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

PRL121(2018)221801

outline

1. MiniBooNE neutrino experiment
2. Oscillation candidate search
3. Discussion

This talk is a shorter version of my CERN seminar, longer version is here https://indico.cern.ch/event/791940/

Teppei Katori for the MiniBooNE collaboration
Queen Mary University of London
NExT workshop, Queen Mary University of London, UK, Apr. 3, 2019

1. MiniBooNE neutrino experiment

2. Oscillation candidate search

3. Discussion

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

Quanta magazine

ABSTRACTIONS BLOG

Evidence Found for a New Fundamental Particle

10

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

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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

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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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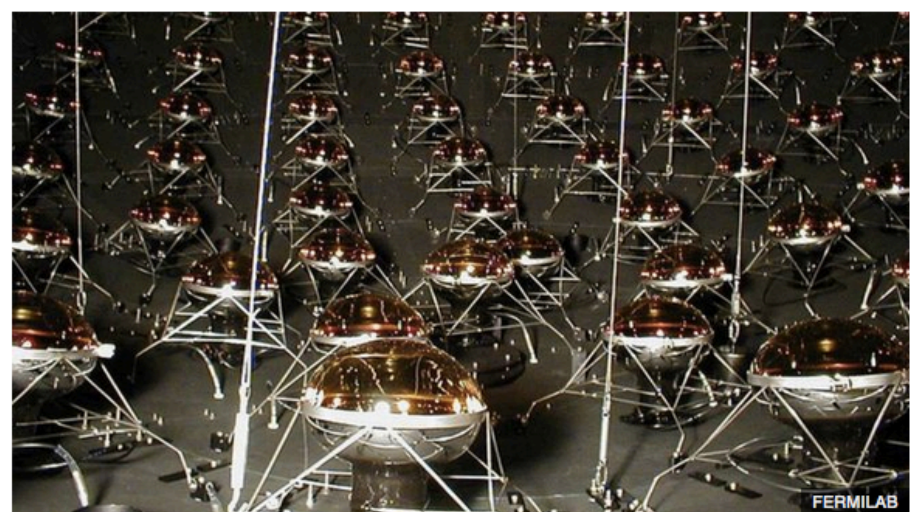

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Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment

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

Physics See Viewpoint: The Plot Thickens for a Fourth Neutrino

The most visible particle physics result of 2018

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of 12,363,617 outputs	of 25,606 outputs	of 270,805 outputs	of 520 outputs

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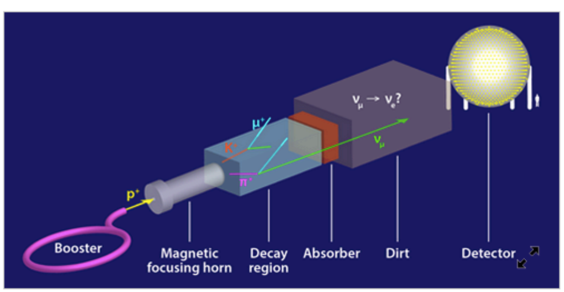
Viewpoint: The Plot Thickens for a Fourth Neutrino

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

November 26, 2018 • *Physics* 11, 122

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



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

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

Physics See Viewpoint: Sizing Up the Top Quark's Interaction with the Higgs

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Observation of Higgs Boson Decay to Bottom Quarks

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

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

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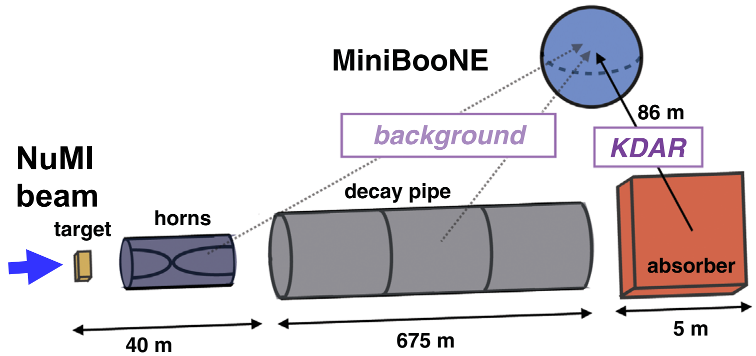
https://physics.aps.org/articles/v11/122



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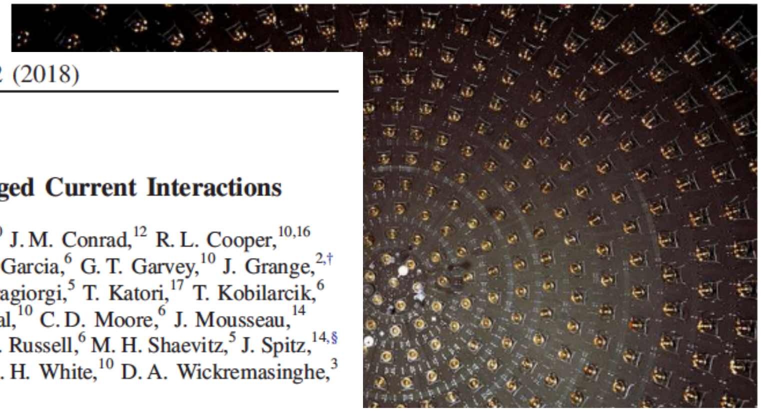
Home » Physics » General Physics » June 5, 2018

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

June 5, 2018 by Savannah Mitchem, Argonne National Laboratory



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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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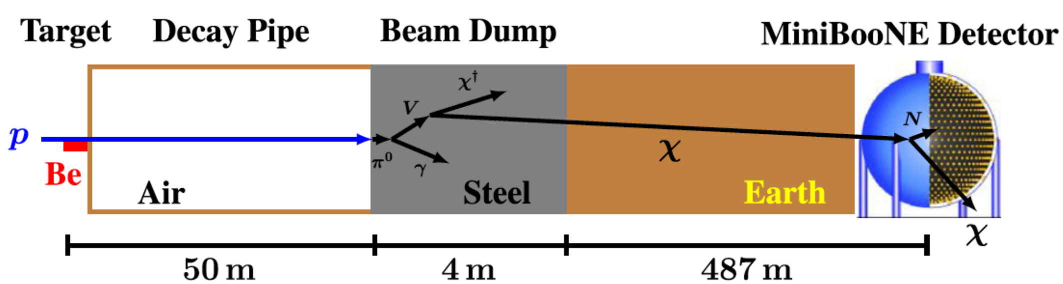


News at work

The MiniBooNE search for dark matter

July 18, 2017 | Ranjan Dharmapalan and Tyler Thornton

Email

PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

A. A. Aguilar-Arevalo,[1] M. Backfish,[2] A. Bashyal,[3] B. Batell,[4] B. C. Brown,[2] R. Carr,[5] A. Chatterjee,[3] R. L. Cooper,[6,7] P. deNiverville,[8] R. Dharmapalan,[9] Z. Djurcic,[9] R. Ford,[2] F. G. Garcia,[2] G. T. Garvey,[10] J. Grange,[9,11] J. A. Green,[10] W. Huelsnitz,[10] I. L. de Icaza Astiz,[1] G. Karagiorgi,[5] T. Katori,[12] W. Ketchum,[10] T. Kobilarcik,[2] Q. Liu,[10] W. C. Louis,[10] W. Marsh,[2] C. D. Moore,[2] G. B. Mills,[10] J. Mirabal,[10] P. Nienaber,[13] Z. Pavlovic,[10] D. Perevalov,[2] H. Ray,[11] B. P. Roe,[14] M. H. Shaevitz,[5] S. Shahsavarani,[3] I. Stancu,[15] R. Tayloe,[6] C. Taylor,[10] R. T. Thornton,[6] R. Van de Water,[10] W. Wester,[2] D. H. White,[10] and J. Yu[3]

MiniBooNE-DM Collaboration

MiniBooNE keep providing high impact results!

PRL118(2017)221803
PRD98(2018)112004

Queen Mary University of London

1. LSND experiment

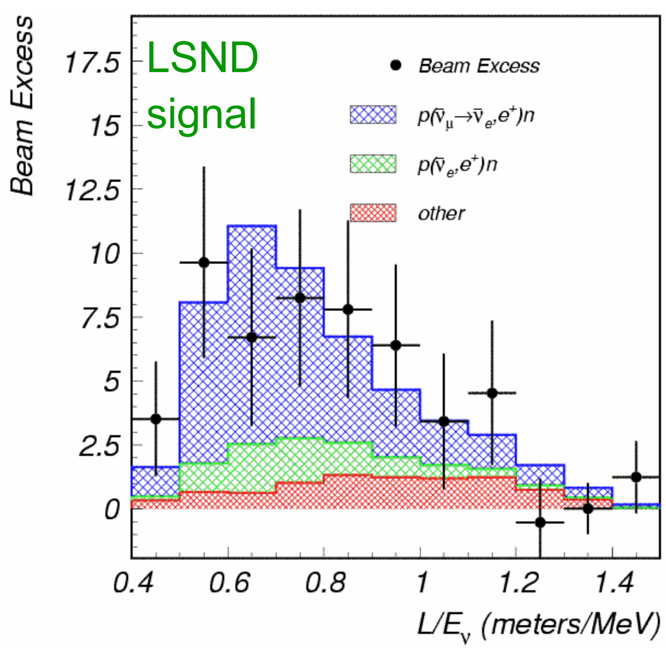
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

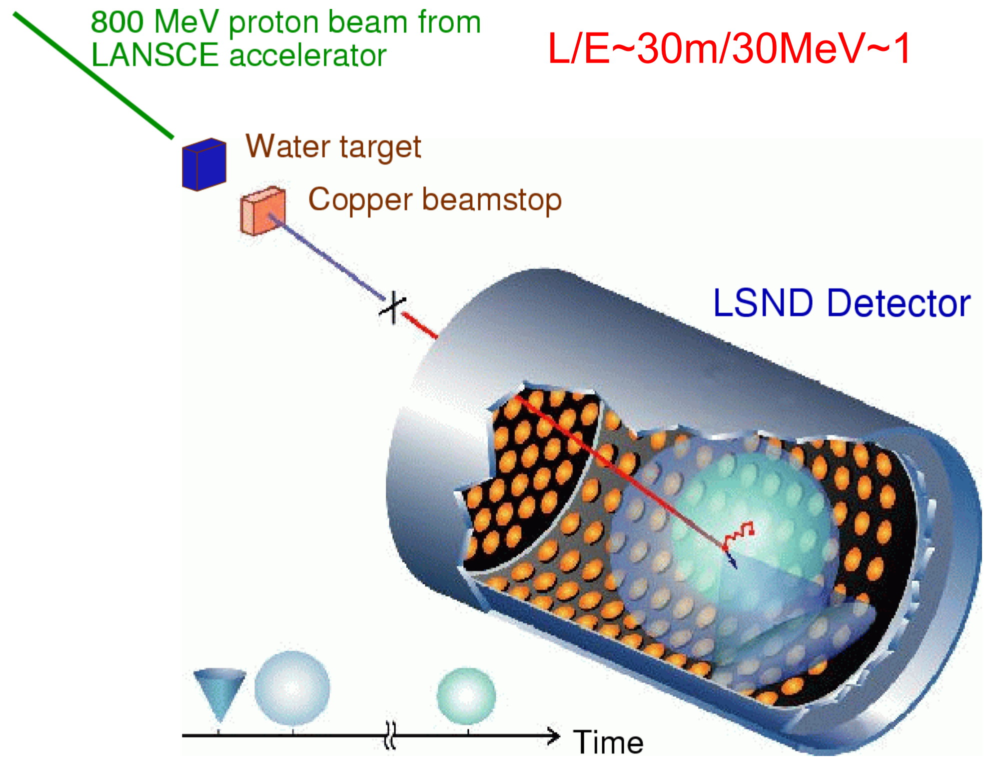
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

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

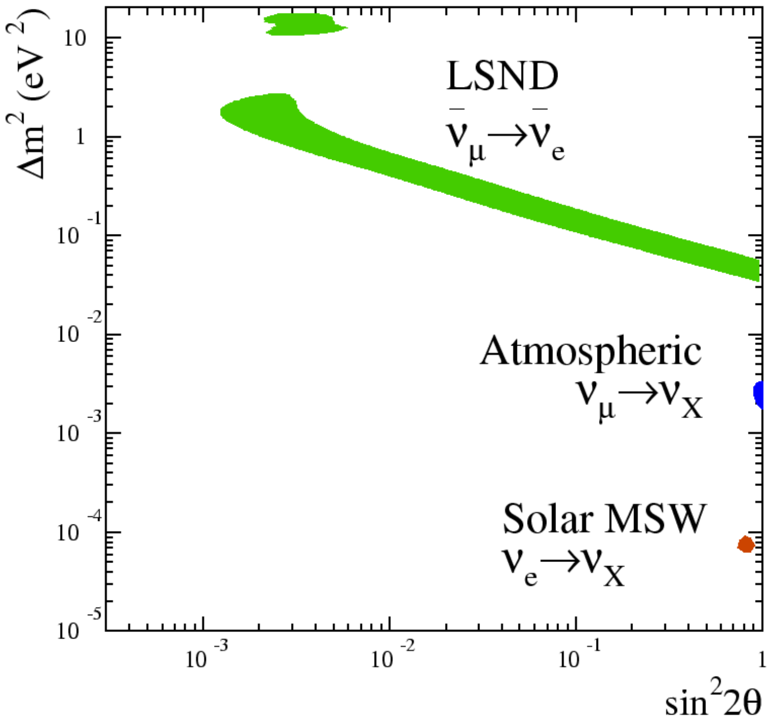
87.9 ± 22.4 ± 6.0 (3.8.σ)



L/E~30m/30MeV~1



1. LSND experiment

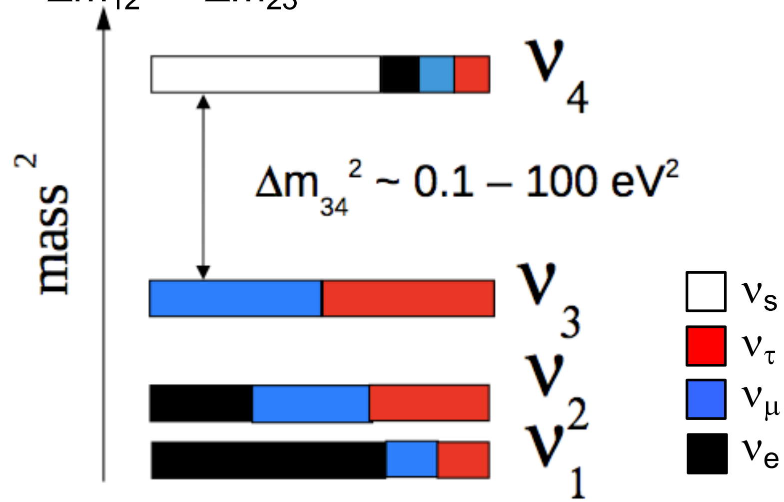


3 types of neutrino oscillations are found:

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

But we cannot have so many Δm^2!

