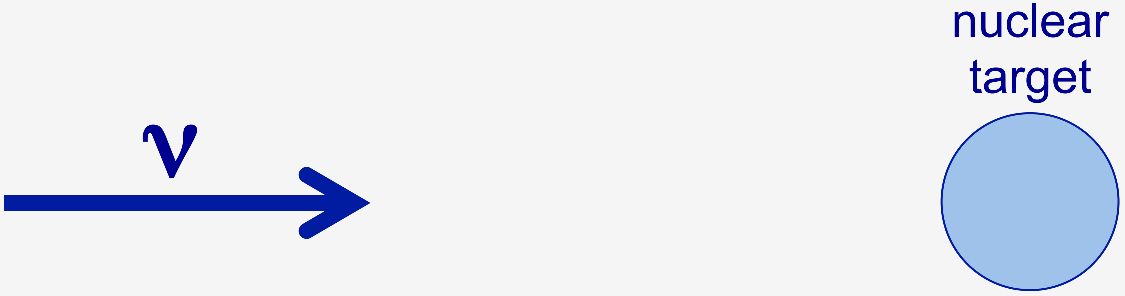
ν
nuclear
target

Fun Timely Intellectual Adorable!

Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

Neutrino Cross-Section Newsletter

Nucleon correlation

EMC effect

electron scattering

Dark matter

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Teppei Katori, Queen Mary University of London

Neutrino Interaction Physics for Neutrino Oscillation experiments

Outline

1. Neutrino oscillations
2. Accelerator-based neutrino oscillation experiment
3. QE-like background
4. NCπ^o bkgd for ν_e appearance experiment
5. Interaction systematics status
6. Realistic oscillation analysis
7. Conclusion

Teppei Katori
Queen Mary University of London
NuSTEC15, Okayama University, Okayama, Nov. 15, 2015

1. Neutrino oscillations

2. Accelerator-based neutrino oscillation experiment

3. QE-like background

4. NCπ^o background for ν_e appearance experiment

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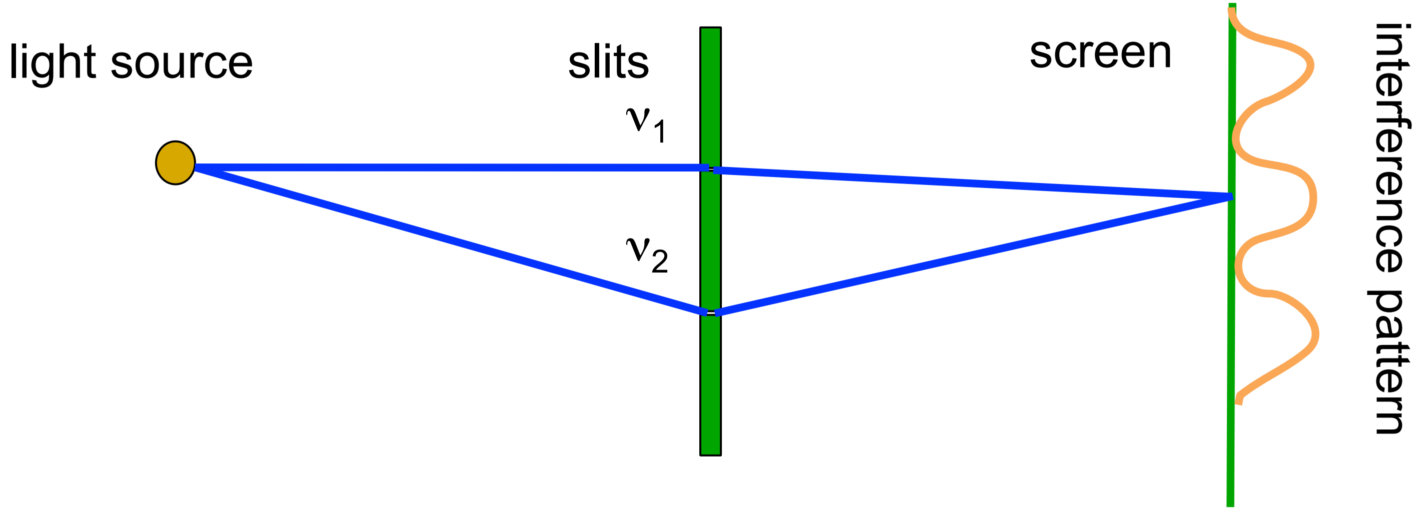
7. Conclusion

1. Neutrino oscillations

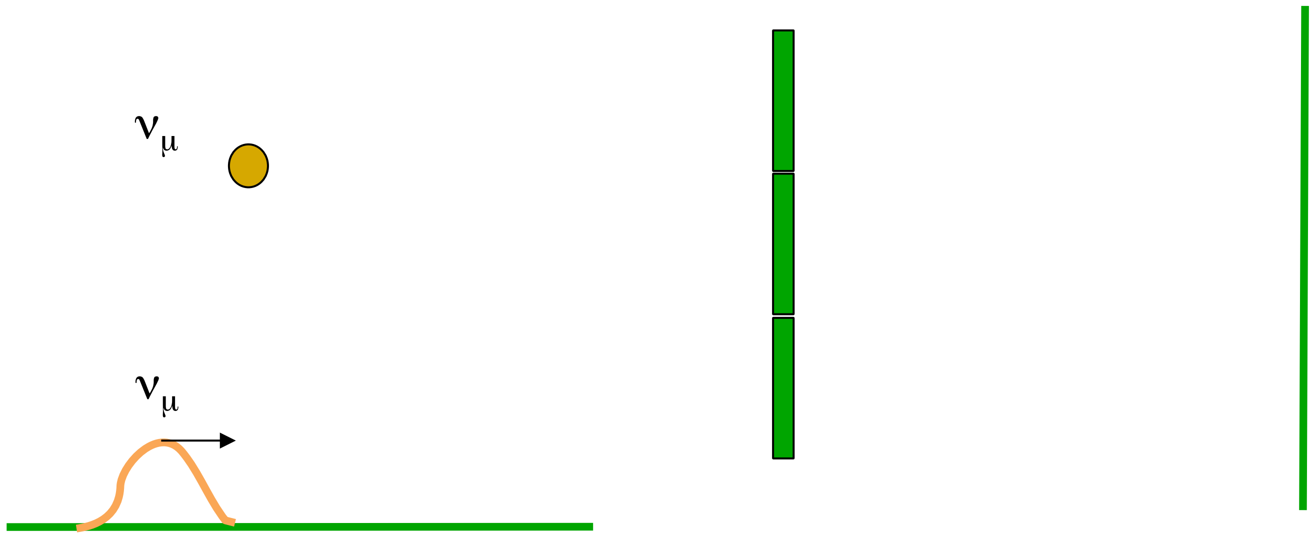
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

1. Neutrino oscillations

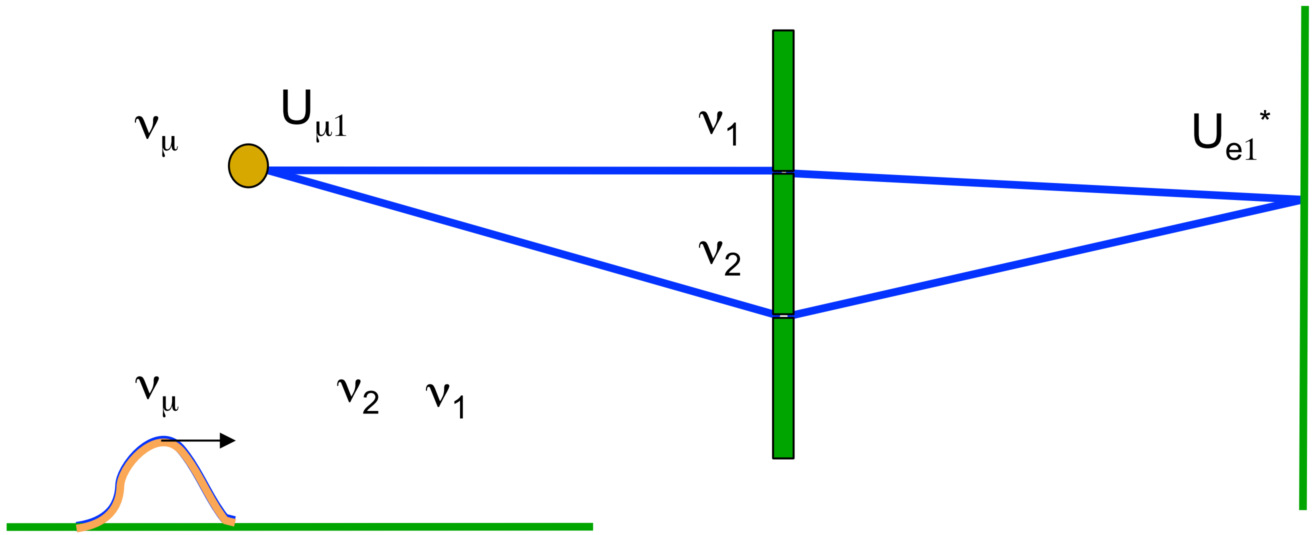
Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

1. Neutrino oscillations

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

1. Neutrino oscillations

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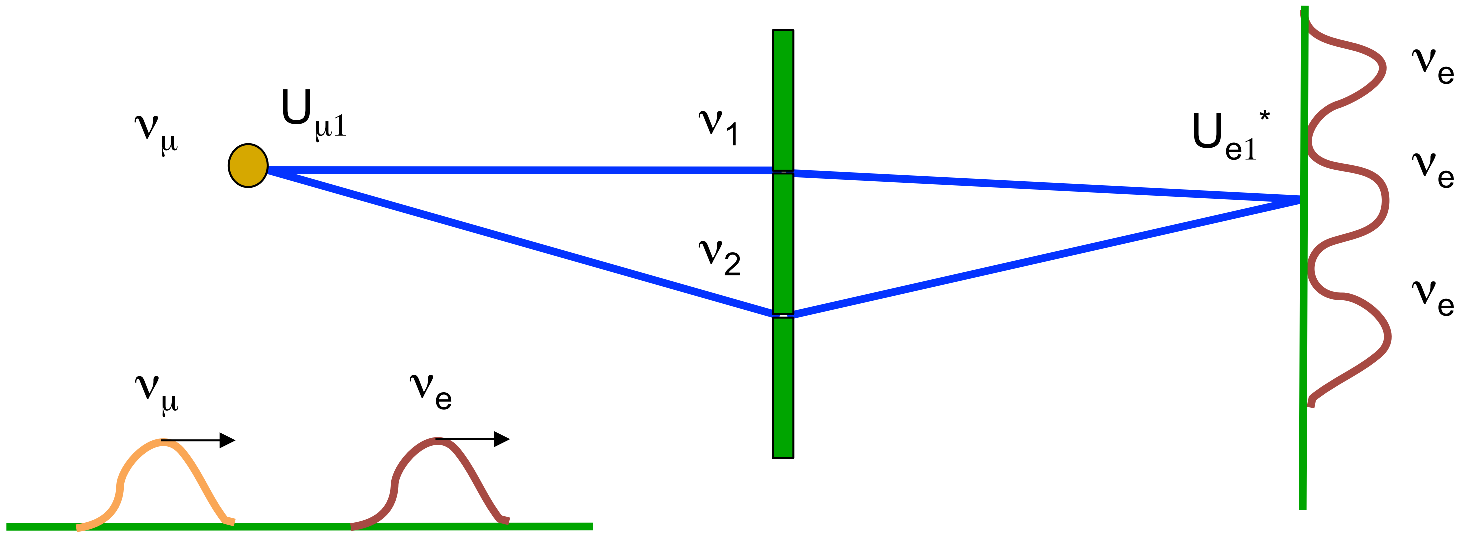


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

The detection may be different flavor (neutrino oscillations).

1. Neutrino oscillations

2 neutrino mixing

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, ν_1 and ν_2, and their mixing matrix elements.

$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle$$

The time evolution of neutrino weak eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1 and ν_2 .

$$|\nu_\mu(t)\rangle = U_{\mu 1}e^{-i\lambda_1 t}|\nu_1\rangle + U_{\mu 2}e^{-i\lambda_2 t}|\nu_2\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is,

$$P_{\mu\to e}(t) = \left|\langle \nu_e | \nu_\mu(t)\rangle\right|^2 = -4U_{e1}U_{e2}U_{\mu 1}U_{\mu 2}\sin^2\left(\frac{\lambda_1-\lambda_2}{2}t\right)$$

1. Neutrino oscillations

In the vacuum, 2 neutrino effective Hamiltonian has a mass term,

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Therefore, 2 massive neutrino oscillation model is ($\Delta m^2=|m_1{}^2-m_2{}^2|$)

$$P_{\mu\rightarrow e}(L/E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

After adjusting the unit

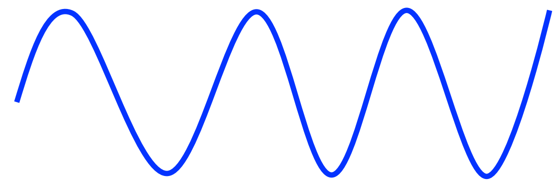
$$P_{\mu\rightarrow e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(m)}{E(MeV)}\right)$$

1. Neutrino oscillations

Q1

real formulation of neutrino oscillations

$$|\nu_\alpha\rangle = \sum U_{\alpha a} |\nu_a\rangle$$



This doesn't make much sense as neutrino oscillation experiment…

Kayser,PRD24(1981)110

1. Neutrino oscillations

real formulation of neutrino oscillations

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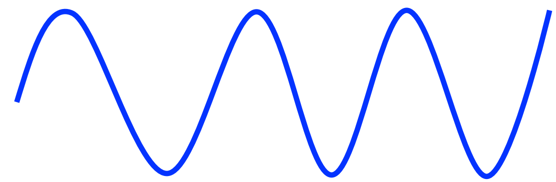
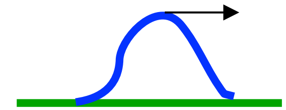


$$|\nu_\alpha\rangle \propto \sum U_{\alpha a} \exp\left(i\bar{p}_a x - \bar{E}_a t - \frac{(x - v_a t)^2}{4\sigma_x^2} \right) |\nu_a\rangle$$



wave packet formalism

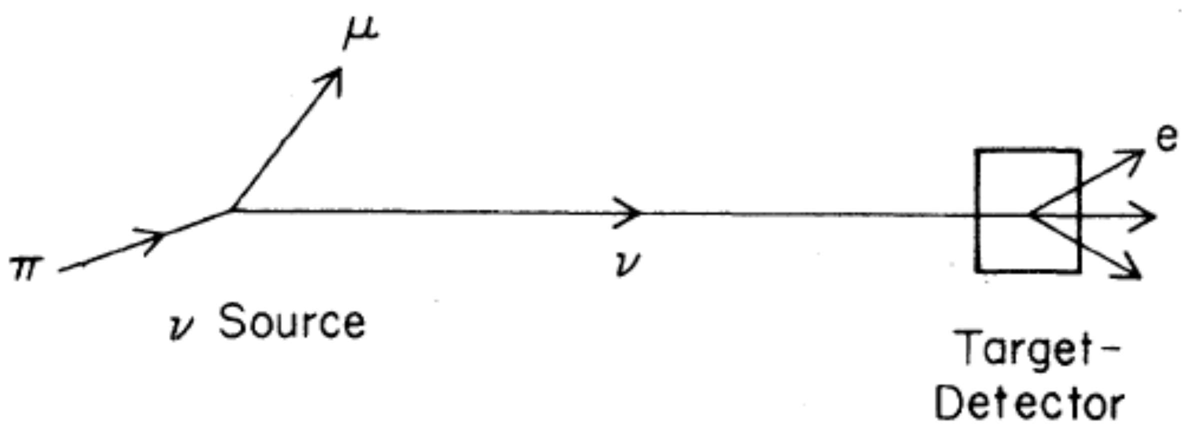


FIG. 1. A typical neutrino-oscillation experiment.

Giunti,Kim,Lee,PRD44(1991)3635
KamLAND,PRD83(2011)052002, Evans,arXiv:1307.0721

1. Realistic neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

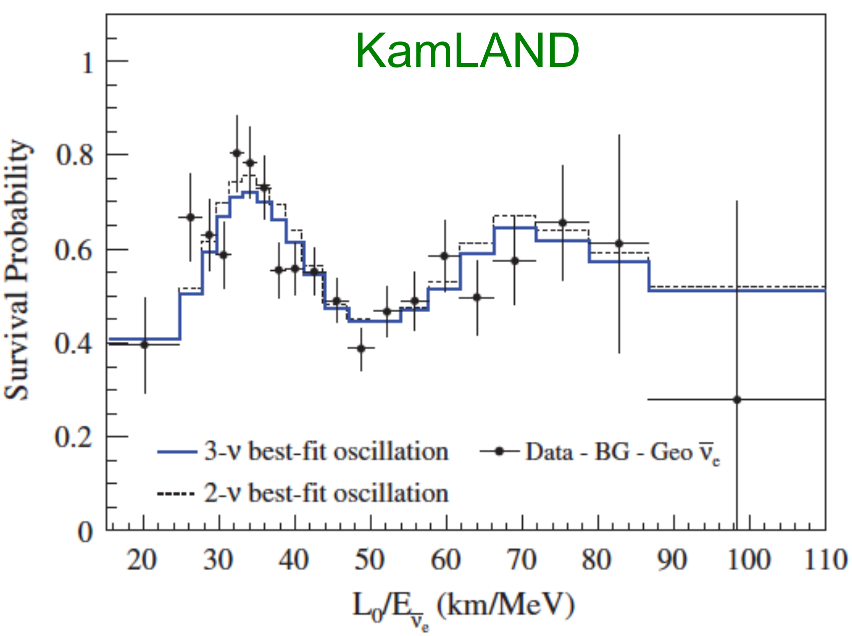
$$L^{osc} \equiv \frac{4\pi E}{\Delta m^2}$$

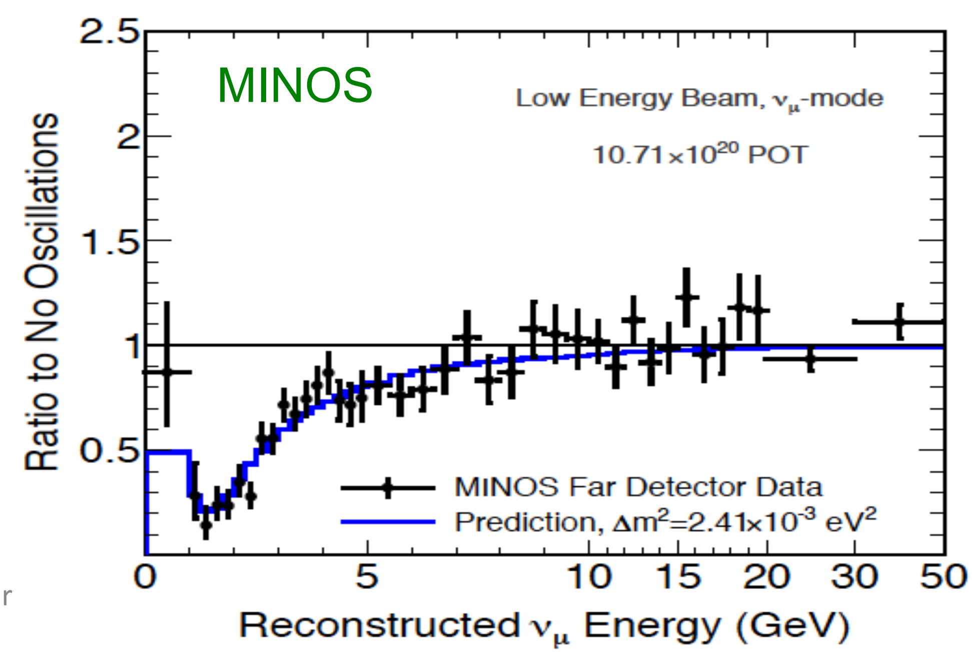
$$P_{\alpha\beta}(L) \propto \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{osc}_{ij}} - 4\pi^2 \left(\frac{\sigma_x}{L^{osc}_{ij}}\right)^2\right]$$

Coherent oscillation

Decoherence at production and detection

oscillation experiments focus to measure the first (and hopefully the second) oscillation maximum





Giunti,Kim,Lee,PRD44(1991)3635
KamLAND,PRD83(2011)052002, Evans,arXiv:1307.0721

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Coherent oscillation
Decoherence at production and detection

oscillation experiments focus to measure the first (and hopefully the second) oscillation maximum

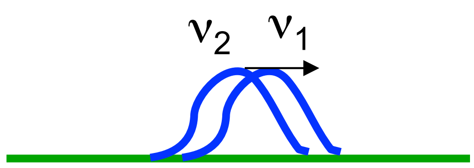
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(m)}{E(MeV)}\right)$$

$$\frac{L(m)}{E(MeV)} = \frac{\pi}{2.54\cdot\Delta m^2(eV^2)} = \begin{cases} \sim 500 & (\Delta m^2 = 2.5\times 10^{-3} eV^2) \\ \sim 16500 & (\Delta m^2 = 7.5\times 10^{-5} eV^2) \end{cases}$$

735km and 3GeV (=MINOS)
295km and 600 MeV (=T2K)

180km and 4.4MeV (=KamLAND)

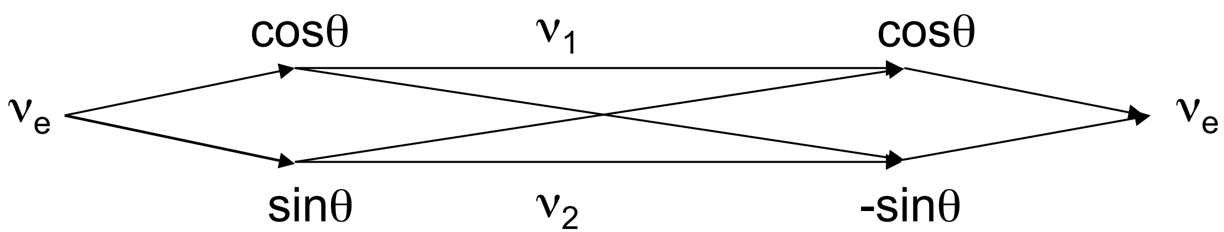
1. Neutrino oscillations



Wave packet formalism

- real formulation of neutrino oscillations

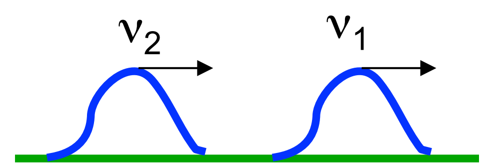
Neutrino oscillation



$$P=|A_1{}^{+}A_2|^2 = 1-\sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

Kopp, Fermilab theory seminar (2012) http://theory.fnal.gov/seminars/seminars.html
Beuthe, Phys.Rept.375(2003)105

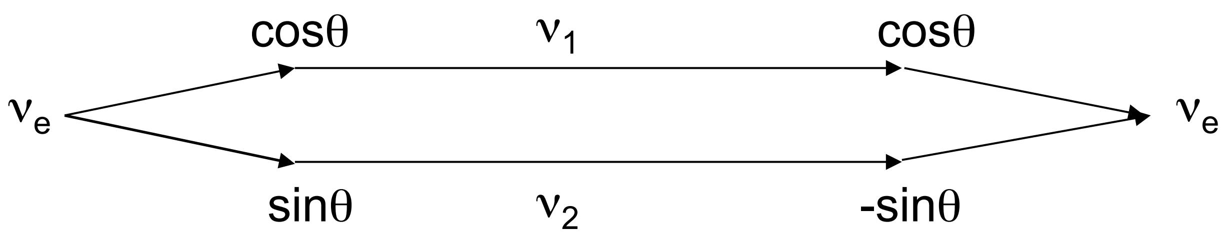
1. Neutrino oscillations



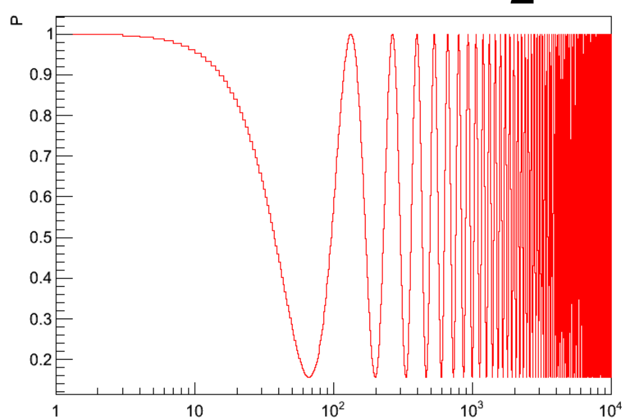
Wave packet formalism

- real formulation of neutrino oscillations

Decoherent neutrino oscillation (time averaged neutrino oscillation)



$$P=|A_1|^2+|A_2|^2 = \cos^4\theta+\sin^4\theta = 1-\sin^2 2\theta\cdot\frac{1}{2} = 1-\sin^2 2\theta\sin^2\left(\frac{\Delta m^2}{4E}L\right)\Bigg|_{L\to\infty}$$



cf. more realistic neutrino oscillation formula

$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j}U_{\alpha k}U^*_{\beta k}U_{\beta j}\exp\left[-2\pi i\frac{L}{L^{\rm osc}_{jk}} - \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2E^2} - 2\pi^2\xi^2\left(\frac{\sigma_x}{L^{\rm osc}_{jk}}\right)^2 - \frac{(m_j^2+m_k^2)^2}{32\sigma_m^2E^2}\right]$$

Queen Mary
University of London

1. Appearance vs. Disappearance experiments

Appearance experiment
$\nu_\mu \rightarrow \nu_e$
$P(\nu_\mu \rightarrow \nu_e)$

Often performed with accelerator-ν

Disappearance experiment
$\nu_\mu \rightarrow \nu_\mu$
$P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_e) - P(\nu_\mu \rightarrow \nu_\tau)$

Often performed with natural-ν (including reactor)

1. Appearance vs. Disappearance experiments

Q2

Appearance experiment
$\nu_\mu \rightarrow \nu_e$
$P(\nu_\mu \rightarrow \nu_e)$

Often performed with accelerator-ν

ν_e appearance, $P(\nu_\mu \rightarrow \nu_e)$

ν_e appearance, $P(\nu_\tau \rightarrow \nu_e)$

ν_μ appearance, $P(\nu_e \rightarrow \nu_\mu)$

ν_μ appearance, $P(\nu_\tau \rightarrow \nu_\mu)$

ν_τ appearance, $P(\nu_e \rightarrow \nu_\tau)$

ν_τ appearance, $P(\nu_\mu \rightarrow \nu_\tau)$

Disappearance experiment
$\nu_\mu \rightarrow \nu_\mu$
$P(\nu_\mu \rightarrow \nu_\mu)=1-P(\nu_\mu \rightarrow \nu_e)-P(\nu_\mu \rightarrow \nu_\tau)$

Often performed with natural-ν (including reactor)

ν_e disappearance (solar)

anti-ν_e disappearance (reactor)

ν_μ+anti-ν_μ disappearance (atmospheric)

ν_μ and anti-ν_μ disappearance

ν_τ disappearance

1. Appearance vs. Disappearance experiments

Appearance experiment
$\nu_\mu \rightarrow \nu_e$
$P(\nu_\mu \rightarrow \nu_e)$

Often performed with accelerator-ν

ν_e appearance, $P(\nu_\mu \rightarrow \nu_e)$
- MINOS, T2K, NOvA (~100-1000km)

ν_e appearance, $P(\nu_\tau \rightarrow \nu_e)$
none: ν_τ beam is not easy to make

ν_μ appearance, $P(\nu_e \rightarrow \nu_\mu)$
none: no high energy ν_e beam

ν_μ appearance, $P(\nu_\tau \rightarrow \nu_\mu)$
none: ν_τ beam is not easy to make

ν_τ appearance, $P(\nu_e \rightarrow \nu_\tau)$
none: no high energy ν_e beam

ν_τ appearance, $P(\nu_\mu \rightarrow \nu_\tau)$
- OPERA, Super-K

Disappearance experiment
$\nu_\mu \rightarrow \nu_\mu$
$P(\nu_\mu \rightarrow \nu_\mu)=1-P(\nu_\mu \rightarrow \nu_e)-P(\nu_\mu \rightarrow \nu_\tau)$

Often performed with natural-ν (including reactor)

ν_e disappearance (solar)
- Homestake, KamII, SuperK, SNO
- Borexino, Gallex, SAGE

anti-ν_e disappearance (reactor)
- CHOOZ, etc (<1km)
- DChooz,RENO,DayaBay (2km)
- KamLAND (long, ~200km)

ν_μ+anti-ν_μ disappearance (atmospheric)
- KamII, SuperK, MACRO, IceCube

ν_μ and anti-ν_μ disappearance
- magnetized: MINOS
- accelerator: MINOS, K2K T2K, NOvA

ν_τ disappearance
none: ν_τ beam is not easy to make

1. ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance

Accelerator based
- neutrino or anti-neutrino mode beam (important for CP violation measurement)
- precise timing, better background rejection, better reconstruction, etc

Future of neutrino oscillation experiment
- Hyper-Kamiokande: water Cherenkov (H_2O target), talk by Dr. Koshio-san
- DUNE: Liquid argon TPC (LArTPC, Ar target), talk by Dr. Flavio Cavanna

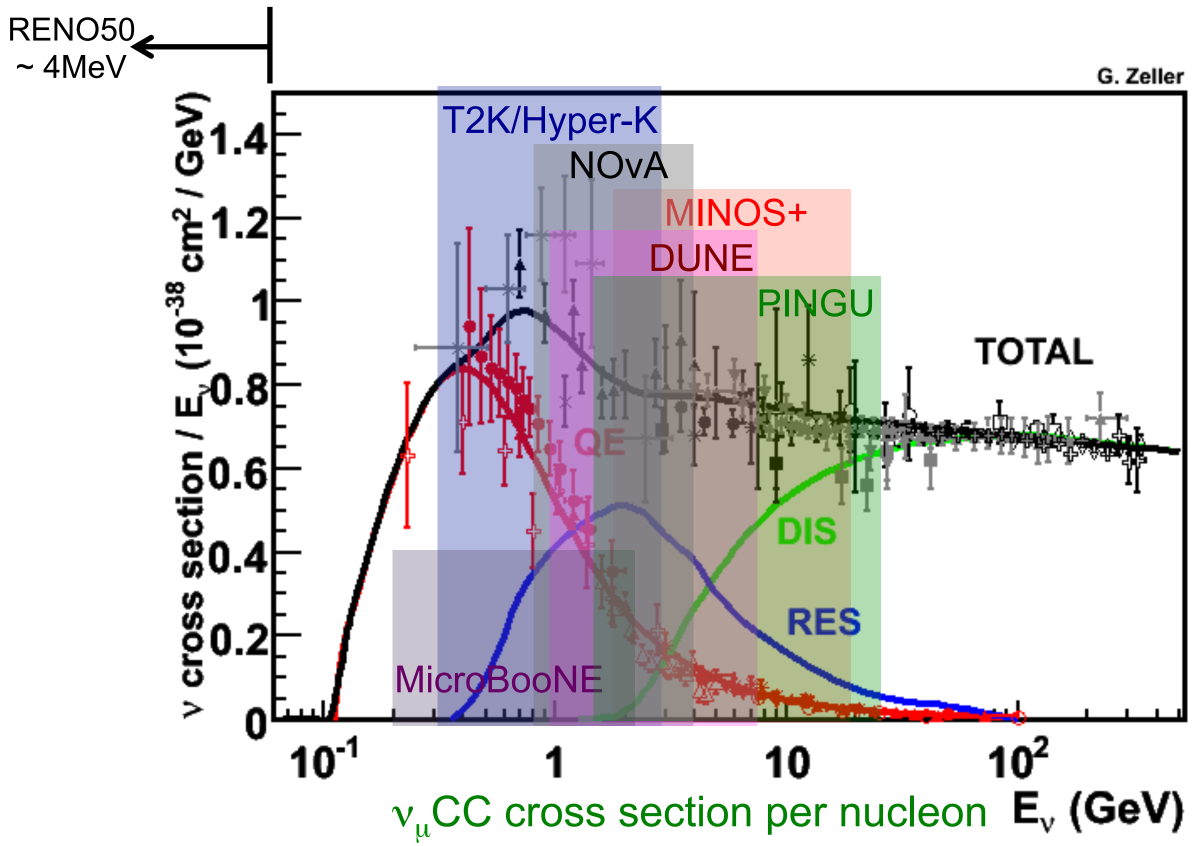
Use ν_μ (anti-ν_μ) beam to for ν_μ (anti-ν_μ) disappearance and ν_e (anti-ν_e) appearance

We focus on these 2 measurements
- QE-like background for ν_μ disappearance
- NCπ^o background for ν_e appearance

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K, DeepCore, Reactors
- Present to Future: T2K, MINOS+, NOvA, PINGU, RENO, Hyper-Kamiokande, DUNE



ν_μCC cross section per nucleon

1-10 GeV region is overwhelmingly important!

1. Neutrino oscillations

2. Accelerator-based neutrino oscillation experiment

3. QE-like background

4. NCπº background for ν_e appearance experiment

5. 5. Interaction systematics status

6. Realistic oscillation analysis

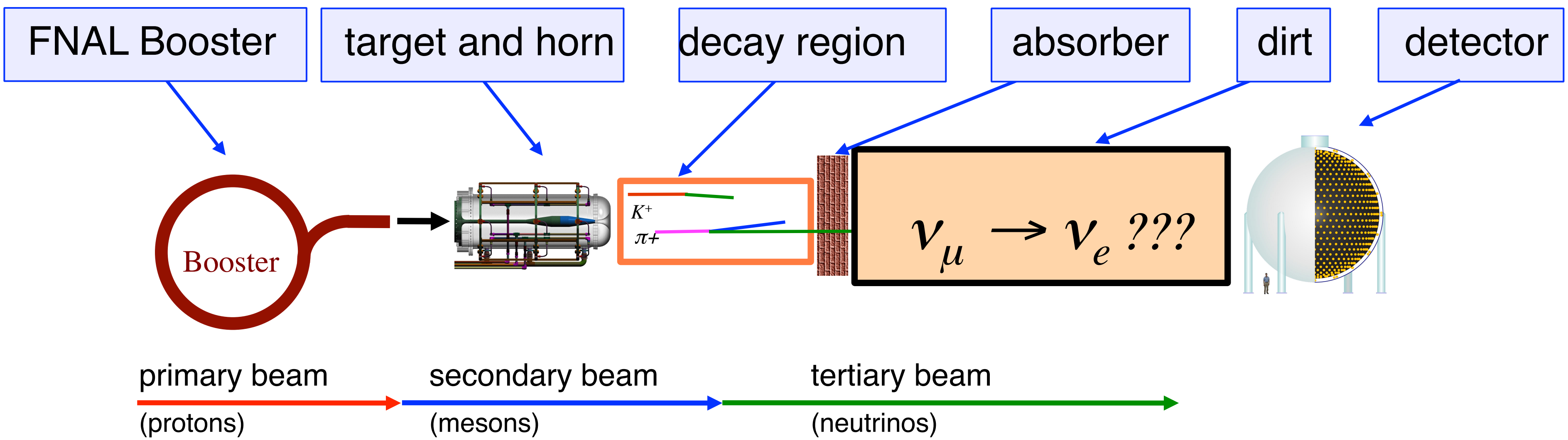
7. Conclusion

2. MiniBooNE experiment

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

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

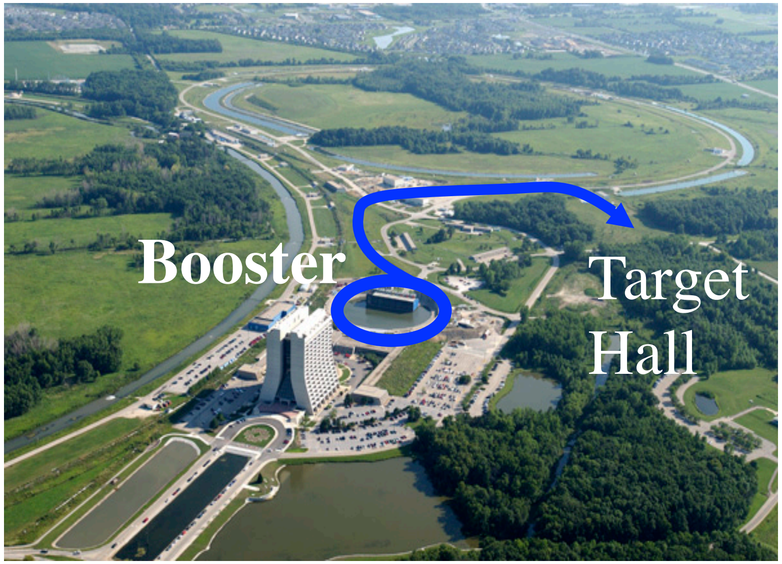
$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow n + \boxed{e^+}$$



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

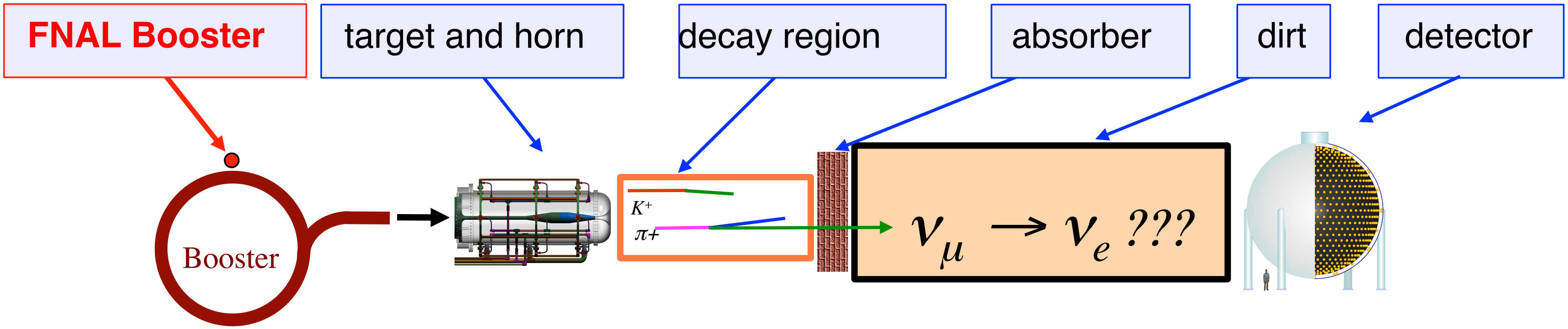
MiniBooNE,PRD79(2009)072002

2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster

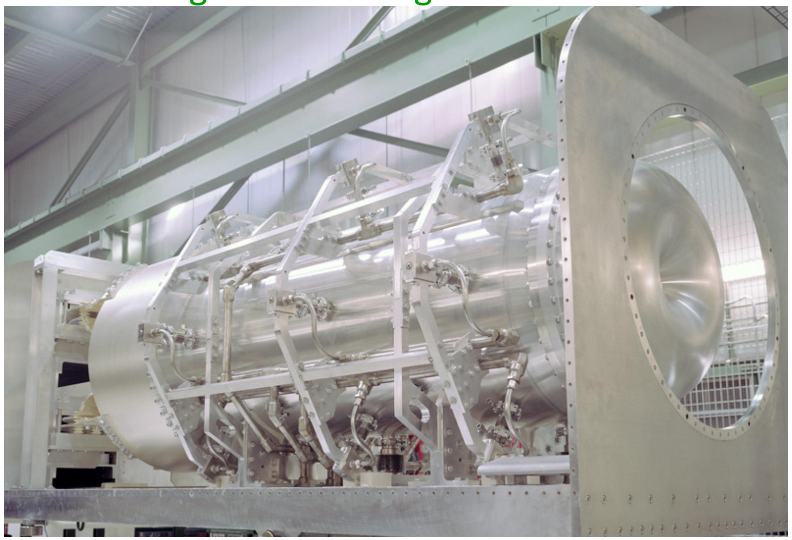
FNAL Booster



primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

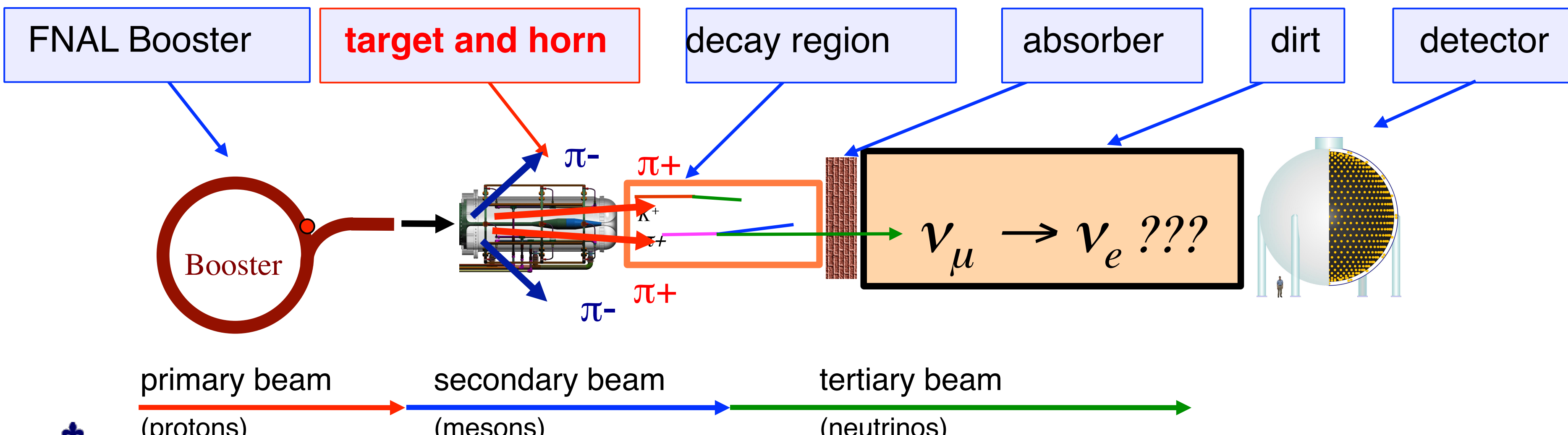
2. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 interaction length Be target

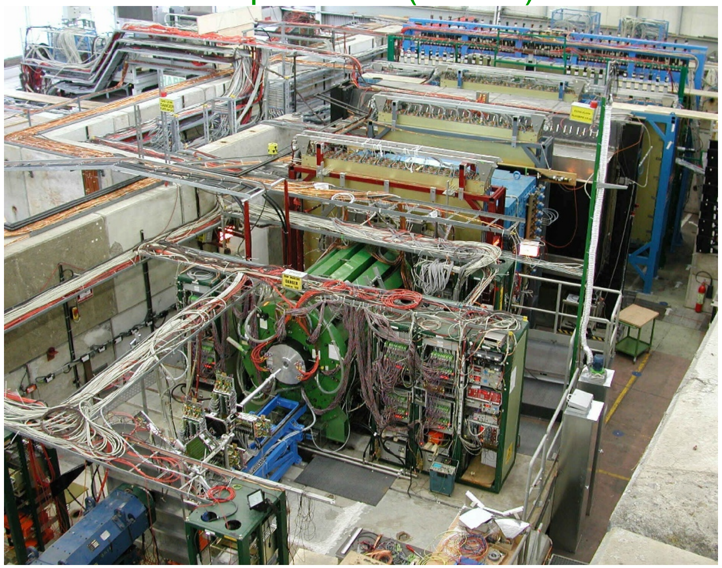
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by × 6



MiniBooNE,PRD79(2009)072002
HARP, EPJC52(2007)29

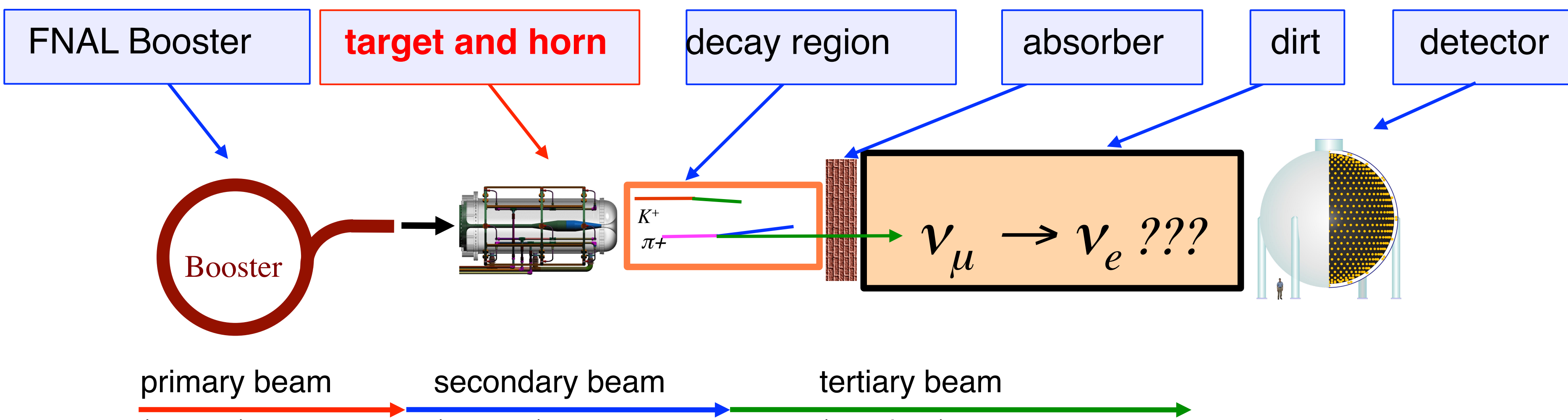
2. Neutrino beam

HARP experiment (CERN)

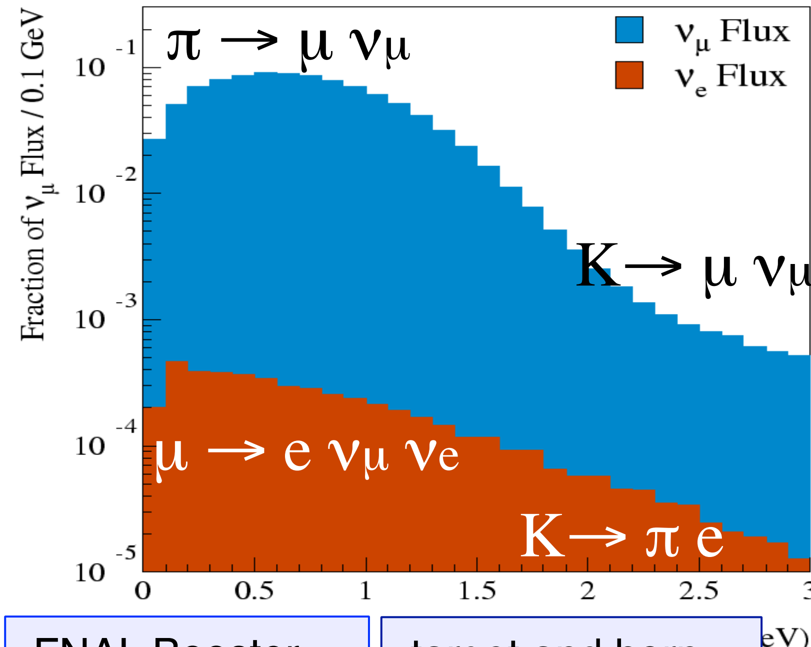


Modeling of meson production is based on the measurement done by HARP collaboration.

