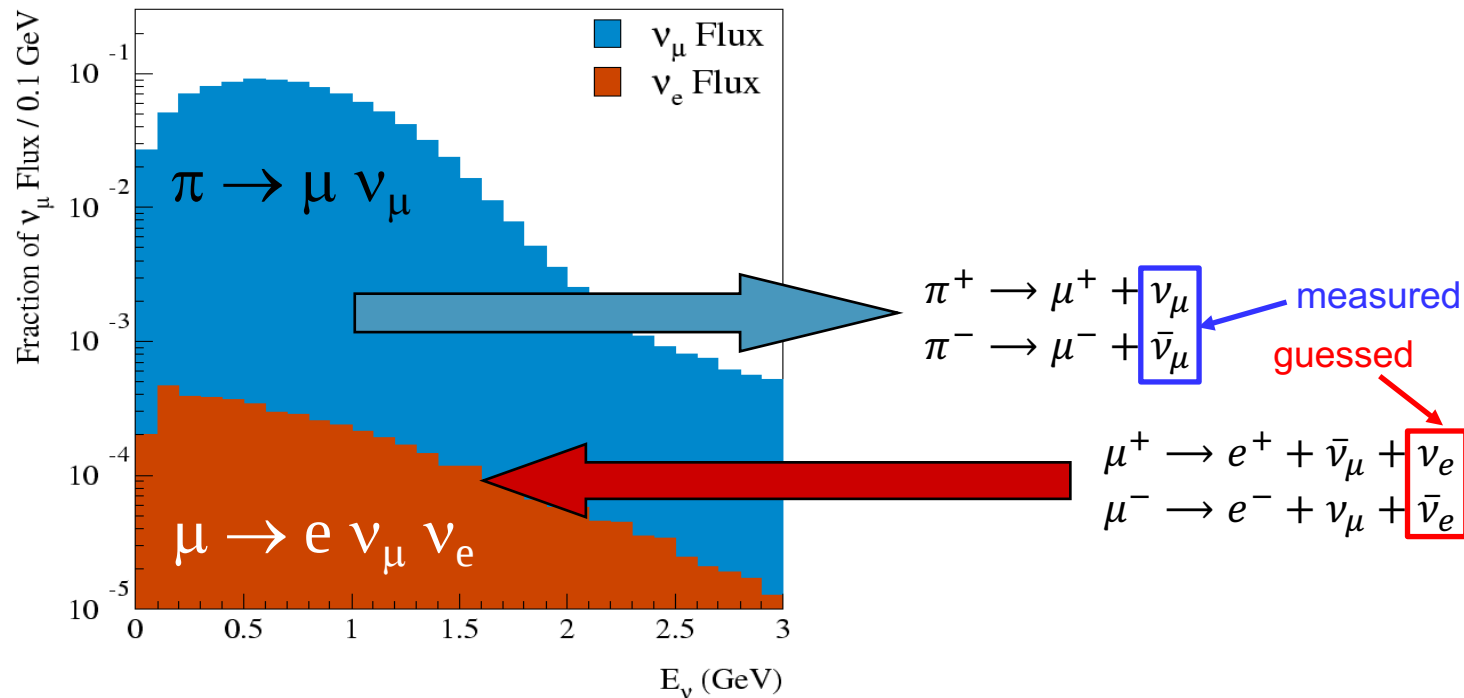
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ν_e from μ decay
is constrained
from ν_μ CCQE
measurement

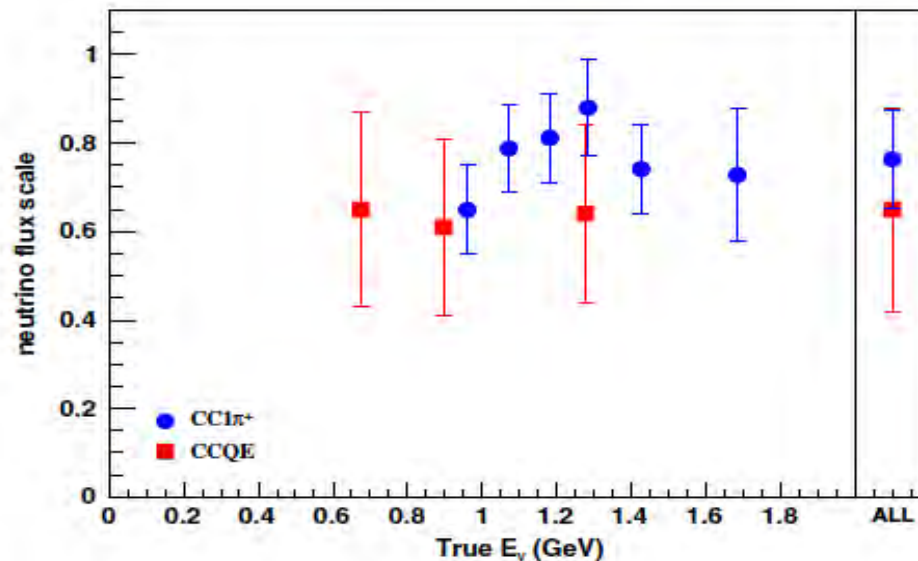
4. ν_e from μ -decay constraint

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



4. Anti-neutrino mode flux tuning

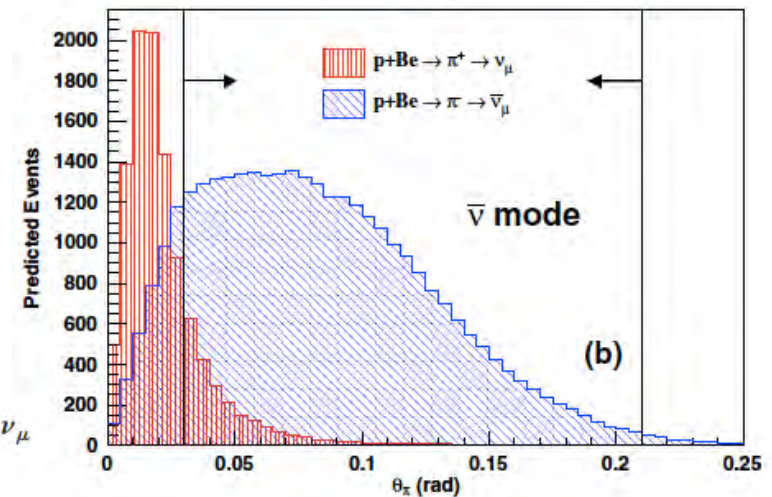
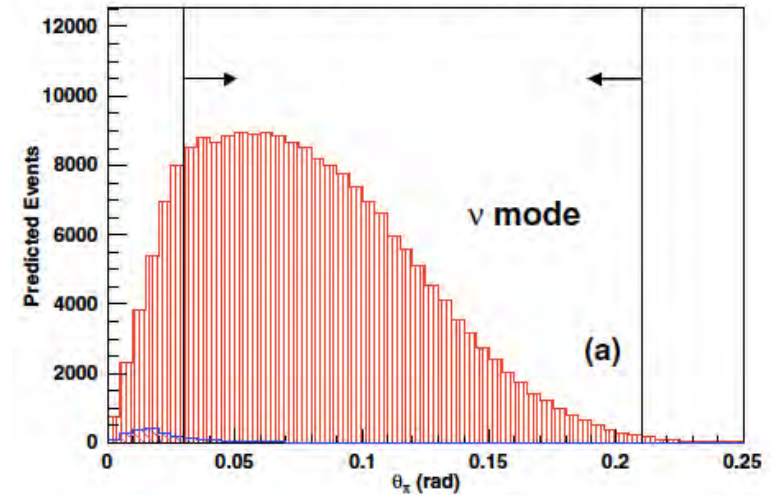
$\bar{\nu}_e$ & $\bar{\nu}_\mu$ flux are harder to predict due to larger wrong sign (ν_e & ν_μ) background, and measured lepton kinematics and π^+ production are used to tune flux
→ they consistently suggest we overestimate antineutrino flux around 20%



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

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

PHYSICAL REVIEW D 84, 072005 (2011)



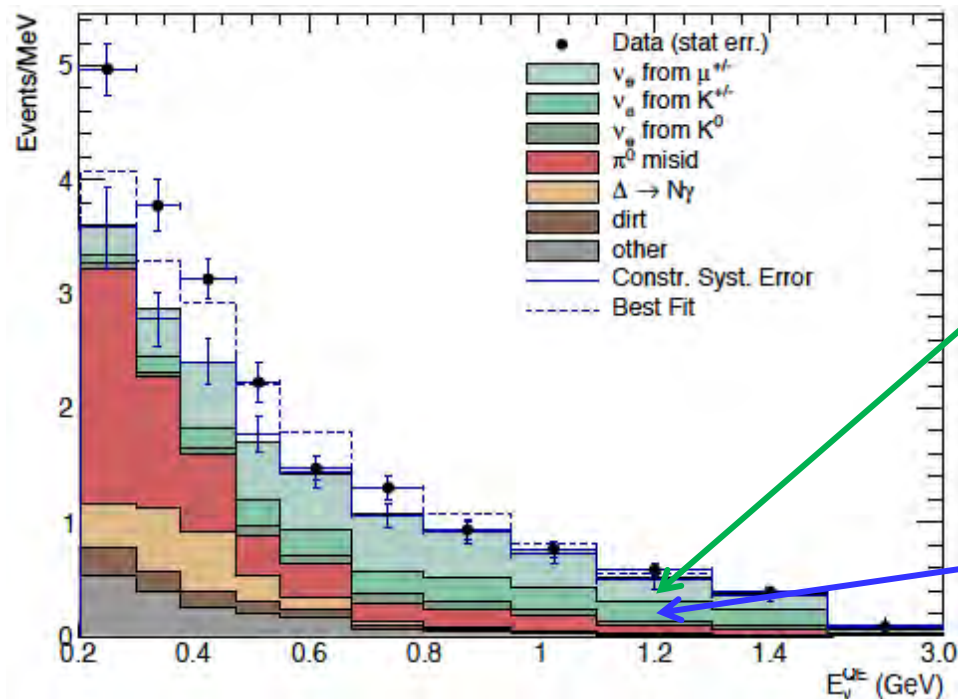
4. ν_e from K^+ -decay constraint

All backgrounds are internally constrained

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→ misID (gamma) = accumulate at low E

