MiniBooNE experiment results

Outline

1. MiniBooNE experiment
2. Neutrino oscillation results
3. Neutrino cross section results
4. Test of Lorentz and CPT violation
5. Light WIMP search
6. Conclusion

Teppei Katori
Queen Mary, University of London
IPA2014, Queen Mary University of London, London, UK, Aug. 19, 2014

1. **MiniBooNE experiment**

2. Neutrino oscillation results

3. Neutrino cross section results

4. Test of Lorentz and CPT violation

5. Light WIMP search

6. Conclusion

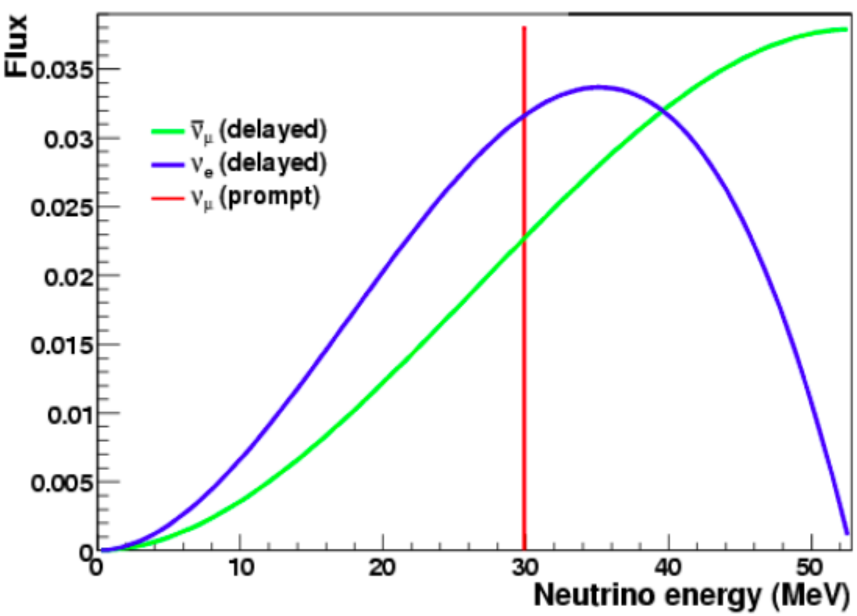
1. LSND

LSND makes muon anti-neutrino beam from decay-at-rest pion beam, to search electron anti-neutrino appearance.

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

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

L/E~30m/40MeV~0.7

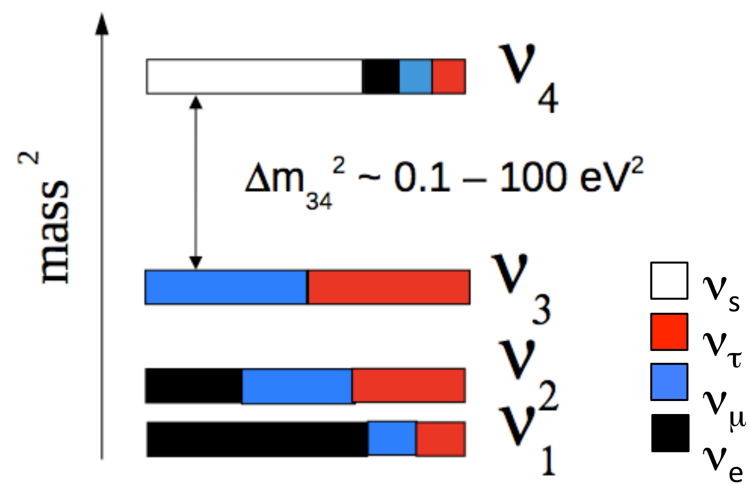


Data is consistent with two massive neutrino oscillation model with $\Delta m^2 \sim 1 eV^2$,
$87.9 \pm 22.4 \pm 6.0$ (3.8σ)

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!

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



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1. MiniBooNE

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

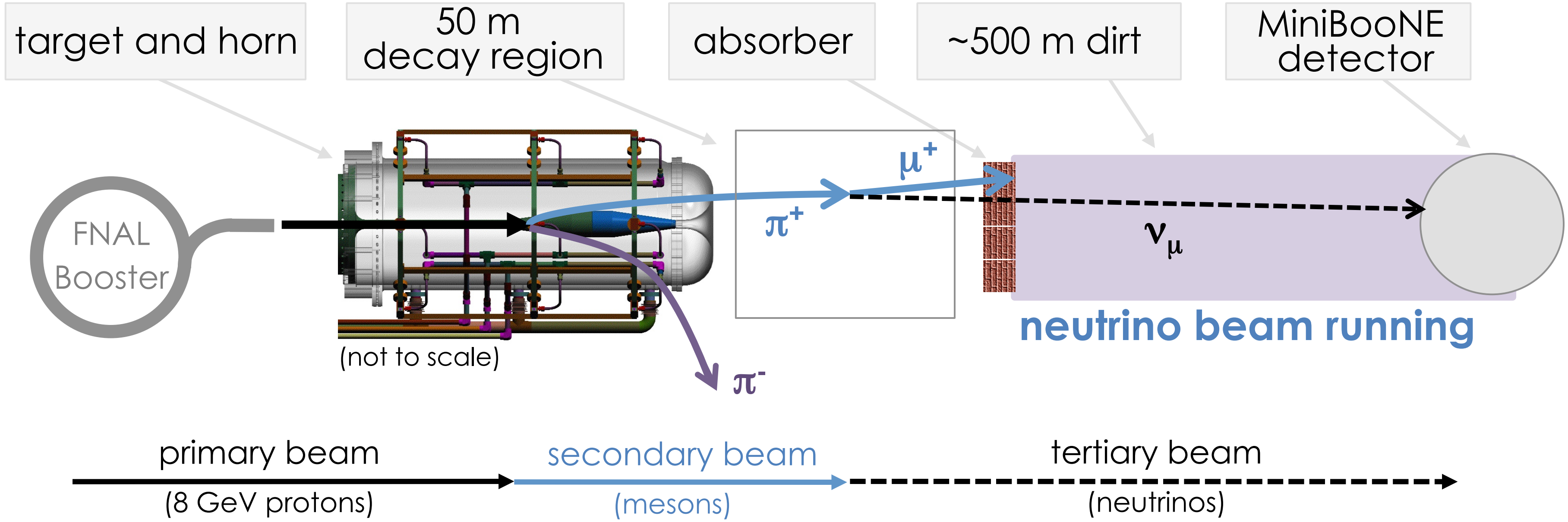
MiniBooNE is designed to test LSND under two-massive-neutrino oscillation model.

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

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

L/E~500m/700MeV~0.7

Booster Neutrino Beamline (BNB) creates ~800(700)MeV neutrino(anti-neutrino) by pion decay-in-flight. Cherenkov radiation from the charged leptons are observed by MiniBooNE Cherenkov detector to reconstruct neutrino energy.



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2. MiniBooNE

MiniBooNE observed event excesses in both mode

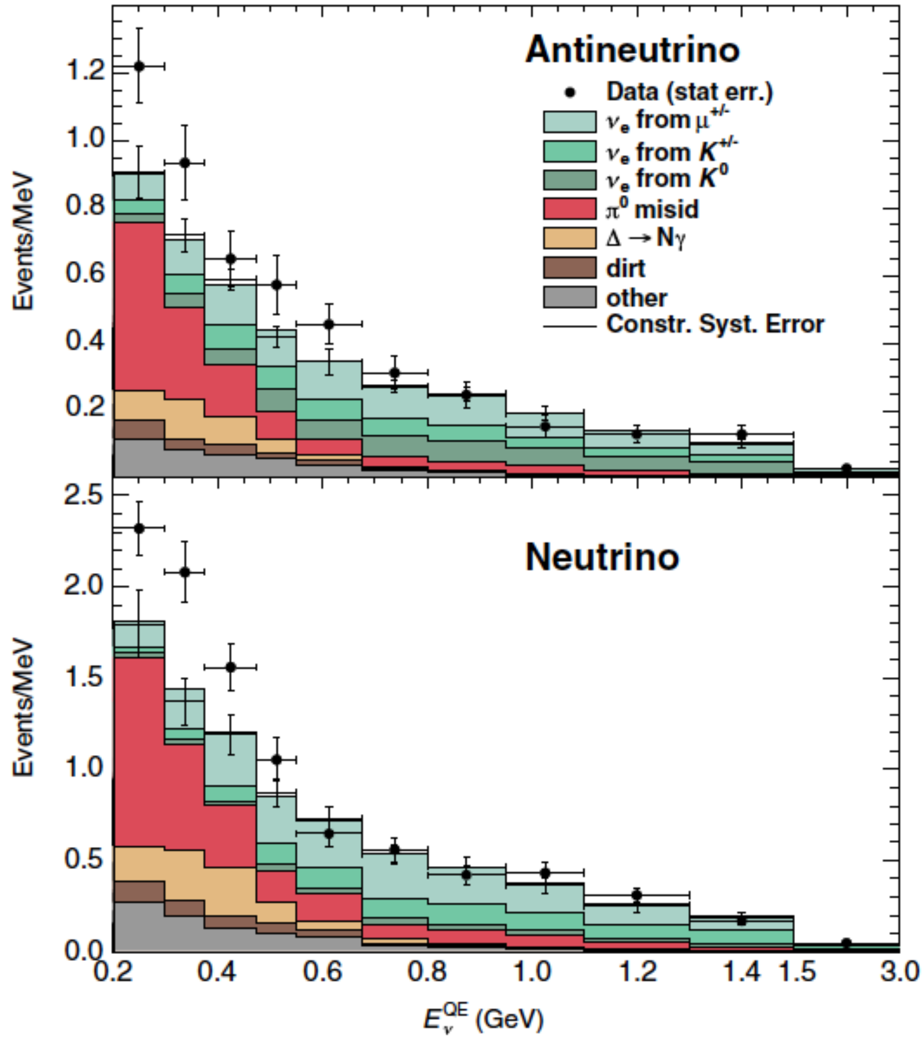
Neutrino mode

162.0 ± 28.1 ± 38.7 (3.4σ)

Antineutrino mode

78.9 ± 20.0 ± 20.3 (2.8σ)

oscillation candidate events



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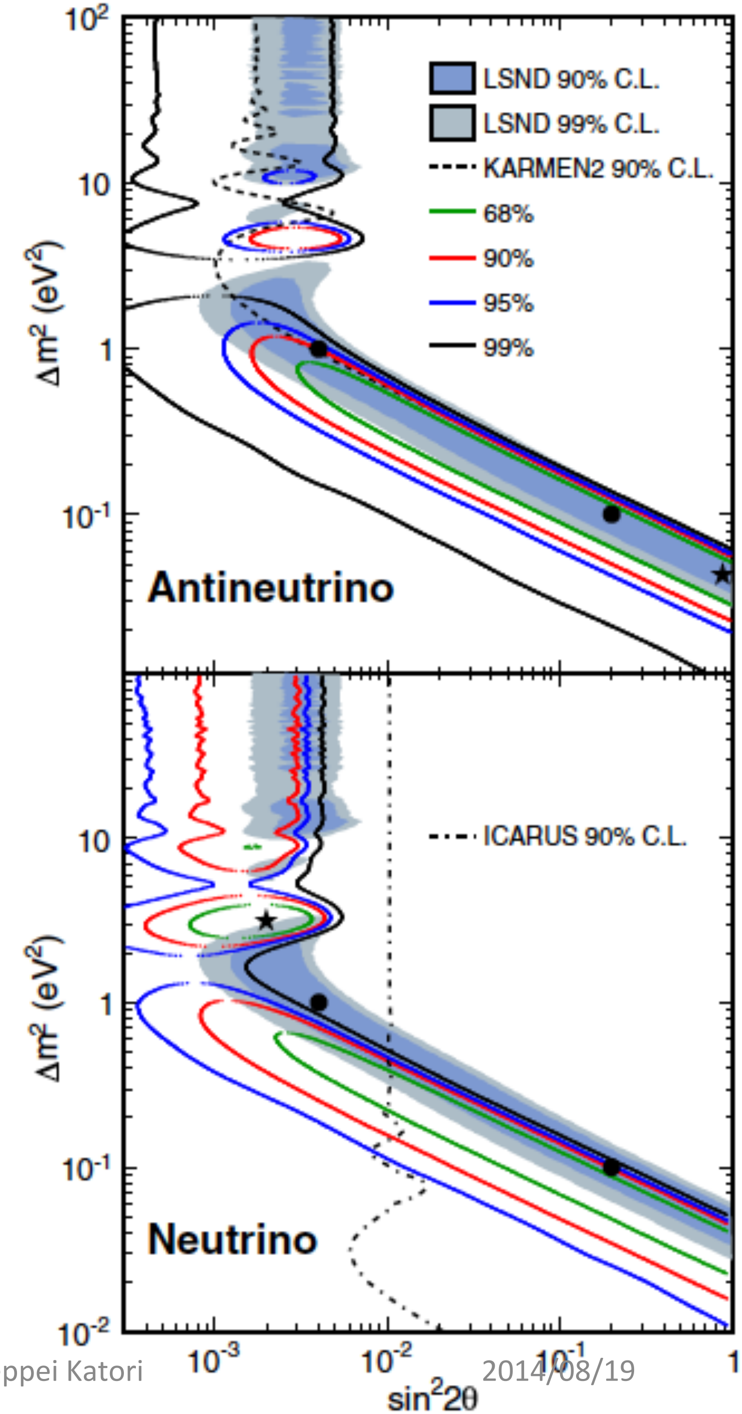
Under two-massive neutrino oscillation model, antineutrino mode result is consistent with LSND, but neutrino mode result shows a little tension.