- Identical, but 5% interaction length Beryllium target
- 8.9 GeV/c proton beam momentum

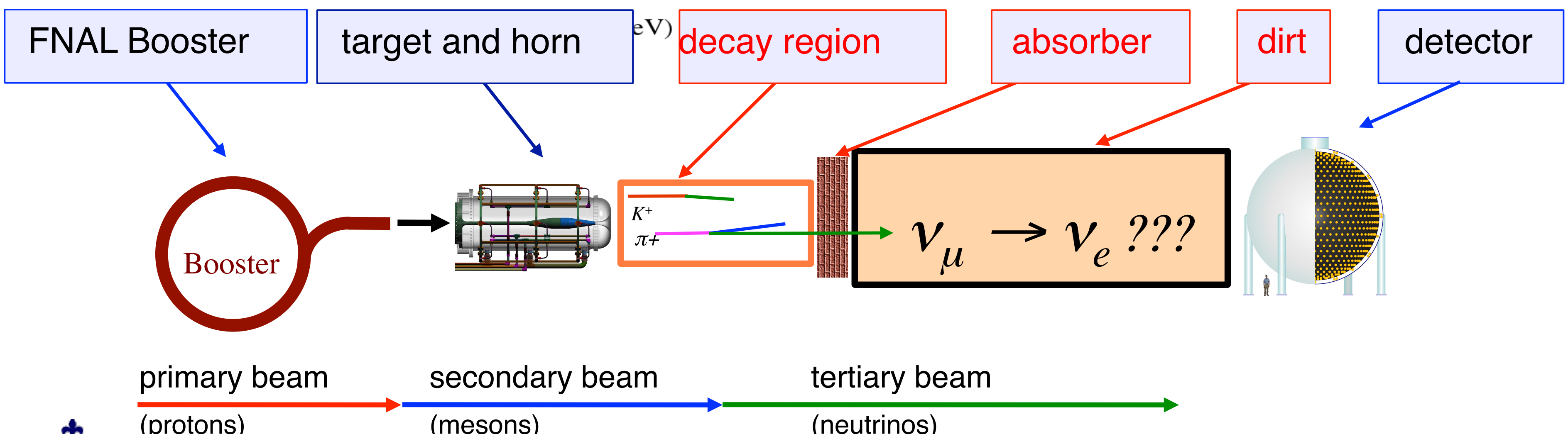


2. Neutrino beam



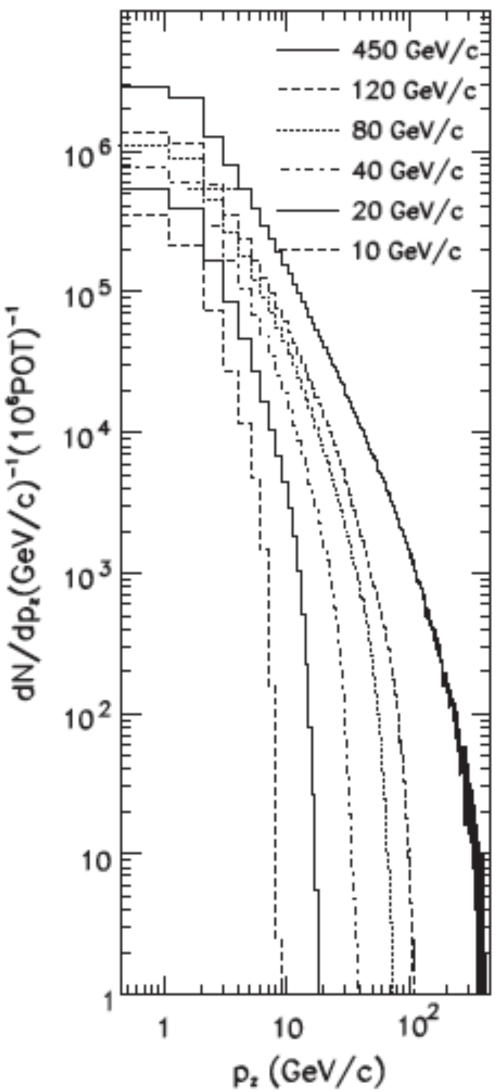
Neutrino flux from simulation by GEANT4

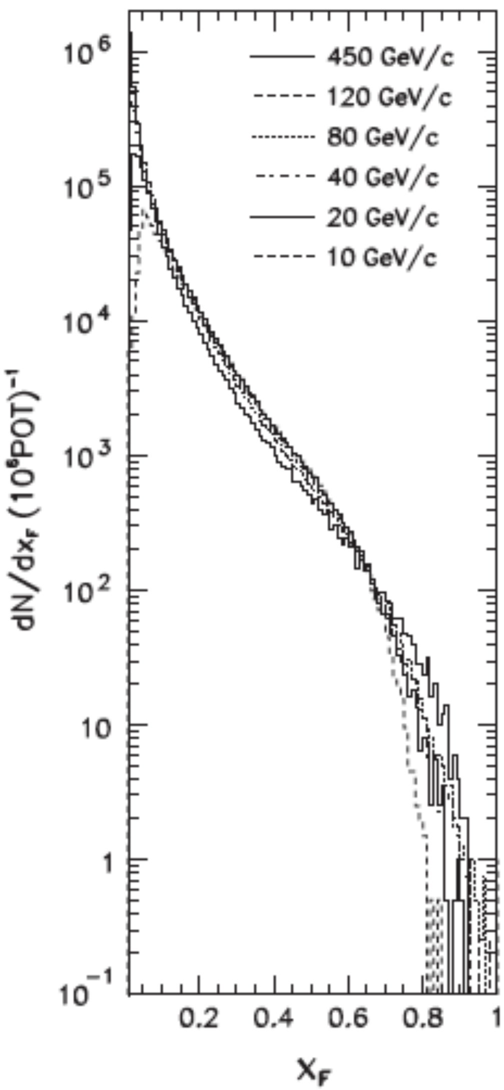
	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%



2. Neutrino beam

Feynman scaling





π^+ from p+C collision ($x_F \sim p_z/p_0$)

- π^+ momentum scale with p_0
- π^+ yield grows with p_0

p_0 (GeV/c)	$n(\pi^+)$
10	0.68
20	1.29
40	2.19
80	3.50
120	4.60
450	10.8

higher energy proton makes higher neutrino flux

2. Neutrino beam

Q3

higher energy proton makes higher neutrino flux, so why don't you use the highest energy protons to make neutrinos?

2. Neutrino beam

higher energy proton makes higher neutrino flux, so why don't you use the highest energy protons to make neutrinos?

higher energy protons also make higher energy neutrinos

(and higher energy protons have lower intensity)

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It requires longer baseline

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

2. Neutrino beam

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Flux goes down with $\sim L^{-2}$

2. Neutrino beam

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Flux goes down with $\sim L^{-2}$
Optimal energy and distance

experiment	energy (GeV)	baseline (km)
T2K	0.6	295
MINOS	3	735
NOvA	2	800
DUNE	4	1300

2. Neutrino

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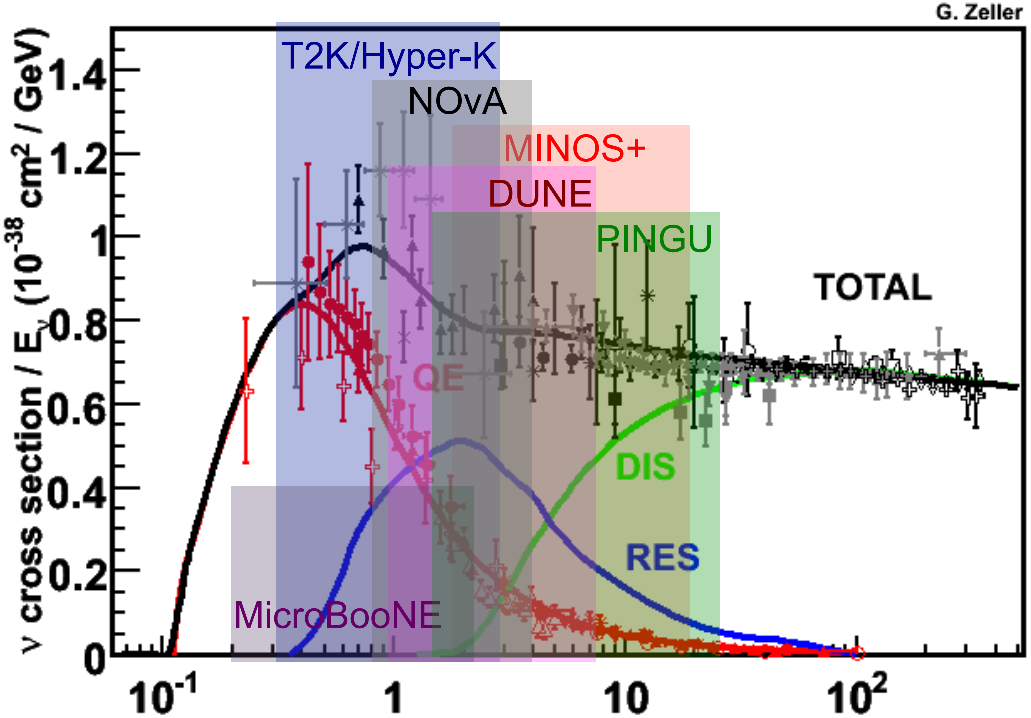
It requires lo

Flux goes dc

Optimal ene

use



ν_μCC cross section per nucleon

1-10 GeV region is the most important energy region

experiment	energy (GeV)	baseline (km)
T2K	0.6	295
MINOS	3	735
NOvA	2	800
DUNE	4	1300

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3. Energy reconstruction

Q4

Cherenkov energy reconstruction

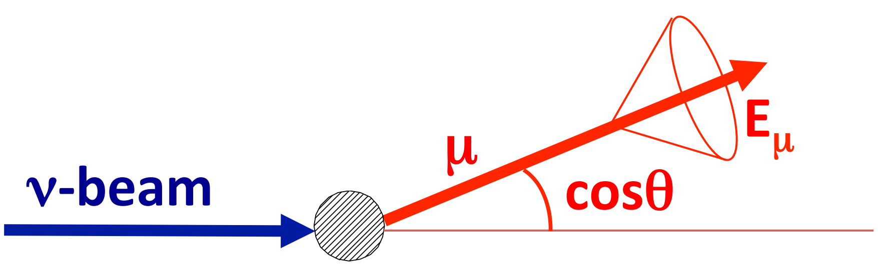
Neutrino energy is reconstructed from 2 observables, muon energy E_μ and muon scattering angle θ_μ

Energy of the neutrino E_ν^{QE} and 4-momentum transfer Q^2_{QE} can be reconstructed by these 2 observables, under the "QE assumption"

1. bound neutron at rest
2. CCQE interaction

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

Any problems?



3. Energy reconstruction

Cherenkov energy reconstruction

Neutrino energy is reconstructed from 2 observables, muon energy E_μ and muon scattering angle θ_μ

Energy of the neutrino E_ν^{QE} and 4-momentum transfer Q^2_{QE} can be reconstructed by these 2 observables, under the "QE assumption"

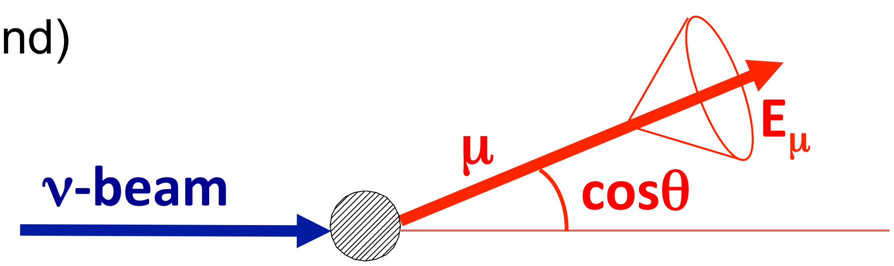
1. bound neutron at rest
2. CCQE interaction

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

Inefficiency is from violation of above assumption

1. Pion production, with pion absorption
2. Interaction with correlated-nucleons

(non-QE background)



3. Energy reconstruction

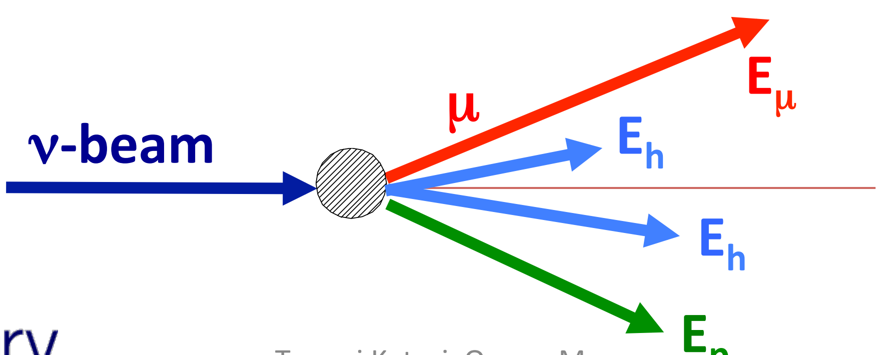
Q5

Calorimetric energy reconstruction

Neutrino energy is reconstructed by summing all visible energy.

Any problems?

$$E_\nu^{Cal} = \varepsilon_n + E_\mu + E_p - M + \sum_i E_{h_i}$$



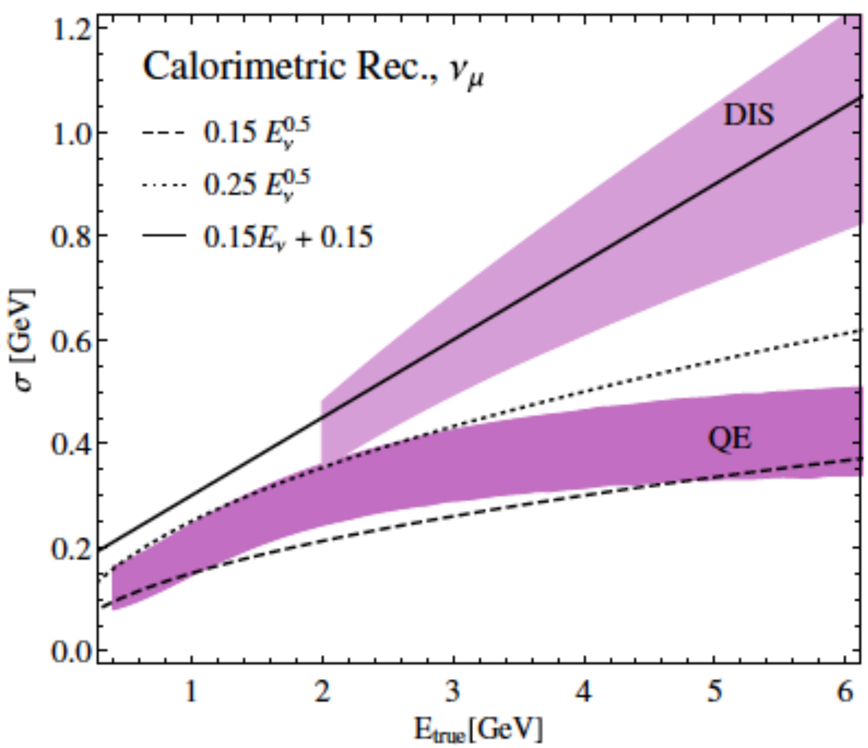
Ankowski et al, Phys.Rev.D92(2015)073014

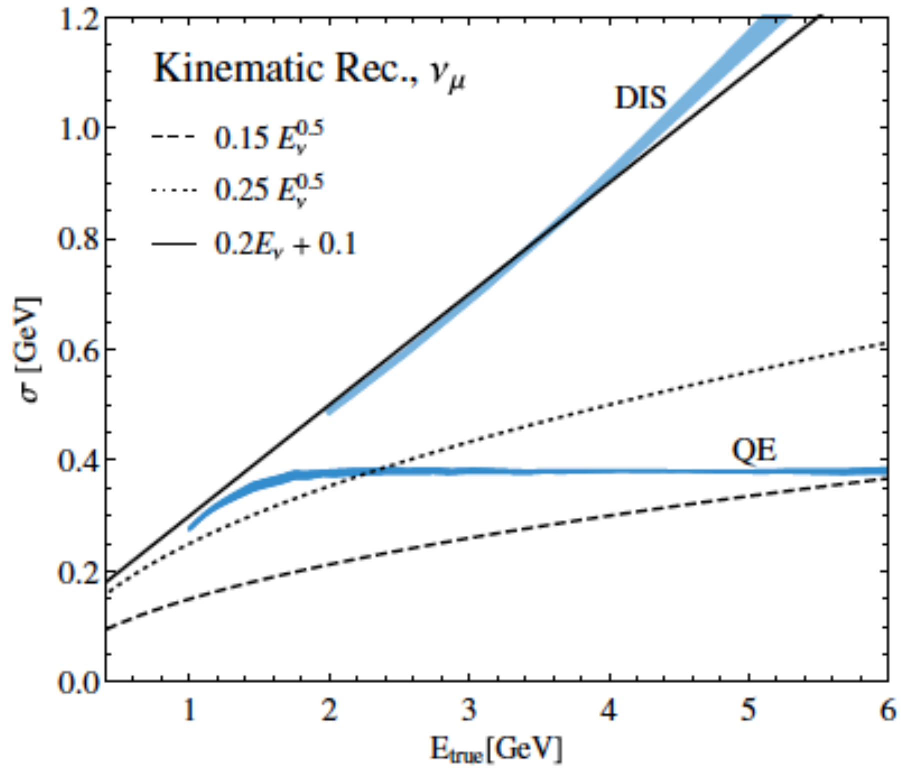
3. Energy reconstruction

Calorimetric energy reconstruction

Neutrino energy is reconstructed by summing all visible energy.

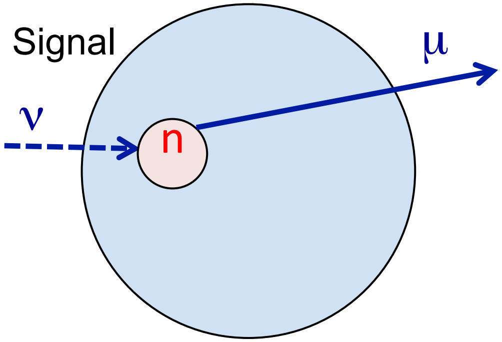
Inefficiency comes from all invisible hadrons (mostly neutrons).
Recent study shows this inefficiency strongly depends on detector performance.
But QE assumption energy reconstruction on QE interaction always gives better energy resolution.





3. non-QE background

non-QE background → shift spectrum



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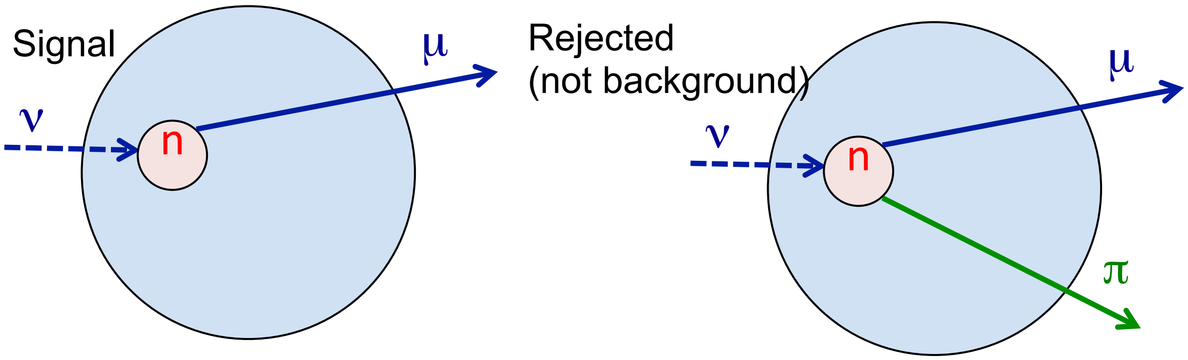

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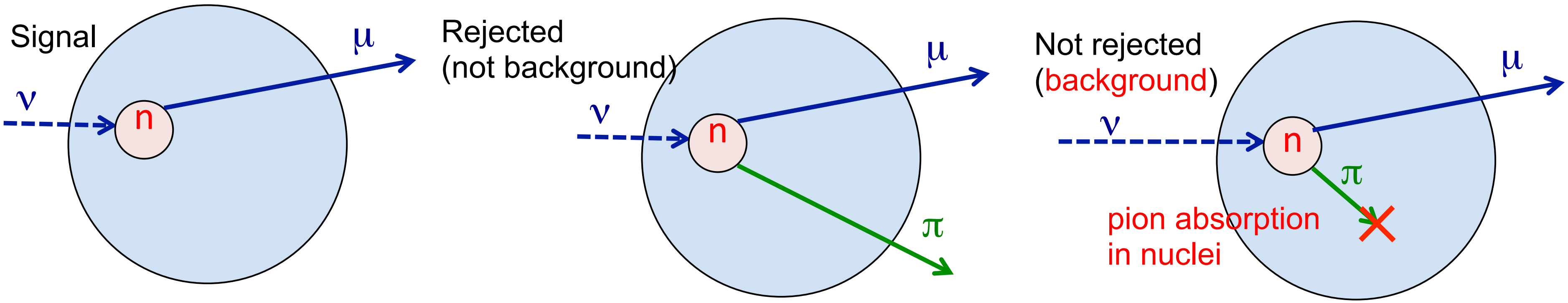

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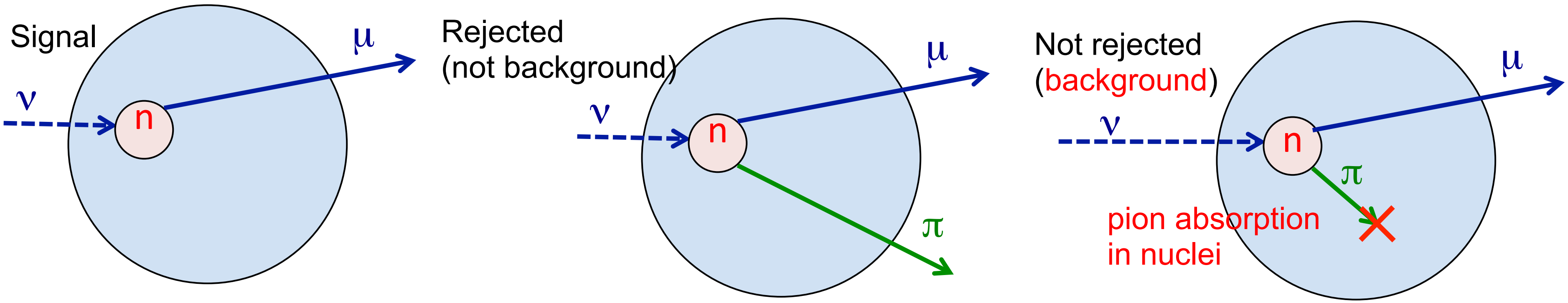
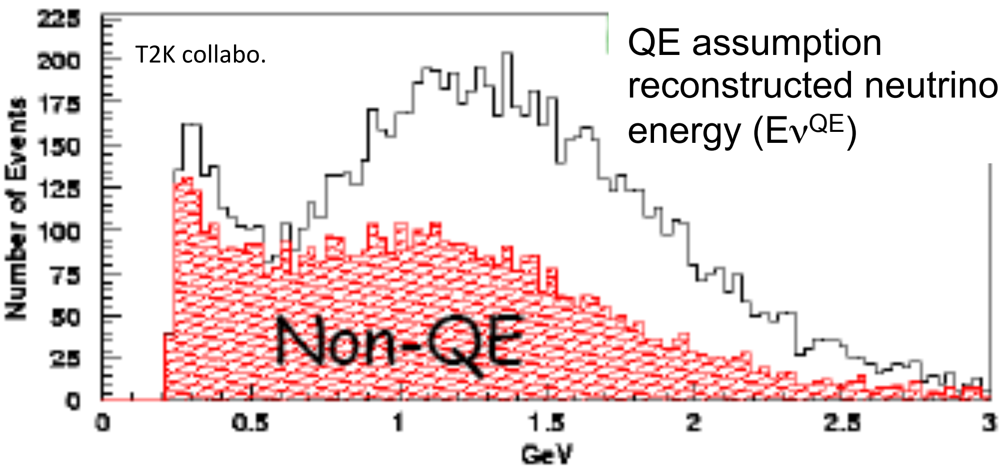
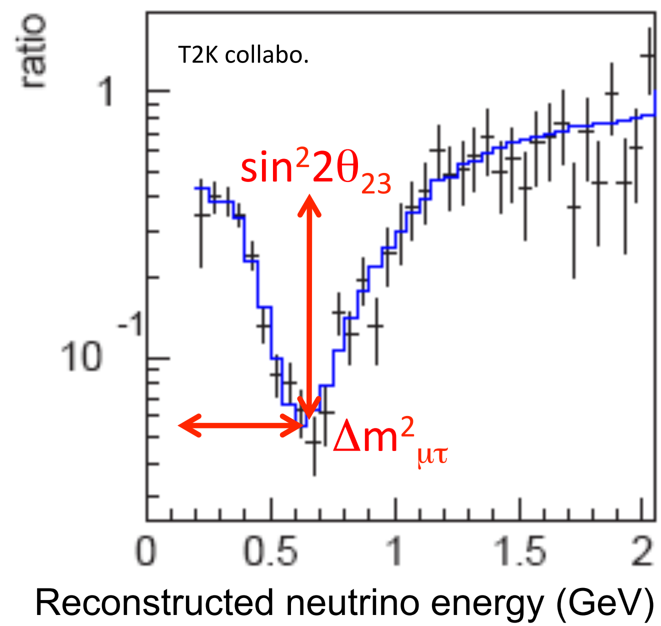




QE assumption reconstructed neutrino energy ($E\nu^{QE}$)

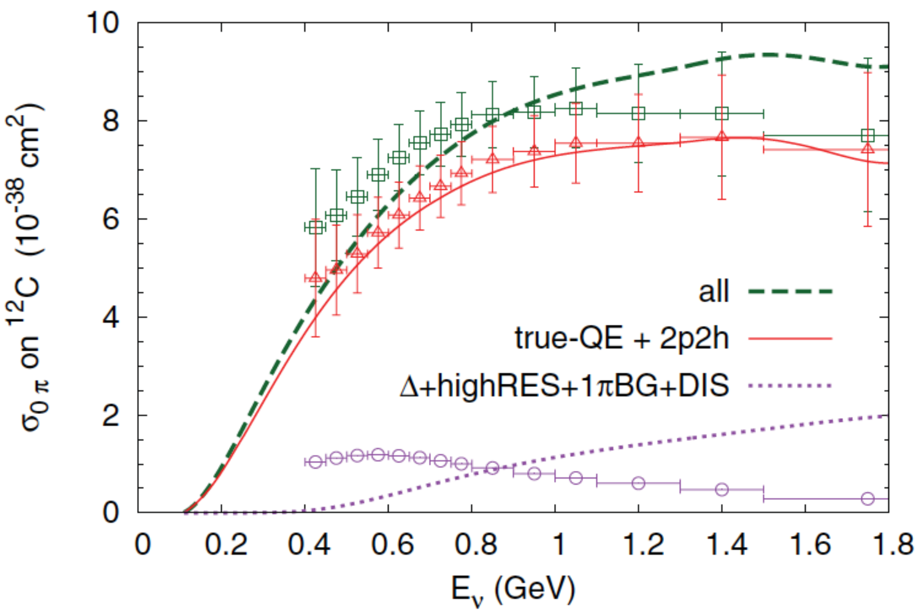


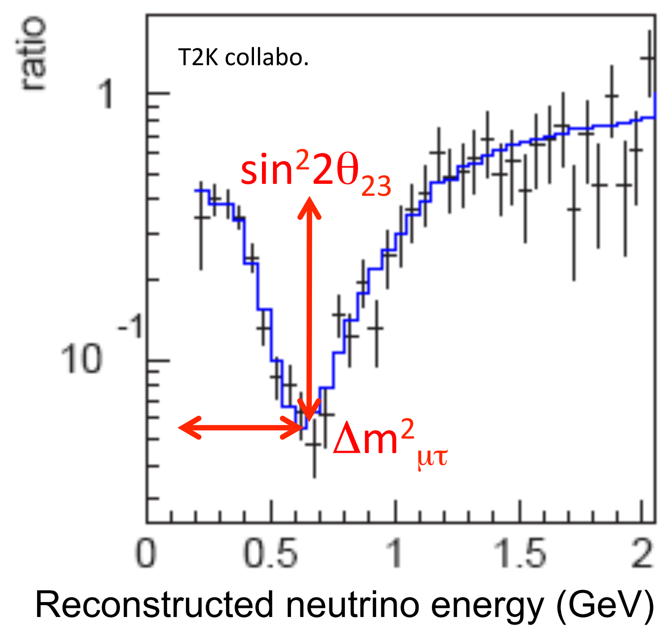
3. non-QE background

non-QE background

- Neutrino energy reconstruction bias flux-unfolded total cross section

PHYSICAL REVIEW C **86**, 054606 (2012)



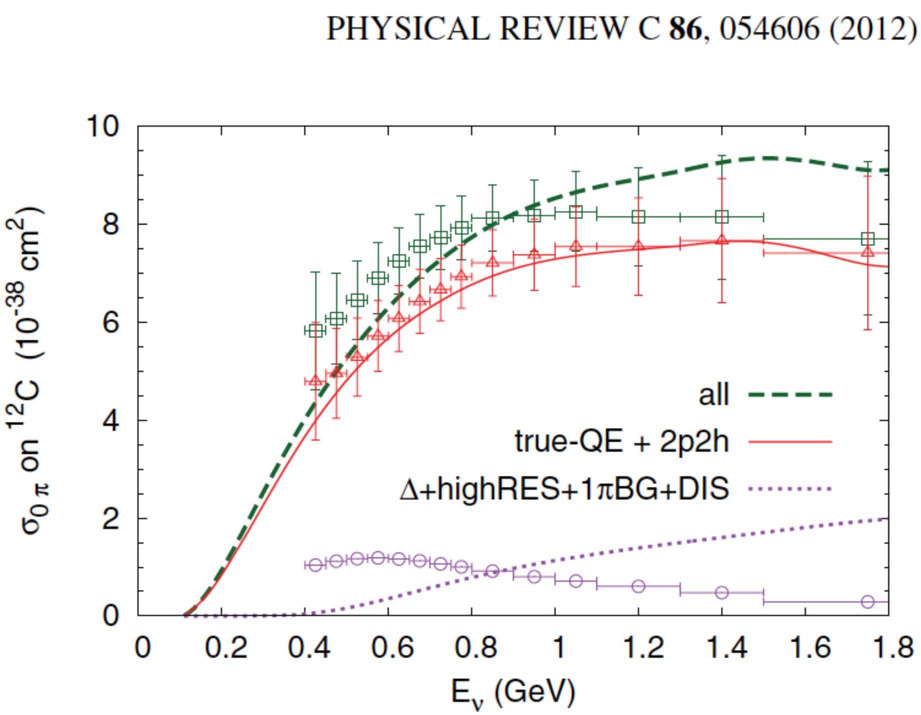


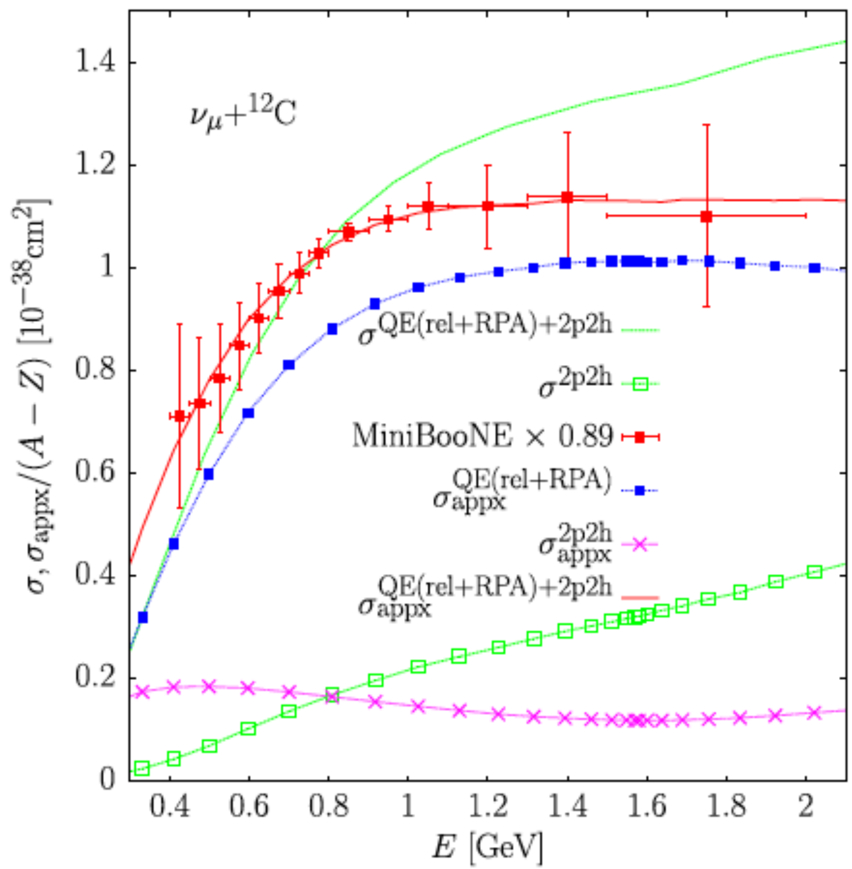
Lalakulich et al, PRC86(2012)054606
Nieves et al, PRD85(2012)113008

3. non-QE background

non-QE background

- Neutrino energy reconstruction bias flux-unfolded total cross section
- This happens by any non-QE channels, such as 2p2h



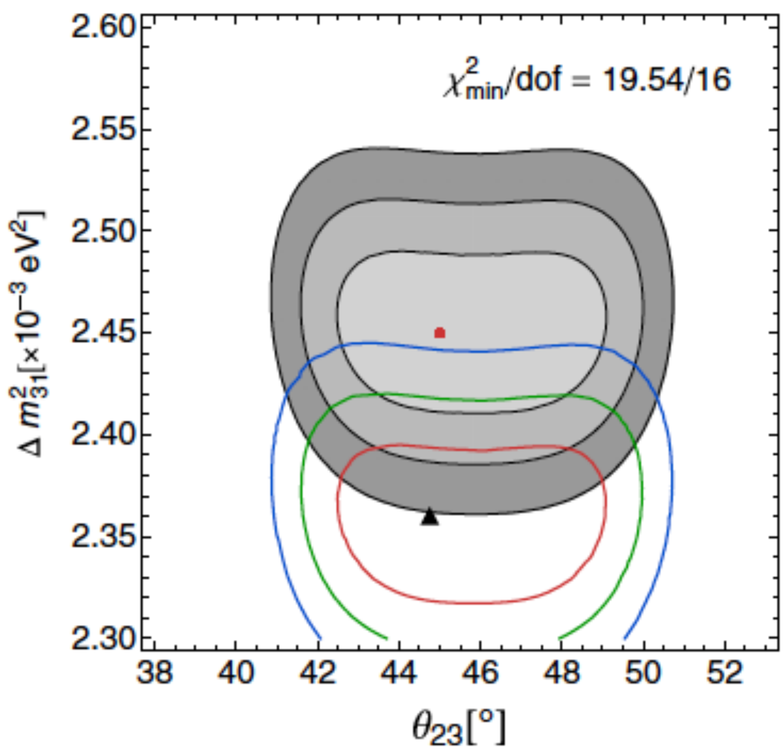


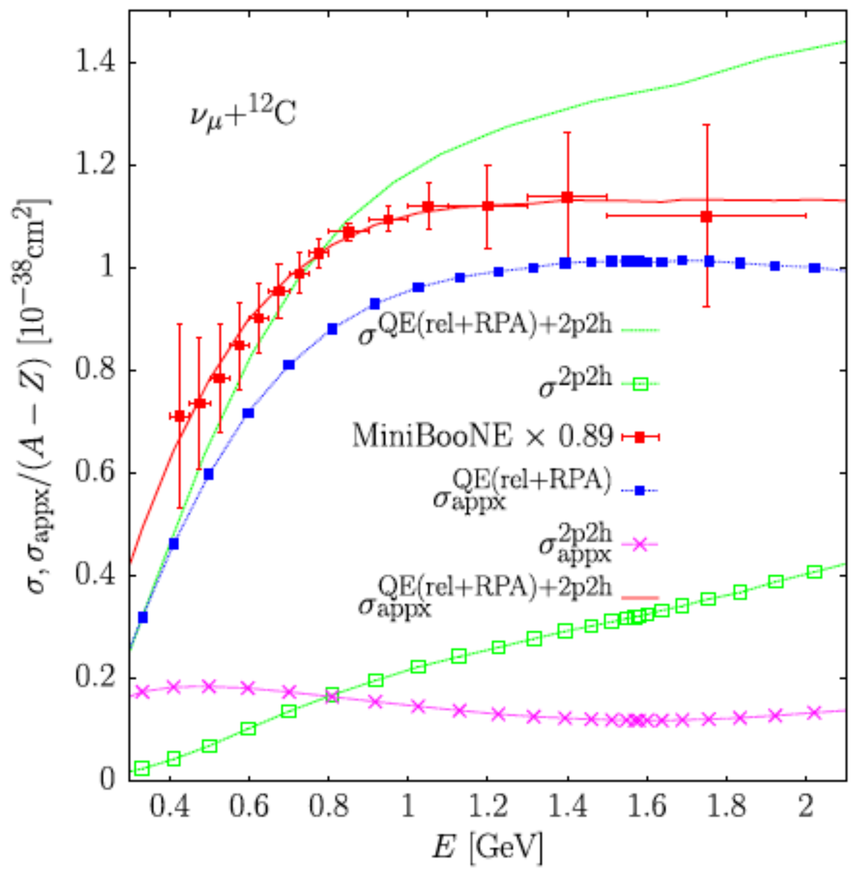
3. non-QE background

non-QE background

- Neutrino energy reconstruction bias flux-unfolded total cross section
- This happens by any non-QE channels, such as 2p2h
- Including 2p2h or not shift oscillation best fit almost 3σ!