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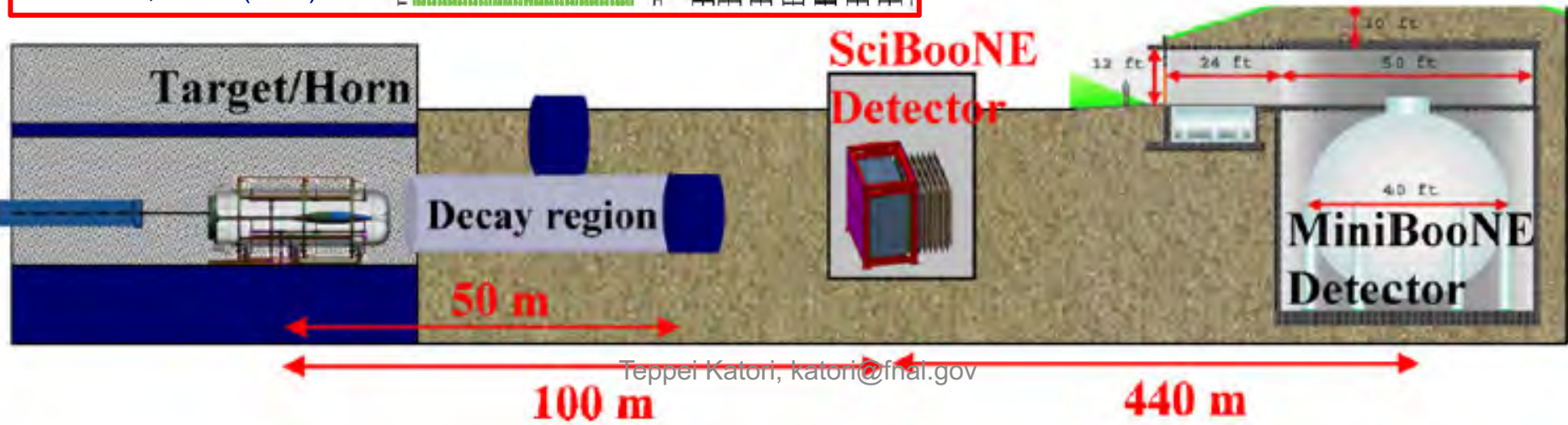
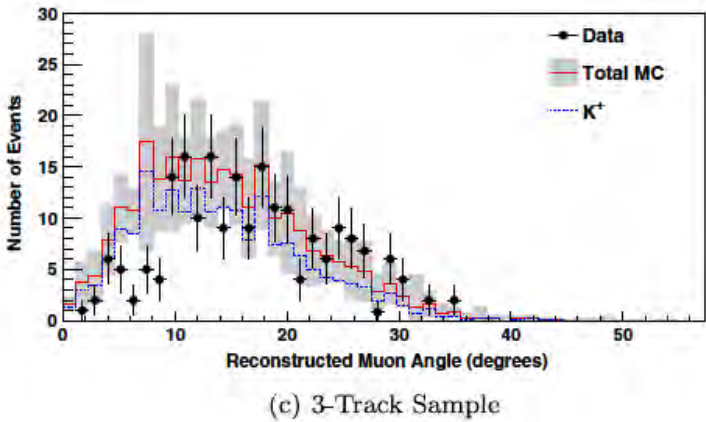
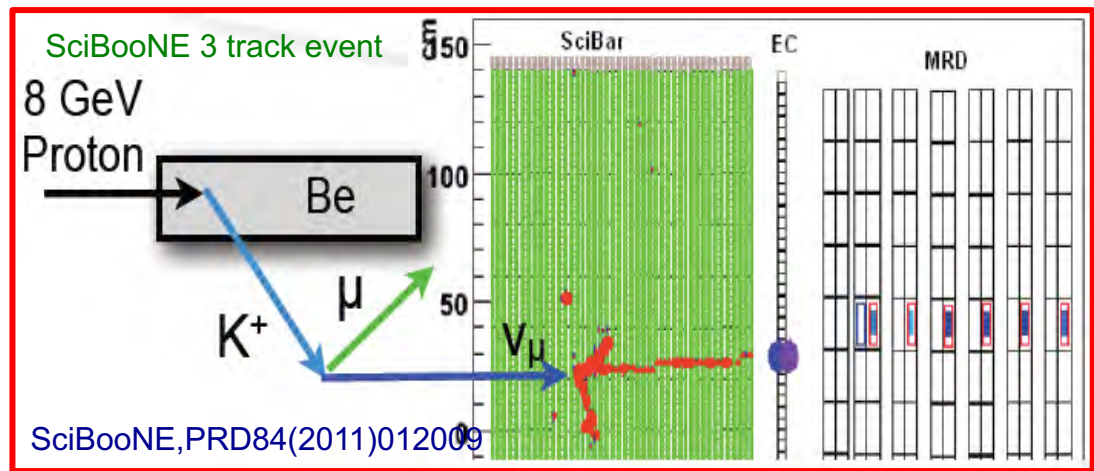


ν_e from μ decay
is constrained
from ν_μ CCQE
measurement

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

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 energy, and tend to make 3 tracks
 - from 3 track analysis, kaon decay neutrinos are constrained (0.85 ± 0.11 , prior is 40% error)



4. ν_e from K^+ -decay constraint

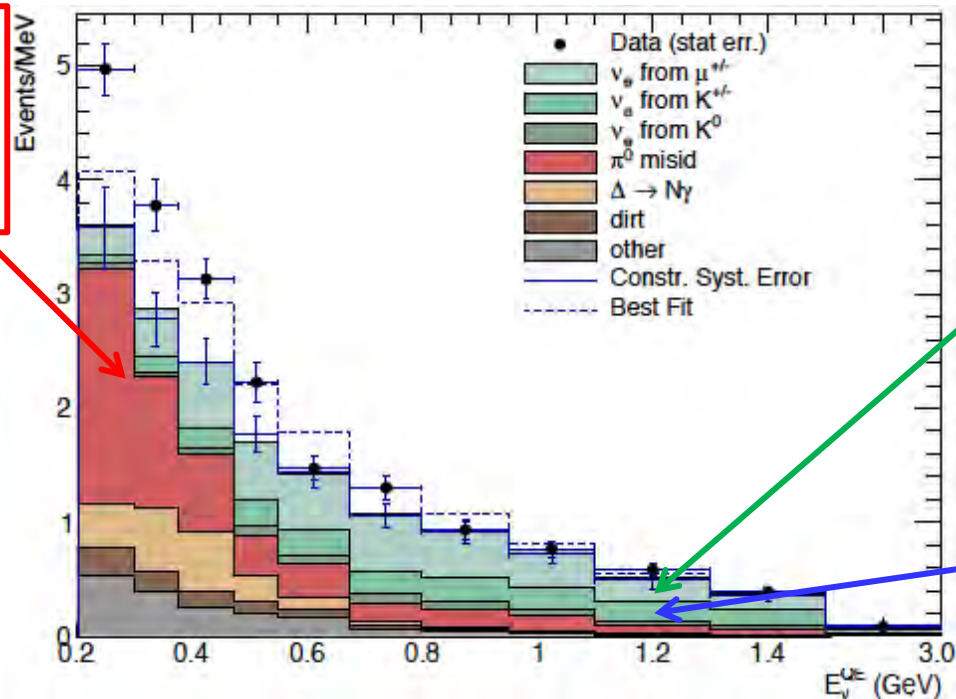
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Asymmetric π^0 decay is constrained from measured NC π^0 rate ($\pi^0 \rightarrow \gamma$)



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

4. γ from π^0 constraint

$\pi^0 \rightarrow \gamma\gamma$

- not background, we can measure

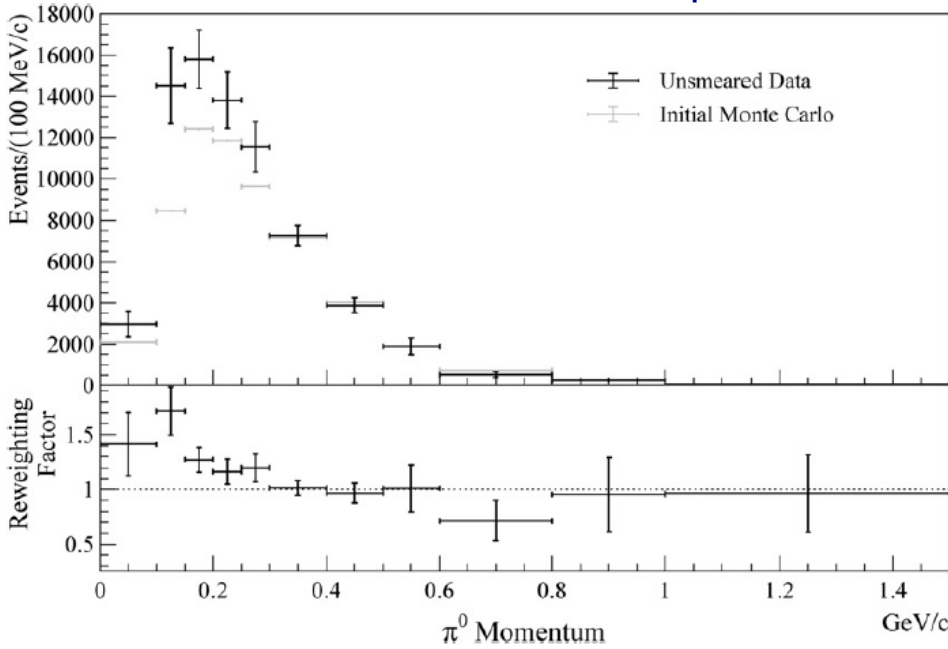
$\pi^0 \rightarrow \gamma$

- misID background, we cannot measure

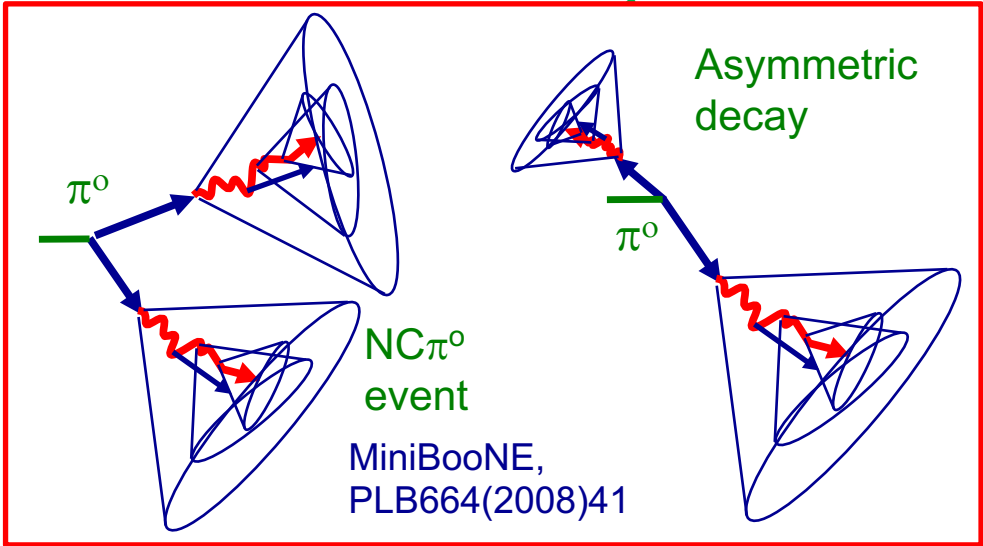
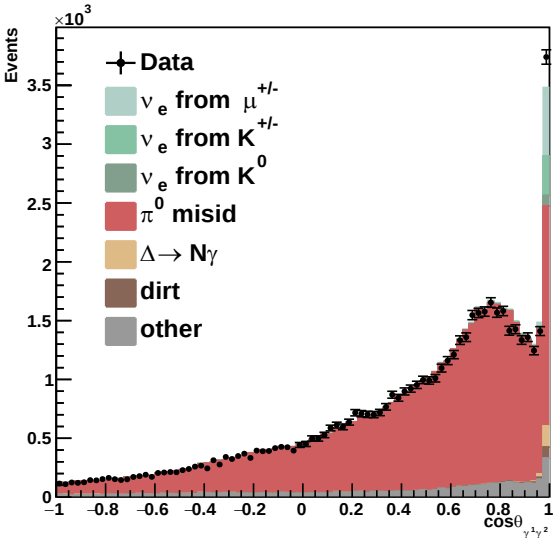
The biggest systematics is production rate of π^0 , because once you find that, the chance to make a single gamma ray is predictable.

We measure π^0 production rate, and correct simulation with function of π^0 momentum

π^0 momentum data-MC comparison



2-gamma-ray opening angle



4. $\text{NC}\gamma$ constraint

All backgrounds are internally constrained

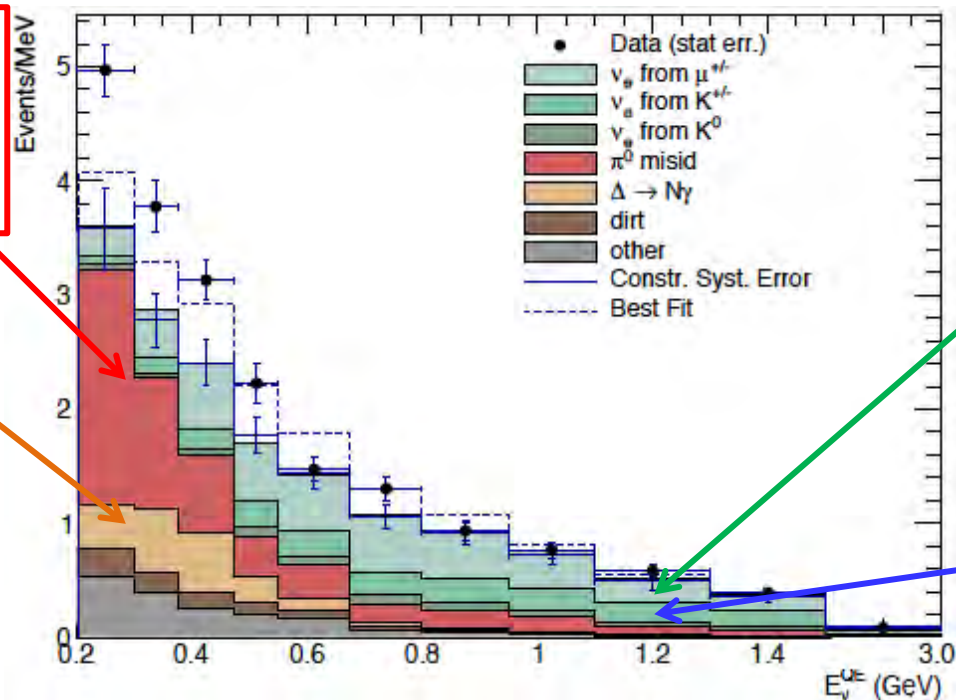
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Asymmetric π^0 decay is constrained from measured $\text{NC}\pi^0$ rate ($\pi^0 \rightarrow \gamma$)