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



LSND signal indicates 4th generation neutrino, but we know there is no additional flavour from Z-boson decay, so it must be sterile neutrino
MiniBooNE is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment

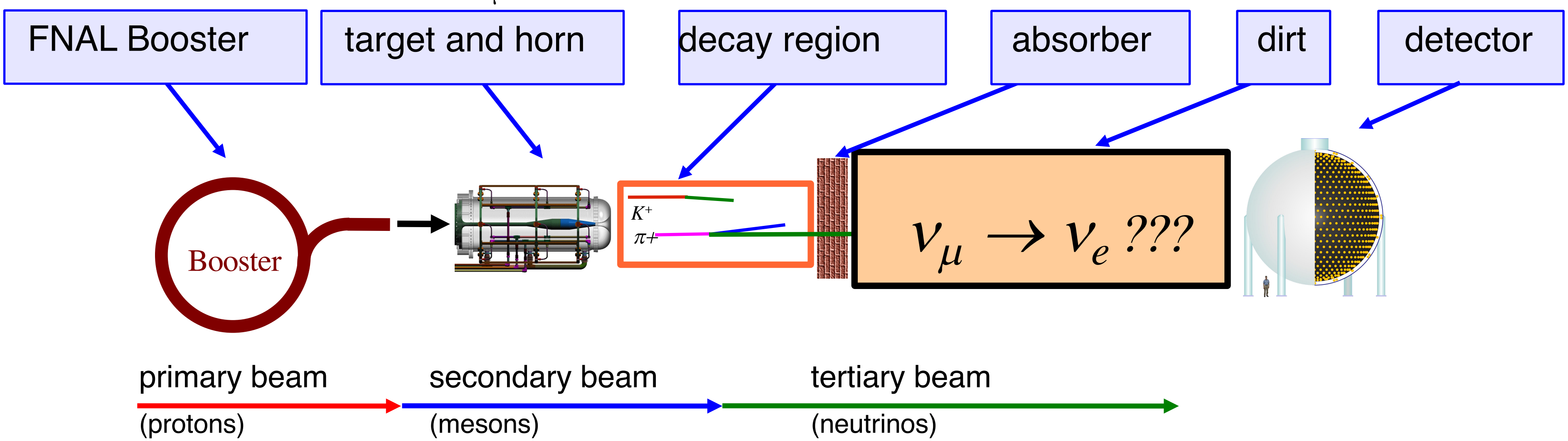
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

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

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

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



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

Queen Mary
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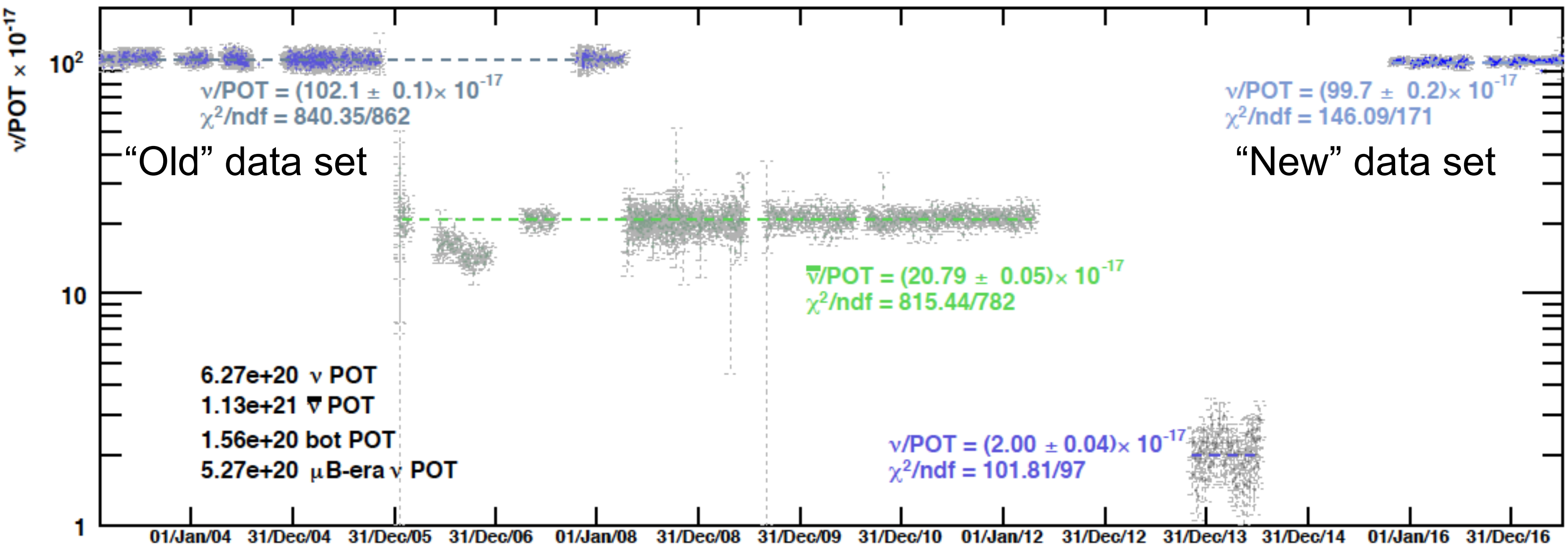
1. Detector stability

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

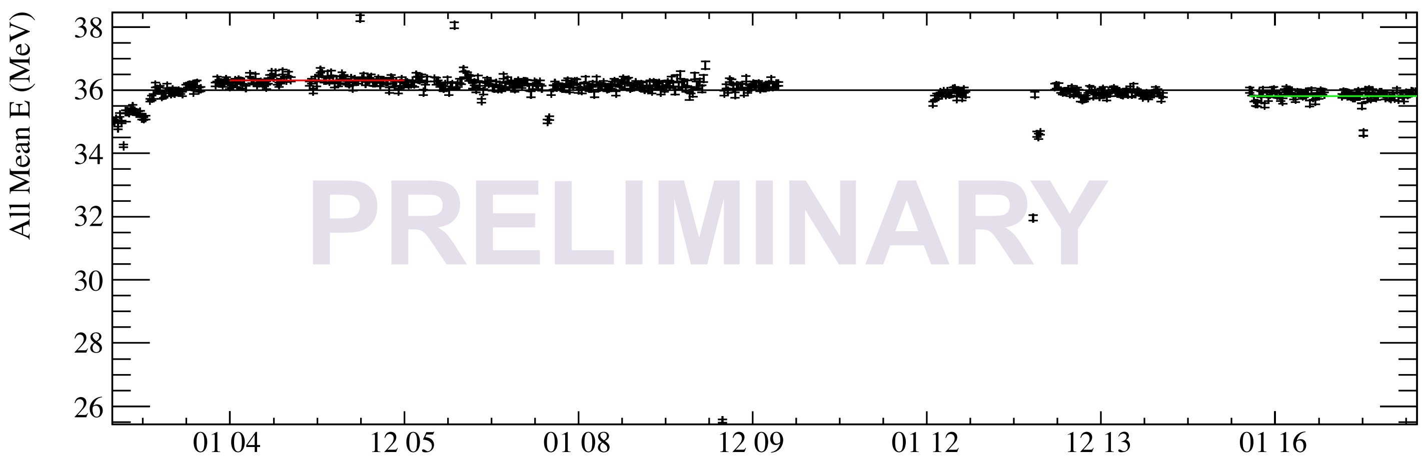
MiniBooNE, PRL118(2017)221803,
PRD98(2018)112004



