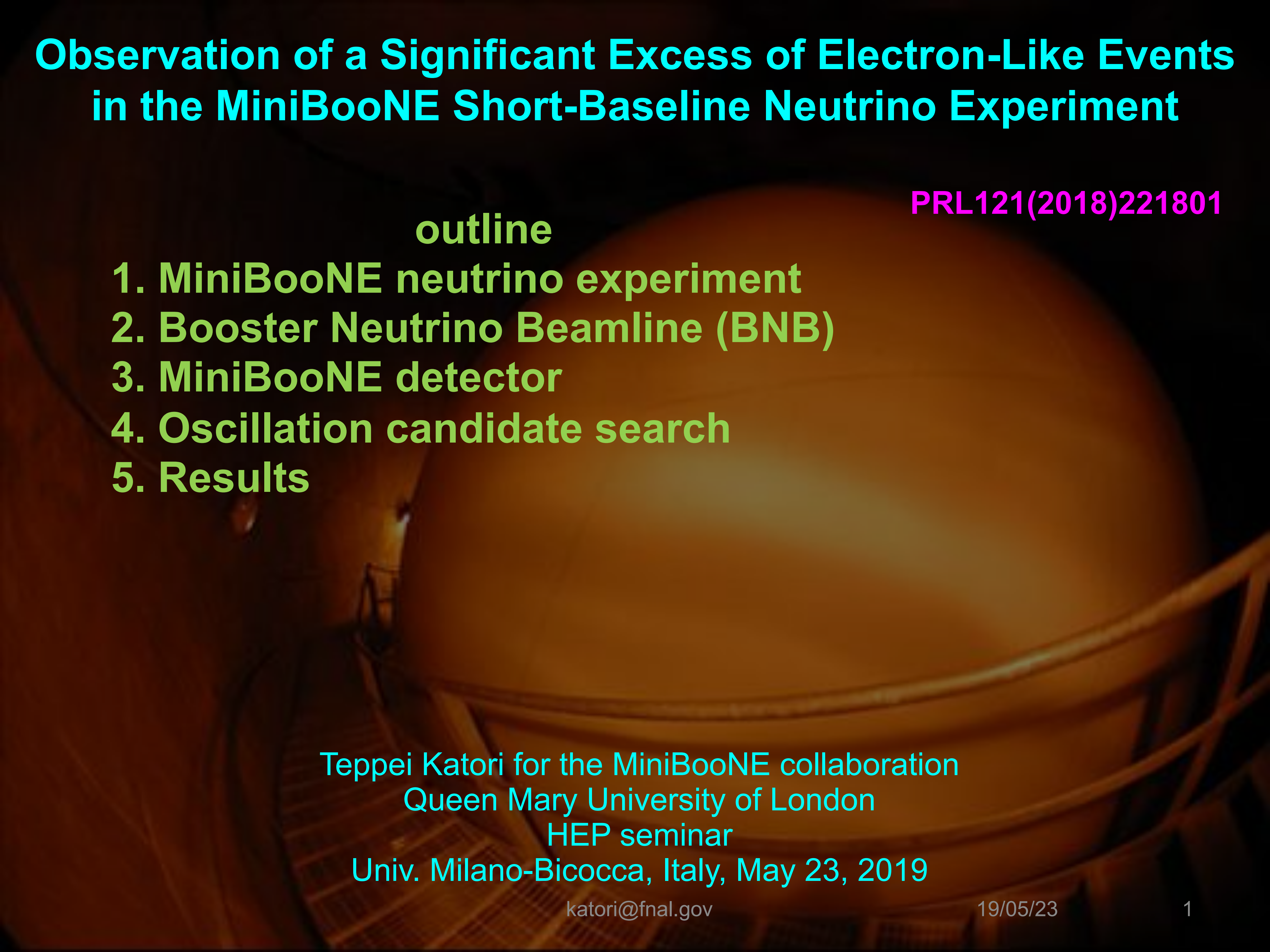


Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

PRL121(2018)221801

outline

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

Teppei Katori for the MiniBooNE collaboration
Queen Mary University of London
HEP seminar
Univ. Milano-Bicocca, Italy, May 23, 2019

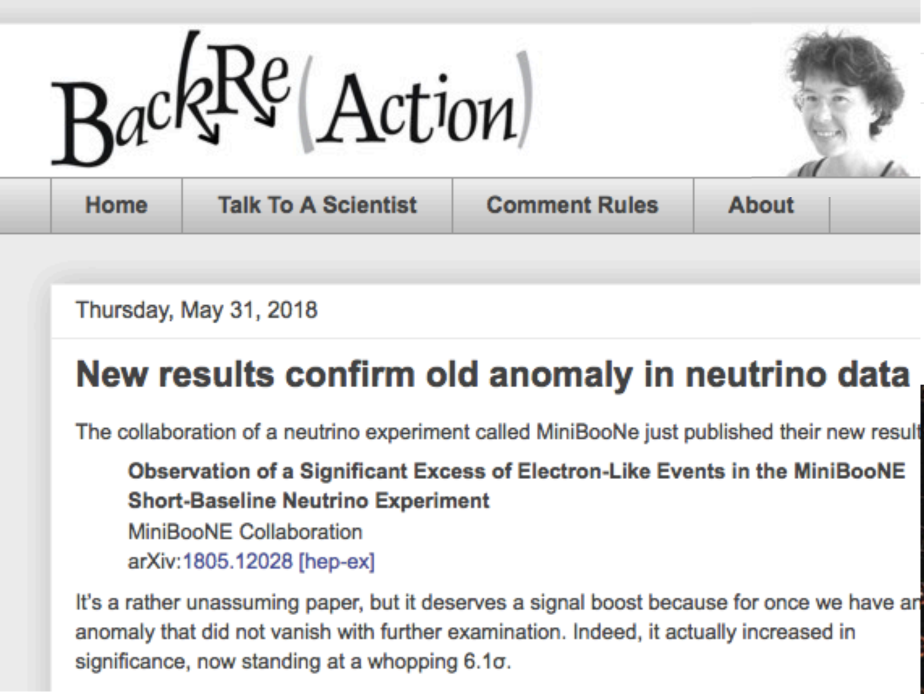
1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Results



Thursday, May 31, 2018

New results confirm old anomaly in neutrino data

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

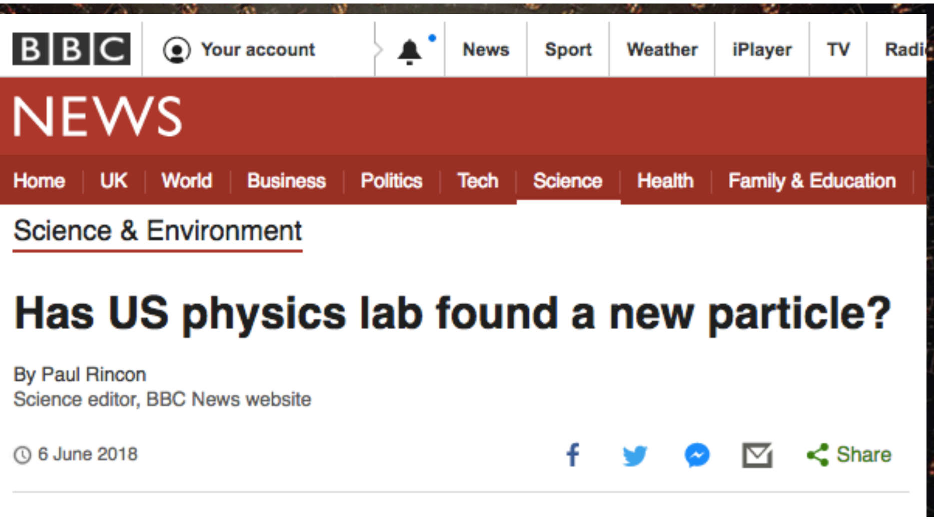
> **Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment**
> MiniBooNE Collaboration
> arXiv:1805.12028 [hep-ex]

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

PHYSICS

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

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

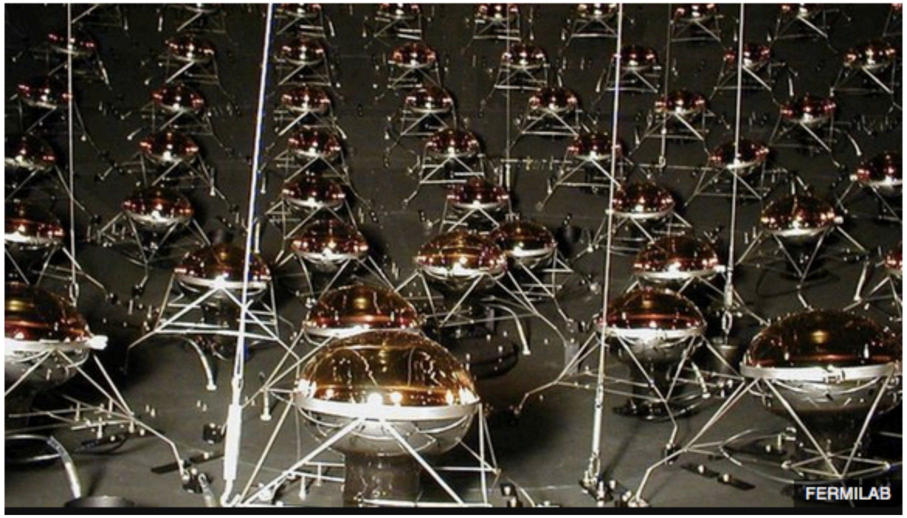


Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

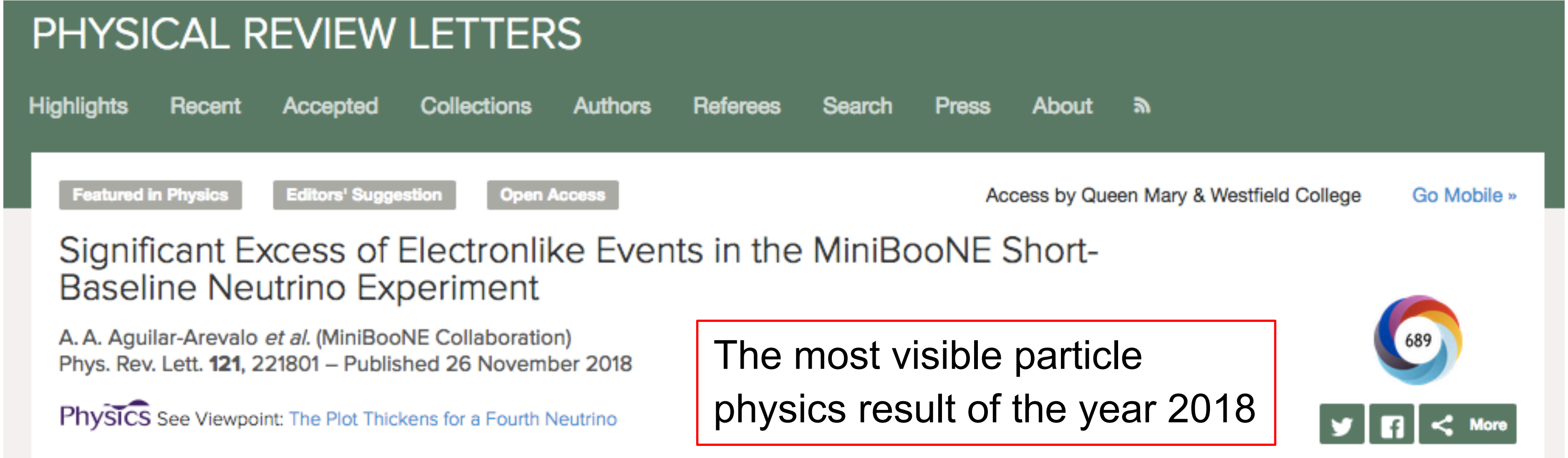
6 June 2018


FERMILAB

ABSTRACTIONS BLOG

Evidence Found for a New Fundamental Particle

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

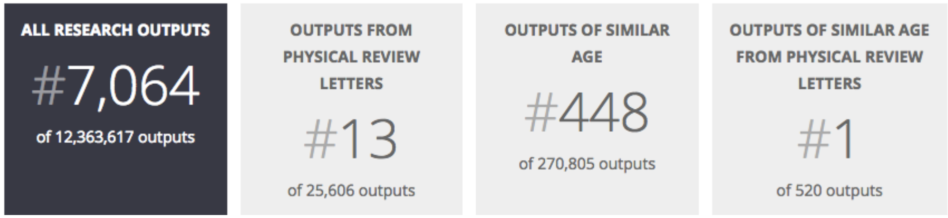


Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment

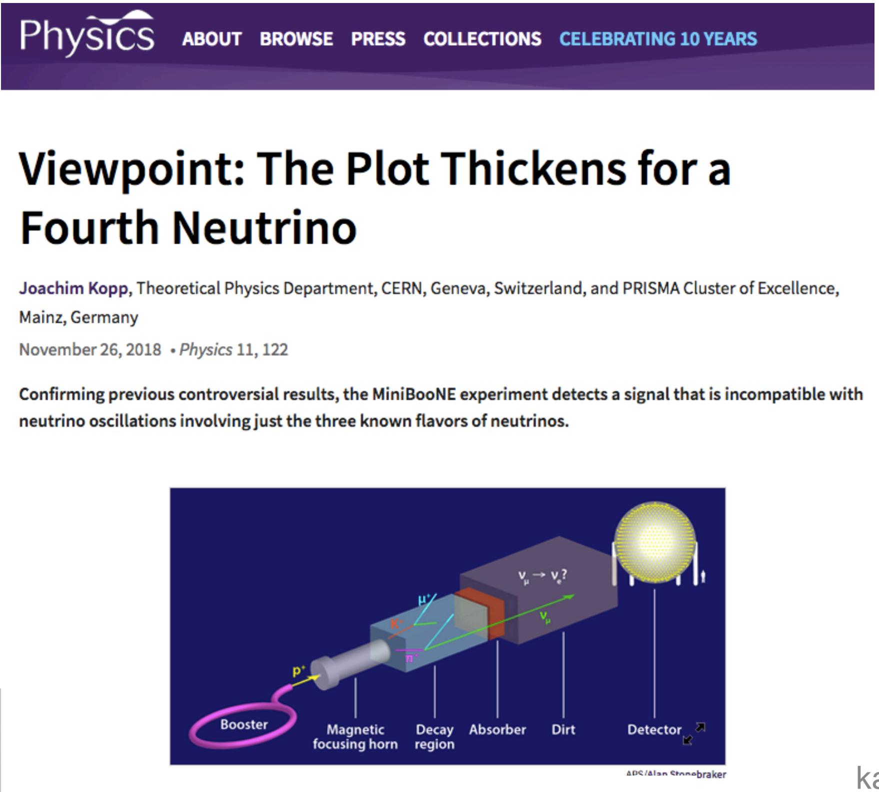
A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration)
Phys. Rev. Lett. **121**, 221801 – Published 26 November 2018

Physics See Viewpoint: The Plot Thickens for a Fourth Neutrino

The most visible particle physics result of the year 2018



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



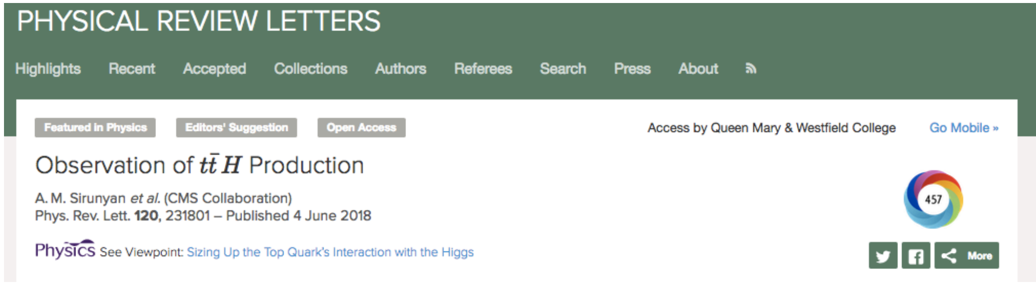
Viewpoint: The Plot Thickens for a Fourth Neutrino

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



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

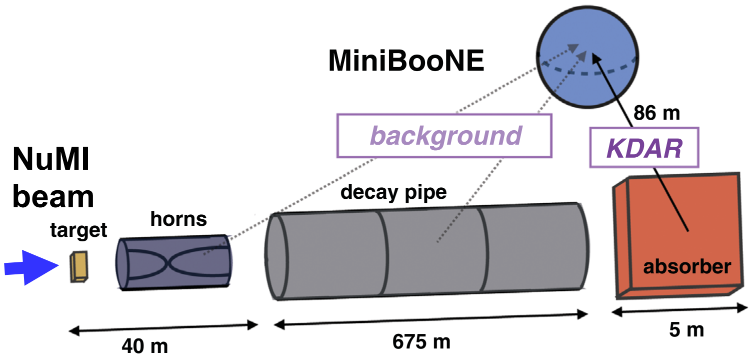
Observation of Higgs Boson Decay to Bottom Quarks

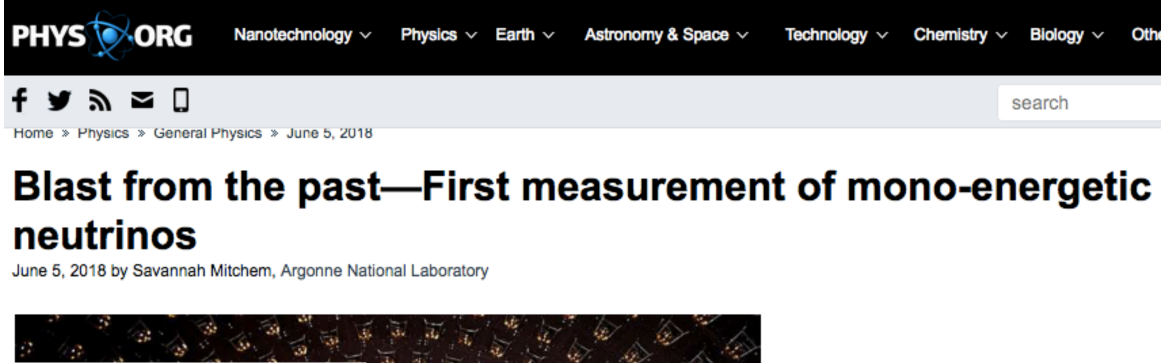
A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **121**, 121801 – Published 17 September 2018

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

ka

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





Home » Physics » General Physics » June 5, 2018

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

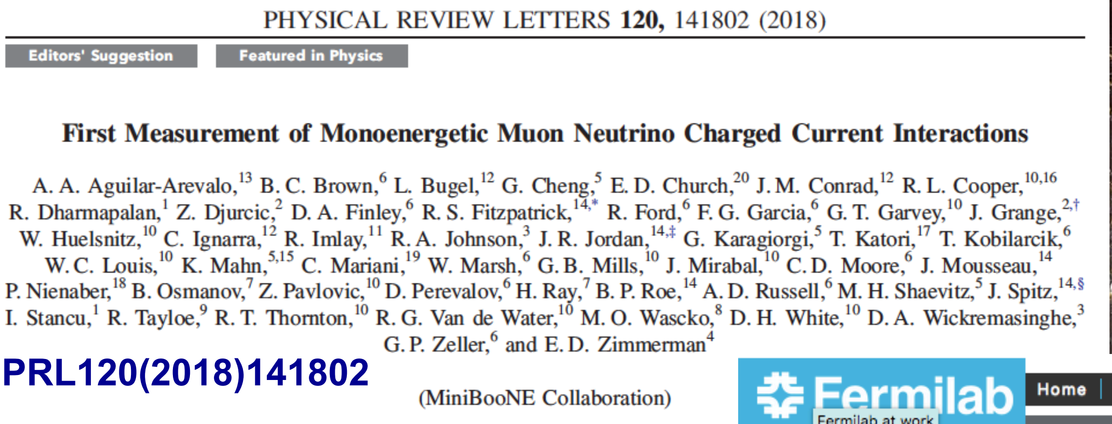
June 5, 2018 by Savannah Mitchem, Argonne National Laboratory

Featured Last comment

Researchers ask Ar does God look like? 27

Speculative wormh revolutionize astrop 2018 19

Choice matters: The



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

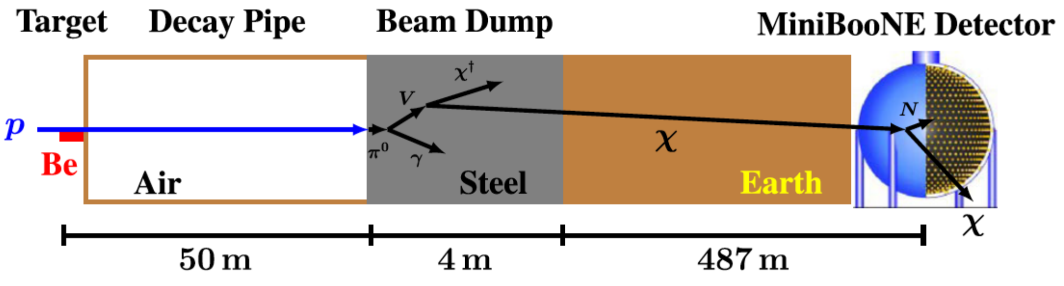
News at work

The MiniBooNE search for dark matter

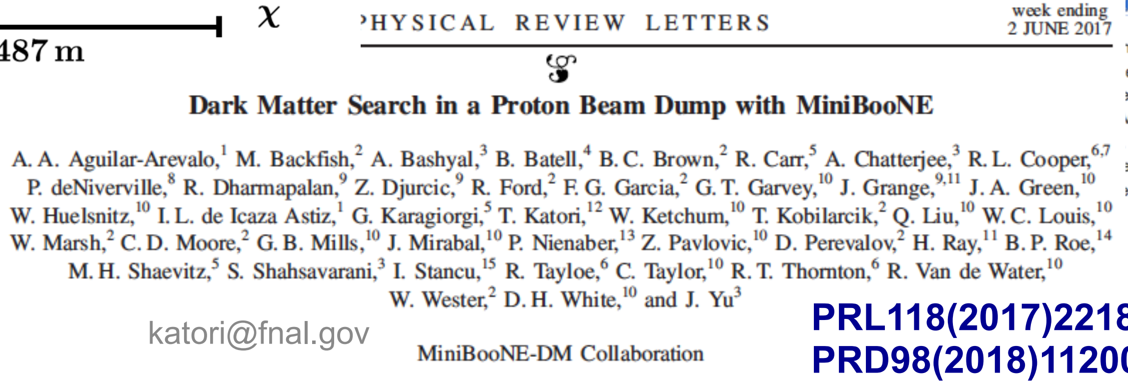
July 18, 2017 | Ranjan Dharmapalan and Tyler Thornton

Email

nd, the
e
en
Model
About
erious
en more



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

PRL118(2017)221803
PRD98(2018)112004

katori@fnal.gov

LSND, PRD64(2002)112007

1. LSND experiment

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

LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam with ~30m baseline and ~30MeV neutrino energy, L/E~30m/30MeV~1.

oscillation, L~30m

$$\bar{\nu}_\mu(30\ MeV) \quad \Longrightarrow \quad \bar{\nu}_e + p \to e^+ + n, n + p \to d + \gamma$$

If this is due neutrino oscillation, Δm^2~1eV^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 Δm^2

$$\begin{aligned} \nu_\mu\ (500\ MeV) \quad &\Longrightarrow \quad \nu_e + n \to e^- + p \\ \bar{\nu}_\mu\ (500\ MeV) \quad &\Longrightarrow \quad \bar{\nu}_e + p \to e^+ + n \end{aligned}$$

oscillation, L~500m

LSND and MiniBooNE are completely different experiments

- LSND: liquid scintillator detector (low energy), neutron capture to tag positron
- MiniBooNE: mineral oil Cherenkov detector (high energy), no neutron tagging

Queen Mary
University of London

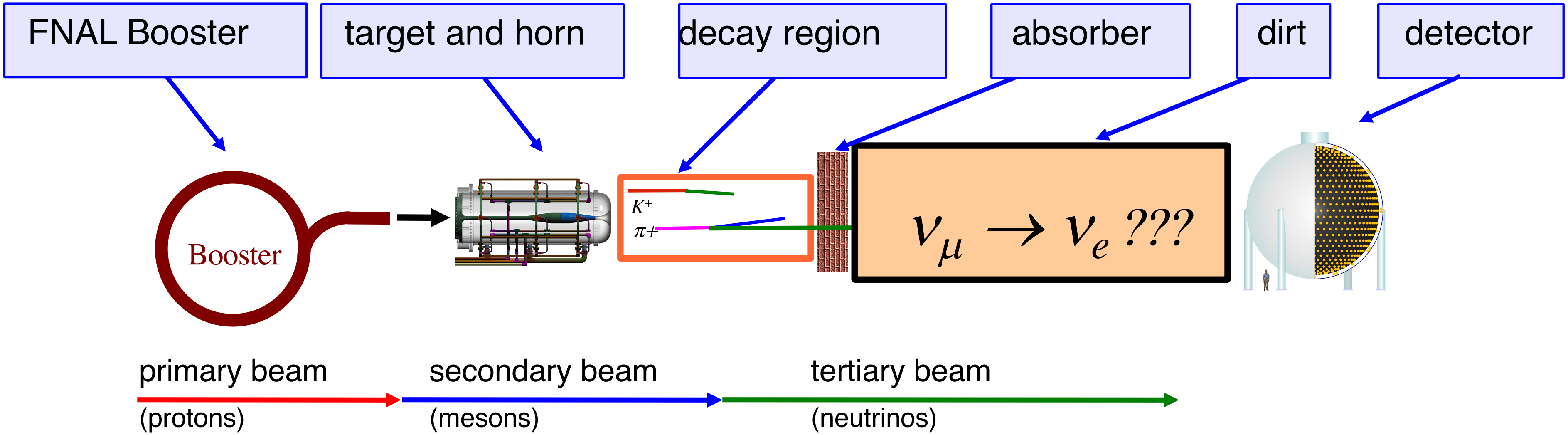
katori@fnal.gov

1. MiniBooNE experiment $P(\nu_\mu \longrightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$

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

$$\begin{aligned} \nu_\mu\ (500\ MeV) &\implies \nu_e + n \rightarrow \boxed{e^-} + p \\ \bar{\nu}_\mu\ (500\ MeV) &\implies \bar{\nu}_e + p \rightarrow \boxed{e^+} + n \end{aligned}$$



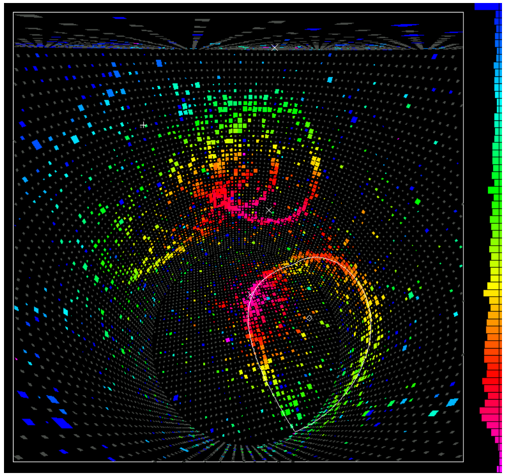
MiniBooNE has;

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

1. MiniBooNE is influential! – Tools

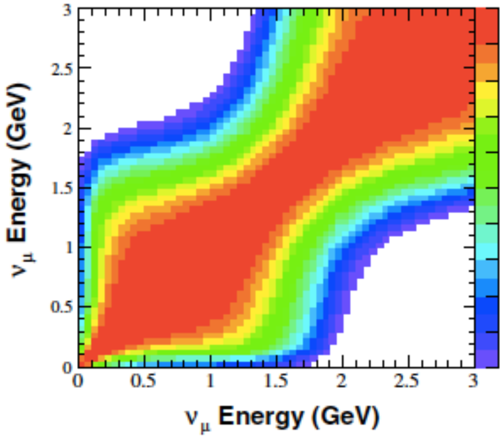
fiTQun:MiniBooNE: NIMA608(2009)206

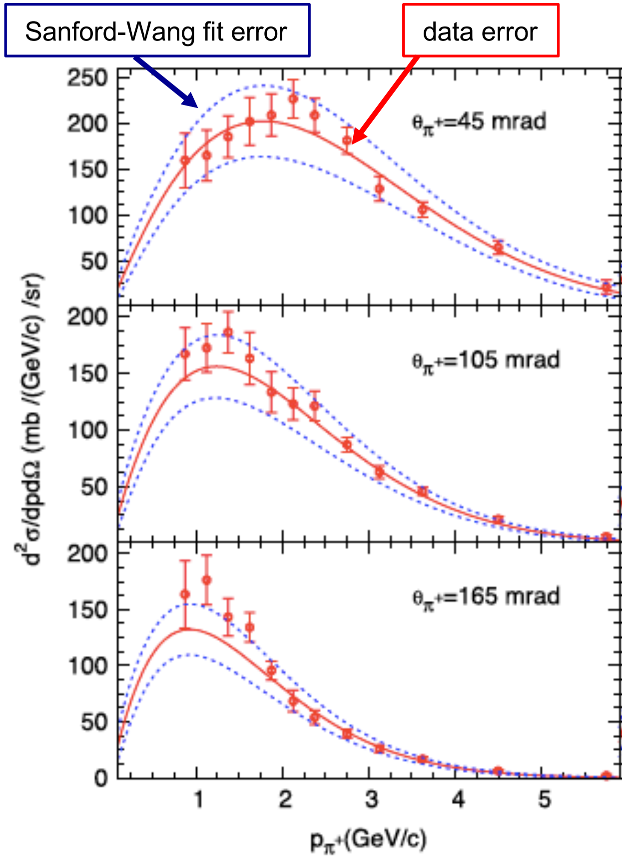
Likelihood-based Cherenkov ring fitter, the main reconstruction used by Super-Kamiokande (LSND→MiniBooNE→SuperK).



