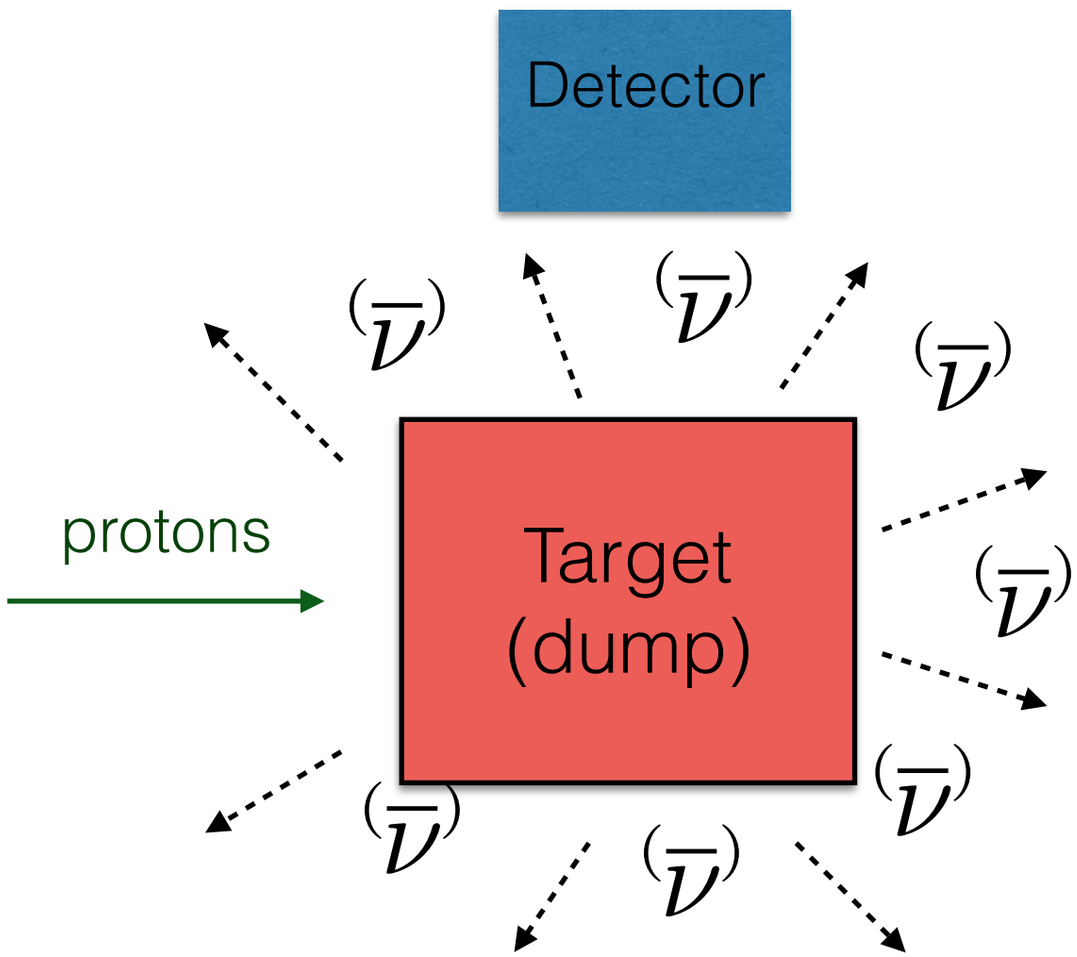
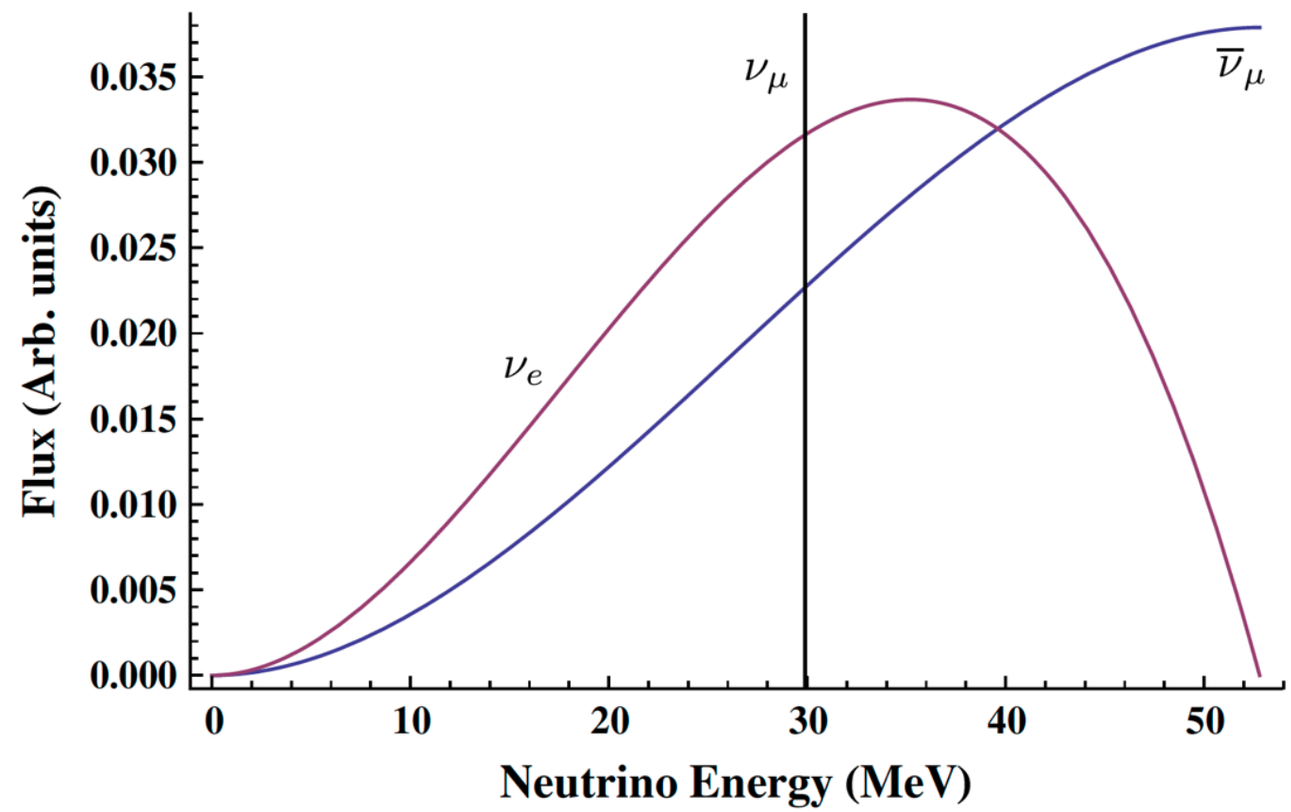
Opportunities with kaon decay-at-rest neutrinos

Joshua Spitz, University of Michigan
FNAL Neutrino Seminar, 10/29/2015

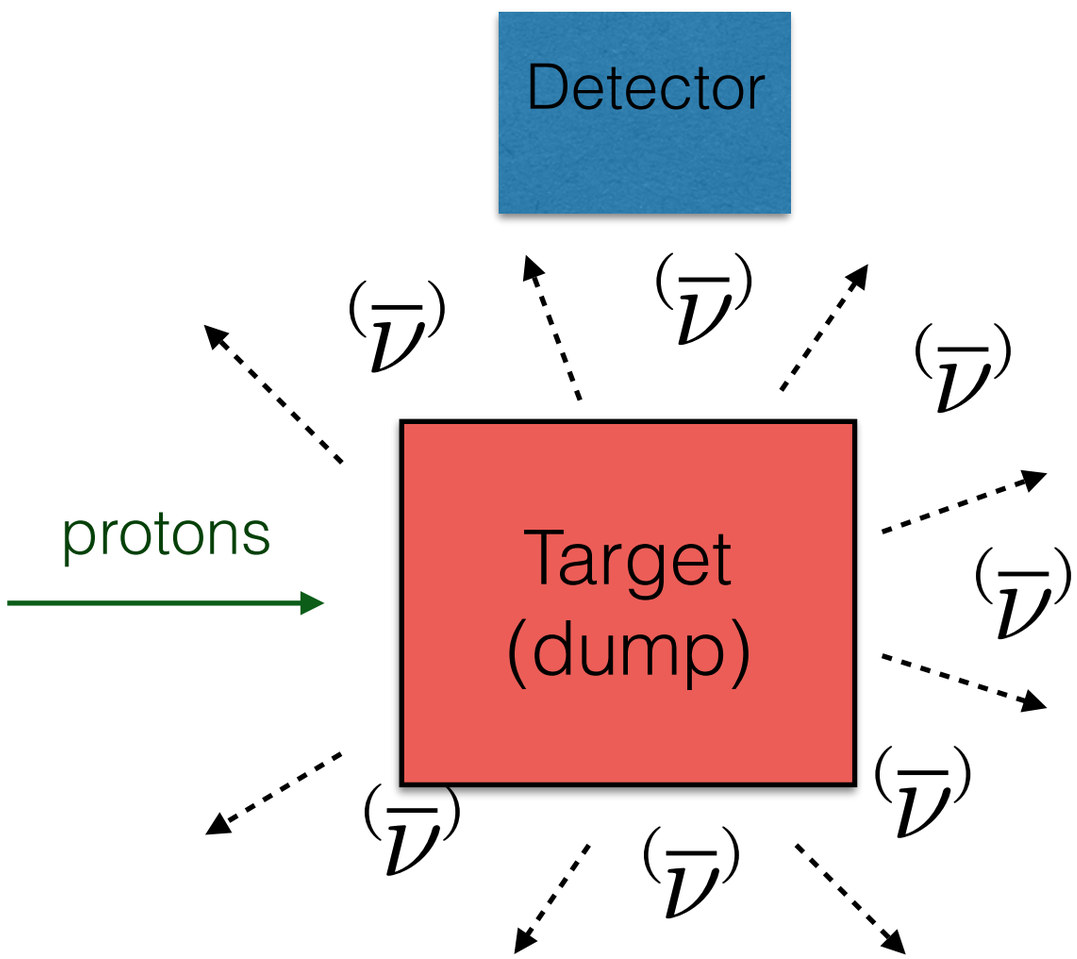
Pion and muon decay-at-rest neutrinos

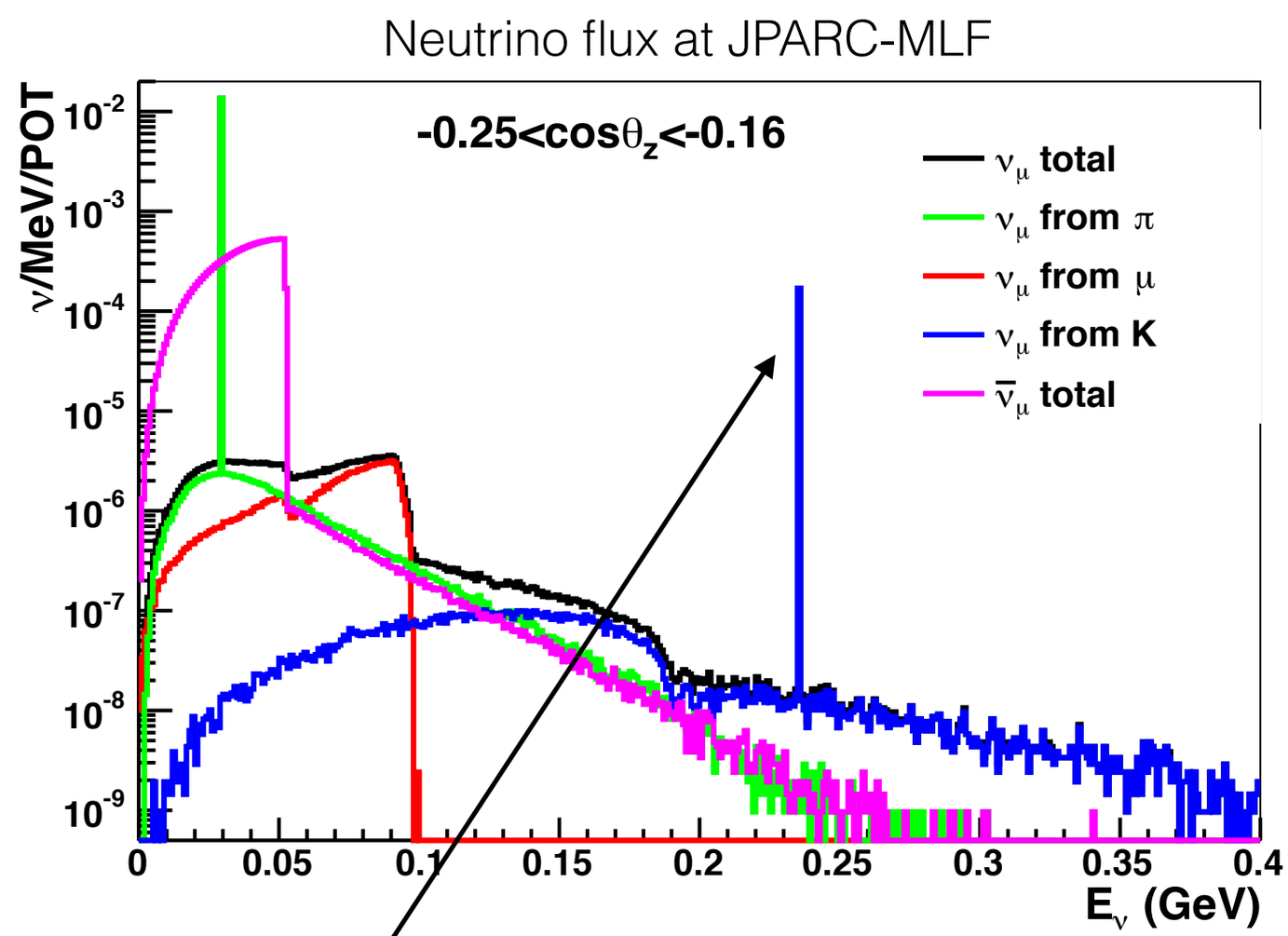




$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

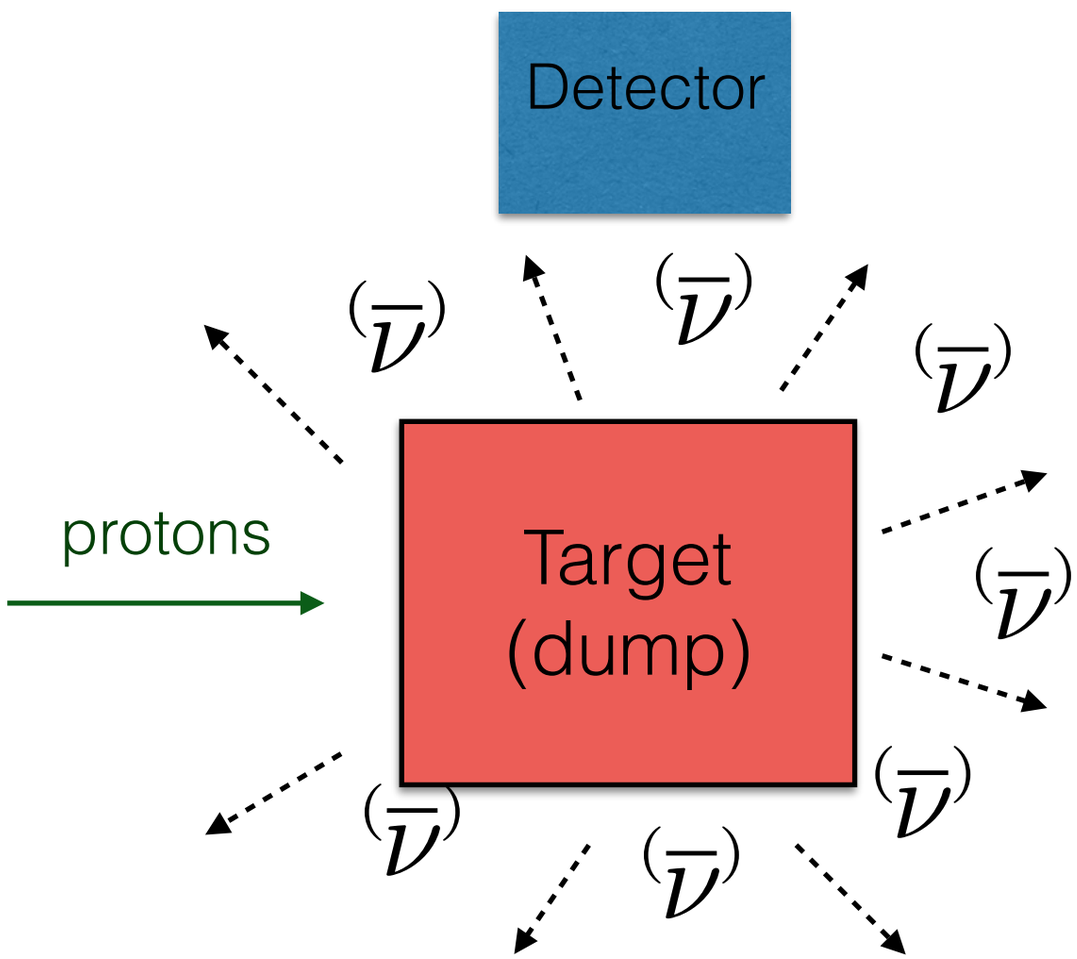
Kaon decay-at-rest neutrinos



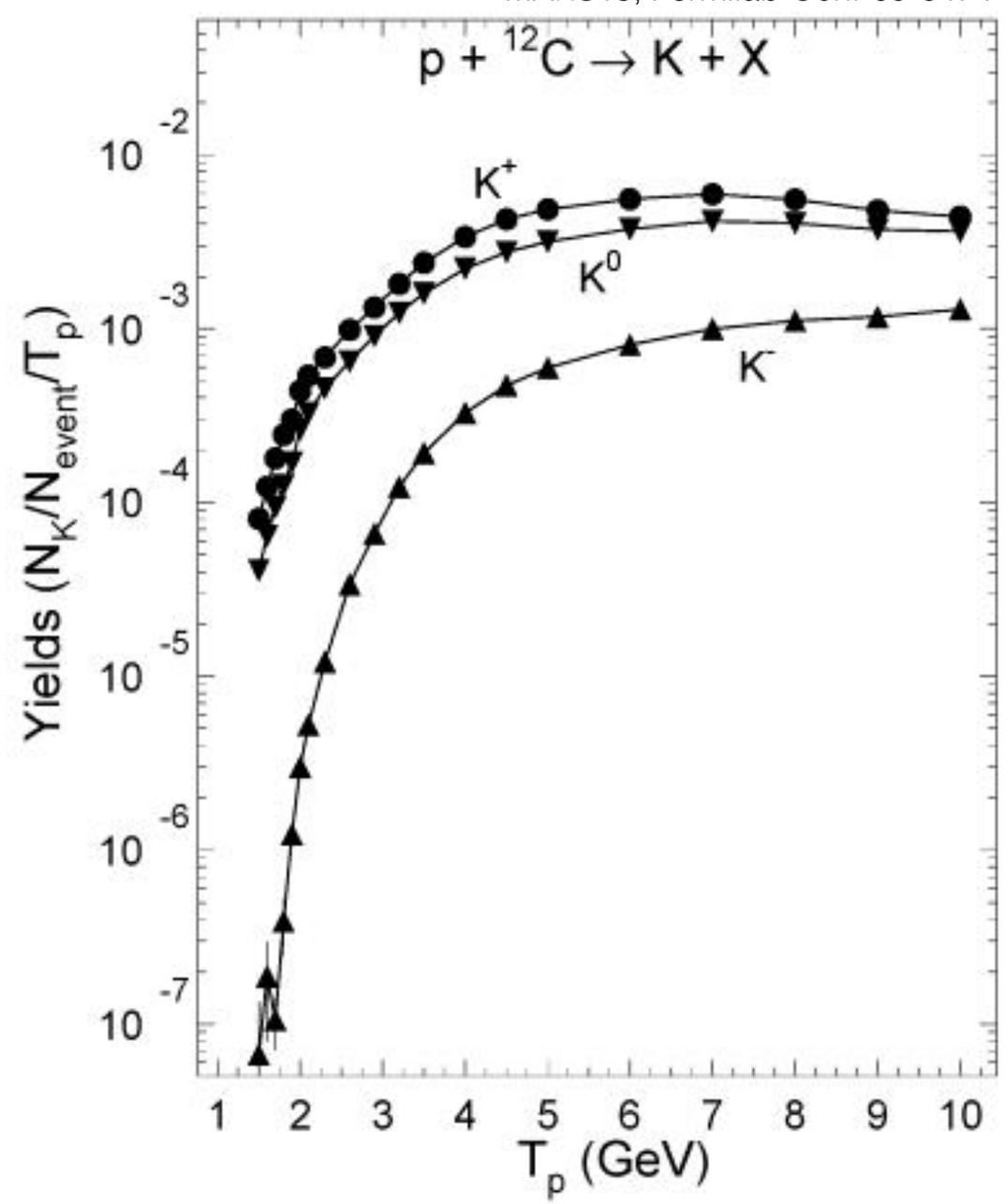


$K^+ \rightarrow \mu^+ \nu_\mu$ (branching ratio=64%)

Kaon production



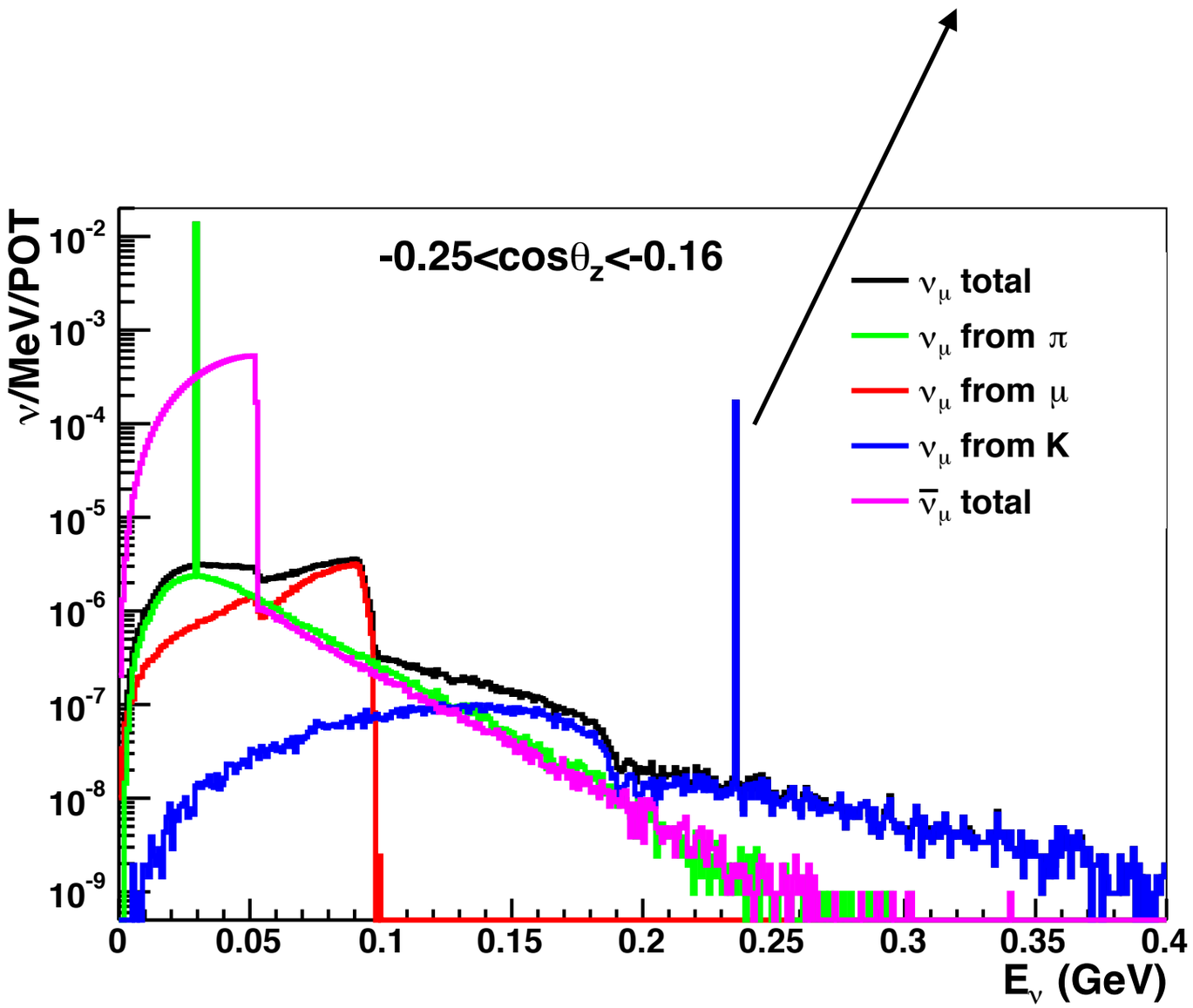
MARS15, Fermilab-Conf-09-647-APC



$K^+ \to \mu^+ \nu_\mu$ (branching ratio=64%)

Basic outline of this talk

This neutrino is a completely unique and important source for multiple physics measurements.

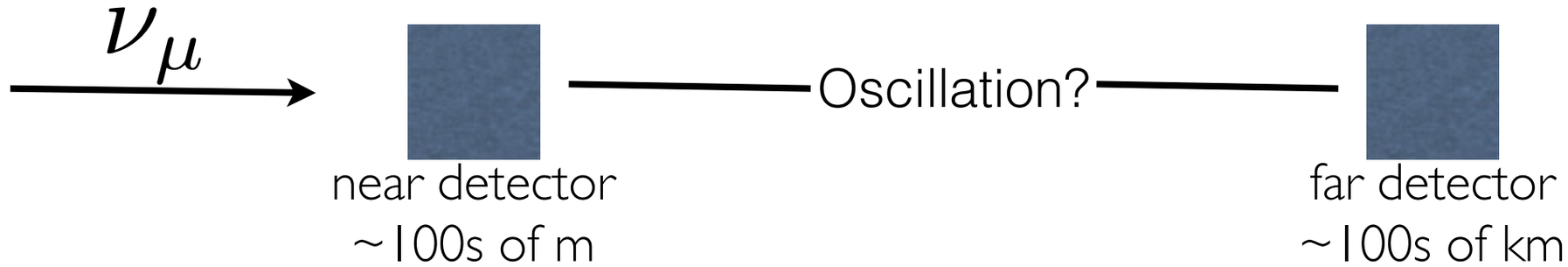


Neutrino flux at JPARC-MLF

Reminder

Compare these ratios
as a function of energy

$\nu_e : \nu_\mu$? ⟷ $\nu_e : \nu_\mu$?



