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
CERN seminar, CERN, Geneva, Feb. 5, 2019

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

BackRe(Action)

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 resul

> **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 ar 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 neutrino a possible harbinger of a revolutionary new elen called the sterile neutrino, though many physicis

GIZMODO

VIDEO SPLOID PALEOFUTURE IO9 SCIENCE REVIEW FIELD GUIDE DESIGN

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

BBC | Your account | News | Sport | Weather | iPlayer | TV | Radi

NEWS

Home | UK | World | Business | Politics | Tech | Science | Health | Family & Education

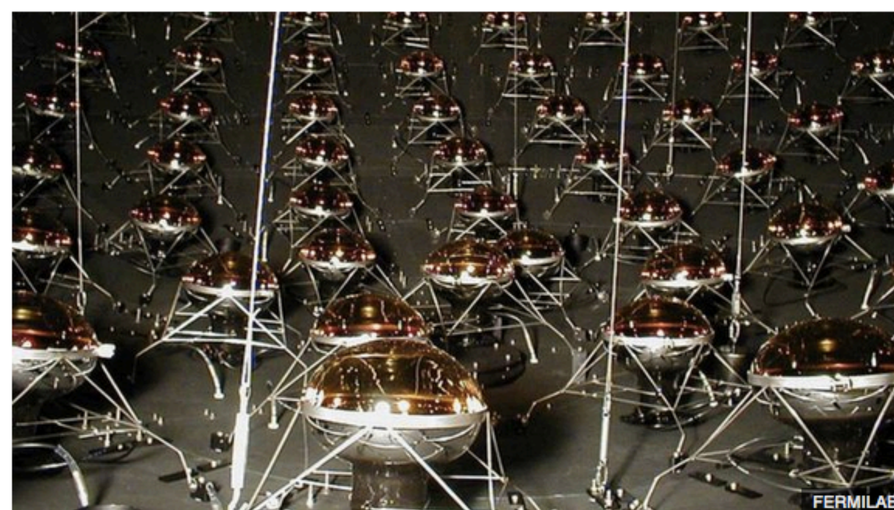
Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

Share



PHYSICAL REVIEW LETTERS

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

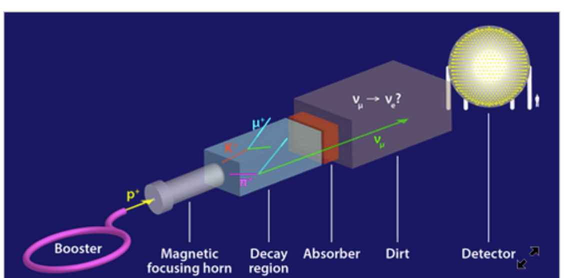
ALL RESEARCH OUTPUTS	OUTPUTS FROM PHYSICAL REVIEW LETTERS	OUTPUTS OF SIMILAR AGE	OUTPUTS OF SIMILAR AGE FROM PHYSICAL REVIEW LETTERS
#7,064	#13	#448	#1
of 12,363,617 outputs	of 25,606 outputs	of 270,805 outputs	of 520 outputs

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.



APS/Alan Stonebraker

PHYSICAL REVIEW LETTERS

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

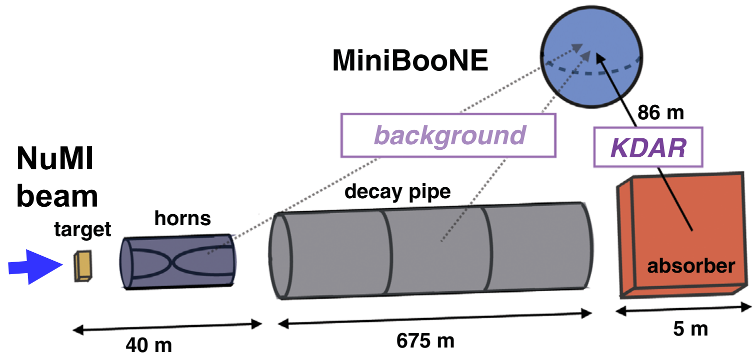
PHYSICAL REVIEW LETTERS

Observation of Higgs Boson Decay to Bottom Quarks

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

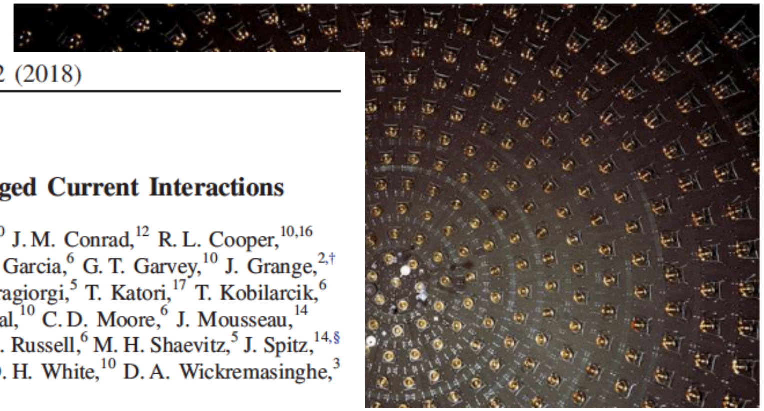
Physics See Viewpoint: Higgs Decay into Bottom Quarks Seen at Last

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



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]

(MiniBooNE Collaboration)

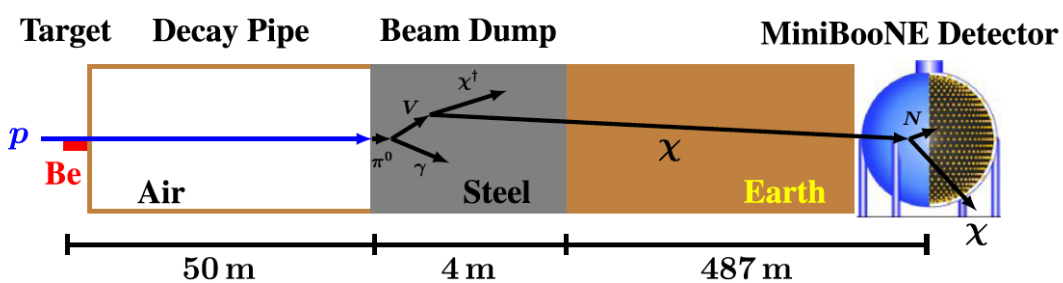
PRL120(2018)141802

News at work

The MiniBooNE search for dark matter

July 18, 2017 | Ranjan Dharmapalan and Tyler Thornton

Email



MiniBooNE keep providing high impact results!

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

nd, the e en Model About erious en more

PRL118(2017)221803
PRD98(2018)112004

1. LSND experiment

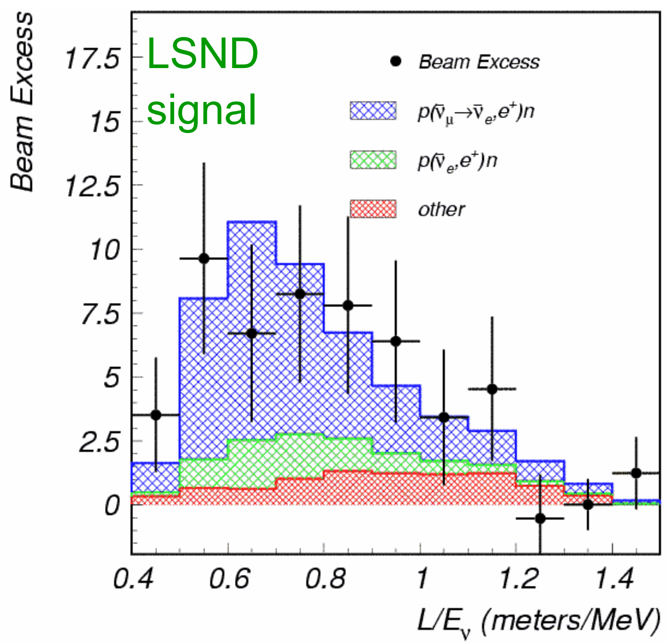
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

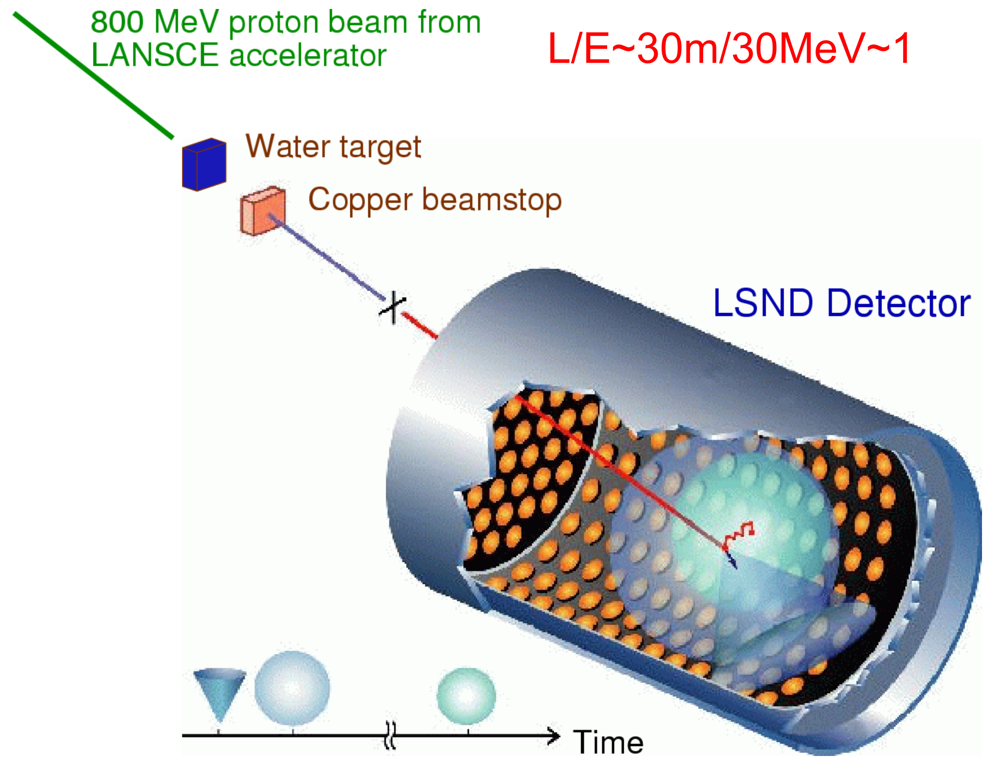
LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

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

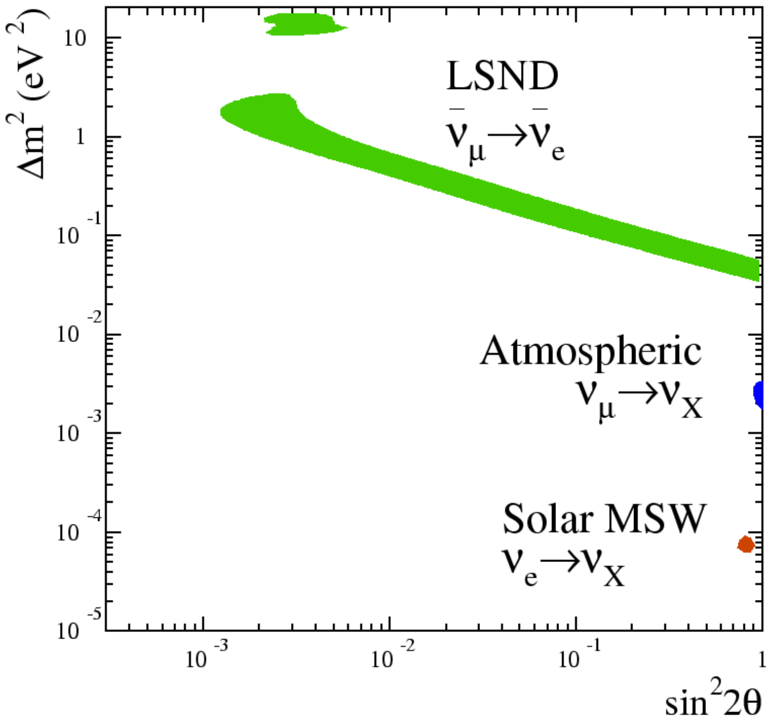
$$n + p \to d + \gamma$$

87.9 ± 22.4 ± 6.0 (3.8.σ)





1. LSND experiment

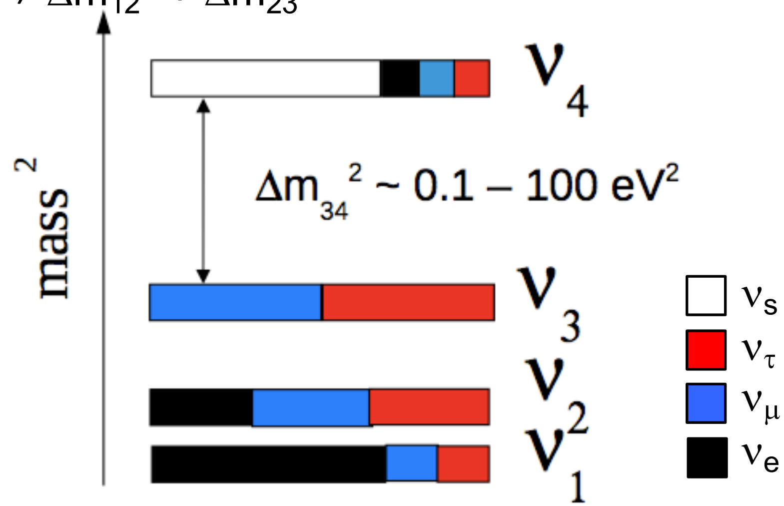


3 types of neutrino oscillations are found:

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

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~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment

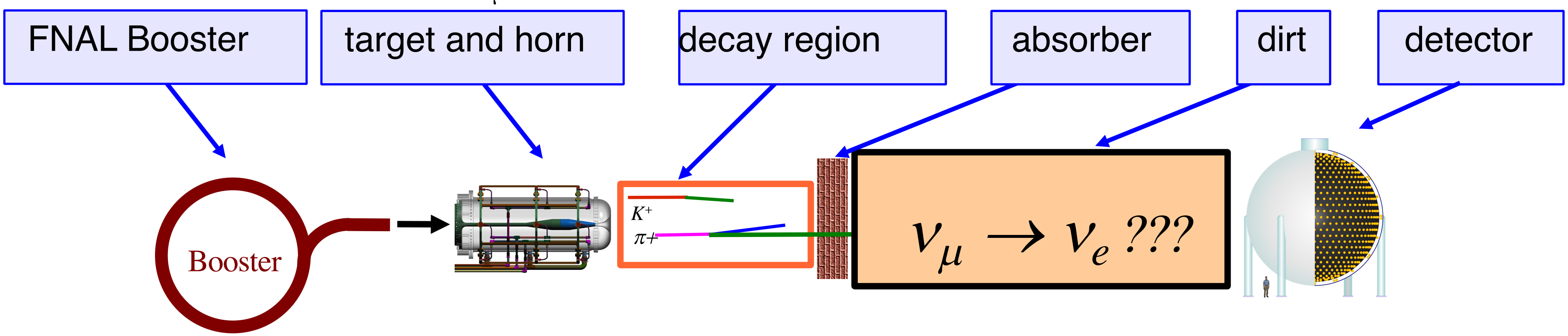
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

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

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

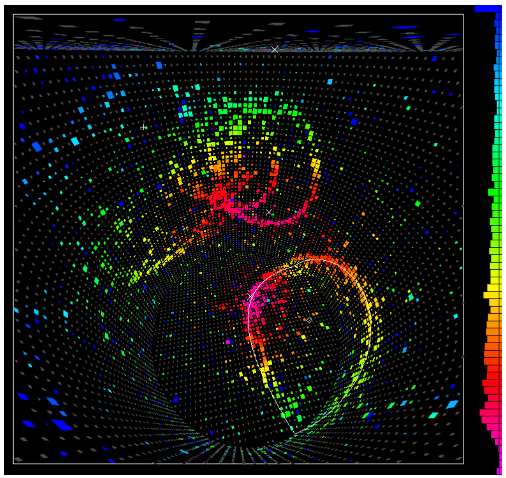


primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

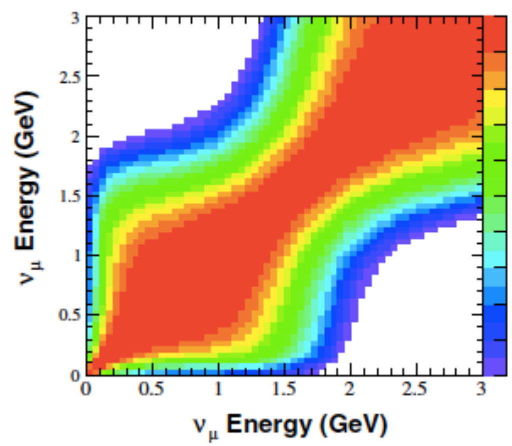
MiniBooNE has;
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

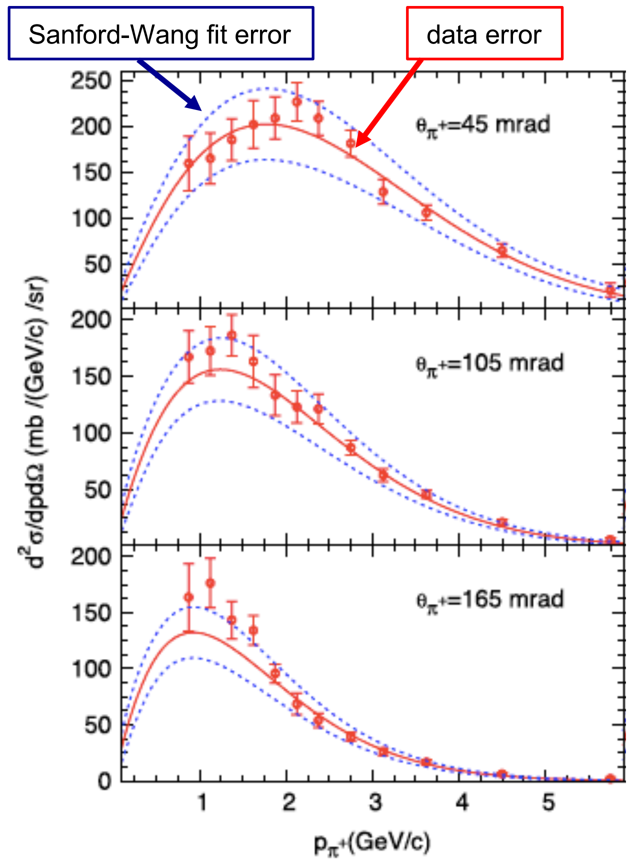
1. MiniBooNE is extremely influential! – Tools

fitQun: MiniBooNE: NIMA608(2009)206
Likelihood-based Cherenkov ring fitter, the main reconstruction used by Super-Kamiokande (LSND→MiniBooNE→SuperK).



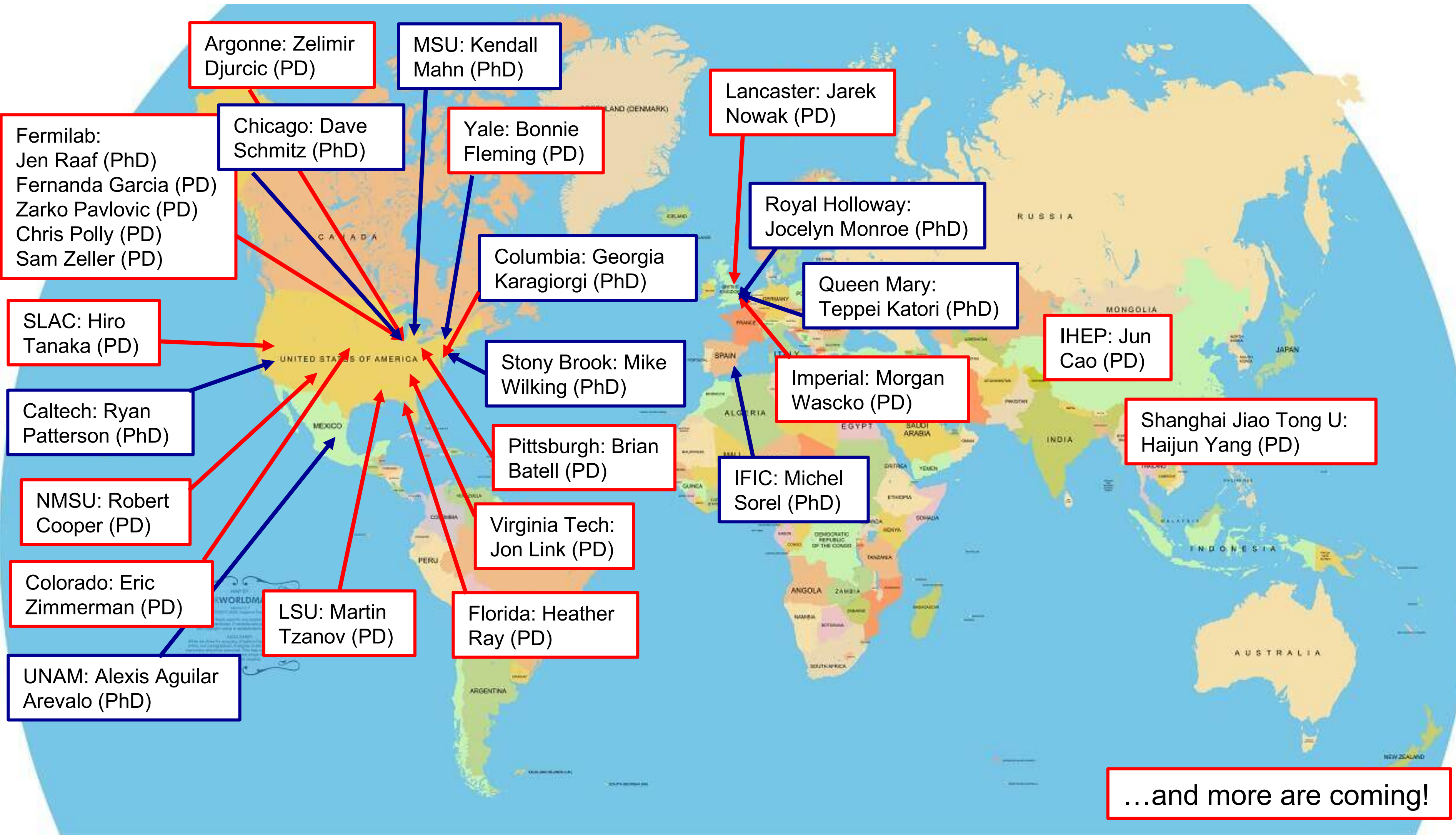
Flux systematic error: MiniBooNE: PRD79(2009)072002
- Errors are derived directly from hadron production data (spline fit), not any flux model.
- Event weighted with multiverse simulation to make a smooth covariance matrix with taking account all correlations correctly.





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

1. MiniBooNE is extremely influential! – Offspring

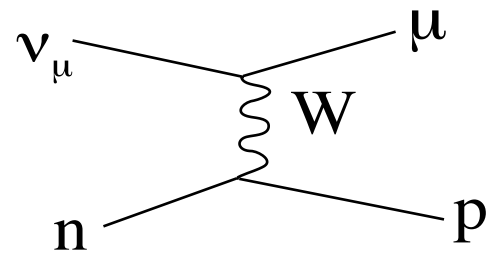


1. MiniBooNE is extremely influential! – Cross Sections

MiniBooNE measured first flux-integrated neutrino-nucleus differential cross section ~1 GeV.

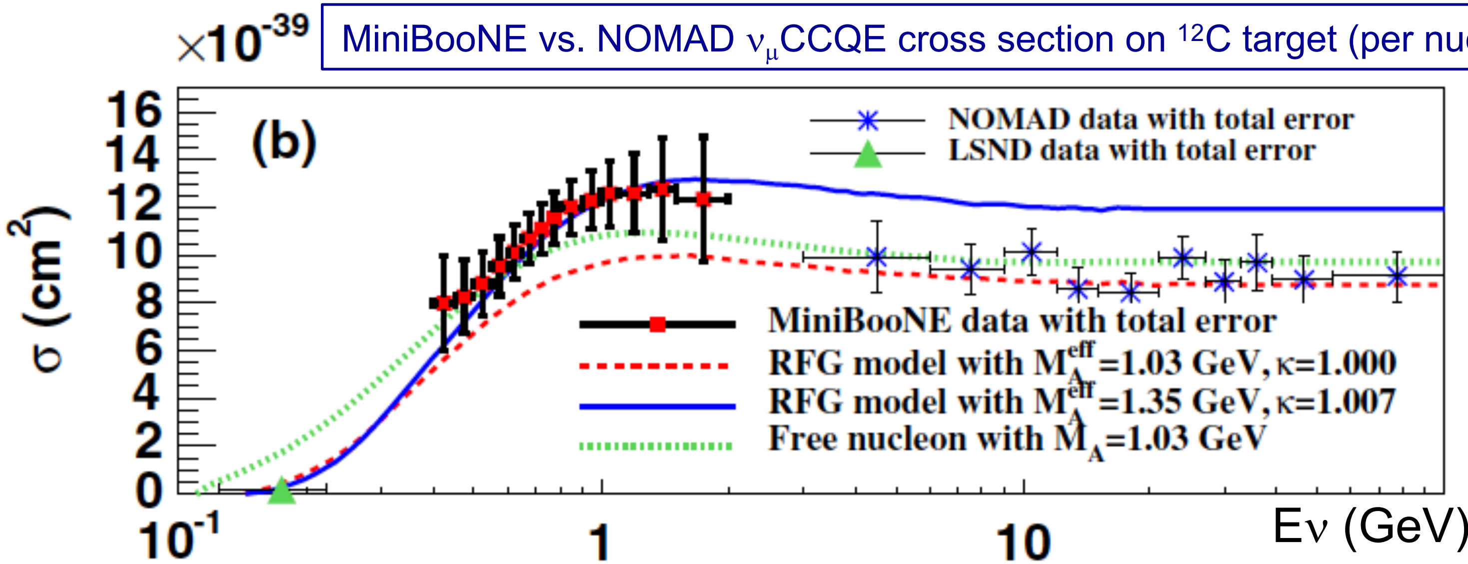
CCQE puzzle

1. low Q2 suppression → Low forward efficiency? (detector?)
2. high Q2 enhancement → Axial mass > 1.0 GeV? (physics?)
3. large normalization → 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...?

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



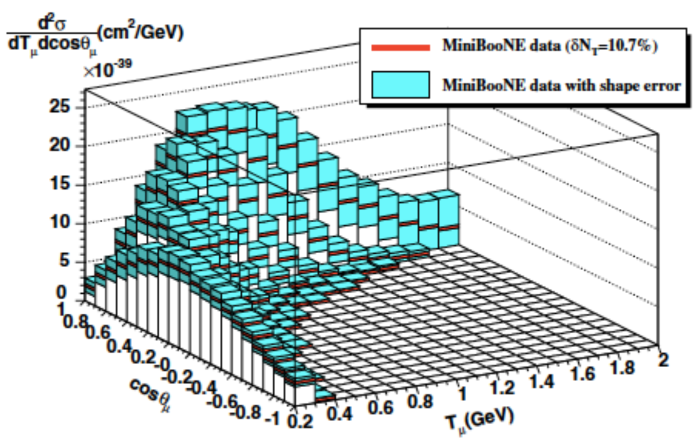
1. MiniBooNE is extremely influential! – Cross Sections

MiniBooNE measured first flux-integrated neutrino-nucleus differential cross section ~1 GeV.