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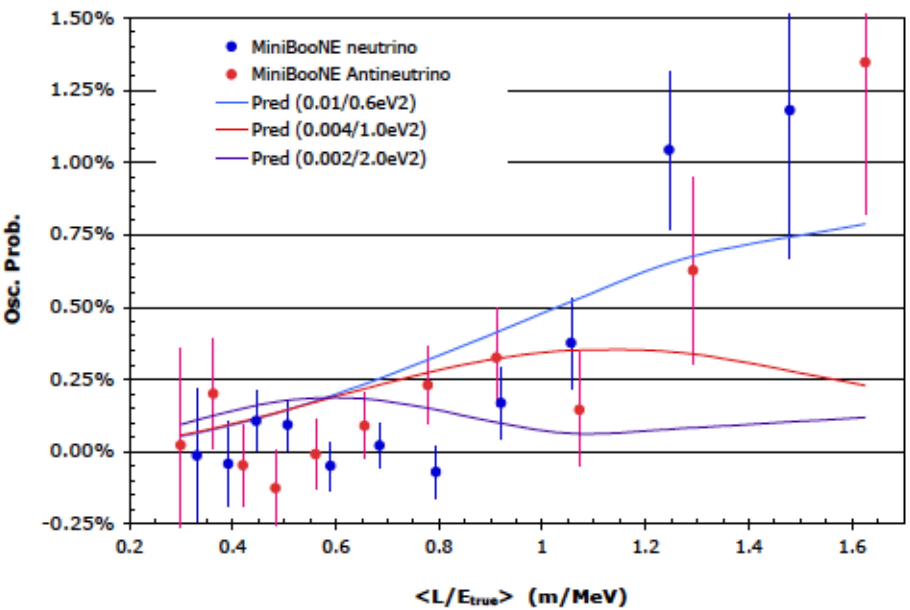

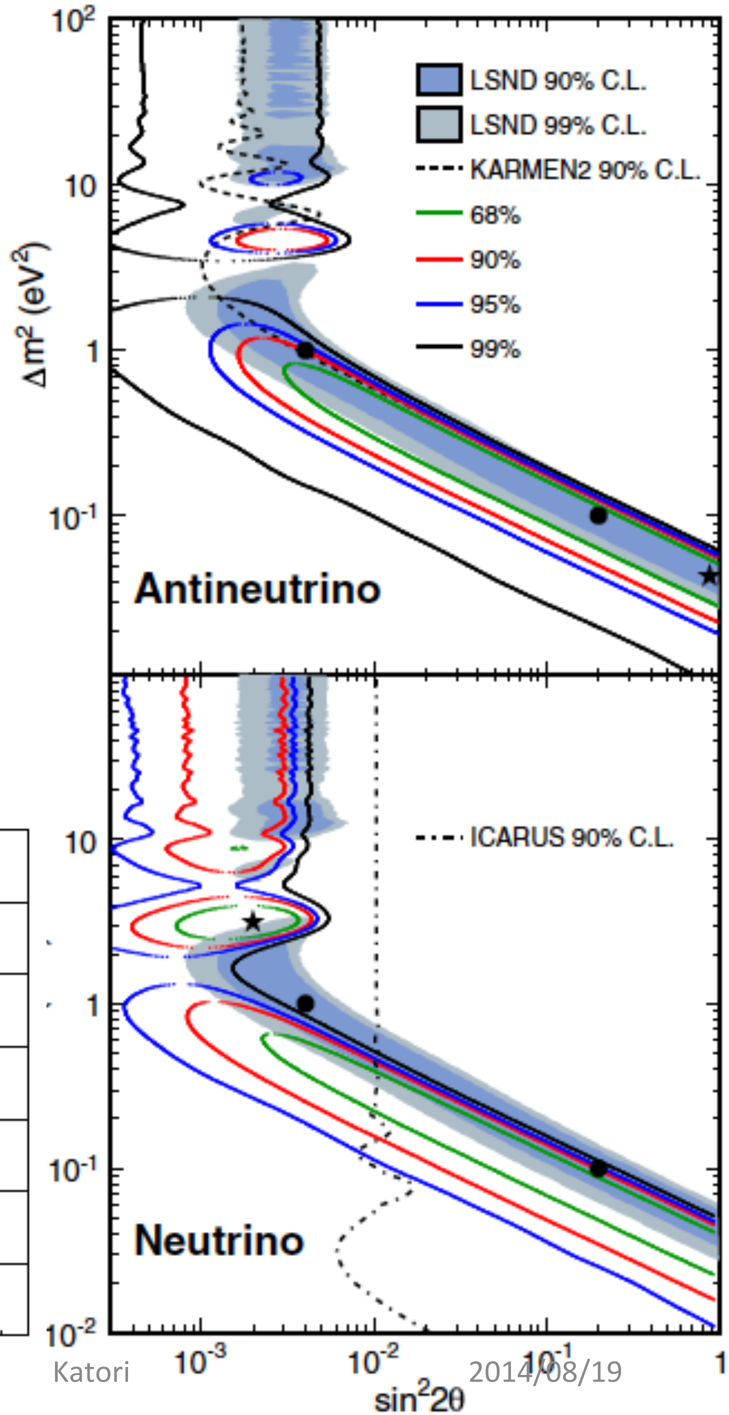

MiniBooNE, arXiv:1407.3304
Martini et al, PRD85(2012)093012

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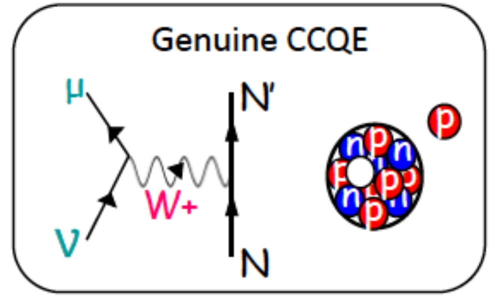
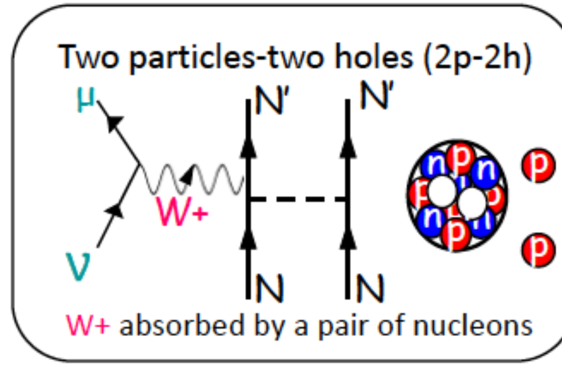
78.9 ± 20.0 ± 20.3 (2.8σ)

2p-2h effect could shift reconstructed neutrino? energy spectrum to higher? (more consistent with LSND)





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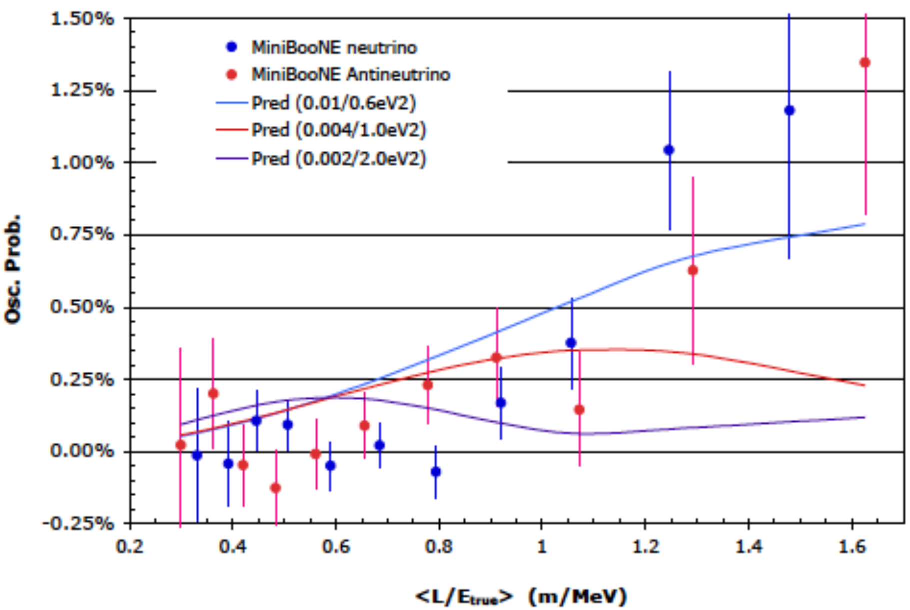

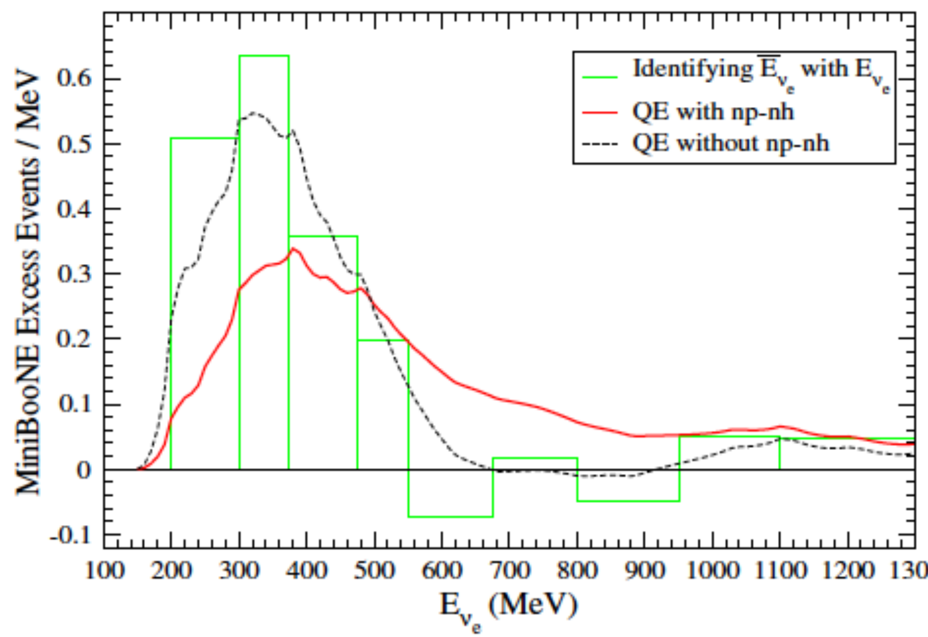

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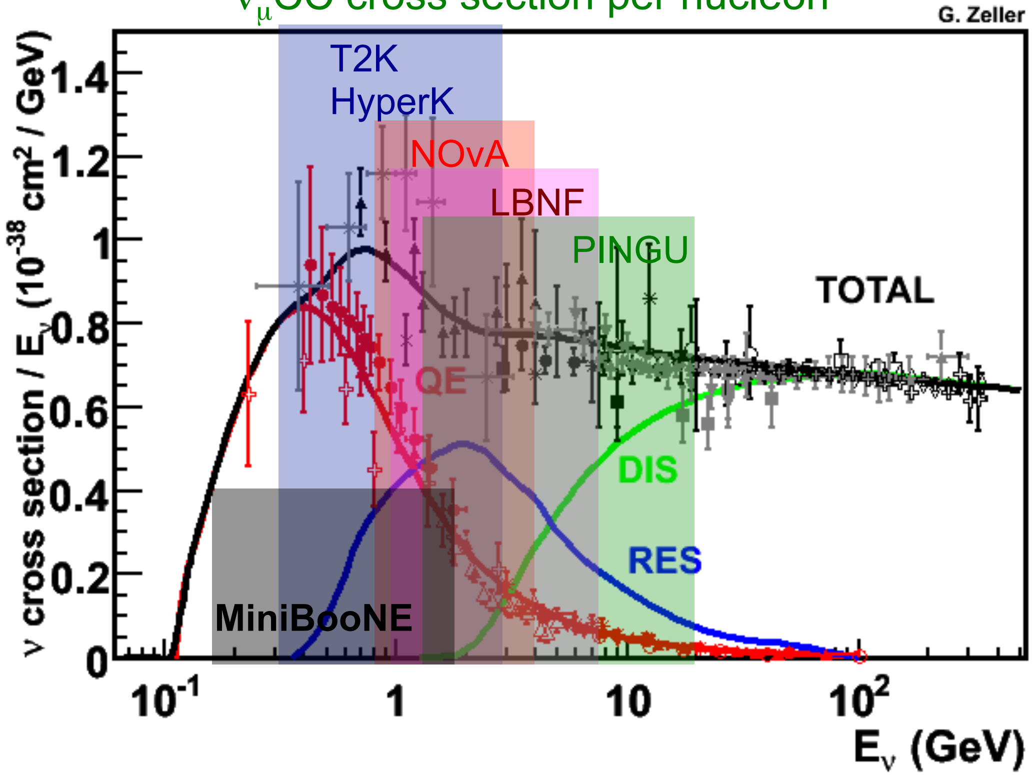
3. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K
- Present to Future: T2K, NOvA, PINGU, JUNO, HyperK, LBNF

Typical oscillation experiment (L~100-1000km) always choose 1-10 GeV energy region (only exception is reactor neutrino experiment)

ν_μCC cross section per nucleon



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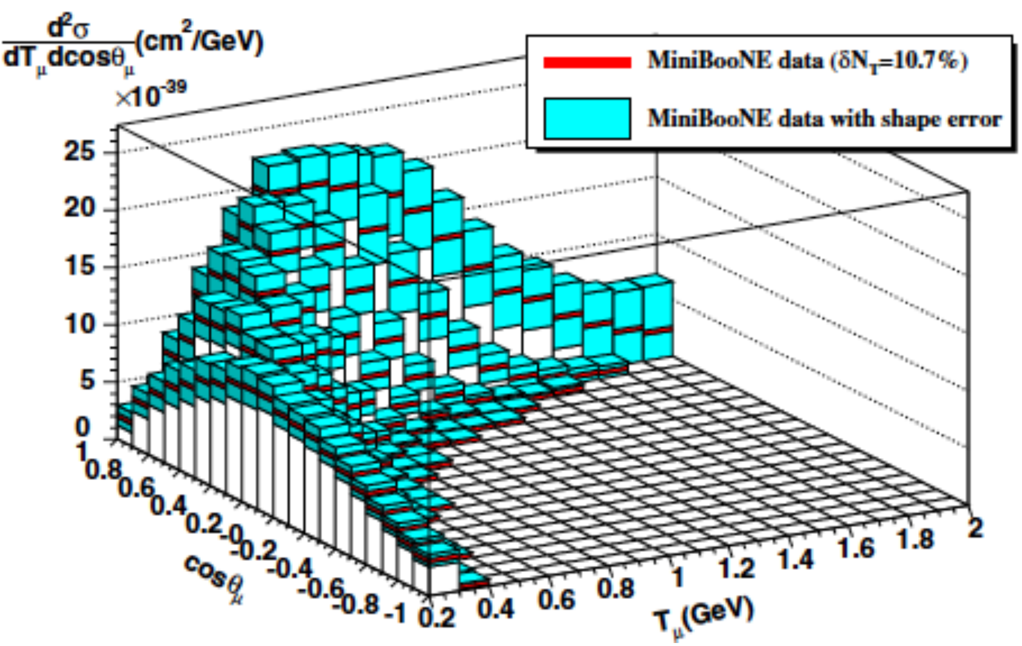
$$P_{\mu\rightarrow e}(L/E)=\sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

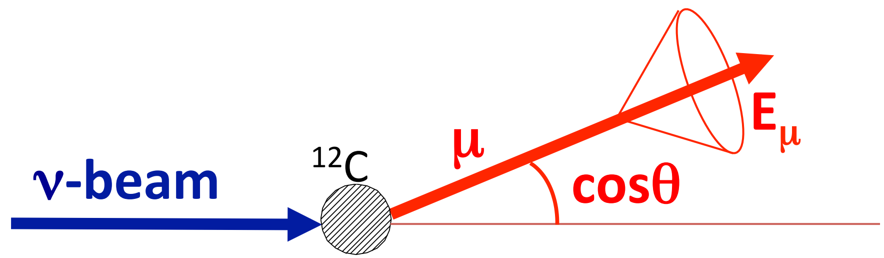
3. MiniBooNE neutrino cross section results

MiniBooNE flux-integrated CCQE double differential cross section

- Detector efficiency is corrected, but neutrino flux is not unfolded
- Data is presented in terms of "measured" variables (muon energy and muon angle)
- Data is incompatible with old bubble chamber data (both shape and normalization)

PHYSICAL REVIEW D 81, 092005 (2010)