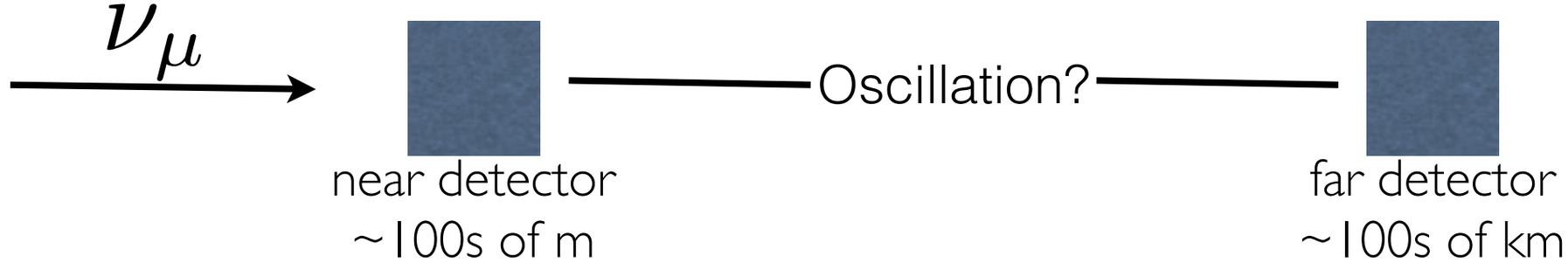
CP violation in the
lepton sector?

$$P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e] \ ?$$

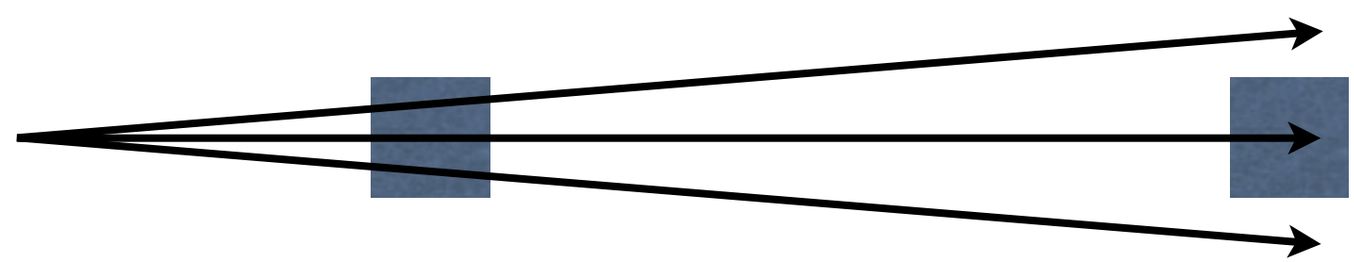
A problem

Compare these ratios
as a function of energy

$\nu_e : \nu_\mu$? ⟷ $\nu_e : \nu_\mu$?



The near and far fluxes are inherently different! So, we need to rely on cross section knowledge for a proper comparison.



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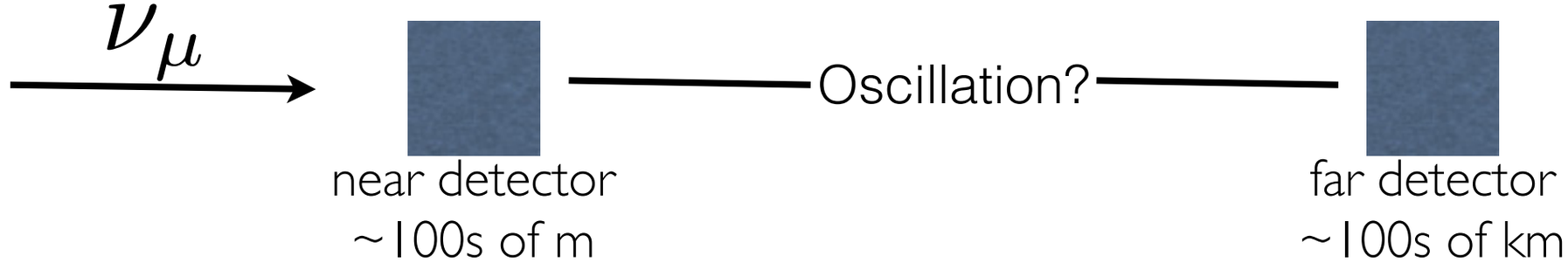

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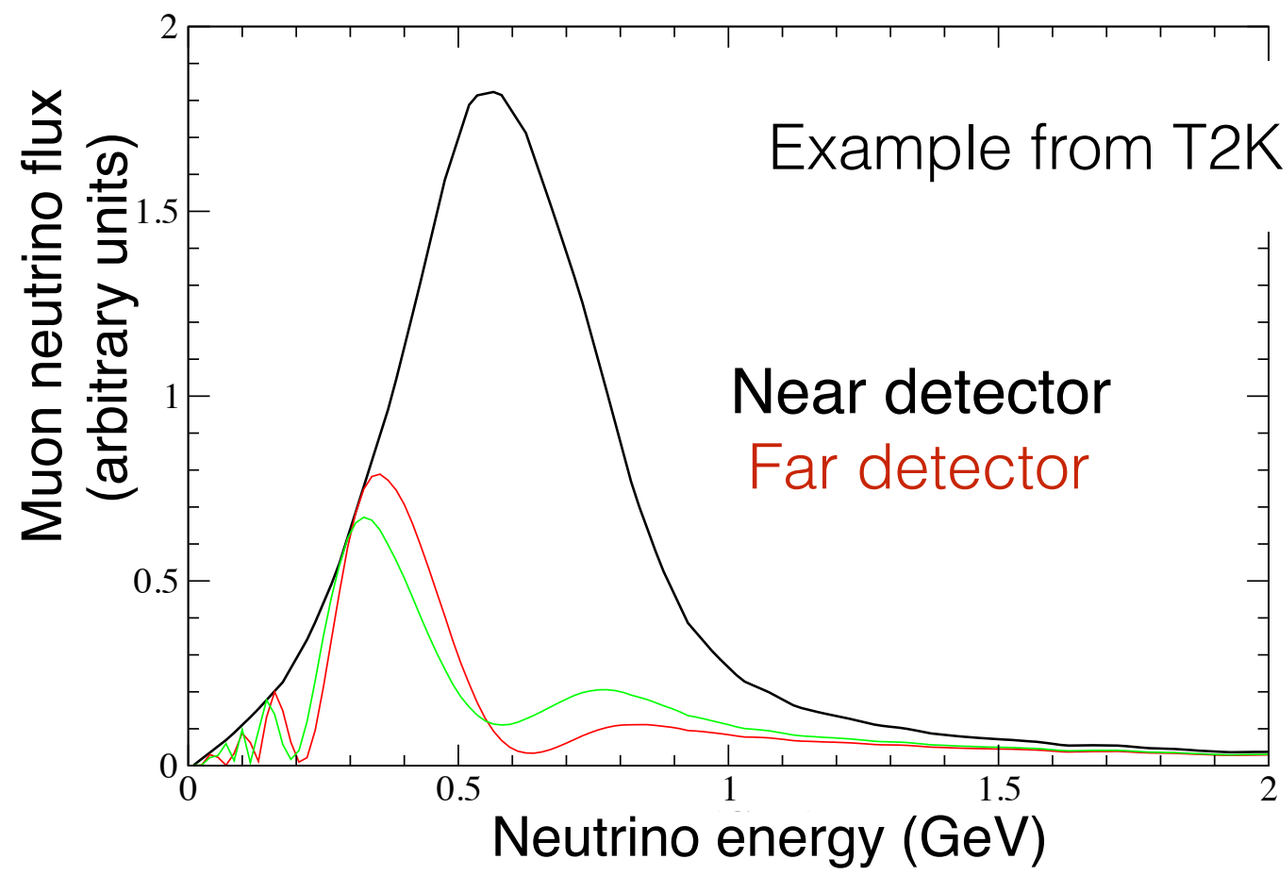

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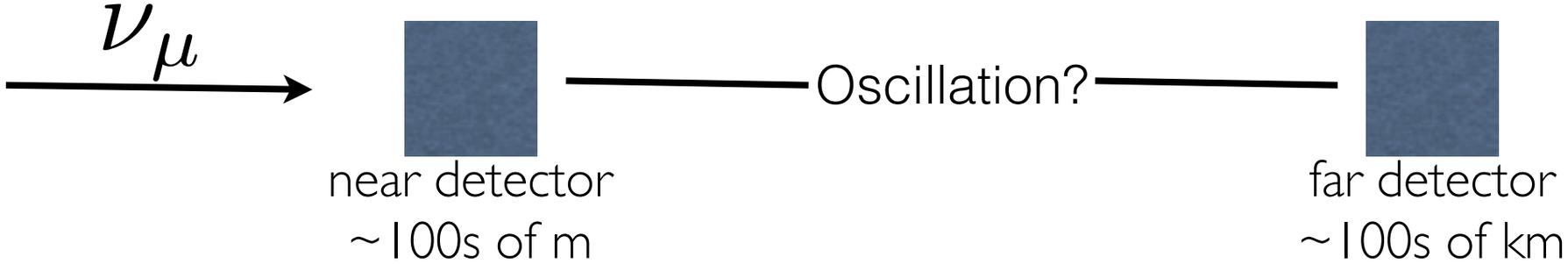
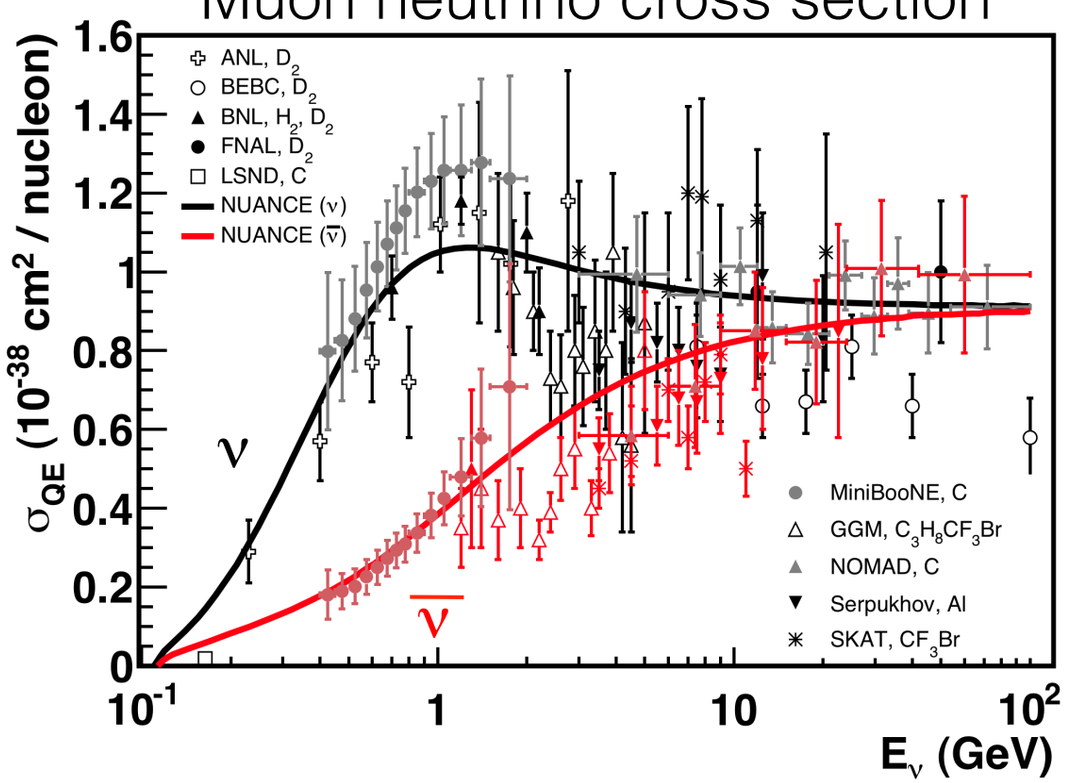
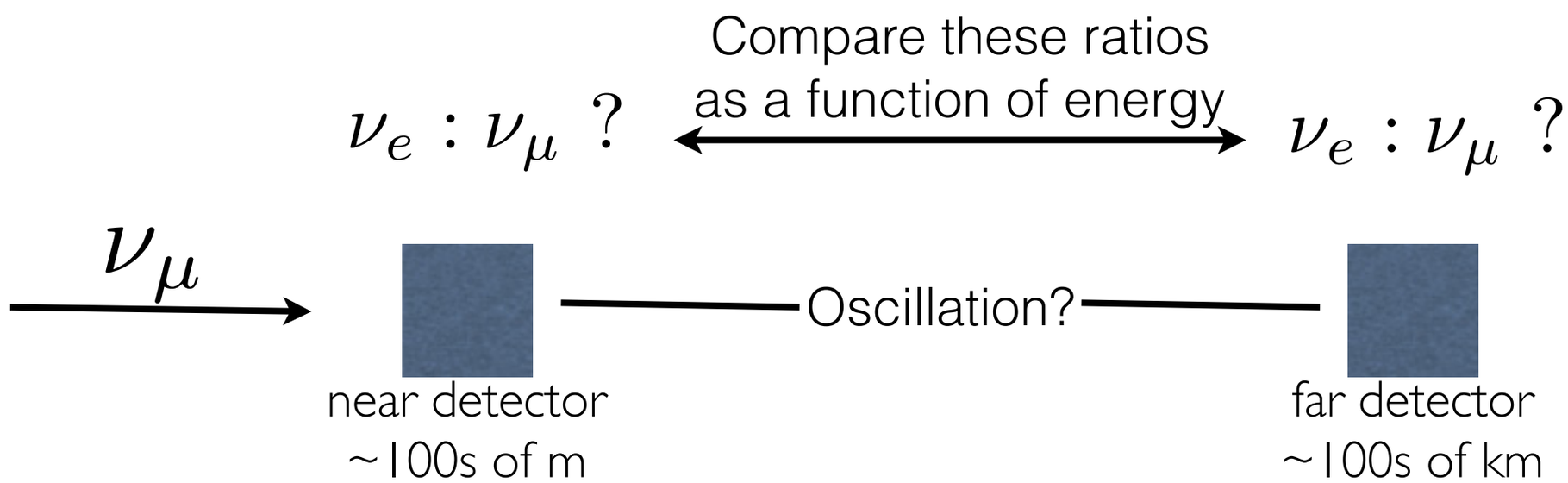


Muon neutrino cross section



Our cross section knowledge is quite weak!

Another problem



The oscillation probability is a function of neutrino energy….
but it's hard to reconstruct the energy of the neutrino!

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

$$\frac{\Delta E}{E} > 20\% \text{ is typical}$$

Another problem

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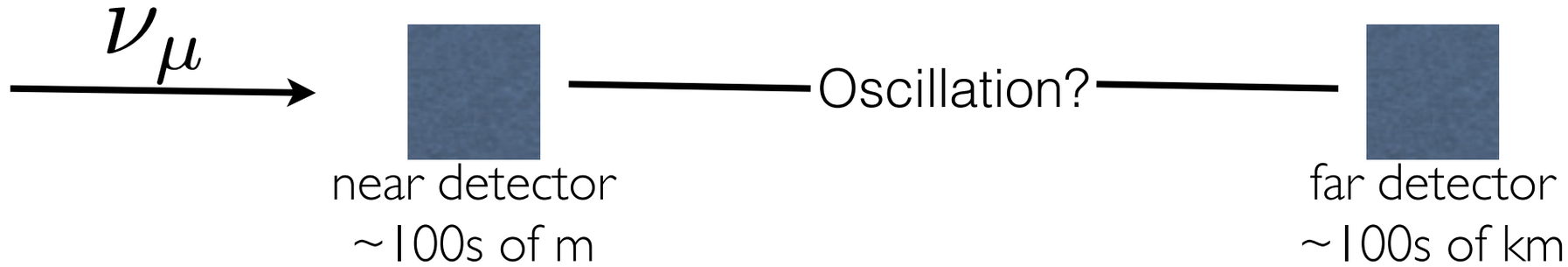

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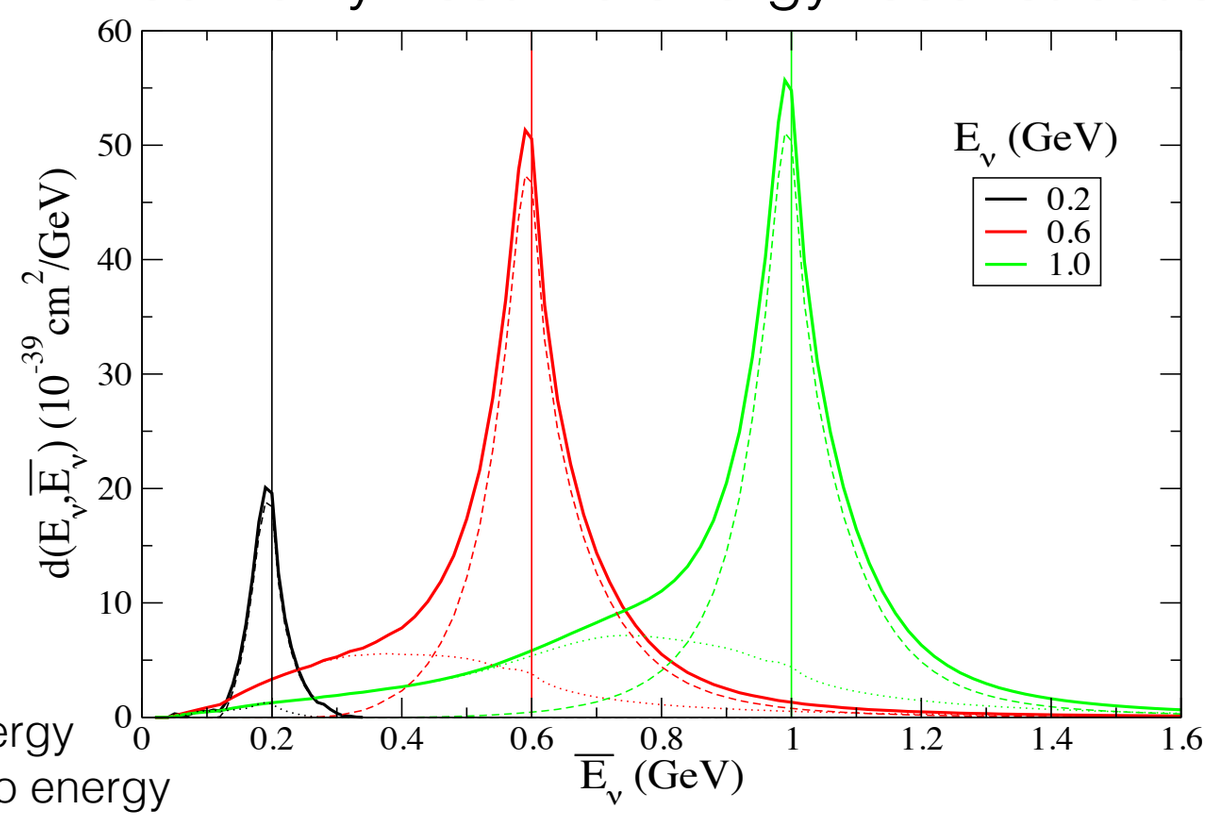
Muon-only neutrino energy reconstruction



vertical lines=true neutrino energy
distributions=reconstructed neutrino energy

M. Martini, M. Ericson, and G. Chanfray, Phys. Rev. D 87, 013009 (2013)

Another problem

Compare these ratios
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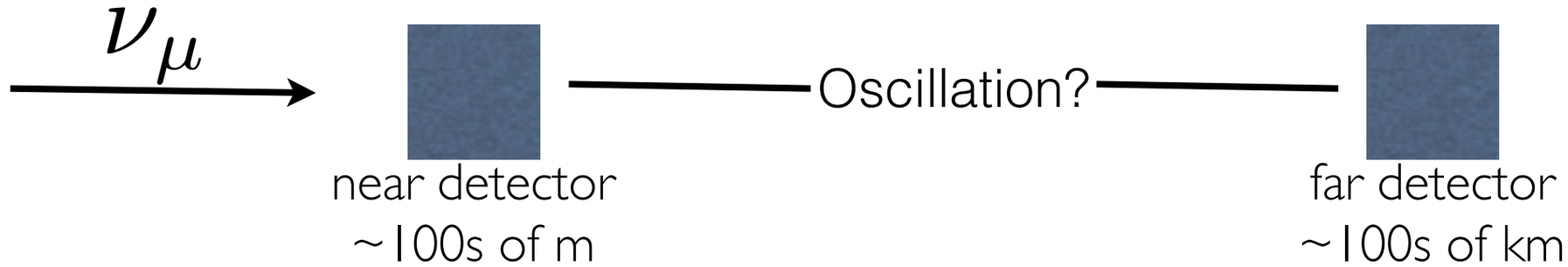
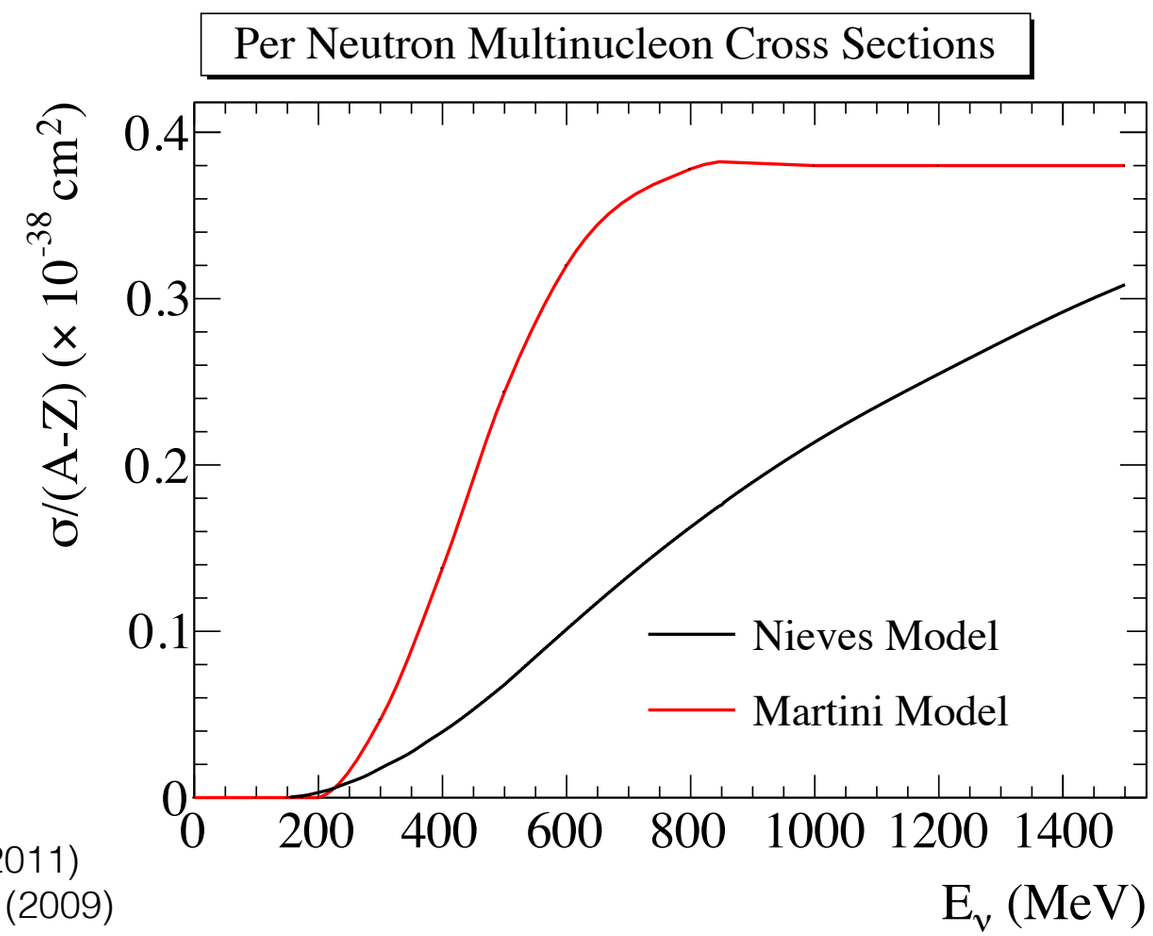


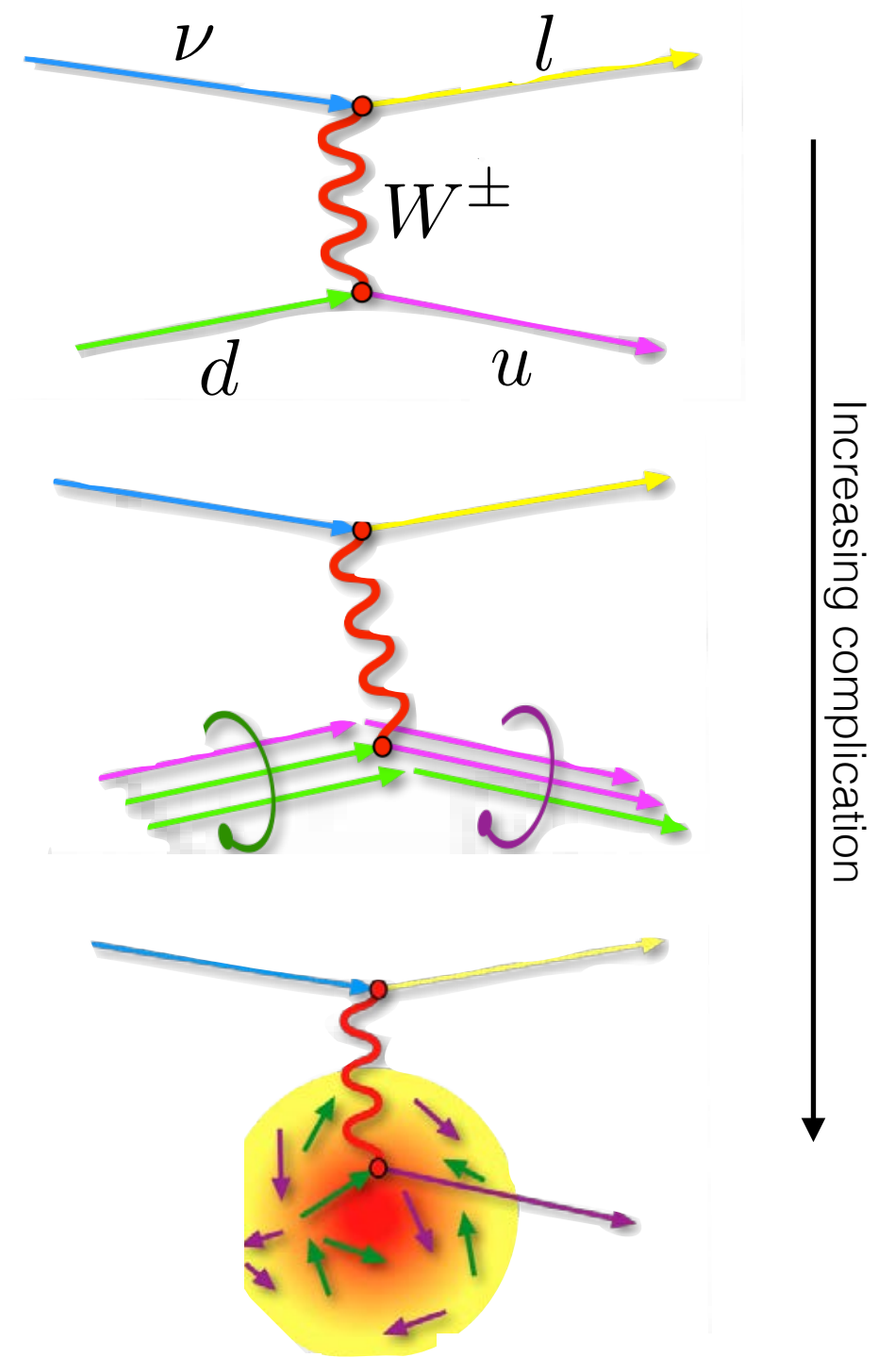
And, the size of the multinucleon effect on energy/xsec is not well understood!



J. Nieves, I. Ruiz Simo, and M.J. Vicente Vacas, PRC 83 045501 (2011)
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)

Calculation and reconstruction issues

- Neutrino interactions with nuclei are complicated!
  - Fermi motion.
  - Correlations between nucleons.
  - Final state interactions.
- Detector limitations
  - Energy resolution.
  - Event classification issues.
  - Cerenkov threshold.



Adapted from K. McFarland

Problem summary

- The systematics associated with the interaction currently lead the uncertainties on the predicted number of electron neutrino appearance candidates in our long baseline experiments.