Flux-integrated differential cross section:

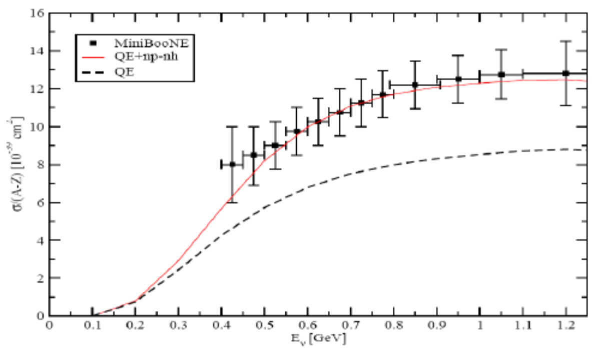
A new concept to measure, and report neutrino cross section data. Now the standard of the community.

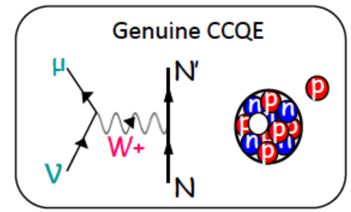
PHYSICAL REVIEW D 81, 092005 (2010)

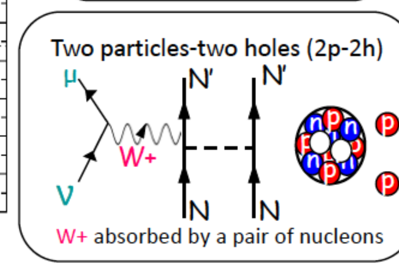


An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Slide from Martini

Discovery of nucleon correlation in neutrino scattering:

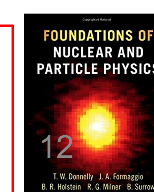
- Significant enhancement of cross section (10-30%)
- modify lepton kinematics and final state hadrons
- the hottest topic for T2K, MINERvA, MicroBooNE, etc

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!

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

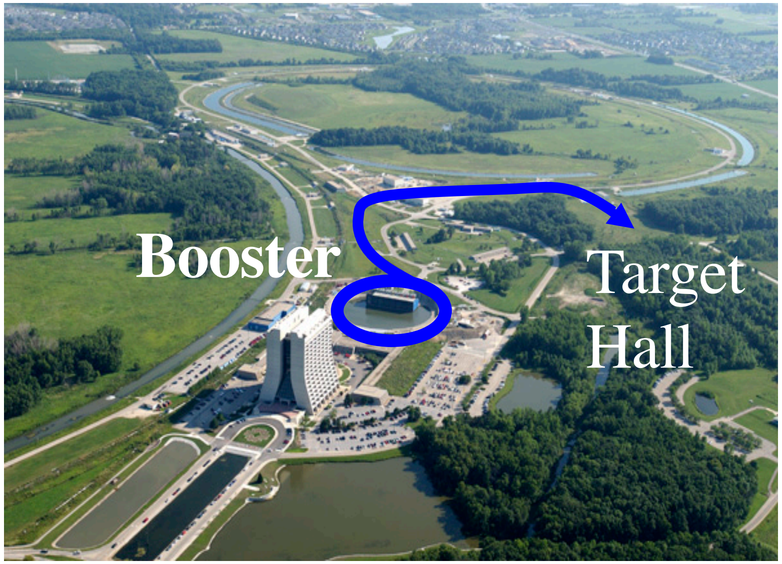
2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

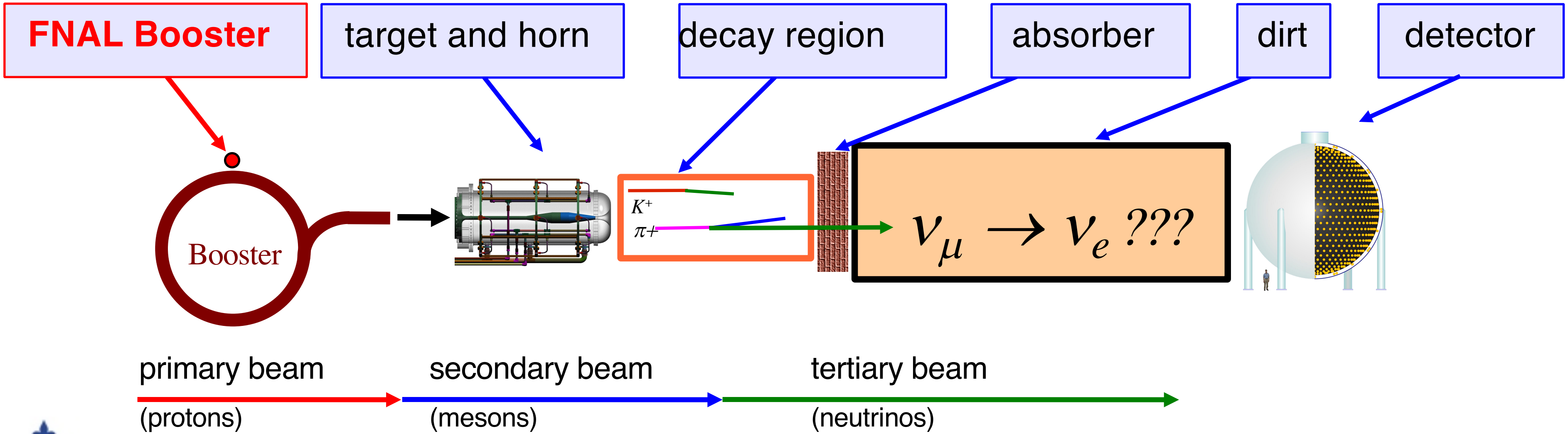
5. Discussion

2. Neutrino beam

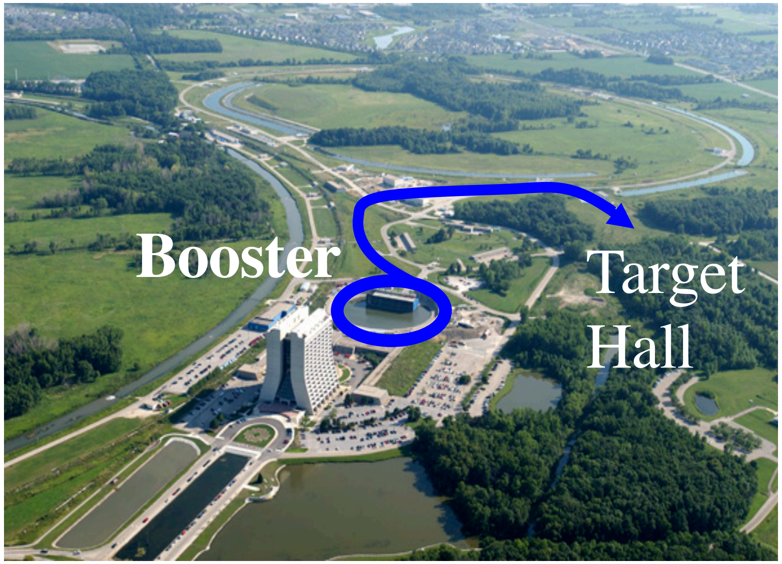


MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster

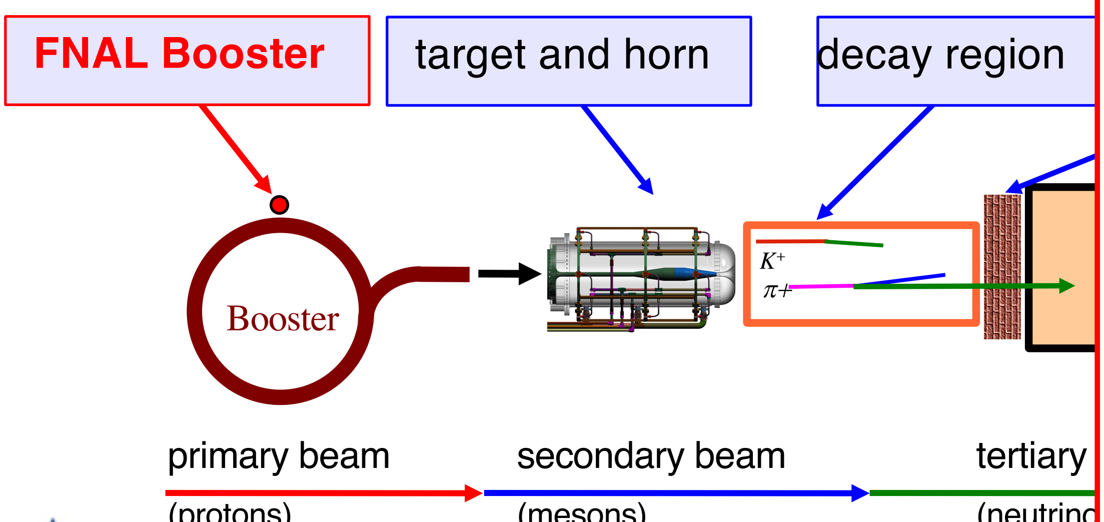


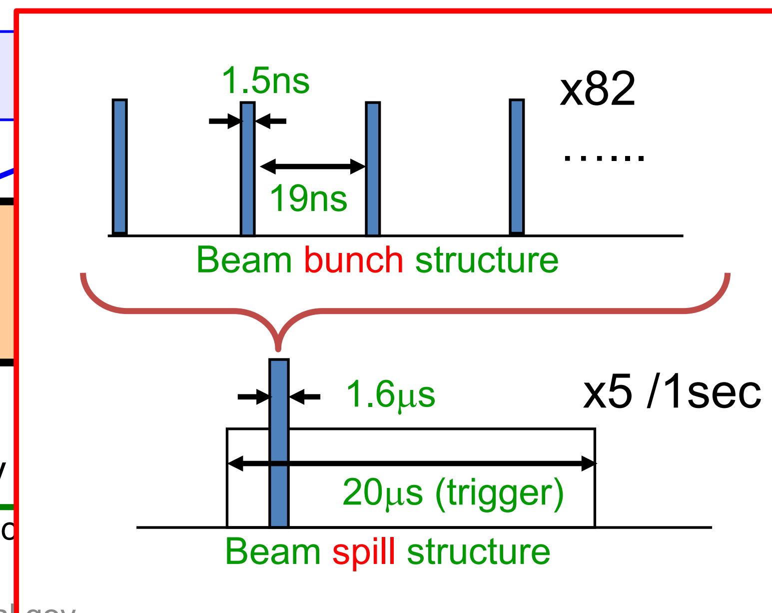
2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster

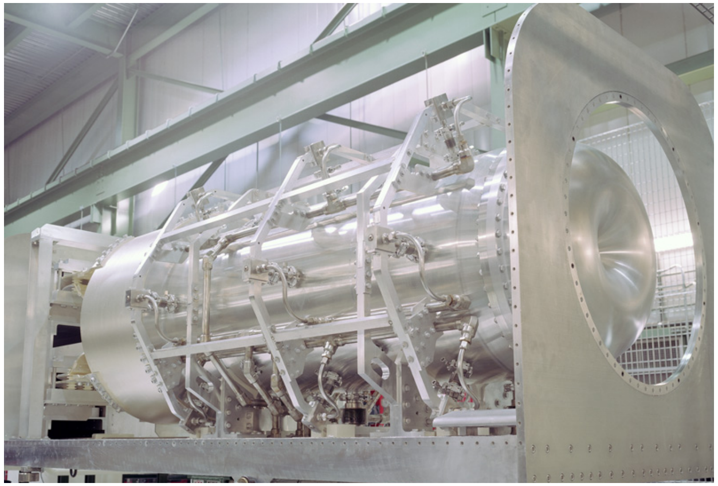




Queen Mary
University of London

2. Neutrino beam

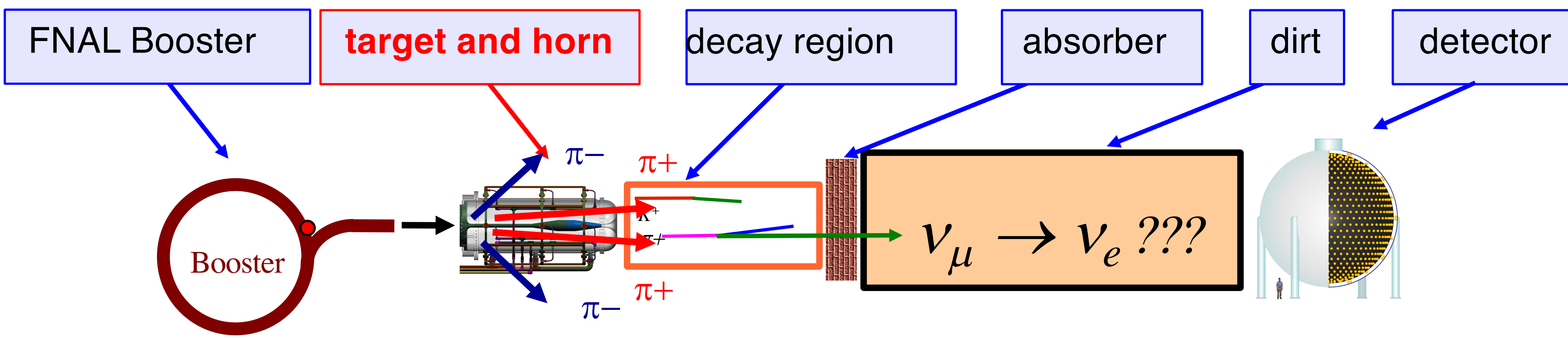
Magnetic focusing horn



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.

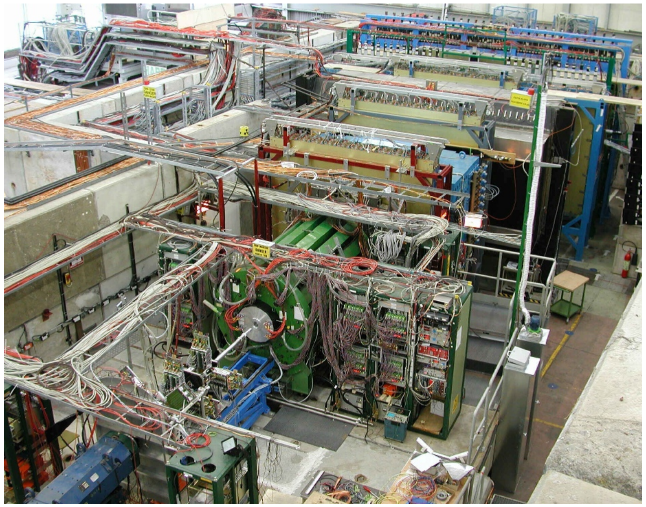


primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

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

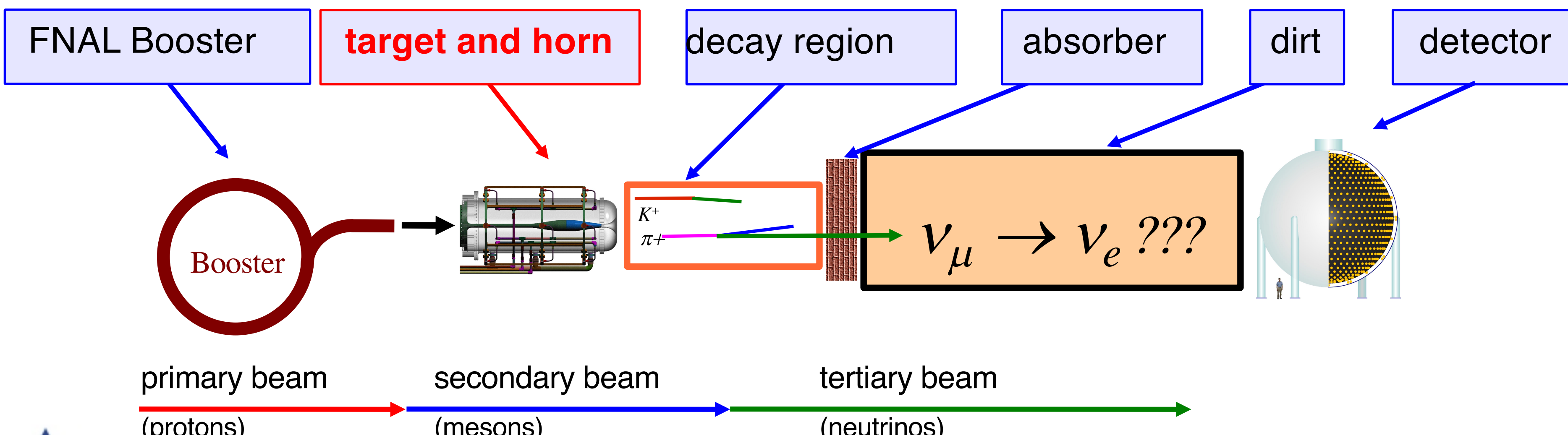
2. Neutrino beam

HARP experiment (CERN)



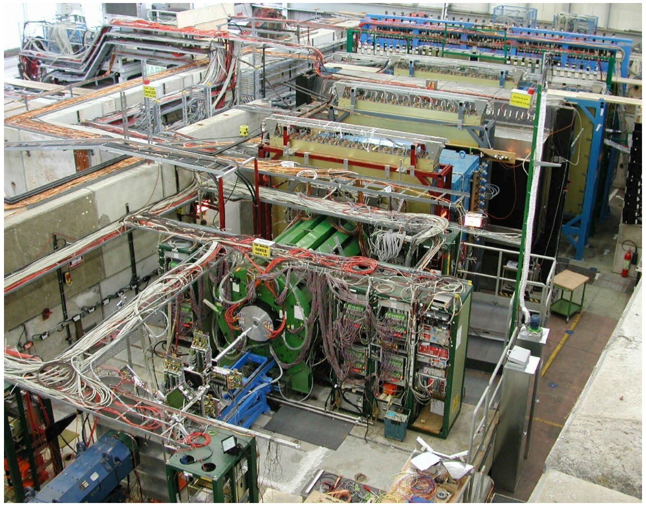
Modeling of meson production is based on the measurement done by HARP collaboration.

- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum
- >80% coverage for π+

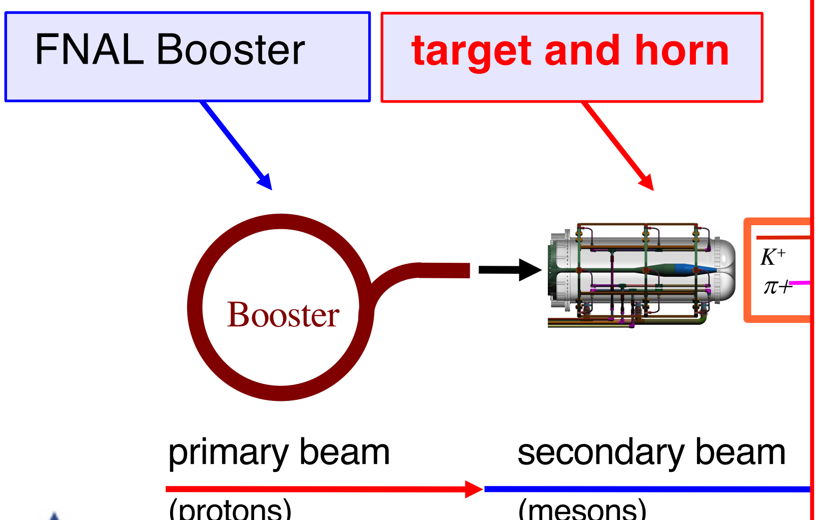


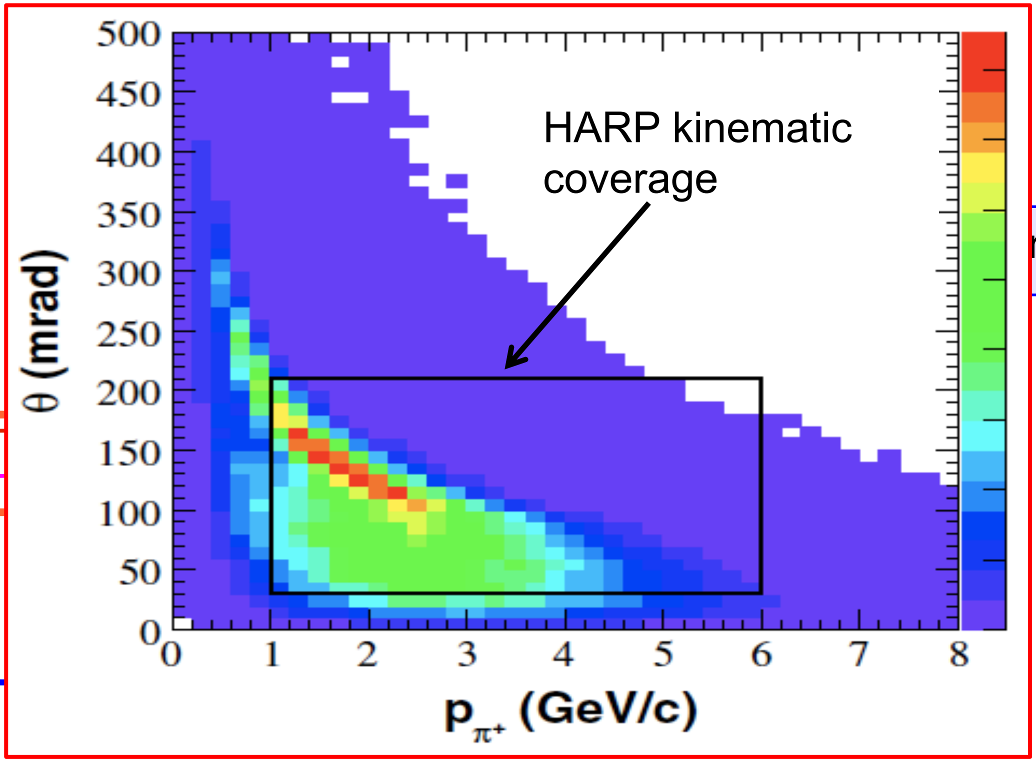
2. Neutrino beam

HARP experiment (CERN)

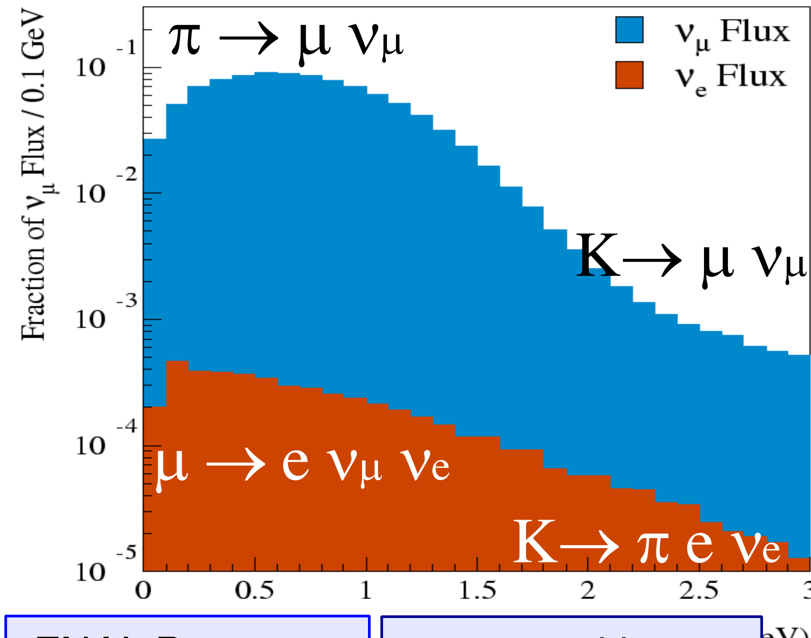


Modeling of meson production is based on the measurement done by HARP collaboration.
- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum
- >80% coverage for π+





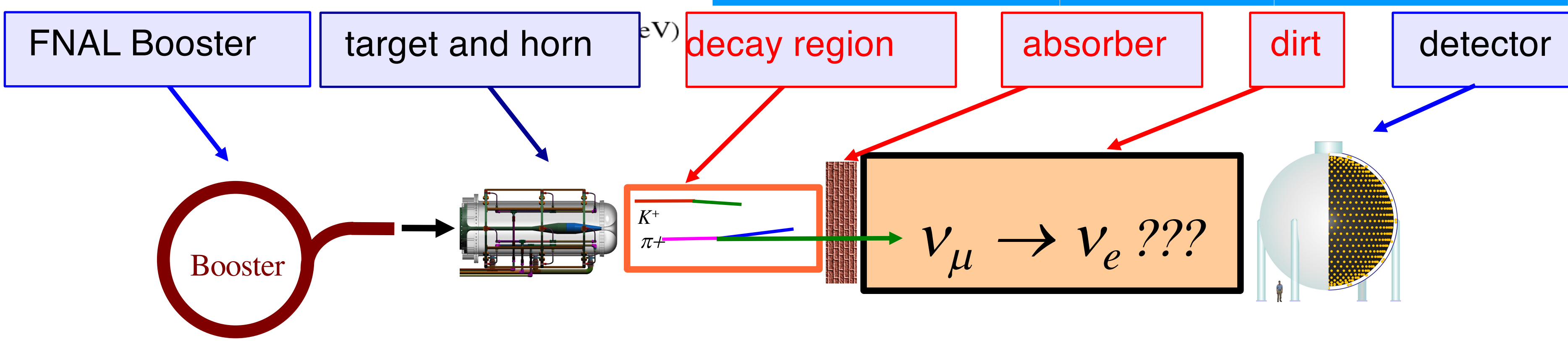
2. Neutrino beam



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)

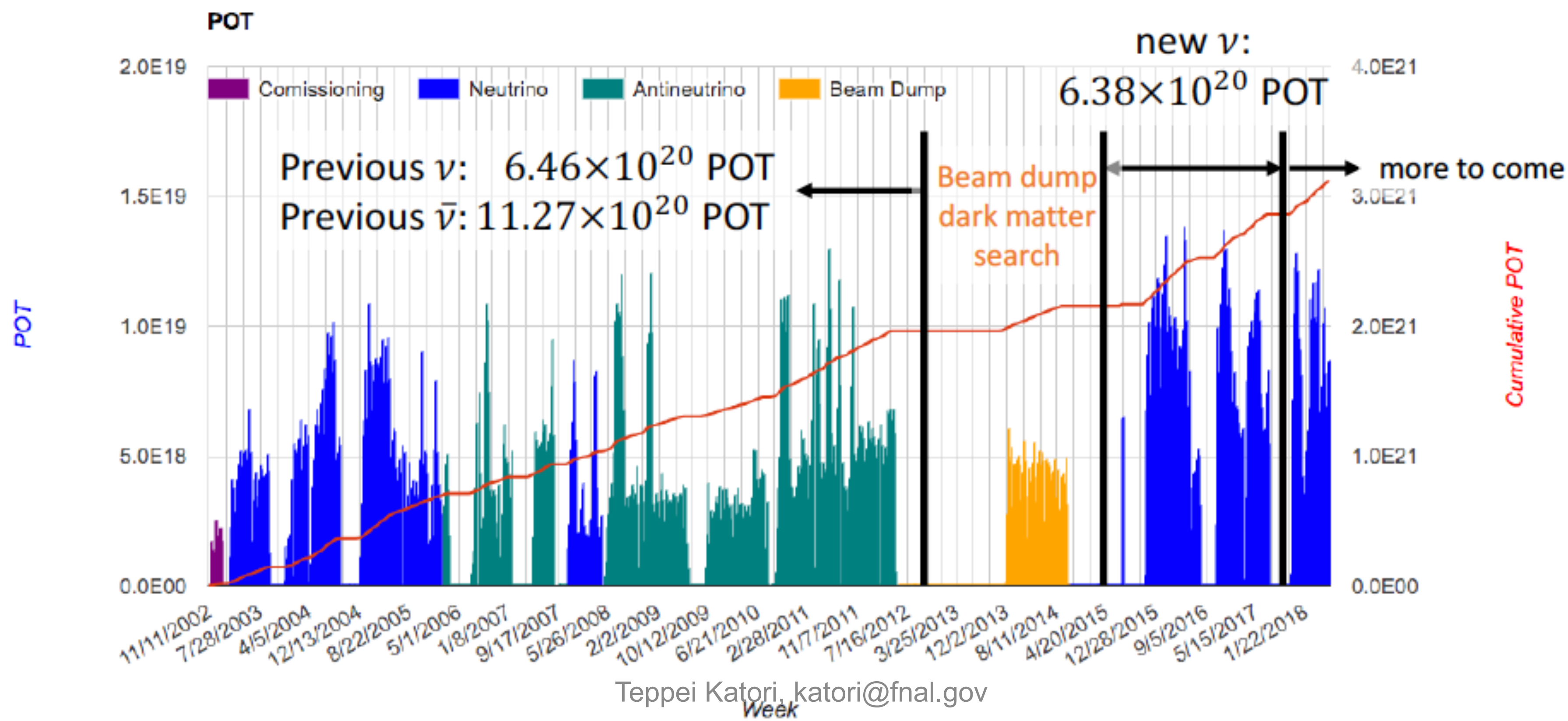
	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%