1. Detector stability

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

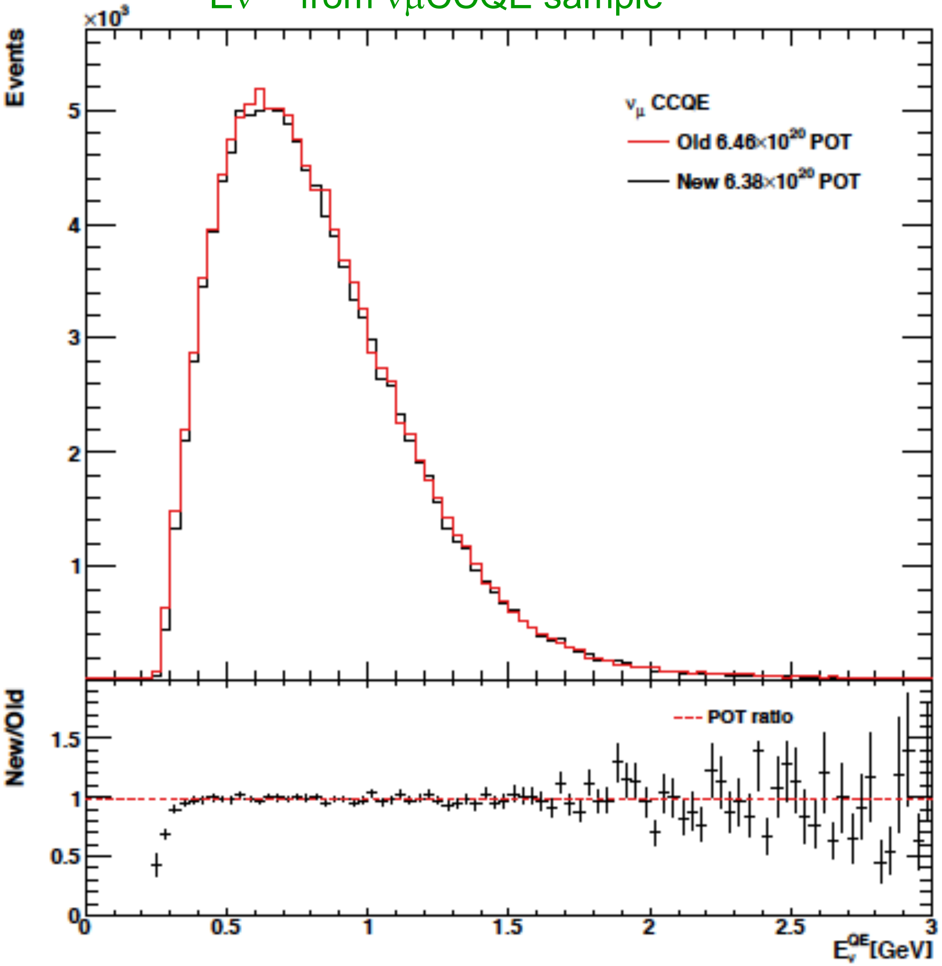
Michel electron spectrum peak



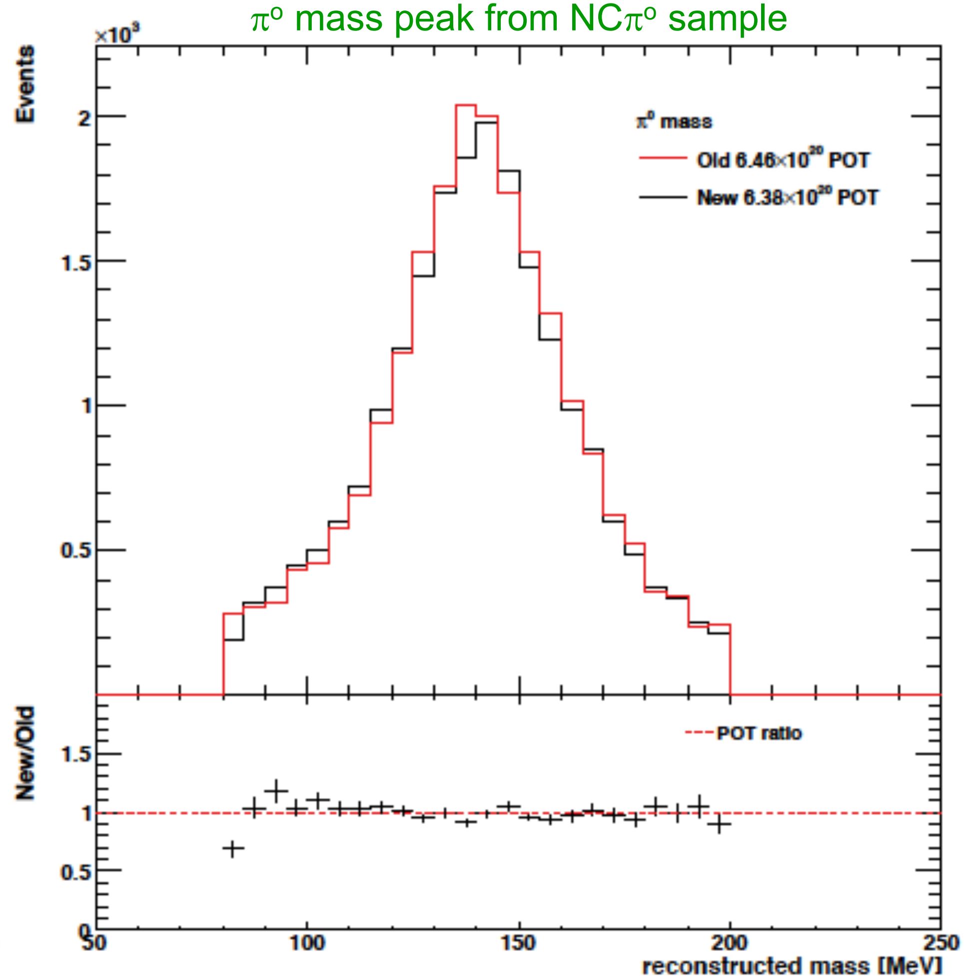
1. Detector stability

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

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



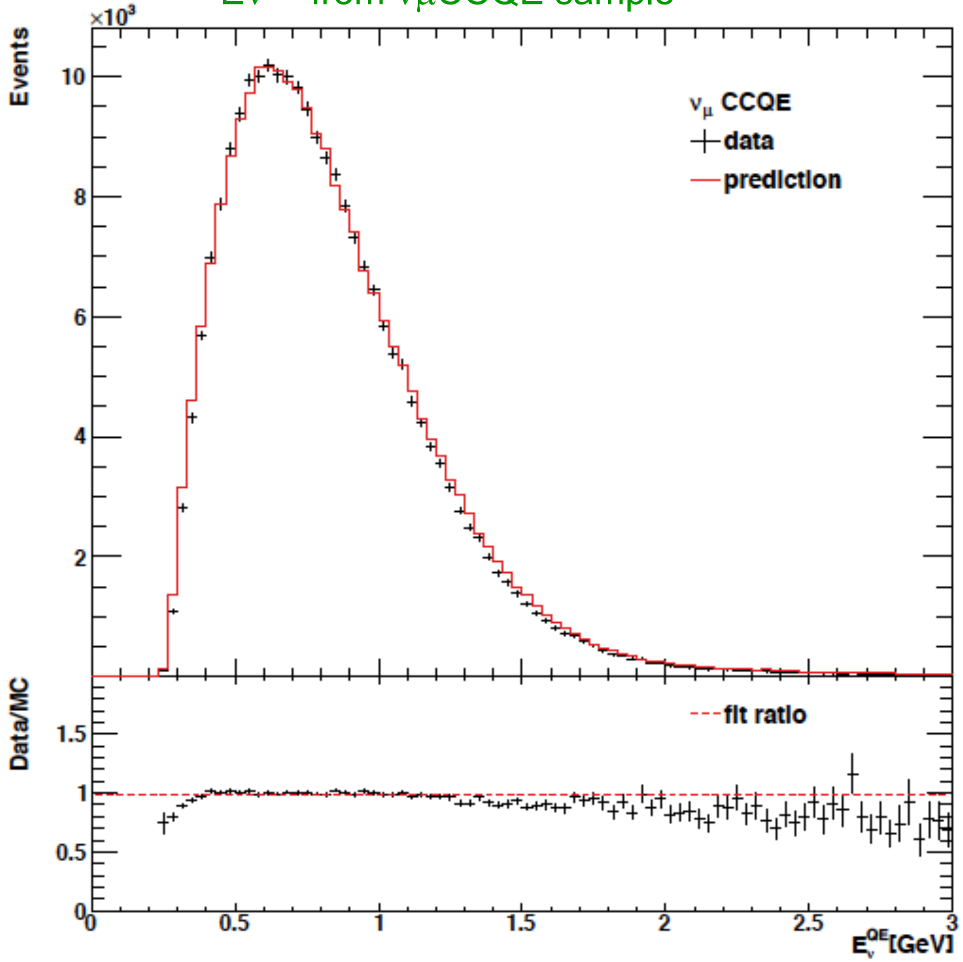
π^o mass peak from NCπ^o sample



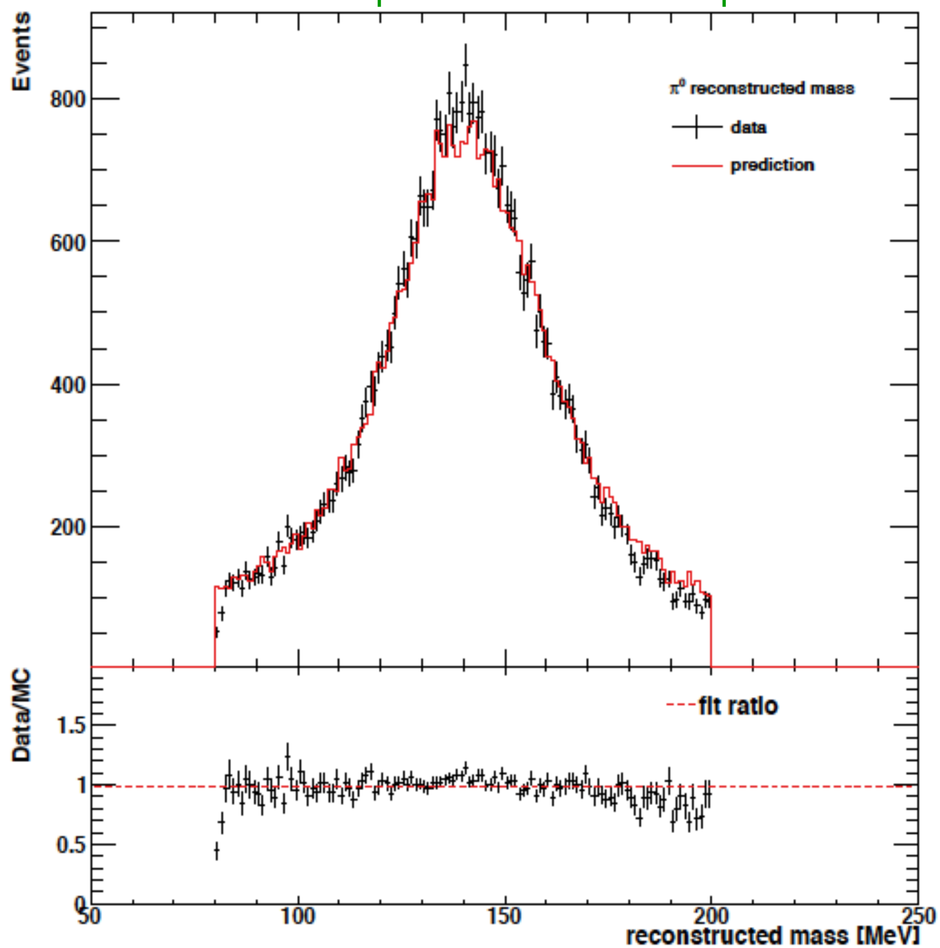
1. Data-Simulation comparison

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

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



π^o mass peak from NCπ^o sample



1. MiniBooNE neutrino experiment

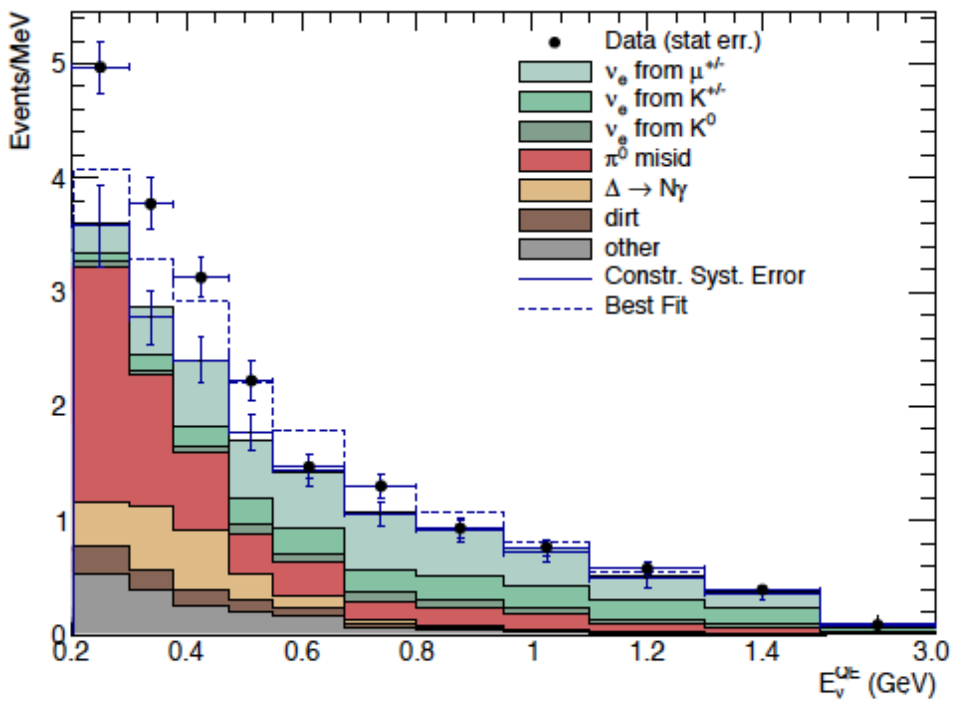
2. Oscillation candidate search

3. Discussion

2. Internal background constraints

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

	Process	Neutrino Mode	Antineutrino Mode
misID	ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
	NC π^0	501.5 ± 65.4	112.3 ± 11.5
	NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
	External Events	75.2 ± 10.9	15.3 ± 2.8
	Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
intrinsic	ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
	ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
	ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
	Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
	Unconstrained Bkgd.	1590.5	398.2
	Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
	Total Data	1959	478
	Excess	381.2 ± 85.2	79.3 ± 28.6



2. ν_e from μ-decay constraint

All backgrounds are internally constrained
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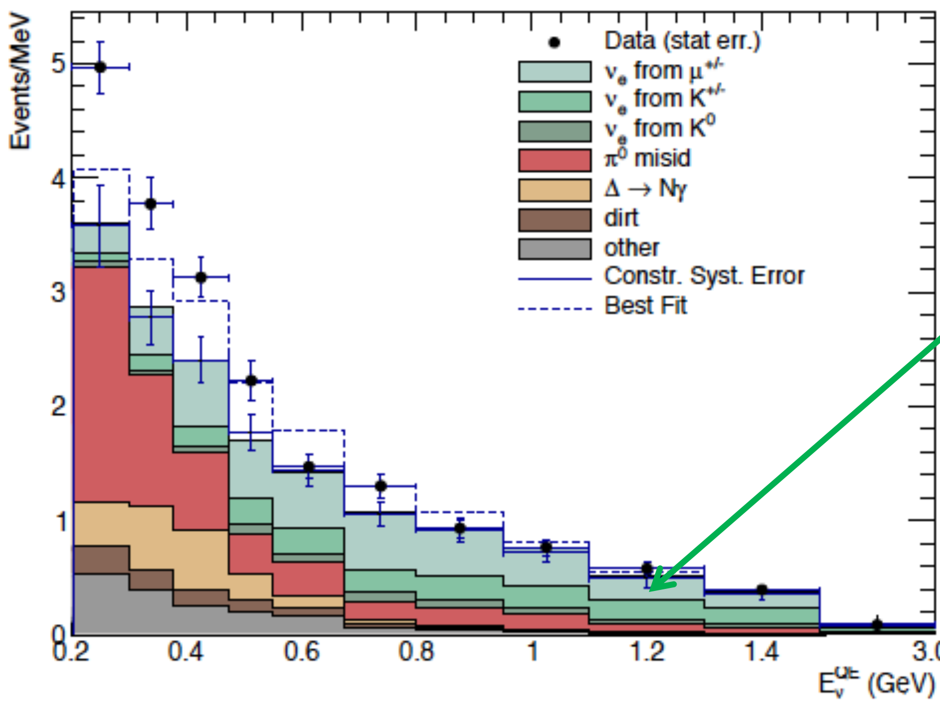

ν_e from μ decay is constrained from ν_μCCQE measurement

2. ν_e from μ-decay constraint

measured

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

guessed

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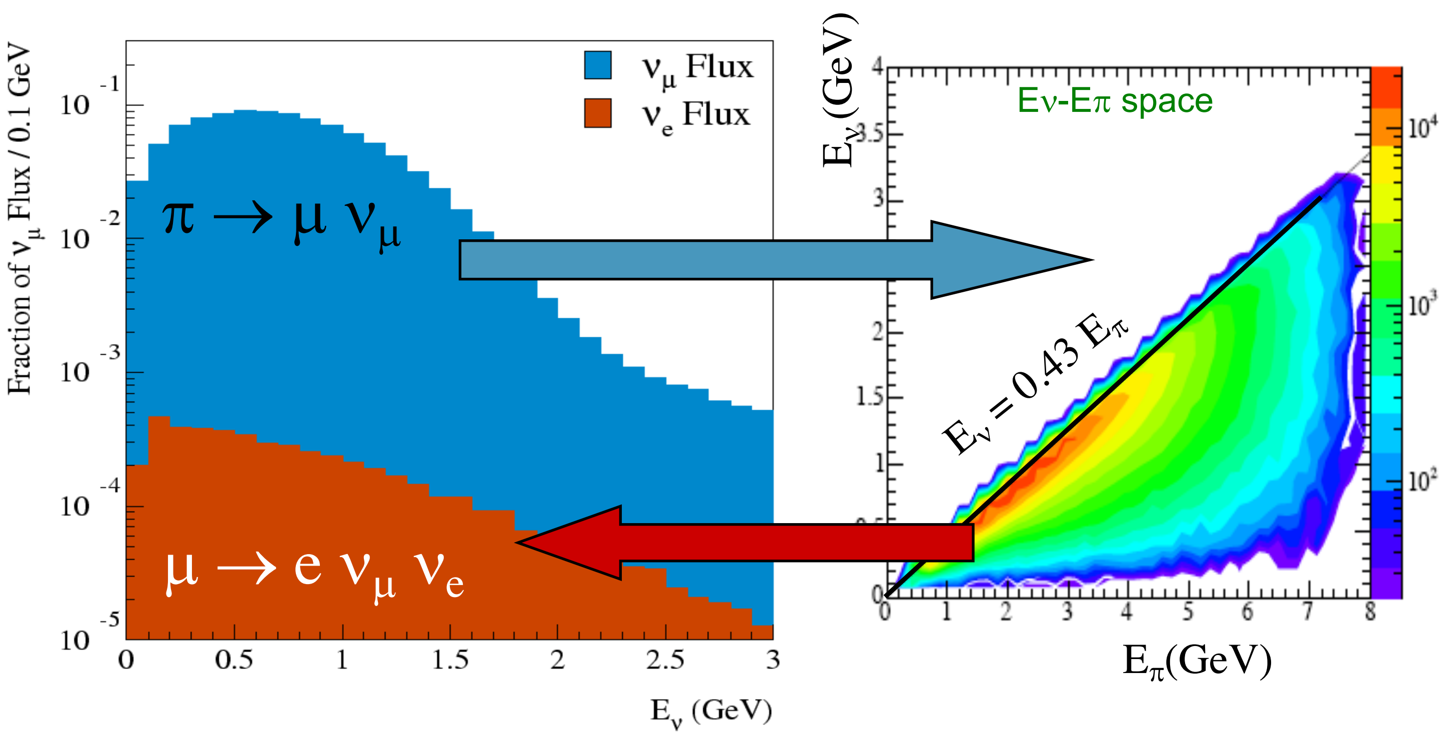
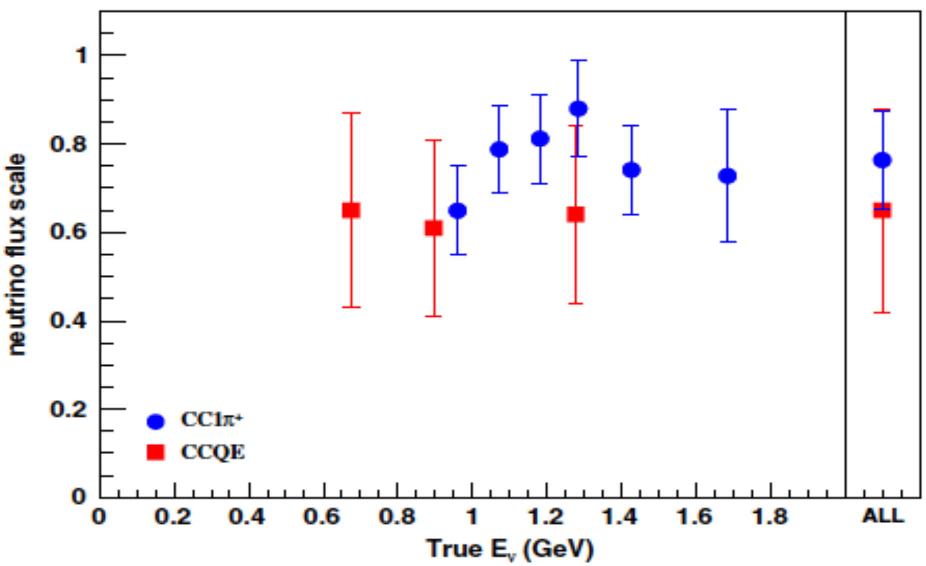
They are large background, but we have a good control of $\nu_e \& \bar{\nu}_e$ background by joint $\nu_e \& \nu_\mu (\bar{\nu}_e \& \bar{\nu}_\mu)$ fit for oscillation search.



2. 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%



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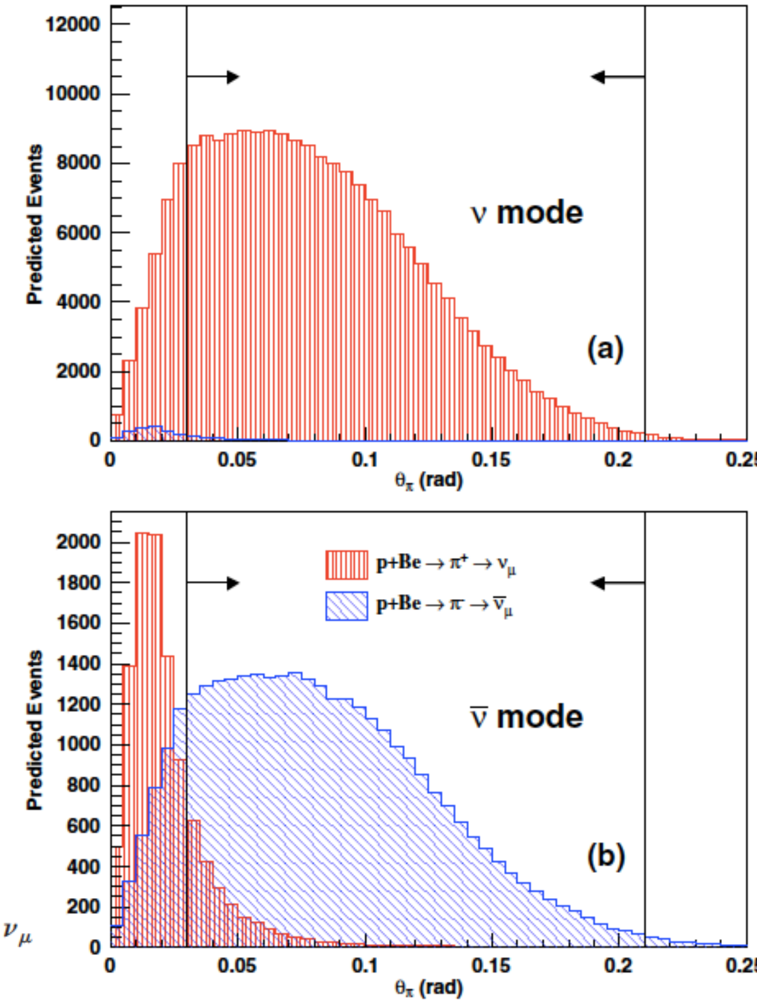

Michel electron counting is sensitive to ν_μ contamination in $\bar{\nu}_\mu$ beam

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

2. ν_e from μ-decay constraint

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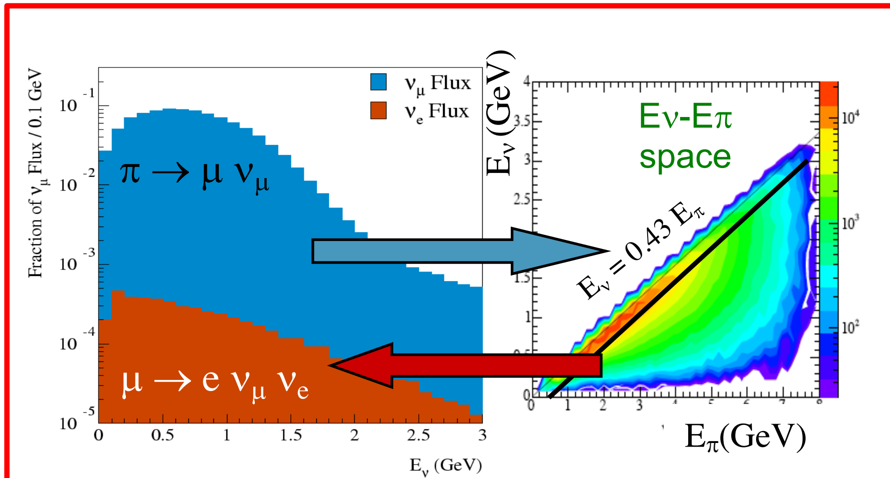

