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, UCL, UK, June 14, 2018

1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

BackRe(Action)

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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 an anomaly that did not vanish with further examination. Indeed, it actually increased in significance, now standing at a whopping 6.1σ.

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PHYSICS

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

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

19.4K 5 9

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Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

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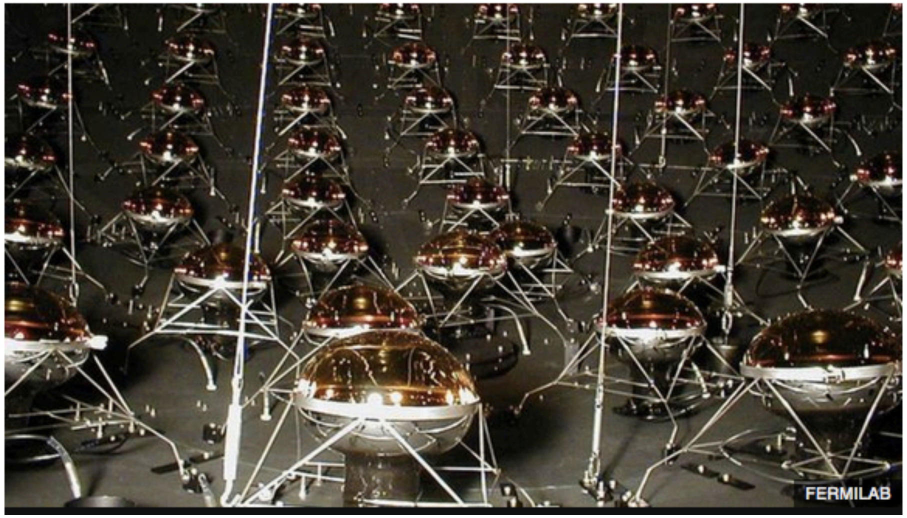
Quanta magazine

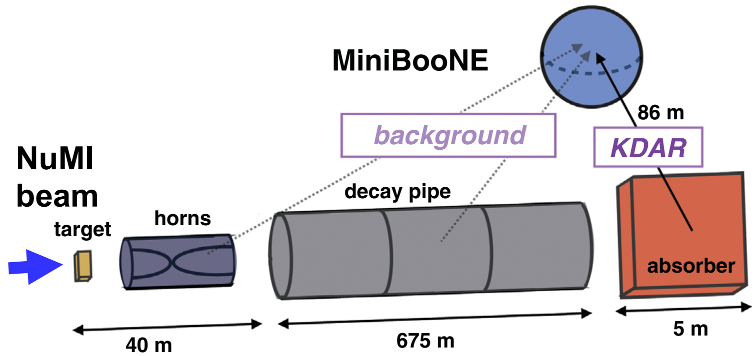
ABSTRACTIONS BLOG

Evidence Found for a New Fundamental Particle

10

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



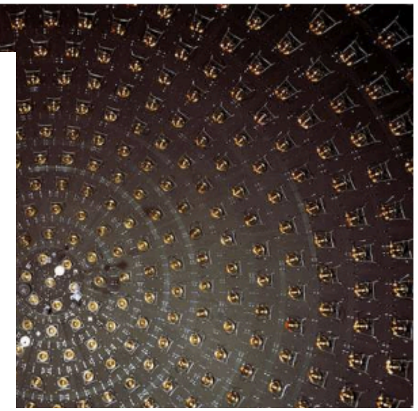


PHYS ORG — Nanotechnology · Physics · Earth · Astronomy & Space · Technology · Chemistry · Biology

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



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

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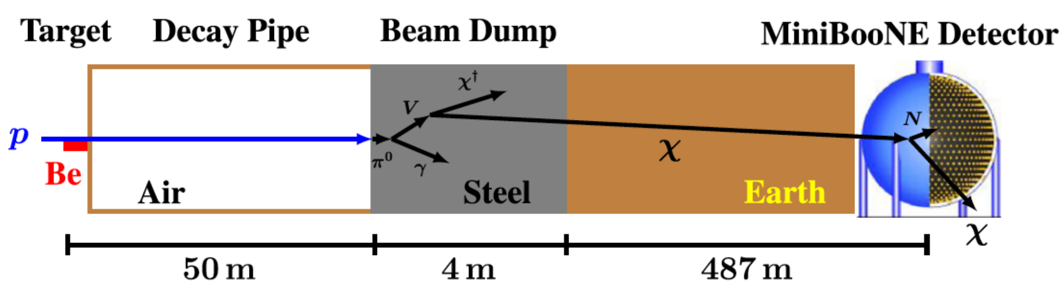

The MiniBooNE search for dark matter

July 18, 2017 | Ranjan Dharmapalan and Tyler Thornton

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CAL 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,[10] R. Van de Water,[10] W. Wester,[2] D. H. White,[10] and J. Yu[3]

MiniBooNE-DM Collaboration

PRL118(2017)221803

MiniBooNE keep providing high impact results!

1. LSND experiment

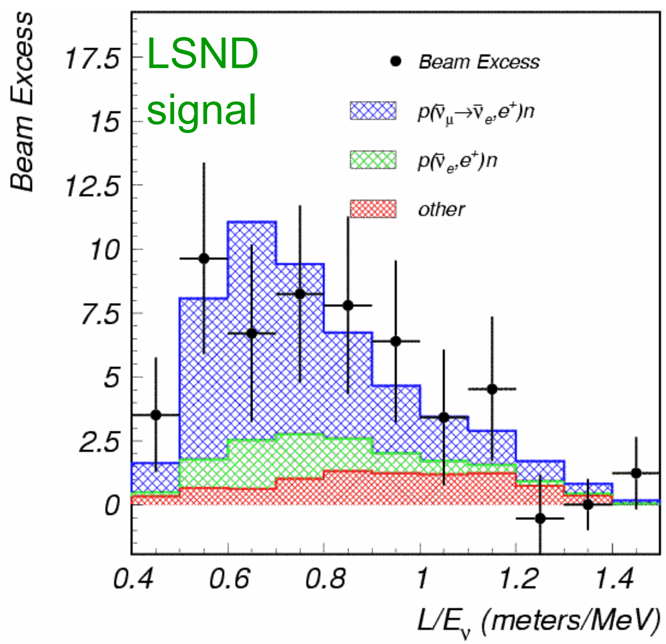
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

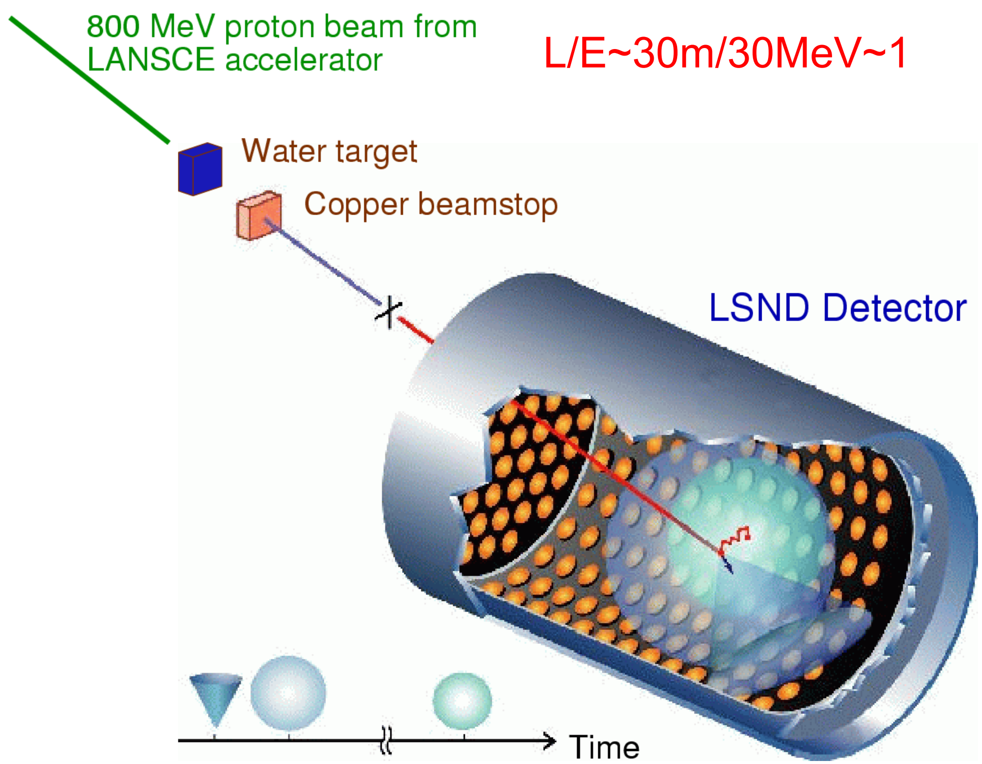
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \to e^+ + n$$

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

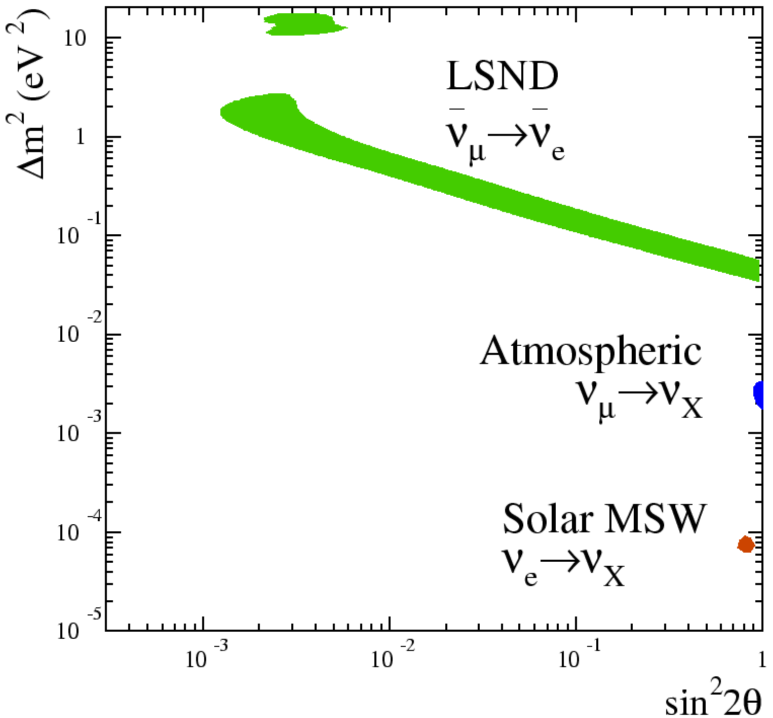
87.9 ± 22.4 ± 6.0 (3.8.σ)



L/E~30m/30MeV~1



1. LSND experiment

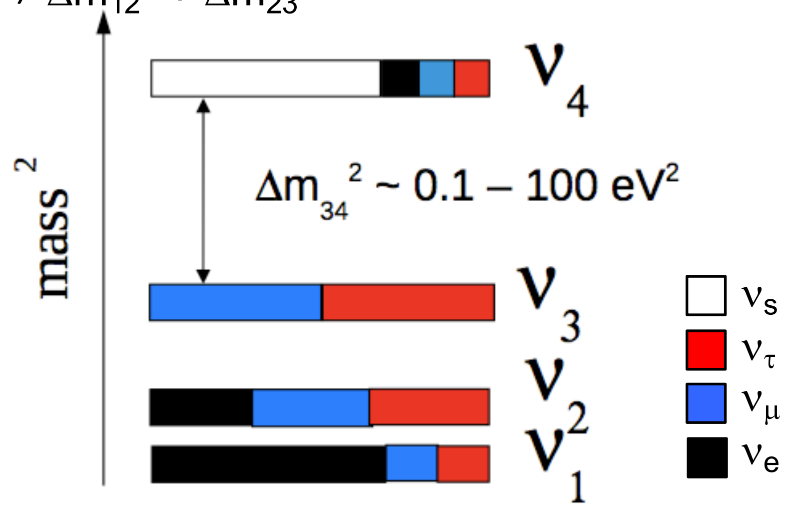


3 types of neutrino oscillations are found:

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

But we cannot have so many 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 flavor from Z-boson decay, so it must be sterile neutrino
MiniBooNE is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment

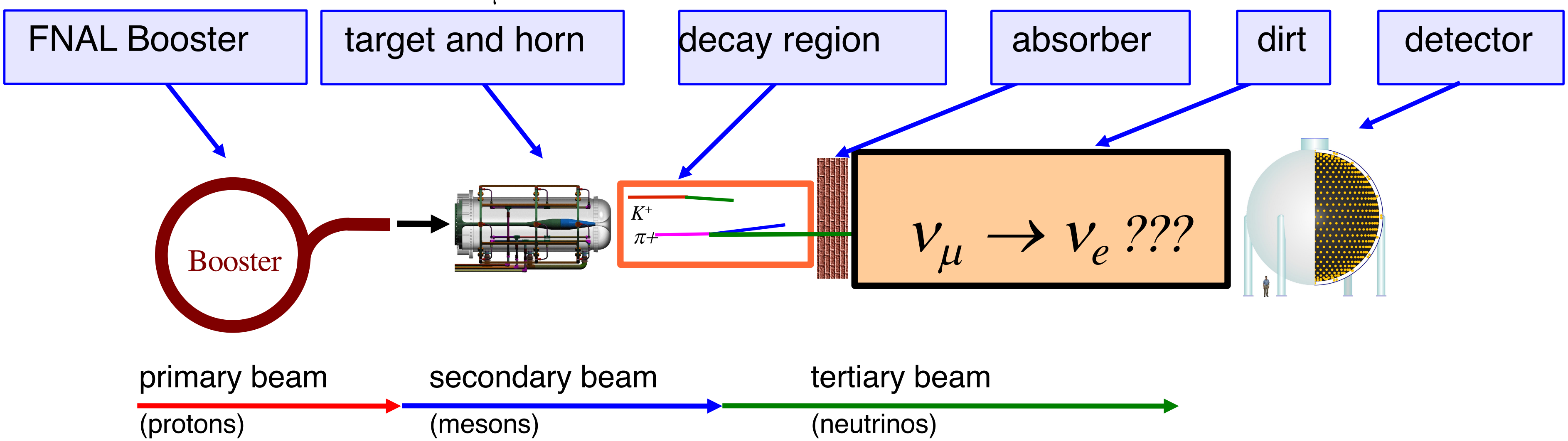
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

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

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

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



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

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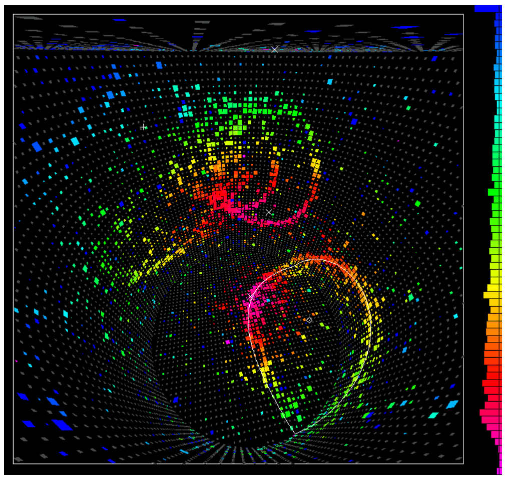
1. MiniBooNE is extremely influential! – Tools

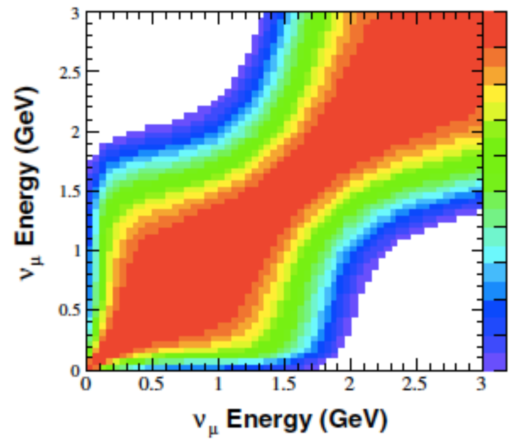
fitQun: MiniBooNE: NIMA608(2009)206

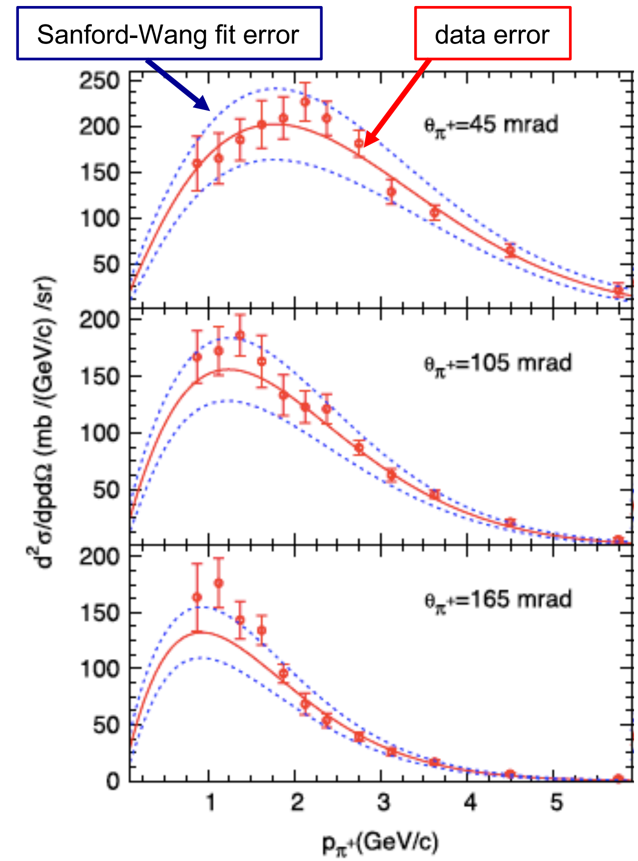
Likelihood-based Cherenkov ring fitter, the main reconstruction used by Super-Kamiokande (LSND→MiniBooNE→SuperK).



Flux systematic error: MiniBooNE: PRD79(2009)072002

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





Online remote shift:

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

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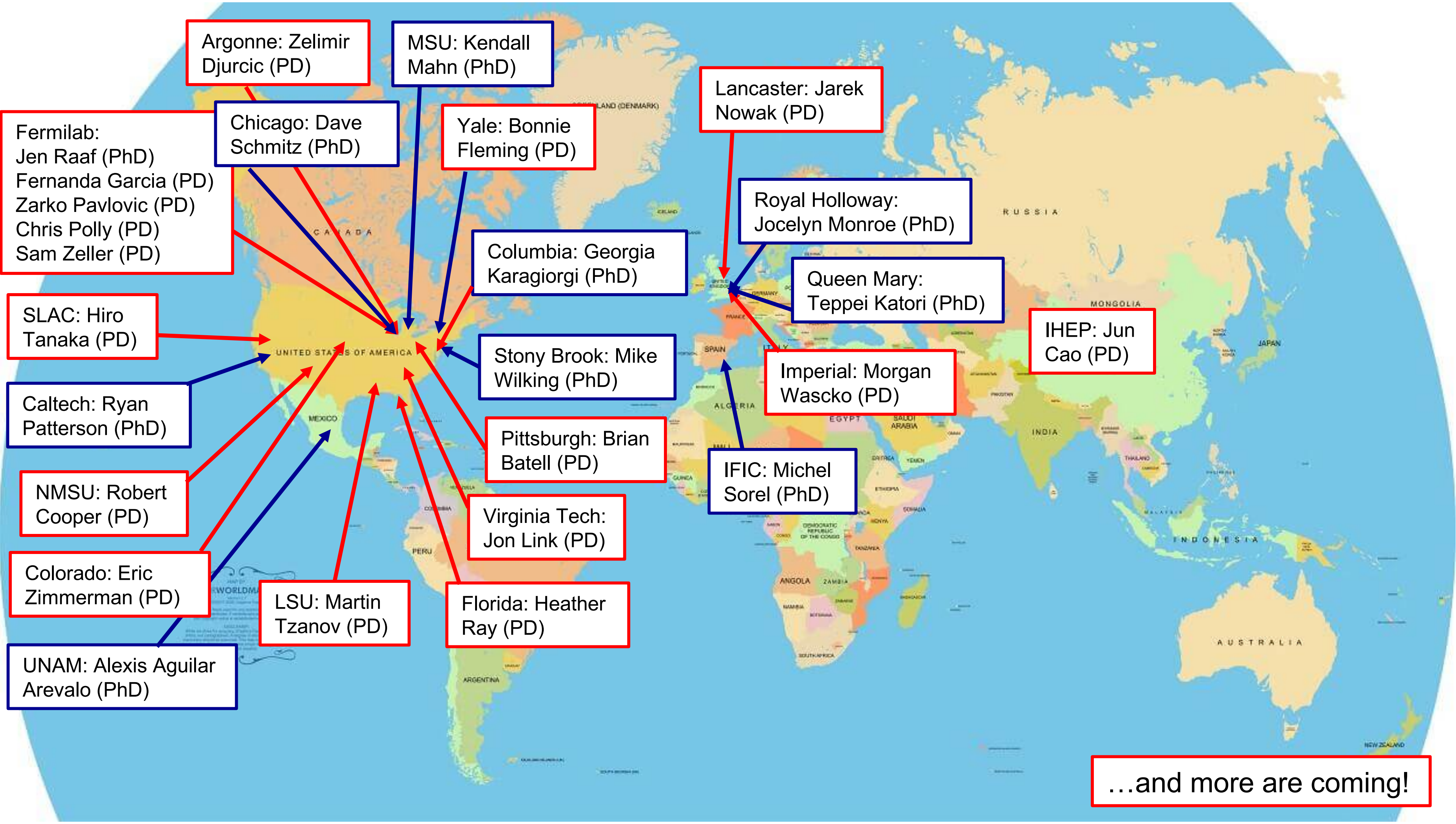
1. MiniBooNE is extremely influential! – Offsprings



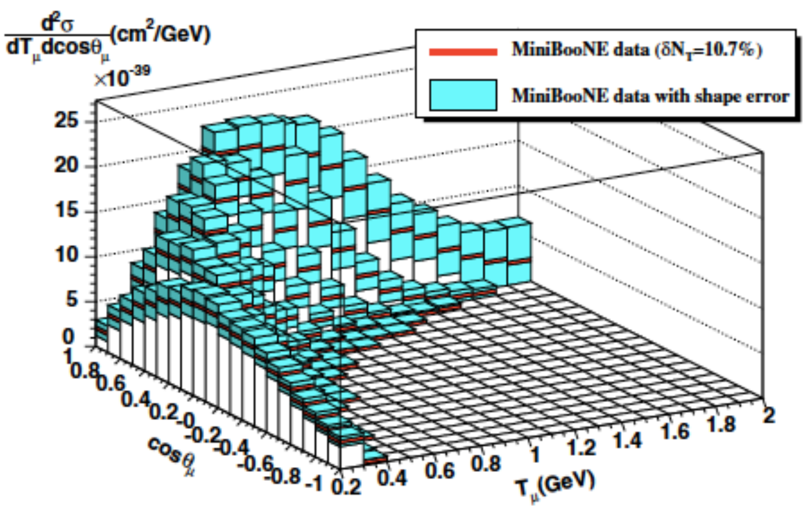
MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

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.

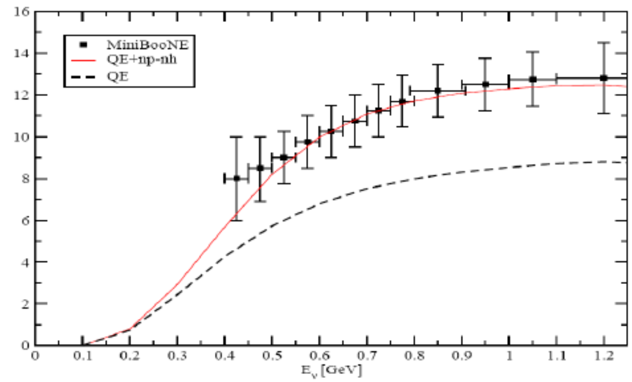
PHYSICAL REVIEW D 81, 092005 (2010)

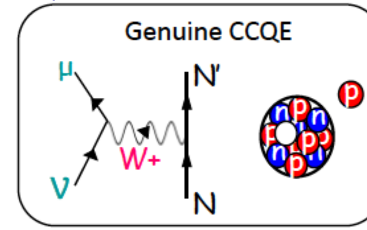


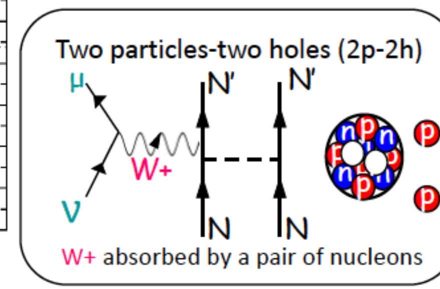
An explanation of this puzzle

(Slide from Marco Martini)

Inclusion of the multinucleon emission channel (np-nh)







Discovery of nucleon correlation in neutrino scattering:

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

Particle Data Group

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

On going effort from MiniBooE initiative!

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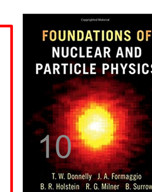
The first textbook of neutrino interaction physics!
“Foundation of Nuclear and Particle Physics”
- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow



1. NuInt18 and nuS&DIS workshop, GSSI, Italy

Register now!