Flux systematic error: MiniBooNE: PRD79(2009)072002

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



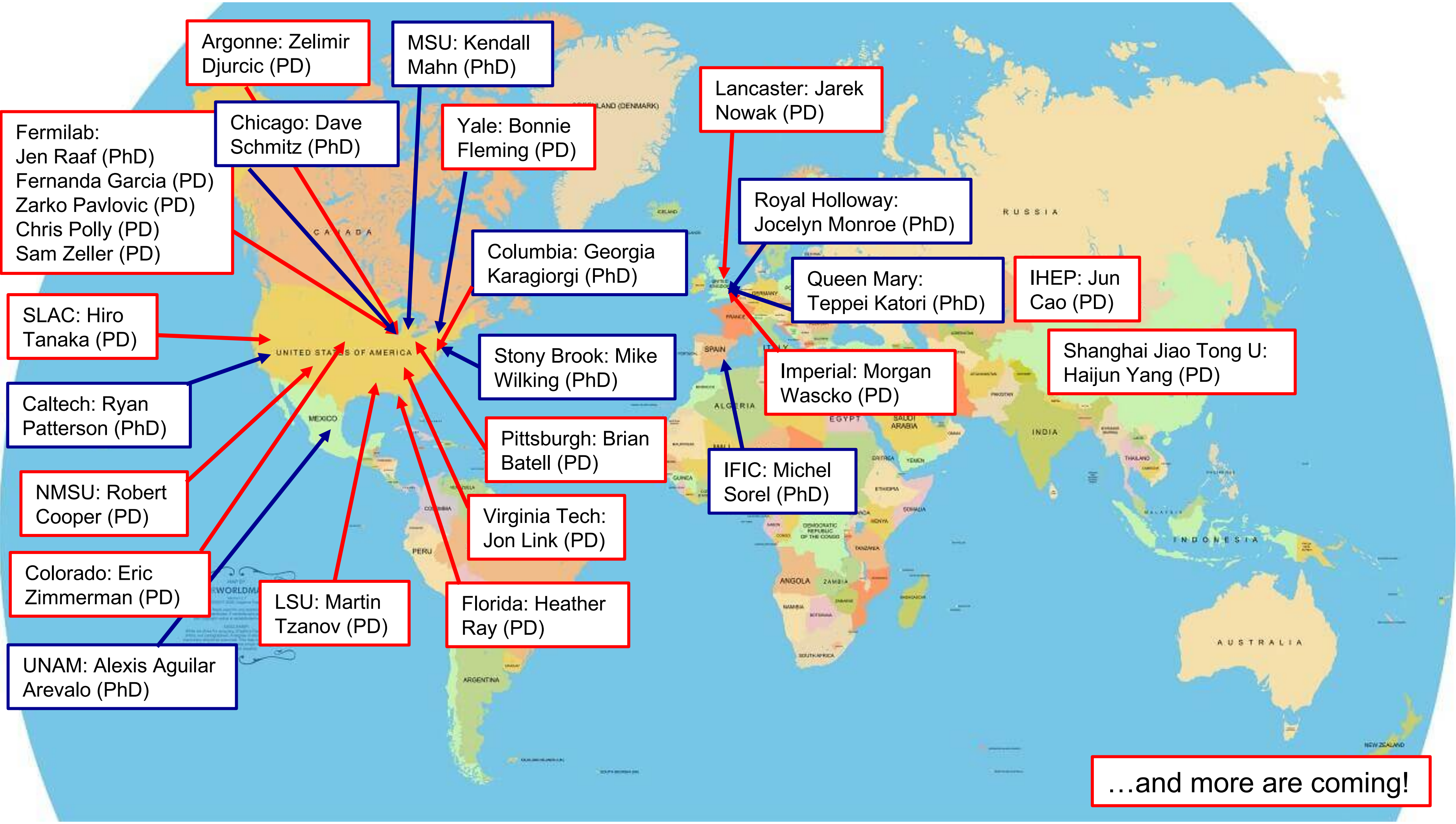


Online remote shift:

- <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

Queen Mary
University of London

1. MiniBooNE is influential! – Offspring



Argonne: Zelimir Djurcic (PD)

MSU: Kendall Mahn (PhD)

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

Chicago: Dave Schmitz (PhD)

Yale: Bonnie Fleming (PD)

Lancaster: Jarek Nowak (PD)

Royal Holloway: Jocelyn Monroe (PhD)

Columbia: Georgia Karagiorgi (PhD)

Queen Mary: Teppei Katori (PhD)

IHEP: Jun Cao (PD)

SLAC: Hiro Tanaka (PD)

Stony Brook: Mike Wilking (PhD)

Imperial: Morgan Wascko (PD)

Shanghai Jiao Tong U: Haijun Yang (PD)

Caltech: Ryan Patterson (PhD)

Pittsburgh: Brian Batell (PD)

IFIC: Michel Sorel (PhD)

NMSU: Robert Cooper (PD)

Virginia Tech: Jon Link (PD)

Colorado: Eric Zimmerman (PD)

LSU: Martin Tzanov (PD)

Florida: Heather Ray (PD)

UNAM: Alexis Aguilar Arevalo (PhD)

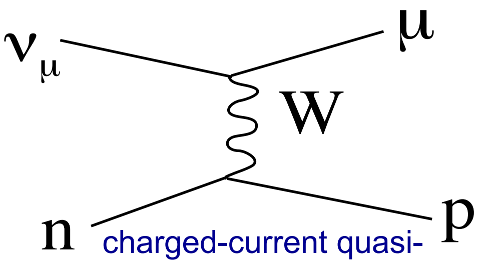
…and more are coming!

katori@fnal.gov

MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

1. MiniBooNE is influential! – Neutrino cross sections

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



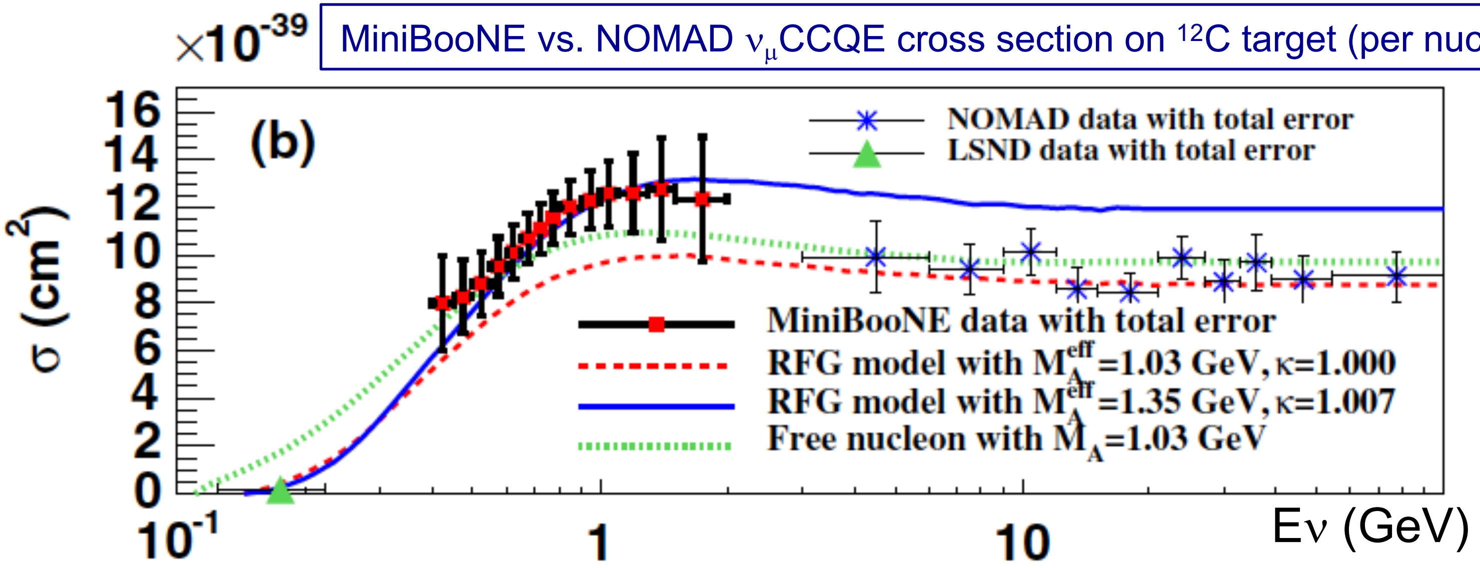
charged-current quasi-elastic scattering (CCQE)

CCQE puzzle

1. low Q^2 suppression → Low forward efficiency? (detector?)
2. high Q^2 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)



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

katori@fnal.gov

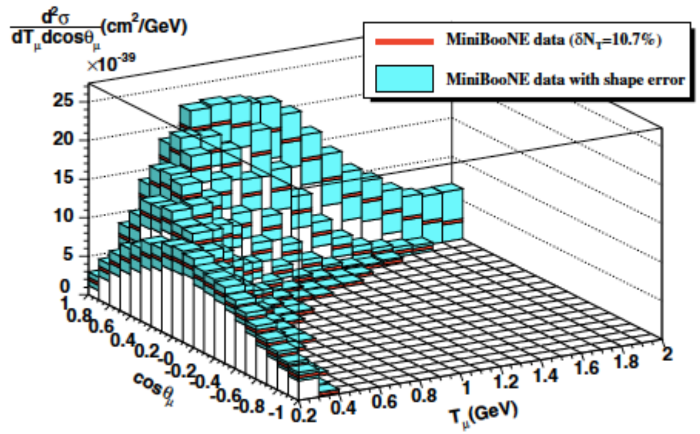
MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

1. MiniBooNE is influential! – Neutrino cross sections

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

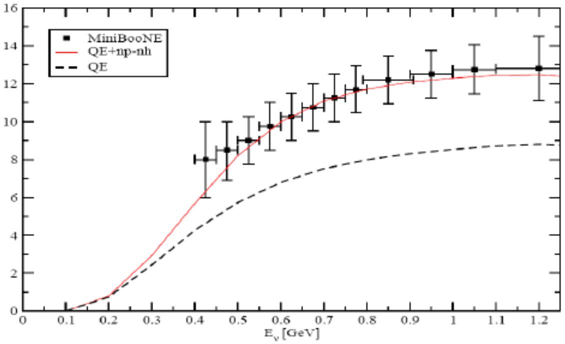
Flux-integrated differential cross section:
A new concept to measure, and report neutrino cross section data. Now the standard of the community.

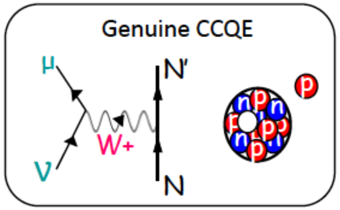
PHYSICAL REVIEW D 81, 092005 (2010)

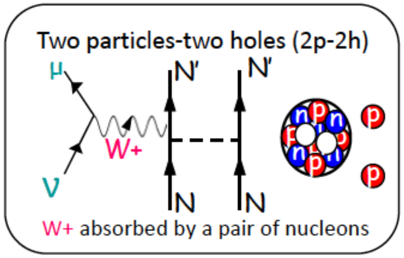


An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







W+ absorbed by a pair of nucleons

Slide from Martini

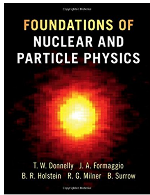
Discovery of nucleon correlation in neutrino scattering:
- Significant enhancement of cross section (10-30%)
- modify lepton kinematics and final state hadrons
- the hottest topic for T2K, MINERvA, MicroBooNE, etc

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!

Queen Mary
University of London

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)

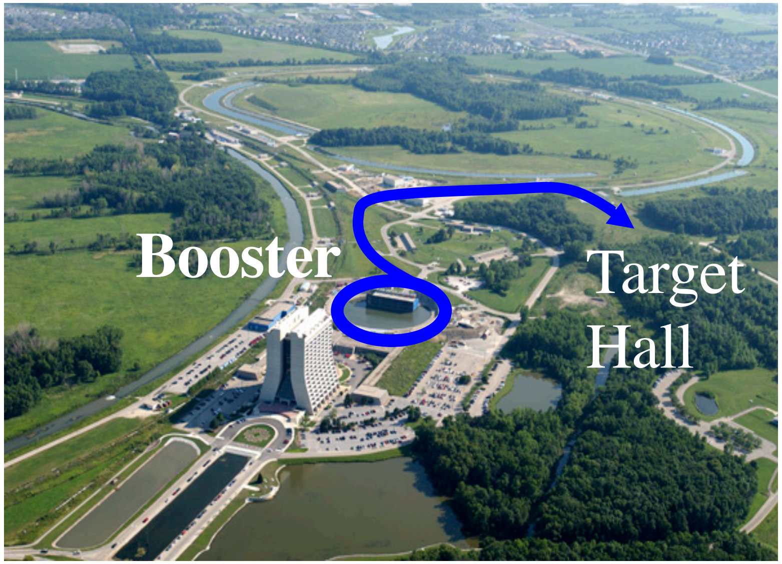
3. MiniBooNE detector

4. Oscillation candidate search

5. Results

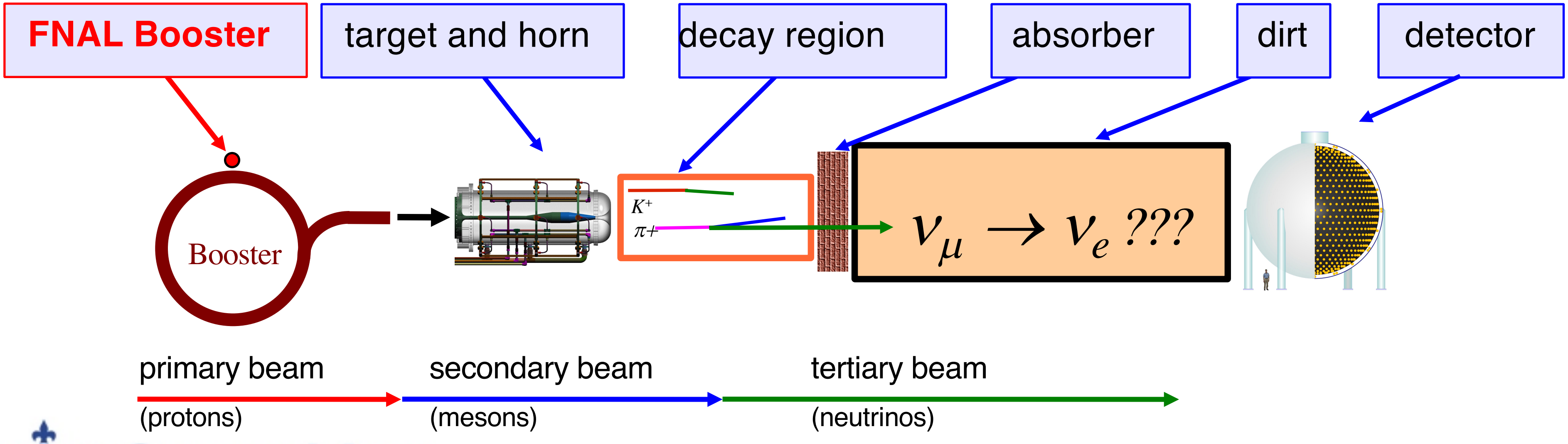
MiniBooNE, PRD79(2009)072002

2. Fermilab Booster



MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster



FNAL Booster

target and horn

decay region

absorber

dirt

detector

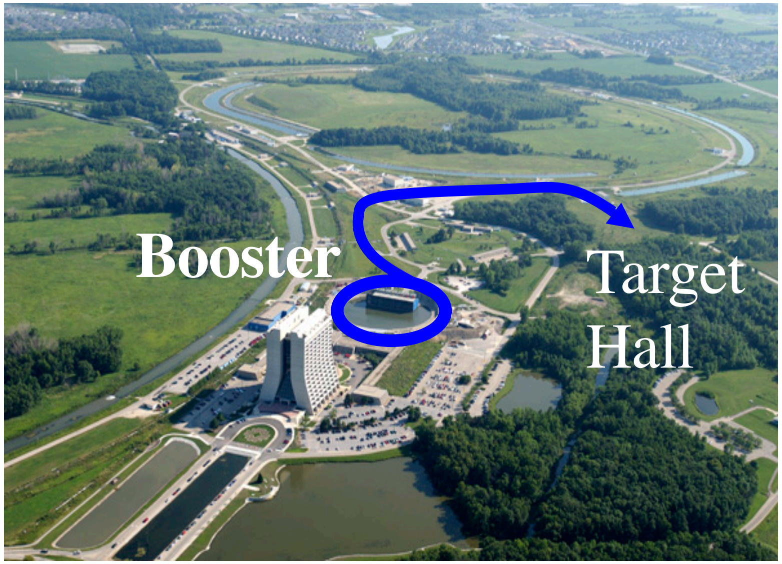
primary beam
(protons)

secondary beam
(mesons)

tertiary beam
(neutrinos)

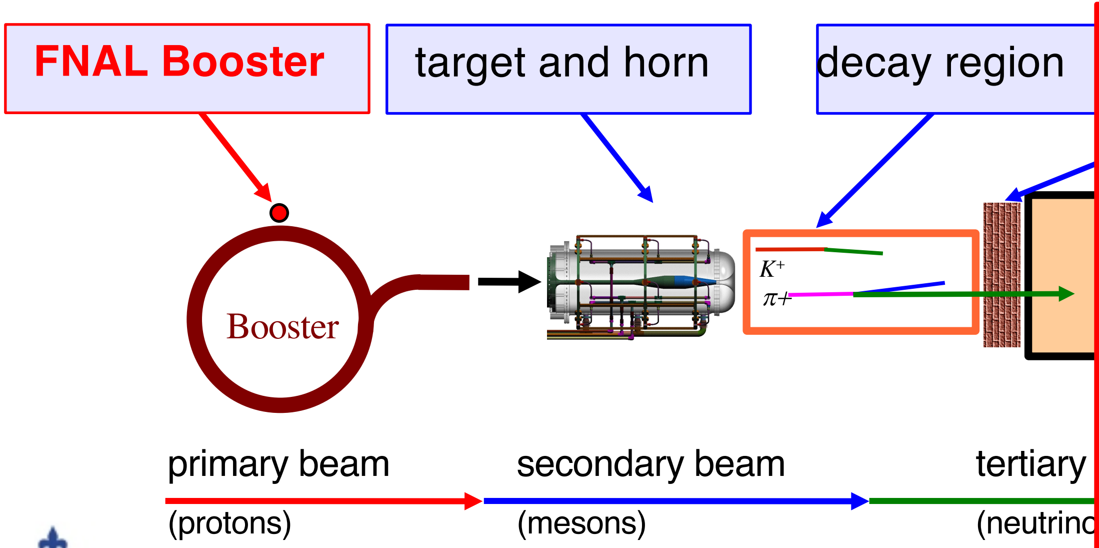
katori@fnal.gov

2. Fermilab Booster



MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster



FNAL Booster

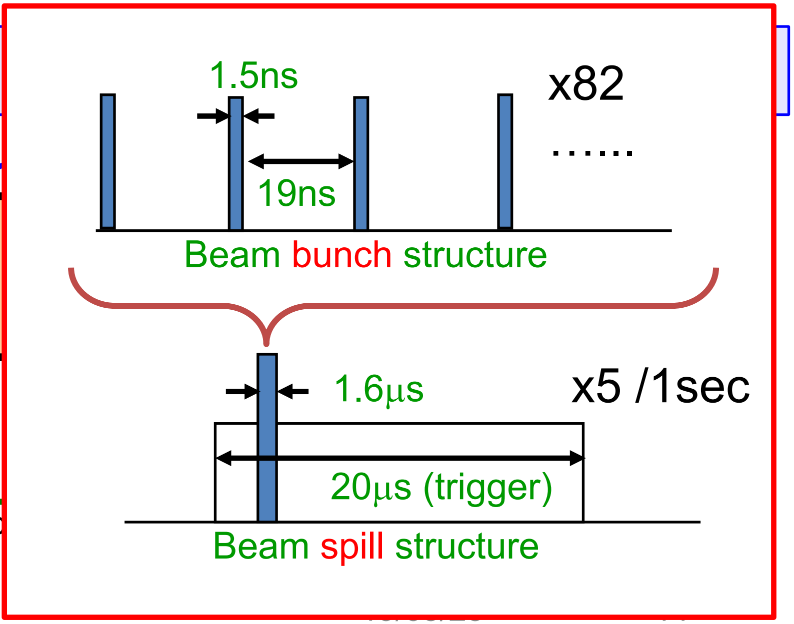
target and horn

decay region

primary beam (protons)

secondary beam (mesons)

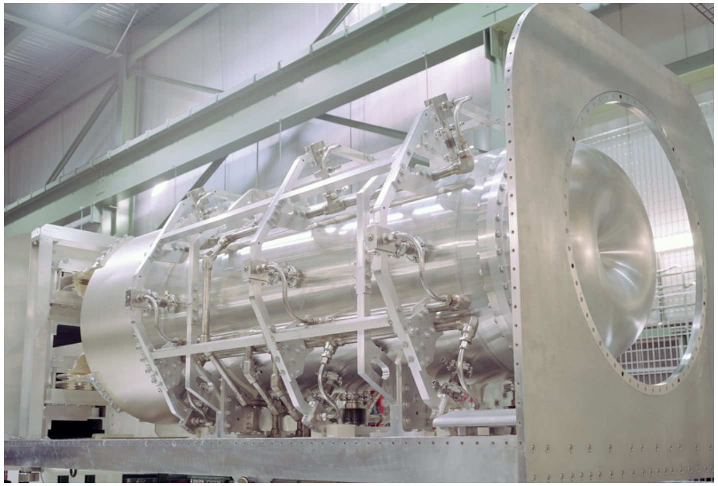
tertiary (neutrino



MiniBooNE, PRD79(2009)072002

2. Magnetic Focusing Horn

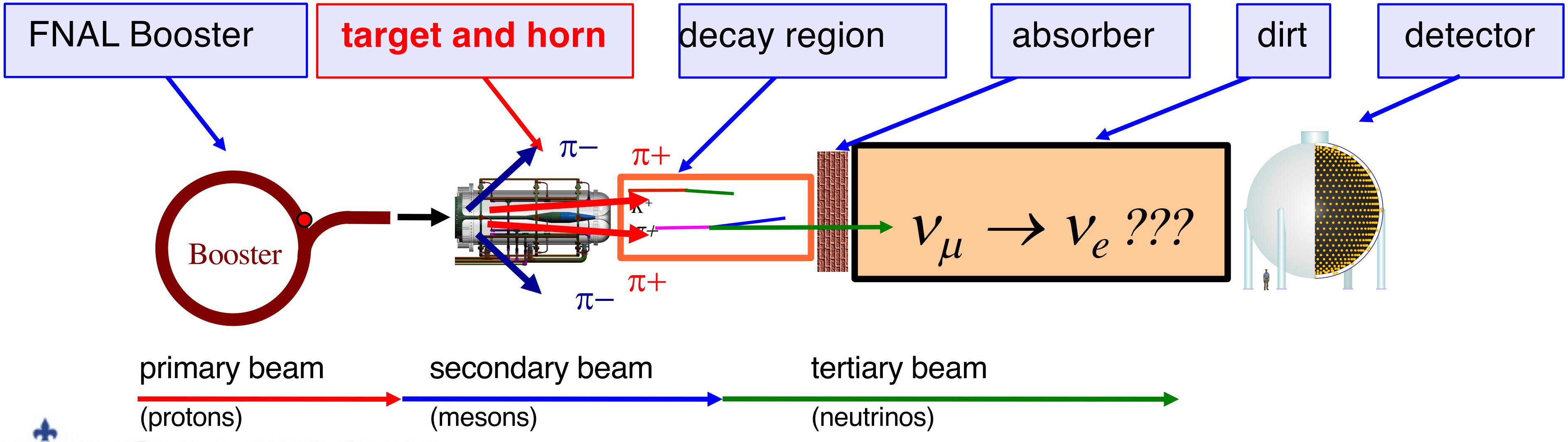
Magnetic focusing horn



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 × 6

By switching the current direction, the horn can focus either positive (neutrino mode) or negative (antineutrino mode) mesons.



FNAL Booster

target and horn

decay region

absorber

dirt

detector

primary beam
(protons)

secondary beam
(mesons)

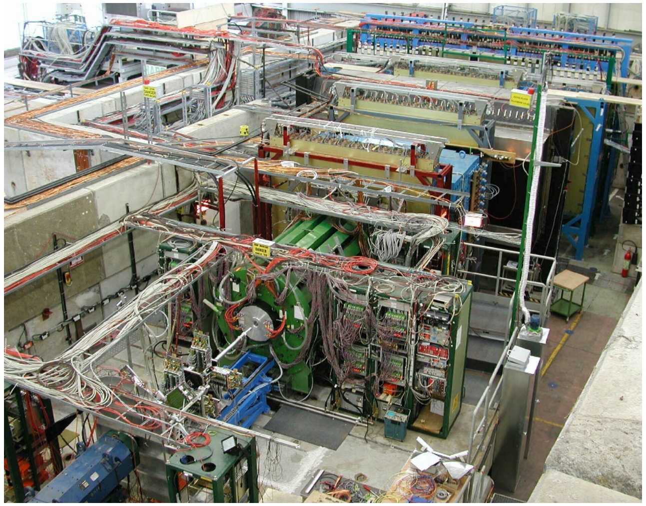
tertiary beam
(neutrinos)

katori@fnal.gov

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

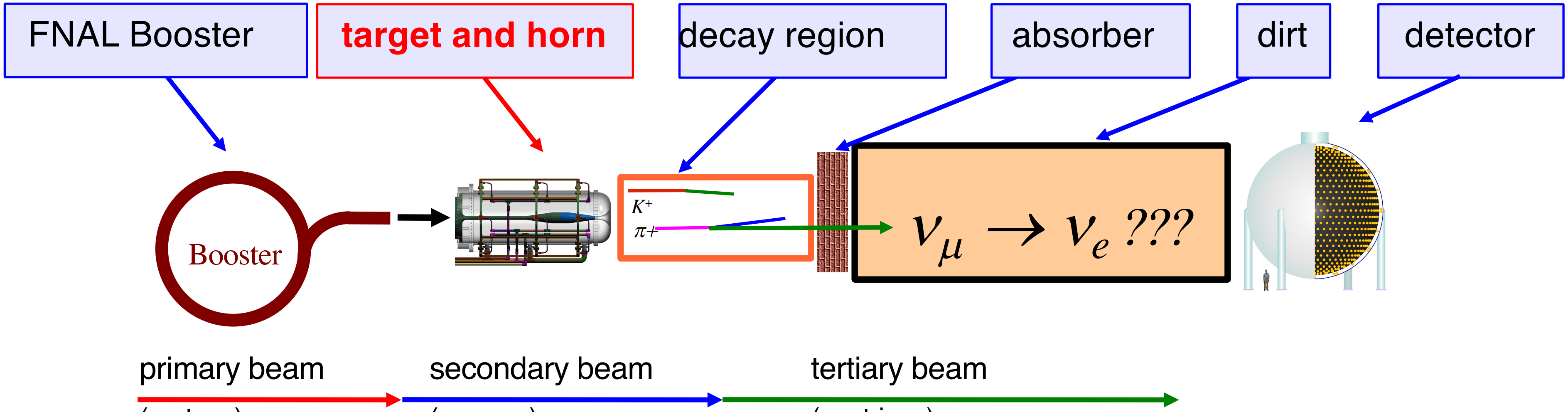
2. Hadron Production

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+



FNAL Booster

target and horn

decay region

absorber

dirt

detector

primary beam
(protons)

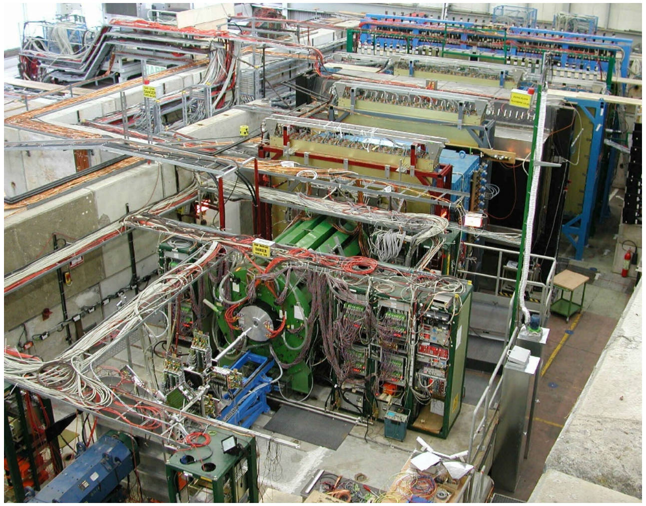
secondary beam
(mesons)

tertiary beam
(neutrinos)

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

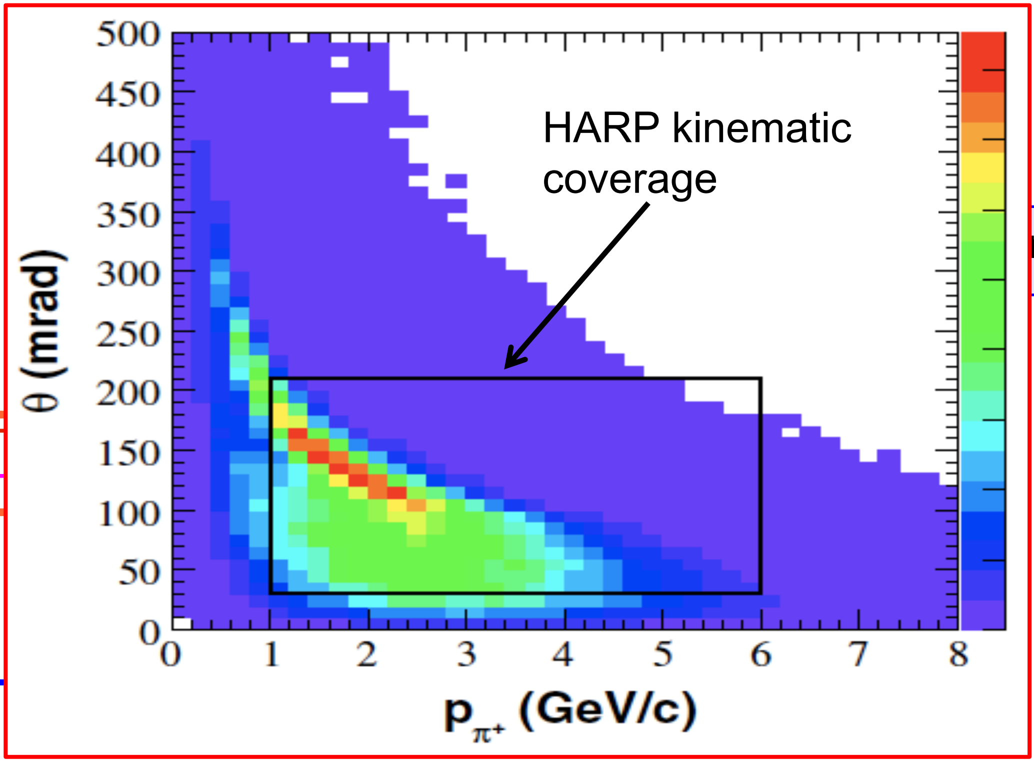
2. Hadron Production

HARP experiment (CERN)

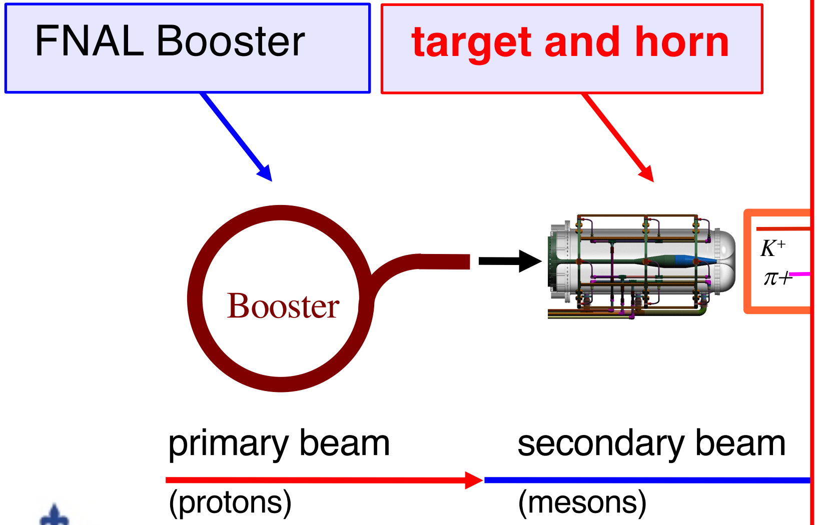


Modeling of meson production is based on the measurement done by HARP collaboration.