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

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

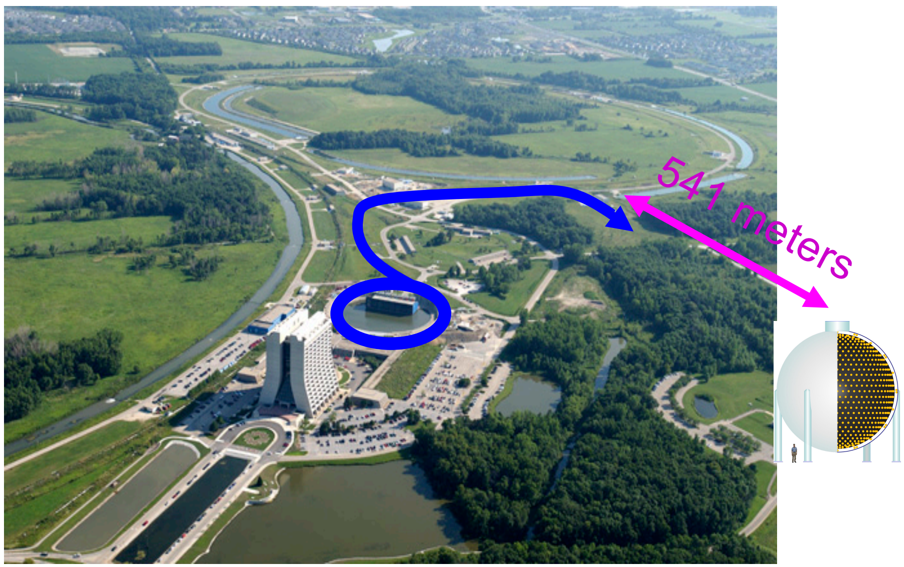
2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

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)

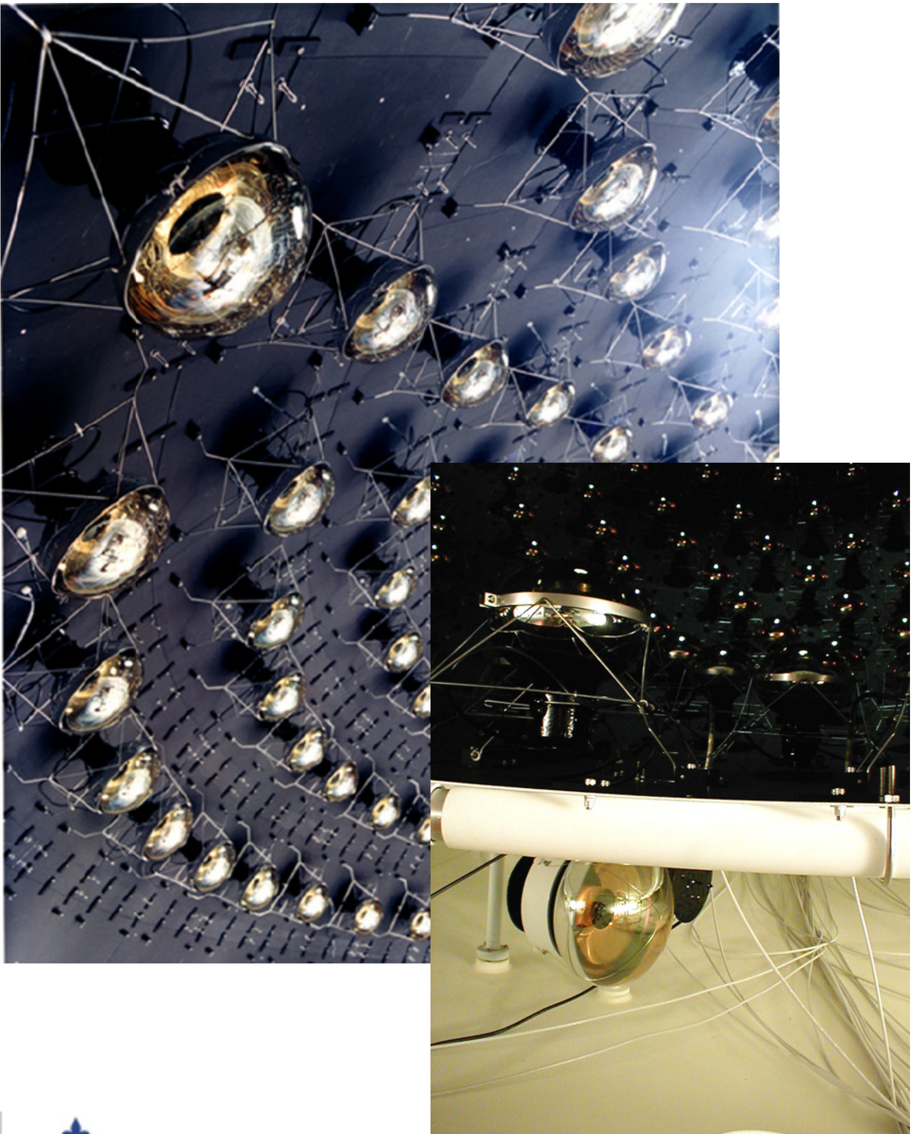
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
- 240 veto phototubes

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

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

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

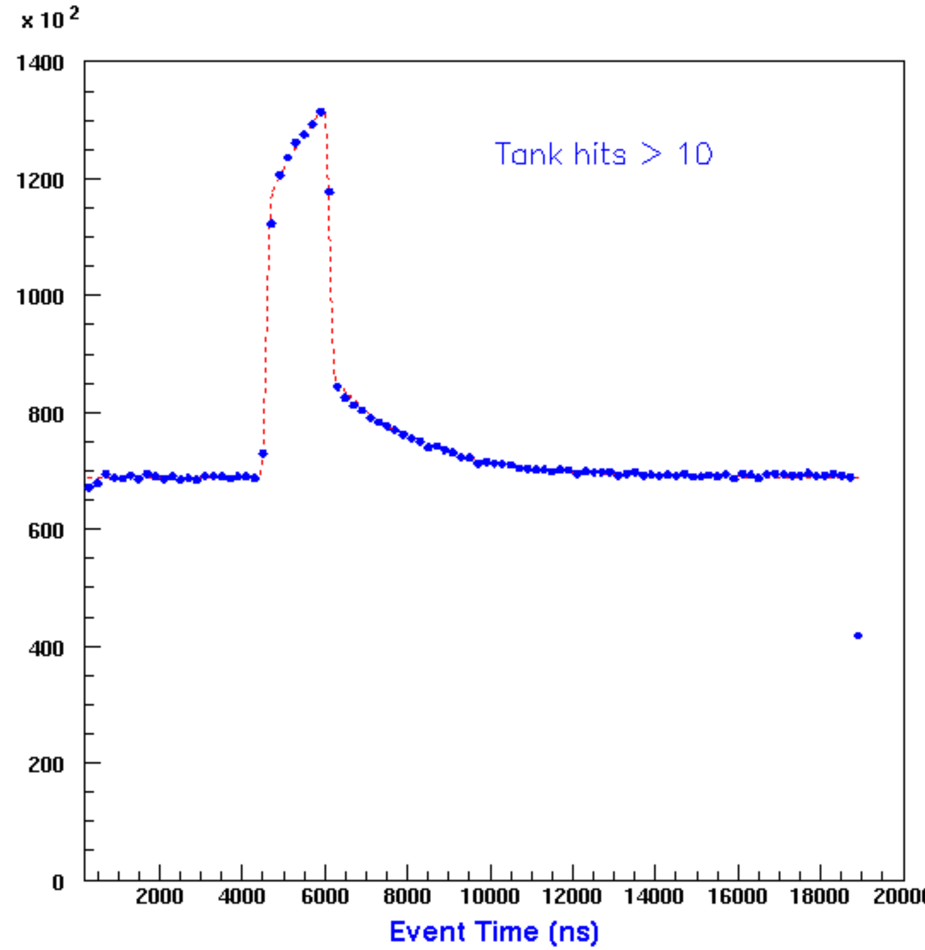
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and Cosmic BG



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

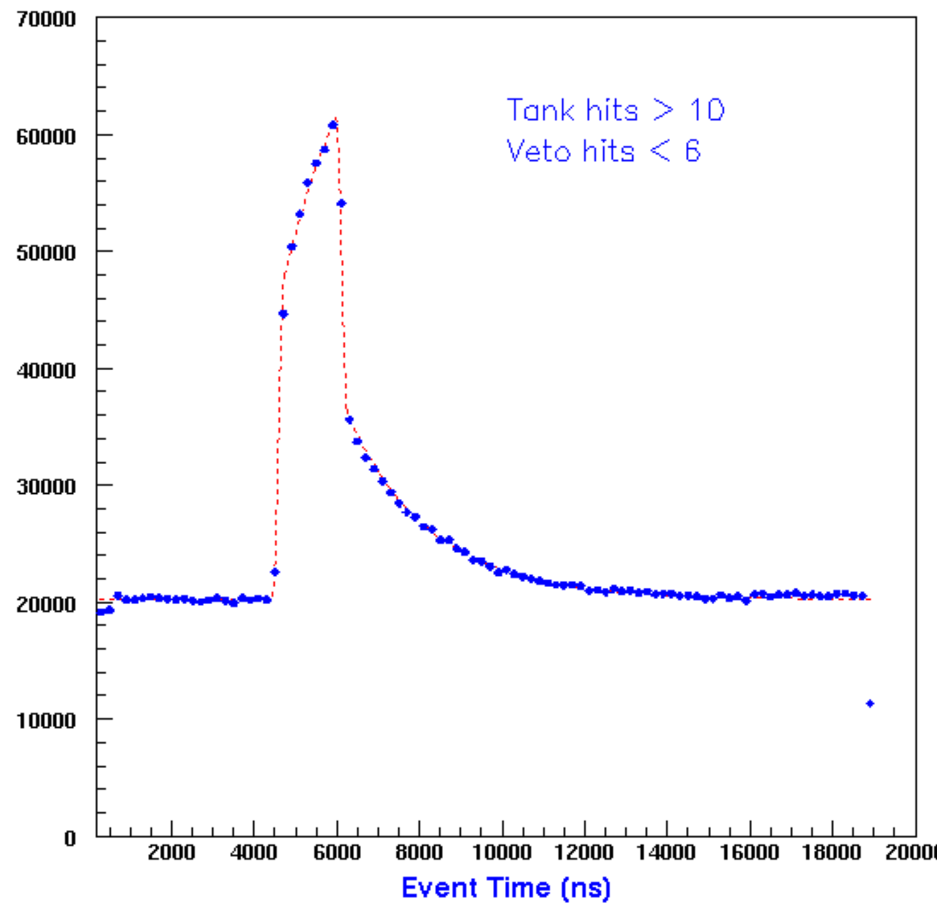
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and Michels



MiniBooNE,NIM.A599(2009)28

3. Events in the Detector

Times of hit-clusters (subevents)

Beam spill (1.6μs) is clearly evident

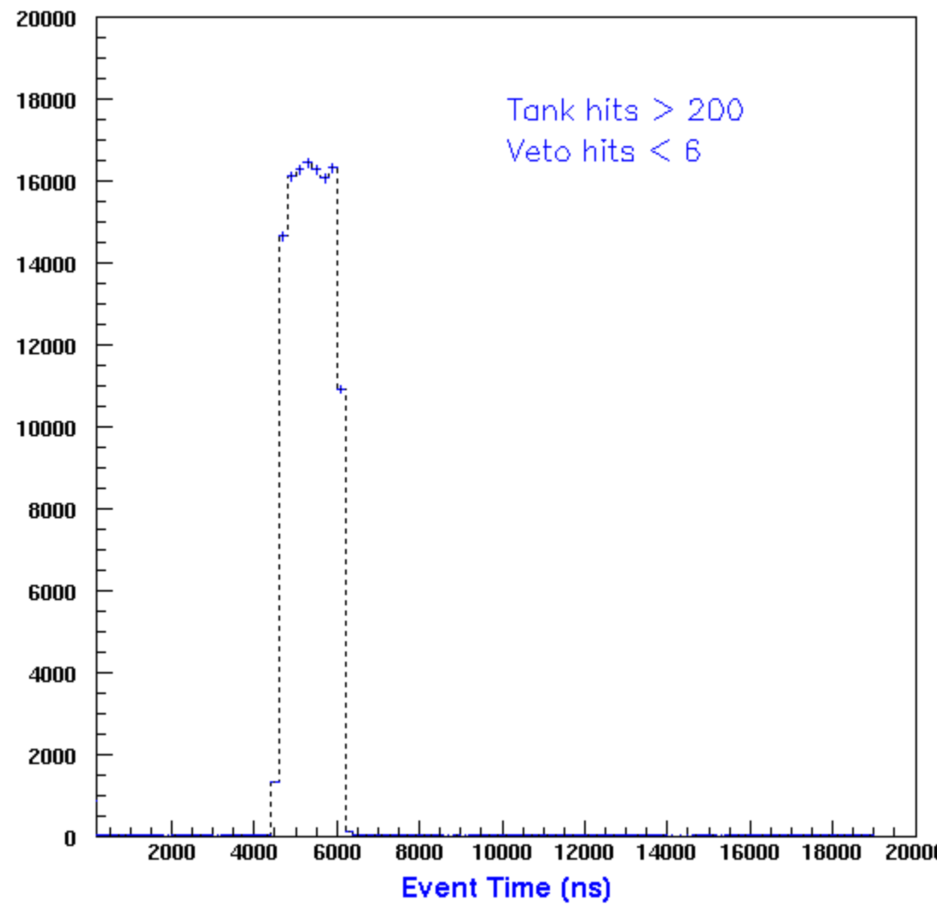
- simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts

- <6 veto PMT hits
  - Gets rid of muons
- >200 tank PMT hits
  - Gets rid of Michels

Only neutrinos are left!

Beam Only



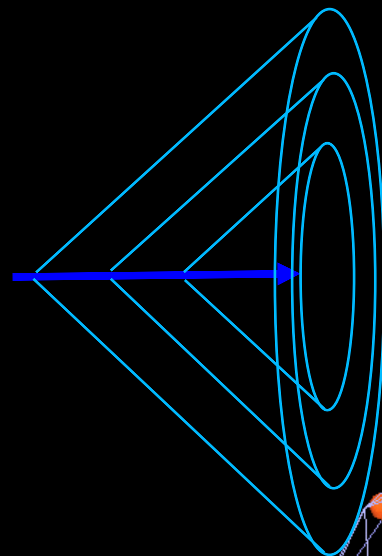
3. Events in the Detector

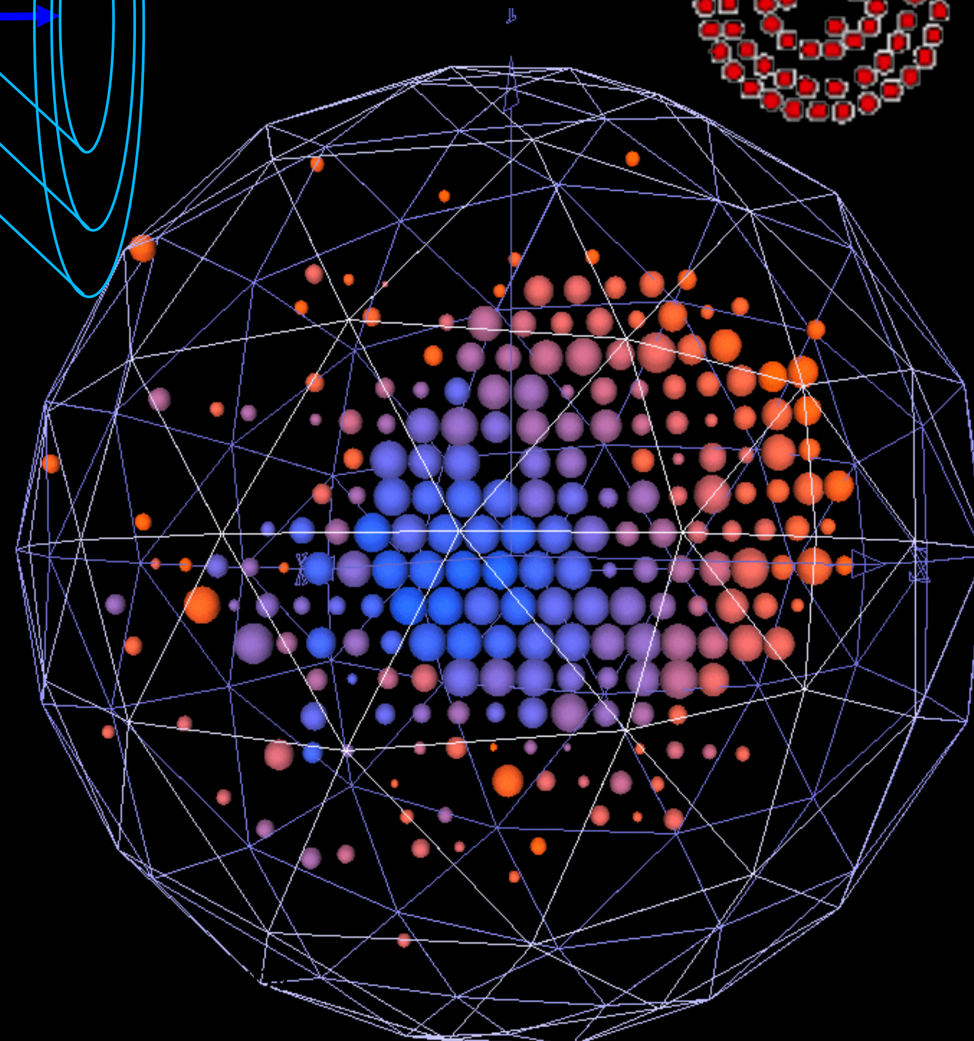
MiniBooNE collaboration, NIM.A599(2009)28

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

3. Events in the Detector

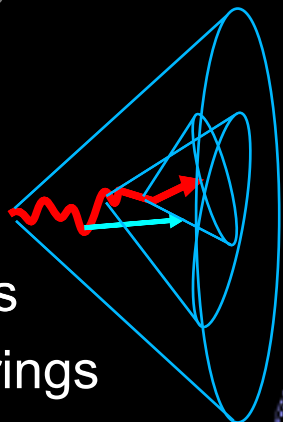
MiniBooNE collaboration, NIM.A599(2009)28

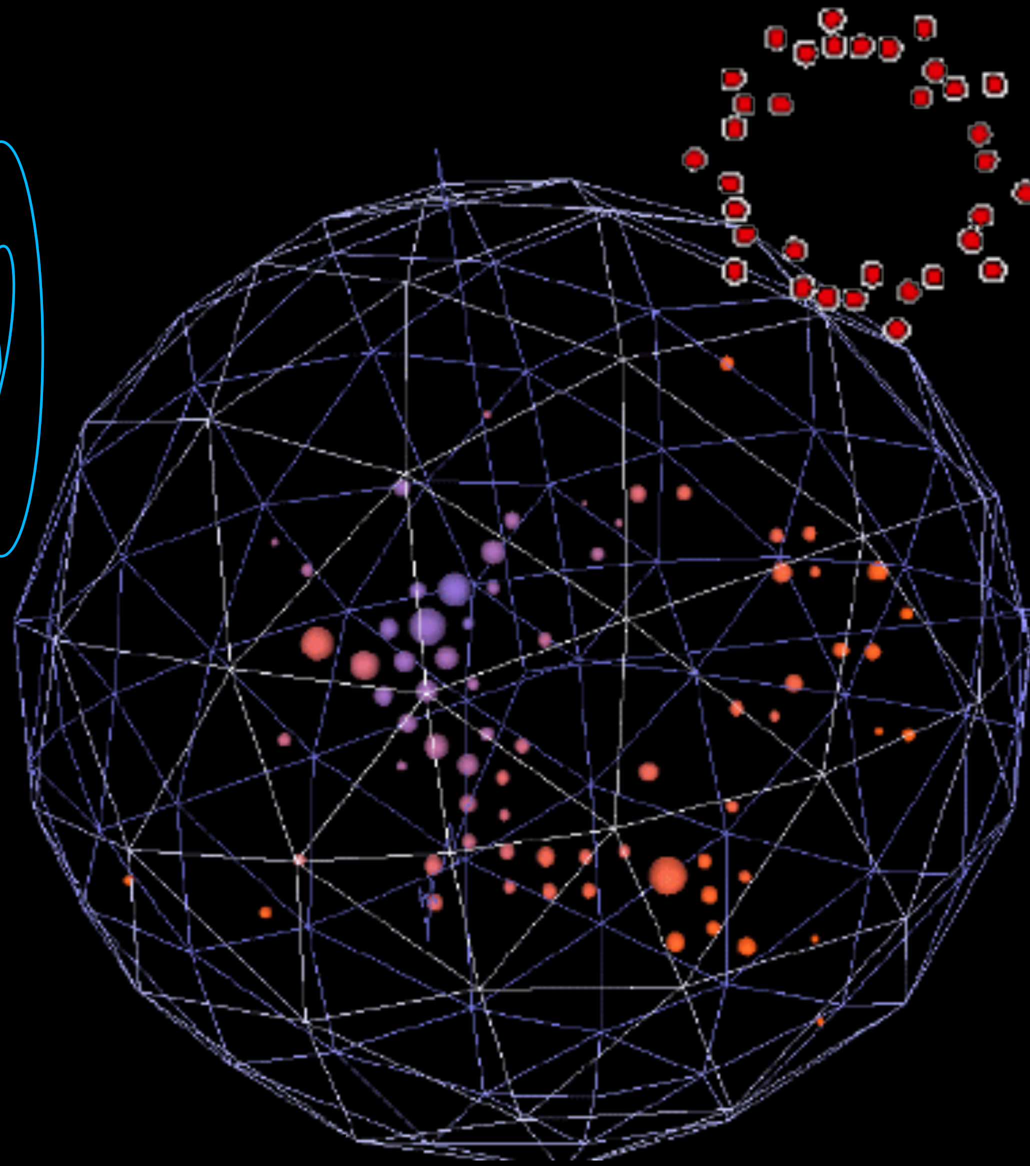
Muons

- 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

3. Events in the Detector

MiniBooNE collaboration, NIM.A599(2009)28

Muons

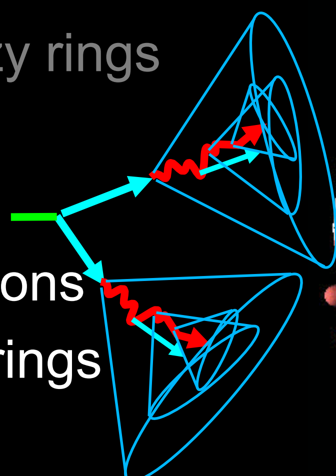
- Long strait tracks
  → Sharp clear rings

Electrons

- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings

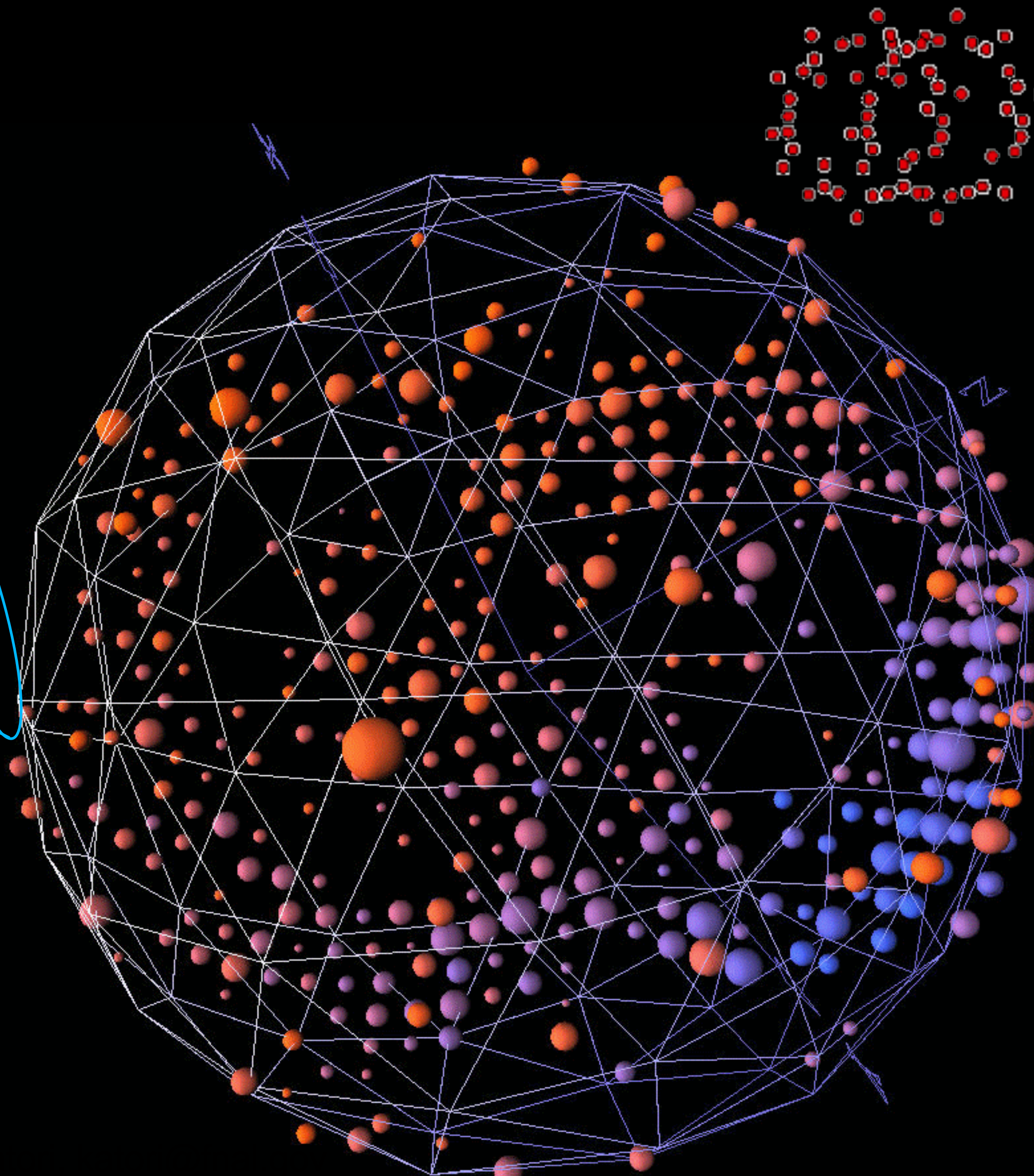
Neutral pions

- Decays to 2 photons
  → Double fuzzy rings



NC elastic scattering

- No Cherenkov radiation
  → Isotropic scintillation hits



3. Events in the Detector

MiniBooNE collaboration,
NIM.A599(2009)28

Muons

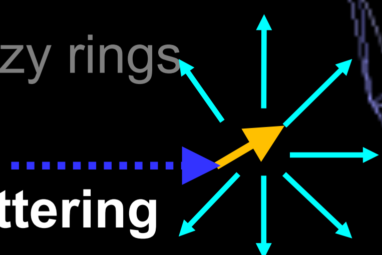
- Long strait tracks
  → Sharp clear rings