Error source [%]	$\sin^2 2\theta_{13} = 0.1$
Beam flux and near detector (without ND280 constraint)	2.9 (25.9)
Uncorrelated ν interaction	7.5
Far detector and FSI + SI + PN	3.5
Total	8.8

T2K Collaboration, PRL 112, 061802 (2014)

- These systematics are expected to continue to dominate in future neutrino CP-violation measurements.

Wait, one more problem!

Experiment name	Type	Oscillation channel	Significance
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	3.4σ
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

See 1508.06275 for a nice look at how a new eigenstate can affect a CP violation measurement

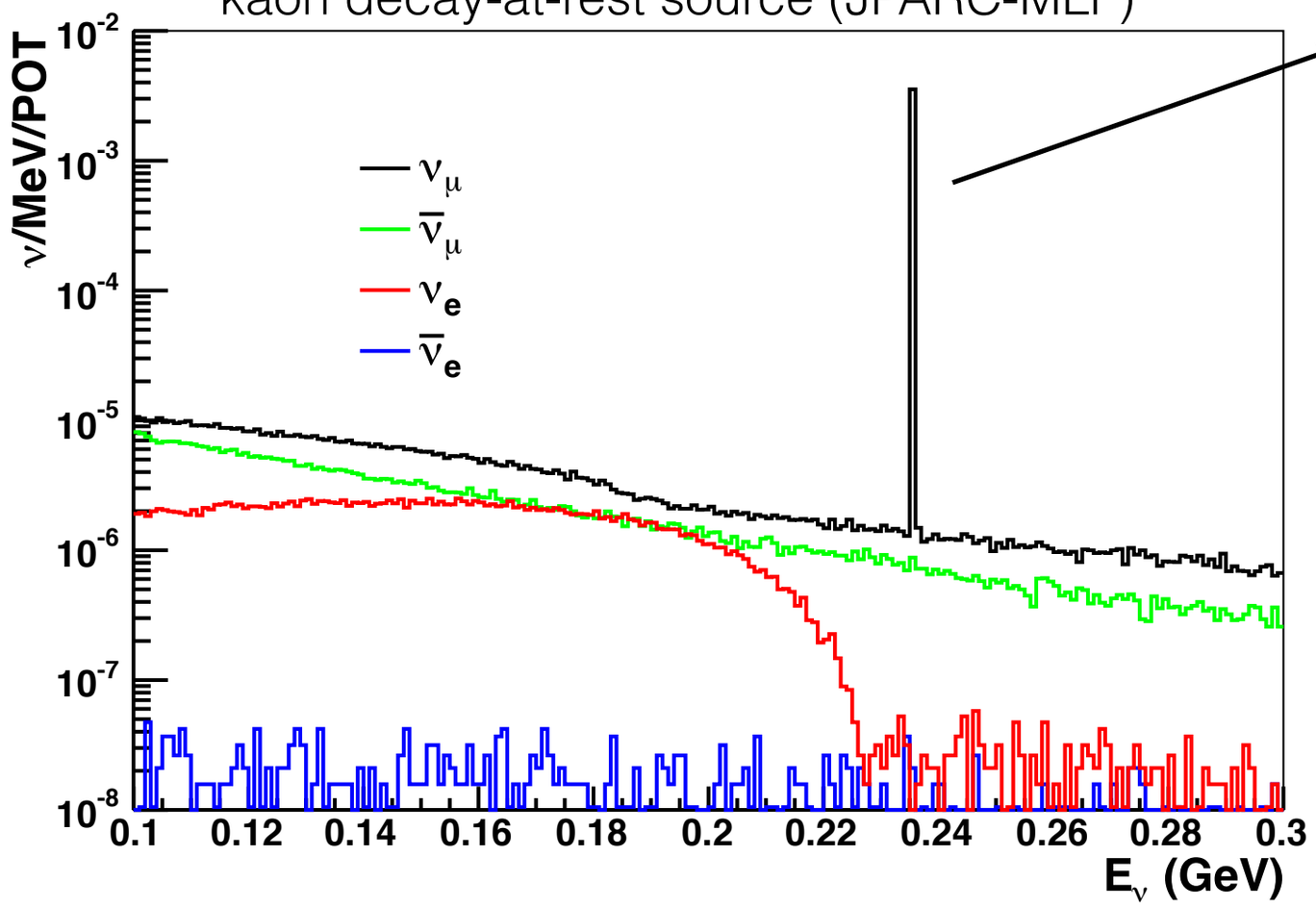
Neutrinos from kaon decay-at-rest can help!

- Cross section and energy reconstruction problems.
- The sterile neutrino problem.

Cross section measurements with monoenergetic muon neutrinos

J. Spitz, Phys. Rev. D 89 073007 (2014)

Neutrino flux from typical
kaon decay-at-rest source (JPARC-MLF)



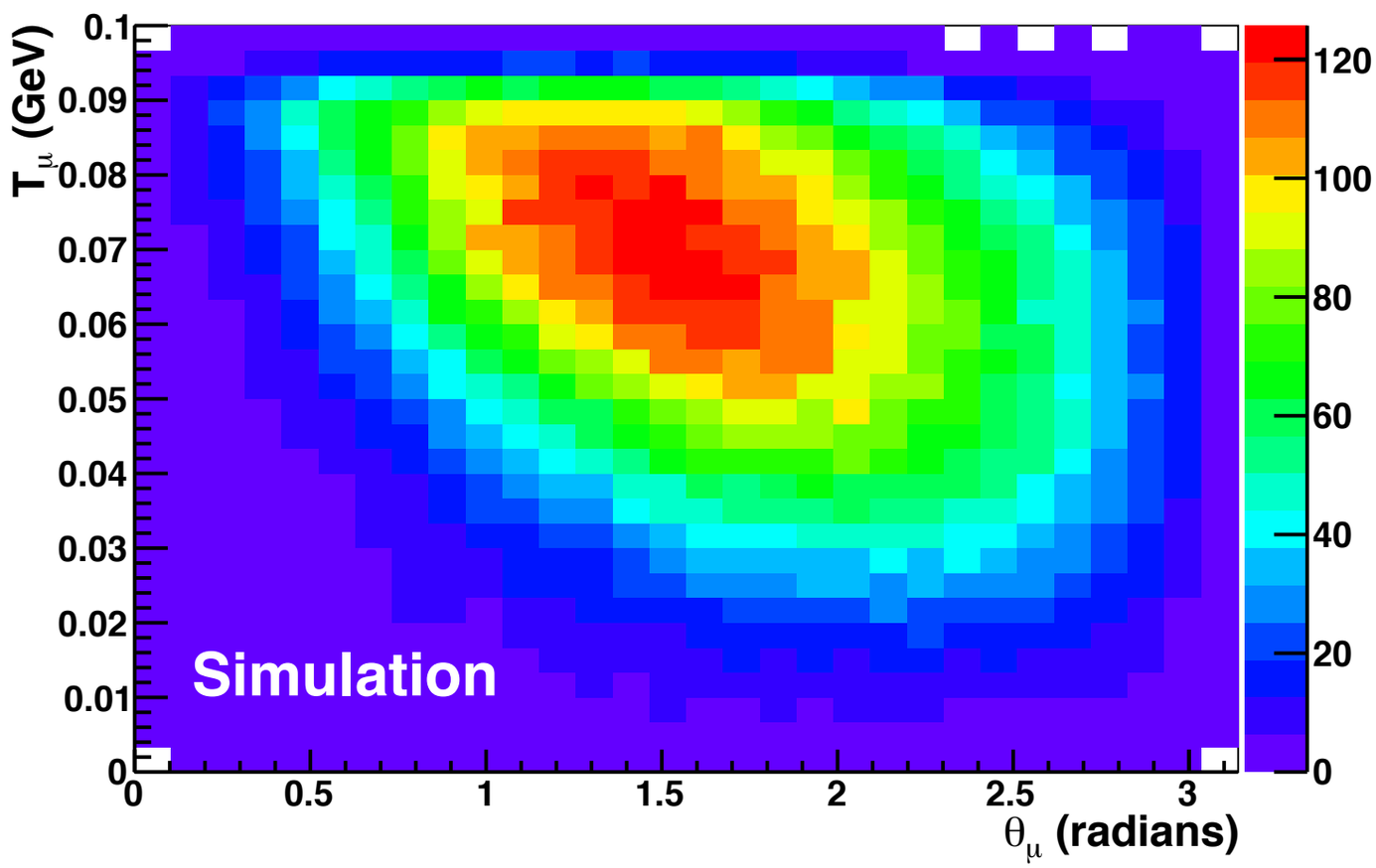
This unique neutrino can be used to provide a set of cross section measurements at a known-energy.

- Reducing systematics associated with near/far comparison.
- Neutrino as a probe of the nucleus.
  - For the first time ever, we can probe the nucleus with a known-energy (muon) neutrino.

Cross section measurements

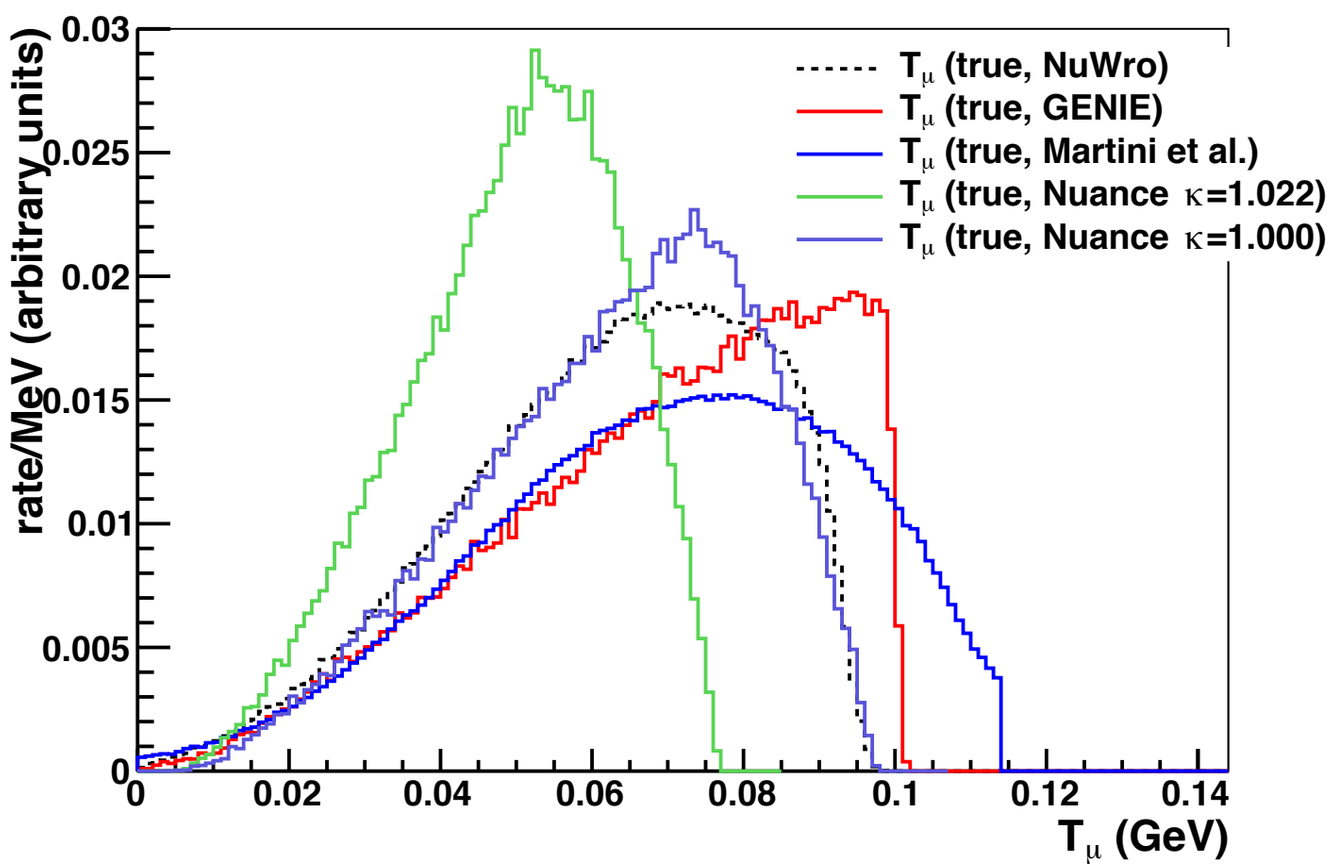
- The 236 MeV muon neutrino can provide a map of muon angle and kinetic energy for a known neutrino energy. This “standard candle” would be unprecedented.
- This is especially relevant for those experiments which solely rely on muon kinematics for reconstructing the neutrino energy.

J. Spitz, Phys. Rev. D 89 073007 (2014)

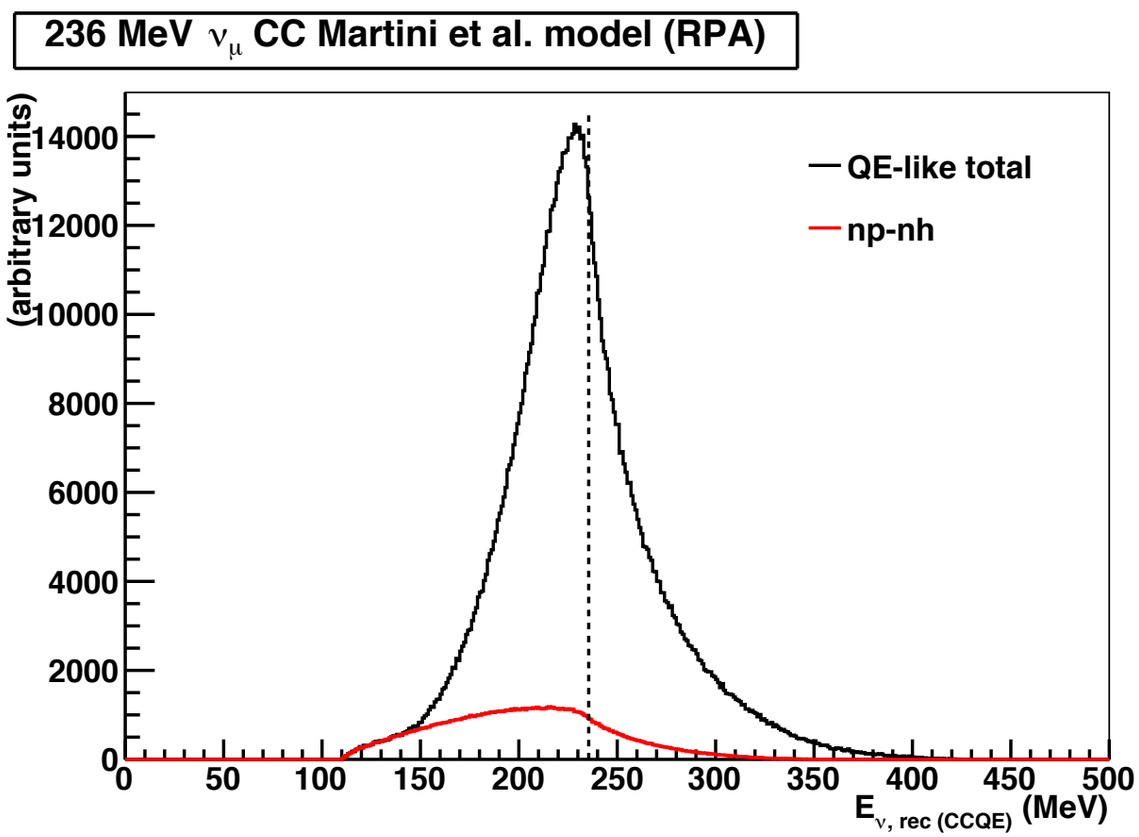


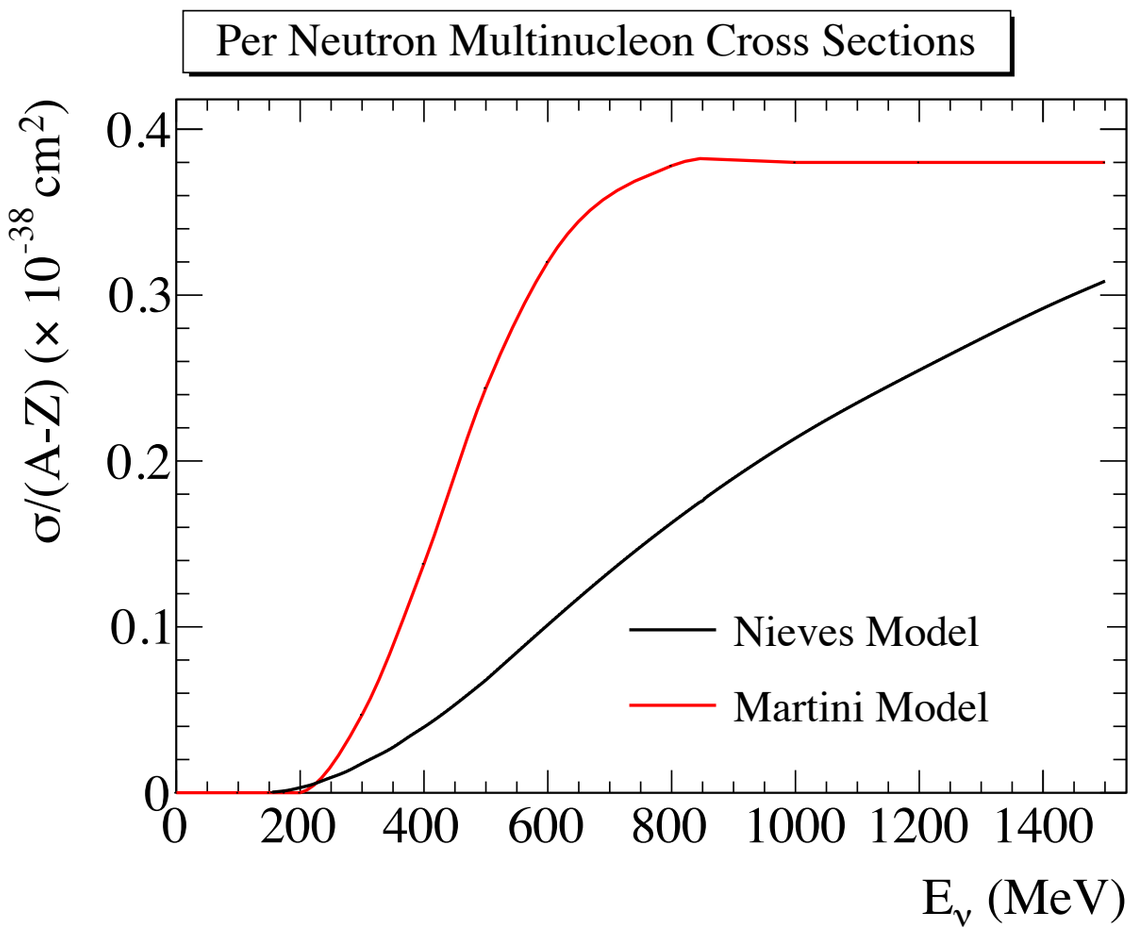
KDAR kinematics

- This neutrino energy (236 MeV) is a challenging one to deal with theoretically.
- The neutrino energy, or rather the characteristic energy transfer, is right at the transition between our neutrino-on-nucleus and neutrino-on-nucleon frame-works. The impulse approximation, in which it is assumed that the neutrino interacts with a single nucleon, breaks down at these lower energies.
- The various generators/models do not agree!