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



HARP kinematic coverage



FNAL Booster

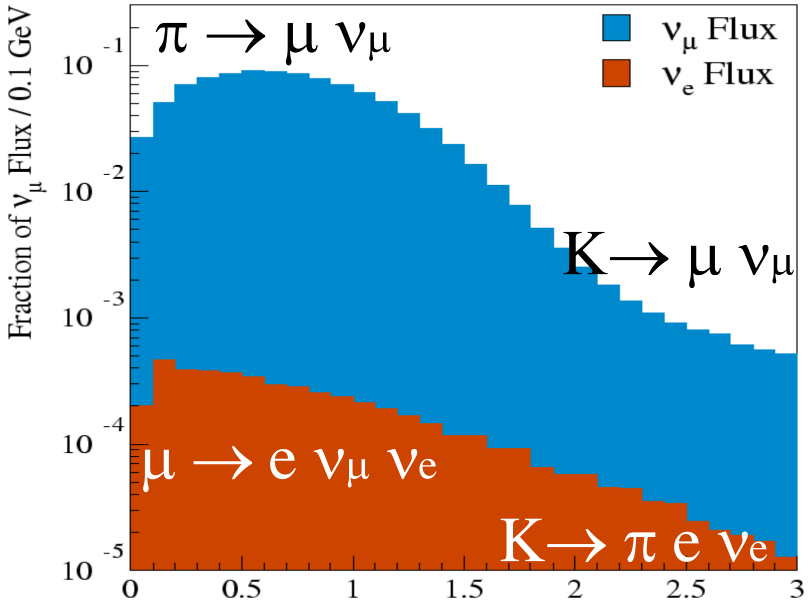
target and horn

primary beam
(protons)

secondary beam
(mesons)

MiniBooNE, PRD79(2009)072002

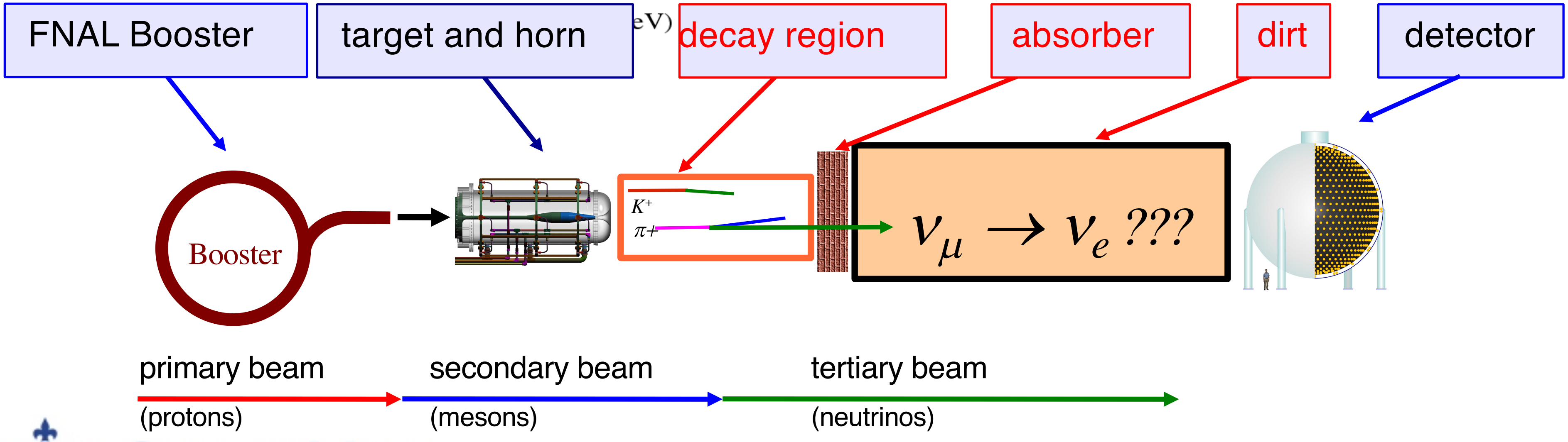
2. Booster Neutrino Beamline (BNB)



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%



FNAL Booster

target and horn

decay region

absorber

dirt

detector

primary beam
(protons)

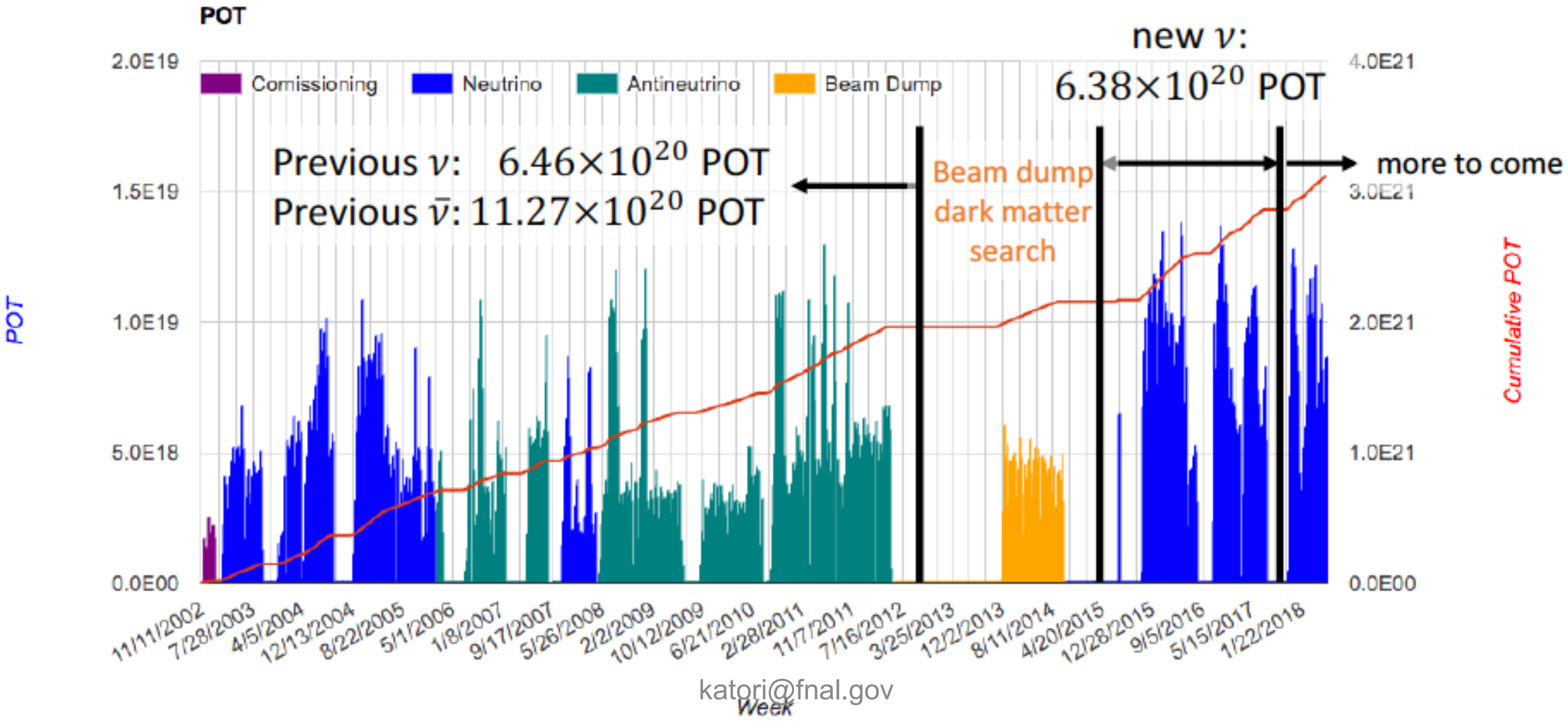
secondary beam
(mesons)

tertiary beam
(neutrinos)

Huang, Neutrino 2018

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



new ν: 6.38×10^{20} POT

Previous ν: 6.46×10^{20} POT

Previous $\bar{\nu}$: 11.27×10^{20} POT

Beam dump dark matter search

more to come

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

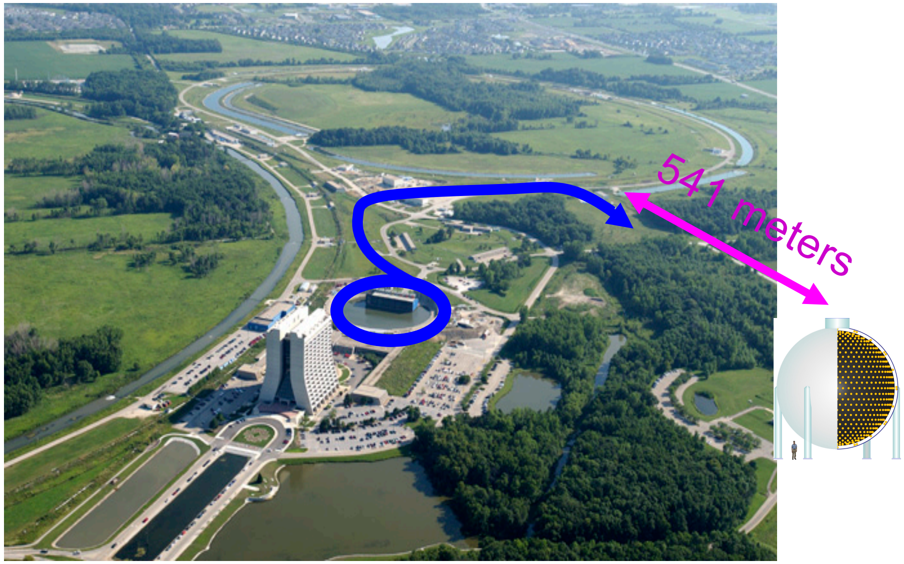
3. MiniBooNE detector

4. Oscillation candidate search

5. Results

MiniBooNE,NIM.A599(2009)28

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

katori@fnal.gov

MiniBooNE,NIM.A599(2009)28

3. Events in the Detector

The MiniBooNE Detector

- 541 meters downstream of target
- 12 meter diameter sphere

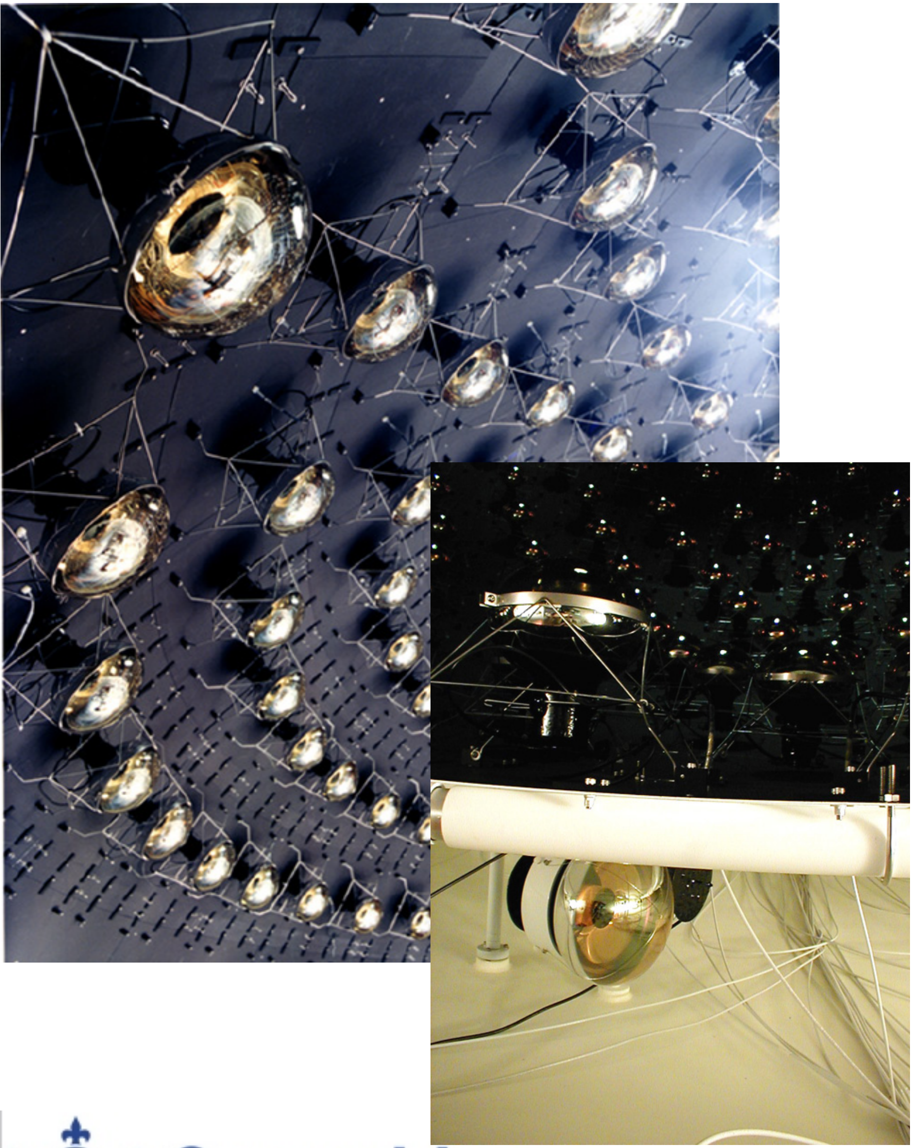
  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH_2)

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

katori@fnal.gov

MiniBooNE,NIM.A599(2009)28

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

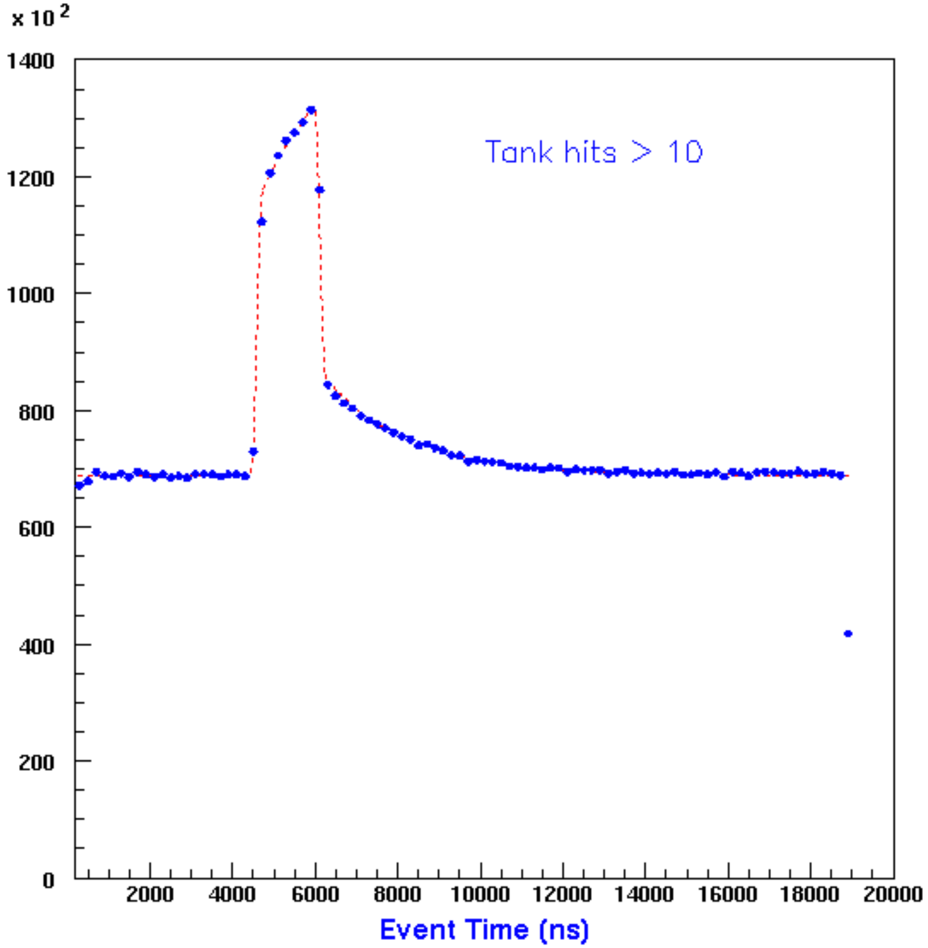
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and
Cosmic BG



katori@fnal.gov

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

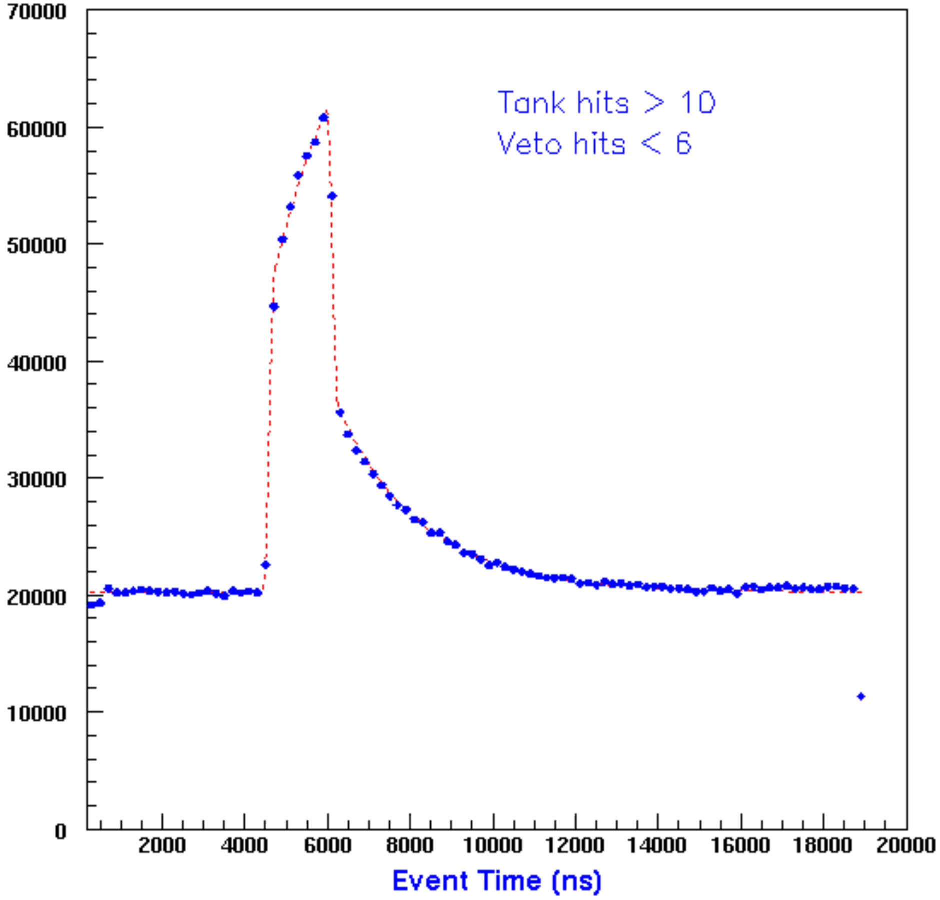
Neutrino Candidate Cuts

- <6 veto PMT hits
  - Gets rid of muons

- >200 tank PMT hits
  - Gets rid of Michels

Only neutrinos are left!

Beam and Michels



katori@fnal.gov

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

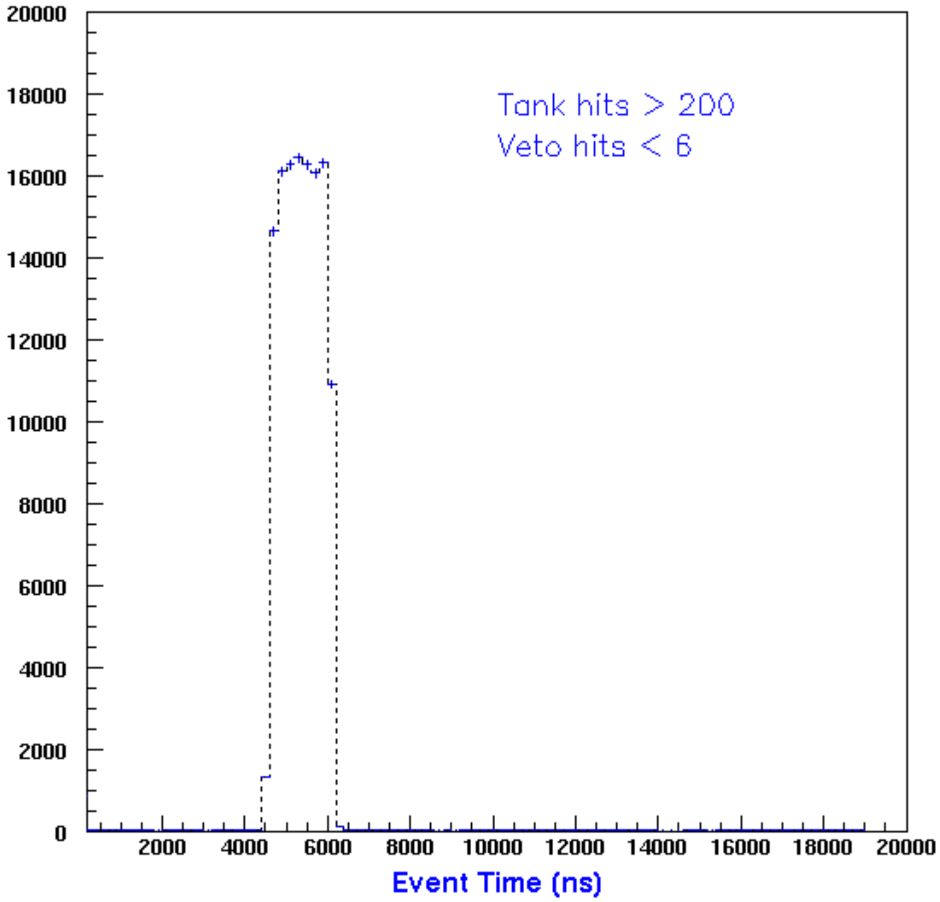
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

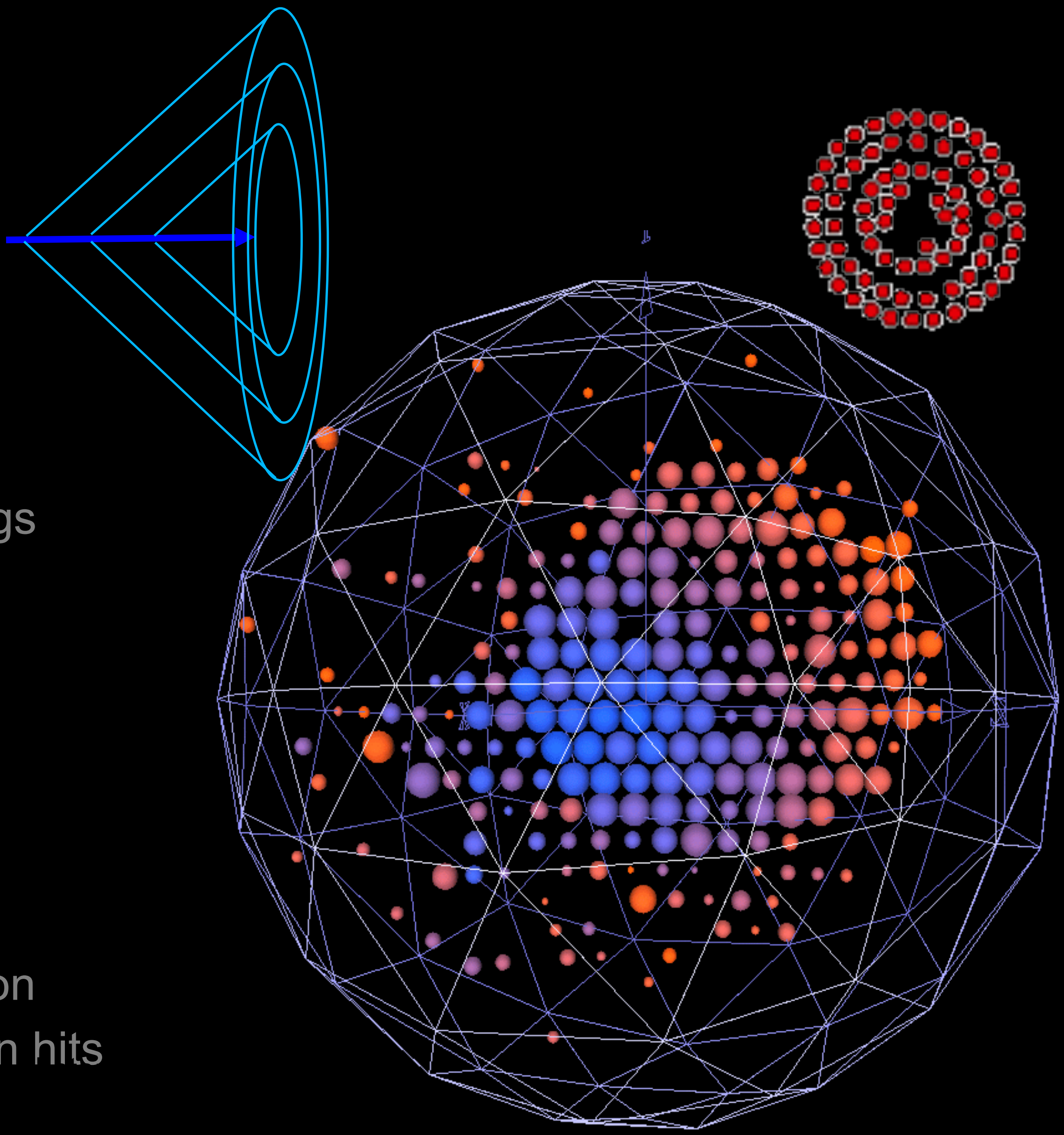
Beam Only



katori@fnal.gov

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

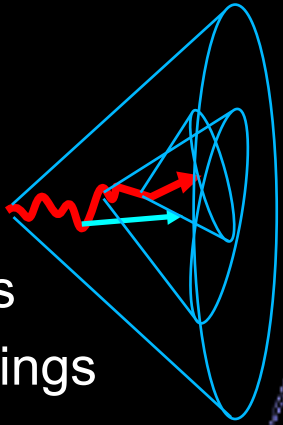
MiniBooNE collaboration,
NIM.A599(2009)28