NuInt18, Oct 15-19 GSSI (Italy) https://indico.cern.ch/event/703880/
- the biggest conference on neutrino interaction physics for oscillations

Neutrino Shallow and Deep-Inelastic scattering, Oct 11-13 GSSI (Italy) http://nustec.fnal.gov/nuSDIS18/
- a dedicated workshop for physics related to DUNE, NOvA, etc

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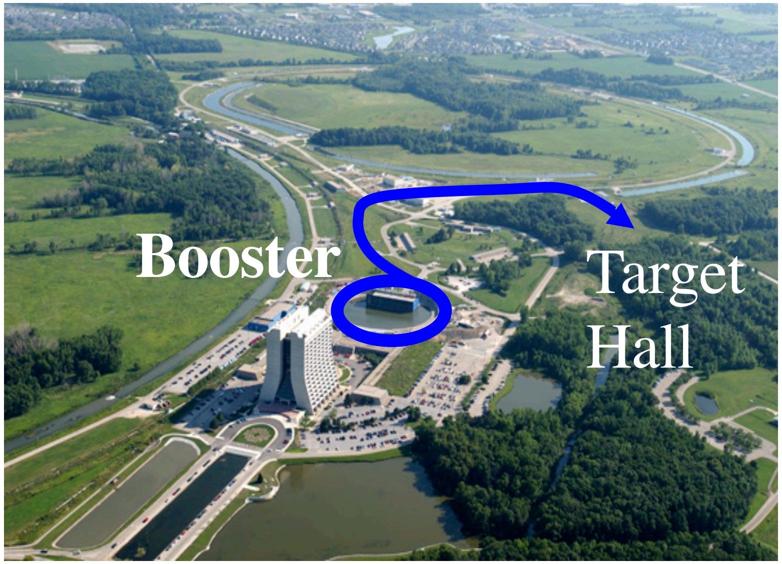
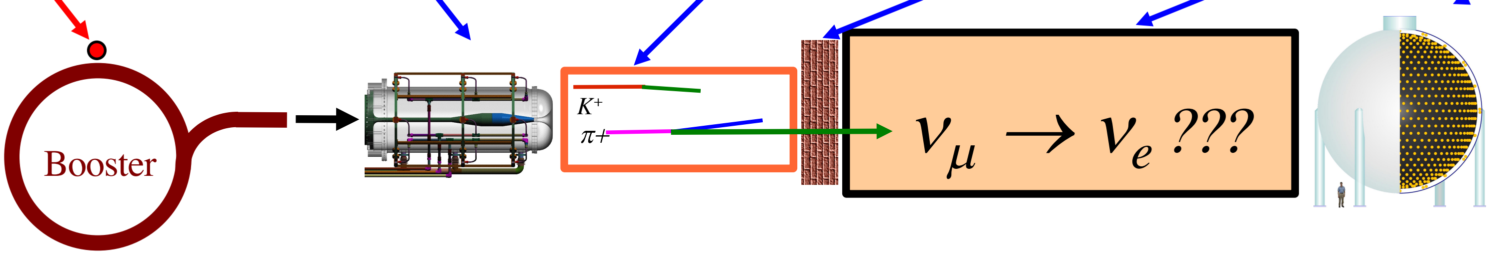
2. Neutrino beam



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)

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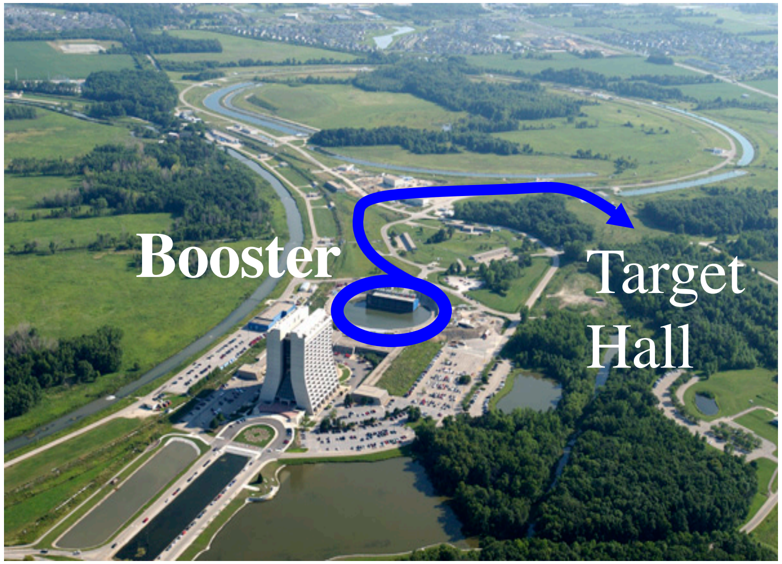
MiniBooNE, PRD79(2009)072002

2. Neutrino beam



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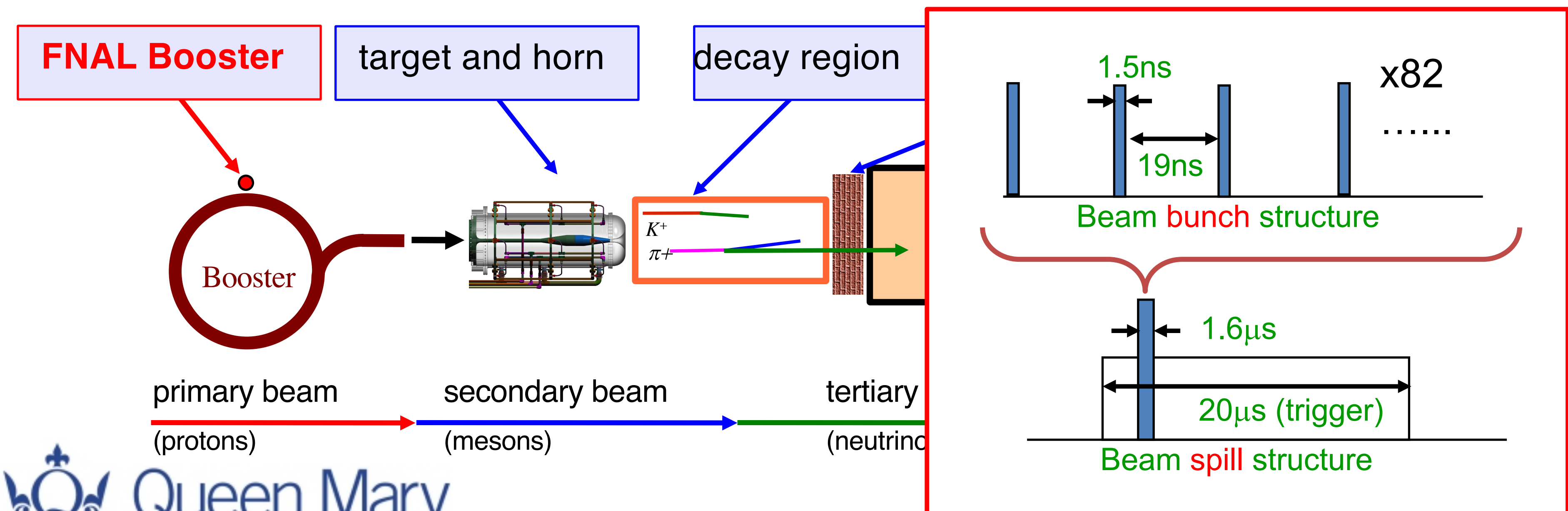
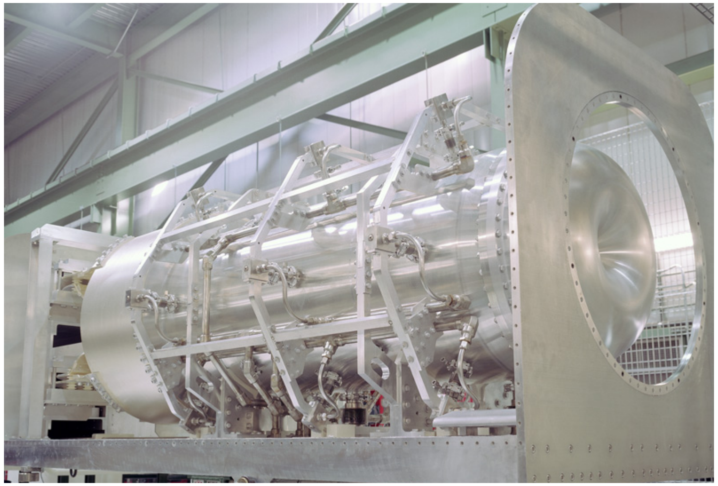


2. Neutrino beam

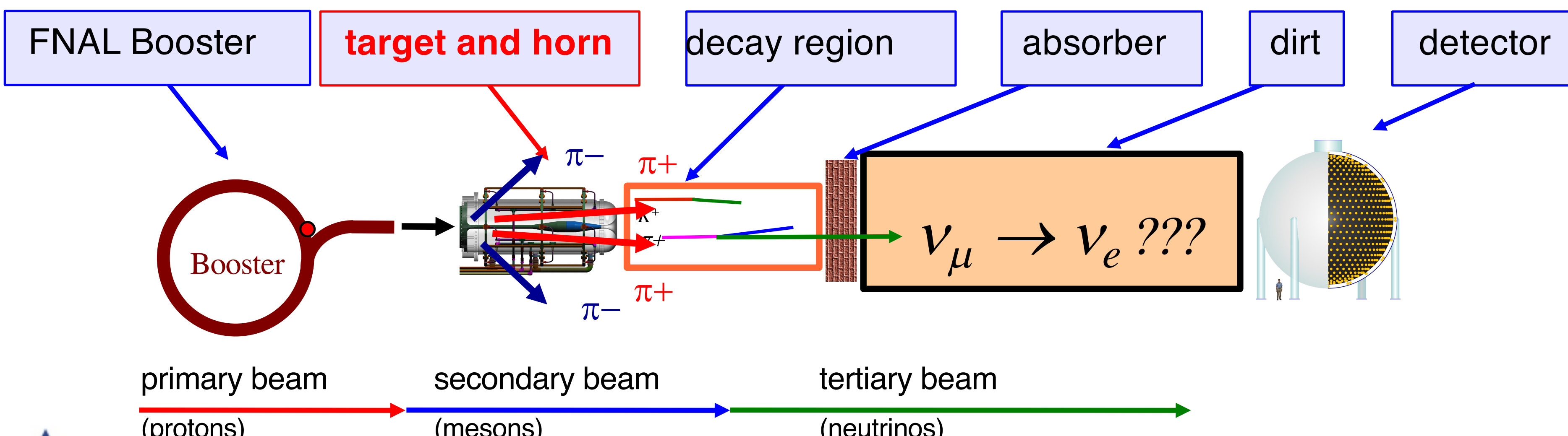
Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

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

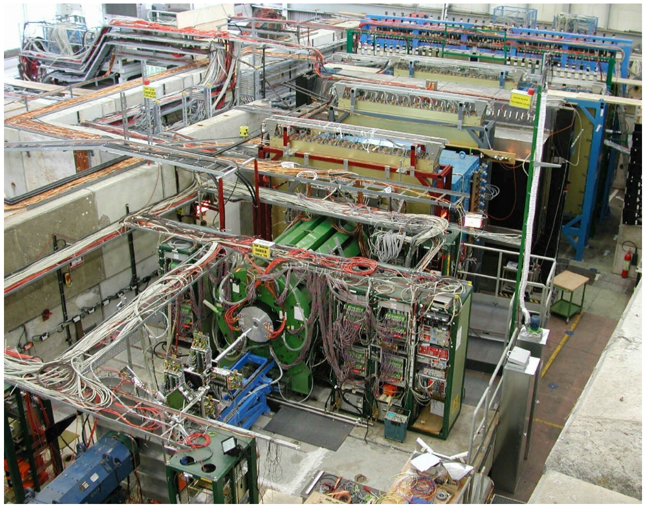
By switching the current direction, the horn can focus either positive (neutrino mode) or negative (antineutrino mode) mesons.



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

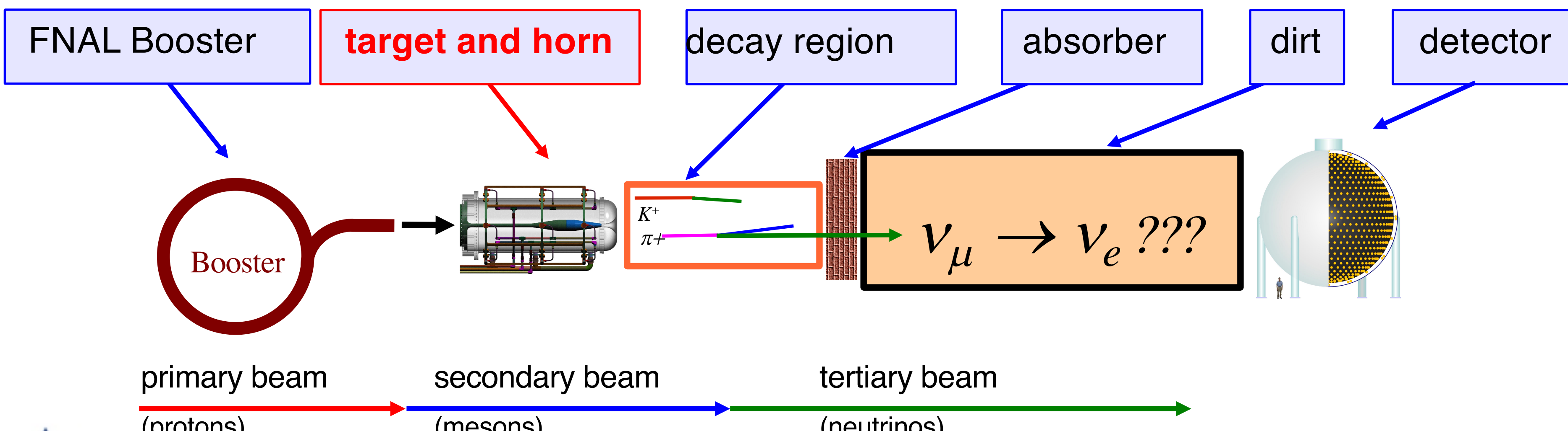
2. Neutrino beam

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+



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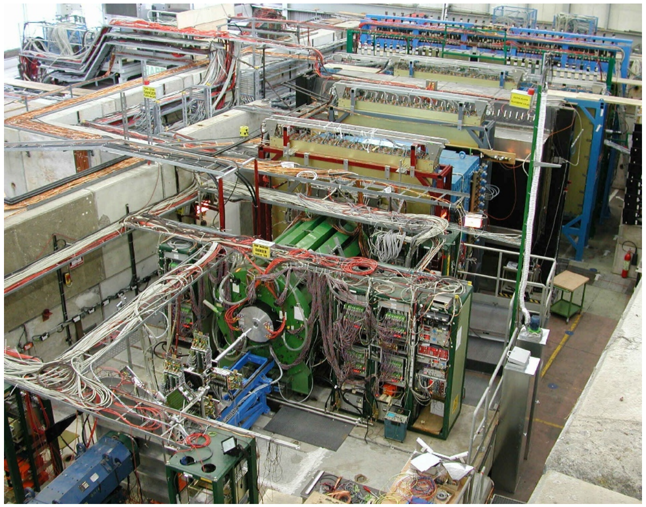

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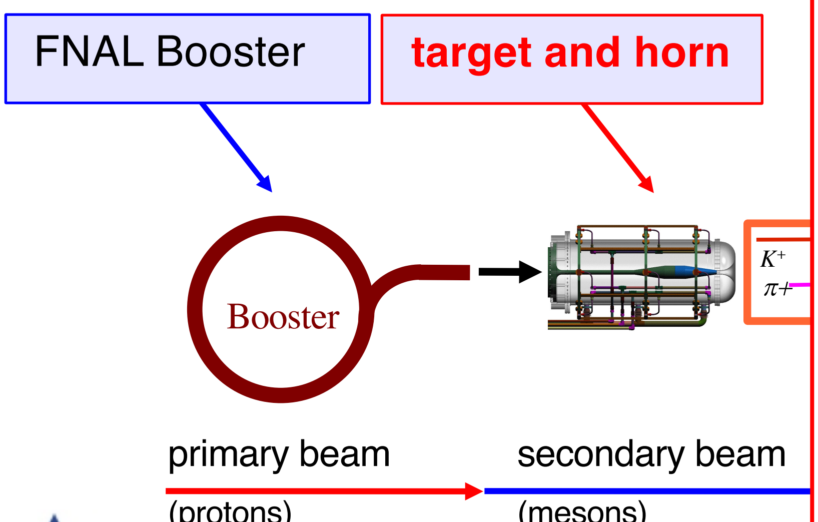

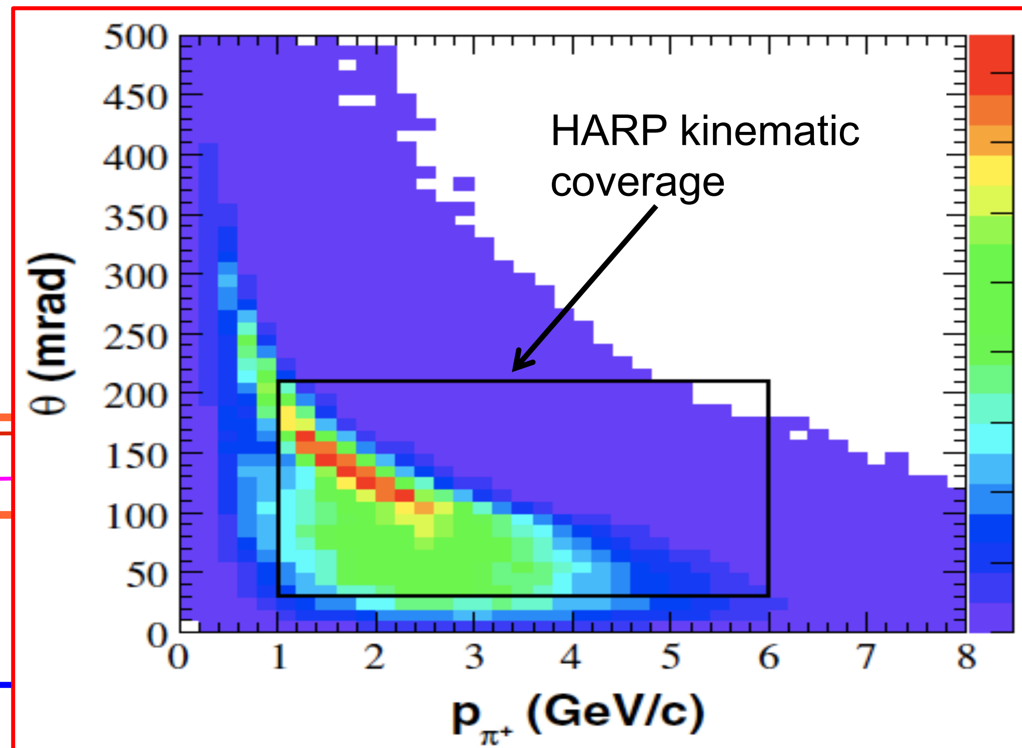

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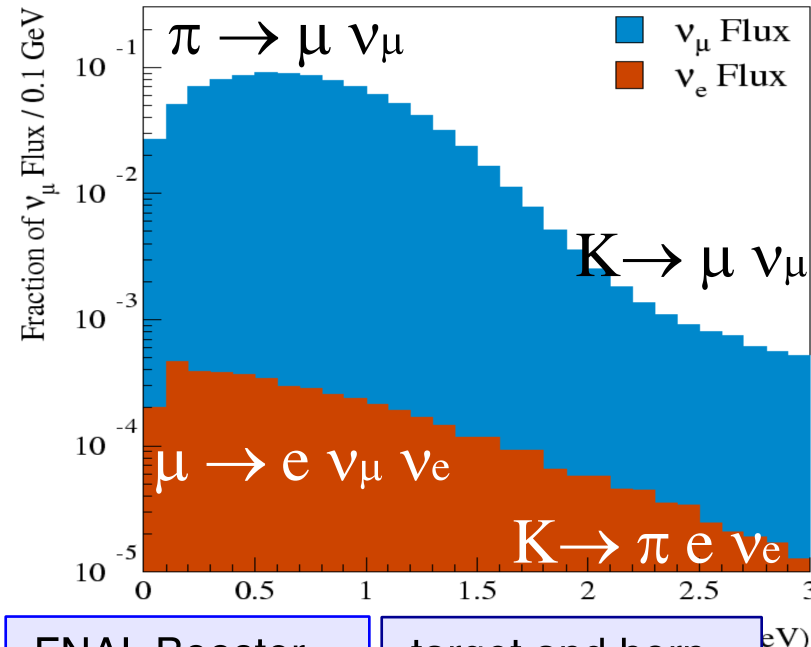
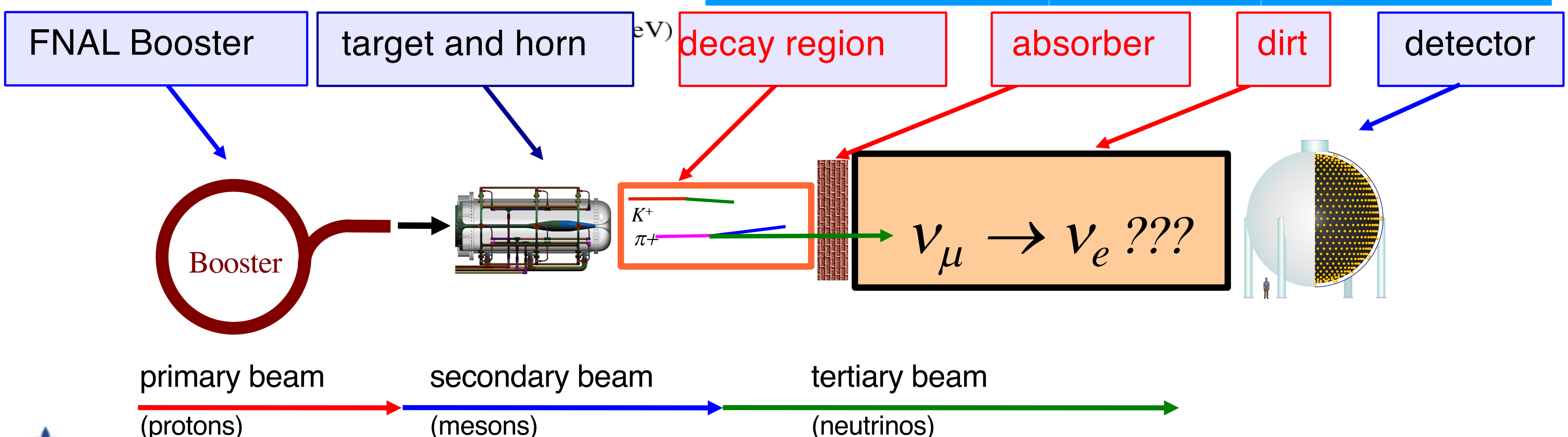


Neutrino flux from simulation by GEANT4

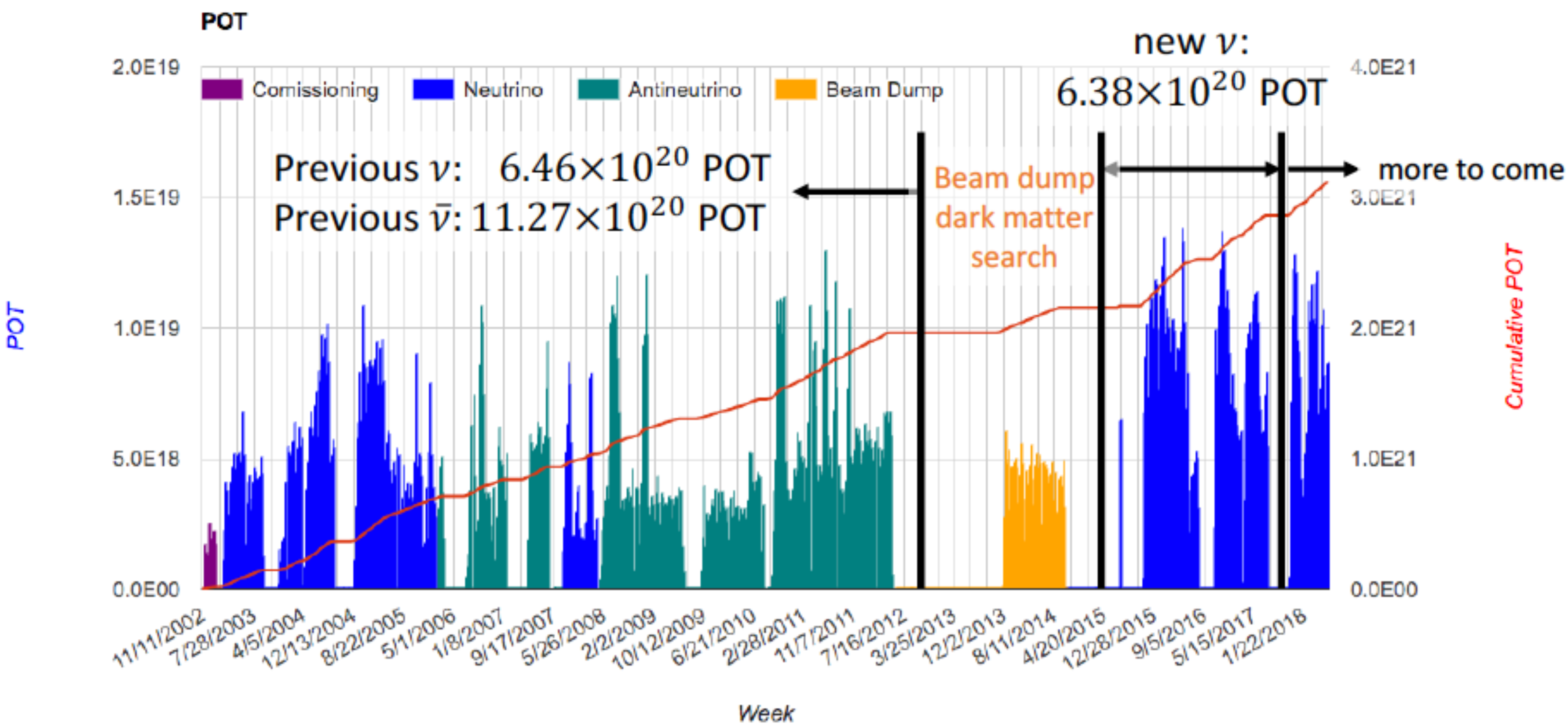
MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	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%