Δ resonance rate is constrained from measured $\text{NC}\pi^0$ rate



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

4. NC γ constraint

All backgrounds are internally constrained

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$$\frac{N(\Delta \rightarrow N\gamma)}{N(\Delta \rightarrow N\pi^0)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^0}\varepsilon}$$

Γ_γ/Γ_π : NC γ to NC π branching ratio
 π^0 fraction (=2/3)
 ε : π escaping factor

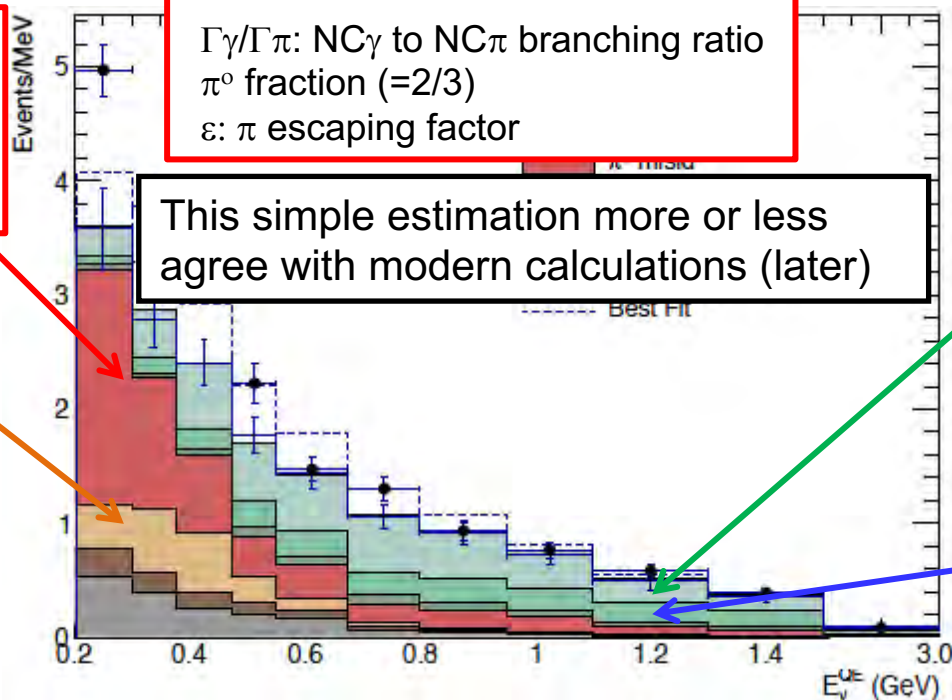
Asymmetric π^0 decay is constrained from measured NC π^0 rate ($\pi^0 \rightarrow \gamma$)

Δ resonance rate is constrained from measured NC π^0 rate

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

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



4. External γ constraint

All backgrounds are internally constrained

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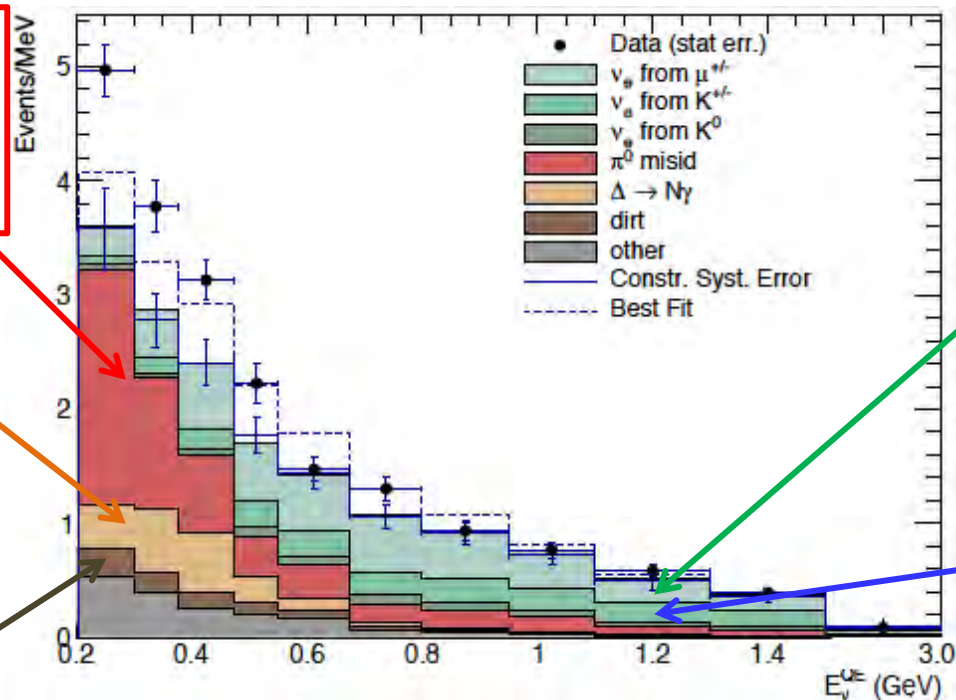
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dirt rate is measured from dirt data sample



ν_e from μ decay is constrained from ν_μ CCQE measurement

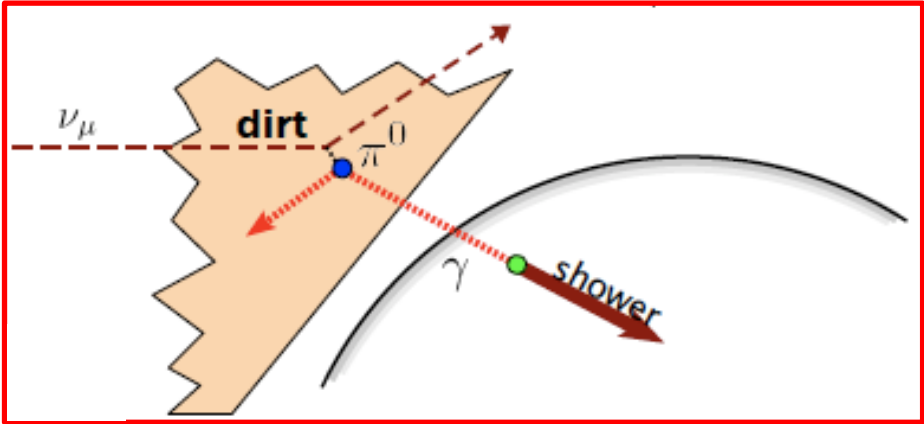
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4. External γ constraint

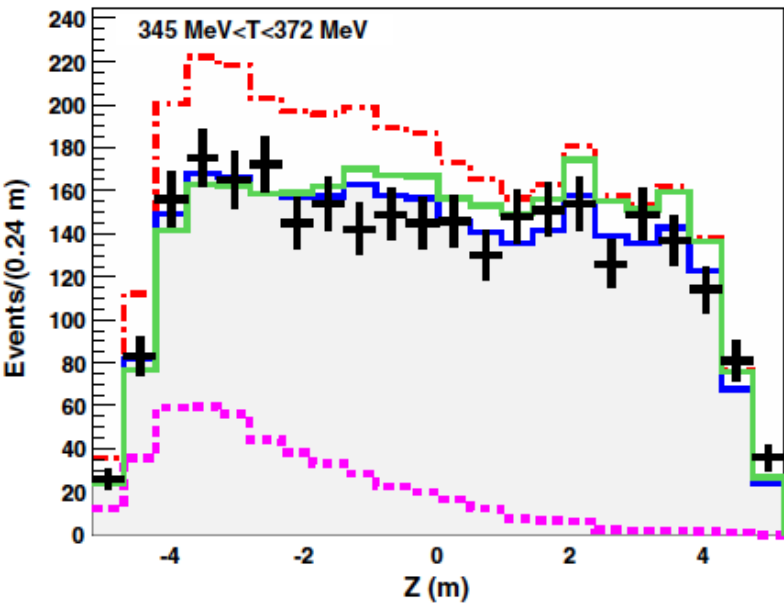
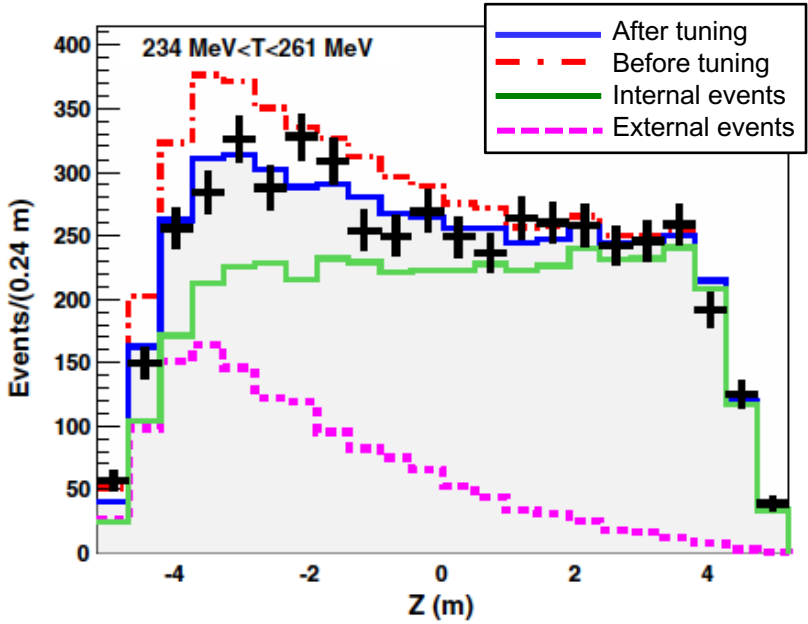
MiniBooNE detector has a simple geometry

- 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



4. Internal background constraints

All backgrounds are internally constrained

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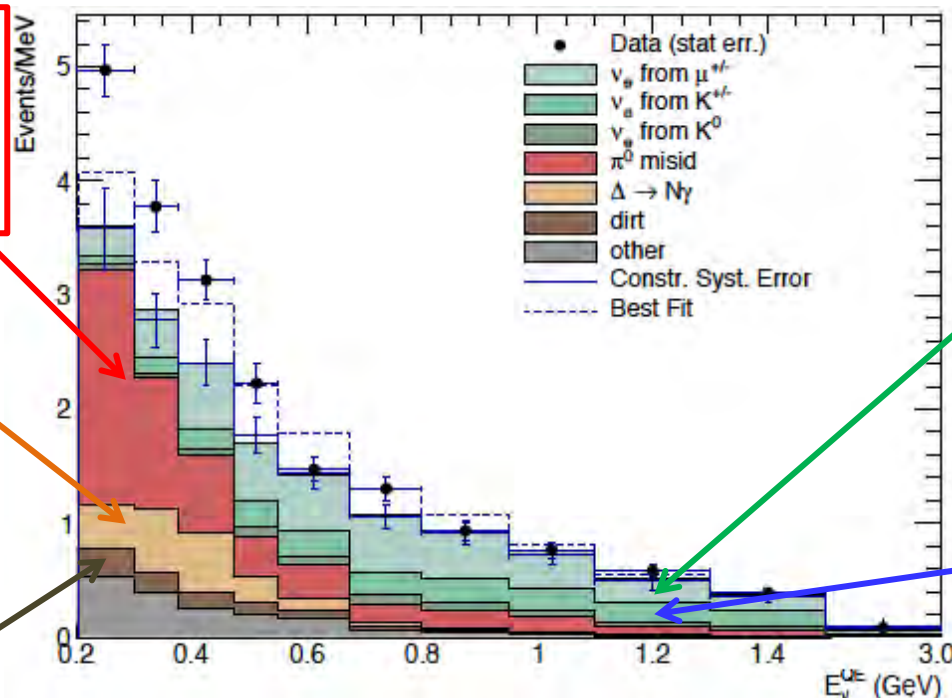
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Major backgrounds are all measured in other data sample and their errors are constrained!