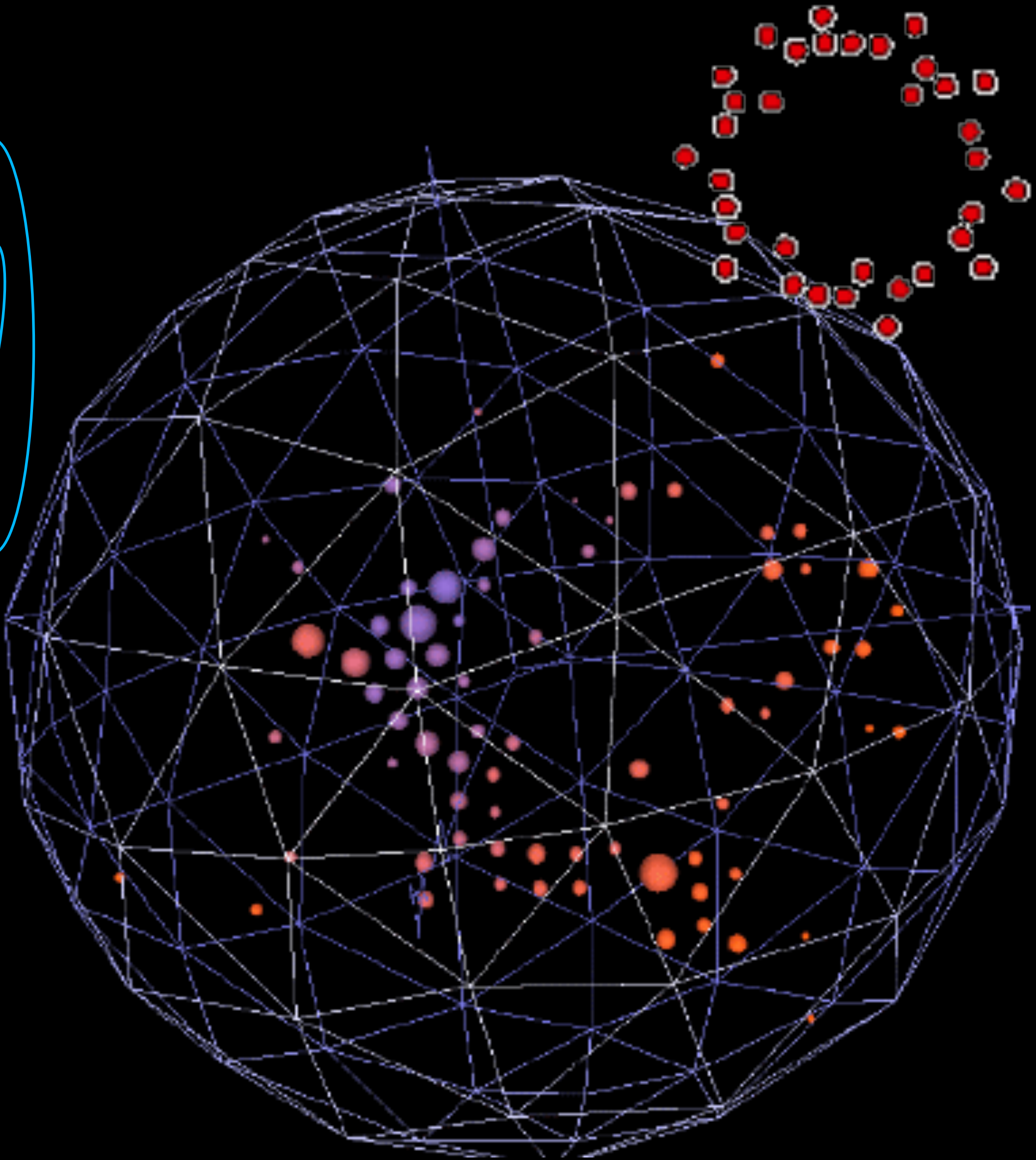
Muons

- 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

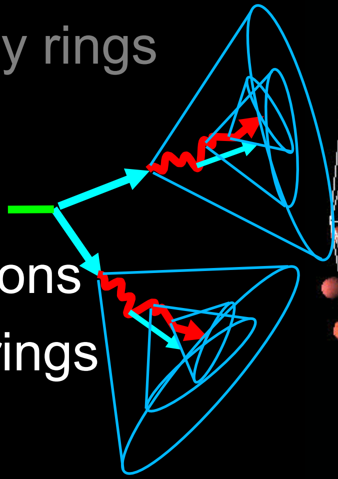
- Long strait tracks
  → Sharp clear rings

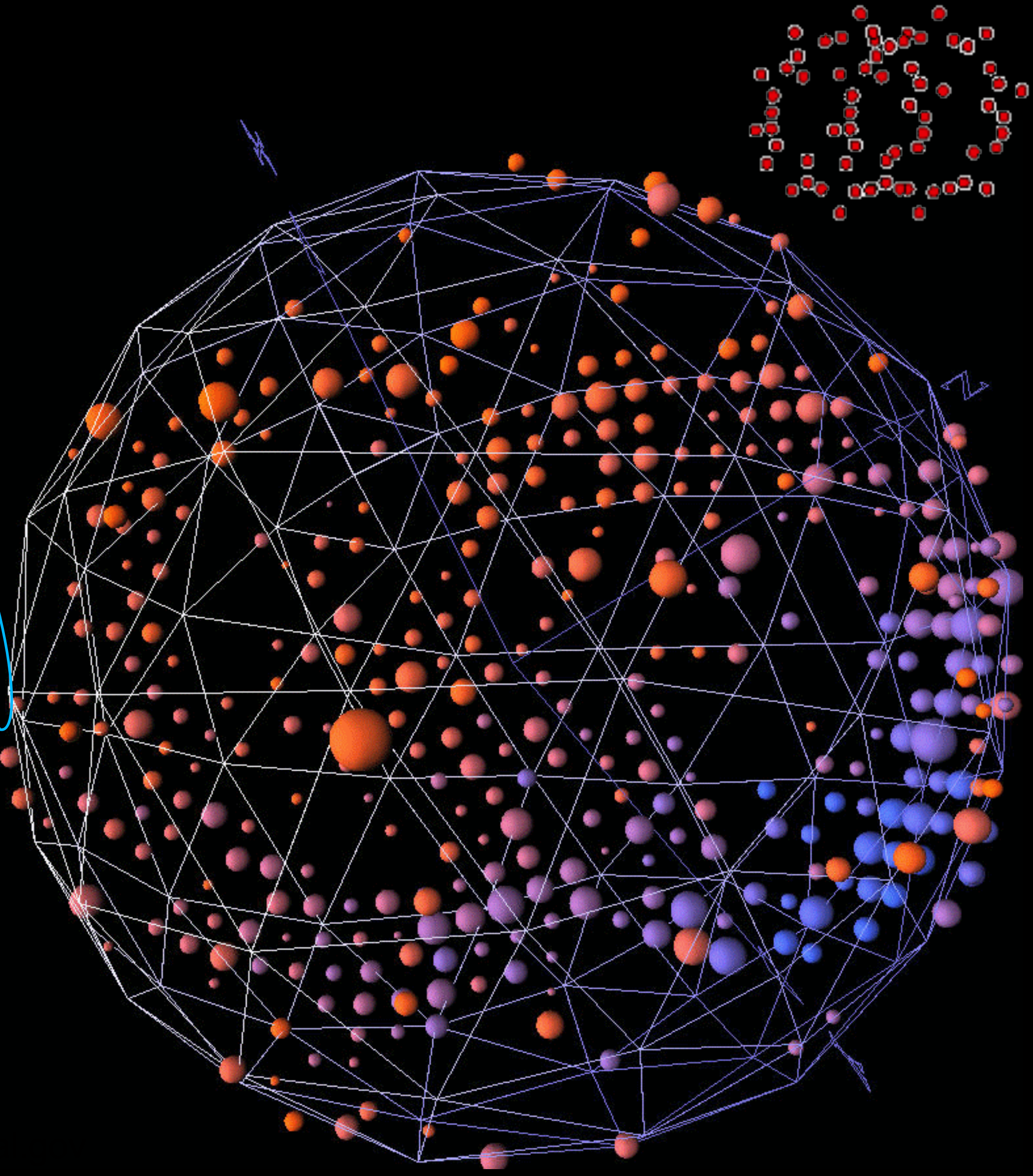
Electrons

- 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

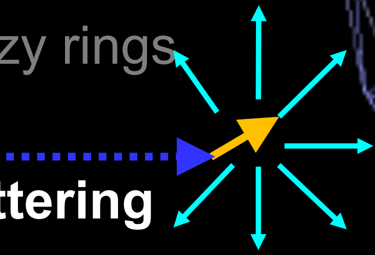
- Long strait tracks
  → Sharp clear rings

Electrons

- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings

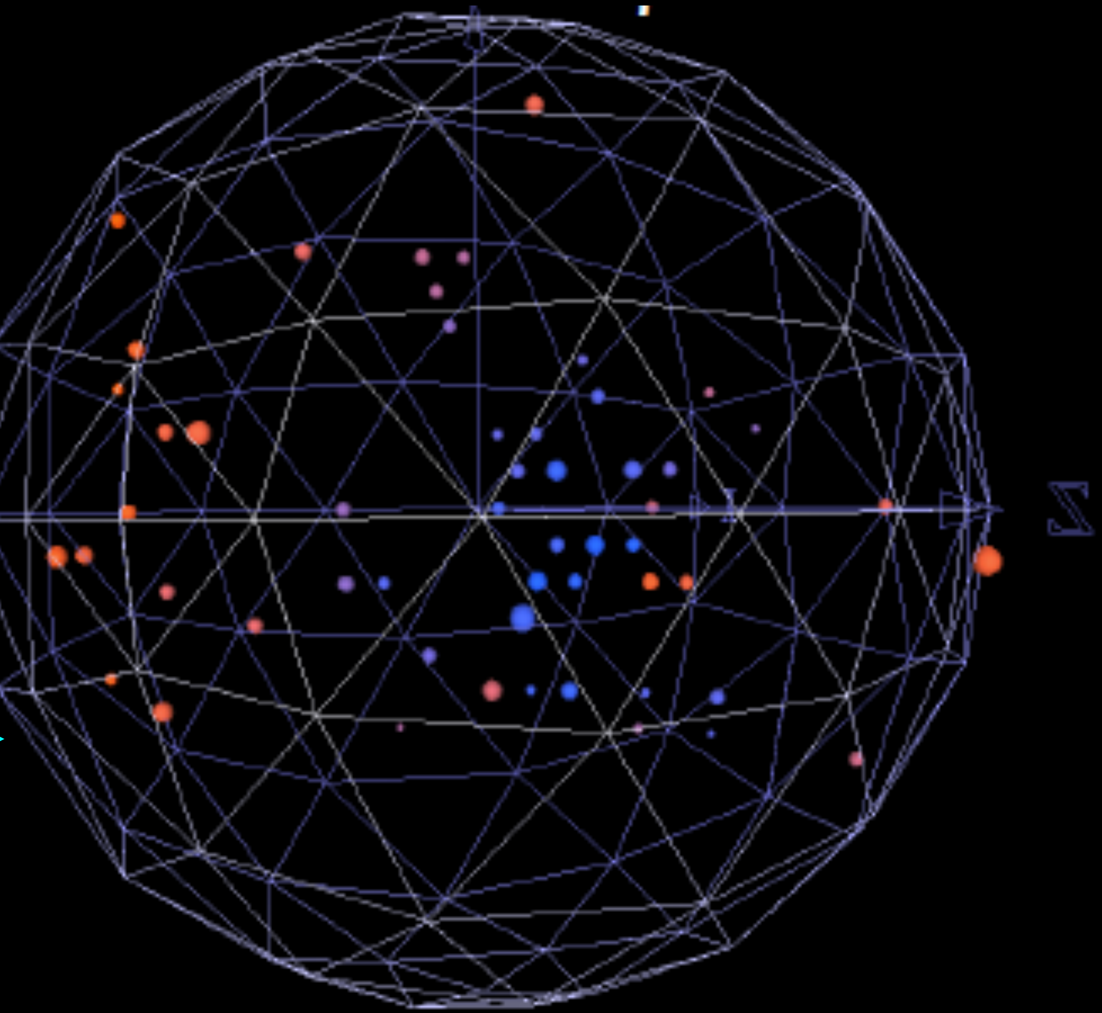
Neutral pions

- Decays to 2 photons
  → Double fuzzy rings



NC elastic scattering

- No Cherenkov radiation
  → Isotropic scintillation hits



MiniBooNE: PRL100(2008)032301

3. QE kinematics based energy reconstruction

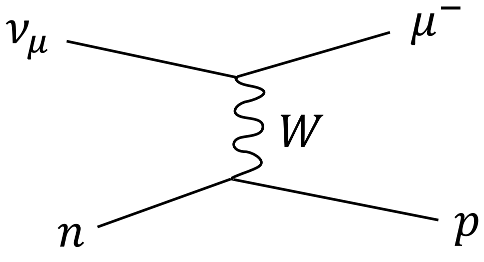
Event reconstruction from Cherenkov ring profile for PID

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

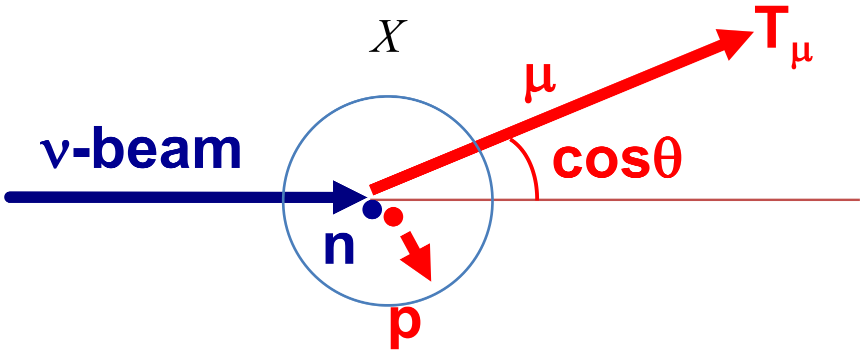
Charged Current Quasi-Elastic (CCQE) interaction

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



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



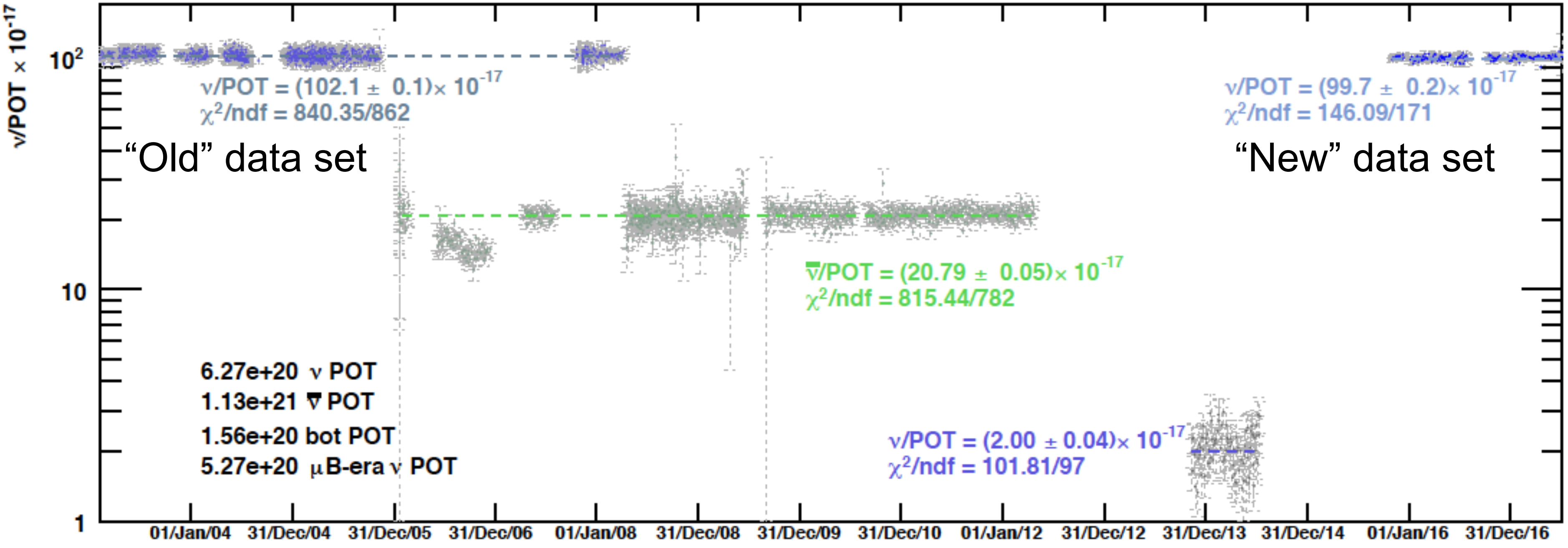
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

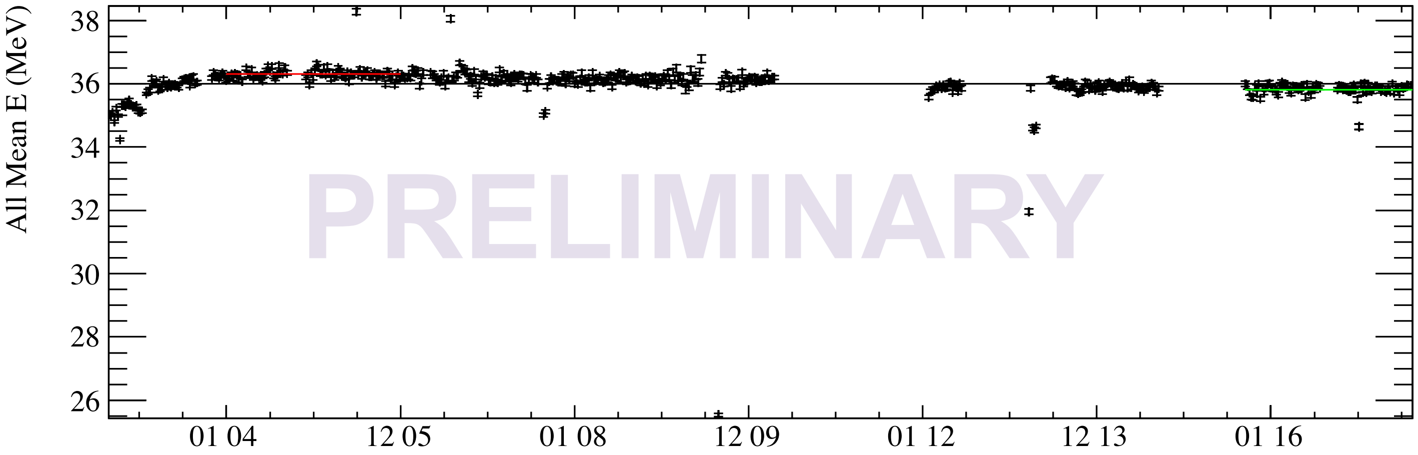


katori@fnal.gov

3. Detector stability

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

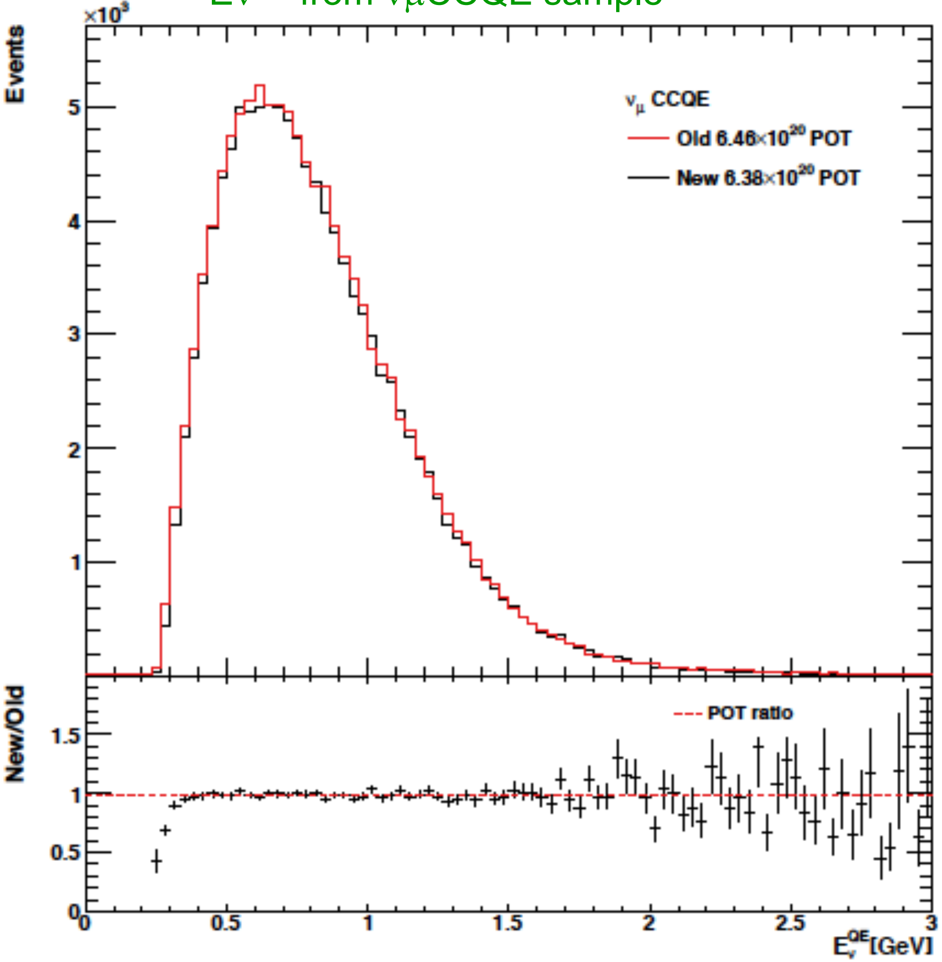
Michel electron spectrum peak



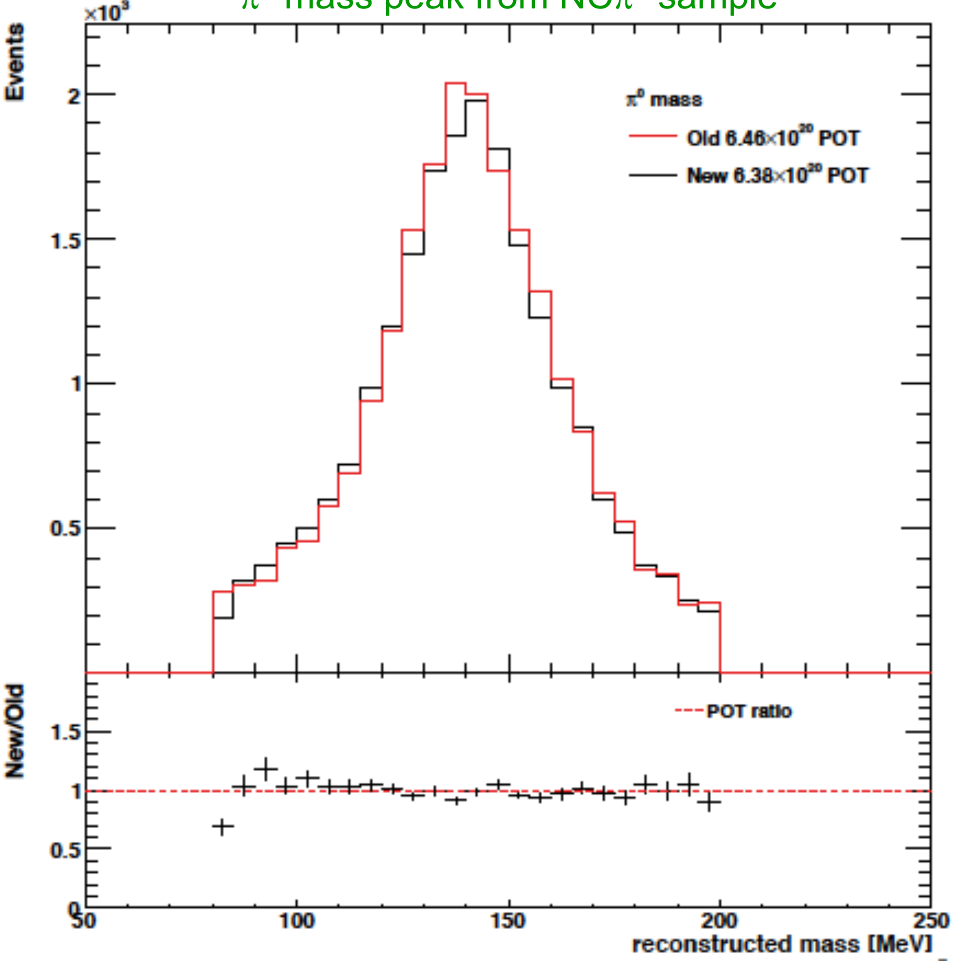
3. Detector stability

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



Queen Mary
University of London

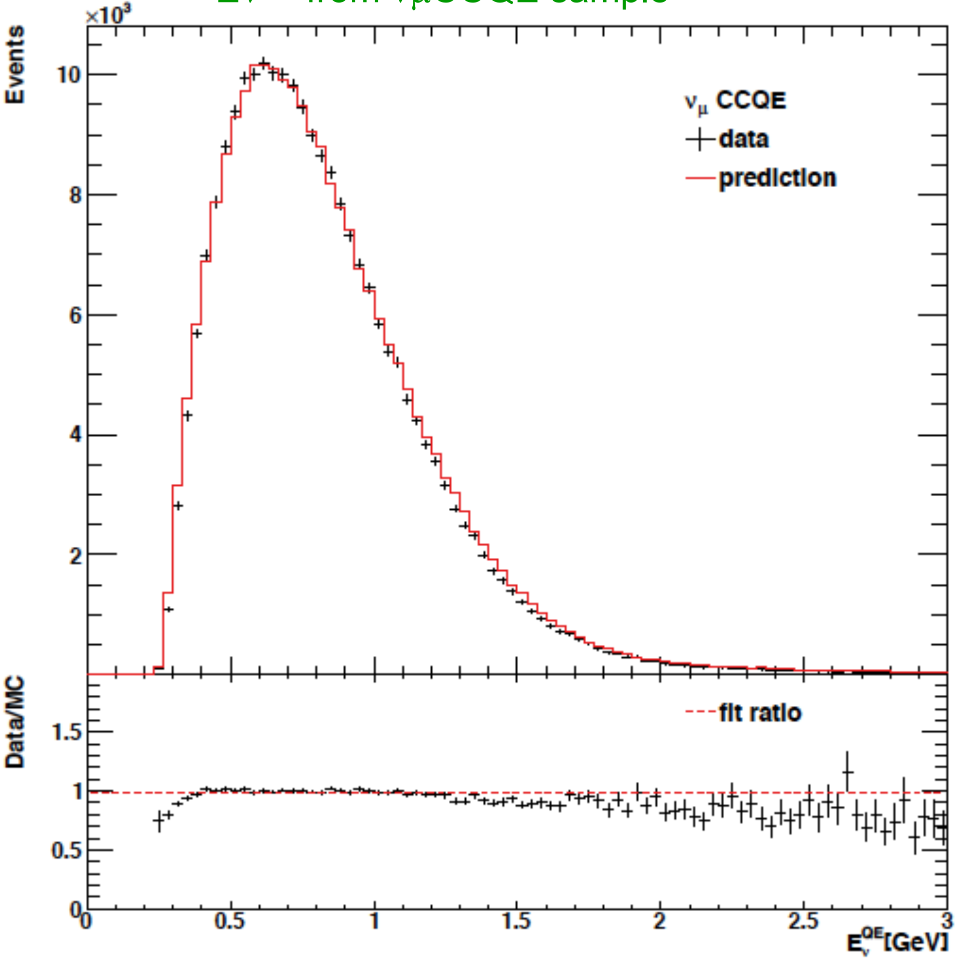
katori@fnal.gov

3. Data-Simulation comparison

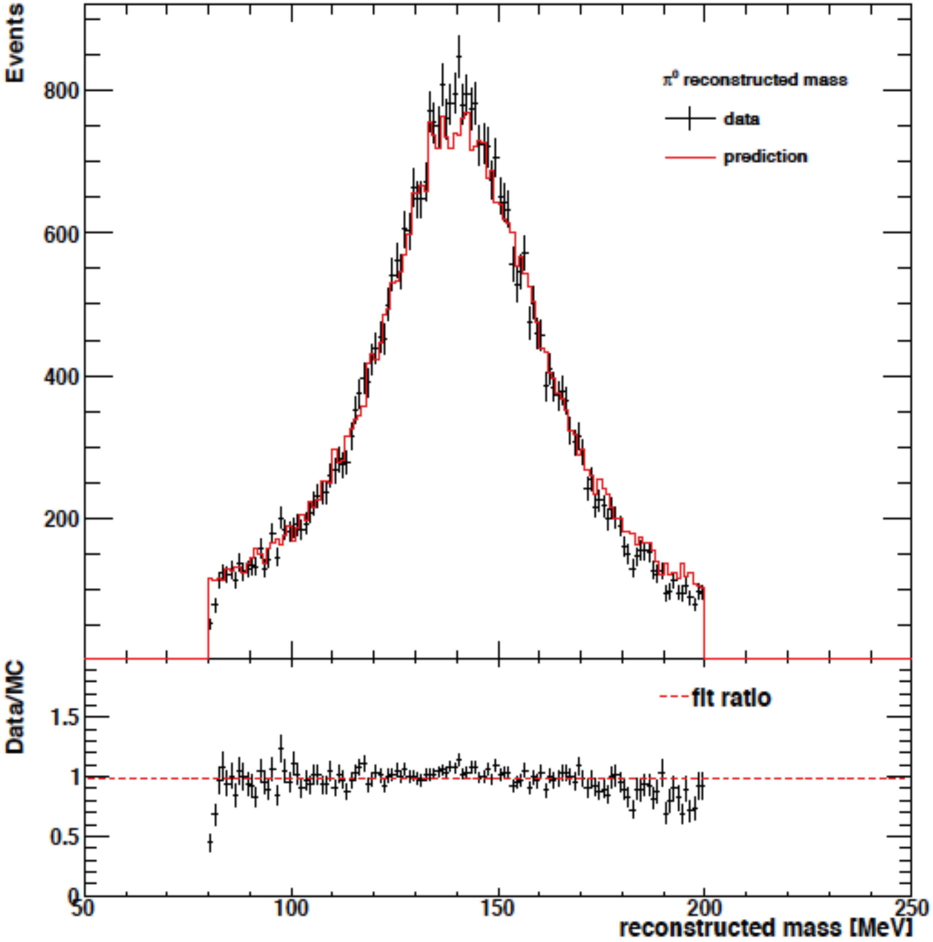
Old and new data agree within 2% over 8 years separation.