Electrons

- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings

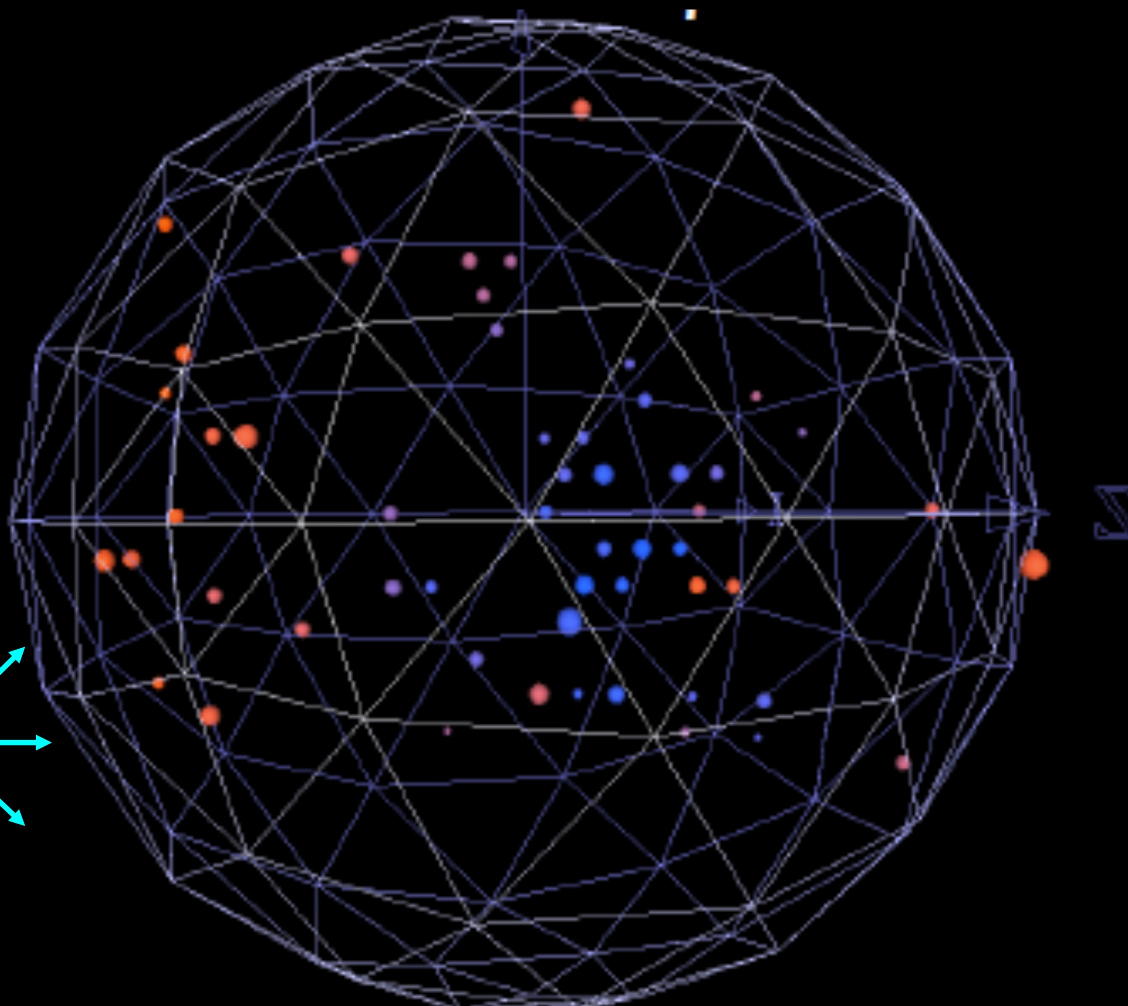
Neutral pions

- Decays to 2 photons
  → Double fuzzy rings



NC elastic scattering

- No Cherenkov radiation
  → Isotropic scintillation hits



3. QE kinematics based energy reconstruction

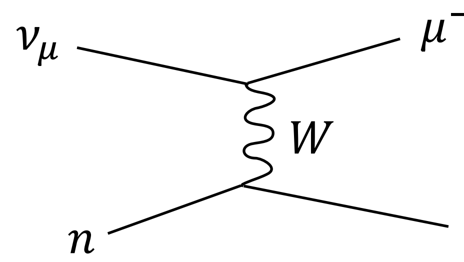
Event reconstruction from Cherenkov ring profile for PID

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

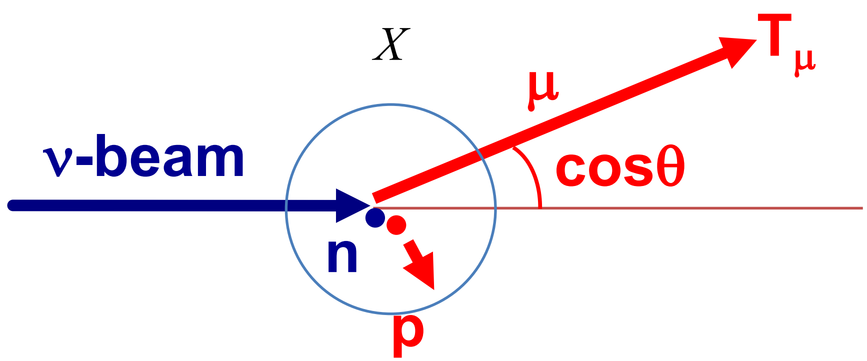
Charged Current Quasi-Elastic (CCQE) interaction

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



$$\nu_\mu + n \longrightarrow p + \mu^- \; (\nu_\mu + X \longrightarrow X' + \mu^-)$$



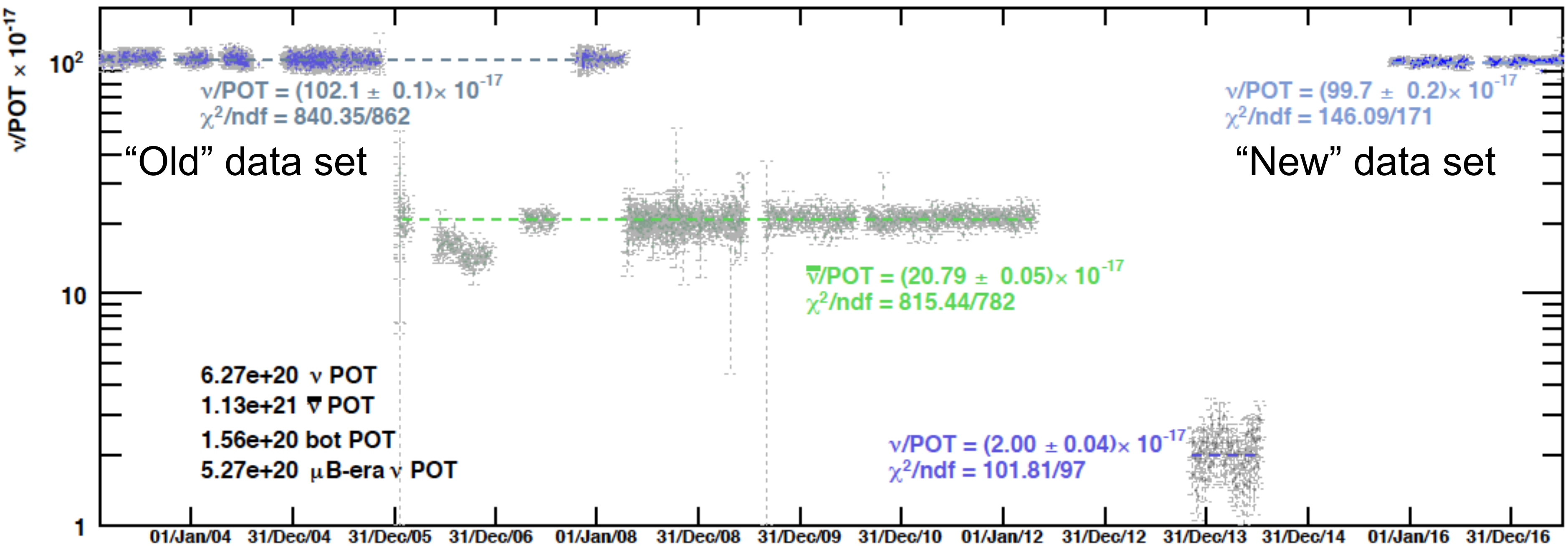
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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)
  - factor ~40 lower flux

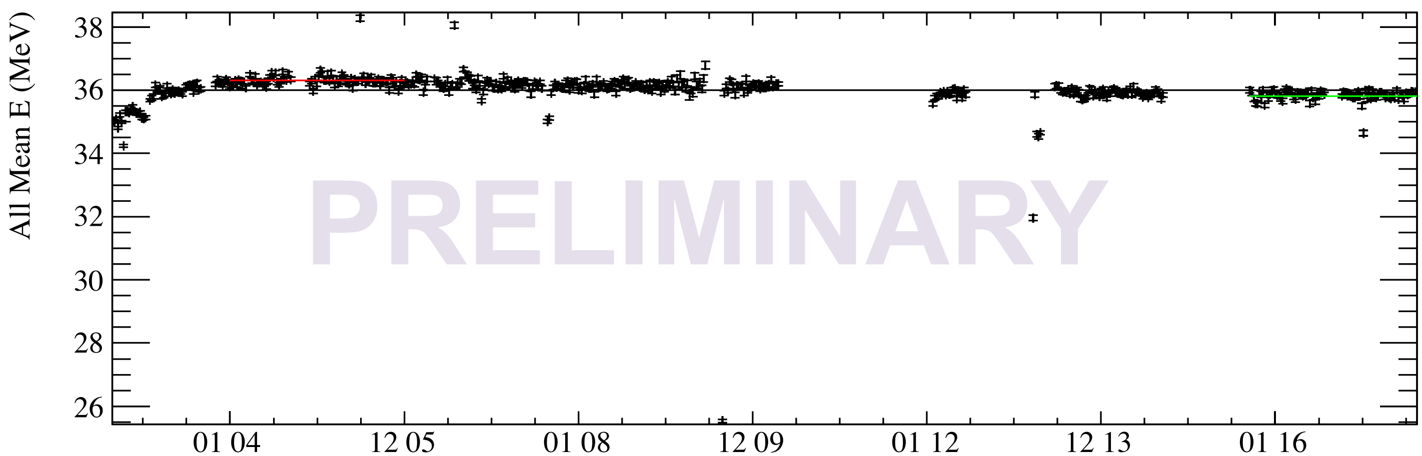
MiniBooNE, PRL118(2017)221803,
PRD98(2018)112004



3. Detector stability

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

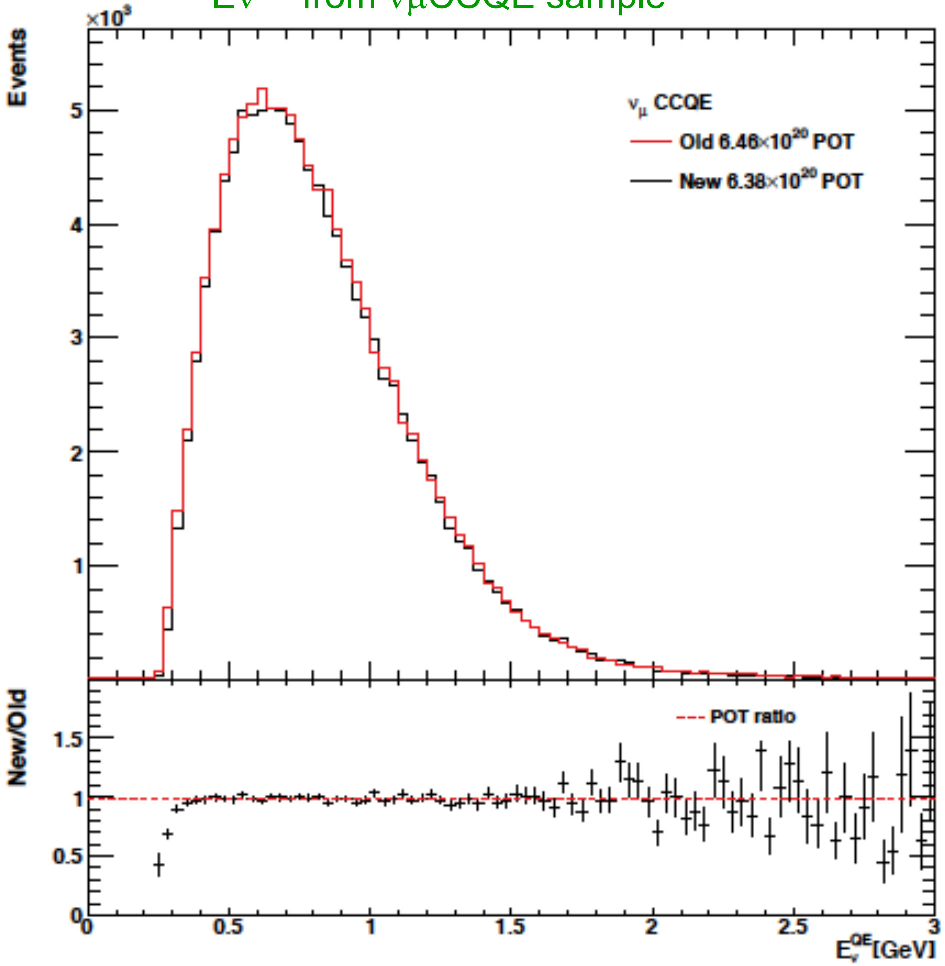
Michel electron spectrum peak



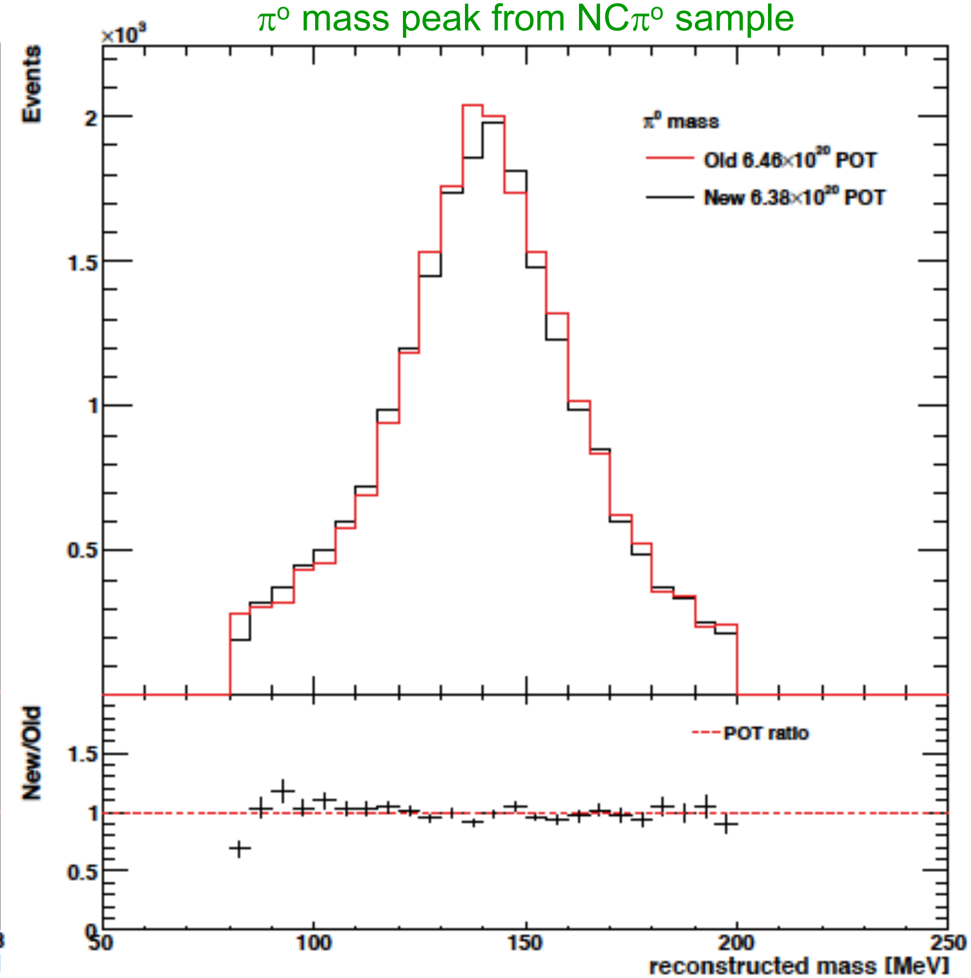
3. Detector stability

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

$E\nu^{QE}$ from $\nu\mu$CCQE sample



π^o mass peak from NCπ^o sample

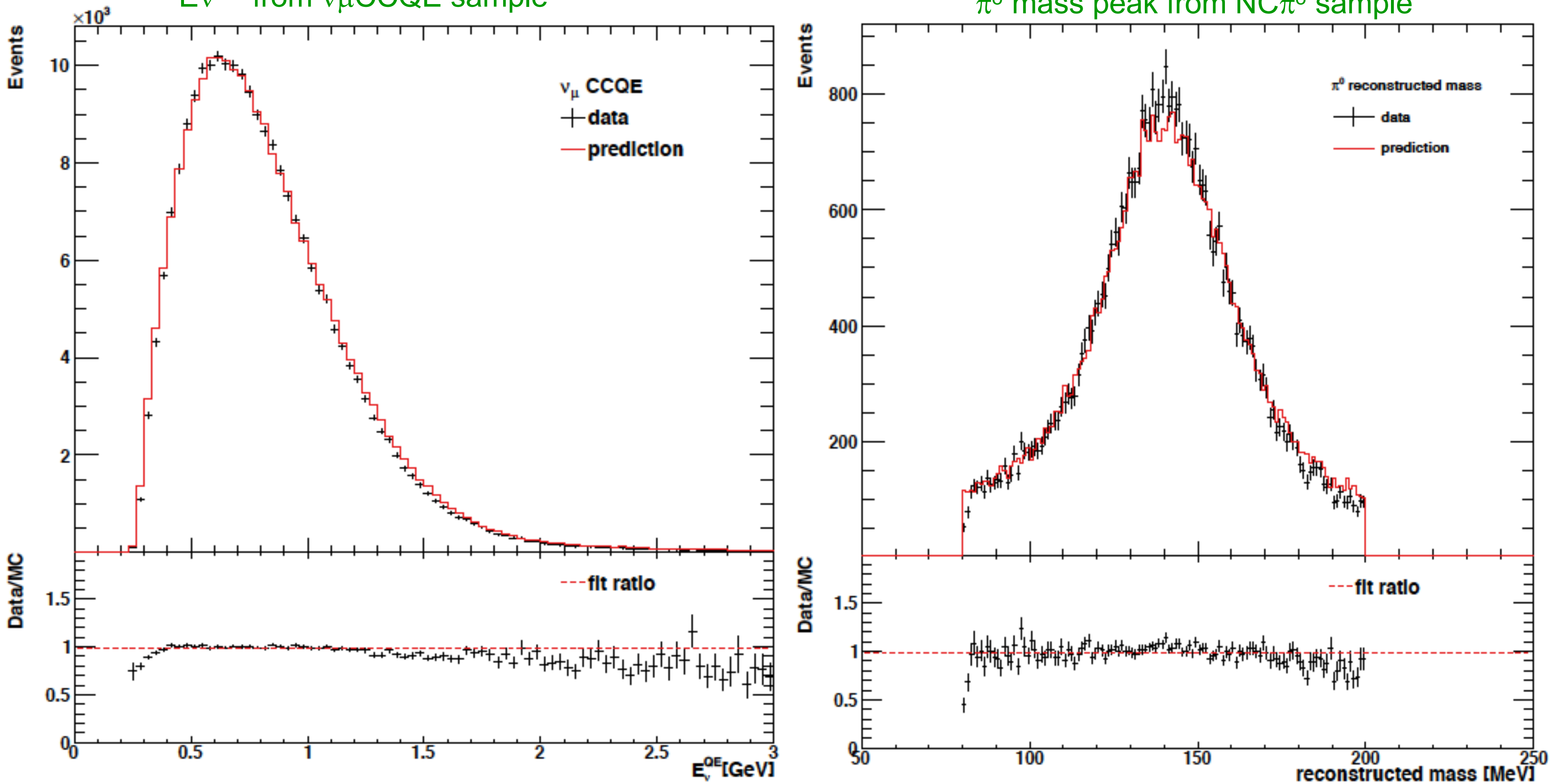


3. Data-Simulation comparison

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

$E\nu^{QE}$ 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

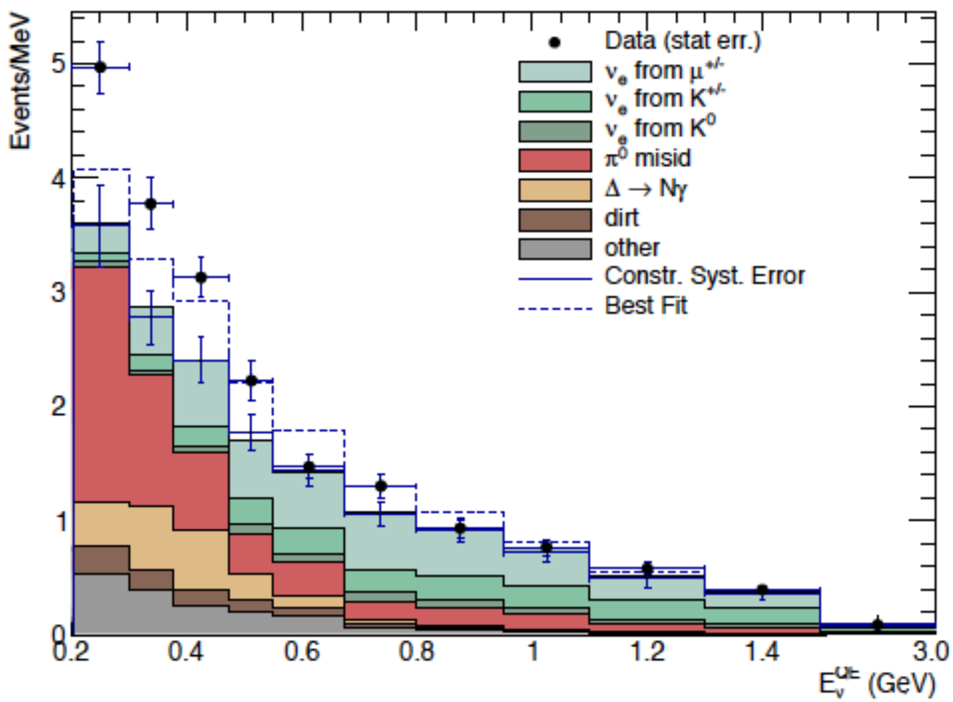
4. Oscillation candidate search

5. Discussion

4. Internal background constraints

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

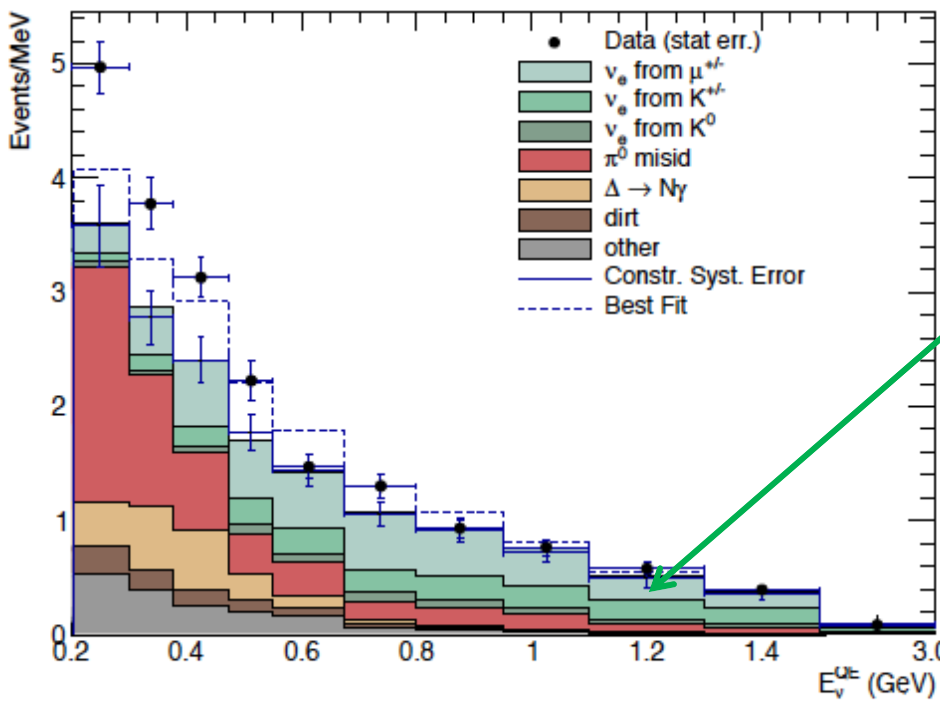
	Process	Neutrino Mode	Antineutrino Mode
misID	ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
	NC π^0	501.5 ± 65.4	112.3 ± 11.5
	NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
	External Events	75.2 ± 10.9	15.3 ± 2.8
	Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
intrinsic	ν_e & $\bar{\nu}_e$ 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
	Excess	381.2 ± 85.2	79.3 ± 28.6



4. ν_e from μ-decay 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
Excess	381.2 ± 85.2	79.3 ± 28.6



ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from μ-decay constraint

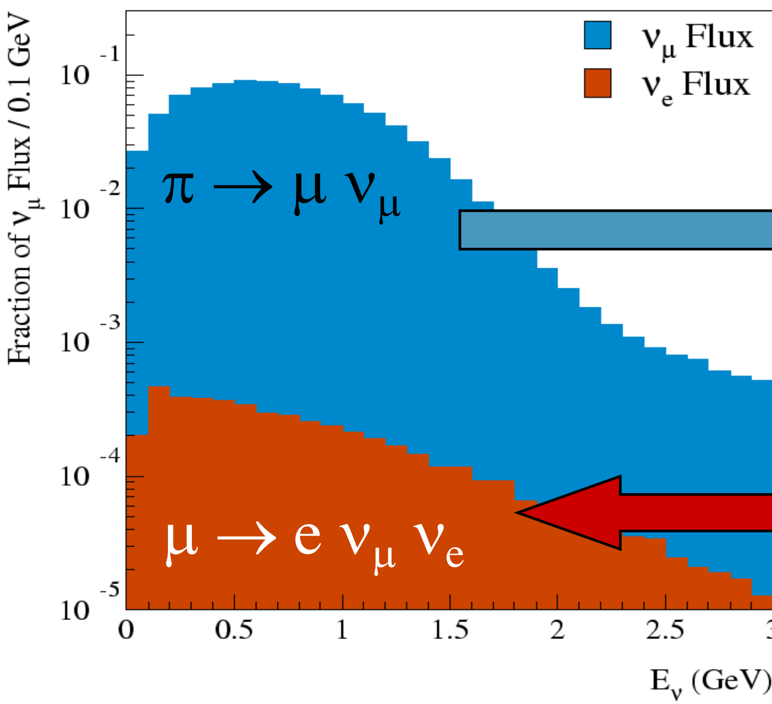
measured

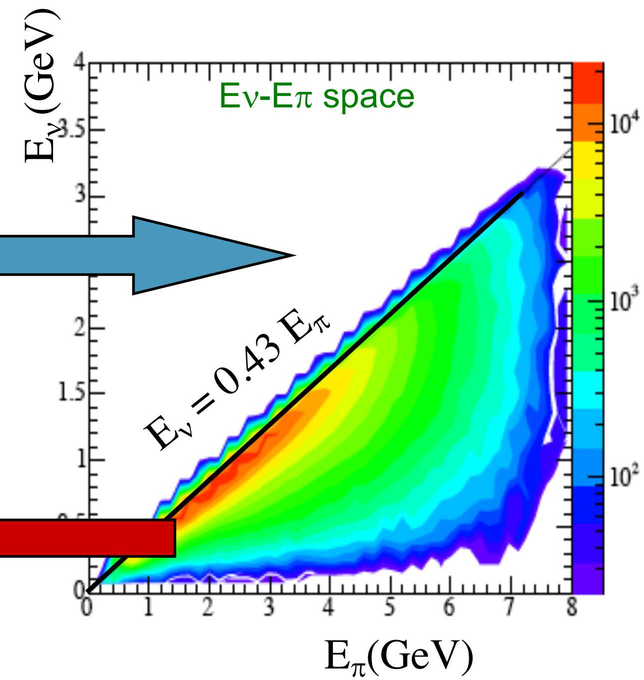
$$\pi^+ \longrightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \boxed{\nu_e}$$
$$\pi^- \longrightarrow \mu^- + \boxed{\bar{\nu}_\mu}$$
$$\mu^- \longrightarrow e^- + \nu_\mu + \boxed{\bar{\nu}_e}$$

guessed

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

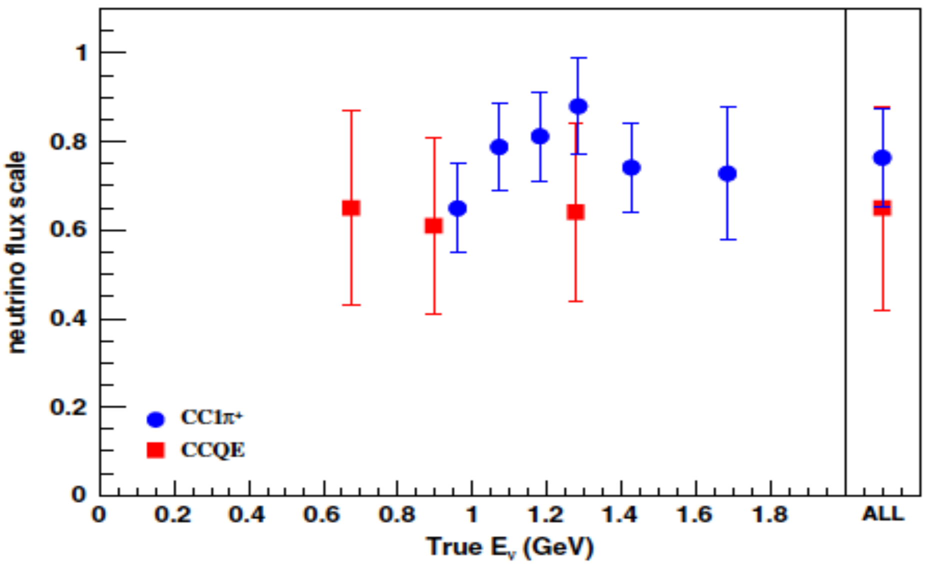
They are large background, but we have a good control of $\nu_e \& \bar{\nu}_e$ background by joint $\nu_e \& \nu_\mu (\bar{\nu}_e \& \bar{\nu}_\mu)$ fit for oscillation search.