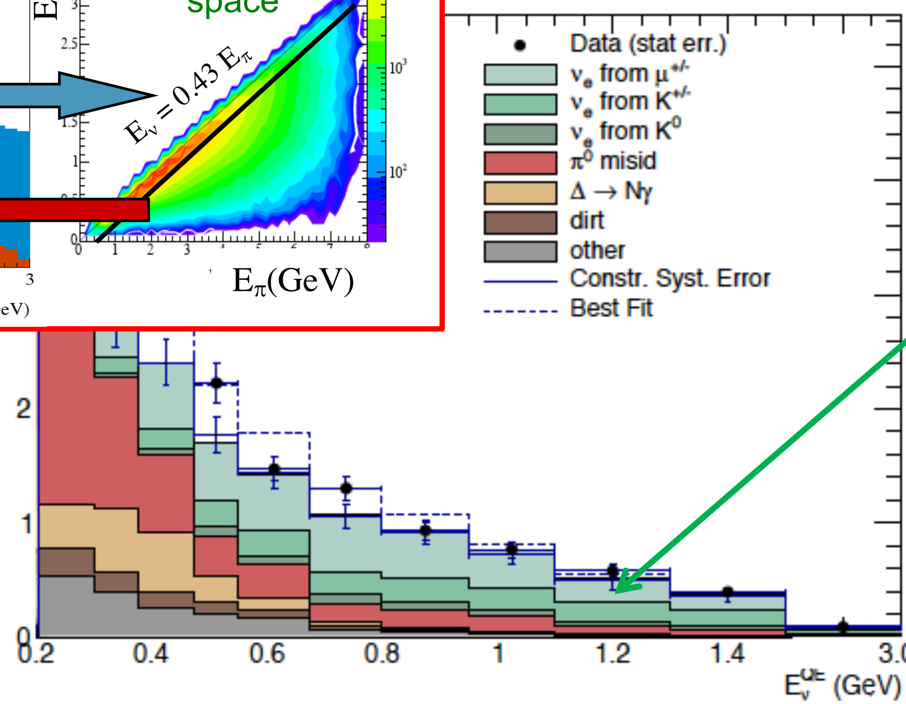

ν_e from μ decay is constrained from ν_μCCQE measurement

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2. ν_e from K^+-decay 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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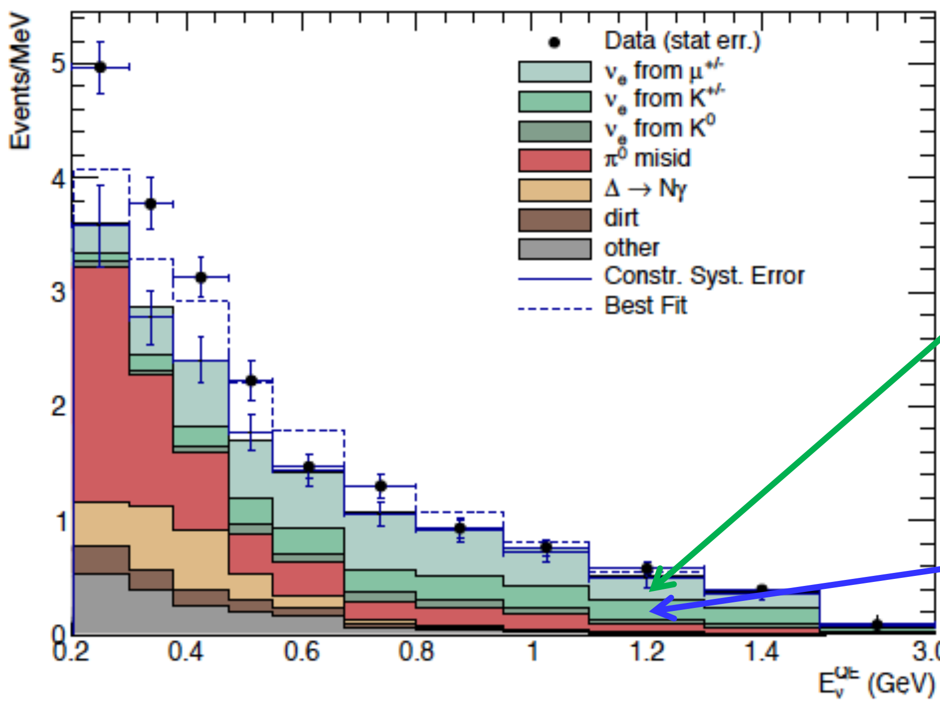
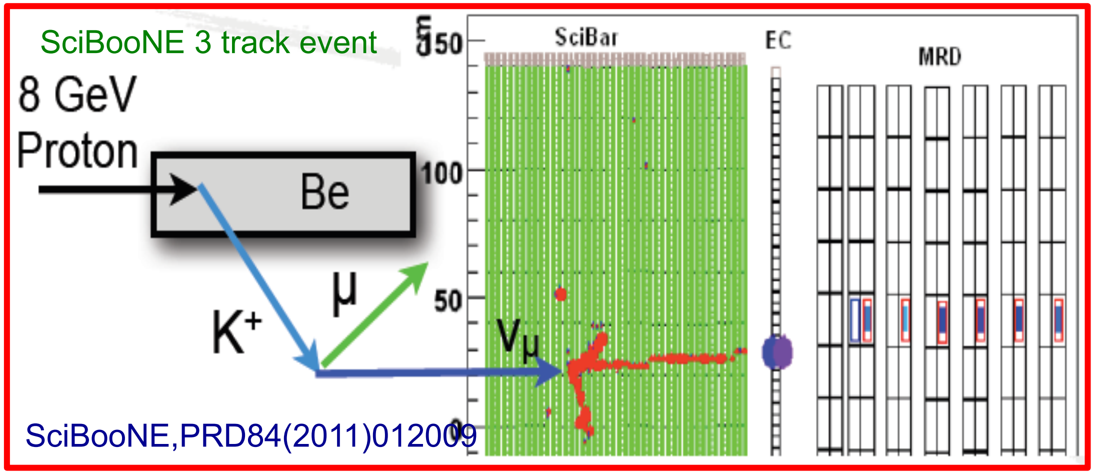


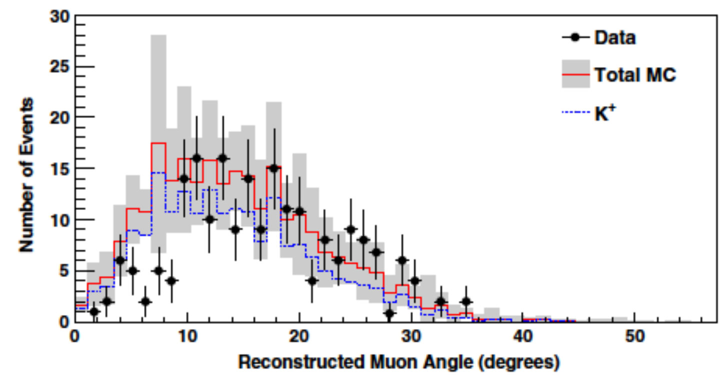
ν_e from μ decay is constrained from ν_μCCQE measurement

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

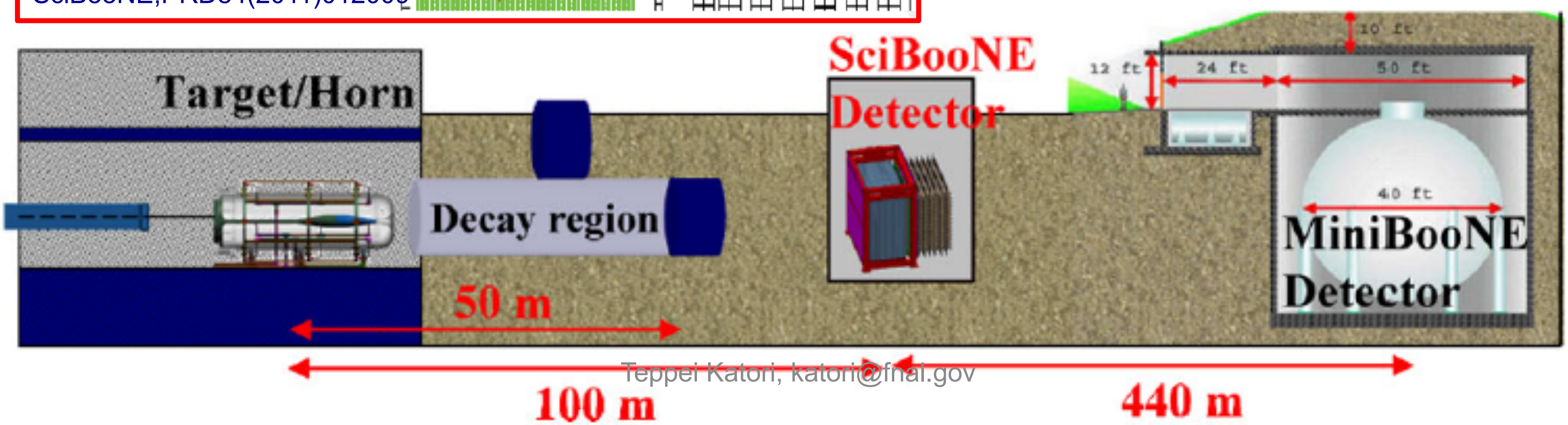
2. ν_e from K^+-decay constraint

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





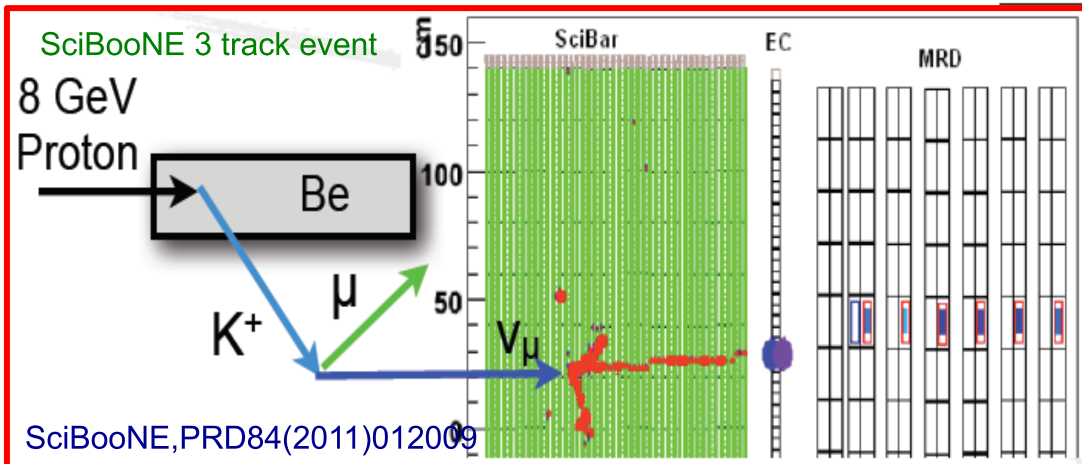
(c) 3-Track Sample

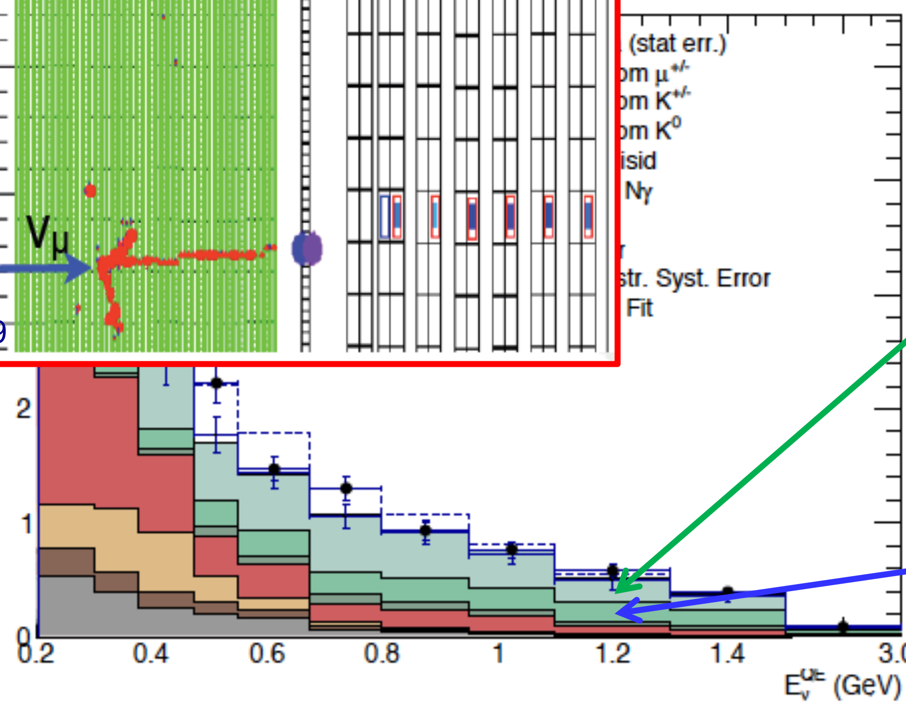


2. ν_e from K^+-decay constraint

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

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6





ν_e from μ decay is constrained from ν_μCCQE measurement

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

2. ν_e from K+-decay constraint

All backgrounds are internally constrained
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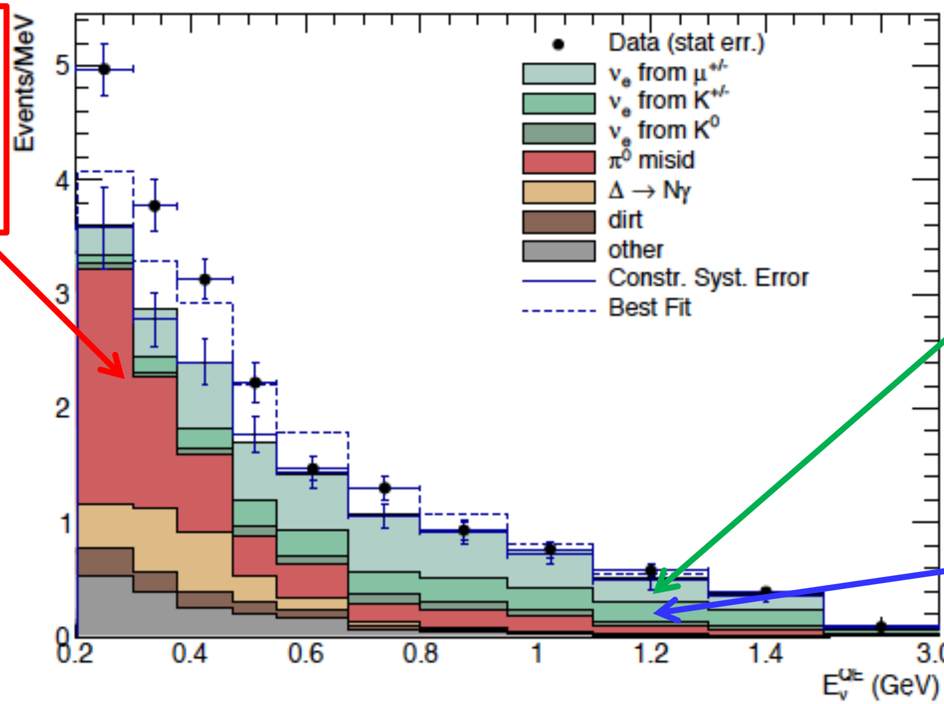
Asymmetric π^o decay is constrained from measured $CC\pi^o$ rate ($\pi^o \rightarrow \gamma$)



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

2. γ from π^o constraint

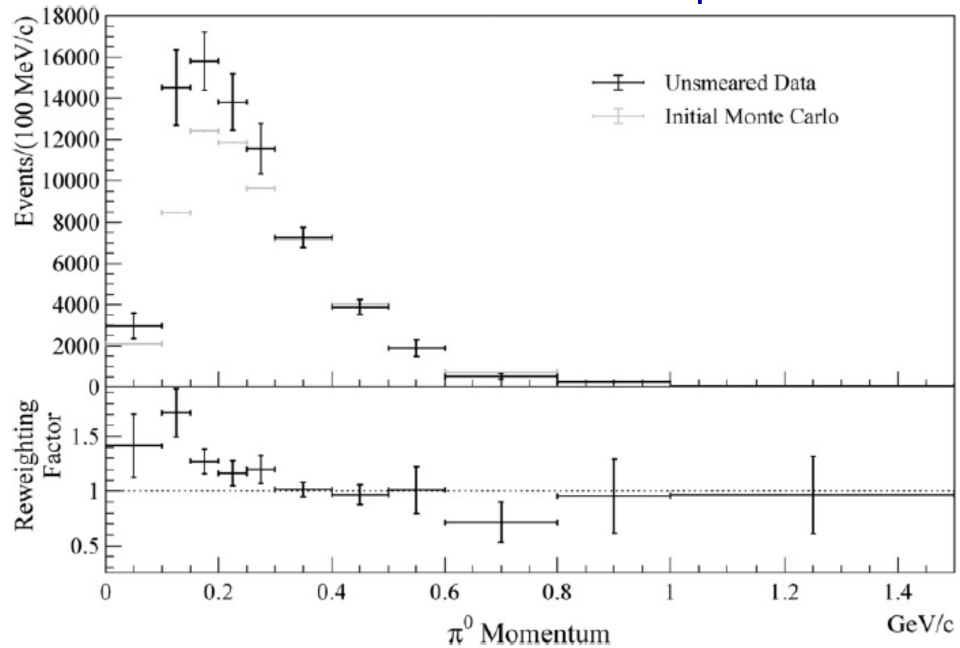
$\pi^o \rightarrow \gamma\gamma$
 - not background, we can measure

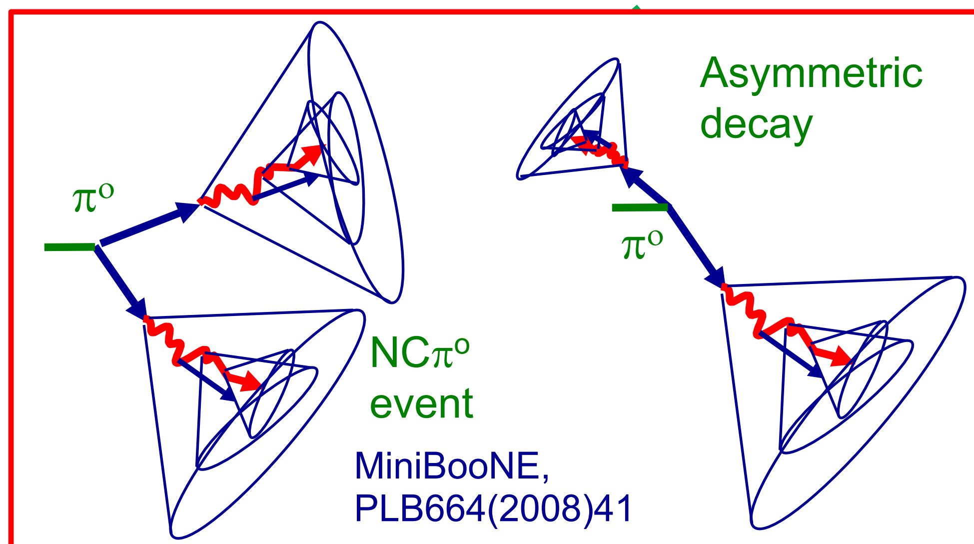
$\pi^o \rightarrow \gamma$
 - misID background, we cannot measure