PHYSICAL REVIEW D 89, 073015 (2014)





Fermilab SBN,arXiv:1503.01520
ArgoNeuT,arXiv:1511.00941

3. non-QE background in future experiments

Water Cherenkov

Dr. Koshio-san
(Okayama U.)

vs.

LArTPC

Dr. Flavio Cavanna
(Yale)

How to improve our situation in the future?

Fermilab SBN,arXiv:1503.01520
ArgoNeuT,arXiv:1511.00941

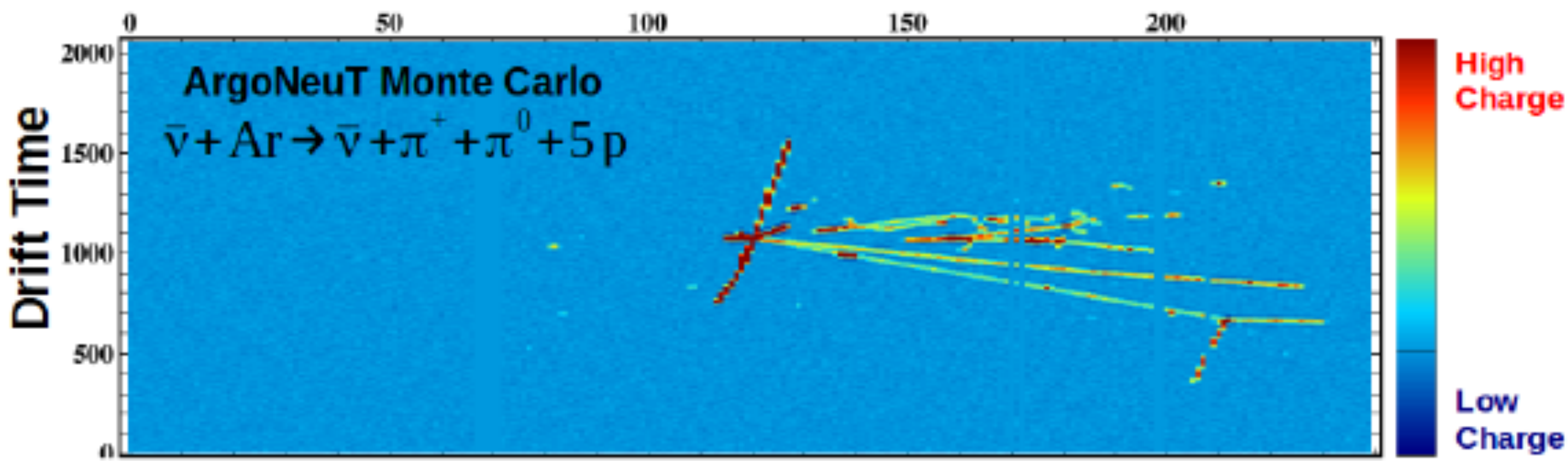
3. non-QE background in future experiments

LArTPC = Modern bubble chamber

- ability to reconstruct all charged particles
- In principle, it can differentiate all charged hadron final states

LArTPC

T2K	SBND	reaction	expected #evts
$CC0\pi^{\pm}$	$CC0\pi^{\pm}$Np	$\nu_\mu + N \rightarrow \mu + Xp$	3,552k
	$CC0\pi^{\pm}$0p	$\nu_\mu + N \rightarrow \mu + 0p$	793k
	$CC0\pi^{\pm}$1p	$\nu_\mu + N \rightarrow \mu + 1p$	2,028k
	$CC0\pi^{\pm}$2p	$\nu_\mu + N \rightarrow \mu + 2p$	359k
	$CC0\pi^{\pm} \geq$3p	$\nu_\mu + N \rightarrow \mu + \geq 3p$	371k
$CC1\pi^{\pm}$	$CC1\pi^{\pm}$	$\nu_\mu + N \rightarrow \mu + 1\pi^{\pm} + Xp$	1,162k
CC others	$CC\geq2\pi^{\pm}$	$\nu_\mu + N \rightarrow \mu + \geq 2\pi^{\pm} + Xp$	98k
	$CC\geq1\pi^{\circ}$	$\nu_\mu + N \rightarrow \mu + \geq \pi^{\circ} + Xp$	498k



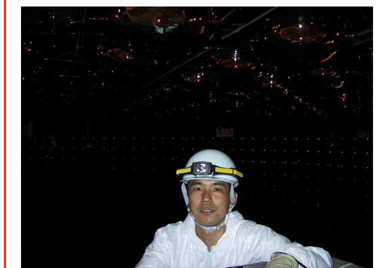
TITUS collaboration, to be published

3. non-QE background in future experiments

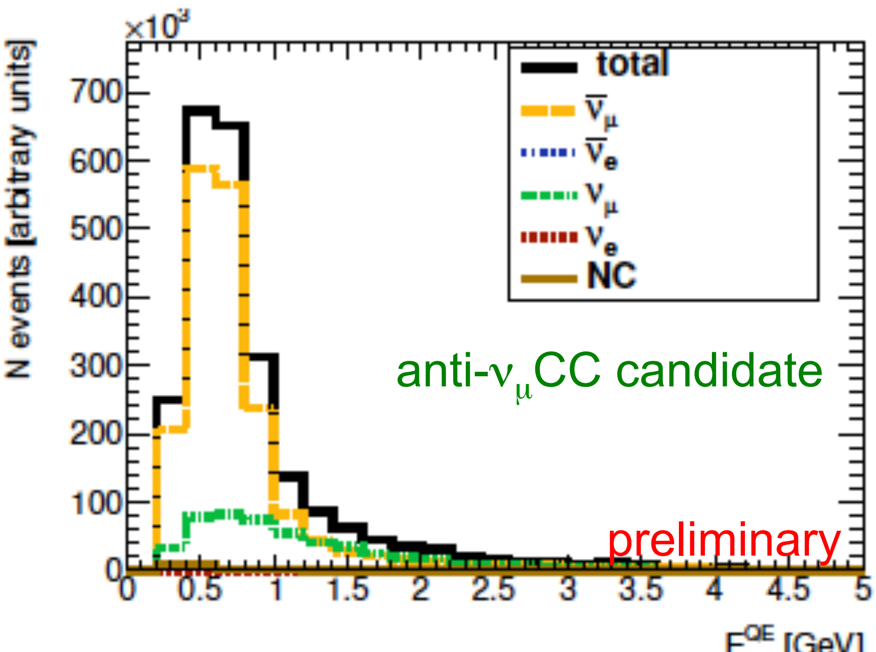
LArTPC = Modern bubble chamber
- ability to reconstruct all charged particles
- In principle, it can differentiate all charged hadron final states

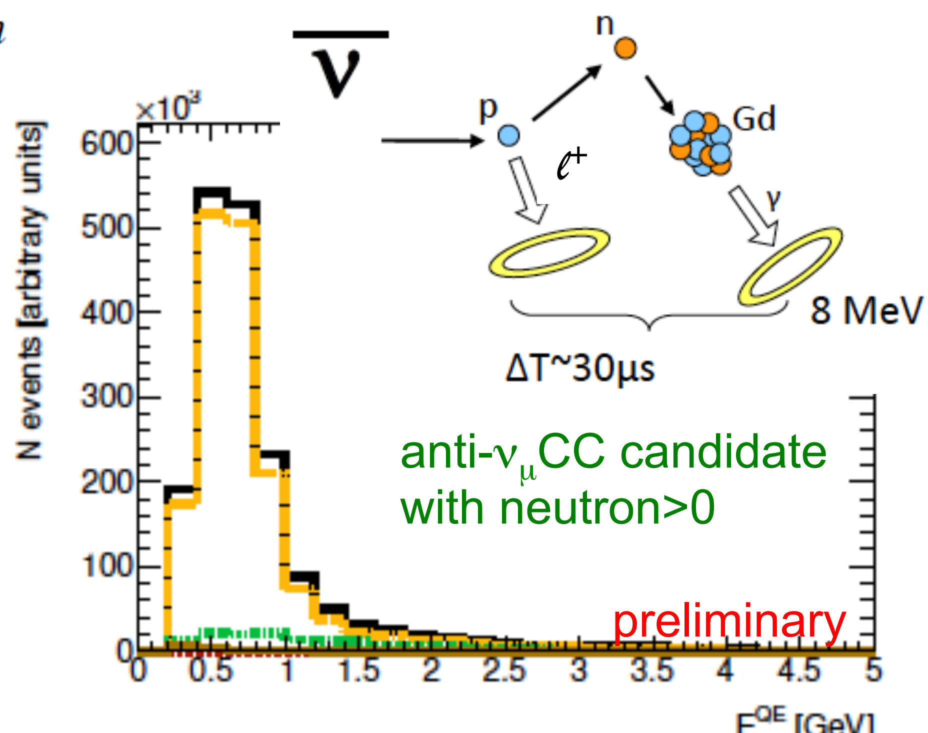
Water Cherenkov with gadolinium = neutron tagging
- Super-K decided to dope gadolinium compound
- In principle, it can differentiate final states by neutron counting

Water Cherenkov



$$\nu_\mu \textbf{CCQE} \;\; \text{n=0}, \; \nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu \textbf{CCQE} \;\; \text{n=1}, \; \nu_\mu + p \to \mu^+ + n$$





3. non-QE background in future experiments

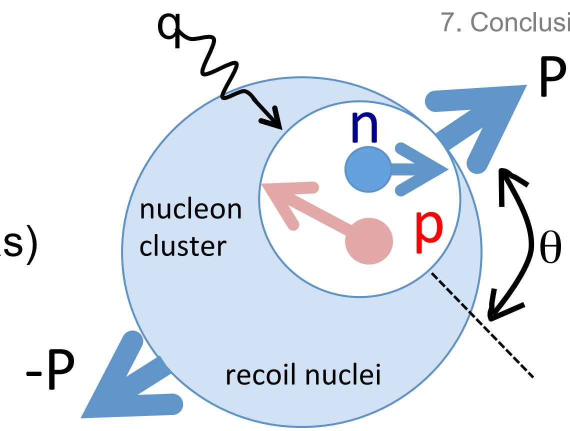
LArTPC = Modern bubble chamber
- ability to reconstruct all charged particles
- In principle, it can differentiate all charged hadron final states

Water Cherenkov with gadolinium = neutron tagging
- Super-K decided to dope gadolinium compound
- In principle, it can differentiate final states by neutron counting

Near future detectors are focusing on hadron measurements. Nucleon counting may shed the light on 2p2h contribution (and pion production) in neutrino interaction physics.

Theorists must predict hadronic final states (multiplicities of proton, neutron, pion, etc) and kinematics (energy and momentum), so that experimentalists can test.

3. Nucleon cluster model



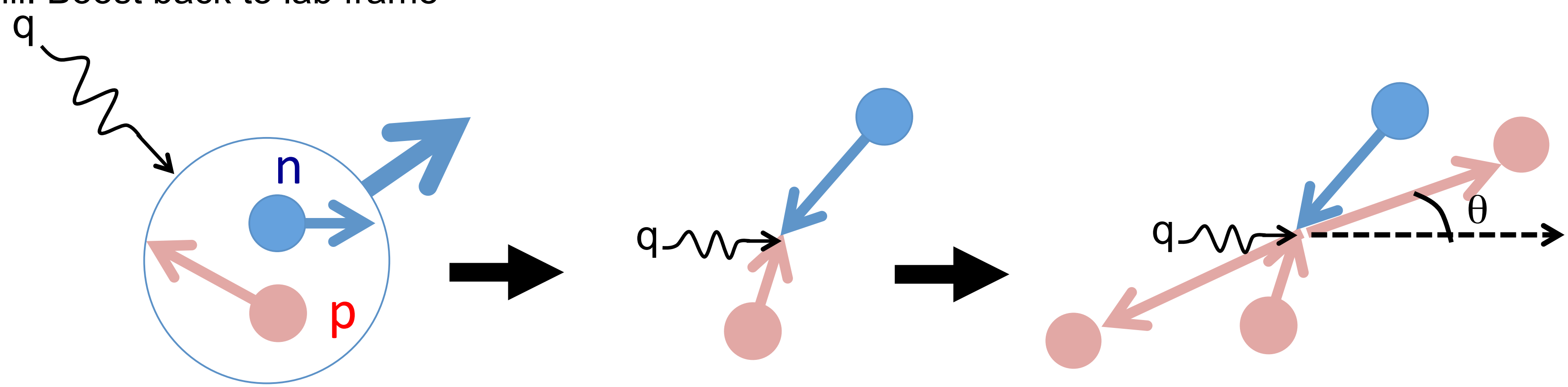
Default model for GENIE. NEUT, NuWro…

For a given Energy-Momentum transfer...

1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)
2. n-n, n-p, p-p pairs are allowed, if interaction is allowed
3. Energy-momentum conservation

Once 2 nucleons from on-shell are choosed

i. ω-q vector and nucleon cluster makes CM system (hadronic system)
ii. Isotropic decay (random θ and φ) of hadronic system creates 2 nucleon emission
iii. Boost back to lab frame



1. Neutrino oscillations

2. Accelerator-based neutrino oscillation experiment

3. QE-like background

4. NCπ^o background for ν_e appearance experiment

5. Interaction systematics status

6. Realistic oscillation analysis

7. Conclusion

4. ν_e appearance experiment

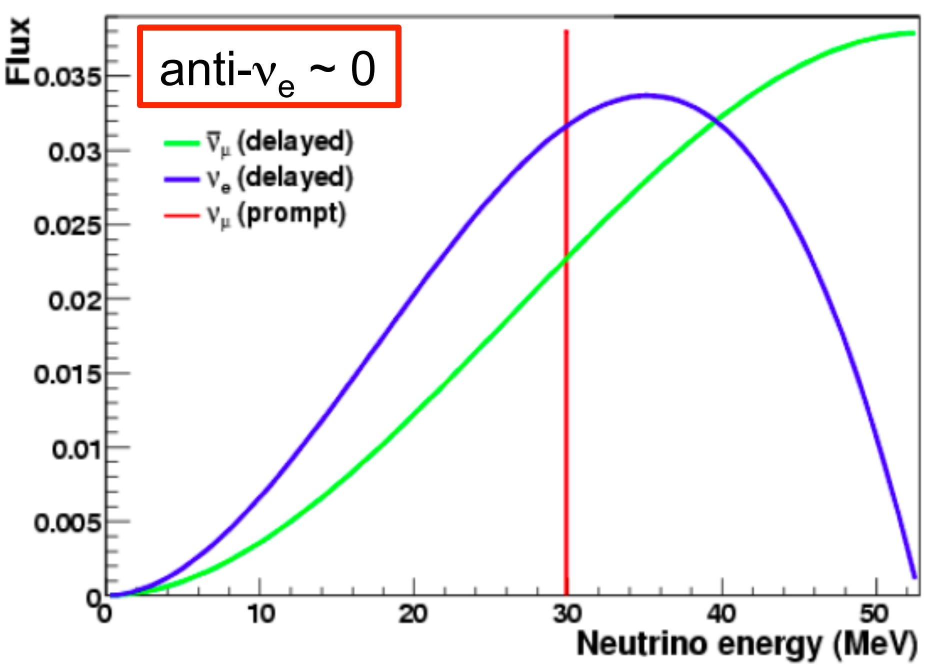
Pion decay-at-rest beam (DAR)

- There is no anti-ν_e component
- best for anti-ν_μ to anti-ν_e oscillation experiment (LSND, πDAR at J-PARC etc)
- Mainly for short baseline (L<1km) exotic oscillation search

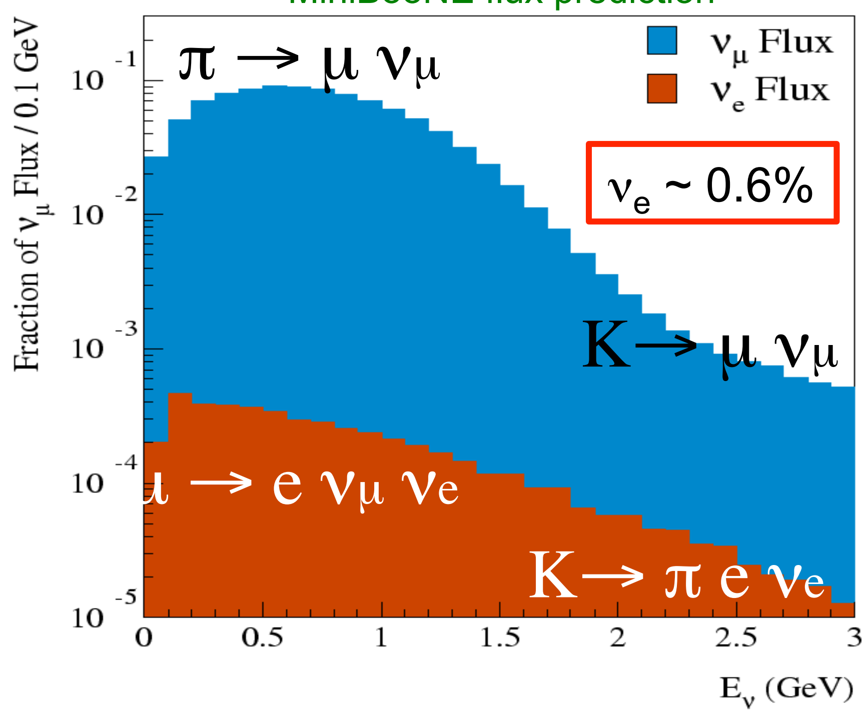
Pion decay-in-flight (DIF) ← Superbeam

- Higher energy, larger flux, very small ν_e and anti-ν_e component
- best for ν_μ to ν_e and anti-ν_μ to anti-ν_e oscillation experiment (T2K, NOvA, DUNE, Hyper-K)
- Mainly for long baseline (L=100-1000km) standard oscillation search

DAR neutrino flux

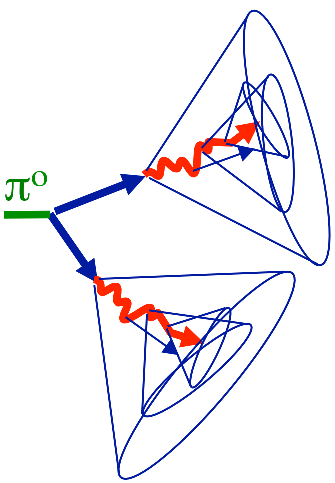


MiniBooNE flux prediction



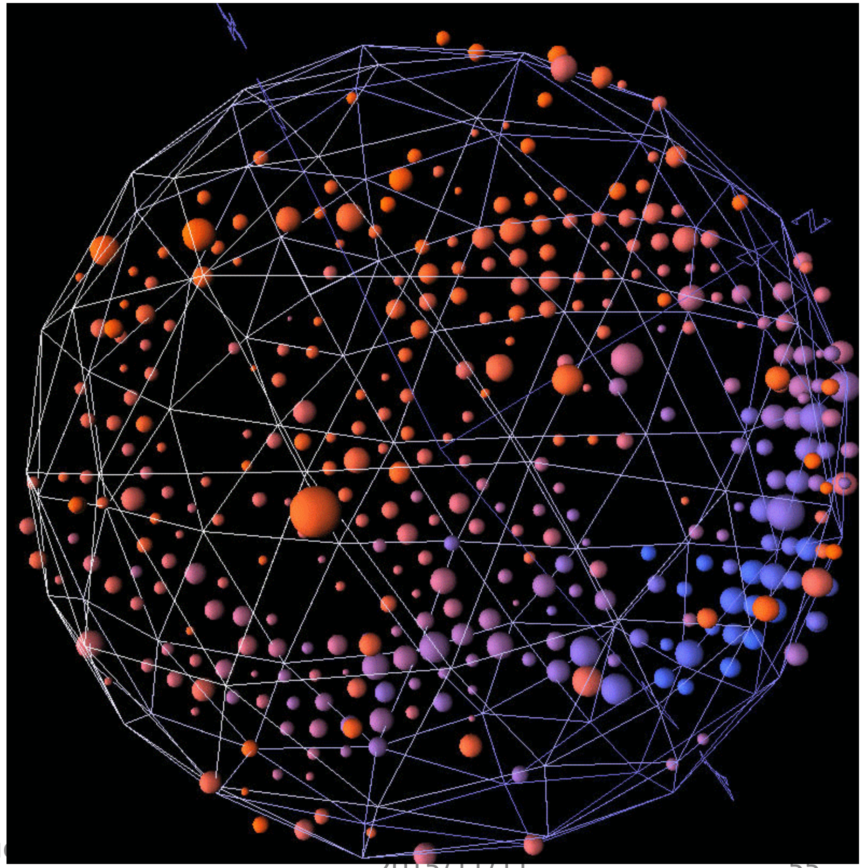
4. NCπº background for ν_e appearance experiment

Pion asymmetric decay
- 1 gamma ray carry most of energy
- gamma ray is the biggest misID of electron



NCπº decay to 2γ
(not background)

πº candidate event



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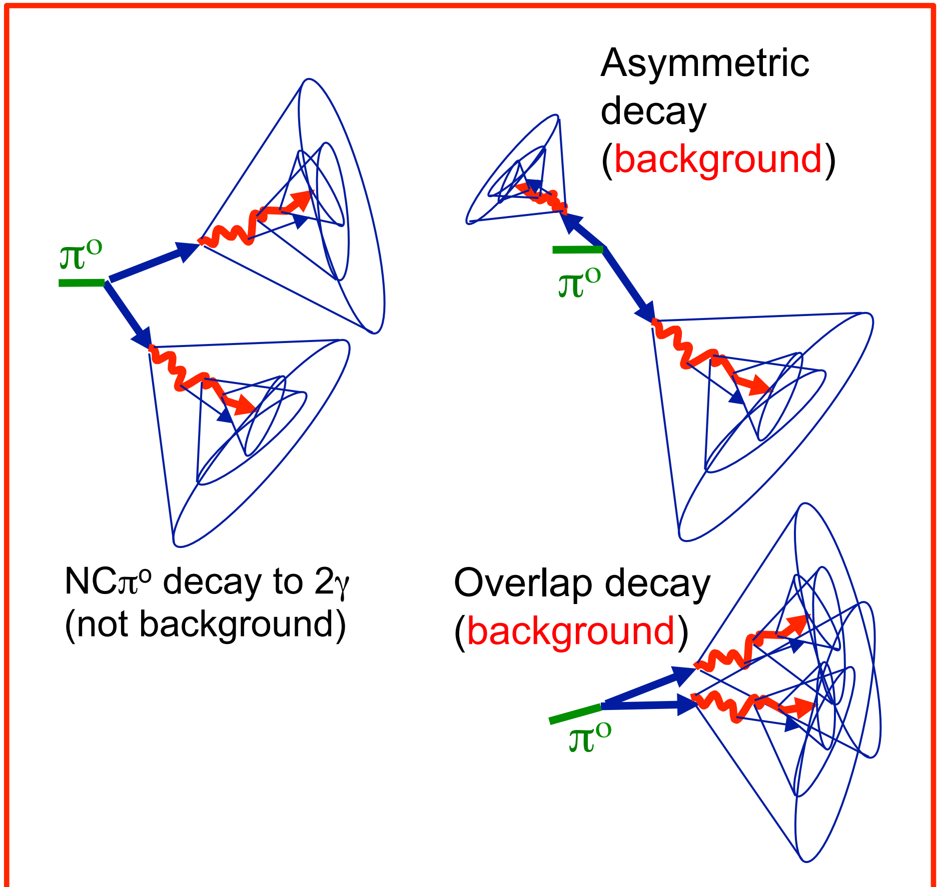
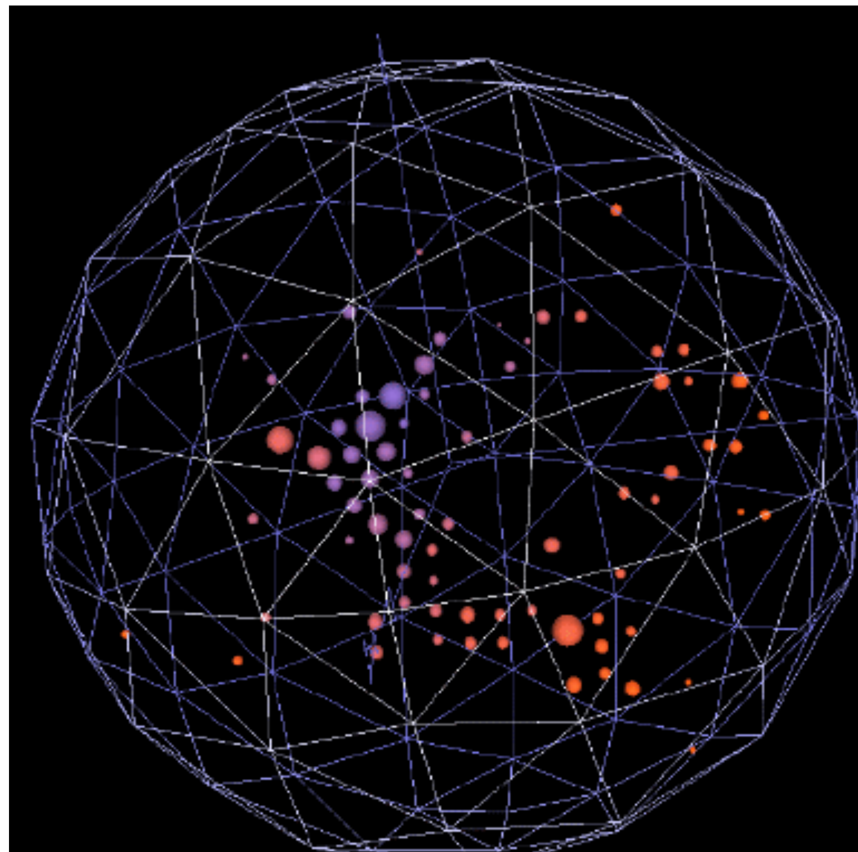


Candidate of single electron (=ν_e) or single gamma (=background)



MiniBooNE,PRL112(2014)061802,PRD91(2015)072010

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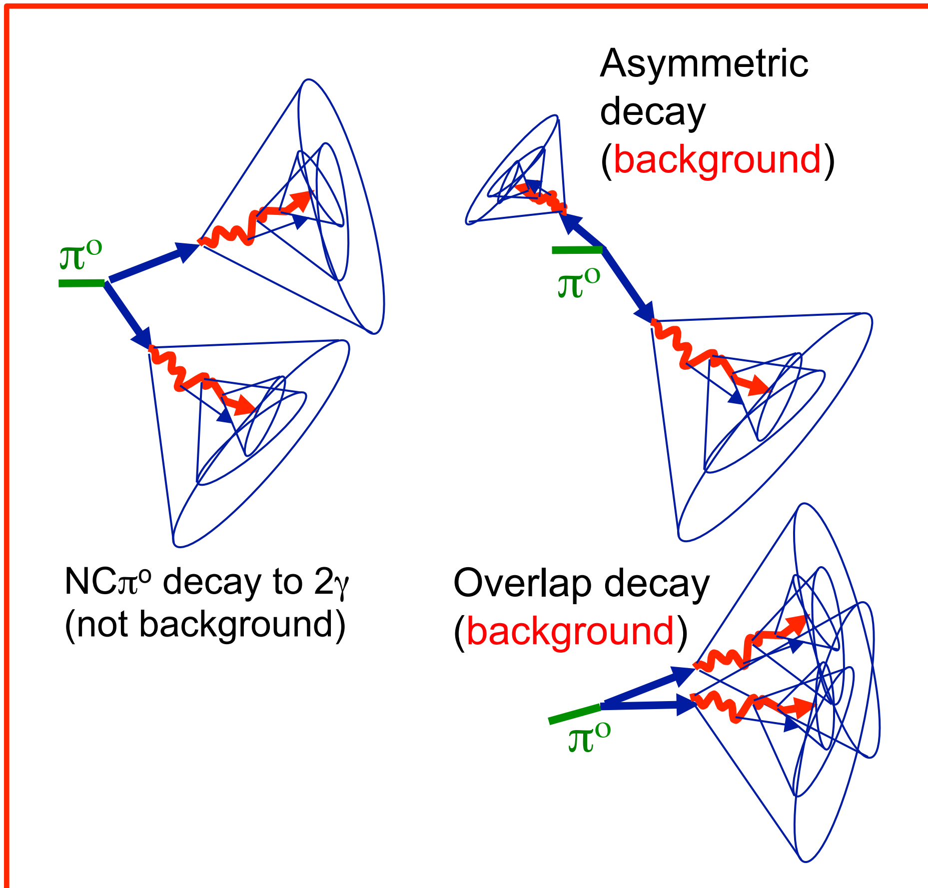
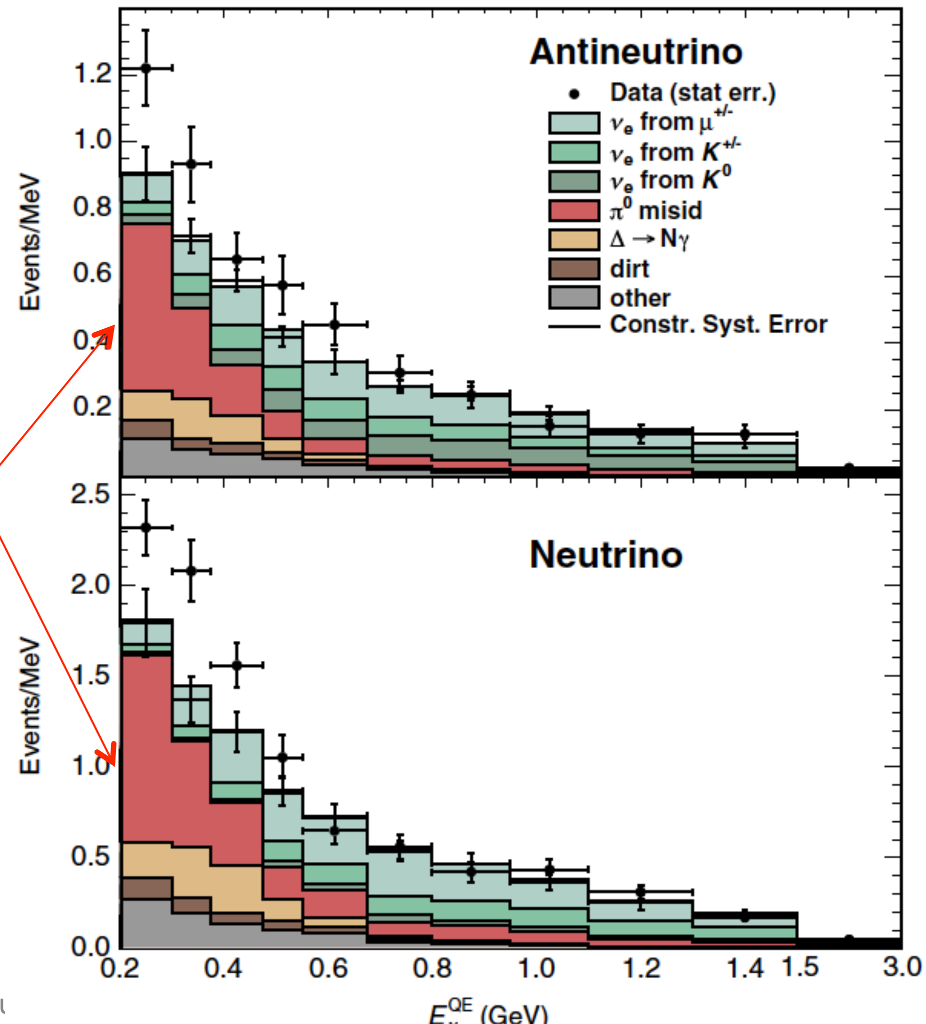


MiniBooNE isolated e- and e+ candidate events
(ν_e and anti-ν_e oscillation candidates)



4. NCπ^o background for ν_e appearance experiment

Pion asymmetric decay
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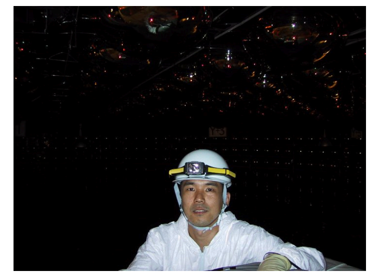
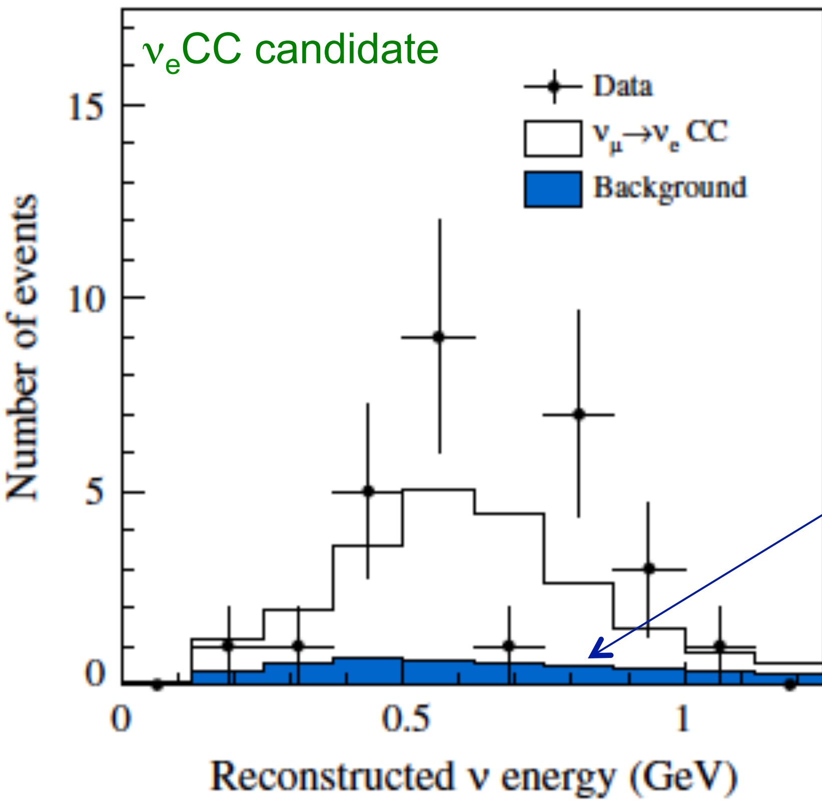
New reconstruction in Super-K
- NCπ^o is no longer large misID

Water Cherenkov





(a)

~75% is beam origin ν_e background, not misID of NCπ^o

T2K,PRL112(2014)061802,PRD91(2015)072010
ArgoNeuT,arXiv:1511.00941

4. NCπ° background for ν_e appearance experiment

Pion asymmetric decay
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New reconstruction in Super-K
- NCπ° is no longer large misID

Liquid Argon TPC (LArTPC)
- single electron and single gamma are separable
  - vertex-shower conversion distance
  - dE/dx (gamma=e^+-e^-) vs. electron

LArTPC

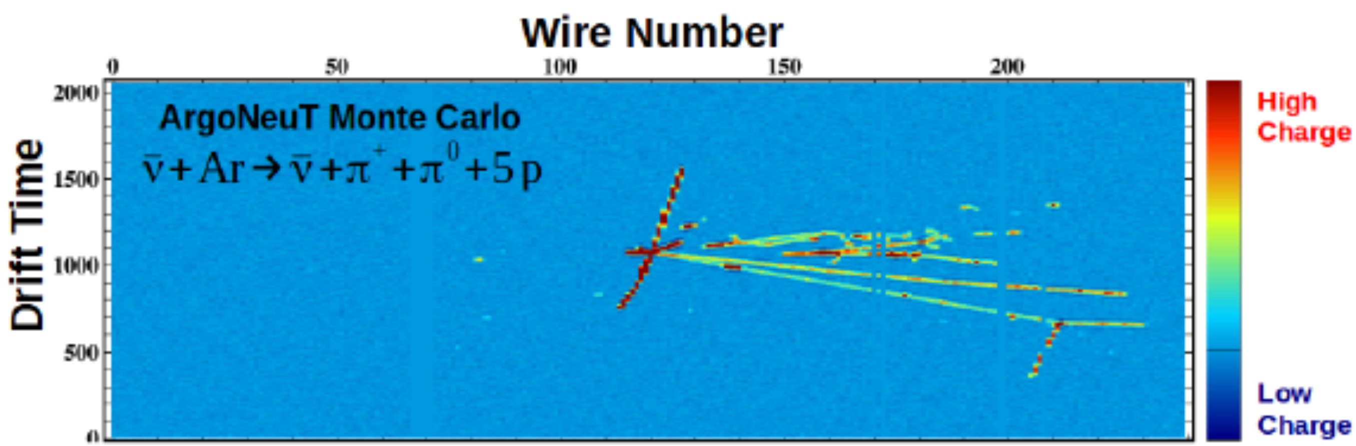

FIG. 2. Event display for a Monte Carlo neutral current π^0 event simulated in the ArgoNeuT detector.

4. NCπ^o background for ν_e appearance experiment

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New reconstruction in Super-K
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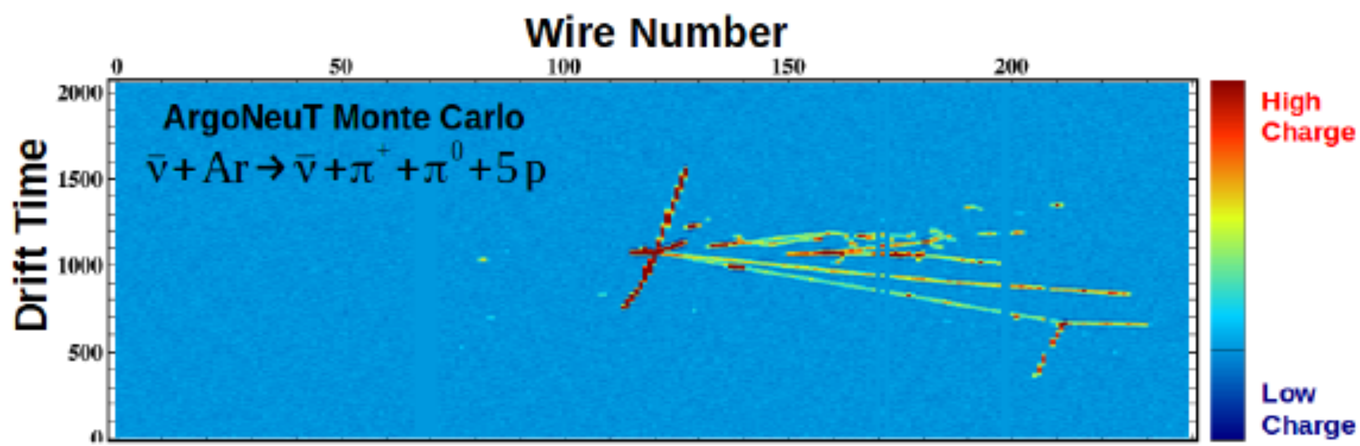
Liquid Argon TPC (LArTPC)
- single electron and single gamma are separable
  - vertex-shower conversion distance
  - dE/dx (gamma=e^+-e^-) vs. electron

Seems to me NCπ^o is getting under controlled as misID of ν_e

…However, it is still important to study to understand pion production (which remain an important systematics)



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5. Open questions of neutrino interaction physics

Although there are many progresses in neutrino interaction, there are open questions that arise in the comparison with new experimental data…

Luis Alvarez-Ruso (Valencia)

CCQE puzzle → case closed (?)
- RPA+2p2h seems right idea, but test is not successful in simulations.