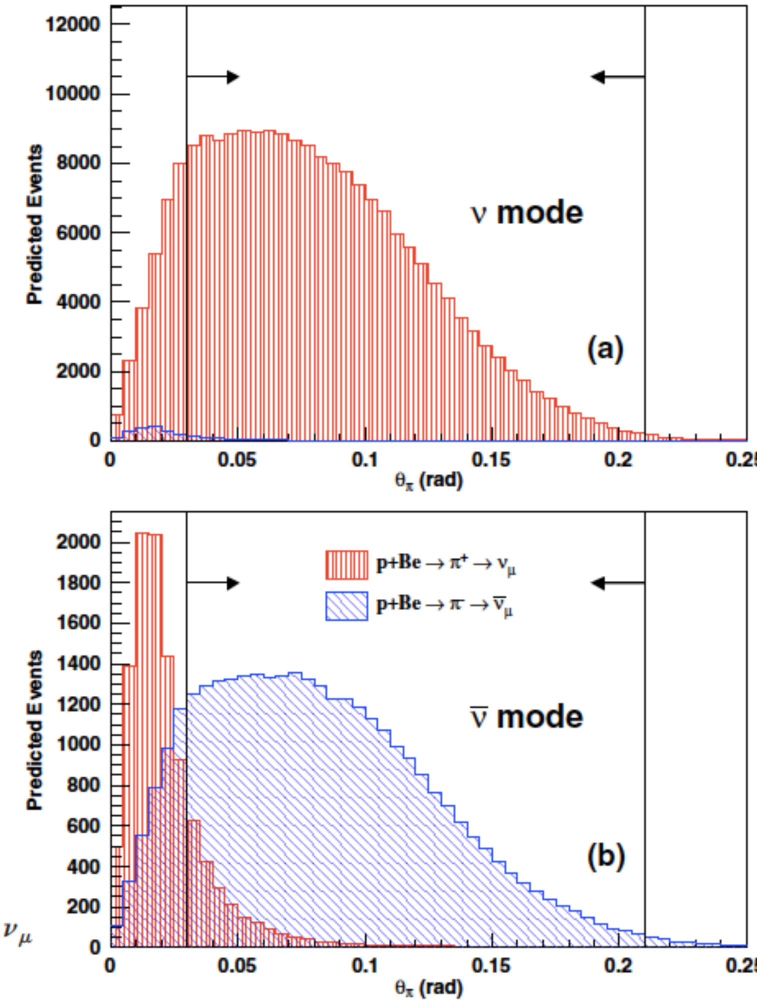


4. Anti-neutrino mode flux tuning

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



PHYSICAL REVIEW D 84, 072005 (2011)



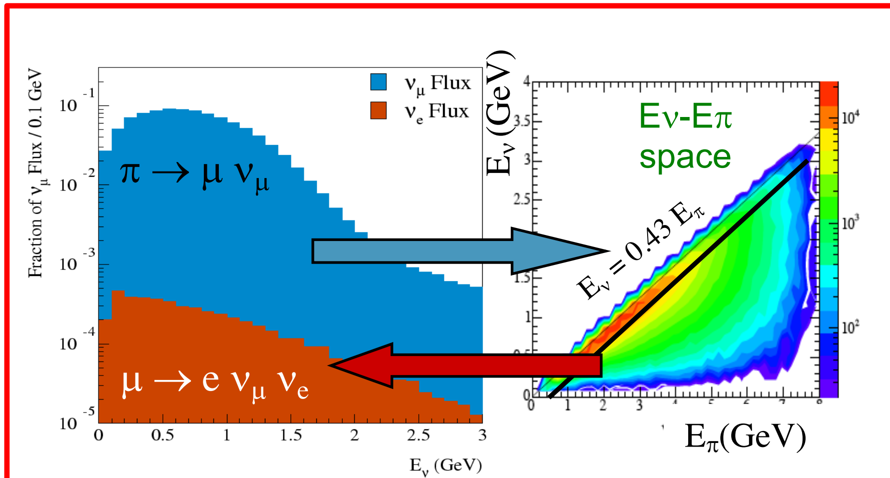
Michel electron counting is sensitive to ν_μ contamination in $\bar{\nu}_\mu$ beam

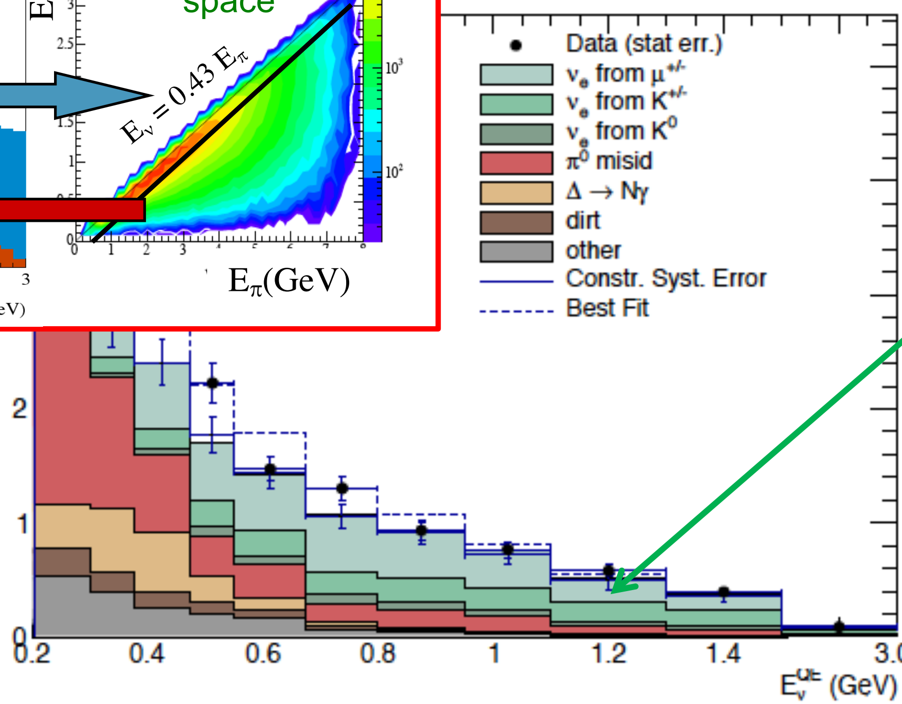
$$
\begin{aligned}
1:&\quad \nu_\mu + p(n) \to \mu^- + p(n) + \pi^+ \hookrightarrow \mu^+ + \nu_\mu \\
2:&\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu \\
3:&\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu .
\end{aligned}
$$

4. ν_e from μ-decay 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
Excess	381.2 ± 85.2	79.3 ± 28.6



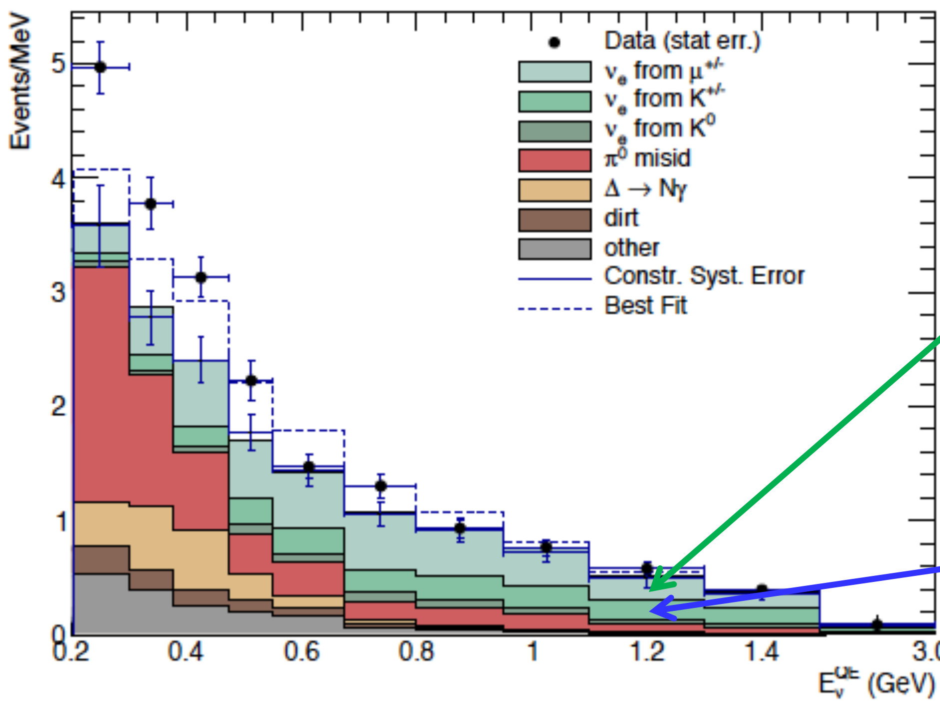


ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from K^+-decay 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
Excess	381.2 ± 85.2	79.3 ± 28.6

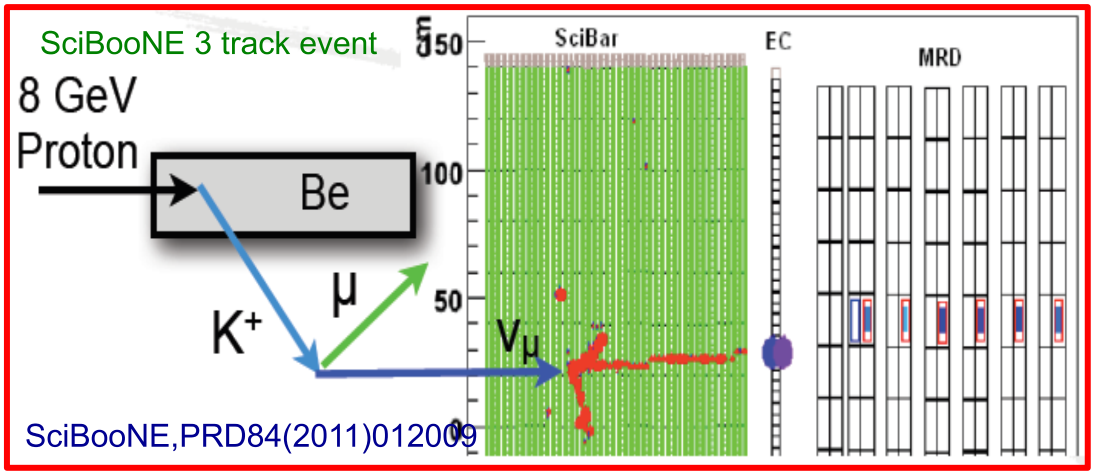


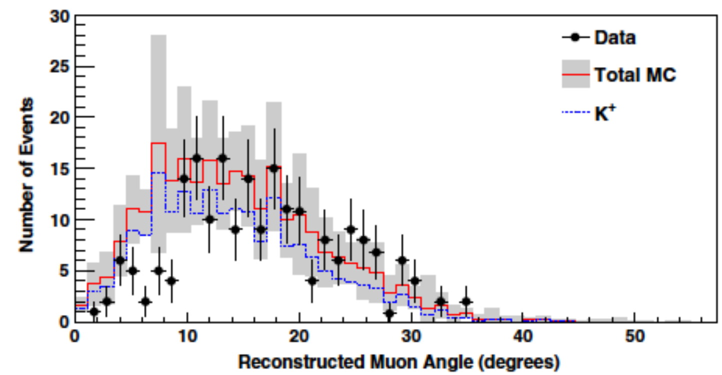
ν_e from μ decay is constrained from ν_μCCQE measurement

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

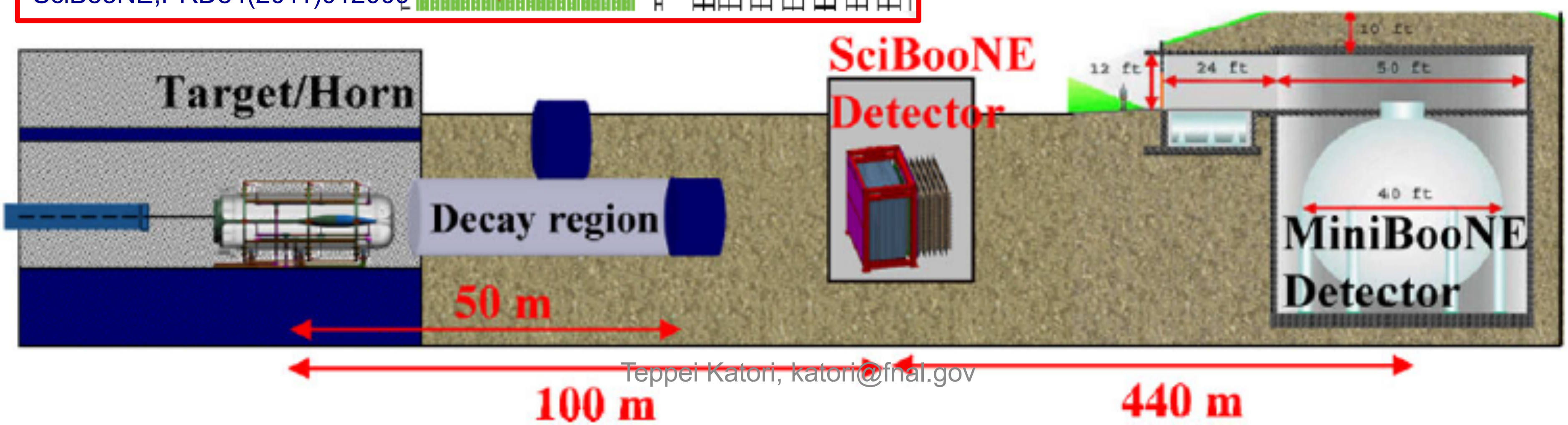
4. ν_e from K^+-decay constraint

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)





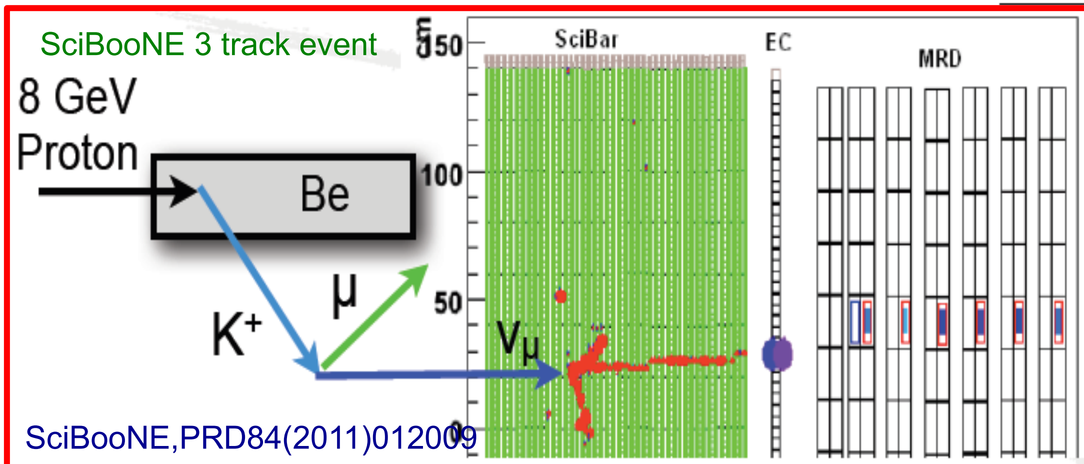
(c) 3-Track Sample

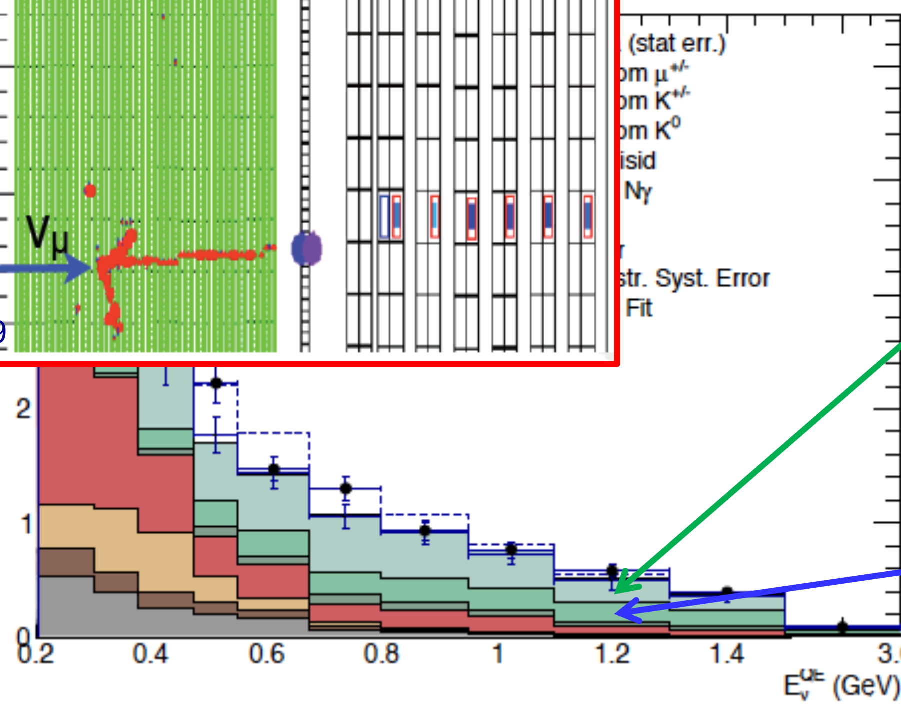


4. ν_e from K^+-decay constraint

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
Excess	381.2 ± 85.2	79.3 ± 28.6





ν_e from μ decay is constrained from ν_μCCQE measurement

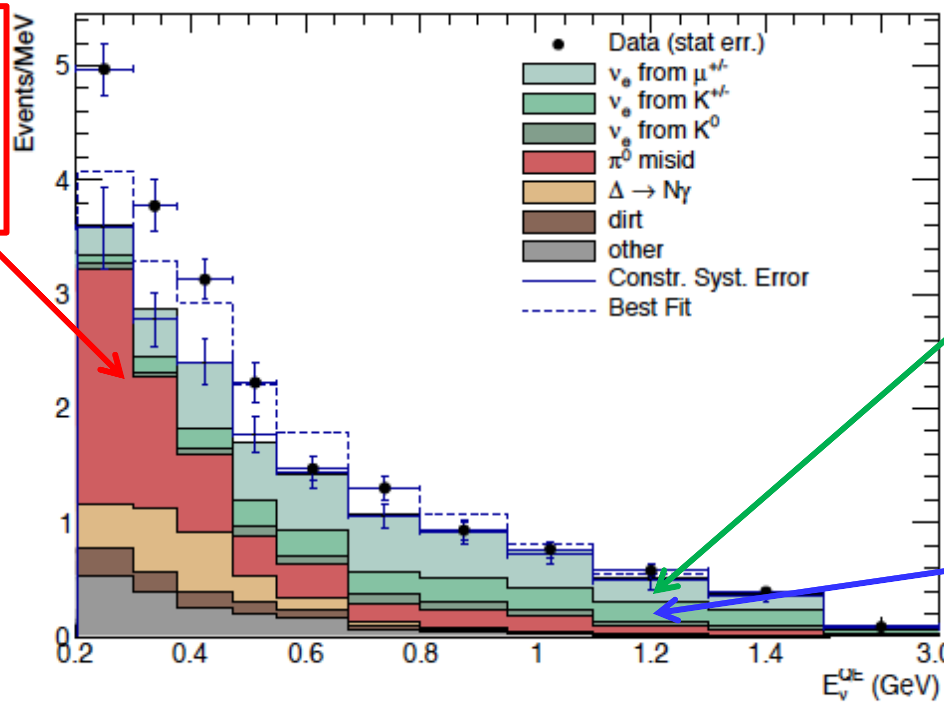
ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

4. ν_e from K^+-decay 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
NC $\Delta \rightarrow N\gamma$	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
Excess	381.2 ± 85.2	79.3 ± 28.6

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

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



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

4. γ from π^o constraint

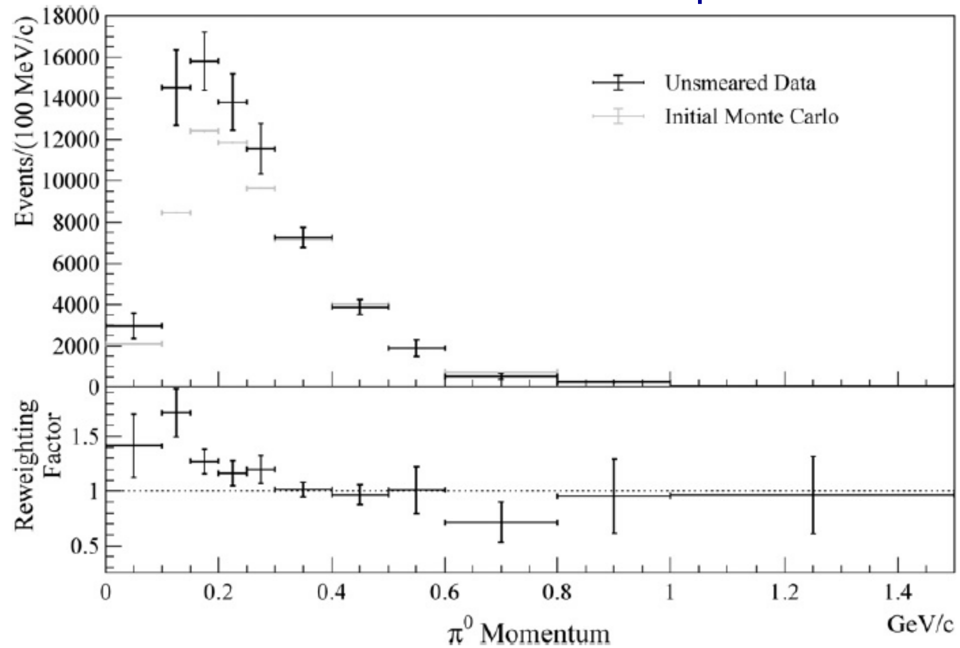
$\pi^o \rightarrow \gamma\gamma$
- not background, we can measure

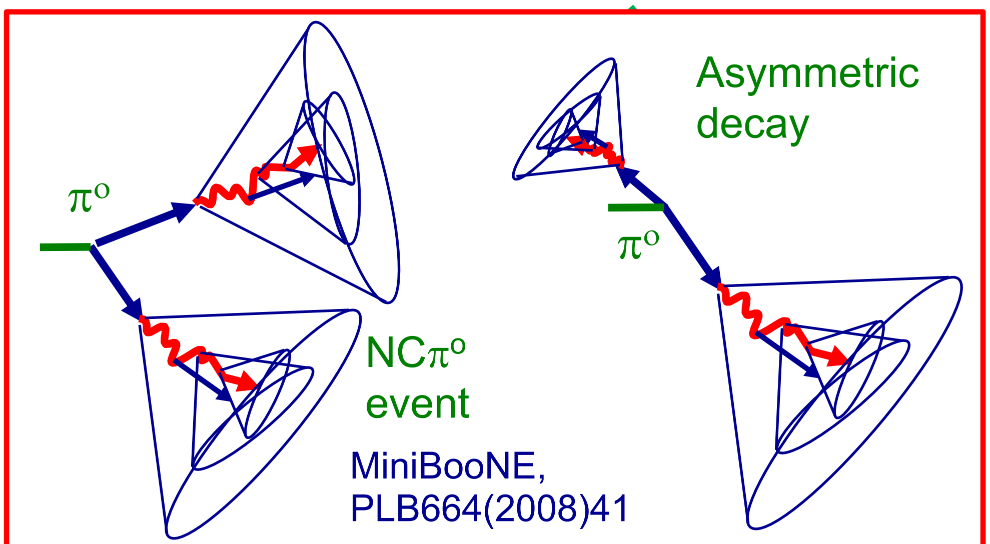
$\pi^o \rightarrow \gamma$
- misID background, we cannot measure