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

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

CCQE definition in MiniBooNE
- single outgoing muon
- no measurement on rest

ν_μCCQE flux-integrated double differential cross section

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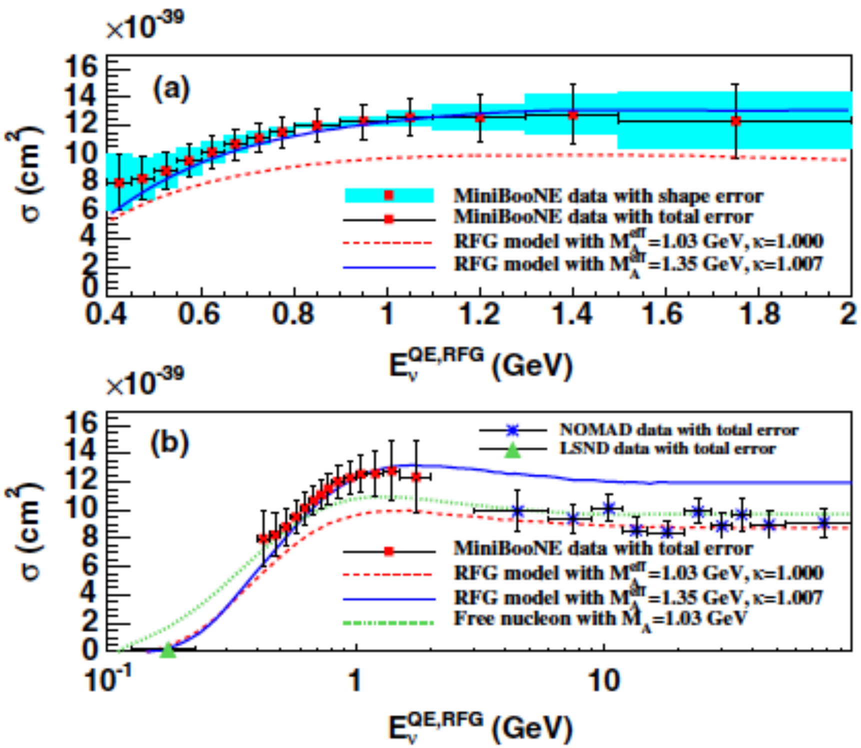

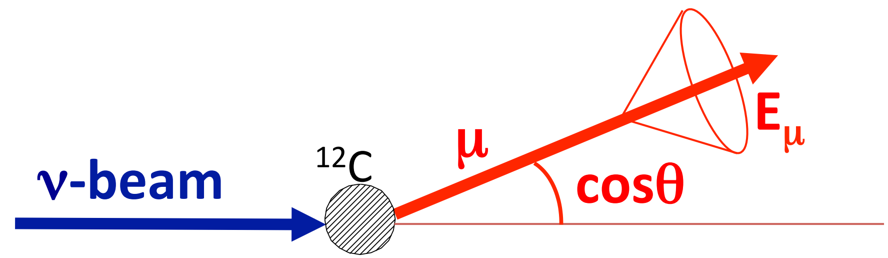

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CCQE definition in MiniBooNE
- single outgoing muon
- no measurement on rest

ν_μCCQE flux-unfolded total cross section

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

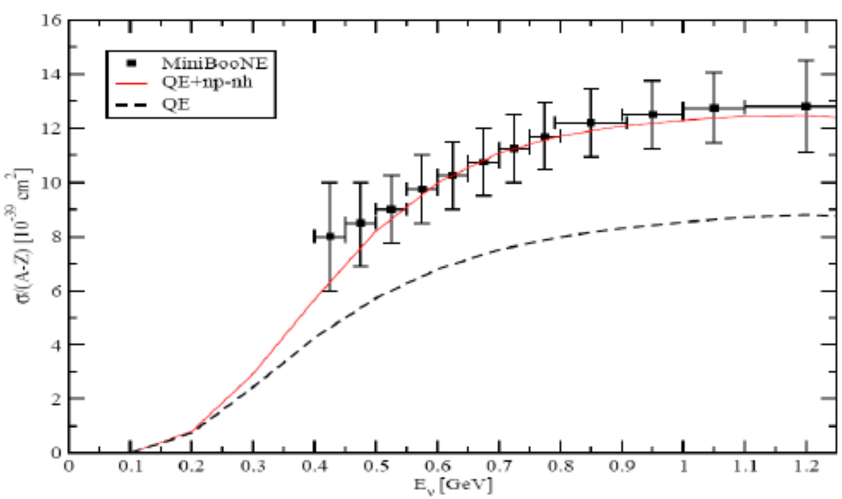
3. MiniBooNE neutrino cross section results

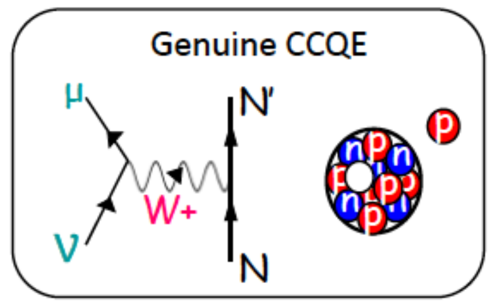
MiniBooNE flux-integrated CCQE double differential cross section

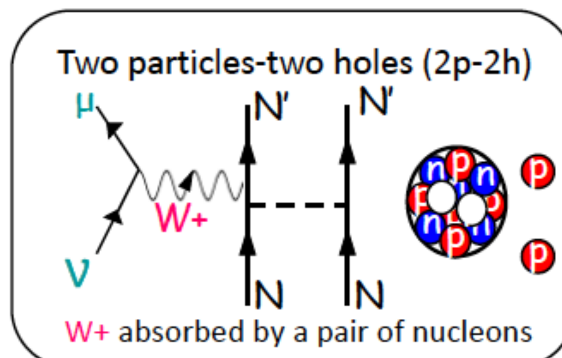
- Detector efficiency is corrected, but neutrino flux is not unfolded
- Data is presented in terms of “measured” variables (muon energy and muon angle)
- Data is incompatible with old bubble chamber data (both shape and normalization)
- Martini et al showed np-nh effect can add up 30-40% more cross section!

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







M. Martini, M. Ericson, G. Chanfray, J. Marteau   Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

Alvarez-Ruso,Hayato,Nieves,ArXiv:1403.2673
Nieves et al, PLB707(2012)72

3. MiniBooNE neutrino cross section results

MiniBooNE flux-integrated CCQE double differential cross section

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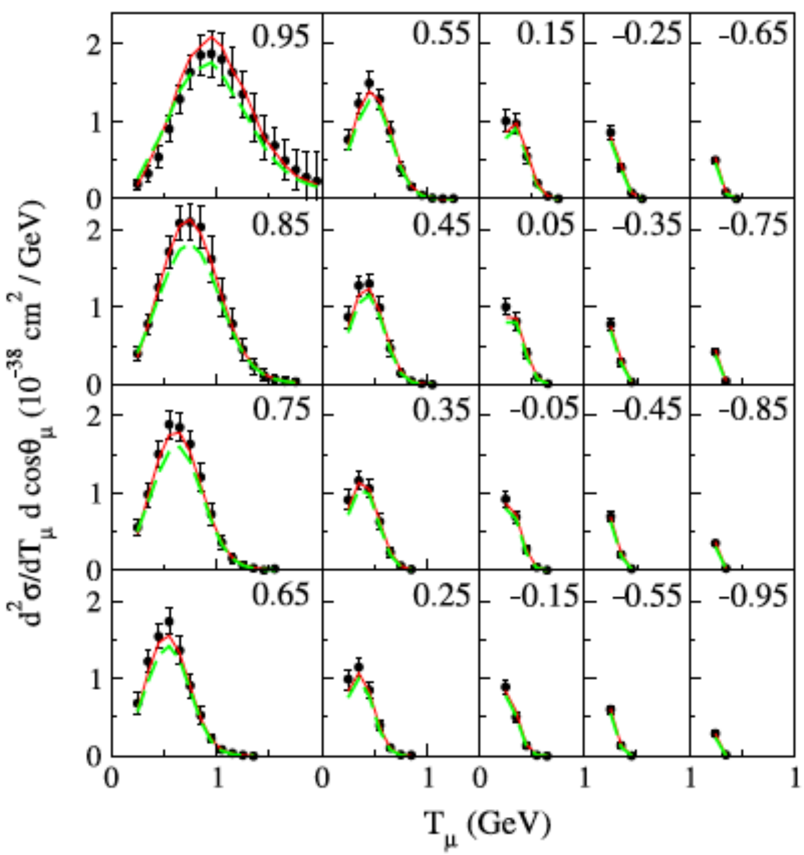
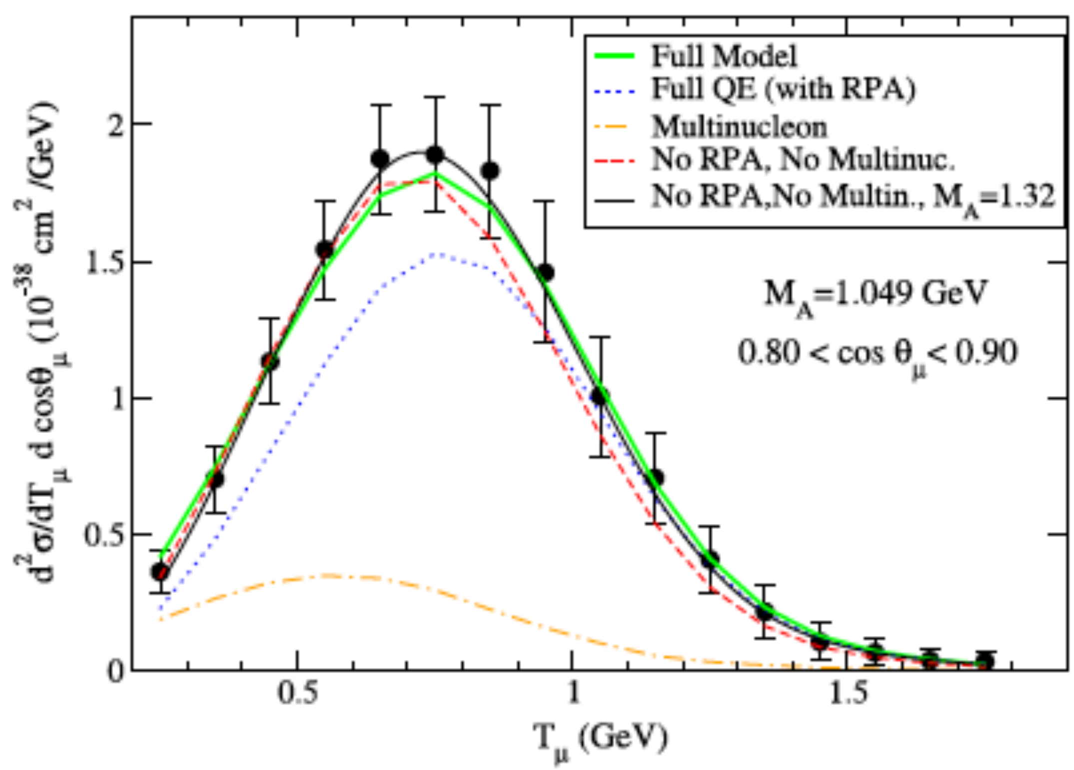
- Data is presented in terms of “measured” variables (muon energy and muon angle)
- Data is incompatible with old bubble chamber data (both shape and normalization)
- Martini et al showed np-nh effect can add up 30-40% more cross section!
- Both shape and normalization are explained by np-nh contribution (and RPA).

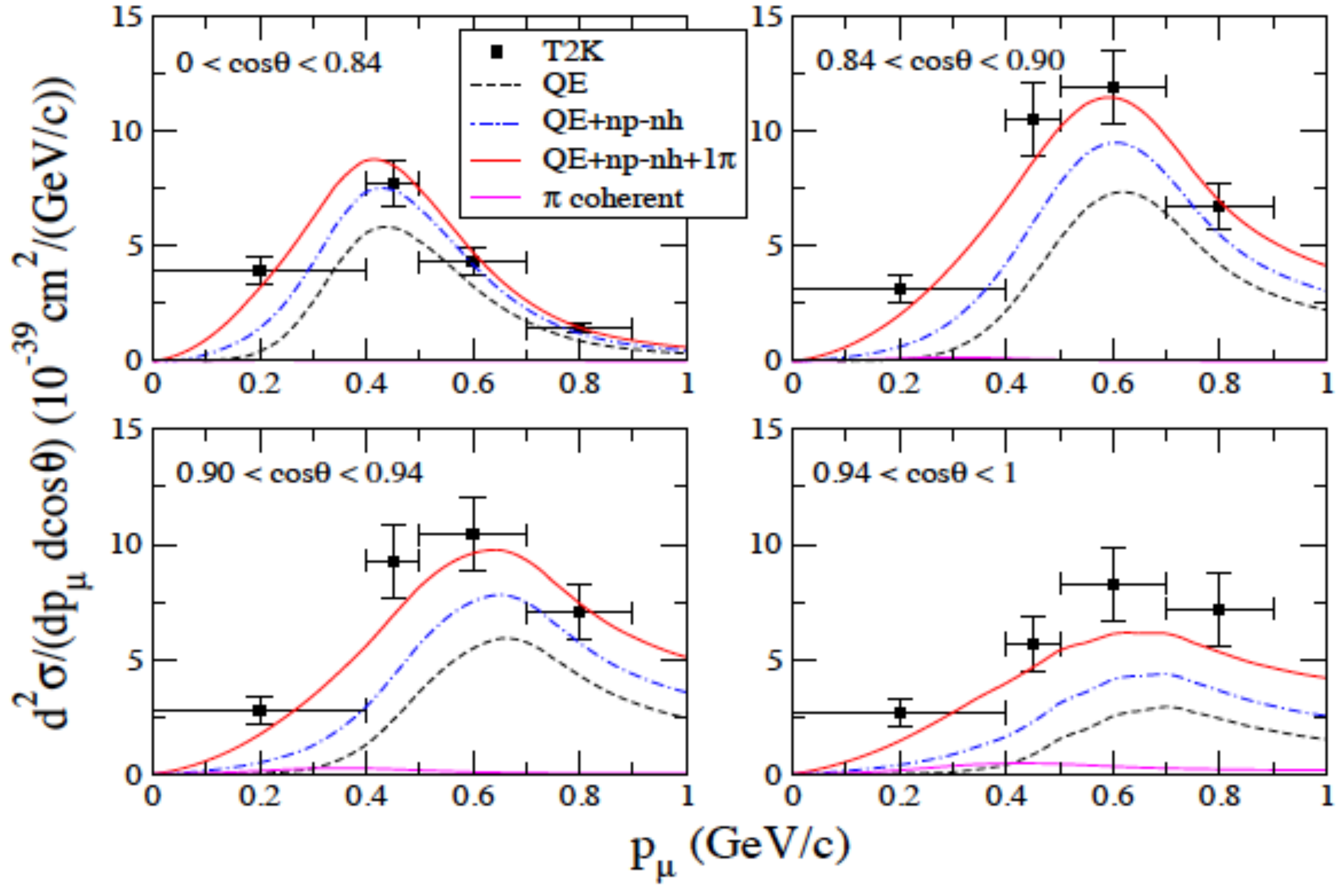




3. MiniBooNE neutrino cross section results

T2K flux-integrated CC inclusive differential cross section

- Martini model also describes T2K data (→ MiniBooNE flux prediction is right)



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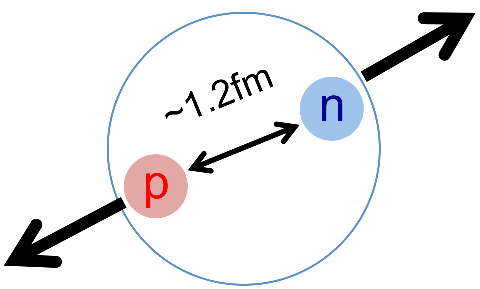
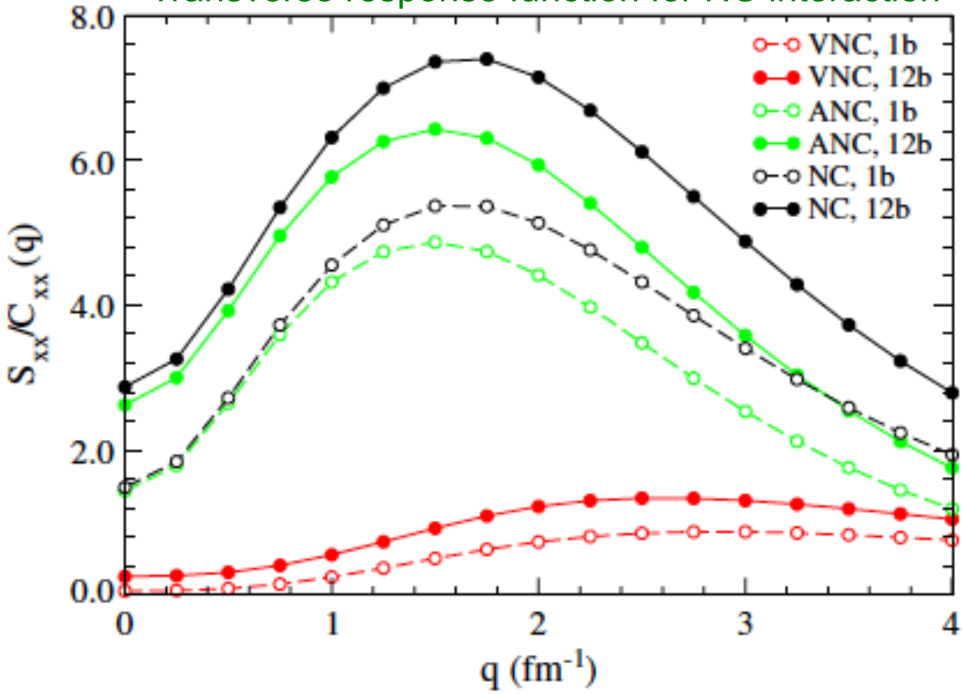
Standard Nuclear Physics Approach (SNPA)

- Consistent result is obtained by ab initio calculation
- Enhancement also arise in axial current

This enhancement is dominated by short range n-p pair (short range correlation?).