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. γ from π^o constraint

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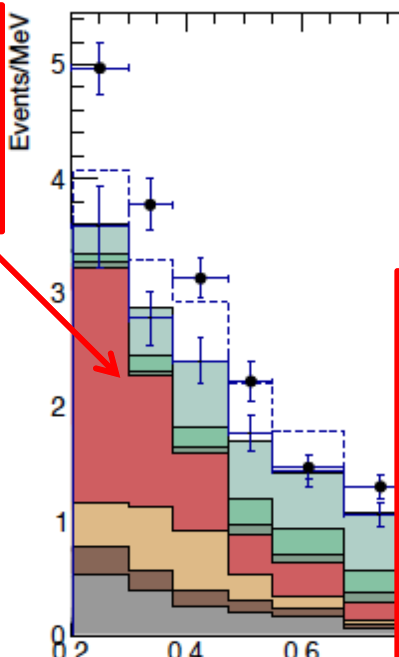
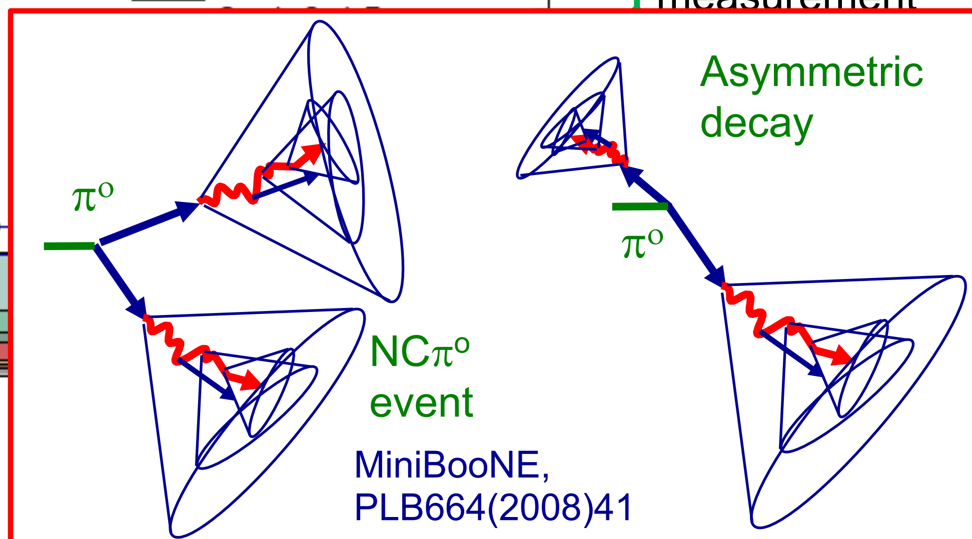
Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)



ν_e from μ decay is constrained from ν_μCCQE measurement



2. NCγ constraint

All backgrounds are internally constrained
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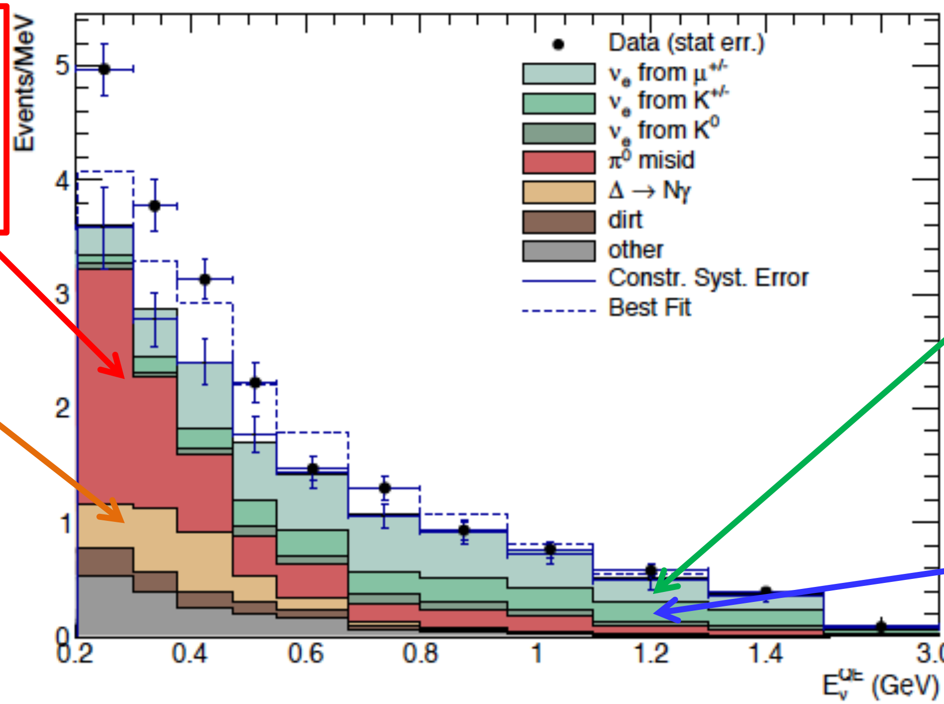
Asymmetric π^o decay is constrained from measured $CC\pi^o$ rate ($\pi^o \rightarrow \gamma$)

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

2. NCγ constraint

Process	Neutrino Mode	Antineutrino Mode
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All backgrounds are internally constrained
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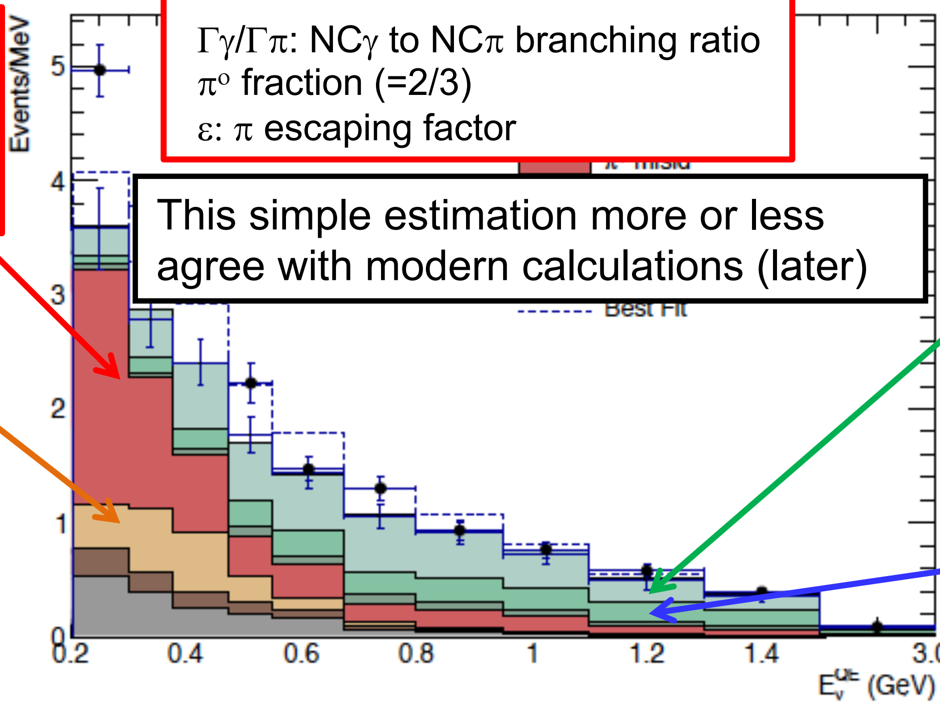
$$\frac{N(\Delta \to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

Γγ/Γπ: NCγ to NCπ branching ratio
πᵒ 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

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

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

2. External γ constraint

All backgrounds are internally constrained

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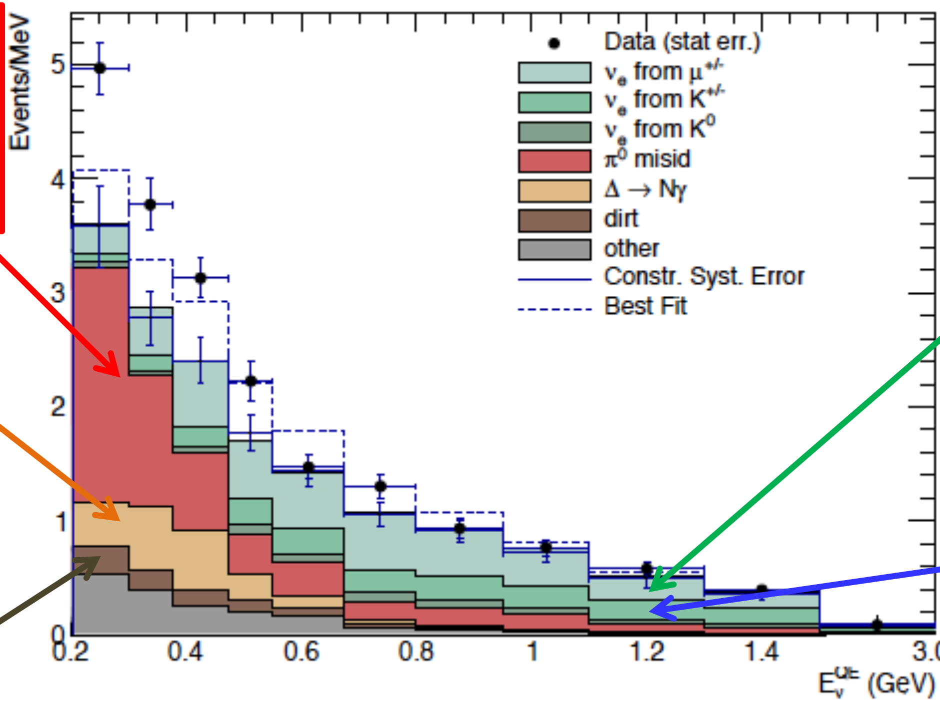
Δ resonance rate is constrained from measured $NC\pi^o$ rate

dirt rate is measured from dirt data sample



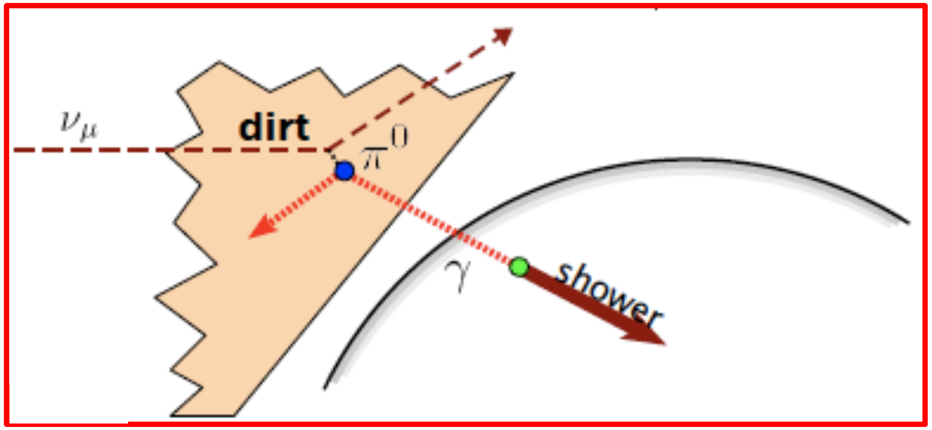
ν_e from μ decay is constrained from ν_μCCQE measurement

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

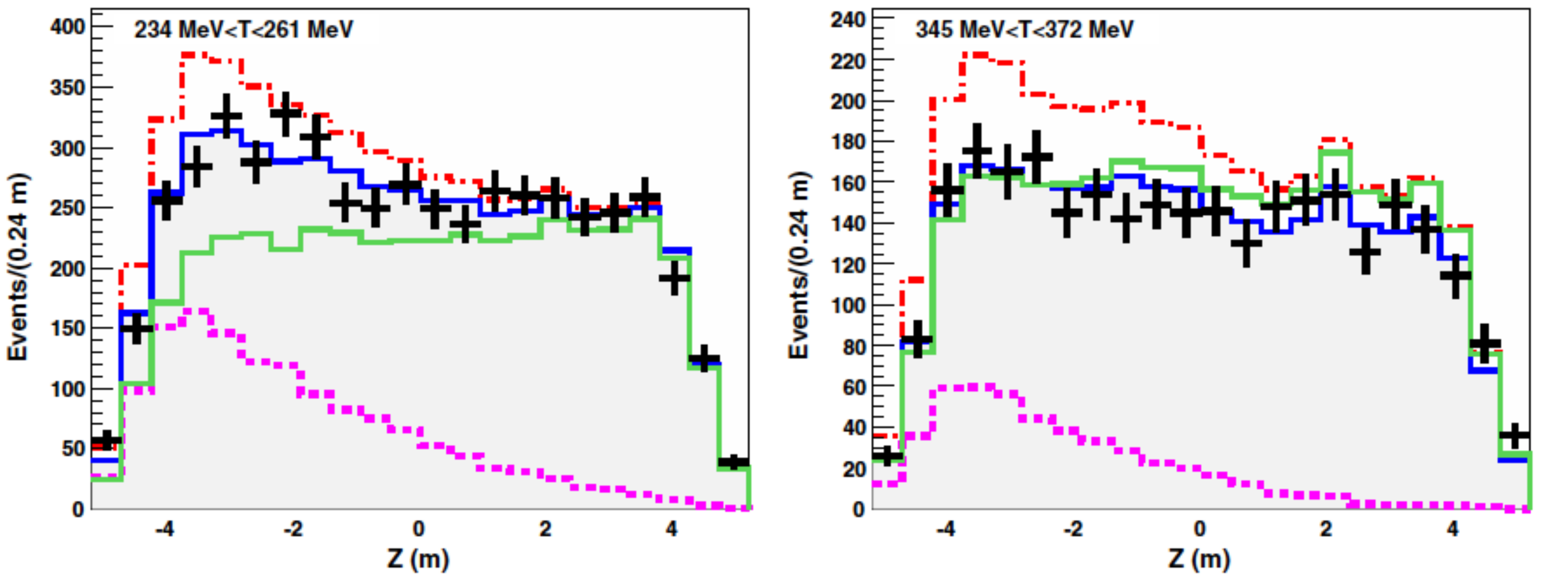
2. External γ constraint

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



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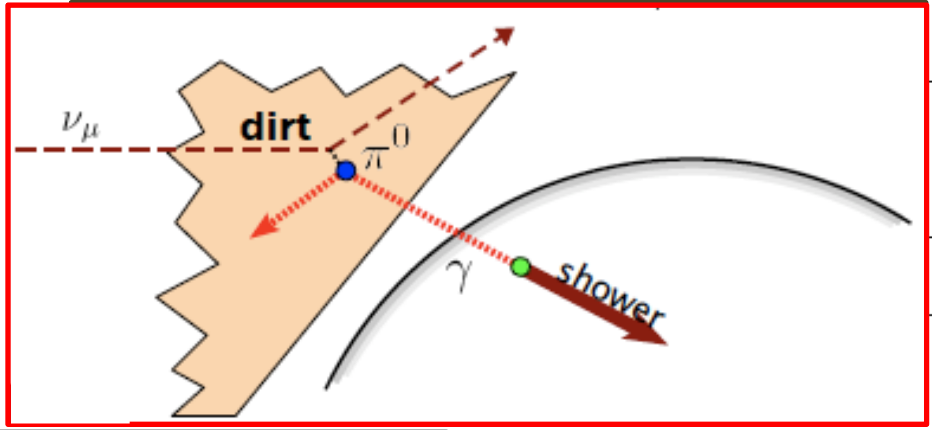

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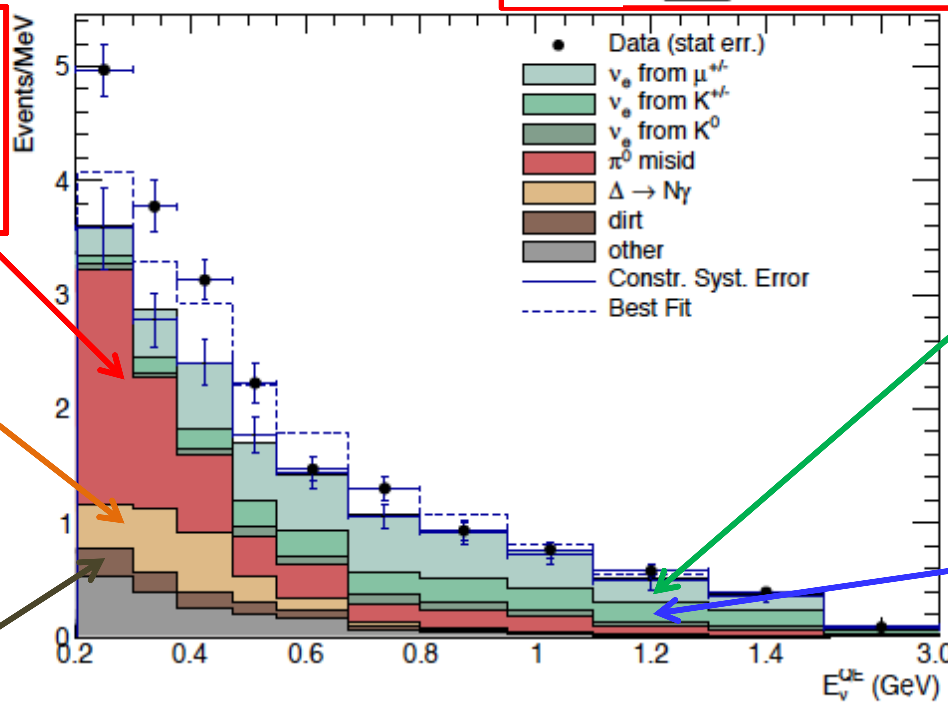