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

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

π^o momentum data-MC comparison



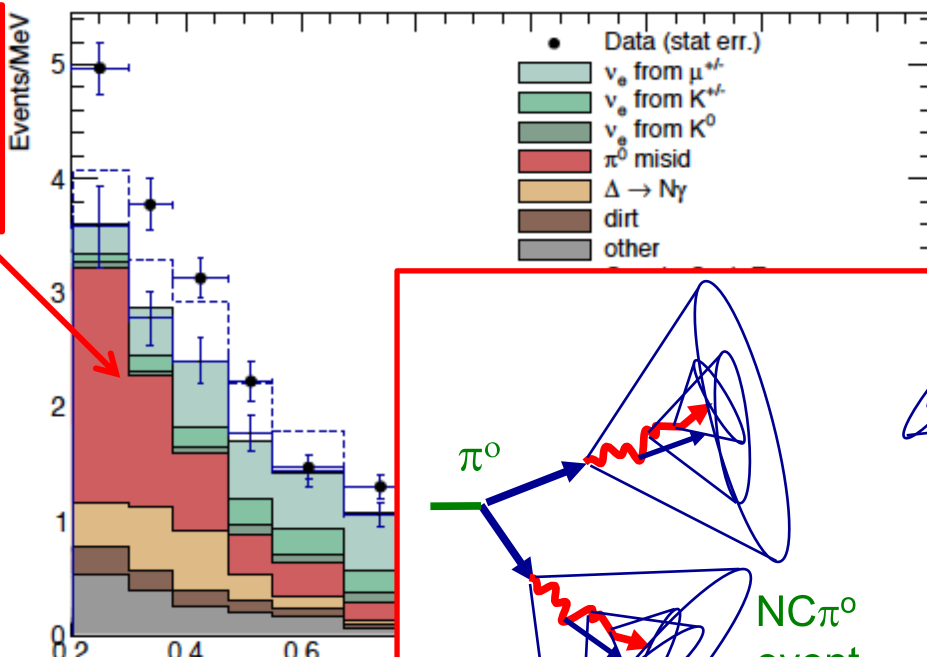


4. γ from π^o constraint

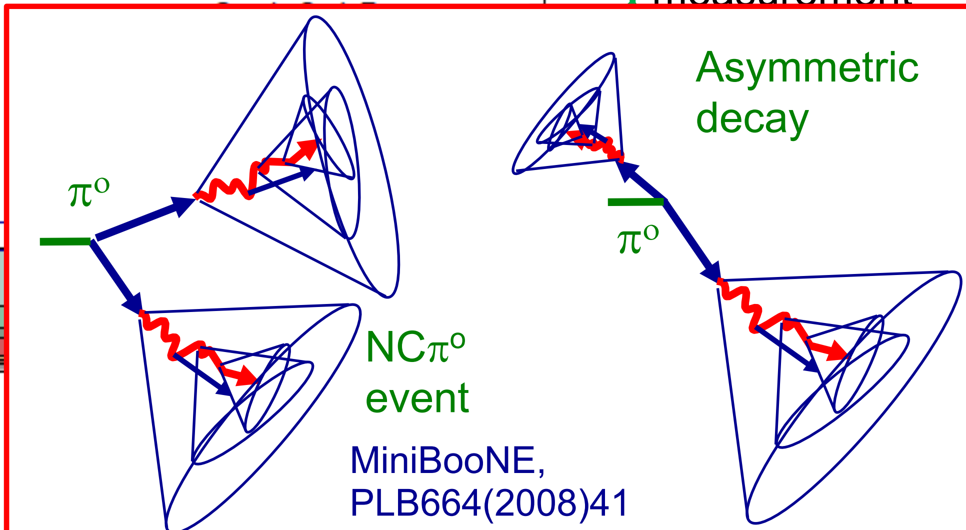
All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

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
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



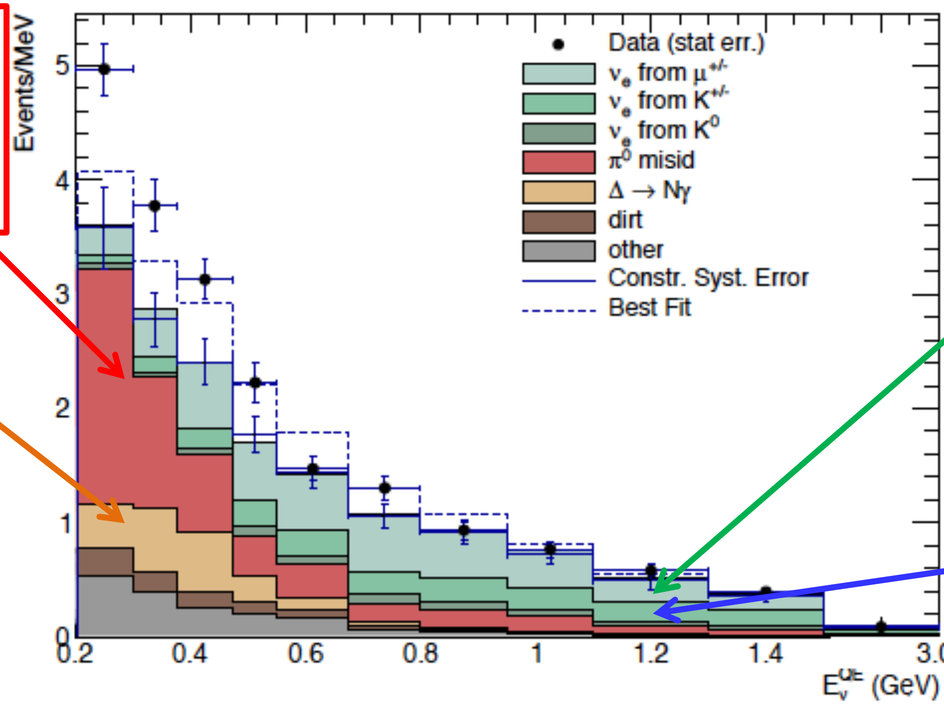
4. NCγ constraint

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
Excess	381.2 ± 85.2	79.3 ± 28.6

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

4. NCγ 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
NC $\Delta \rightarrow N\gamma$	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
d 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

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

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

Γγ/Γπ: NCγ to NCπ branching ratio
π^o fraction (=2/3)
ε: π escaping factor

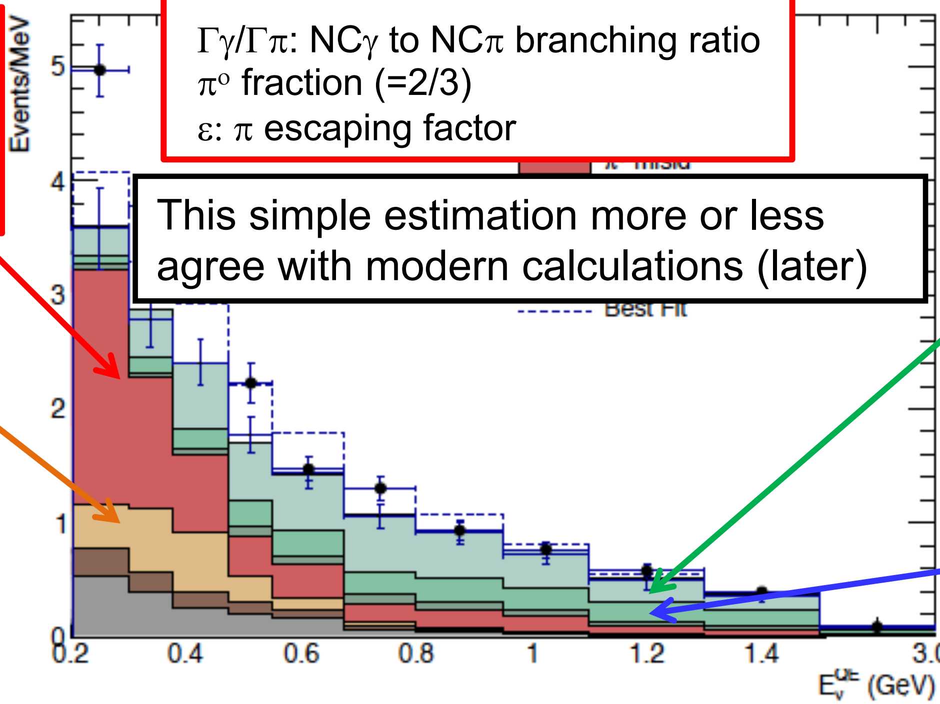
This simple estimation more or less agree with modern calculations (later)

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

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. External γ constraint

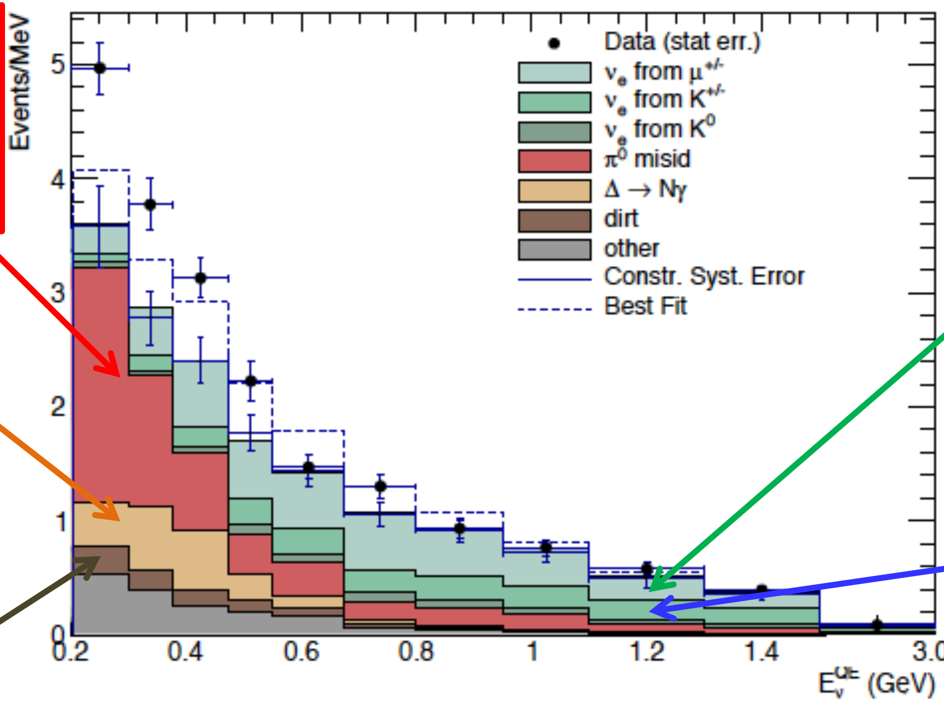
Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	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
Excess	381.2 ± 85.2	79.3 ± 28.6

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ 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



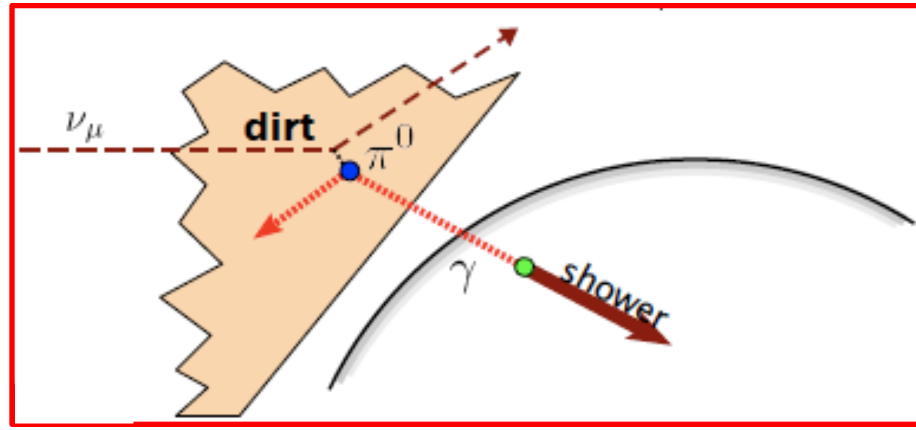
ν_e from μ decay is constrained from ν_μCCQE measurement

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

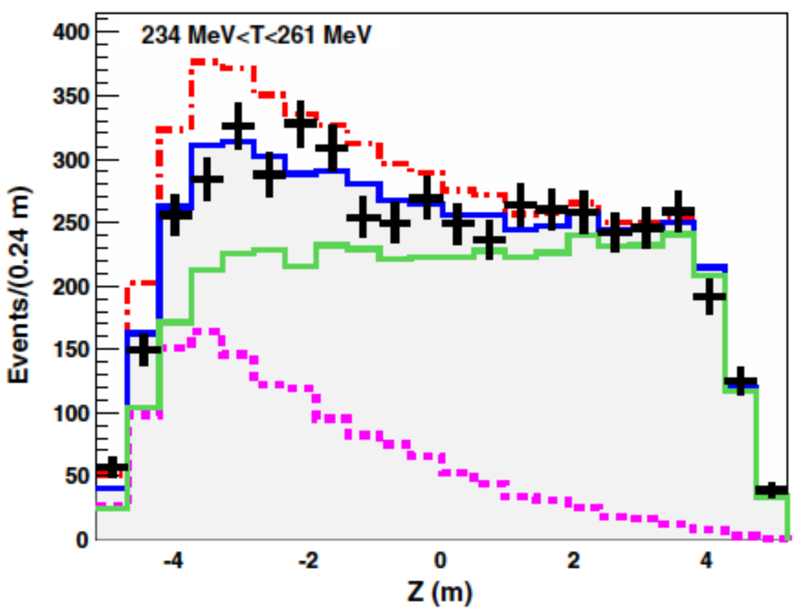
4. External γ constraint

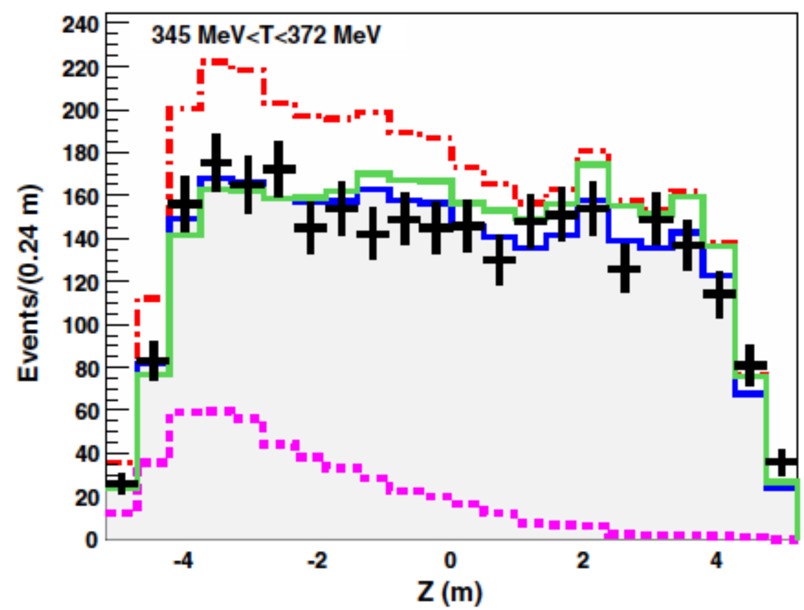
MiniBooNE detector has a simple geometry
- Spherical Cherenkov detector
- Homogeneous, large active veto

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

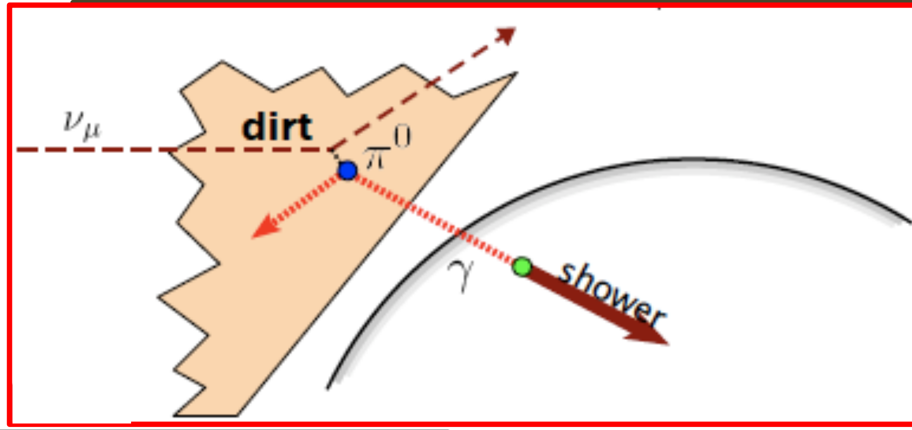




Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4

4. External γ constraint

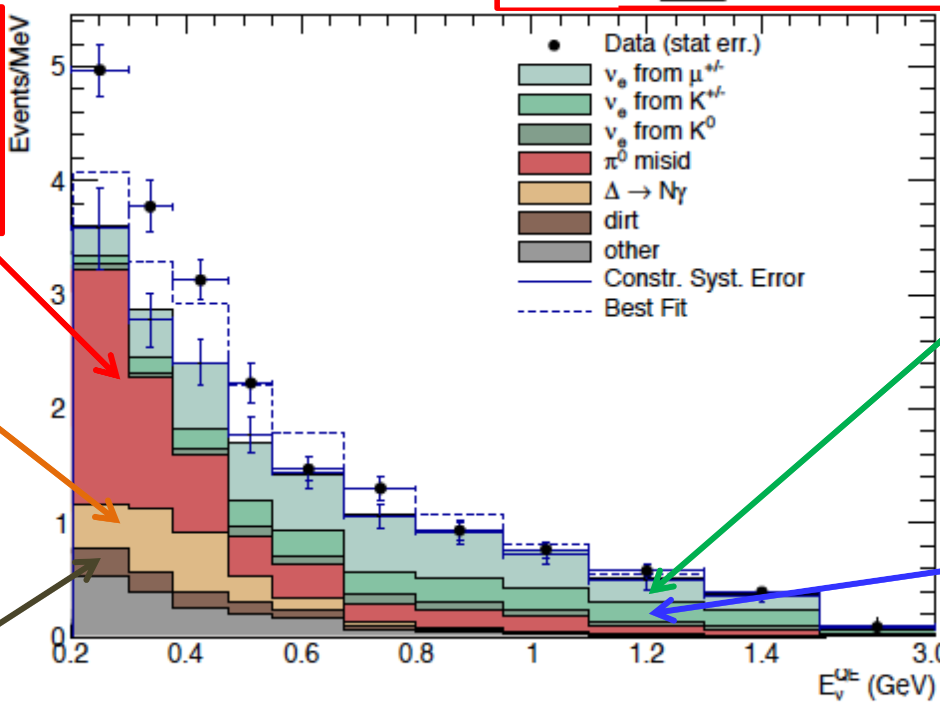
All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E



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

4. Internal background constraints

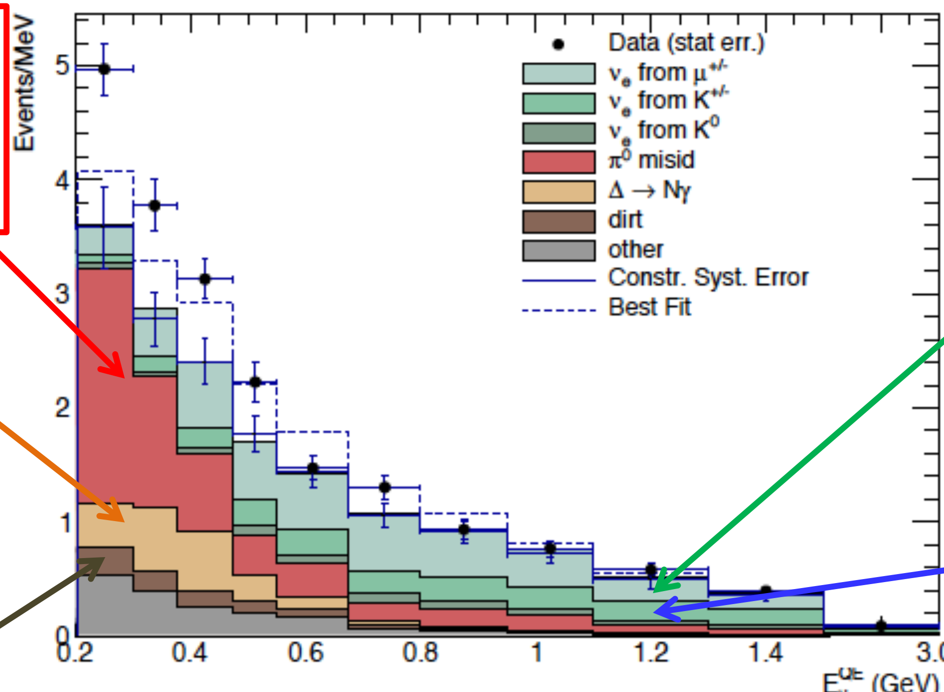
All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

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
Excess	381.2 ± 85.2	79.3 ± 28.6

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

Δ resonance rate is constrained from measured $NC\pi^o$ 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

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

5. Oscillation candidate event excess

200 < EνQE < 1250 MeV

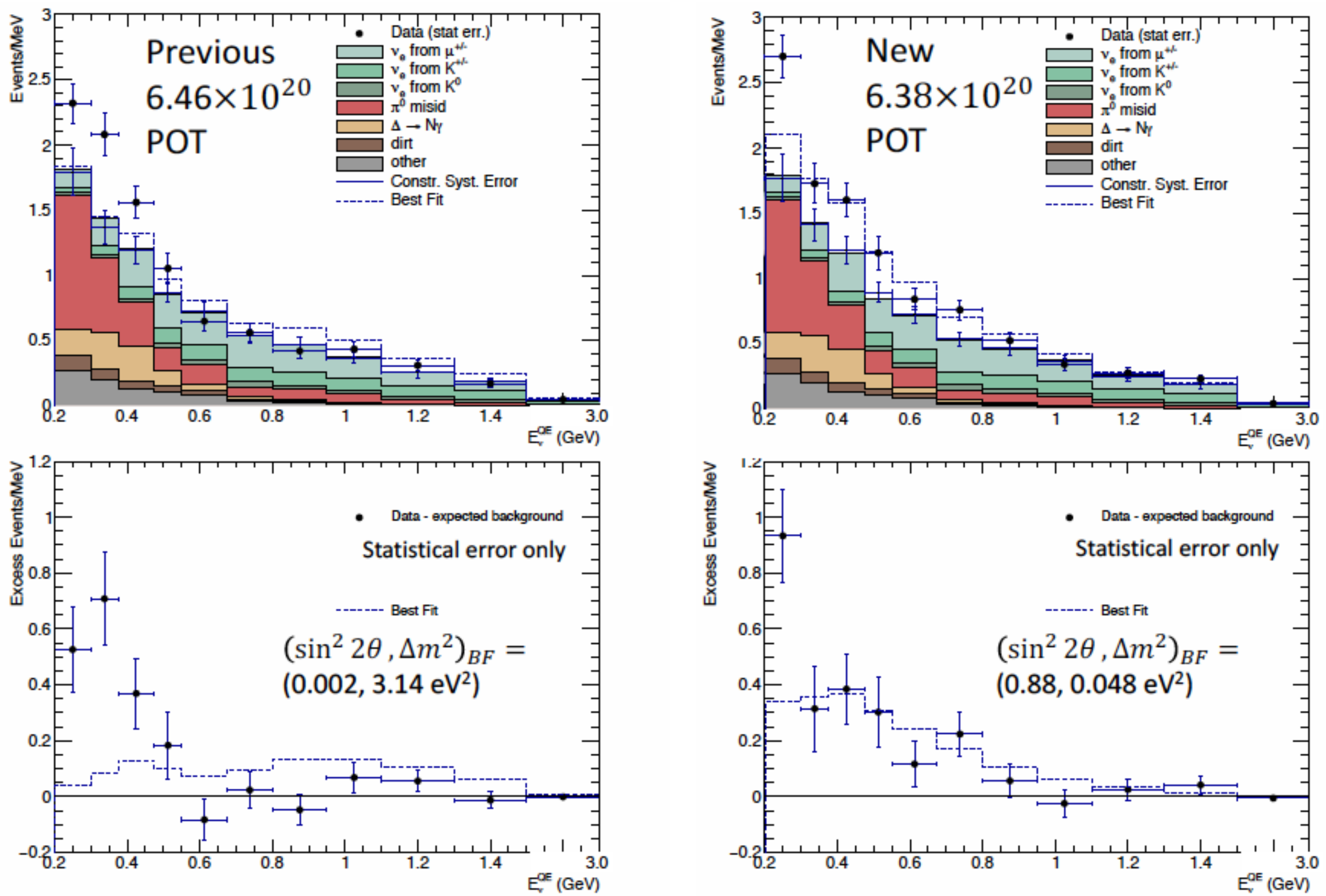
- neutrino mode: Data = 1959 events

Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)

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%



Queen Mary
University of London

5. Oscillation candidate event excess

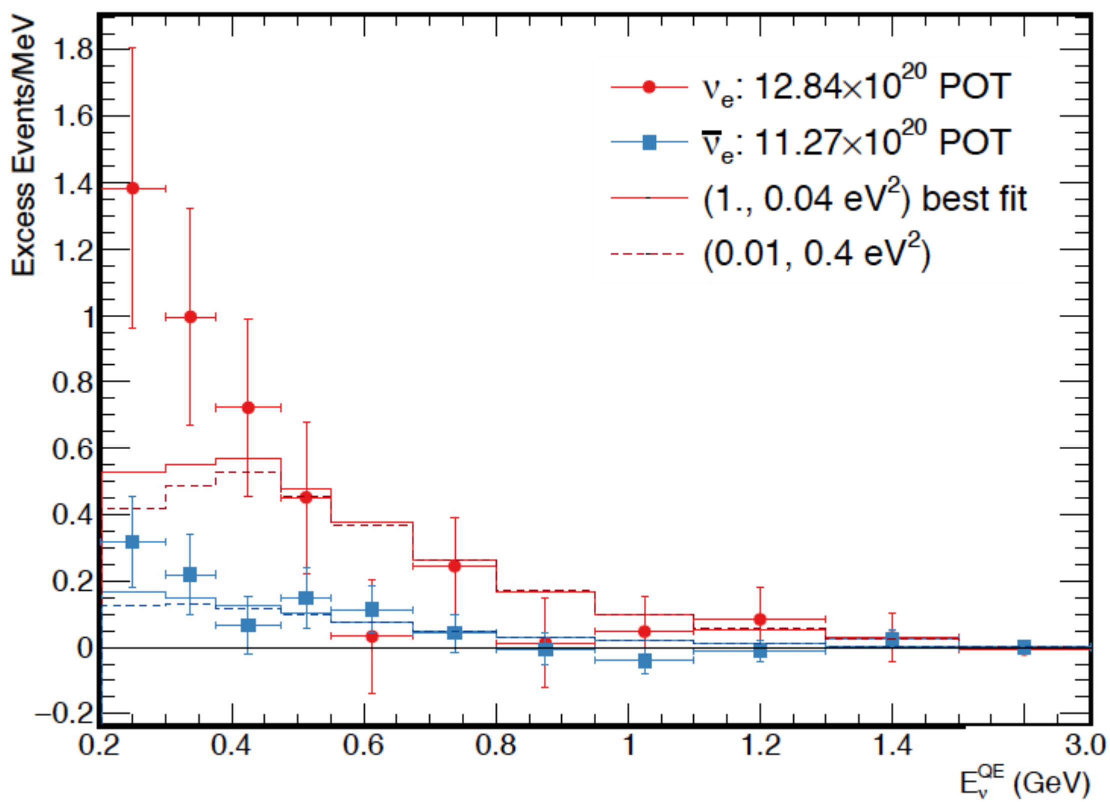
200 < EνQE < 1250 MeV

- neutrino mode: Data = 1959 events

Bkgd = 1577.8 $\pm$ 39.7(stat) $\pm$ 75.4(syst) → 381.2 $\pm$ 85.2 excess (4.5σ)

- antineutrino mode: Data = 478 events

Bkgd = 398.7 $\pm$ 20.0(stat) $\pm$ 20.3(syst) → 79.3 $\pm$ 28.6 excess (2.8σ)