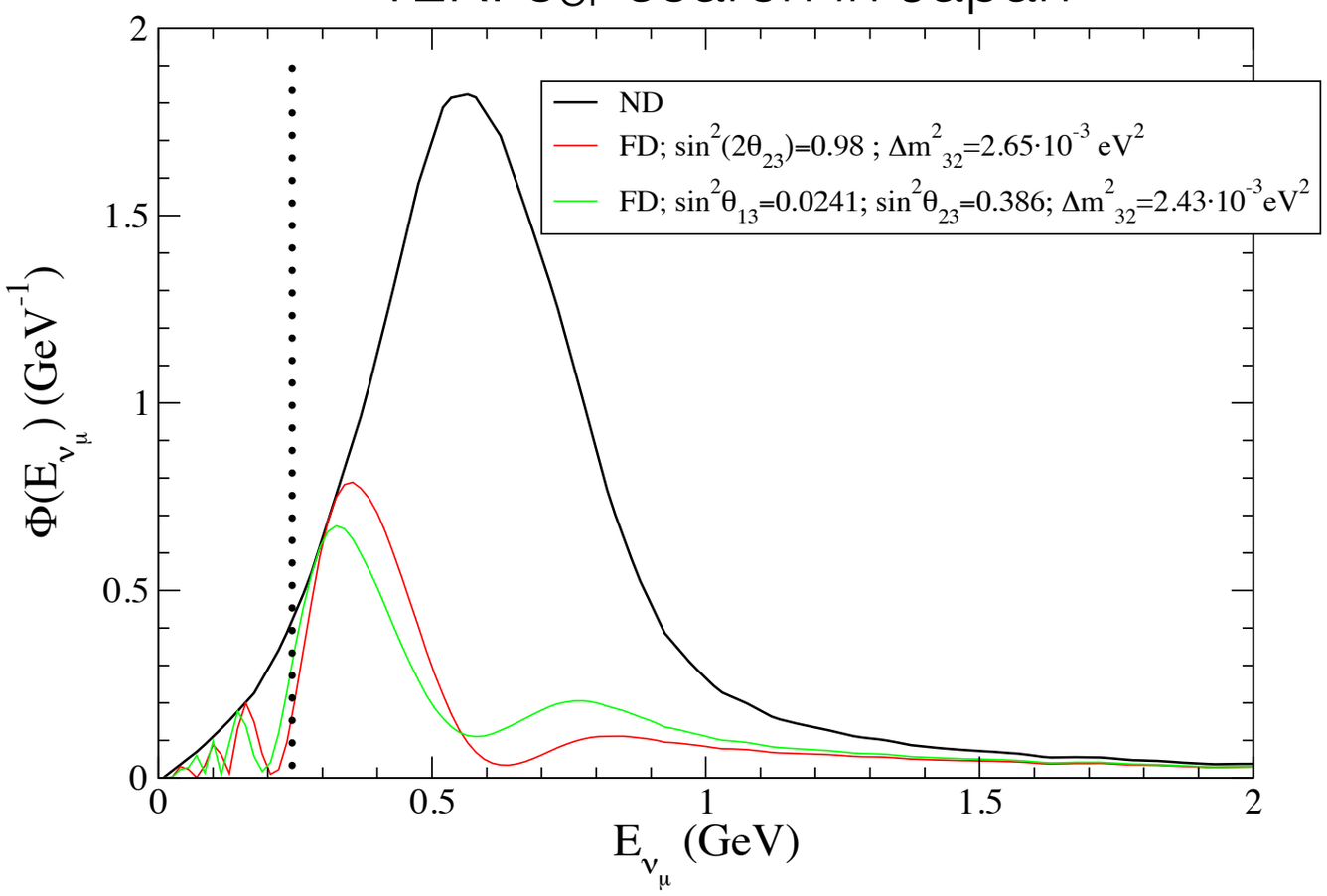
KDAR kinematics and np-nh



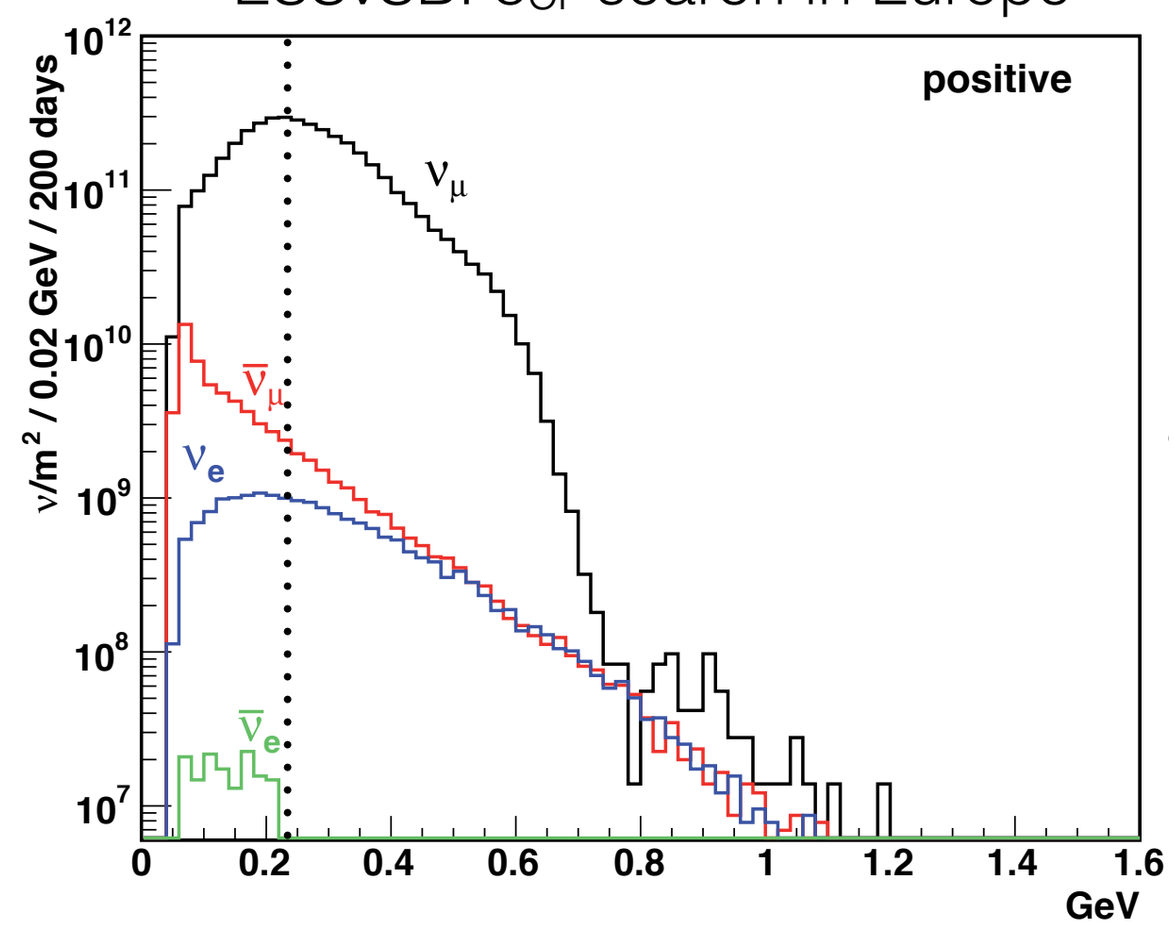


Direct relevance to future CP violation searches

T2K: δ_{CP} search in Japan

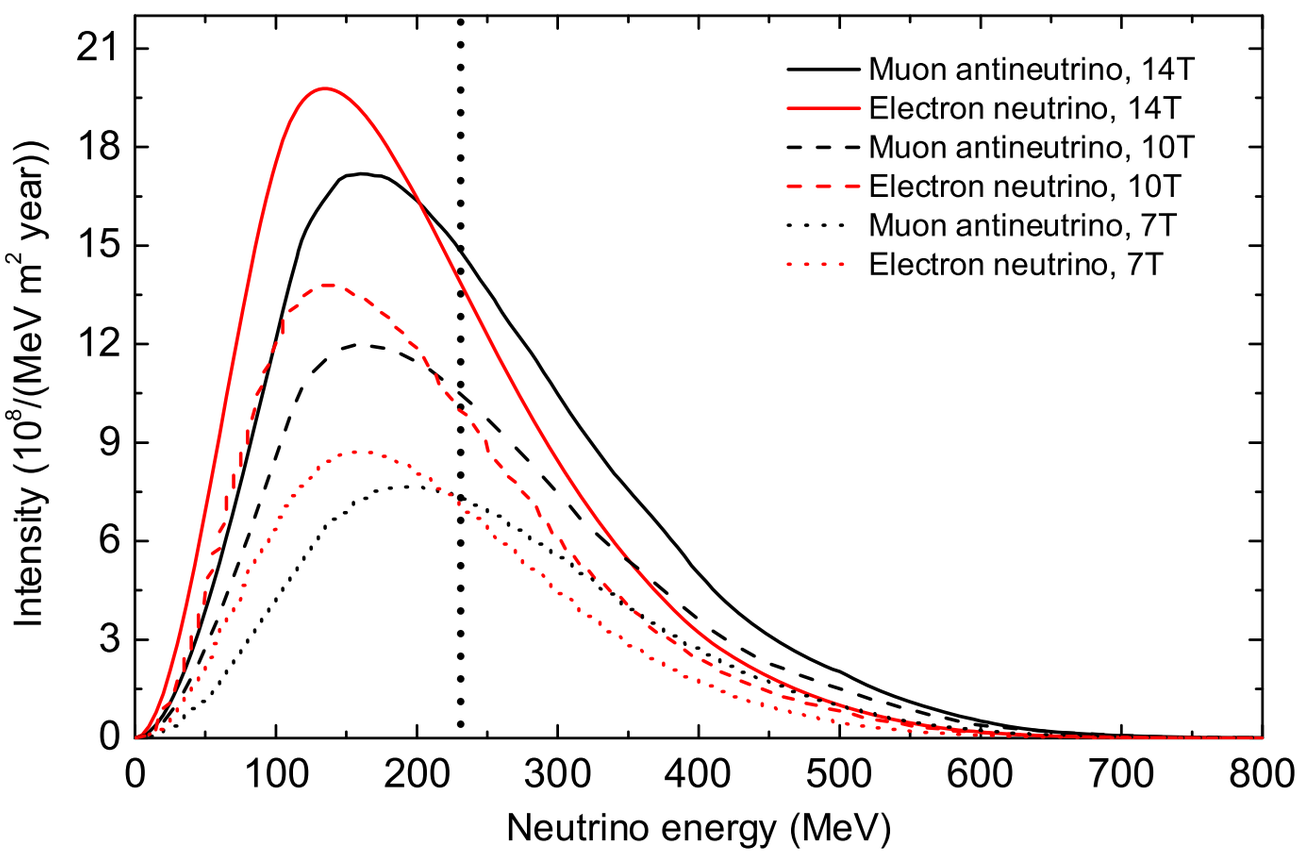


ESSνSB: δ_{CP} search in Europe

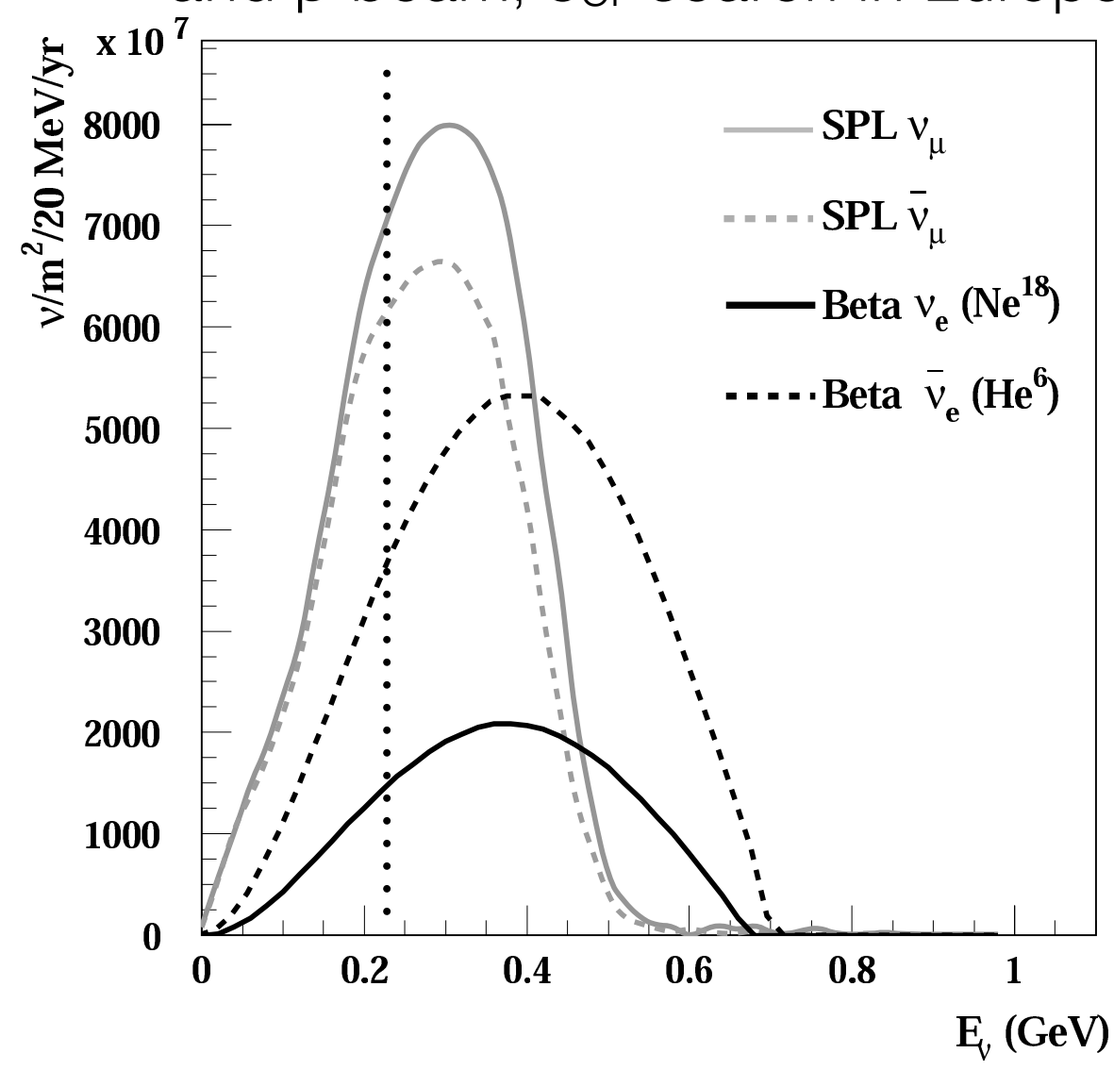


Direct relevance to future CP violation searches

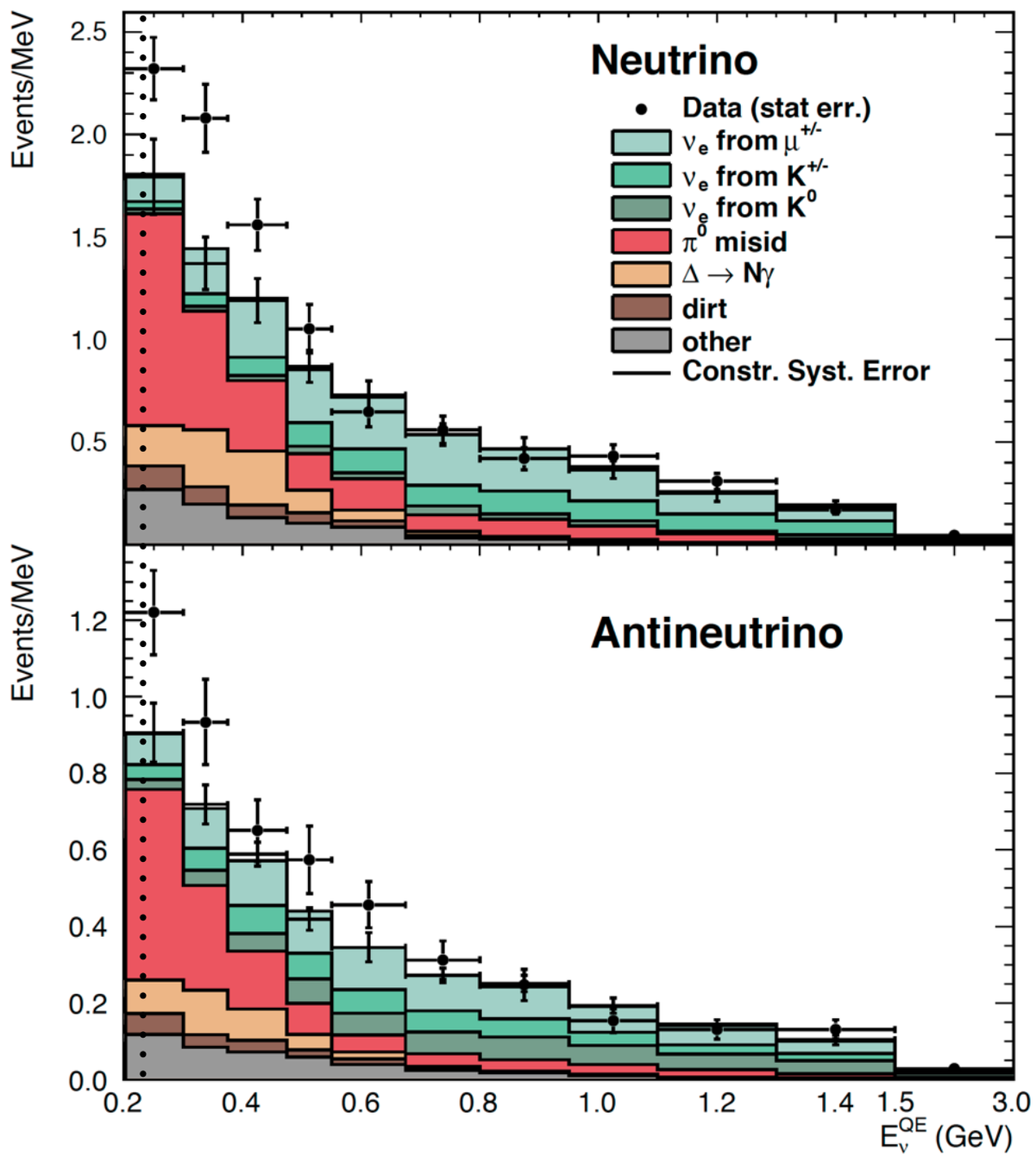
MOMENT; δ_{CP} search in China



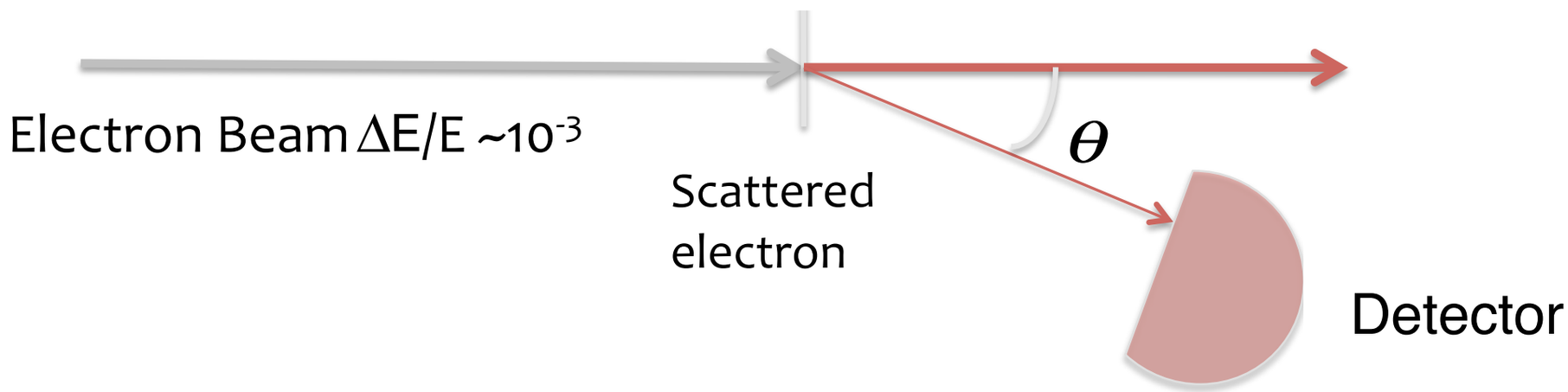
CERN Super Proton Linac and β-beam; δ_{CP} search in Europe

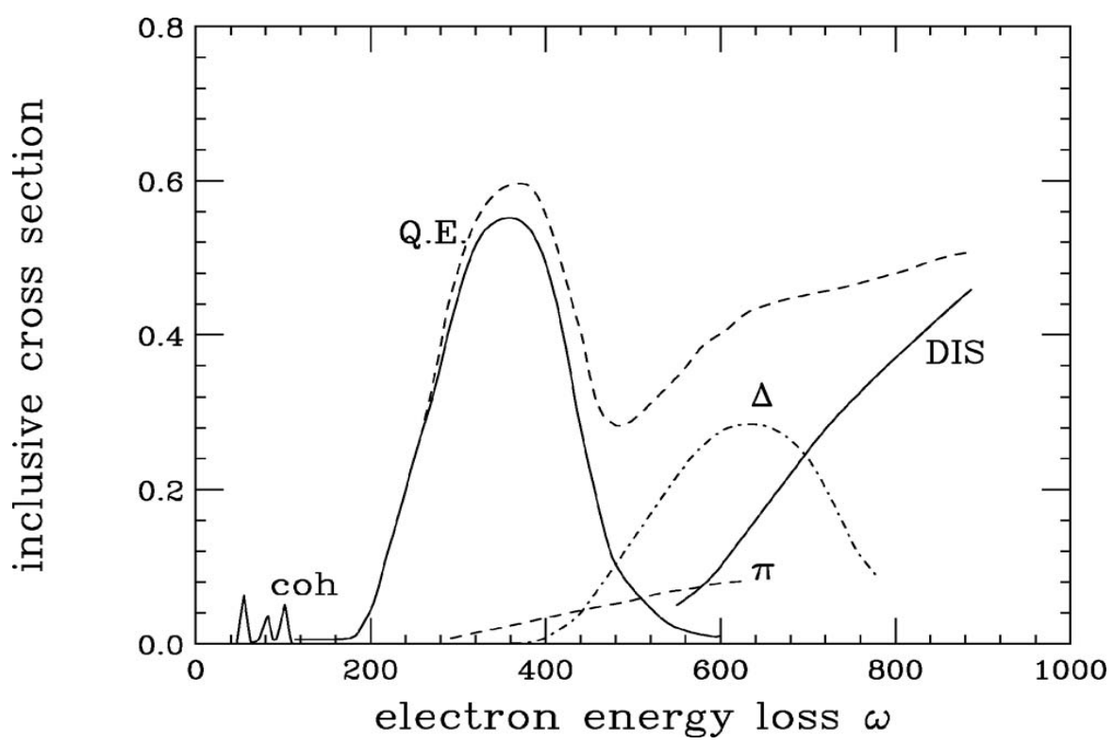


Direct relevance to the MiniBooNE low-E excess



Probing the nucleus





Slide adapted from G. Garvey

$$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$$

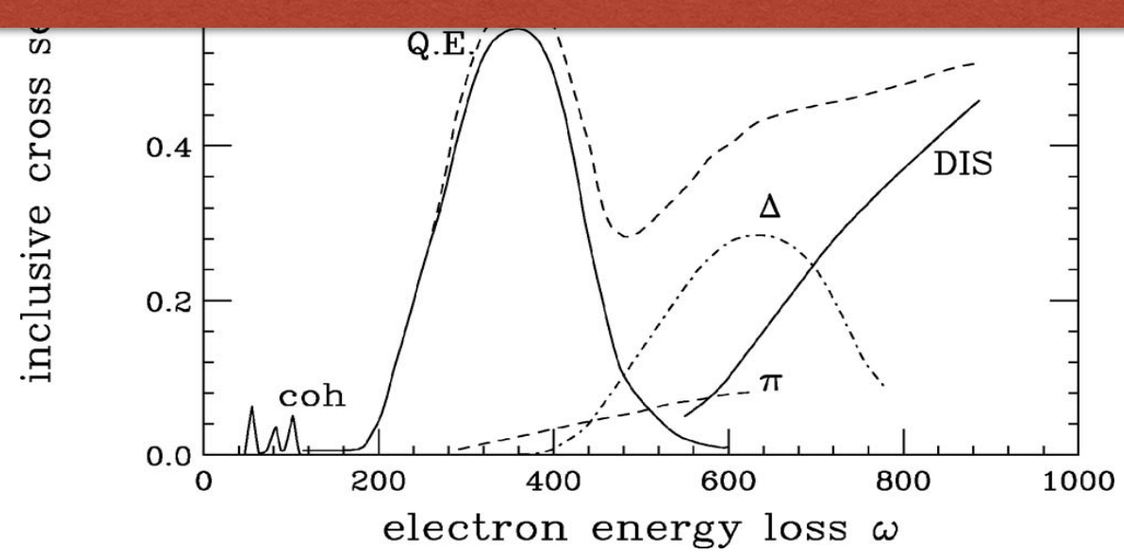
$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}'$$

Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

Probing the nucleus

Not possible with neutrinos…until now!



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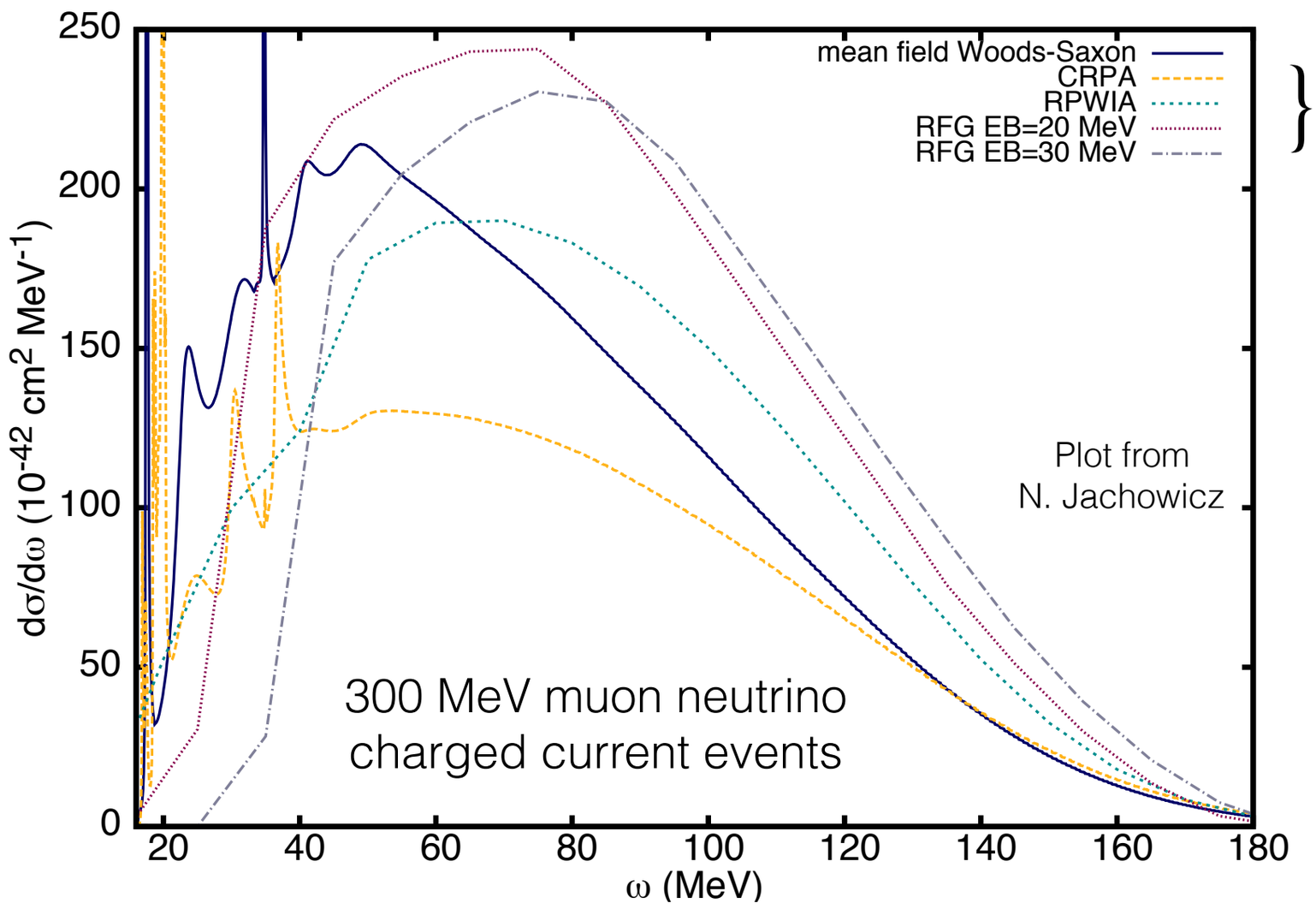
Neutrinos as a nuclear probe

J. Spitz, Phys. Rev. D 89 073007 (2014)

- For the first time, we can make these measurements with neutrinos!

- A known-energy, purely weak interacting probe of the nucleus.



} Various ways to treat the nucleus

Which model of the nucleus, relevant for neutrinos, is correct?

[nu-xsec newsletter] arXiv:1412.4624, CRPA based CCQE calculation

Inbox x

Teppei Katori <t.katori@qmul.ac.uk>
to Neutrino

Hi all,

Ho, ho, ho, there is a new paper from Ghent group,
http://arxiv.org/abs/1412.4624
about CRPA based calculation for CCQE cross section.

Conclusion, CRPA predicts low energy nuclear excitation structure in outgoing lepton spectrum.
This might be observable by mono-energetic neutrino beam
with extremely good energy resolution detector.

The main results are presented at NuFact2014,
http://www.lists.qmul.ac.uk/sympa/arc/nu-xsec/2014-09/msg00000.html
Note anti-neutrino results were published in the last year.
http://arxiv.org/abs/1310.6885

CRPA (continuum random phase approximation) is famous (or infamous?) because of its complexity.
The structure of low energy nuclear excitations remain in outgoing lepton spectrum (Fig. 4),
as sharp peaks for low energy and momentum transfer.
Interestingly, this feature remains even for high energy beam (~1GeV),
as long as energy transfer is low (=forward scattering).
However, this structure would be washed out in typical wide-band neutrino beams
(this was shown in previous anti-neutrino paper).
So in principle, mono-energetic neutrino beam with extremely good energy resolution detector
can study nuclear excitation structure,
just from forward going muons (Fig. 10).

The only such proposed experiment would be KDAR,
LArTPC detector with kaon decay-at-rest (DAR) beam
which produces mono-energetic 236 MeV muon neutrinos.
http://www.lists.qmul.ac.uk/sympa/arc/nu-xsec/2014-02/msg00009.html

(LArTPC is just one option)

236 MeV muon neutrino interaction-physics

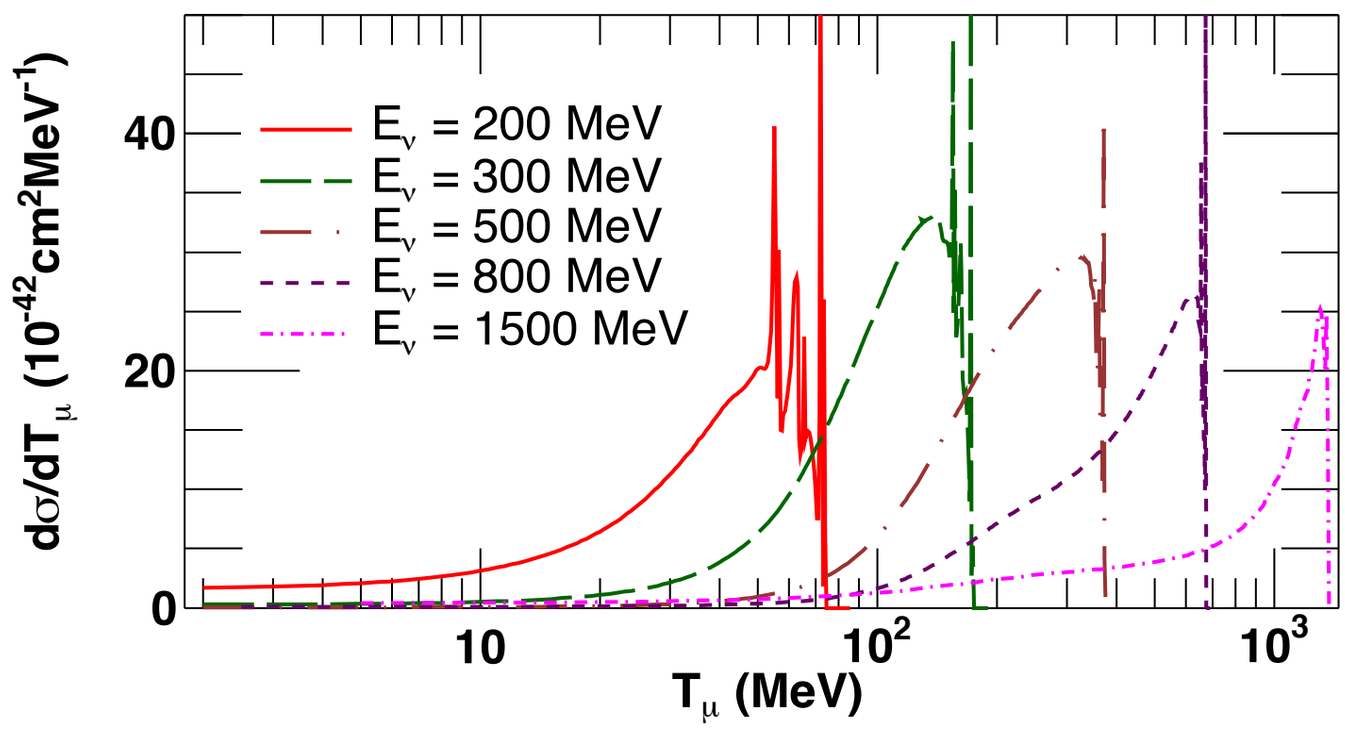
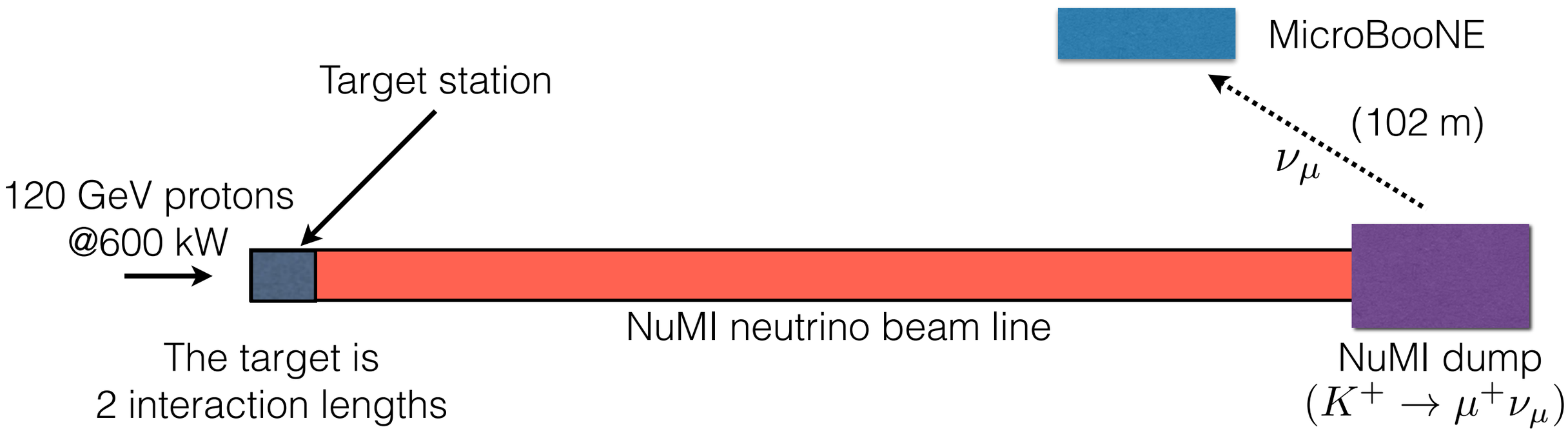


FIG. 10: (Color online) The cross section for $^{12}C(\nu_\mu, \mu^-)$ as a function of outgoing muon kinetic energy T_μ, for different incoming neutrino energies. Note the log scale on the horizontal axis.

arXiv:1412.4624

Where to?