Transverse response function for NC interaction

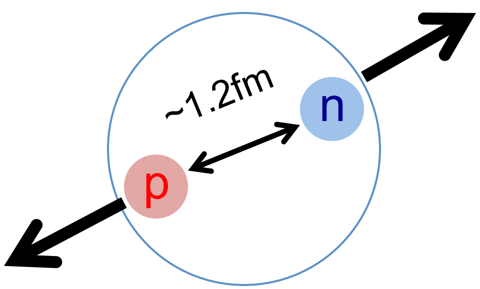


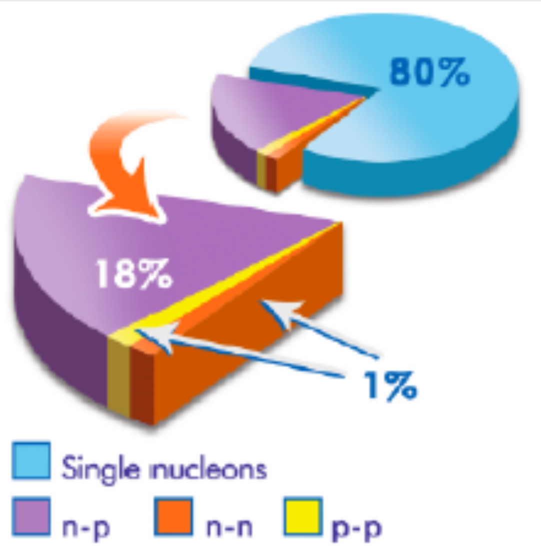
3. MiniBooNE neutrino cross section results

Short range correlation

^{12}C From (e,e'), (e,e'p), and (e,e'pN) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs (quasi-deuteron)
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
- Less than 1% multi-nucleon correlations





INT Workshop 4 December 2013

Jefferson Lab

from Higinbotham

Sobczyk, Neutrino2014
Weinstein et al, PRL106(2011)052301

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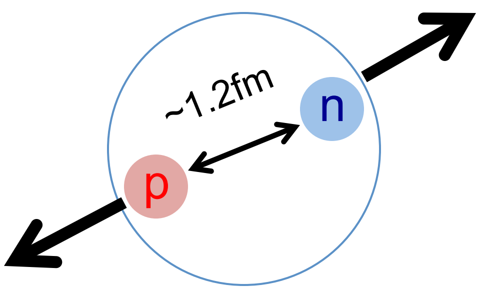

SRC as a origin of EMC effect?

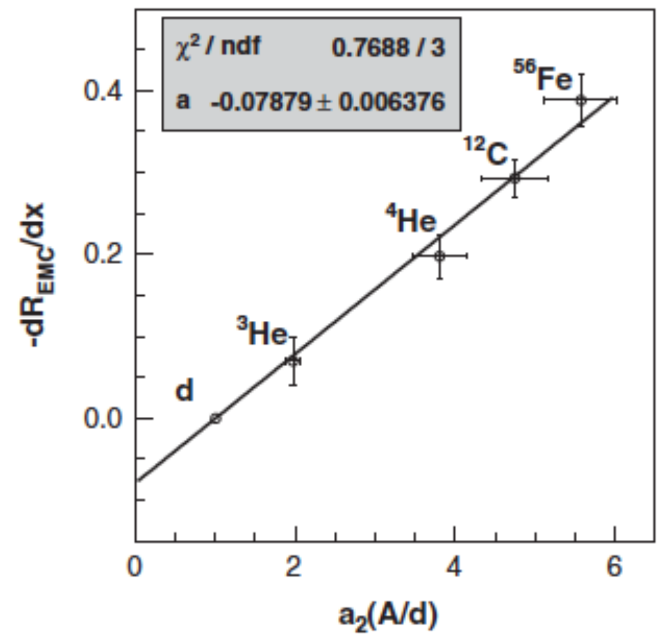

FIG. 1. The EMC slopes versus the SRC scale factors. The uncertainties include both statistical and systematic errors added in quadrature. The fit parameter is the intercept of the line and also the negative of the slope of the line.

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from Higinbotham

MiniBooNE, PRD82(2010)092005:
de Florian et al, PRL113(2014)012001

3. MiniBooNE neutrino cross section results

MiniBooNE flux-integrated NCE differential cross section

- Total scintillation light is used to estimate total nucleon kinetic energy
- Isoscalar axial current is sensitive to additional spin contribution beyond SU(2) (→ strange quark spin)
- large uncertainty for spin-dependent dark matter search

$$\int_0^1 dx \Delta s(x) \equiv \Delta s \equiv G_A^s(Q^2 = 0)$$

"proton spin crisis"

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

gluon longitudinal
polarization ~ 0.2

quark longitudinal polarization
ΔΣ=Δu+Δd+Δs ~ 0.25

quark and gluon orbital
angular momentum ~?

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- Isoscalar axial current is sensitive to additional spin contribution beyond SU(2) (→ strange quark spin)
- large uncertainty for spin-dependent dark matter search
- Data is not sensitive enough to find Δs, but first time we demonstrate this method in Cherenkov detector
- Major background channel for beam dump dark matter search

"proton spin crisis"

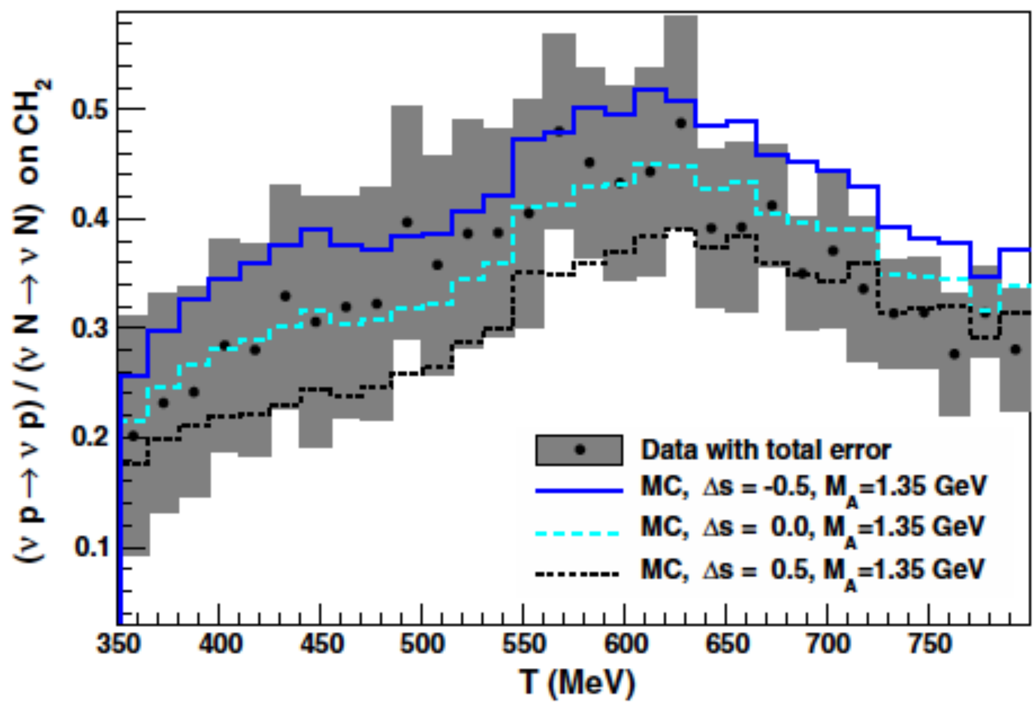
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

gluon longitudinal polarization ~ 0.2

quark longitudinal polarization $\Delta\Sigma=\Delta u+\Delta d+\Delta s \sim 0.25$

quark and gluon orbital angular momentum ~?

νp to ν(n+p) NC rate ratio



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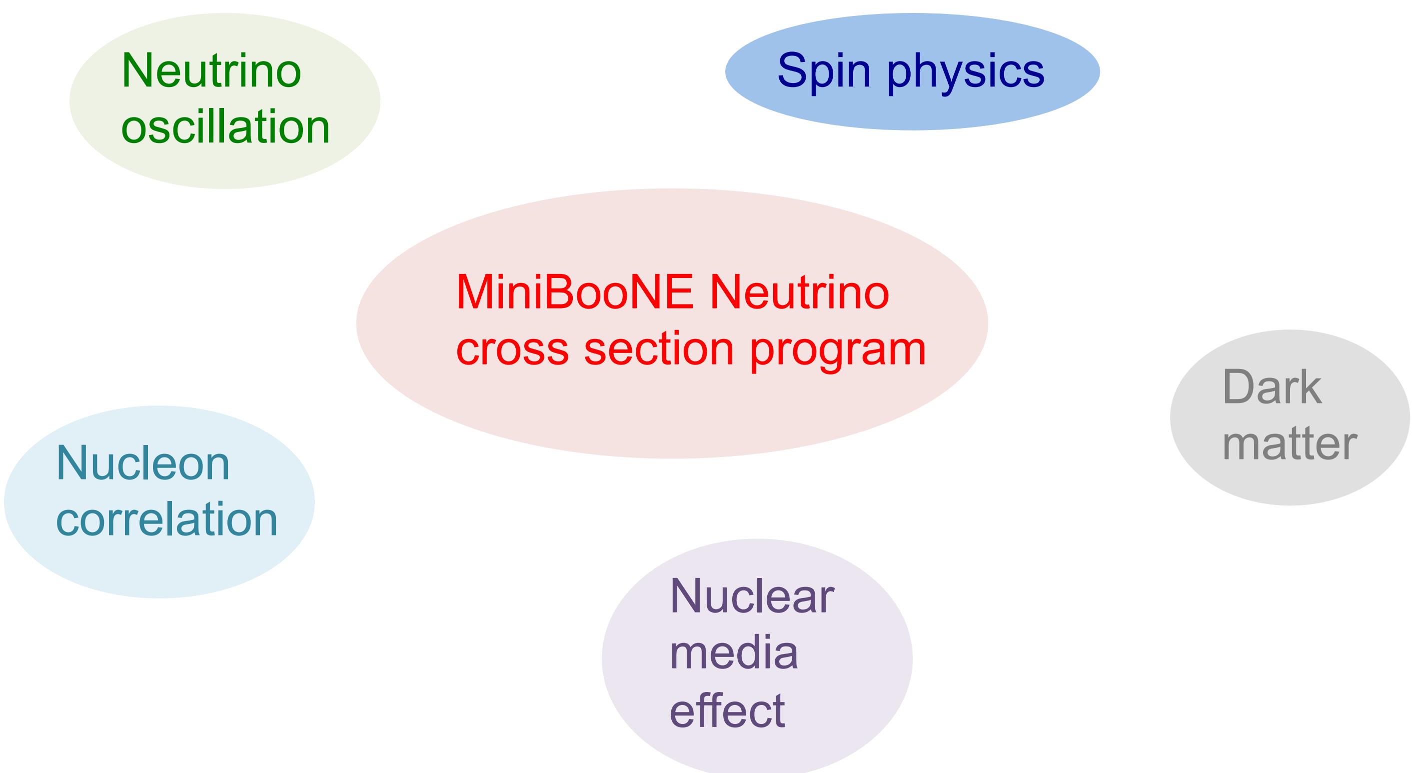
Alvarez-Ruso,Hayato,Nieves,ArXiv:1403.2673
TK and Grange, MPLA29(2014)1430011

3. MiniBooNE neutrino cross section results

MiniBooNE published >90% of interactions possible measured in MiniBooNE detector.
- Unexpected by-product of oscillation physics, over >1000 citation total
- MiniBooNE cross-section results are relevant from nuclear physics to exotic physics



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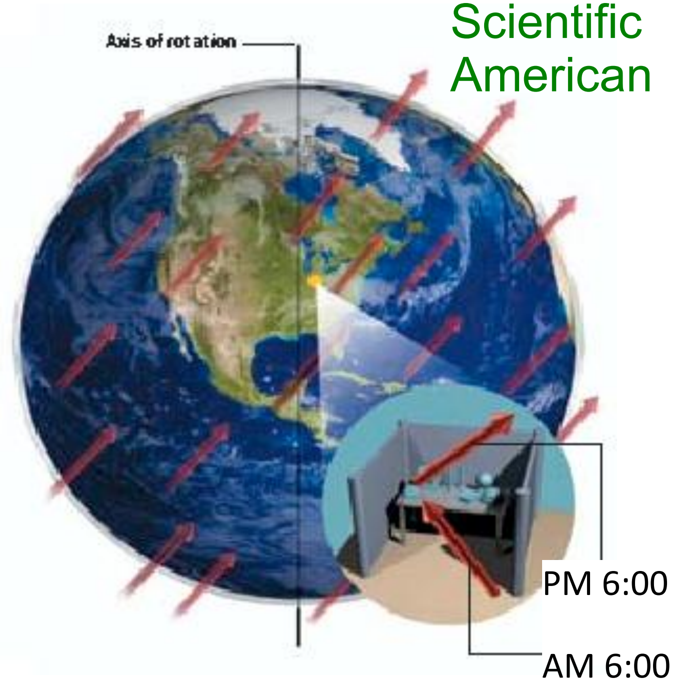
4. Lorentz violating neutrino oscillation

Lorentz and CPT violation

- Potential signal of Planck scale physics
- Standard Model Extension (SME) is the formalism of SM with particle Lorentz violation
- It was proposed LSND signal might be caused by Lorentz violation, not sterile neutrinos



Scientific American

SME Lagrangian in neutrino sector

$$L = \frac{1}{2} i\bar{\psi}_A \Gamma^{\nu}_{AB} \partial_\nu \psi_B - M_{AB} \bar{\psi}_A \psi_B + h.c.$$