3. Data taking

- 15+ years of running in neutrino, antineutrino, and beam dump mode. More than 30×10^{20} POT to date.
- Result of a combined 12.84×10^{20} POT in ν mode + 11.27×10^{20} POT in $\bar{\nu}$ mode is presented in this talk



1. MiniBooNE neutrino experiment

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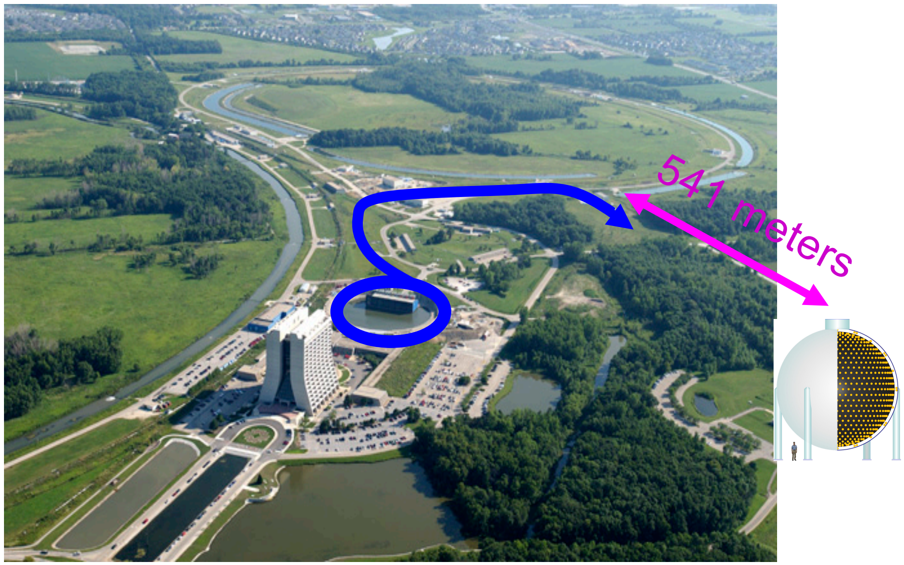
3. Events in the Detector



The MiniBooNE Detector

- 541 meters downstream of target
- 12 meter diameter sphere
  (10 meter "fiducial" volume)
- Filled with 800 t of pure mineral oil (CH_2)
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
- 240 veto phototubes

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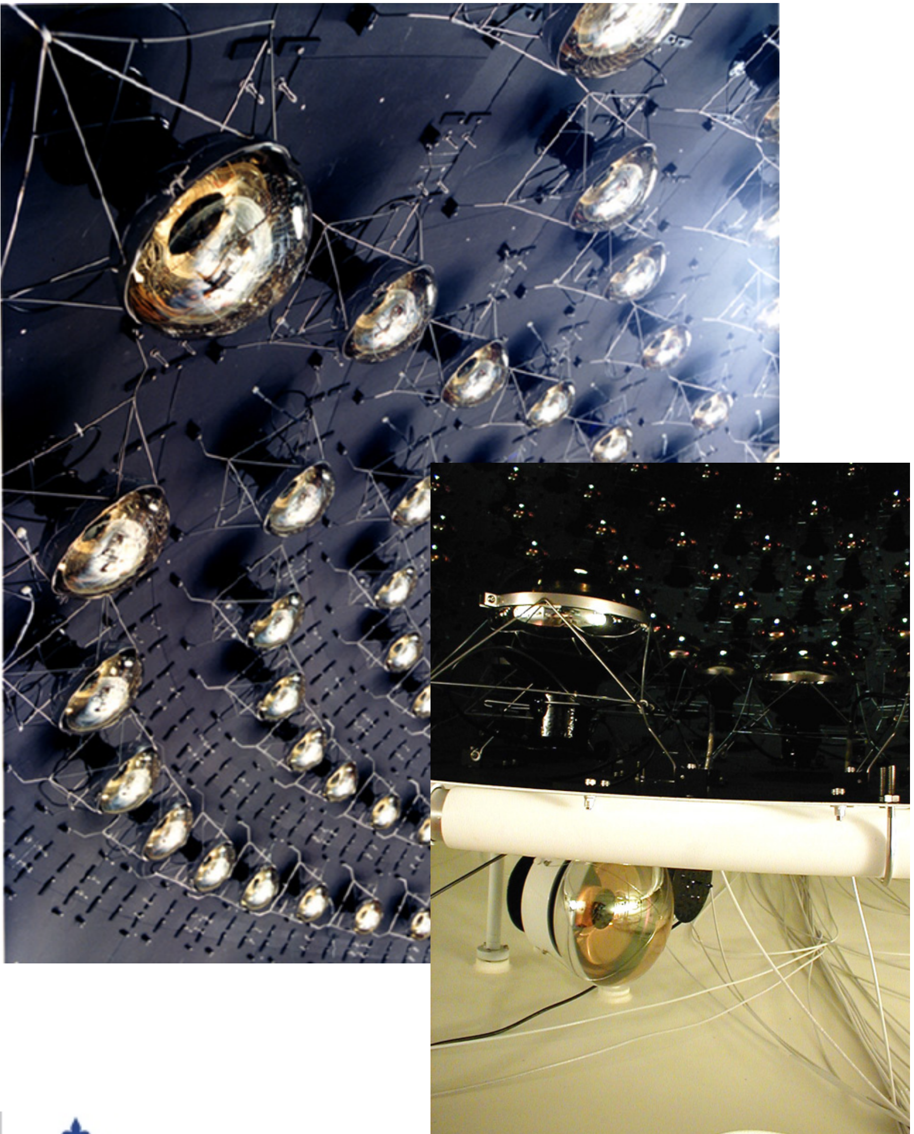

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3. Events in the Detector

Times of hit-clusters (subevents)

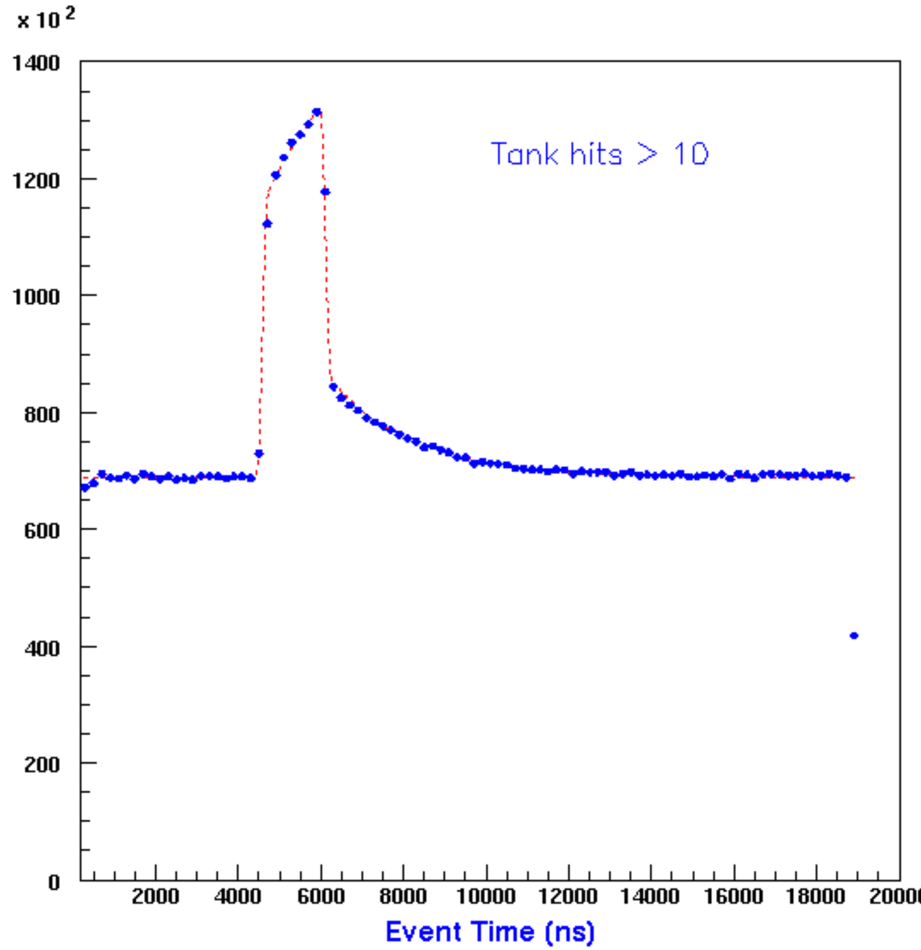
Beam spill (1.6μs) is clearly evident

- simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts

- <6 veto PMT hits
  - Gets rid of muons
- >200 tank PMT hits
  - Gets rid of Michels
- Only neutrinos are left!

Beam and Cosmic BG



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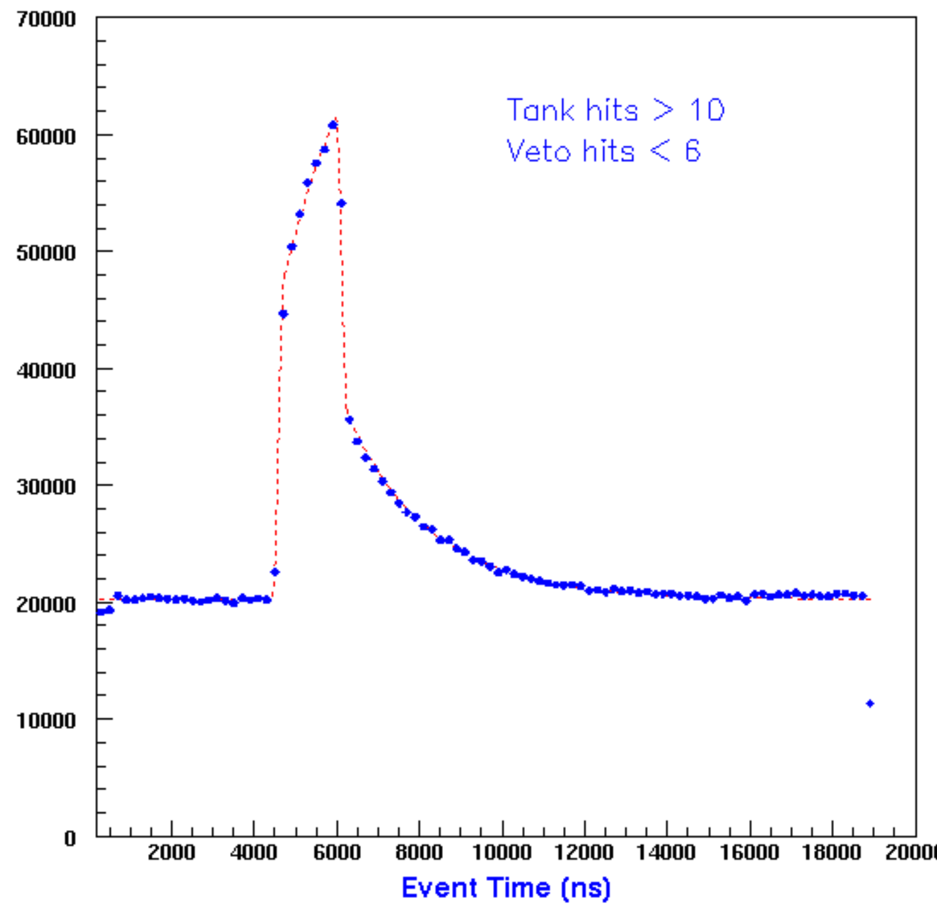

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Neutrino Candidate Cuts

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>200 tank PMT hits

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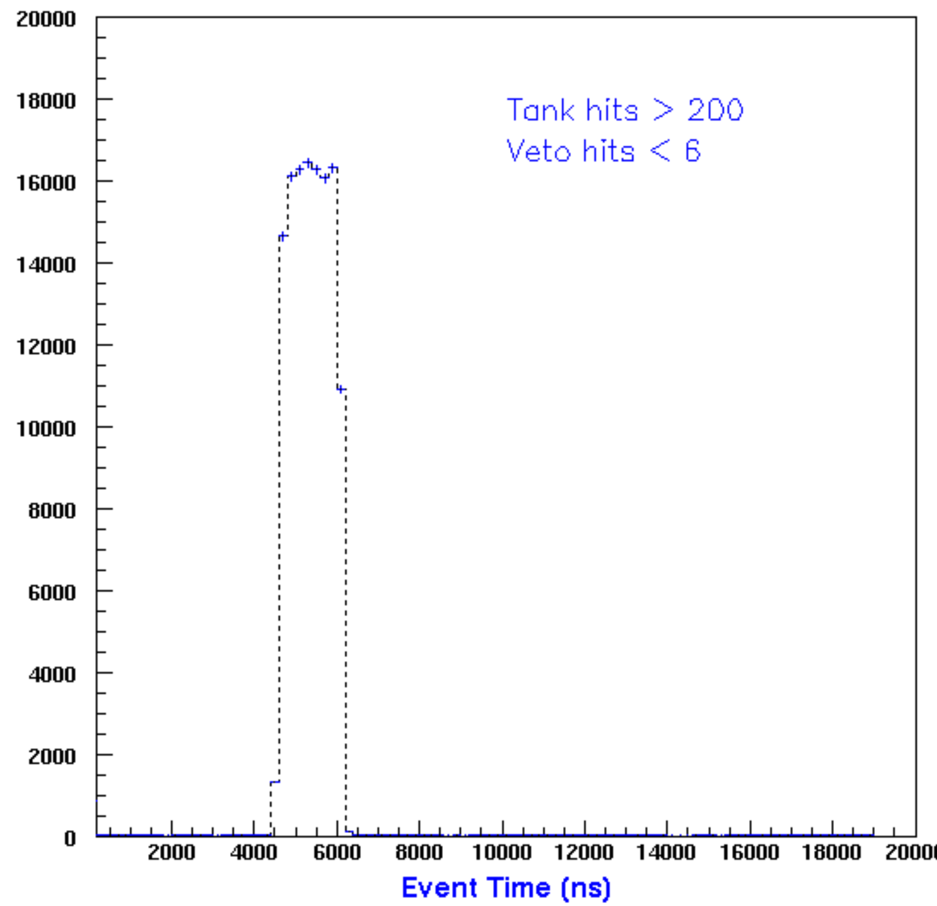
Only neutrinos are left!

Beam Only



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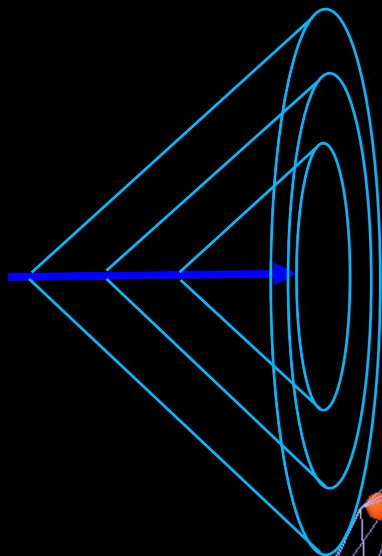
3. Events in the Detector

MiniBooNE collaboration, NIM.A599(2009)28

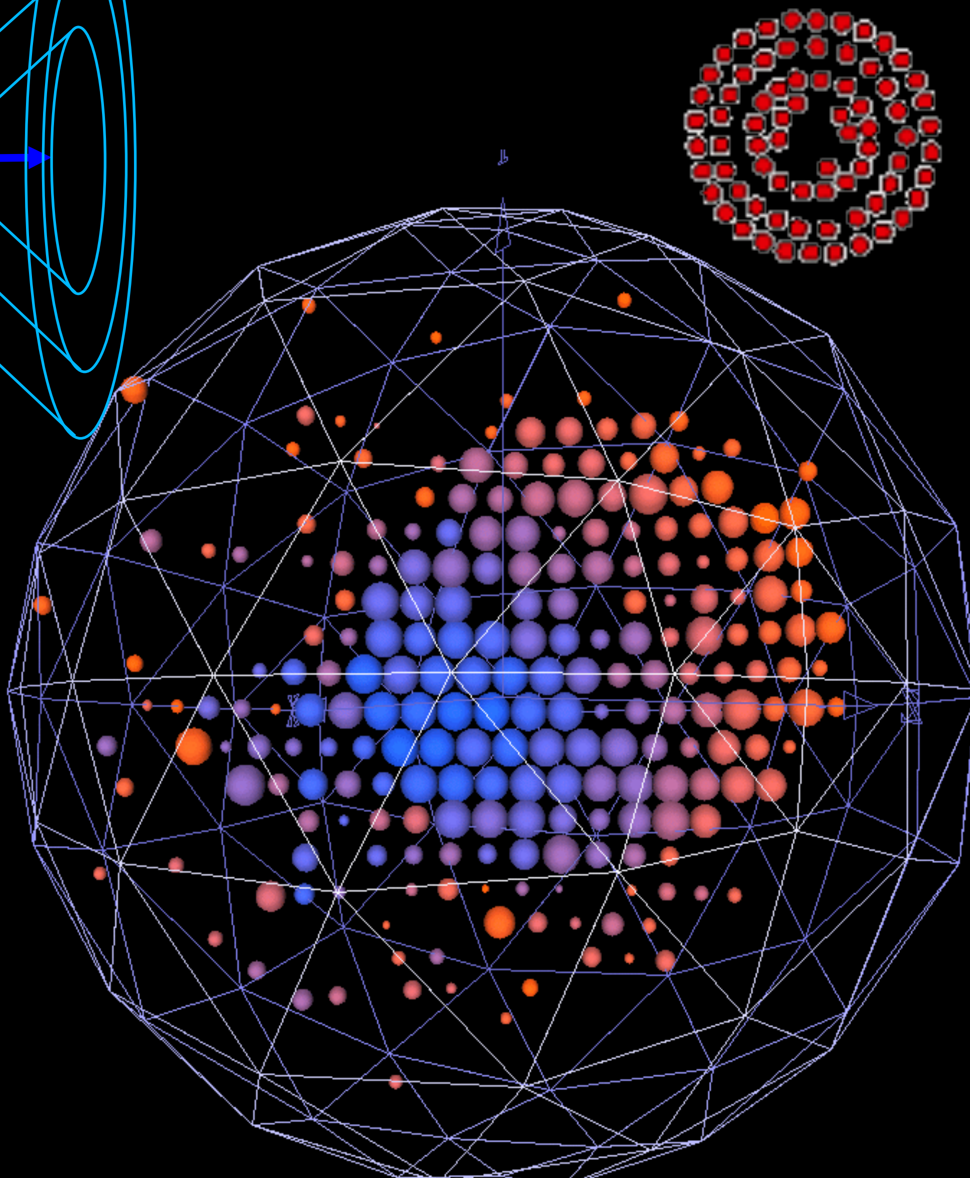
Muons

- 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

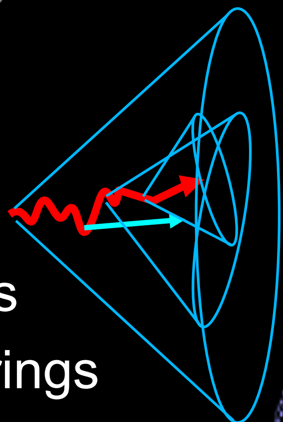
MiniBooNE collaboration,
NIM.A599(2009)28

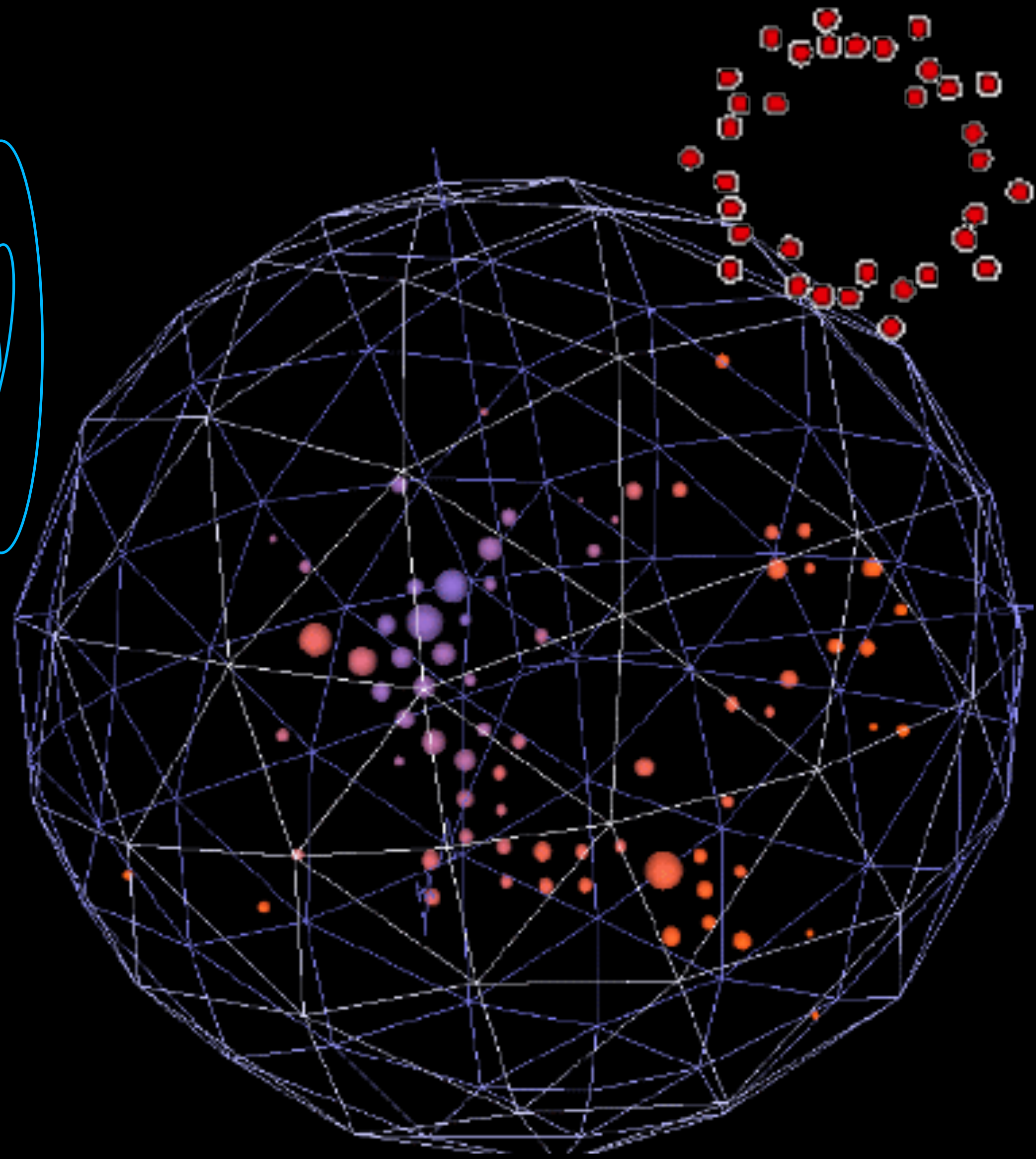
Muons

- Long strait tracks
  → Sharp clear rings

Electrons

- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings





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3. Events in the Detector

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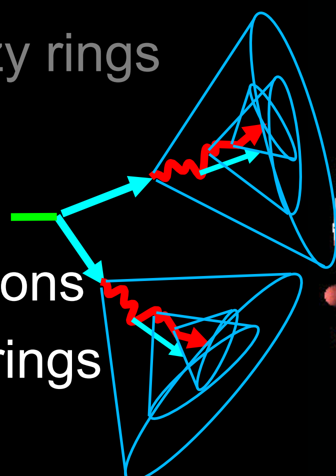
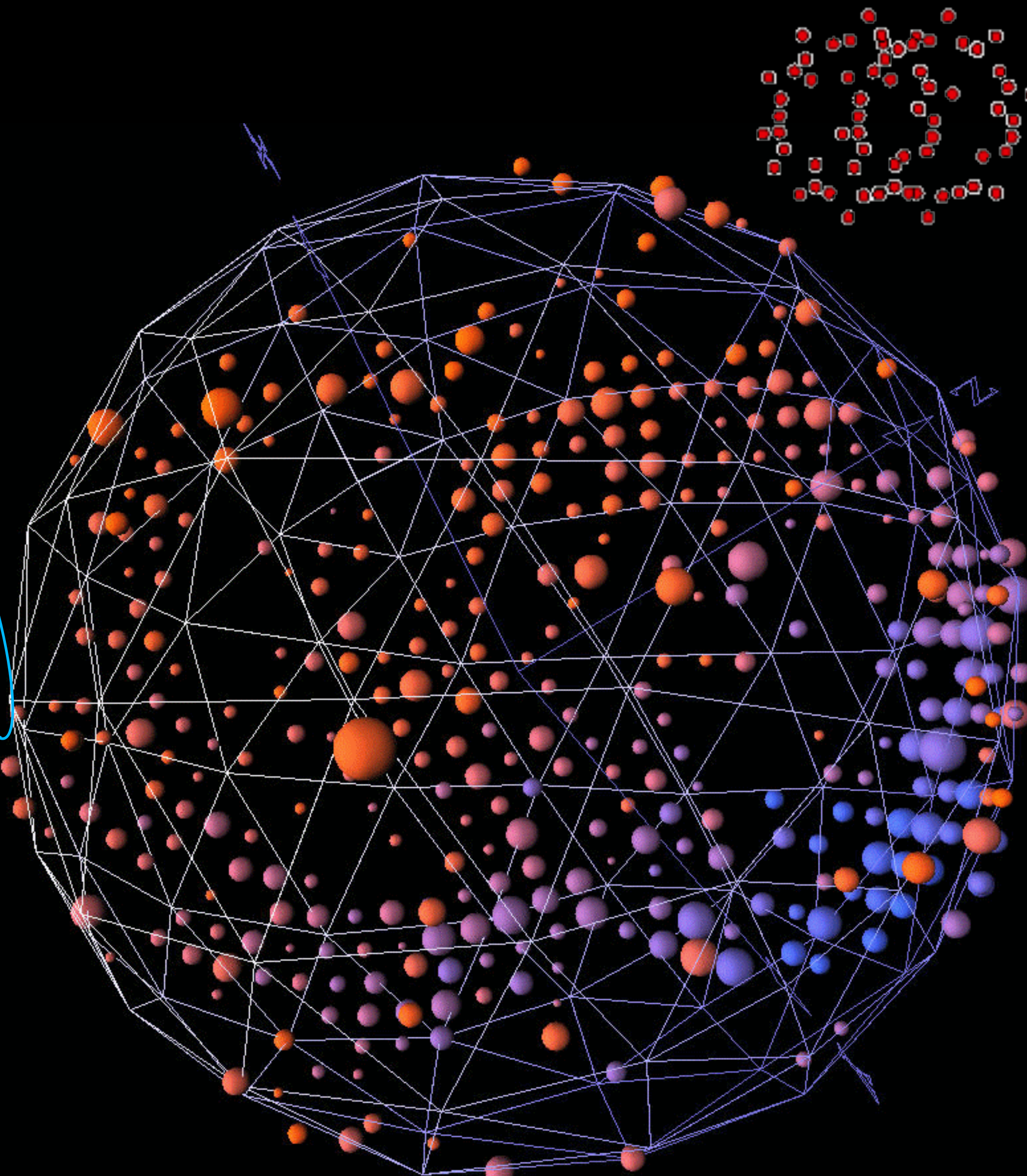