- There are basically two places in the world where one can currently do neutrino physics with kaon decay-at-rest.
  - NuMI beam dump at Fermilab



Where to?

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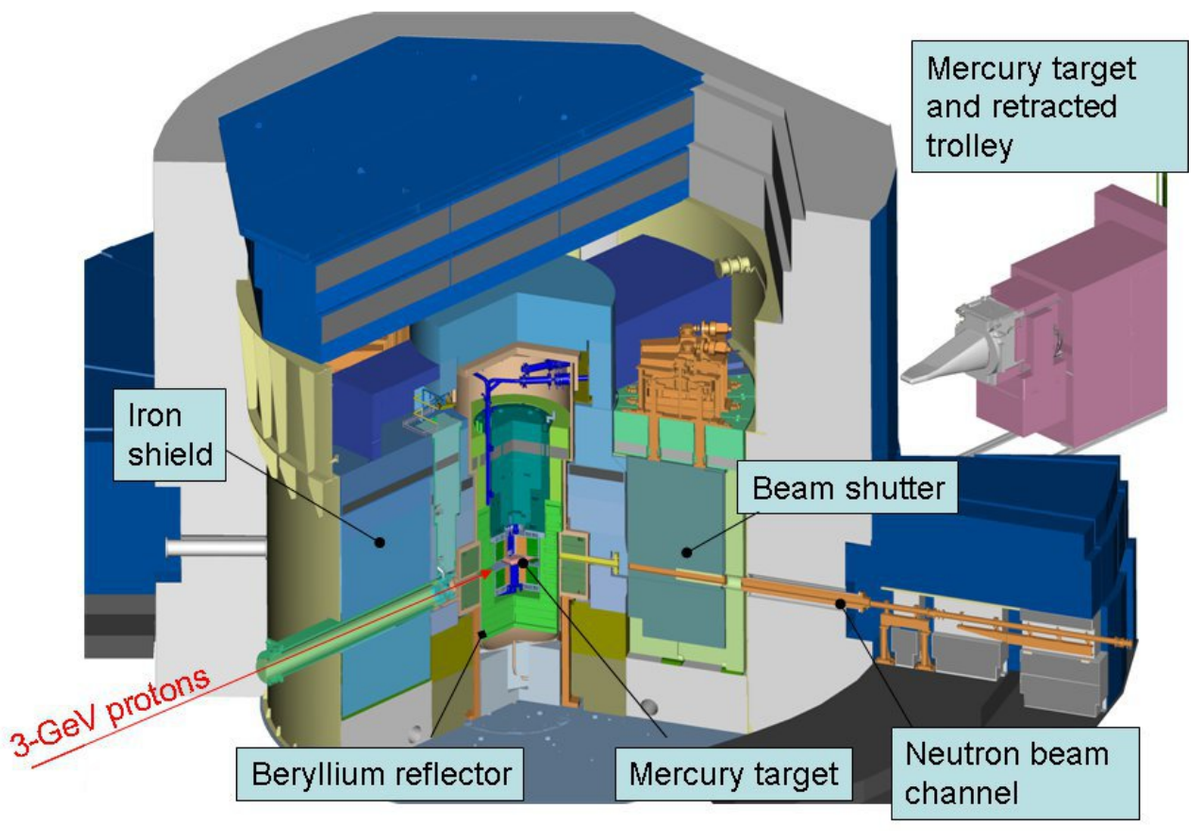
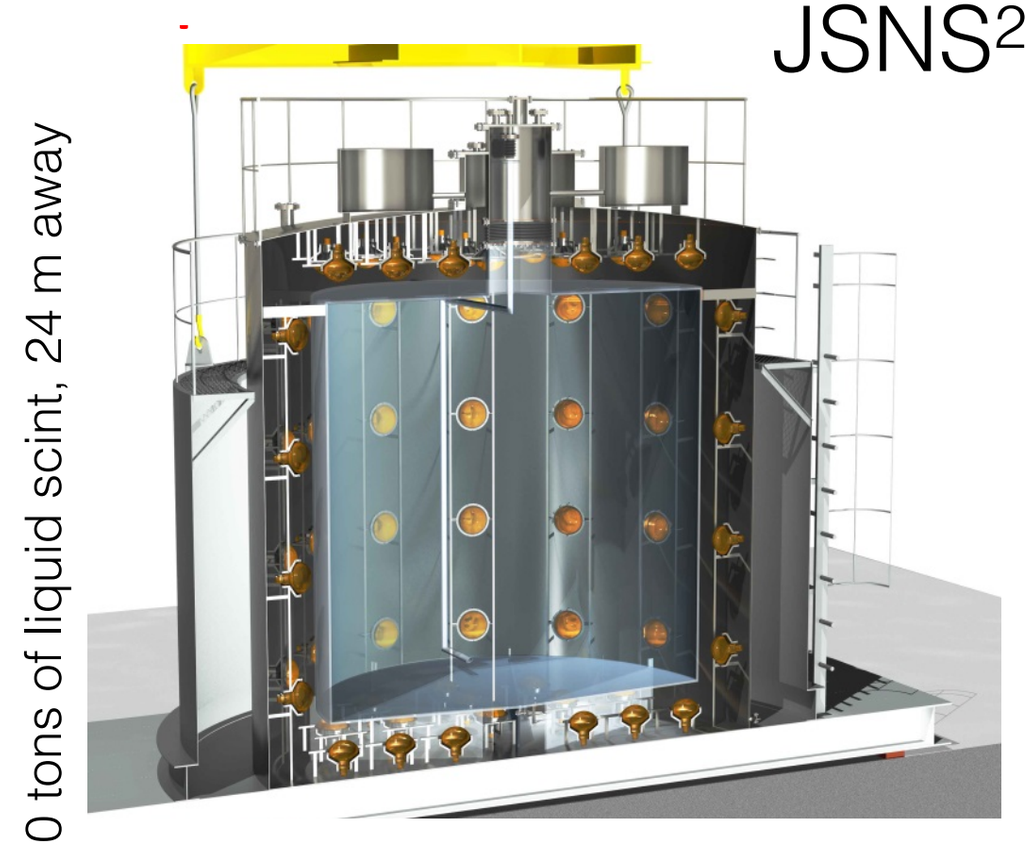
  - JPARC 3 GeV spallation neutron source



JSNS^2

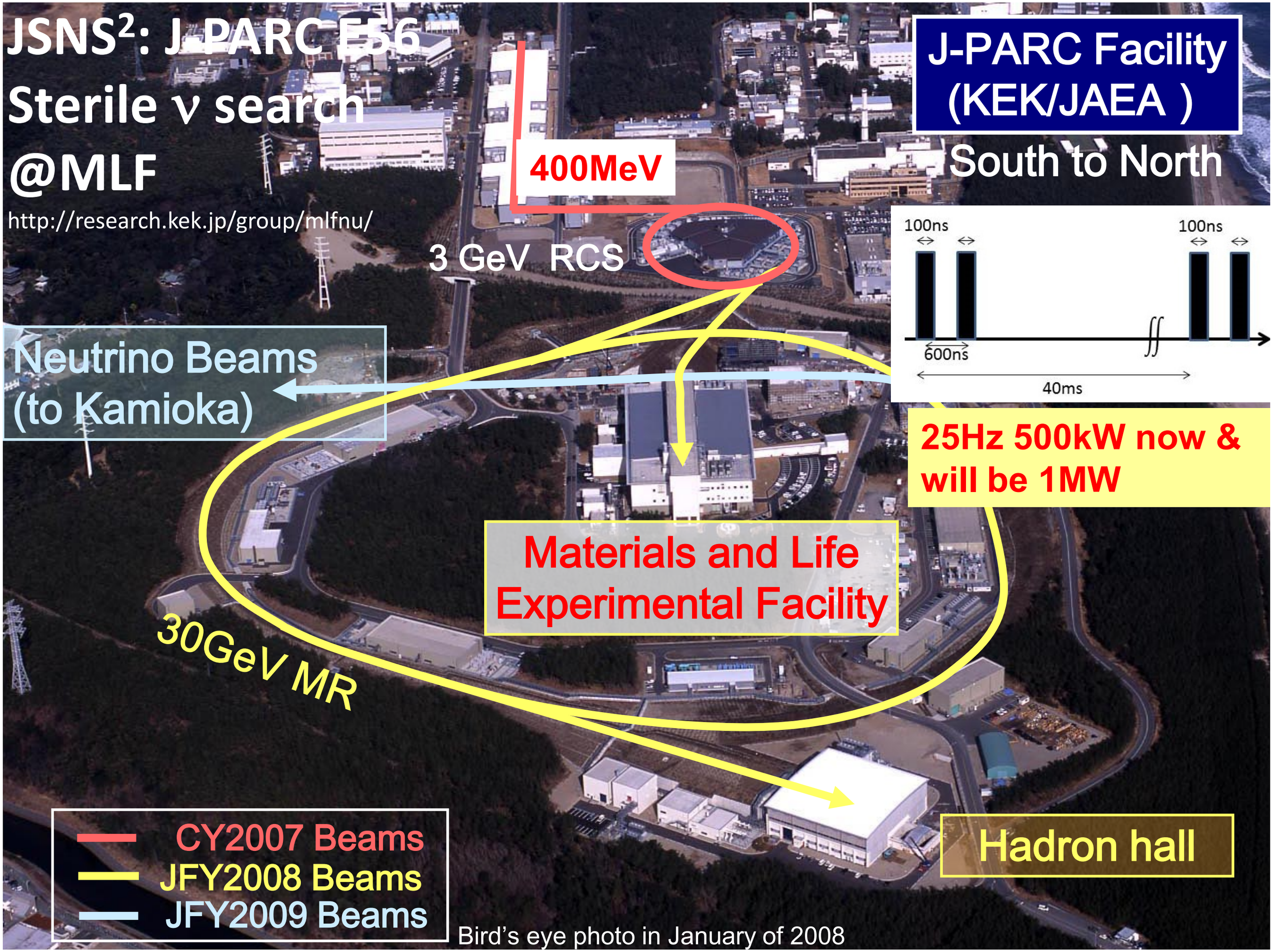


arXiv:1310.1437 [hep-ex]

(nominally an LSND-like experiment)

JSNS^2: J-PARC E56 Sterile ν search @MLF

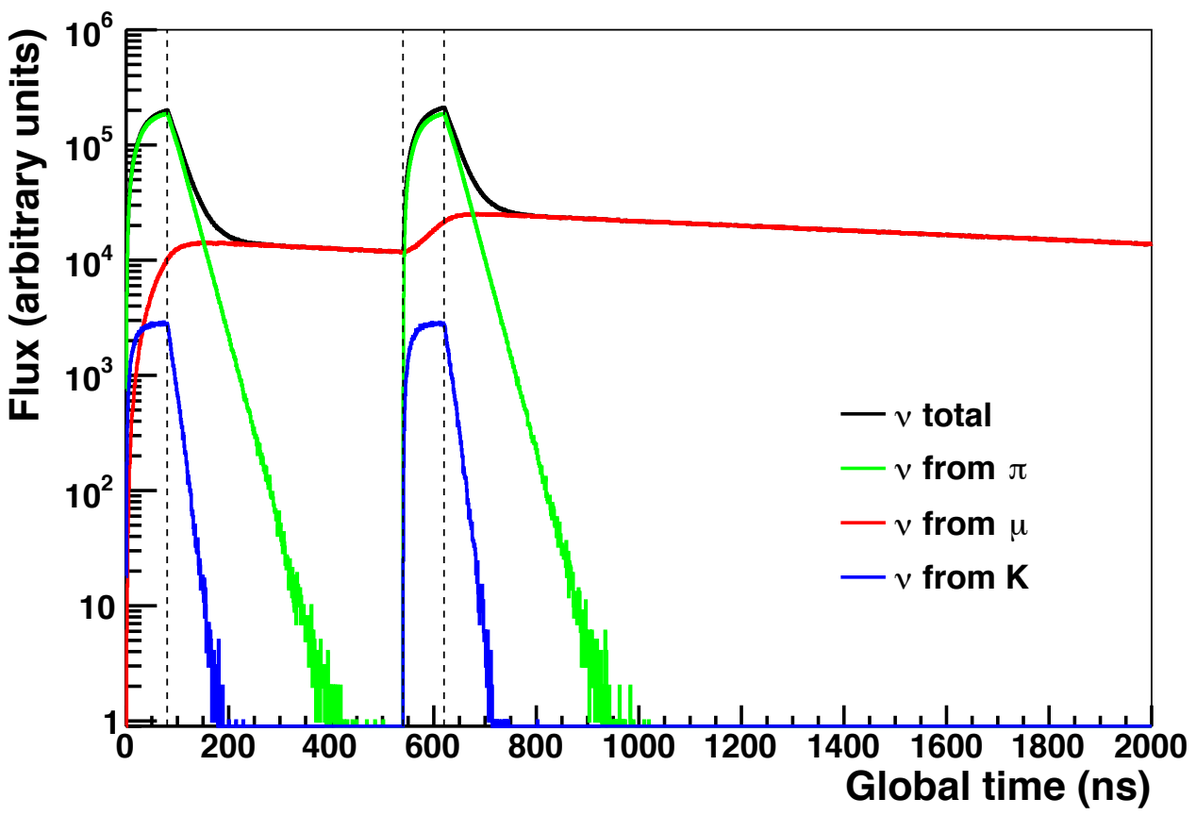
http://research.kek.jp/group/mlfnu/

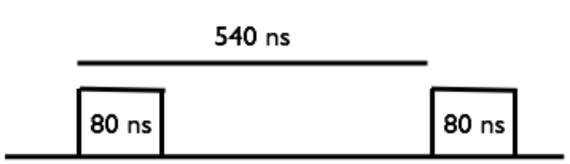


Bird's eye photo in January of 2008

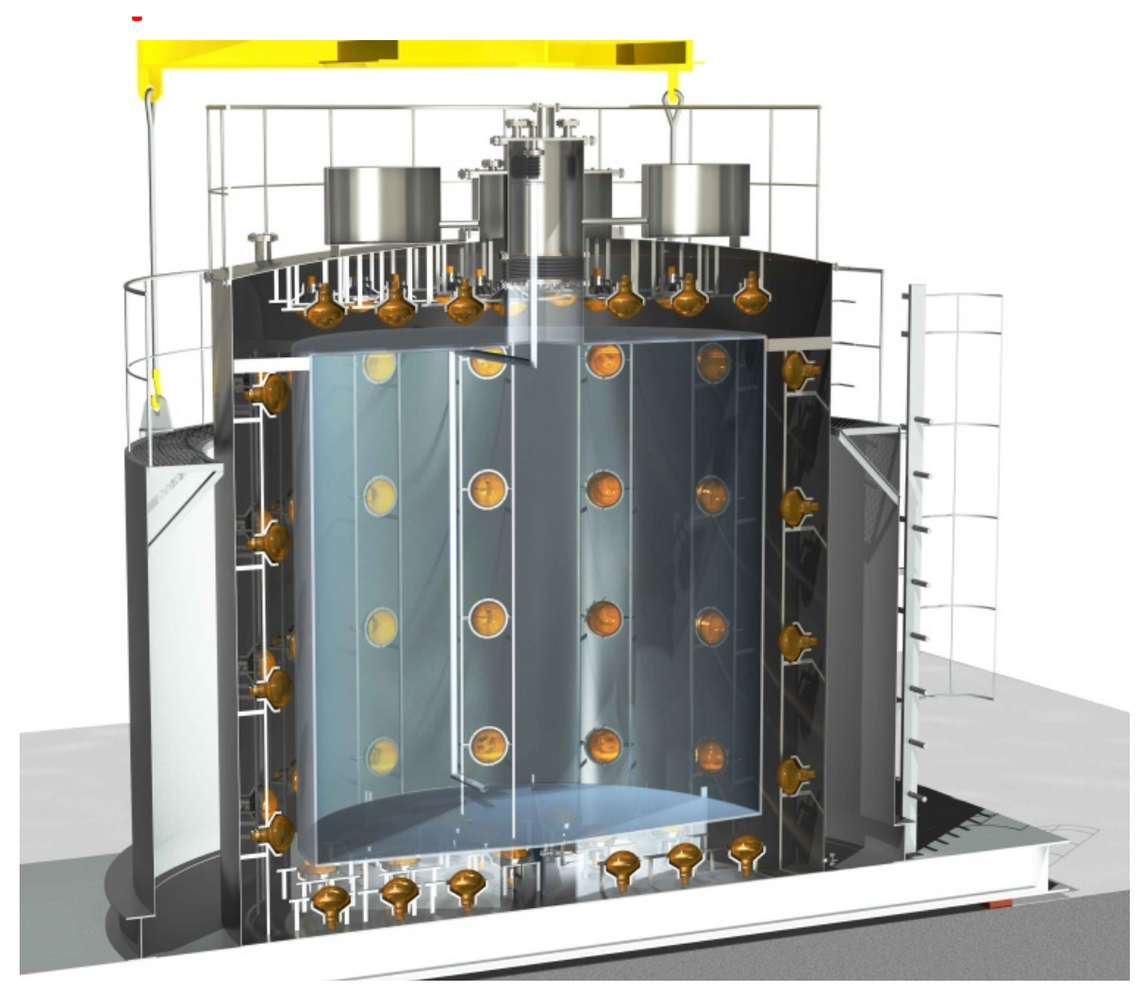
JSNS² KDAR ν_μ signal

$$K^+ \to \mu^+ \nu_\mu$$





Beam structure 25 Hz

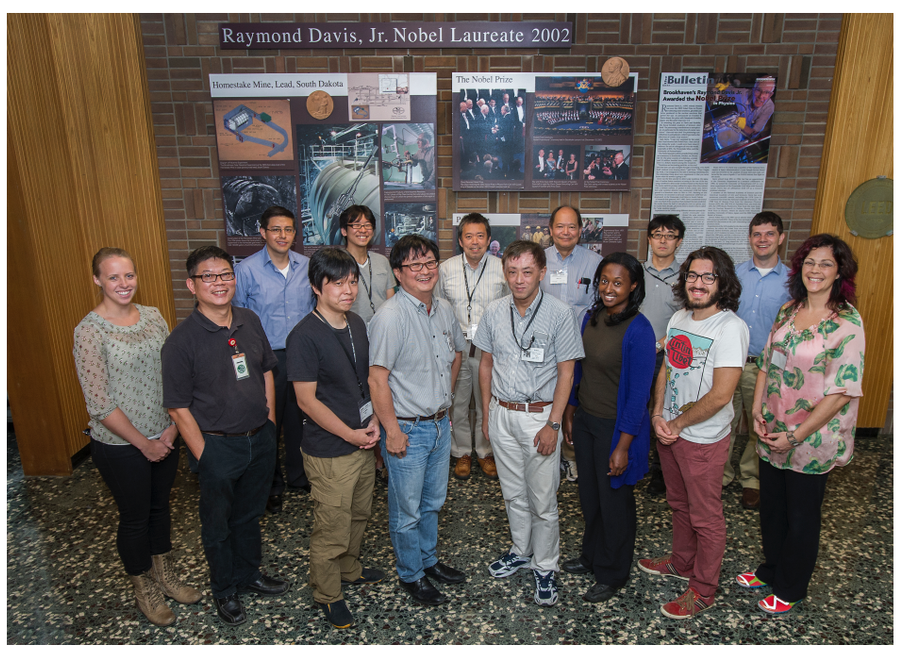


Prompt signal: $\nu_\mu n \to \mu^- p$

Delayed signal: $\mu^- \to e^- \overline{\nu}_e \nu_\mu$

J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source ($JSNS^2$)

- $JSNS^2$ received Stage-1 approval from the KEK and J-PARC directorates in 4/2015.
- The experiment is expected to begin taking data within 3 years from now.



M. Harada, S. Hasegawa, Y. Kasugai, S. Meigo, K. Sakai, S. Sakamoto, K. Suzuya
JAEA, Tokai, JAPAN

E. Iwai, T. Maruyama[1], S. Monjushiro, K. Nishikawa, M. Taira
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M. Niiyama
Department of Physics, Kyoto University, JAPAN

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RCNP, Osaka University, JAPAN

T. J. C. Bezerra, E. Chauveau, H. Furuta, F. Suekane
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G. T. Garvey, C. Mauger, W. C. Louis, G. B. Mills, R. Van de Water
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

J. Spitz
University of Michigan, Ann Arbor, MI 48109, USA

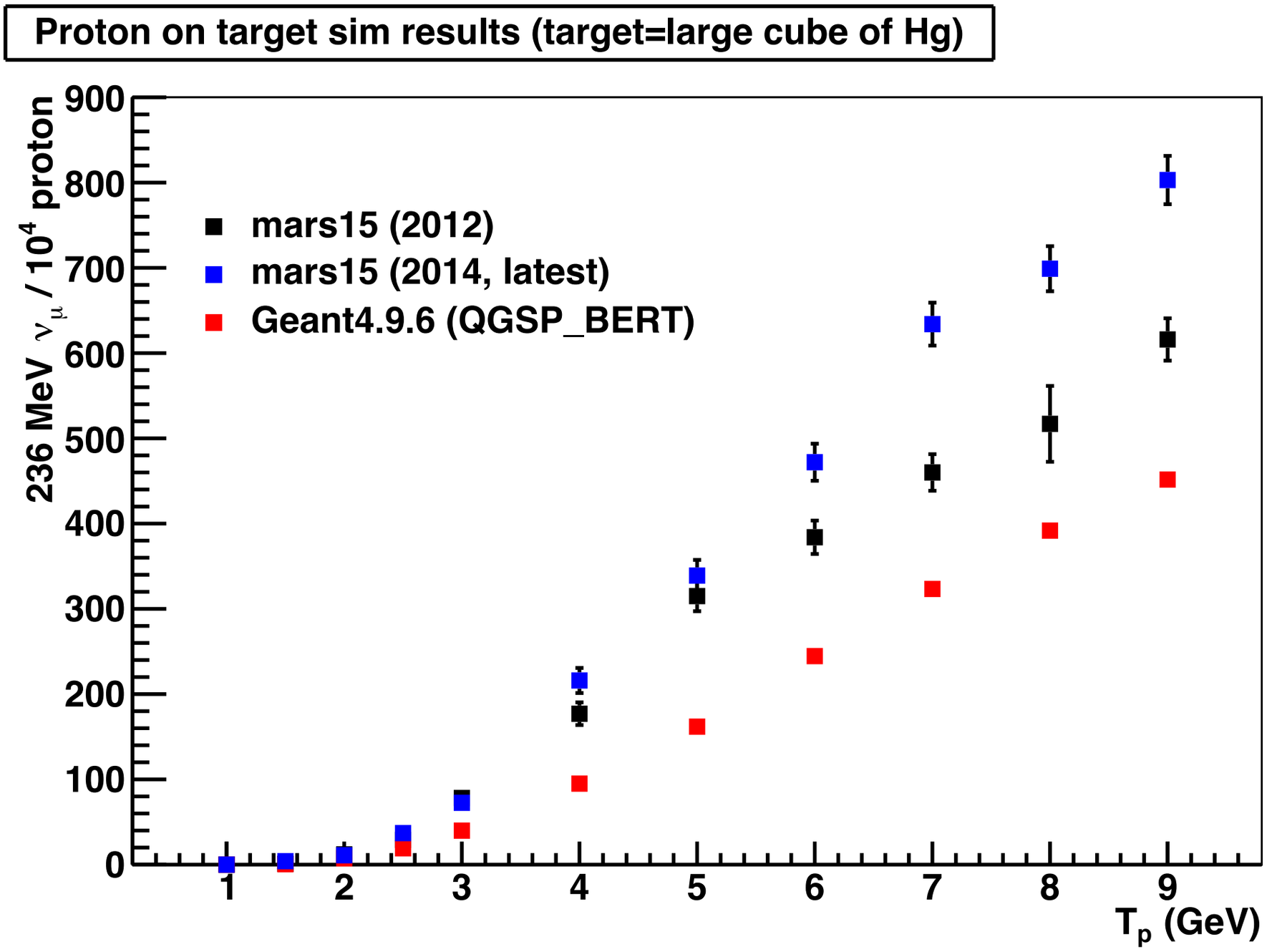
Prospects

- The JSNS^2 experiment will detect 150k-300k KDAR muon neutrino charged current events in 5 years.
  - **Unprecedented xsec measurements and nuclear probe.**
  - **Sensitivity to KDAR electron neutrino appearance.**
  - **(Nominally, an LSND-like experiment using muon DAR)**

- MicroBooNE will collect a much more modest sample, but detect enough events to provide an important input for understanding the MiniBooNE low energy excess.

Detector (source)	Target (mass)	Exposure	Distance from source	236 MeV ν_μ CC events
MicroBooNE (NuMI dump)	LAr (90 ton)	1.2×10^{21} POT (2 years)	102 m	2300
JSNS^2 (JPARC-MLF)	Gd-LS (50 ton)	1.875×10^{23} POT (5 years)	24 m	152000

(Kaon production is uncertain)



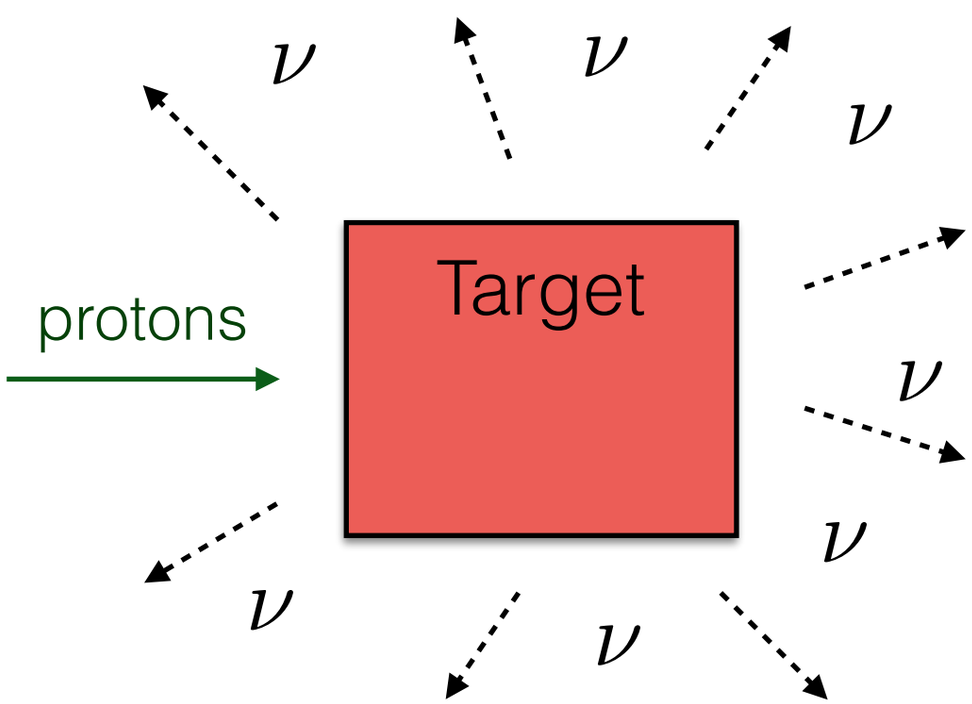
Neutrinos from kaon decay-at-rest can help!