SME coefficients

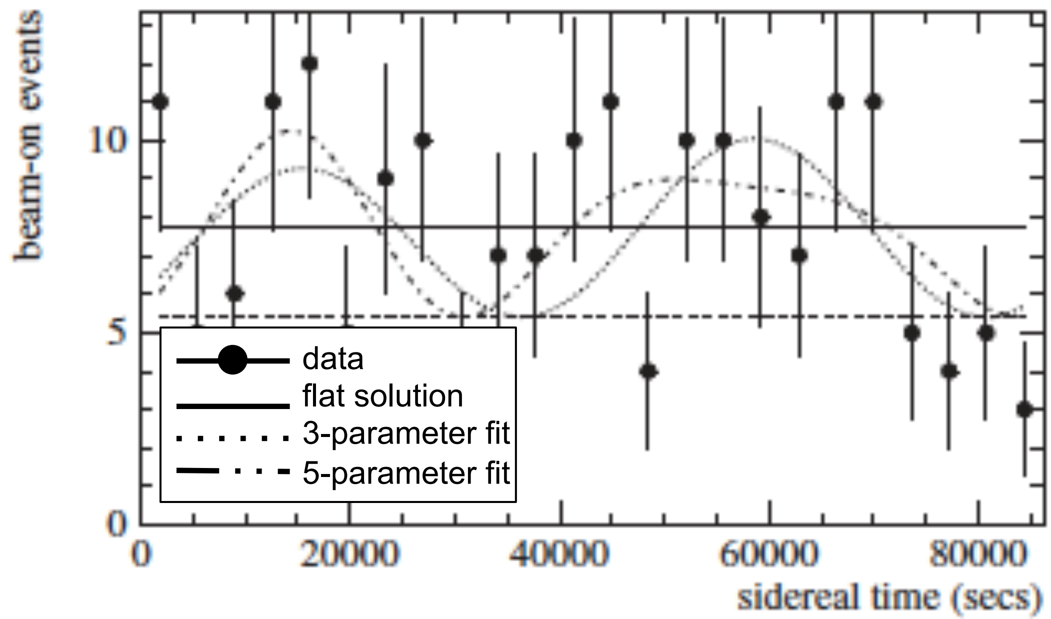
$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + c^{\mu\nu}_{AB}\gamma_\mu + d^{\mu\nu}_{AB}\gamma_\mu\gamma_5 + e^{\nu}_{AB} + if^{\nu}_{AB}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu} \cdots$$

$$M_{AB} = m_{AB} + im_{5AB}\gamma_5 + a^{\mu}_{AB}\gamma_\mu + b^{\mu}_{AB}\gamma_5\gamma_\mu + \frac{1}{2} H^{\mu\nu}_{AB}\sigma_{\mu\nu} \cdots$$

4. Lorentz violating neutrino oscillation

Lorentz and CPT violation
- Potential signal of Planck scale physics
- Standard Model Extension (SME) is the formalism of SM with particle Lorentz violation
- It was proposed LSND signal might be caused by Lorentz violation, not sterile neutrinos
- Small Lorentz violation could be the solution of LSND excess

LSND oscillation candidate sidereal time distribution

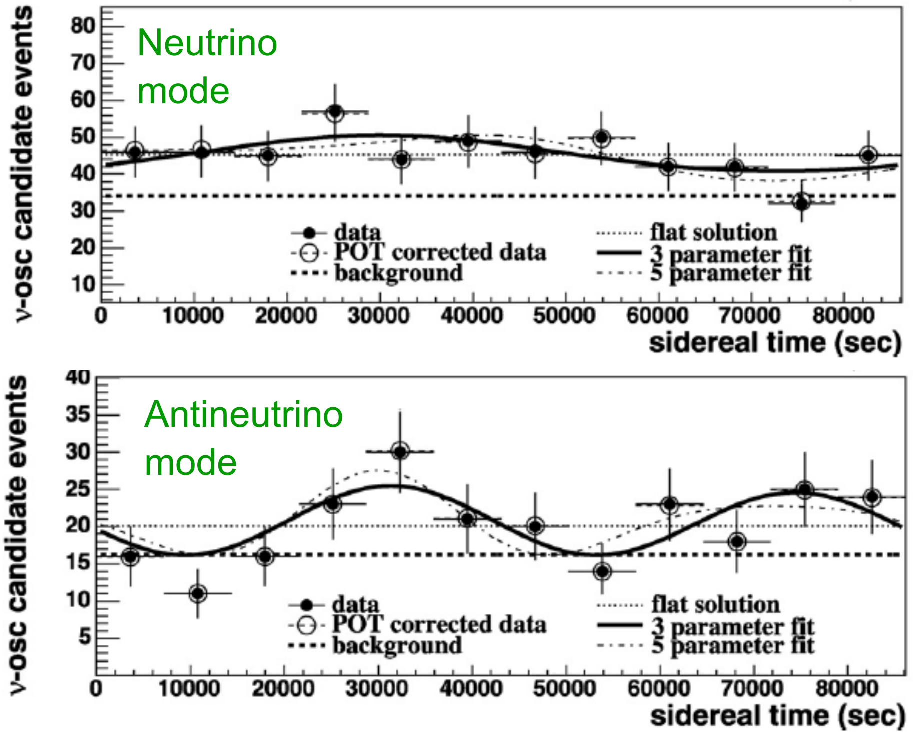


MiniBooNE, PLB718(2013)1303
TK, MPLA27(2012)1230024

4. Lorentz violating neutrino oscillation

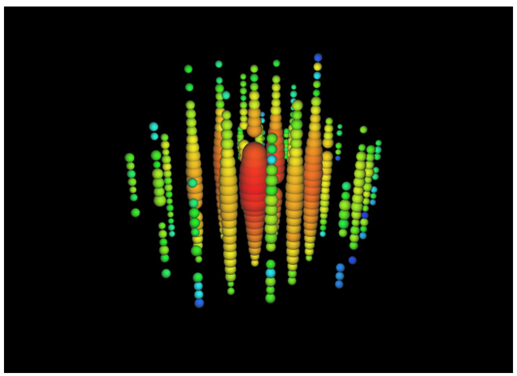
Lorentz and CPT violation
- Potential signal of Planck scale physics
- Standard Model Extension (SME) is the formalism of SM with particle Lorentz violation
- It was proposed LSND signal might be caused by Lorentz violation, not sterile neutrinos
- Small Lorentz violation could be the solution of LSND excess
- MiniBooNE data are consistent with flat
- 8 new limits on SME are obtain

These new limits exclude SME values to explain LSND data, therefore there is no simple Lorentz violation motivated scenario to accommodate LSND and MiniBooNE results simultaneously



4. Lorentz violating neutrino oscillation

By combining all work, chance to see the Lorentz violation in terrestrial experiments will be very small



astrophysical neutrino?
(next talk)

MiniBooNE MINOS ND → $e\mu$; Double Chooz → $e\tau$; IceCube MINOS FD → $\mu\tau$

$d=3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–
	$\mathrm{Re}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	–

$d=4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}
	$\mathrm{Re}\,(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-23}
	$\mathrm{Re}\,(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{ZZ}$	10^{-19}	10^{-16}	–
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	10^{-17}	–
	$\mathrm{Re}\,(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}
	$\mathrm{Re}\,(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-27}
	$\mathrm{Re}\,(c_L)^{TZ}$	10^{-20}	10^{-16}	–

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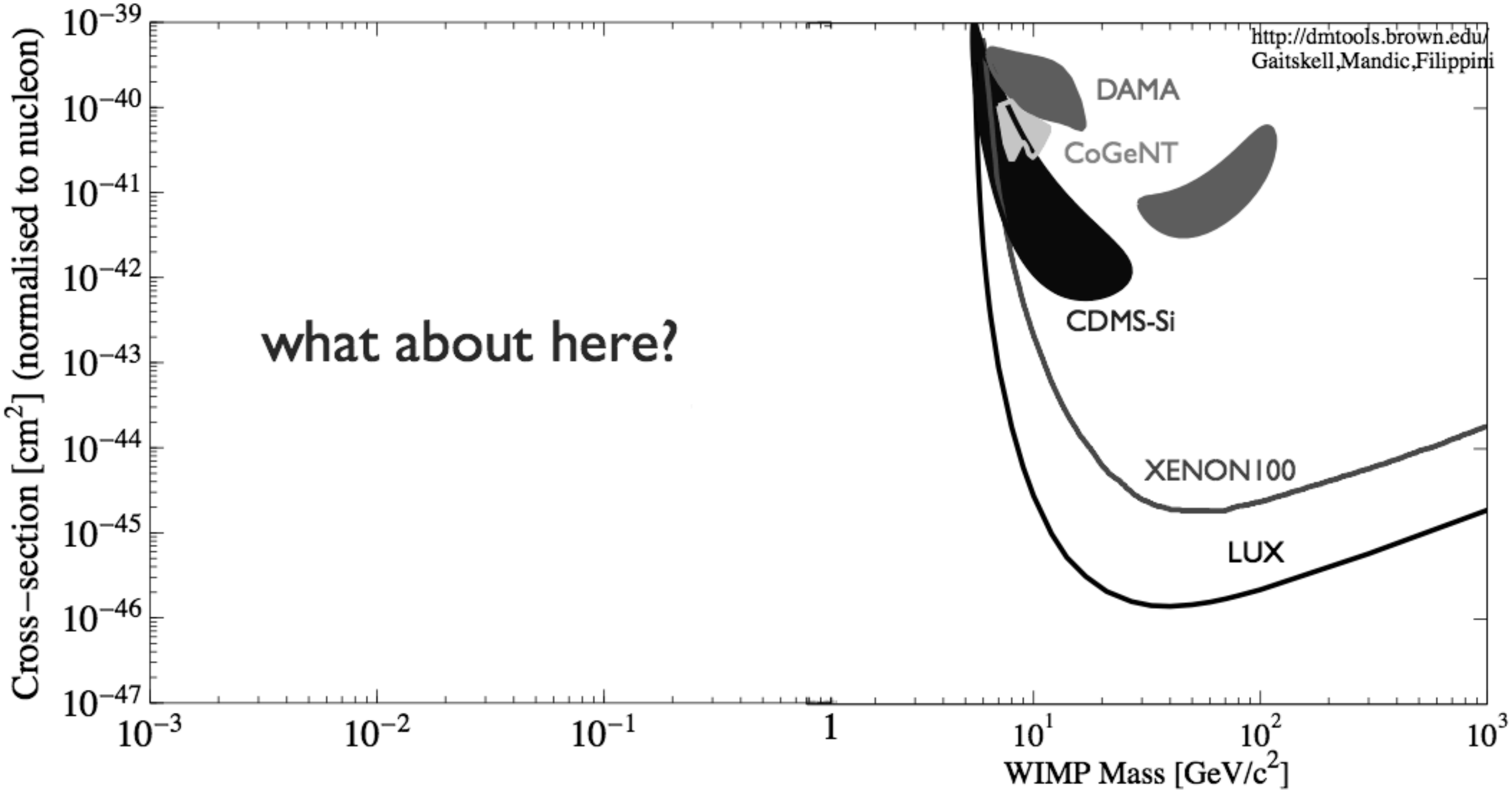
6. Light WIMP search in MiniBooNE

Light WIMP with new U(1) gauge boson (dark photon)
- Candidate of cold dark matter
- Not accessible with popular direct dark matter techniques
→ beam dump experiments

$$\mathcal{L}_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F^{\mu\nu} + |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'},$$



6. Light WIMP search in MiniBooNE

Light WIMP with new U(1) gauge boson (dark photon)
- Candidate of cold dark matter
- Not accessible with popular direct dark matter techniques
→ beam dump experiments

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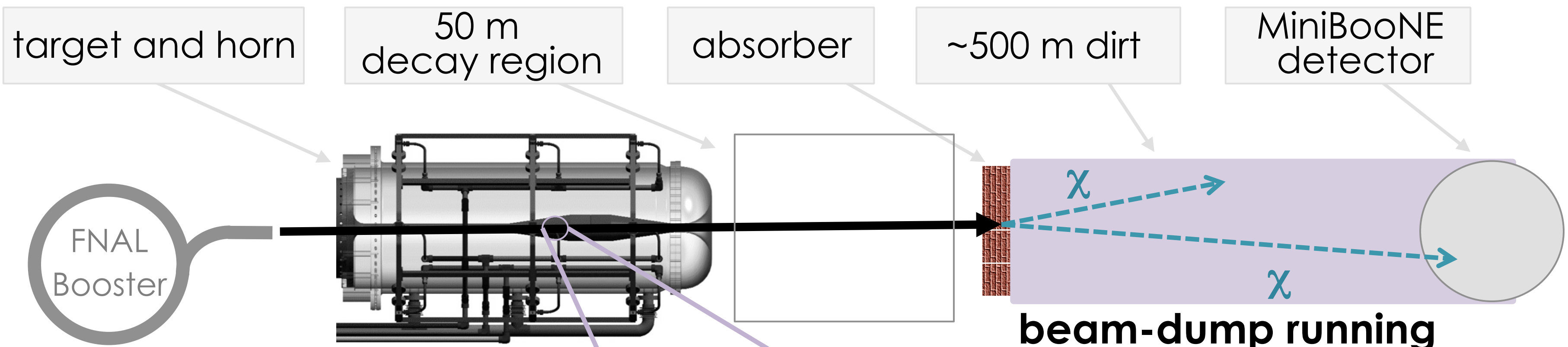
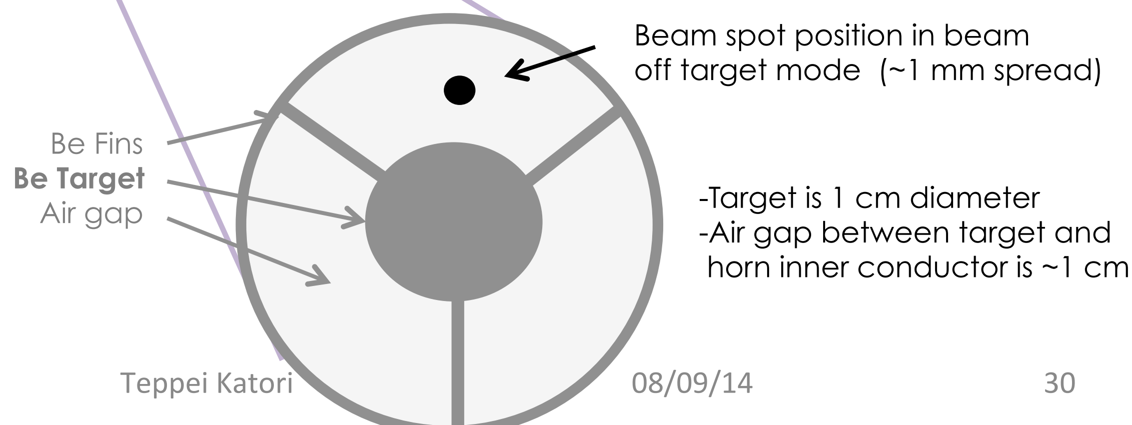


MiniBooNE has the capability to steer the protons past the target and onto the 50 m iron dump (absorber)

target (beam-dump) running



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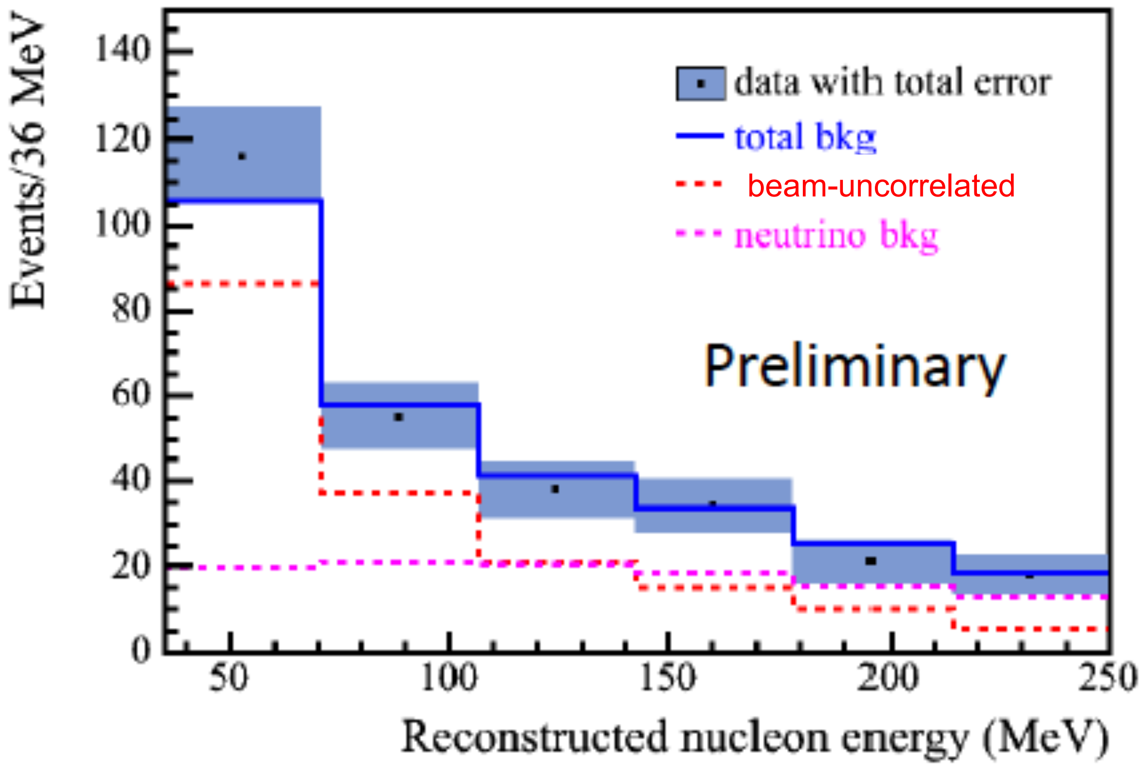


First 30% of beam-dump mode data
2 types of backgrounds
- beam-uncorrelated events
- neutrino interactions

Very conservative systematic errors are assigned.