NC elastic scattering

- No Cherenkov radiation
  → Isotropic scintillation hits

3. Events in the Detector

MiniBooNE collaboration,
NIM.A599(2009)28

Muons

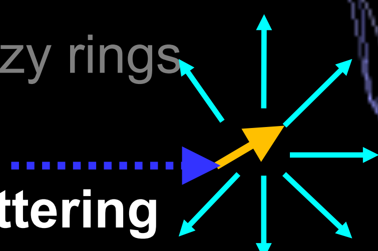
- Long strait tracks
  → Sharp clear rings

Electrons

- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings

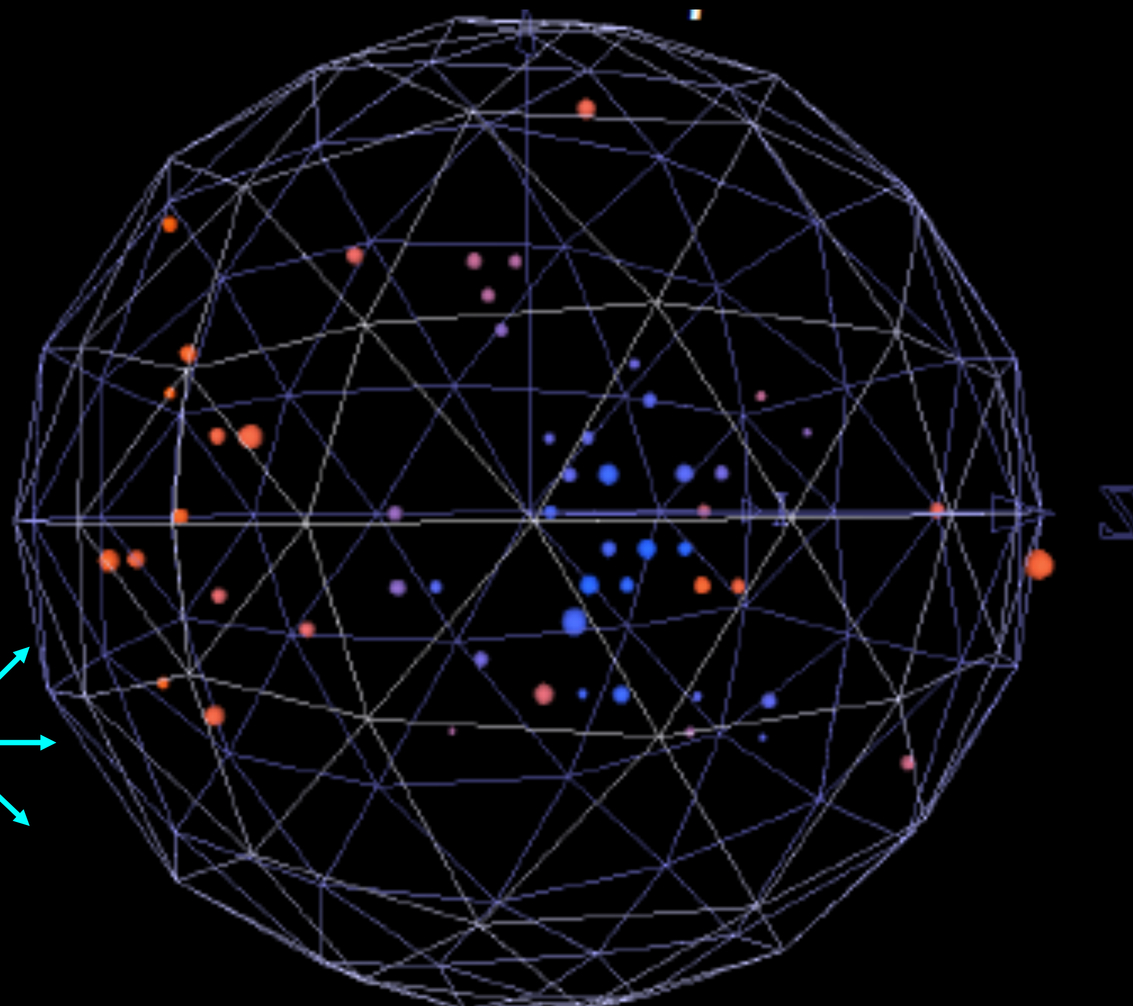
Neutral pions

- Decays to 2 photons
  → Double fuzzy rings



NC elastic scattering

- No Cherenkov radiation
  → Isotropic scintillation hits



3. QE kinematics based energy reconstruction

Event reconstruction from Cherenkov ring profile for PID

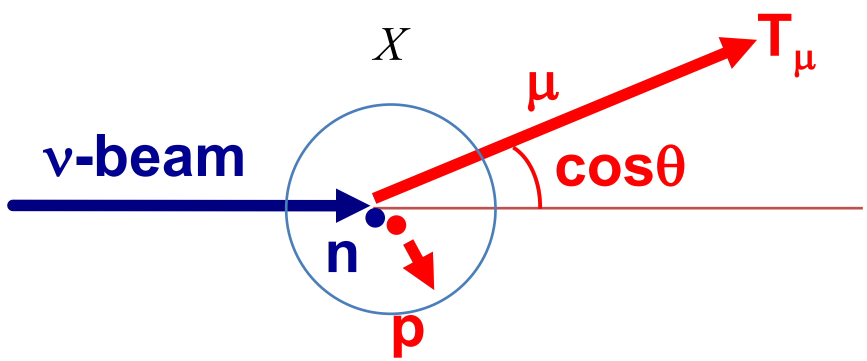
- scattering angle θ and kinetic energy of charged lepton T are estimated

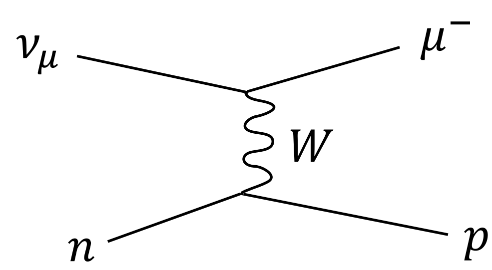
Charged Current Quasi-Elastic (CCQE) interaction

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

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





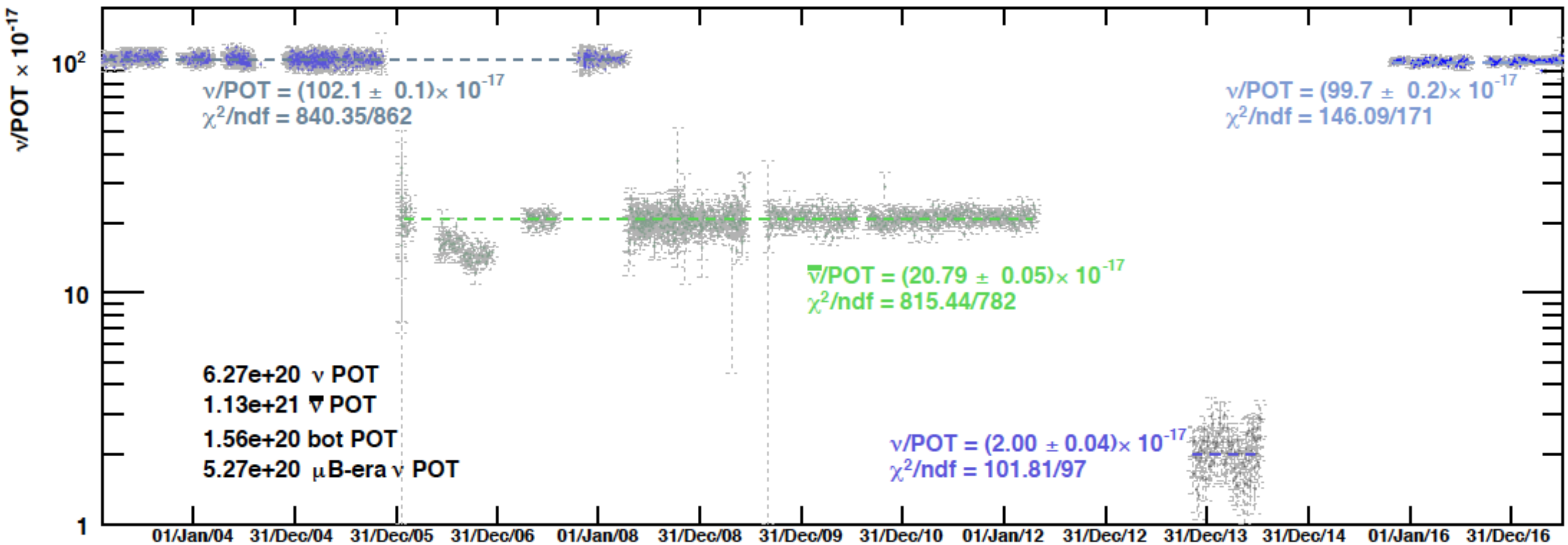
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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



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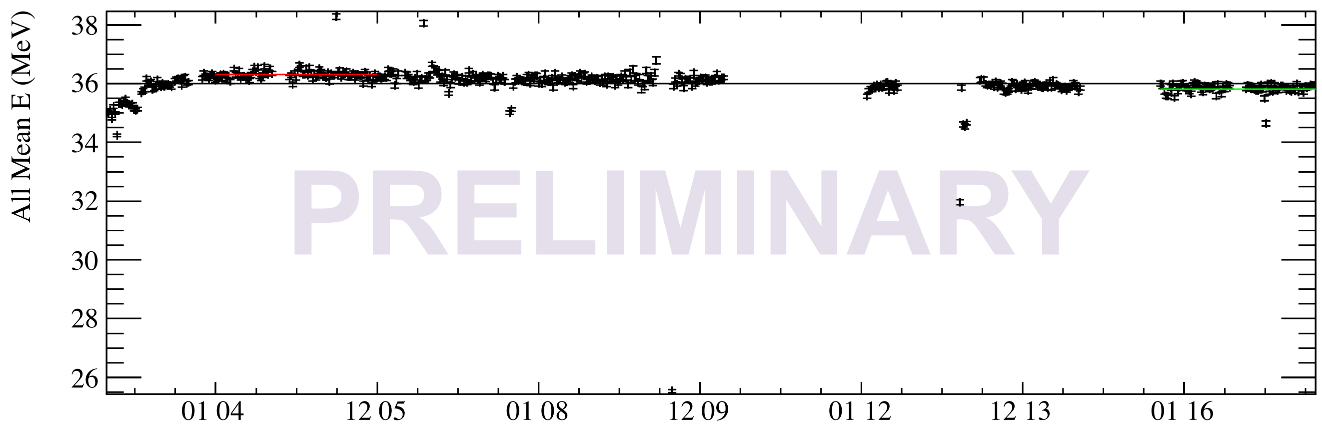
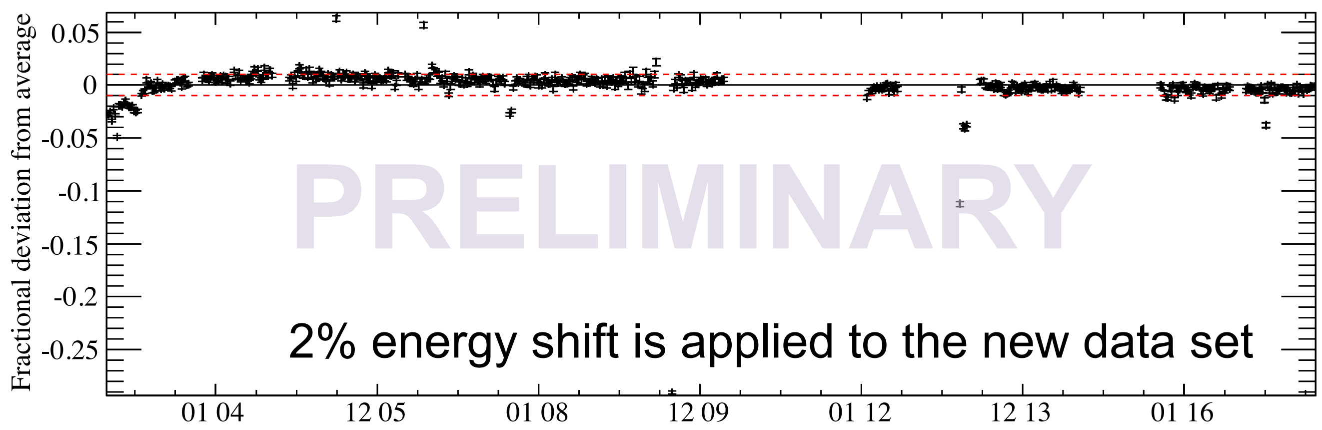
3. Detector stability

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

Michel electron spectrum peak





3. Detector stability

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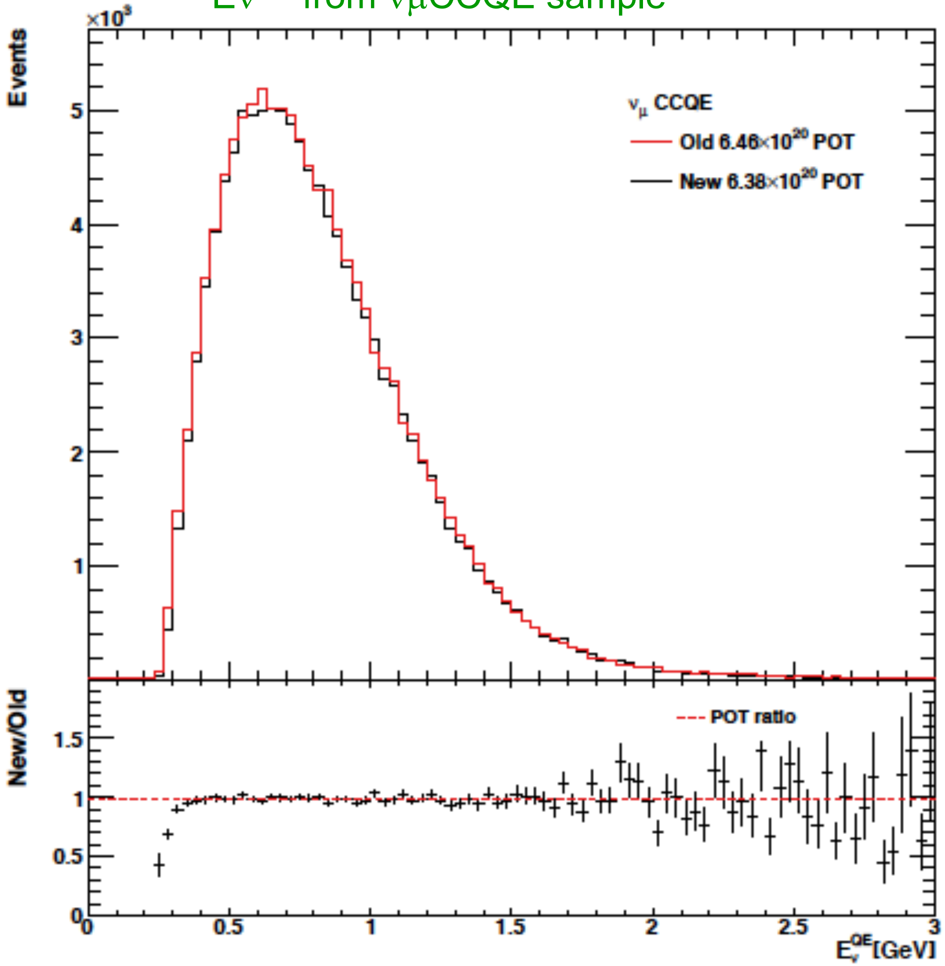
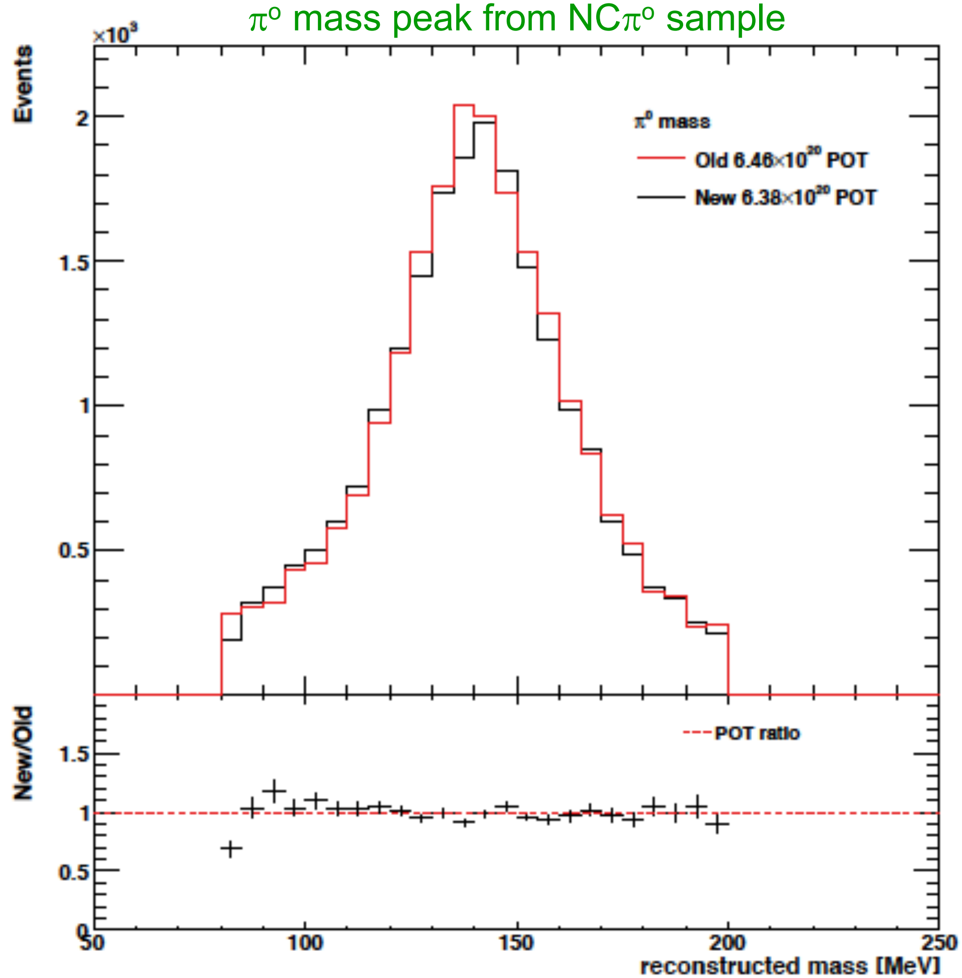
$E\nu^{QE}$ from $\nu\mu$CCQE sample



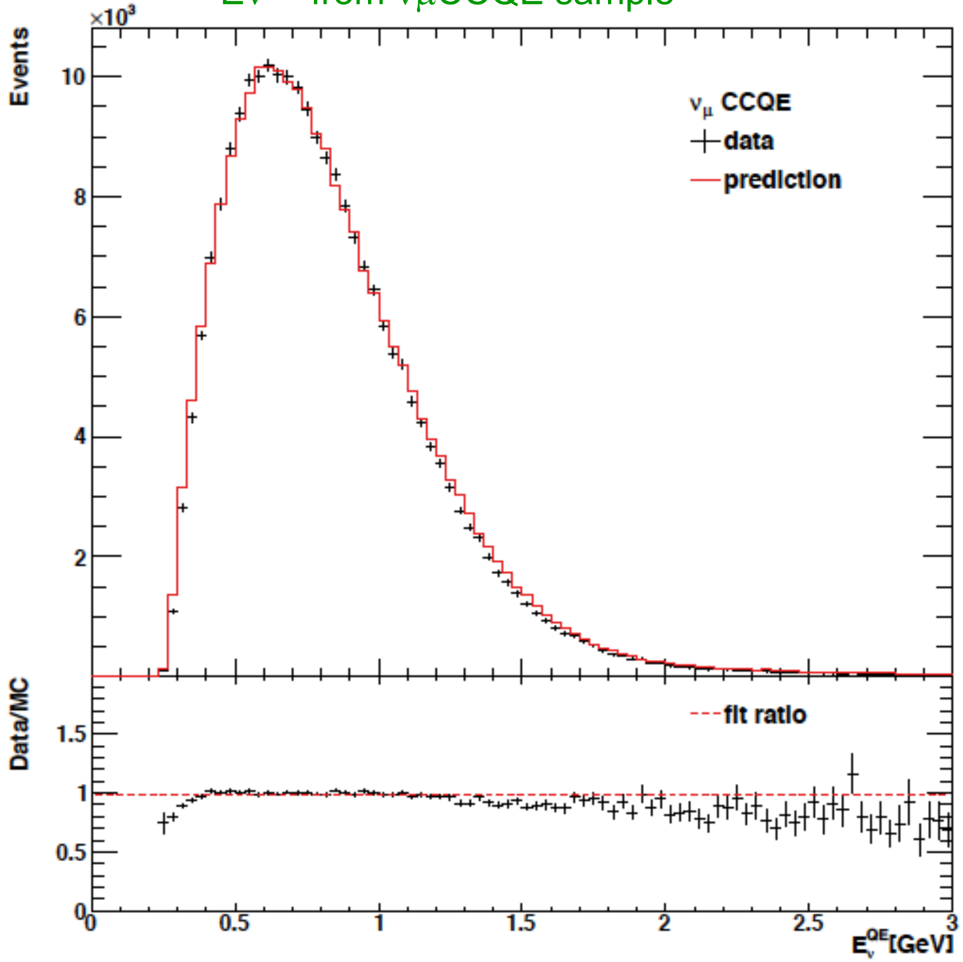
π^o mass peak from NCπ^o sample



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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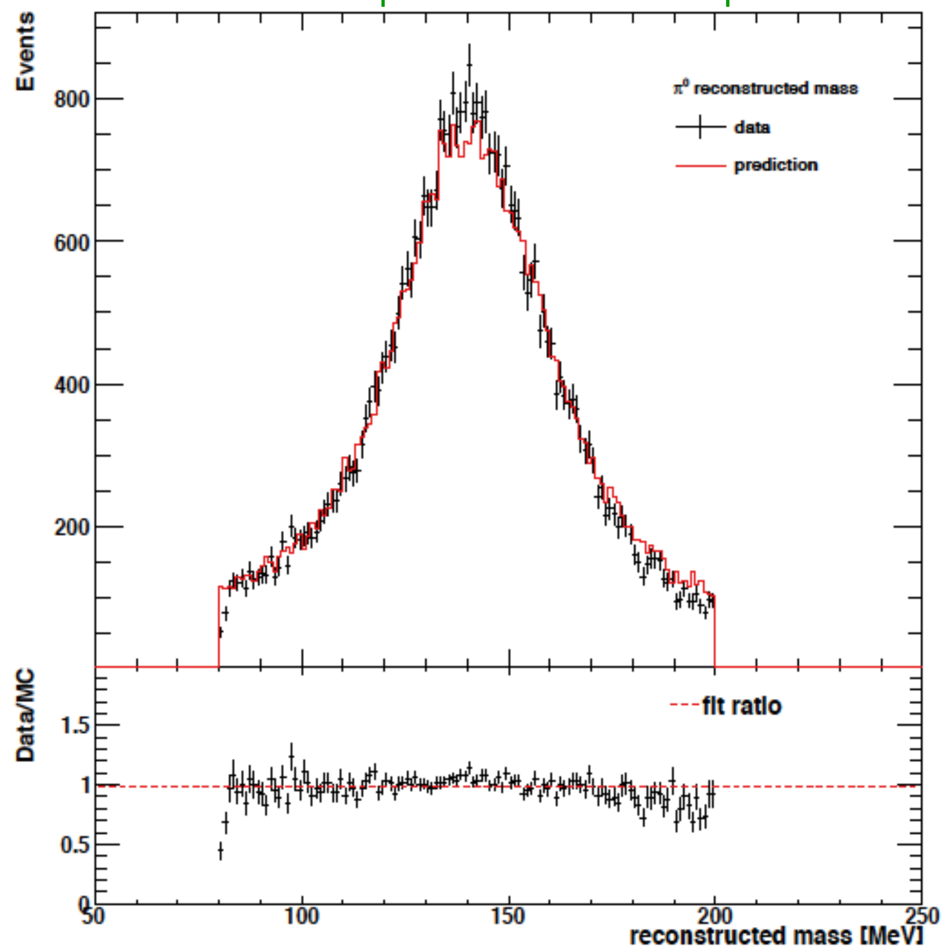