ANL-BNL puzzle → case closed
- BNL had a wrong flux normalization.

Pion puzzle → ongoing
- MiniBooNE vs. MINERvA vs. theories, 2 out of 3 are wrong?!

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- NC single gamma produciton is unlike source of MiniBooNE excess

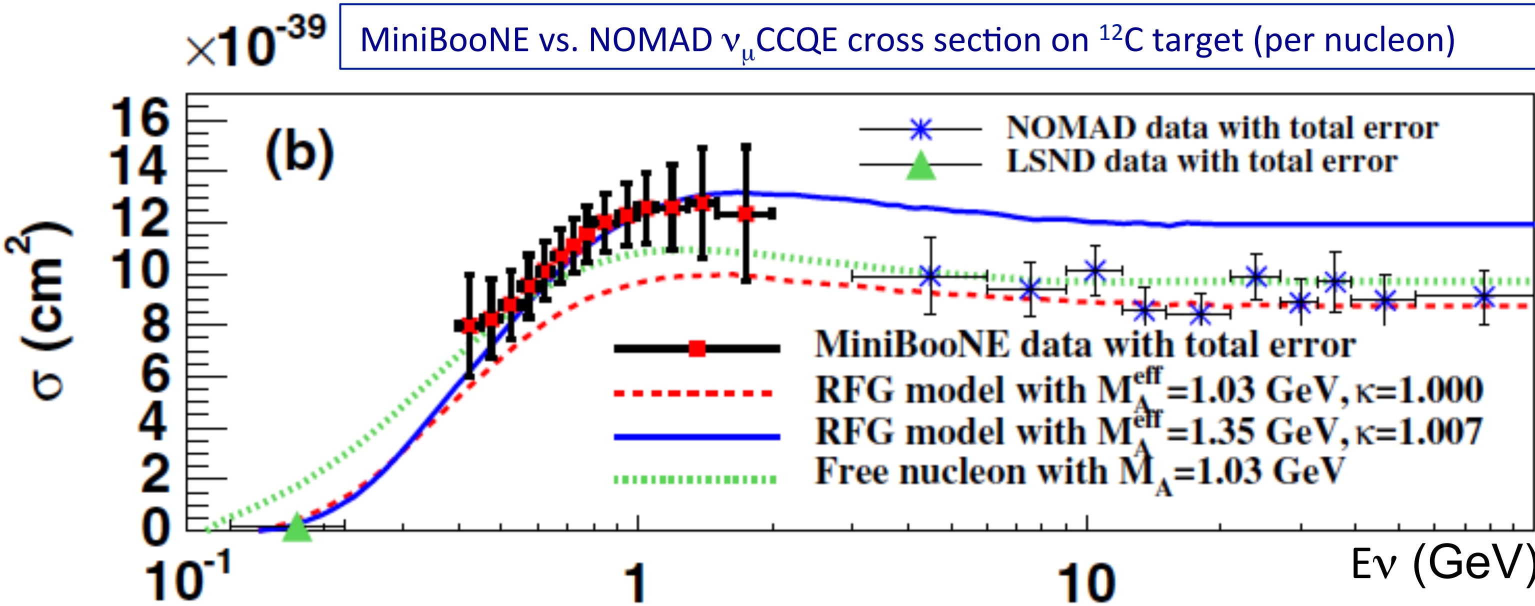
Shallow Inelastic Scattering (SIS) → anybody have any consistent models for CC inclusive cross section from for 2-10 GeV?

5. CCQE puzzle

Simulation disagree with many modern accelerator based neutrino experiment data, neither shape (low Q^2 and high Q^2) nor normalization. MiniBooNE successfully reproduce their data by fitting M_A~1.3. However, this interaction was measured by bubble chamber experiments and NOMAD experiment with M_A~1 (CCQE puzzle).

→ origin of ~20-30% error on M_A in GENIE and NEUT

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



Martini et al,PRC80(2009)065501

5. The solution of CCQE puzzle

Presence of 2-body current

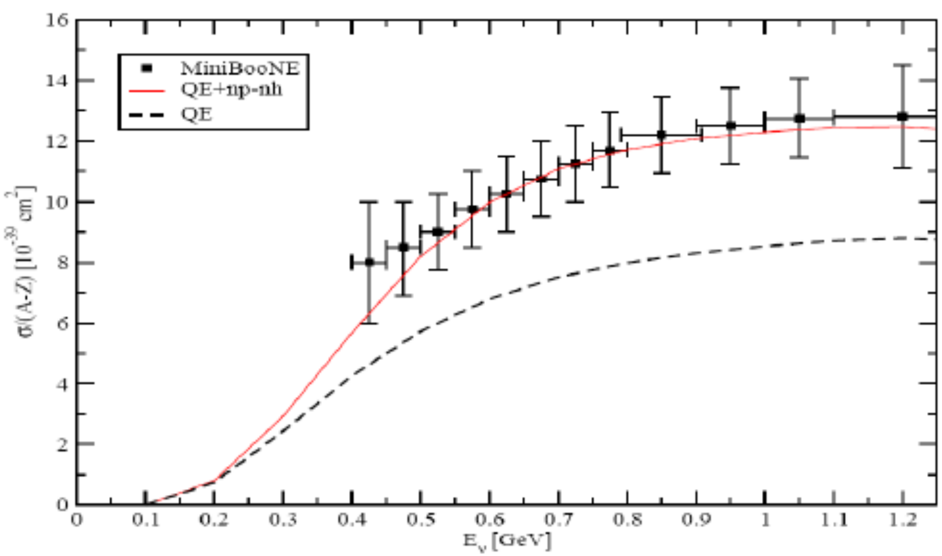
- Martini et al showed 2p-2h effect can add up 30-40% more cross section

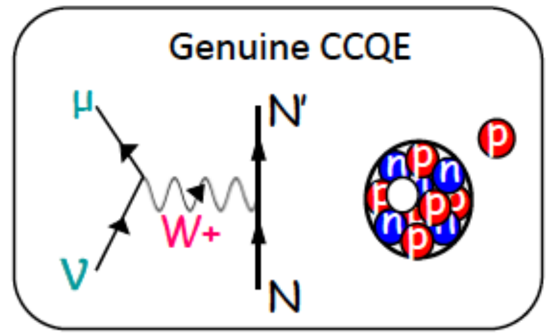
What experimentalists call "CCQE" is not genuine CCQE!

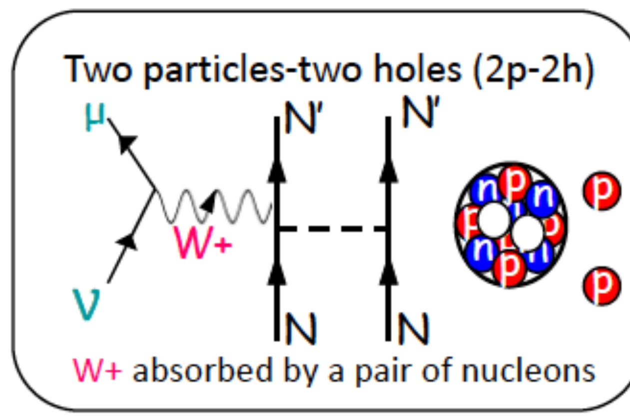
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Martini et al,PRC80(2009)065501
Nieves et al,PLB707(2012)72; NPA627(1997)543

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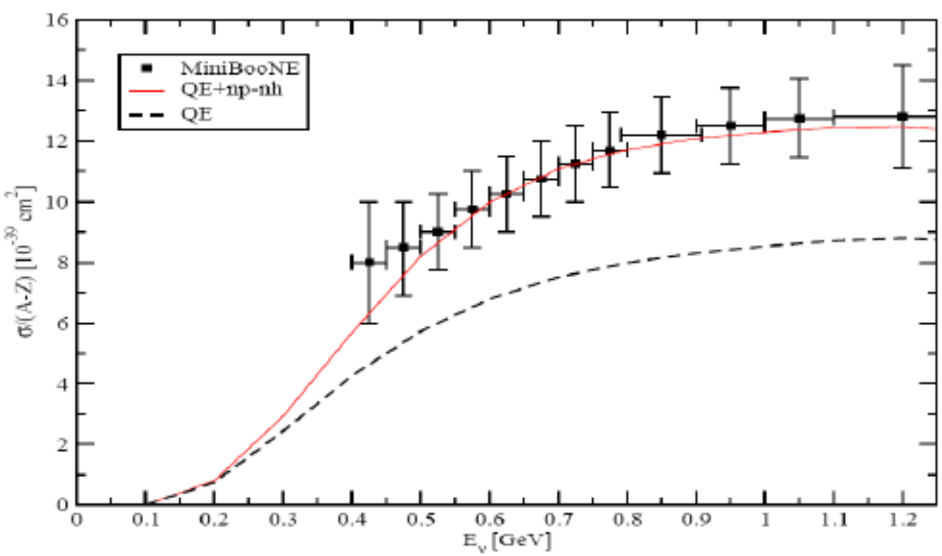
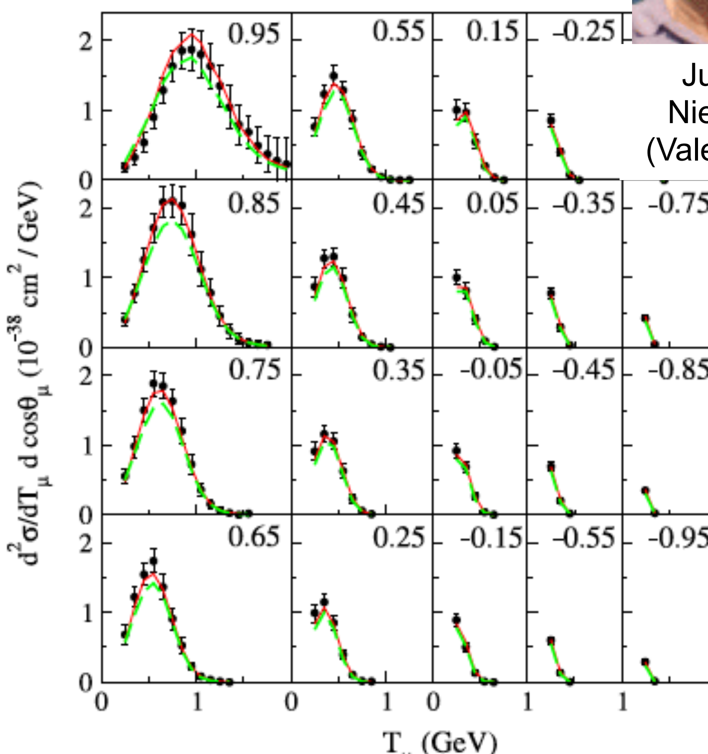
The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)





Valencia model vs. MiniBooNE CCQE double differential cross-section data

Martini et al, PRC80(2009)065501, PRC90(2014)025501
Nieves et al, PLB707(2012)72, NPA627(1997)543

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Presence of 2-body current

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- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

Marco Martini (Saclay)

Juan Nieves (Valencia)

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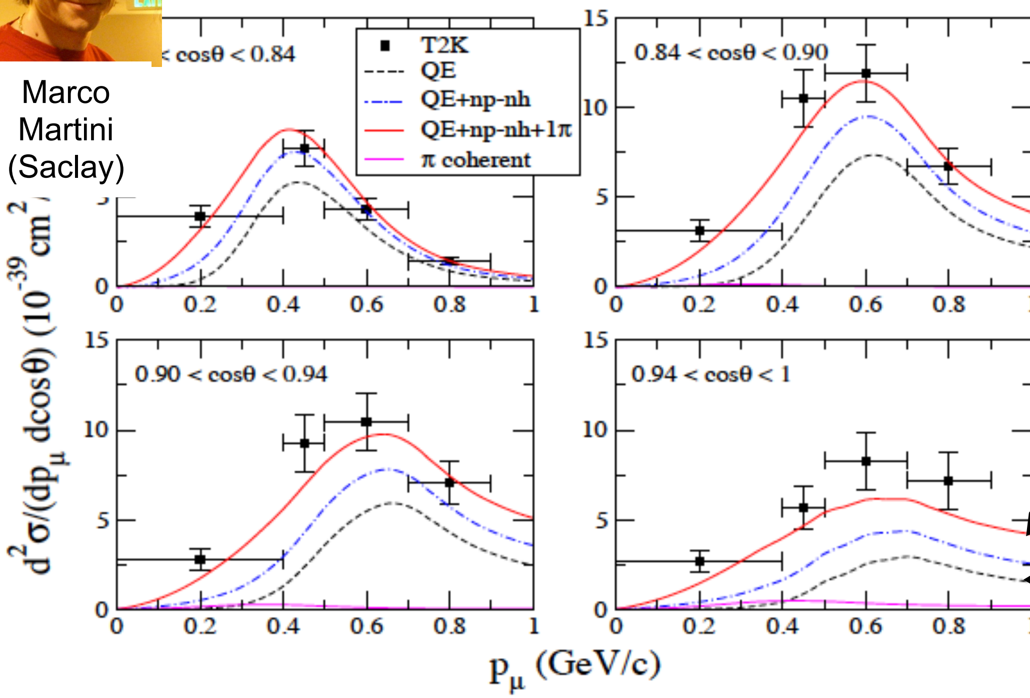
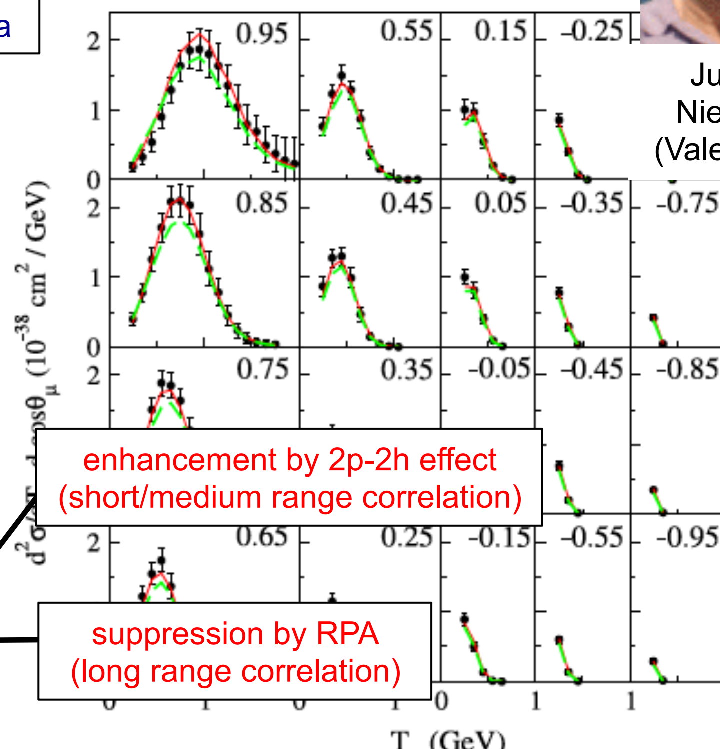
Martini model vs. T2K CC double differential cross-section data





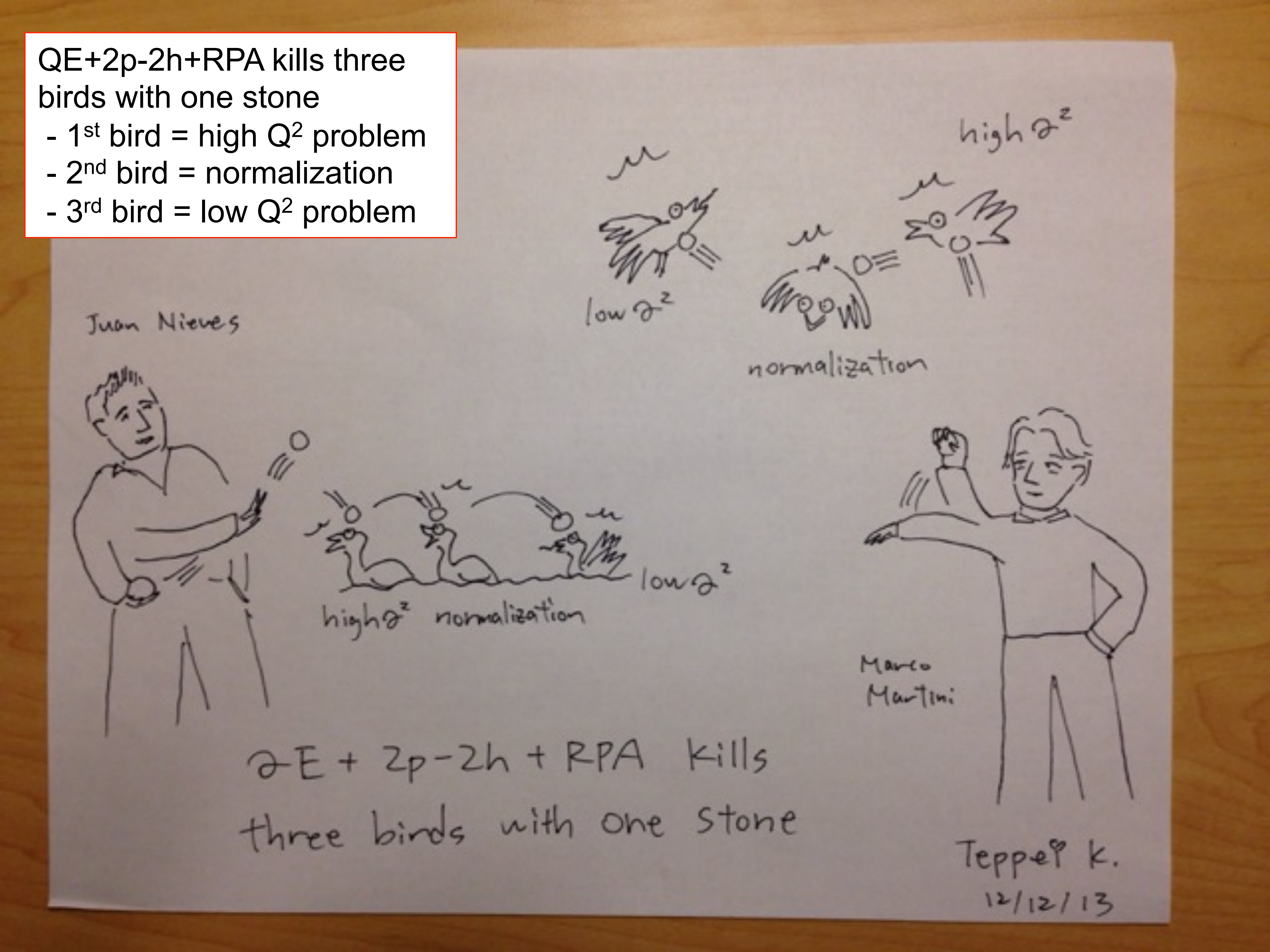
enhancement by 2p-2h effect (short/medium range correlation)

suppression by RPA (long range correlation)

Valencia model vs. MiniBooNE CCQE double differential cross-section data

QE+2p-2h+RPA kills three birds with one stone

- 1st bird = high Q^2 problem
- 2nd bird = normalization
- 3rd bird = low Q^2 problem



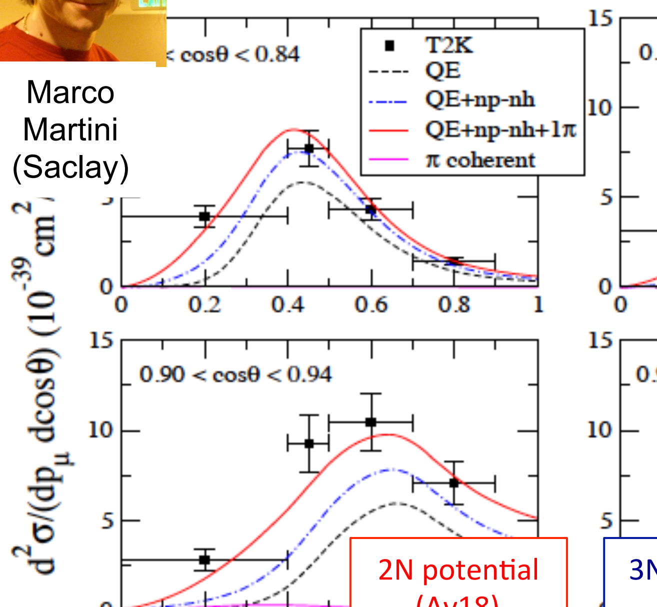
Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72, NPA627(1997)543: Lovato et al, PRC91(2015)062501

5. The solution of CCQE puzzle

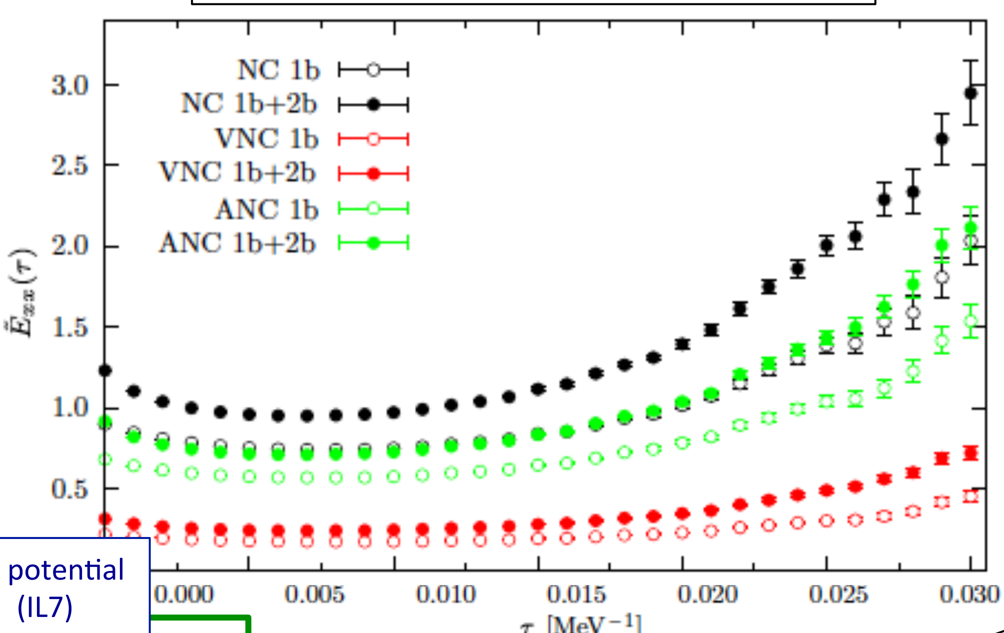
Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously
  - ab initio calculation shows consistent result

Marco Martini (Saclay)



NC Euclidean transverse response function



The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)

Alessandro Lovato (Argonne)

Ab initio calculation reproduce same feature

$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}^{A}\left[1 + U_{ij} + \sum_{k\neq i,j}^{A} \tilde{U}^{TNI}_{ijk}\right]|\Psi_J\rangle$$

5. Valencia MEC model

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation

- Valencia MEC model is available in NEUT
  - being implemented in GENIE, officially ready for GENIE v2.12

This moment…
Valencia MEC model does not fit T2K (and Super-K) data very well, people are working on all kind of checkings

large M_A error → large 2p2h error

It is crucial to have correct CCQE, MEC, pion production models to understand MiniBooNE, MINERvA, T2K data simultaneously. Otherwise M_A error stays around 20-30%.

Also, we have good theorists who make models, and good experimentalists who measure data, but we are still lacking people between them.

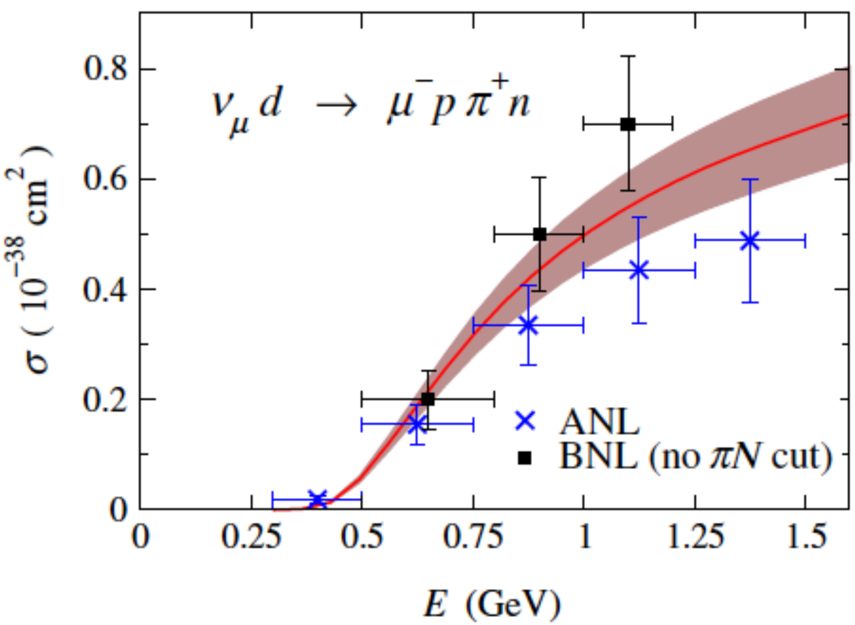
Hernandez et al,PRD87(2013)113009
Alvarez-Ruso et al,PRC89(2014)015503

5. ANL-BNL puzzle

Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25% (ANL-BNL puzzle).

→ origin of ~20-30% error on M_A^{RES} in GENIE and NEUT

ANL vs. BNL



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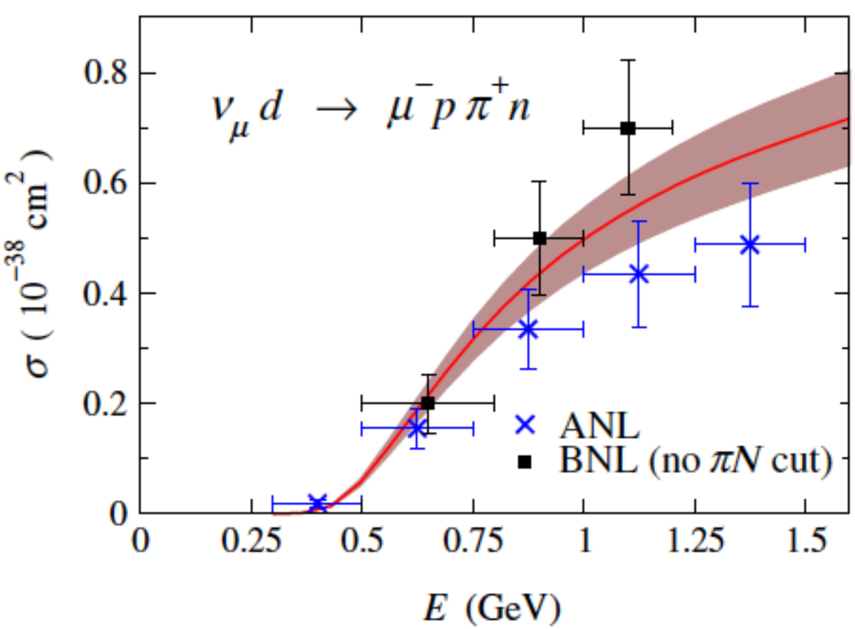
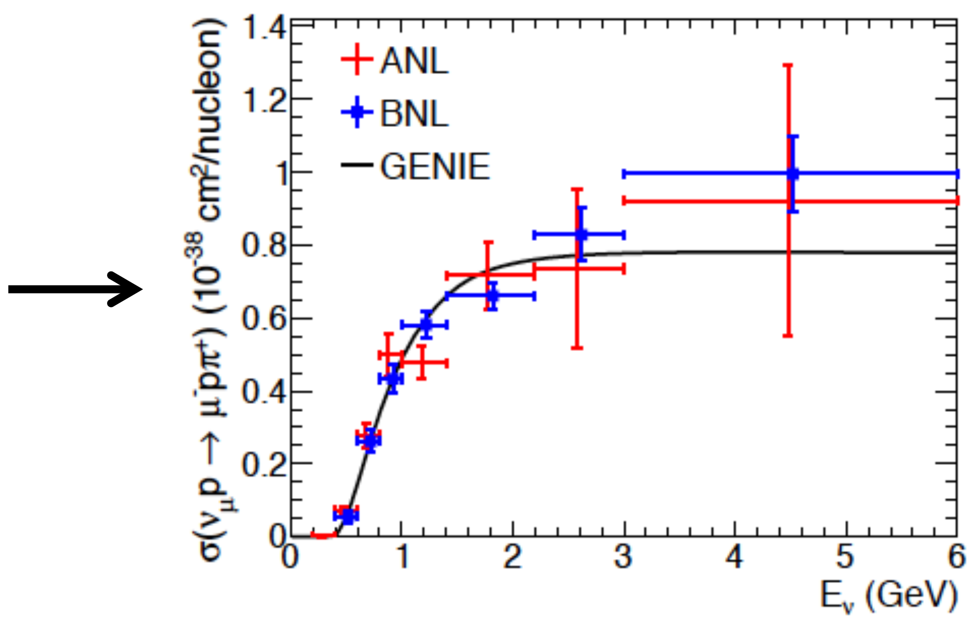
Recent re-analysis found a normalization problem on BNL

ANL vs. BNL





5. ANL-BNL puzzle

Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25% (ANL-BNL puzzle).

→ origin of 20-30% error on M_A^{RES}

Recent re-analysis found a normalization problem on BNL

Recent fit on re-analyzed ANL-BNL data shows on $C^A_5(0)$ error is 6%. This would give ~6-10% error on M_A^{RES} for experimentalist.

…However, recently Wu et al pointed out there might be significant contribution of nuclear effect in bubble chamber data. This mean, perhaps, cross section extracted by re-analyzed ANL-BNL would be underestimated?!

M_A^{RES} imitates all normalization errors associated with SPP data ($C^A_5(0)$, M_A^{RES}, nuclear effect, etc). Unless all mysteries are solved (including MiniBooNE-MINERvA tension, pion puzzle), M_A^{RES} error stays ~20-30%.

5. GENIE update

Many new neutrino pion production data are available from T2K and MINERvA, but theories are not successful to reproduce them. For GENIE, having correct pion production model and FSI (final state interaction) is an urgent issue (for DUNE, NOvA, T2K, etc)

Updates to GENIE

- v2.6.2 – used in all Minerva results shown today
- v2.8.6 – present production release
  - Improved FSI
  - Will be used for Minerva ME results
- v2.10.0 – imminent – same default (new alternate models)
  - Effective spectral function
  - Improved pion production form factors
  - Improved FSI (better A dependence)
- v2.12.0 – in progress
  - Spectral function nuclear model
  - Valencia MEC
  - Oset-Salcedo FSI model
  - Nieves QE/ local Fermi Gas nuclear model

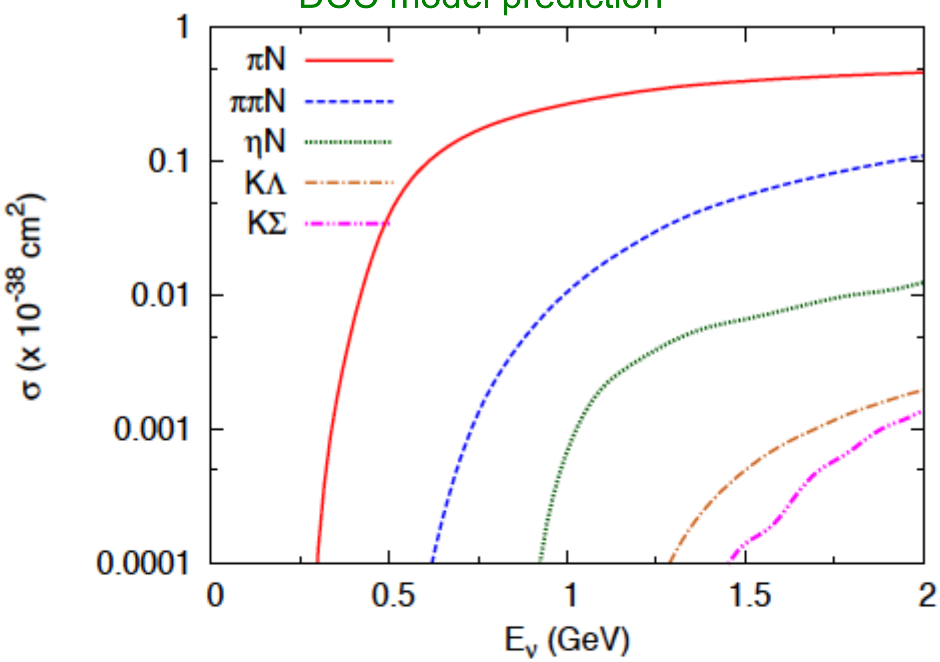
46 FNAL Seminar I October, 2015

5. Shallow Inelastic Scattering (SIS)

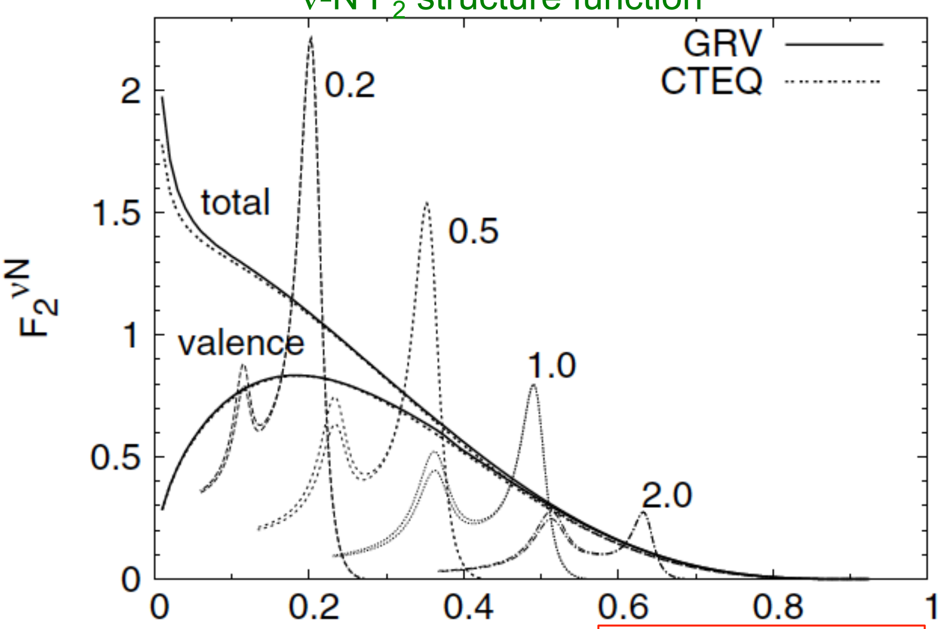
Resonance to DIS transition region

- state-of-the-art resonance model predicts varieties of hadrons at 2 GeV.
- quark-hadron duality offers smooth transition from RES to DIS.