We expect ~1.8E20 POT data at the end of the run (Sept. 2014).

Queen Mary University of London

TK and Conrad, arXiv:1404.7759

6. Conclusions

MiniBooNE finishes oscillation run in 2012.

The final oscillation result of anti-neutrino mode agrees with LSND, but neutrino mode shows a tension within two massive neutrino oscillation model.

The cross section results from MiniBooNE drastically change the view of this field.

MiniBooNE set stringent limits on Lorentz violation, and we rejected simple Lorentz violation motivated models to explain LSND signal and MiniBooNE data.

MiniBooNE is currently running in “beam-dump” mode, for light WIMP search.

Thank you for your attention!

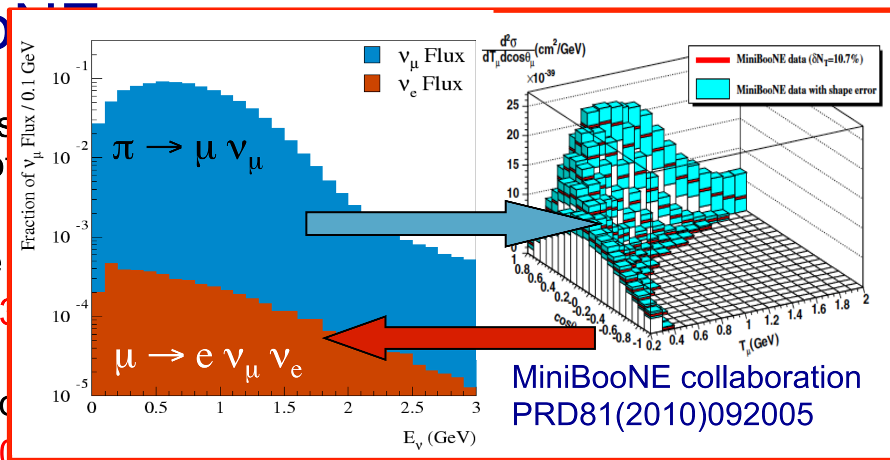
Backup

2. MiniBoo

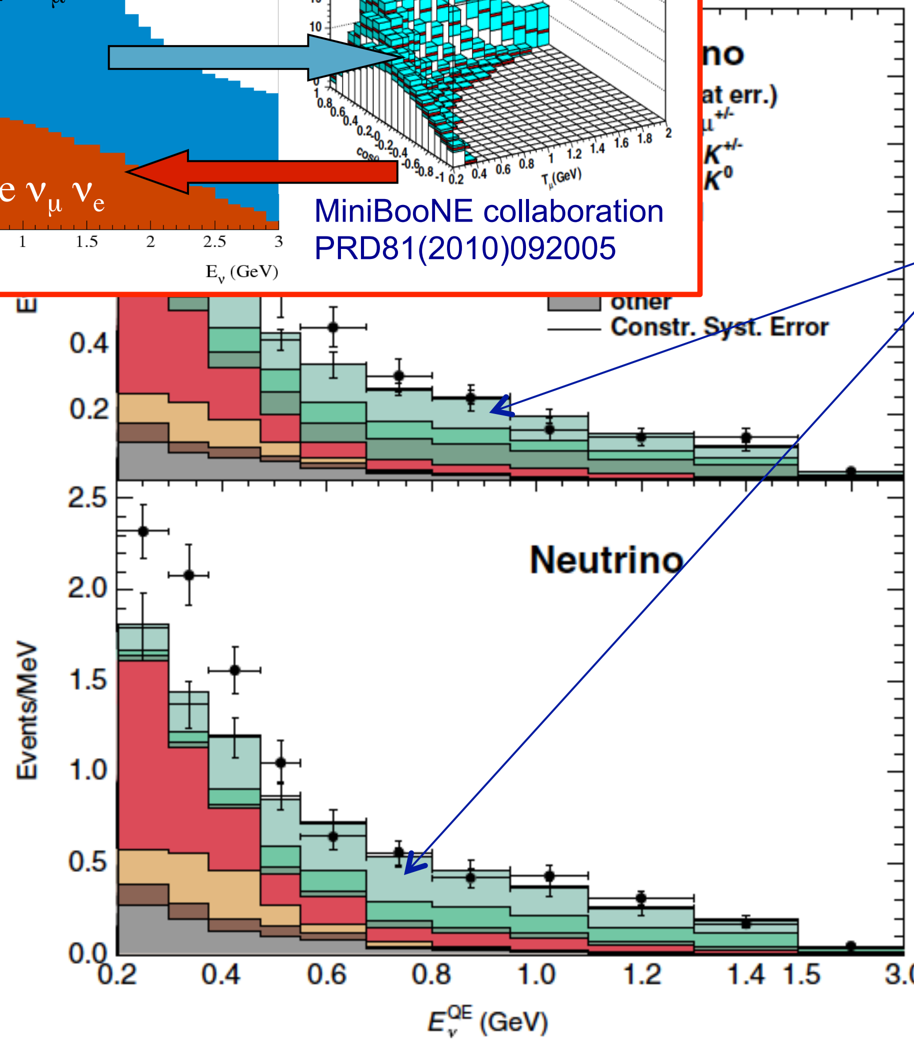
MiniBooNE obs
excesses in bo

Neutrino mode
162.0 ± 28.1 ± 3

Antineutrino mo
78.9 ± 20.0 ± 20

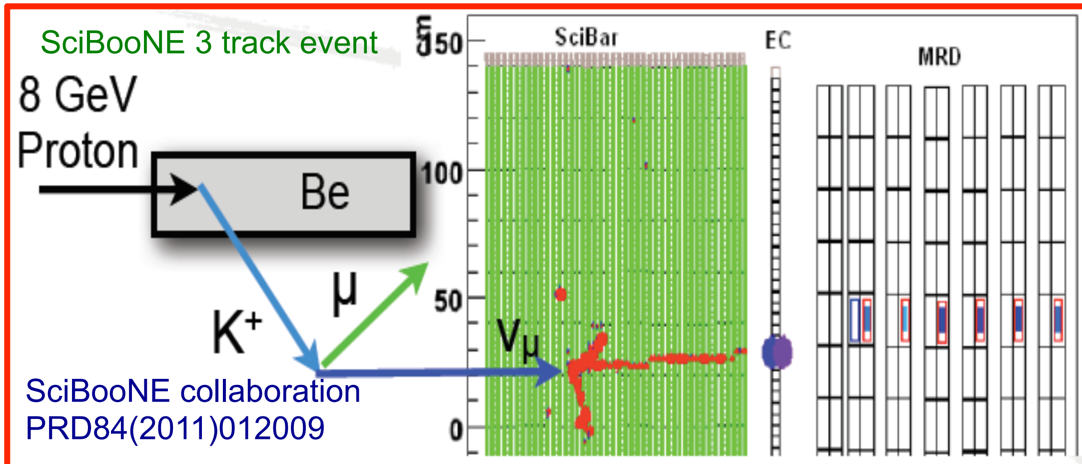


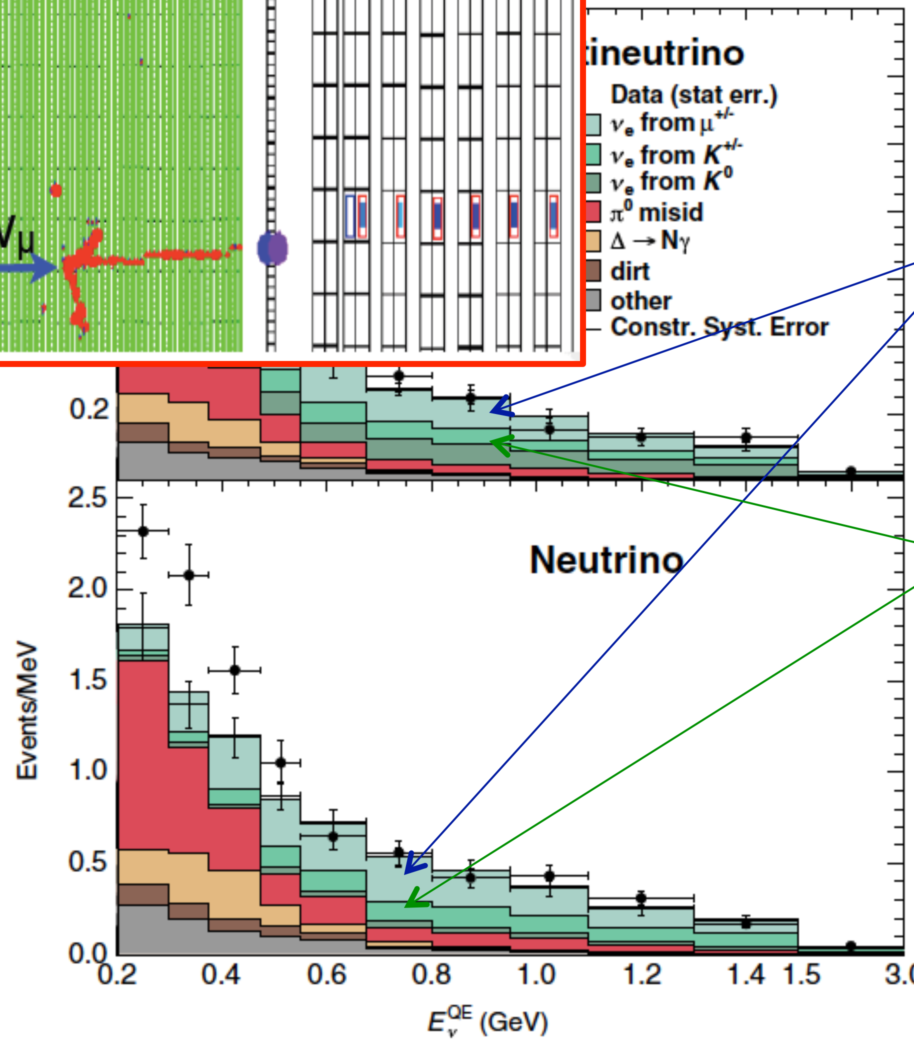
MiniBooNE collaboration
PRD81(2010)092005



ν_e from μ decay is constrained from ν_μCCQE measurement

2. MiniBooNE





ν_e from μ decay is constrained from ν_μCCQE measurement

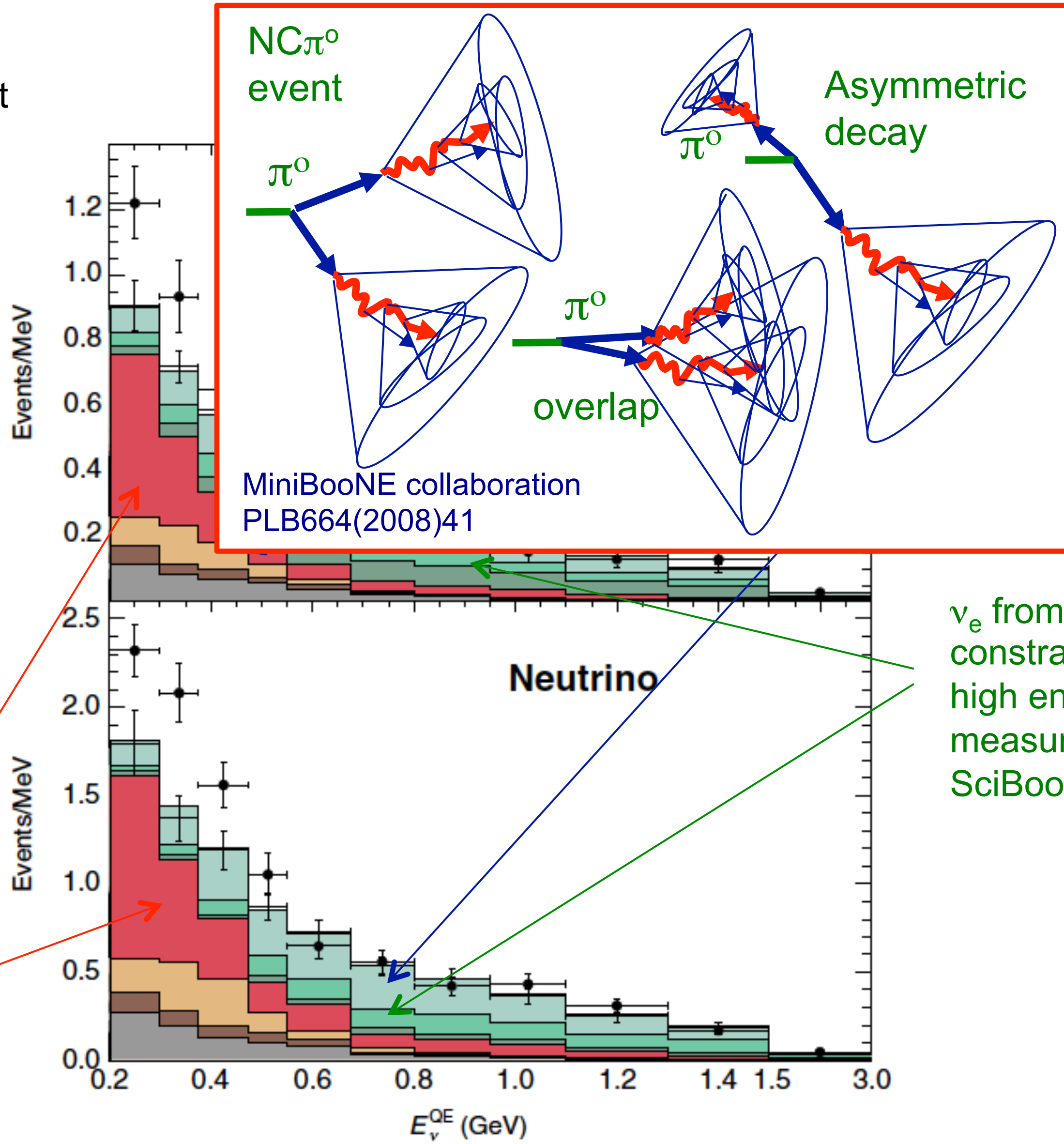
ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

