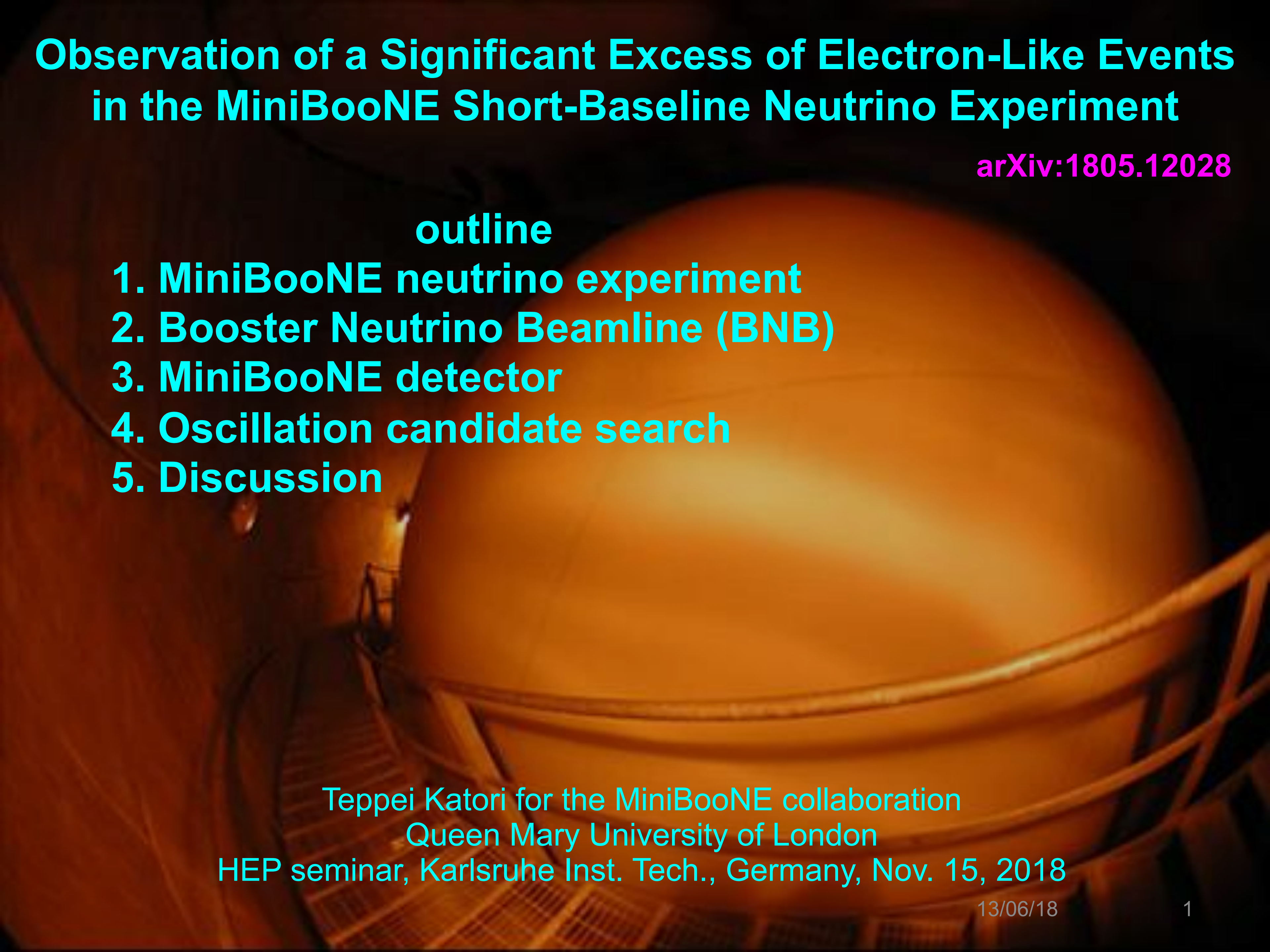


Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

arXiv:1805.12028

outline

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

Teppei Katori for the MiniBooNE collaboration
Queen Mary University of London
HEP seminar, Karlsruhe Inst. Tech., Germany, Nov. 15, 2018

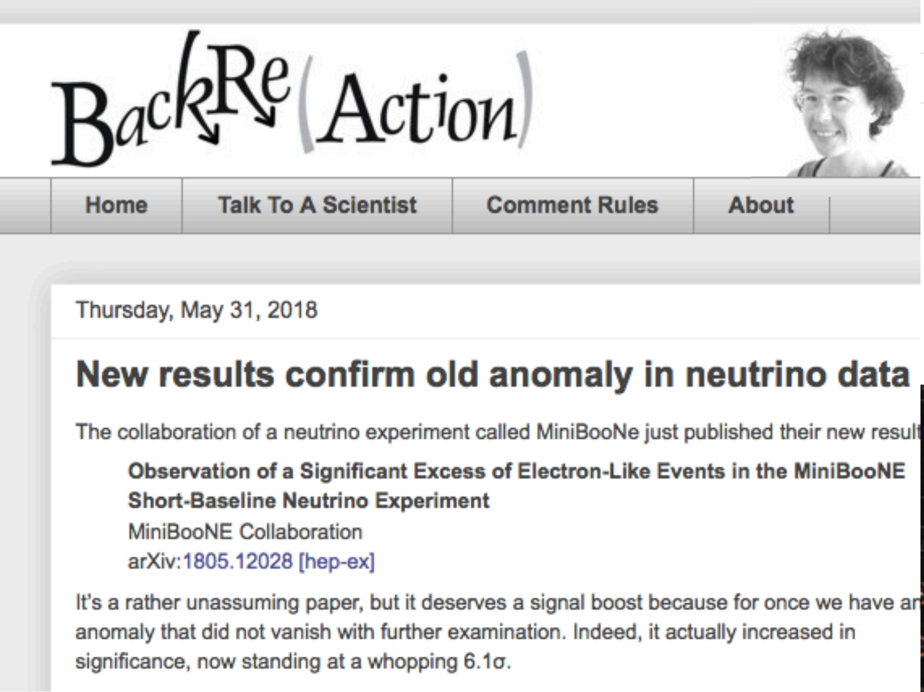
1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion



Thursday, May 31, 2018

New results confirm old anomaly in neutrino data

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

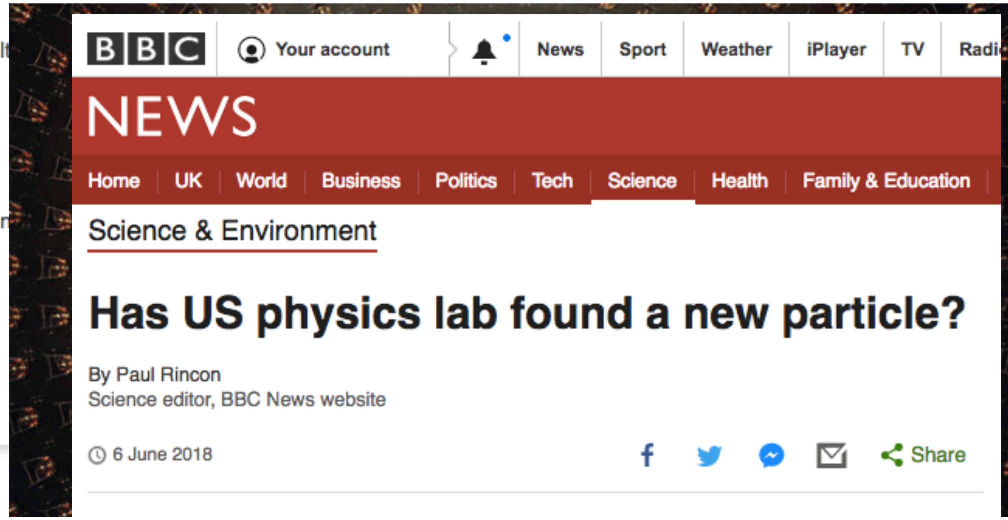
Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment
MiniBooNE Collaboration
arXiv:1805.12028 [hep-ex]

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.

PHYSICS

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

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

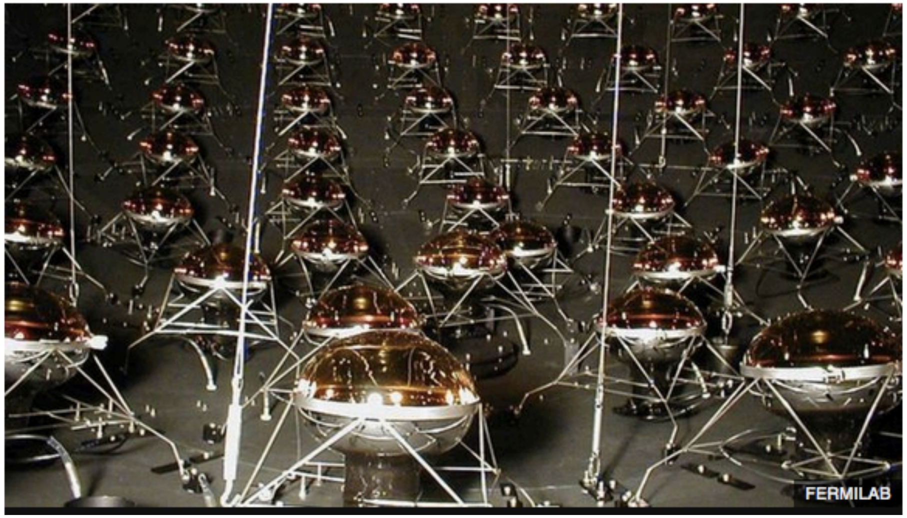


Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

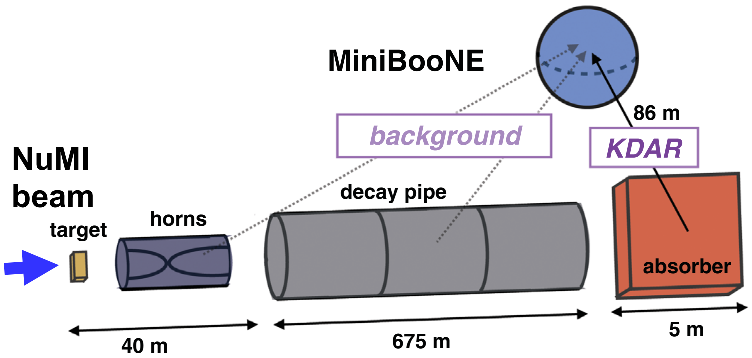
6 June 2018

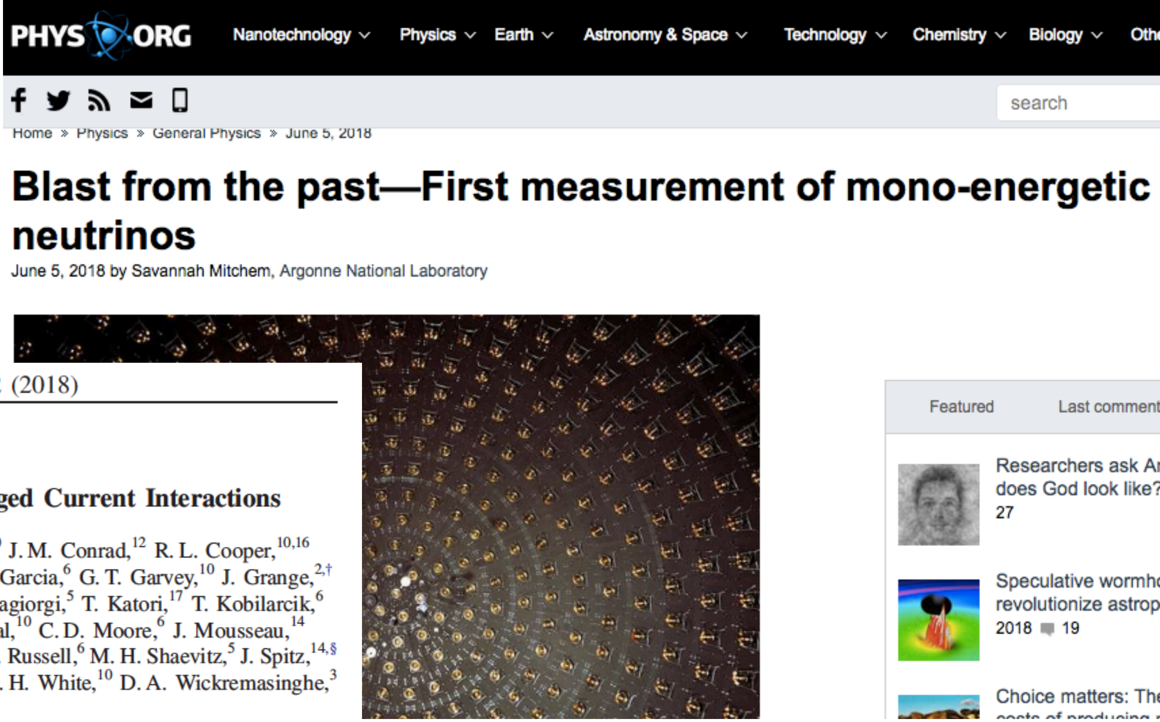

FERMILAB

ABSTRACTIONS BLOG

Evidence Found for a New Fundamental Particle

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





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

Researchers ask Ar
does God look like?
27

Speculative wormh
revolutionize astrop
2018 19

Choice matters: The
costs of producing

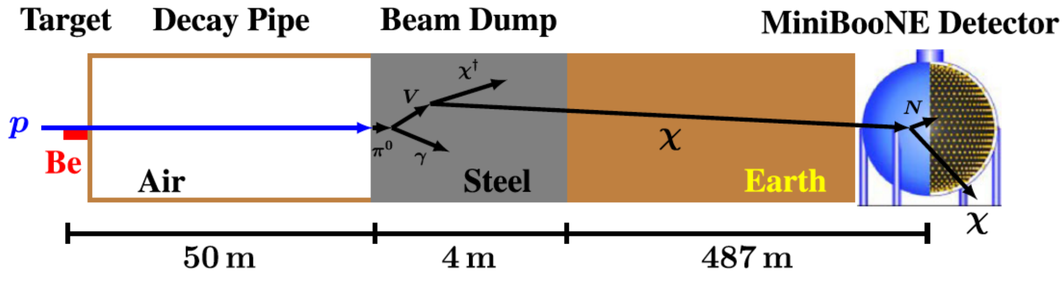
PHYSICAL REVIEW LETTERS **120,** 141802 (2018)

Editors' Suggestion **Featured in Physics**

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions

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

PRL120(2018)141802 (MiniBooNE Collaboration)



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!

HYSICAL 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

LSND, PRD64(2002)112007

1. LSND experiment

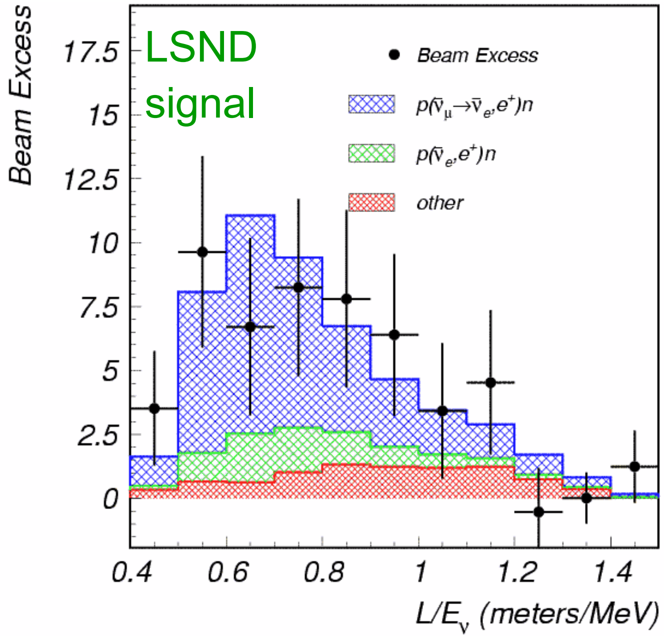
$$P(\nu_\mu \longrightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

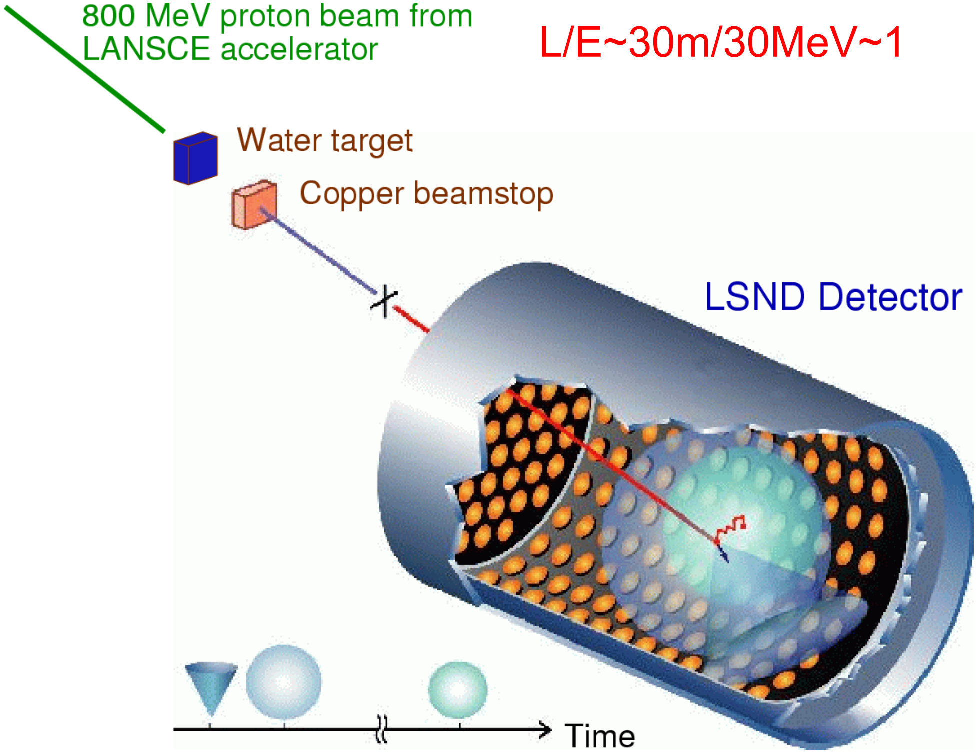
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

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

87.9 ± 22.4 ± 6.0 (3.8.σ)

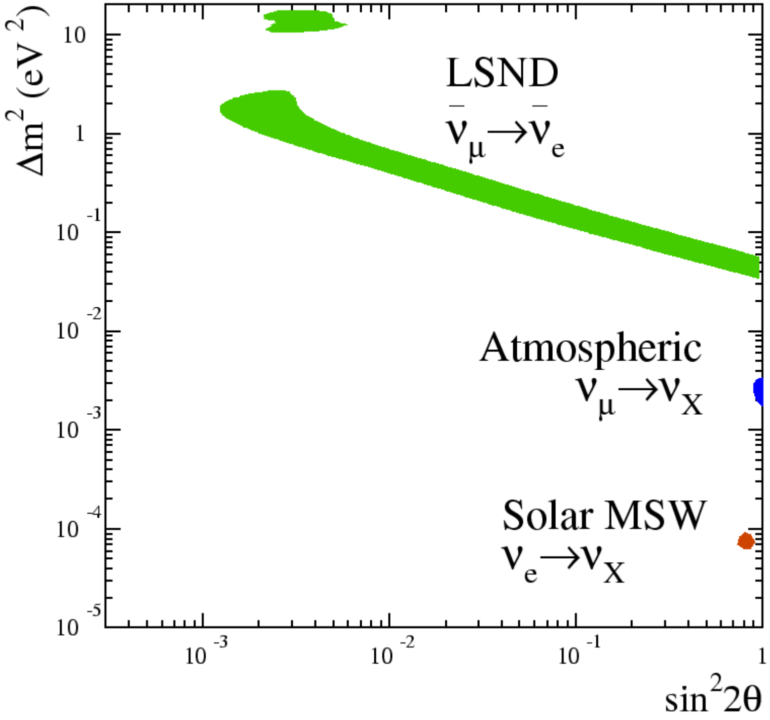


L/E~30m/30MeV~1



LSND, PRD64(2002)112007

1. LSND experiment

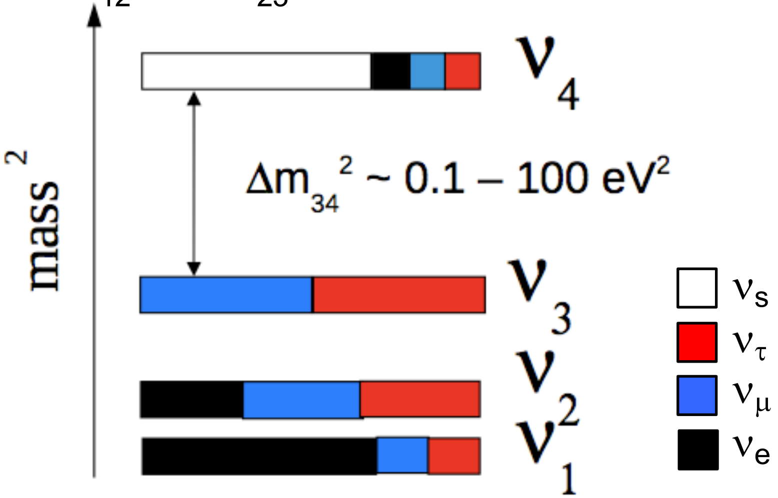


3 types of neutrino oscillations are found:

LSND neutrino oscillation: Δm^2~1eV^2
Atmospheric neutrino oscillation: Δm^2~10-3eV^2
Solar neutrino oscillation : Δm^2~10-5eV^2

But we cannot have so many Δm2!

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



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 Δm^2~1eV^2

1. MiniBooNE experiment

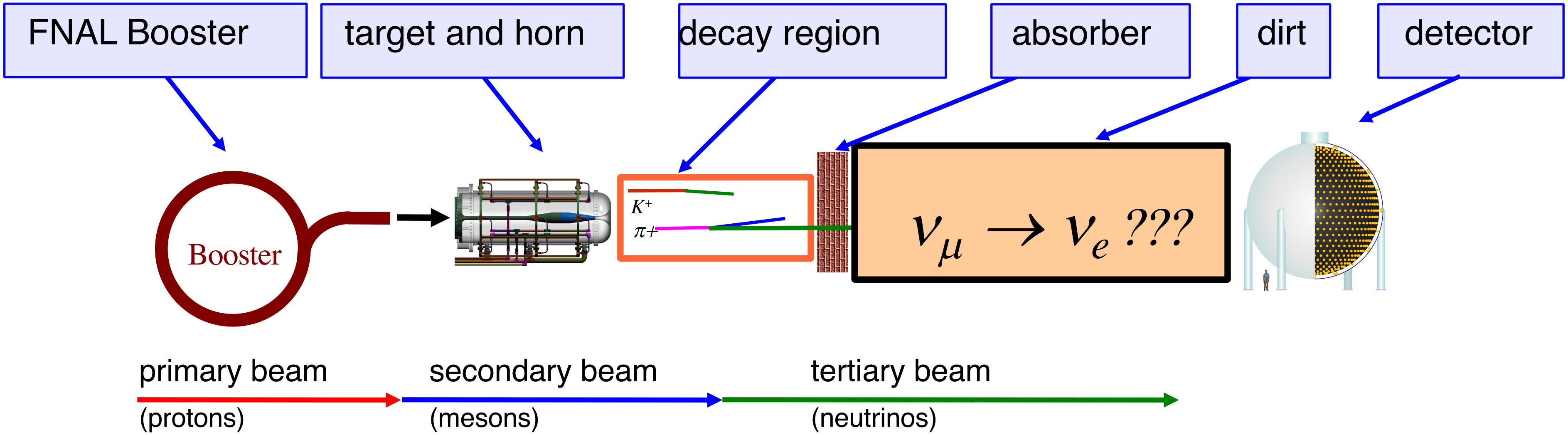
$$P(\nu_\mu \longrightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

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

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



FNAL Booster

target and horn

decay region

absorber

dirt

detector

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

primary beam
(protons)

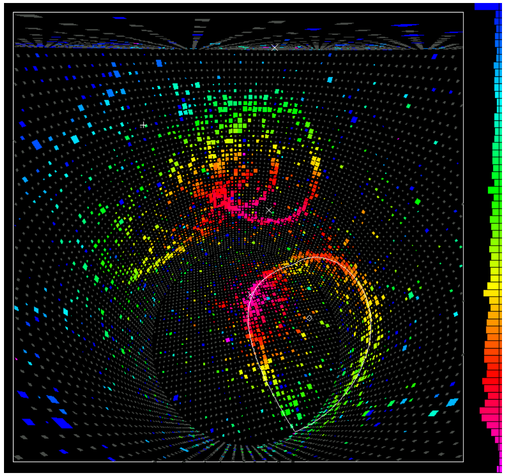
secondary beam
(mesons)

tertiary beam
(neutrinos)

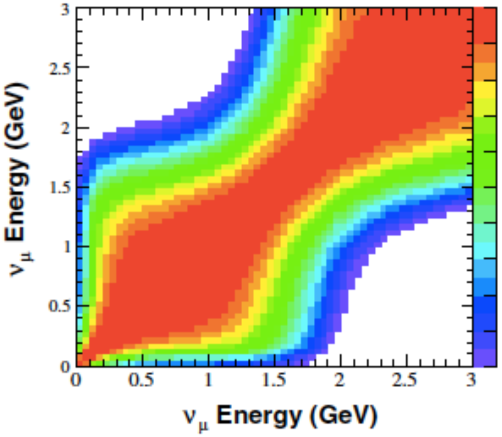
MiniBooNE has;
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

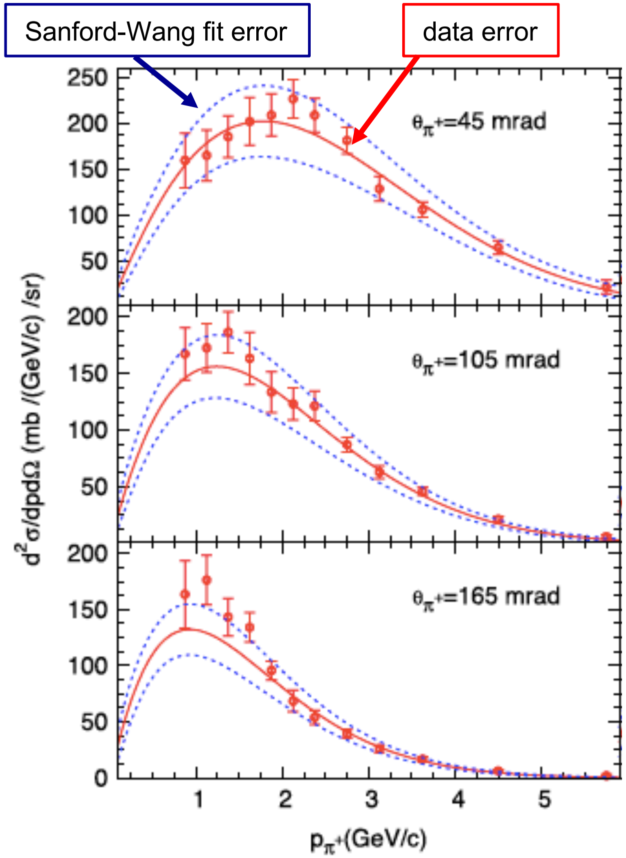
1. MiniBooNE is extremely influential! – Tools

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



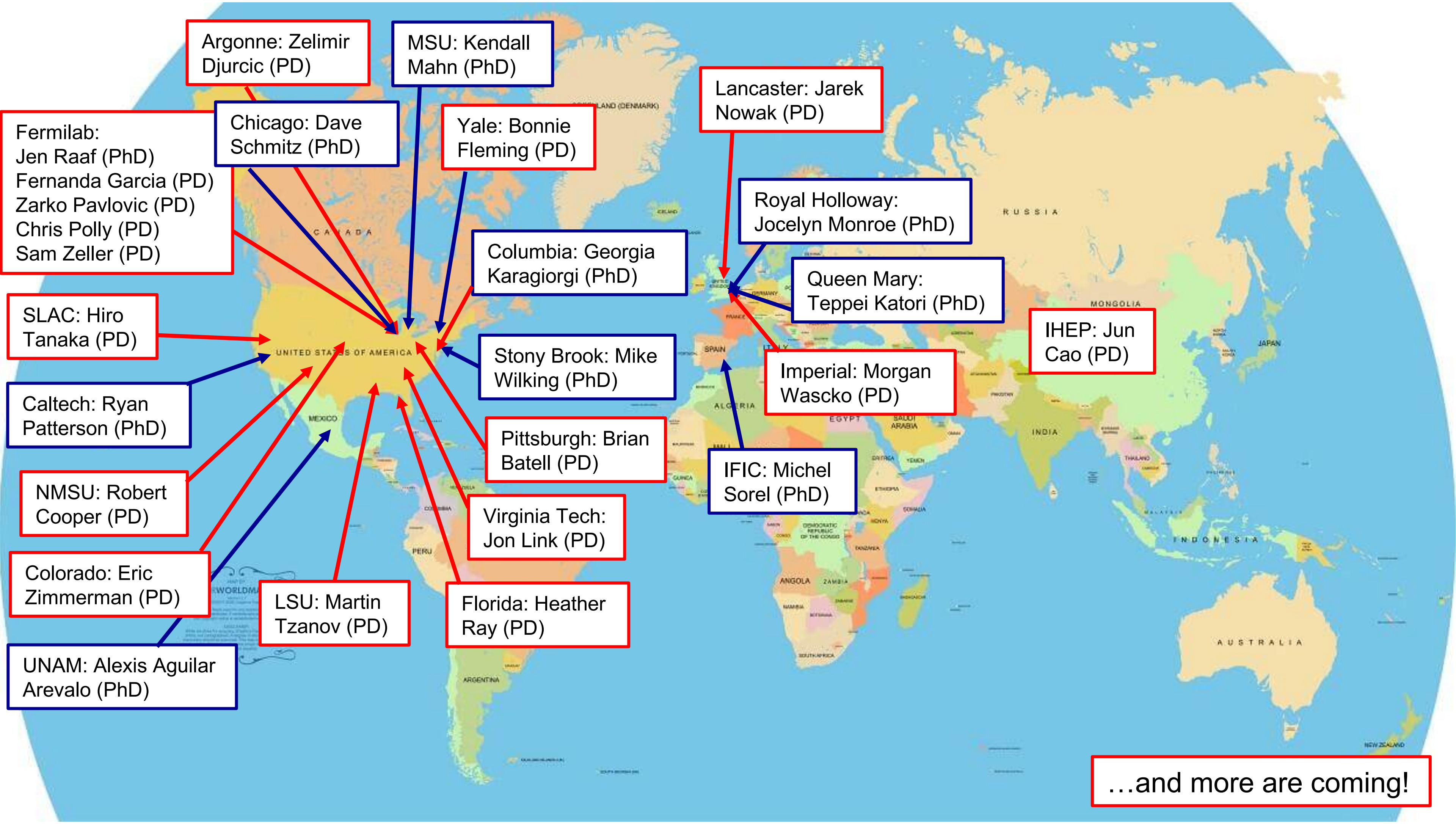
Flux systematic error: MiniBooNE: PRD79(2009)072002
- Errors are derived directly from hadron production data (spline fit), not any flux model.
- Event weighted with multiverse simulation to make a smooth covariance matrix with taking account all correlations correctly.