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1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

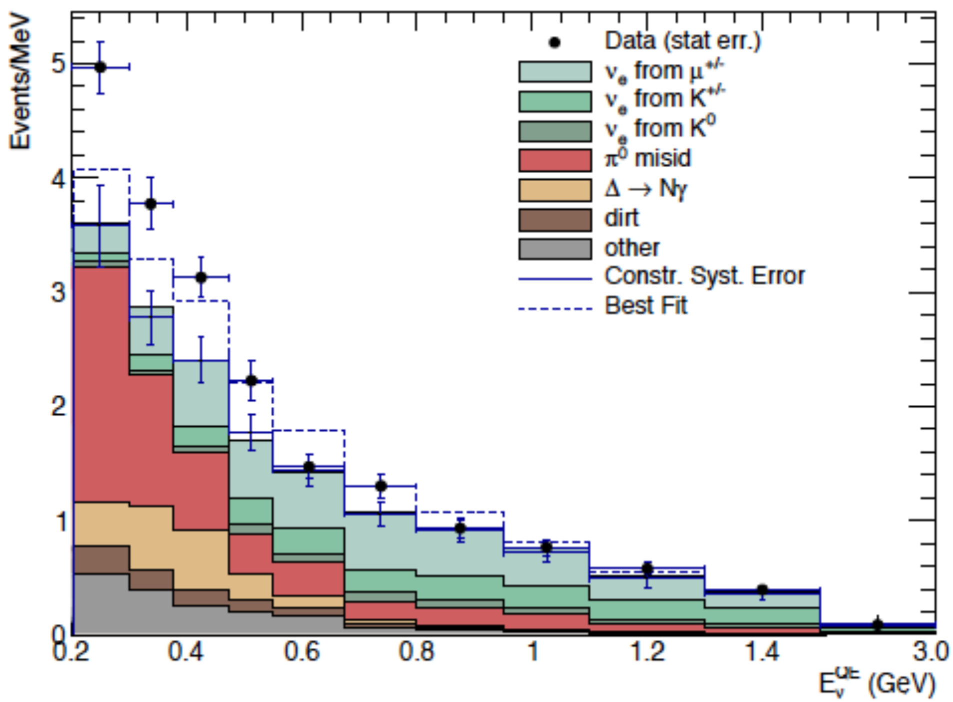
4. Oscillation candidate search

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
misID	NC π^0	501.5 ± 65.4	112.3 ± 11.5
misID	NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
misID	External Events	75.2 ± 10.9	15.3 ± 2.8
misID	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
intrinsic	ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
intrinsic	ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
intrinsic	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

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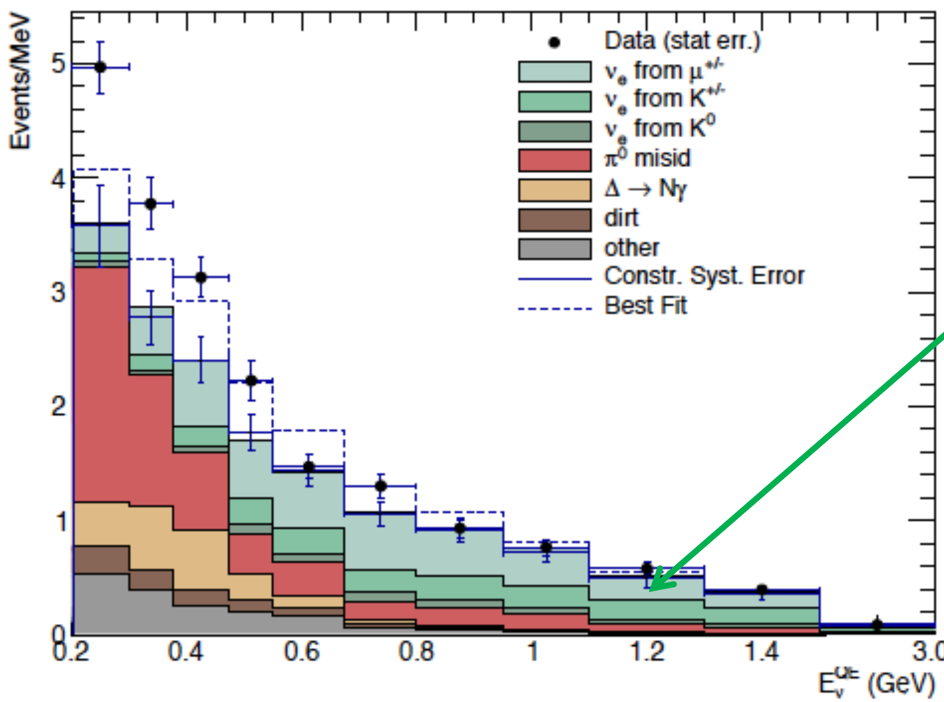

ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from μ-decay constraint

measured

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

guessed

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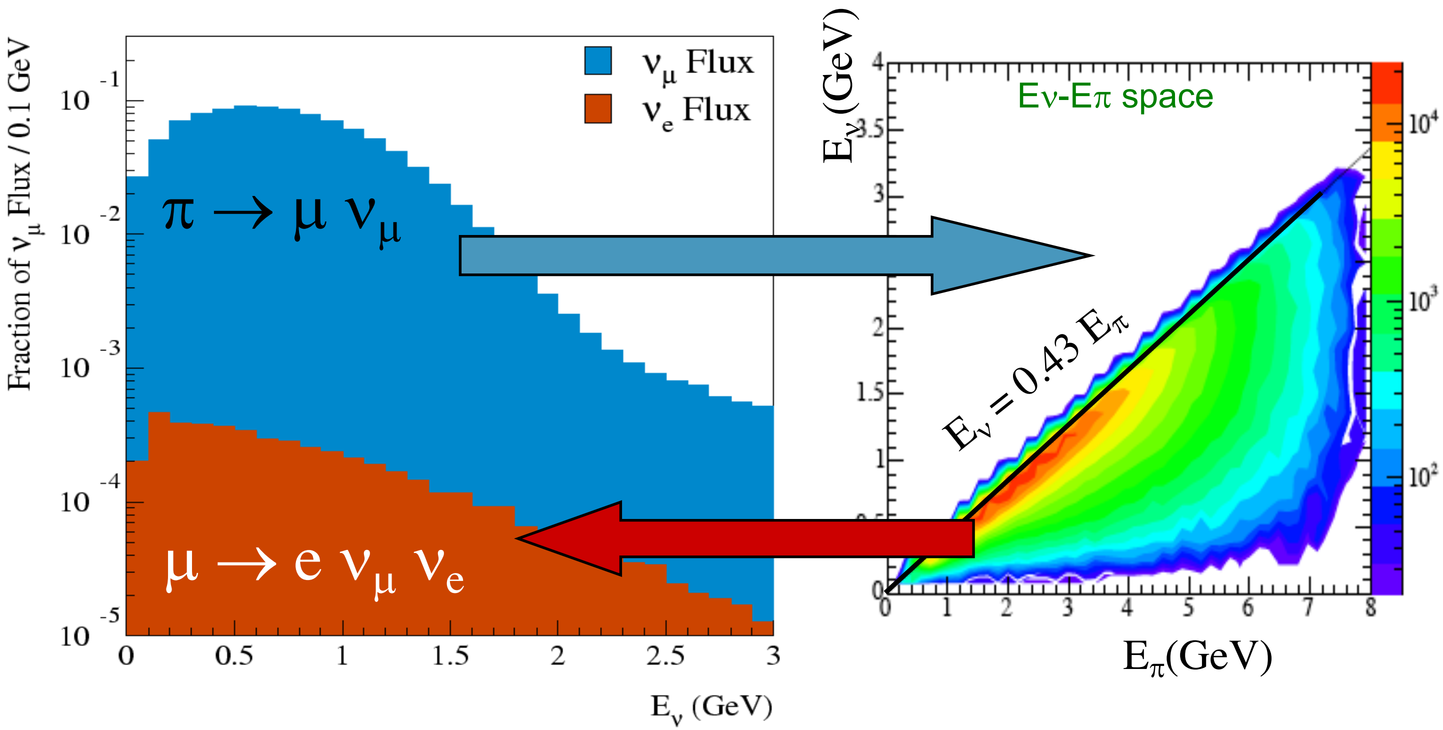
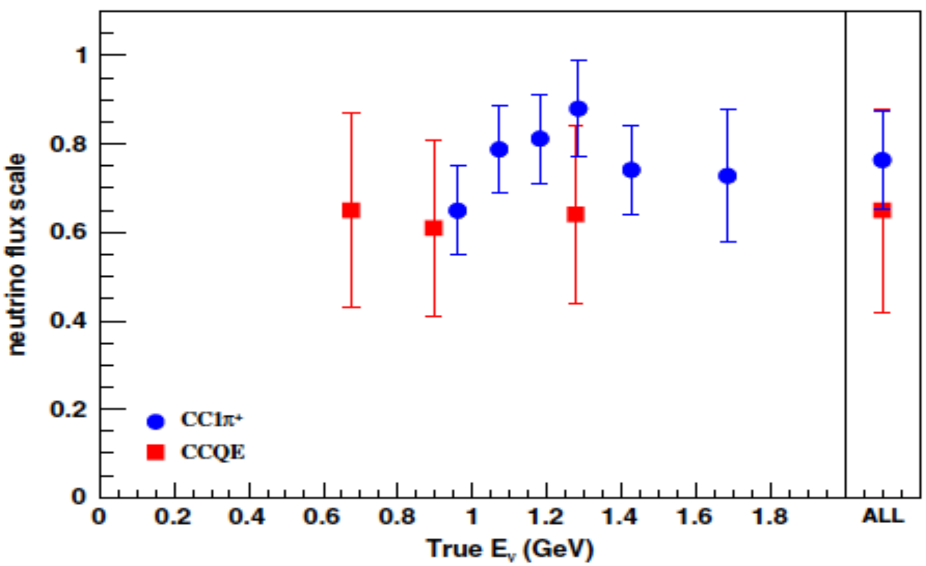
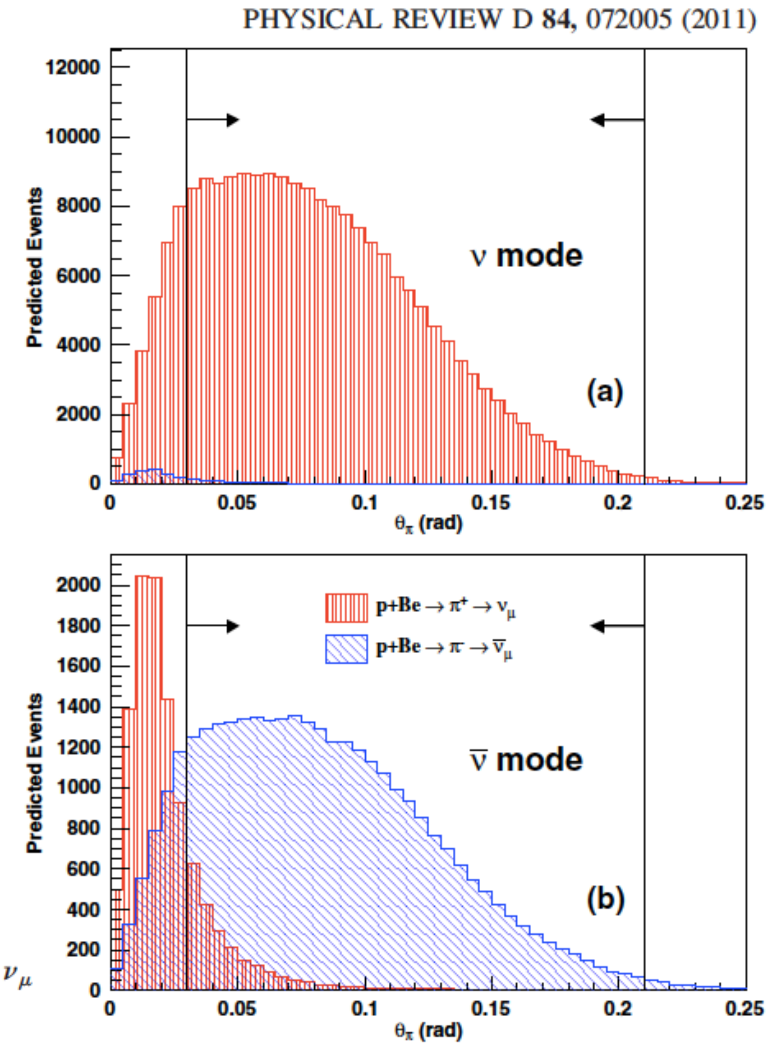
They are large background, but we have a good control of $\nu_e \& \bar{\nu}_e$ background by joint $\nu_e \& \nu_\mu (\bar{\nu}_e \& \bar{\nu}_\mu)$ fit for oscillation search.



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

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

4. ν_e from μ-decay constraint

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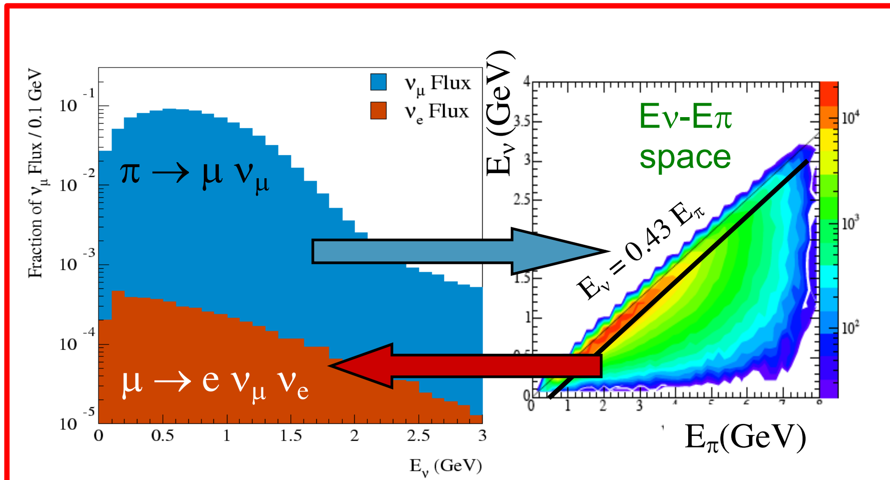

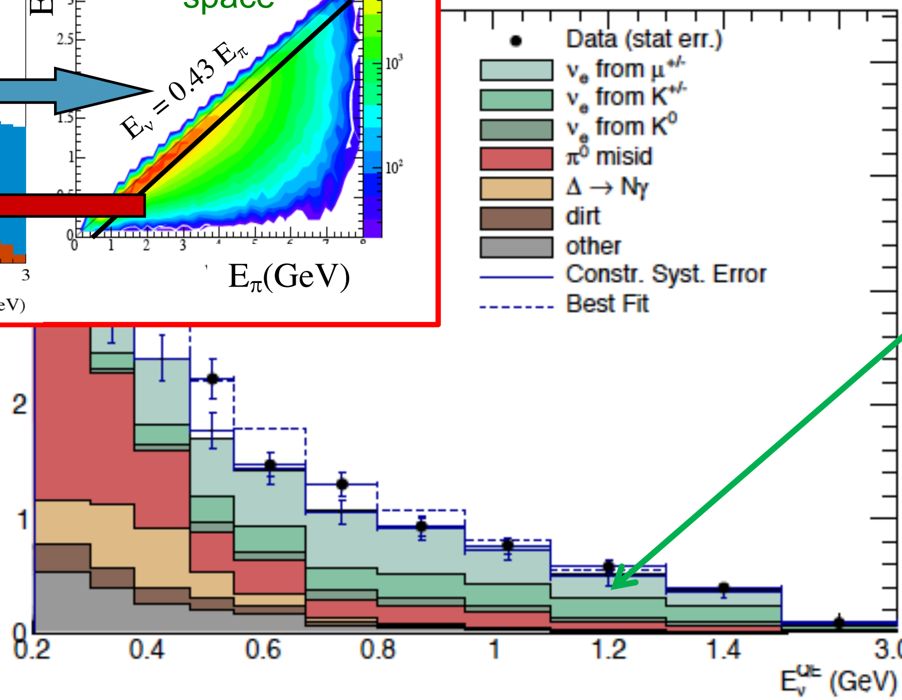

ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from K^+-decay constraint

All backgrounds are internally constrained
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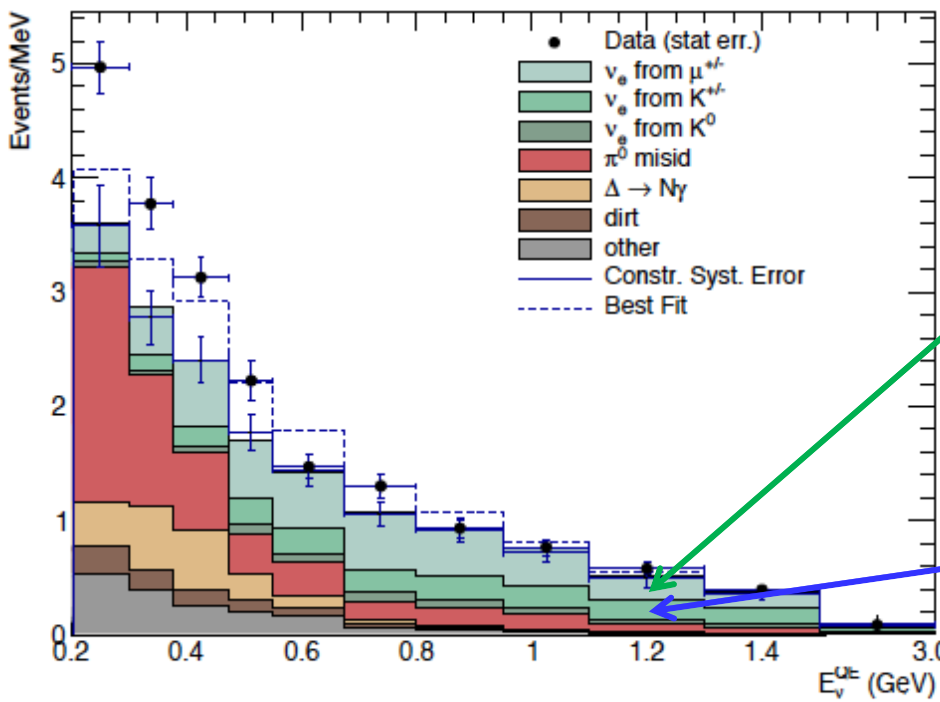


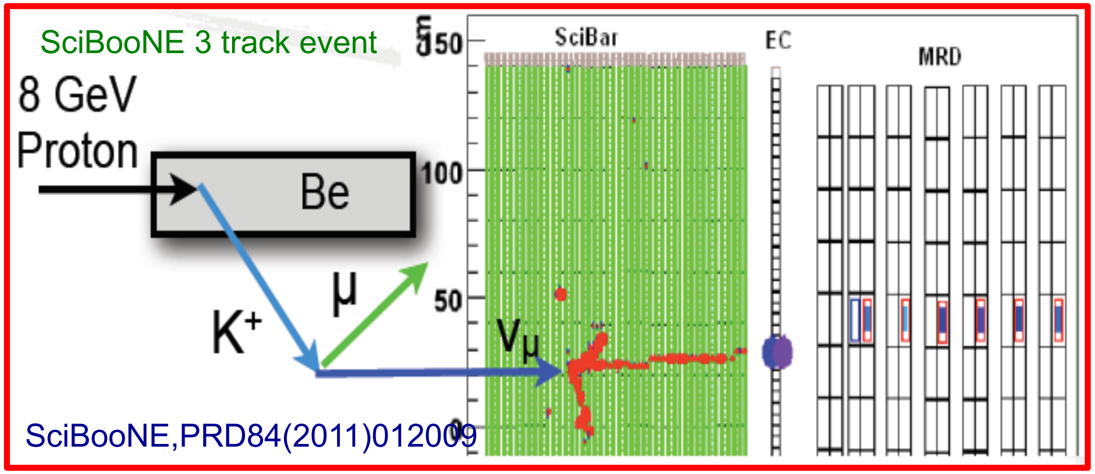
ν_e from μ decay is constrained from ν_μCCQE measurement

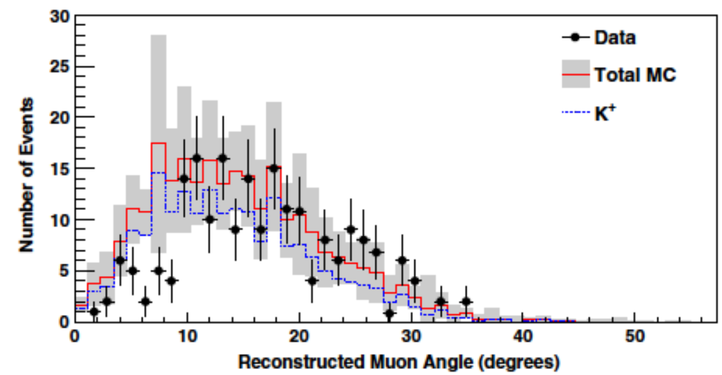
ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

SciBooNE,PRD84(2011)012009

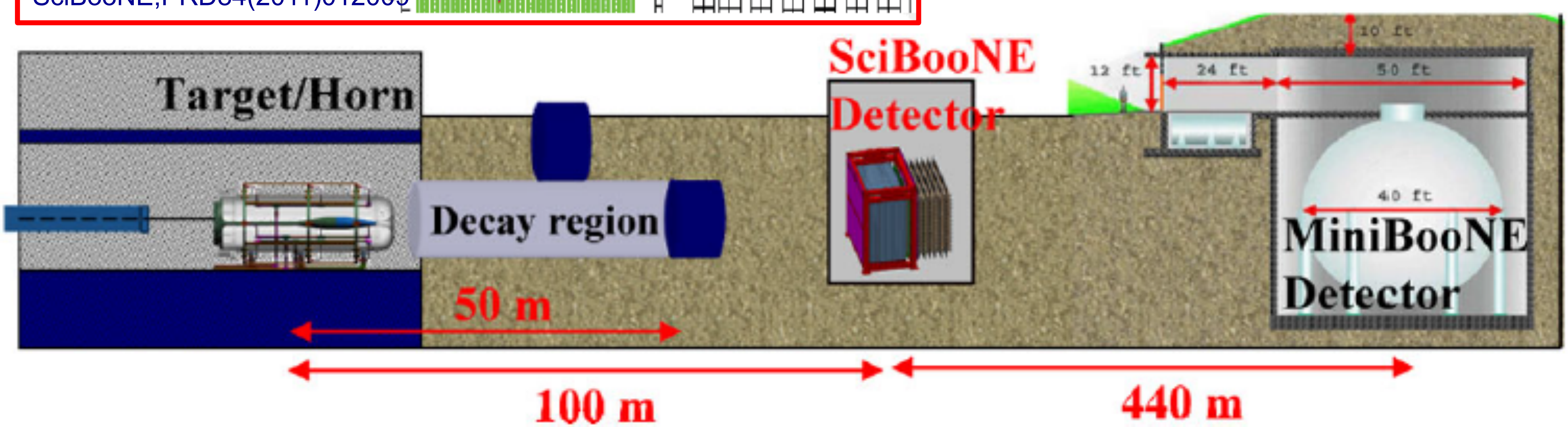
4. ν_e from K^+-decay constraint

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)