2. MiniBooNE

MiniBooNE observed event excesses in both mode

Neutrino mode
162.0 ± 28.1 ± 38.7 (3.4σ)

Antineutrino mode
78.9 ± 20.0 ± 20.3 (2.8σ)



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

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

2. MiniBooNE

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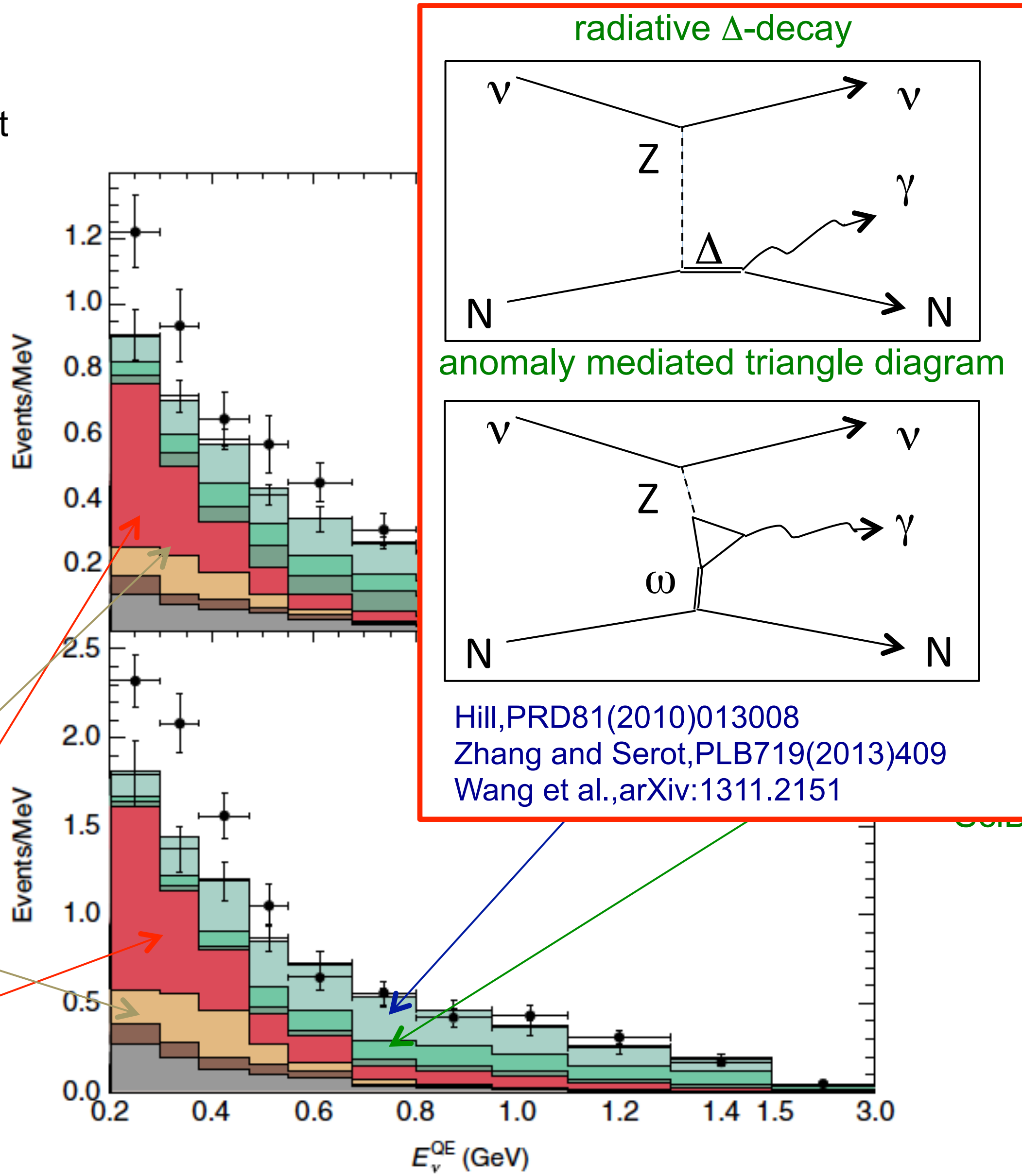

om K decay is
trained from
energy ν_μ event
surement in
oBooNE

Radiative Δ-decay ($\Delta \rightarrow N\gamma$) rate is constrained from measured $NC\pi^o$

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

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University of London

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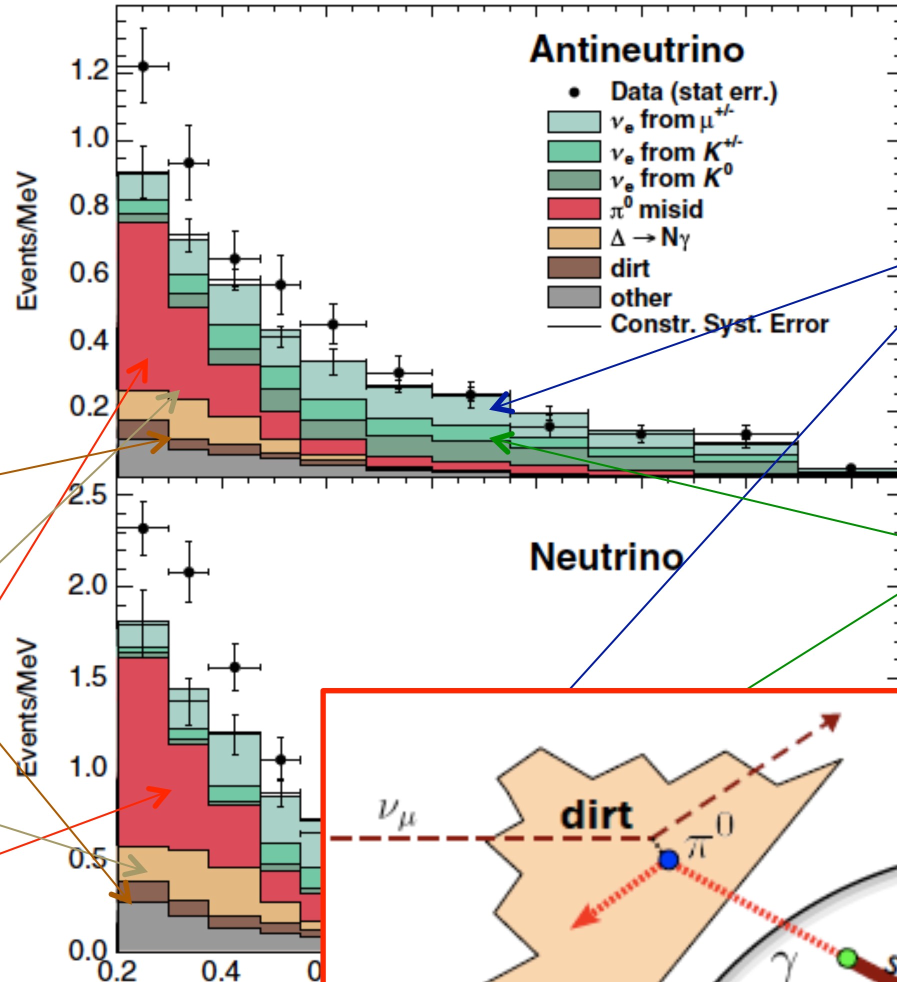


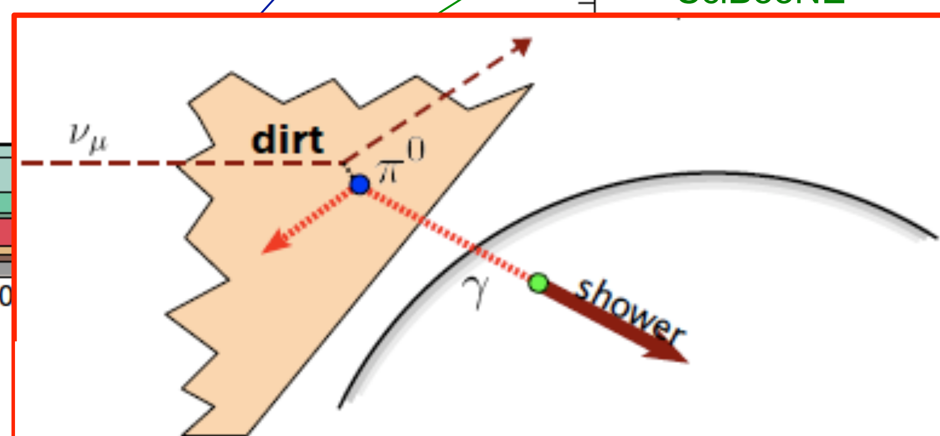
ν_e from μ decay is constrained from ν_μCCQE measurement

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

dirt rate is measured from dirt enhanced data sample

Radiative Δ-decay (Δ→Nγ) rate is constrained from measured NCπ^o

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



Queen Mary University of London

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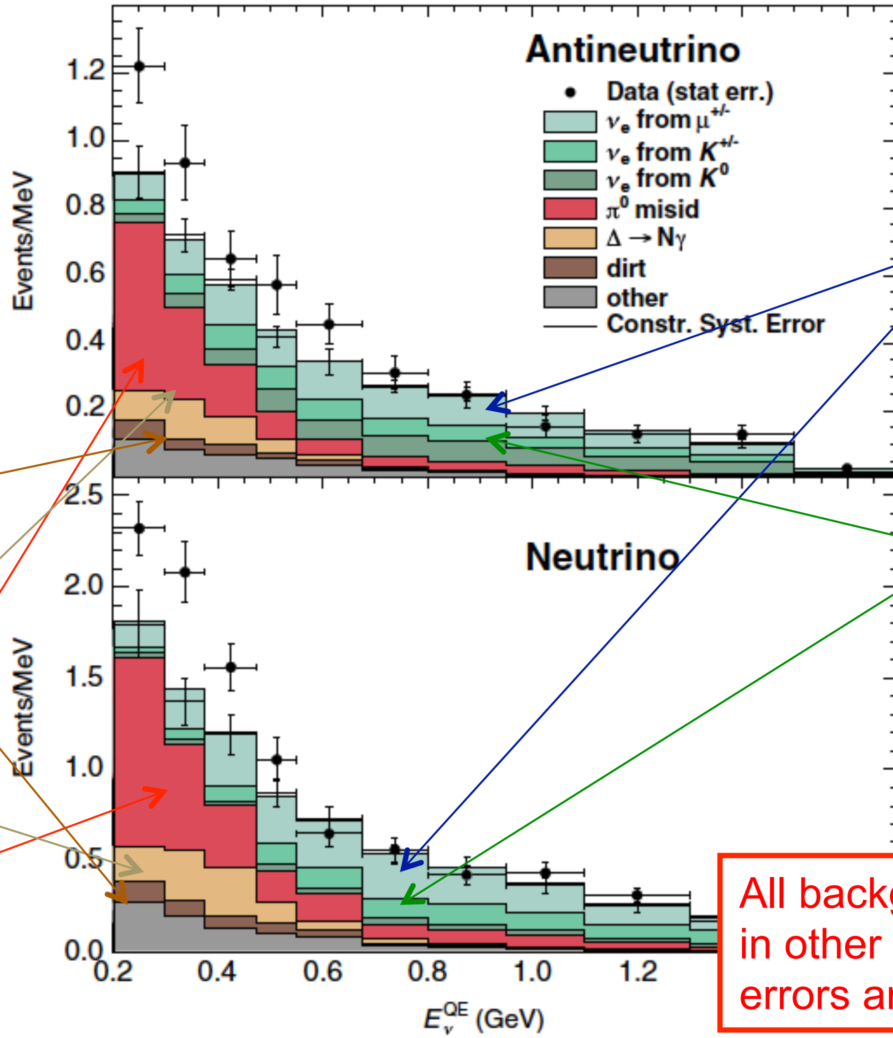

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dirt rate is measured from dirt enhanced data sample

Radiative Δ-decay (Δ→Nγ) rate is constrained from measured NCπ^o

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

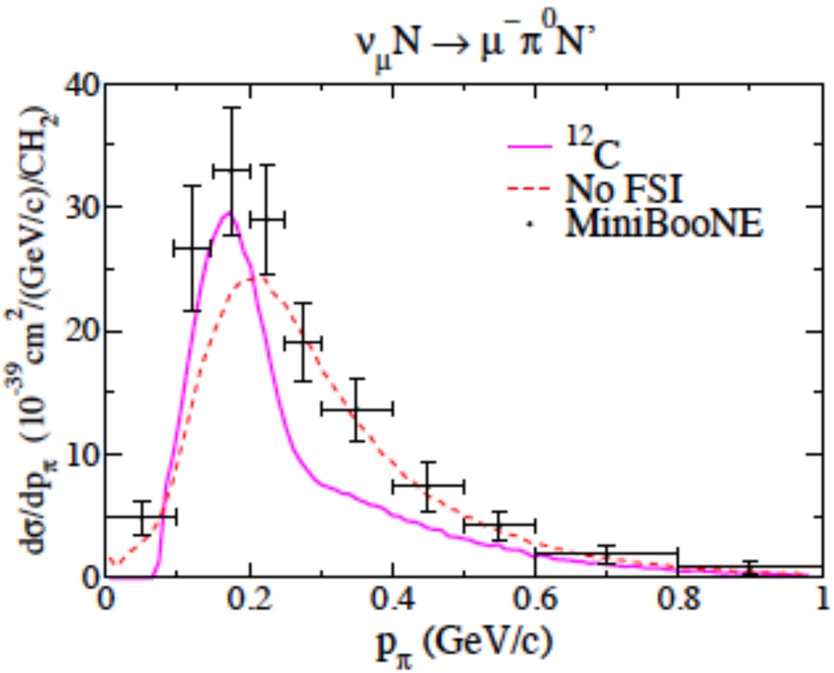
All backgrounds are measured in other data sample and their errors are constrained!