Online remote shift:
- <1 event per minute
- Even 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



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)

SLAC: Hiro Tanaka (PD)

IHEP: Jun Cao (PD)

Stony Brook: Mike Wilking (PhD)

Imperial: Morgan Wascko (PD)

Caltech: Ryan Patterson (PhD)

Pittsburgh: Brian Batell (PD)

IFIC: Michel Sorel (PhD)

NMSU: Robert Cooper (PD)

Virginia Tech: Jon Link (PD)

Colorado: Eric Zimmerman (PD)

LSU: Martin Tzanov (PD)

Florida: Heather Ray (PD)

UNAM: Alexis Aguilar Arevalo (PhD)

…and more are coming!

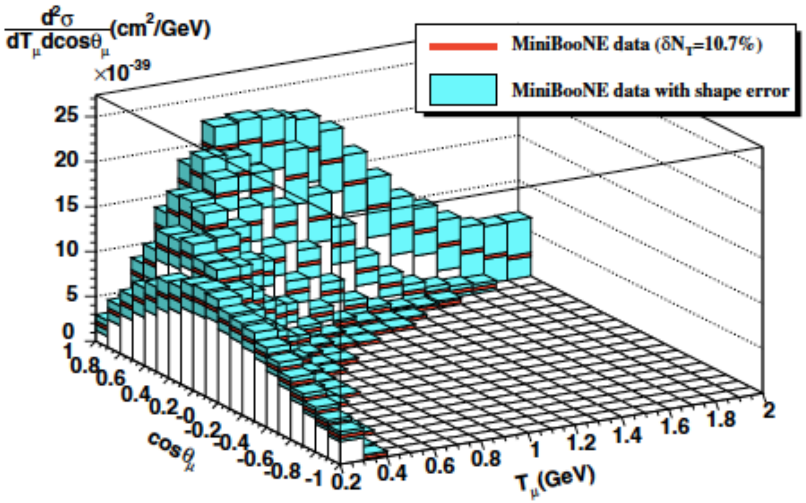
MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

1. MiniBooNE is extremely influential! – Cross Sections

Flux-integrated differential cross section:

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

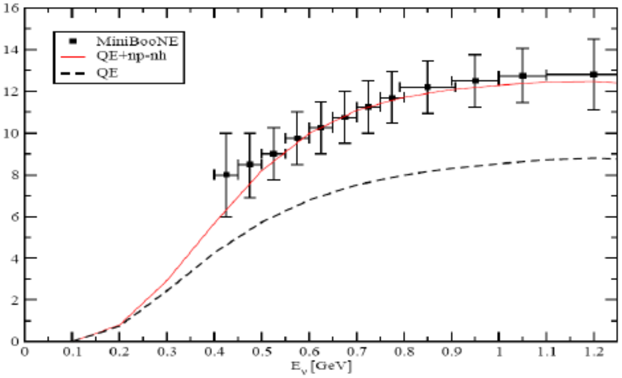
PHYSICAL REVIEW D 81, 092005 (2010)

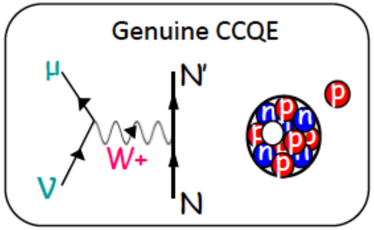


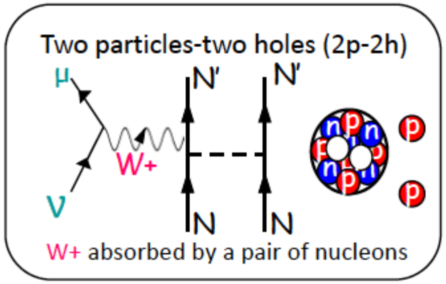
An explanation of this puzzle

(Slide from Marco Martini)

Inclusion of the multinucleon emission channel (np-nh)







W+ absorbed by a pair of nucleons

Discovery of nucleon correlation in neutrino scattering:

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

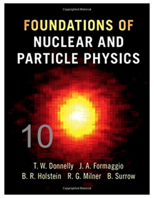
Particle Data Group

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

On going effort from MiniBooE initiative!

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

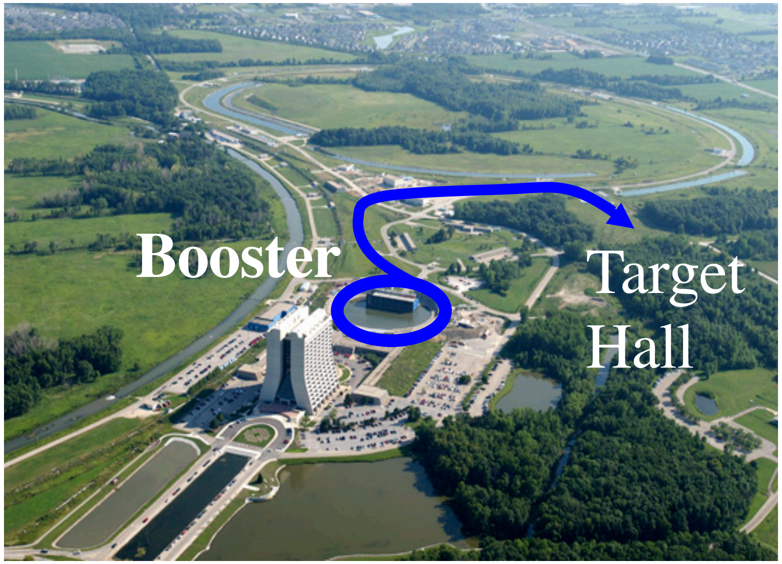
2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

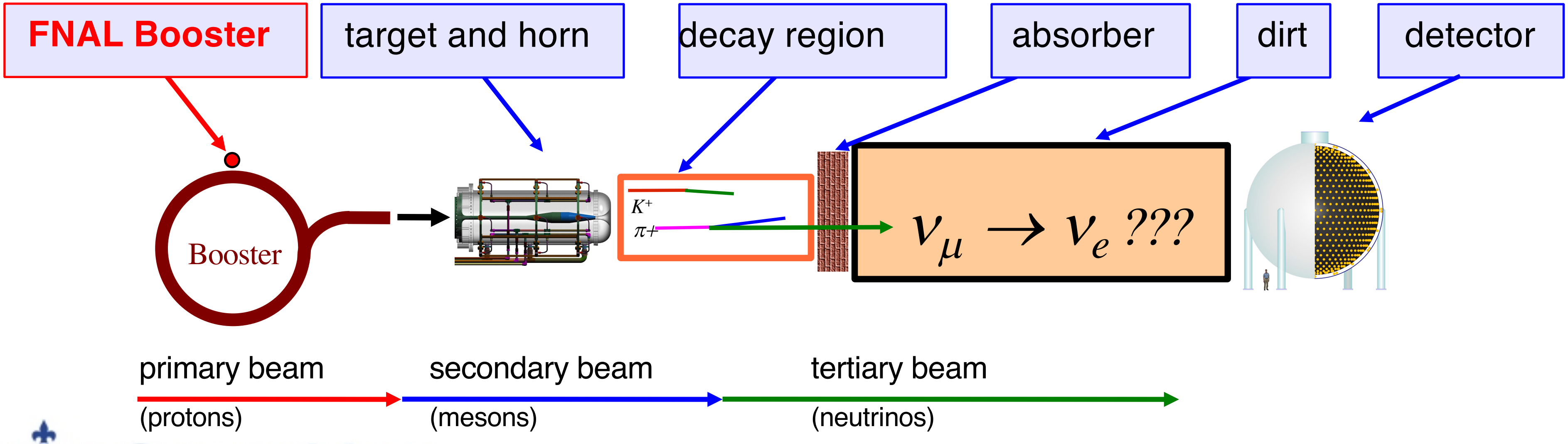
5. Discussion

2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster



FNAL Booster

target and horn

decay region

absorber

dirt

detector

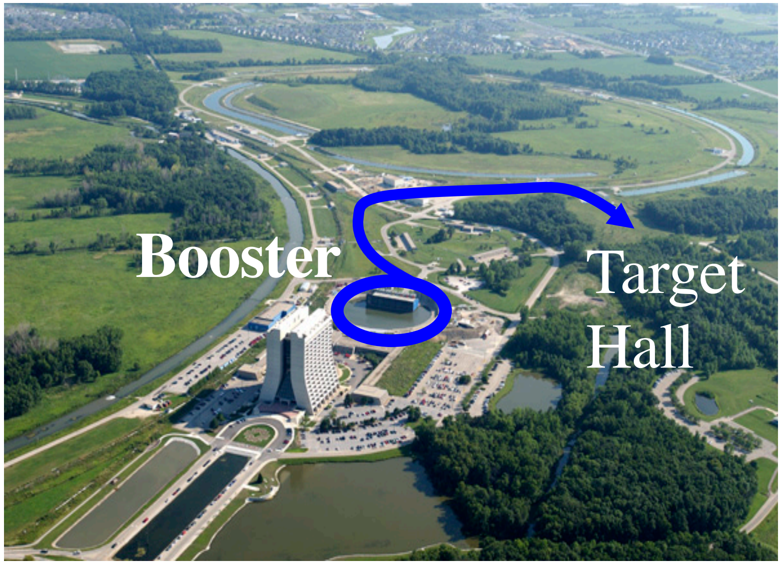
$$\nu_\mu \rightarrow \nu_e\ ???$$

primary beam
(protons)

secondary beam
(mesons)

tertiary beam
(neutrinos)

2. Neutrino beam



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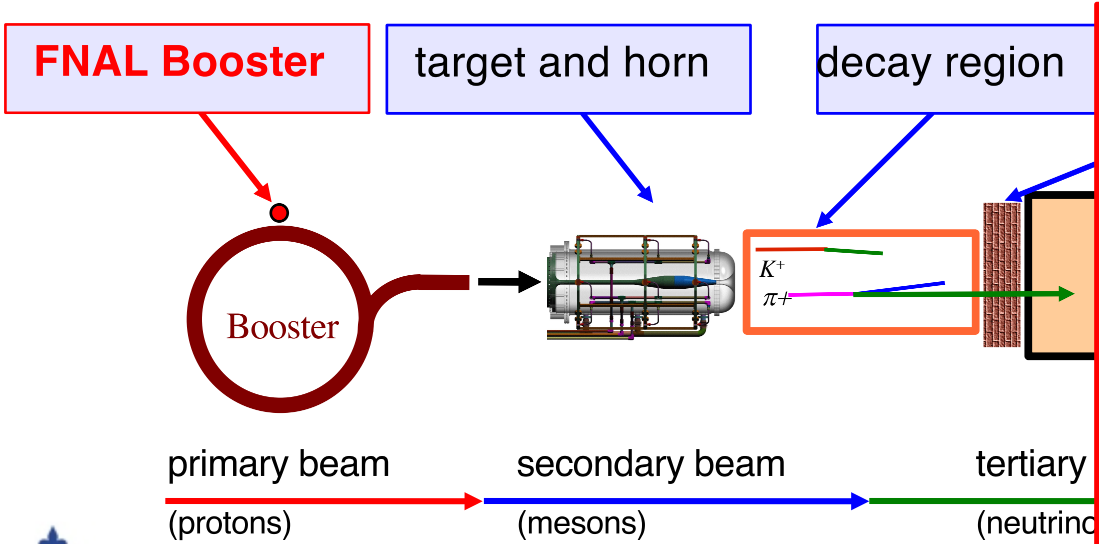
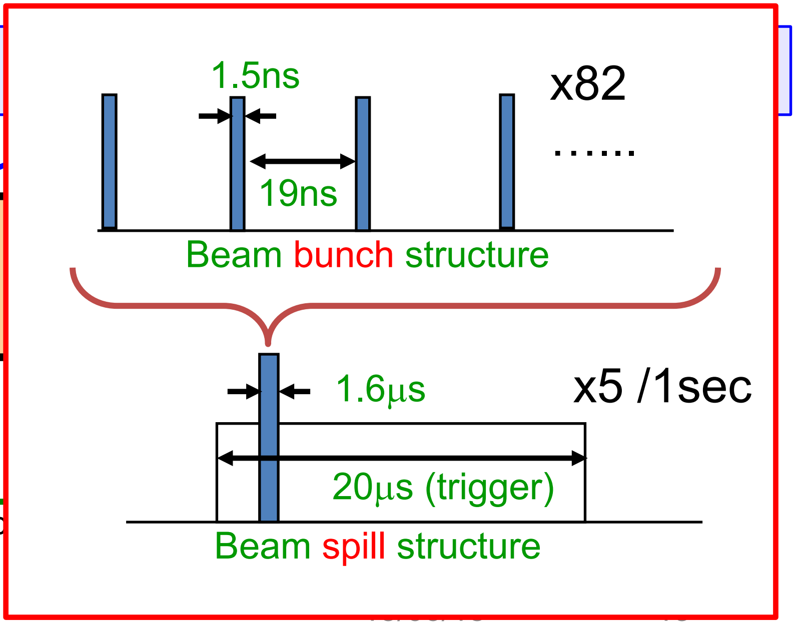
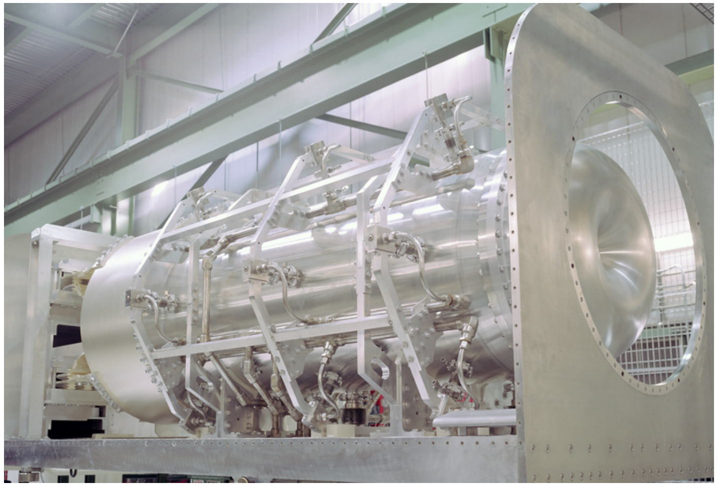




MiniBooNE, PRD79(2009)072002

2. Neutrino beam

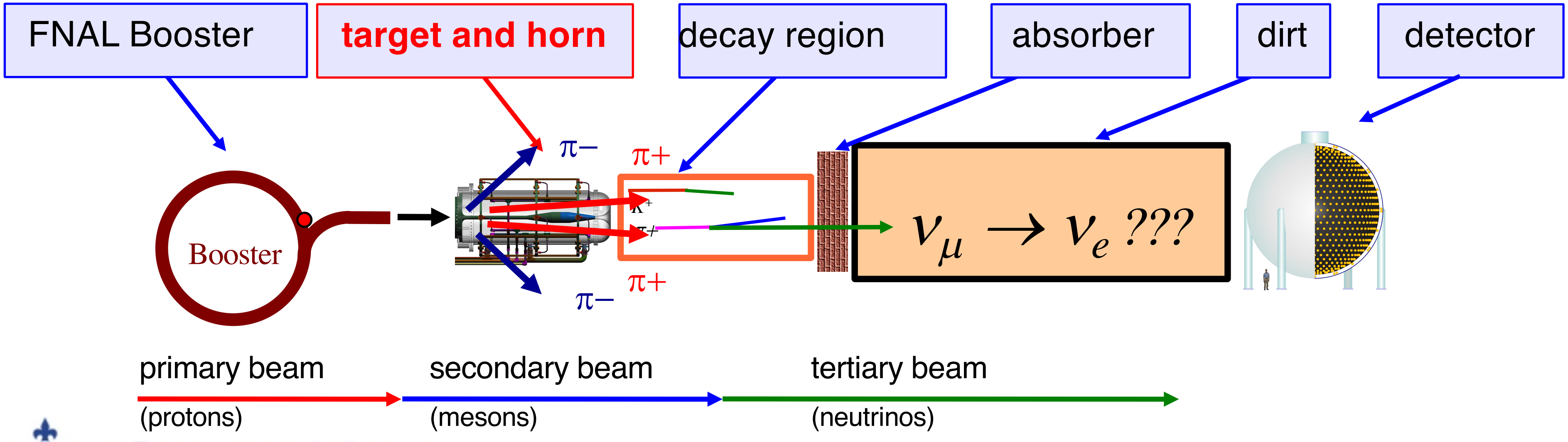
Magnetic focusing horn



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 × 6

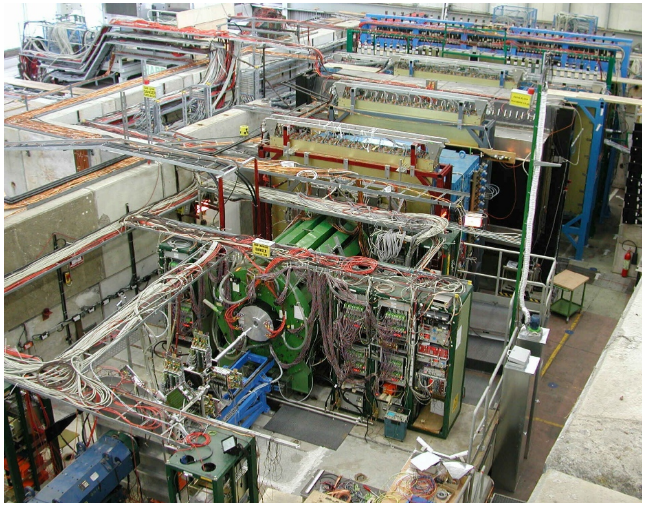
By switching the current direction, the horn can focus either positive (neutrino mode) or negative (antineutrino mode) mesons.



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

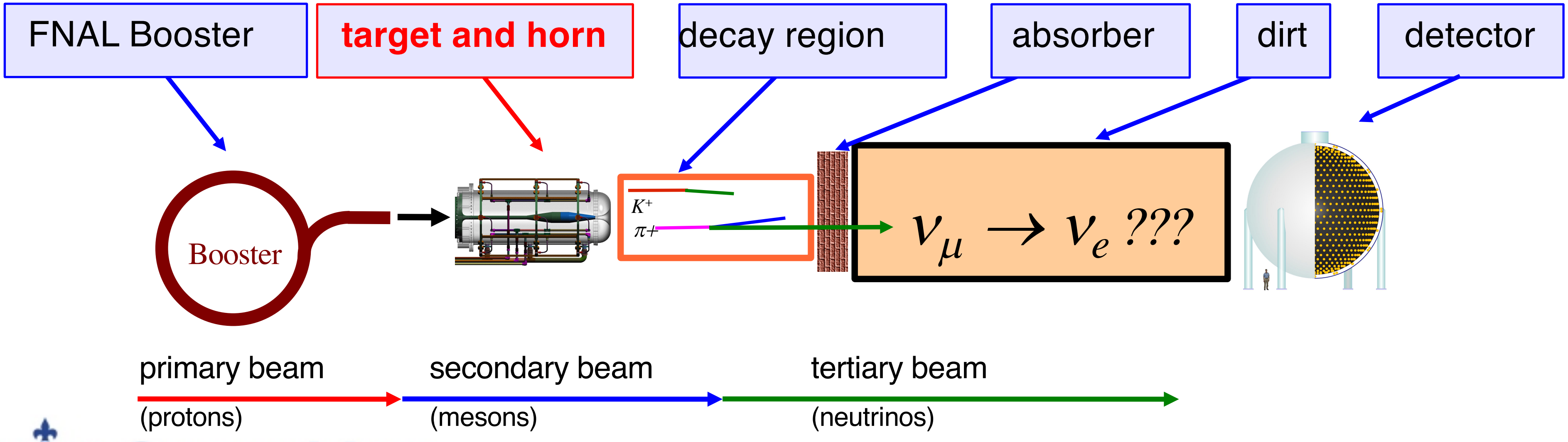
2. Neutrino beam

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+


FNAL Booster

target and horn

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primary beam
(protons)

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tertiary beam
(neutrinos)

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

2. Neutrino beam

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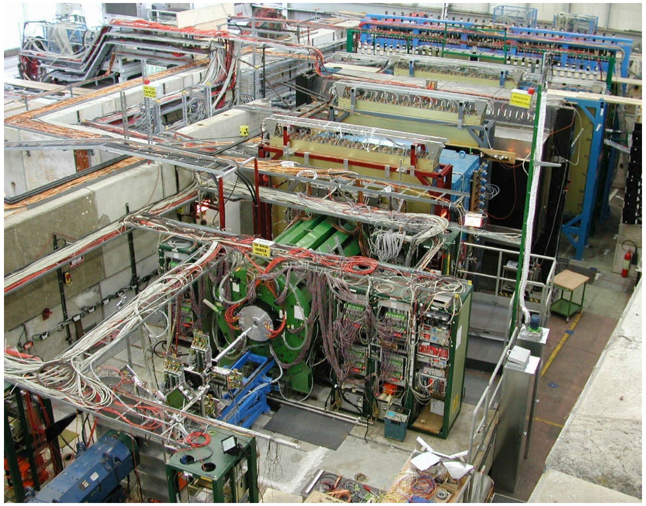

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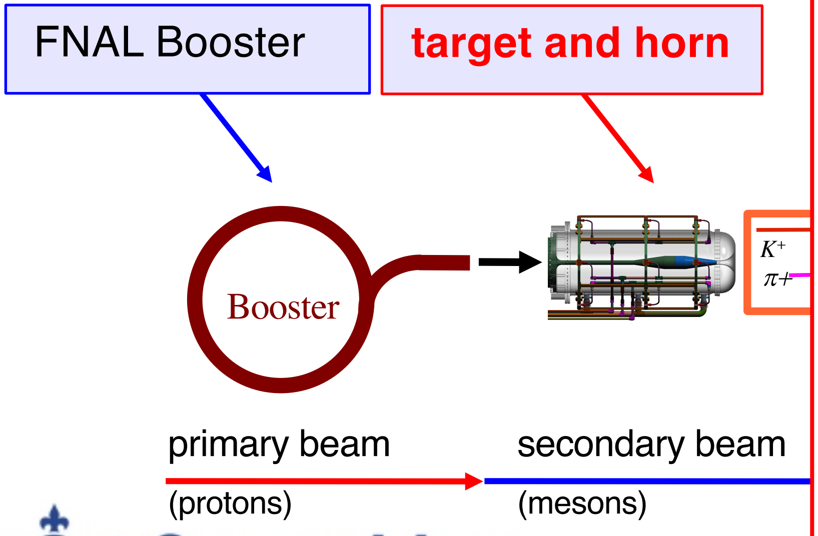
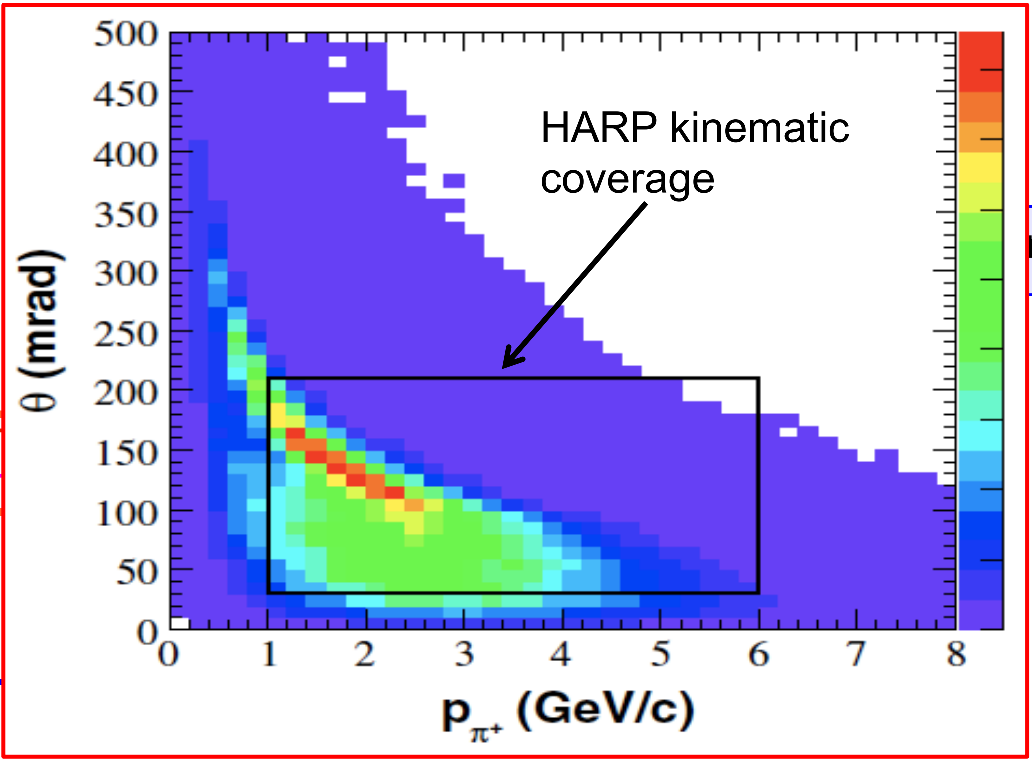


FNAL Booster

target and horn

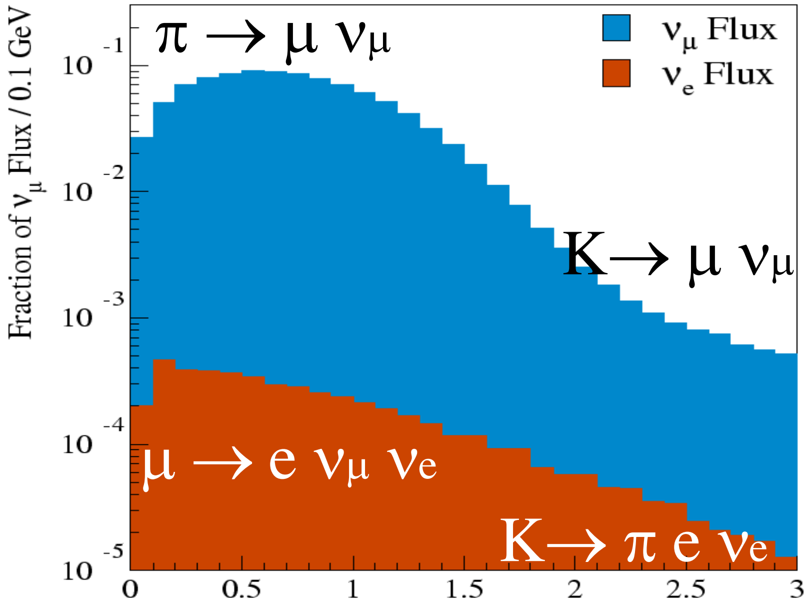
primary beam (protons)

secondary beam (mesons)