ν_e from μ decay is constrained from ν_μCCQE measurement

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2. Internal background constraints

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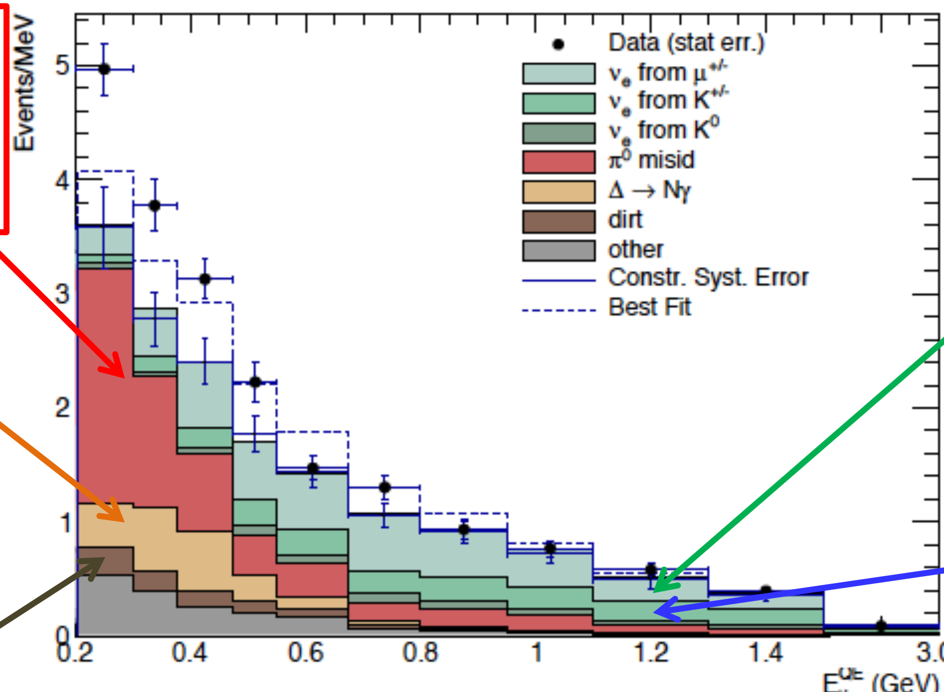

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ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

Queen Mary University of London

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

1. MiniBooNE neutrino experiment

2. Oscillation candidate search

3. Discussion

3. Oscillation candidate event excess

200 < EνQE < 1250 MeV

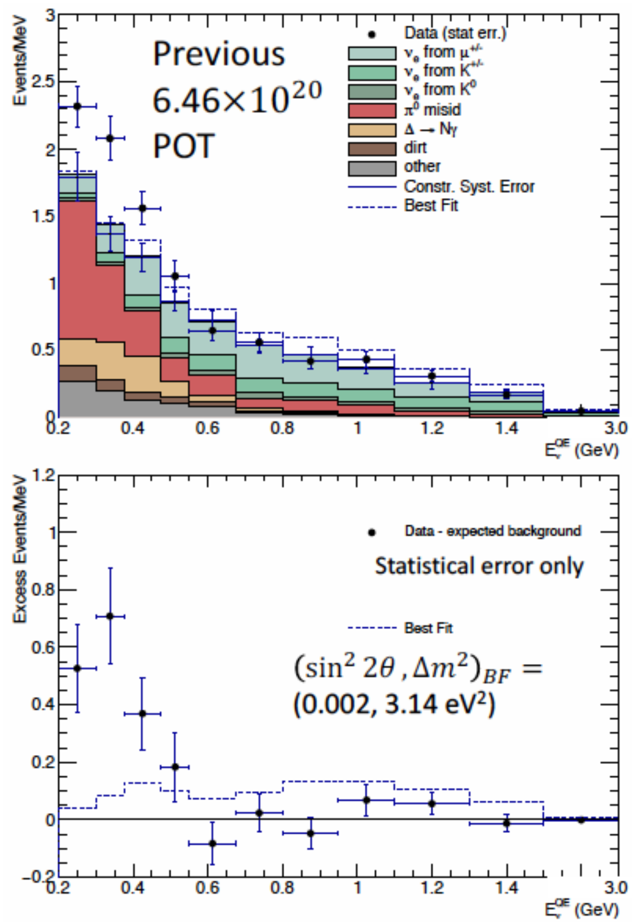
- neutrino mode: Data = 1959 events

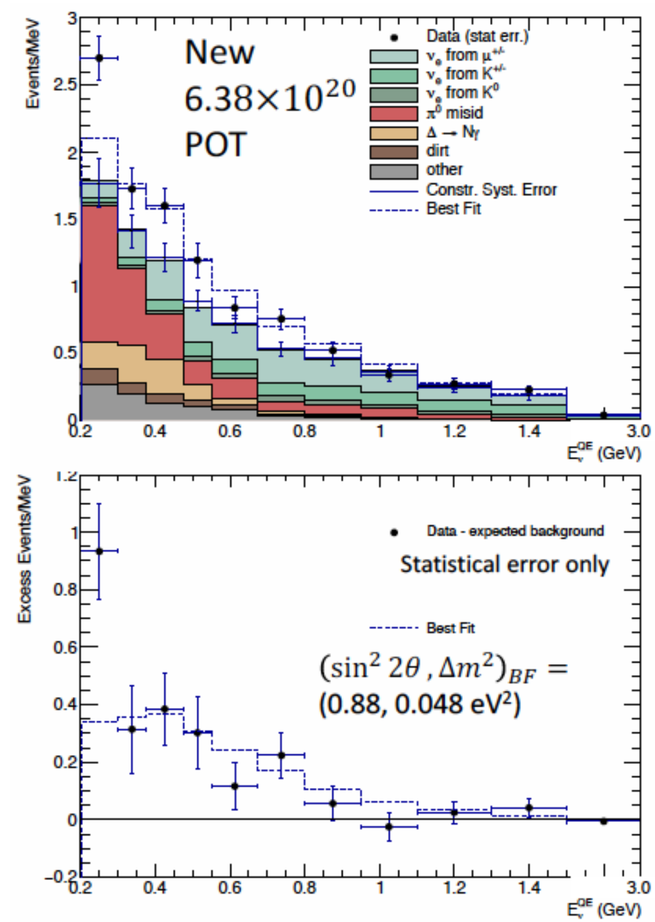
Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)

Old data (50.3%)
162.0 event excess

New data (49.7%)
219.2 event excess

KS test suggests they are compatible
P(KS)=76%





Queen Mary
University of London

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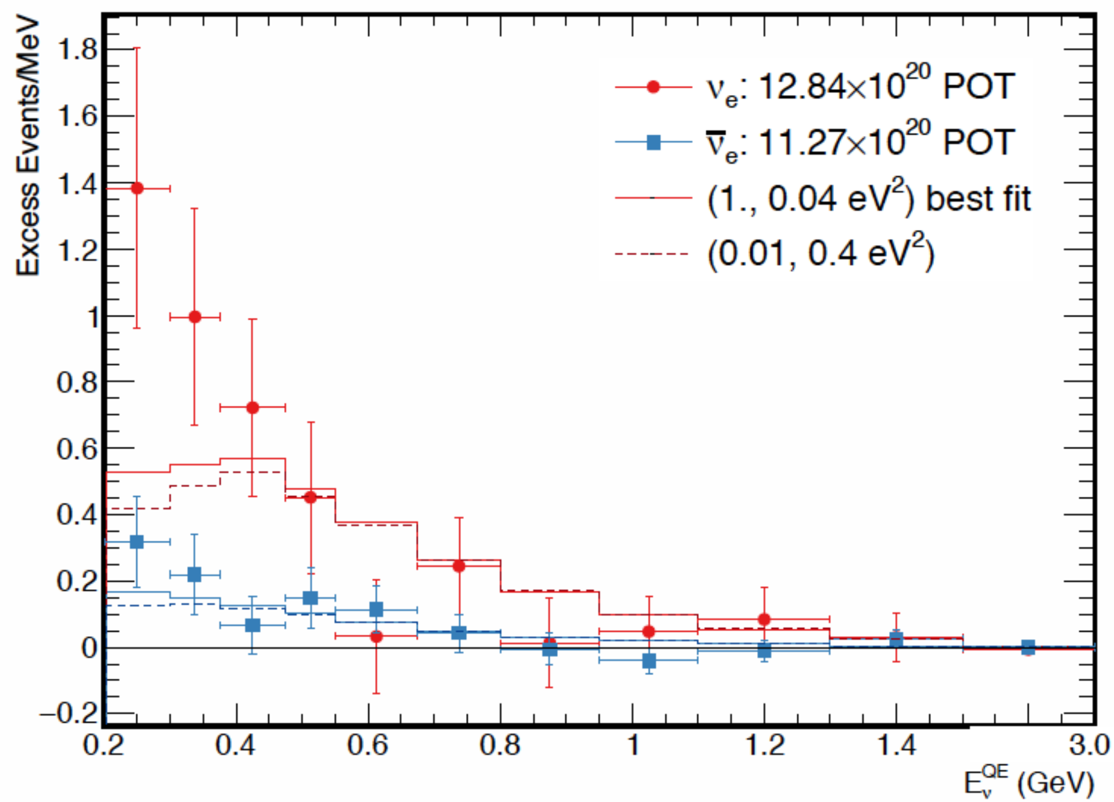
Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)

- antineutrino mode: Data = 478 events

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



Detler et al., JHEP08(2018)010

3. Sterile neutrino hypothesis?

200 < EνQE < 1250 MeV

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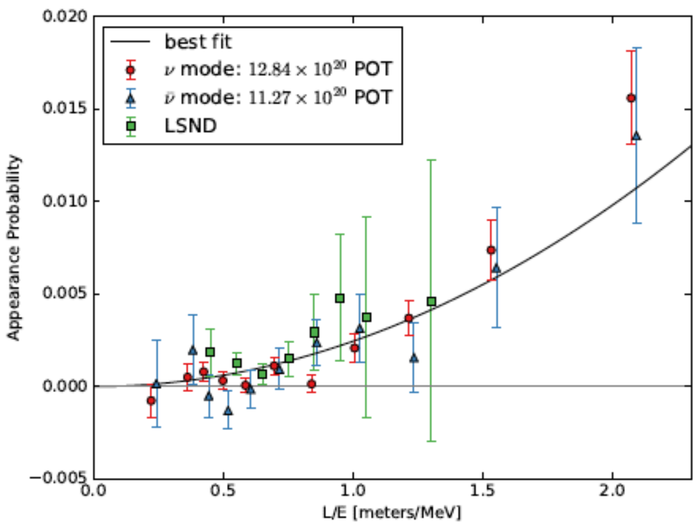
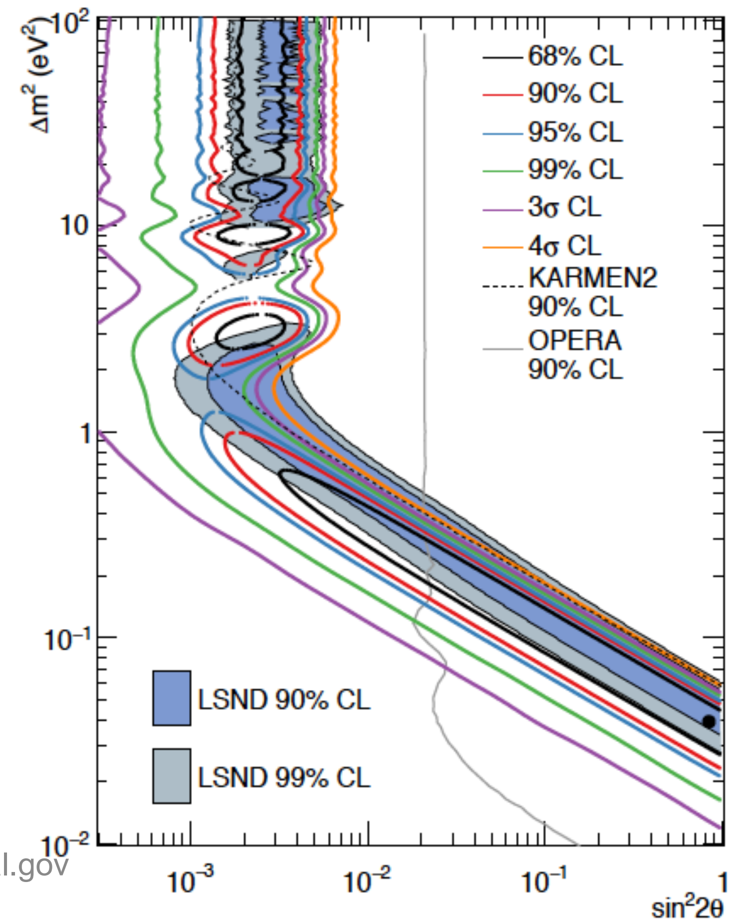
Compatible with LSND excess within 2-neutrino oscillation hypothesis





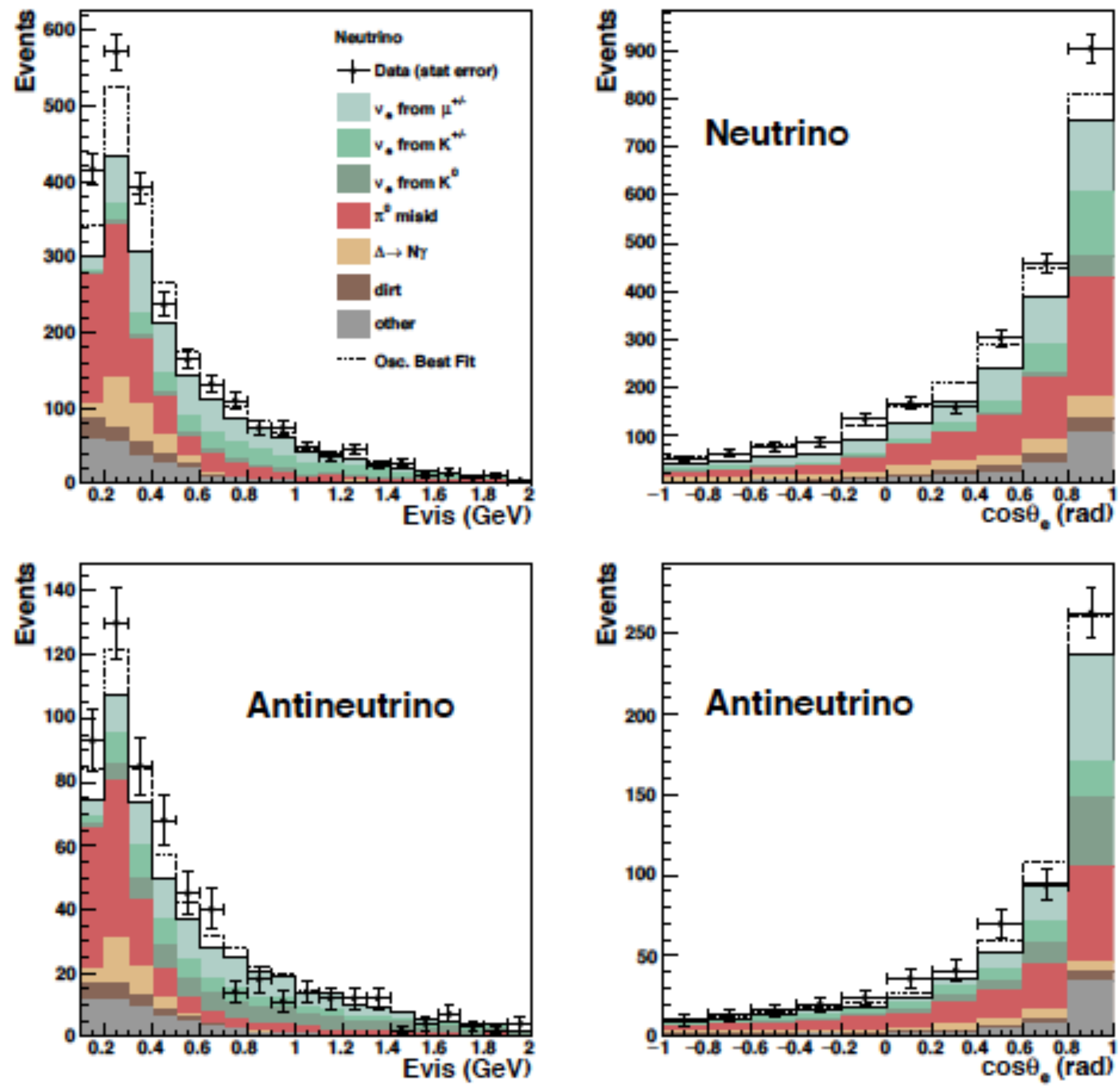
However, appearance and disappearance data have a strong tension (Maltoni, Neutrino 2018)

3. Alternative photon production models?

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

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

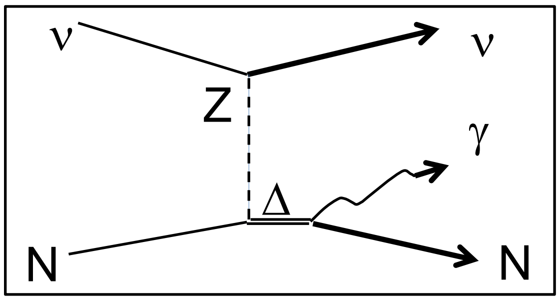
or BSM physics?
- BSM γ production process?
- BSM e-scattering process?
- BSM oscillation physics?