- 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

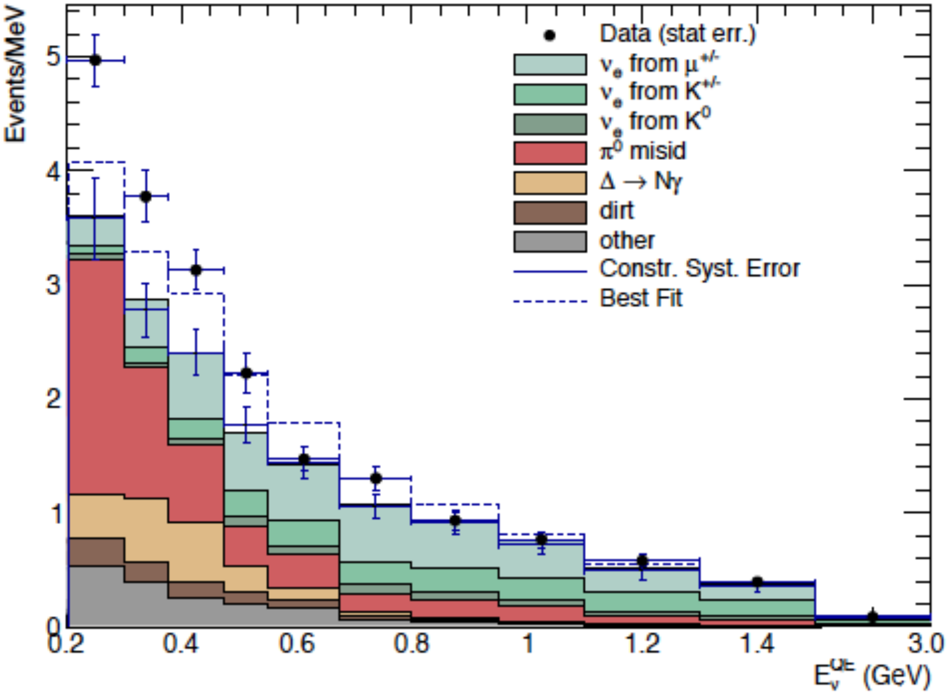
4. Oscillation candidate search

5. Results

4. Internal background constraints

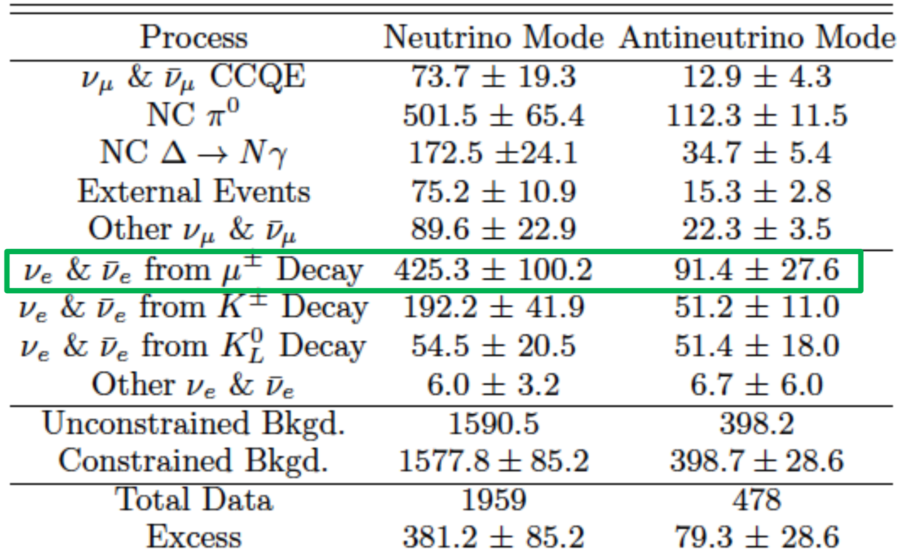
All backgrounds are internally constrained
 → intrinsic (beam ν_e) = flat
 → misID (gamma) = accumulate at low E

	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 $\Delta \rightarrow N\gamma$	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
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

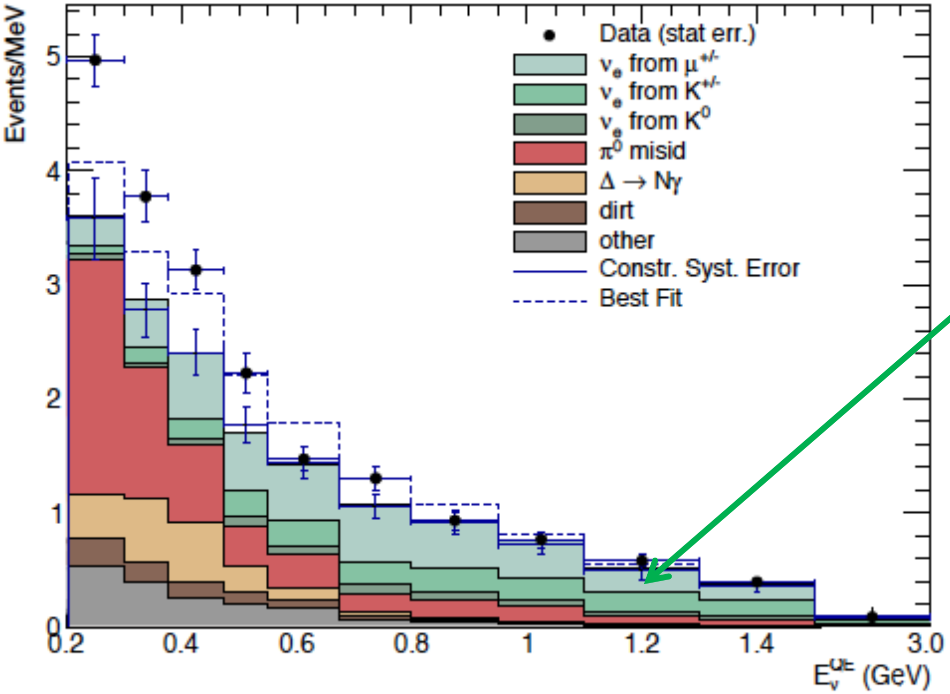


4. ν_e from μ-decay constraint

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



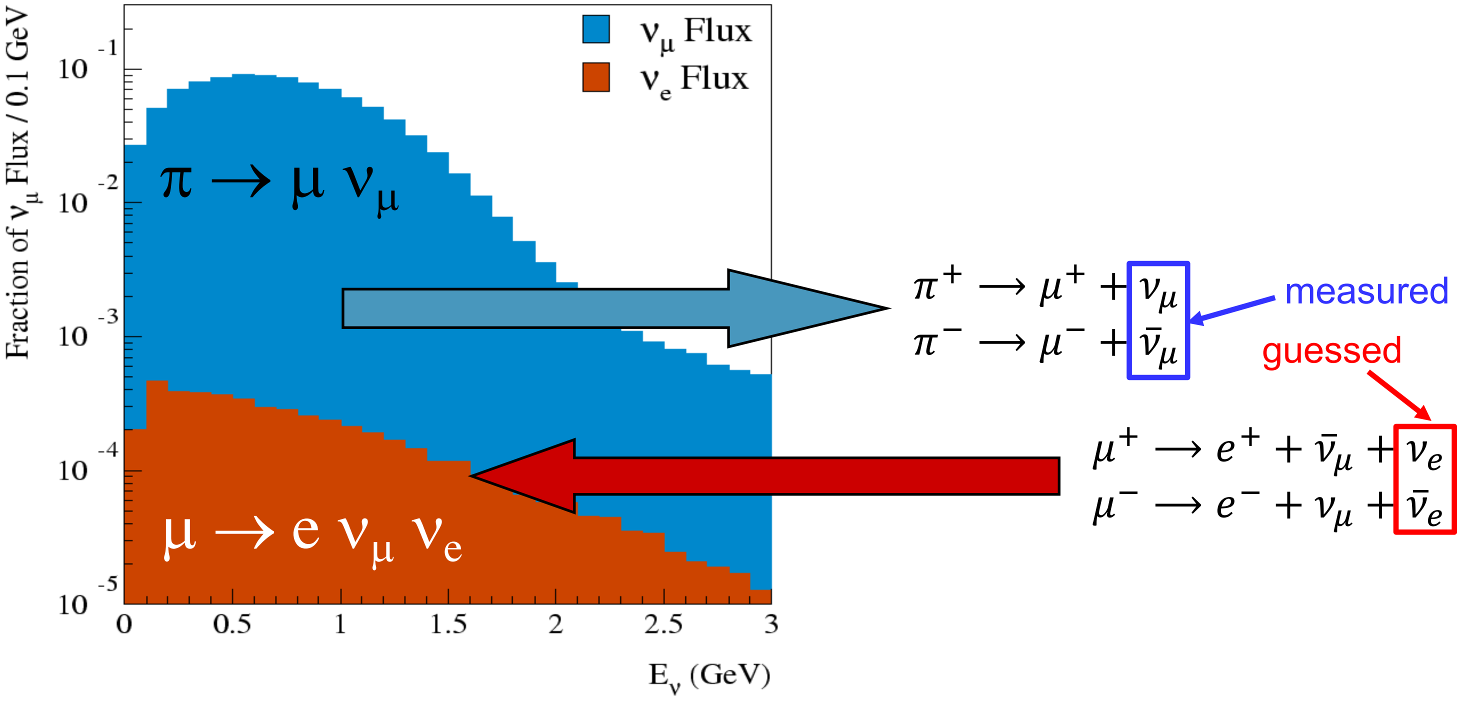
Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$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



ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from μ-decay constraint

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.



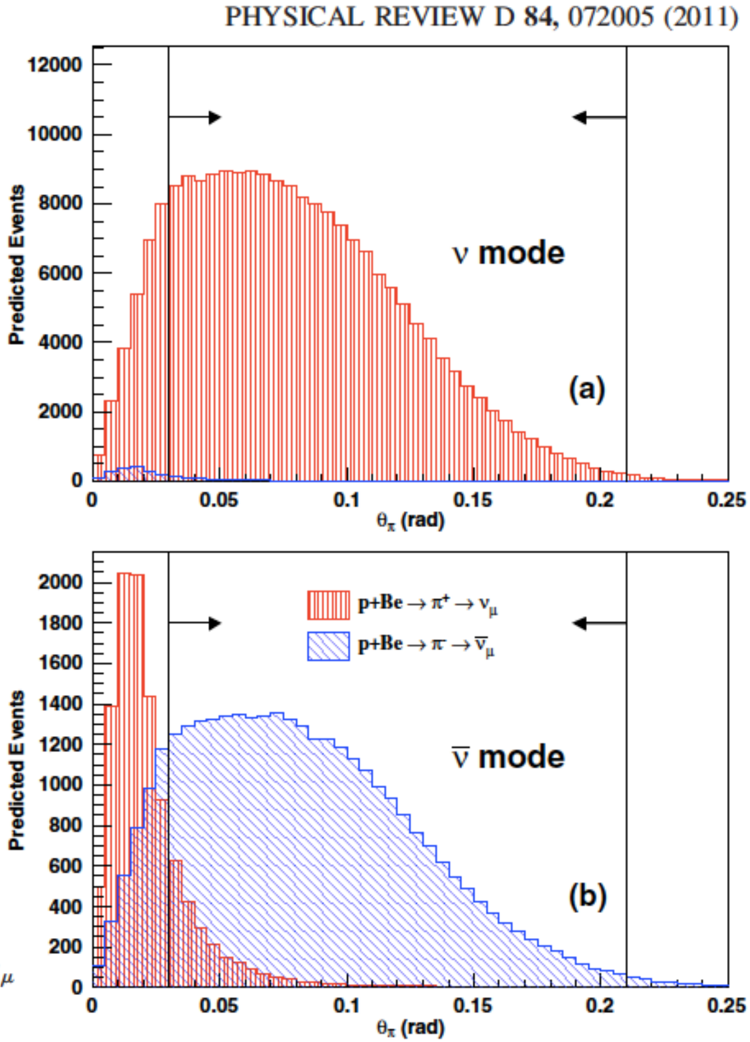
$$\pi^+ \longrightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\pi^- \longrightarrow \mu^- + \boxed{\bar{\nu}_\mu}$$

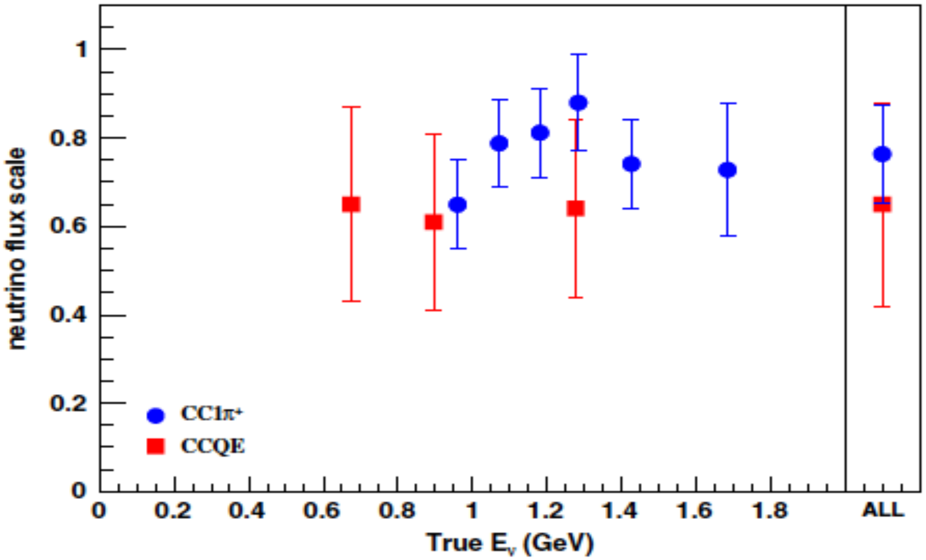
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \boxed{\nu_e}$$
$$\mu^- \longrightarrow e^- + \nu_\mu + \boxed{\bar{\nu}_e}$$

MiniBooNE, PRD84(2011)072005

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%





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

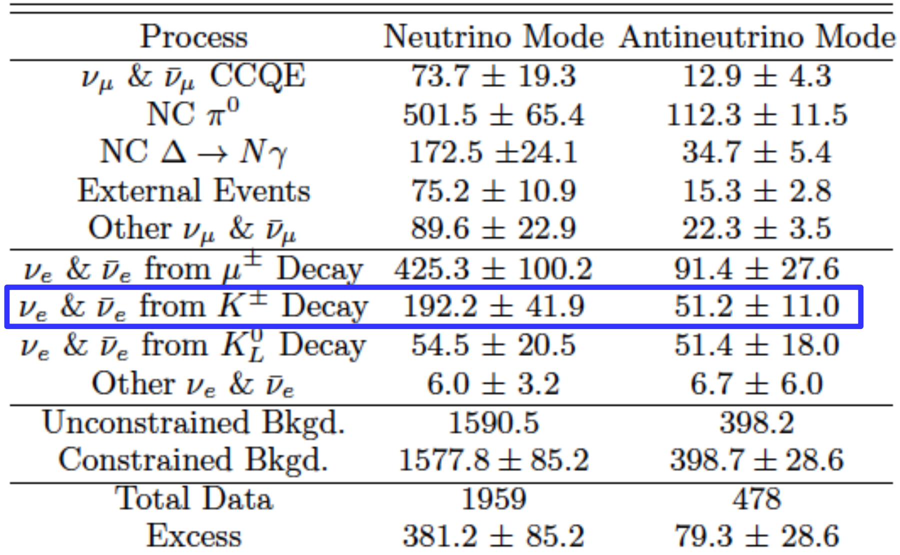
1: $\nu_\mu + p(n) \to \mu^- + p(n) + \pi^+ \hookrightarrow \mu^+ + \nu_\mu$

2: $\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

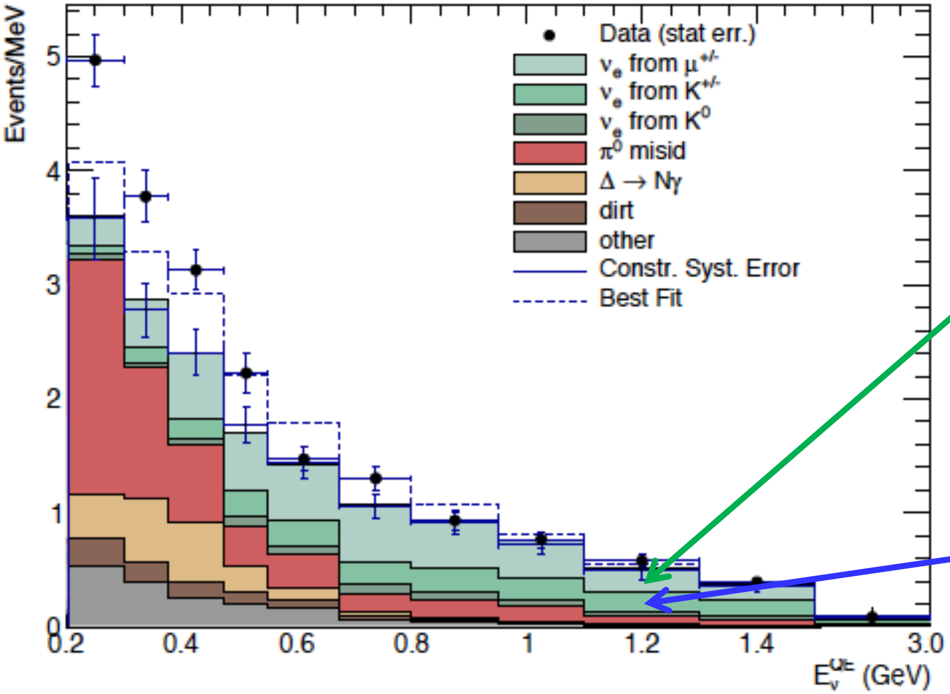
3: $\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.$

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 $\Delta \rightarrow N\gamma$	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



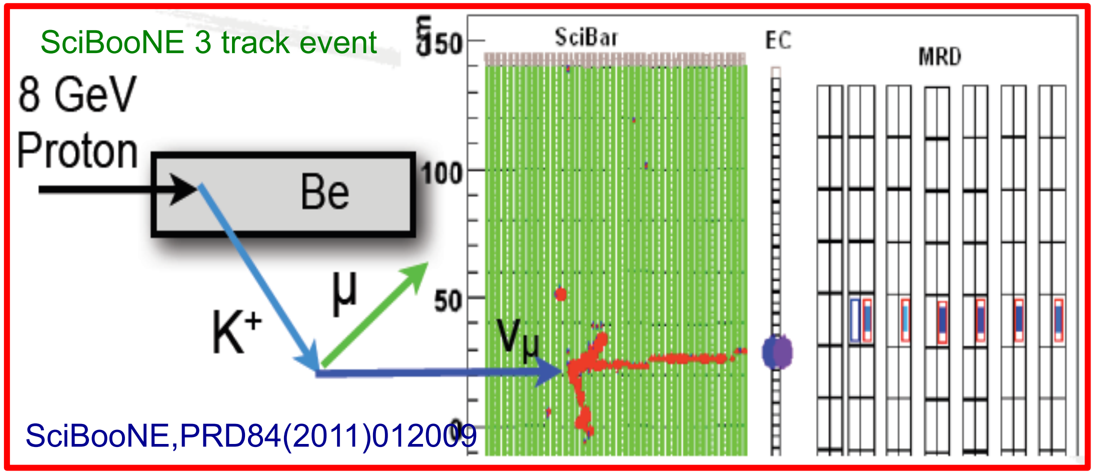
ν_e from μ decay is constrained from ν_μCCQE measurement

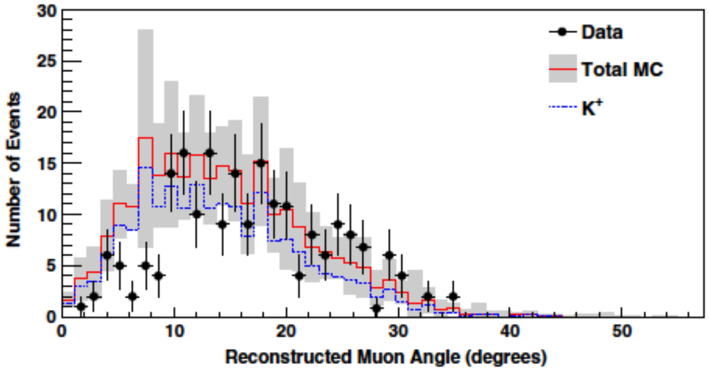
ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

SciBooNE,PRD84(2011)012009

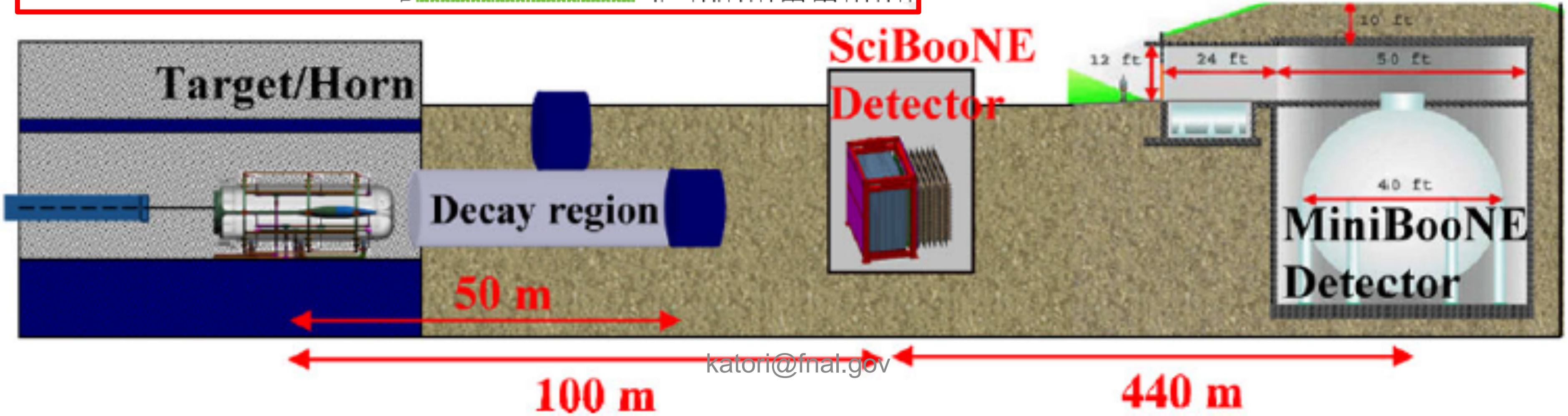
4. ν_e from K^+-decay constraint

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



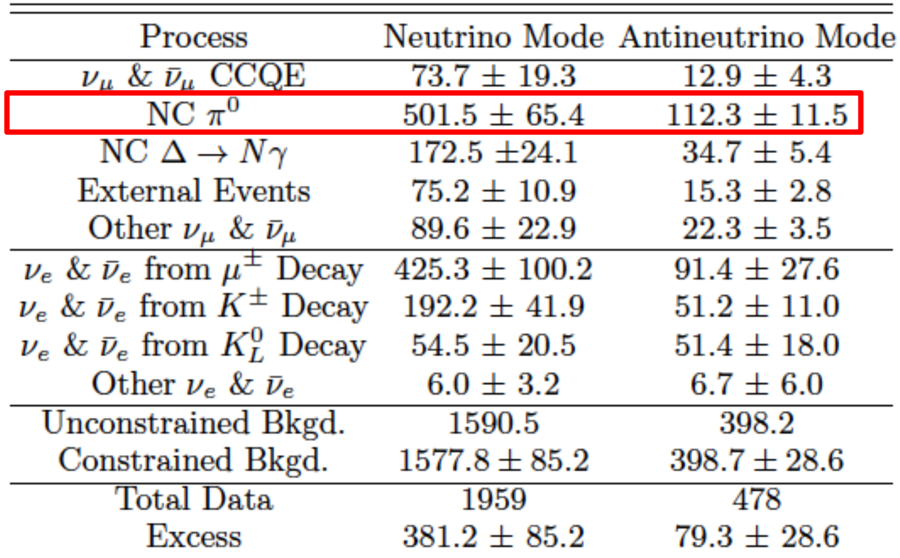
katori@fnal.gov

4. ν_e from K$^+$-decay constraint

All backgrounds are internally constrained

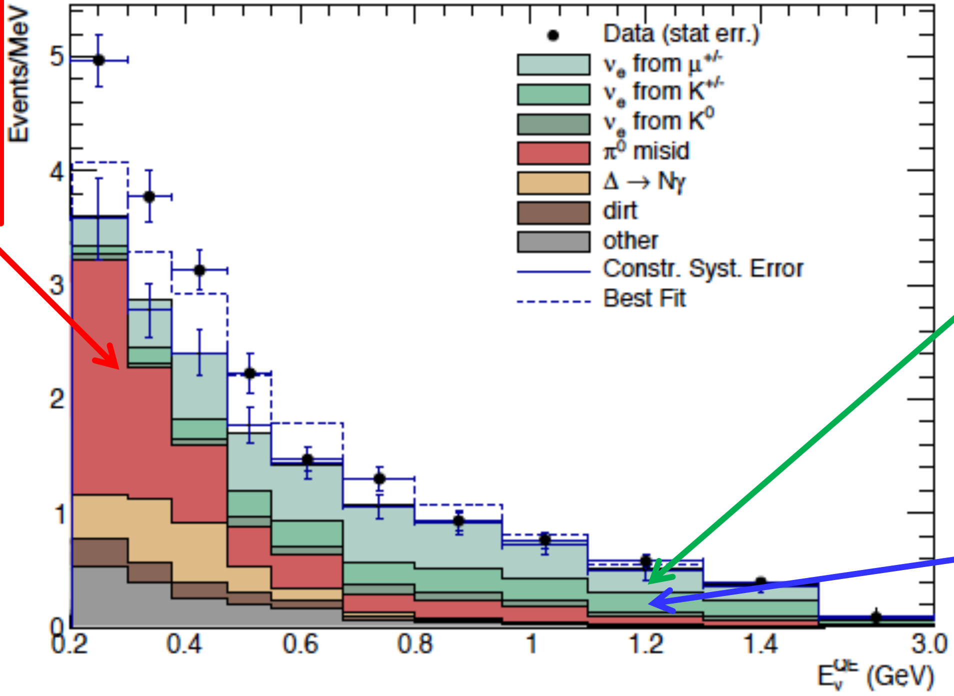
→ intrinsic (beam ν_e) = flat

→ 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

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



ν_e from μ decay is constrained from ν_μCCQE measurement

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

MiniBooNE, PLB664(2008)41

4. γ from π^o constraint

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

- not background, we can measure

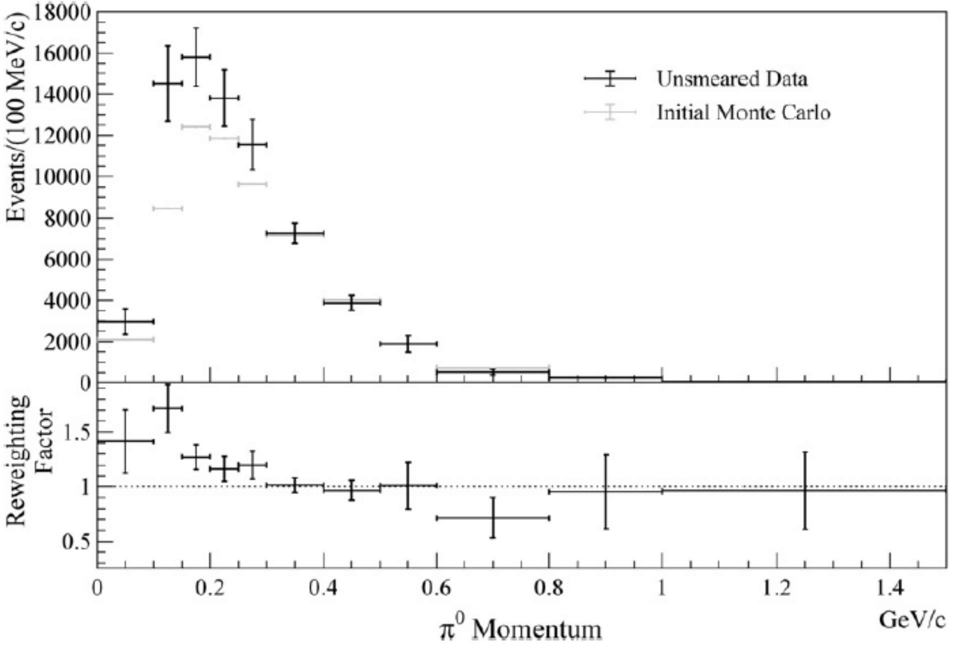
$\pi^o \rightarrow \gamma$

- misID background, we cannot measure

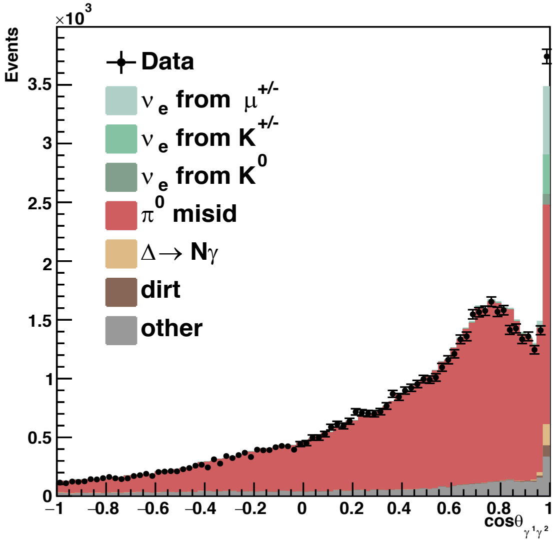
The biggest systematics is production rate of π^o, because once you find that, the chance to make a single gamma ray is predictable.