(c) 3-Track Sample



4. ν_e from K^+-decay constraint

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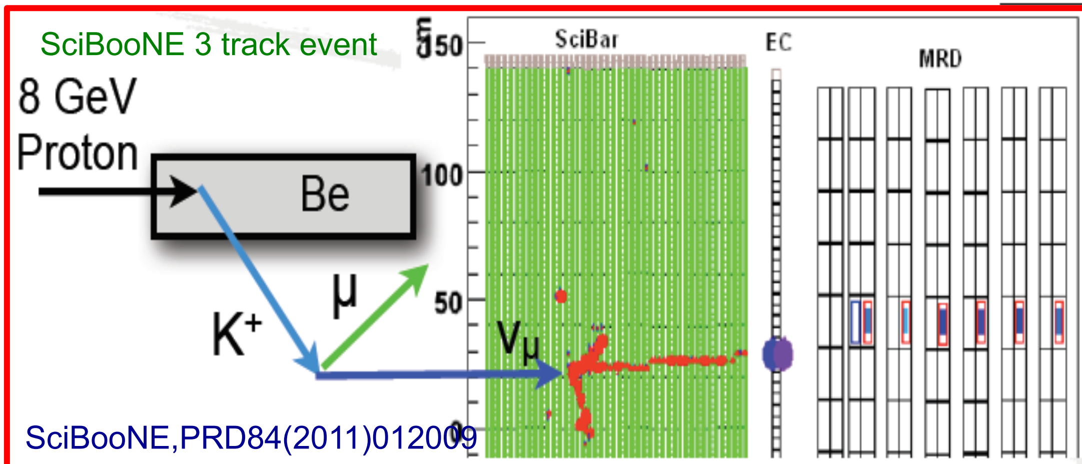

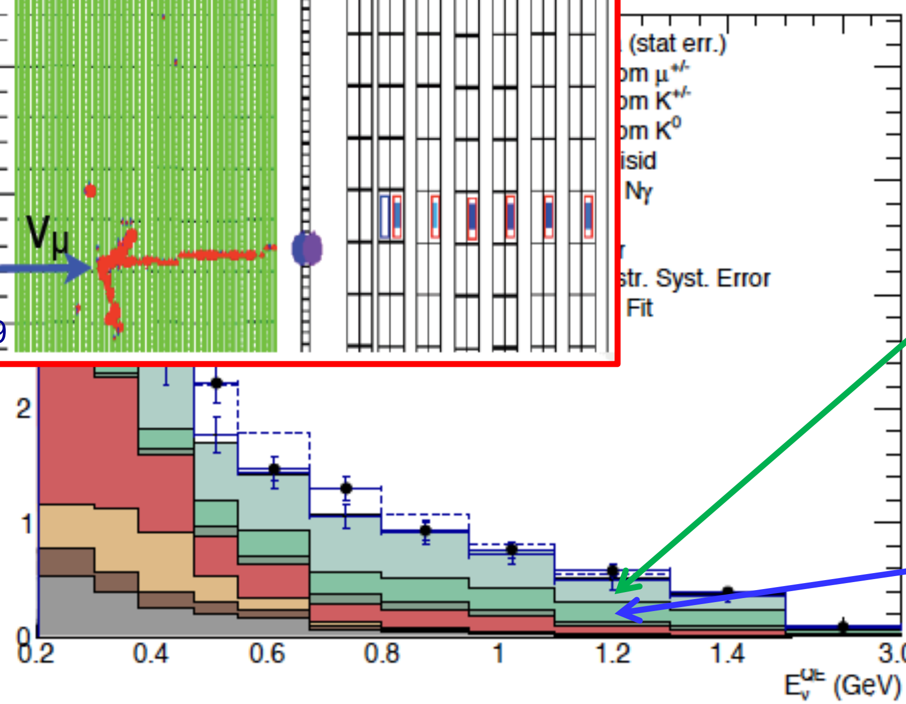

ν_e from μ decay is constrained from ν_μCCQE measurement

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

4. ν_e from K⁺-decay constraint

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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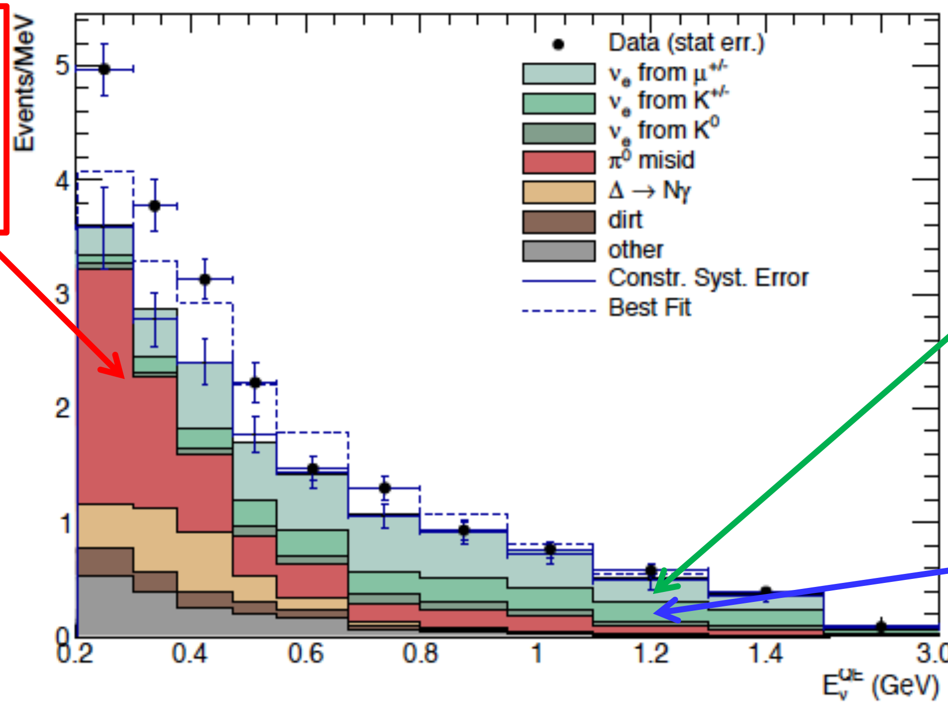
Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)



ν_e from μ decay is constrained from ν_μCCQE measurement

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

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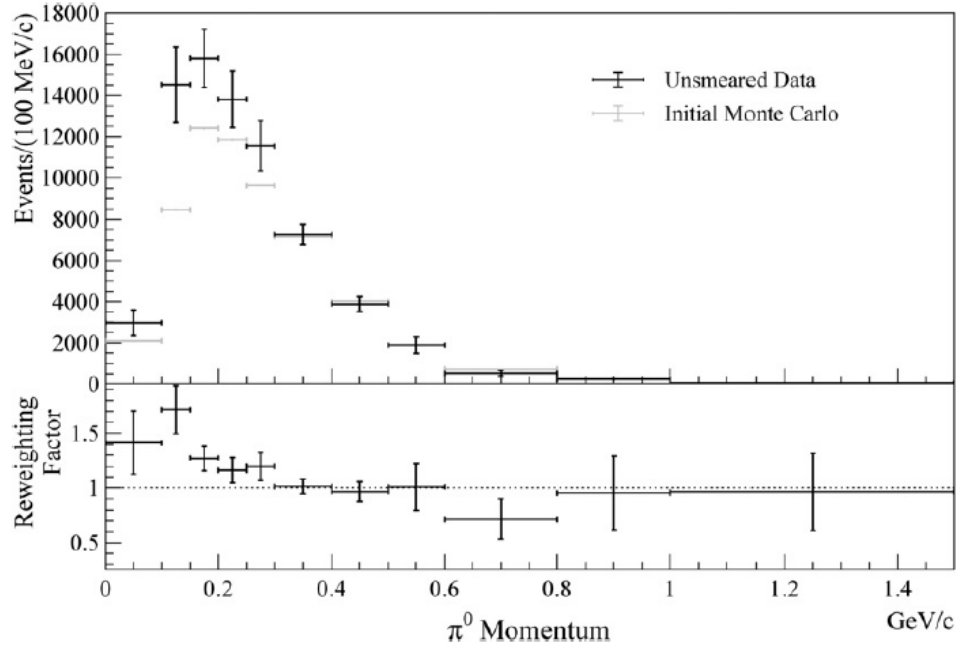
4. γ from π^o constraint

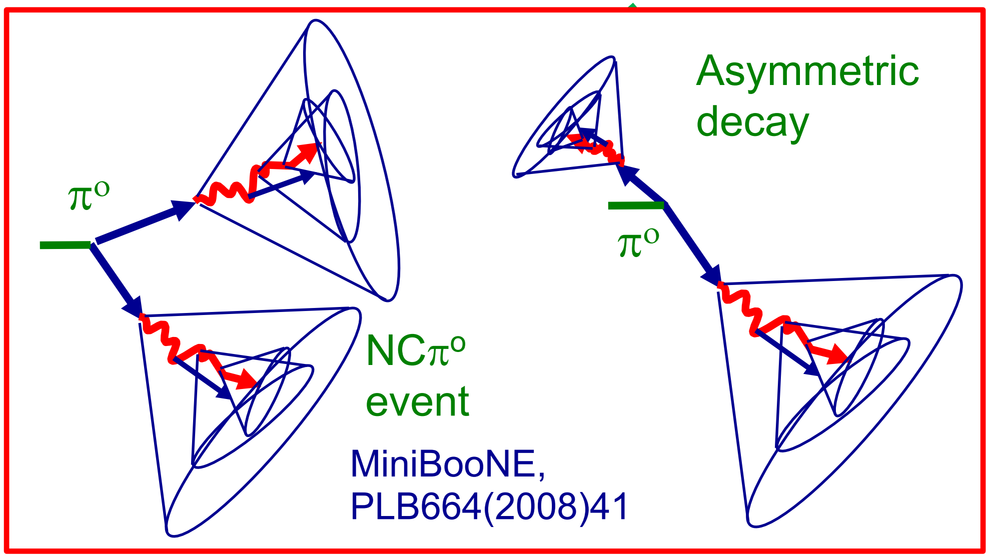
$\pi^o \rightarrow \gamma\gamma$
- not background, we can measure

$\pi^o \rightarrow \gamma$
- 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 po production rate, and correct simulation with function of π^o momentum





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4. γ from π° constraint

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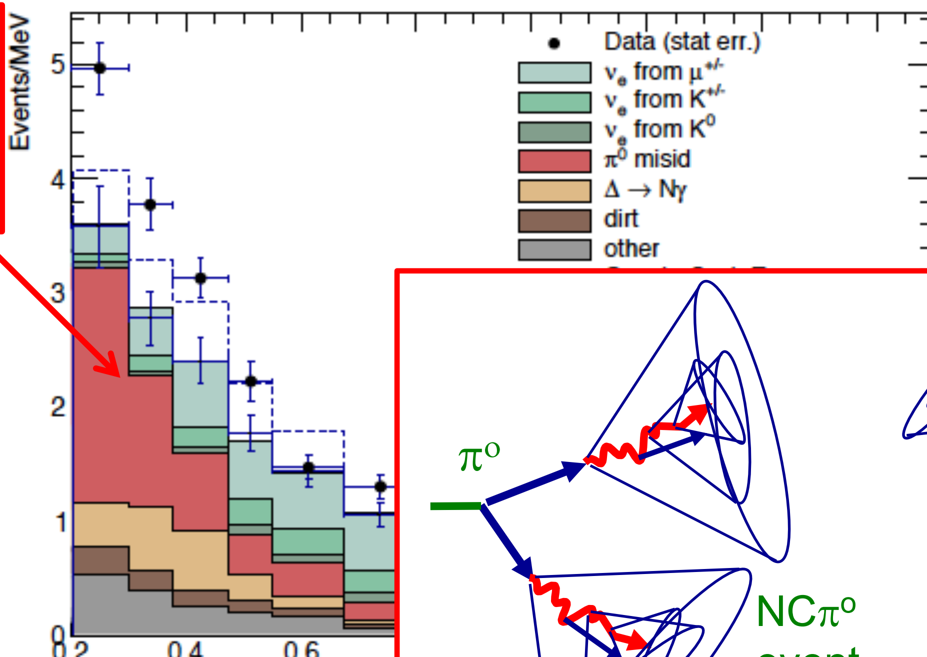
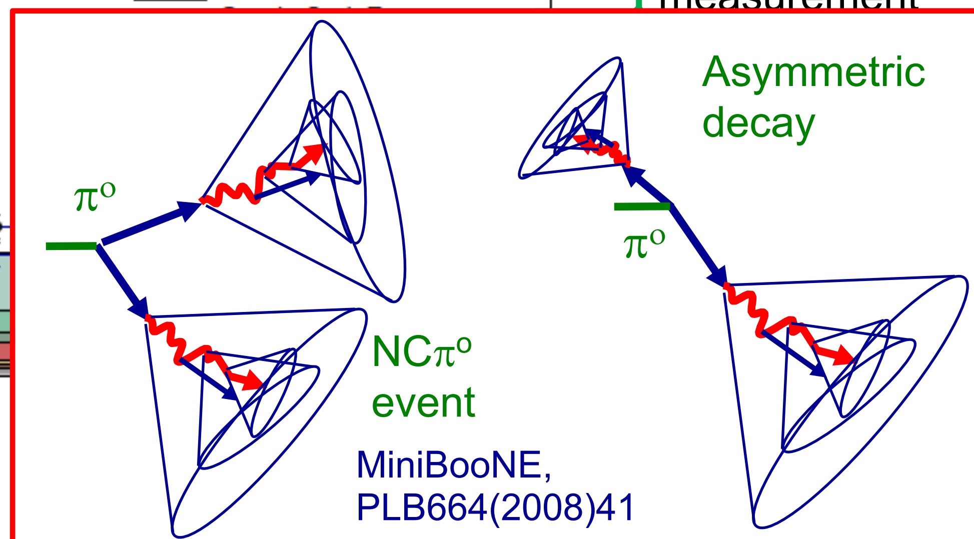
Excess	381.2 ± 85.2	79.3 ± 28.6

Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)



ν_e from μ decay is constrained from ν_μCCQE measurement



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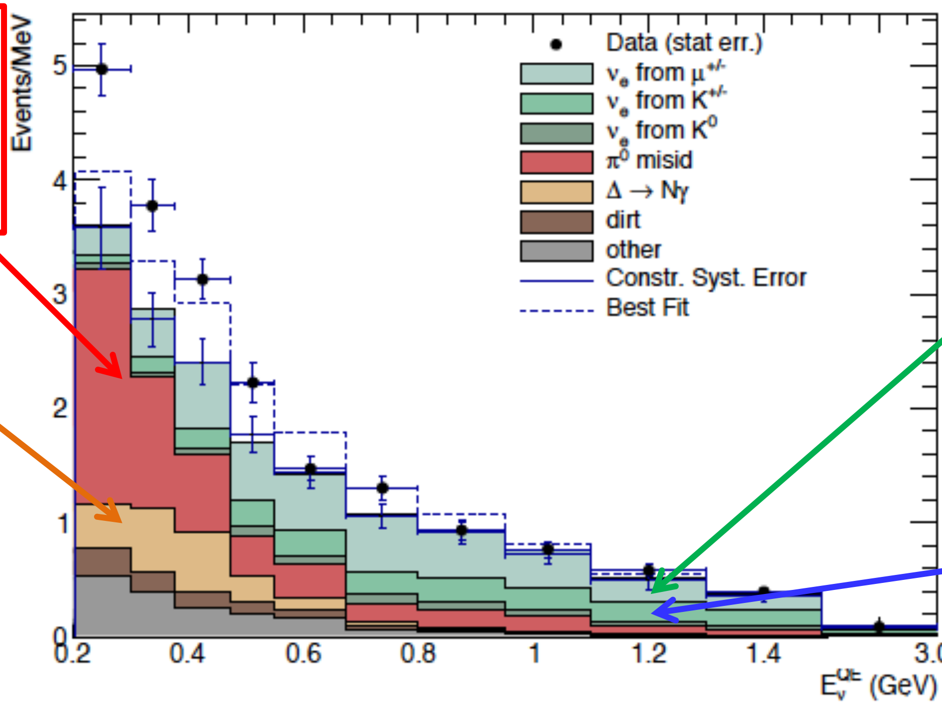
4. NCγ constraint

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 $CC\pi^o$ rate ($\pi^o \to \gamma$)

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



ν_e from μ decay is constrained from ν_μCCQE measurement

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

4. NCγ constraint

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	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
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All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

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

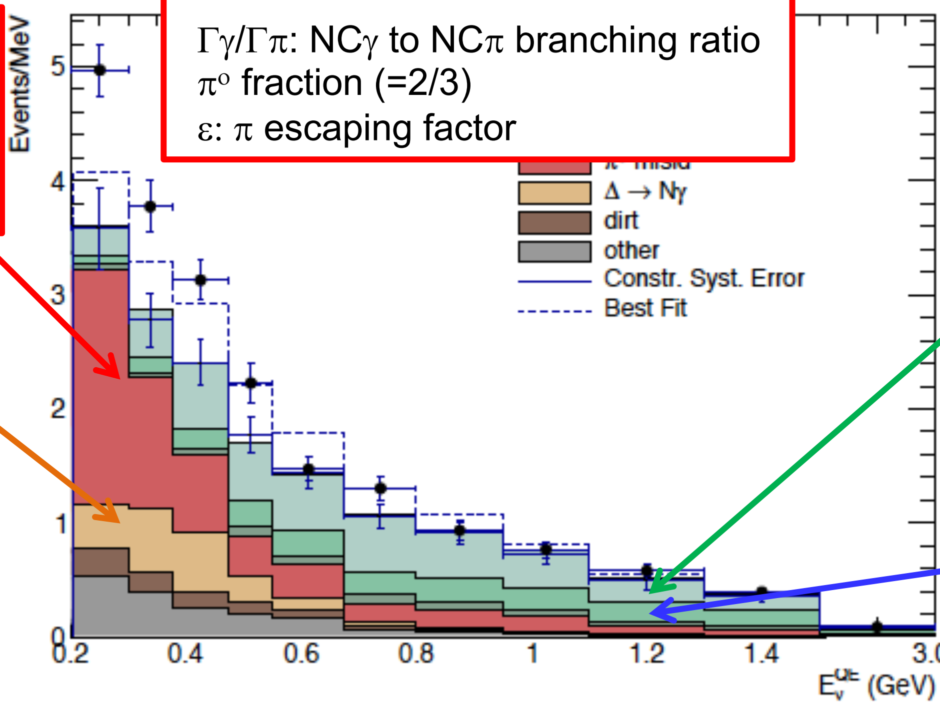
$\Gamma\gamma/\Gamma\pi$: NCγ to NCπ branching ratio
π^o fraction (=2/3)
ε: π escaping factor

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

Δ resonance rate is constrained from measured NCπ^o rate

ν_e from μ decay is constrained from ν_μCCQE measurement

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



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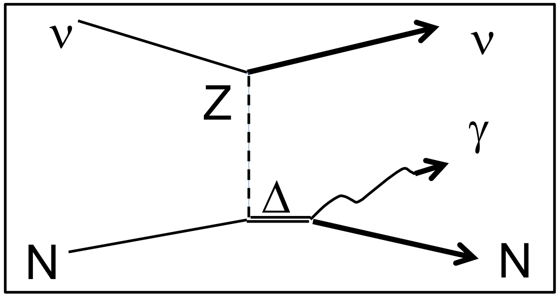
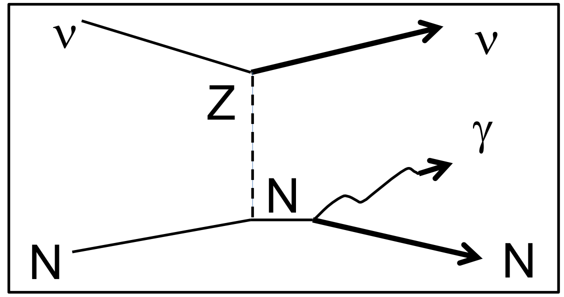
Lasorak, arXiv:1602.00084
T2K, to be published (2018)

4. Neutrino NC single gamma production

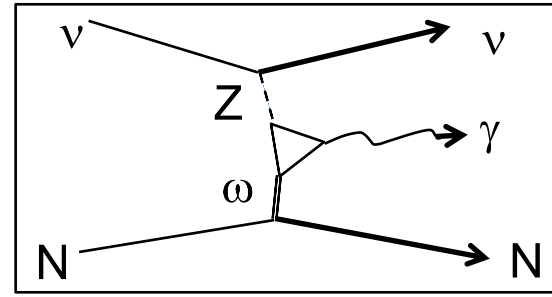
radiative Δ-decay



generalized Compton scattering

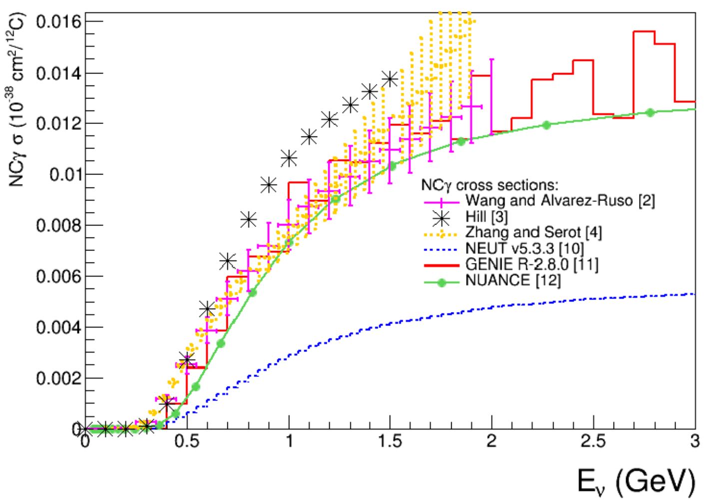


anomaly mediated triangle diagram



A lot of new calculations

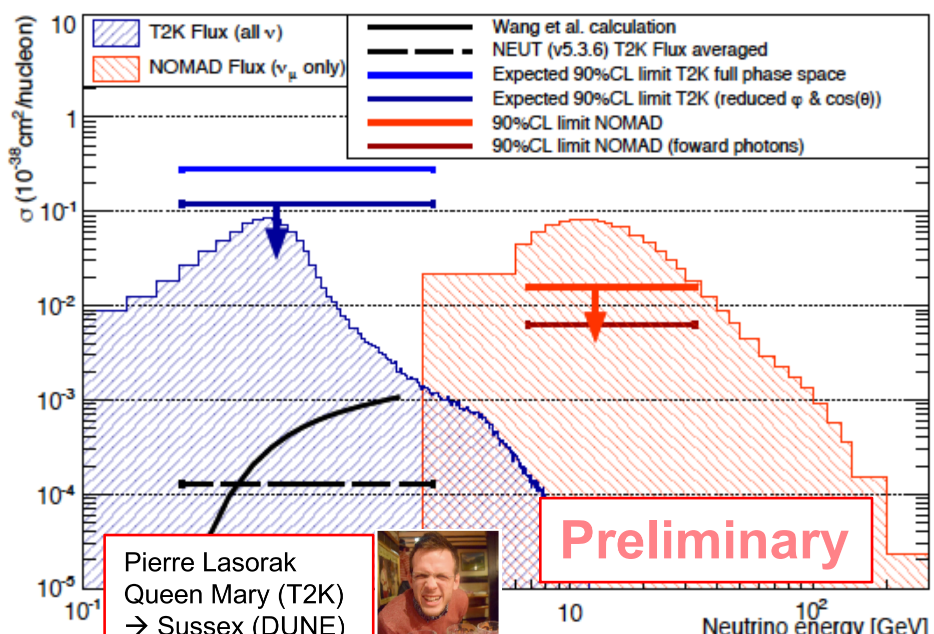
- all theoretical models and generators more or less agree. NEUT has been fixed.



[2] E. Wang, L. Alvarez-Ruso and J. Nieves, Phys.Rev. **C89**, (2014)015503 [arXiv:1311.2151]
[3] R. J. Hill, Phys.Rev. **D81**, (2010)013008 [arXiv:0905.0291]
[4] X. Zhang, B. D. Serot, Phys.Lett. **B719**, (2013)409 [arXiv:1210.3610]
[10] Y. Hayato, Acta Phys.Polon. **B40** (2009)2477
[11] C. Andreopoulos *et al.* Nucl.Instrum.Meth. **A614** (2010)87 [arXiv:0905.2517]
[12] D. Casper, Nucl.Phys.Proc.Suppl. **112** (2002)161 [arXiv:0208030]

T2K near detector measurement

- T2K can only set a limit. Waiting Fermilab SBN to measure this channel.