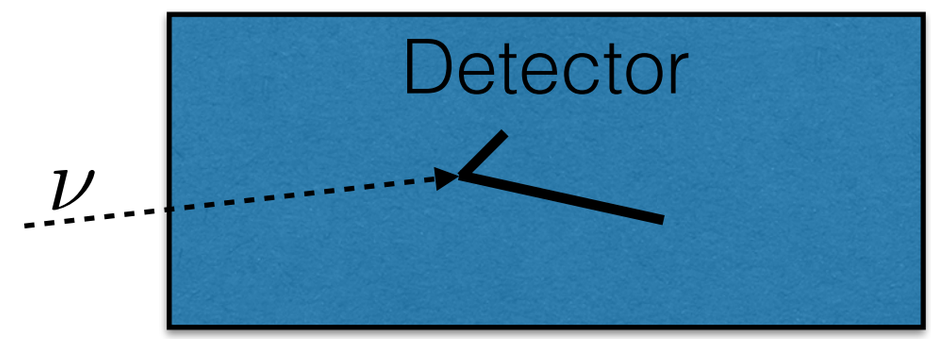
- Cross section and energy reconstruction problems.
- The sterile neutrino problem.

Searching for a sterile neutrino w/ kaon decay at rest

$\nu_\mu \to \nu_x \quad ?$ → will discuss later

$\nu_\mu \to \nu_e \quad ?$





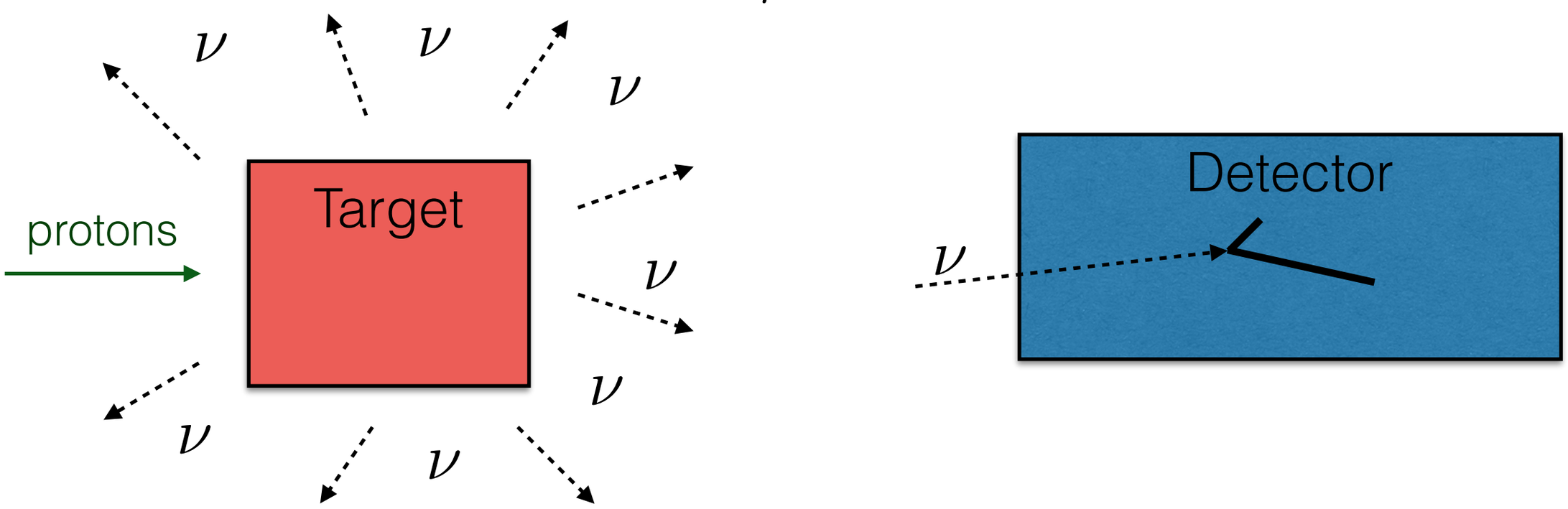
Monoenergetic (236 MeV) neutrino!

$K^+ \to \mu^+ \nu_\mu$

J. Spitz, Phys. Rev. D 85 093020 (2012)

Searching for a sterile neutrino w/ kaon decay at rest

$$\nu_\mu \to \nu_e \quad ?$$



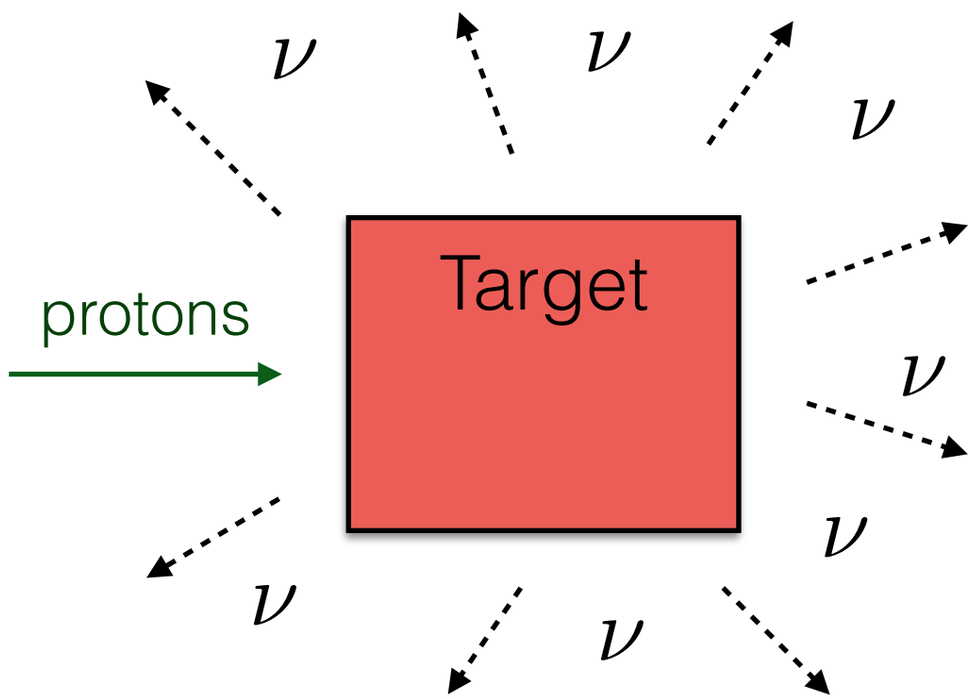
Monoenergetic (236 MeV) neutrino!

$$K^+ \to \mu^+ \nu_\mu$$

Backgrounds $\left\{ \begin{array}{l} K^+ \to \pi^0 e^+ \nu_e \\ K_L^0 \to \pi^- e^+ \nu_e \end{array} \right.$

J. Spitz, Phys. Rev. D 85 093020 (2012)

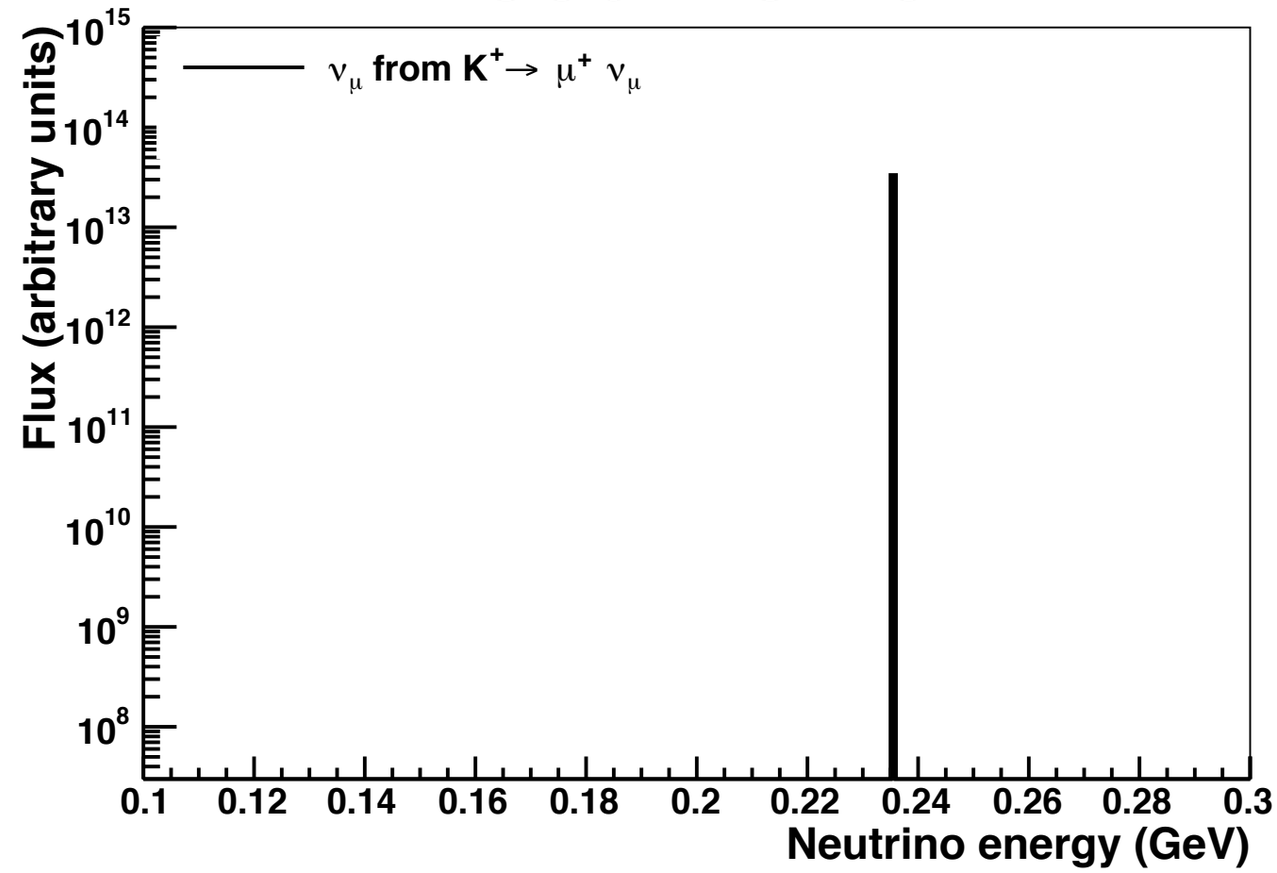
Searching for a sterile neutrino w/ kaon decay at rest



$$K^+ \to \mu^+ \nu_\mu$$

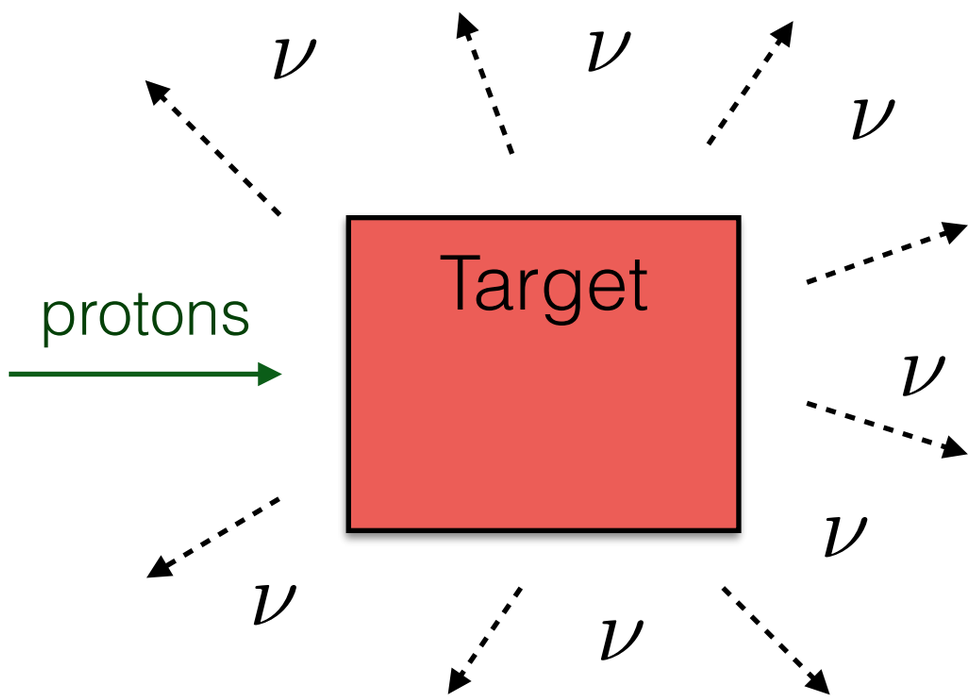
$$\nu_\mu \to \nu_e \quad ?$$

Neutrino flux



J. Spitz, Phys. Rev. D 85 093020 (2012)

Searching for a sterile neutrino w/ kaon decay at rest



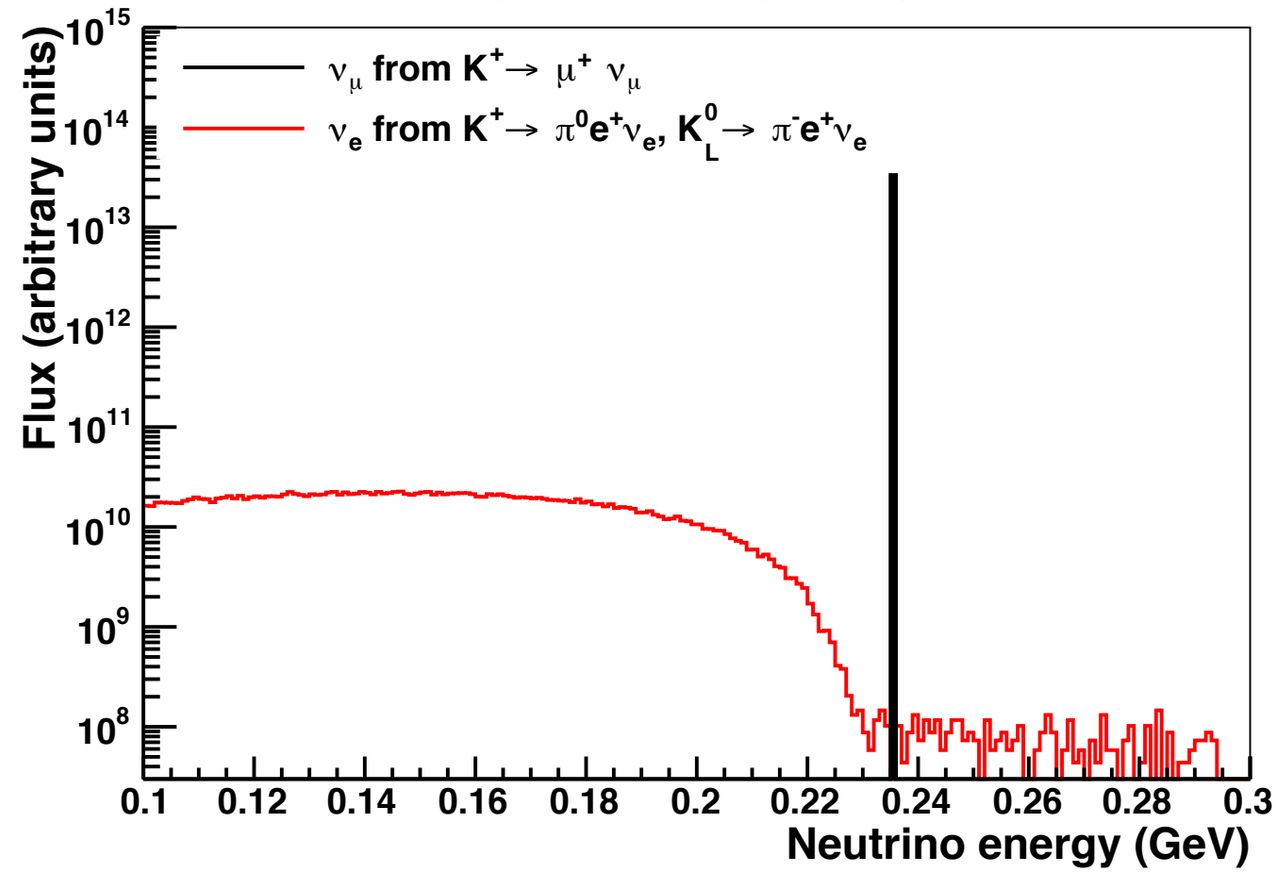
$$K^+ \to \mu^+ \nu_\mu$$

$$K^+ \to \pi^0 e^+ \nu_e$$

$$K_L^0 \to \pi^- e^+ \nu_e$$

$$\nu_\mu \to \nu_e \quad ?$$

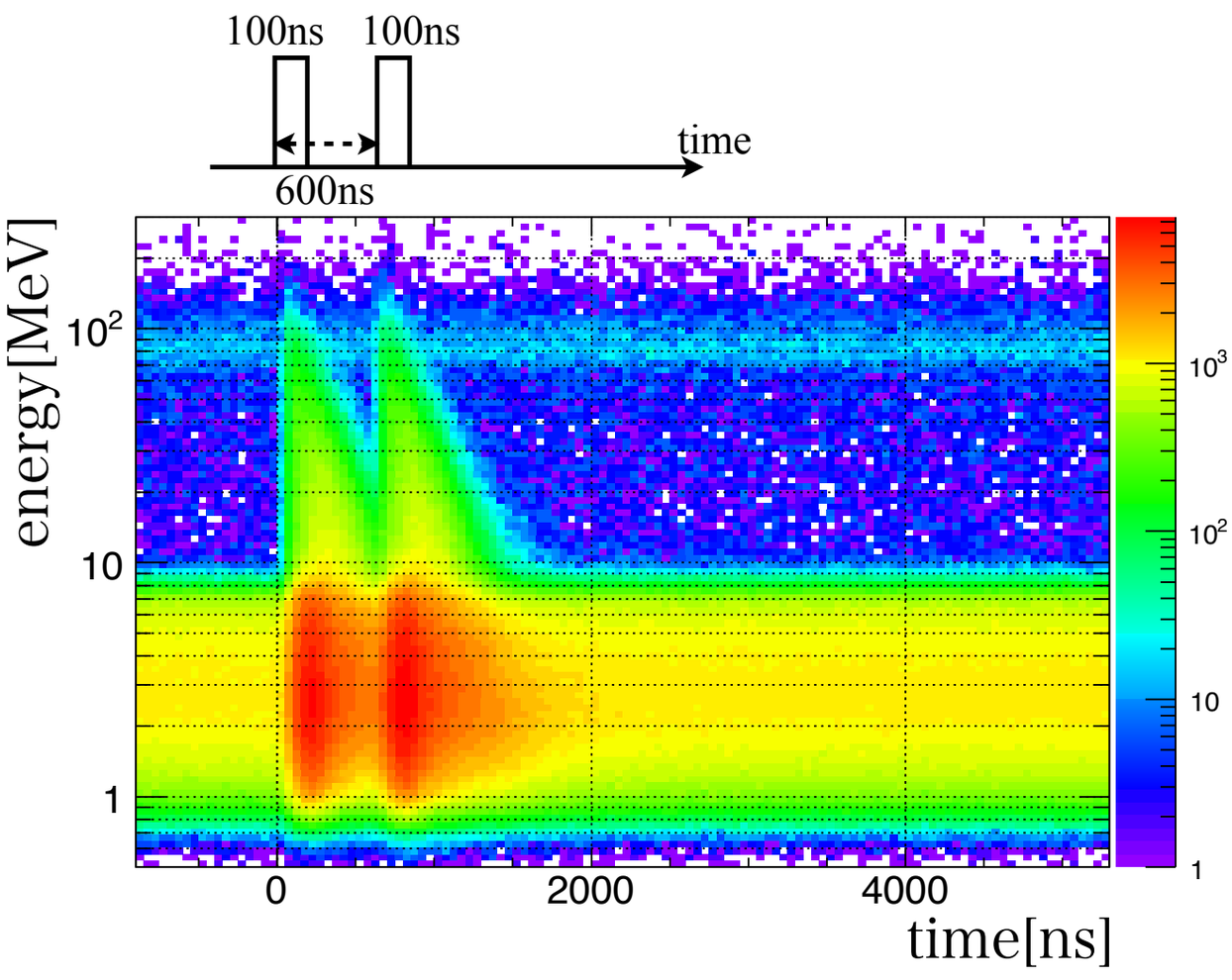
Neutrino flux



J. Spitz, Phys. Rev. D 85 093020 (2012)

JSNS^2 KDAR ν_e appearance

- KDAR electron neutrino appearance with JSNS^2 is challenging because of beam-related background. Enhanced shielding and/or a phase 2 “far detector” will make this possible in the future.
- The LSND-like muon decay-at-rest electron antineutrino appearance search is very promising, however. [not discussed here]



500 kg plastic scintillator background measurement @20 m from J-PARC MLF source

1502.02255

One more KDAR idea

What about muon disappearance?

Experiment name	Type	Oscillation channel	Significance
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	3.4σ
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

If sterile neutrinos exist, there must be some amount of ν_μ disappearance!

What about muon disappearance?

Experiment name	Type	Oscillation channel	Significance
Accelerator-based experiments (e.g. MicroBooNE, SBN program at FNAL, JSNS^2,…)		muon to electron (antineutrino)	3.8σ
		muon to electron (antineutrino)	2.8σ
		muon to electron (neutrino)	3.4σ
Remeasuring reactor neutrinos up close, high intensity neutrino sources up close (e.g. Nucifer, Prospect, SOX, IsoDAR, …)		electron disappearance (antineutrino)	1.4-3.0σ (varies)
		electron disappearance (neutrino)	2.8σ

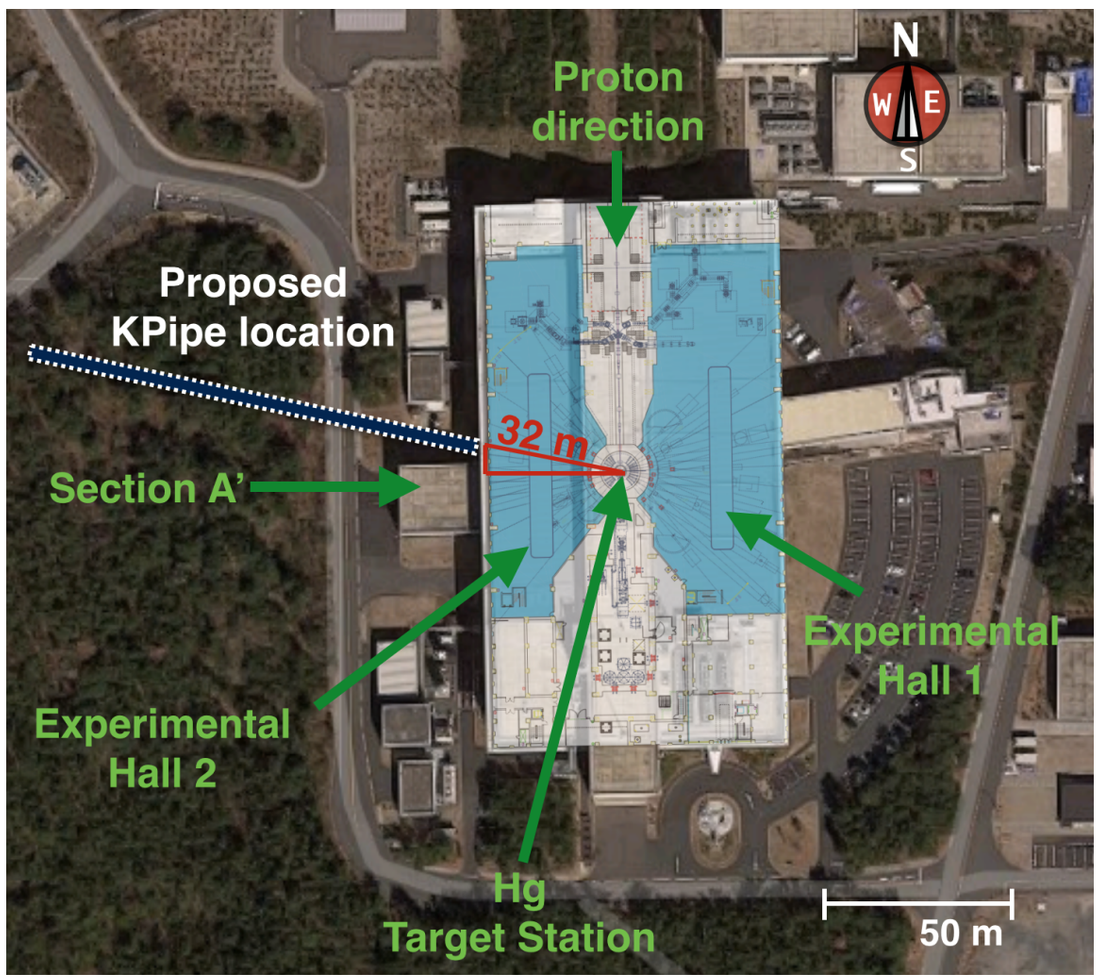
If sterile neutrinos exist, there must be some amount of ν_μ disappearance!