DCC model prediction



ν-N F_2 structure function



Nachtmann variable

$$\xi(x, Q^2) = \frac{2x}{1+\sqrt{1+4x^2M^2/Q^2}}$$

5. Shallow Inelastic Scattering (SIS)

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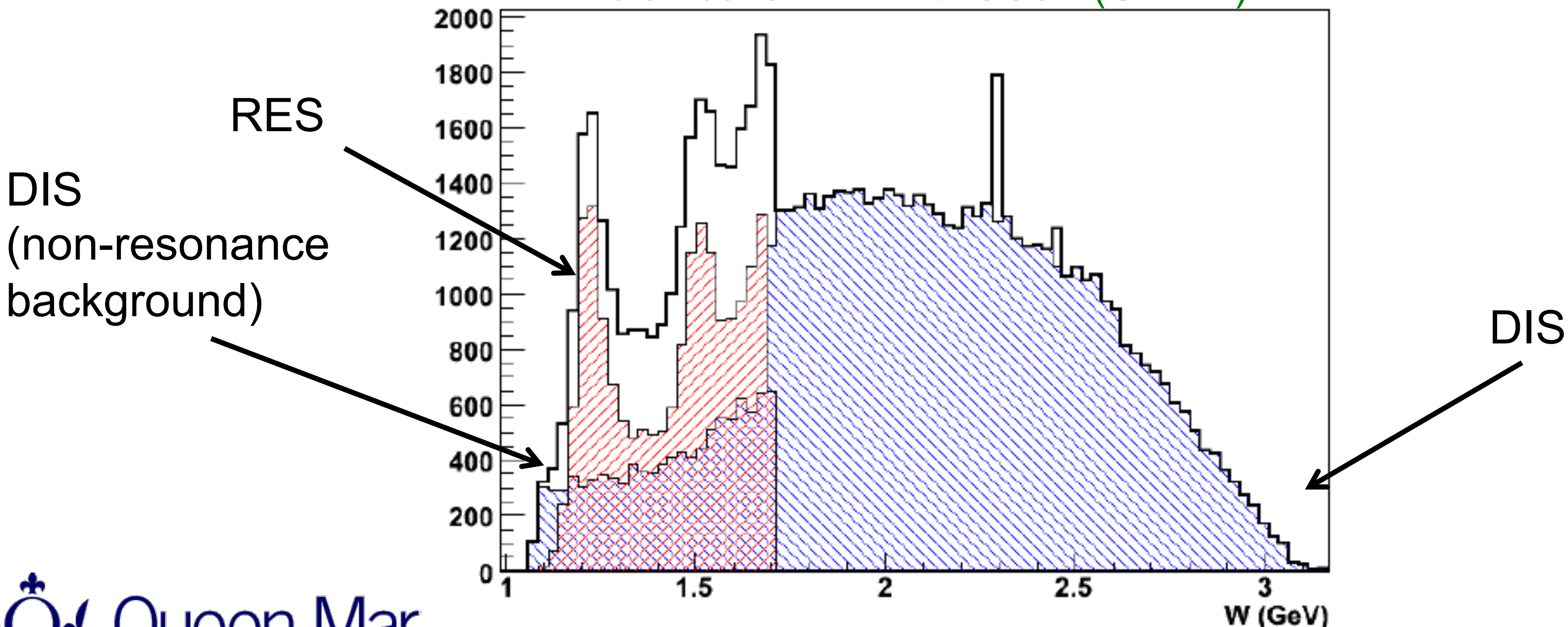
Neutrino interaction generator

- SIS is based on ad hoc model
- low W hadronization model is also ad hoc

W distribution with Eν=5GeV (GENIE)



Spitz, PhD thesis (2011)
TK and Mandalia, JPhysG42(2015)115004

5. Shallow Inelastic Scattering (SIS)

CCQE
Resonance
SIS

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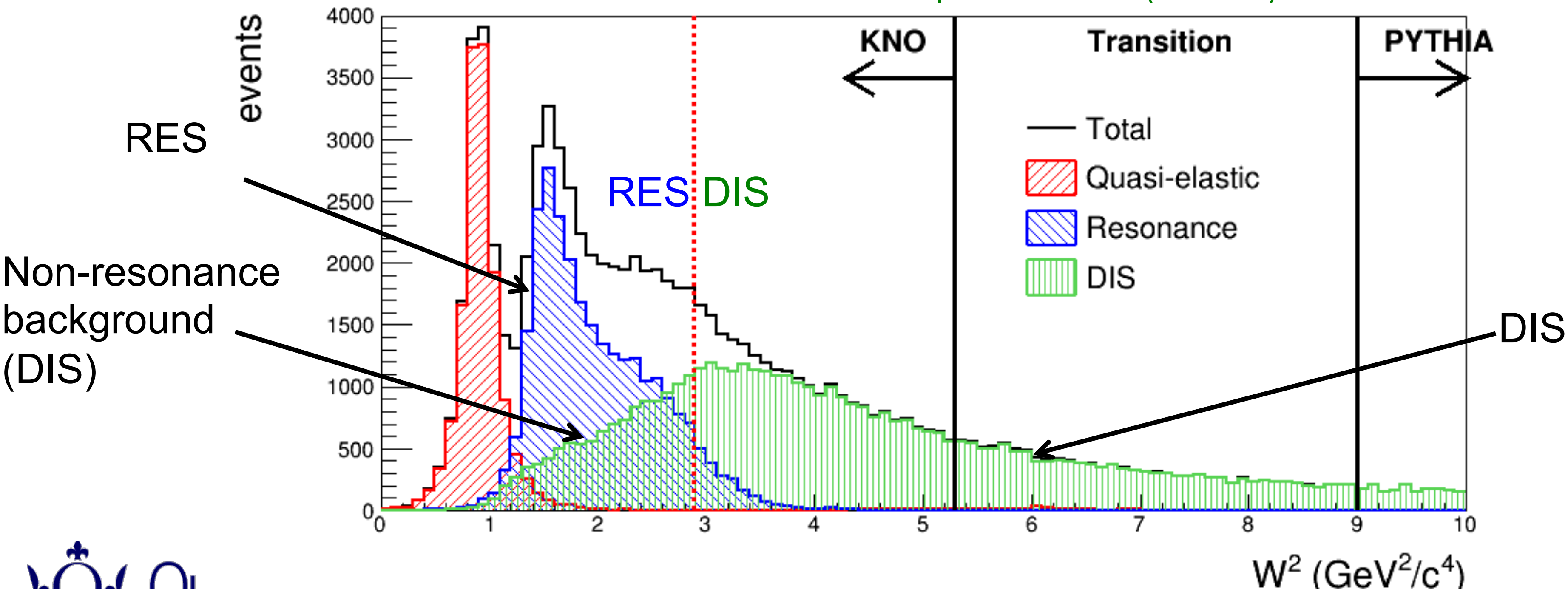
W distribution with atmospheric-ν flux (GENIE)



Spitz, PhD thesis (2011)
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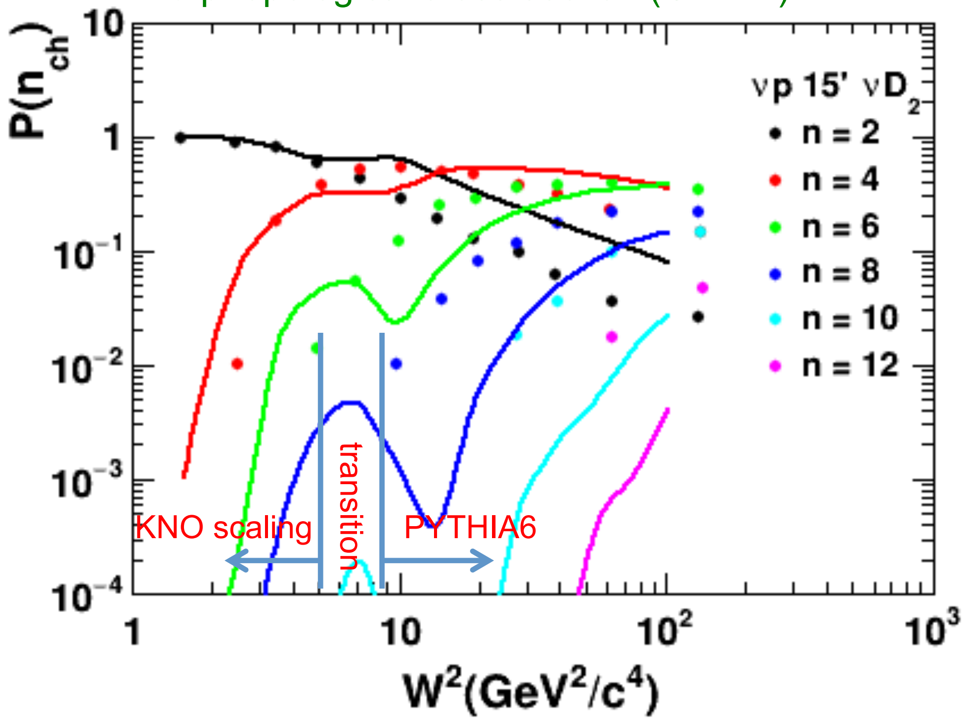
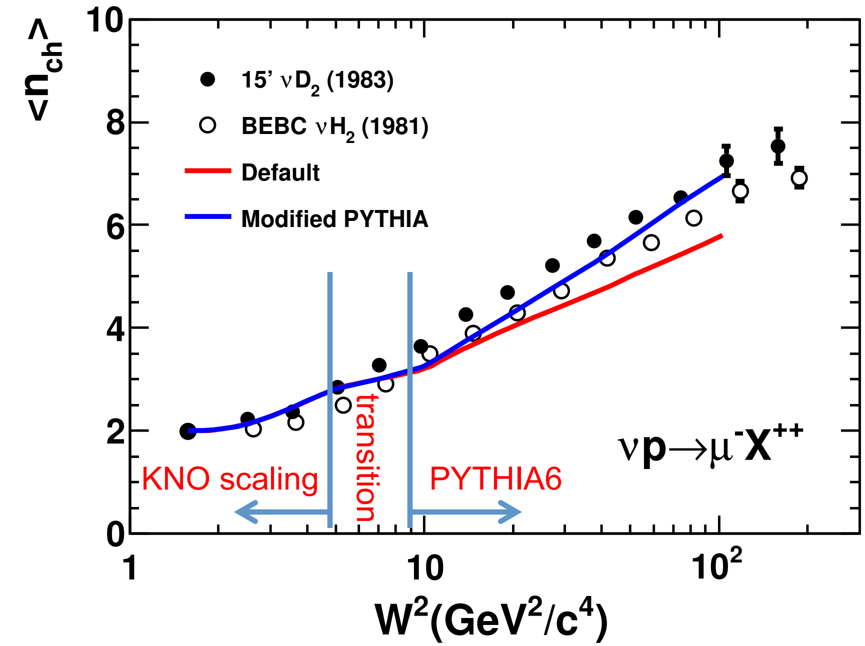
ν-p topological cross section (GENIE)



ν-p averaged charged hadron multiplicity (GENIE)



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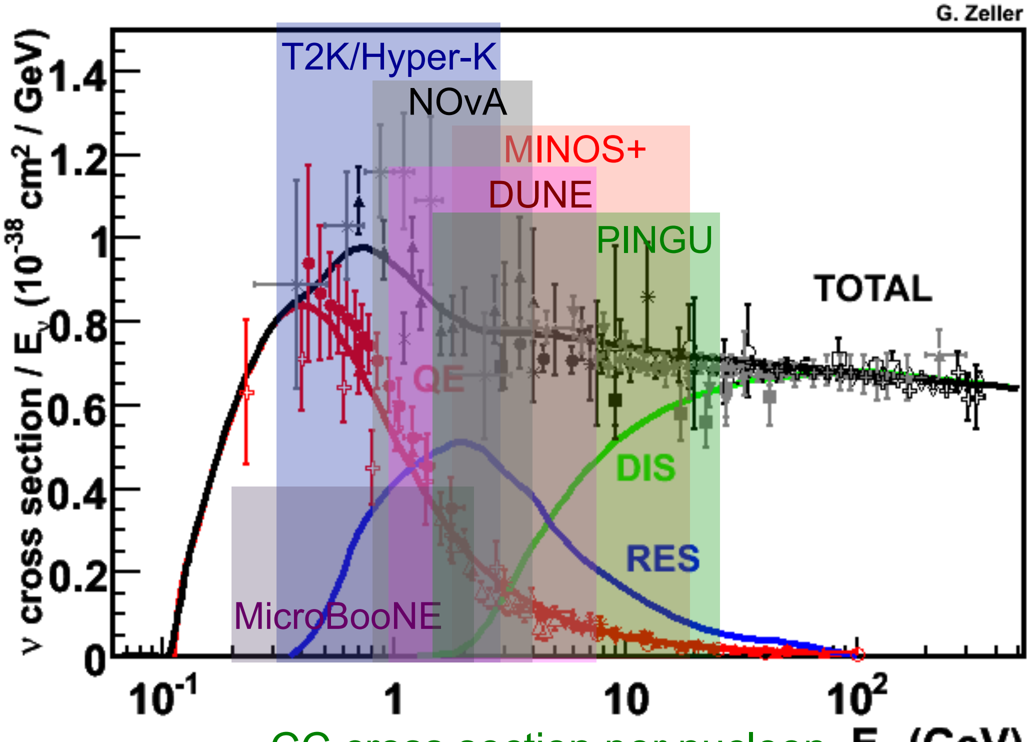


ν_μCC cross section per nucleon

Importance of SIS region is evident. How to model this?

(NuInt15 has a discussion session of SIS)

1. Neutrino oscillations

2. Accelerator-based neutrino oscillation experiment

3. QE-like background

4. NCπ° background for ν_e appearance experiment

5. Interaction systematics status

6. Realistic oscillation analysis

7. Conclusion

6. Three neutrino oscillations

Neutrino Standard Model (νSM) is established

- SM + 3 active massive neutrino is established

Unknown parameters of νSM

1. Dirac CP phase
2. θ_{23} (θ_{23}=40° and 50° are same for $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$)
3. normal mass ordering $m_1<m_2<m_3$ or inverted mass ordering $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase
6. absolute neutrino mass

(4–6) not relevant to neutrino oscillation experiment(?)

$$P(\nu_\mu \to \nu_e) = | \, U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} \, |^2$$
$$= |2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21}|^2$$
$$\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E}$$

where $\sqrt{P_{atm}} = 2|U_{\mu 3}||U_{e3}| \sin\Delta_{31} = \sin\theta_{23} \sin 2\theta_{13} \sin\Delta_{31}$

and $\sqrt{P_{sol}} \approx \cos\theta_{23} \sin 2\theta_{12} \sin\Delta_{21}.$

6. Neutrino oscillation experiment

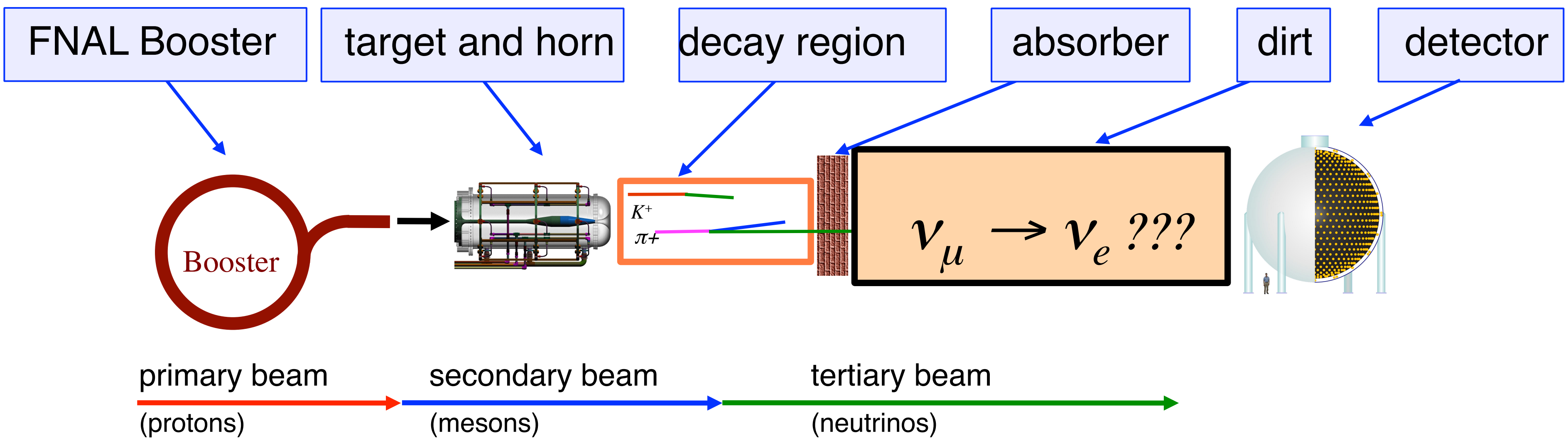
Data (nature)

Simulation (theory)

6. Neutrino oscillation experiment

Data (nature) | **Simulation (theory)**

Produce neutrino beam



6. Neutrino oscillation experiment

Data (nature)

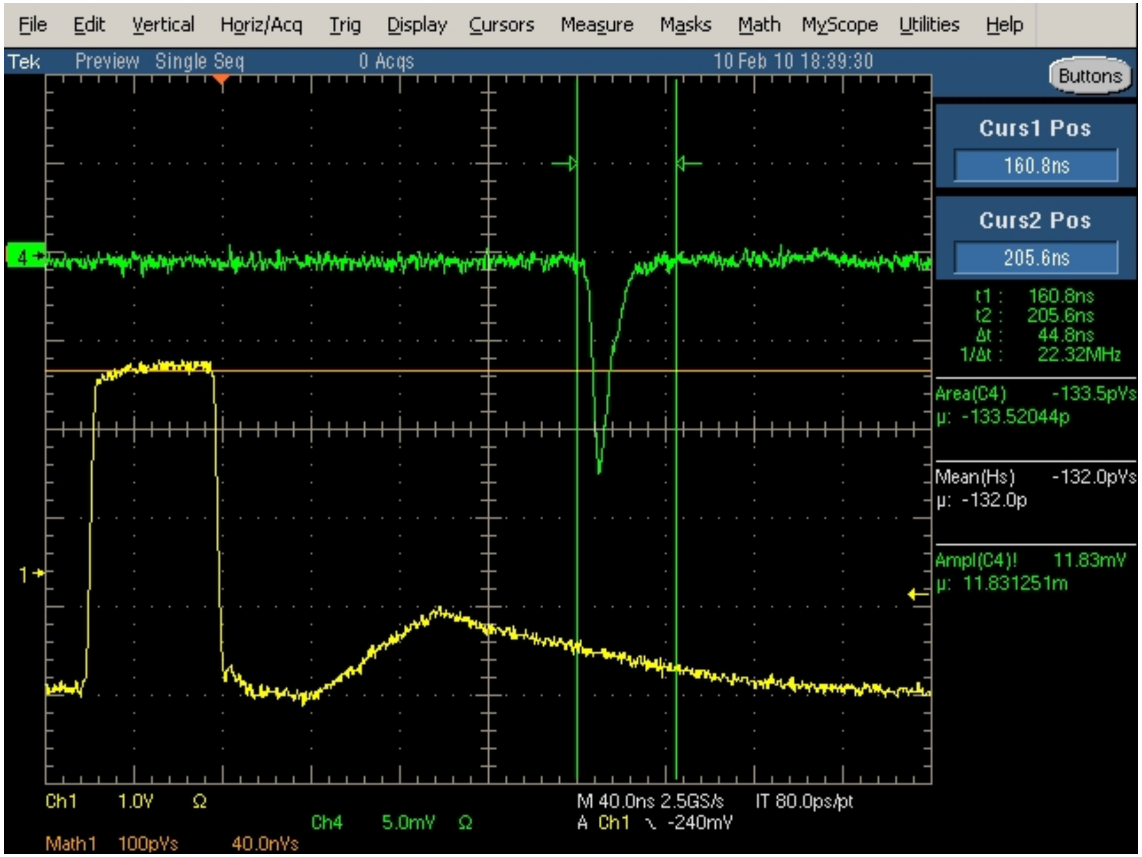
Produce neutrino beam

↓

Interaction in the detector makes observables (electric signal)

Simulation (theory)

Typical PMT pulse



6. Neutrino oscillation experiment

Q6

Data (nature)

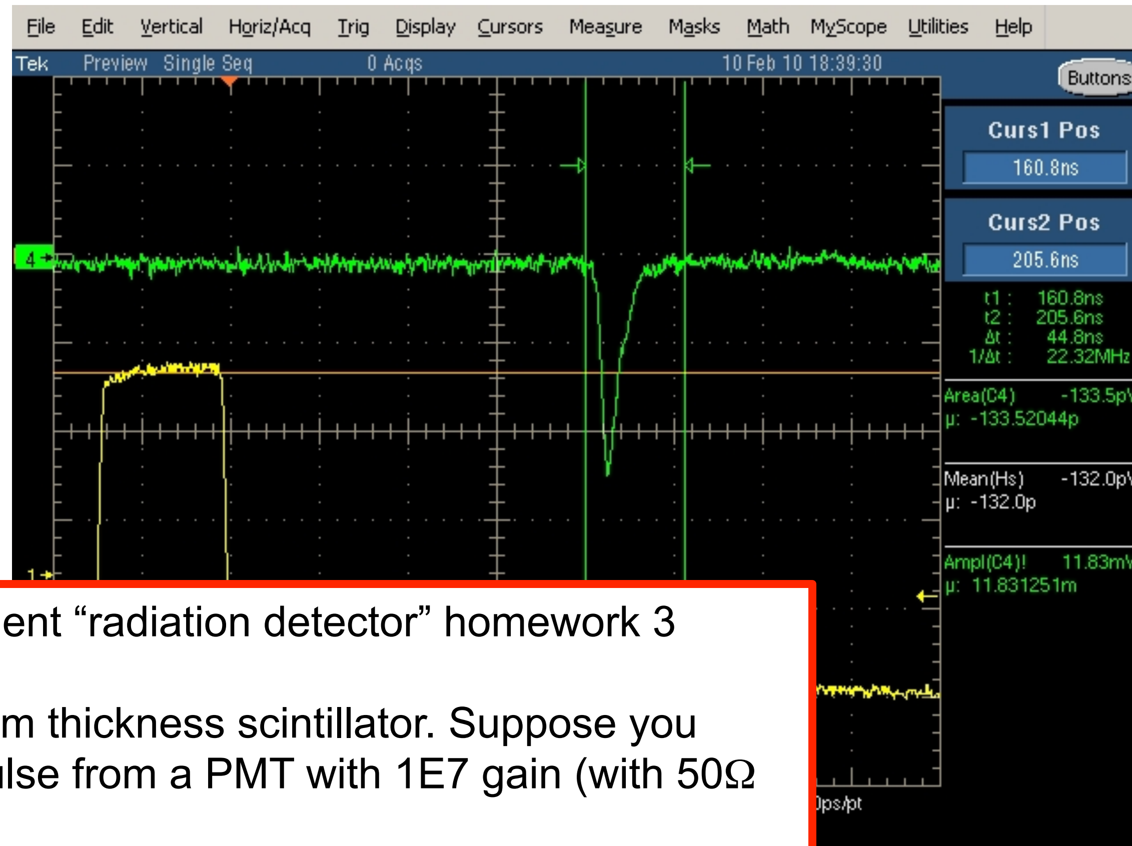
Produce neutrino beam

↓

Interaction in the detector makes observables (electric signal)

Simulation (theory)

Typical PMT pulse



Queen Mary university 3rd year student "radiation detector" homework 3

A MIP particle passed through a 1 cm thickness scintillator. Suppose you observe 10ns width 16mV height pulse from a PMT with 1E7 gain (with 50Ω termination oscilloscope).

How many photo-electron produced per MeV in this scintillator in this setting? (this is called a calibration constant)

6. Neutrino oscillation experiment

Data (nature)

Produce neutrino beam

↓

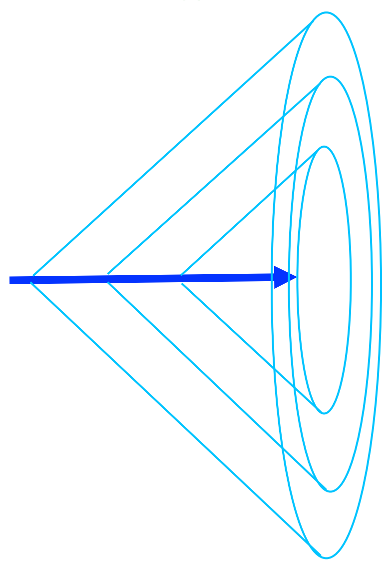
Interaction in the detector makes observables (electric signal)

↓

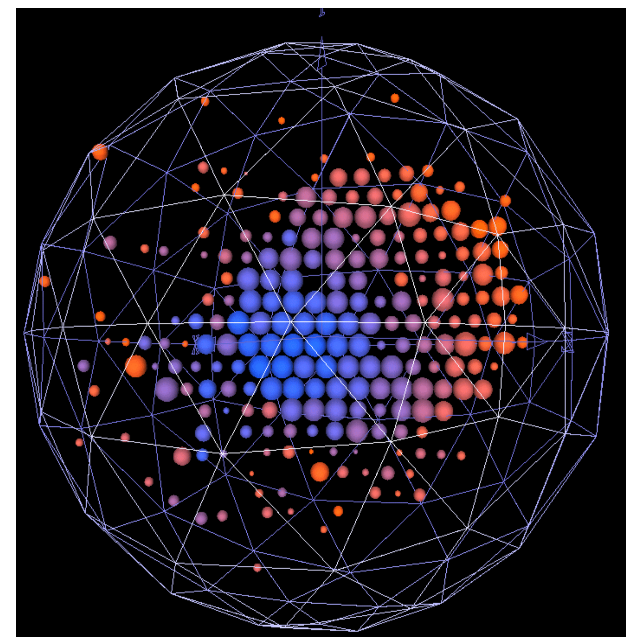
Particle kinematics are reconstructed from observables

Simulation (theory)

muon (sharp edge Cherenkov ring)



MiniBooNE event display of muon candidate event



6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

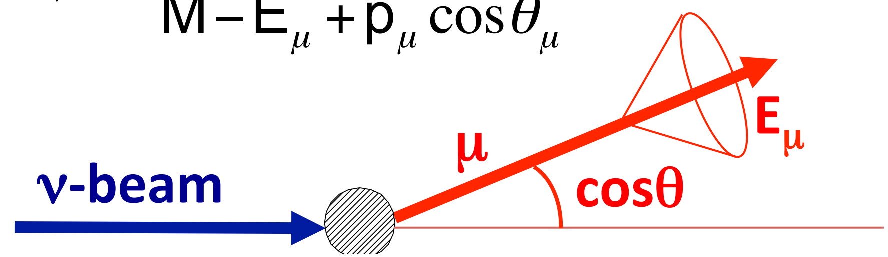
Interaction in the detector makes observables (electric signal)

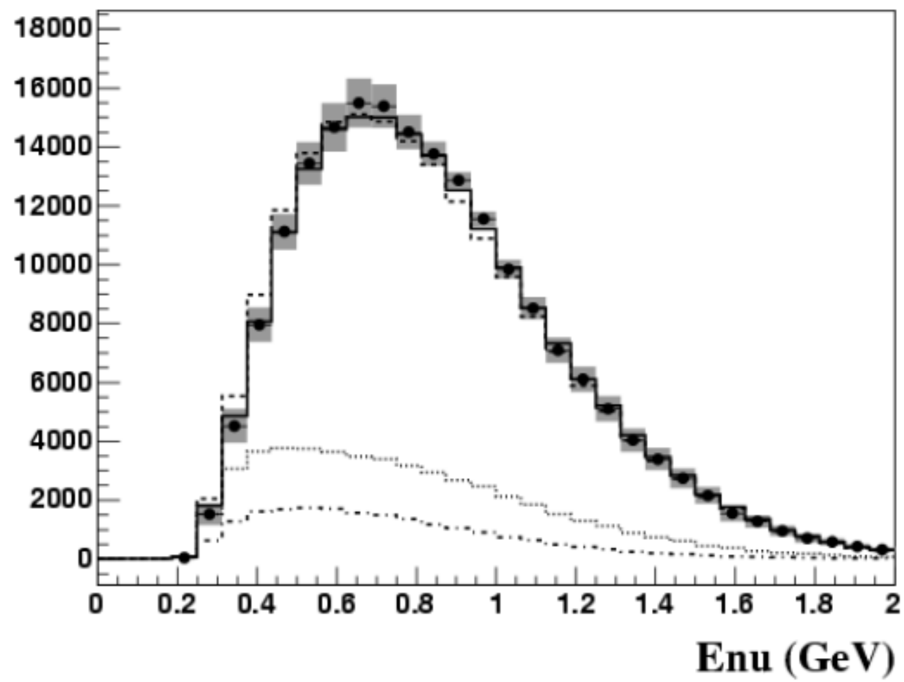
Particle kinematics are reconstructed from observables

Neutrino energy is reconstructed from particle kinematics

Simulation (theory)

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





6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

↓

Interaction in the detector makes observables (electric signal)

↓

Particle kinematics are reconstructed from observables

↓

Neutrino energy is reconstructed from particle kinematics

Simulation (theory)

Simulate neutrino beam

E_ν^{true}

6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

↓

Interaction in the detector makes observables (electric signal)

↓

Particle kinematics are reconstructed from observables

↓

Neutrino energy is reconstructed from particle kinematics

Simulation (theory)

Simulate neutrino beam — E_ν^{true}

↓

Add neutrino oscillation — E_ν^{true}

6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

↓

Interaction in the detector makes observables (electric signal)

↓

Particle kinematics are reconstructed from observables

↓

Neutrino energy is reconstructed from particle kinematics

Simulation (theory)

Simulate neutrino beam — E_ν^{true}

↓

Add neutrino oscillation — E_ν^{true}

↓

Simulate neutrino interaction to predict particle kinematics — E_μ^{true}

← compare →

6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

↓

Interaction in the detector makes observables (electric signal)

↓

Particle kinematics are reconstructed from observables

↓

Neutrino energy is reconstructed from particle kinematics

Simulation (theory)

Simulate neutrino beam — $E\nu^{true}$

↓

Add neutrino oscillation — $E\nu^{true}$

↓

Simulate neutrino interaction to predict particle kinematics — $E\mu^{true}$

↓

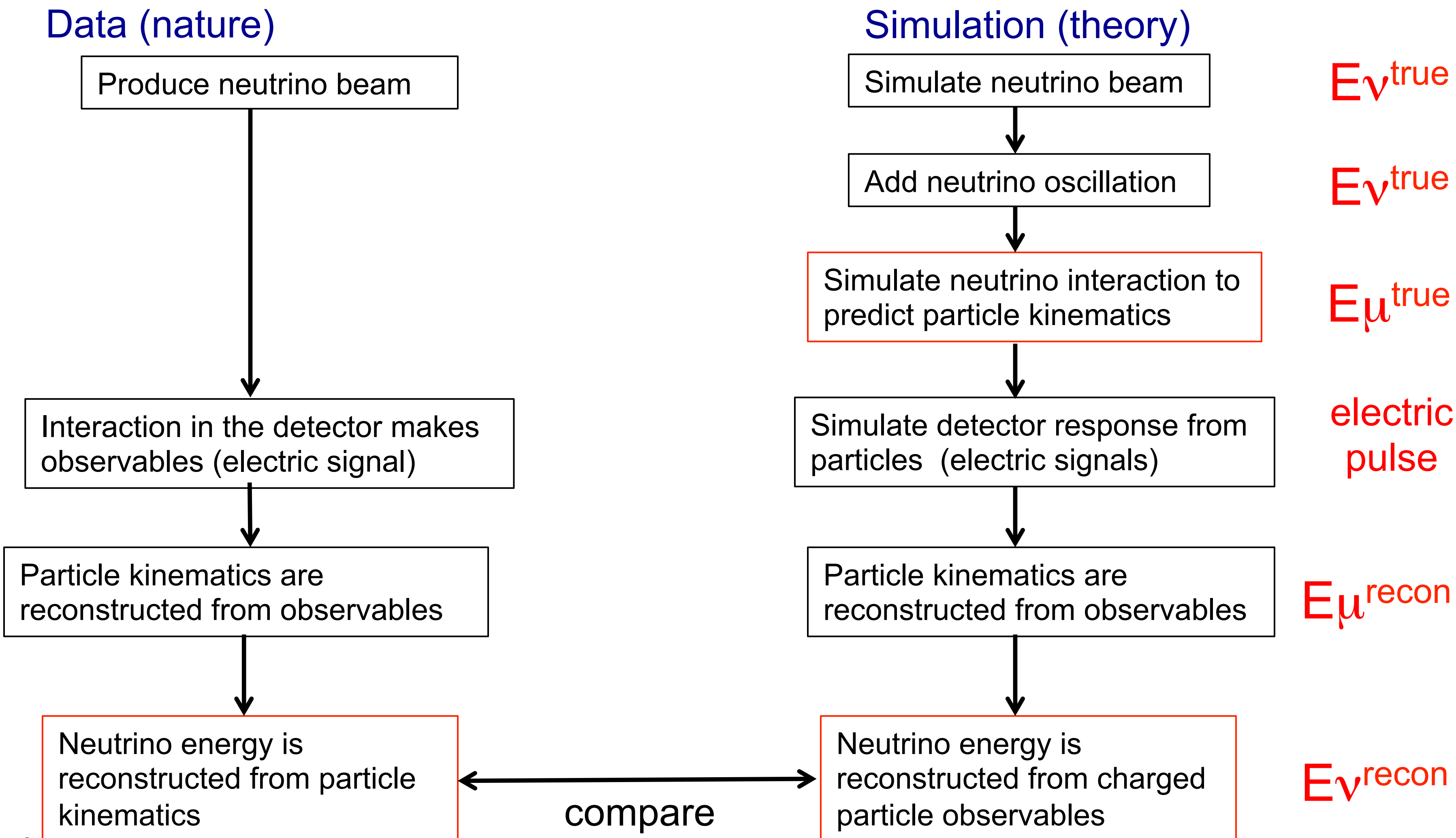
Simulate detector response from particles (electric signals) — electric pulse

← compare →

Queen Mary University of London

6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes



6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

- Produce neutrino beam
- ↓
- Interaction in the detector makes observables (electric signal)
- ↓
- Particle kinematics are reconstructed from observables
- ↓
- Neutrino energy is reconstructed from particle kinematics

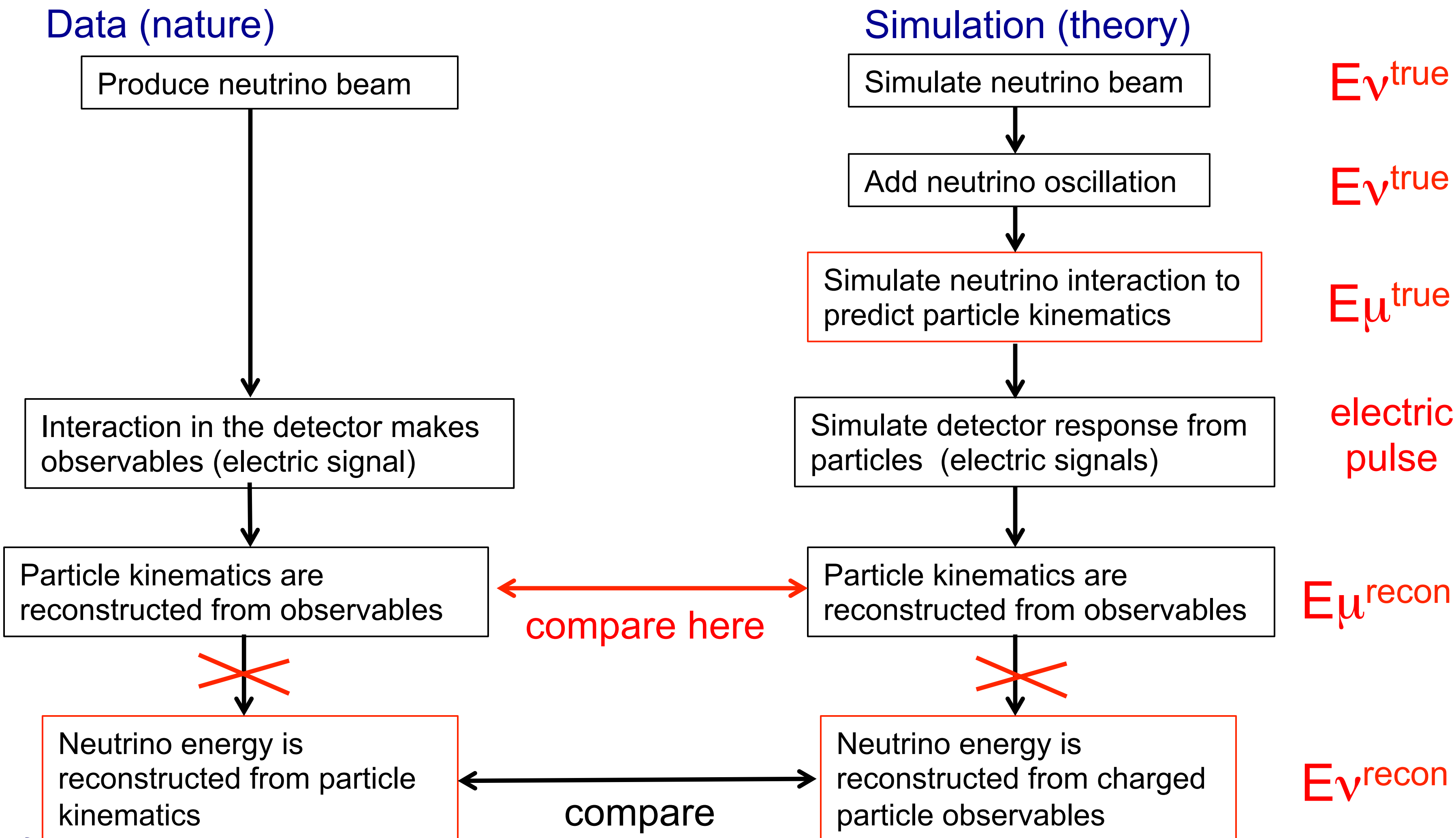
Simulation (theory)

- Simulate neutrino beam — $E\nu^{true}$
- ↓
- Add neutrino oscillation — $E\nu^{true}$
- ↓
- Simulate neutrino interaction to predict particle kinematics — $E\mu^{true}$
- ↓
- Simulate detector response from particles (electric signals) — electric pulse
- ↓
- Particle kinematics are reconstructed from observables — $E\mu^{recon}$
- ↓
- Neutrino energy is reconstructed from charged particle observables — $E\nu^{recon}$

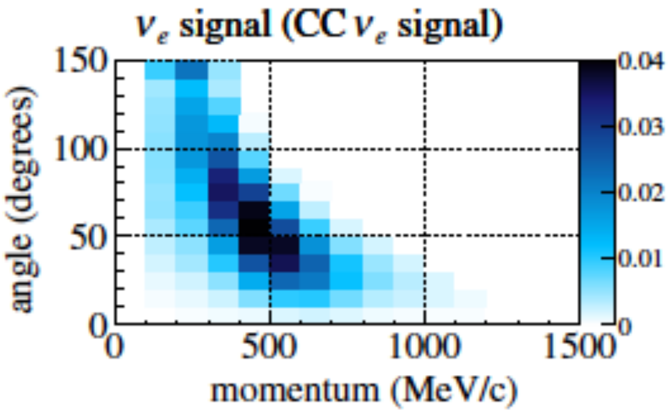
Data ↔ Simulation: compare

6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

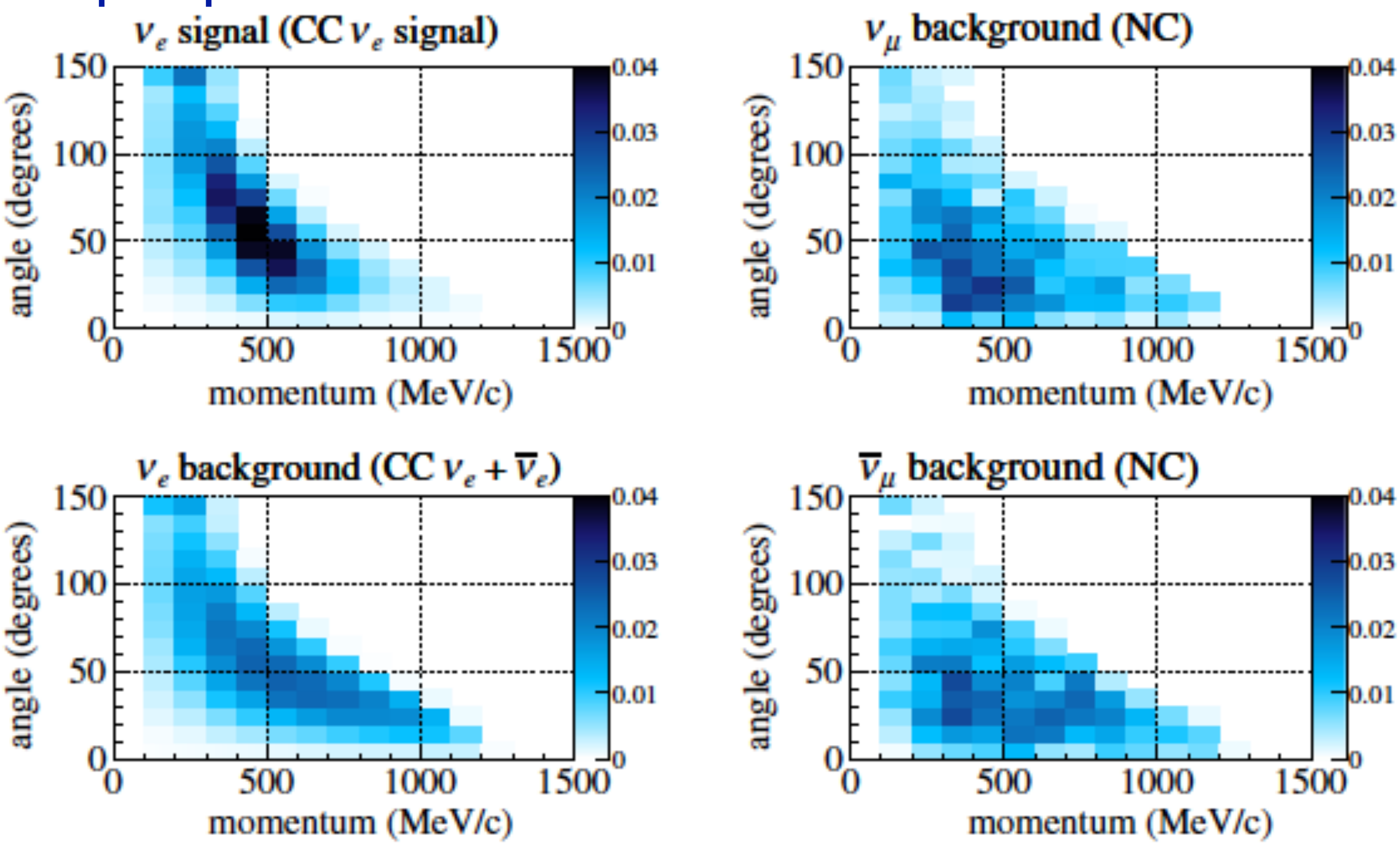


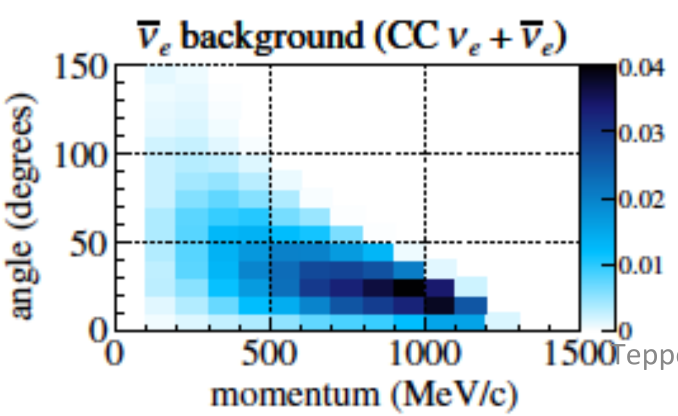
6. p-θ plane fit



Instead of reconstructed neutrino energy, electron momentum and angle are fit to find $\nu_\mu \rightarrow \nu_e$ oscillations

6. p-θ plane fit

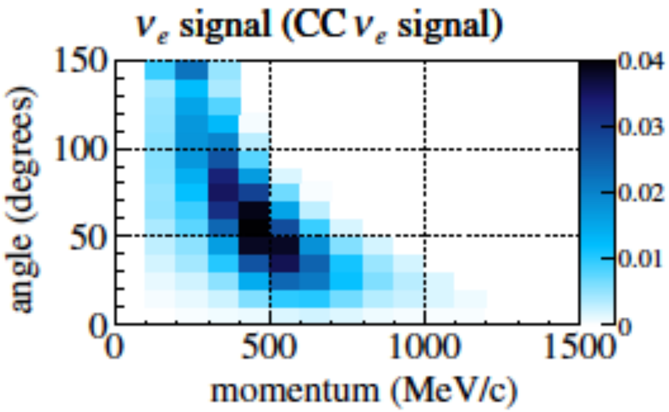


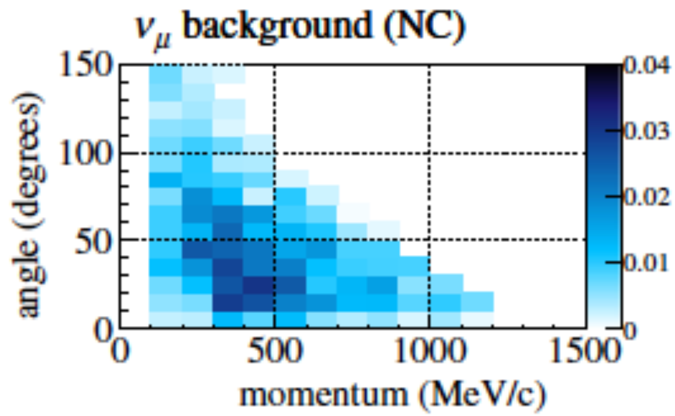


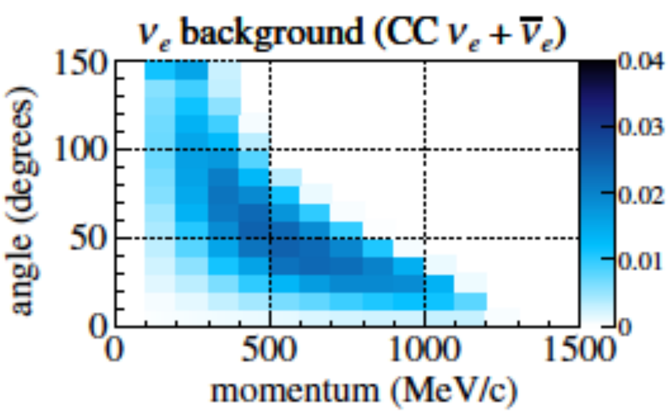
We simultaneously fit other distributions to maximize constraints of systematics from all information available