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

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

5. Oscillation candidate event excess

$200 < E_{\nu QE} < 1250 \text{ MeV}$

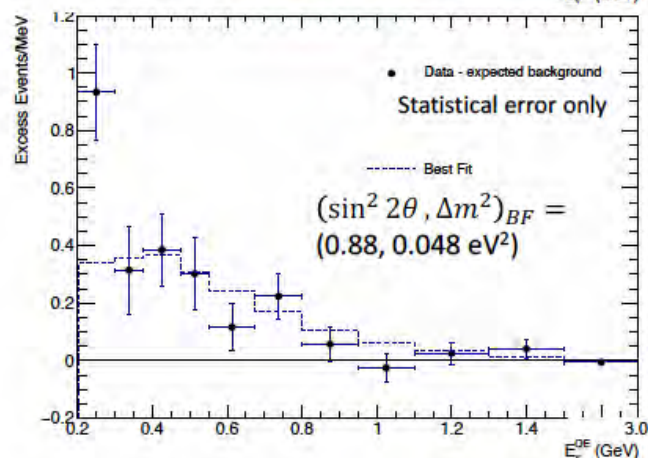
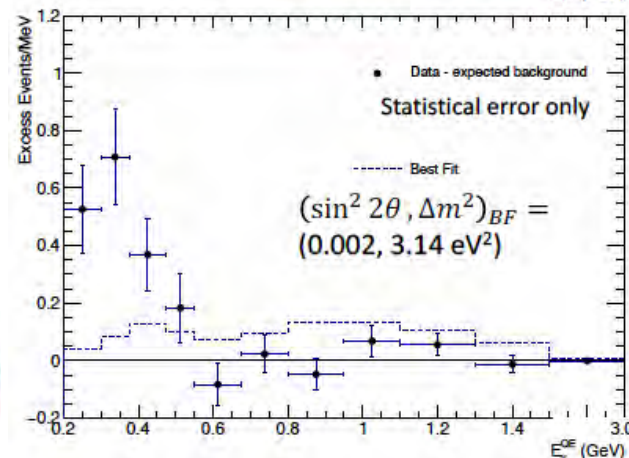
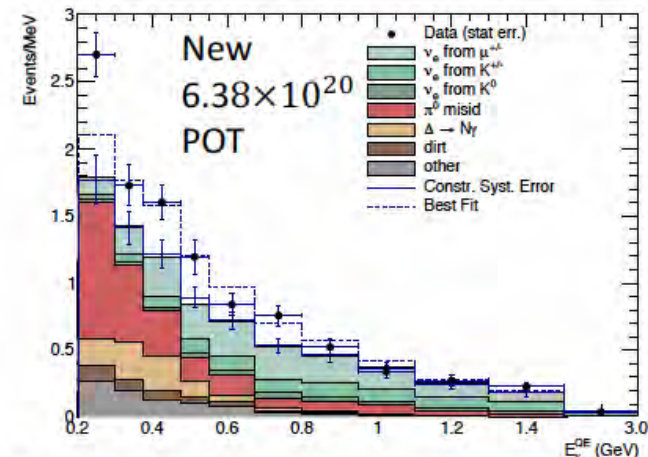
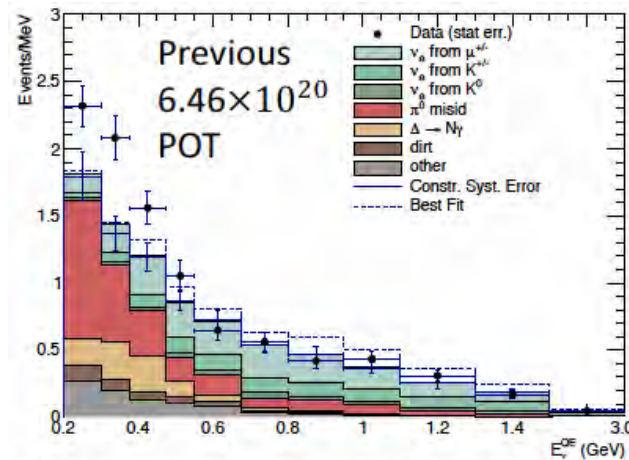
- neutrino mode: Data = 1959 events

Bkgd = $1577.8 \pm 39.7(\text{stat}) \pm 75.4(\text{syst}) \rightarrow 381.2 \pm 85.2 \text{ excess } (4.5\sigma)$

Old data (50.3%)
162.0 event excess

New data (49.7%)
219.2 event excess

KS test suggests
they are compatible
 $P(\text{KS})=76\%$



5. Oscillation candidate event excess

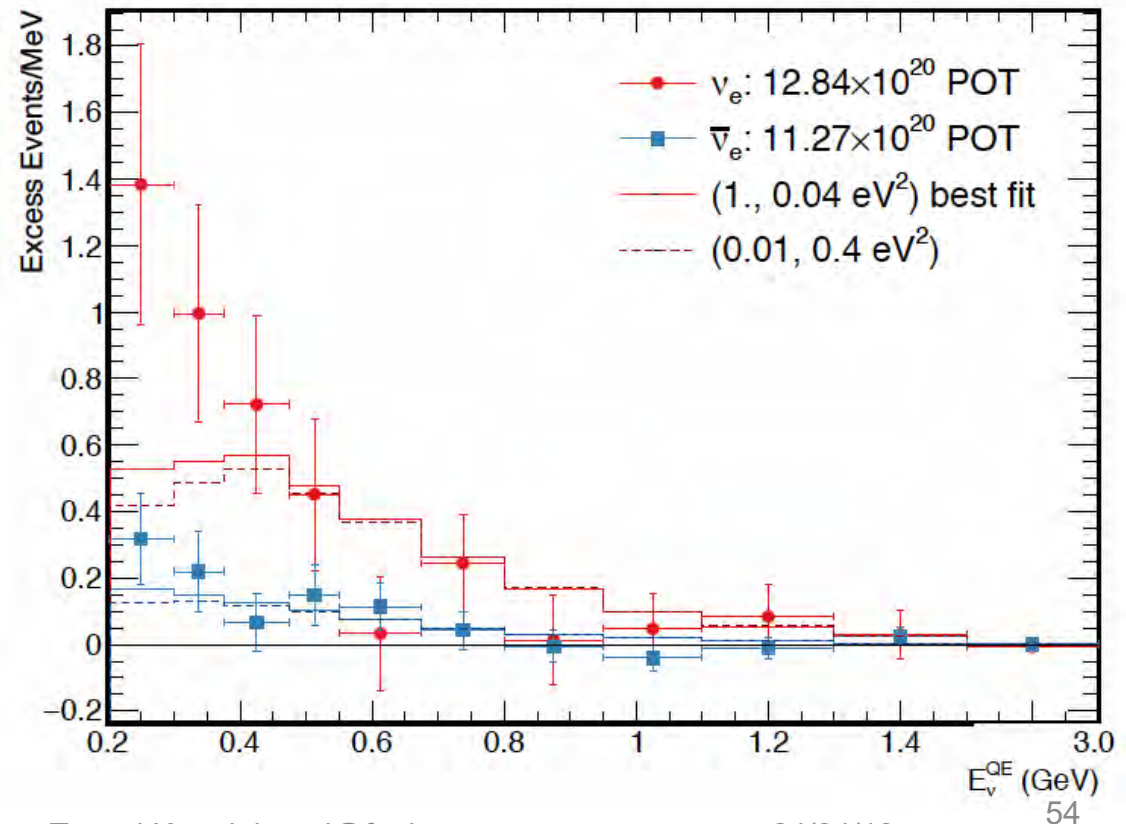
$200 < E_{\nu QE} < 1250 \text{ MeV}$

- neutrino mode: Data = 1959 events

Bkgd = $1577.8 \pm 39.7(\text{stat}) \pm 75.4(\text{syst}) \rightarrow 381.2 \pm 85.2 \text{ excess } (4.5\sigma)$

- antineutrino mode: Data = 478 events

Bkgd = $398.7 \pm 20.0(\text{stat}) \pm 20.3(\text{syst}) \rightarrow 79.3 \pm 28.6 \text{ excess } (2.8\sigma)$



5. Sterile neutrino hypothesis

200 < E_{νQE} < 1250 MeV

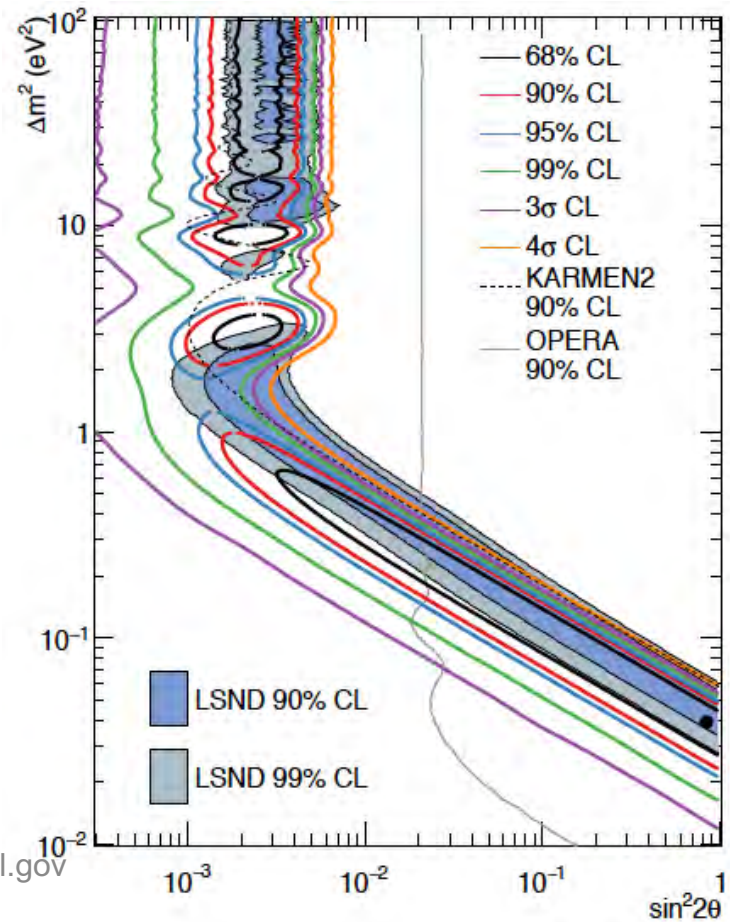
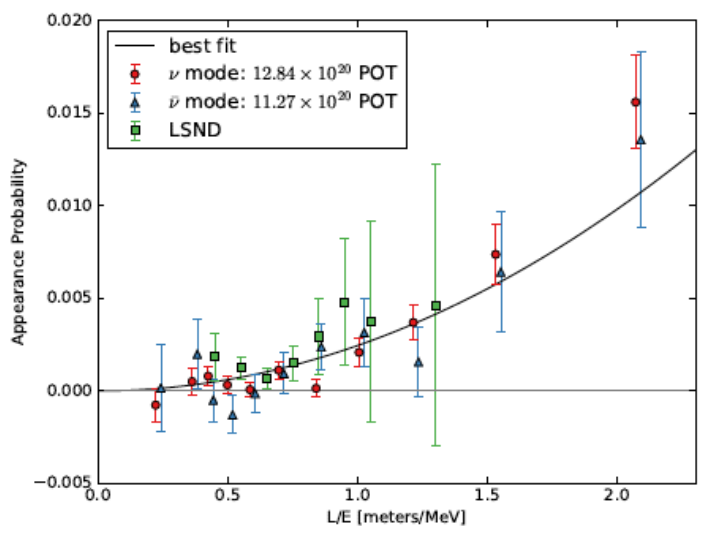
- neutrino mode: Data = 1959 events

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)