5. Sterile neutrino hypothesis

200 < EνQE < 1250 MeV

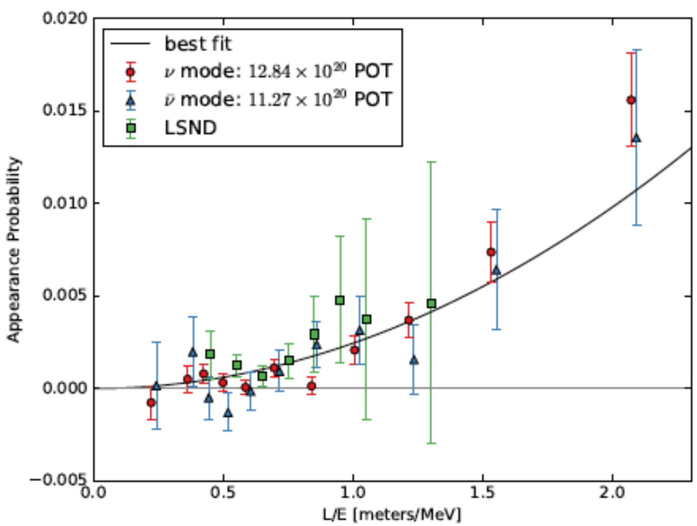
- neutrino mode: Data = 1959 events

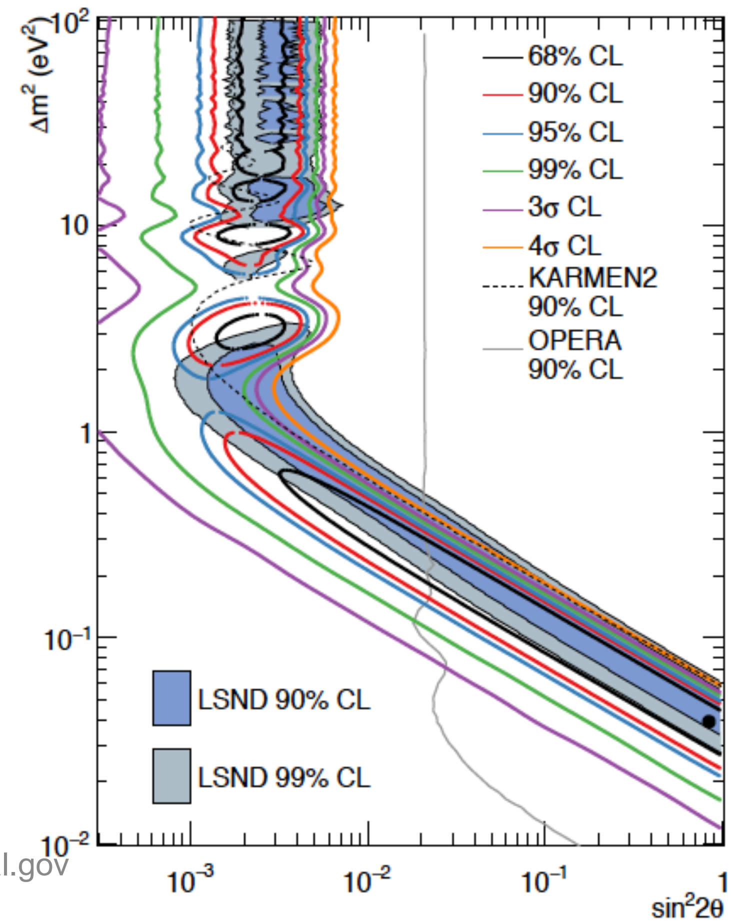
Bkgd = 1577.8 $\pm$ 39.7(stat) $\pm$ 75.4(syst) → 381.2 $\pm$ 85.2 excess (4.5σ)

- antineutrino mode: Data = 478 events

Bkgd = 398.7 $\pm$ 20.0(stat) $\pm$ 20.3(syst) → 79.3 $\pm$ 28.6 excess (2.8σ)

Compatible with LSND excess within 2-neutrino oscillation hypothesis





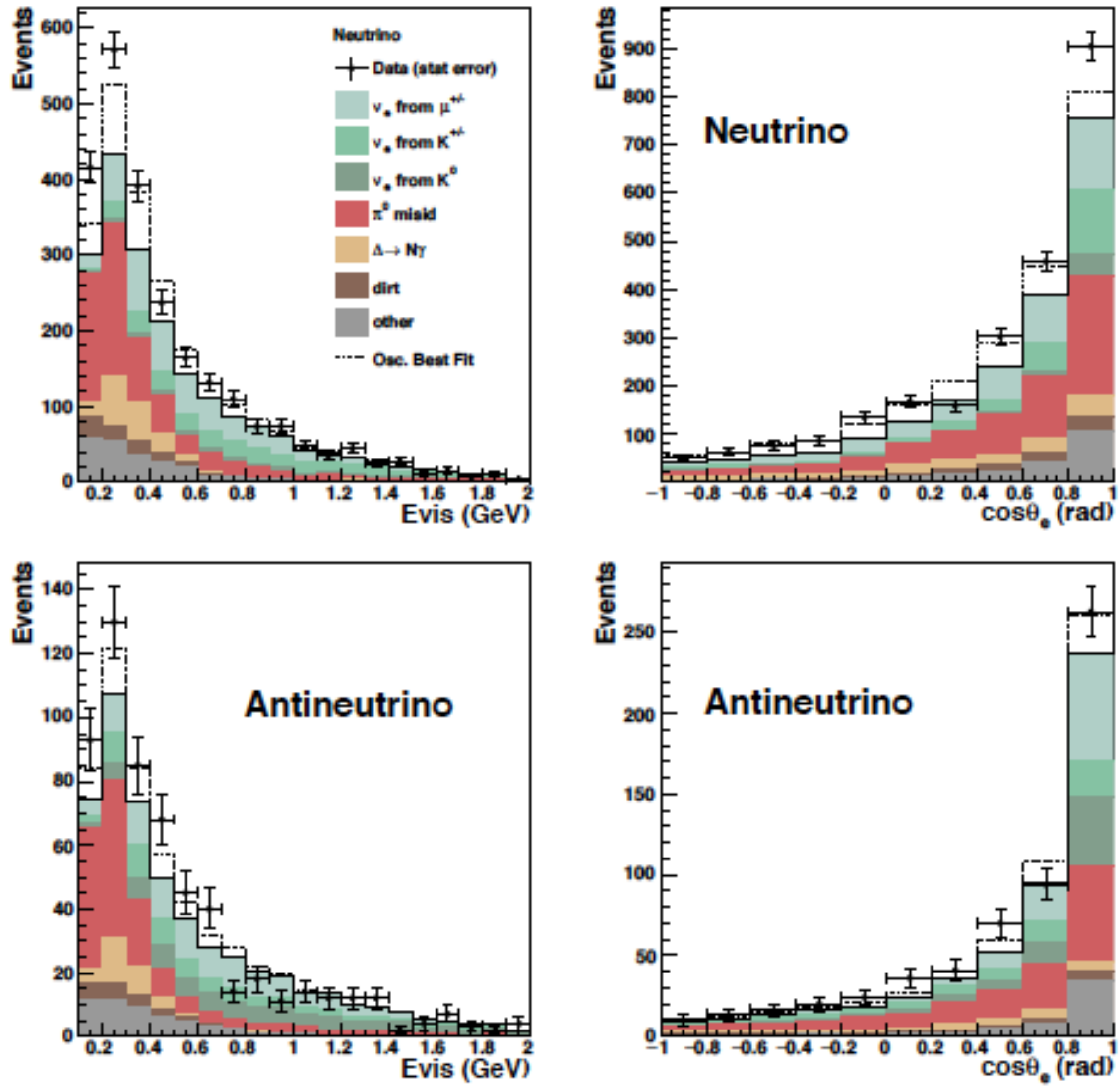
However, appearance and disappearance data have a strong tension (Maltoni, Neutrino 2018)

5. Alternative photon production models?

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

Any misID background missing?
- New NCγ process?
- New NCπ^o process?

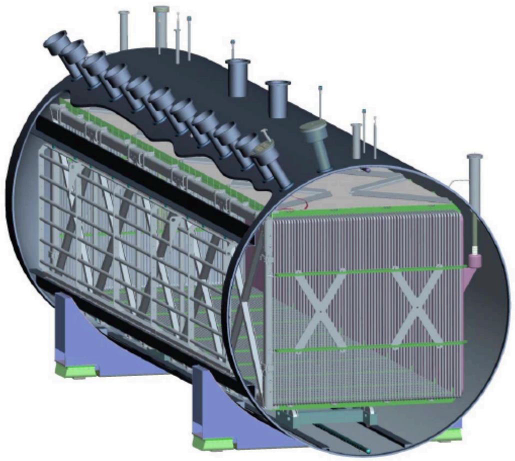
or BSM physics?
- BSM γ production process?
- BSM e-scattering process?
- BSM oscillation physics?

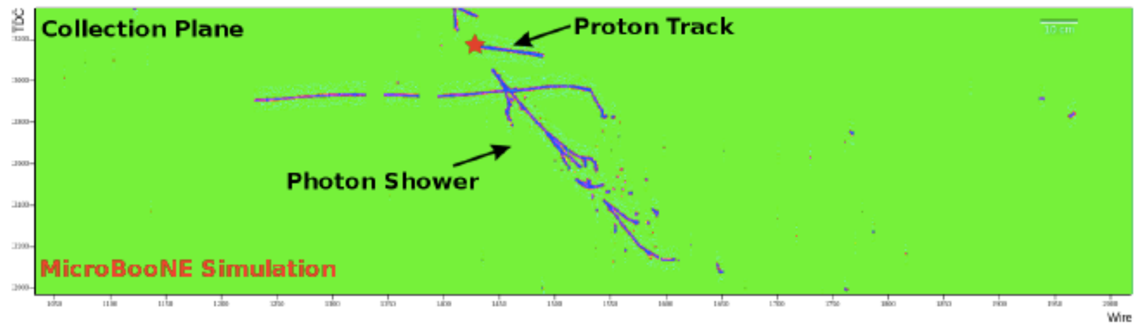


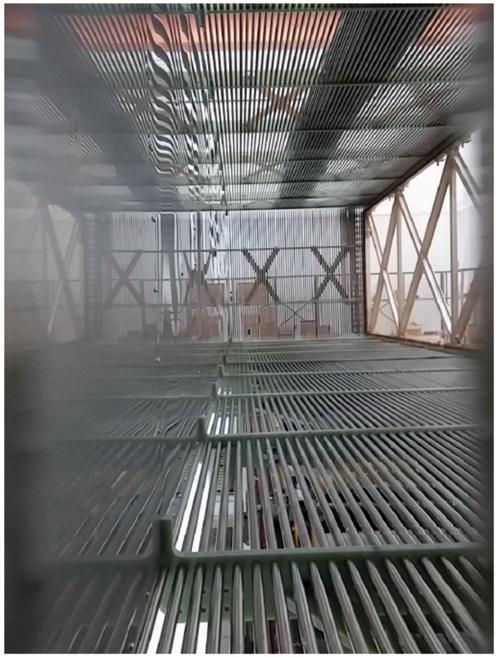
5. Liquid argon time projection chamber

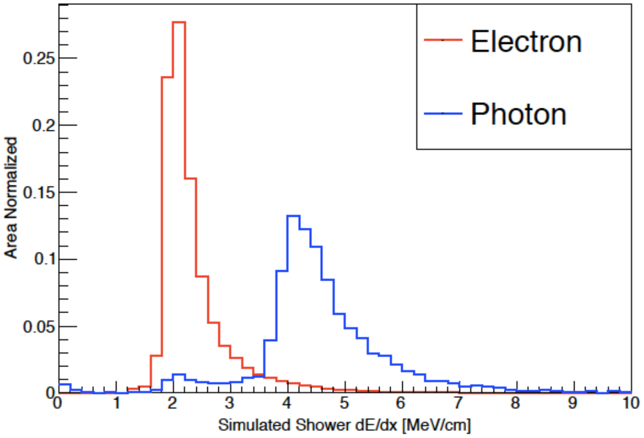
High resolution detector with e/γ separation

- Original motivation of US LArTPC program







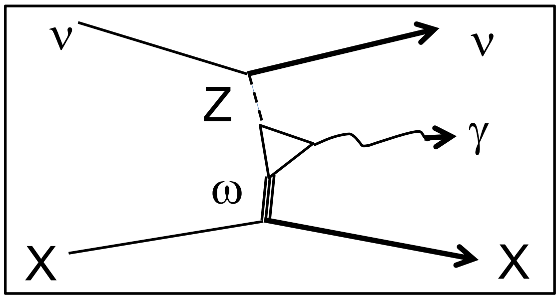


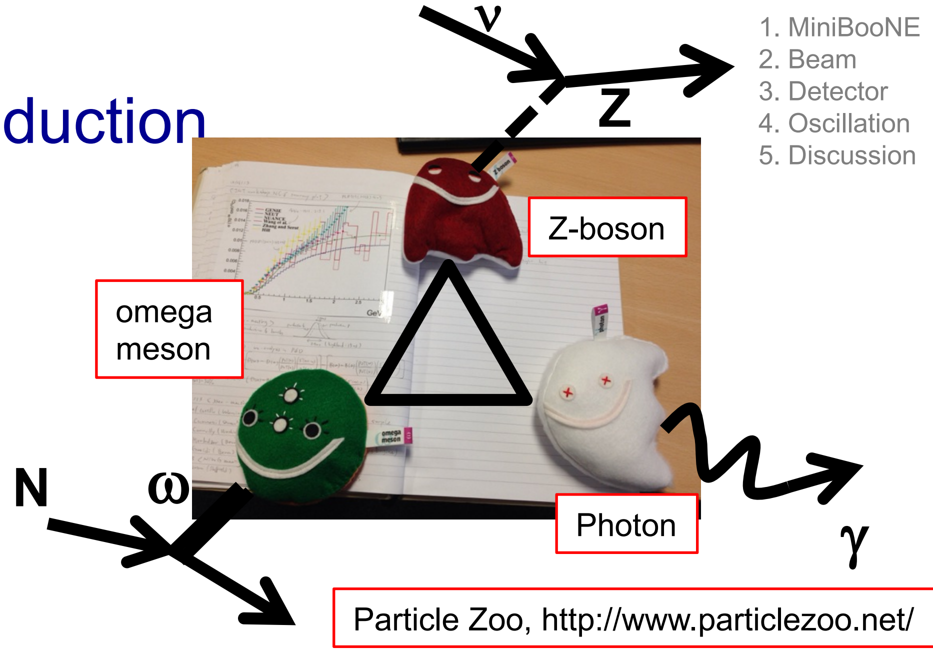
dE/dx of first 4cm track (simulation)

5. Neutrino NC single photon production

Anomaly mediated γ production

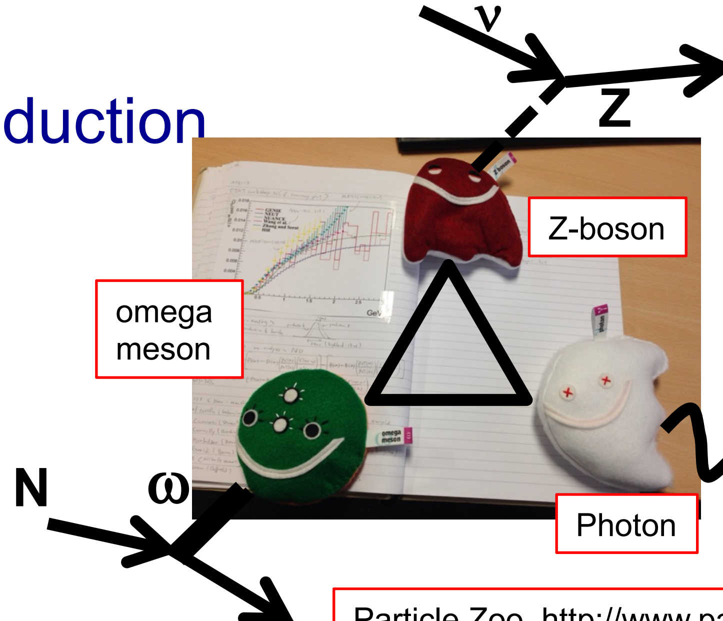
- process within SM, but not considered.





Harvey,Hill,Hill, PRL99(2007)261601
Lasorak, PhD thesis (Queen Mary, 2018)

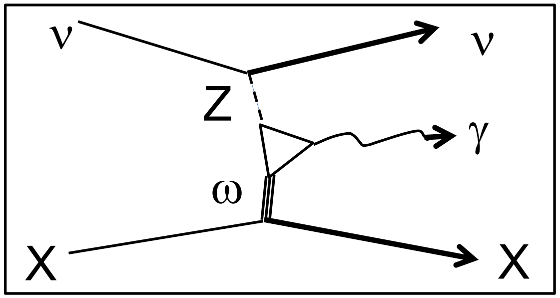
5. Neutrino NC single photon production



Particle Zoo, http://www.particlezoo.net/

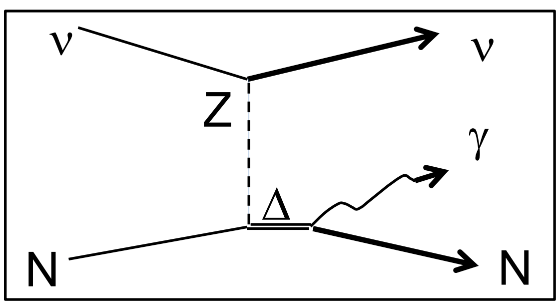
Anomaly mediated γ production

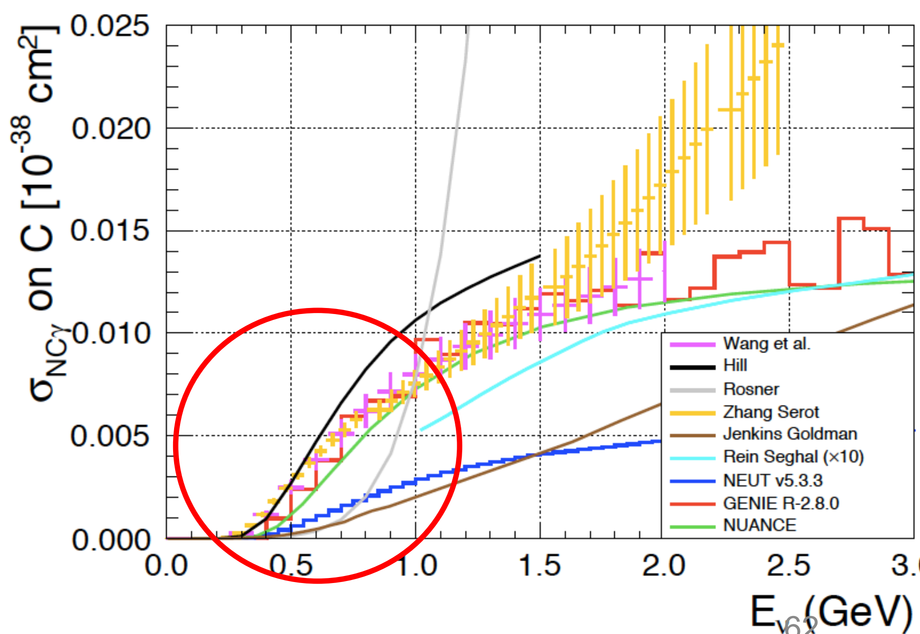
- process within SM, but not considered.



A lot of new calculations

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



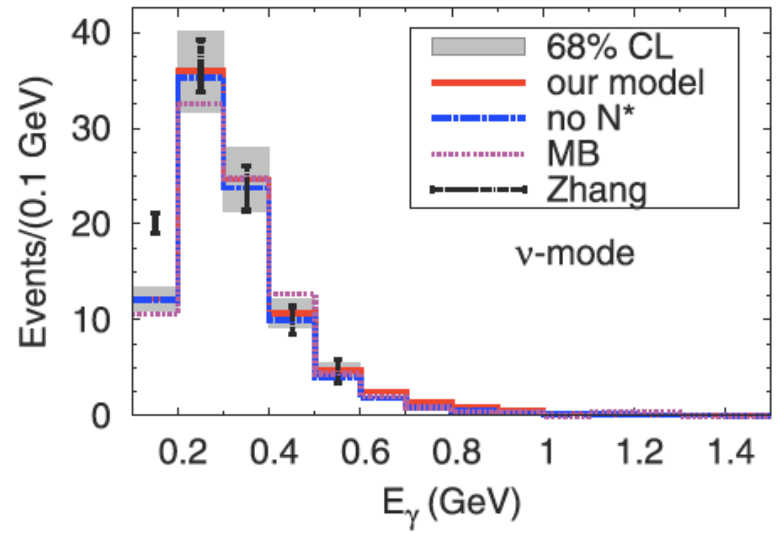


5. Neutrino NC single photon production

NC γ production prediction for MiniBooNE

- MiniBooNE provides efficiency tables to convert theory → experimental distribution
- New models are more or less consistent with MiniBooNE NCγ model

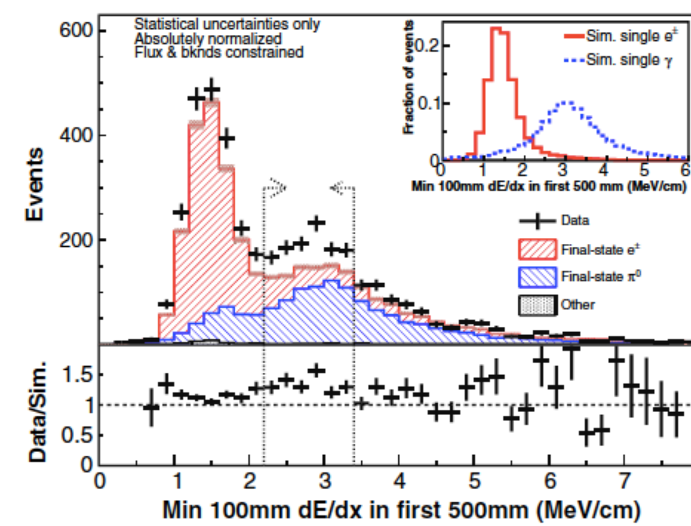
Hill, PRD84(2011)017501
Zhang and Serot, PLB719(2013)409
Wang et al, PLB740(2015)16



Are we missing any other background processes?

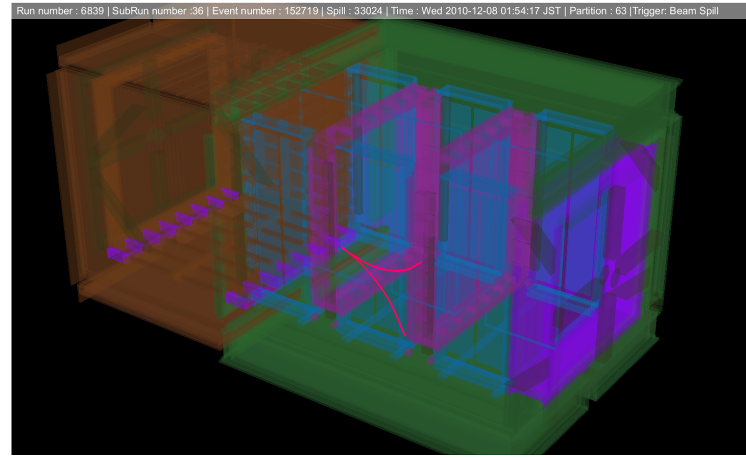
- It's easy to forget processes with $\sigma \sim 10^{-41}$ cm^2 (e.g., diffractive π^o production σ(1GeV) ~ 10^{-41} cm^2 was identified very recently by MINERvA, also neglected by all simulations)

MINERvA, PRL117(2016)111801



MicroBooNE, public note 1041 (2018)
Lasorak, PhD thesis (Queen Mary, 2018)

5. Neutrino NC single photon production



T2K near detector

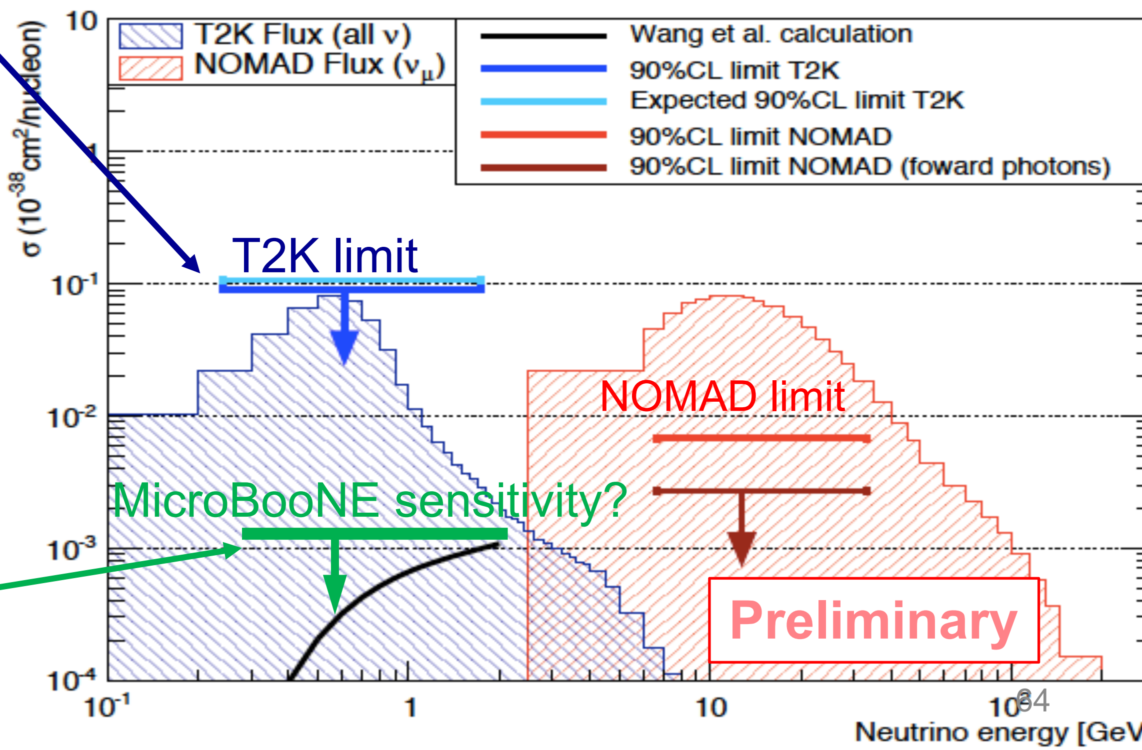
- 95% pure photon sample (M_{inv}<50 MeV)
- Large external photon background and internal π^o production background. T2K can only set a limit.

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

MicroBooNE

- First large ν-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)

Queen Mary
University of London

Coleman and Glashow, PRD59(1999)116008, TK et al,PRD74(2006)105009, Diaz and Kostelecky, PLB700(2011)25, Barger et al, PRD84(2011)056014

5. BSM neutrino oscillation model

Lorentz violation as alternative neutrino oscillation model

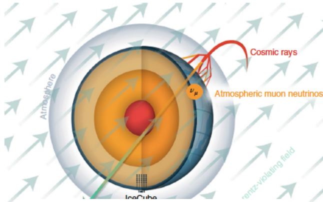
- Making a new texture in Hamiltonian to control oscillations.
- Could explain all signals, including LSND and MiniBooNE.
- This moment, no LV-motivated models can explain all signals.