KPIPE

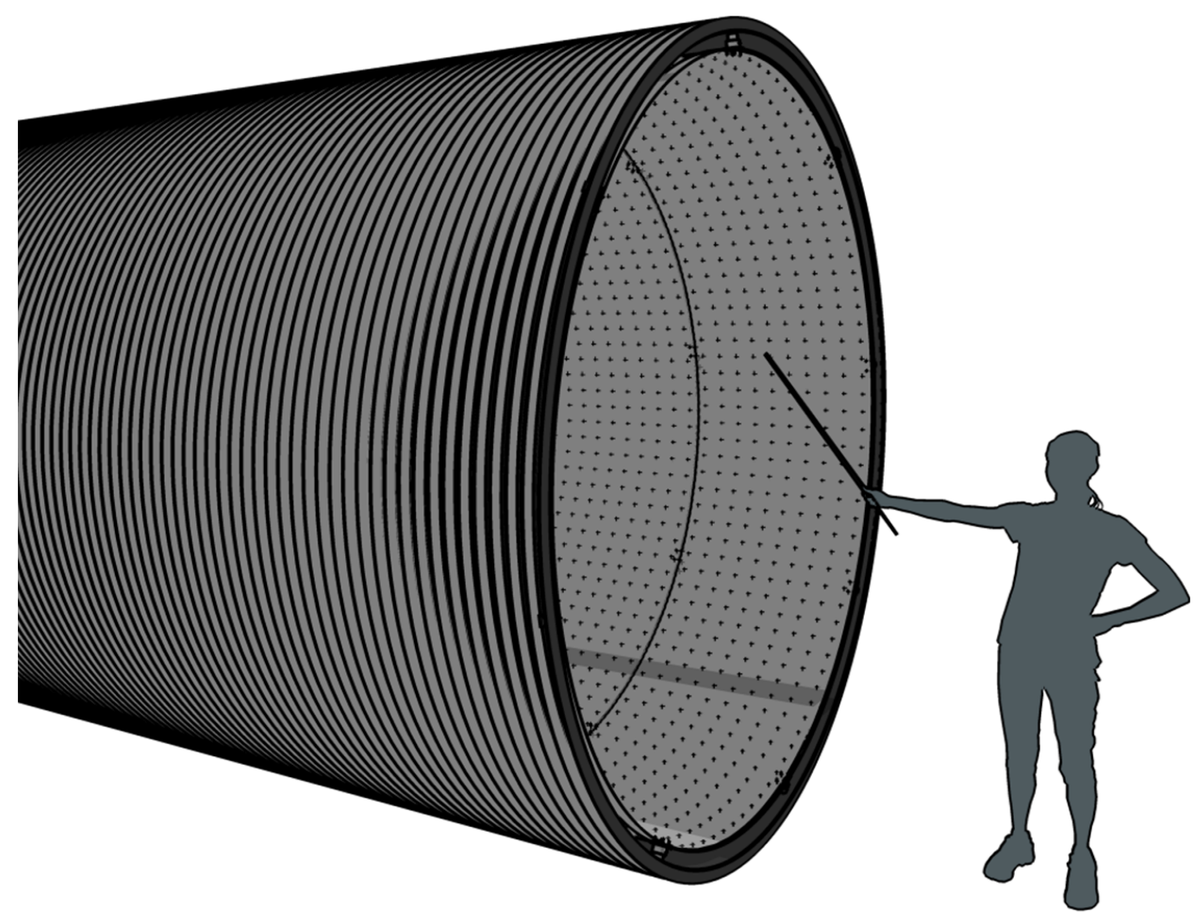
Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, arXiv:1506.05811

The idea:

Use a very long liquid scintillator detector to look for ν_μ disappearance (in *L*) using 236 MeV KDAR ν_μ CC events



@ J-PARC MLF

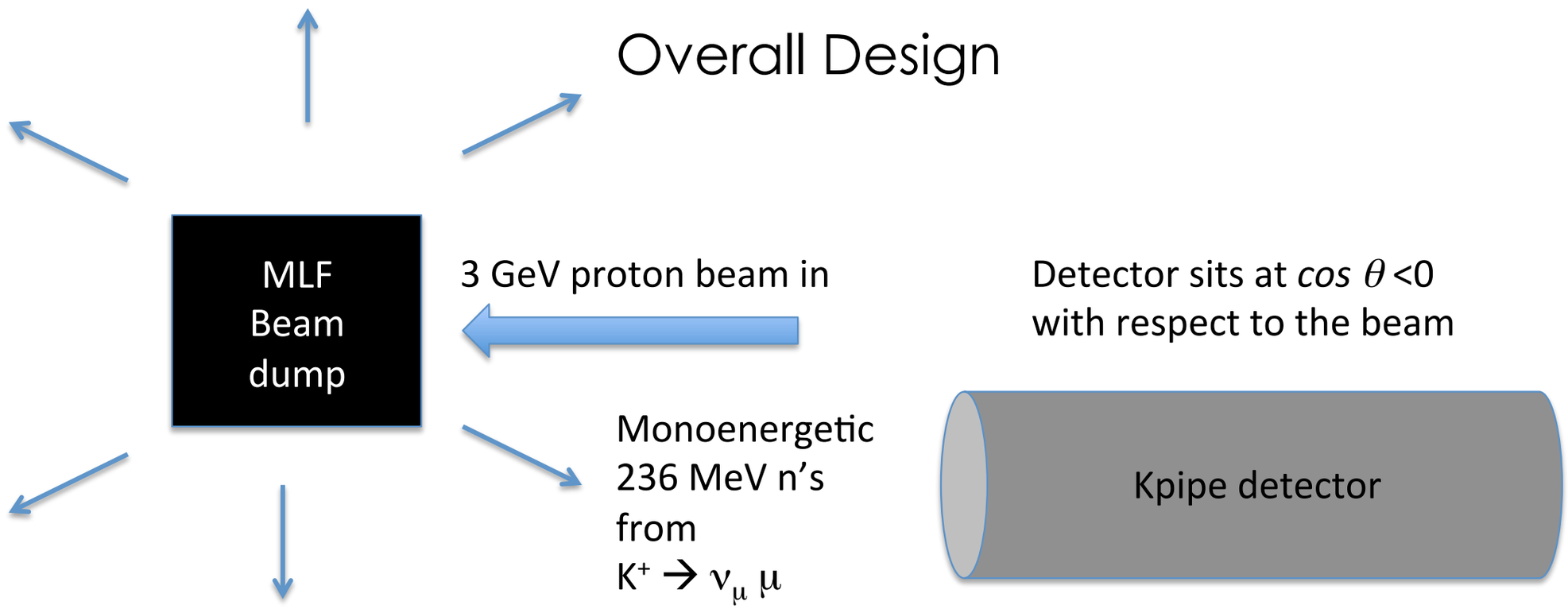


Long LS detector surrounded by SiPMs

KPIPE

Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, arXiv:1506.05811

Overall Design



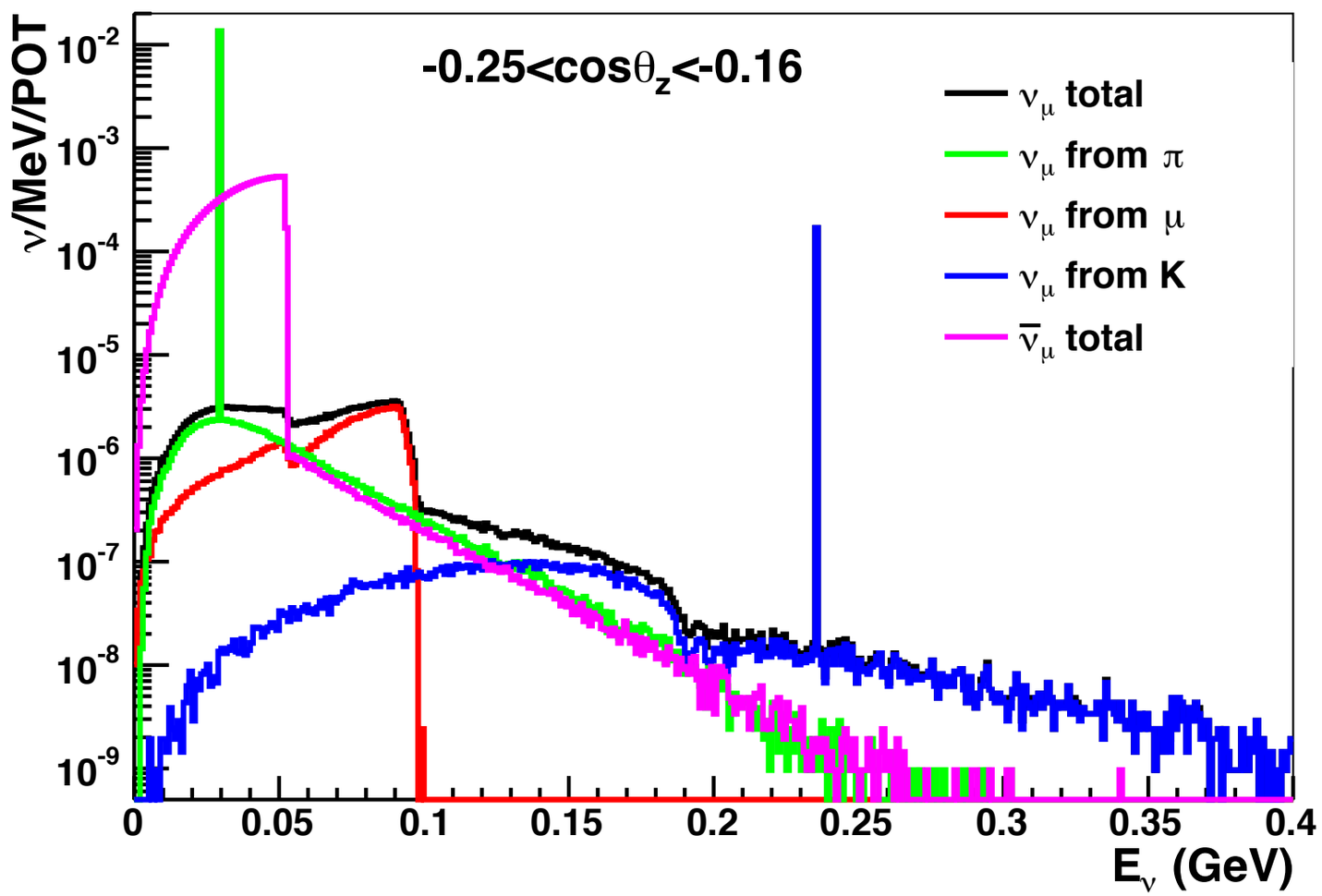
(1) pure, mono-energetic flux of muon neutrinos

(2) long detector to measure the oscillation wave

KPIPE

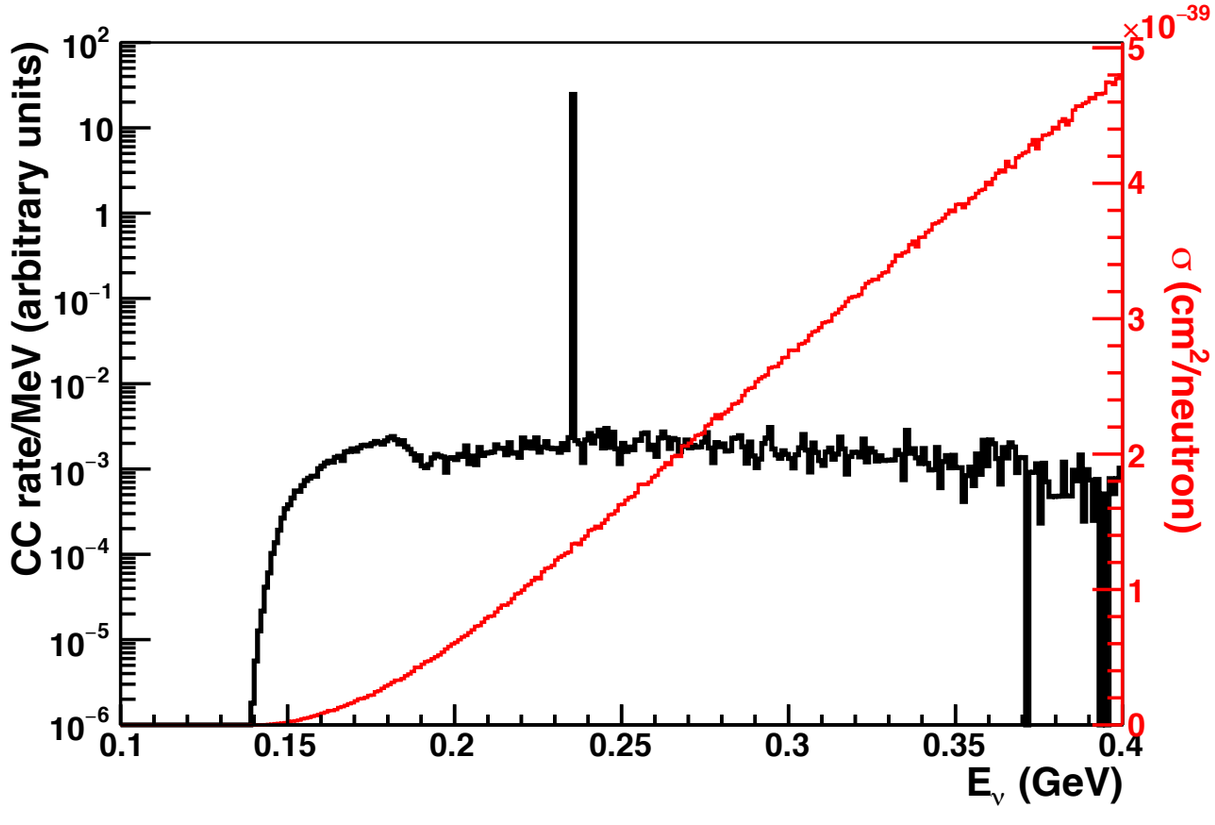
Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, arXiv:1506.05811

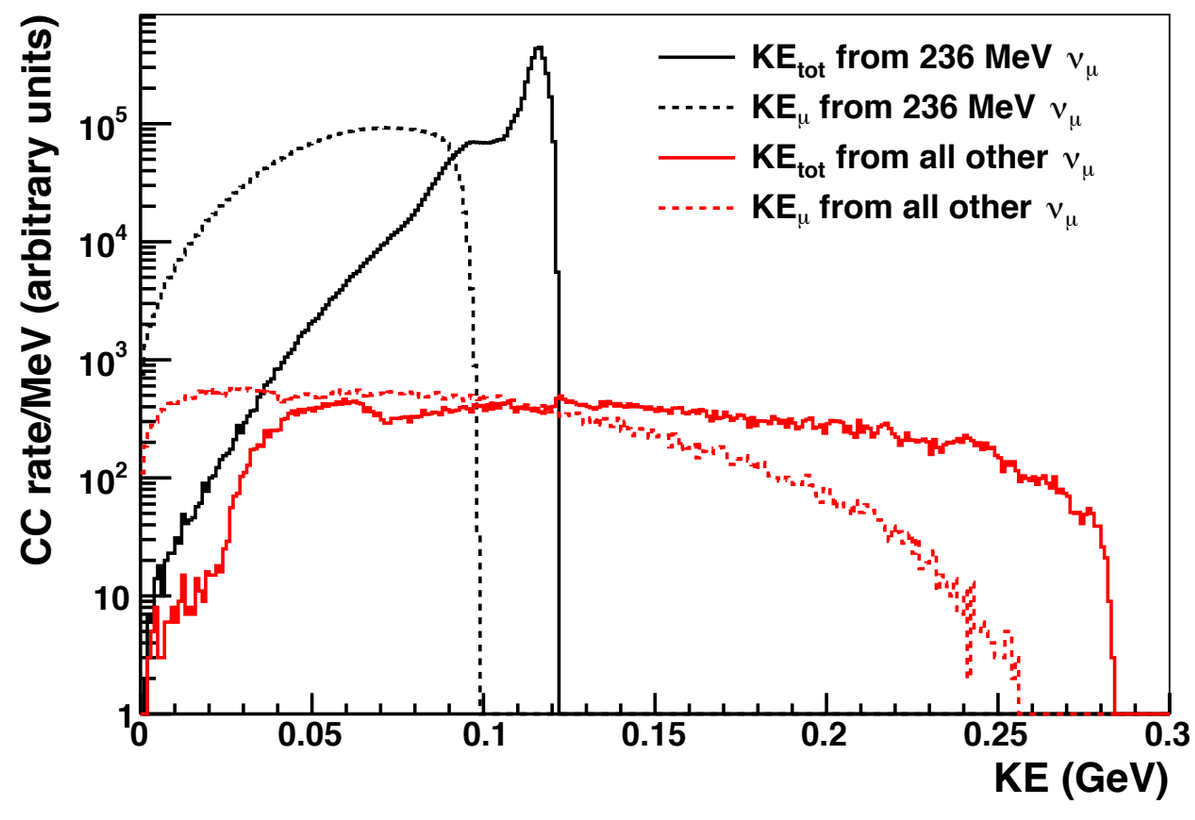
A very pure flux of KDAR neutrinos!



The beauty of KPIPE

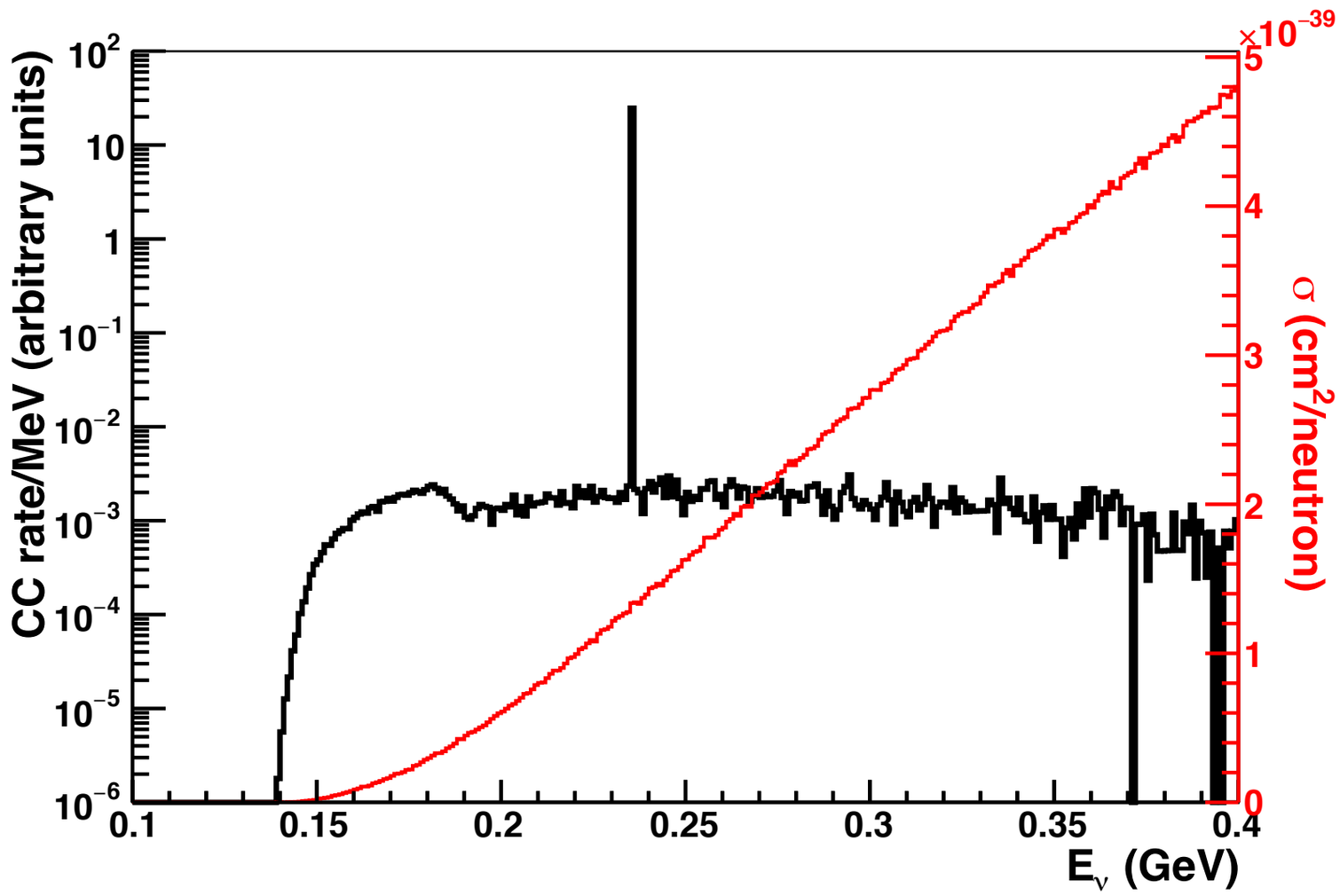
If you detect a numu CC event, you can be 98.5% sure that it was a 236 MeV muon neutrino!





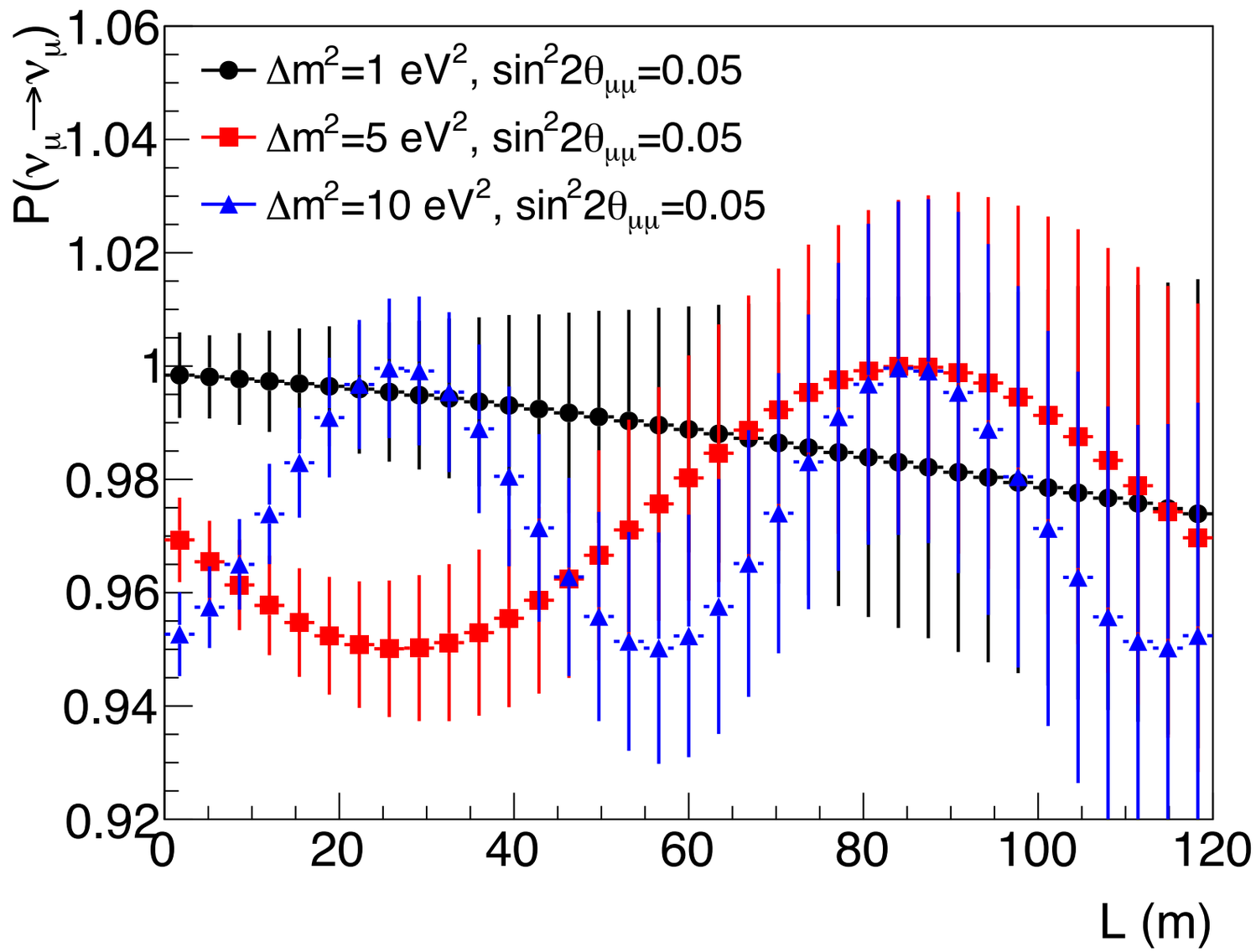
The beauty of KPIPE

Since you know the energy of the neutrino, you don't need to worry about energy resolution. KPIPE calls for 0.4% photocoverage.
Estimated cost of experiment: $4.5M



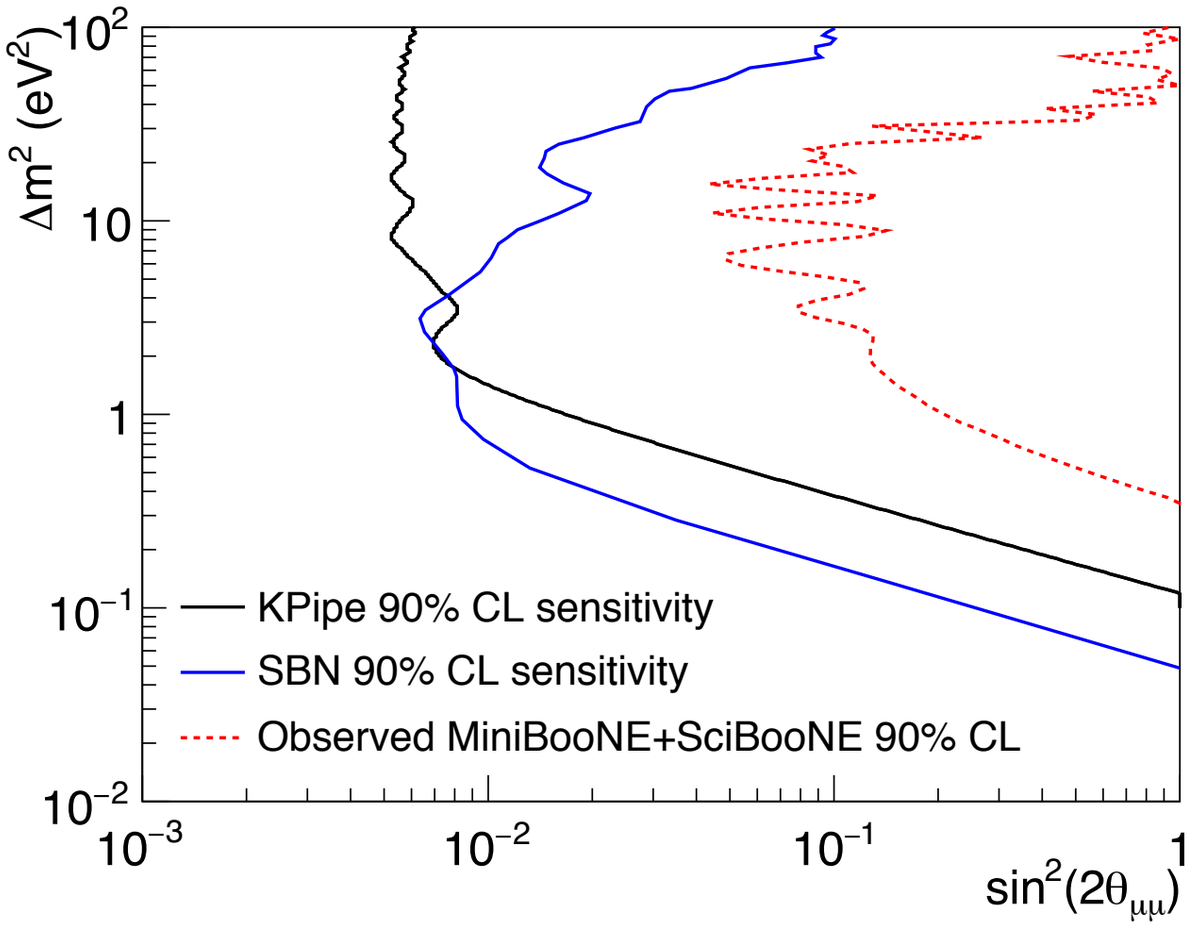
KPIPE cost document: http://hdl.handle.net/1721.1/98388

KPIPE; what would a signal look like?