5. Alternative photon production models?

Excess look like more photons
(misID) than electrons

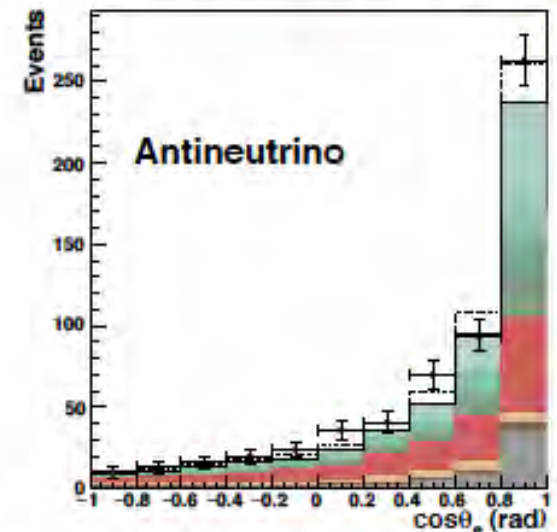
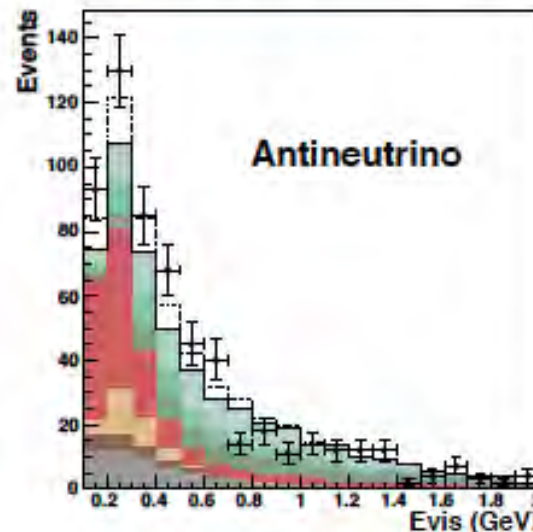
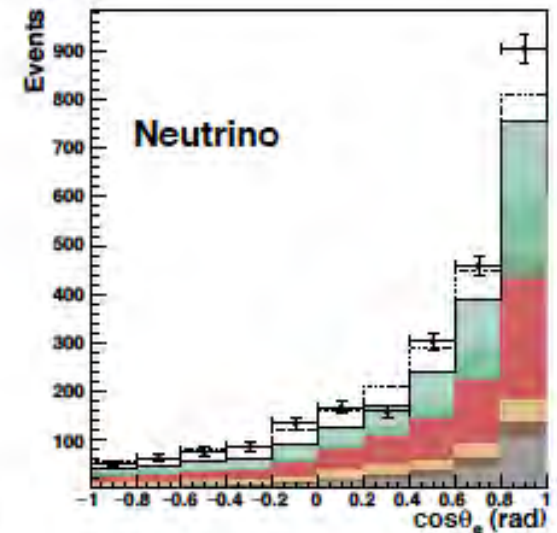
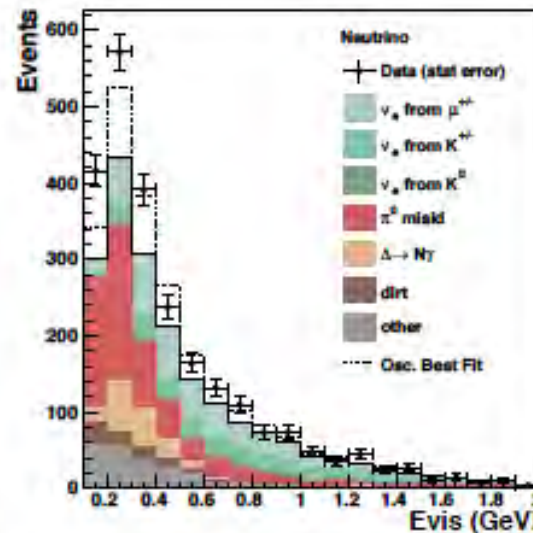
- peaked forward direction
- shape match with π^0 spectrum

Any misID background missing?

- New NC γ process?
- New NC π^0 process?

or BSM physics?

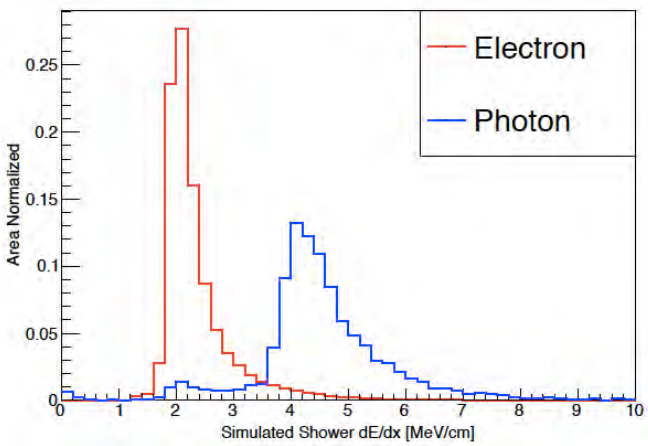
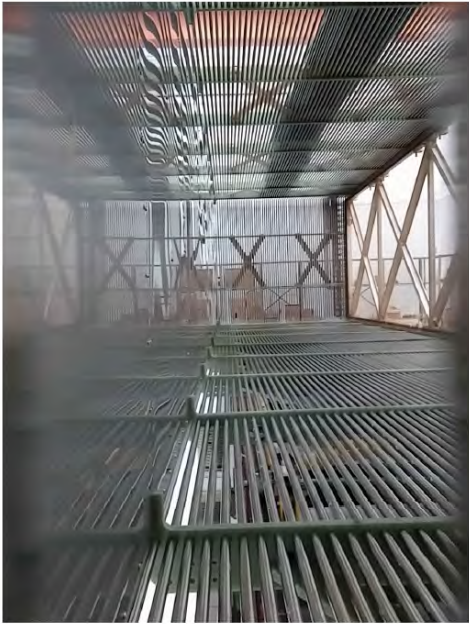
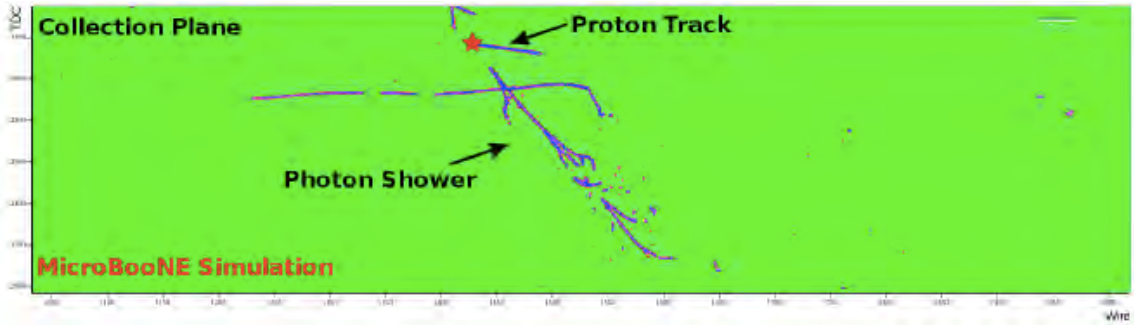
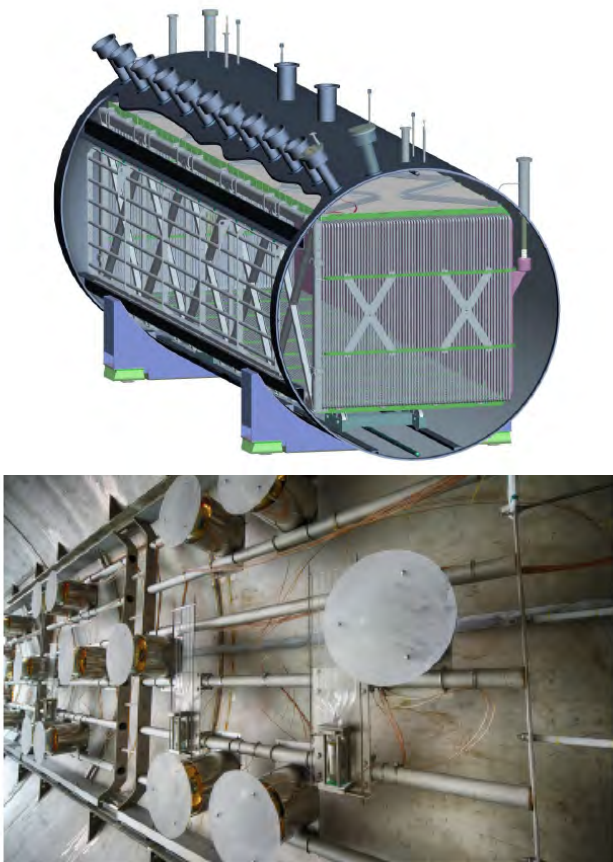
- BSM γ production process?
- BSM e-scattering process?
- BSM oscillation physics?



5. Liquid argon time projection chamber

MicroBooNE experiment at Fermilab

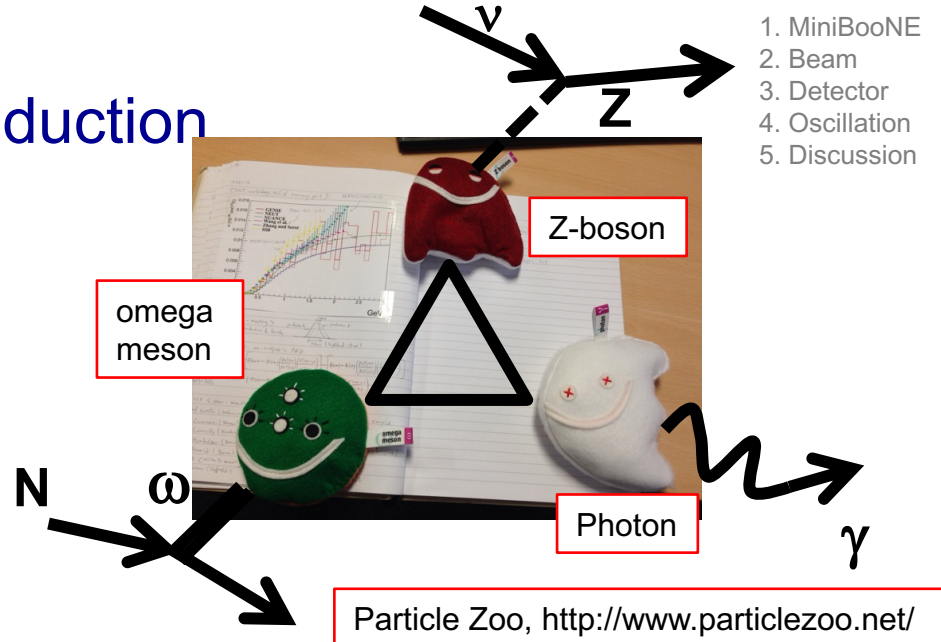
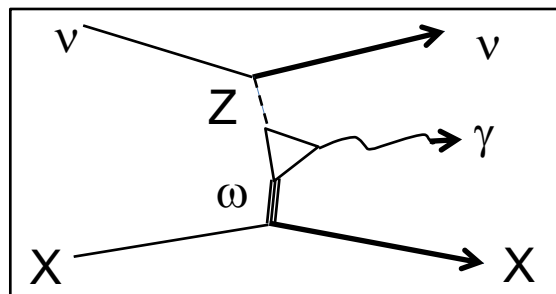
- High resolution detector with e/ γ separation on BNB
- Original motivation of US LArTPC program



dE/dx of first 4cm track (simulation)

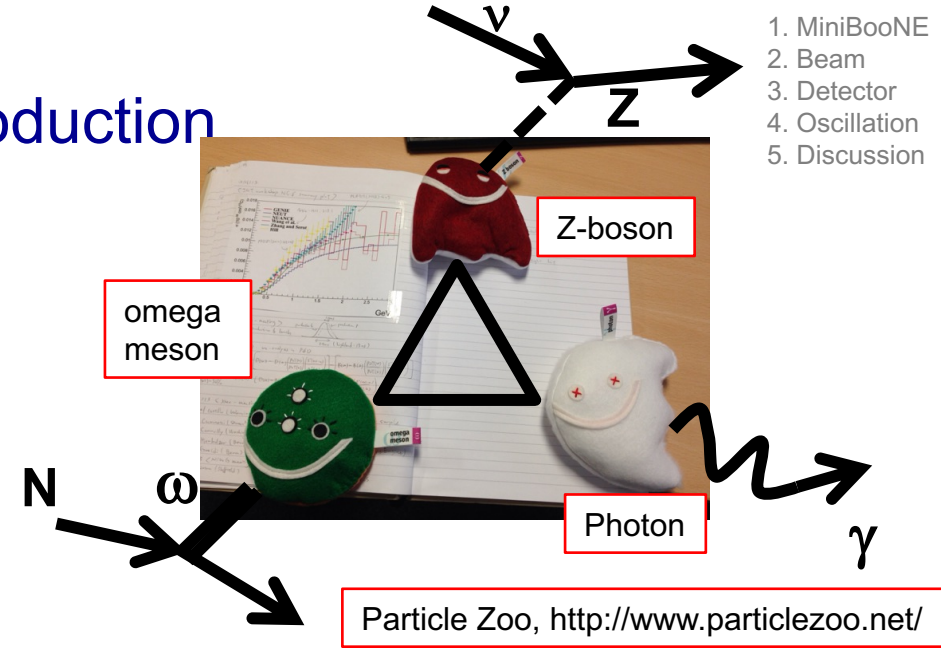
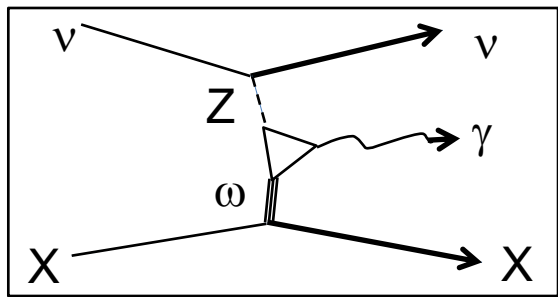
1. MiniBooNE
2. Beam
3. Detector
4. Oscillation
5. Discussion

- process within SM, but not considered.