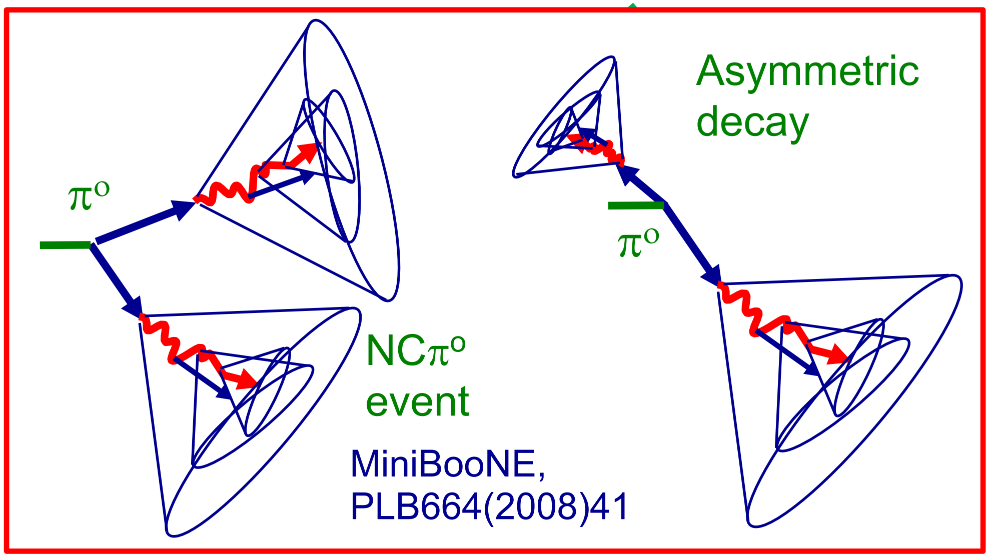
We measure π^o production rate, and correct simulation with function of π^o momentum

π^o momentum data-MC comparison



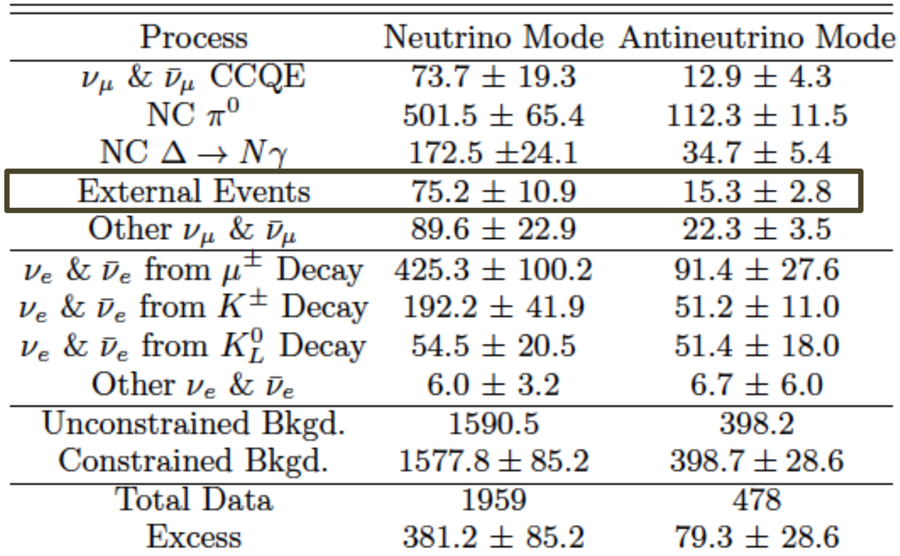
2-gamma-ray opening angle





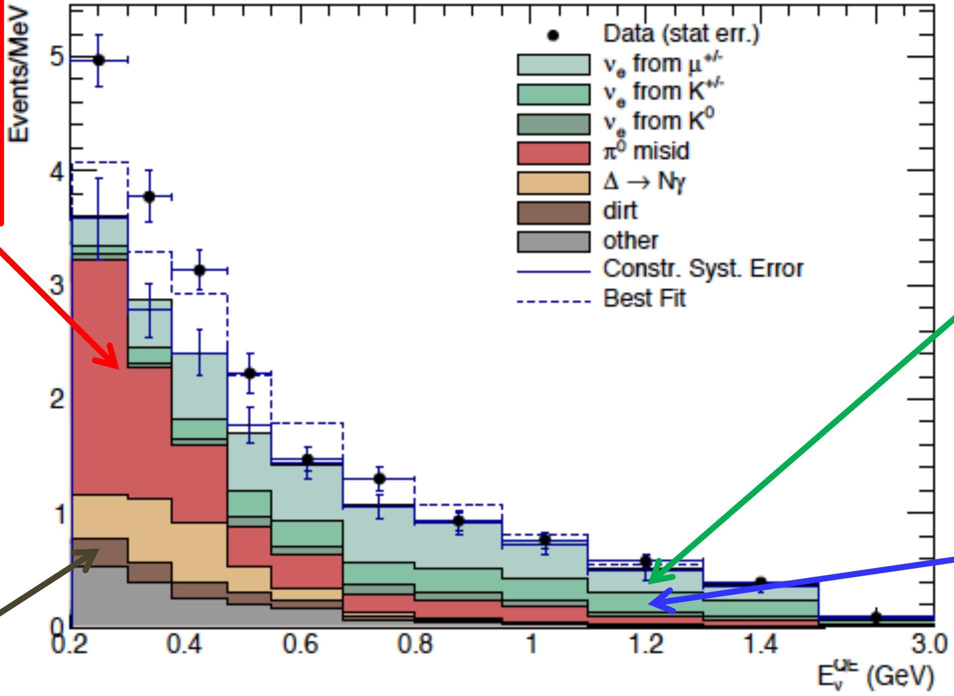
MiniBooNE, PLB664(2008)41

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 NCπ^o rate ($\pi^o \to \gamma$)

ν_e from μ decay is constrained from ν_μCCQE measurement

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

dirt rate is measured from dirt data sample

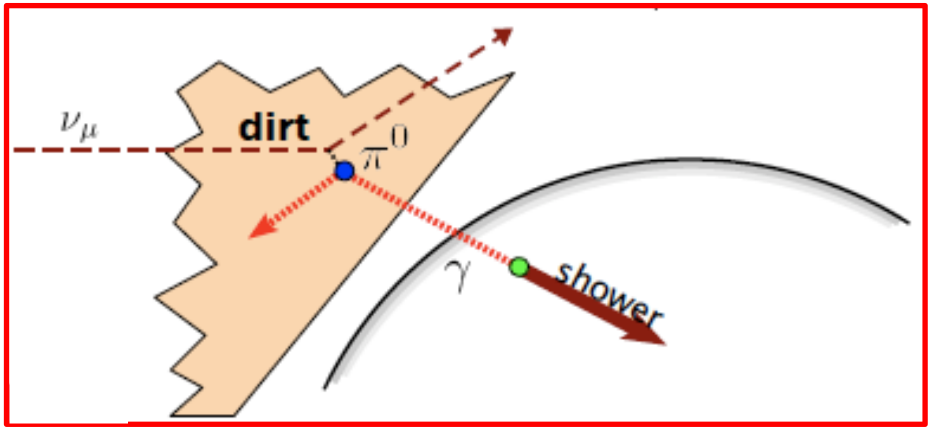
katori@fnal.gov

MiniBooNE, PRD82(2010)092005

4. External γ constraint

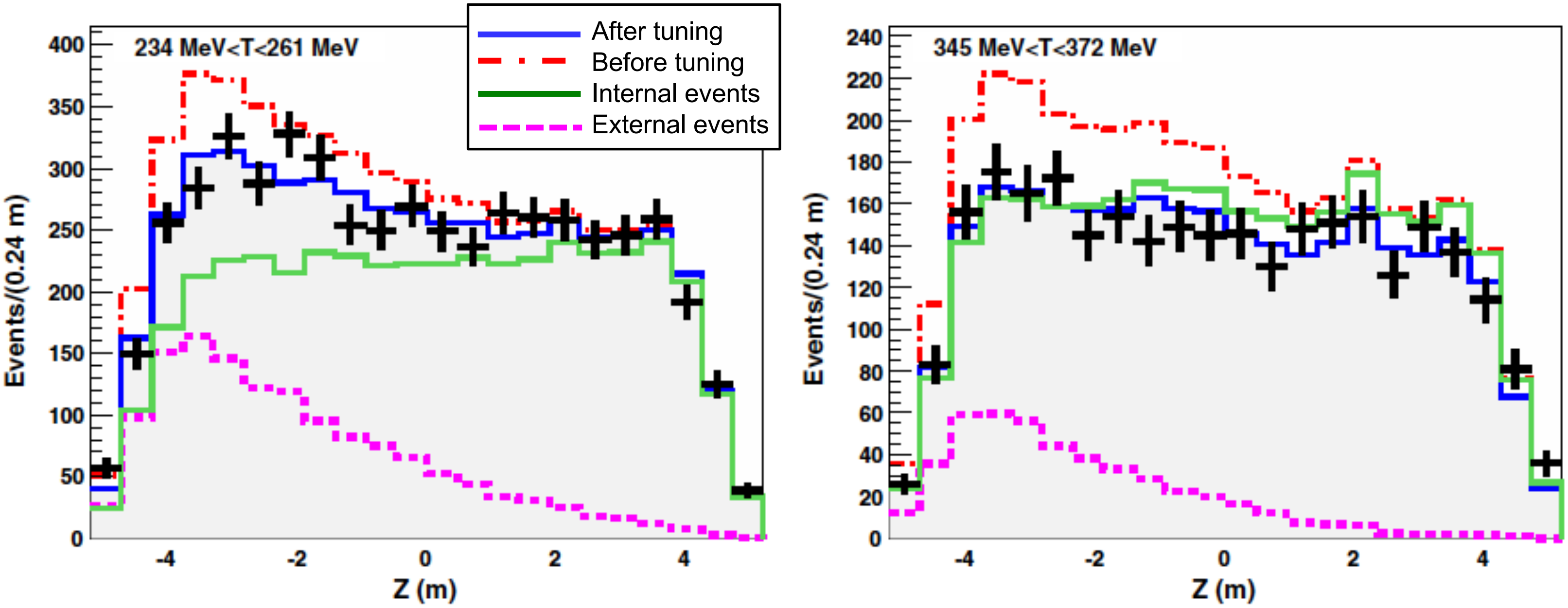
MiniBooNE detector has a simple geometry
- Spherical Cherenkov detector
- Homogeneous, large active veto

We have number of internal measurement to understand distributions of external events.



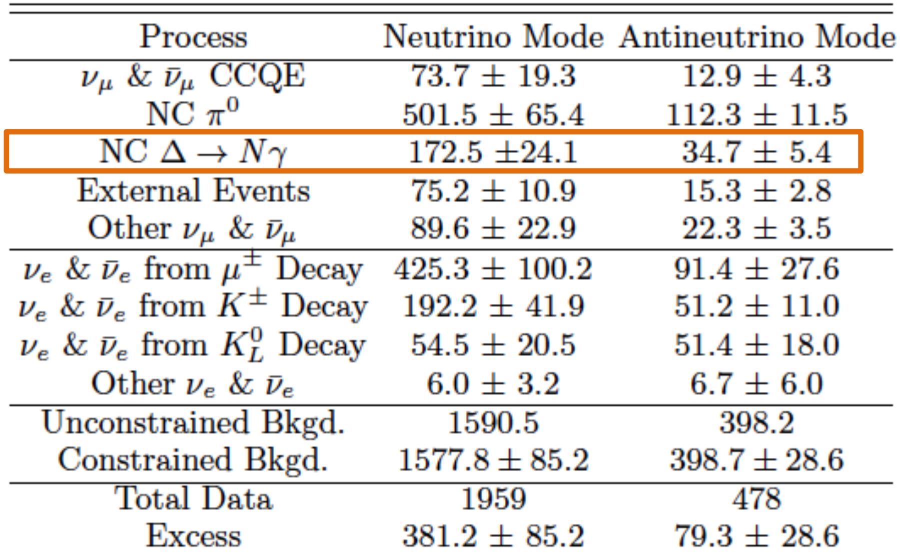
e.g.) NC elastic candidates with function of Z

Mis-modelling of external background is visible



4. NCγ constraint

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

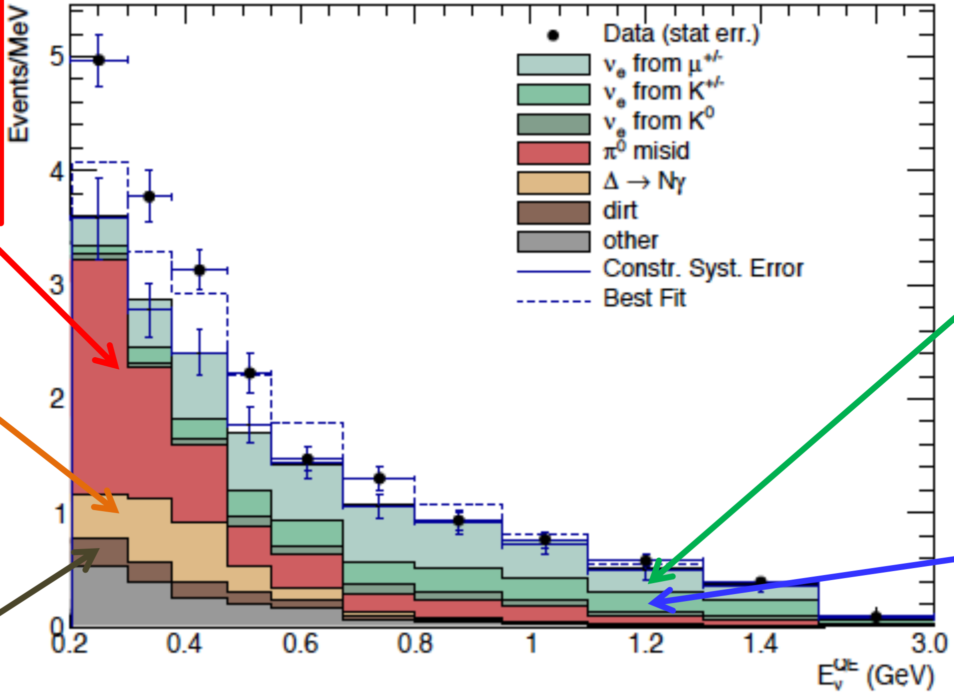


Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	172.5 ±24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay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

Δ resonance rate is constrained from measured NCπ^o rate

dirt rate is measured from dirt data sample

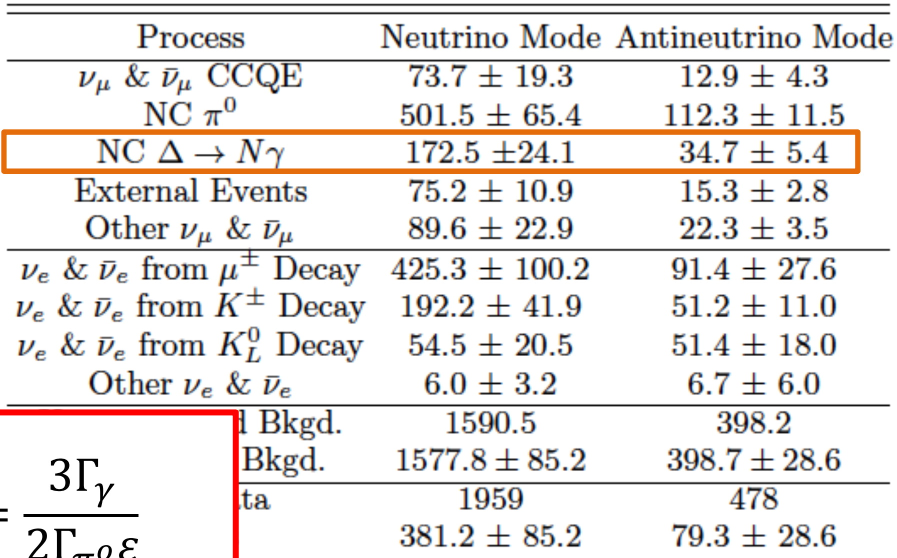


ν_e from μ decay is constrained from ν_μCCQE measurement

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

4. NCγ constraint

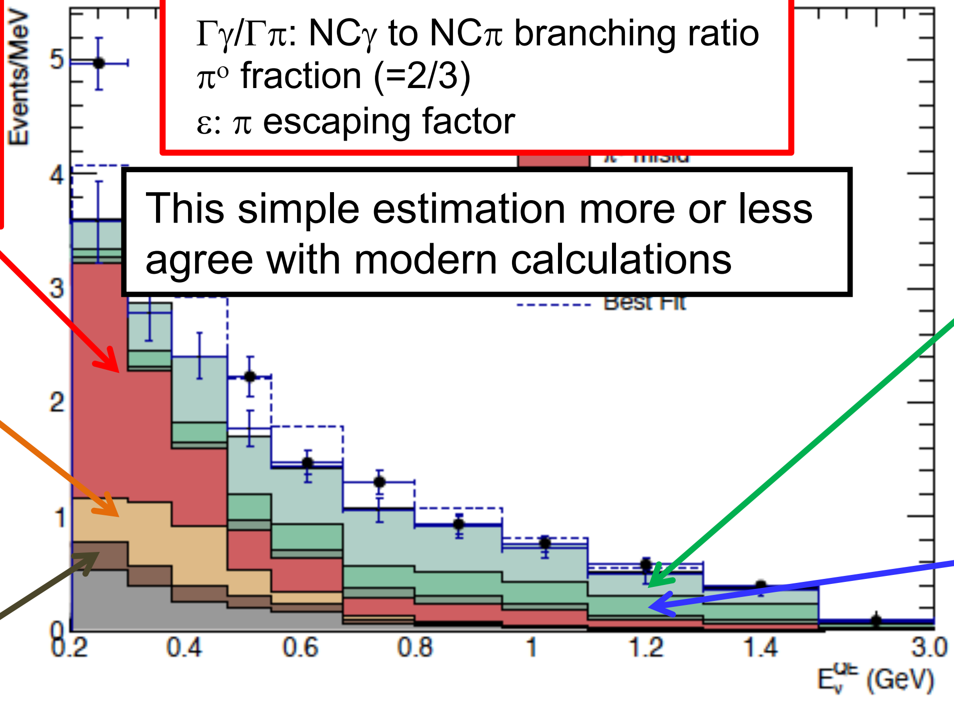
All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E



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 $\Delta \rightarrow N\gamma$	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

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

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

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

Δ resonance rate is constrained from measured NCπ^o rate

dirt rate is measured from dirt data sample

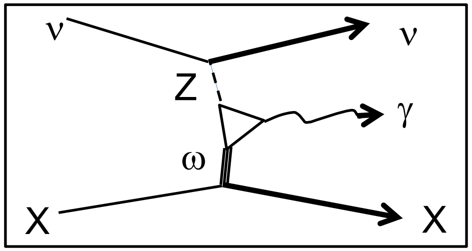
ν_e from μ decay is constrained from ν_μCCQE measurement

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

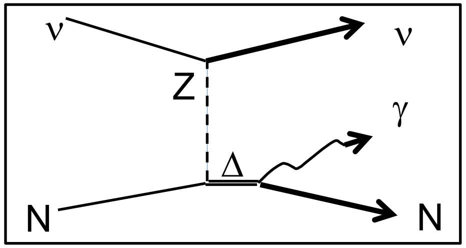
Harvey,Hill,Hill, PRL99(2007)261601, Lasorak, PhD thesis (Queen Mary, 2018)
Hill, PRD84(2011)017501, Zhang and Serot, PLB719(2013)409, Wang et al, PLB740(2015)16

5. Neutrino NC single photon production

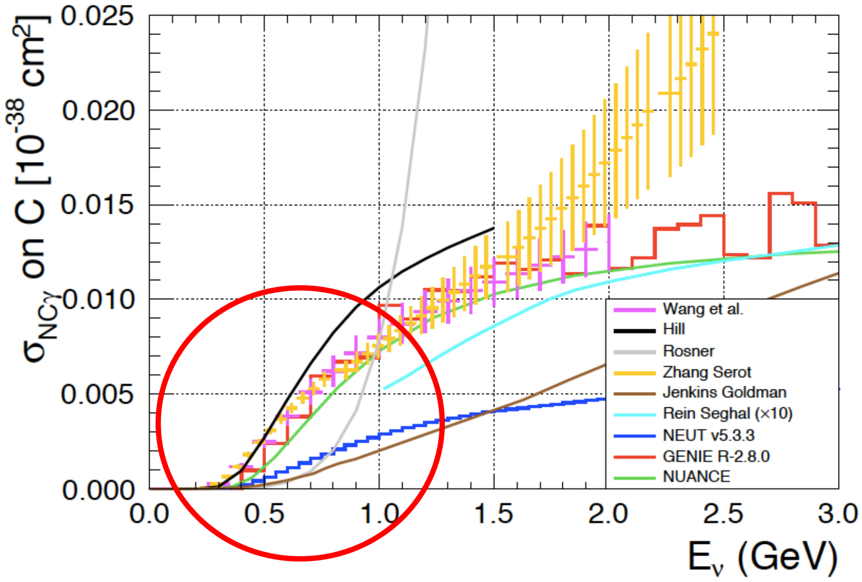
Many new calculations about NCγ process
- Within SM but not previously considered



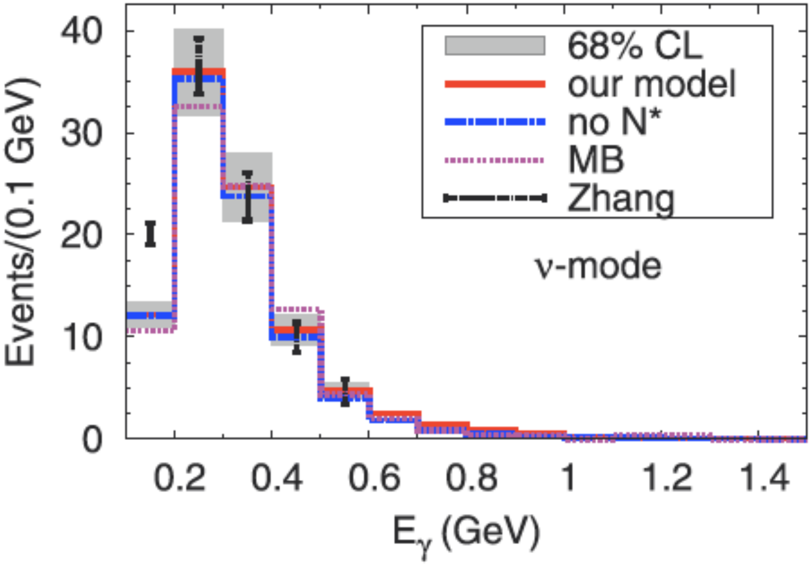
Anomaly mediated γ production



Δ-radiative decay
(with nuclear in-media effect)



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



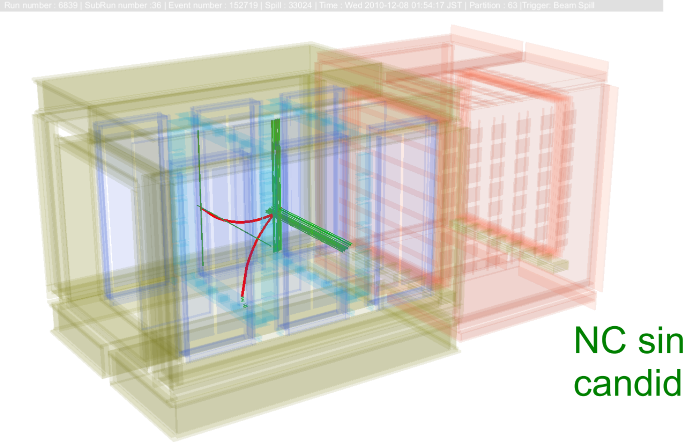
katori@fnal.g

T2K, ArXiV:1902.03848

5. Neutrino NC single photon production

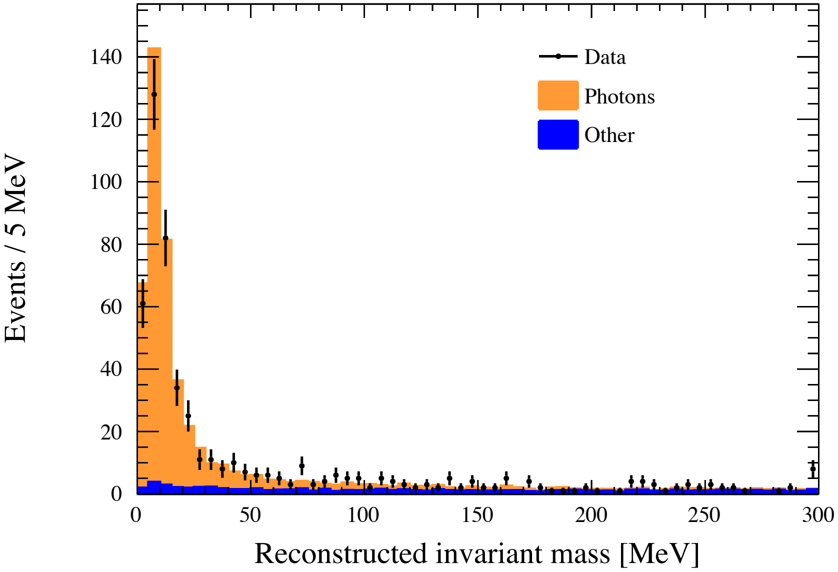
T2K near detector

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

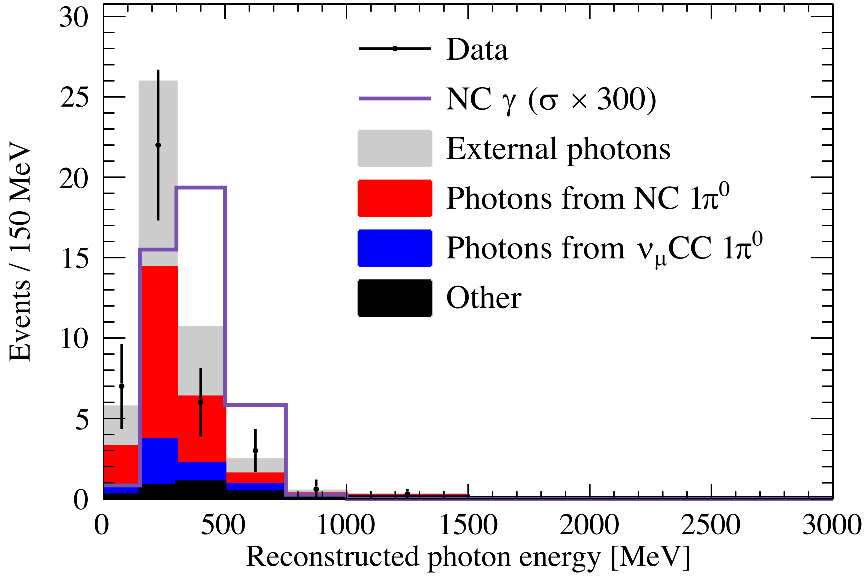


NC single gamma candidate event

Photon sample



NC single gamma sample



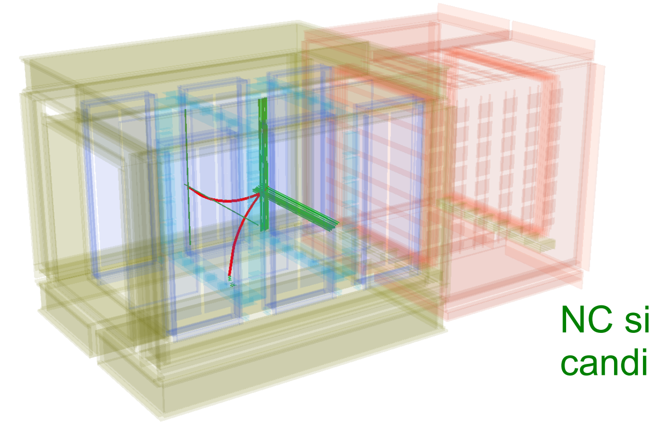
katori@fnal.gov

T2K, ArXiV:1902.03848
MicroBooNE, public note 1041 (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 on this process.



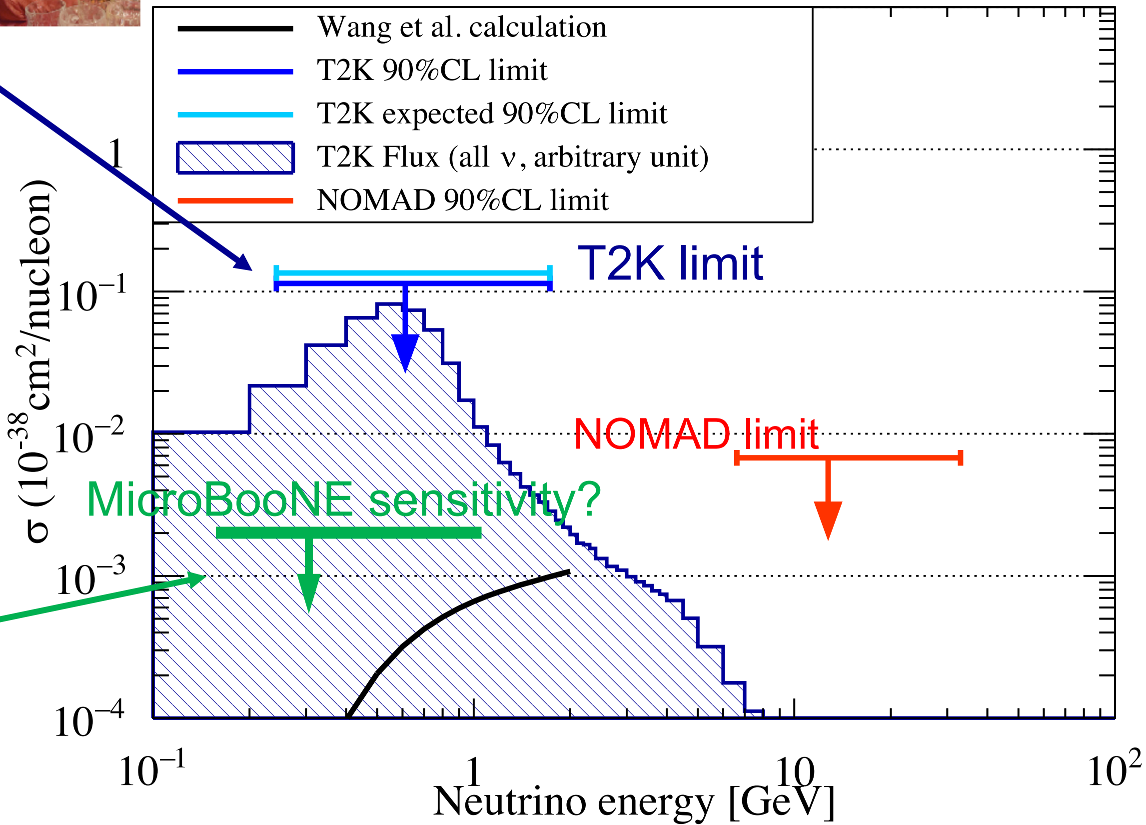
NC single gamma candidate event

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^o measurement

→ Good chance to measure the first positive signal of this channel.