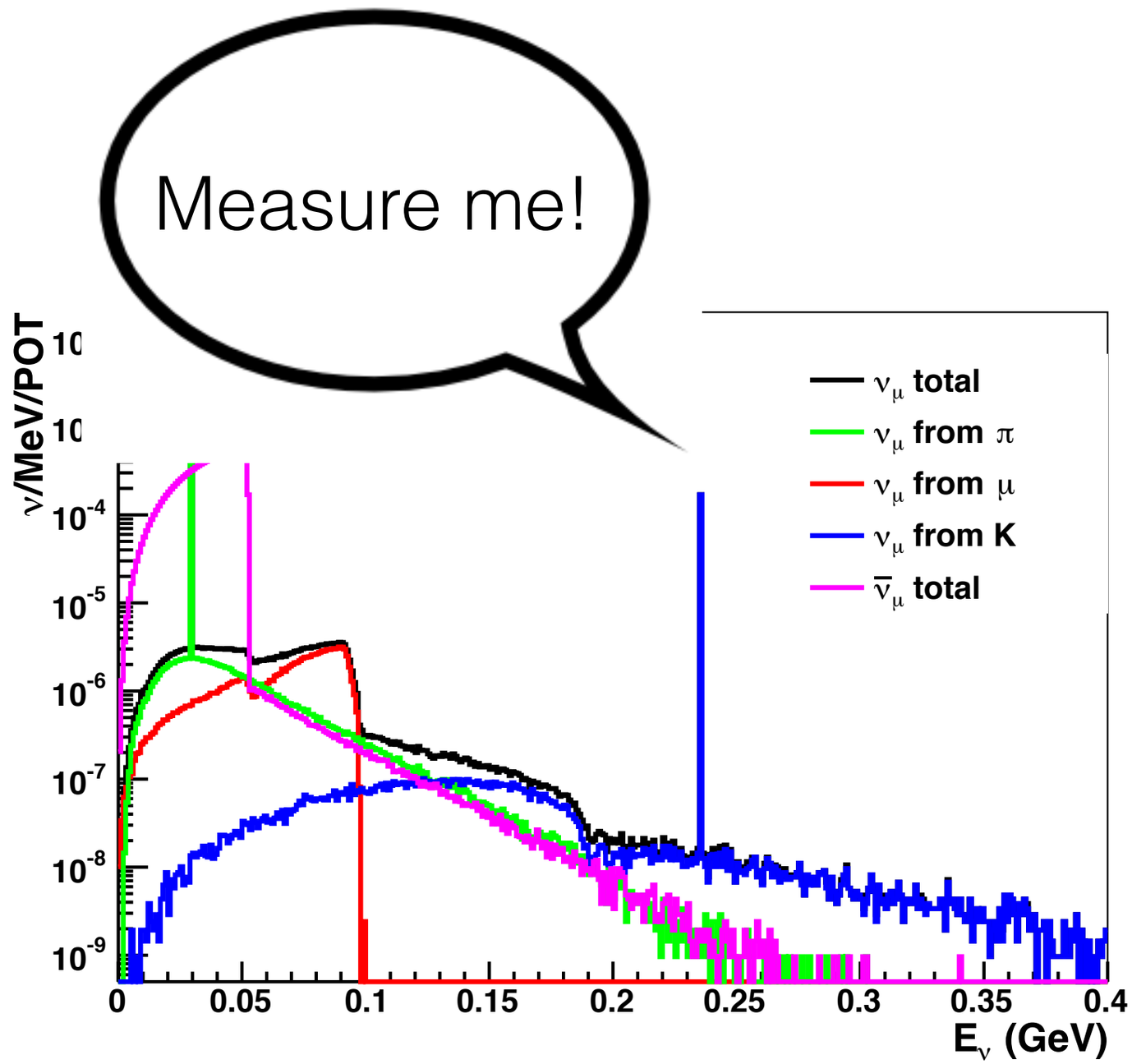
KPIPE sensitivity

- 6 years of running
- Extends limit at high-Δm^2 by an order of magnitude.
- Highly complementary to SBN program.
  - 6 years of MicroBooNE
  - 3 years of T600 and SBND.



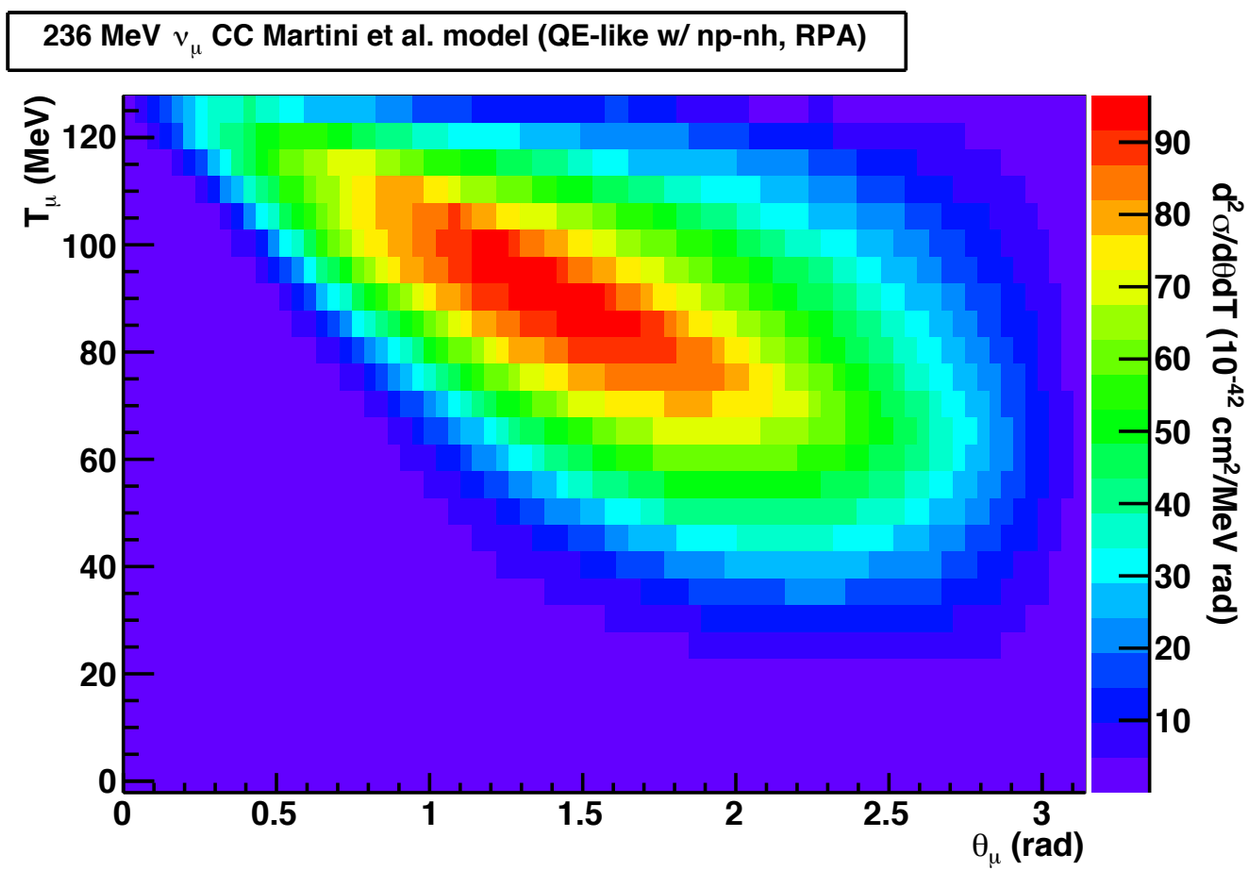
Conclusion

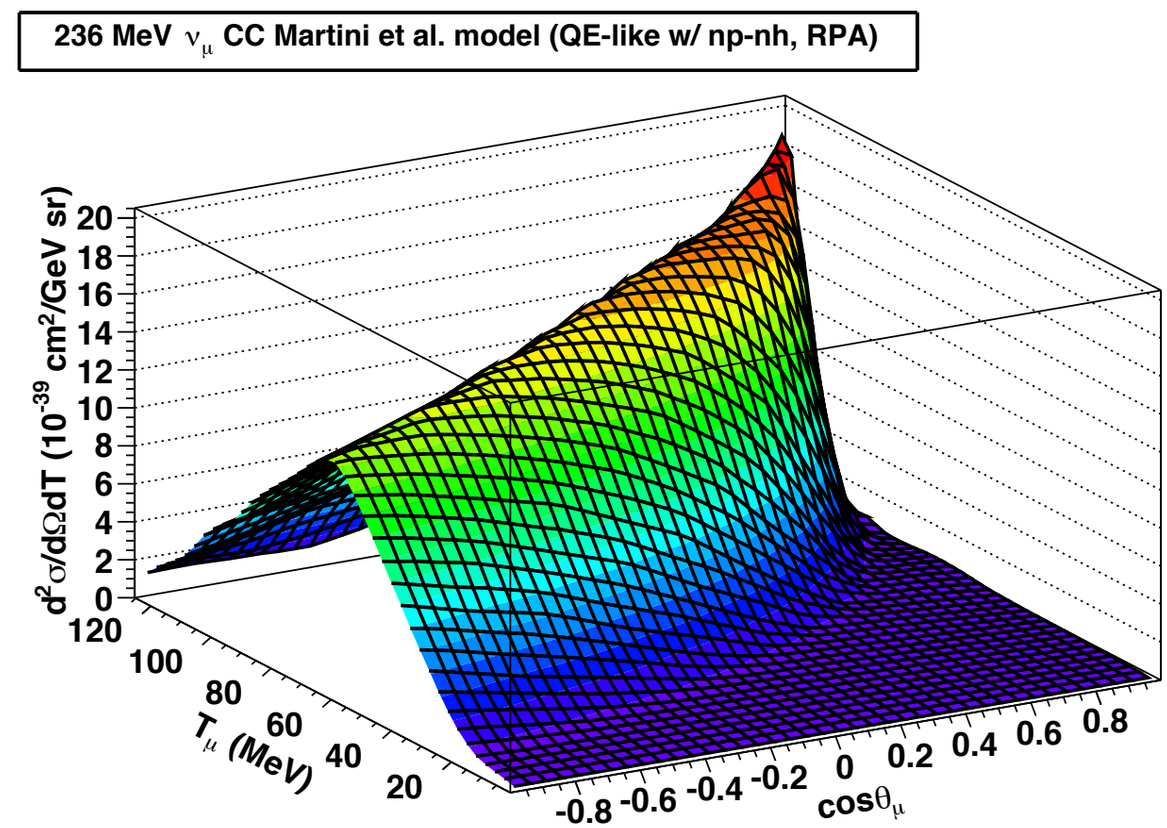
- Standard candle for muon kinematics.
- First measurement of ω with neutrinos.
- Check of CCQE formula.
- First known energy, weak-interaction-only nuclear probe.
- Electron neutrino appearance.
- Muon neutrino disappearance.



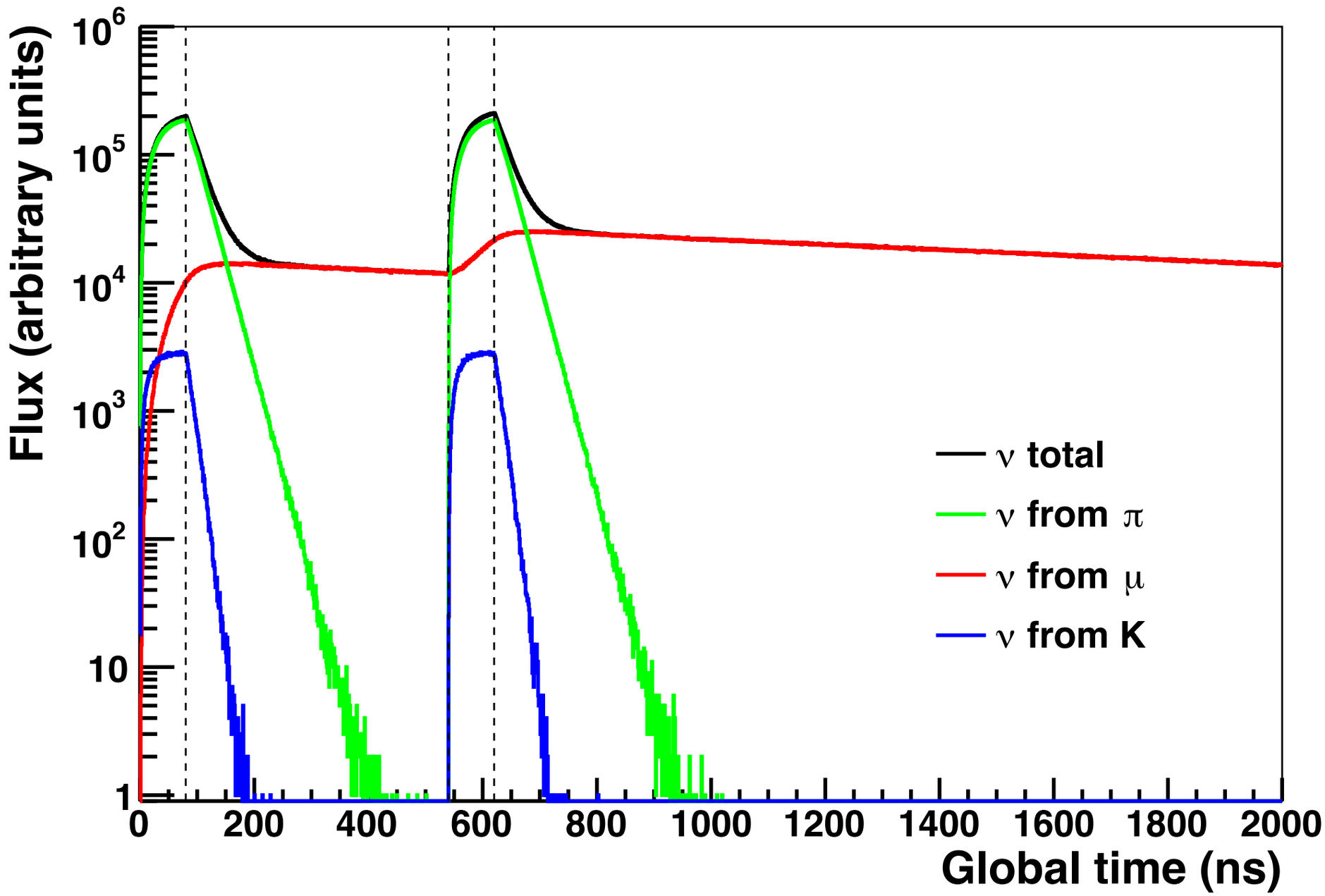
Backup

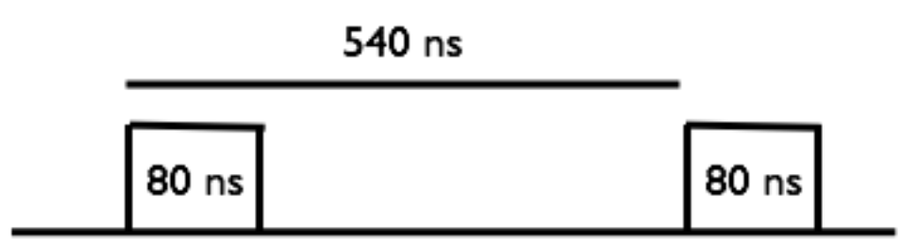
The Martini et al. RPA model





J-PARC MLF Timing



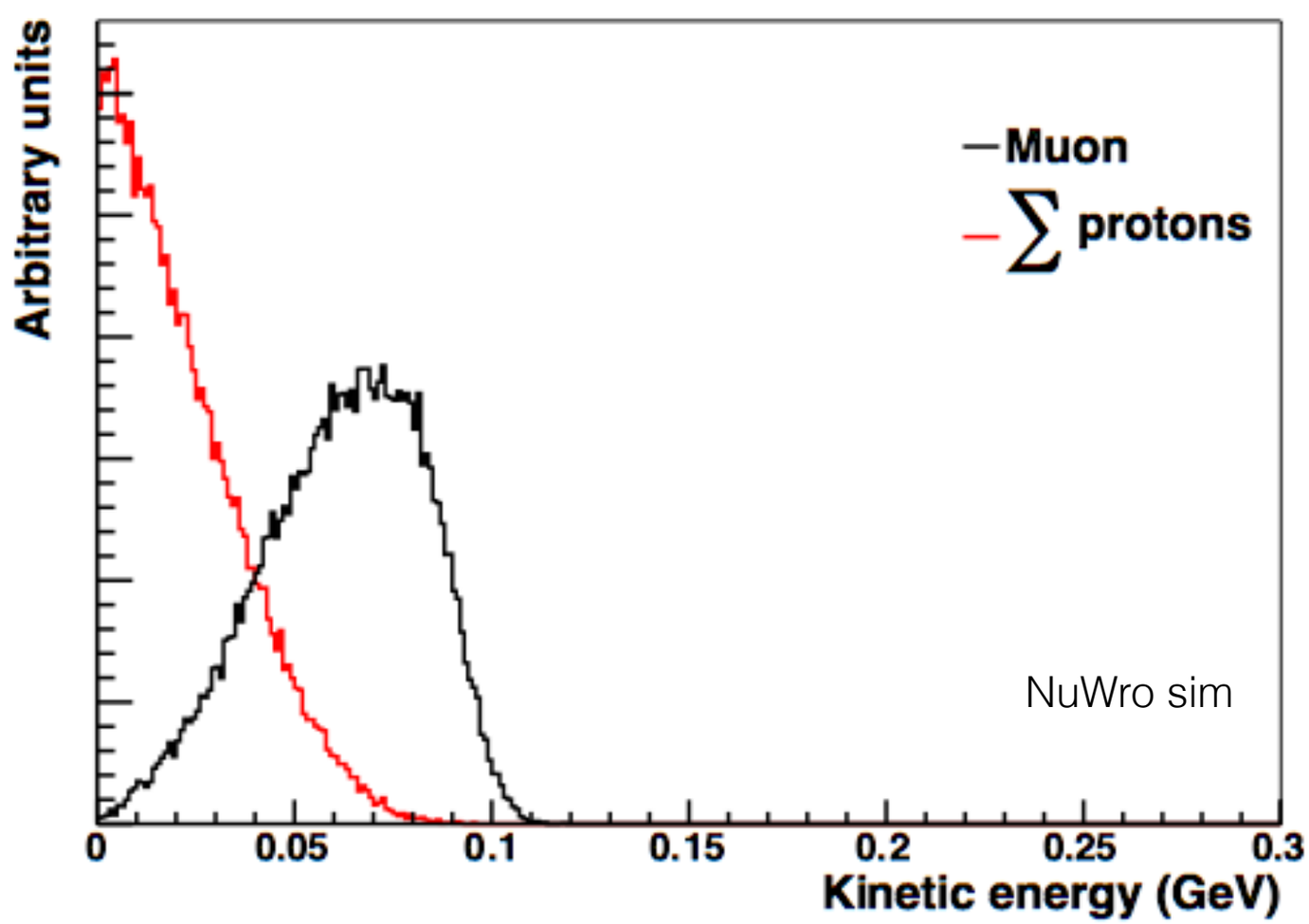


Beam structure

25 Hz

How to differentiate signal from background?

Event class	236 MeV ν_μ CC
Physics	xsec and nuclear probe
Prompt signal	μ-like, 0-110 MeV
Double coincidence?	Yes
Total KE of outgoing particles	$\sim$130 MeV



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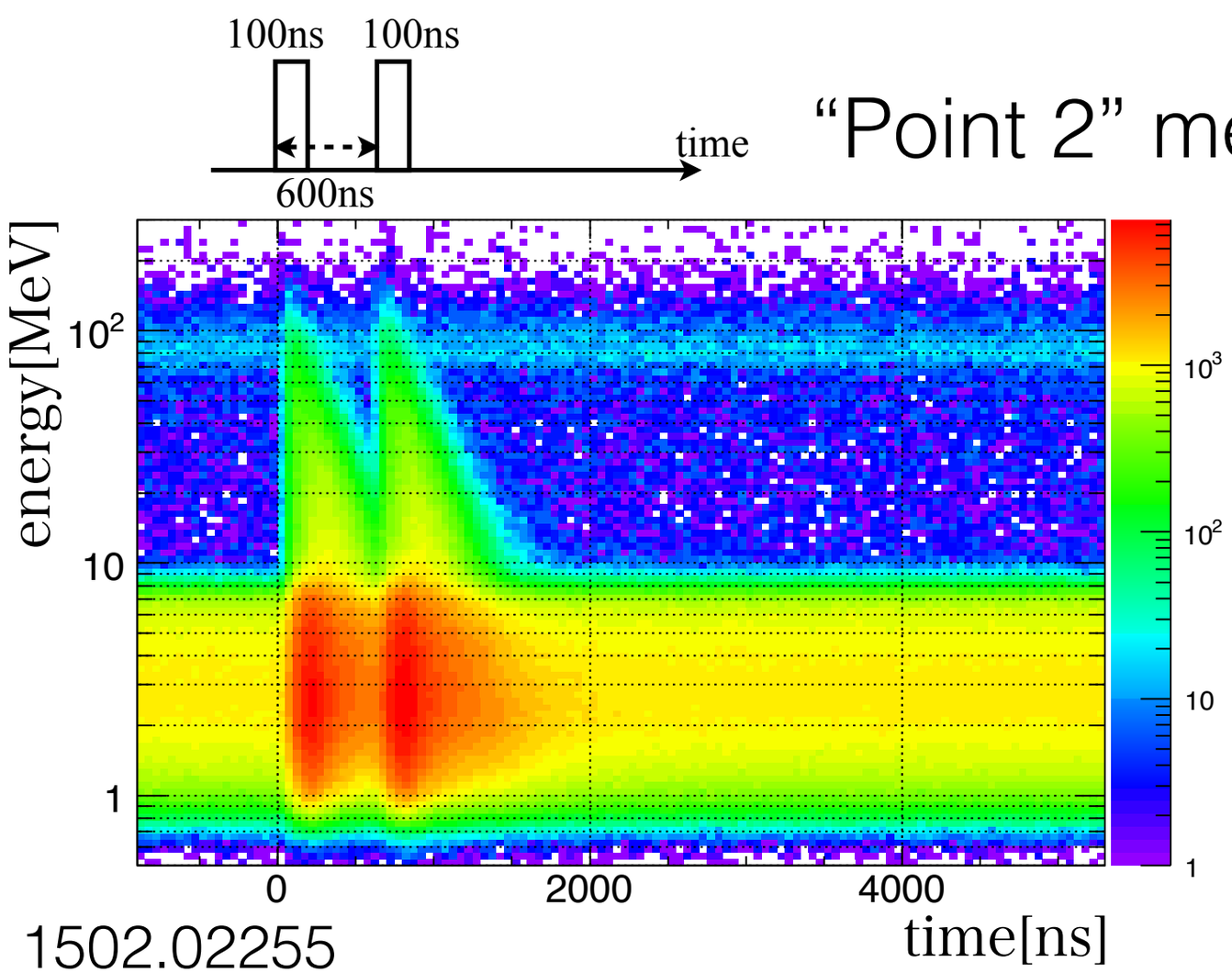
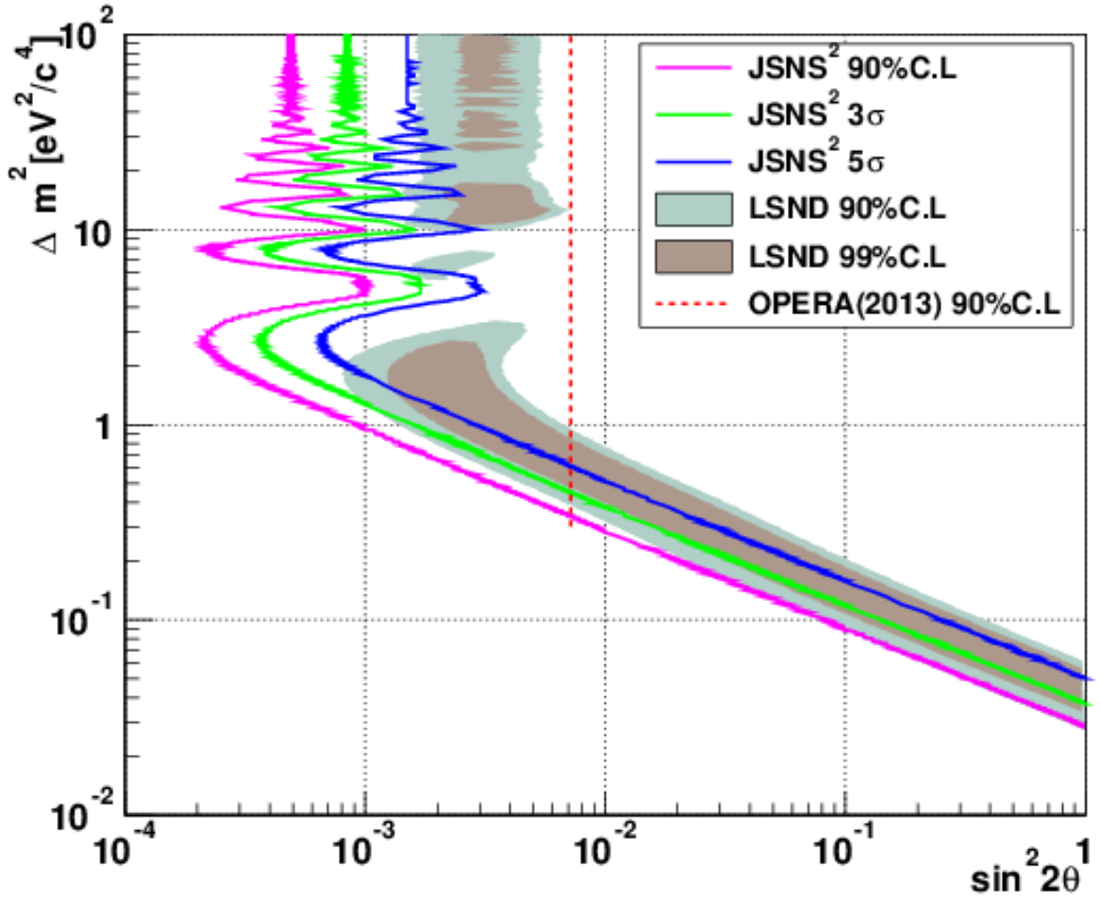


"Point 2" measurement

1502.02255

J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source ($JSNS^2$)

- Nominally, an experiment to test LSND using pi/mu decay-at-rest.



Kappa

Pauli blocking parameter κ

Currently, MiniBooNE is using the NUANCE neutrino interaction generator [7]. In NUANCE, CCQE interactions on carbon are modeled by the Relativistic Fermi Gas (RFG) model [4]. To achieve our goal within the RFG model, we introduced a new parameter "kappa", κ,

$$E_{\rm hi} = \sqrt{p_F^2 + M_n^2} \quad E_{\rm lo} = \kappa(\sqrt{p_F^2 + M_p^2} - \omega + E_B) \tag{2}$$

where M_n is the target neutron mass, M_p is the outgoing proton mass, P_F is Fermi momentum (=220MeV), E_B is binding energy (=34MeV), and ω is the energy transfer. In the RFG model, $E_{\rm hi}$ is the energy of an initial nucleon on the Fermi surface and $E_{\rm lo}$ is the lowest energy of an initial nucleon that leads to a final nucleon just above the Fermi momentum. The function of parameter κ is to squeeze down the phase space of the nucleon Fermi sea, especially when the energy transfer is small. From Fig. 3, one can see that this parameter controls the Q^2 distribution only in the low Q^2 region. This is quite complementary to the role of M_A, since M_A mainly controls the Q^2 distribution in the high Q^2 region.

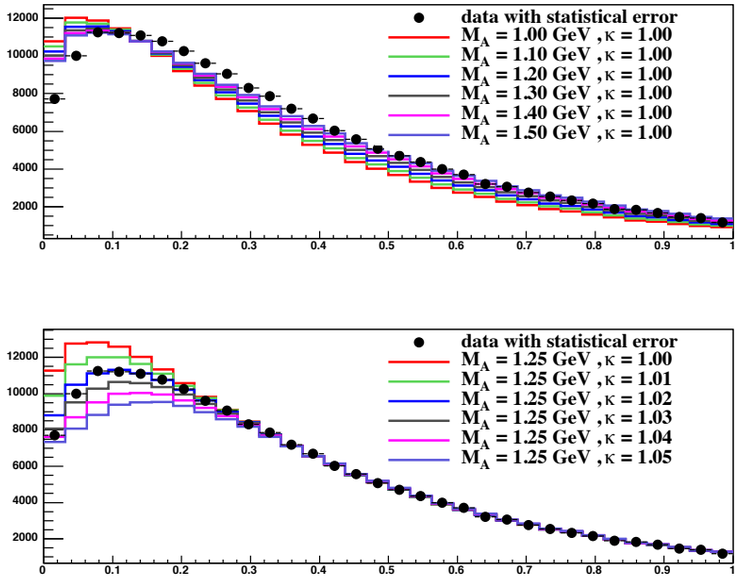


FIGURE 3. Effect of M_A and κ variations on the MiniBooNE, flux integrated Q^2 distribution. The top plot shows various M_A with fixed κ, and bottom plot shows various κ with fixed M_A. Note, the M_A variation has large impact at high Q^2 while the κ variation has a significant impact only for Q^2 below $\sim 0.2 GeV^2$.

T. Katori, arXiv:0709.4498