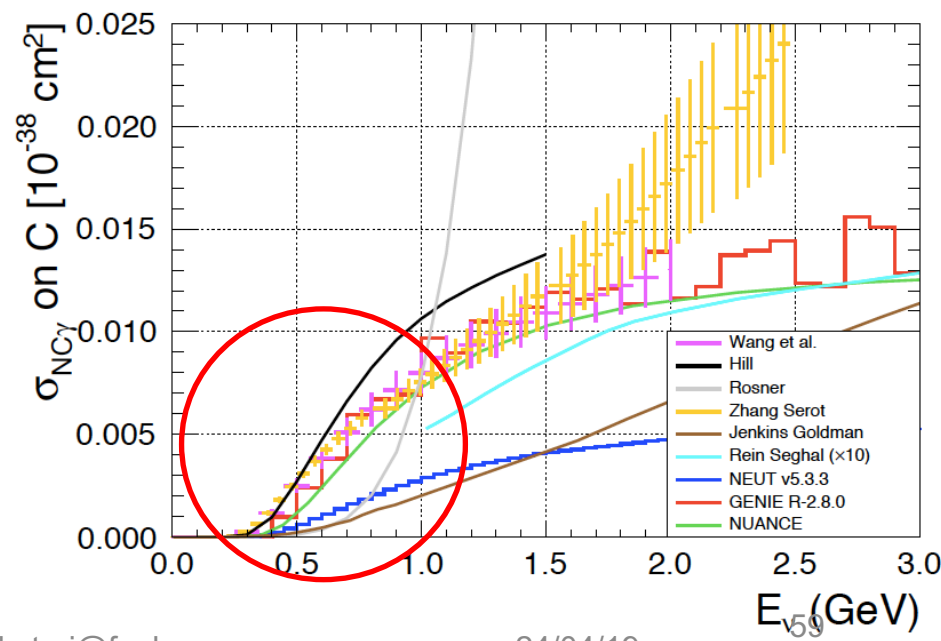
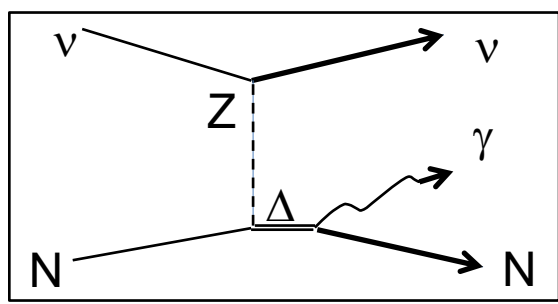


5. Neutrino NC single photon production

Anomaly mediated γ production
- process within SM, but not considered.



A lot of new calculations
- Δ -radiative decay with nuclear corrections.
- all theoretical models and generators more or less agree in MiniBooNE energy region.



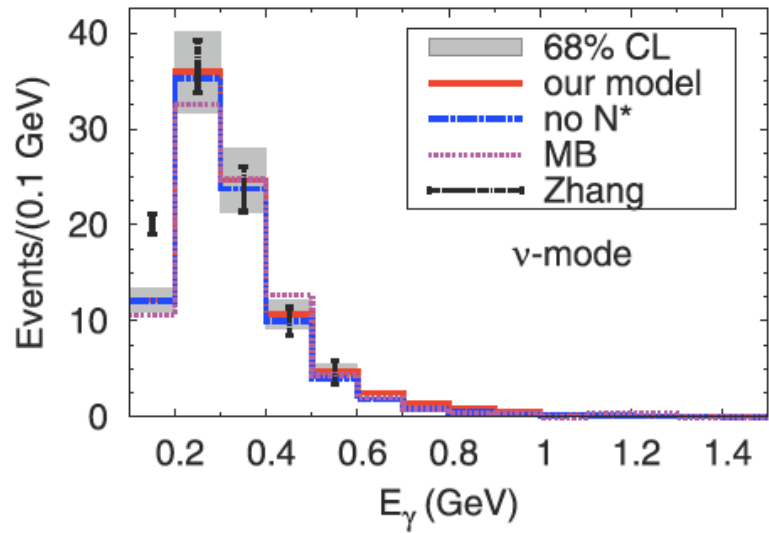
5. Neutrino NC single photon production

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

NC γ production prediction for MiniBooNE

- MiniBooNE provides efficiency tables to convert theory $\rightarrow$ experimental distribution
- New models are more or less consistent with MiniBooNE NC γ model

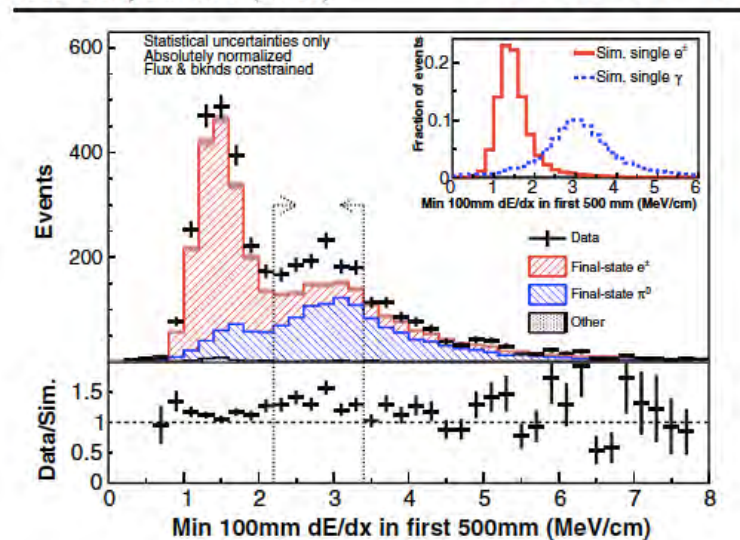
Hill, PRD84(2011)017501
Zhang and Serot, PLB719(2013)409
Wang et al, PLB740(2015)16



Are we missing any other background processes?

- It's easy to forget processes with $\sigma \sim 10^{-41}$ cm² (e.g., diffractive π^0 production $\sigma(1\text{GeV}) \sim 10^{-41}$ cm² was identified very recently by MINERvA, also neglected by all simulations)

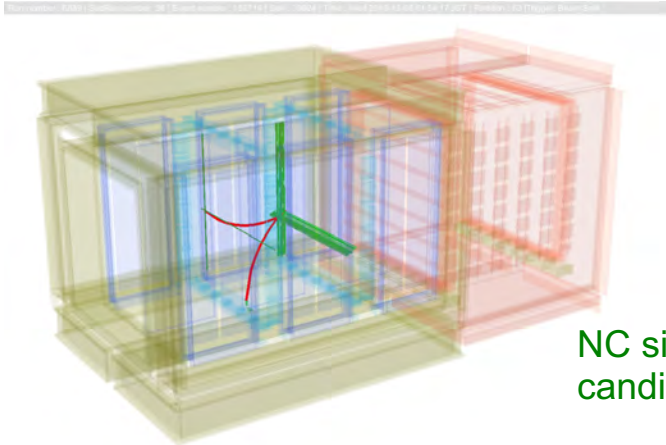
MINERvA, PRL117(2016)111801



5. Neutrino NC single photon production

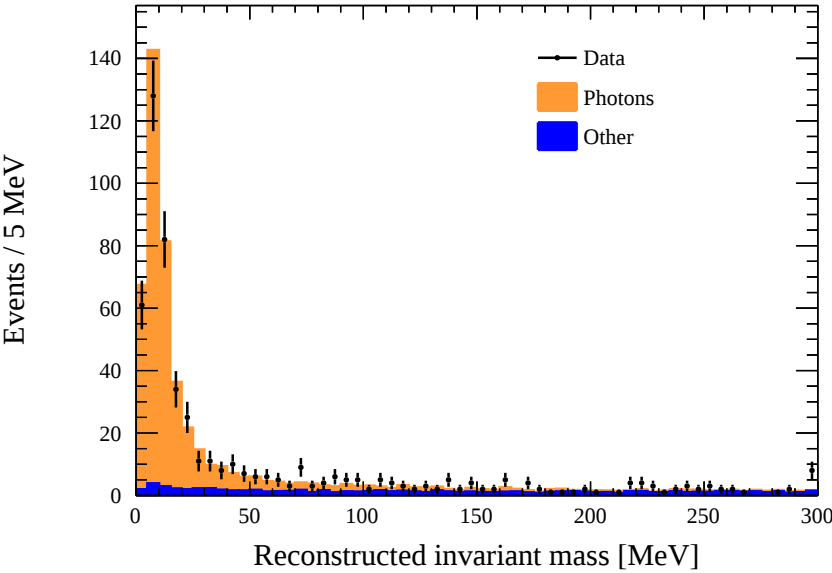
T2K near detector

- 95% pure photon sample ($M_{inv} < 50$ MeV)
- Large external photon background and internal π^0 production background. T2K can only set a limit on this process.

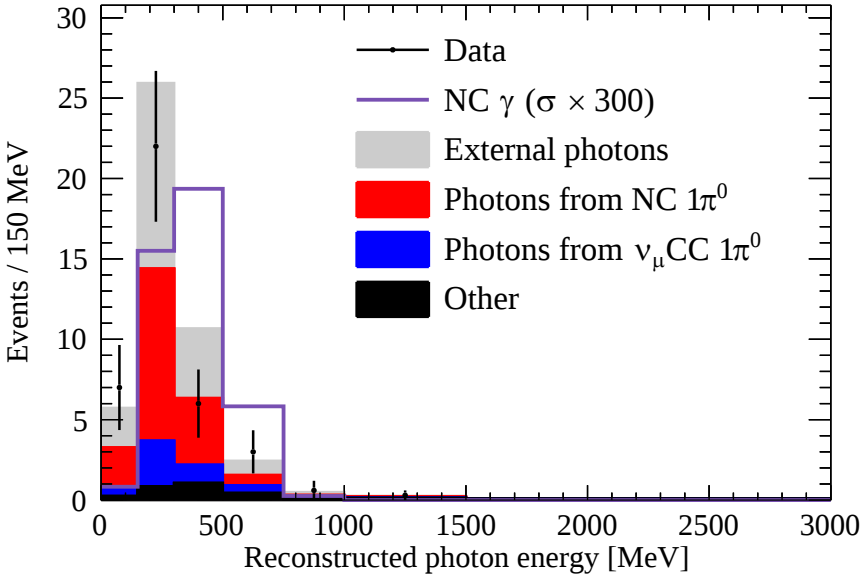


NC single gamma candidate event

Photon sample



NC single gamma sample

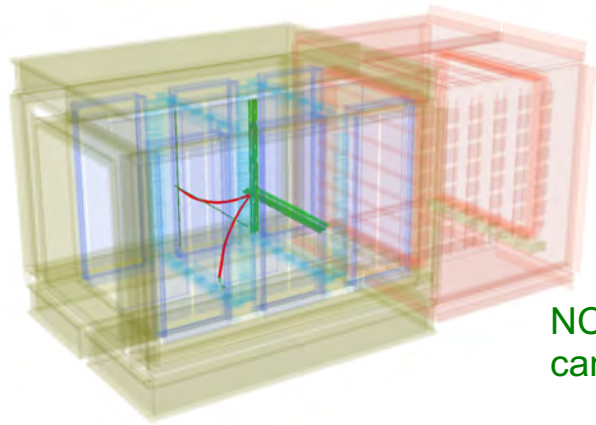


5. Neutrino NC single photon production

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

T2K near detector

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NC single gamma candidate event