Bobby Murrell
Manchester
(MicroBooNE)

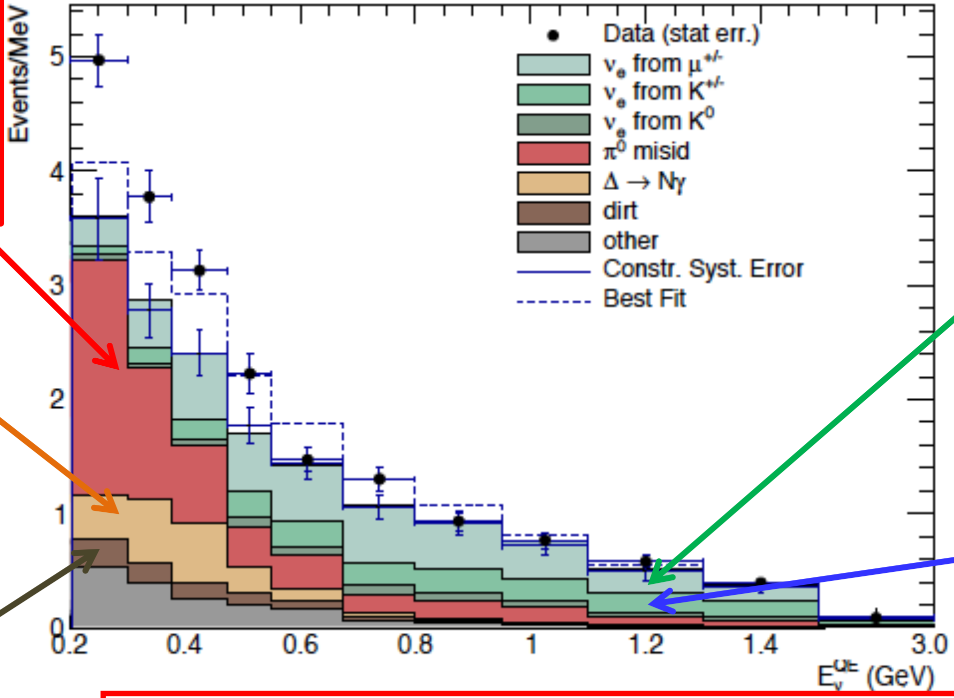
4. Internal background constraints

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

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. Results

5. Oscillation candidate event excess

200 < EνQE < 1250 MeV

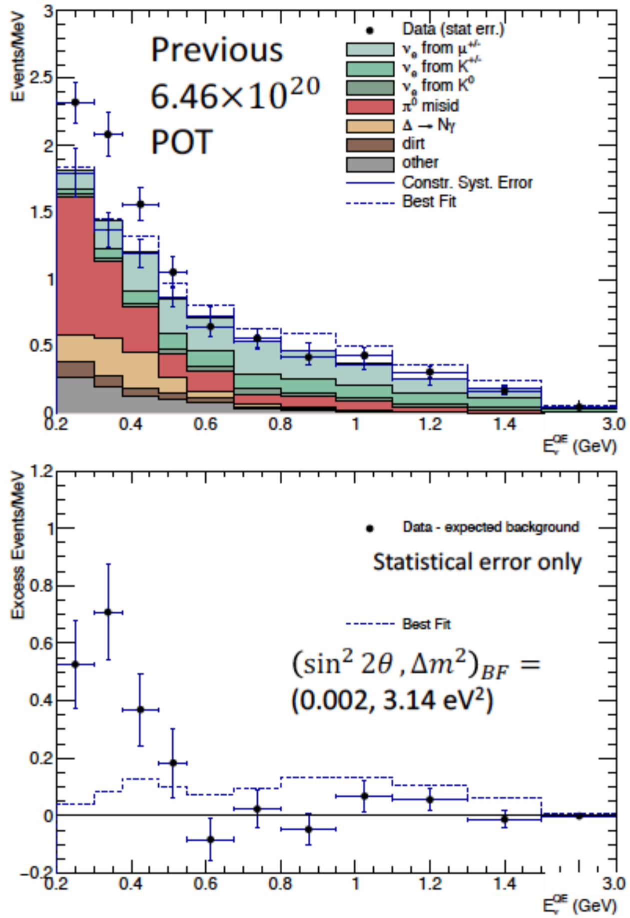
- neutrino mode: Data = 1959 events

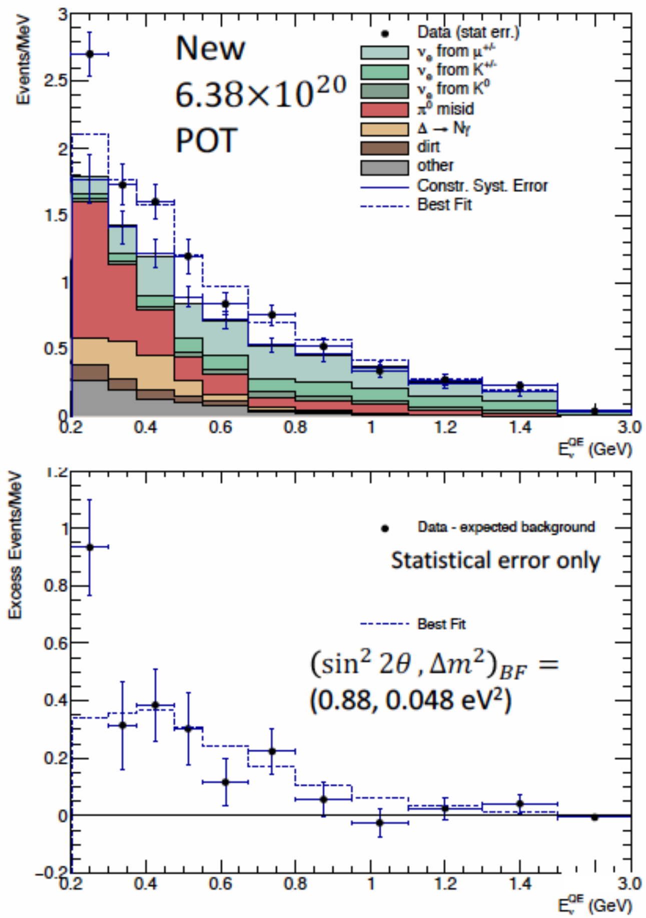
Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)

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

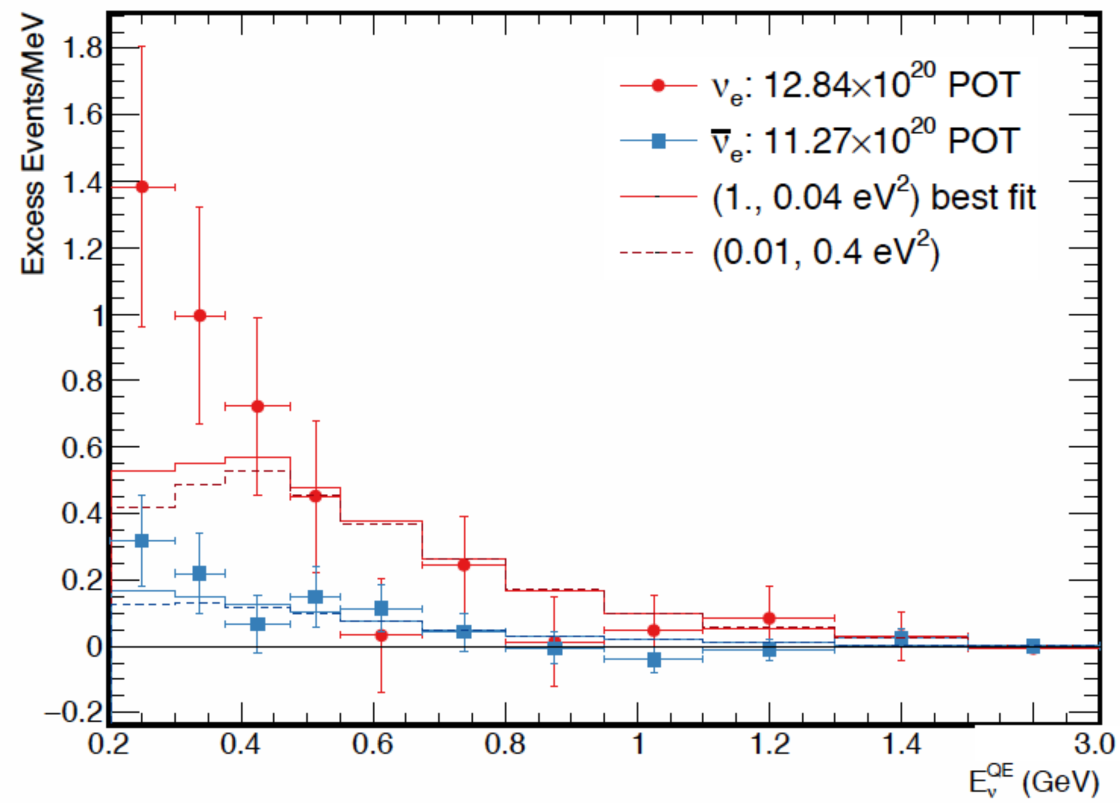
200 < EνQE < 1250 MeV

- neutrino mode: Data = 1959 events

Bkgd = 1577.8 ± 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)



Queen Mary University of London

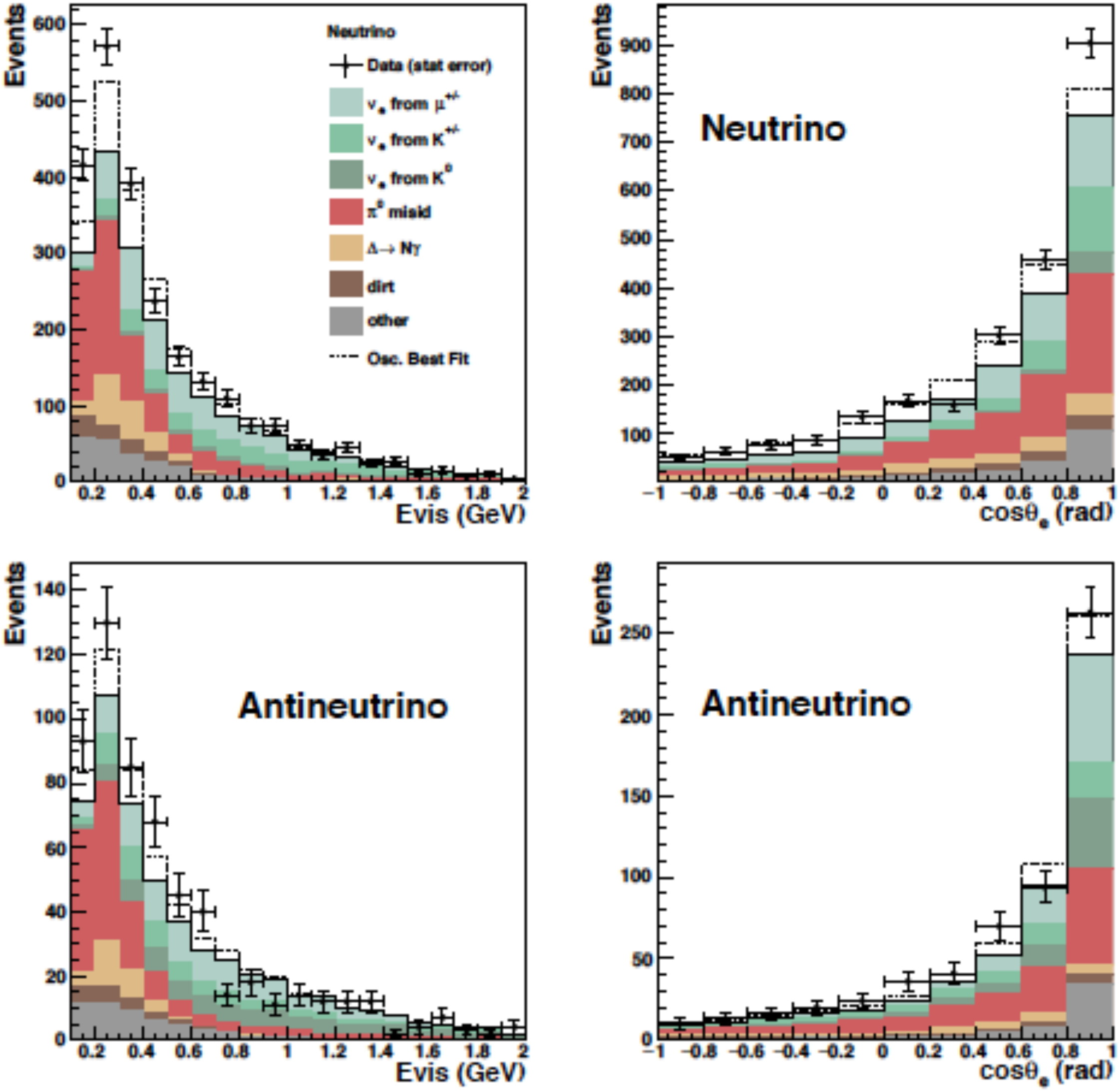
5. Explanations of MiniBooNE data

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?

Any intrinsic background (beam ν_e contamination) mismodeled? (unlikely)

or BSM physics?
 - BSM γ production process?
 - BSM e-scattering process?
 - BSM oscillation physics? (sterile neutrinos?)



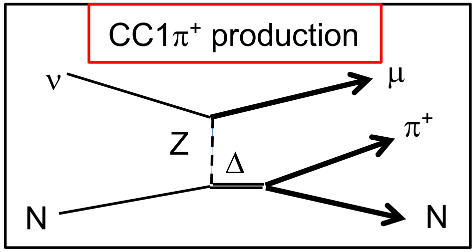
MINERvA,ArXiv:1903.01558

5. Pion puzzle (2019)

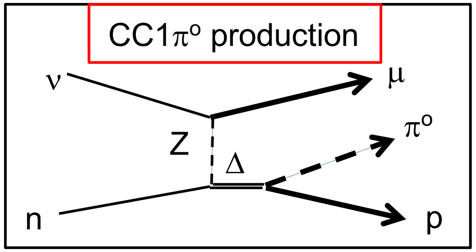
MINERvA CC1π^+, CCNπ^+, $\bar{\nu}$CC1π^o, νCC1π^o data for FSI + cross section models tuning

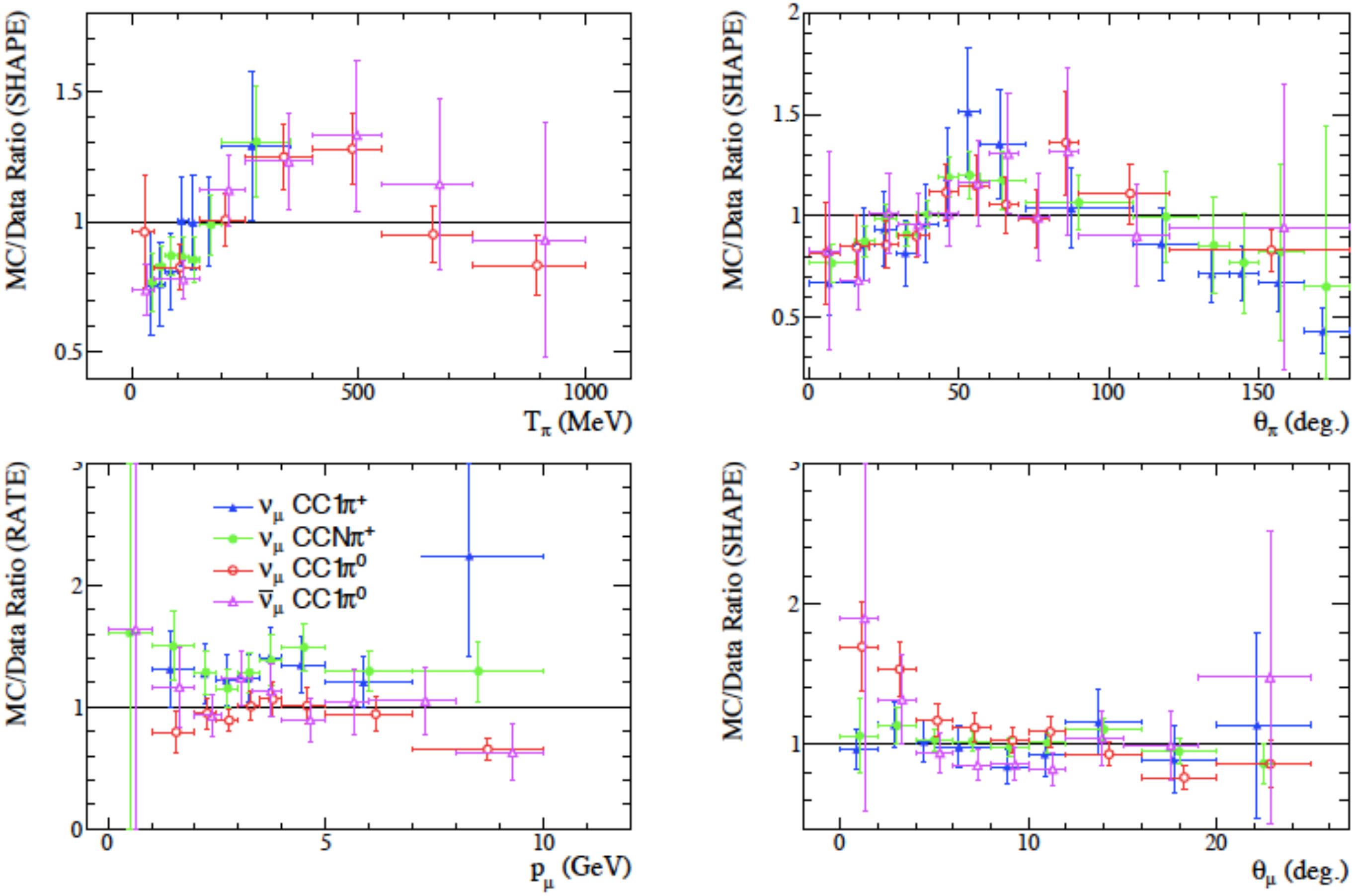
- state-of-the-art data-MC comparison for neutrino single pion production channels
- this moment, there is no clear way to tune MC to agree with data…

CC1π^+ and CCNπ^+ data have better shape agreement with GENIE



νCC1π^o and $\bar{\nu}$CC1π^o data have better normalization agreement with GENIE





Queen Mary
University of London

katori@fnal.gov

5. NuSTEC workshop on neutrino pion production

2019 October 2-5, PITTPACC, Univ. Pittsburgh
https://nustec.fnal.gov/pion19/

"The goal of the workshop is to bring experimentalists and theorists together to discuss the state and systematic uncertainties of the models in this critical region for the current and future long-baseline neutrino oscillation program. Although we aim to have detailed discussions amongst the experts, we strongly encourage early-career physicists working on this topic to attend. Below is a list of topics we expect to cover at the workshop."

Future of MiniBooNE

MiniBooNE run will be end on June 2019

- Expected to reach ~ 18E20POT in ν-mode
- The excess may reach ~ 5σ

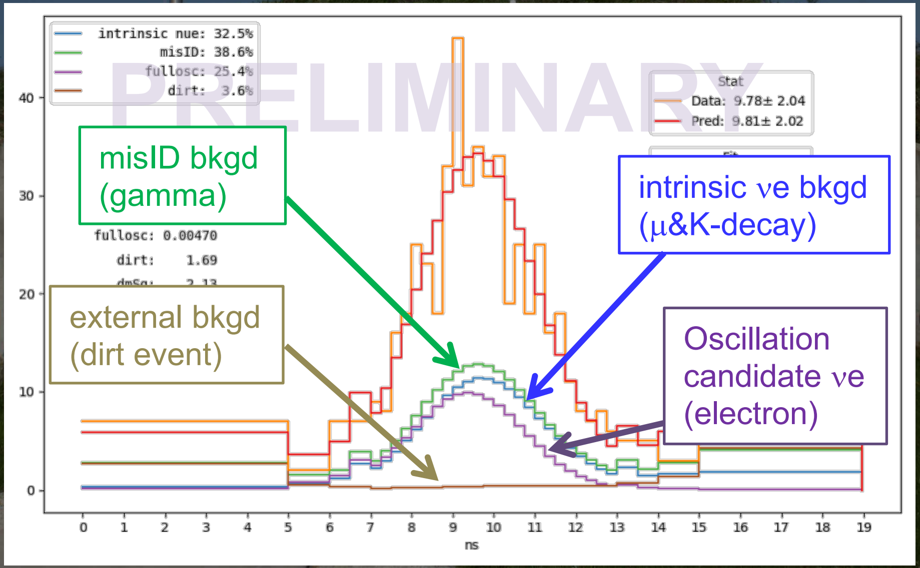
katori@fnal.gov

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



misID bkgd (gamma)

intrinsic νe bkgd (μ&K-decay)

external bkgd (dirt event)

Oscillation candidate νe (electron)

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!

katori@fnal.gov

backup

katori@fnal.gov

LSND, PRD64(2002)112007

1. LSND experiment

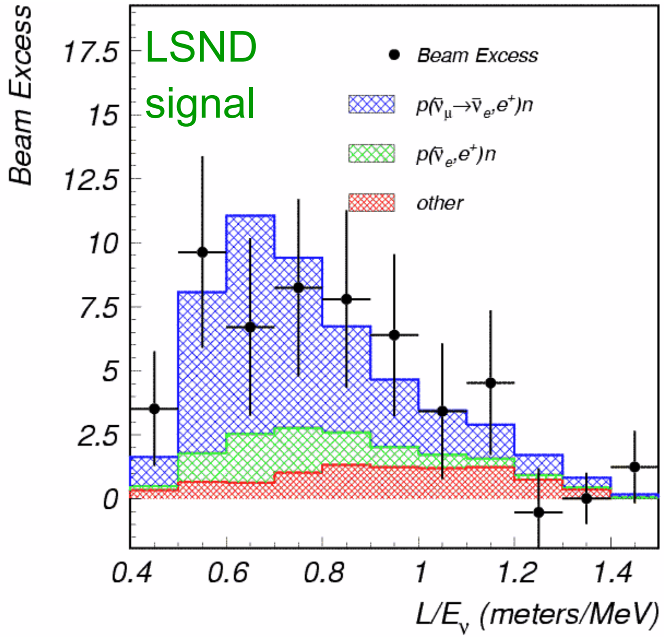
$$P(\nu_\mu \longrightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

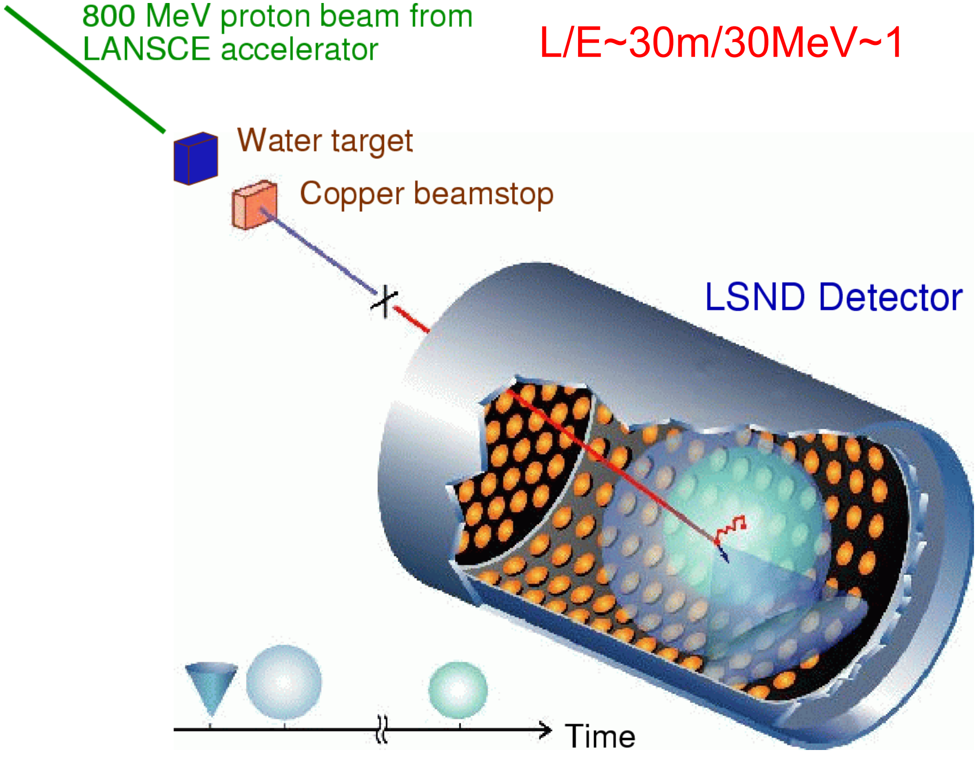
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

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

87.9 ± 22.4 ± 6.0 (3.8.σ)



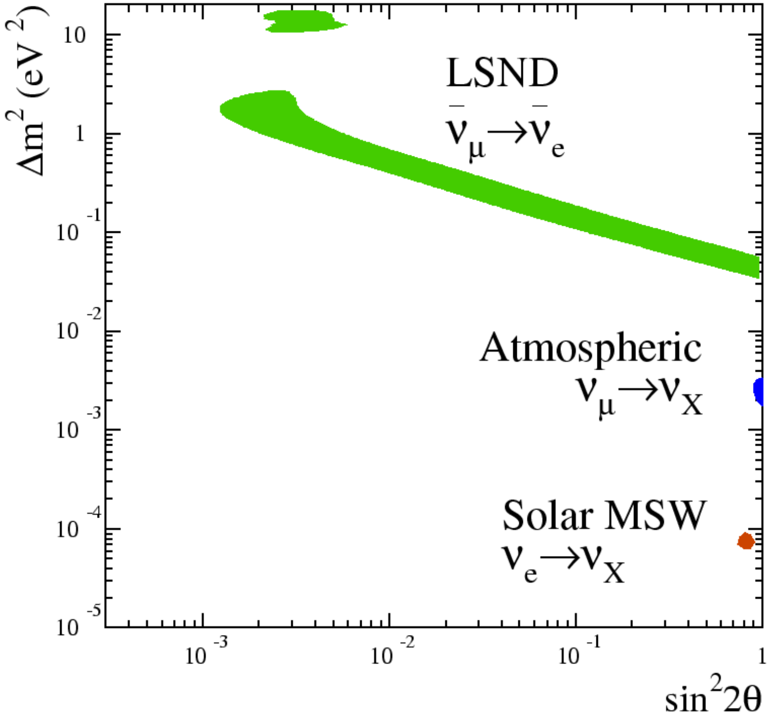
L/E~30m/30MeV~1



LSND, PRD64(2002)112007

1. LSND experiment

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

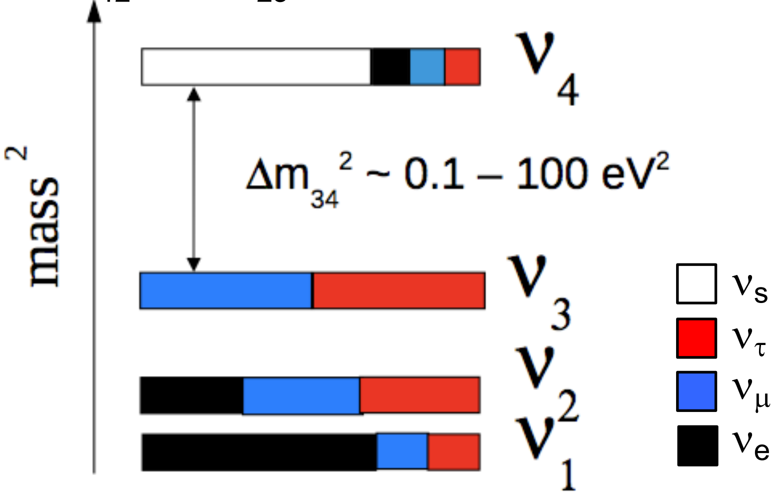


3 types of neutrino oscillations are found:

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

But we cannot have so many Δm^2!