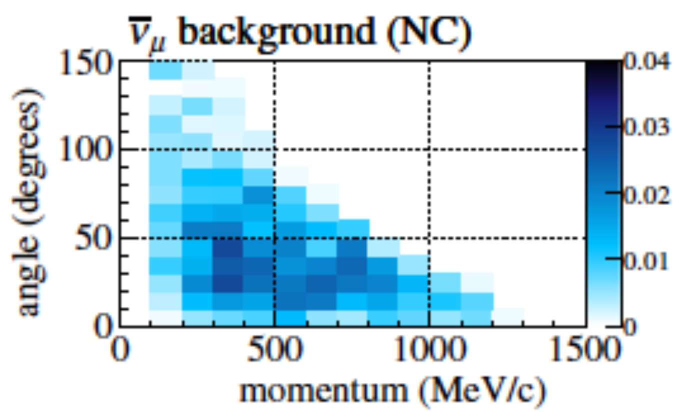
so it is misleading to emphasize neutrino energy reconstruction bias as nuclear effect

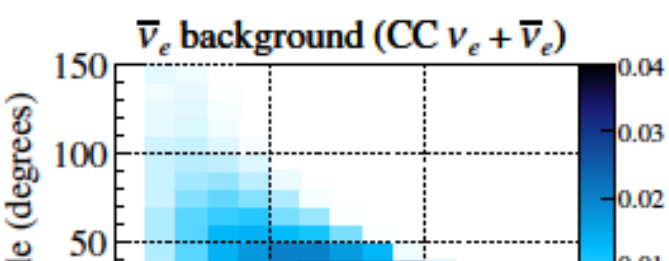
6. p-θ plane fit











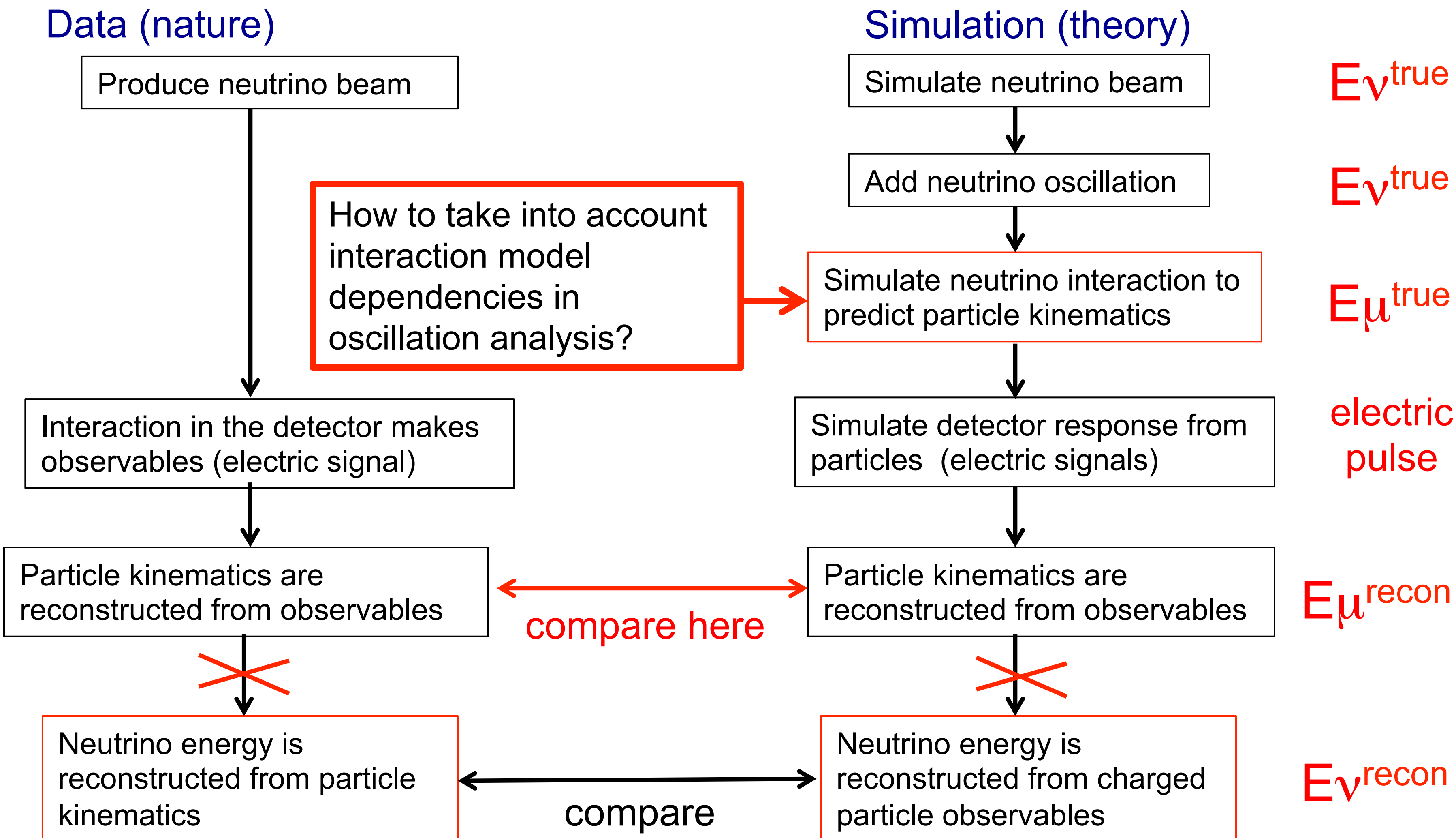
We simultaneously fit other distributions to maximize constraints of systematics from all information available

so it is misleading to emphasize neutrino energy reconstruction bias as nuclear effect

But all of these template are made based on some interaction models, so we need good models for both signal and background (pion production)

6. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes



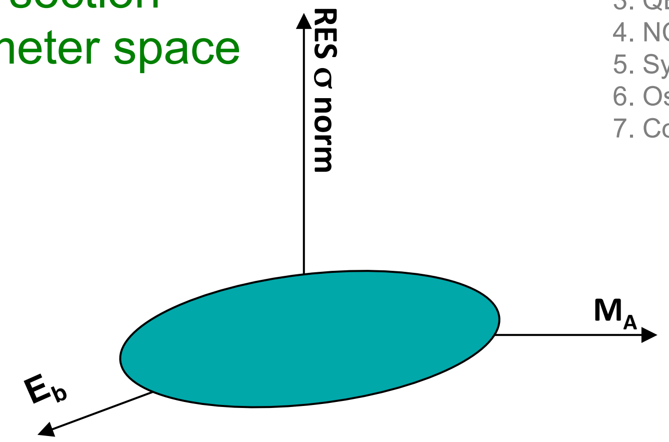
6. Error propagation

ex) cross section uncertainties

M_A 6%
E_b 2%
RES σ norm 10%

correlated (M_A, E_b)
uncorrelated (RES σ norm)

cross section parameter space



Input cross section error matrix

$$M_{input}(xs) = \begin{pmatrix} var(M_A) & cov(M_A, E_b) & 0 \\ cov(M_A, E_b) & var(E_b) & 0 \\ 0 & 0 & var(\sigma - norm) \end{pmatrix}$$

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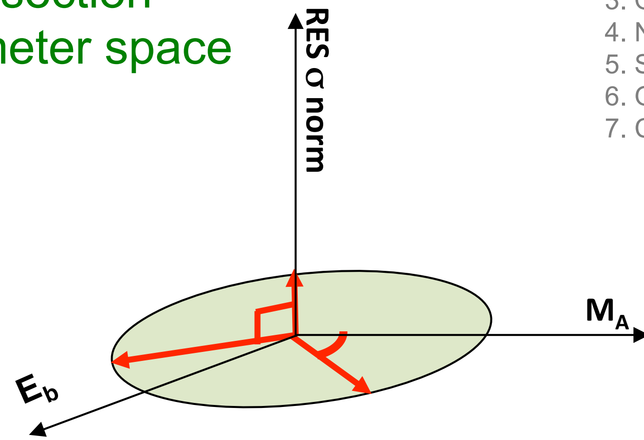
RES σ norm 10%

correlated (M_A, E_b)
uncorrelated (RES σ norm)

cross section parameter space



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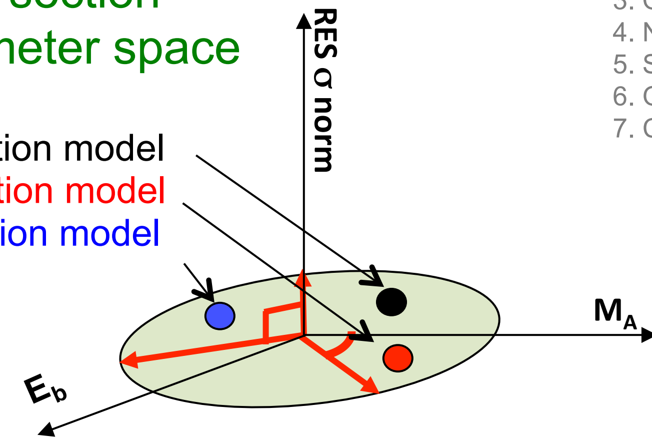

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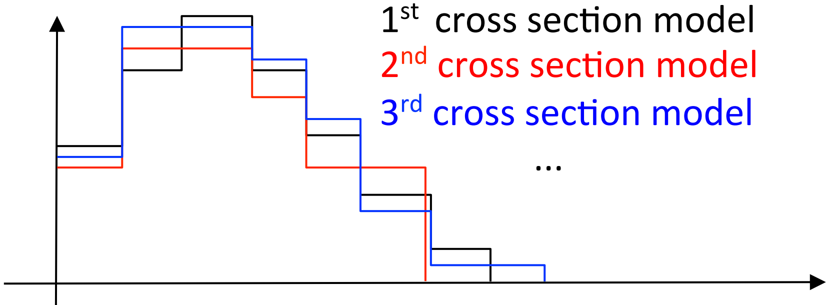
cross section error for Eμ



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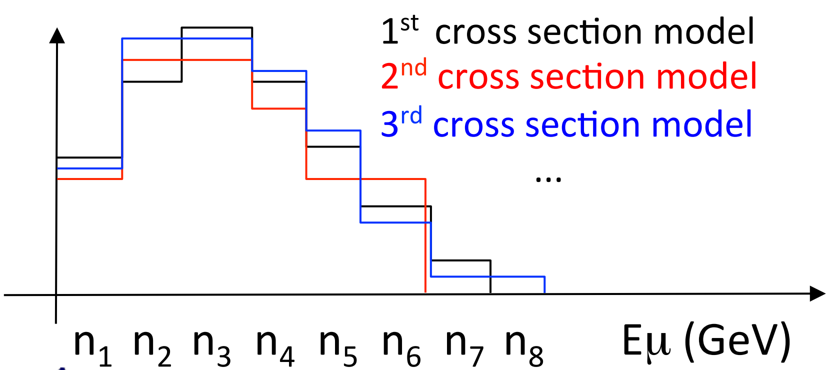
6. Error propagation

Output cross section error matrix for Eμ

$$\left[M_{output}(xs)\right]_{ij} \approx \frac{1}{S}\sum_{k}^{S}\left(N_i^k(xs) - N_i^{MC}\right)\left(N_j^k(xs) - N_j^{MC}\right)$$

$$M_{output}(xs) = \begin{pmatrix} var(n_1) & cov(n_1,n_2) & cov(n_1,n_3) & \cdots \\ cov(n_1,n_2) & var(n_2) & cov(n_2,n_3) & \cdots \\ cov(n_1,n_3) & cov(n_2,n_3) & var(n_3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

cross section error for Eμ



MC can propagate correlations of input parameters to bins of muon energy distribution.

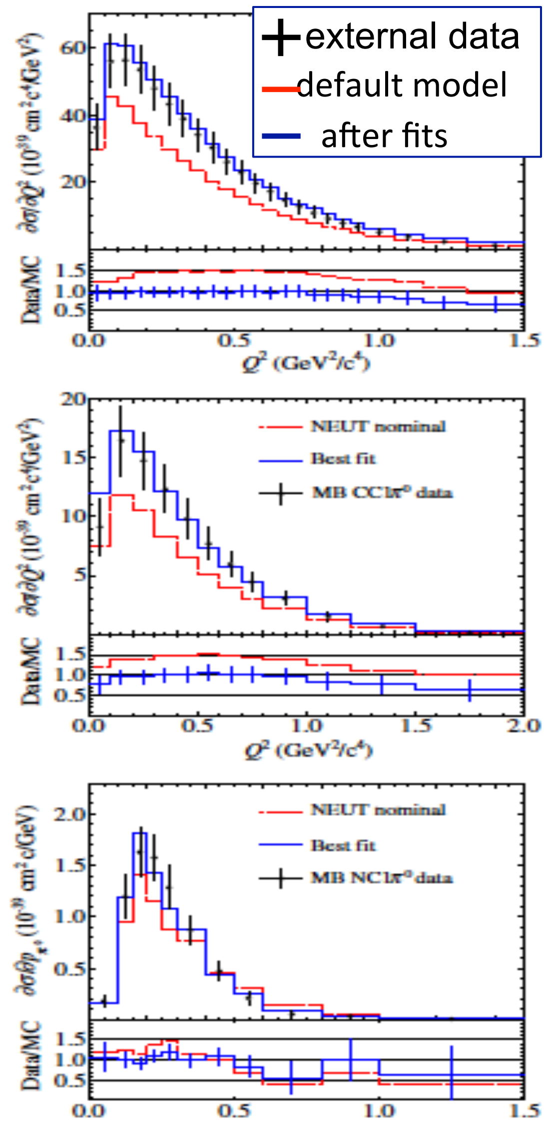
Repeat this many times to propagate all errors to make total error matrix.

6. External constraint

Output error matrices are made from external data
→ this is the initial guess of parameters and errors

Interaction model parameters and errors

Parameter	Input value	Uncertainty
M_A^{QE} (GeV)	1.21	0.43
x_1^{QE}	1.00	0.11
x_2^{QE}	1.00	0.30
x_3^{QE}	1.00	0.30
x_{SF}	0.0	1.0
$p_F(^{12}C)$ (MeV/c)	217	30
$p_F(^{16}O)$ (MeV/c)	225	30
M_A^{RES} (GeV)	1.16	0.11
$x_1^{CC1\pi}$	1.63	0.43
$x_2^{CC1\pi}$	1.00	0.40
$x^{NC1\pi^0}$	1.19	0.43
$x_{1\pi E_\nu}$	off	on
W_{eff}	1.0	0.51
$x_{\pi\text{-less}}$	0.2	0.2
$x^{CC\ coh}$	1.0	1.0
$x^{NC\ coh}$	1.0	0.3
$x^{NC\ other}$	1.0	0.3
$x_{CC\ other}$ (GeV)	0.0	0.4
x_{ν_e/ν_μ}	1.0	0.03



External data fit

CCQE cross section	
M_A^{QE}	The mass parameter in the axial dipole form factor for quasielastic interactions.
x_1^{QE}	The normalization of the quasielastic cross section for $E_\nu < 1.5$ GeV.
x_2^{QE}	The normalization of the quasielastic cross section for $1.5 < E_\nu < 3.5$ GeV.
x_3^{QE}	The normalization of the quasielastic cross section for $E_\nu > 3.5$ GeV.
Nuclear model for CCQE interactions (separate parameters for interactions on O and C)	
x_{SF}	Smoothly changes from a relativistic Fermi gas nuclear model to a spectral function model.
p_F	The Fermi surface momentum in the relativistic Fermi gas model.
Resonant pion production cross section	
M_A^{RES}	The mass parameter in the axial dipole form factor for resonant pion production interactions.
$x_1^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu < 2.5$ GeV.
$x_2^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu > 2.5$ GeV.
$x^{NC1\pi^0}$	The normalization of the NC1π^0 cross section.
$x_{1\pi E_\nu}$	Varies the energy dependence of the 1π cross section for better agreement with MiniBooNE data.
W_{eff}	Varies the distribution of $N\pi$ invariant mass in resonant production.
$x_{\pi\text{-less}}$	Varies the fraction of Δ resonances that decay or are absorbed without producing a pion.
Other	
$x^{CC\ coh}$	The normalization of CC coherent pion production.
$x^{NC\ coh}$	The normalization of NC coherent pion production.
$x^{NC\ other}$	The normalization of NC interactions other than NC1π^0 production.
$x_{CC\ other}$	Varies the CCmulti-π cross section normalization, with a larger effect at lower energy.
$\vec{x}_{FSI}$	Parameters that vary the microscopic pion scattering cross sections used in the FSI model.
x_{ν_e/ν_μ}	Varies the ratio of the CC ν_e and ν_μ cross sections.

T2K, PRD88(2013)032002

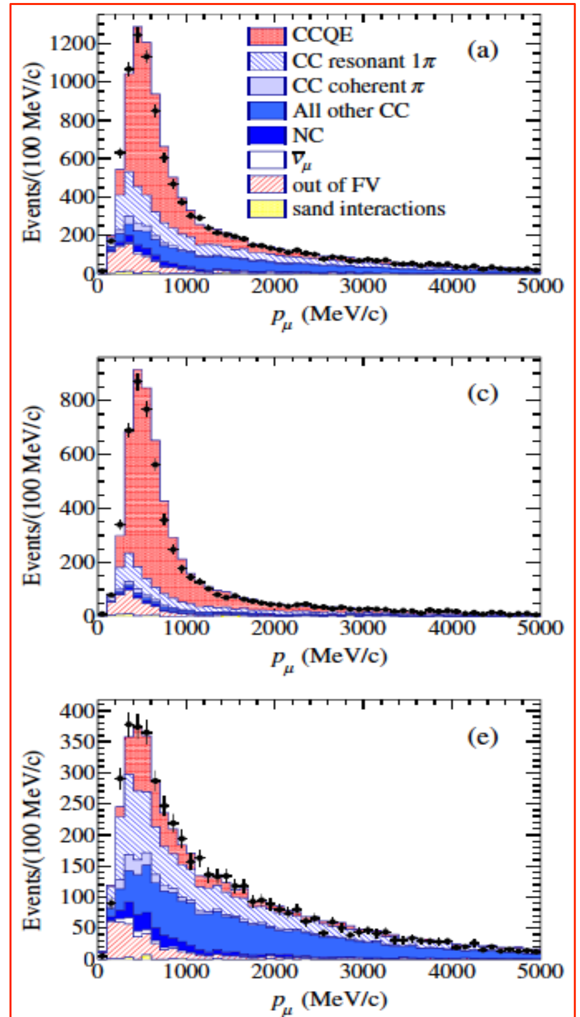
6. Internal constraint

Output error matrices are made from external data
→ this is the initial guess of parameters and errors

Then this output error matrices are fit with T2K near detector data. This improves parameters and errors

Internal model parameters and errors after the fit

Parameter	Prior value	Fitted value
M_A^{QE} (GeV)	1.21 ± 0.45	1.33 ± 0.20
M_A^{RES} (GeV)	1.16 ± 0.11	1.15 ± 0.10
x_1^{QE}	1.00 ± 0.11	0.96 ± 0.09
$x_1^{CC1\pi}$	1.63 ± 0.43	1.61 ± 0.29
$x_1^{NC1\pi^0}$	1.19 ± 0.43	1.19 ± 0.40



T2K ND280 data fit

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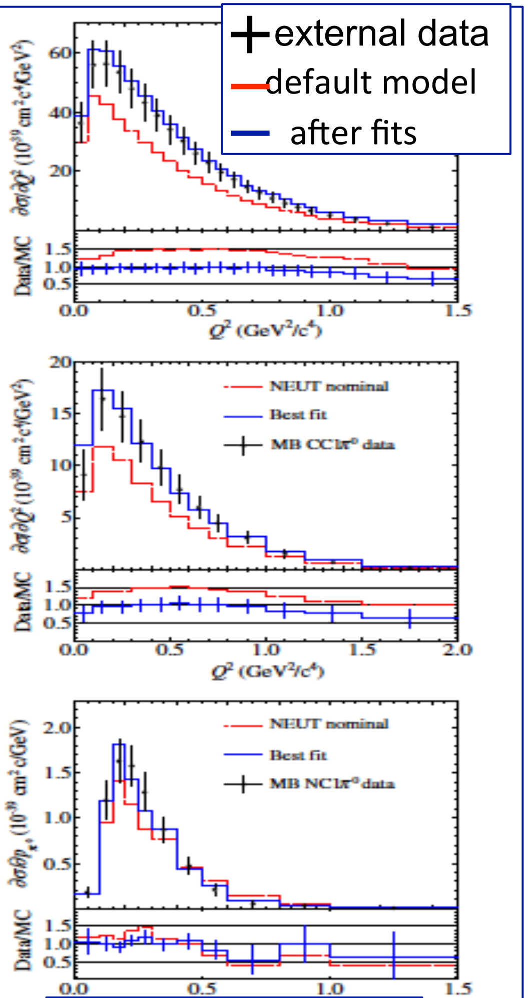
6. T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics

6. T2K oscillation experiments

External constraint

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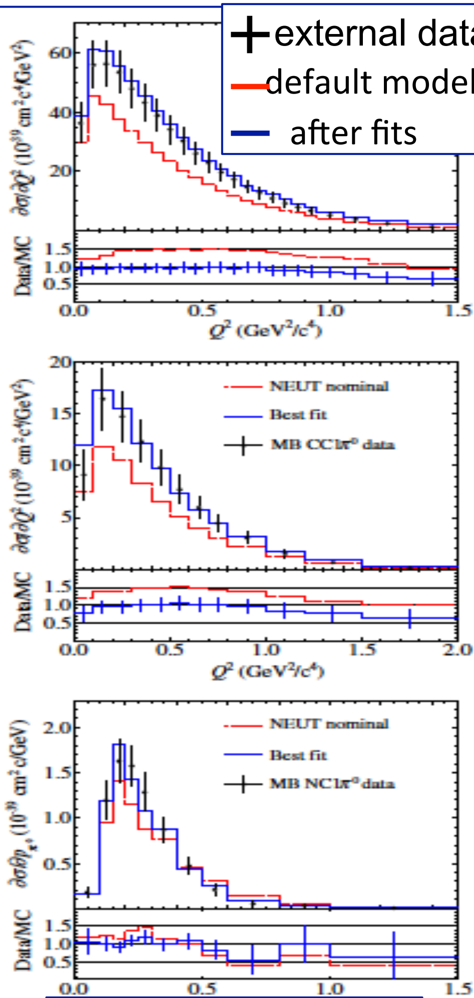
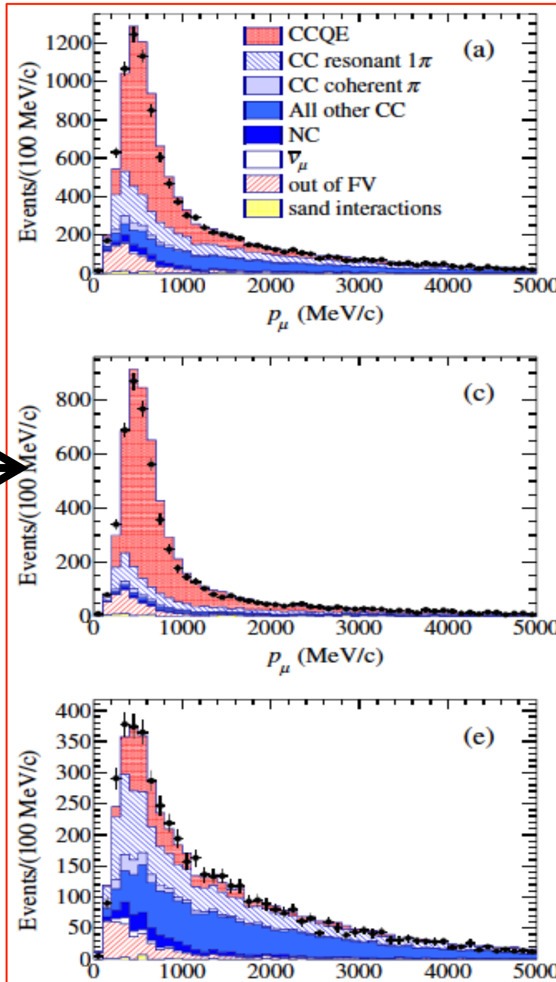


External data fit

Internal constraint

Near detector
oscillation non-sensitive channels



T2K ND280 data fit

Constraint from internal data find actual size of cross-section errors

6. T2K oscillation experiments

External constraint
MiniBooNE, MINERvA, SciBooNE
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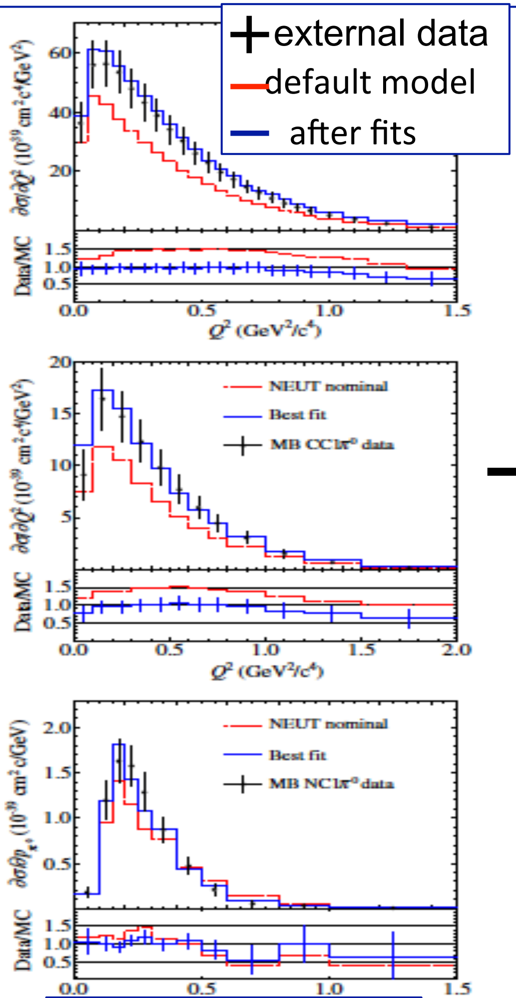

External data fit

Internal constraint
Near detector
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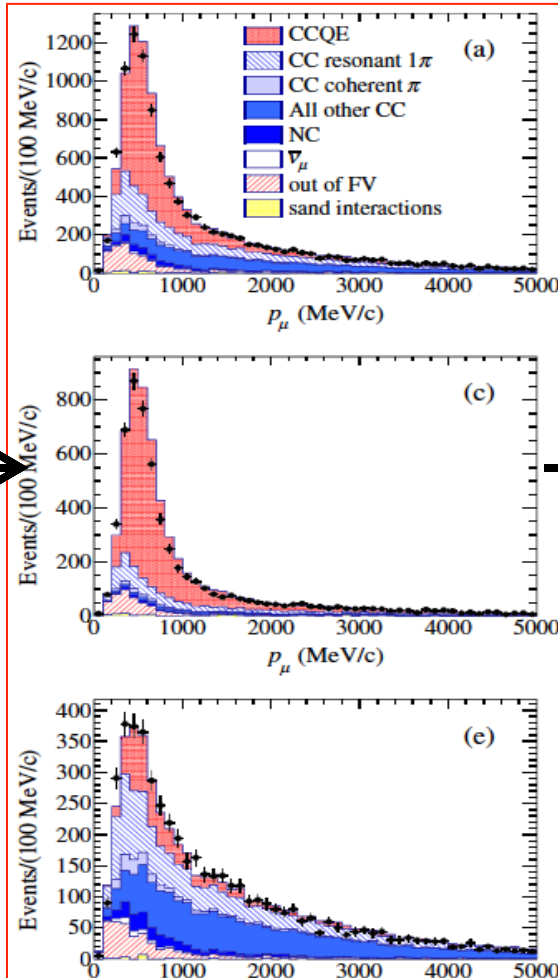
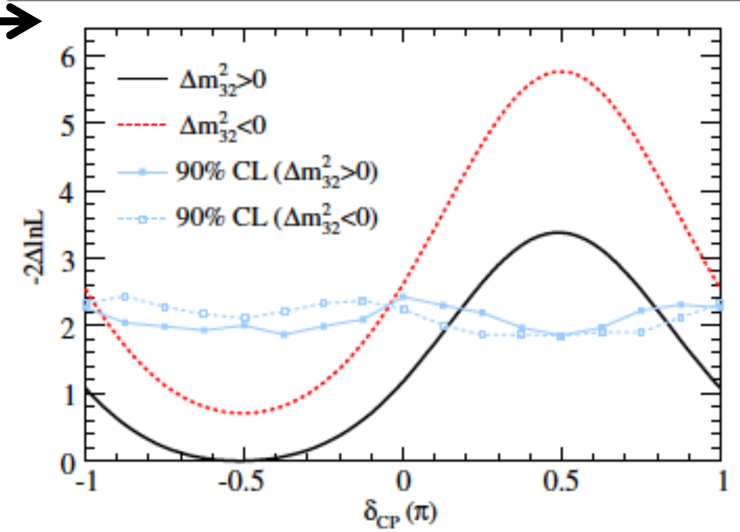


T2K ND280 data fit

Neutrino interaction model is a large systematics of neutrino oscillation experiment

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

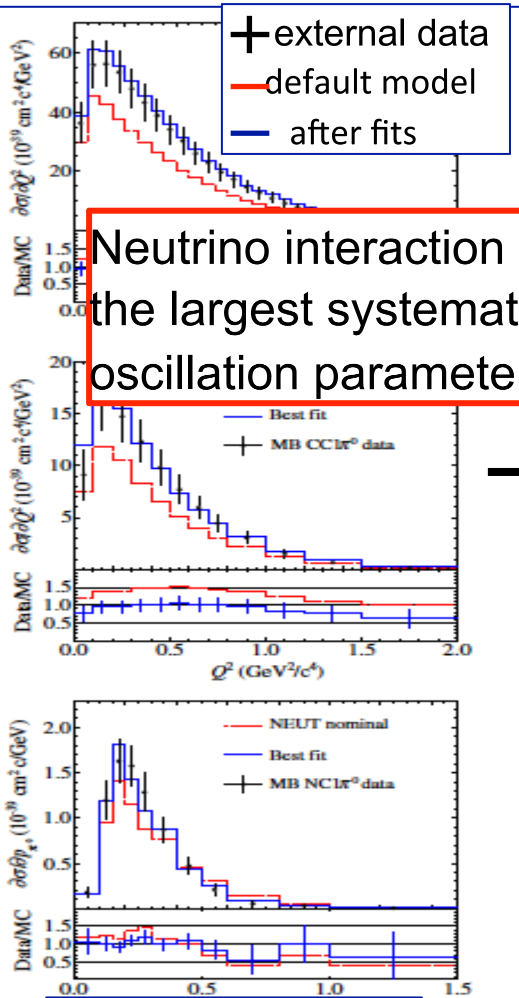


oscillation result

6. T2K oscillation experiments

External constraint

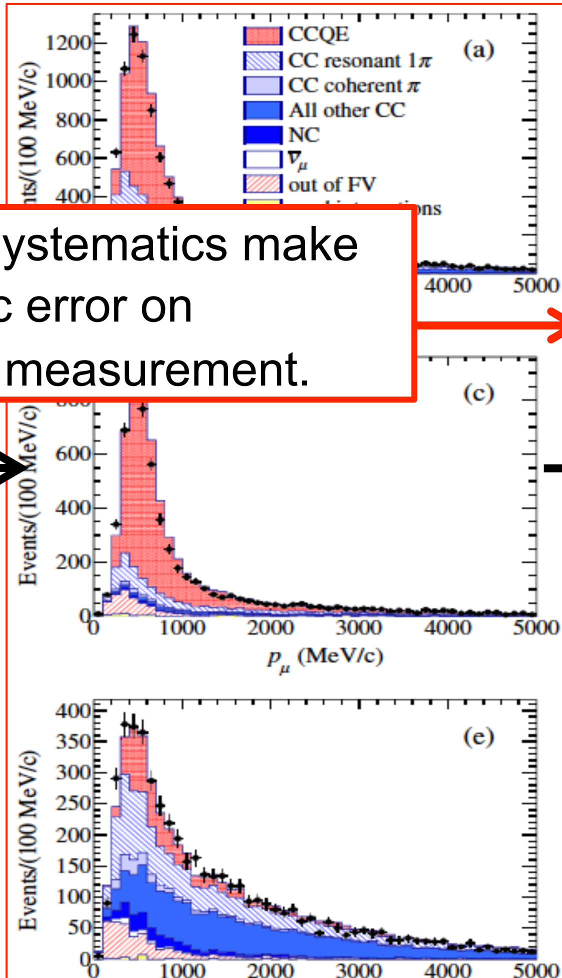
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

Internal constraint

Near detector
oscillation non-sensitive channels



T2K ND280 data fit

Neutrino interaction systematics make the largest systematic error on oscillation parameter measurement.

Neutrino interaction model is a large systematics of neutrino oscillation experiment

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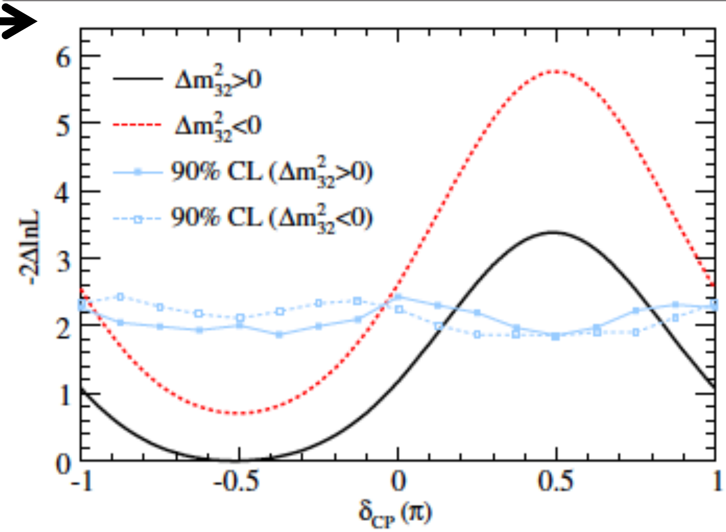
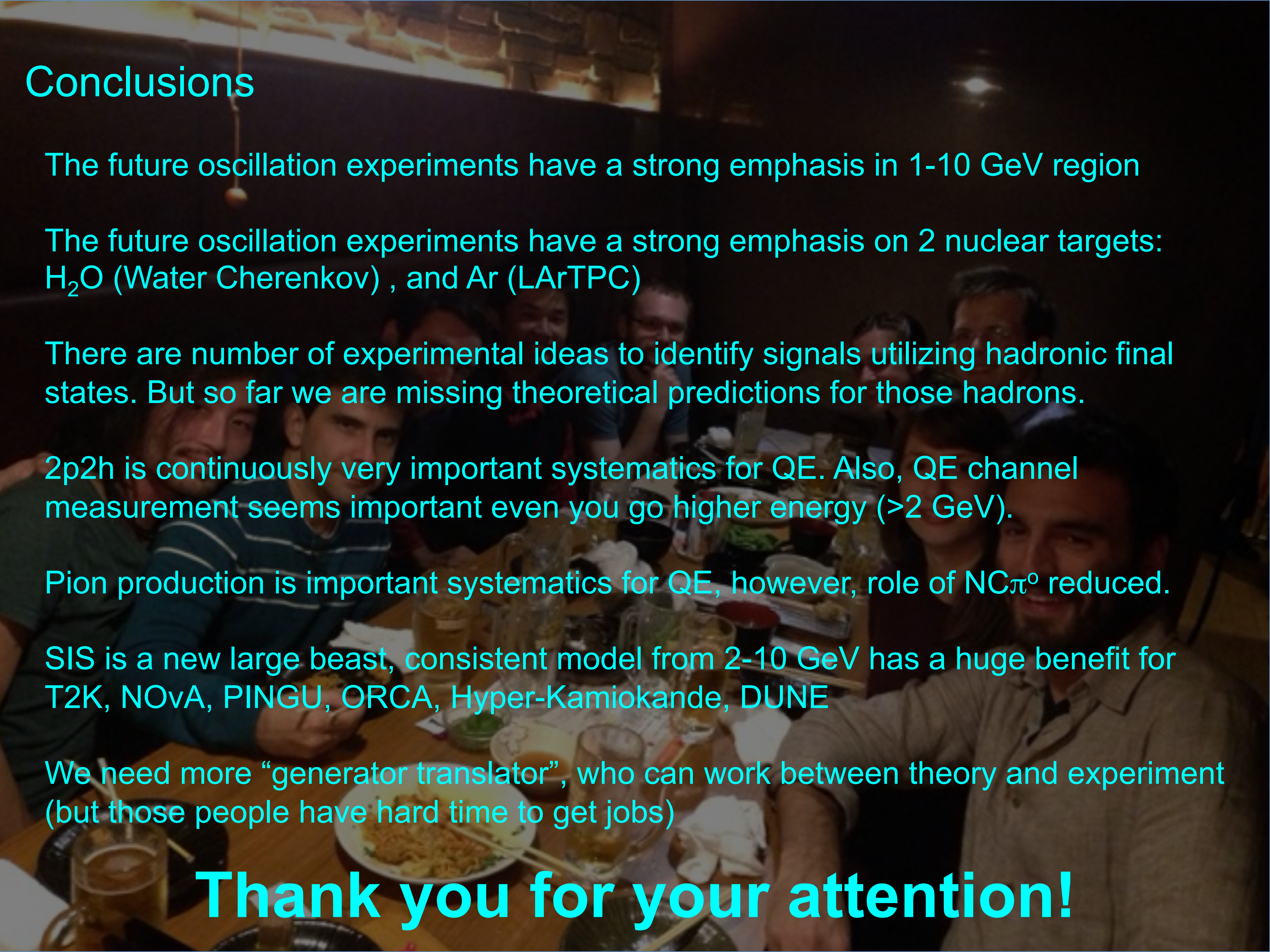


oscillation result



Conclusions

The future oscillation experiments have a strong emphasis in 1-10 GeV region

The future oscillation experiments have a strong emphasis on 2 nuclear targets: H_2O (Water Cherenkov) , and Ar (LArTPC)

There are number of experimental ideas to identify signals utilizing hadronic final states. But so far we are missing theoretical predictions for those hadrons.

2p2h is continuously very important systematics for QE. Also, QE channel measurement seems important even you go higher energy (>2 GeV).

Pion production is important systematics for QE, however, role of NCπ^o reduced.

SIS is a new large beast, consistent model from 2-10 GeV has a huge benefit for T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE

We need more “generator translator”, who can work between theory and experiment (but those people have hard time to get jobs)

Thank you for your attention!

Backup

Giunti,Kim,Lee,PRD44(1991)3635

1. Neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

$$P_{\alpha\beta}(L) \propto \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{osc}_{ij}} - \left(\frac{L}{L^{coh}_{ij}}\right)^2 - 4\pi^2 \left(\frac{\sigma_x}{L^{osc}_{ij}}\right)^2\right]$$

Coherent oscillation

Decoherence during propagation

Decoherence at production and detection

Giunti,Kim,Lee,PRD44(1991)3635

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$$\sim \sin^2 2\theta \sin^2\left(\pi \frac{L}{L^{osc}}\right)$$

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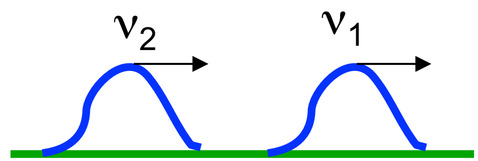
Giunti,Kim,Lee,PRD44(1991)3635

1. Neutrino oscillations



Wave packet formalism

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Coherent oscillation

Decoherence during propagation

Decoherence at production and detection

$$P \propto \left[-\left(\frac{L}{L^{coh}} \right)^2 \right] \quad , \quad L^{coh} \propto \frac{\sigma_x}{| v_i - v_j |}$$

Decoherence happens faster for narrower wave packet (small σ_x) and bigger group velocity difference difference (bigger Δm^2, lower energy)

How to estimate σ_x?