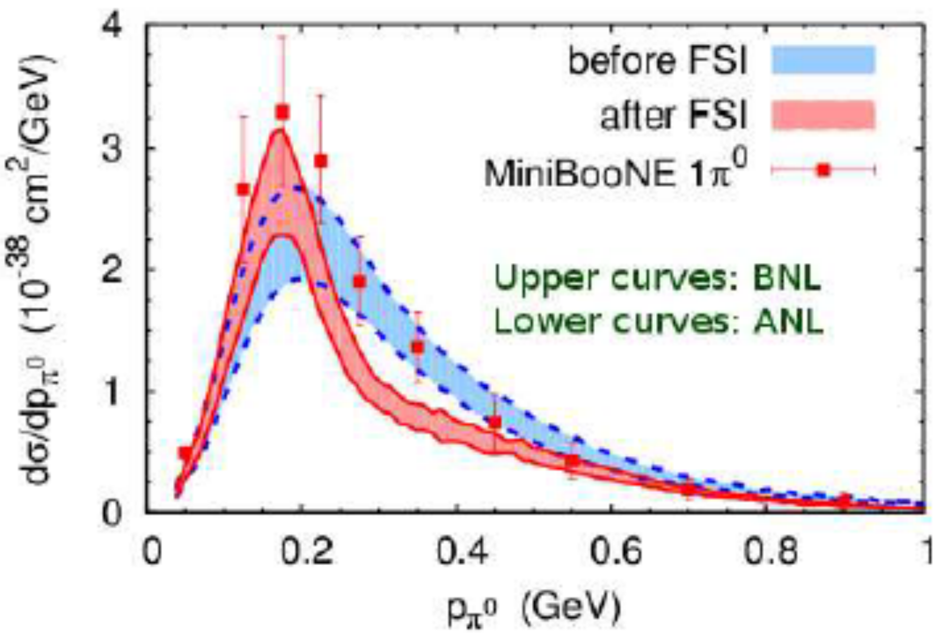
MiniBooNE, PRD81(2010)013005;83(2011)052007;83(2011)052009
Alvarez-Ruso,Hayato,Nieves,ArXiv:1403.2673

3. MiniBooNE neutrino cross section results

MiniBooNE flux-integrated single pion measurements

- Pion kinematics are reconstructed
- It looks data is incompatible with state-of-the-art theories
- One of the "open question in neutrino cross section physics"





MiniBooNE π^o momentum differential cross section of CC1π^o interaction with models

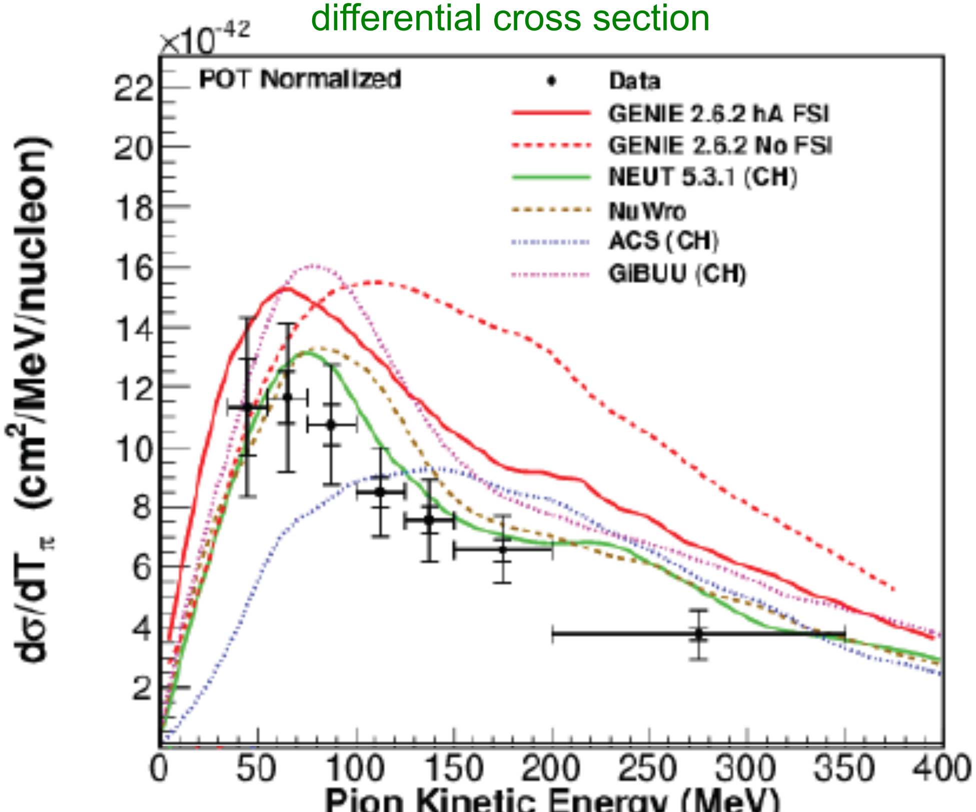
3. MiniBooNE neutrino cross section results

MINERvA flux-integrated single pion measurements

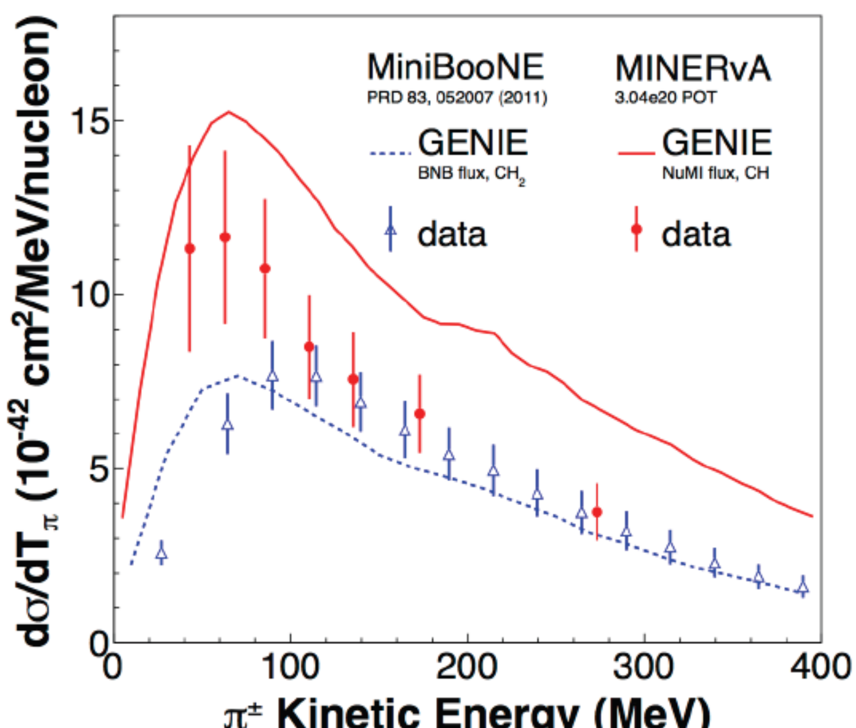
- Recent data from MINERvA are incompatible from mny theories and MiniBooNE data

→ We are overlooking something? (media effect on pion in nucleus)

MINERvA pion flux-integrated differential cross section



MiniBooNE-MINERvA flux-integrated differential cross section comparison



3. MiniBooNE neutrino cross section results

MiniBooNE flux-integrated anti-neutrino cross section measurements

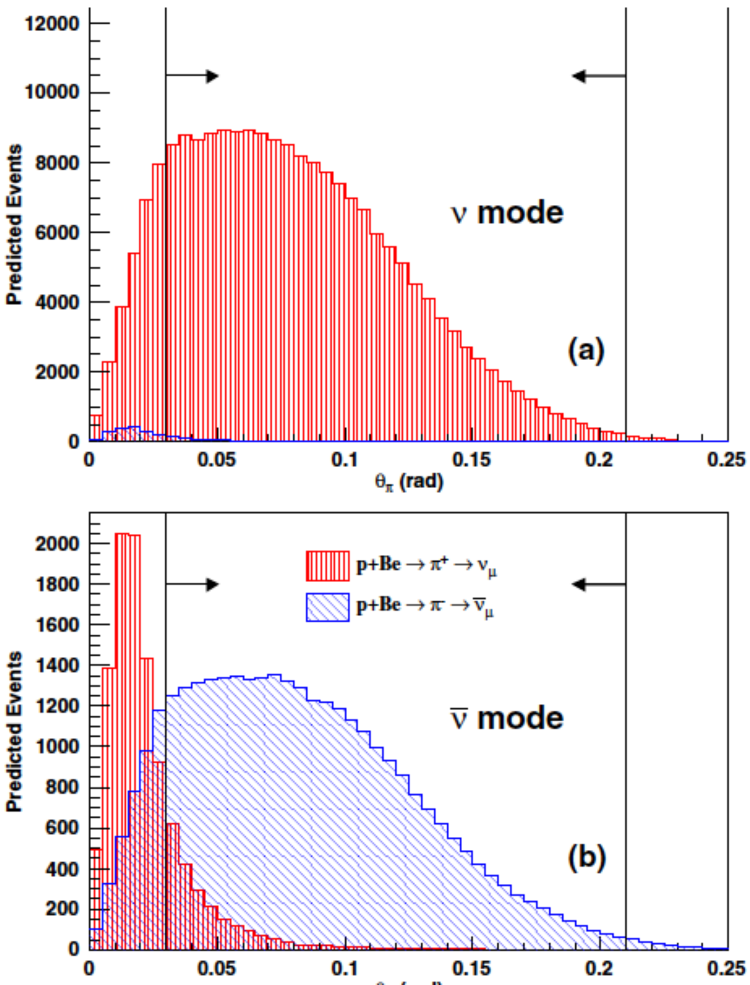
- MiniBooNE demonstrated statistical charge separation to understand "wrong sign" background
- Critical for delta CP oscillation physics (→ anti-neutrino beam)

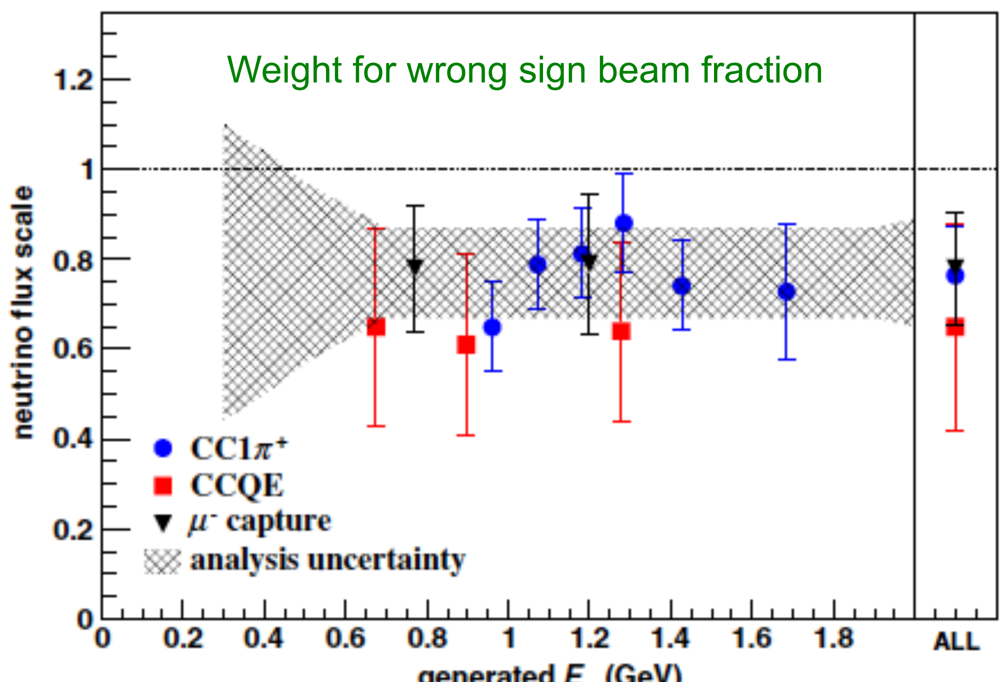
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + p + \pi^-$$

high nuclear absorption

$$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$$

decay (delayed electron)





MiniBooNE, FERMILAB-PROPOSAL-1032
Karagiorgi, New Frontier Physics 2014

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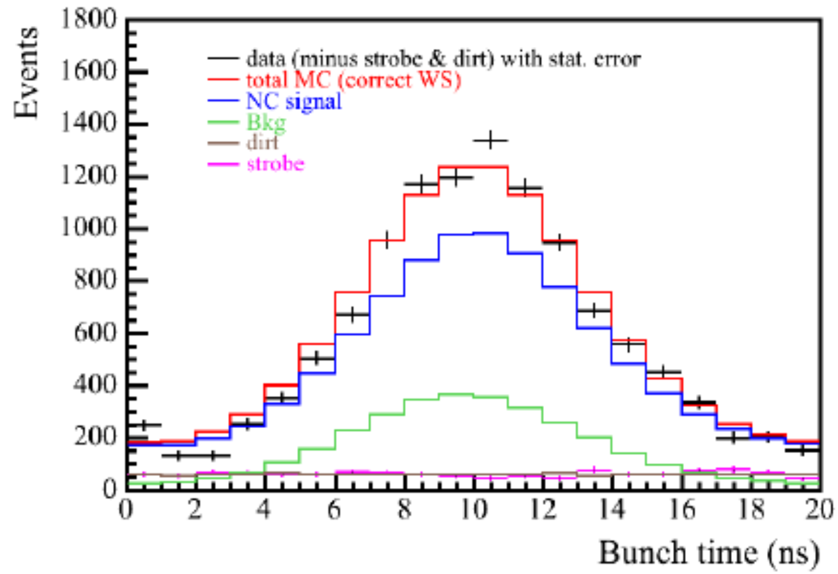
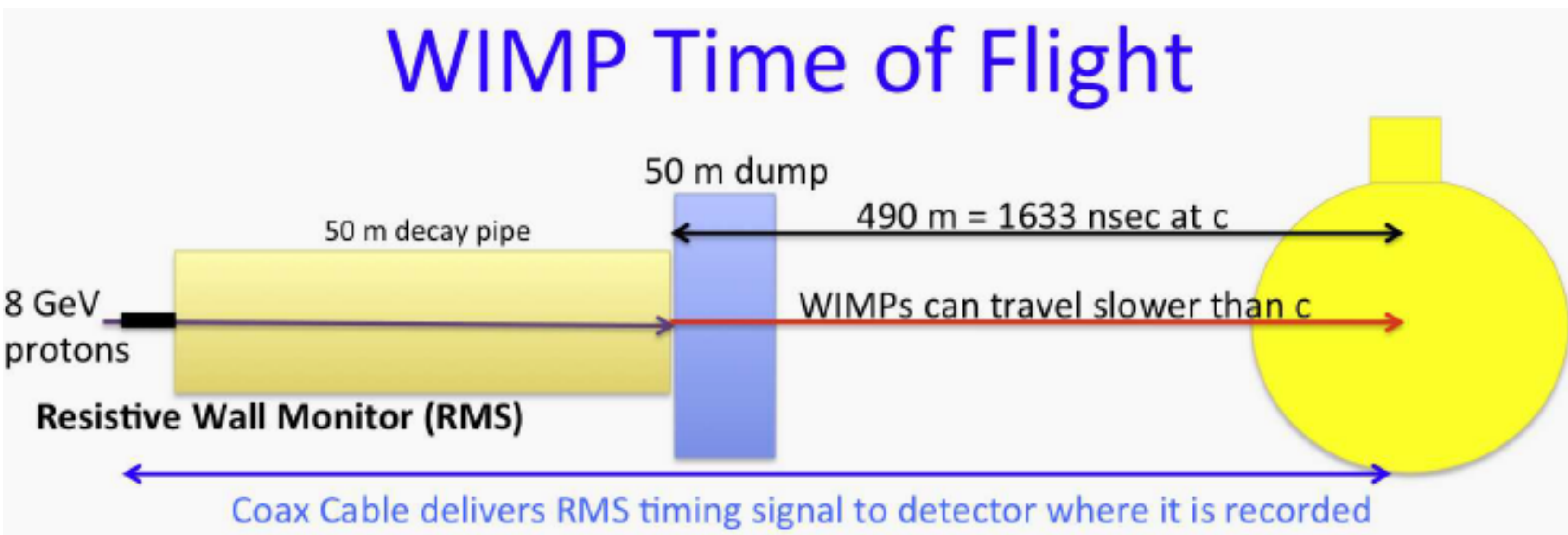
Light WIMP signature ~ neutral current-like interaction
- Neutrino background can be reduced by "WIMP ToF" in some parameter space.





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The experiment can potentially exclude the “g-2” parameter space.

m_χ < 100 MeV