MiniBooNE, PRD79(2009)072002

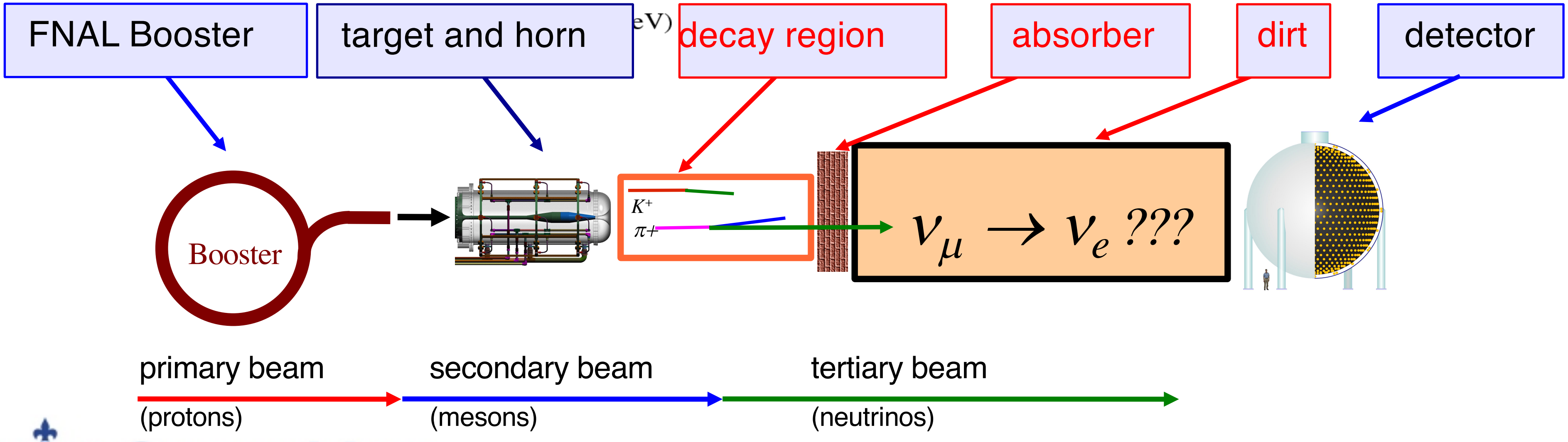
2. Neutrino beam



Neutrino flux from simulation by GEANT4

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

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



FNAL Booster

target and horn

decay region

absorber

dirt

detector

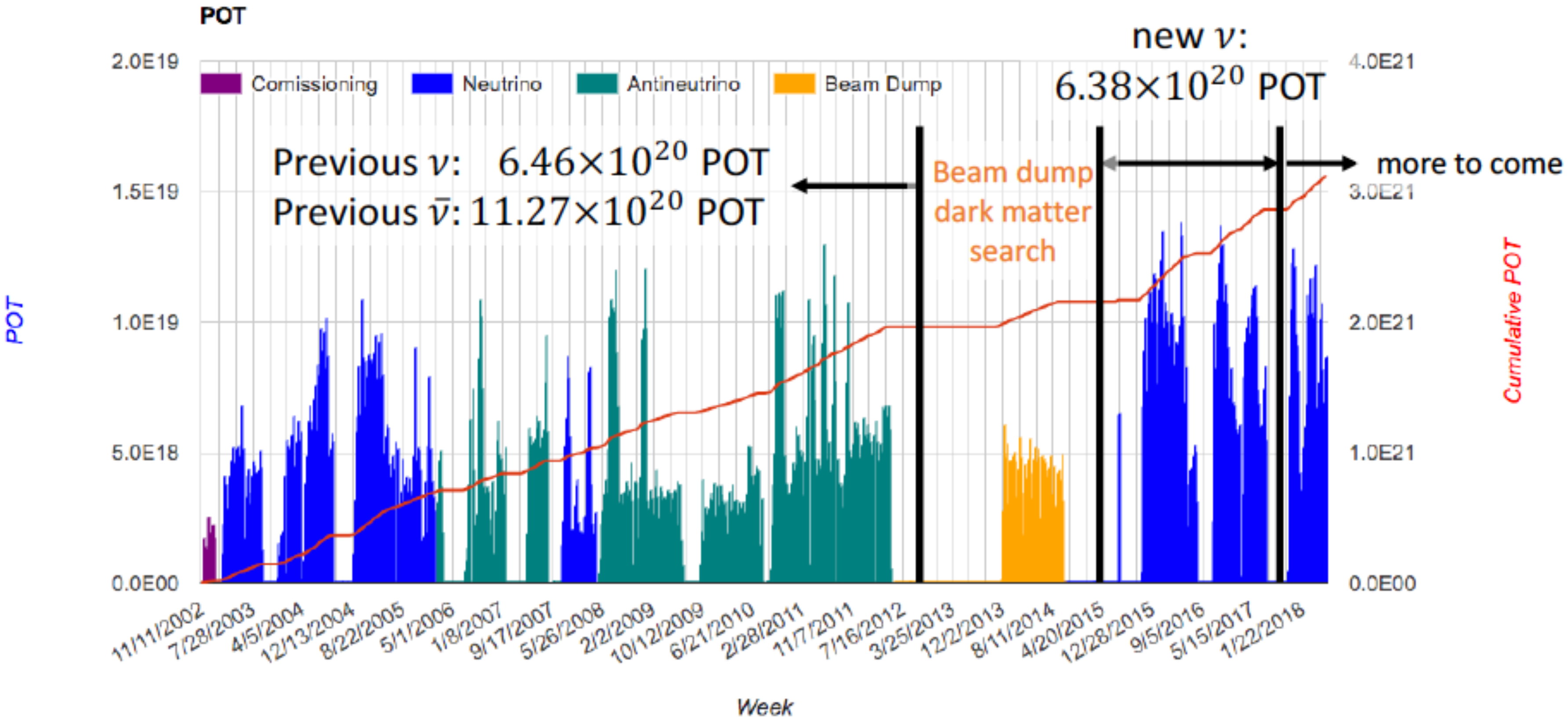
primary beam
(protons)

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



Previous ν: 6.46×10^{20} POT
Previous $\bar{\nu}$: 11.27×10^{20} POT

Beam dump dark matter search

new ν: 6.38×10^{20} POT

more to come

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

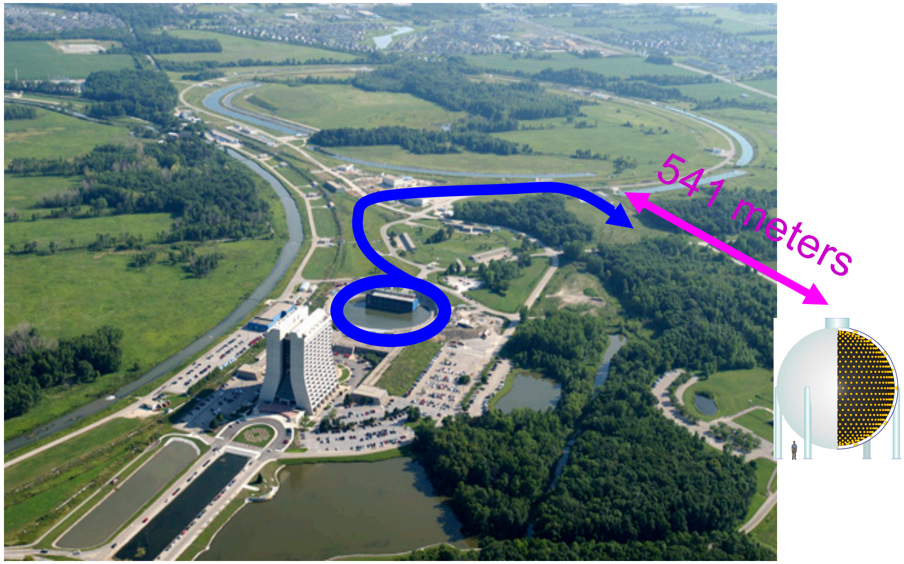
3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

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

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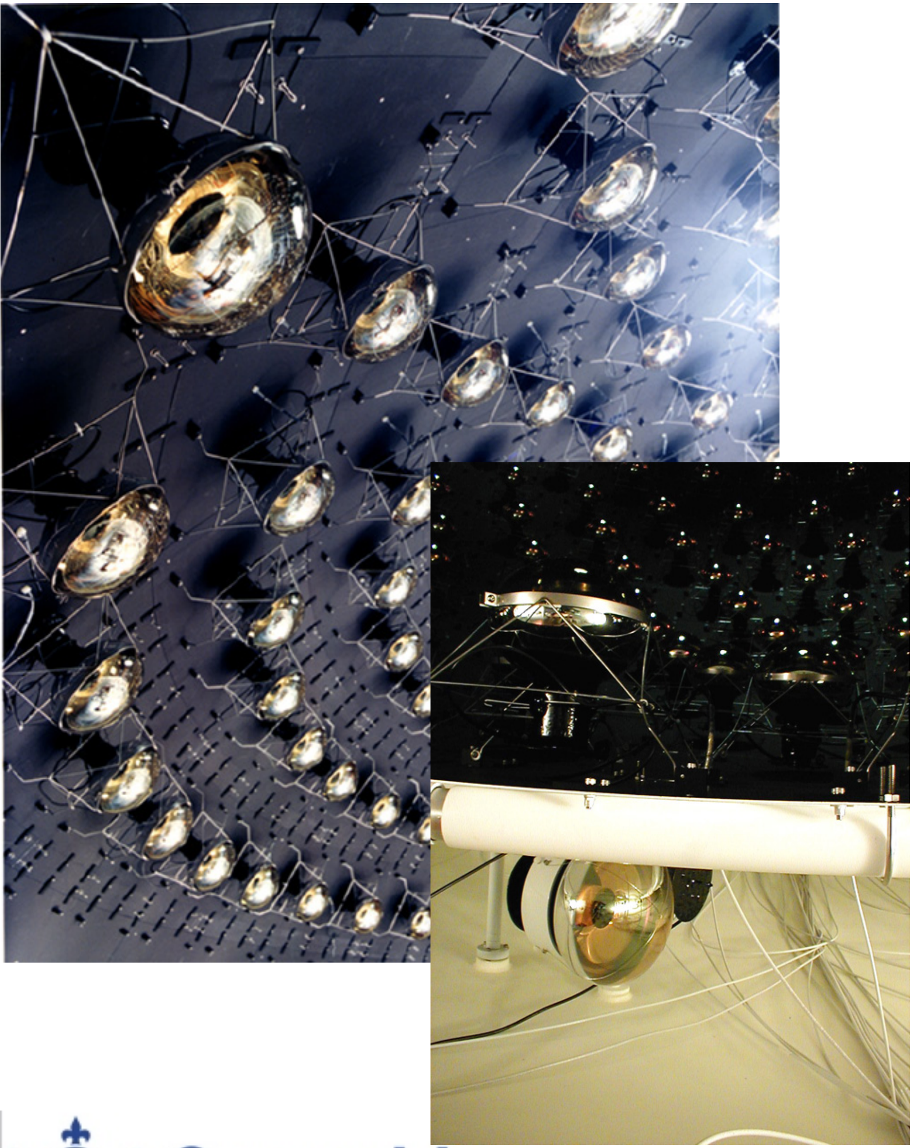
MiniBooNE,NIM.A599(2009)28

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

MiniBooNE,NIM.A599(2009)28

3. Events in the Detector

Times of hit-clusters (subevents)

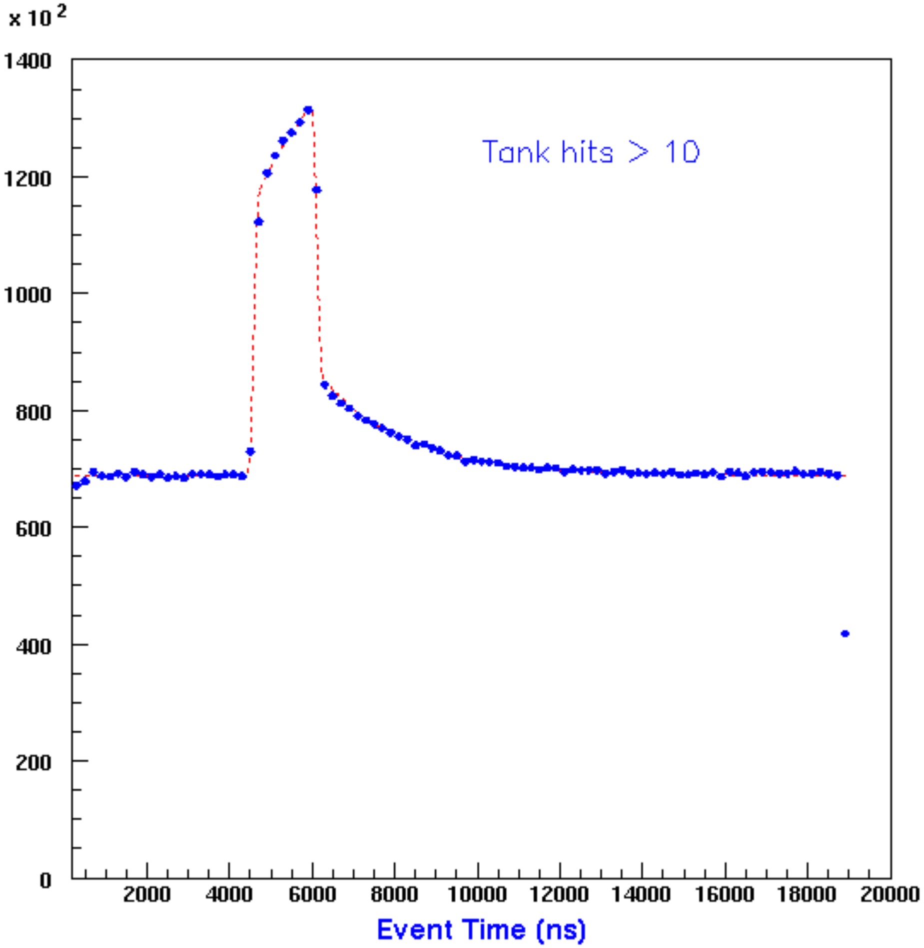
Beam spill (1.6μs) is clearly evident

- 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 Cosmic BG



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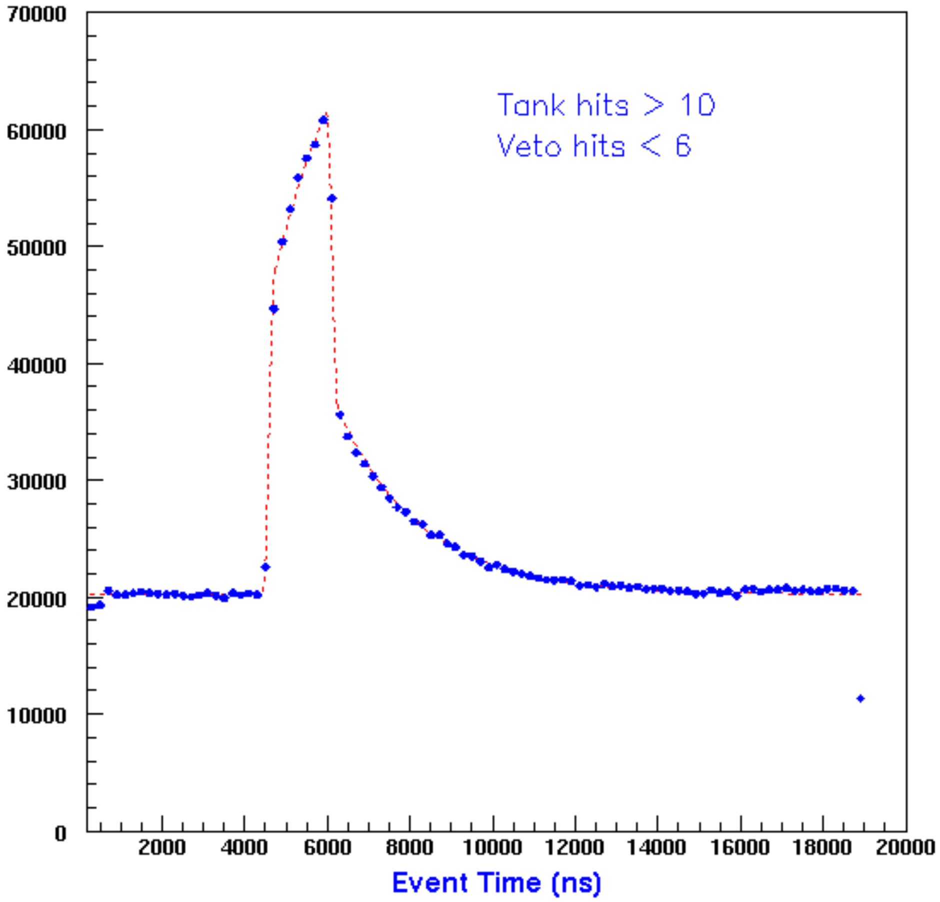

MiniBooNE,NIM.A599(2009)28

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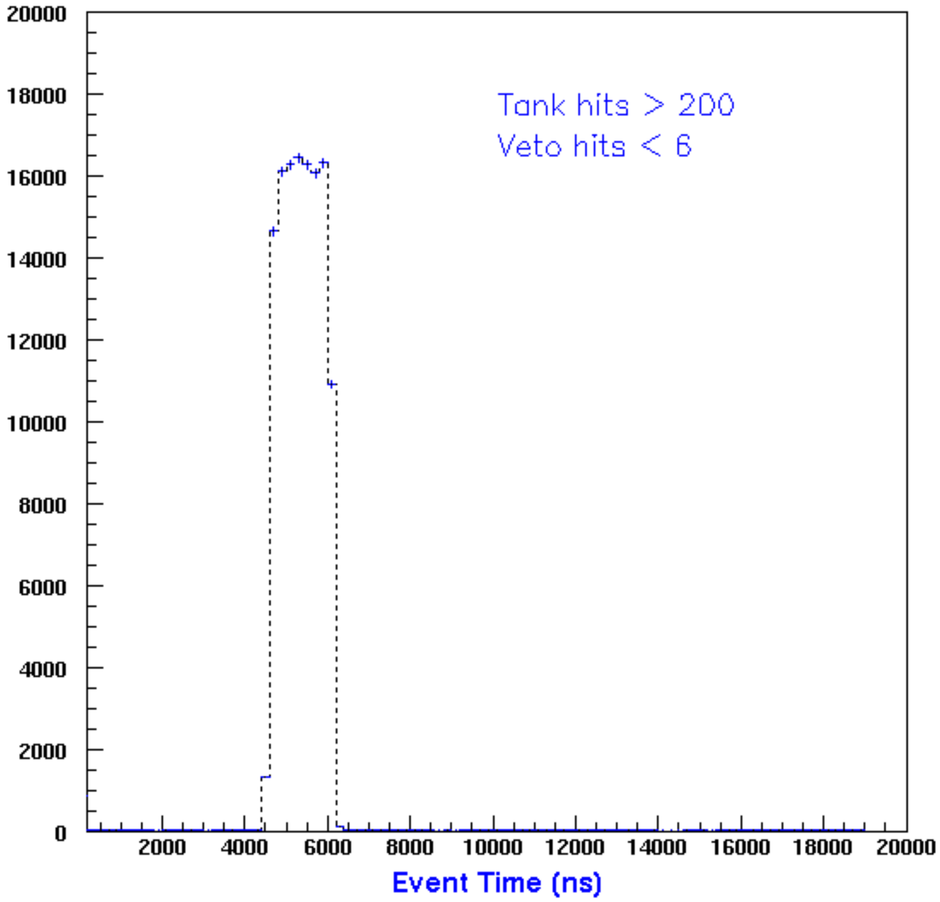
Beam Only



3. Events in the Detector

MiniBooNE collaboration,
NIM.A599(2009)28

Muons

- Long strait tracks
  - → Sharp clear rings

Electrons

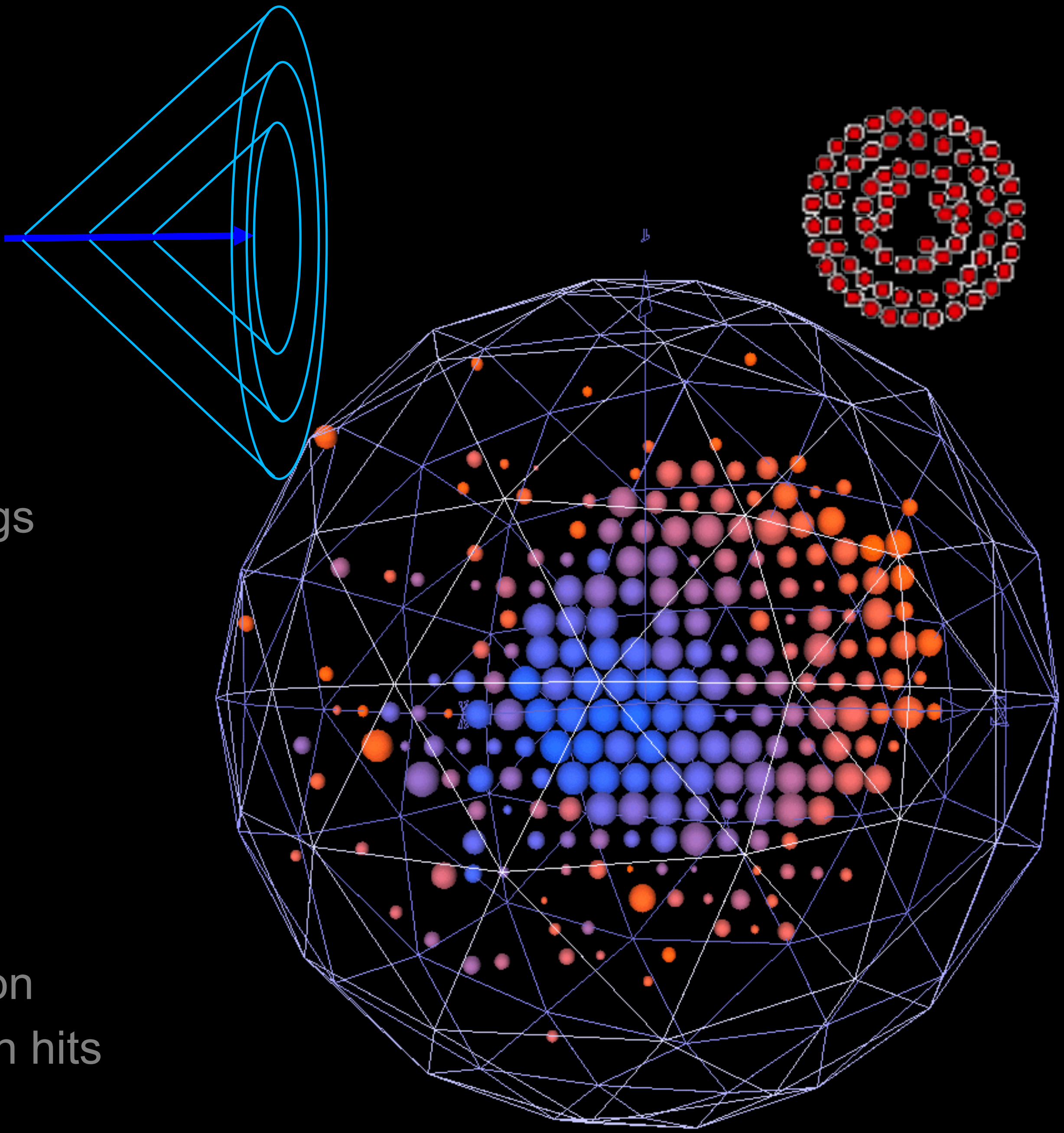
- Multiple scattering
- Radiative processes
  - → Scattered fuzzy rings

Neutral pions

- Decays to 2 photons
  - → Double fuzzy rings

NC elastic scattering

- No Cherenkov radiation
  - → Isotropic scintillation hits



3. Events in the Detector

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NIM.A599(2009)28

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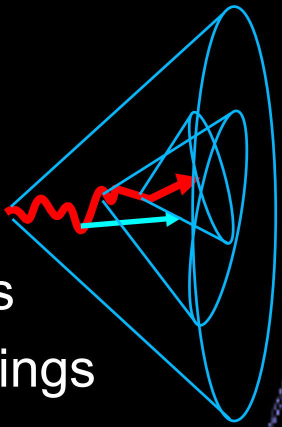

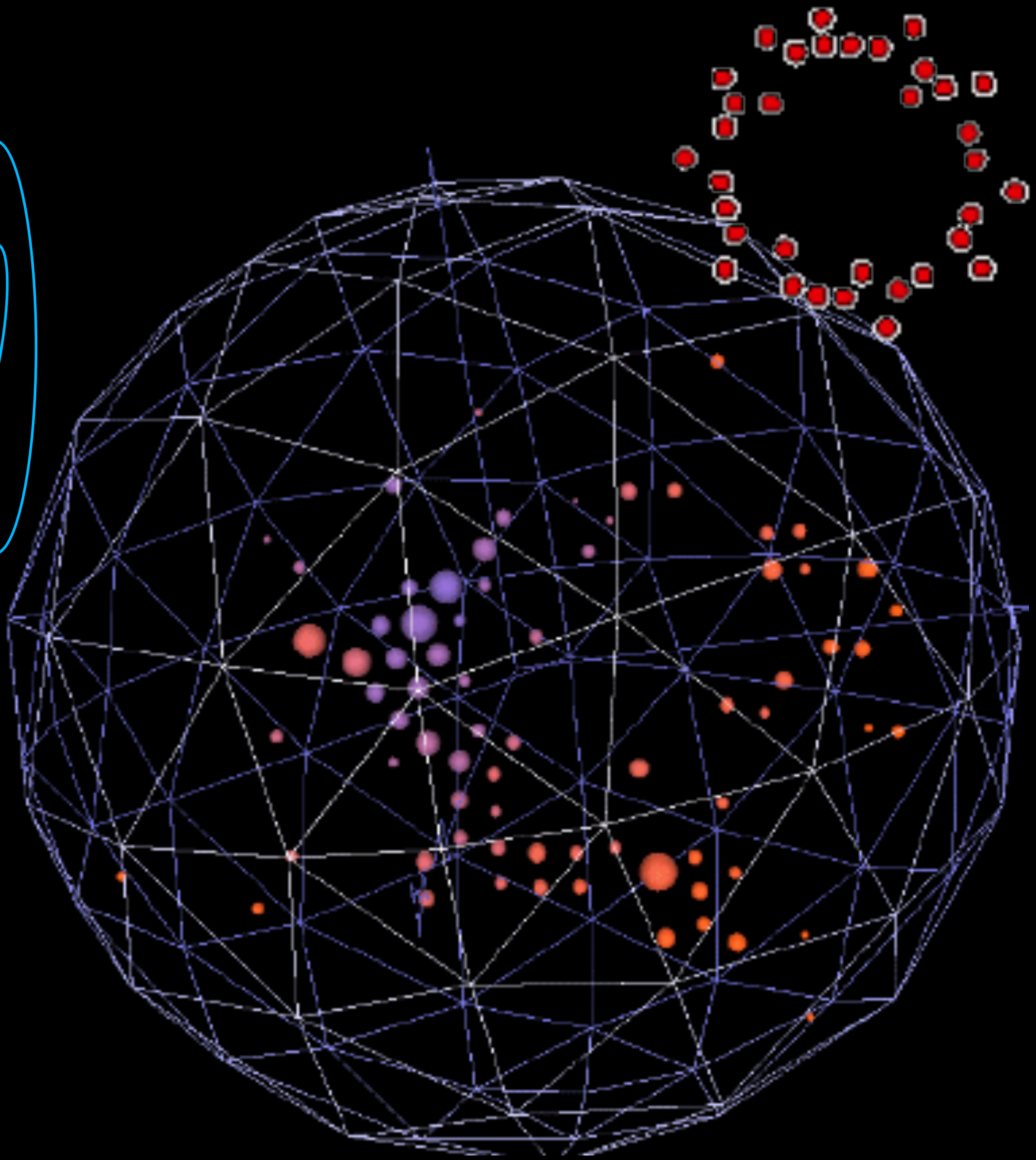

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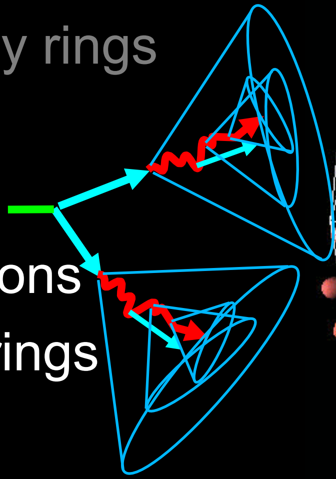

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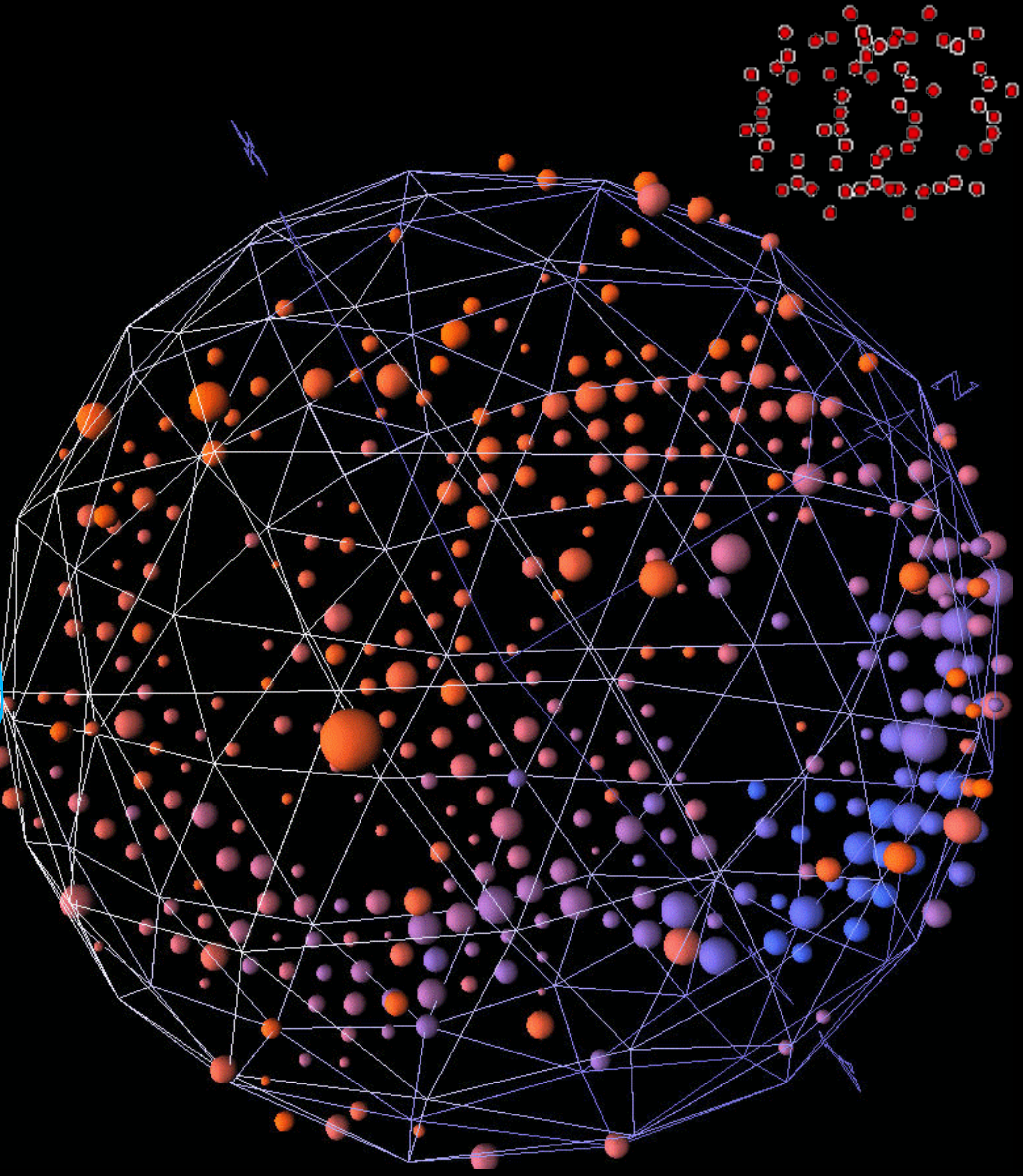