LV-motivated effective Hamiltonian

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

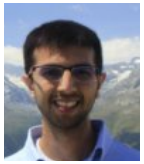
where $A(E)=m^2/2E$, $B(E)=\mathring{a}E^2$, and $C(E)=\mathring{c}E^5$

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



Nature Physics 14(2018)961

IceCube

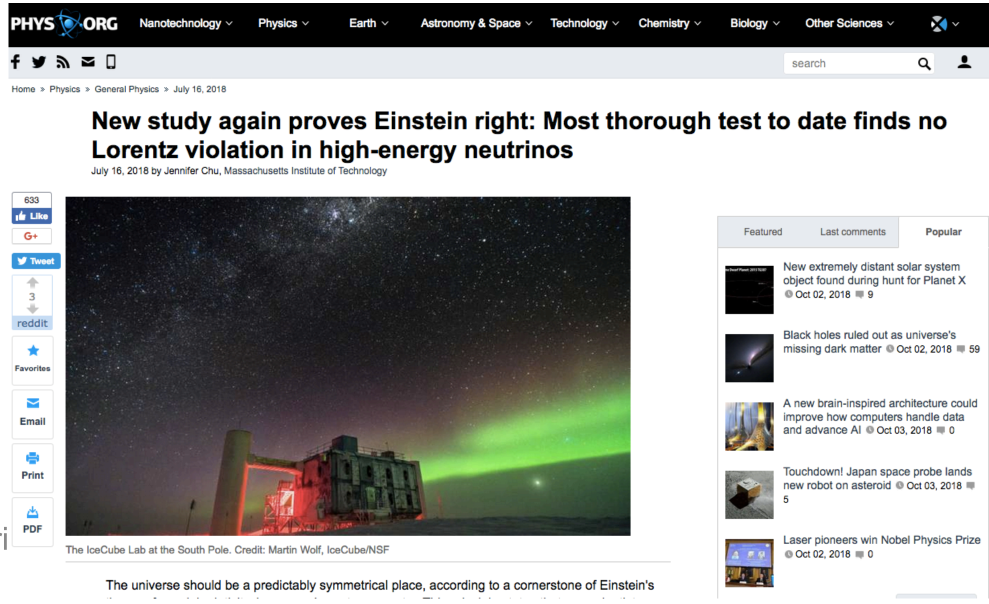


Shivesh Mandalia (Queen Mary)

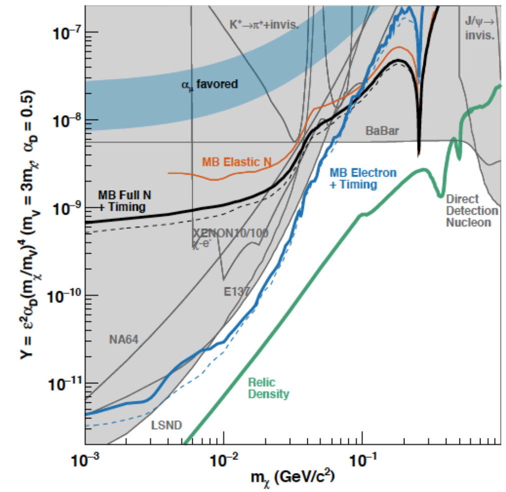
Test of Lorentz violation with neutrinos

- 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!



5. BSM electron scattering



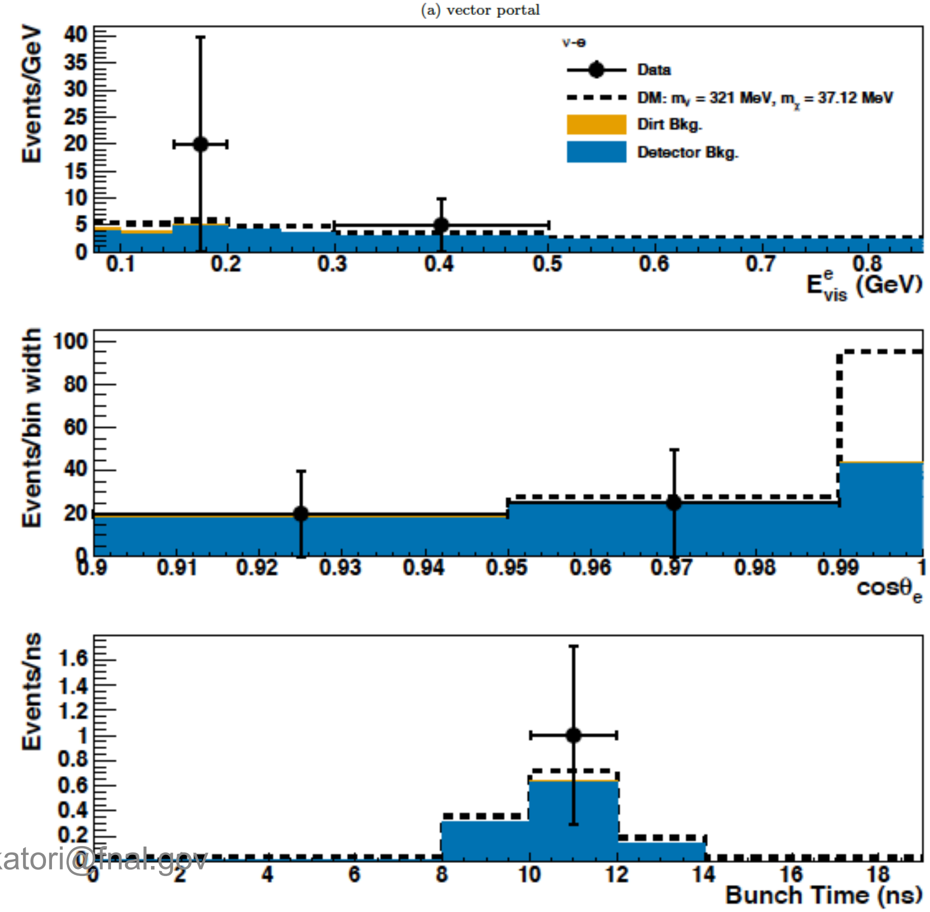
(a) vector portal

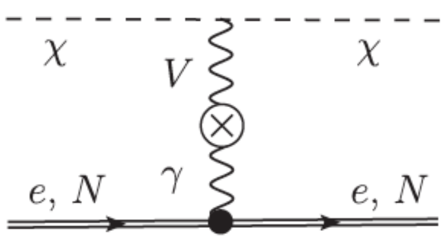
Dark matter particle - electron scattering

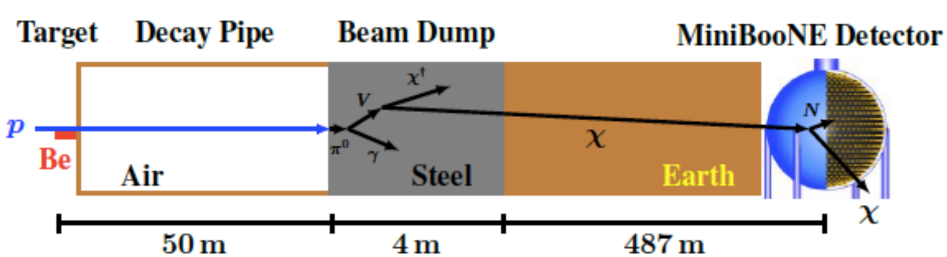
New particles created in the beam dump can scatter electrons in the detector.

However, MiniBooNE beam dump mode data shows no excess.

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

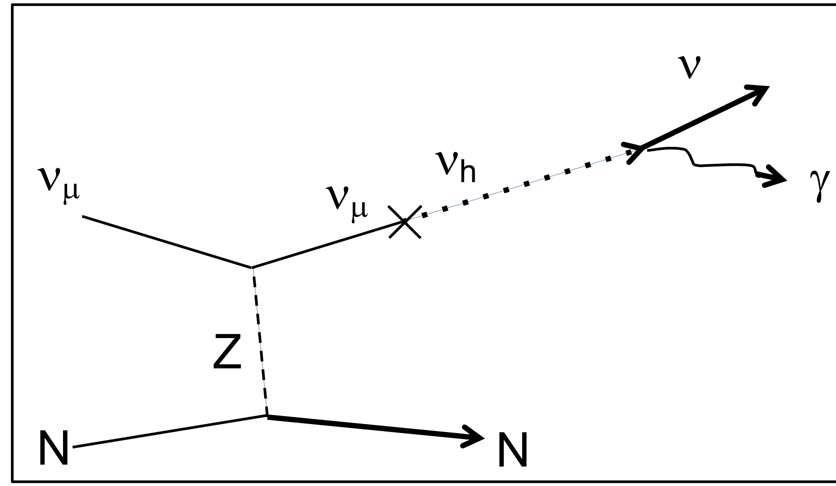






5. BSM photon production

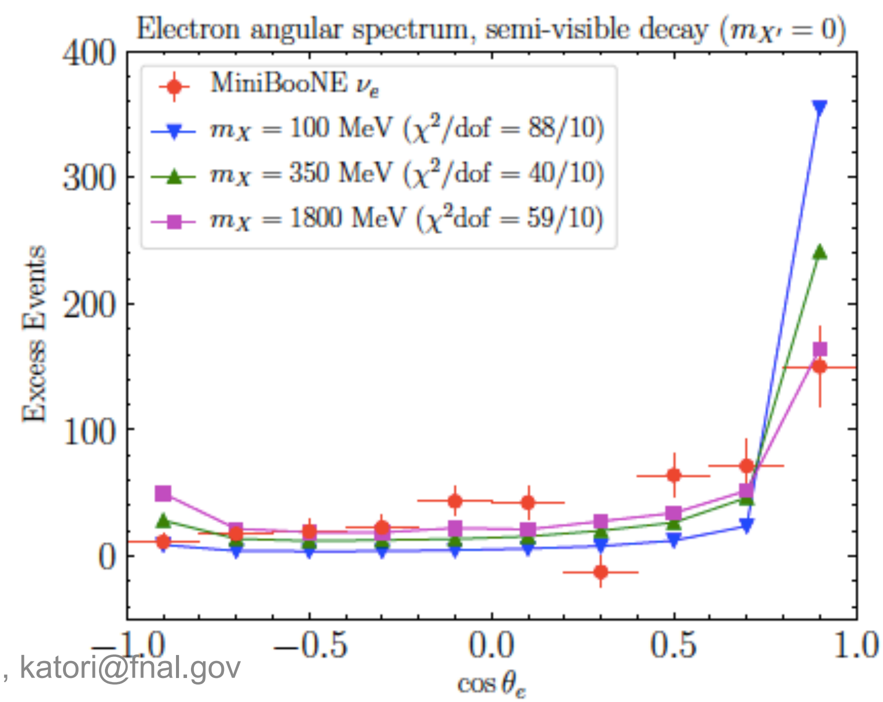
heavy neutrino decay



Heavy neutrino decay γ production

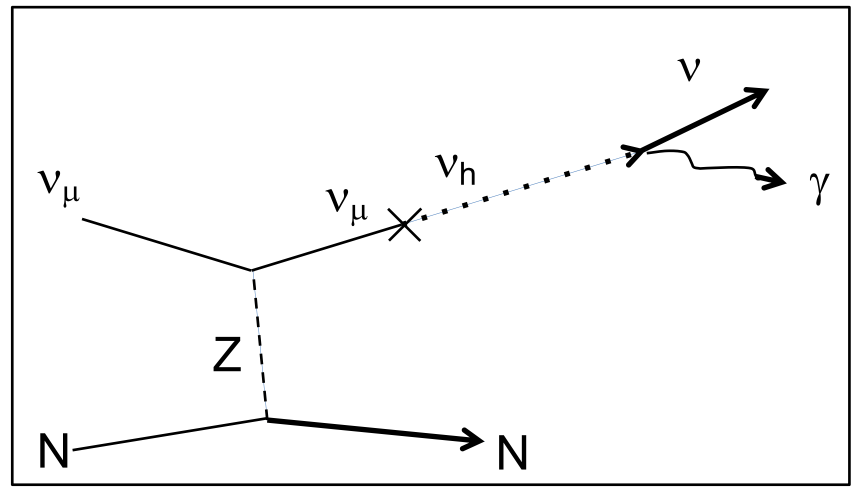
- Minimum extension of the SM
- Heavy neutrinos are produced in the beamline by kinetically mix with SM neutrinos
- Heavy neutrinos decay to SM neutrinos in the detector.

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

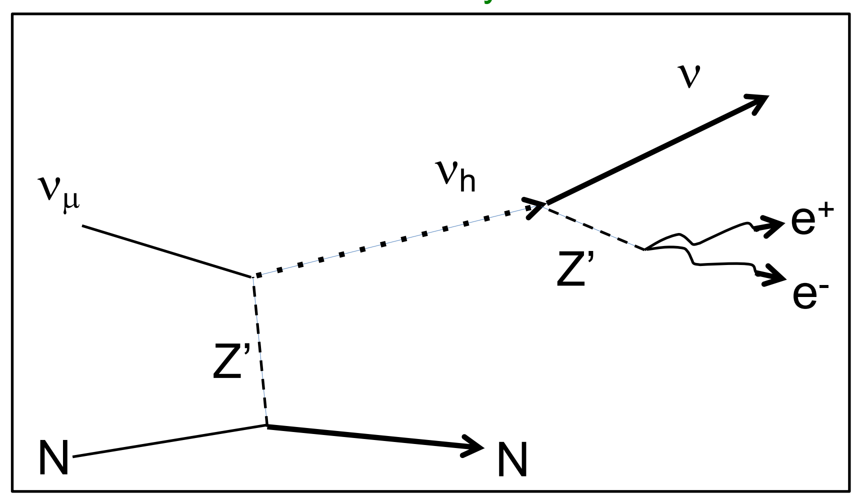


5. BSM e+e- production

heavy neutrino decay



Z' decay



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.

Future of MiniBooNE

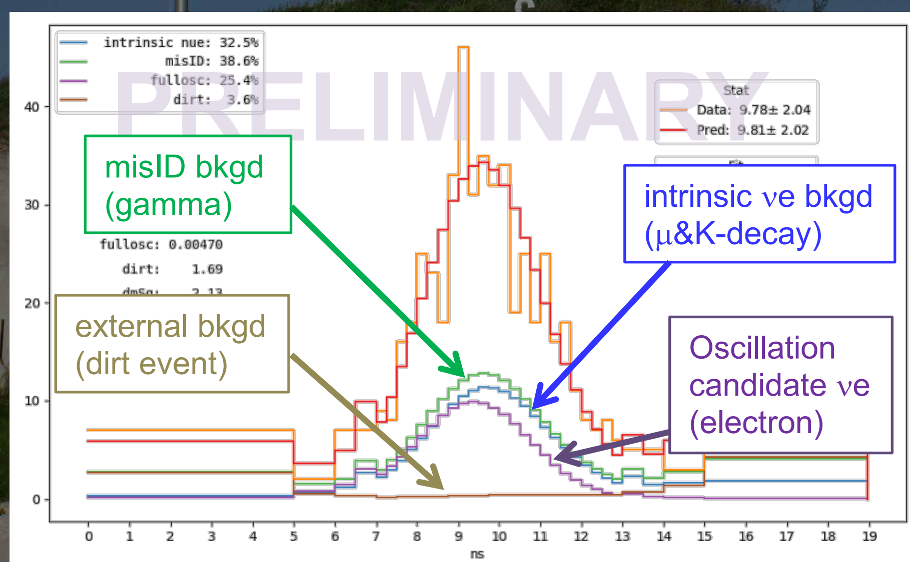
MiniBooNE run will be end on June 2019
- Expected to reach ~ 18E20POT in ν-mode
- The excess may reach ~ 5σ

Future of MiniBooNE

MiniBooNE run will be end on June 2019
- Expected to reach ~ 18E20POT in ν-mode
- The excess may reach ~ 5σ

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 νe, K-decay νe → slow
- misID bkgd: photon conversion → slow



Conclusion

MiniBooNE is a short-baseline neutrino oscillation experiment

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

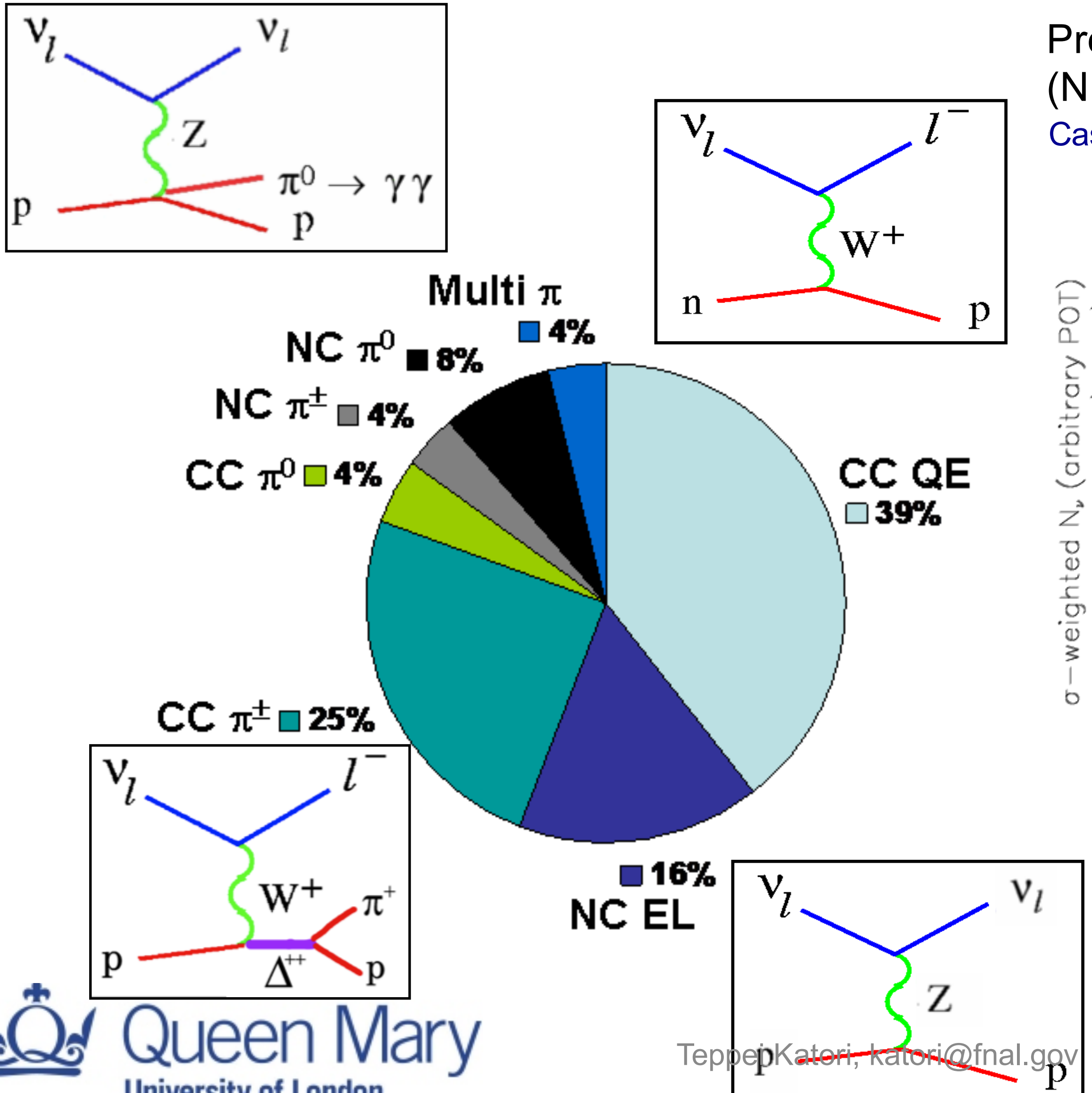
MiniBooNE has many legacies in this community
- Many useful tools
- Many useful people
- Many new topics - Neutrino cross section measurements
  - Test of Lorentz violation with neutrinos
  - Direct production & detection Dark Matter search with ν-detector
  - etc.

But the biggest legacy is the short-baseline anomaly

Thank you for your attention!

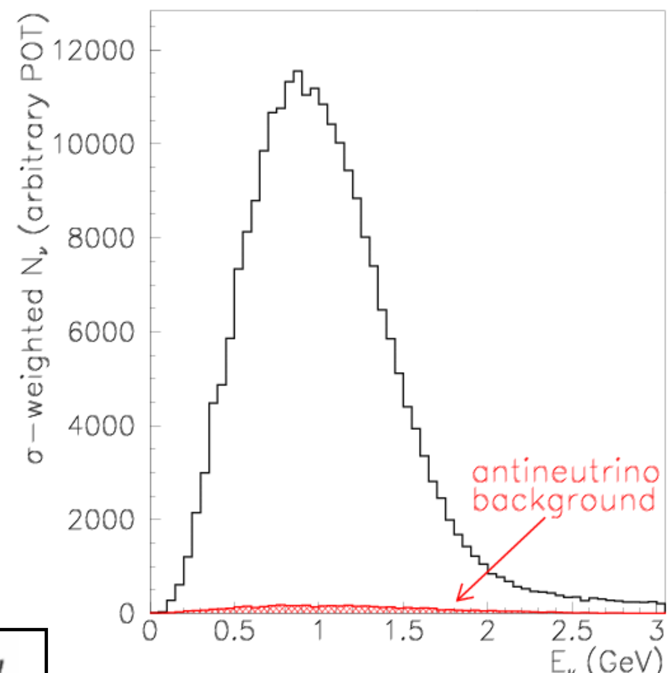
backup

3. Cross section model



Predicted event rates before cuts (NUANCE Monte Carlo)

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

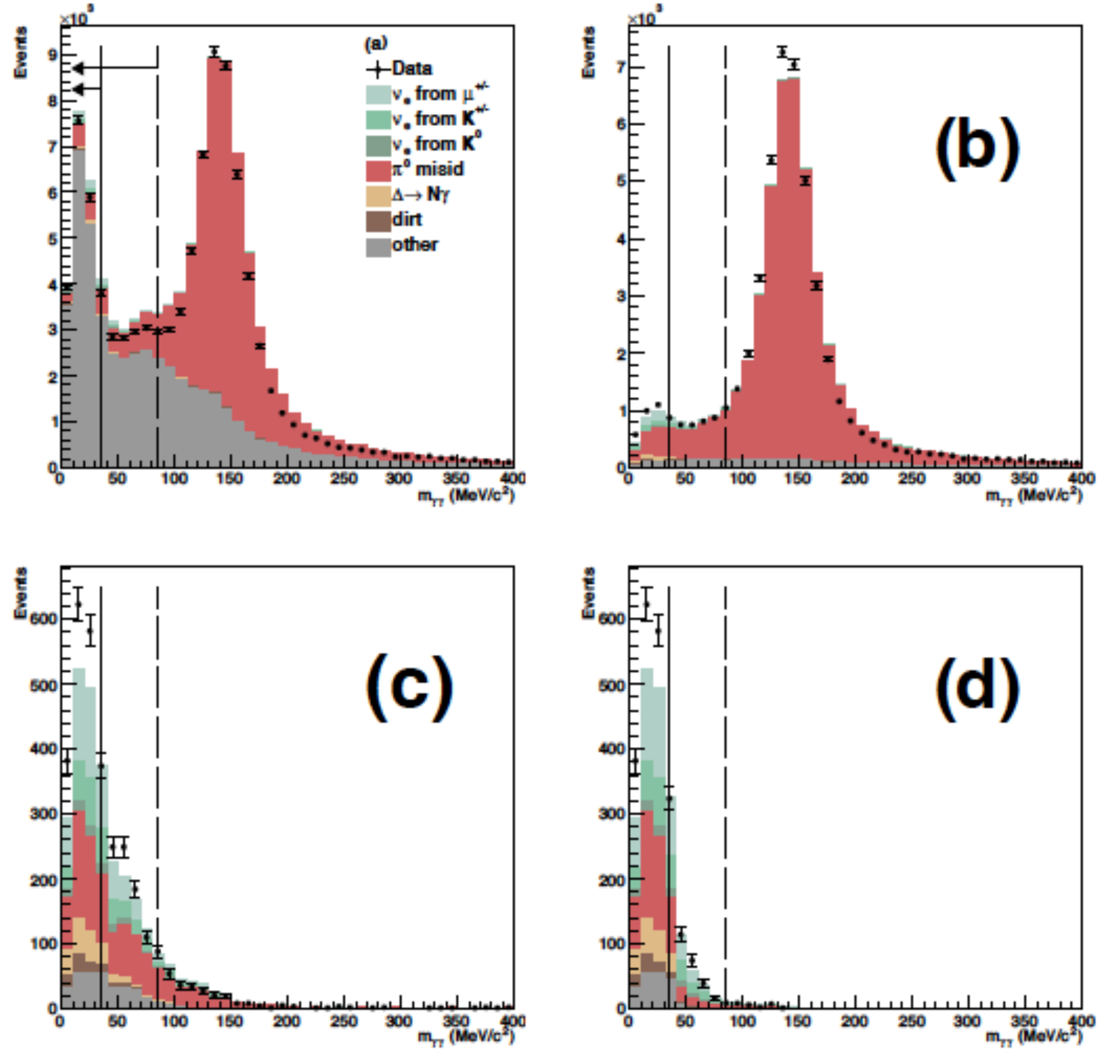


Event neutrino energy (GeV)

4. PID cuts Oscillation candidate events

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

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



4. γ from π^o constraint

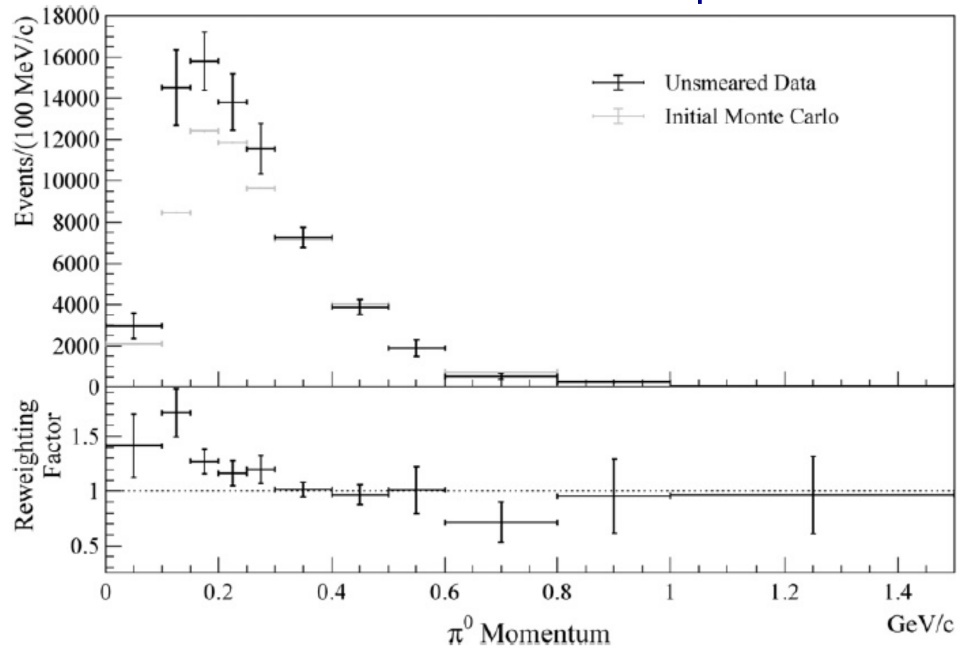
$\pi^o \rightarrow \gamma\gamma$
- not background, we can measure

$\pi^o \rightarrow \gamma$
- misID background, we cannot measure

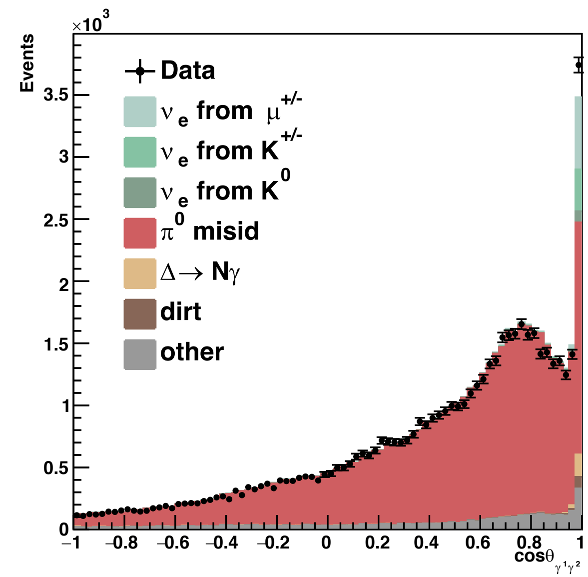
The biggest systematics is production rate of π^o, because once you find that, the chance to make a single gamma ray is predictable.

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

π^o momentum data-MC comparison



2-gamma-ray opening angle



Teppei Katori, katori@fnal.gov