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

4. NCγ constraint

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	172.5 ±24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
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Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
ta	1959	478
	381.2 ± 85.2	79.3 ± 28.6

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

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

Γγ/Γπ: NCγ to NCπ branching ratio
π° fraction (=2/3)
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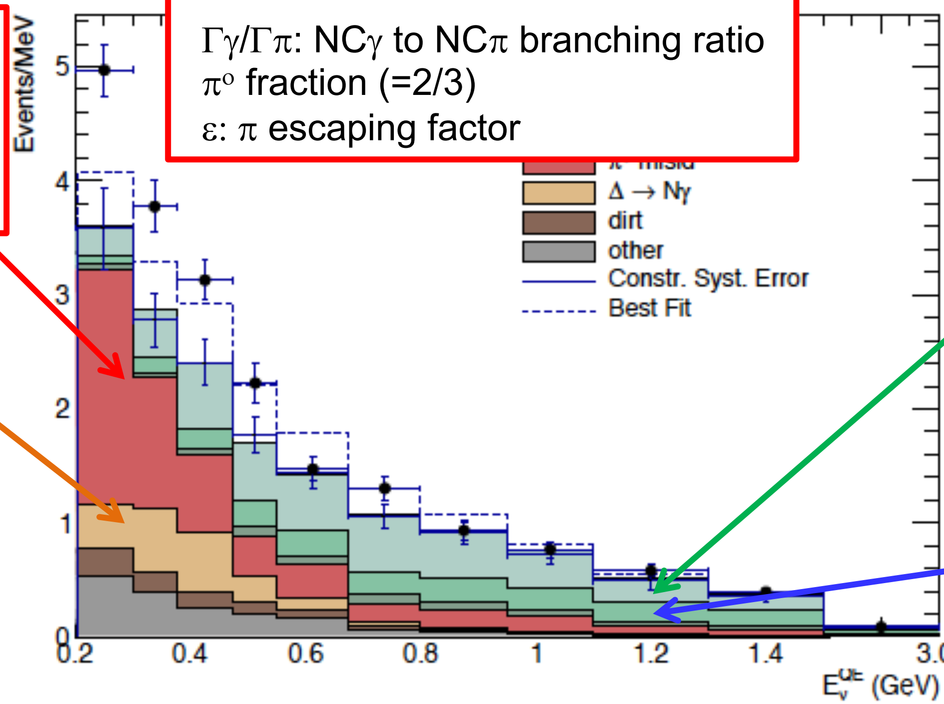
Δ resonance rate is constrained from measured NCπ° rate



ν_e from μ decay is constrained from ν_μCCQE measurement

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

4. External γ constraint

All backgrounds are internally constrained

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Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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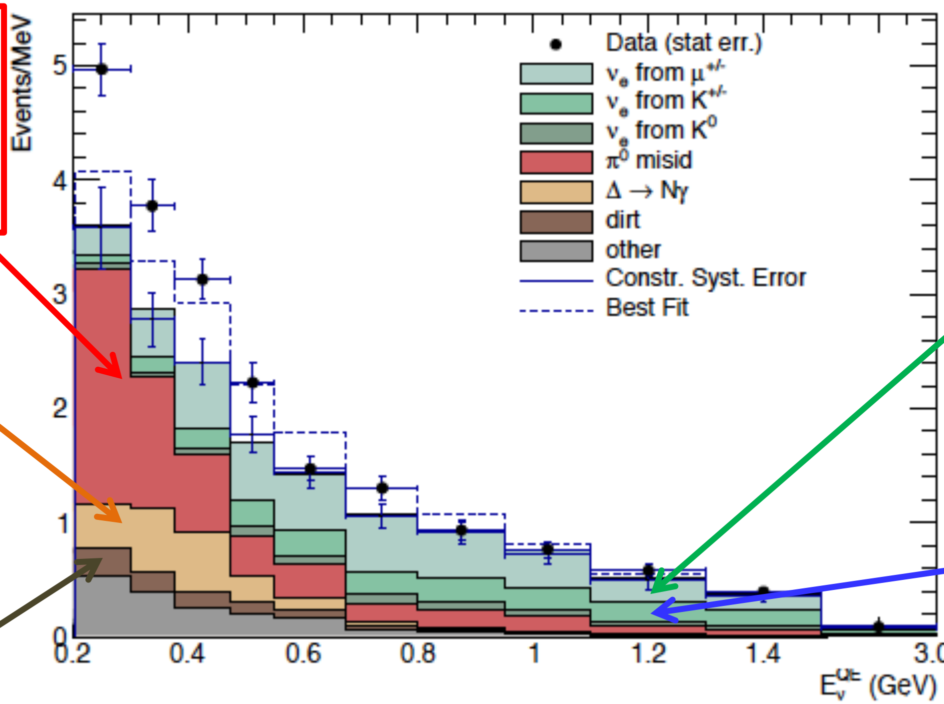
Δ resonance rate is constrained from measured $NC\pi^o$ rate

dirt rate is measured from dirt data sample



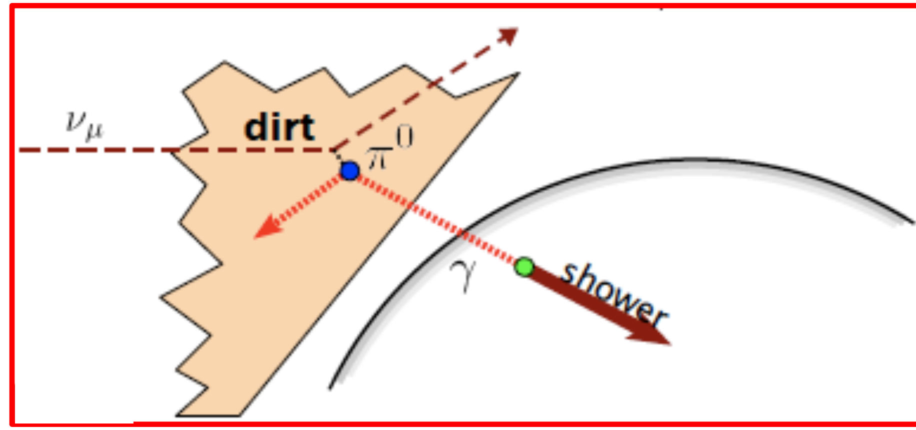
ν_e from μ decay is constrained from ν_μCCQE measurement

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

4. External γ constraint

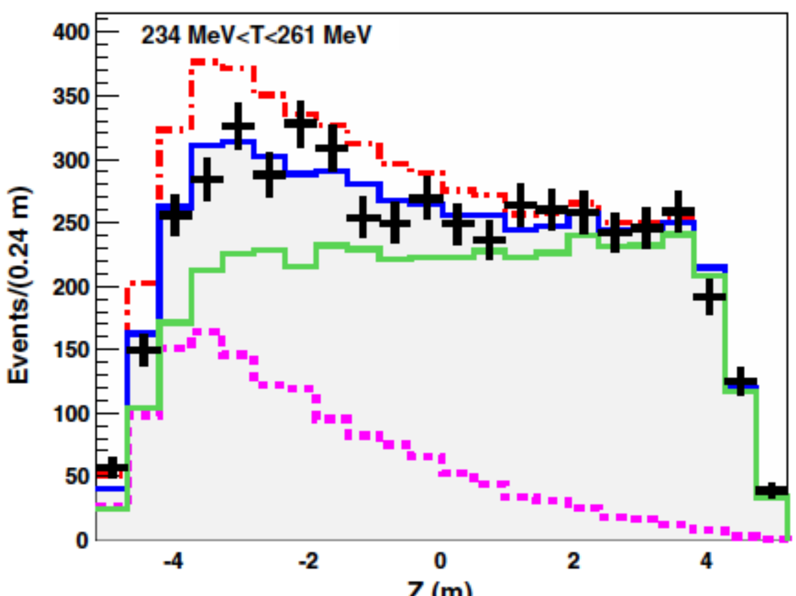
MiniBooNE detector has a simple geometry
- Spherical Cherenkov detector
- Homogeneous, large active veto

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



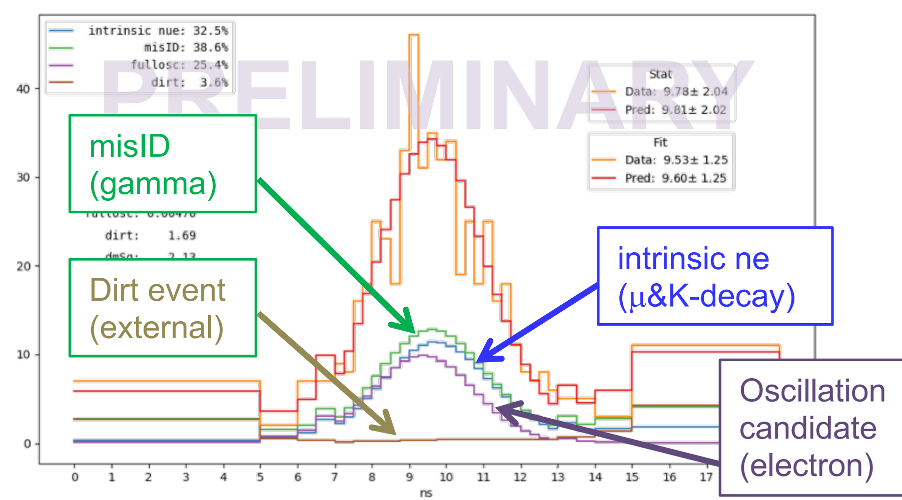
e.g.) NC elastic candidates with function of Z

Mis-modelling of external background is visible



e.g.) Time of Flight

Dirt related events is consistent with ToF data including oscillation hypothesis



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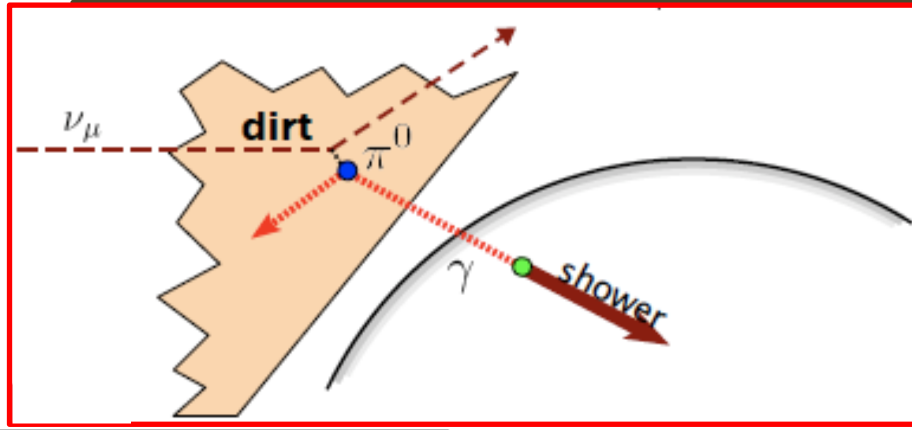

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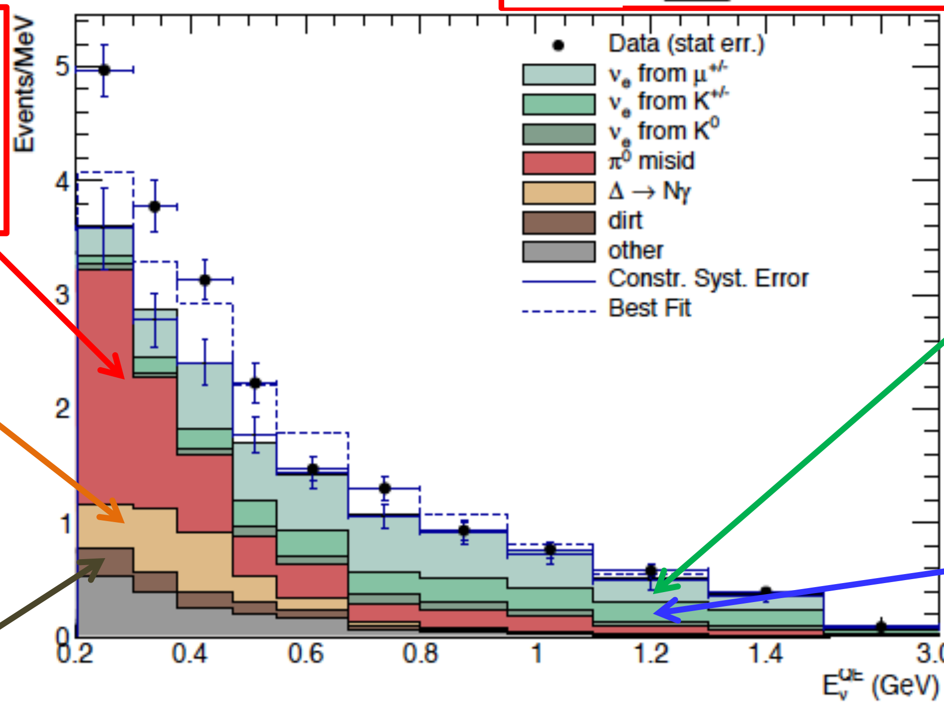

ν_e from μ decay is constrained from ν_μCCQE measurement

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

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4. Internal background constraints

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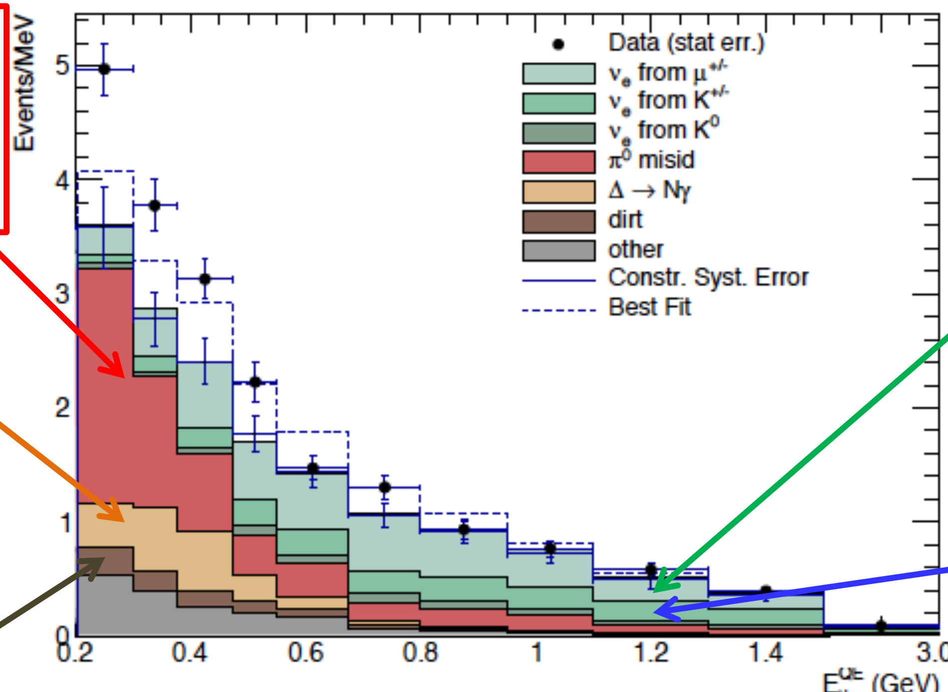

ν_e from μ decay is constrained from ν_μCCQE measurement

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

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

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1. MiniBooNE neutrino experiment

2. Booster Neutrino Beamline (BNB)

3. MiniBooNE detector

4. Oscillation candidate search

5. Discussion

5. Oscillation candidate event excess

200 < EνQE < 1250 MeV

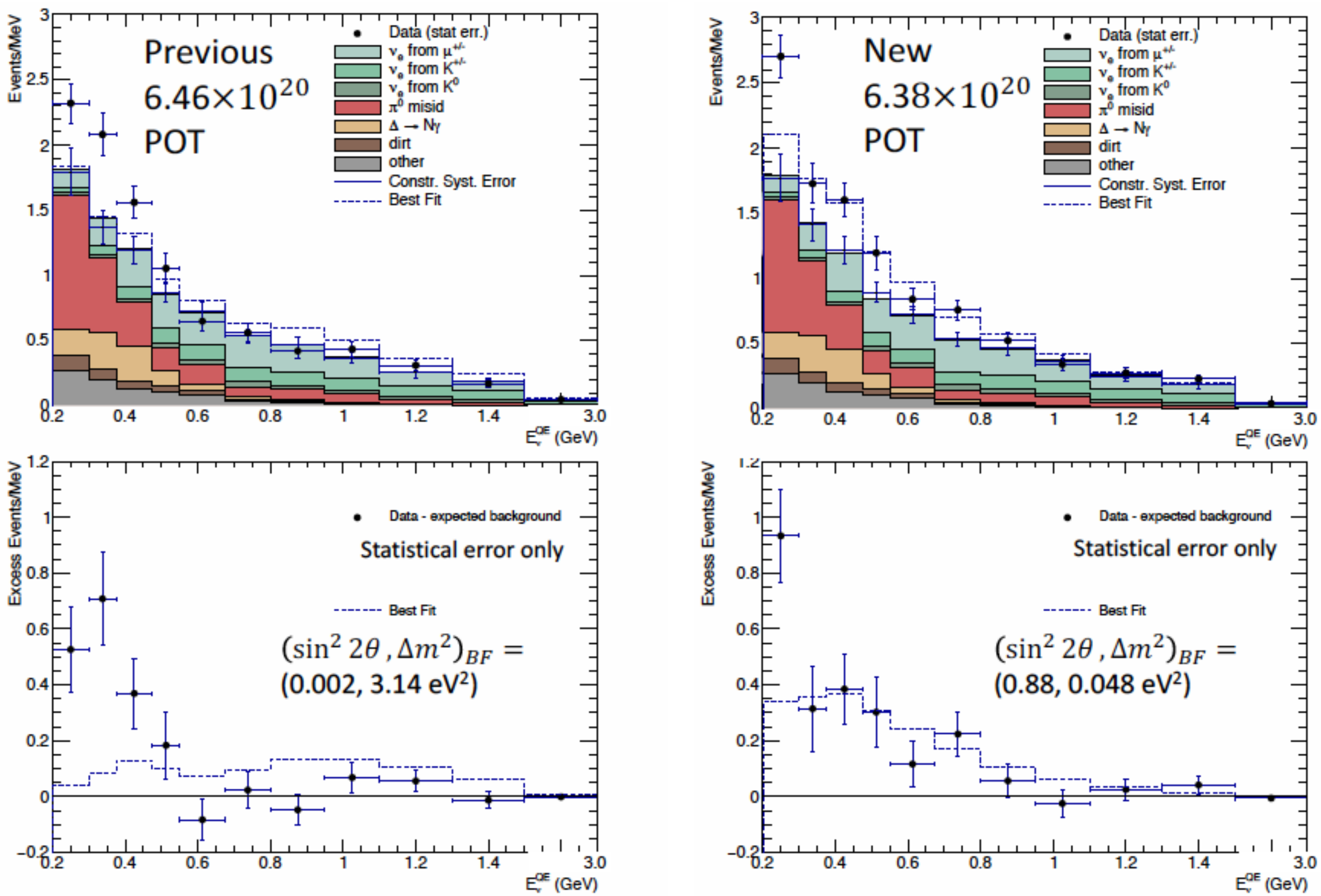
- neutrino mode: Data = 1956 events

Bkgd = 1577.8 ± 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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5. Oscillation candidate event excess

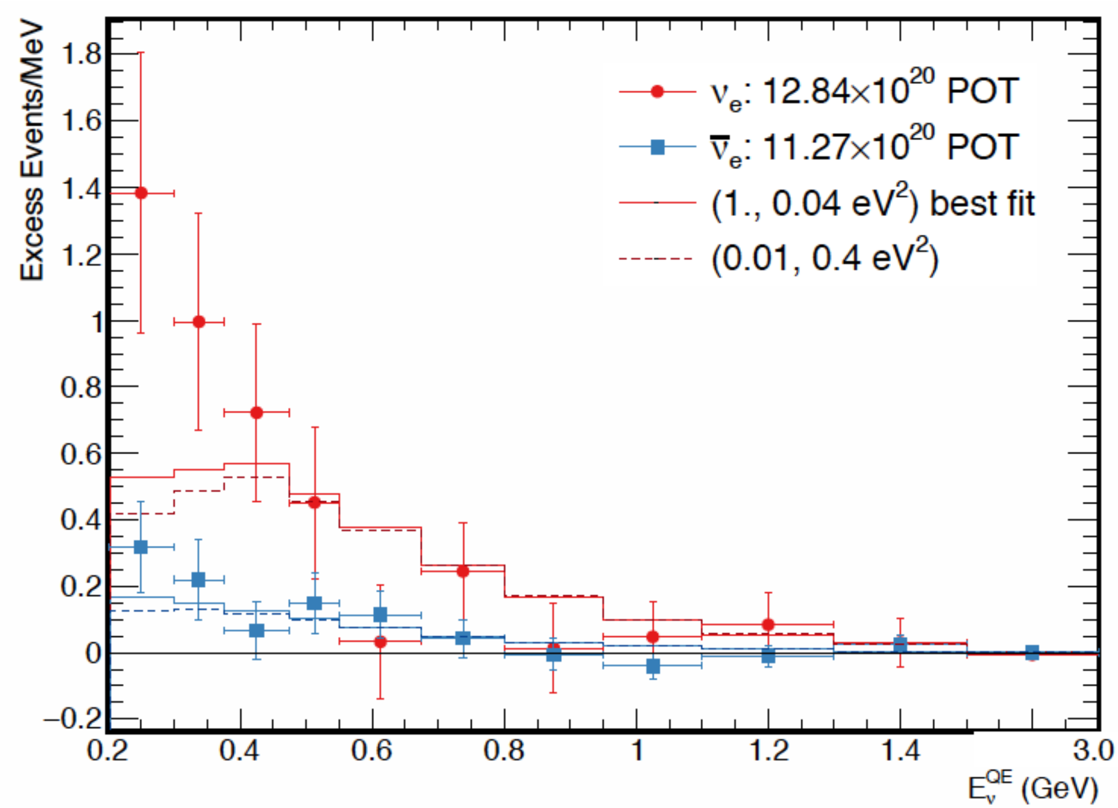
200 < EνQE < 1250 MeV

- 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)



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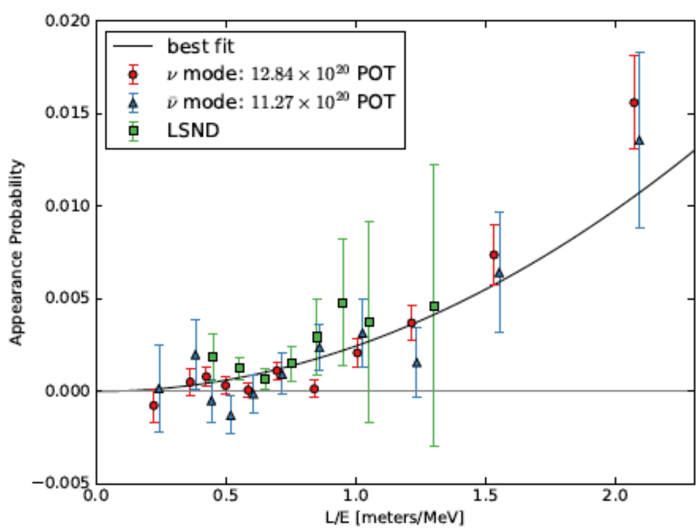
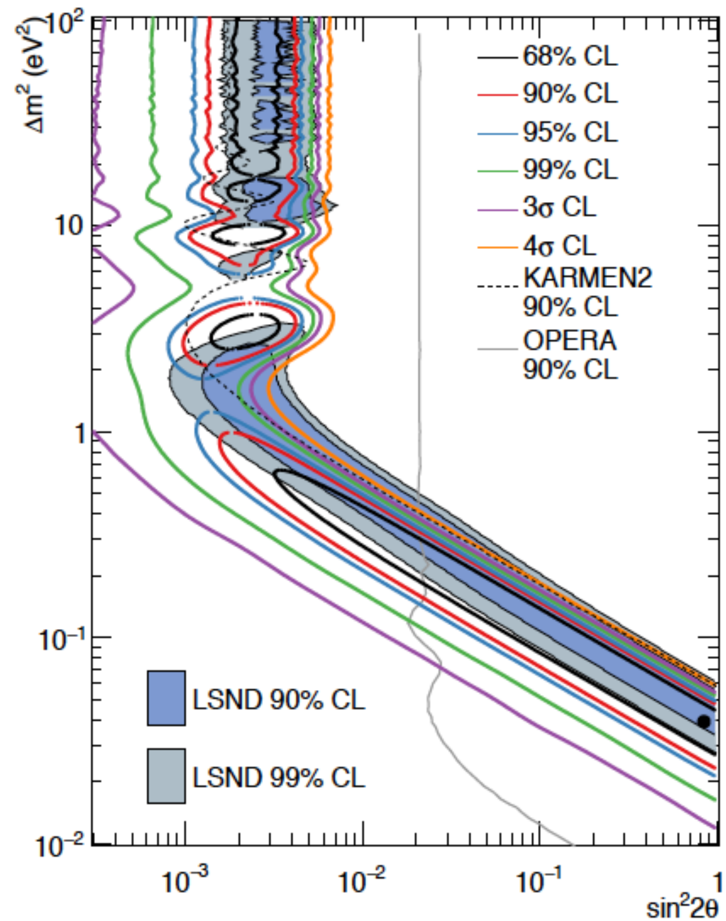
- antineutrino mode: Data = 478 events