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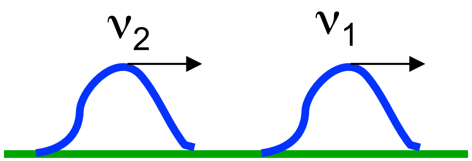
1. Neutrino oscillations



Wave packet formalism

- real formulation of neutrino oscillations

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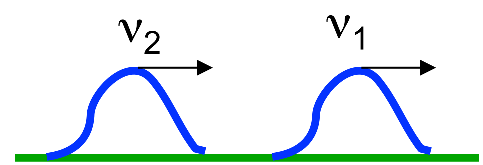
How to estimate σ_x?

e.g.) NuMI beam (from Joachim Kopp's Fermilab theory seminar)
10^{-9}cm << σ_x < 10cm (probably bigger than atomic distance, but smaller than detector resolution)

Giunti,Kim,Lee,PRD44(1991)3635

1. Neutrino oscillations



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Coherent oscillation

Decoherence during propagation

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$$P \propto \left[-\left(\frac{L}{L^{coh}}\right)^2\right] \quad , \quad L^{coh} \propto \frac{\sigma_x}{|v_i - v_j|}$$

Decoherence happens faster for narrower wave packet (small σ_x) and bigger group velocity difference difference (bigger Δm^2, lower energy)

How to estimate σ_x?

e.g.) NuMI beam (from Joachim Kopp's Fermilab theory seminar)
10^{-9}cm << σ_x < 10cm (probably bigger than atomic distance, but smaller than detector resolution) → L^{coh} > 6×10^5 light year

Giunti,Kim,Lee,PRD44(1991)3635

1. Neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

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Coherent oscillation

Decoherence during propagation

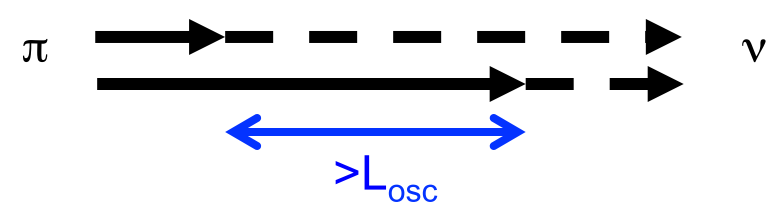
Decoherence at production and detection

$$P \propto \exp\left[-4\pi^2 \left(\frac{\sigma_x}{L^{osc}}\right)^2\right]$$

If the production uncertainty is bigger than oscillation length, oscillation doesn't happen (time averaged oscillation)

neutrino production uncertainty

cf. solar neutrino



1. Neutrino oscillations

Wave packet formalism

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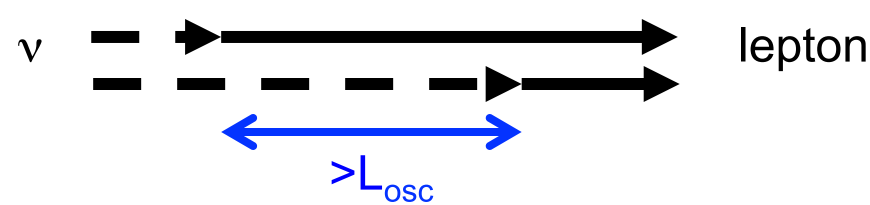
Coherent oscillation
Decoherence during propagation
Decoherence at production and detection

$$P \propto \exp\left[-4\pi^2 \left(\frac{\sigma_x}{L^{osc}}\right)^2\right]$$

If the detection uncertainty is bigger than oscillation length, oscillation doesn't happen (time averaged oscillation)

neutrino detection uncertainty



1. Neutrino oscillations

Wave packet formalism

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$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} U_{\beta j} \exp\Bigg[-2\pi i \frac{L}{L^{\rm osc}_{jk}} - \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} - 2\pi^2\xi^2 \left(\frac{\sigma_x}{L^{\rm osc}_{jk}}\right)^2 - \frac{(m_j^2 + m_k^2)^2}{32\sigma_m^2 E^2}\Bigg],$$

Beuthe,Phys.Rept.375(2003)105

Five terms:

- Oscillation ($L^{\rm osc}_{jk} = 4\pi E/\Delta m^2_{jk}$)
- Decoherence during propagation
- Decoherence at production/detection
- Localization: Typically requires size of neutrino wave packet σ_x smaller than oscillation length (ξ = process-dependent parameter, can also be ~ 0)
- Approximate conservation of average energies/momenta

1. Neutrino oscillations

Neutrino oscillation is a natural interferometer

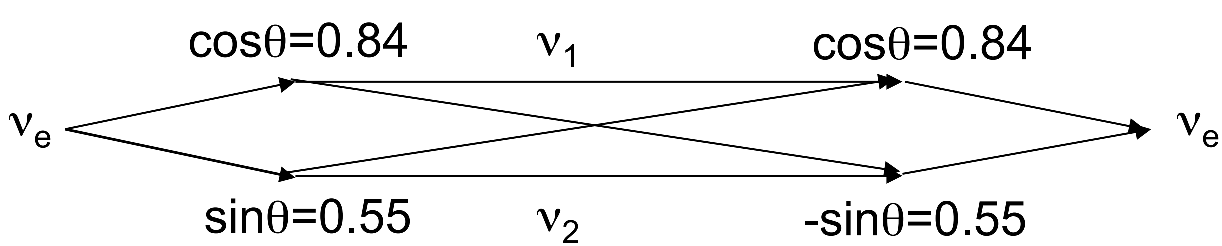
Formal description of neutrino oscillation is not easy, just because quantum mechanics is not easy

Wolfenstein,PRD17(1978)2369
Mikheyev and Smirnov,Sov.J.Ncl.Phys,42(1986)913

3.1 Neutrino oscillation in matter

3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

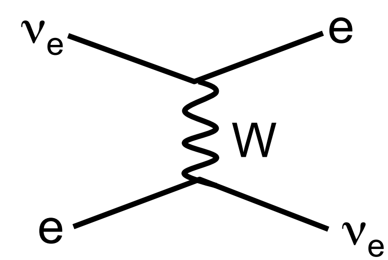
$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$



$$P=|A_1+A_2|^2$$

Wolfenstein,PRD17(1978)2369
Mikheyev and Smirnov,Sov.J.Ncl.Phys,42(1986)913

3.1 Neutrino oscillation in matter



3 major discoveries
- Solar neutrino problem
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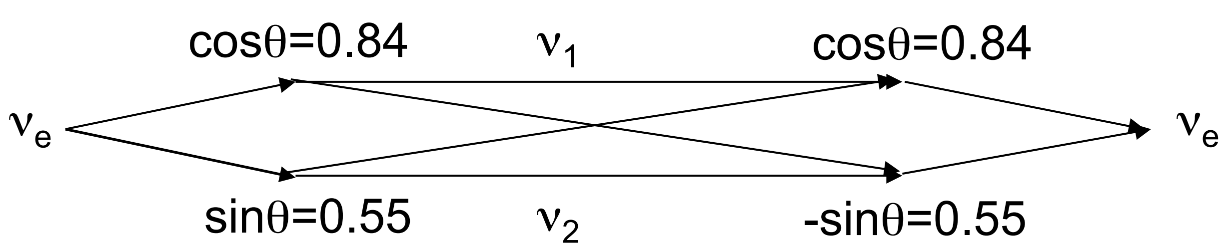
Wolfenstein term

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m^2_{ee}}{2E} + \sqrt{2}G_F n_e & \frac{m^2_{e\mu}}{2E} \\ \frac{m^2_{e\mu}}{2E} & \frac{m^2_{\mu\mu}}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta_m & -\sin\theta_m \\ \sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \frac{(m^2_1)'}{2E} & 0 \\ 0 & \frac{(m^2_2)'}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix}$$

No matter effect If density and/or energy is too low



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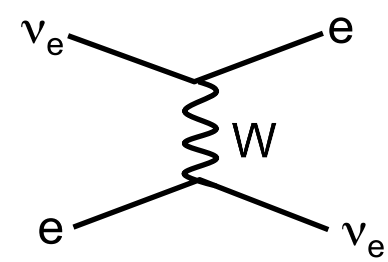

3 major discoveries
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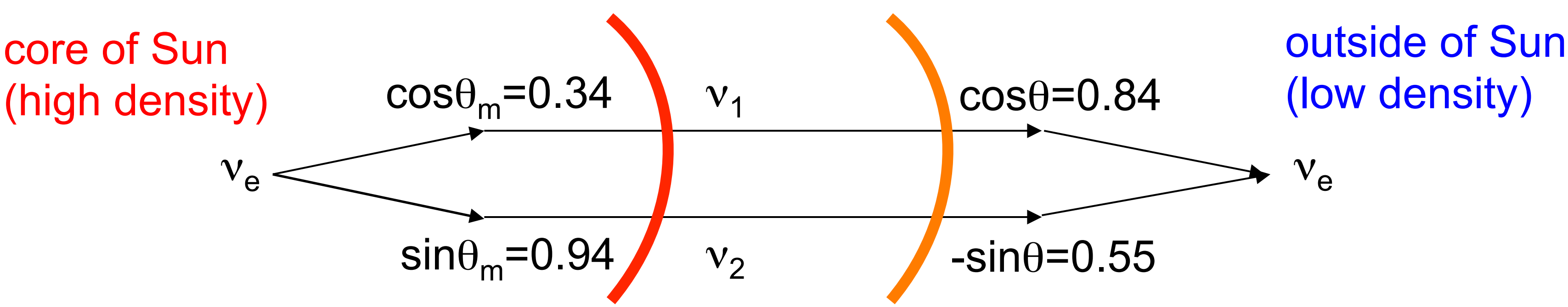
No matter effect If density and/or energy is too low
- the Sun happens to have right density n_e~150 cm^{-3} and E(^{8}B-ν)~10 MeV



$$P=|A_1|^2+|A_2|^2 = \cos^2\theta_m\cdot\cos^2\theta+\sin^2\theta_m\cdot\sin^2\theta < \cos^4\theta+\sin^4\theta$$

~0.35 (MSW) ~0.6 (no MSW)

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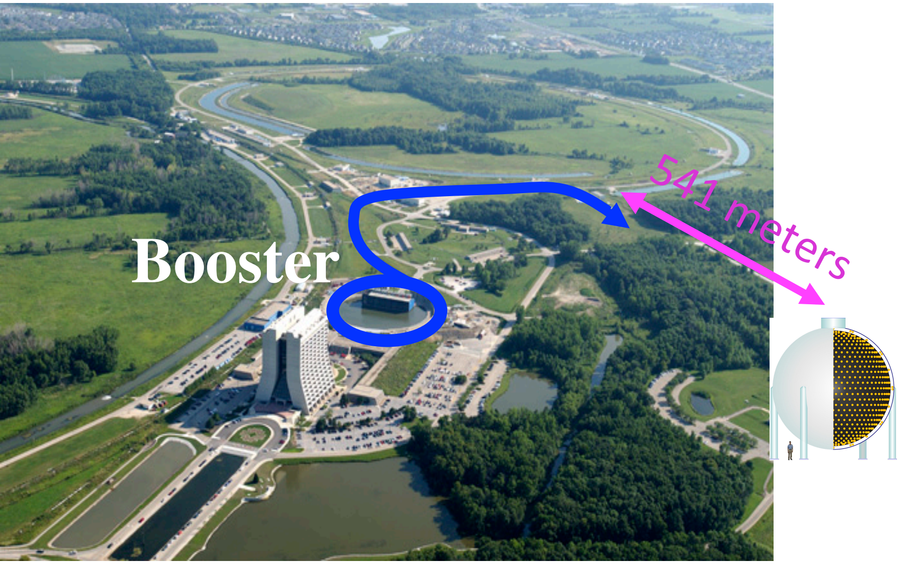
2. Events in the Detector



The MiniBooNE Detector

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

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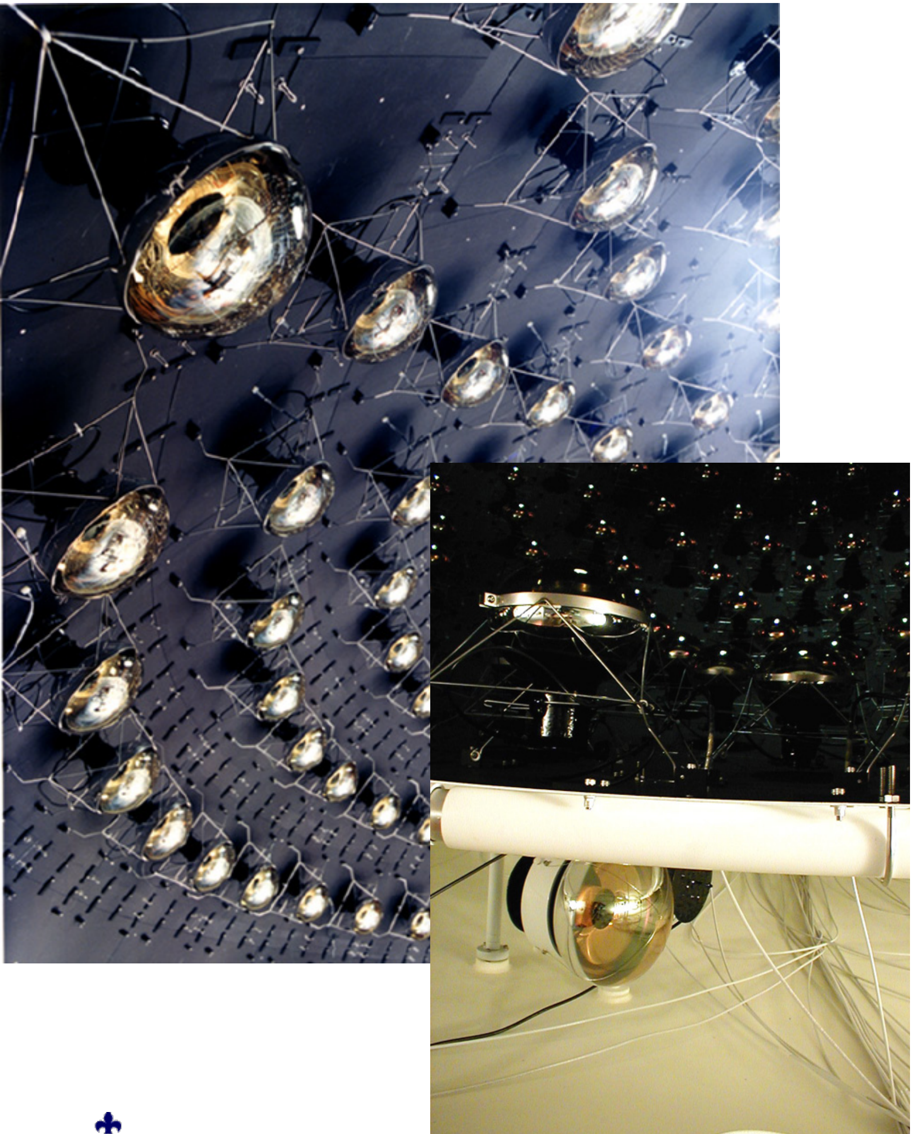
- 240 veto phototubes

2. Events in the Detector



The MiniBooNE Detector

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

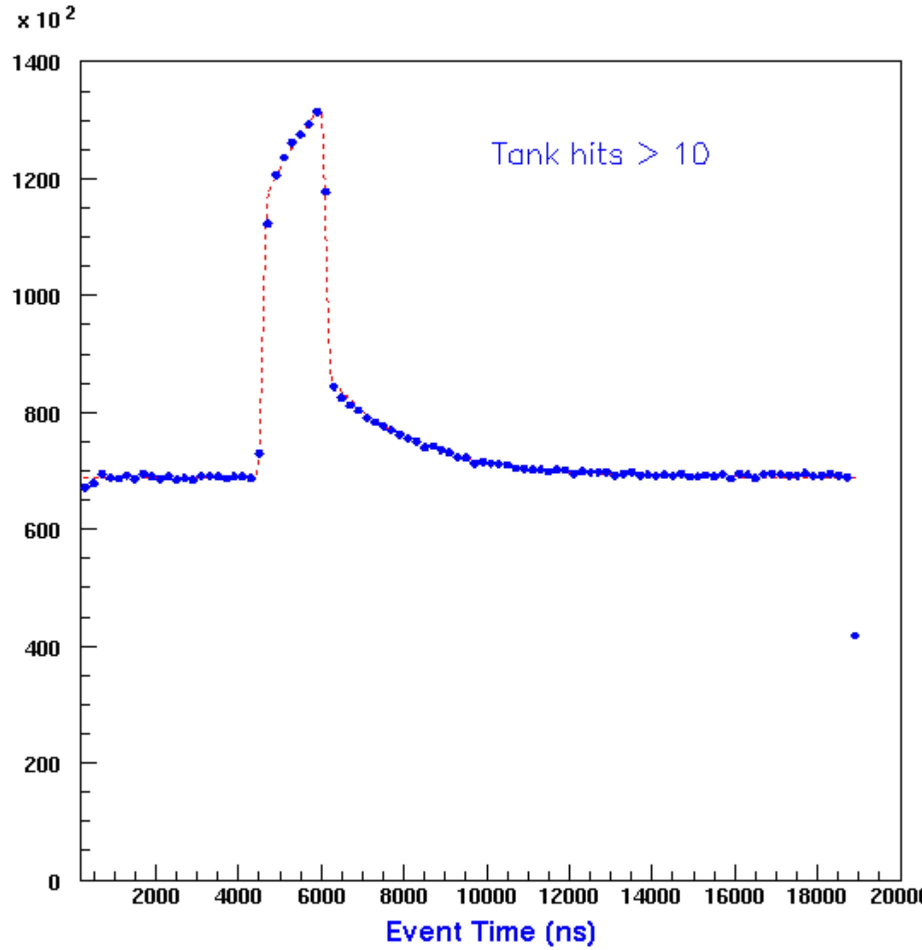
2. Events in the Detector

Times of hit-clusters (subevents)

Beam spill (1.6ms) is clearly evident

- simple cuts eliminate cosmic backgrounds

Beam and Cosmic BG



Neutrino Candidate Cuts

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

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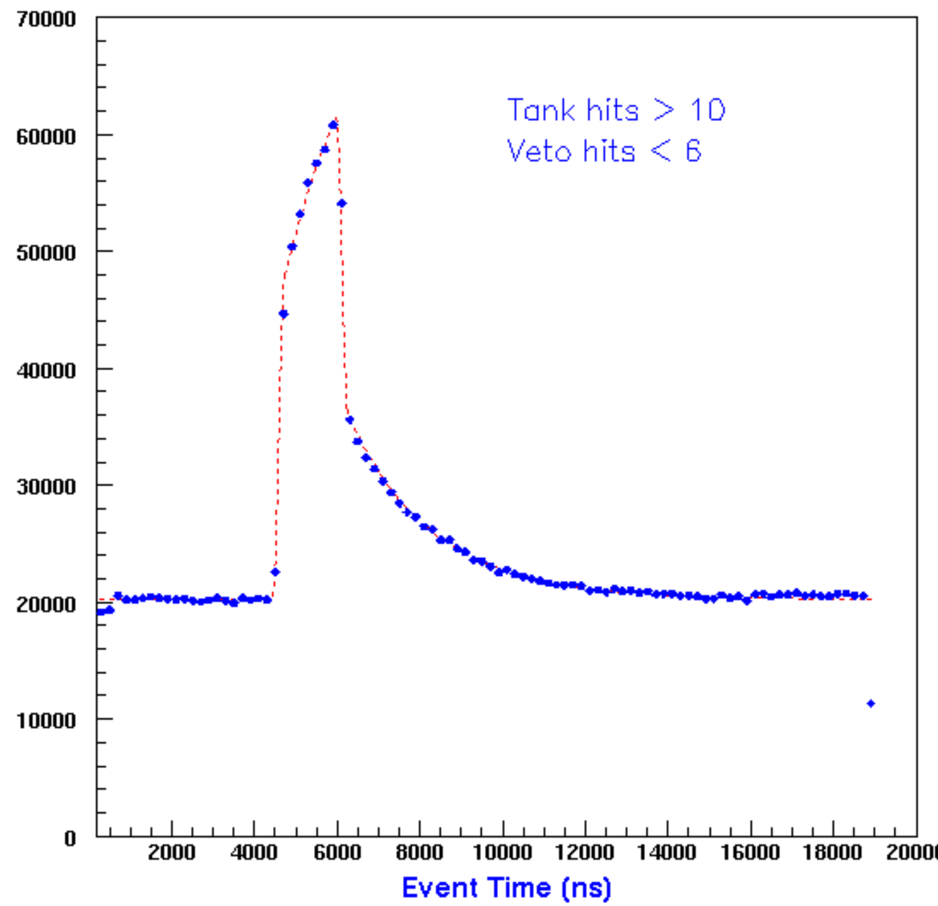

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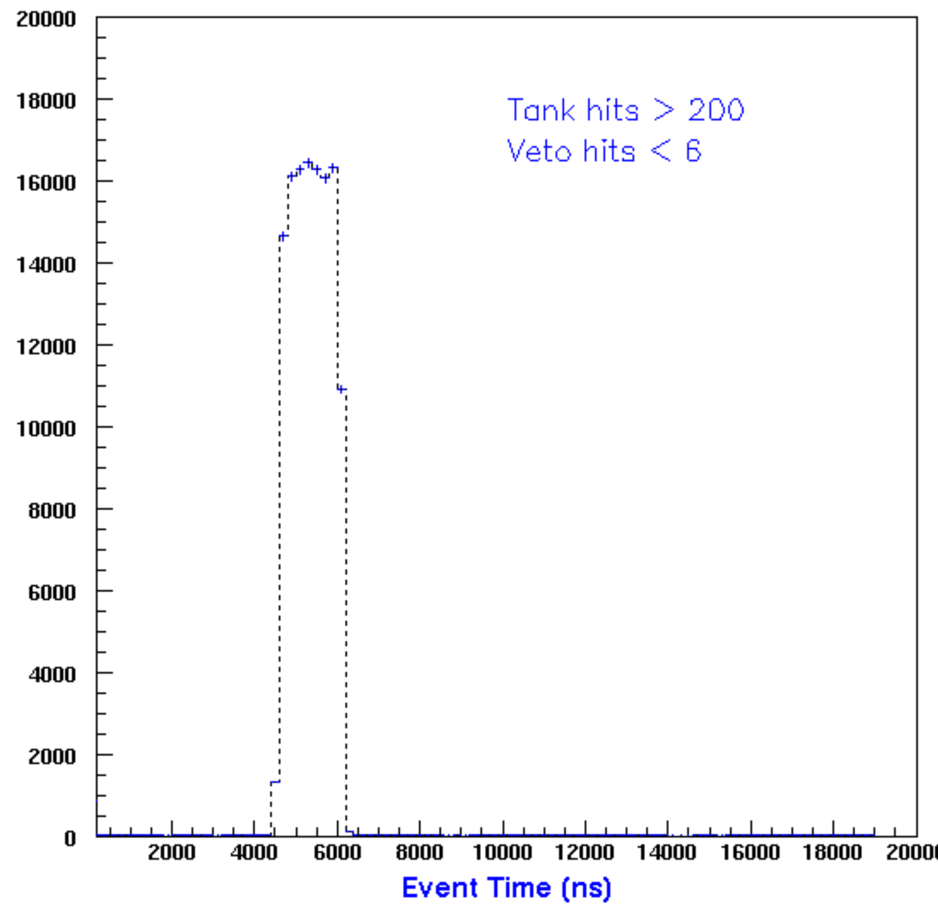
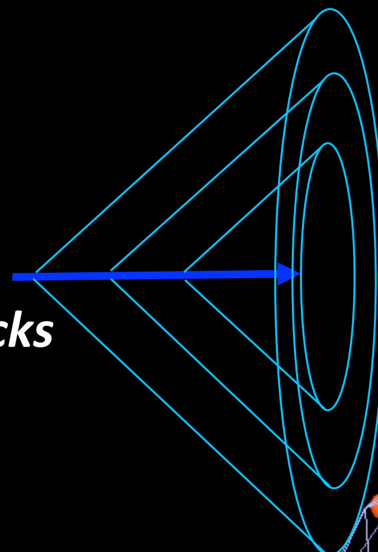
Beam Only

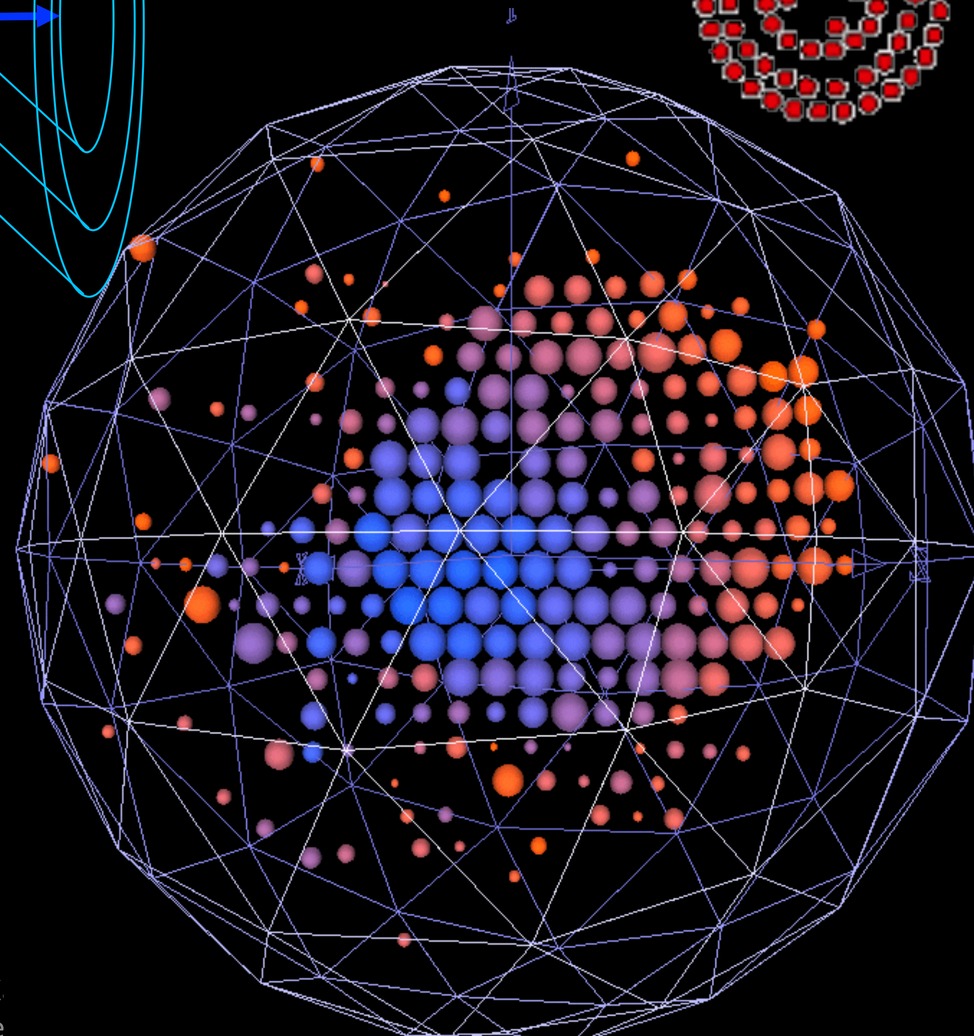


MiniBooNE,NIM.A599(2009)28

2. Events in the Detector

- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons





MiniBooNE,NIM.A599(2009)28

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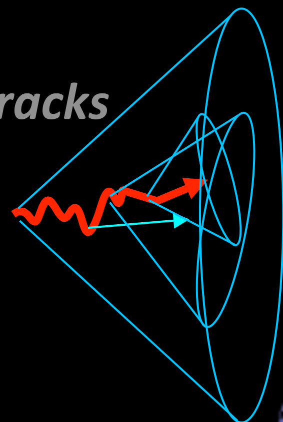

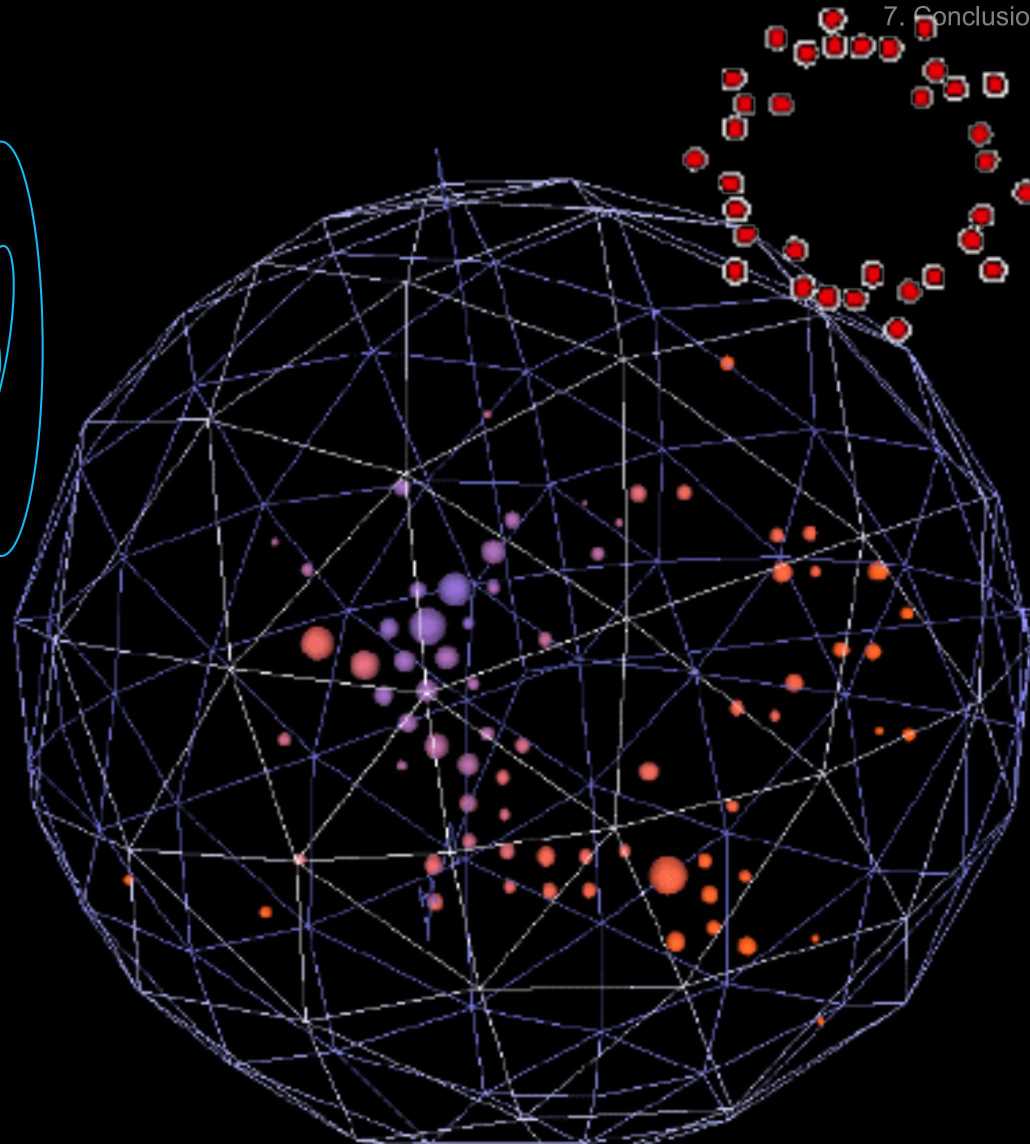

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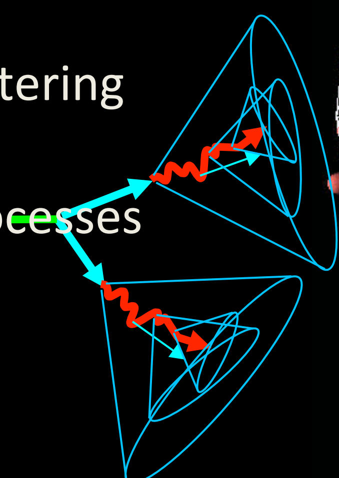
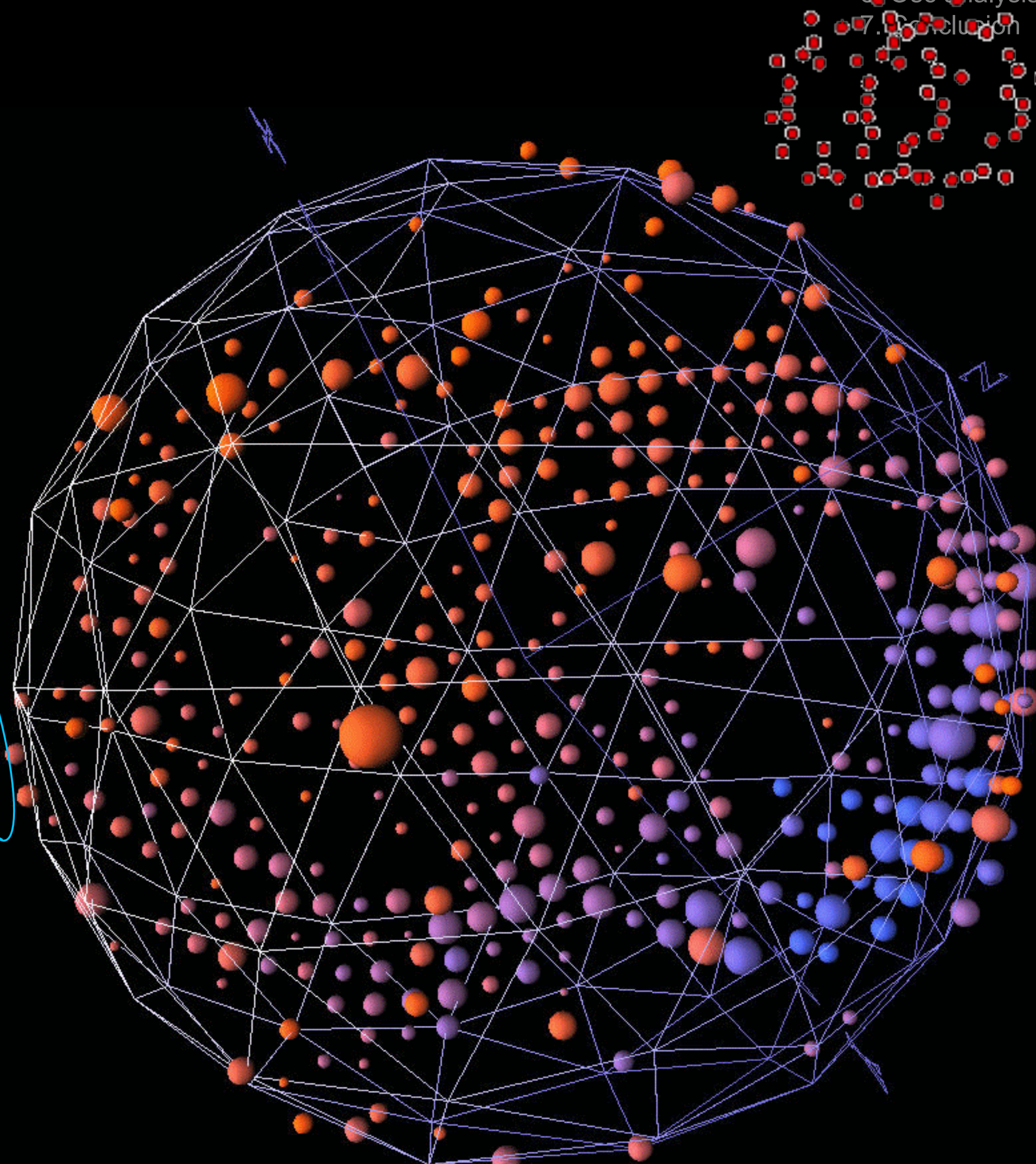


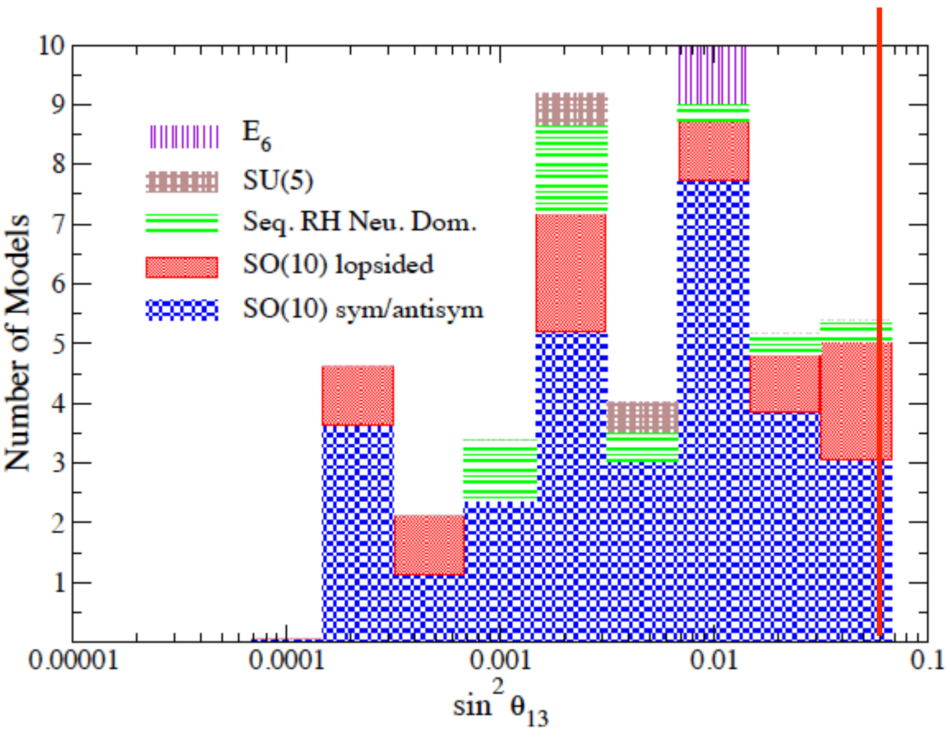


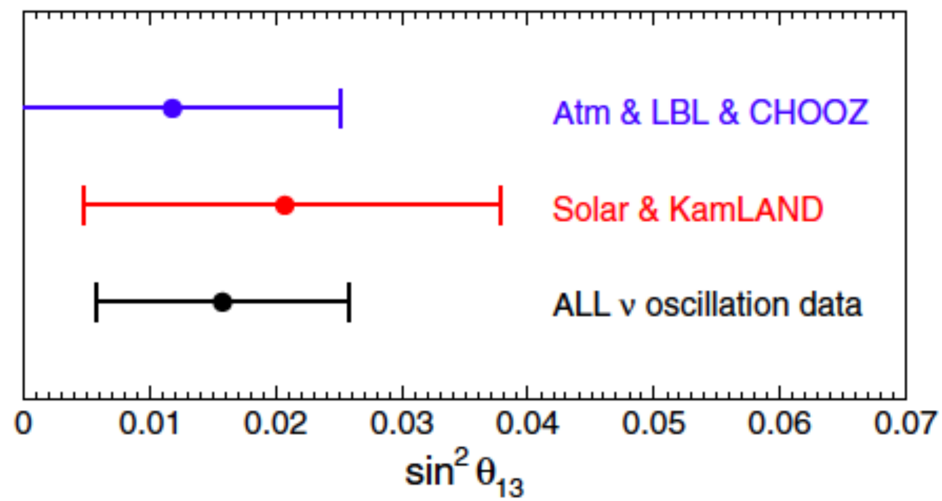
Albright, ArXiv:0905.0146
Fogli et al,PRL101(2008)141801

6. Boom of θ_{13}

T2K, Double Chooz, Daya Bay, Reno
- θ_{13} was truly unknown parameter
- there was a "hint" from Solar-KamLAND tension

Limit of θ_{13} (2009)





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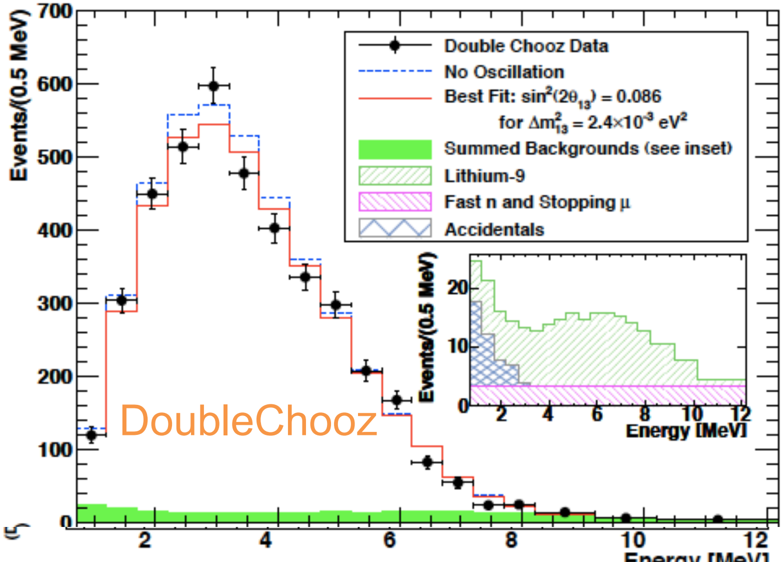
  - anti-ν_e reactor disappearance

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)$$



DoubleChooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,PRL108(2012)191802

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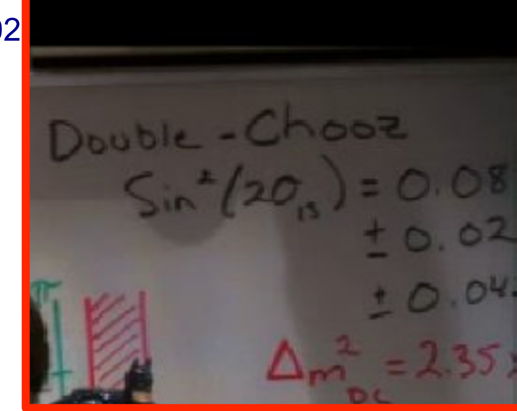