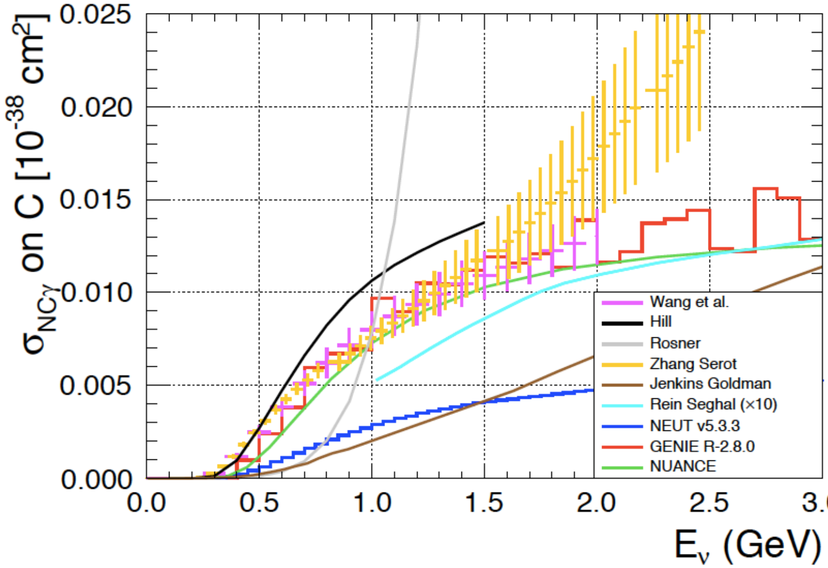


3. Neutrino NC single photon production

A lot of new calculations

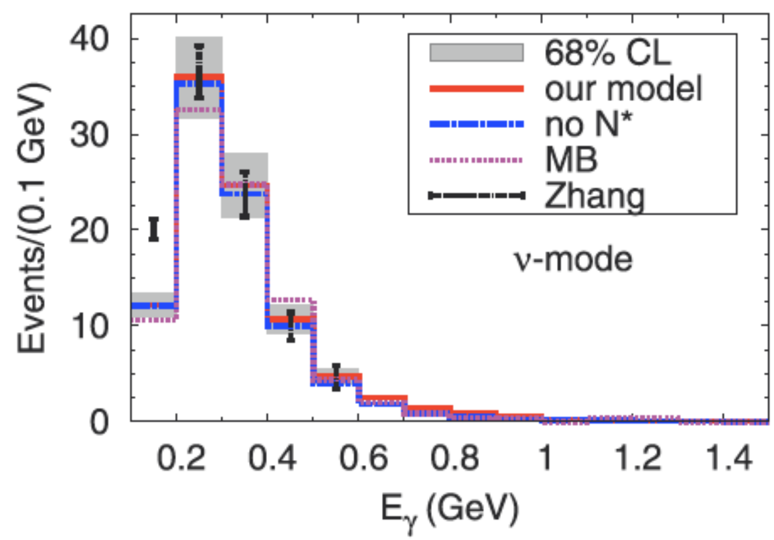
- Δ-radiative decay with nuclear corrections.
- all theoretical models and generators more or less agree in MiniBooNE energy region.





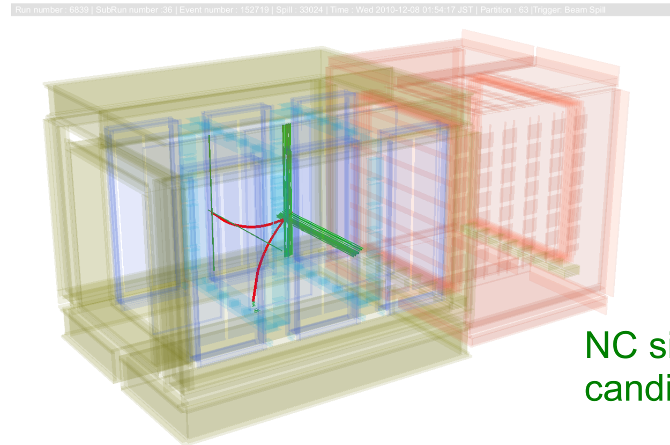
NC γ production prediction for MiniBooNE

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



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

3. Neutrino NC single photon production

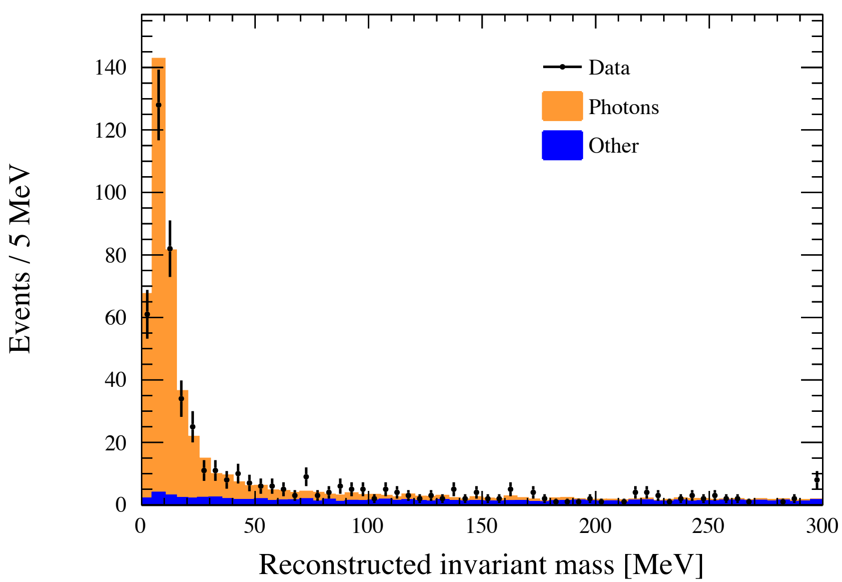


NC single gamma candidate event

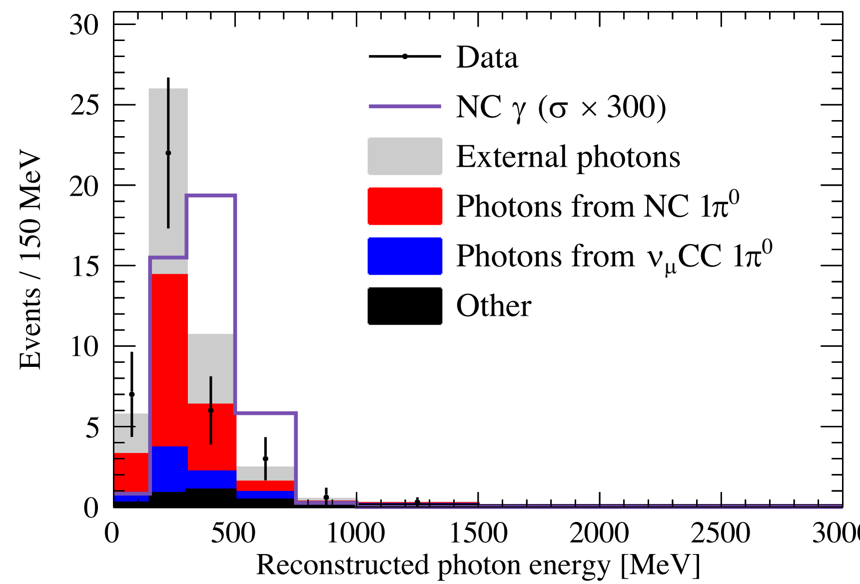
T2K near detector

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

Photon sample



NC single gamma sample



T2K, ArXiV:1902.03848
MicroBooNE, public note 1041 (2018)

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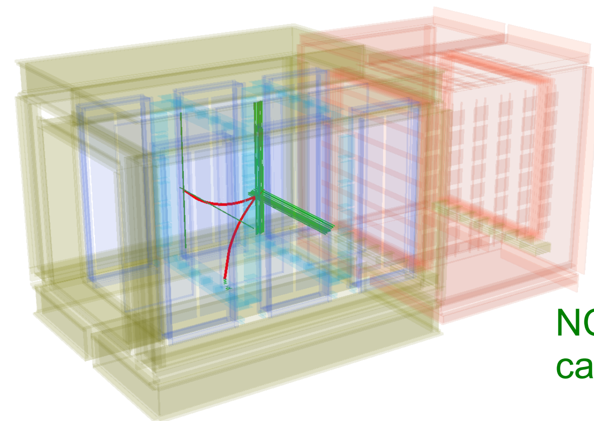


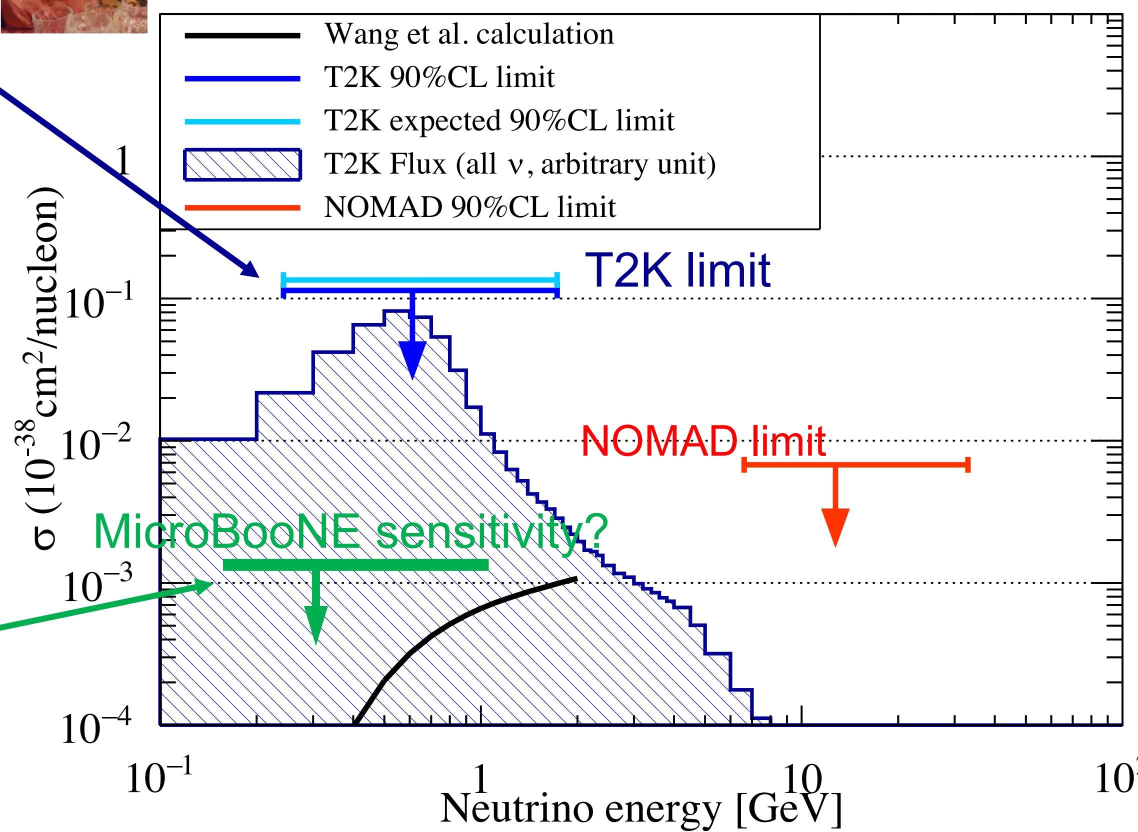
NC single gamma candidate event

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

MicroBooNE

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

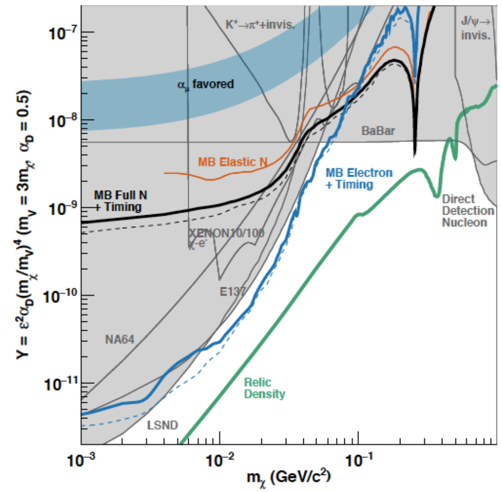
→ Good chance to measure the first positive signal of this channel.



Bobby Murrell
Manchester
(MicroBooNE)

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

3. BSM electron scattering



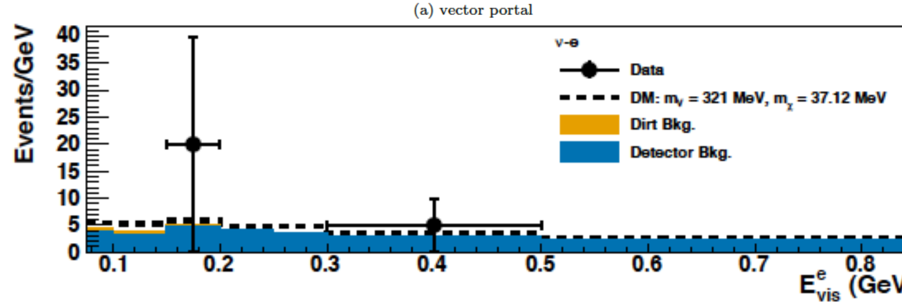
(a) vector portal

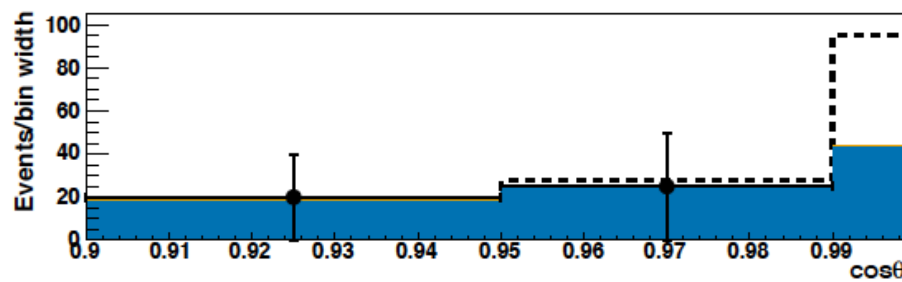
Dark matter particle - electron scattering

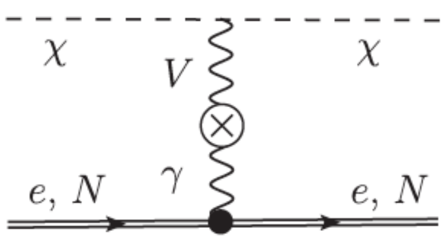
New particles created in the beam dump can scatter electrons in the detector.

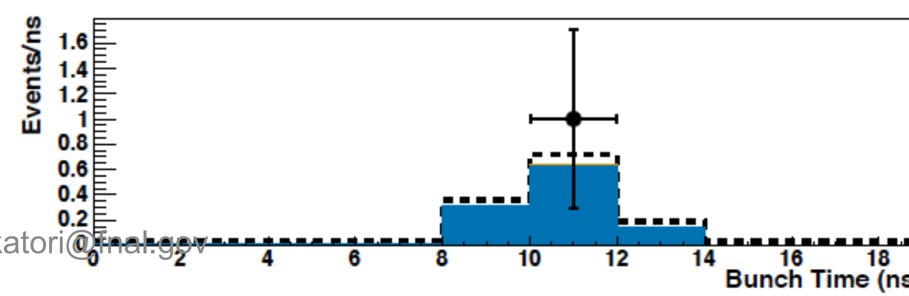
However, MiniBooNE beam dump mode data shows no excess.

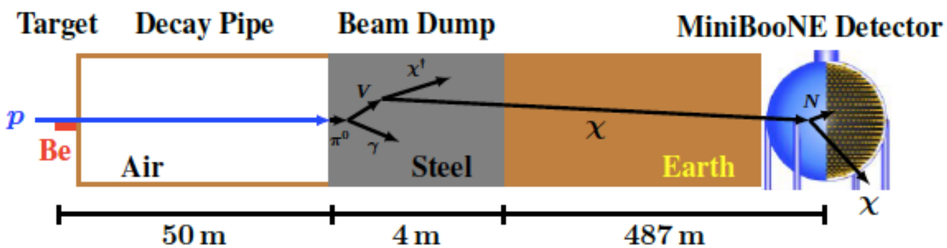
This result set limits on beam dump produced new particle – electron scattering interpretation.