3. Events in the Detector

MiniBooNE collaboration,
NIM.A599(2009)28

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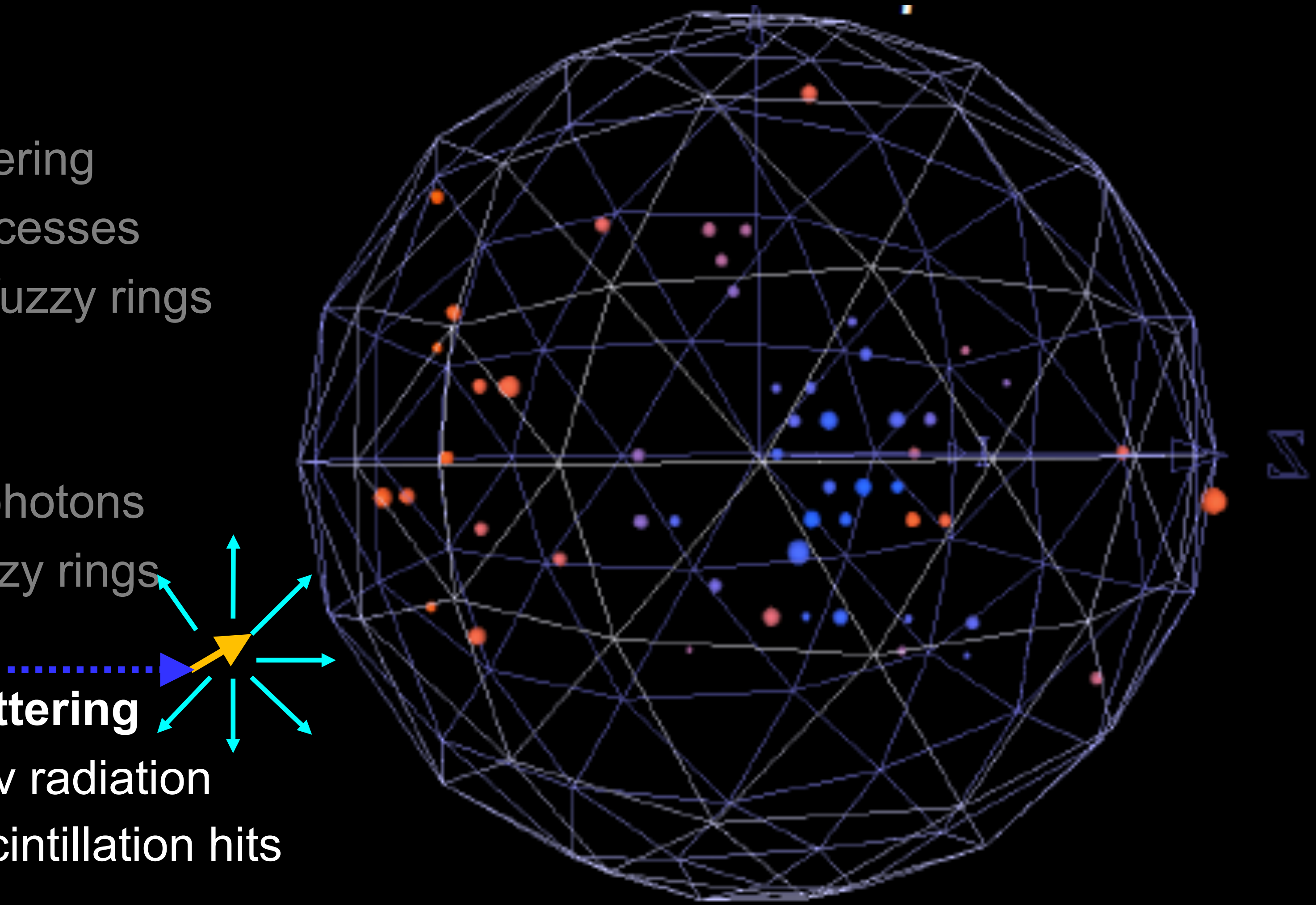

NC elastic scattering
- No Cherenkov radiation
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MiniBooNE: PRL100(2008)032301

3. QE kinematics based energy reconstruction

Event reconstruction from Cherenkov ring profile for PID

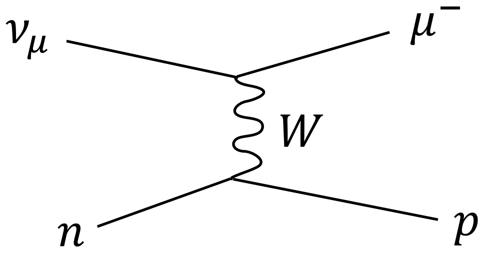
- scattering angle θ and kinetic energy of charged lepton T are estimated

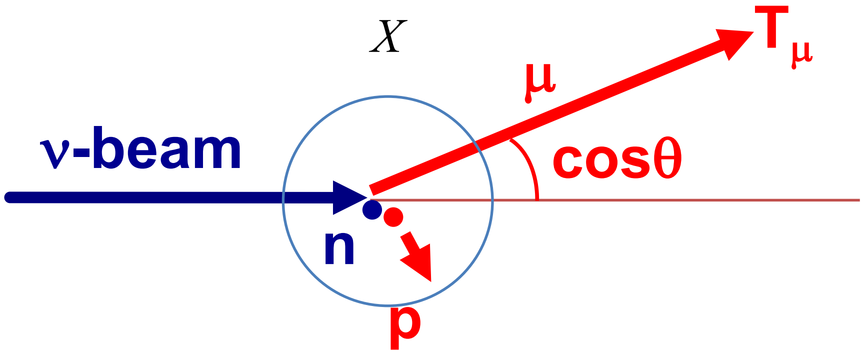
Charged Current Quasi-Elastic (CCQE) interaction

The simplest and the most abundant interaction around ~1 GeV. Neutrino energy is reconstructed from the observed lepton kinematics “QE assumption”

1. assuming neutron at rest
2. assuming interaction is CCQE

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





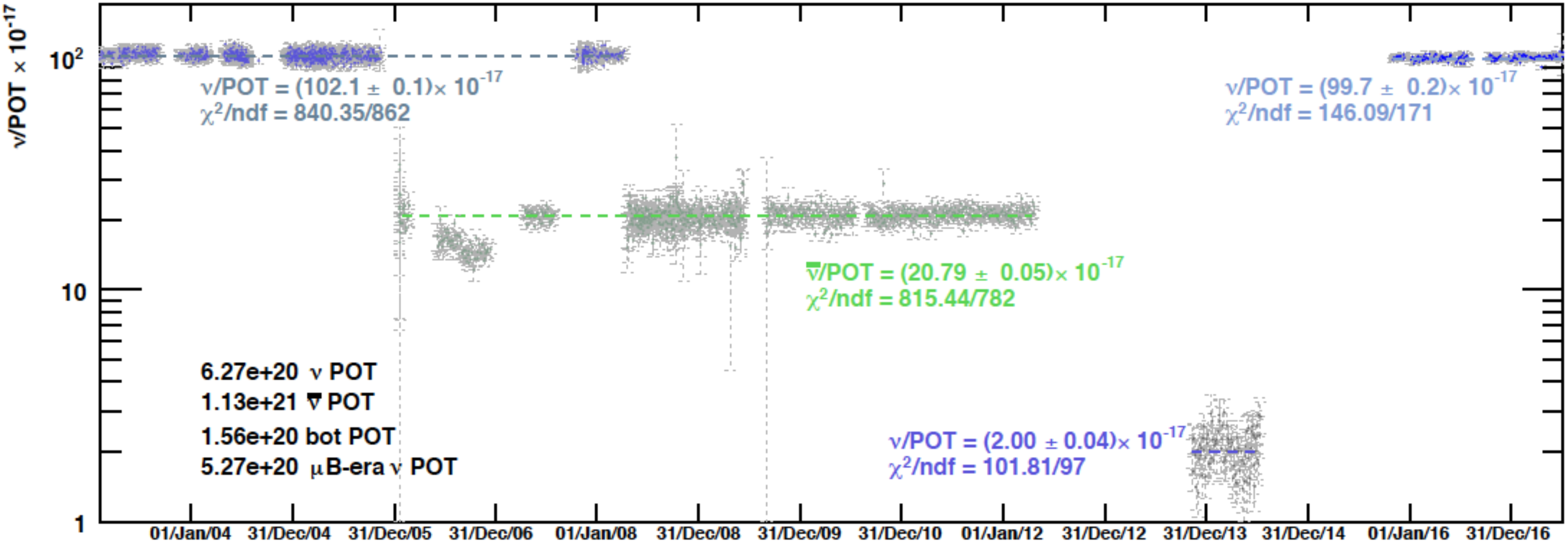
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

3. Detector stability

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

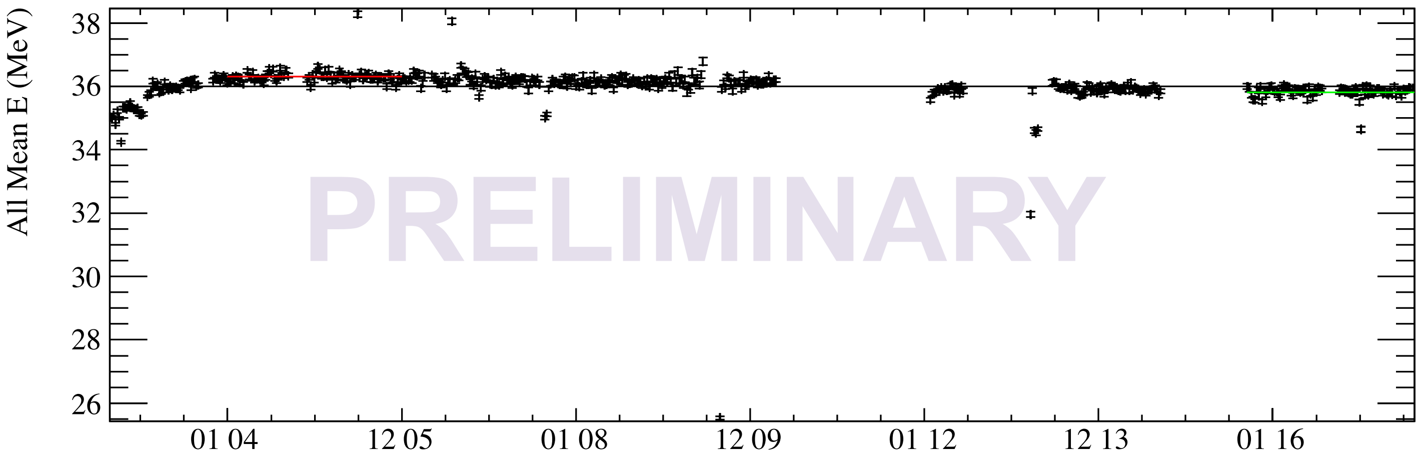
MiniBooNE, PRL118(2017)221803



3. Detector stability

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

Michel electron spectrum peak



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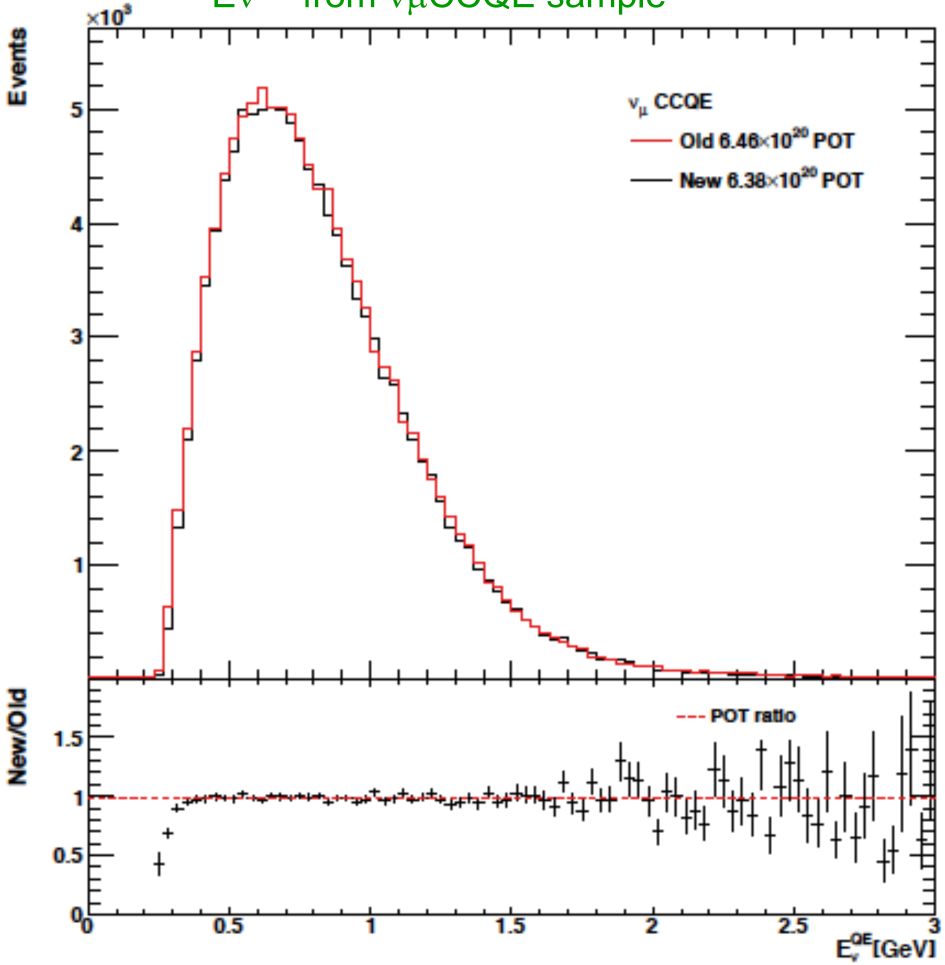
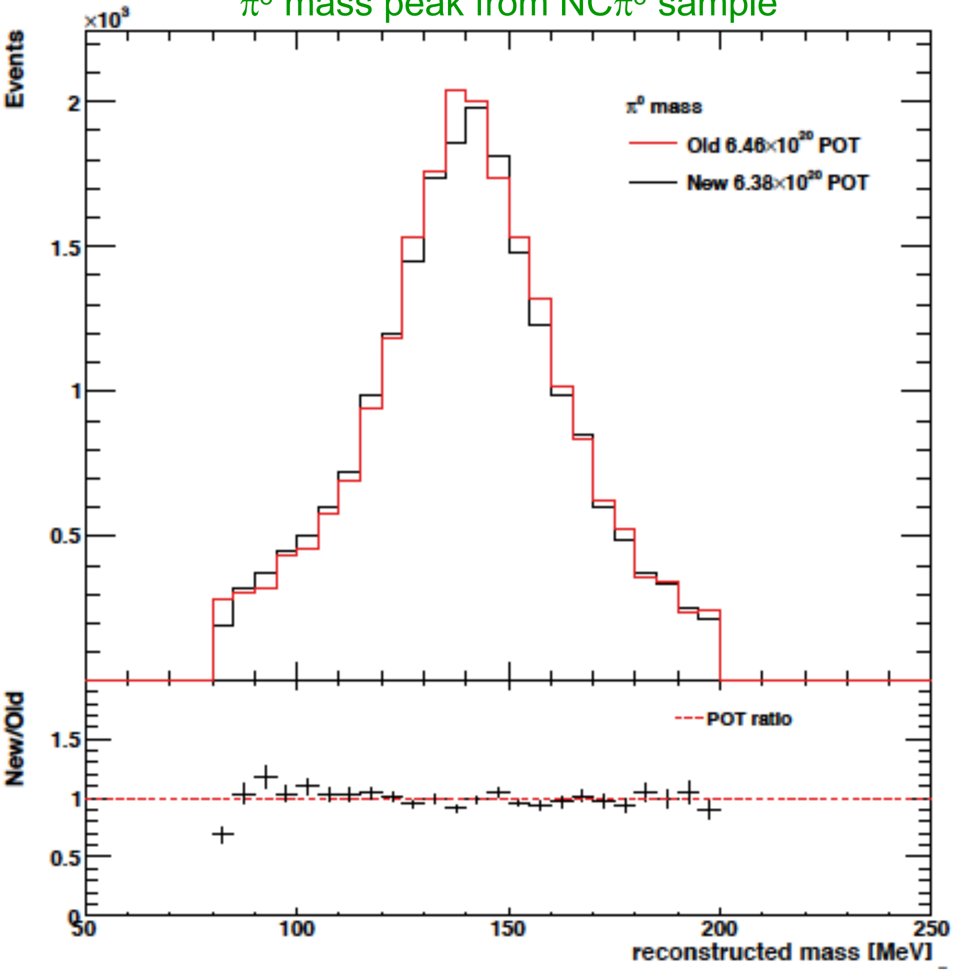
$E\nu^{QE}$ from $\nu\mu$CCQE sample



π^o mass peak from NCπ^o sample

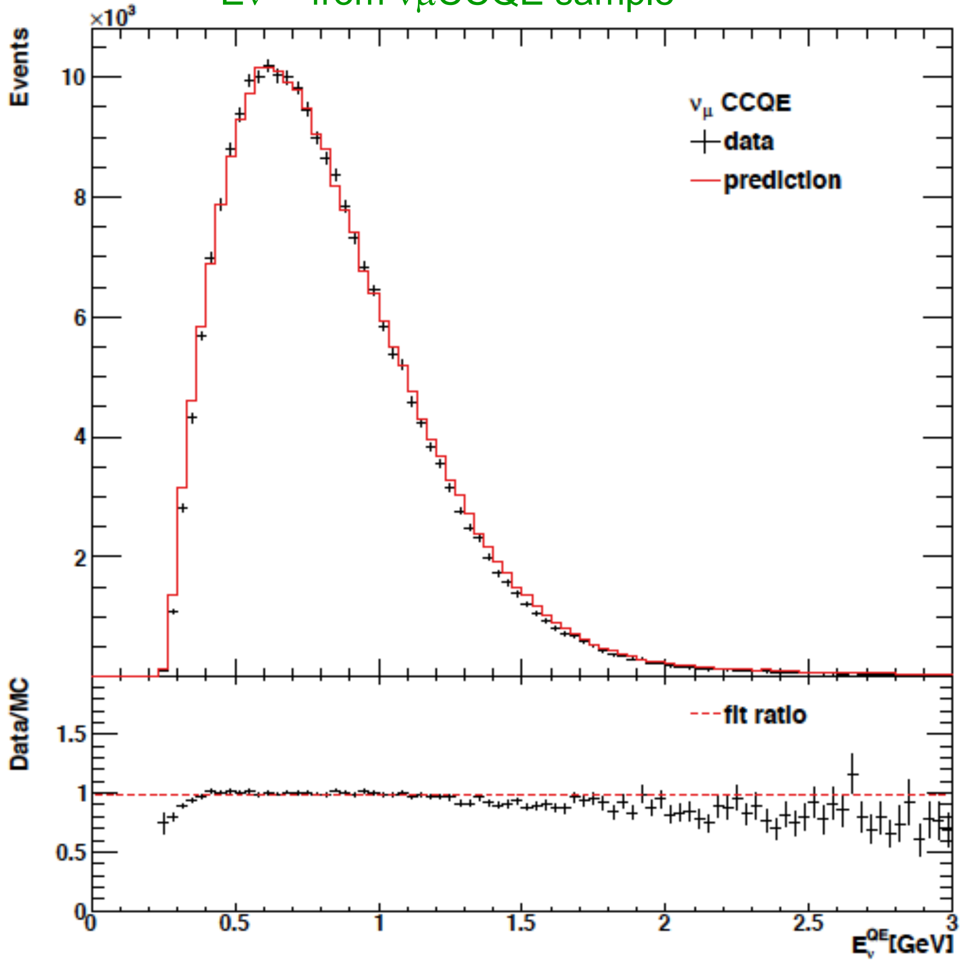


3. Data-Simulation comparison

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

- Excellent agreements with MC.

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



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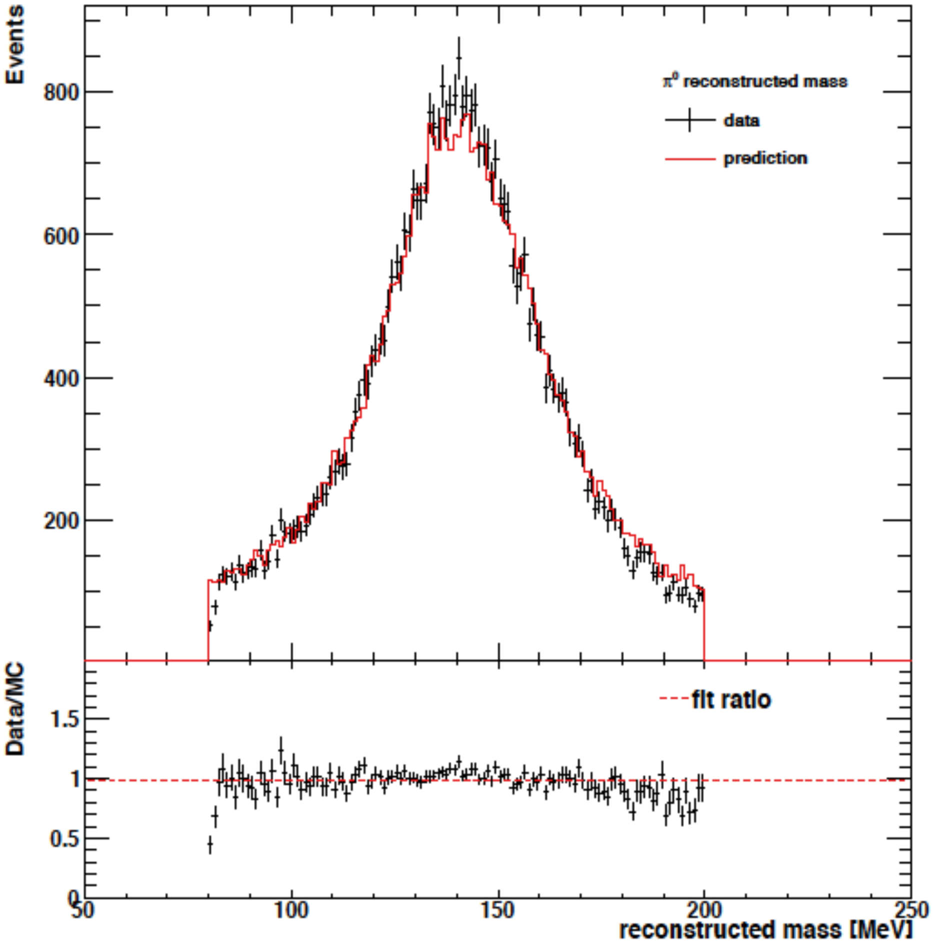

1. MiniBooNE neutrino experiment

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
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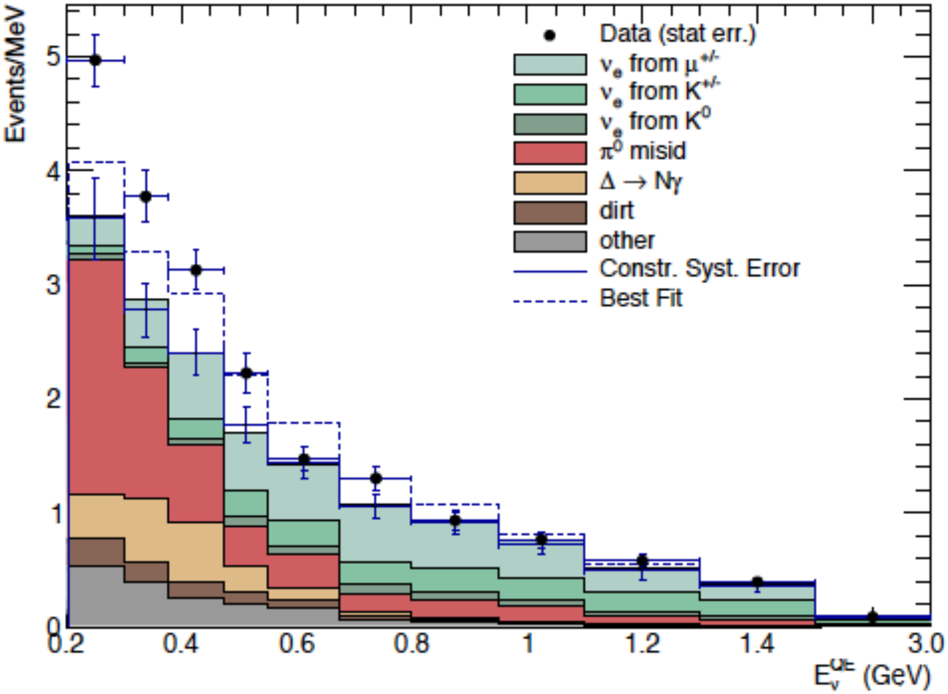

4. ν_e from μ-decay constraint

All backgrounds are internally constrained
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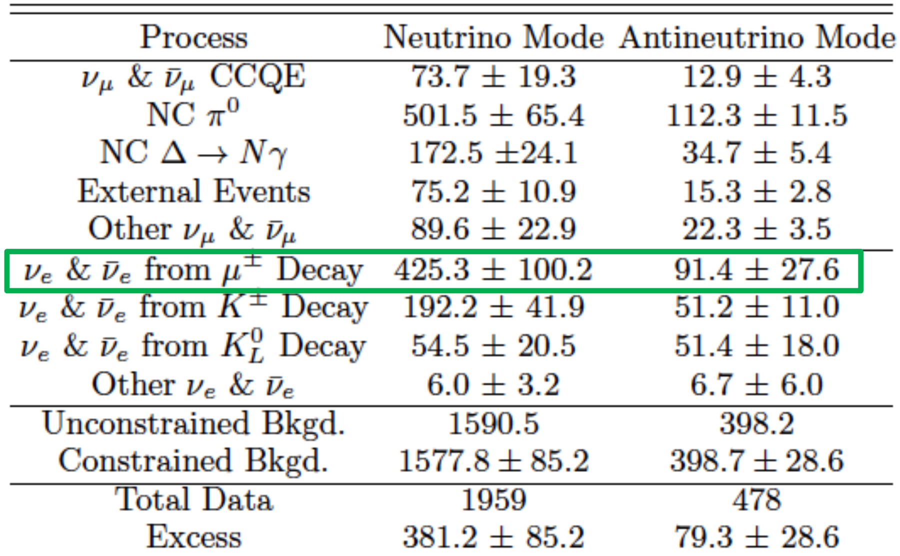

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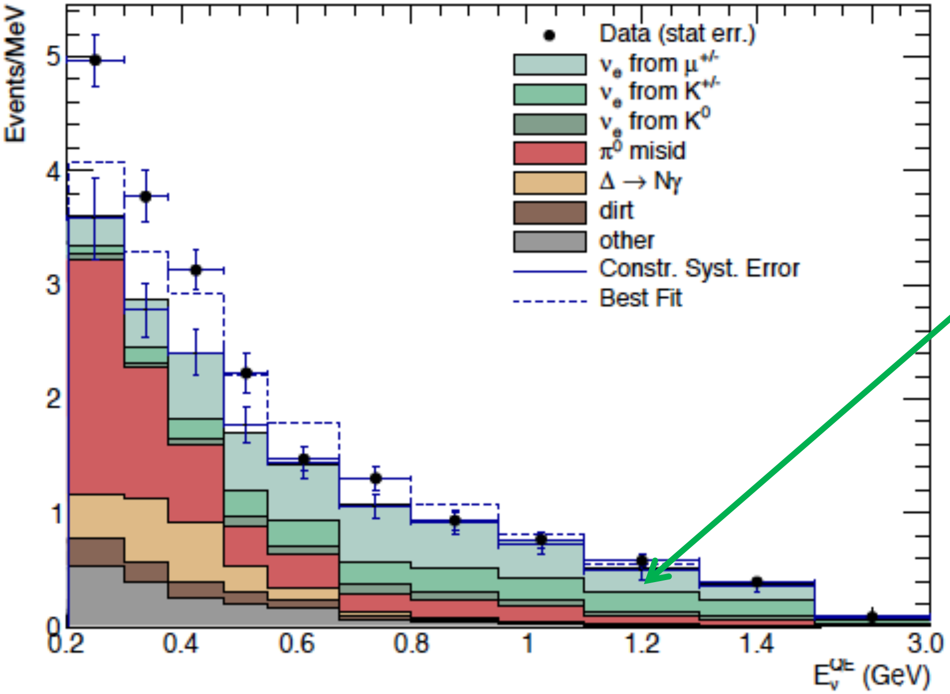
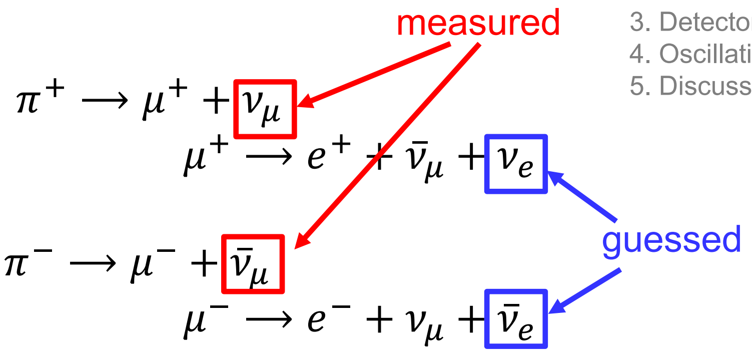


ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from μ-decay constraint



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

measured

guessed

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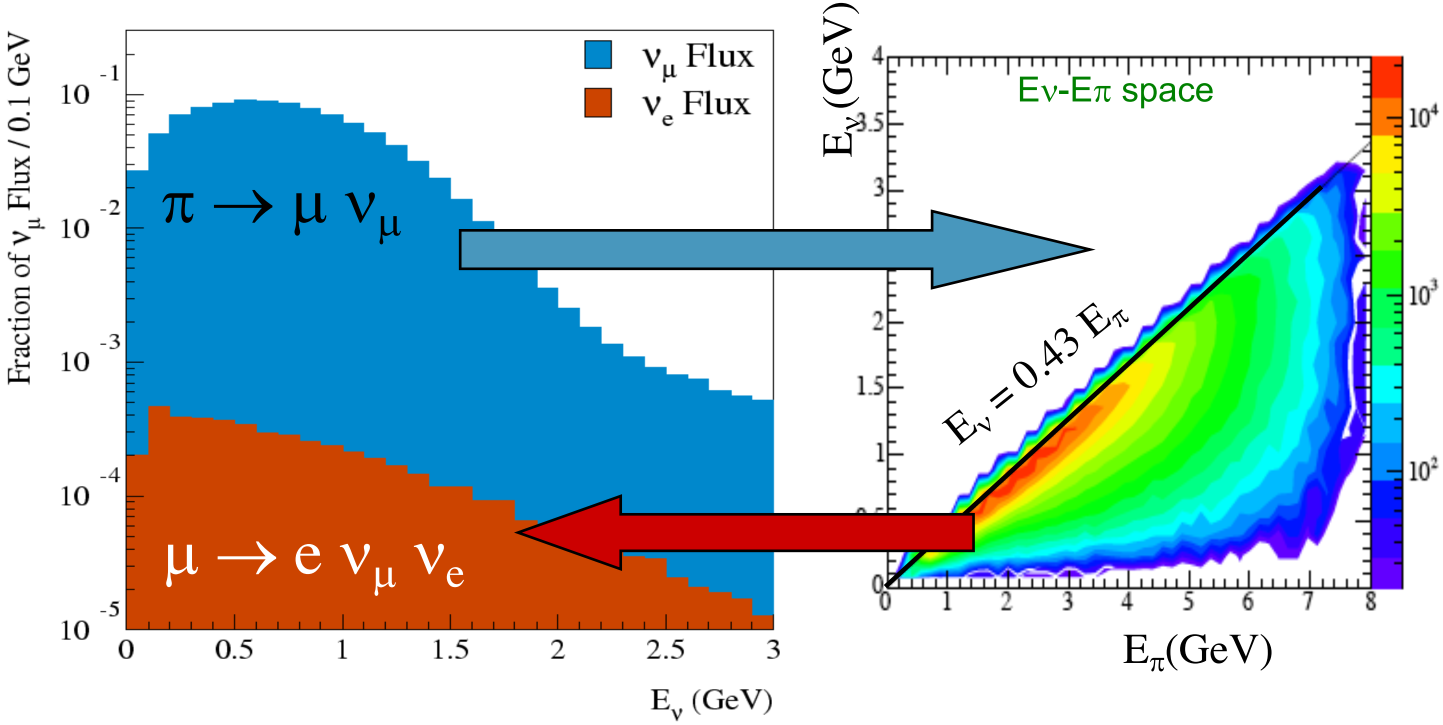
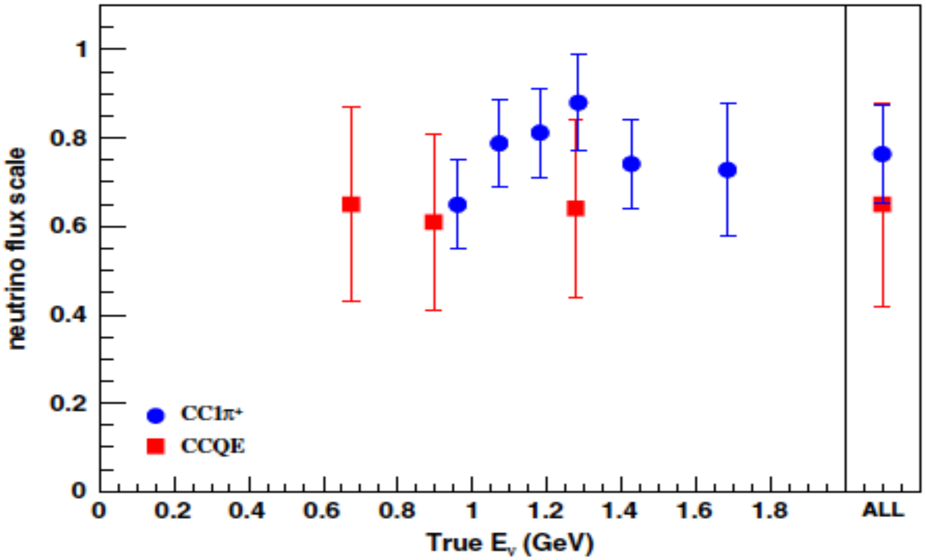
They are large background, but we have a good control of $\nu_e \& \bar{\nu}_e$ background by joint $\nu_e \& \nu_\mu (\bar{\nu}_e \& \bar{\nu}_\mu)$ fit for oscillation search.



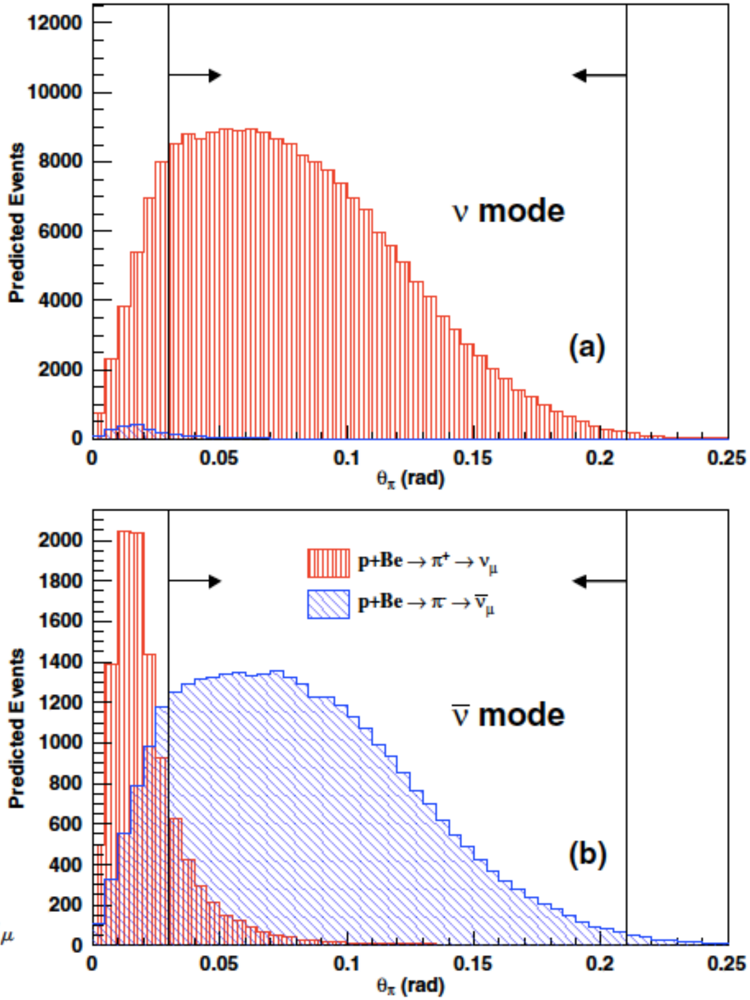
MiniBooNE, PRD84(2011)072005

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%



PHYSICAL REVIEW D 84, 072005 (2011)



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

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

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

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

4. ν_e from μ-decay constraint

All backgrounds are internally constrained
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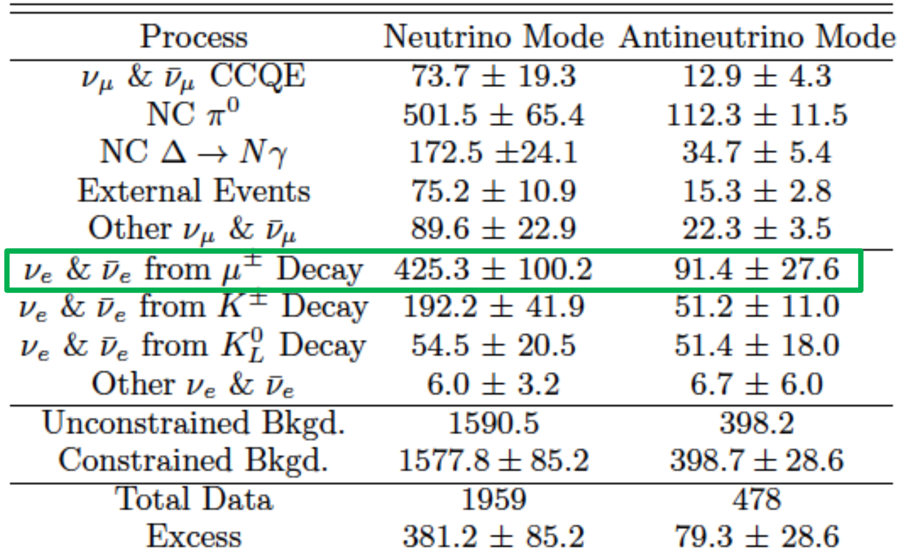

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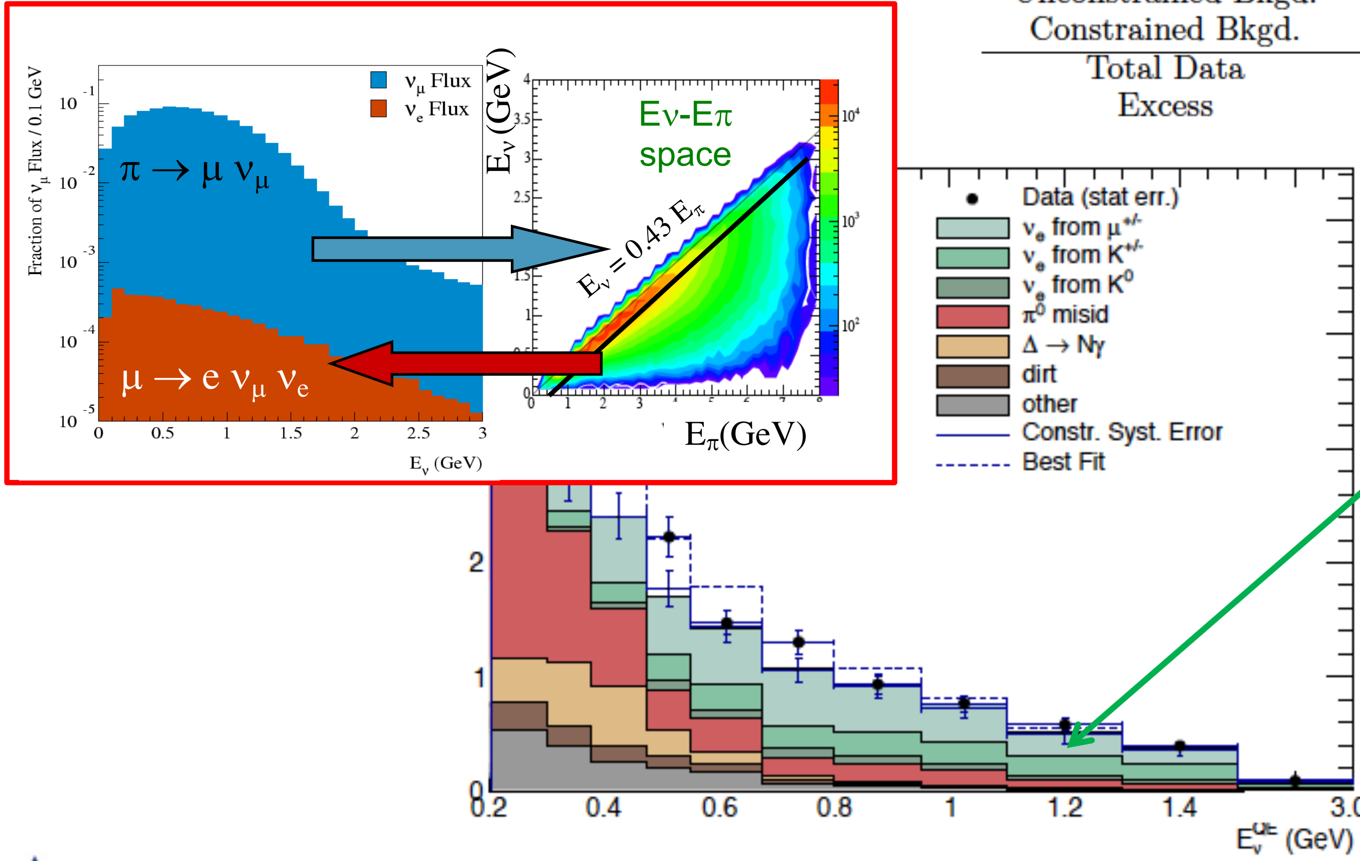

ν_e from μ decay is constrained from ν_μCCQE measurement

Queen Mary
University of London

4. ν_e from K^+-decay constraint

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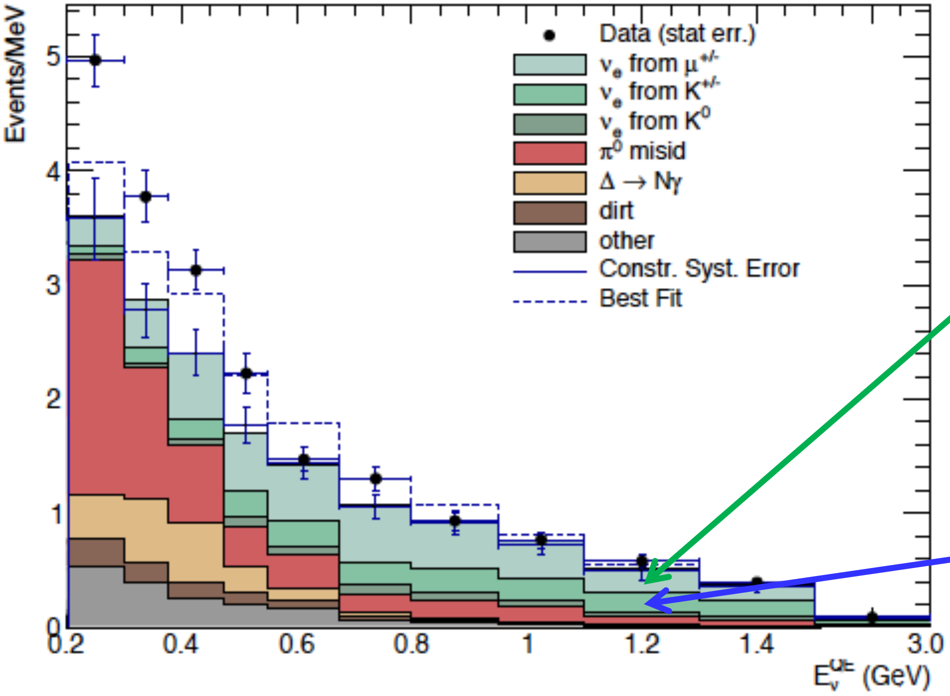


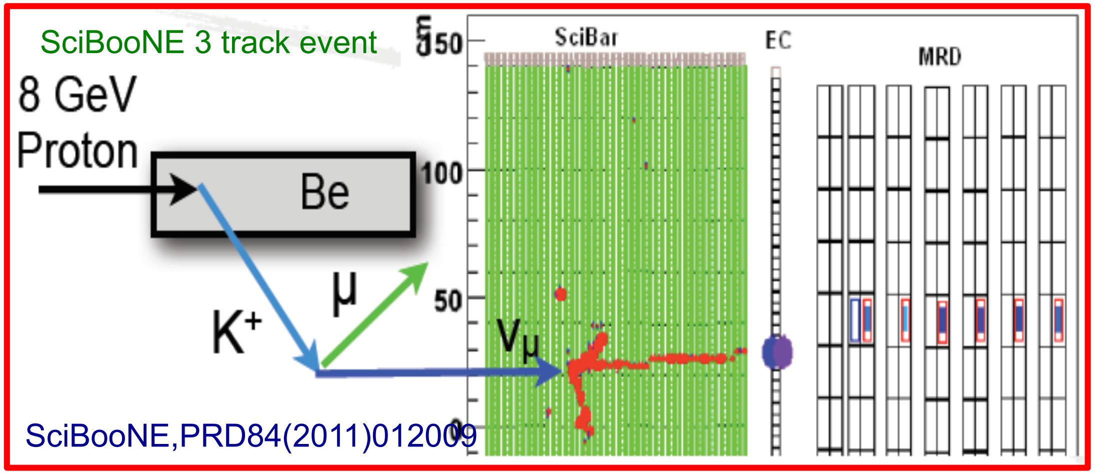
ν_e from μ decay is constrained from ν_μCCQE measurement

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

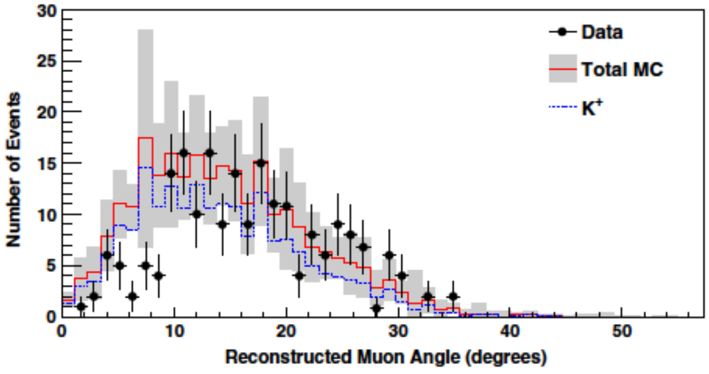
SciBooNE,PRD84(2011)012009

4. ν_e from K^+-decay constraint

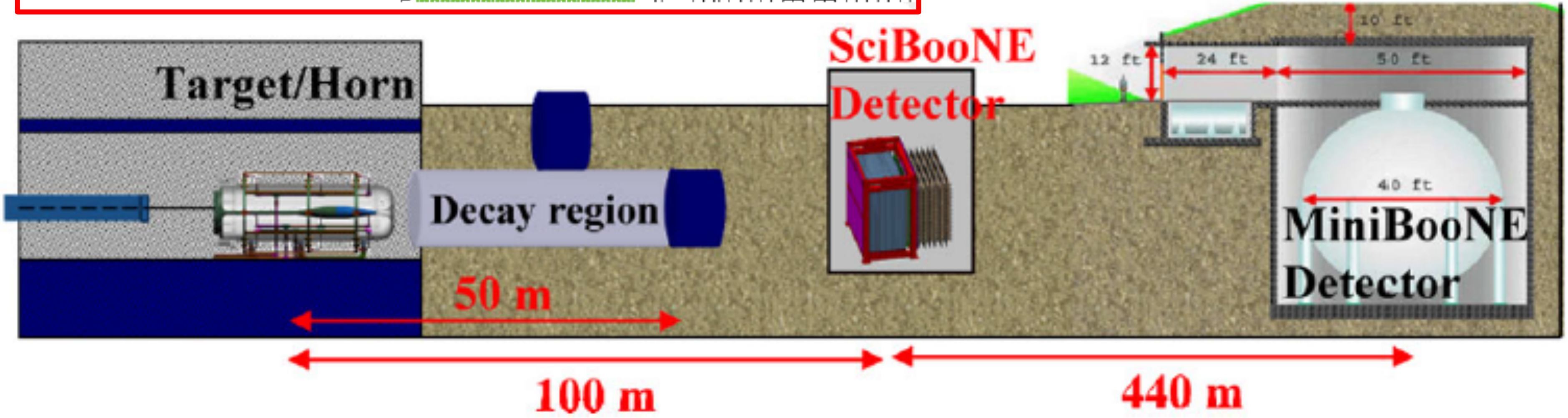
SciBooNE is a scintillator tracker located on BNB (detector hall is used by ANNIE now)
- neutrinos from kaon decay tend to be higher, and tend to make 3 tracks
- from 3 track analysis, kaon decay neutrinos are constrained (0.85±0.11, prior is 40% error)


SciBooNE 3 track event

SciBooNE,PRD84(2011)012009



(c) 3-Track Sample



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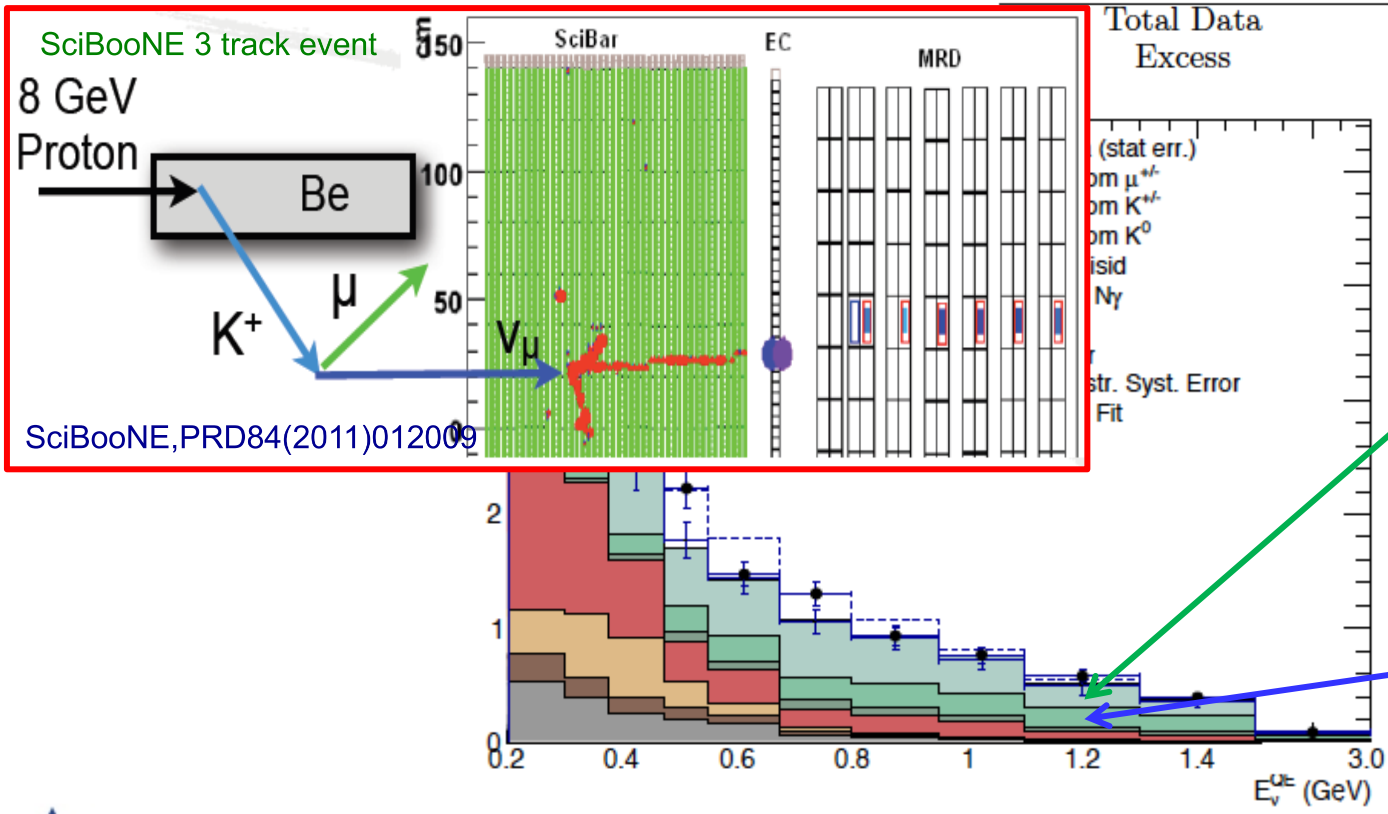

SciBooNE,PRD84(2011)012009

ν_e from μ decay is constrained from ν_μCCQE measurement

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

4. ν_e from K^+-decay constraint

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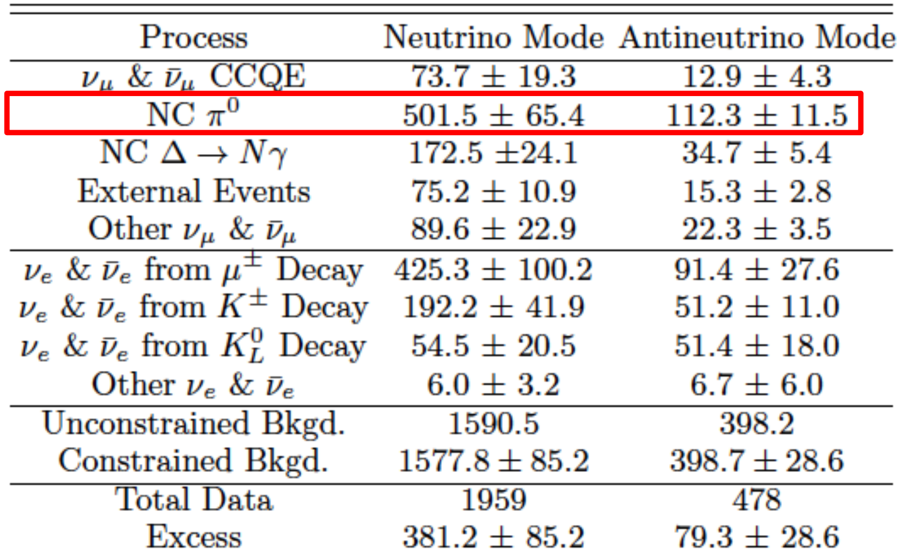

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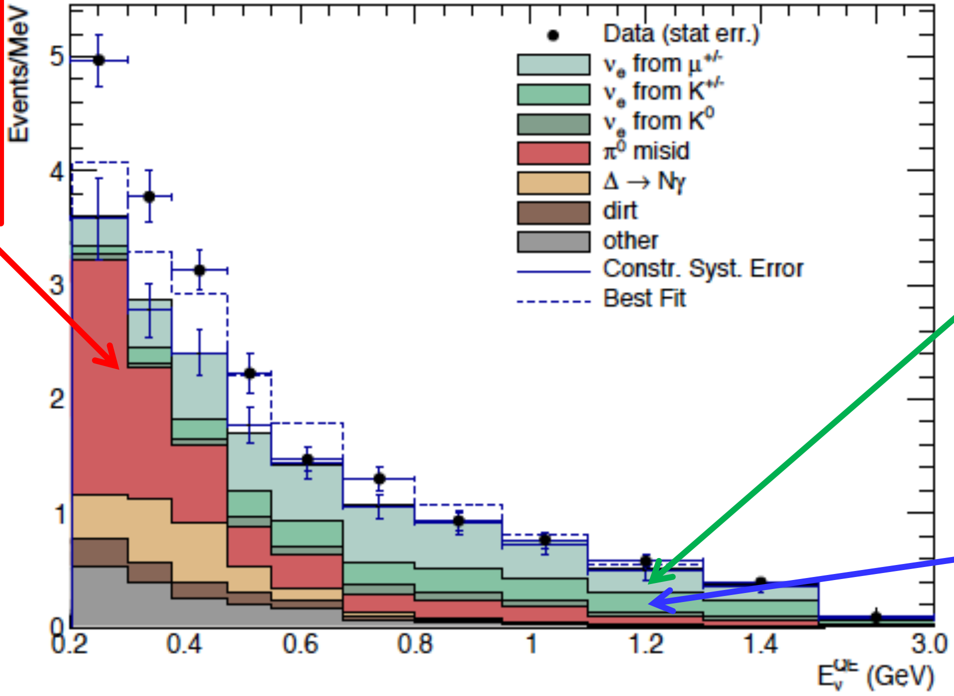

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MiniBooNE, PLB664(2008)41

4. γ from π^o constraint

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

- not background, we can measure

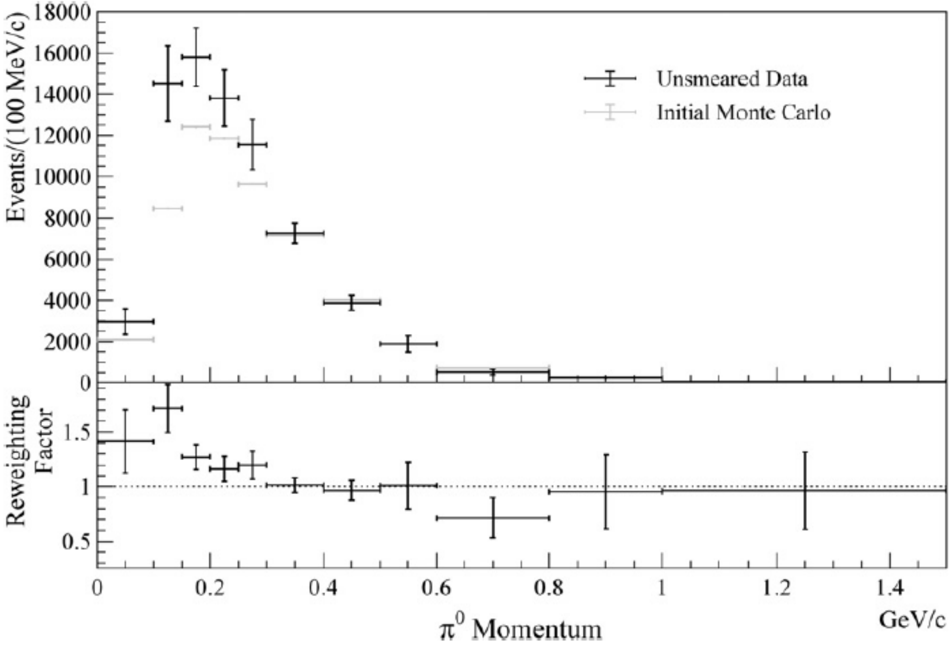
$\pi^o \rightarrow \gamma$

- misID background, we cannot measure

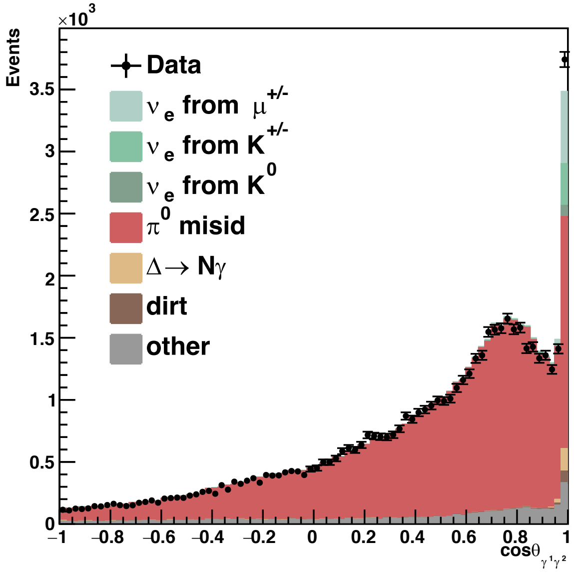
The biggest systematics is production rate of π^o, because once you find that, the chance to make a single gamma ray is predictable.