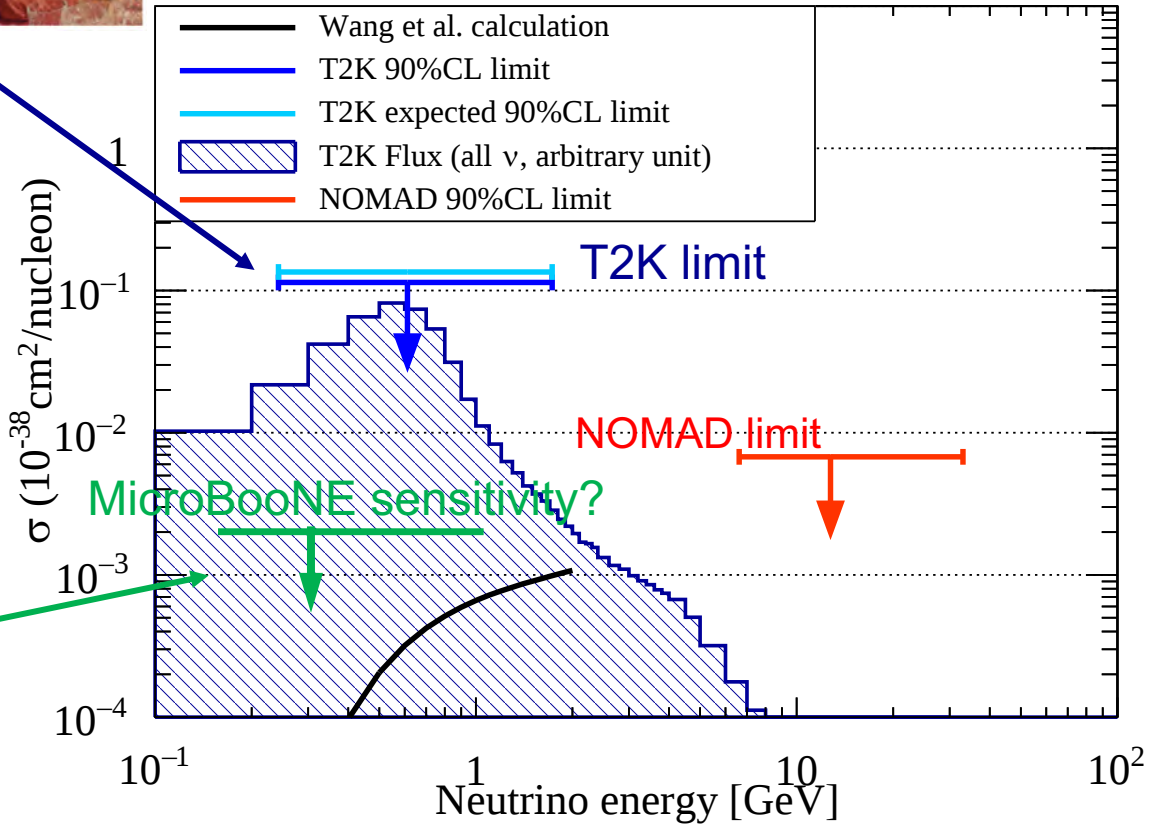
Pierre Lasorak
Queen Mary (T2K)
→ Sussex (DUNE)



MicroBooNE

- First large ν -LArTPC in USA
- Good e/γ PID
- Large active veto region
- Good internal π^0 measurement
→ Good chance to measure the first positive signal of this channel.

Bobby Murrell
Manchester
(MicroBooNE)

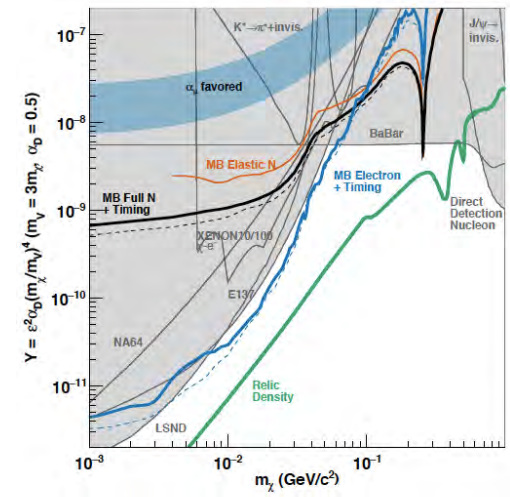
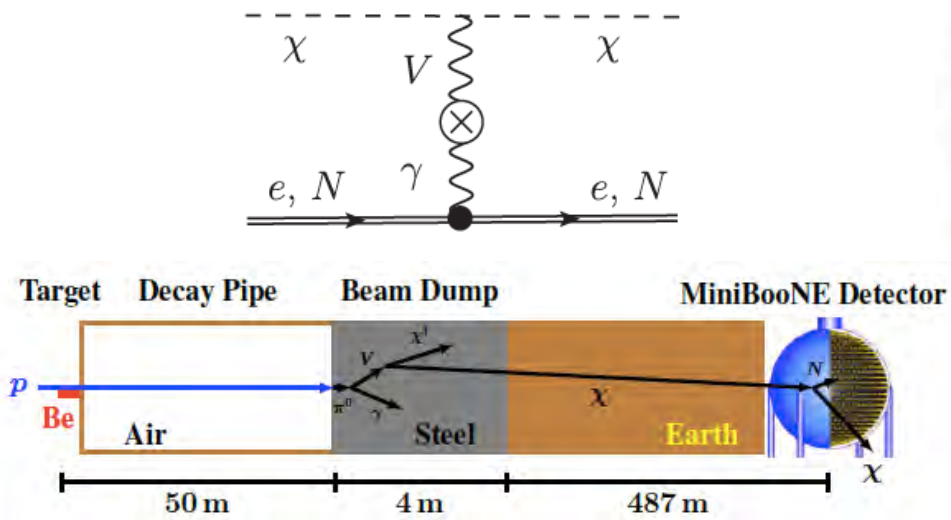


5. BSM electron scattering models

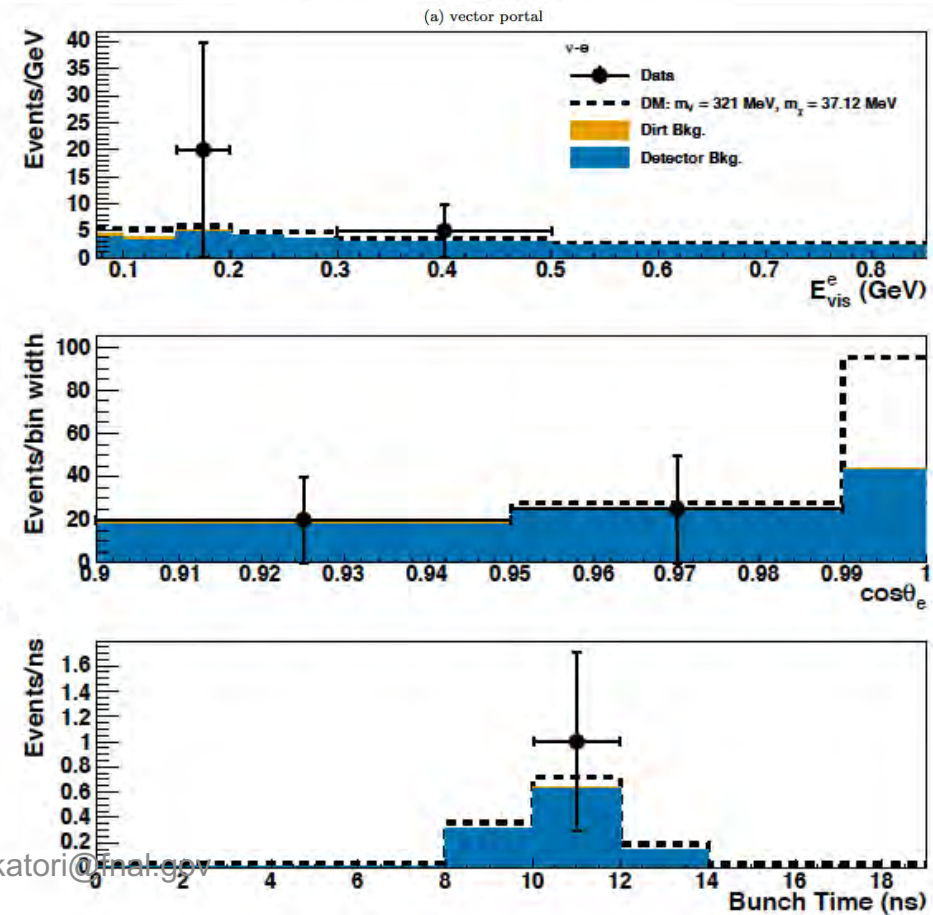
Dark matter particle - electron scattering
New particles created in the beam dump can scatter electrons in the detector.

However, MiniBooNE beam dump mode data shows no excess.

This result set limits on beam dump produced new particle – electron scattering interpretation.



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



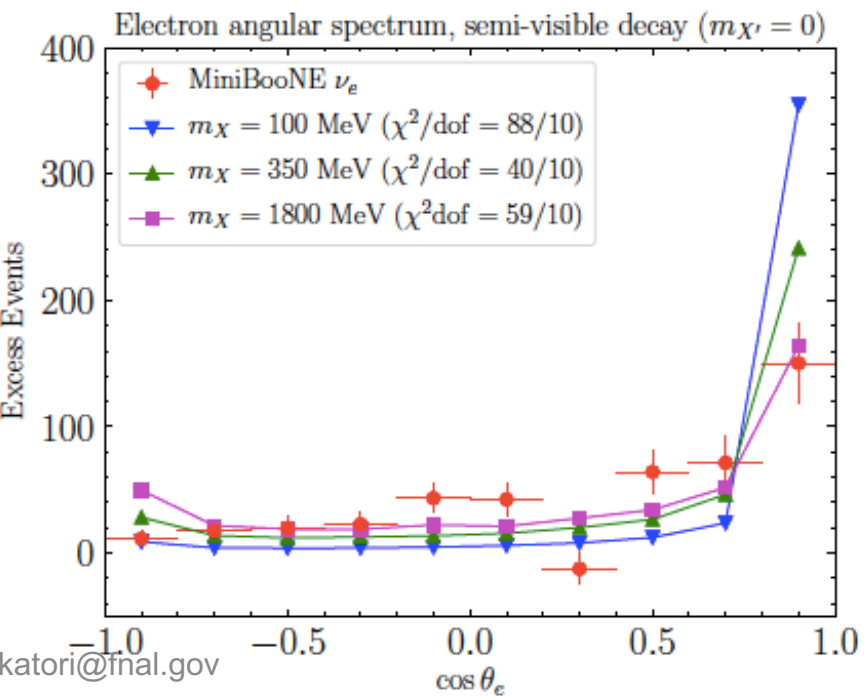
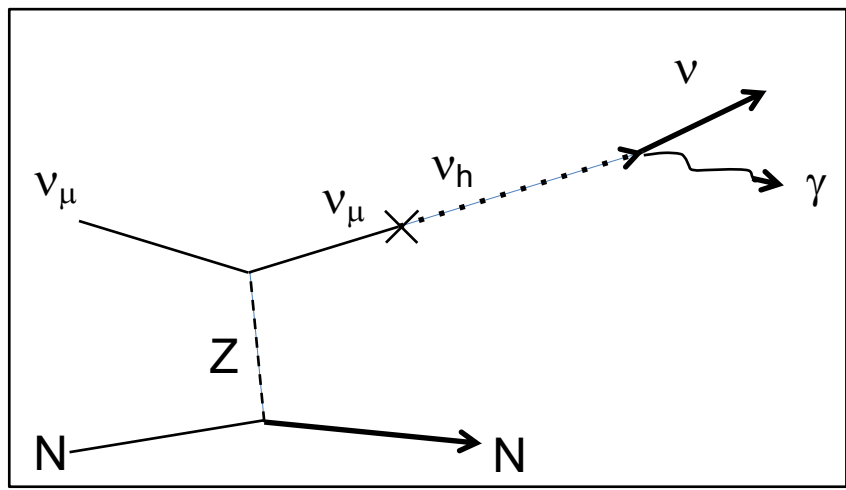
5. BSM photon production models

Heavy neutrino decay γ production

- Minimum extension of the SM
- Heavy neutrinos are produced in the beamline by kinetically mix with SM neutrinos
- Heavy neutrinos decay to SM neutrinos in the detector.

These models have problems because they cannot reproduce the angular distribution of oscillation candidates.

heavy neutrino decay



5. BSM e+e- production models

Heavy neutrino decay γ production

- Minimum extension of the SM
- Heavy neutrinos are produced in the beamline by kinetically mix with SM neutrinos
- Heavy neutrinos decay to SM neutrinos in the detector.