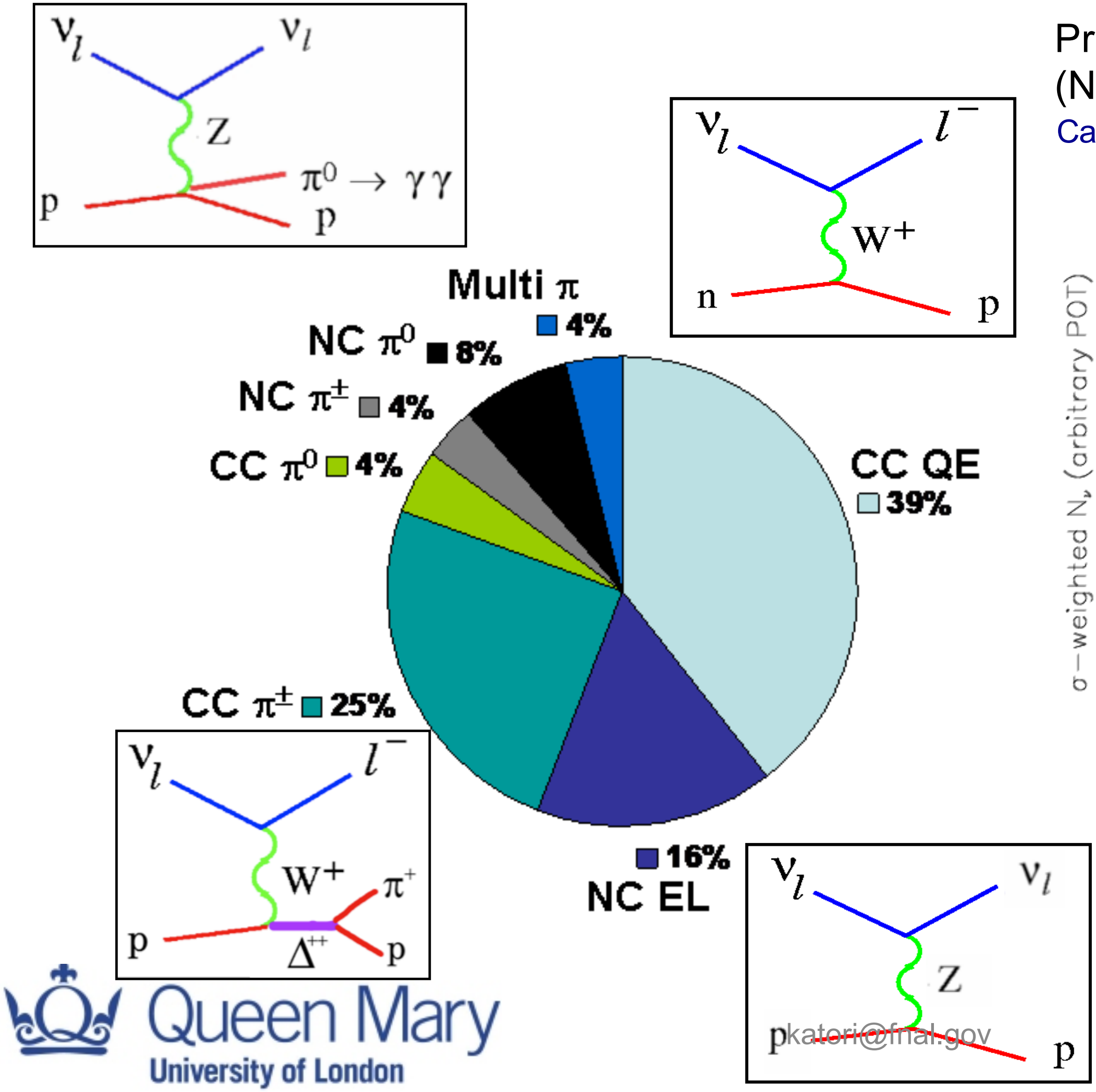
$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$



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

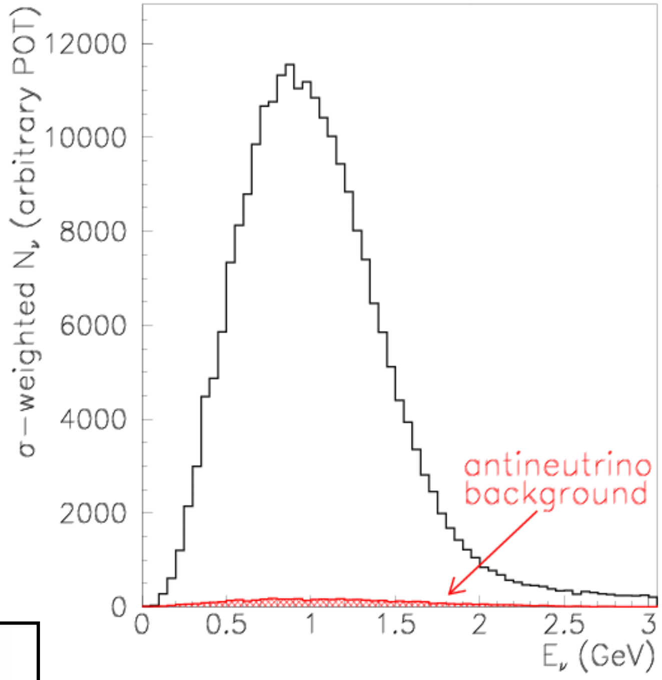
MiniBooNE is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

3. Cross section model



Predicted event rates before cuts (NUANCE Monte Carlo)

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

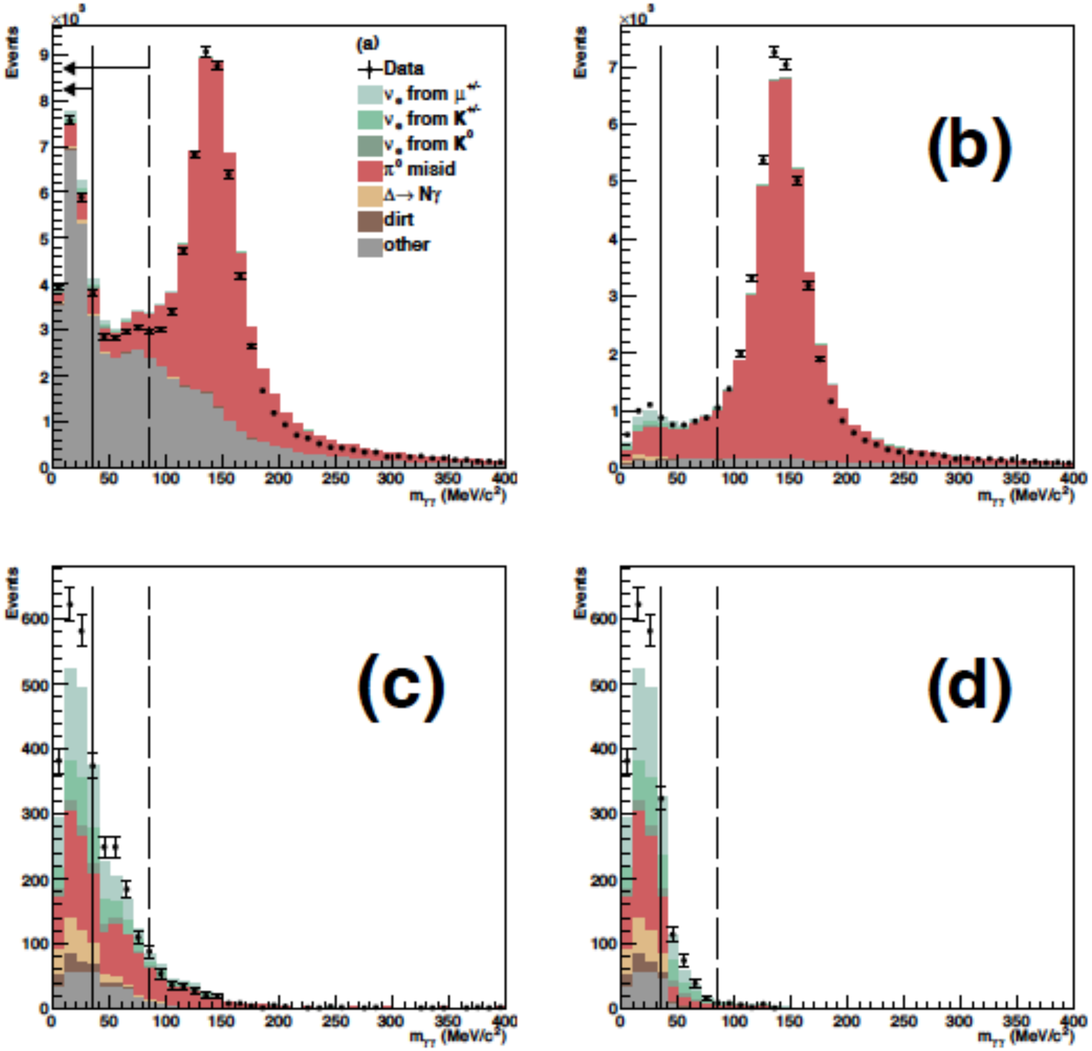


Event neutrino energy (GeV)

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.



Detler et al., JHEP08(2018)010

5. Sterile neutrino hypothesis

200 < EνQE < 1250 MeV

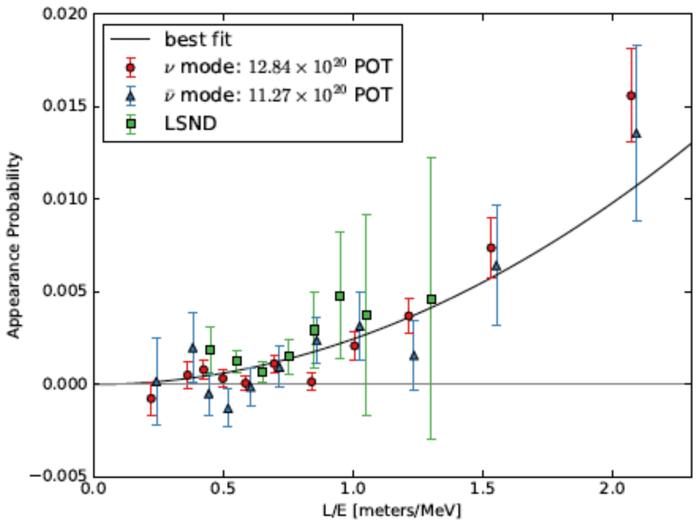
- neutrino mode: Data = 1959 events

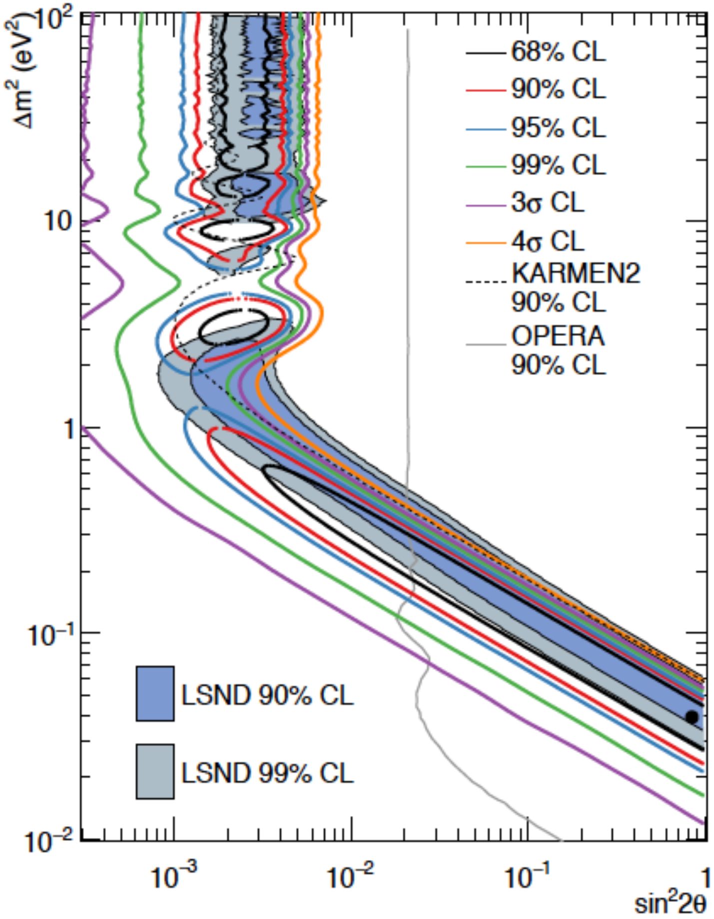
Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)

- antineutrino mode: Data = 478 events

Bkgd = 398.7 ± 20.0(stat) ± 20.3(syst) → 79.3 ± 28.6 excess (2.8σ)

Compatible with LSND excess within 2-neutrino oscillation hypothesis





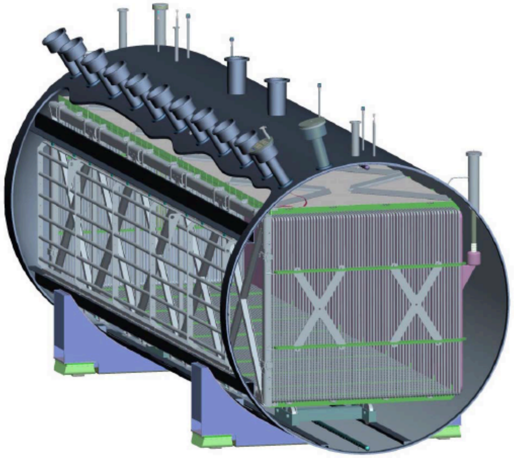
However, appearance and disappearance data have a strong tension (Maltoni, Neutrino 2018)

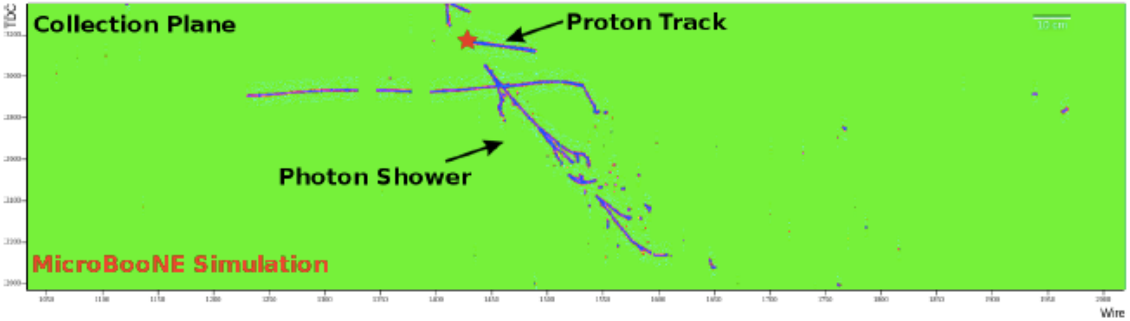
MicroBooNE,JINST12(2017)P02017, Public Note: 1041

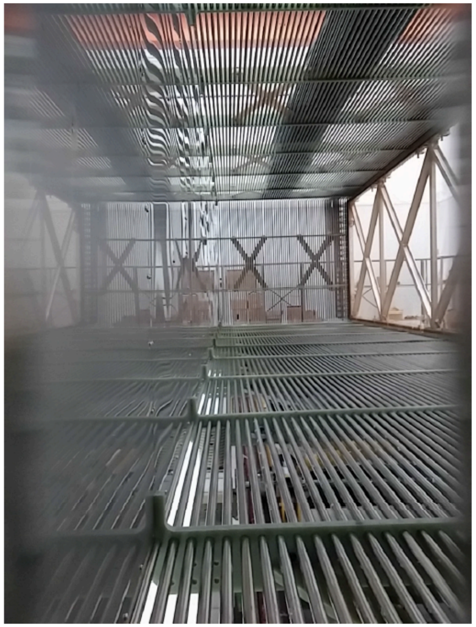
5. Liquid argon time projection chamber

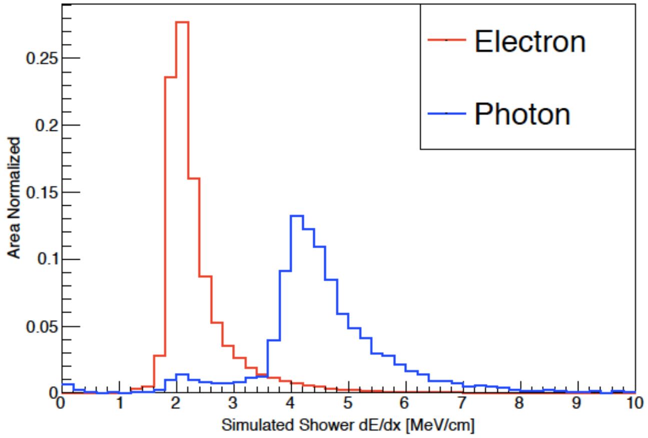
MicroBooNE experiment at Fermilab

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





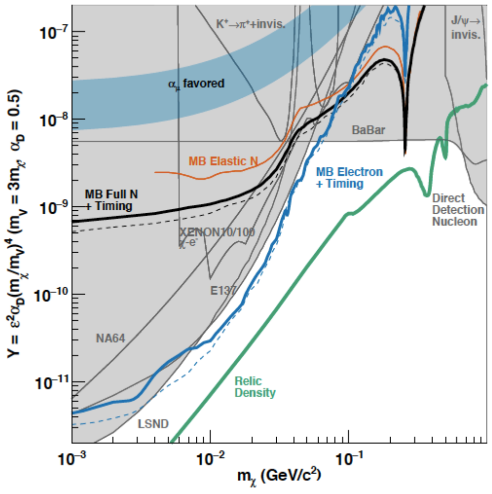




dE/dx of first 4cm track (simulation)

deNiverville et al, PRD84(2011)075020
MiniBooNE-DM, PRD98(2018)112004

5. BSM electron scattering models



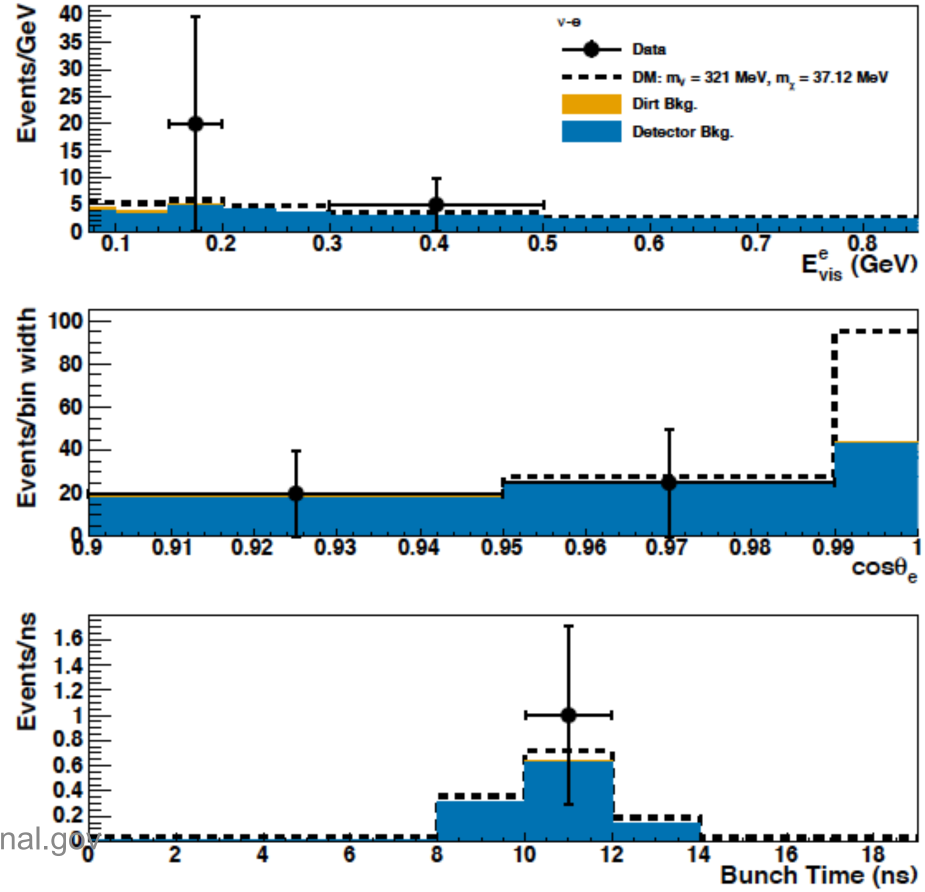
(a) vector portal

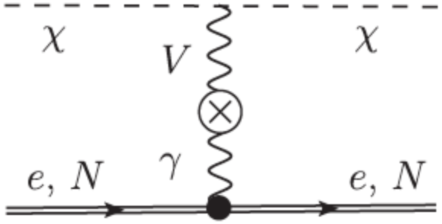
Dark matter particle - electron scattering

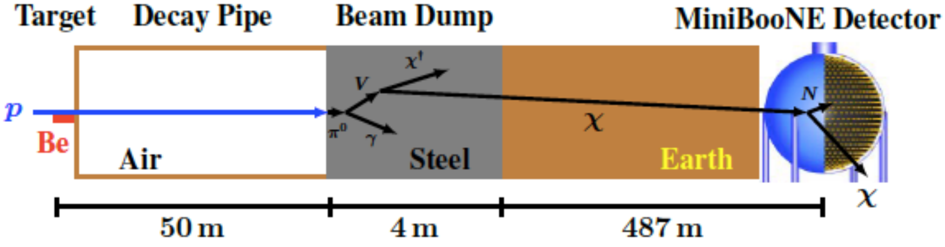
New particles created in the beam dump can scatter electrons in the detector.

However, MiniBooNE beam dump mode data shows no excess.

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



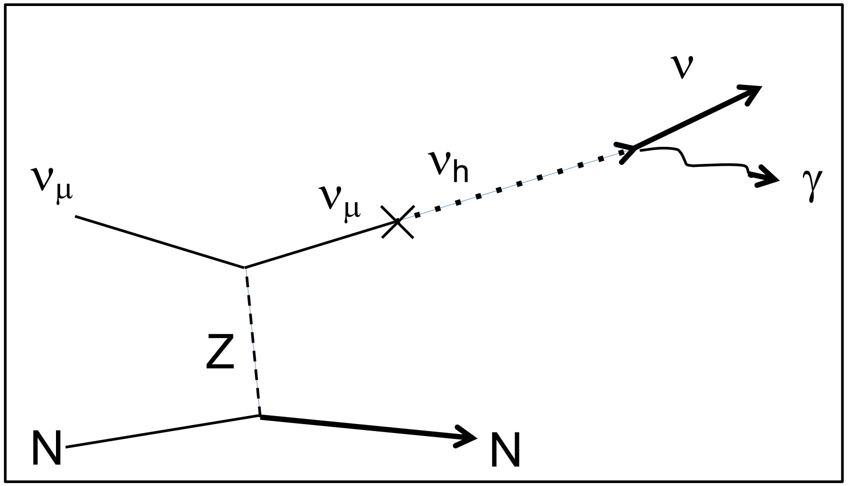




Gninenko, PRL103(2009)241802 and many others, Jordan et al.,ArXiv:1810.07185

5. BSM photon production models

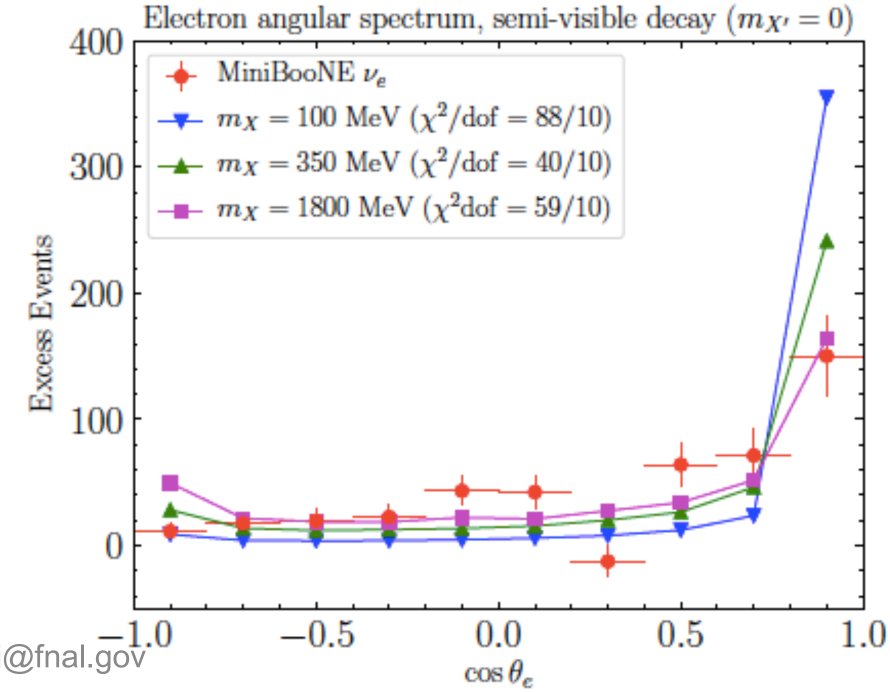
heavy neutrino decay



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.



katori@fnal.gov

Gninenko, PRL103(2009)241802 and many others, Jordan et al.,ArXiv:1810.07185
Ballett, et al, JHEP04(2017)102, Bertuzzo et al.,PRL121(2018)241801, Argüelles et al., ArXiv:1812.08768

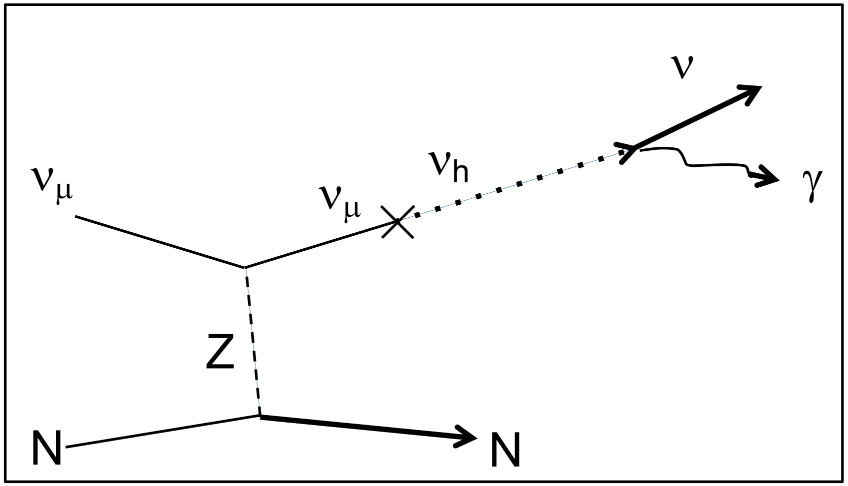
5. BSM e+e- production models

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.

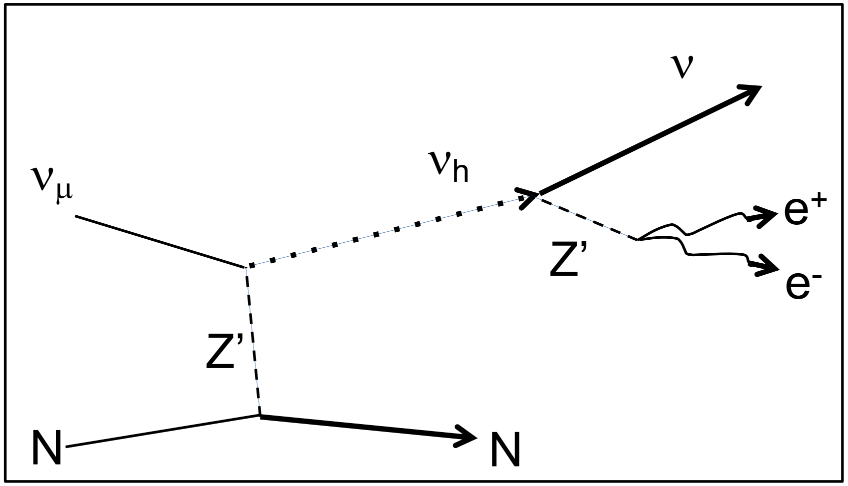
These models have problems because they cannot reproduce the angular distribution of oscillation candidates.

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



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

5. BSM neutrino oscillation models

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

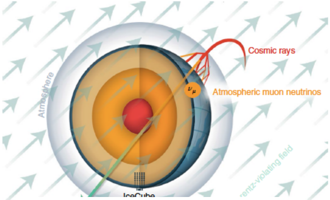
$$h^{\nu}_{\rm eff} = A\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

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.

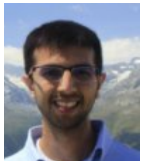
Test of Lorentz violation with neutrinos

- Almost all neutrino experiments look for Lorentz violation.
- Current best limits of Lorentz violation by neutrinos;
  - CPT-odd (dimension-3) $< 2.0\times10^{-24}$ GeV
  - CPT-even (dimension-4) $< 2.8\times10^{-28}$



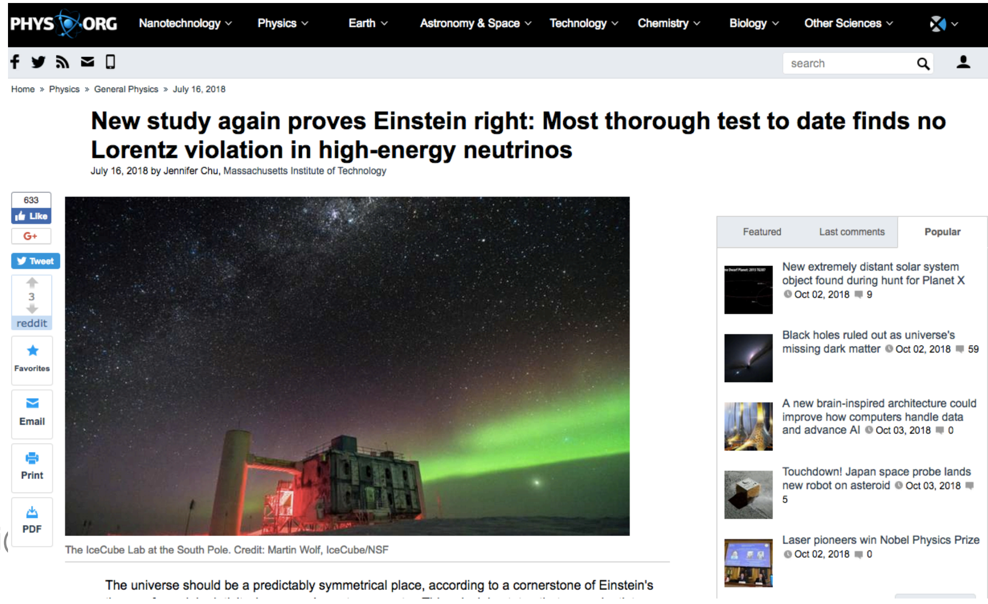
Nature Physics 14(2018)961

IceCube



Shivesh Mandalia (Queen Mary)

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



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

New extremely distant solar system object found during hunt for Planet X Oct 02, 2018 9

Black holes ruled out as universe's missing dark matter Oct 02, 2018 59

A new brain-inspired architecture could improve how computers handle data and advance AI Oct 03, 2018 0

Touchdown! Japan space probe lands new robot on asteroid Oct 03, 2018 5

Laser pioneers win Nobel Physics Prize Oct 02, 2018 0