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



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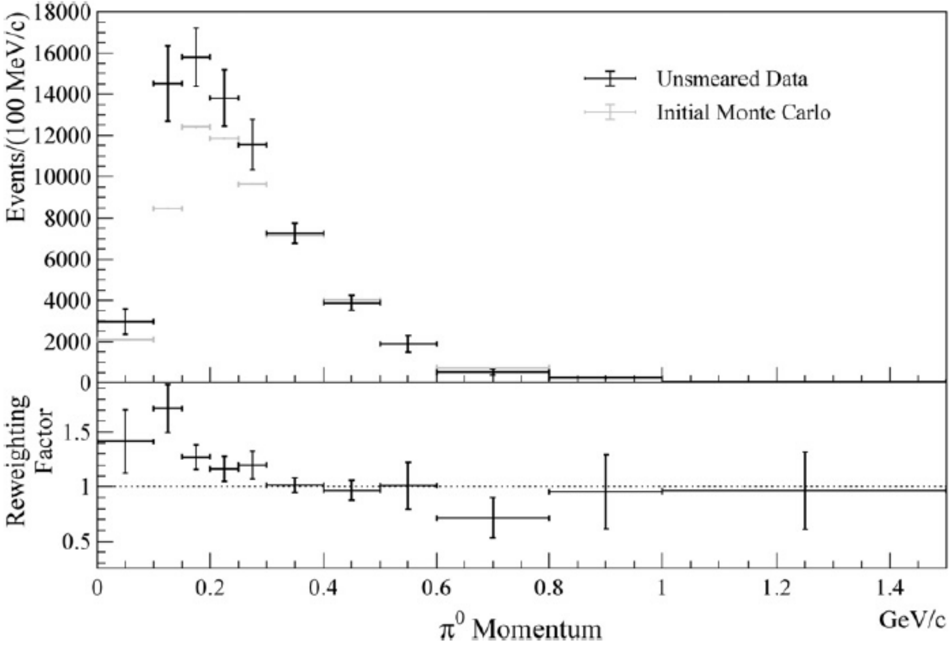
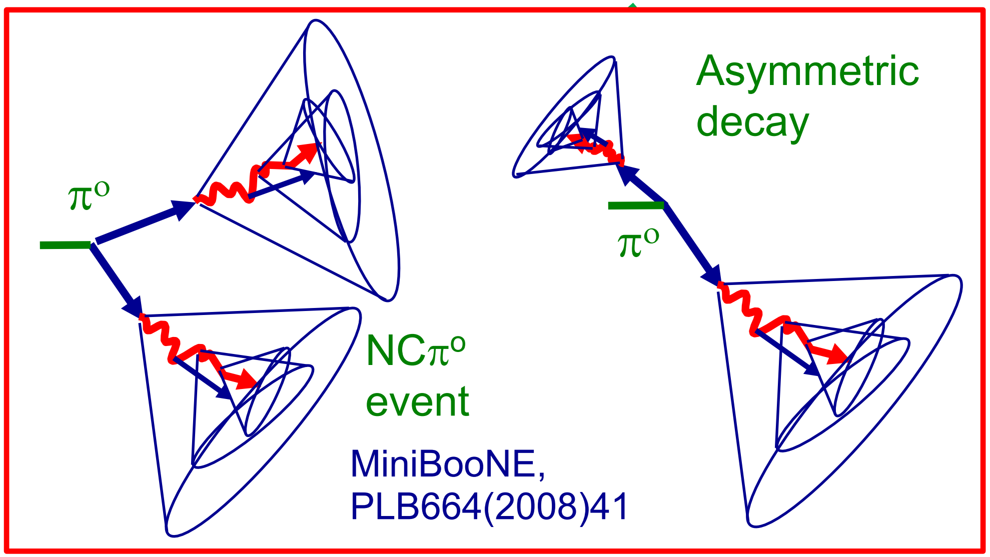
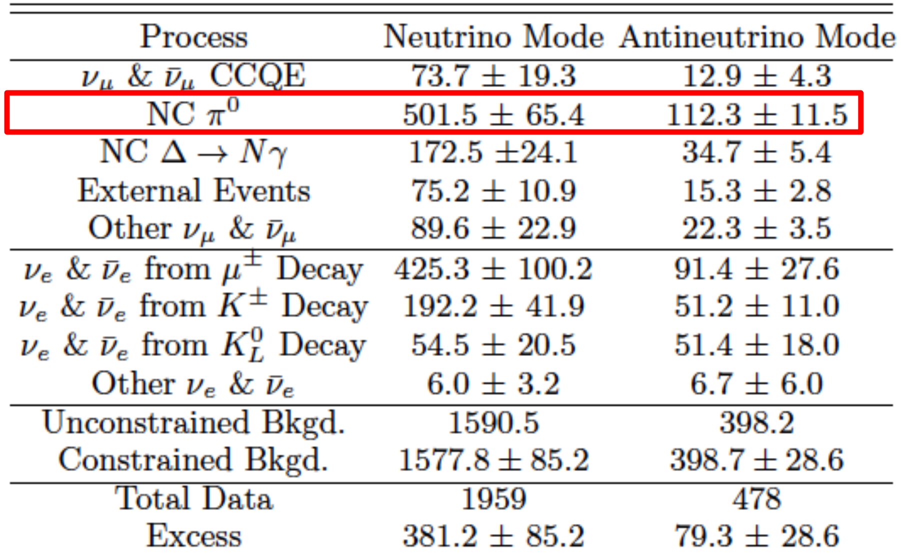




MiniBooNE, PLB664(2008)41

4. γ from π° constraint



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

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
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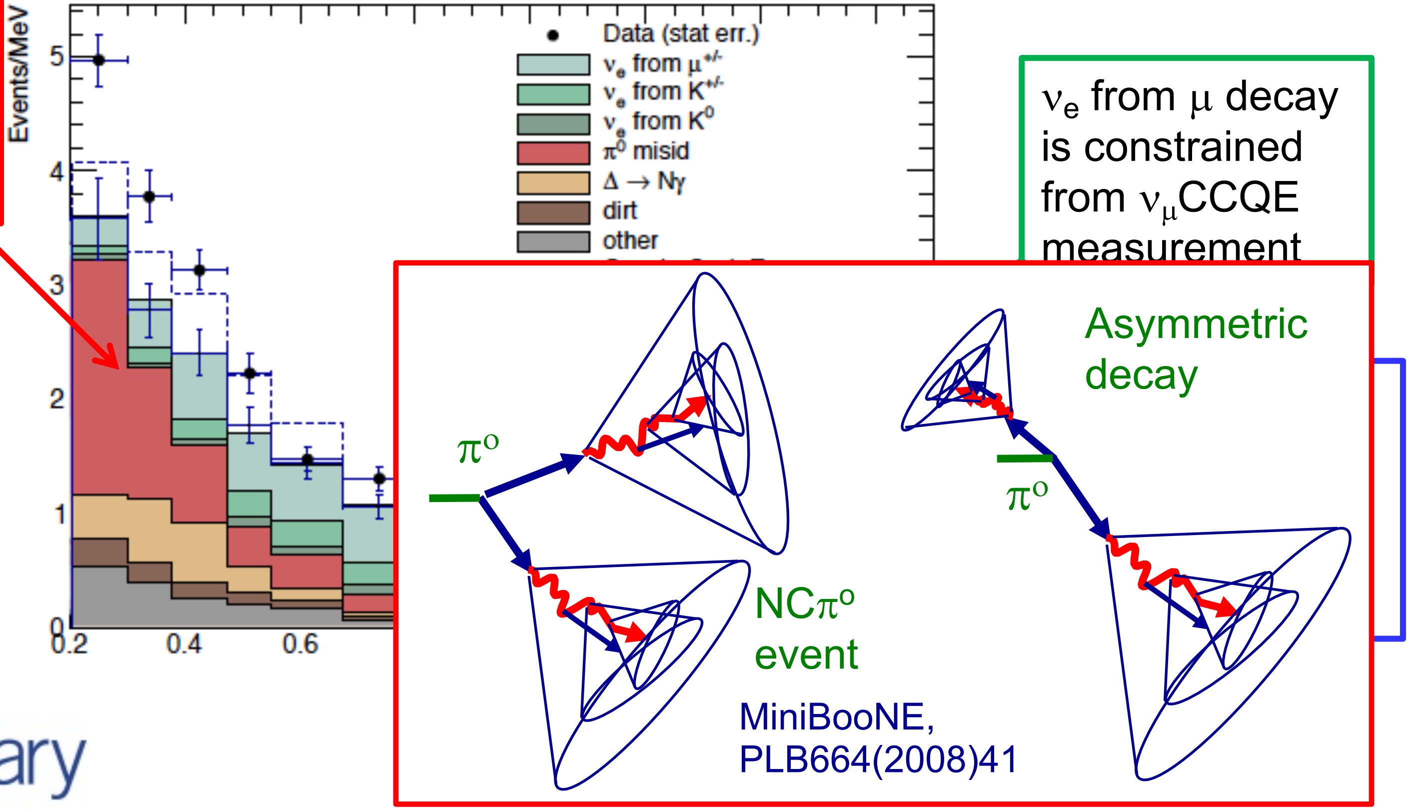
Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)



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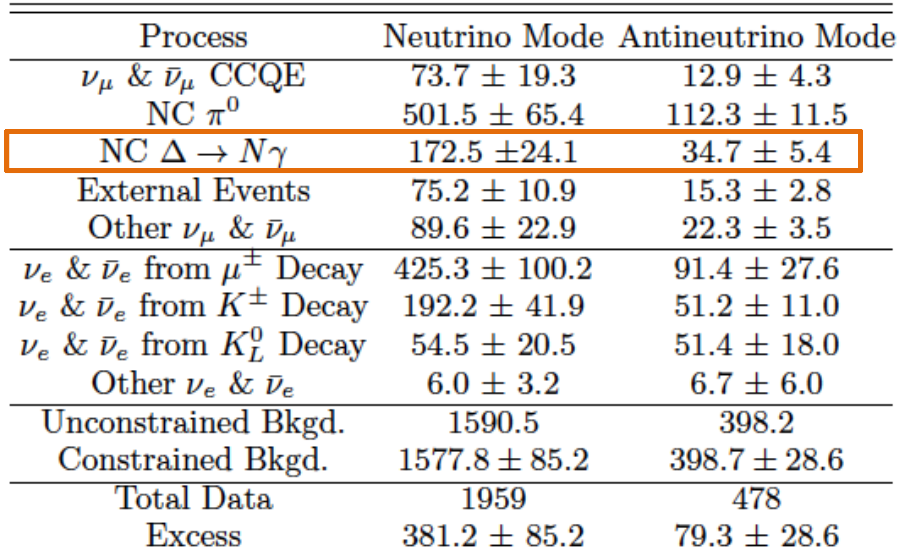
MiniBooNE, PLB664(2008)41

4. NCγ constraint



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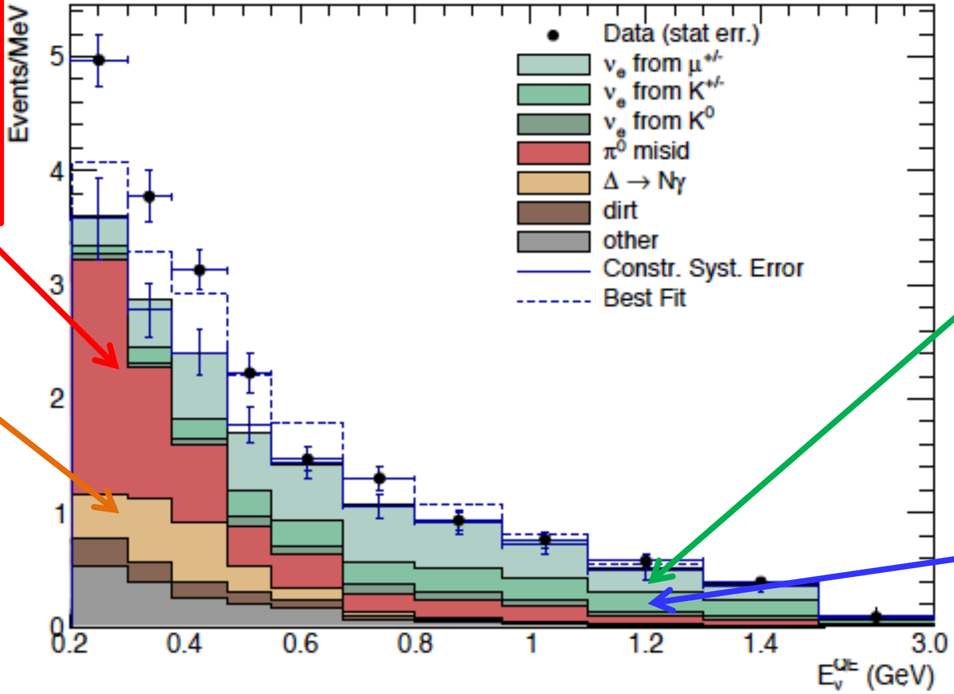

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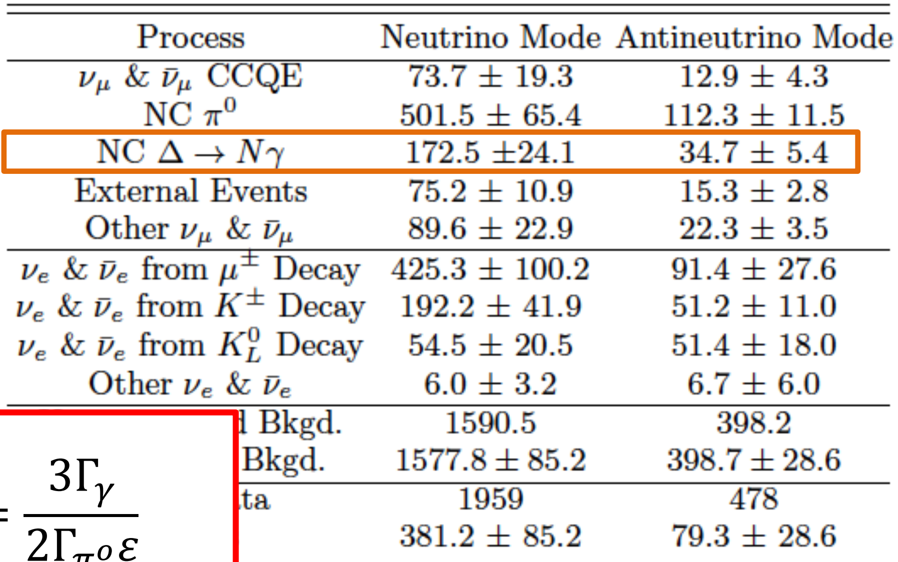

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$$\frac{N(\Delta\to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

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

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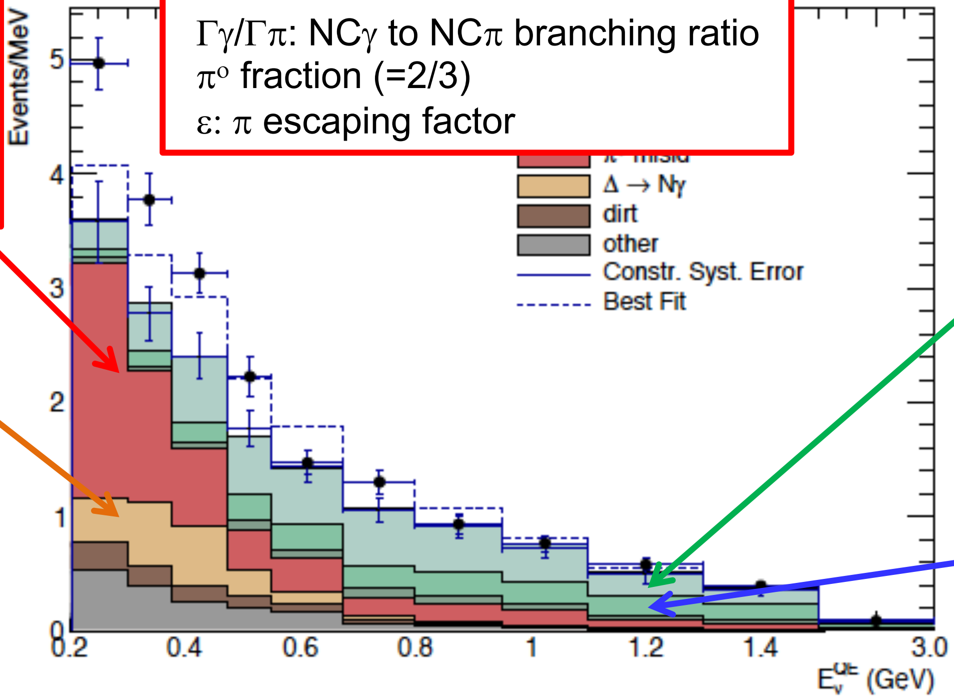

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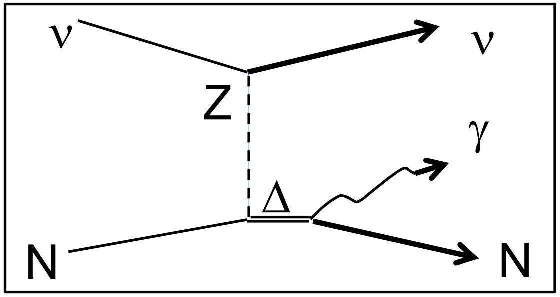
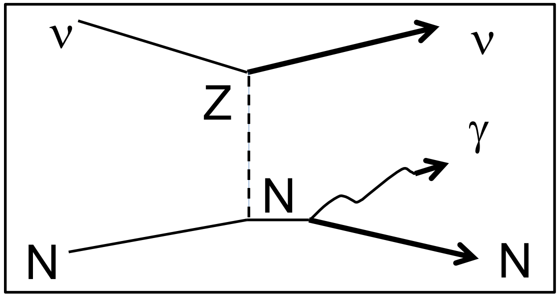
Wang, Alvarez-Ruso, Nieves,PLB740(2015)16, Hill,PRD84(2011)017501, Zhang and Serot,PLB719(2013)409
Lasorak, arXiv:1602.00084

4. Neutrino NC single gamma production

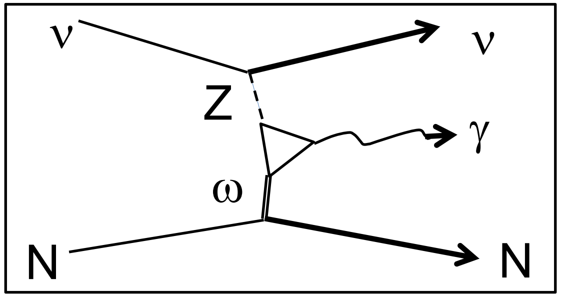
radiative Δ-decay

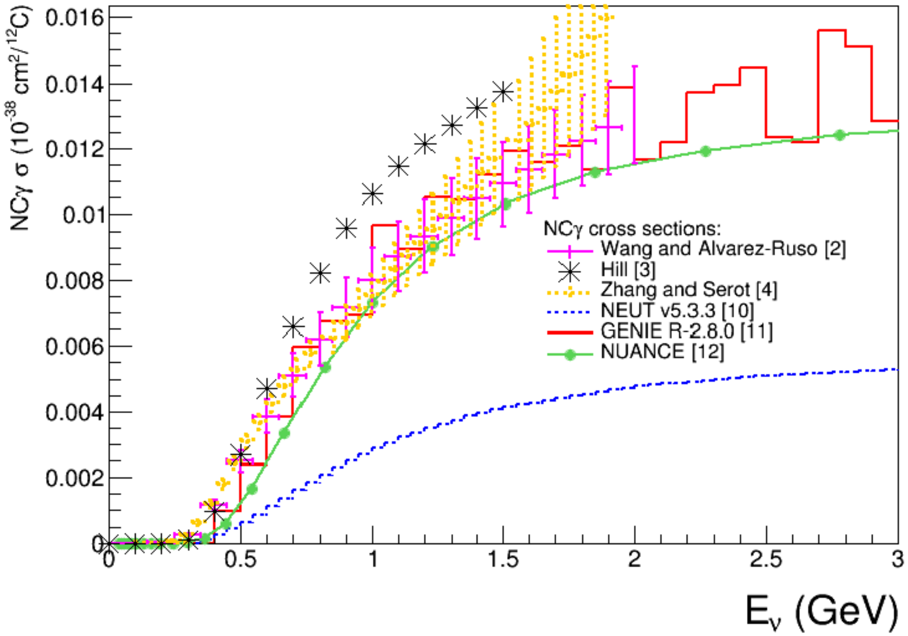


generalized Compton scattering



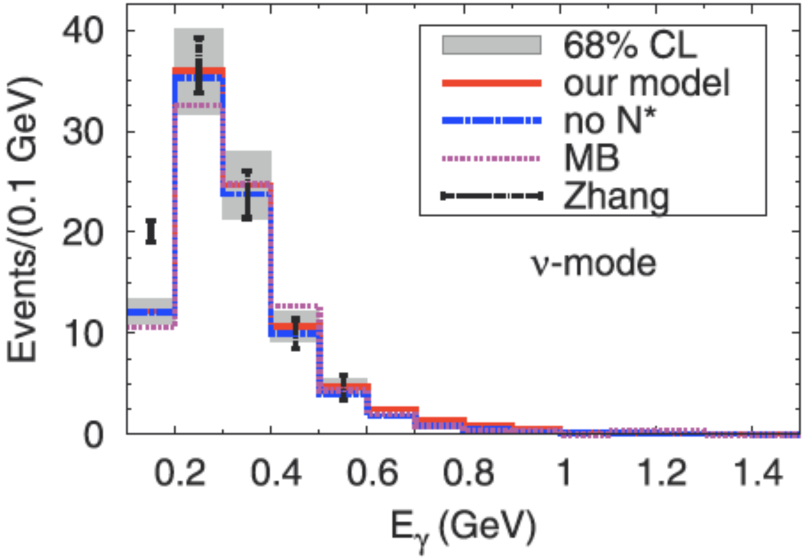
anomaly mediated triangle diagram





A lot of new calculations

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



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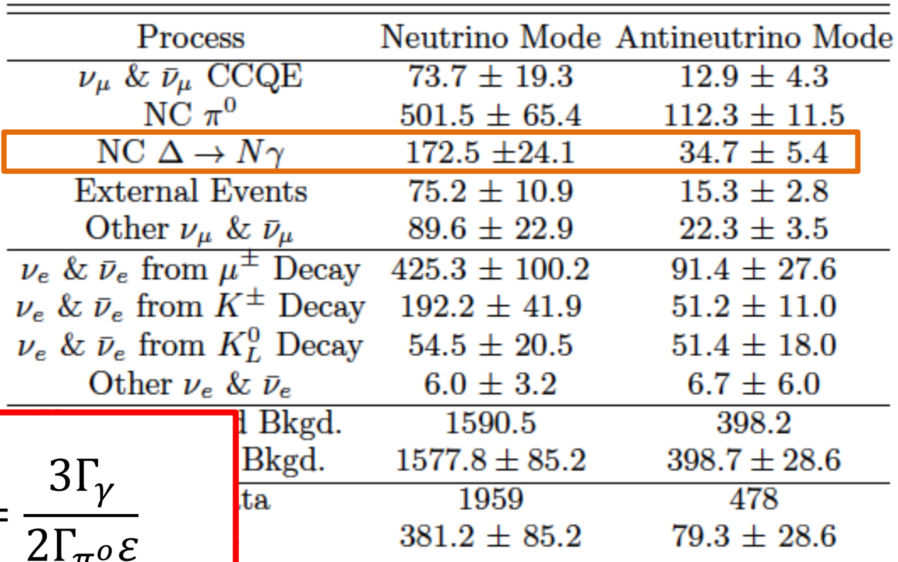

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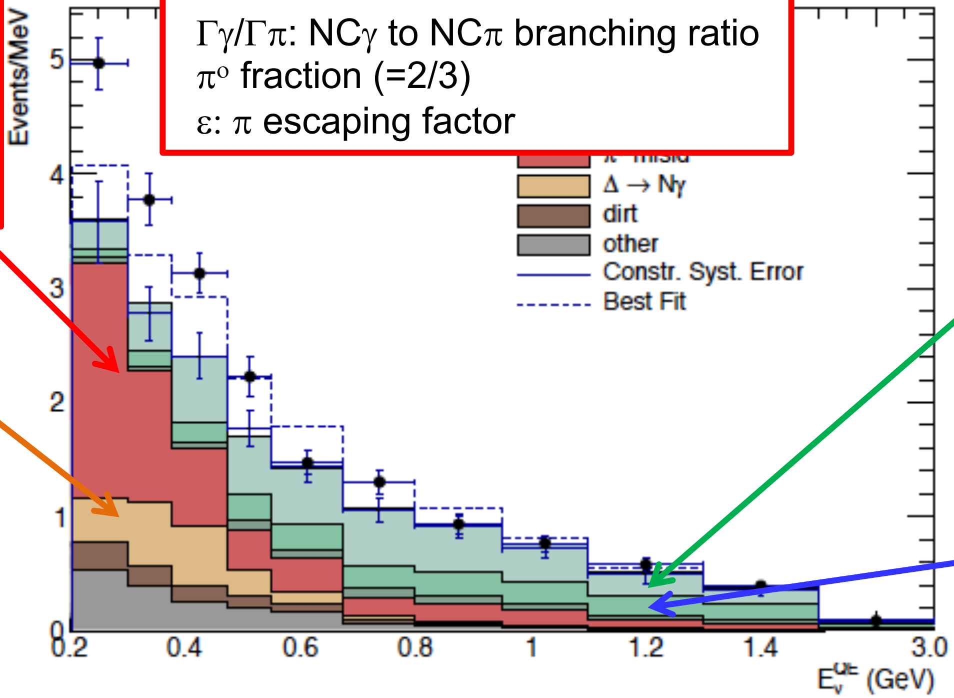

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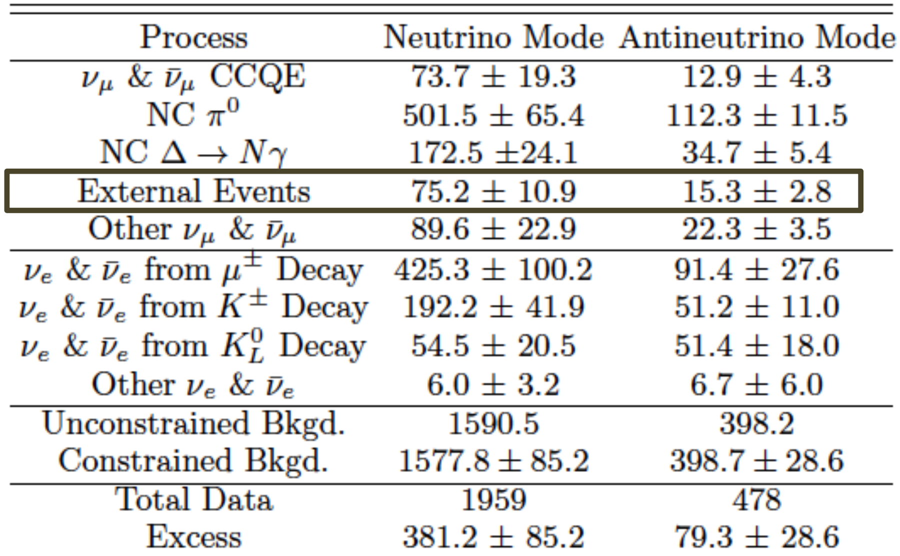

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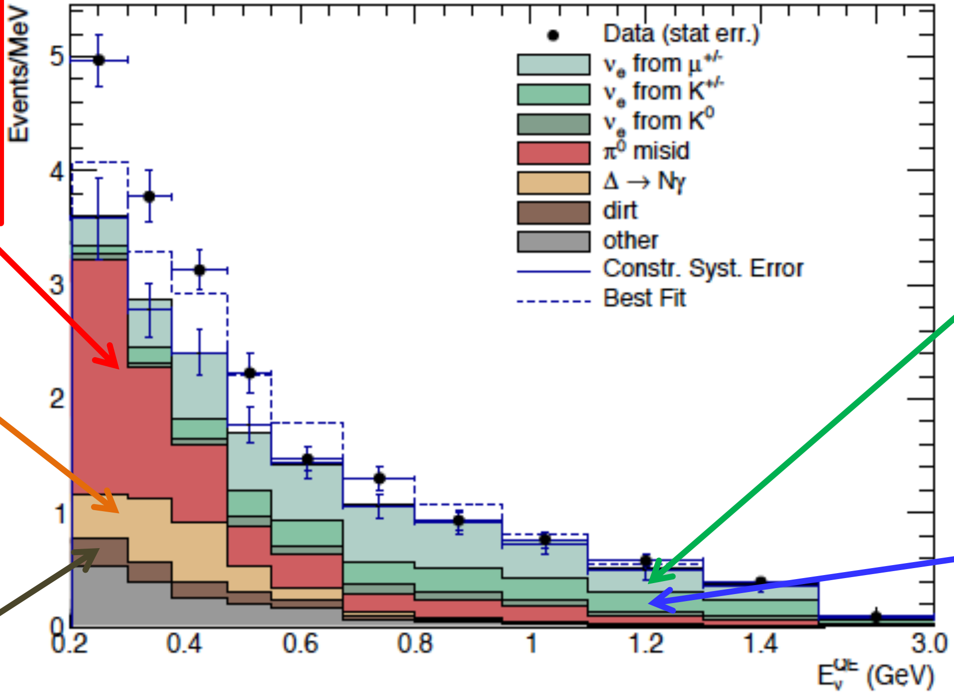