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

Compatible with LSND excess within 2-neutrino oscillation hypothesis



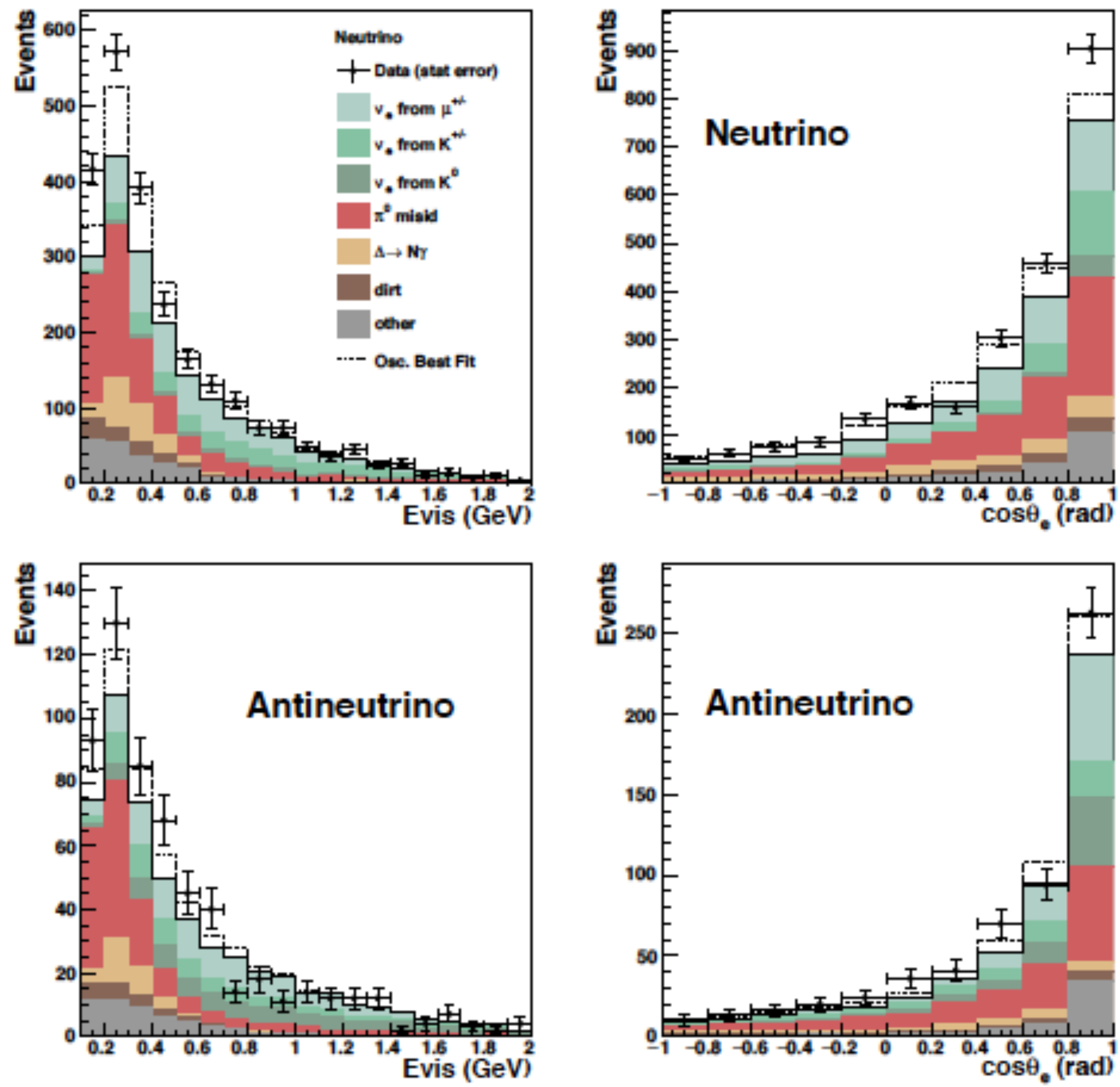


However, appearance and disappearance data have a strong tension (Maltoni, Neutrino 2018)

5. Alternative photon production models?

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

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



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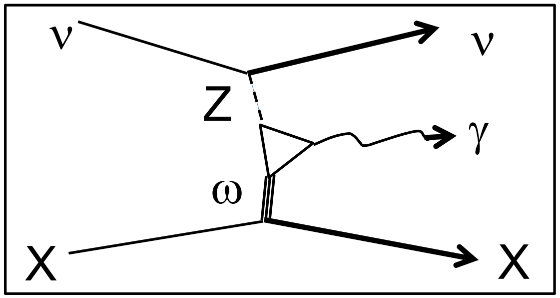
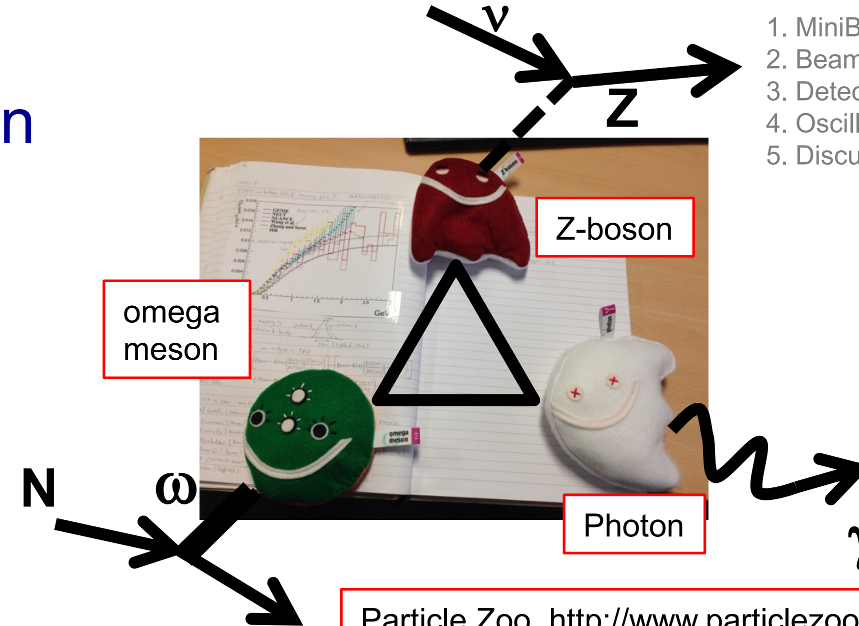
Harvey,Hill,Hill, PRL99(2007)261601

5. Anomaly mediated γ production

A process within SM, but not considered.

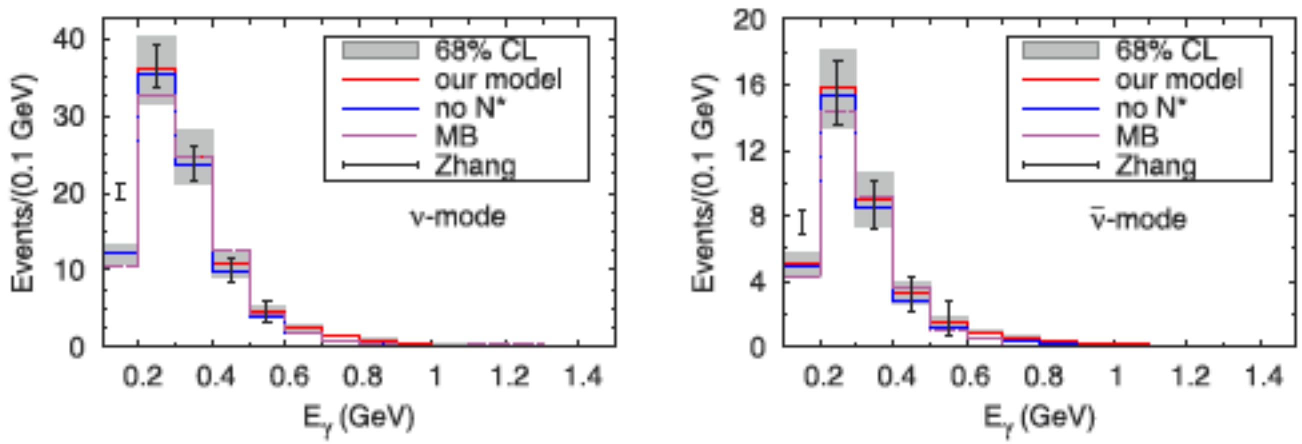




Particle Zoo, http://www.particlezoo.net/

Later study found the contribution is small.

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

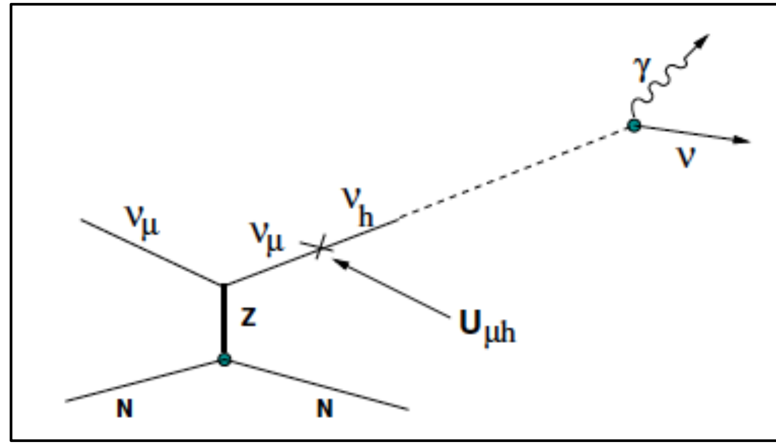


It looks it's easy to forget any processes with $\sigma \sim 10^{-41}$ cm^2
(e.g., diffractive π^o production $\sigma \sim 10^{-41}$ cm^2 was identified very recently by MINERvA)

MINERvA, PRL117(2016)111801

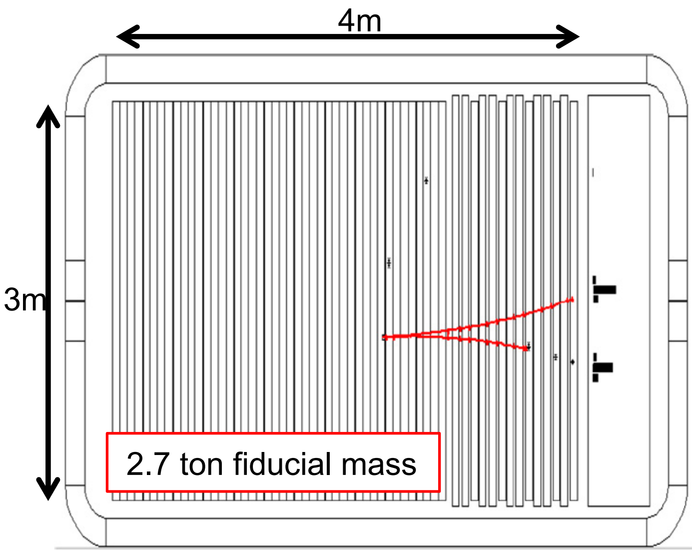
5. Heavy neutrino decay γ production

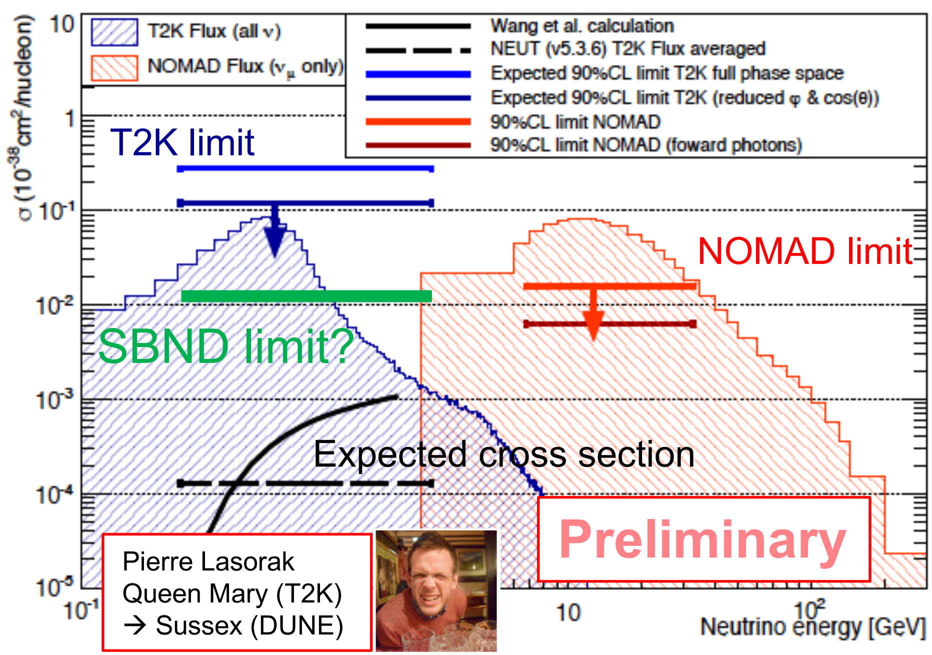
Carefully designed to avoid Karmen constraint.
 - The model works, but there are many "tricks" to avoid existing constraints, making the model bit artificial.



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





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

5. Alternative neutrino oscillation model?

e.g.) Lorentz violation motivated neutrino oscillation model
Making a new texture in Hamitonian to control oscillations.
 - my "tandem" model reproduce all data and LSND at the time of 2006 → not really reproduce details.

tandem model effective Hamiltonian

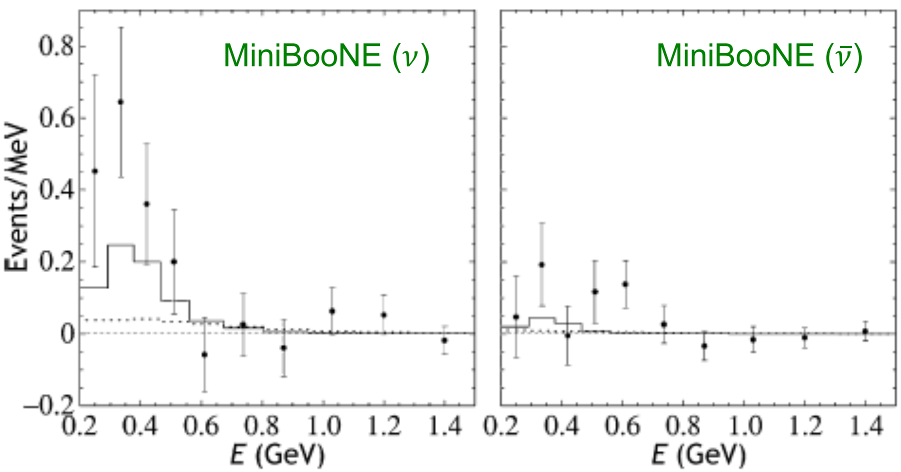
$$h^{\nu}_{\rm eff} = \begin{pmatrix} -\frac{4}{3}(c_L)_{ee}E & (a_L)_{e\mu} & (a_L)_{e\tau} \\ (a_L)_{\mu e} & 0 & (a_L)_{\mu\tau} \\ (a_L)_{\tau e} & (a_L)_{\tau\mu} & (m^2)_{\tau\tau}/2E \end{pmatrix}.$$

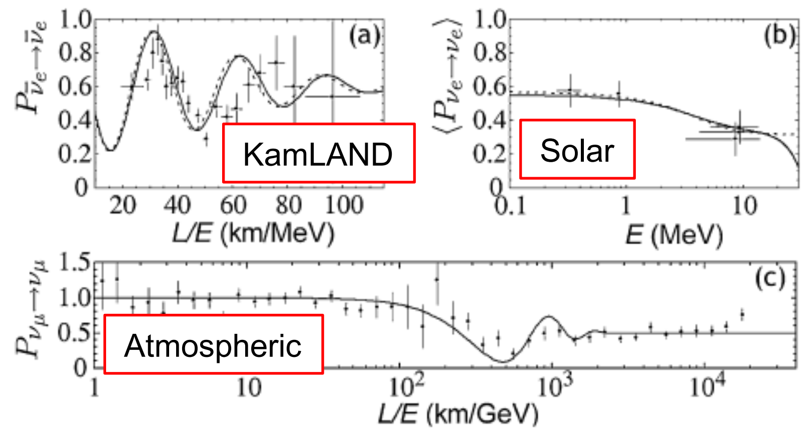
Advanced "puma" model was proposed, but this doesn't reproduce long-baseline ν_e appearance data.

puma model 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 $C(E) = \mathring{c}E^5$





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.

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Super-Kamiokande, PRL(2004)101801

Conclusion

MiniBooNE is the short-baseline neutirno 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
  – Dark Matter production/detection search with neutrino detector (ongoing)

MiniBooNE, PRL118(2017)221803

But the biggest legacy is the short-baseline anomaly

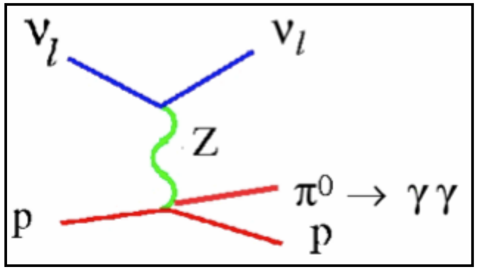
Thank you for your attention!

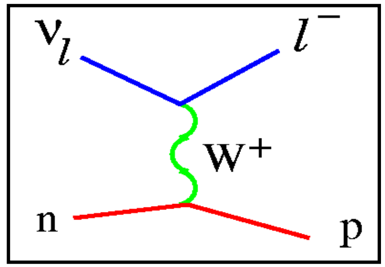
backup

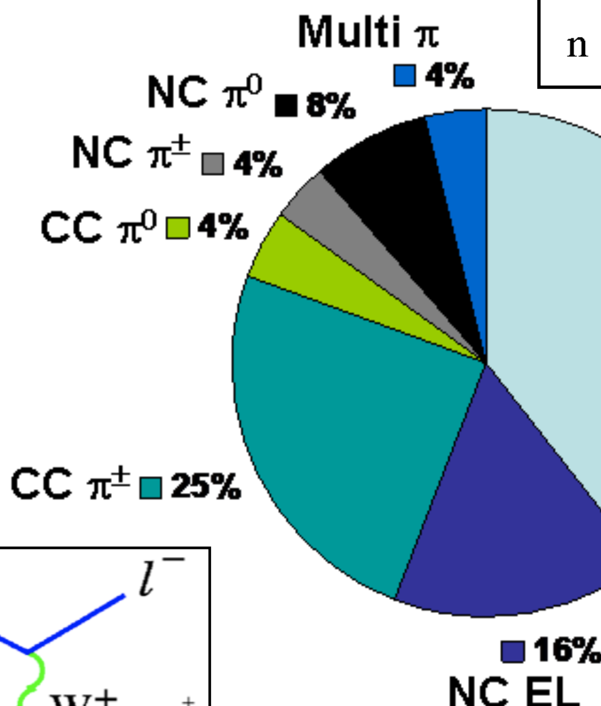
1. Cross section model

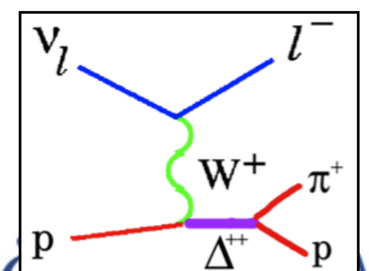
Predicted event rates before cuts (NUANCE Monte Carlo)

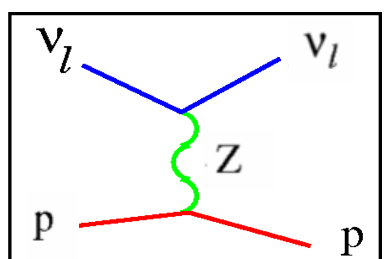
Casper, Nucl.Phys.Proc.Suppl.112(2002)161

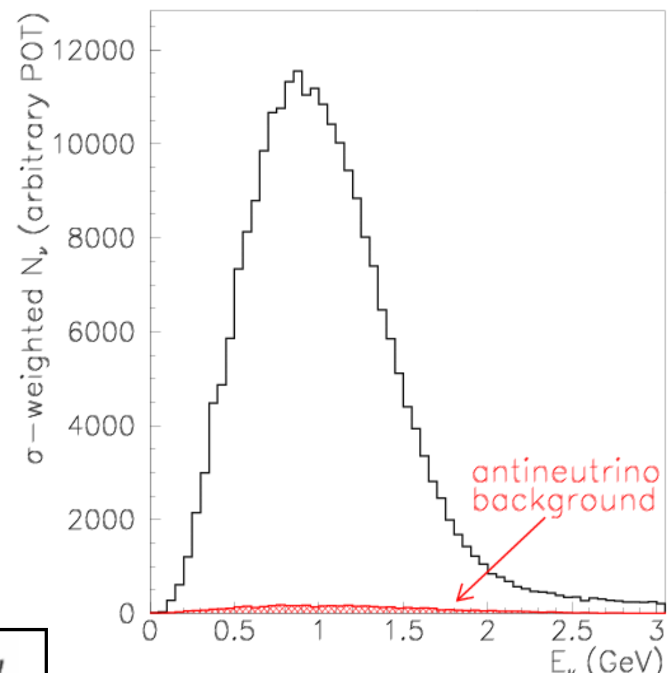










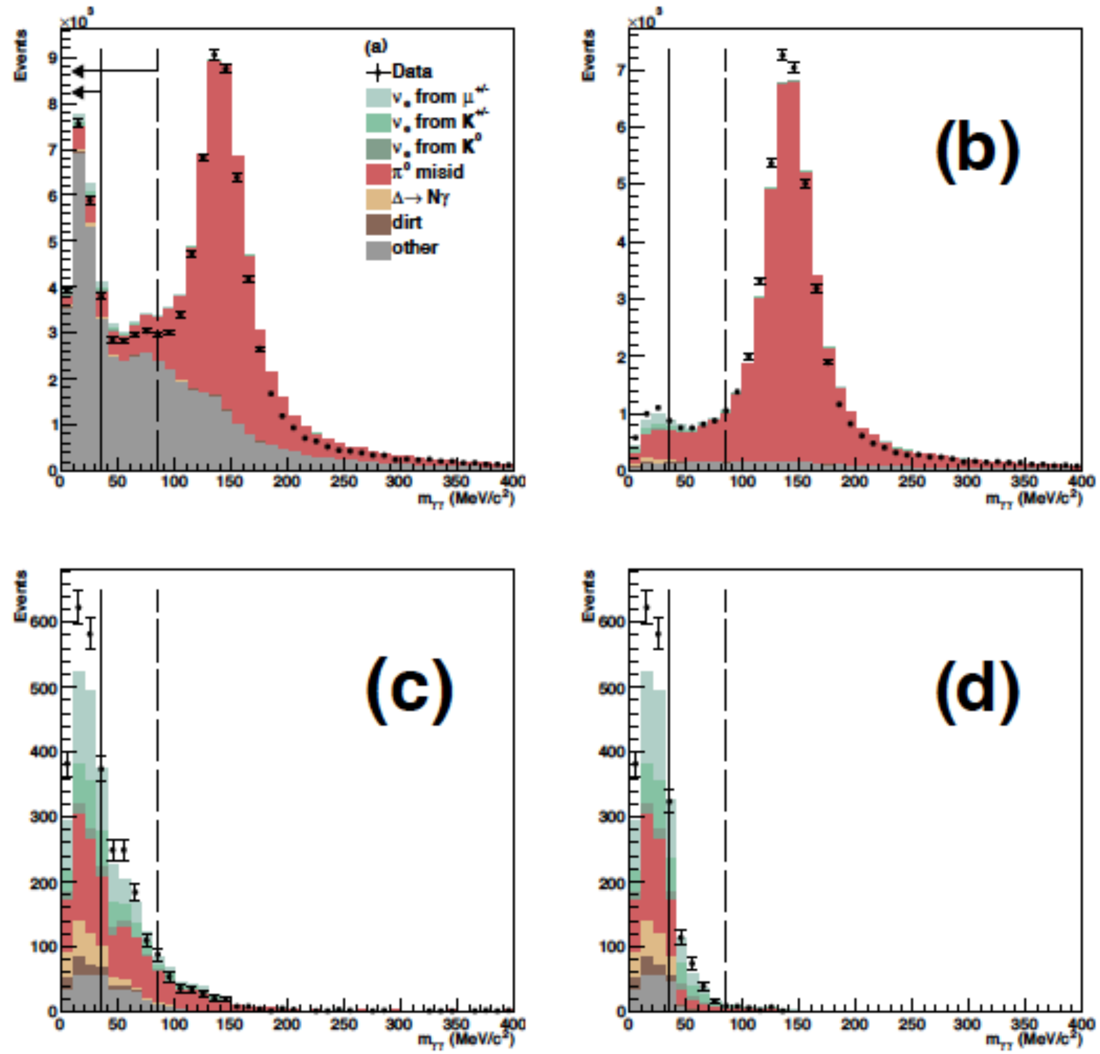


Event neutrino energy (GeV)

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.



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