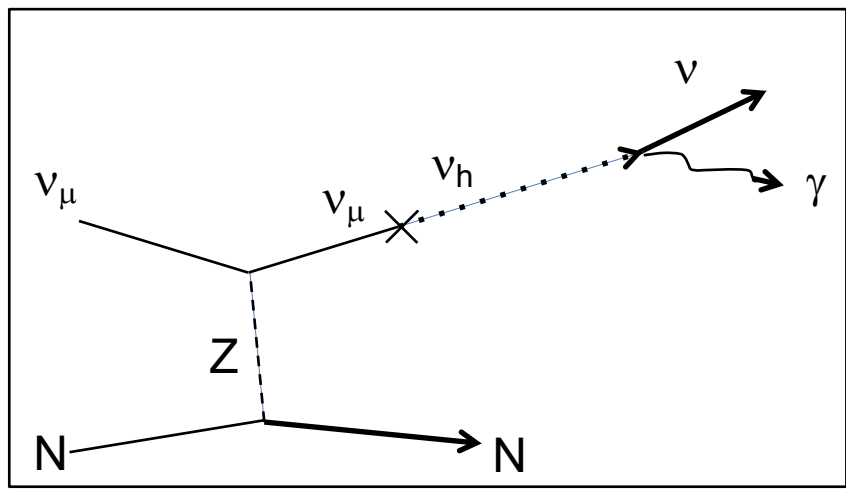
These models have problems because they cannot reproduce the angular distribution of oscillation candidates.

Z' decay model

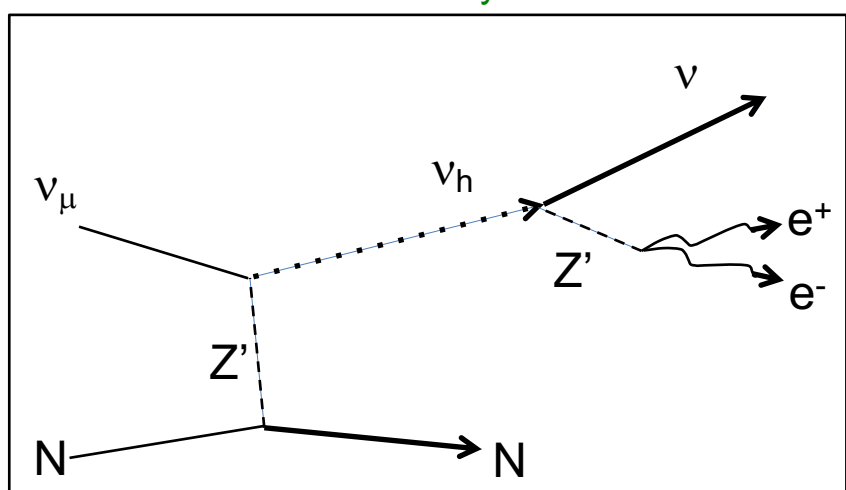
A new class of models predict a heavy neutrino and a neutral heavy boson decaying to e+e-.

These models explain both energy and angular distributions of MiniBooNE oscillation candidate data.

heavy neutrino decay



Z' decay



5. BSM neutrino oscillation models

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

Lorentz violation as alternative neutrino oscillation model

- Making a new texture in Hamiltonian to control oscillations.
- Could explain all signals, including LSND and MiniBooNE.
- This moment, no LV-motivated models can explain all signals.

LV-motivated effective Hamiltonian

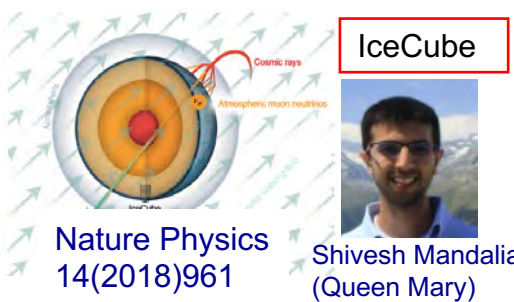
$$h_{\text{eff}}^\nu = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

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

It is extremely difficult to make a neutrino oscillation model without neutrino mass, but consistent with all high-precision data.

Test of Lorentz violation with neutrinos

- Almost all neutrino experiments look for Lorentz violation.
- Current best limits of Lorentz violation by neutrinos;
 - CPT-odd (dimension-3) < 2.0×10^{-24} GeV
 - CPT-even (dimension-4) < 2.8×10^{-28}



It turns out neutrino experiments are one of the highest-precision tests of space-time effects!

PHYS ORG Nanotechnology Physics Earth Astronomy & Space Technology Chemistry Biology Other Sciences

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

The universe should be a predictably symmetrical place, according to a cornerstone of Einstein's

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Future of MiniBooNE

MiniBooNE run will be end on June 2019

- Expected to reach $\sim 18E20POT$ in ν -mode
- The excess may reach $\sim 5\sigma$



Future of MiniBooNE

MiniBooNE run will be end on June 2019

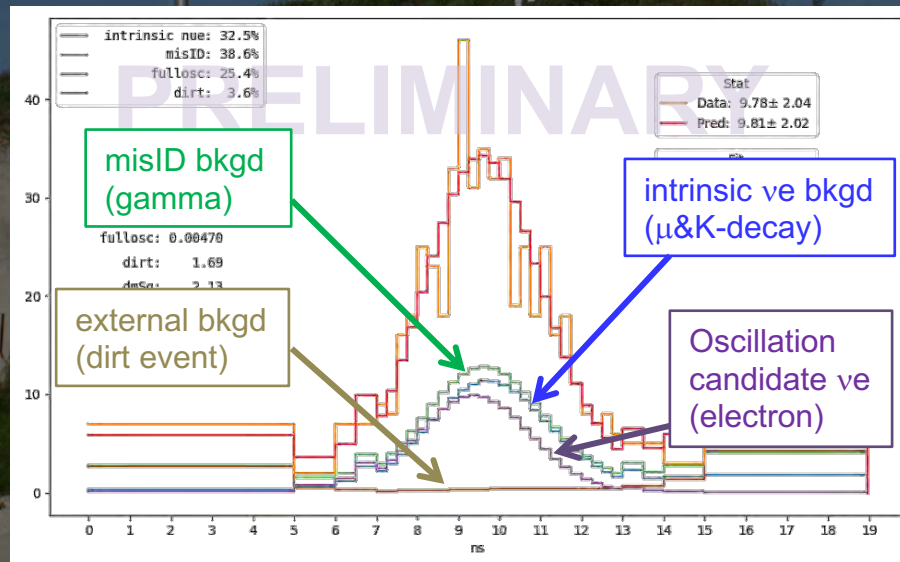
- Expected to reach $\sim 18\text{E}20\text{POT}$ in ν -mode
- The excess may reach $\sim 5\sigma$

Next oscillation analysis: timing background rejection

- It is possible to reject both intrinsic and misID backgrounds by timing (ongoing)

Bunch structure, data-MC comparison

- intrinsic bkgd: μ -decay ν_e , K-decay $\nu_e \rightarrow$ slow
- misID bkgd: photon conversion $\rightarrow$ slow



Conclusion

MiniBooNE is a short-baseline neutrino oscillation experiment

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

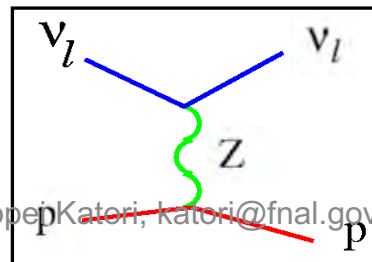
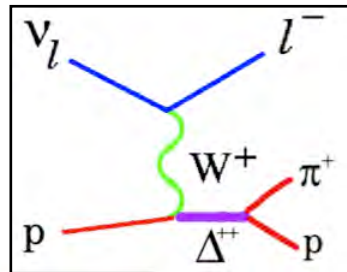
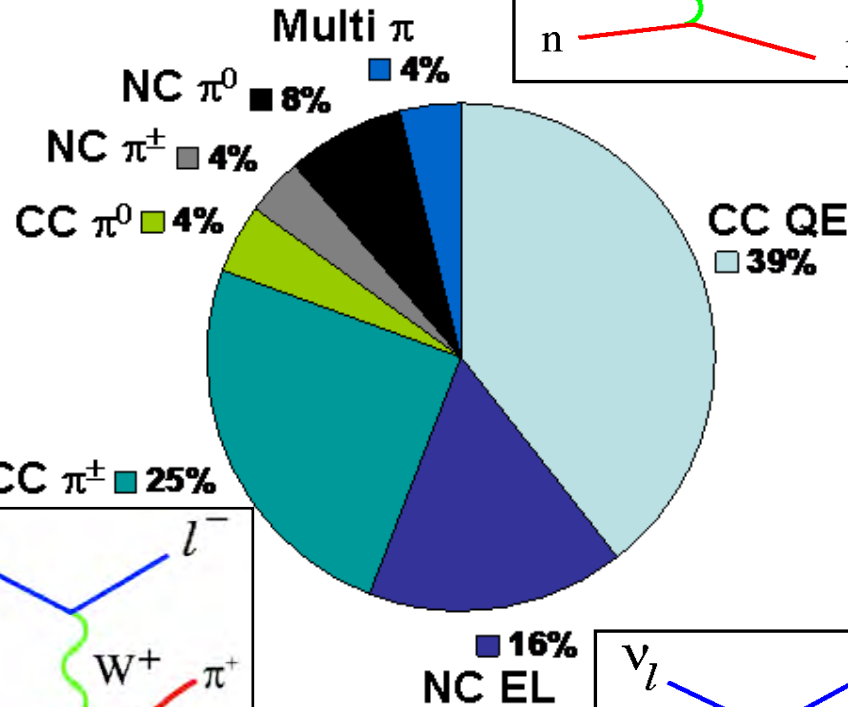
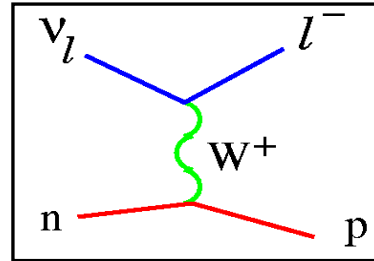
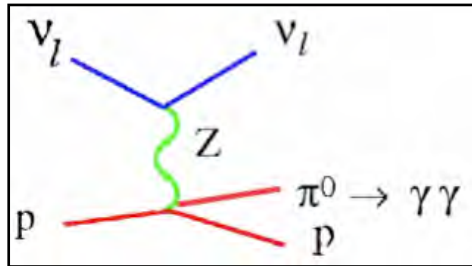
- Many useful tools
- Many useful people
- Many new topics
 - Neutrino cross section measurements
 - Test of Lorentz violation with neutrinos
 - Direct production & detection Dark Matter search with ν -detector
 - etc.

But the biggest legacy is the **short-baseline anomaly**

Thank you for your attention!

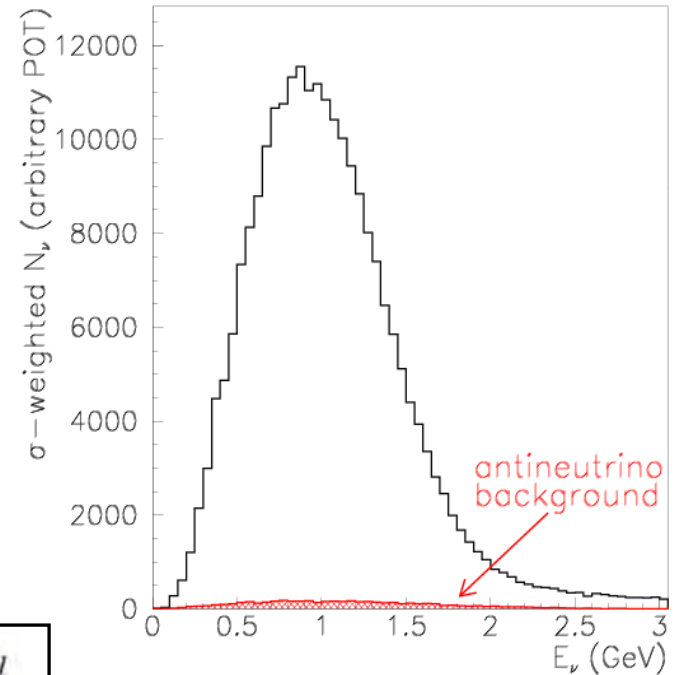
backup

3. Cross section model



Predicted event rates before cuts
(NUANCE Monte Carlo)

Casper, Nucl.Phys.Proc.Suppl.112(2002)161



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 $L(e/\pi^0)$ cut
- (d) After $m_{\gamma\gamma}$ cut

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