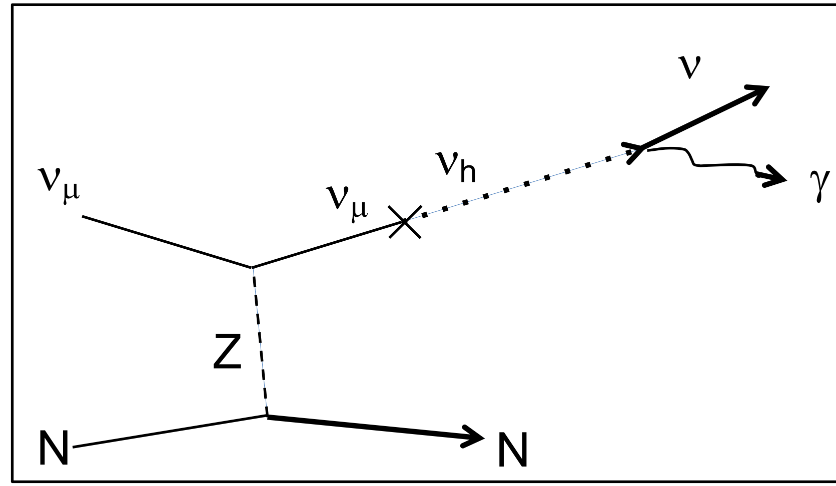






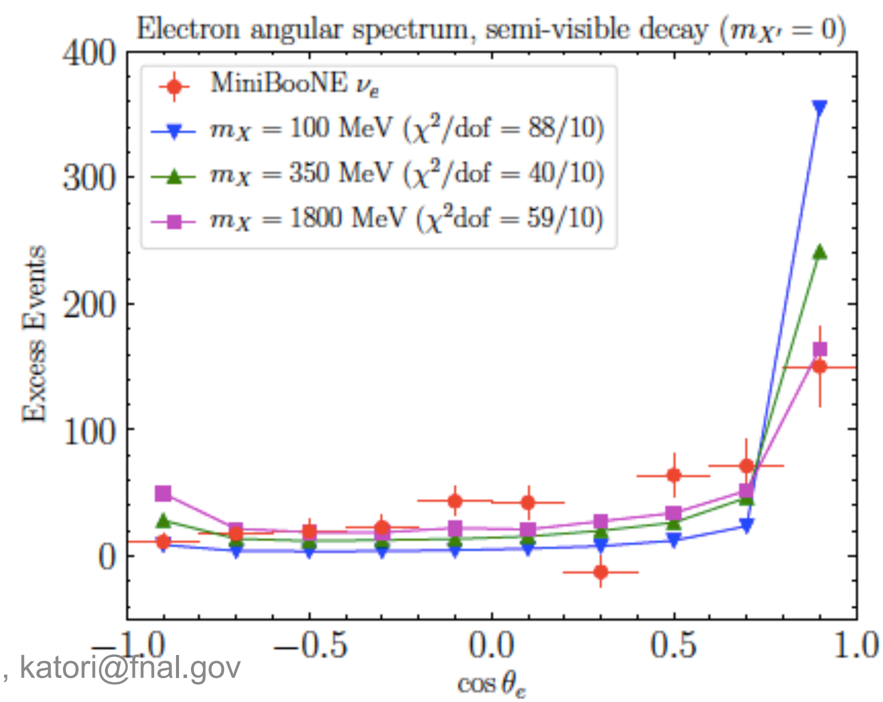
3. BSM photon production

heavy neutrino decay



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

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



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

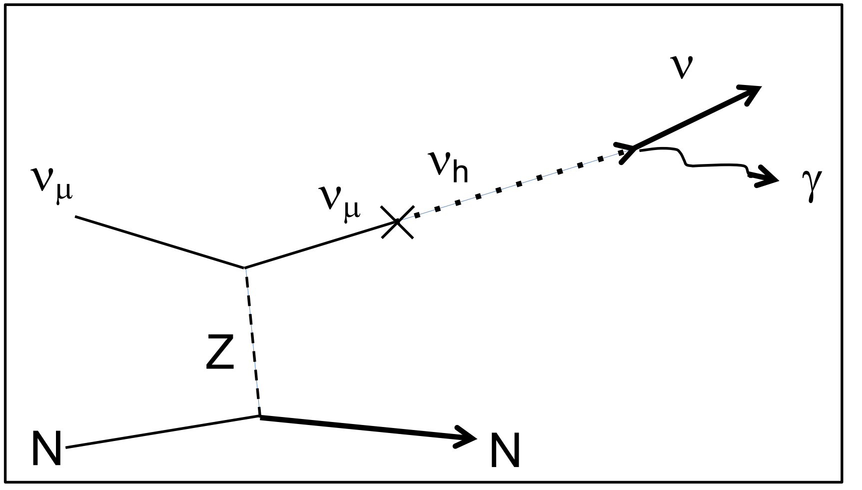
3. BSM e+e- production

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

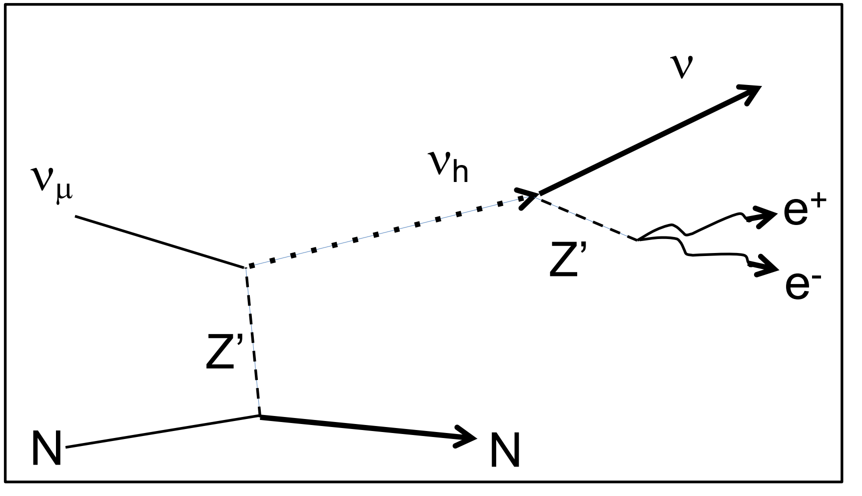
These models have problems because they cannot reproduce the angular distribution of oscillation candidates.

Z' decay model
A new class of models predict a heavy neutrino and a neutral heavy boson decaying to e+e-. These models explain both energy and angular distributions of MiniBooNE oscillation candidate data.

heavy neutrino decay



Z' decay



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

3. BSM neutrino oscillation model

Lorentz violation as alternative neutrino oscillation model

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

LV-motivated effective Hamiltonian

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

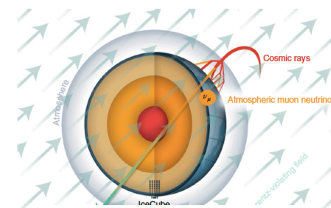
where $A(E) = m^2/2E$, $B(E) = \mathring{a}E^2$, and $C(E) = \mathring{c}E^5$

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

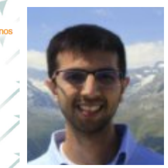
Test of Lorentz violation with neutrinos

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

IceCube

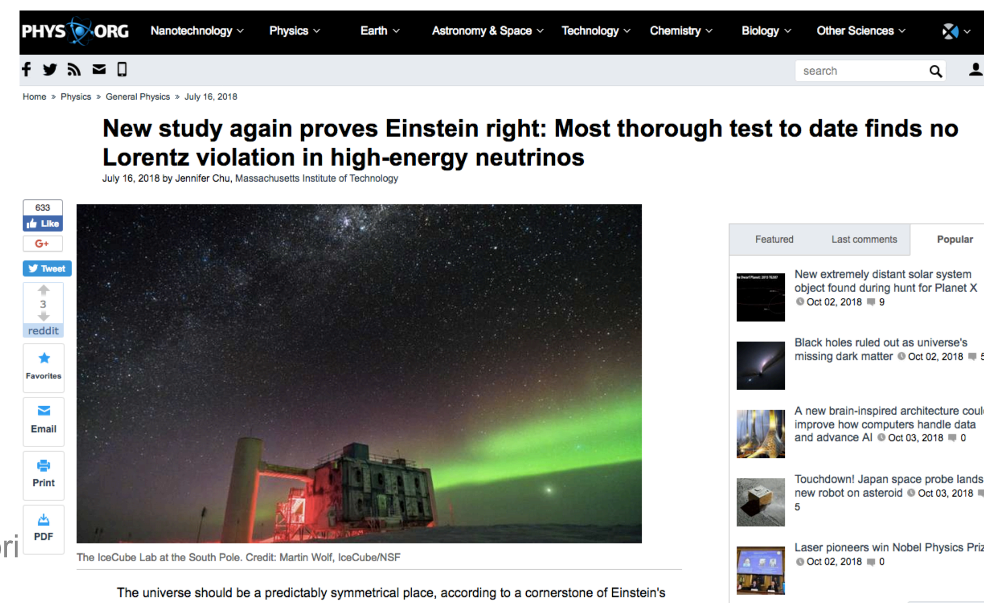


Nature Physics 14(2018)961



Shivesh Mandalia (Queen Mary)

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



Queen Mary
University of London

Future of MiniBooNE

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

Future of MiniBooNE

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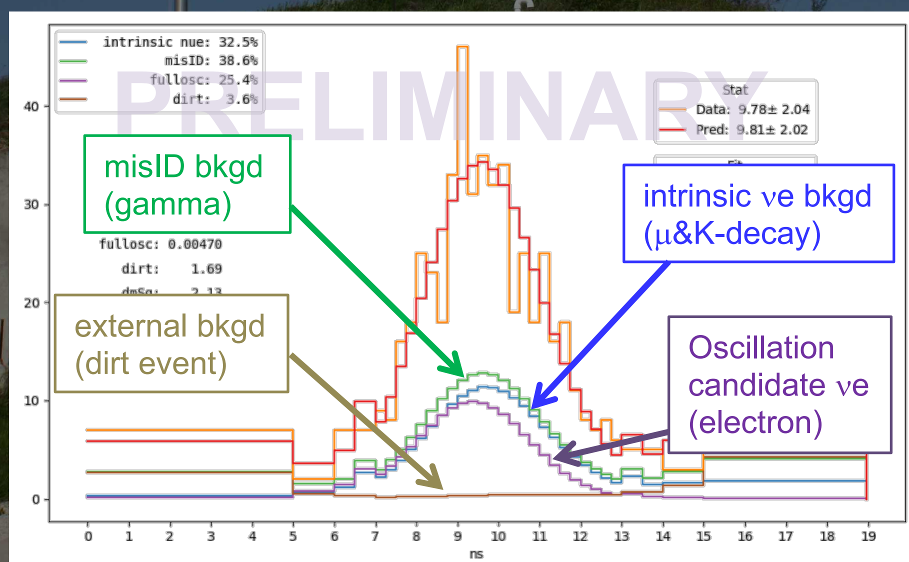
Next oscillation analysis: timing background rejection
- It is possible to reject both intrinsic and misID backgrounds by timing (ongoing)

Bunch structure, data-MC comparison
- intrinsic bkgd: μ-decay νe, K-decay νe → slow
- misID bkgd: photon conversion → slow



Conclusion

MiniBooNE is a short-baseline neutrino oscillation experiment

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

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

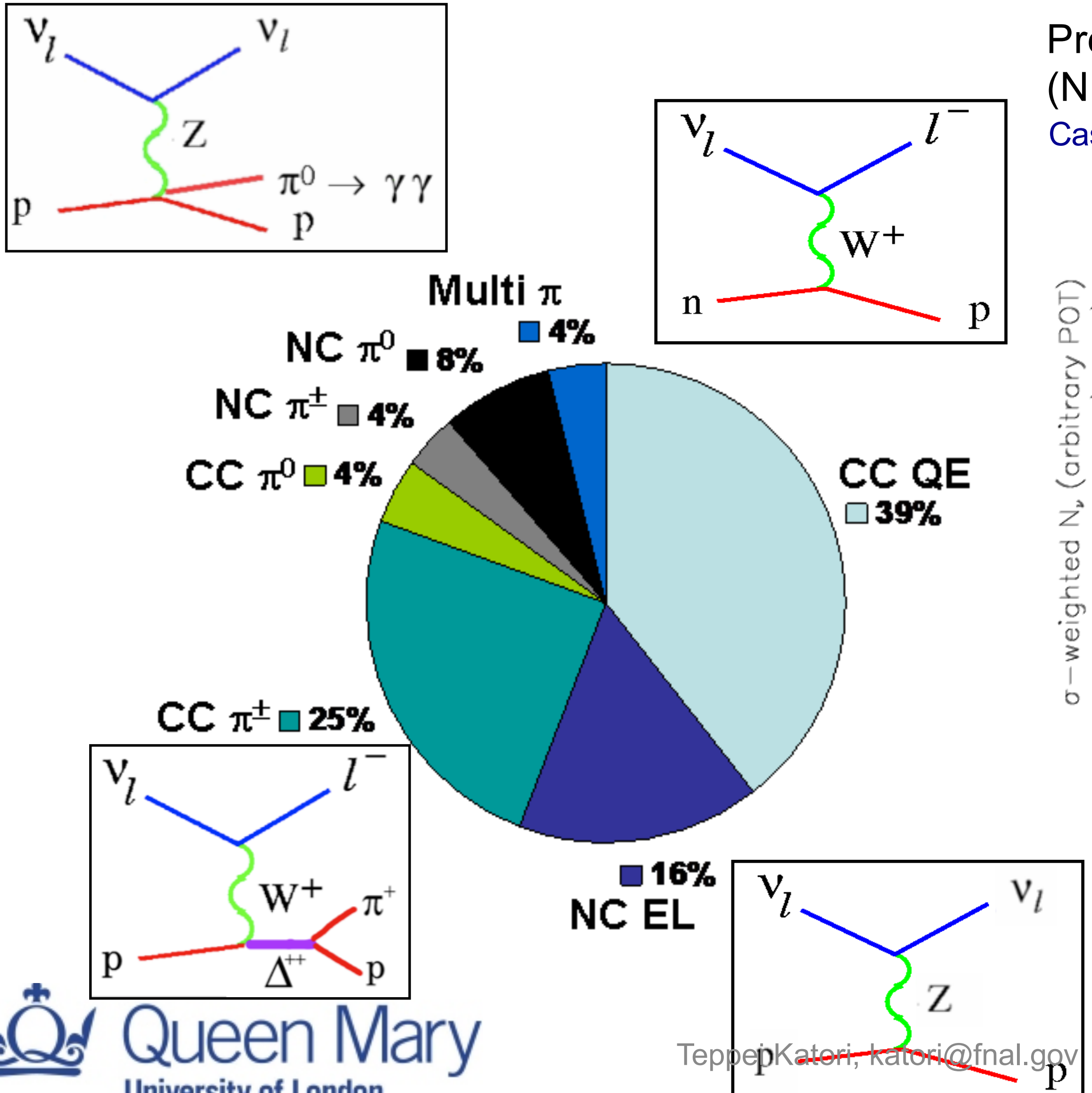
But the biggest legacy is the short-baseline anomaly

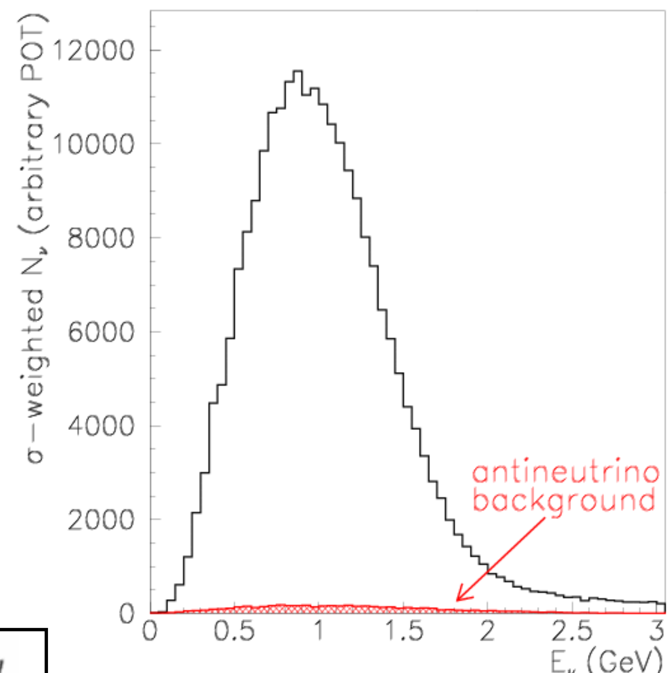
Thank you for your attention!

backup

3. Cross section model

Predicted event rates before cuts
(NUANCE Monte Carlo)
Casper, Nucl.Phys.Proc.Suppl.112(2002)161





Event neutrino energy (GeV)