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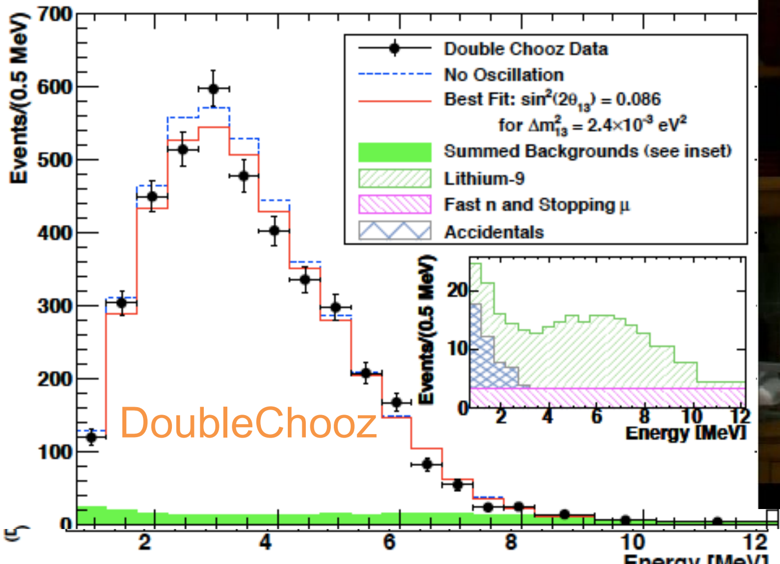

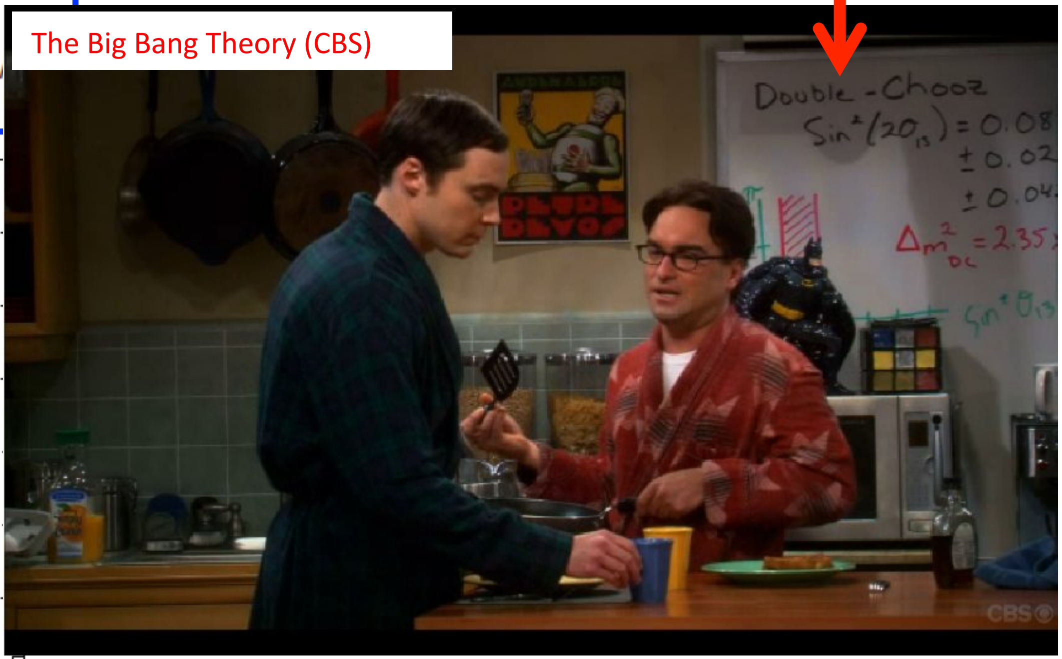

DoubleChooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,PRL108(2012)191802
Daya Bay, PRL112(2014)061801

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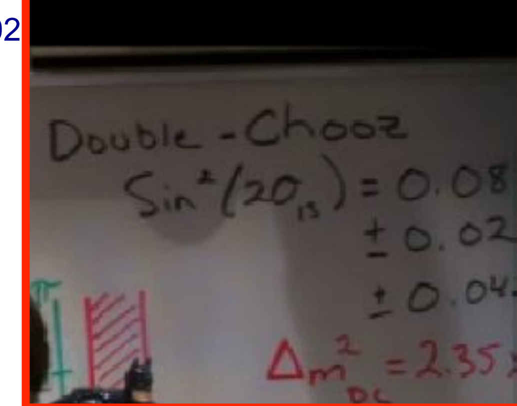

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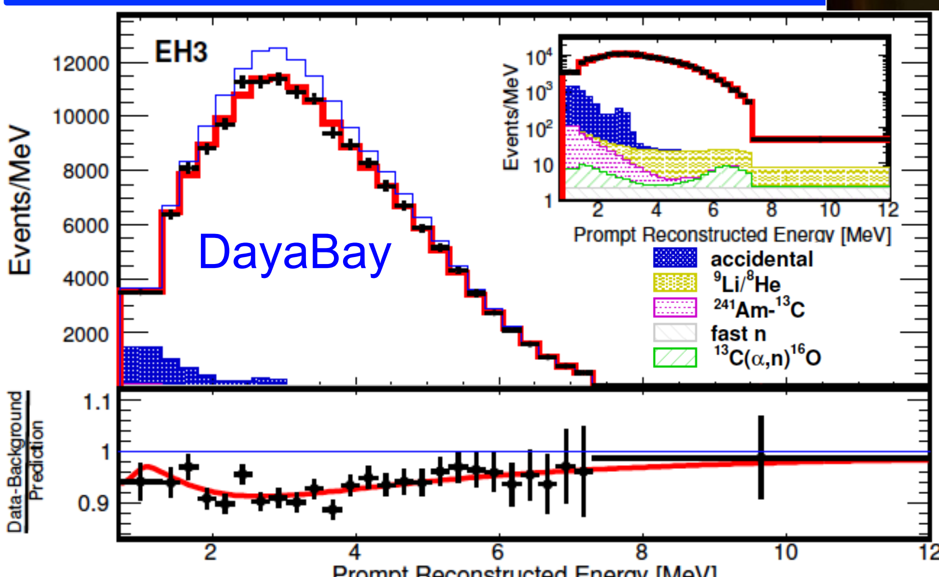

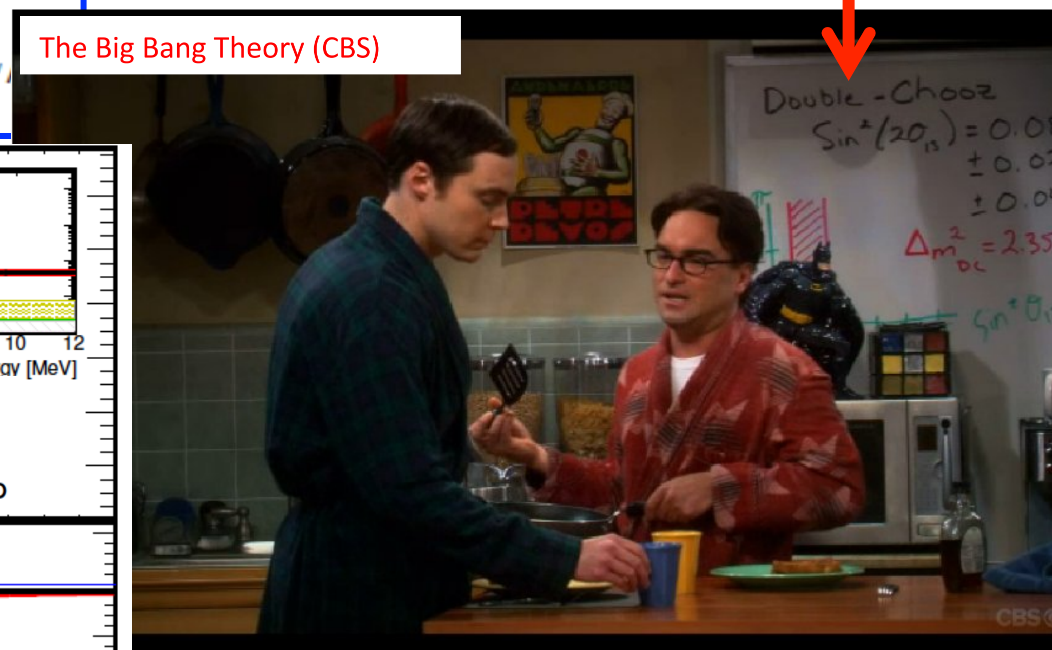

DoubleChooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,PRL108(2012)191802
Daya Bay, PRL112(2014)061801, T2K, PRL112(2014)061802

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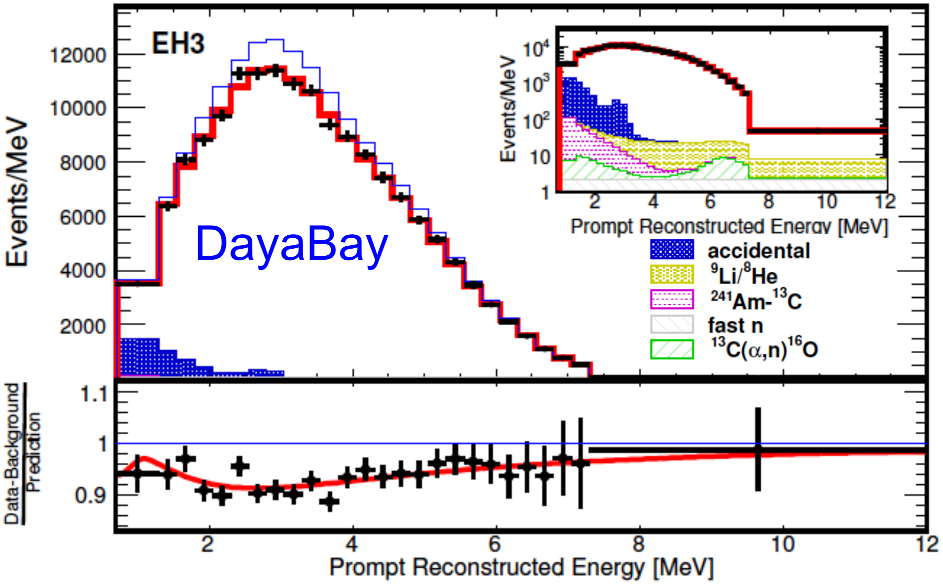
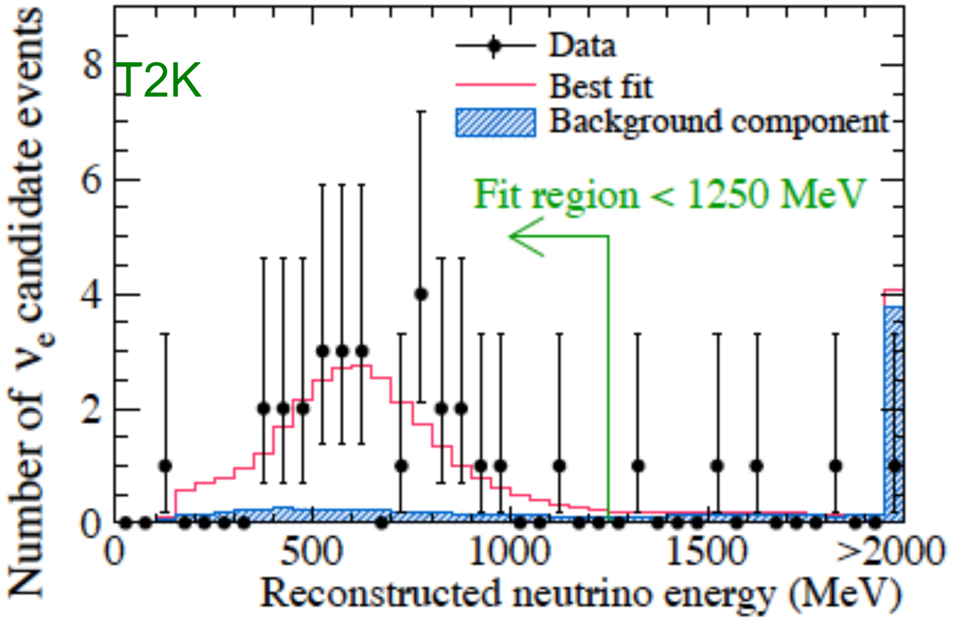
- there was a "hint" from Solar-KamLAND tension
- Mother Nature was kind again!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation
- nonzero θ_{13} → leptonic CP violation

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)$$

$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$





6. three neutrino oscillation

T2K, Double Chooz, Daya Bay, Reno
- θ_{13} was truly unknown parameter
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- Mother Nature was kind again!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation
- nonzero θ_{13} → leptonic CP violation

It is no longer adequate to use 2 neutrino oscillation model, it must be 3 neutrinos

$$P(\nu_\mu \to \nu_e) = |\, U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} \,|^2$$
$$= |2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21}|^2$$
$$\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E}$$

where $\sqrt{P_{atm}} = 2|U_{\mu 3}||U_{e3}| \sin\Delta_{31} = \sin\theta_{23} \sin 2\theta_{13} \sin\Delta_{31}$

and $\sqrt{P_{sol}} \approx \cos\theta_{23} \sin 2\theta_{12} \sin\Delta_{21}$.

6. Current issues

Unknown parameters of νSM

δ_{CP}: Dirac CP phase

θ_{23}: θ_{23}=40^o and 50^o are same how $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$

MH: mass hierarchy, normal hierarchy $m_1<m_2<m_3$ or inverted hierarchy $m_3<m_1<m_2$

Long baseline neutrino oscillations

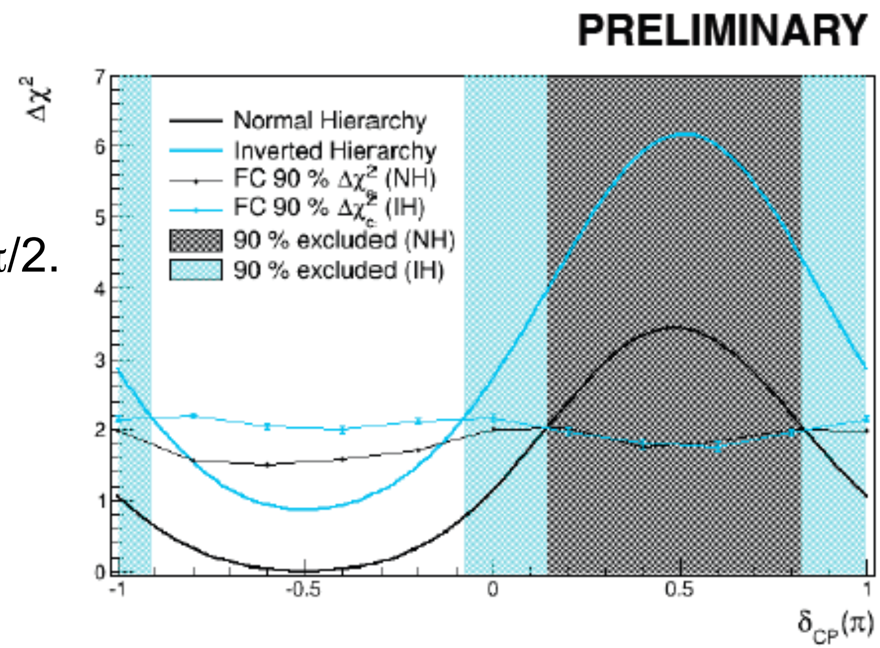
- T2K (running)
- NOvA (running)
- PINGU/ORCA (planned)
- JUNO/RENO50 (planned)
- INO (planned)
- DUNE (planned)
- Hyper-K (planned)

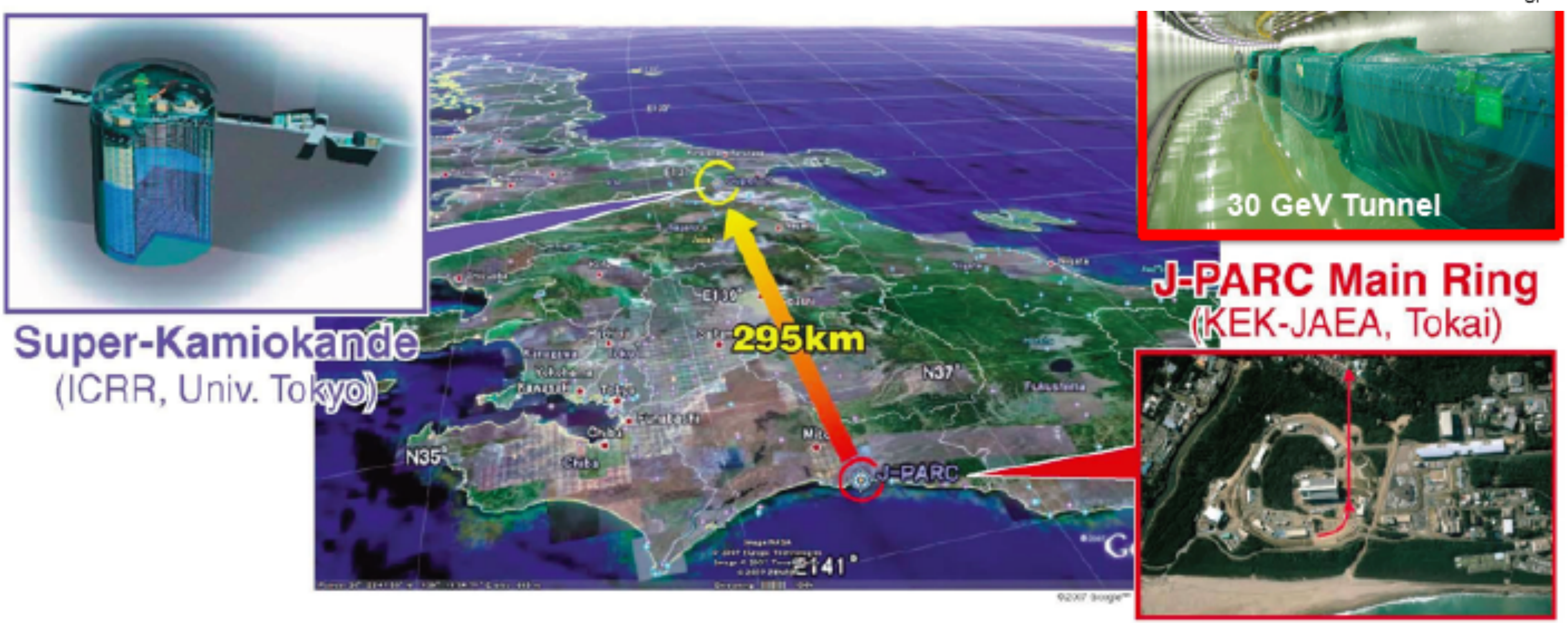
6. T2K

δ_{CP} limit Joint ν_μ+ν_e fit

- data prefer normal hierarchy with δ_{CP}~ $-\pi/2$.

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$



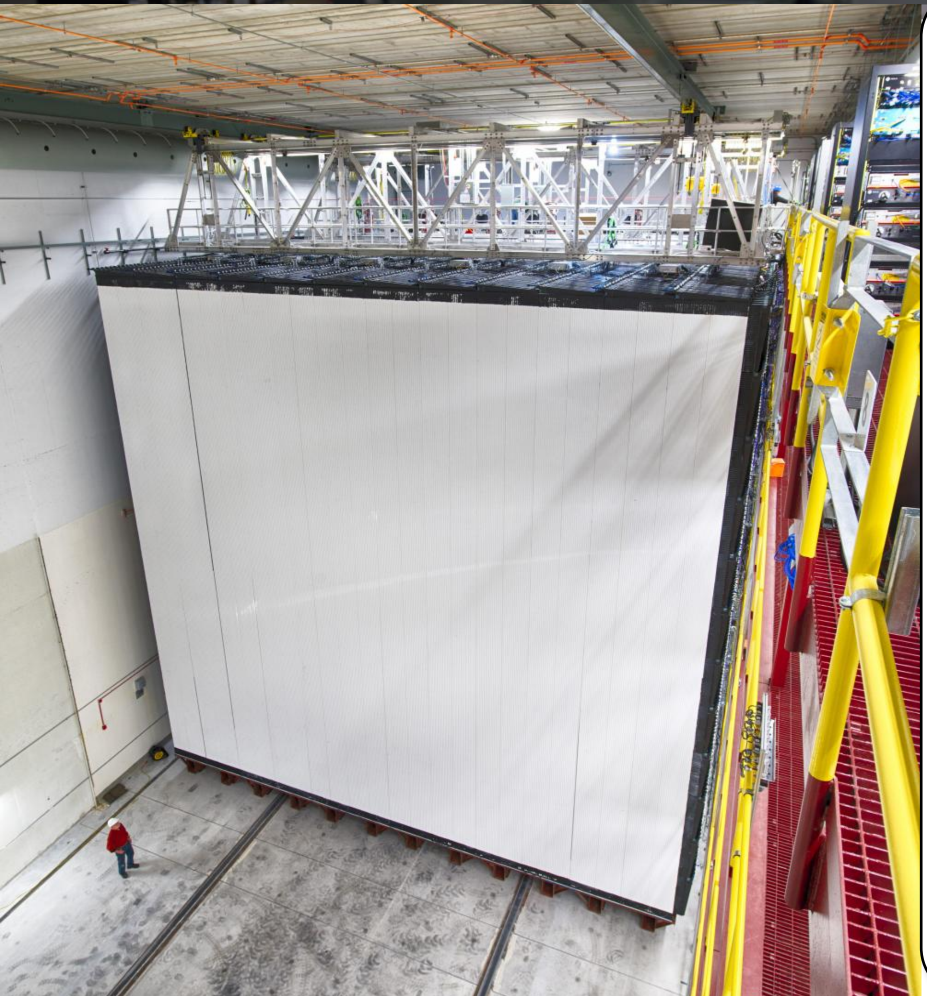


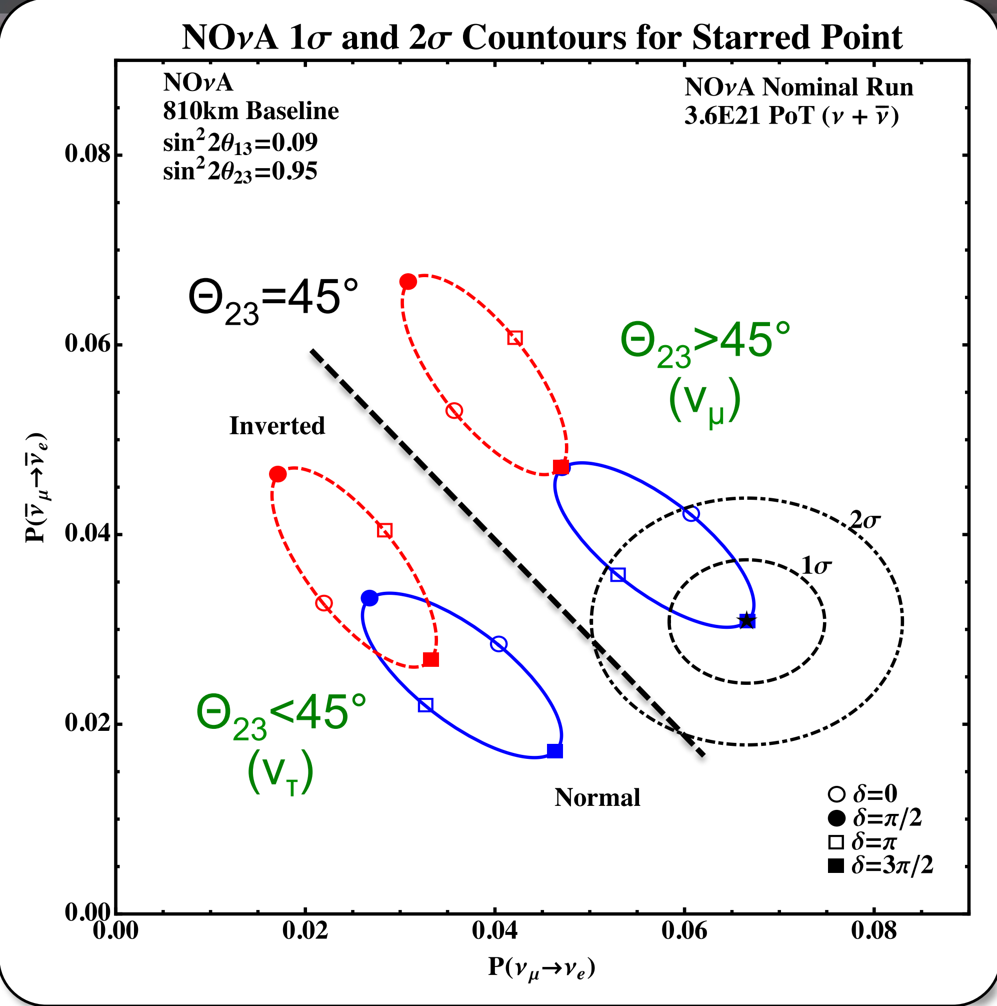
6. NOvA

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

Massive plastic tubes with liquid scintillator

- 14 kton total, 810 km from Fermilab (E~2GeV)
- NOvA has a chance to solve degeneracy and find all (δ_{CP}, θ_{23}, MH)





Grant (PINGU), Neutrino2014

6. PINGU/ORCA

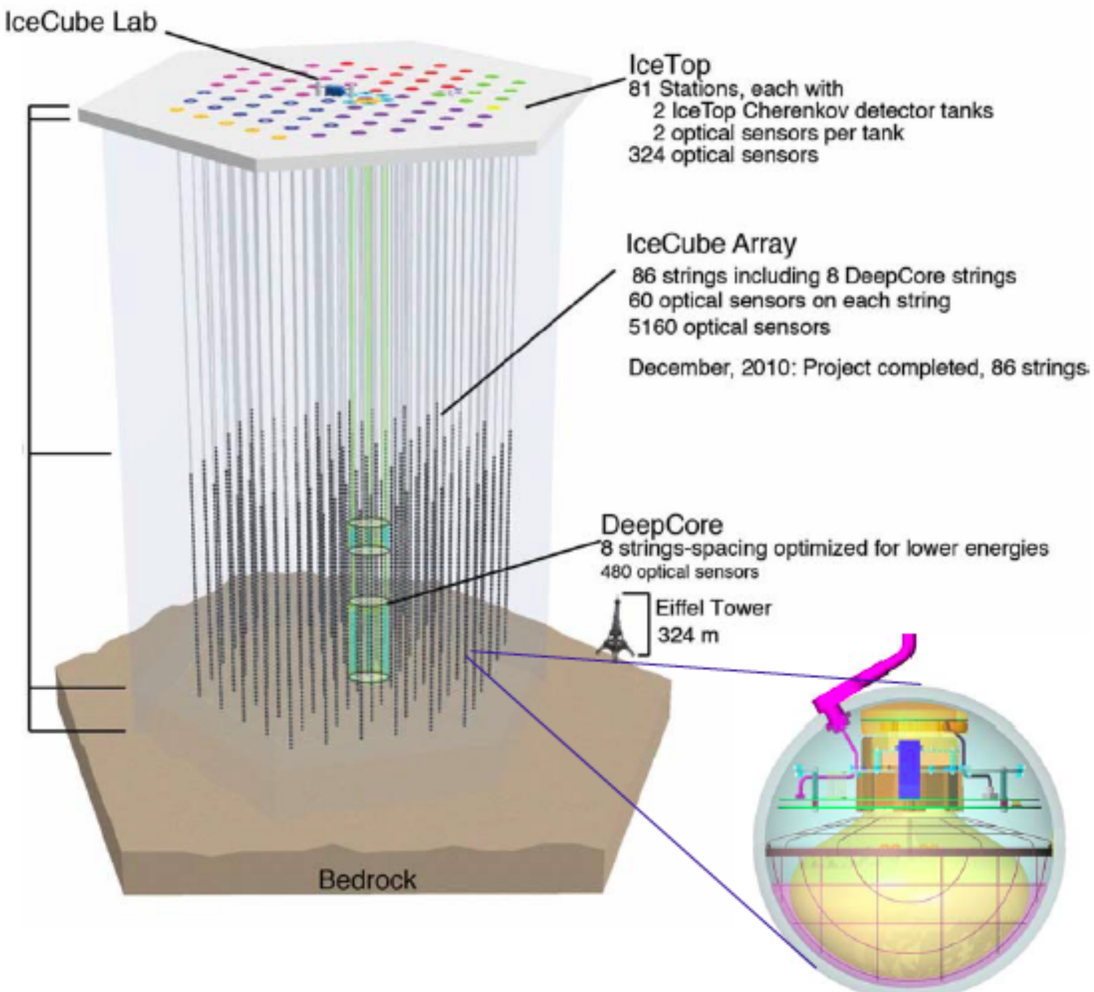
effective 2-ν matter oscillation

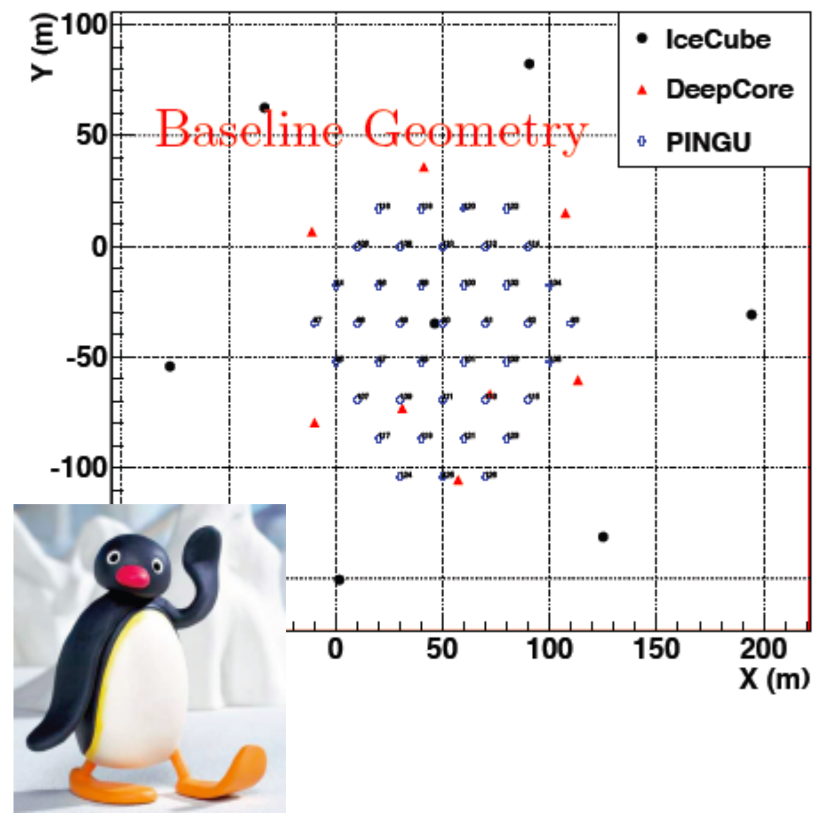
interference of propagation states

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23} - s_{23}^4 P_A + \frac{1}{2}\sin^2 2\theta_{23}\sqrt{1 - P_A}\cos\phi_X$$

More strings in IceCube/KM3NeT

- They know how to do it (no R&D), also they know how to estimate cost
- more strings in central area → reduce threshold down to ~few GeV
- It can find mass hierarchy in few years from ν_μ disappearance

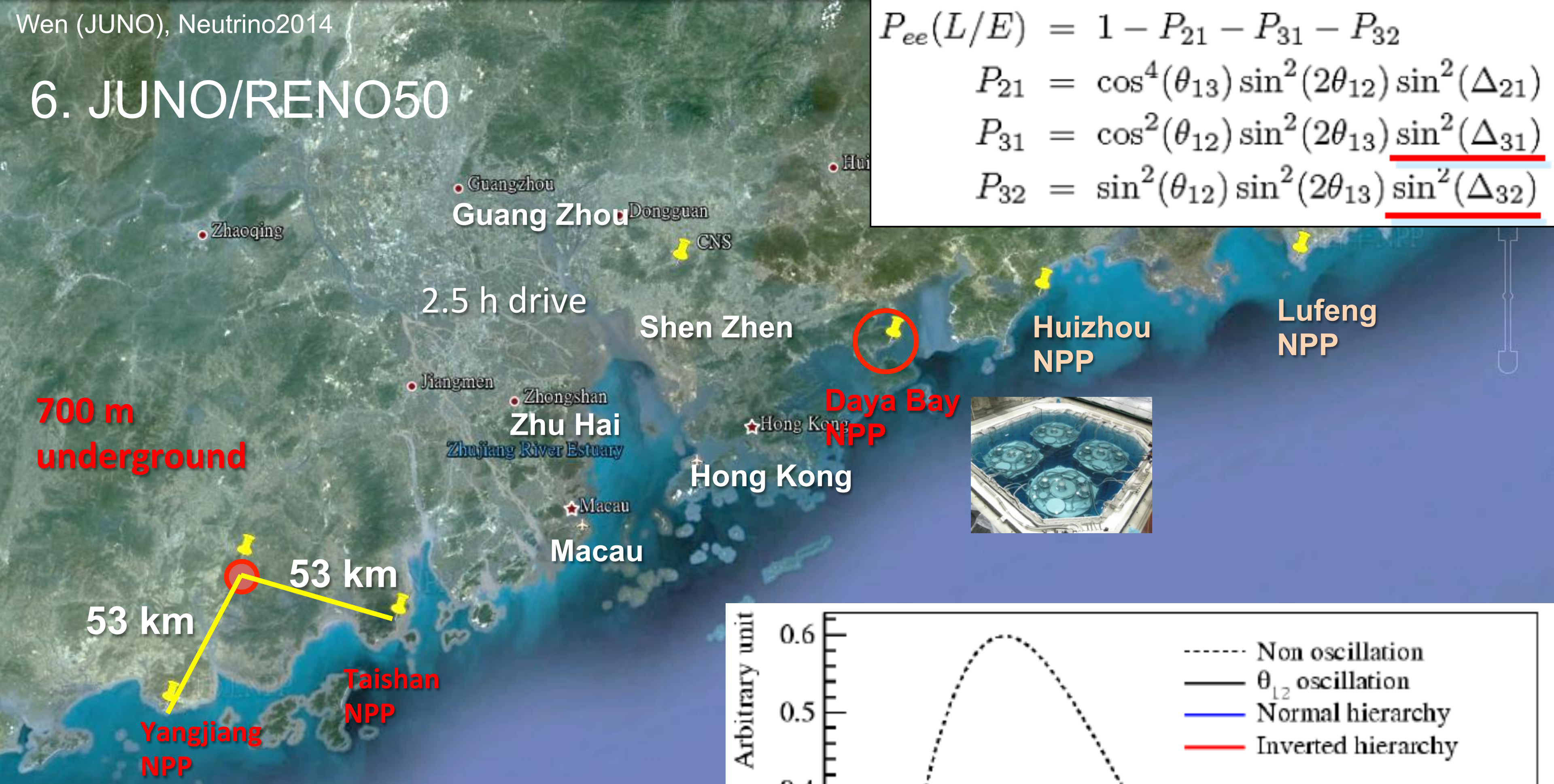




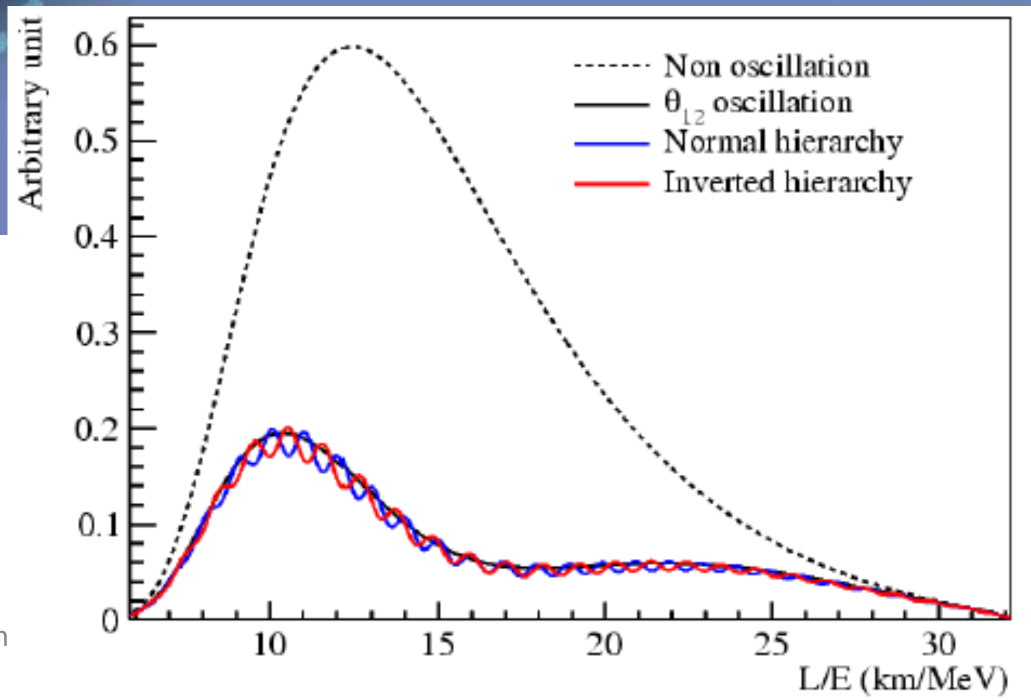
Wen (JUNO), Neutrino2014

6. JUNO/RENO50

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\underline{\sin^2(\Delta_{31})} \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\underline{\sin^2(\Delta_{32})}
\end{aligned}
$$



Significant sensitivity improvement is required, It can find mass hierarchy in few years

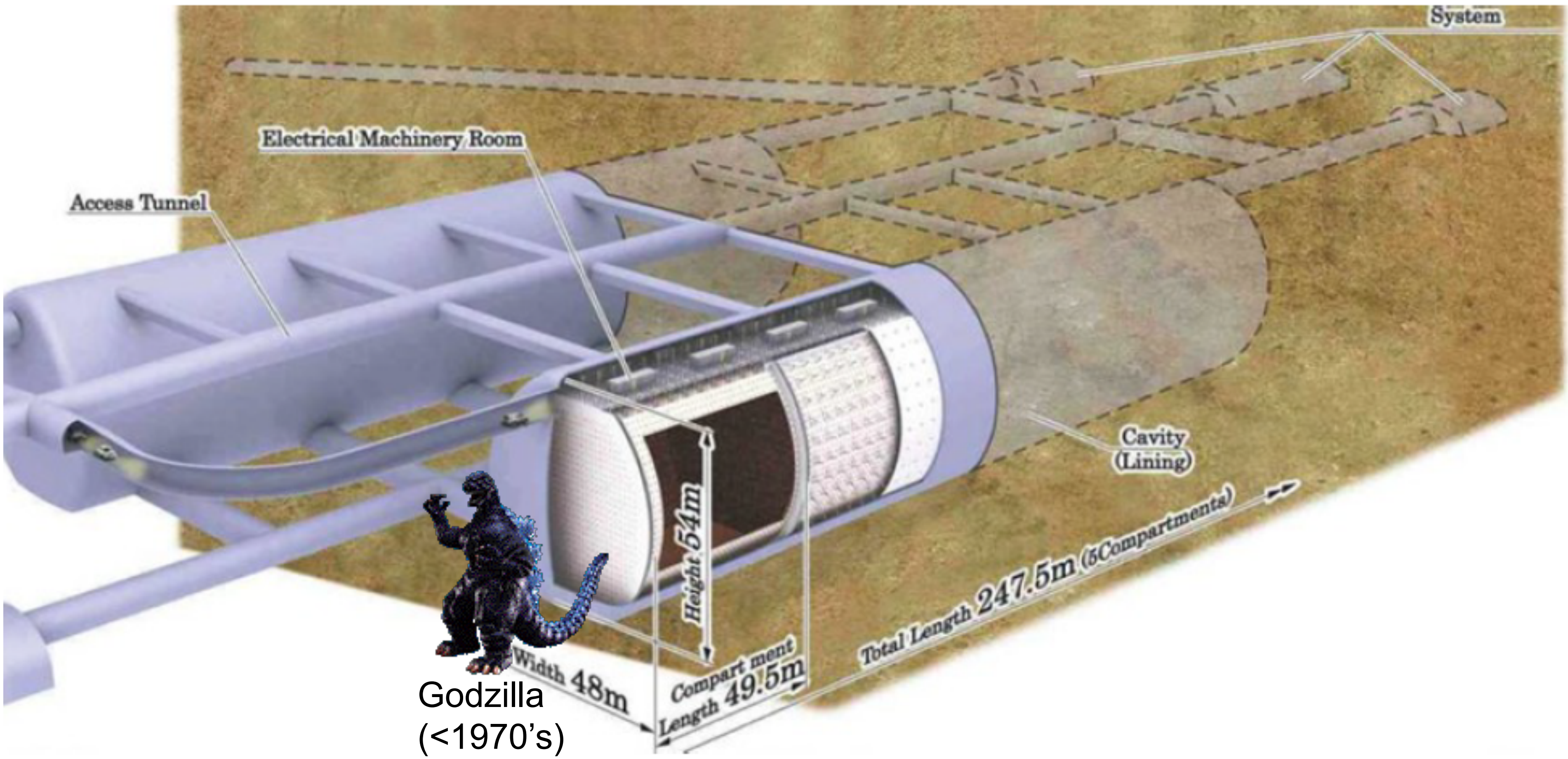


Queen Mary
University of London

6. Hyper-Kamiokande

Hyper-Kamiokande with upgraded J-PARC beam

- 560 kton water Cherenkov x 2 (each tank can contain more than 10 Godzillas!)
- Known technology
- δ_{CP} from ν_e appearance, θ_{23} from ν_μ disappearance, MH from atmospheric ν
- All kind of other physics (p-decay, solar/atmospheric/supernova neutrinos, etc)



6. DUNE

New beamline and new detector

- 34 kton Liquid argon time projection chamber
- New beamline to South Dakota
- “Reformation” is recommended in P5 report