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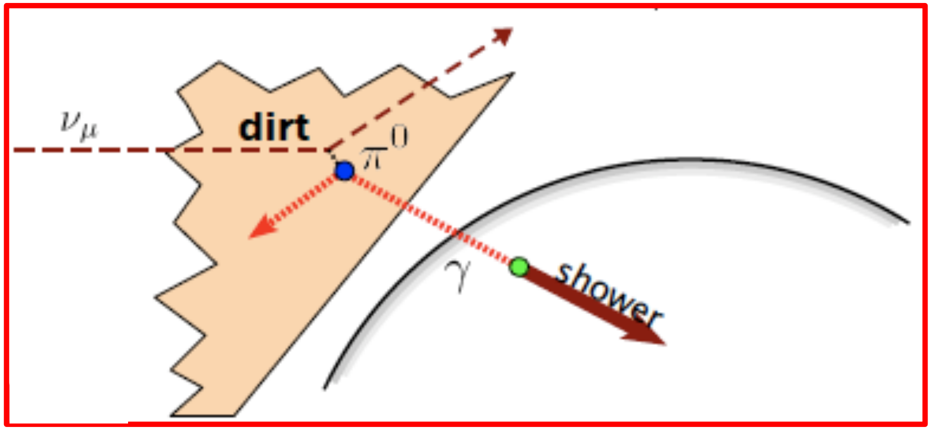
MniBooNE, PRD82(2010)092005

4. External γ constraint

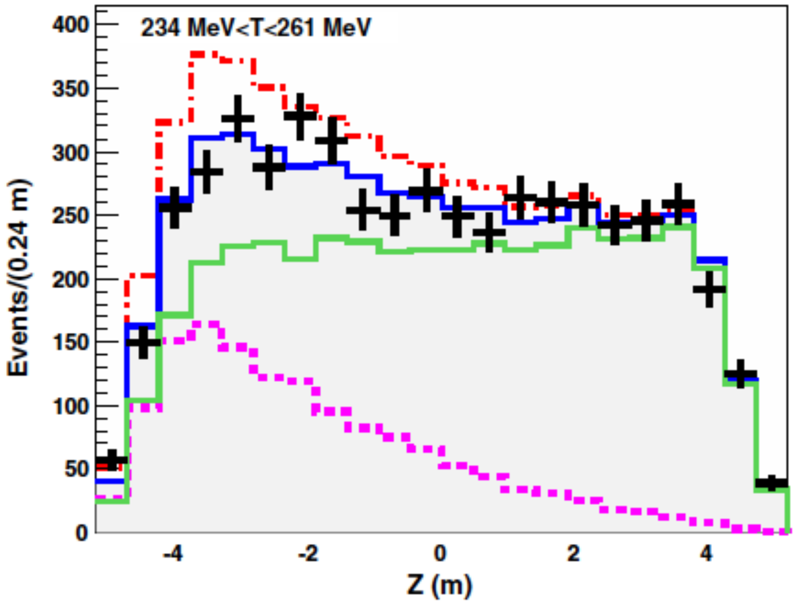
MiniBooNE detector has a simple geometry
- Spherical Cherenkov detector
- Homogeneous, large active veto

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



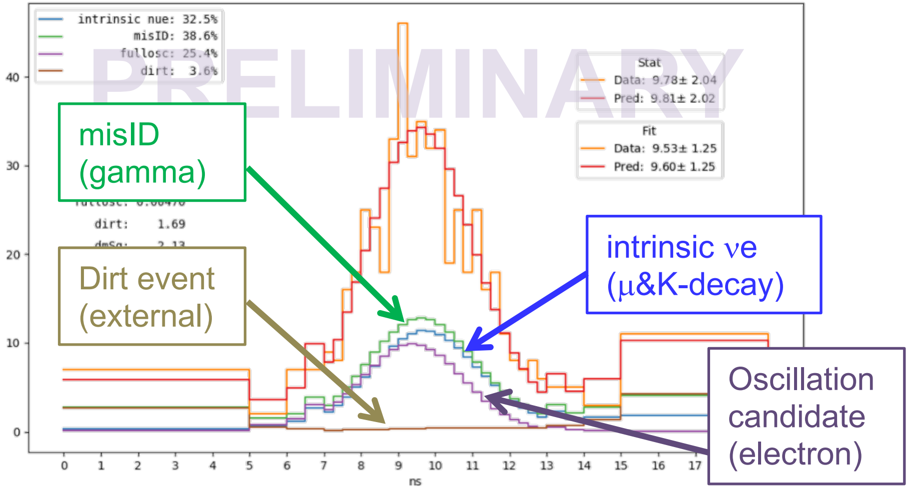
e.g.) NC elastic candidates with function of Z

Mis-modelling of external background is visible



e.g.) Time of Flight

Dirt related events is consistent with ToF data including oscillation hypothesis



misID (gamma)

Dirt event (external)

intrinsic νe (μ&K-decay)

Oscillation candidate (electron)

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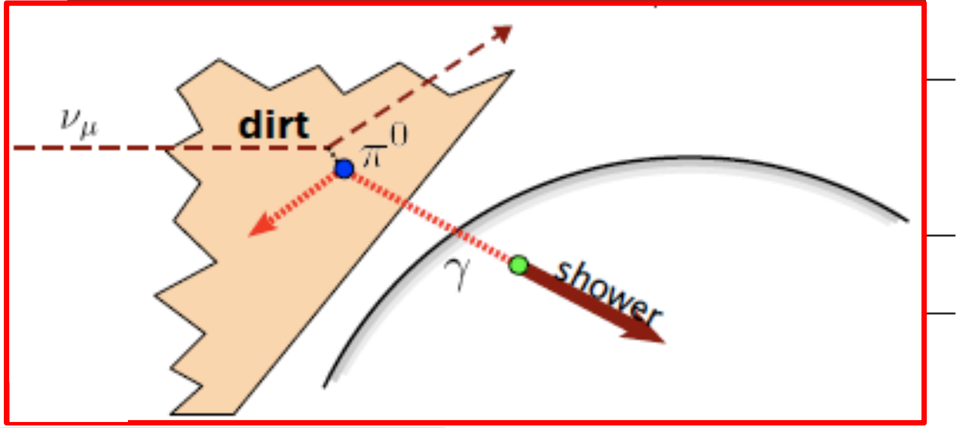

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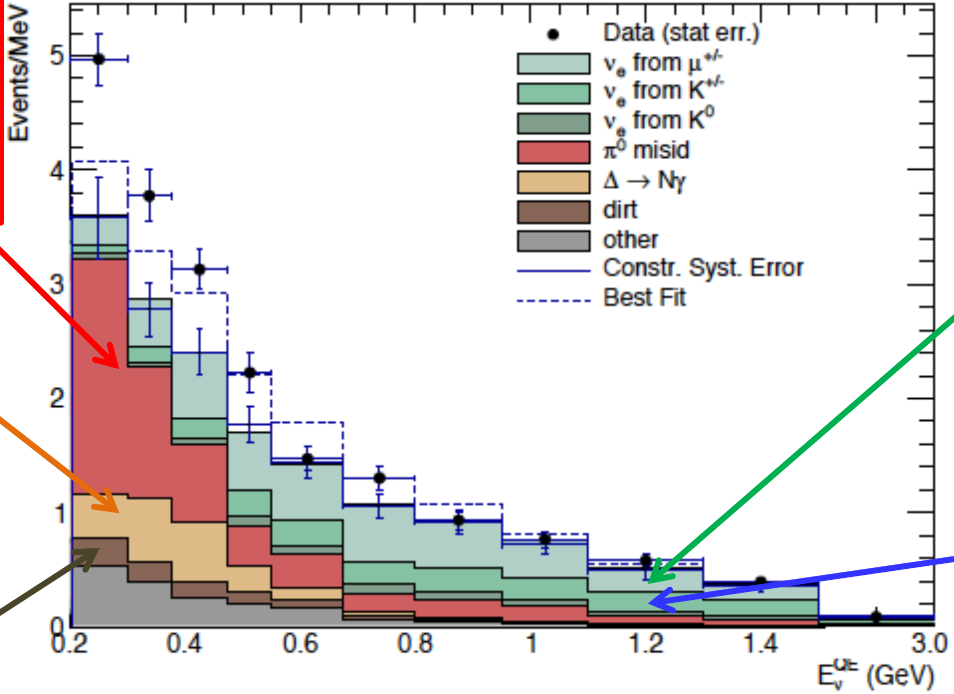

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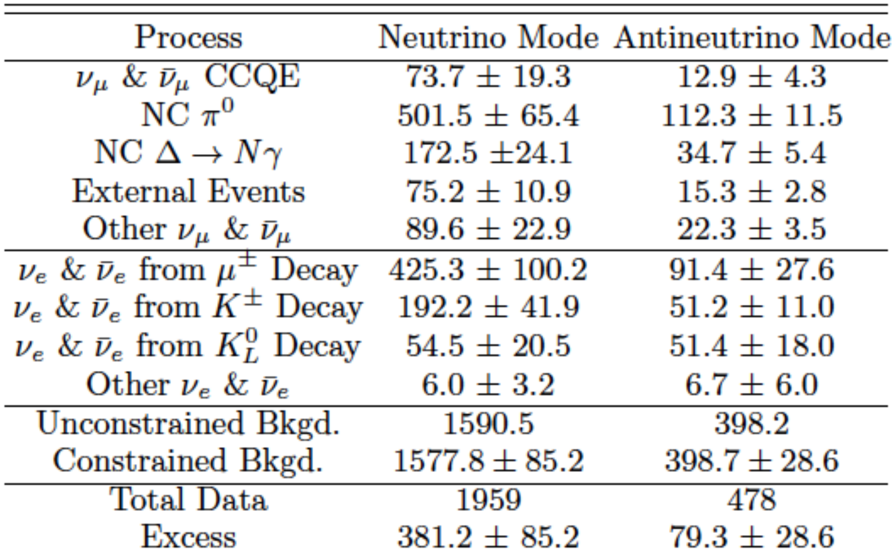

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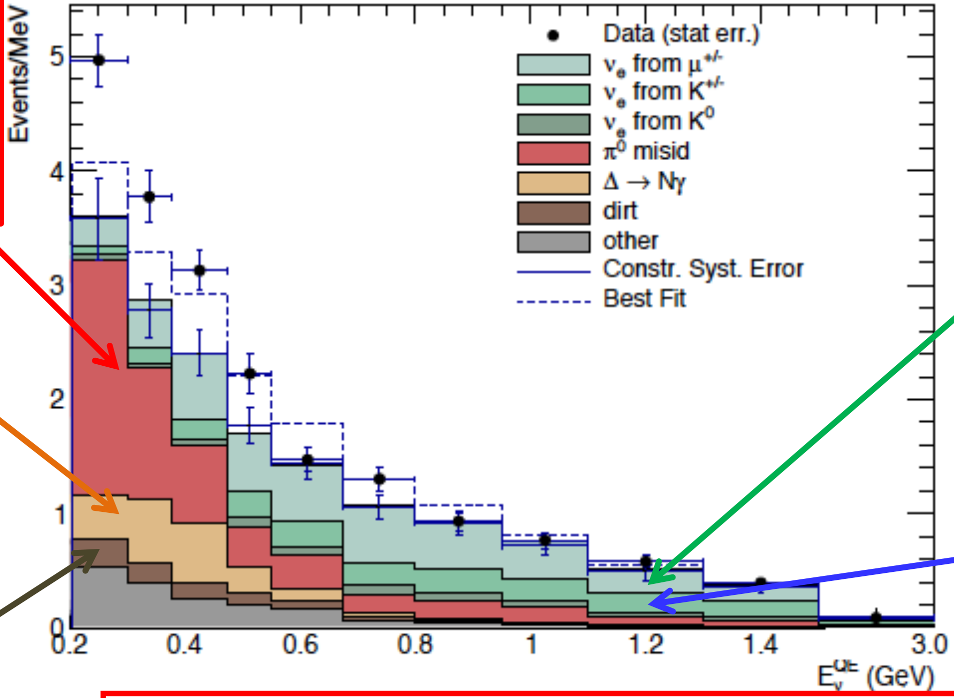

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Major backgrounds are all measured in other data sample and their errors are constrained!

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

5. Oscillation candidate event excess

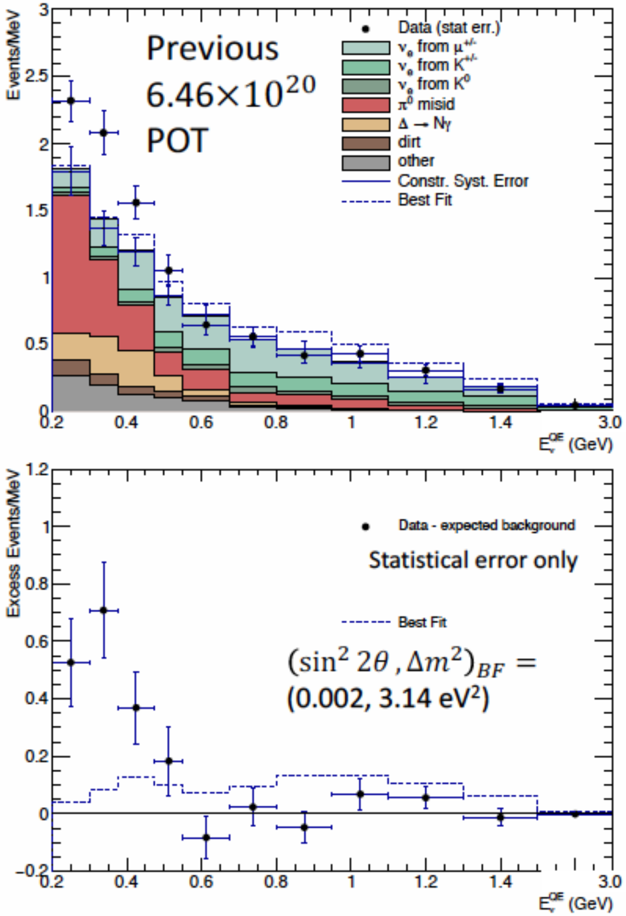
200 < EνQE < 1250 MeV
- neutrino mode: Data = 1956 events

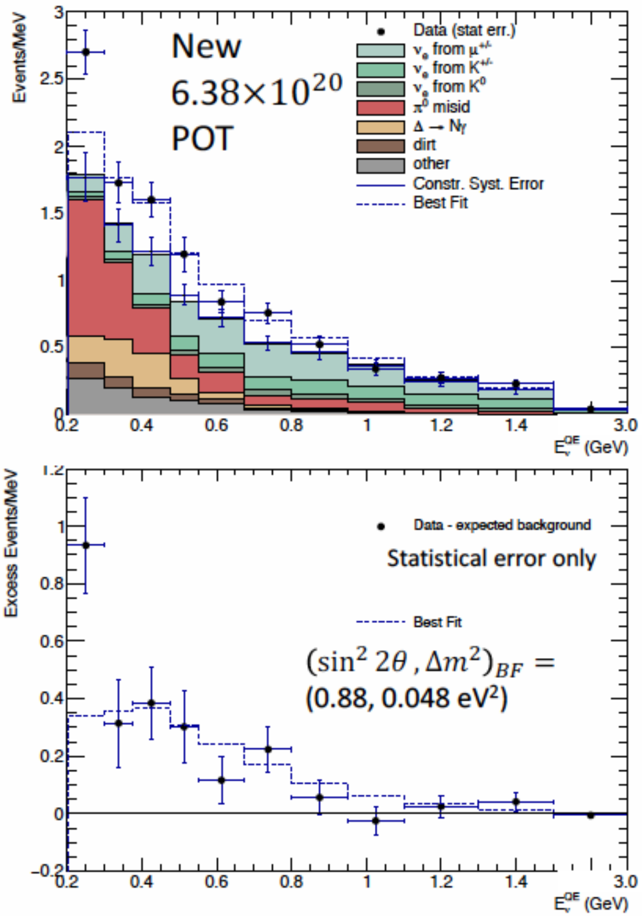
Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)

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%





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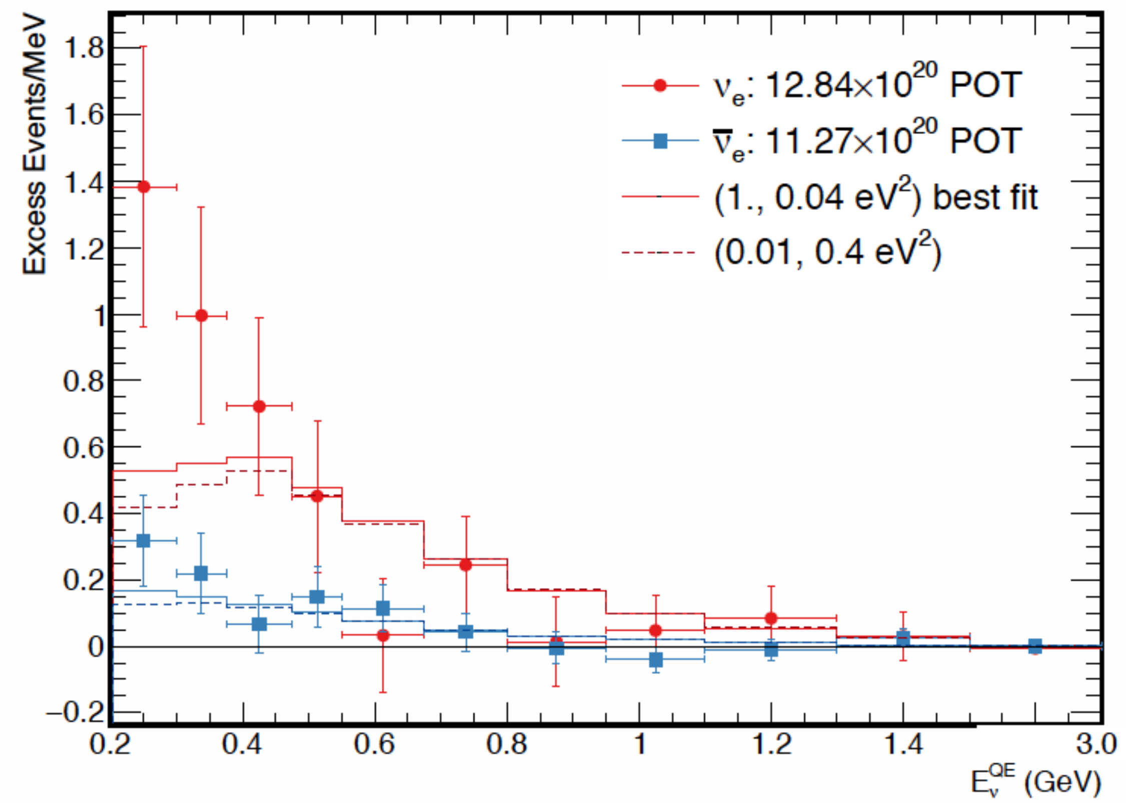
Bkgd = 398.7 ± 20.0(stat) ± 20.3(syst) → 79.3 ± 28.6 excess (2.8σ)



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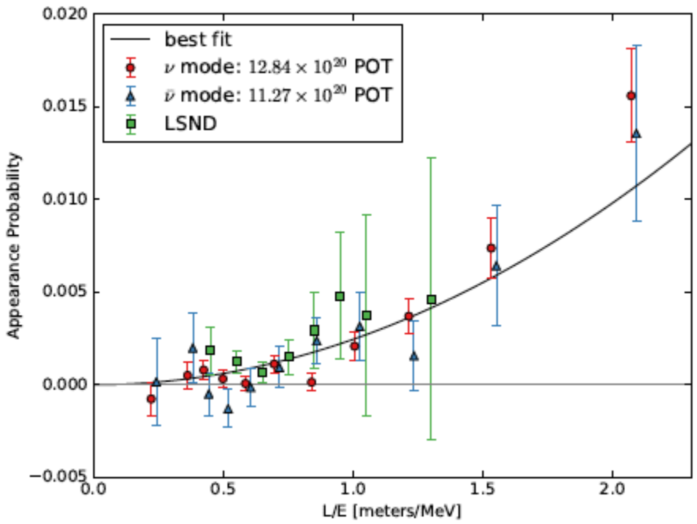
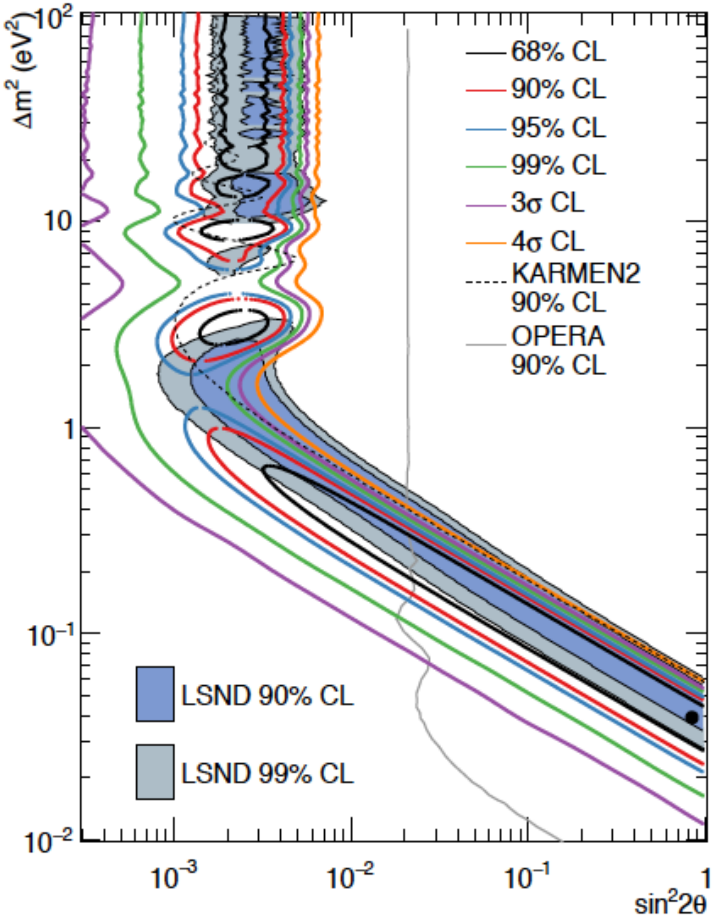
Compatible with LSND excess within 2-neutrino oscillation hypothesis



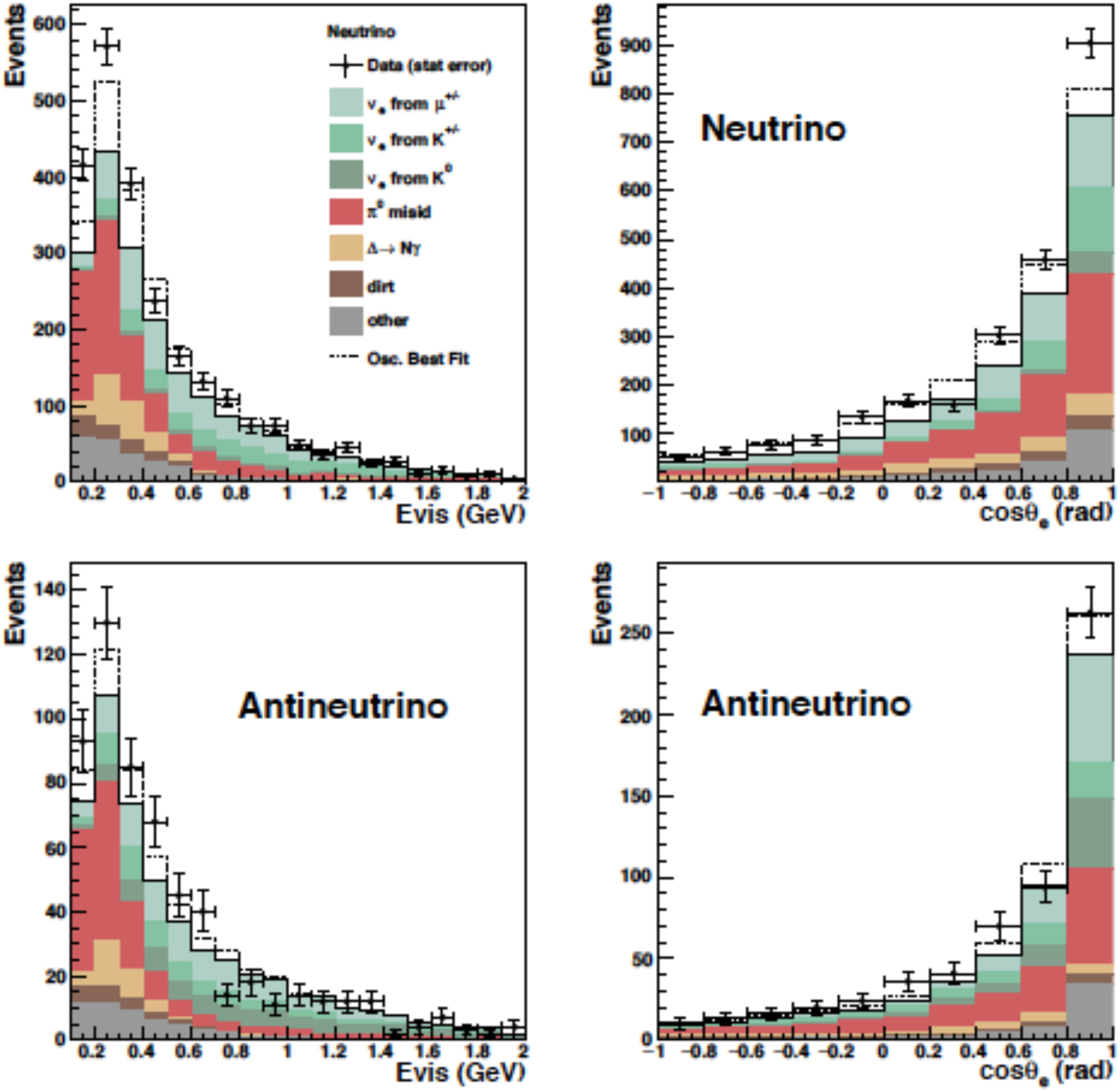


However, appearance and disappearance data have a strong tension (Maltoni, Neutrino 2018)

5. Alternative photon production models?

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

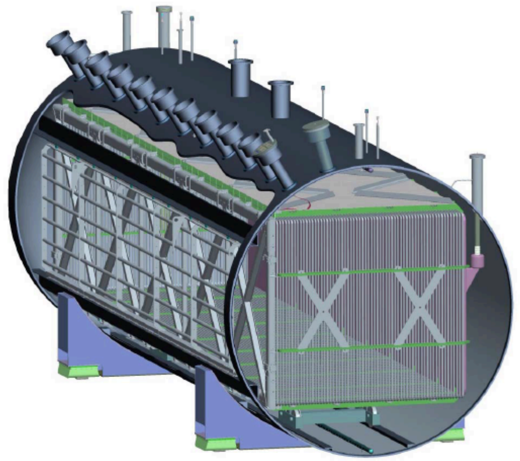
Any misID background missing?
 - Internal π^o?
 - external π^o?
 - New NCγ process?
 - New γ production process?

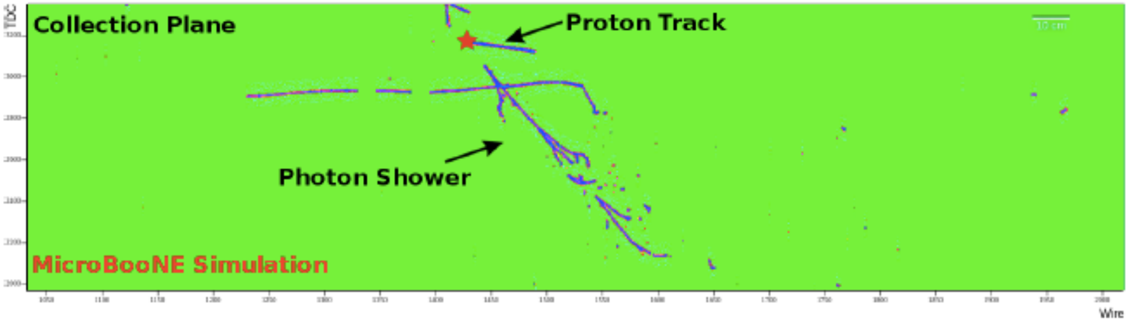


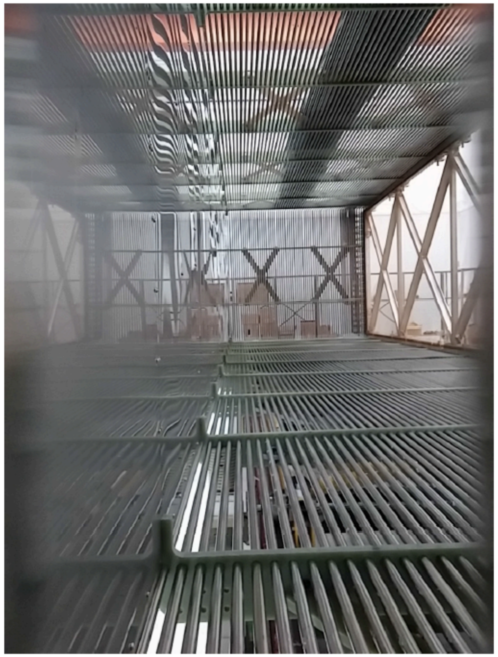
MicroBooNE,JINST12(2017)P02017
Murrells, PhD thesis (2018)

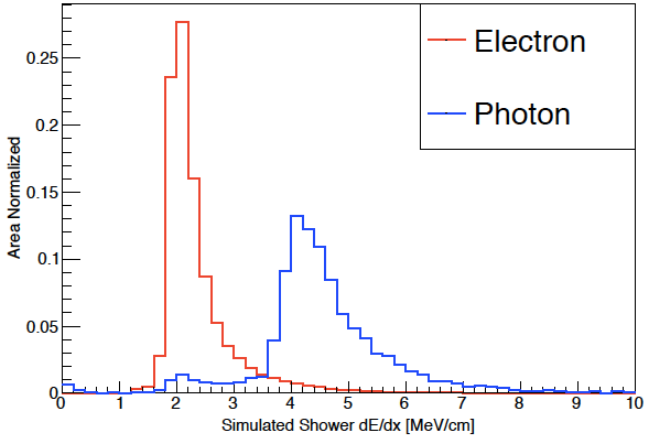
5. Liquid argon time projection chamber γ production

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







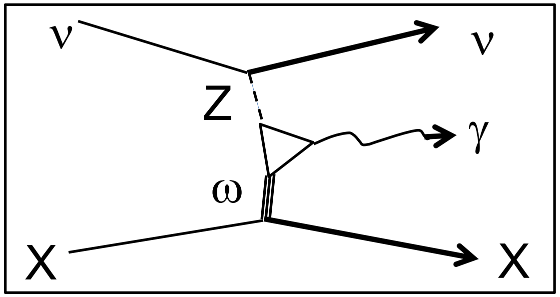


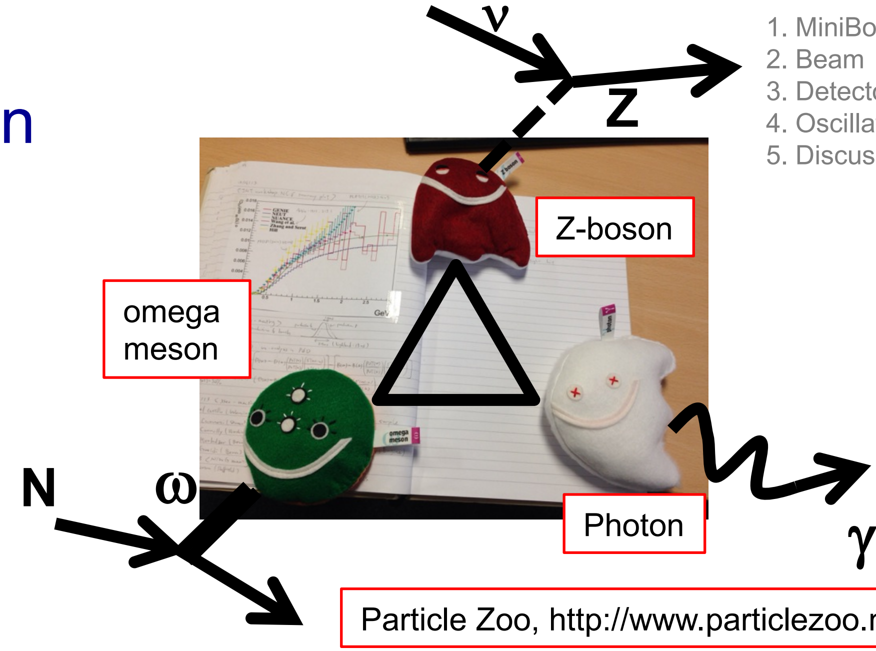
dE/dx of first 4cm track (simulation)

Harvey,Hill,Hill, PRL99(2007)261601

5. Anomaly mediated γ production

A process within SM, but not considered.

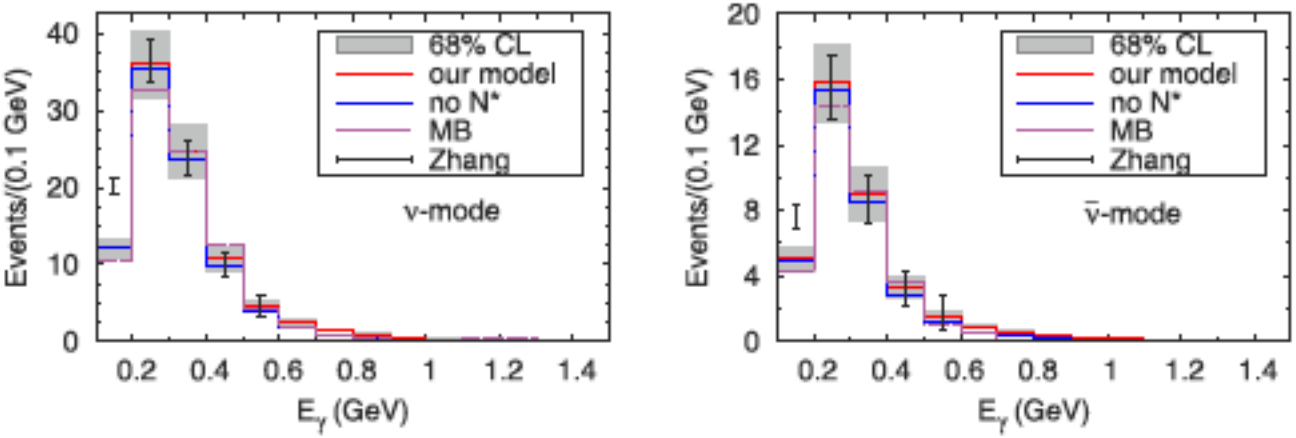




Particle Zoo, http://www.particlezoo.net/

Later study found the contribution is small.

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

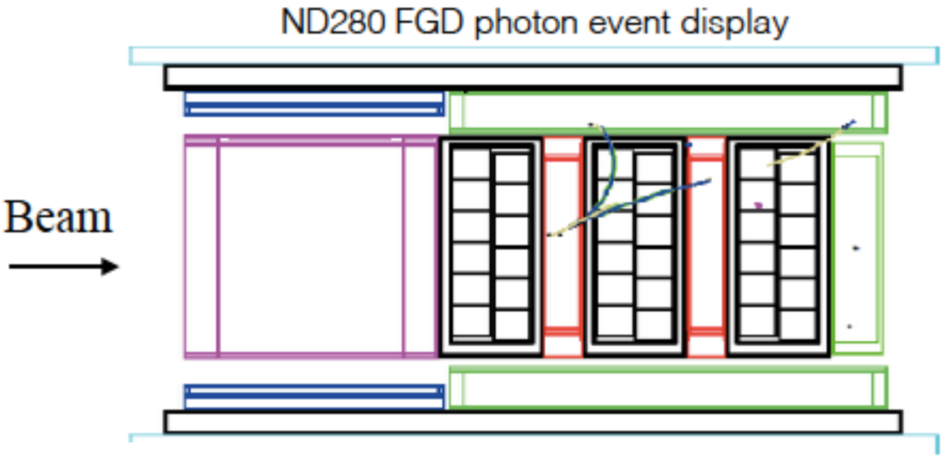


It looks it’s easy to forget any processes with $\sigma \sim 10^{-41}$ cm^2
(e.g., diffractive π^o production $\sigma \sim 10^{-41}$ cm^2 was identified very recently by MINERvA)

MINERvA, PRL117(2016)111801

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

5. NC single photon search in T2K



T2K near detector measurement

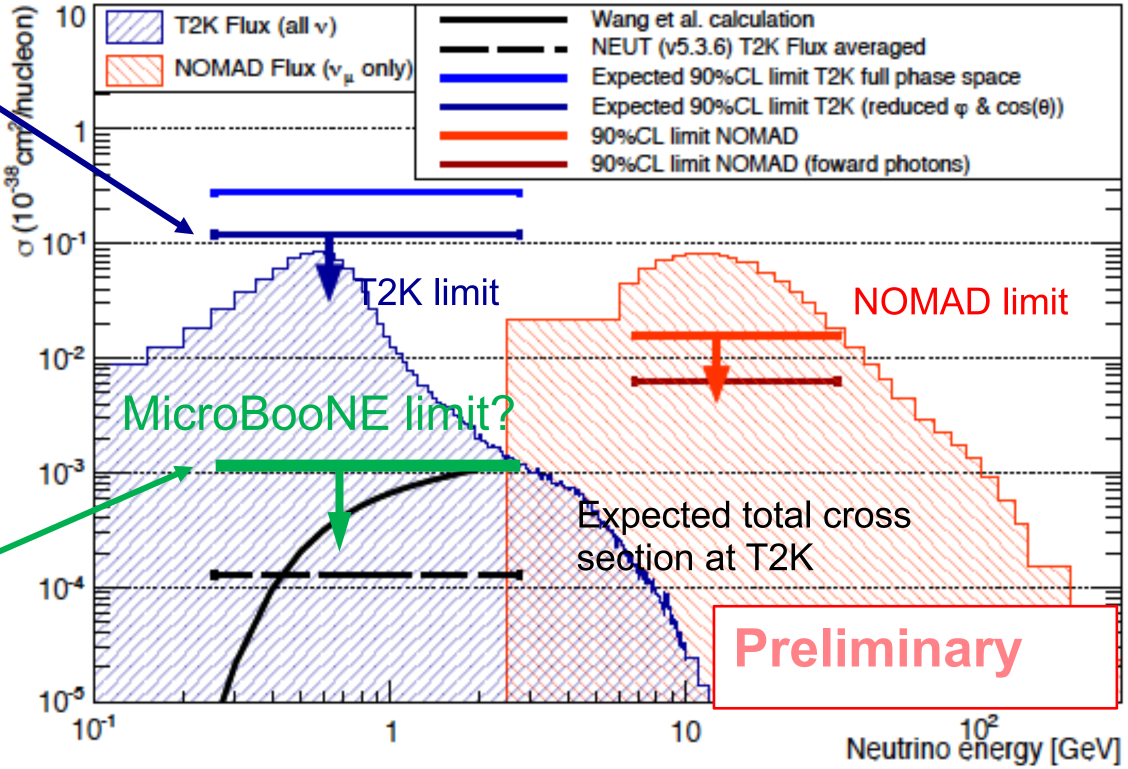
- 95% pure photon sample (M_{inv}<50 MeV)
- Large external photon background and internal π^o production background. T2K can only set a limit.

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

MicroBooNE

- First large LArTPC in USA
- Good e/γ PID
- Large active veto region
- Good internal π^o measurement

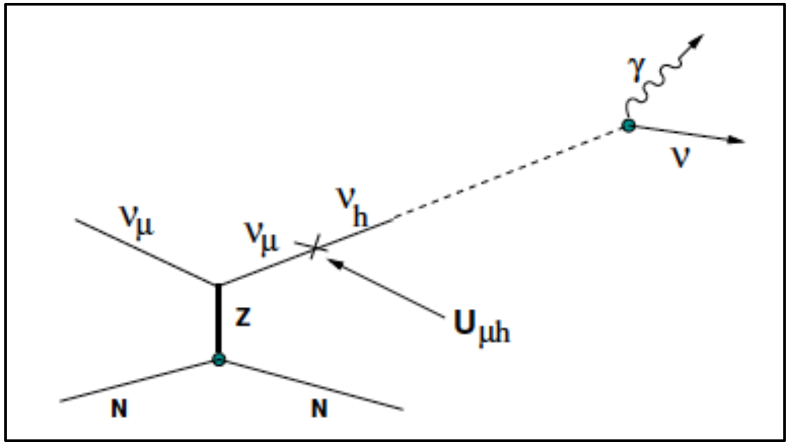
→ Good chance to measure the first positive signal of this channel.



Bobby Murrell
Manchester
(MicroBooNE)

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

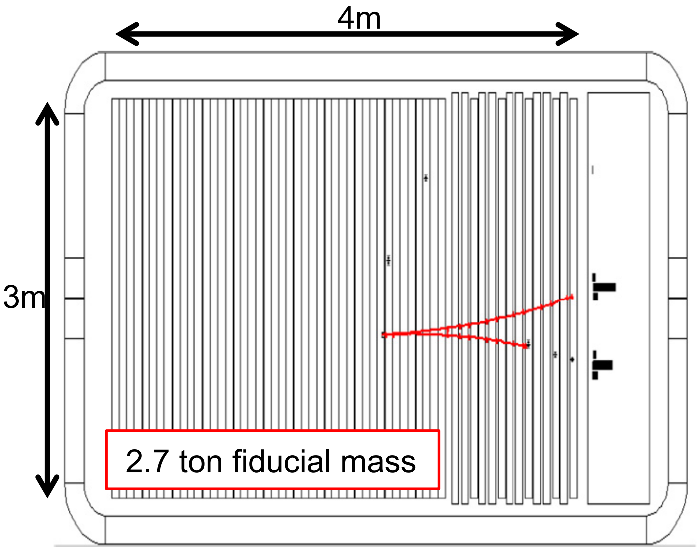
5. Beyond the Standard Model γ production



Heavy neutrino decay γ production

Carefully designed to avoid Karmen constraint.
 - The model works, but there are many “tricks” to avoid existing constraints, making the model bit artificial.

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



NOMAD, PLB706(2012)268

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

5. Lorentz violating neutrino oscillation

Alternative oscillation explanation of LSND signal

Making a new texture in Hamiltonian to control oscillations.

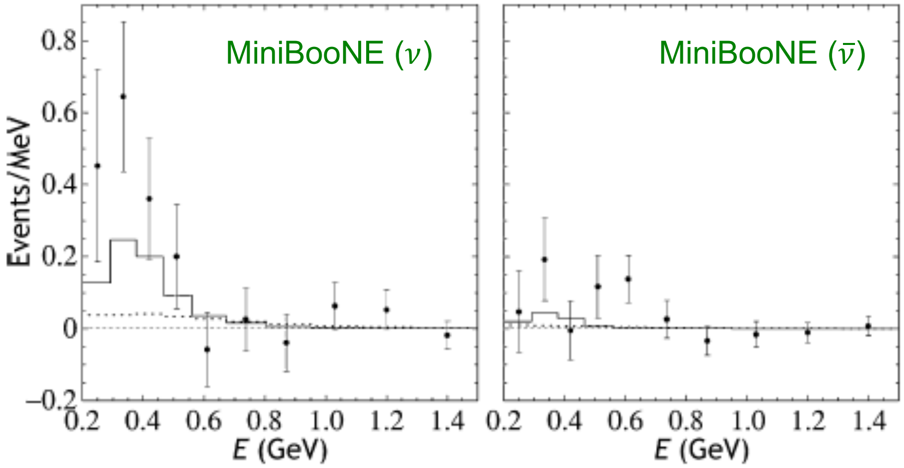
- LV-motivated model reproduce all data and LSND

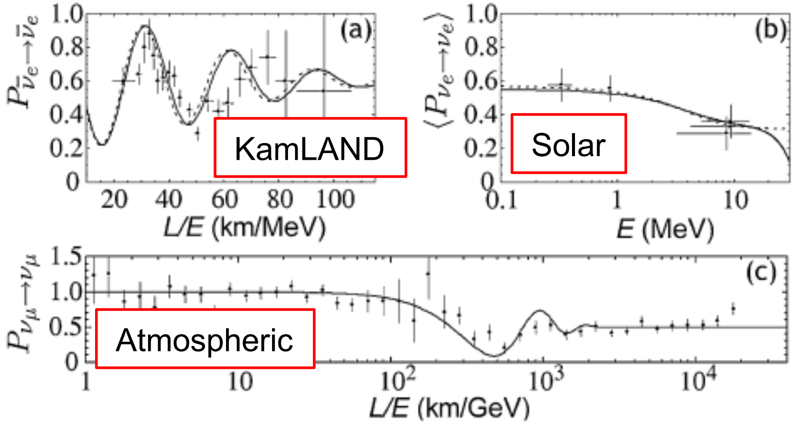
→ not really reproduce details (no ν_e appearance).

puma model effective Hamiltonian

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

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




KamLAND

Solar

Atmospheric

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

Super-Kamiokande, PRL(2004)101801

TK, MPLA27(2012)1230024
IceCube, Nature Physics 14 (2018) 961

5. Lorentz violating neutrino oscillation

Search of Lorentz violation using neutrinos

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

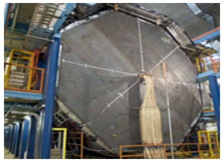
The latest IceCube atmospheric neutrino Lorentz violation search set one of the strongest limits on anomalous space-time effect, from table top experiment to cosmology.

- highest energy (~20 TeV)
- longest baseline (~12700 km)

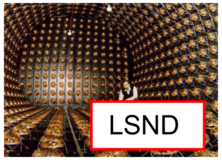
Neutrinos are one of the most sensitive tools to study space-time properties!


MINOS ND

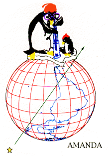
PRL101(2008)151601


MINOS FD

PRL105(2010)151601

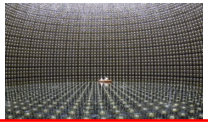

LSND

PRD72(2005)076004

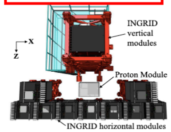


AMANDA

PRD79(2009)102005


Super-Kamiokande

PRD91(2015)052003

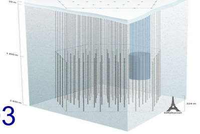


T2K ND

PRD95(2017)111101


MiniBooNE

PLB718(2013)1303


IceCube-40

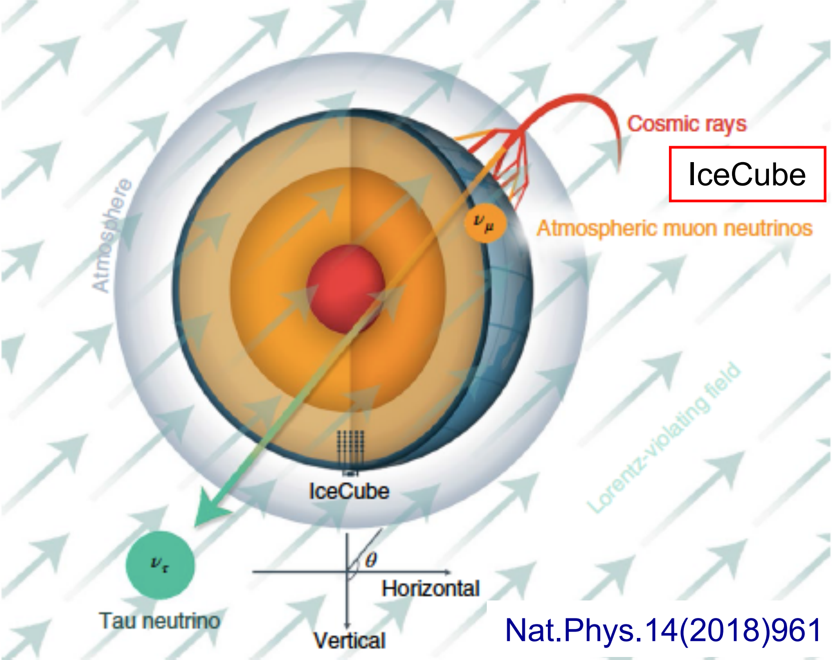
PRD82(2010)112003

Double Chooz

PRD86(2013)112009

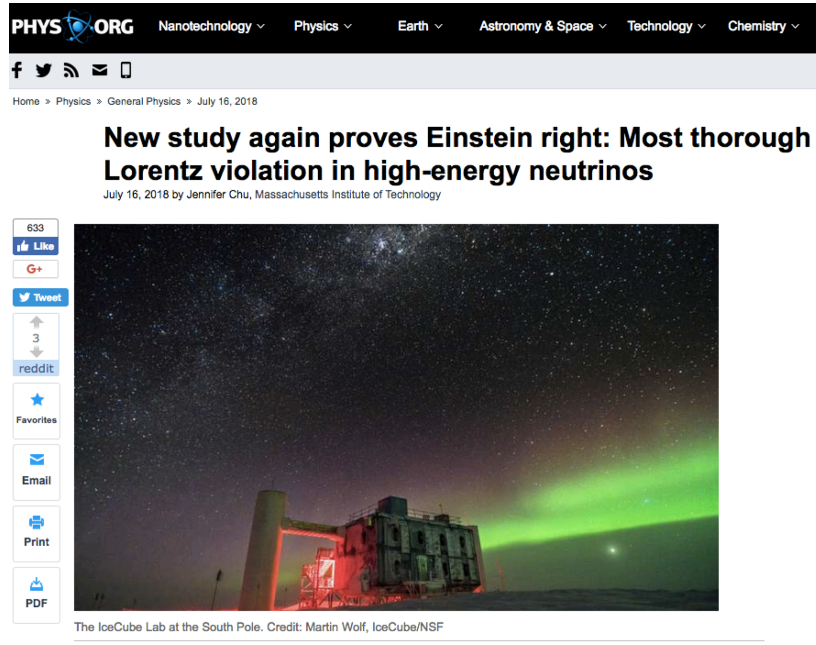

Daya Bay

arXiv:1809.04660



IceCube

Nat.Phys.14(2018)961

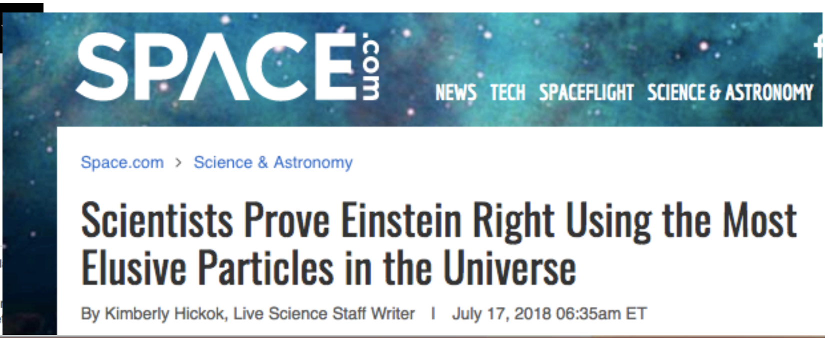


Home » Physics » General Physics » July 16, 2018

New study again proves Einstein right: Most thorough test to date finds no Lorentz violation in high-energy neutrinos

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

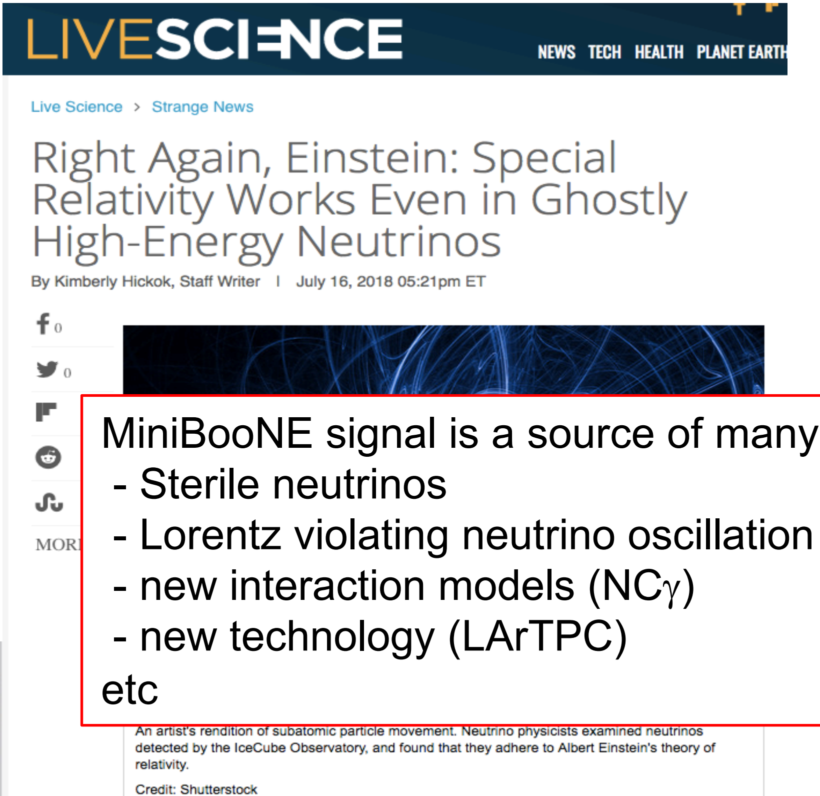
The IceCube Lab at the South Pole. Credit: Martin Wolf, IceCube/NSF



Space.com › Science & Astronomy

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

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



Live Science › Strange News

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

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

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

Credit: Shutterstock

PHYSICS · Published July 17 · Last Update July 17

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

By Kimberly Hickok, Staff Writer | LiveScience

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

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

Florida residents warne carrying New Guinea fl invading part of the sta

Mysterious hole shooti Arkansas stumps offici out' Satan

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

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

etc

Conclusion

MiniBooNE is the short-baseline neutrino oscillation experiments

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

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

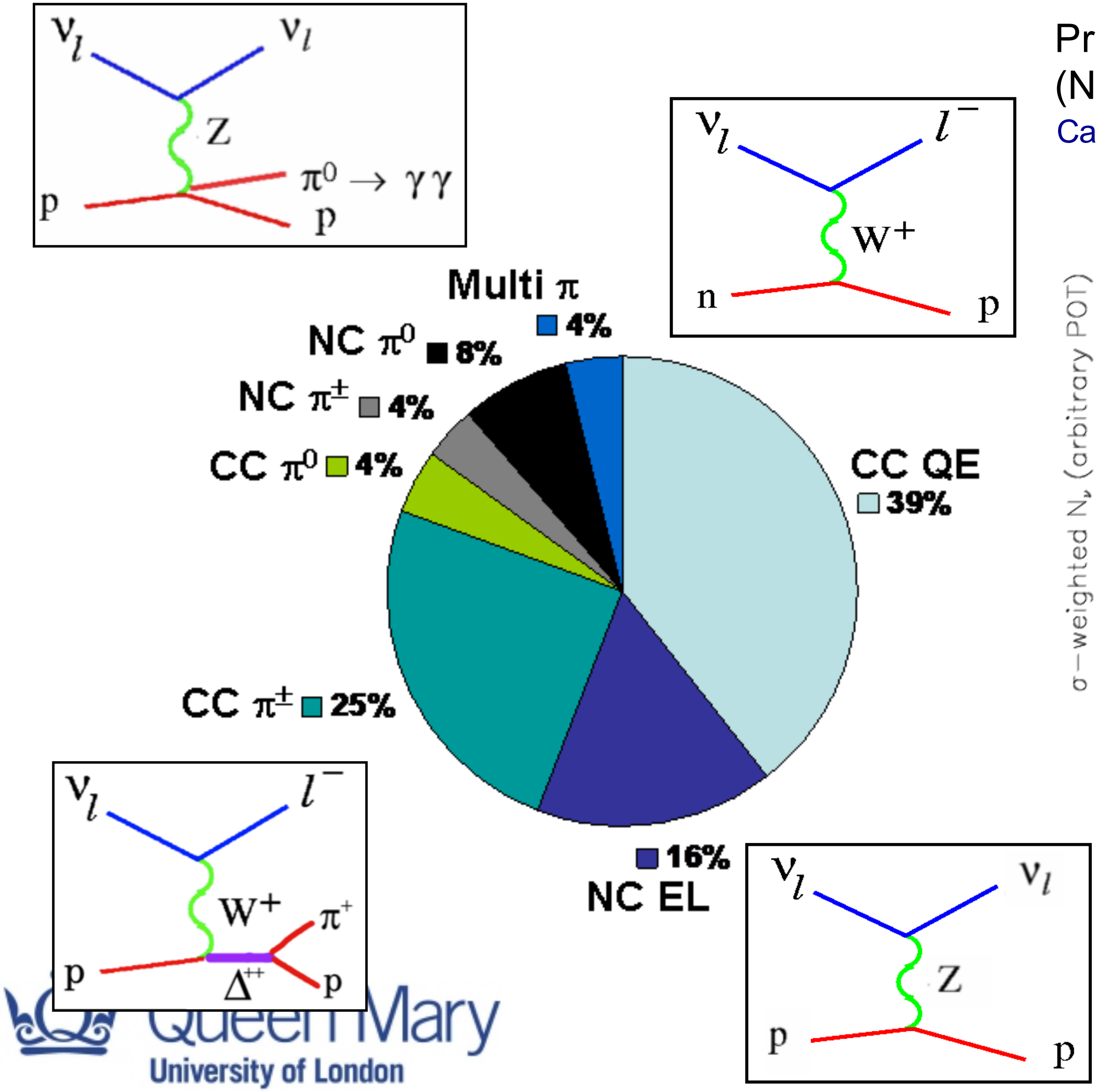
MiniBooNE, PRL118(2017)221803

But the biggest legacy is the short-baseline anomaly

Thank you for your attention!

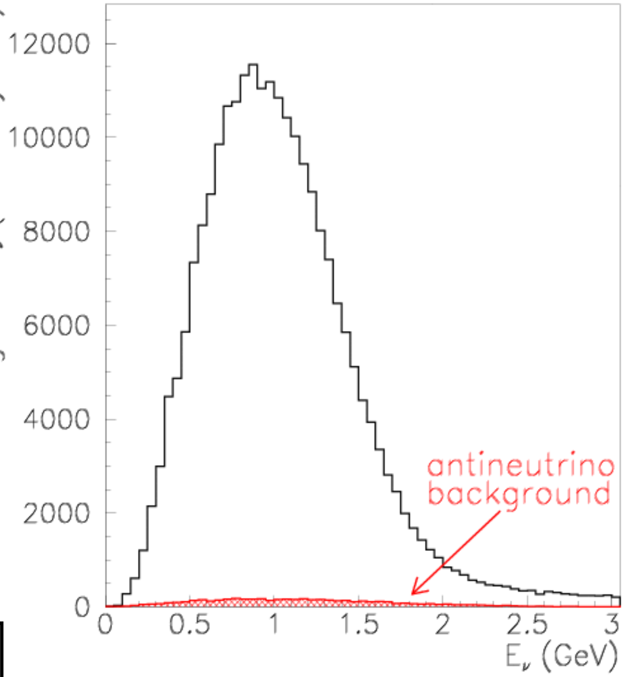
backup

1. Cross section model



Predicted event rates before cuts (NUANCE Monte Carlo)

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



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.