Theoretical review on systematic uncertainties for CP violation searches

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NNN'15

Stony Brook University, Oct 29th, 2015

Outline

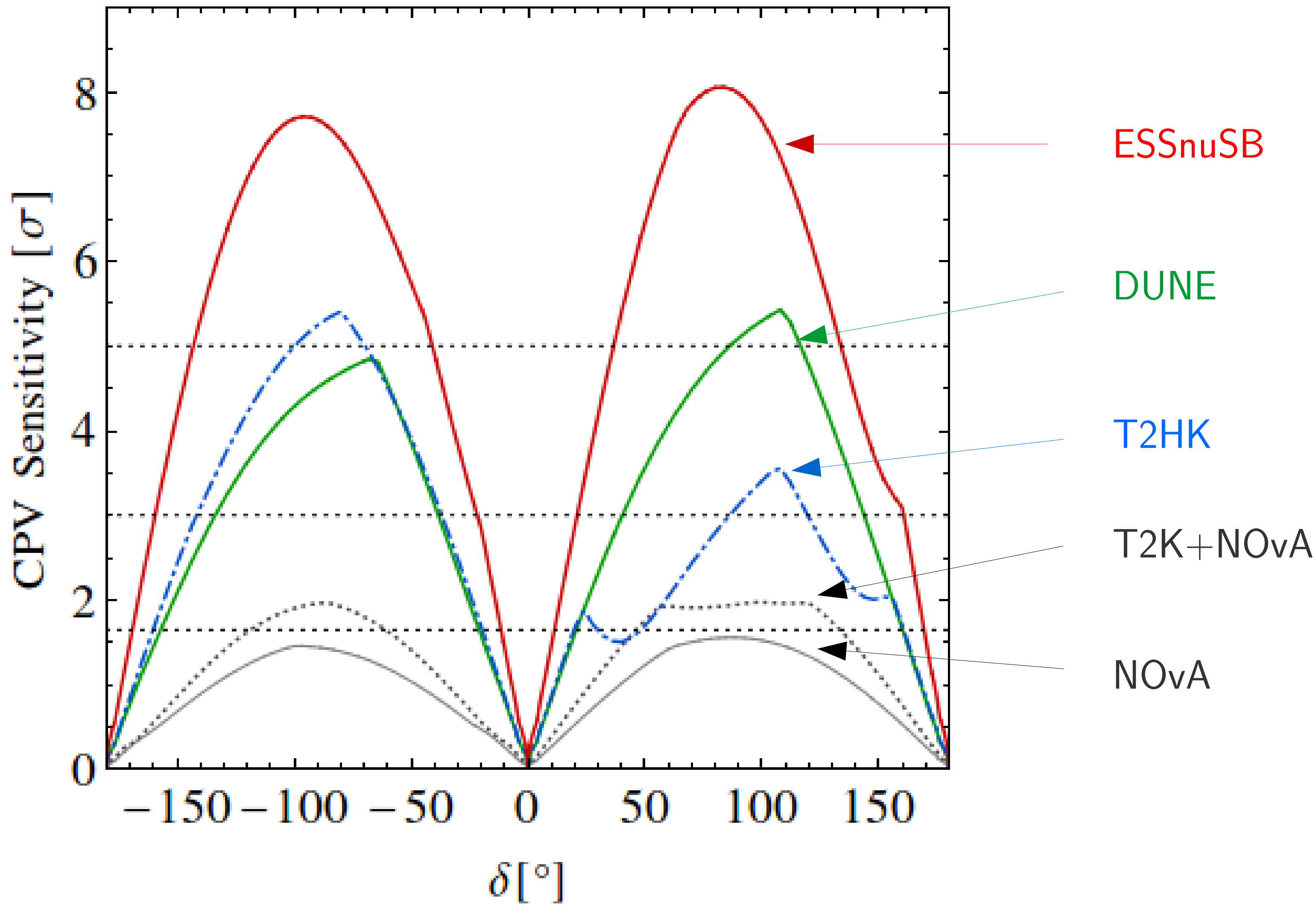
1) Introduction

2) Normalization uncertainties

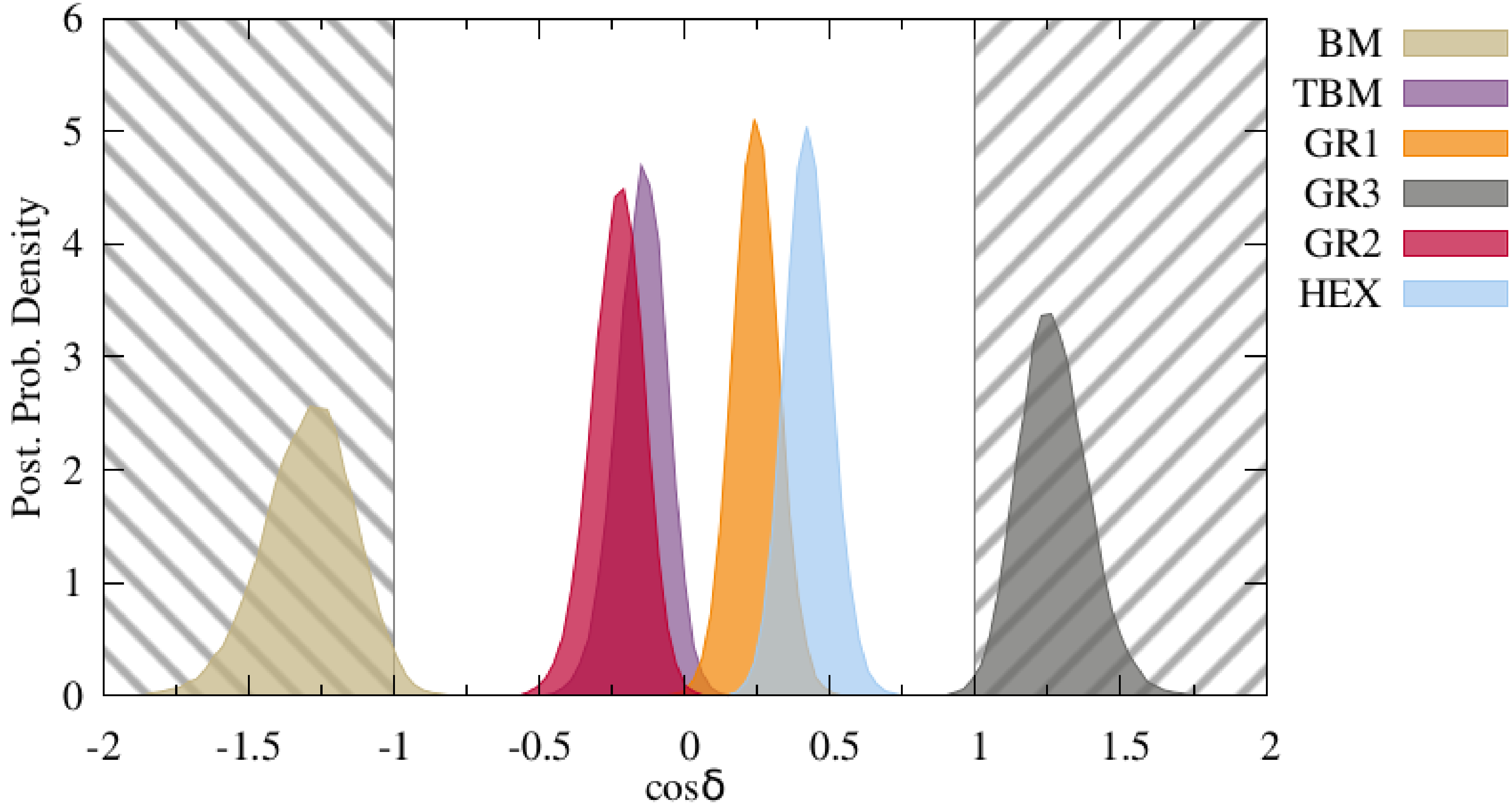
3) Shape uncertainties

4) Summary

Proposed experiments for CPV searches



Why precision?



Ballett, King, Luhn, Pascoli, Schmidt, 1410.7573 [hep-ph]
(see also, e.g., Girardi et al, 1410.8056, Meloni, 1308.4578)

(See talks in the UD2 afternoon session today)

CP violation measurements

The golden channel in neutrino oscillations is:

$$P^{\pm}_{e\mu} \equiv P(\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_\mu}) = \overbrace{s^2_{23}\, \sin^2 2\theta_{13}\, \sin^2\left(\frac{\Delta_{31}\, L}{2}\right)}^{\text{atmospheric}} + \overbrace{c^2_{23}\, \sin^2 2\theta_{12}\, \sin^2\left(\frac{\Delta_{21}\, L}{2}\right)}^{\text{solar}}$$

$$\underbrace{+\ \tilde{J} \cos\left(\pm\delta - \frac{\Delta_{31}\, L}{2}\right) \sin\left(\frac{\Delta_{21}\, L}{2}\right) \sin\left(\frac{\Delta_{31}\, L}{2}\right)}_{\text{CP - violating interference}}\,,$$

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

Cervera et al., hep-ph/0002108

CP violation measurements

$$P^{\pm}_{e\mu} \equiv P(\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_\mu}) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{31} L}{2}\right) + c^2_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{21} L}{2}\right)$$

$$\boxed{+ \tilde{J} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right) \sin\left(\frac{\Delta_{21} L}{2}\right) \sin\left(\frac{\Delta_{31} L}{2}\right),}$$

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

Different for neutrinos and antineutrinos

Narrow band beams exploit this

CP violation measurements

$$P^{\pm}_{e\mu} \equiv P(\overset{(-)}{\nu_e} \rightarrow \overset{(-)}{\nu_\mu}) \; = \; s^2_{23}\, \sin^2 2\theta_{13}\, \sin^2\left(\frac{\Delta_{31}\, L}{2}\right) + c^2_{23}\, \sin^2 2\theta_{12}\, \sin^2\left(\frac{\Delta_{21}\, L}{2}\right)$$

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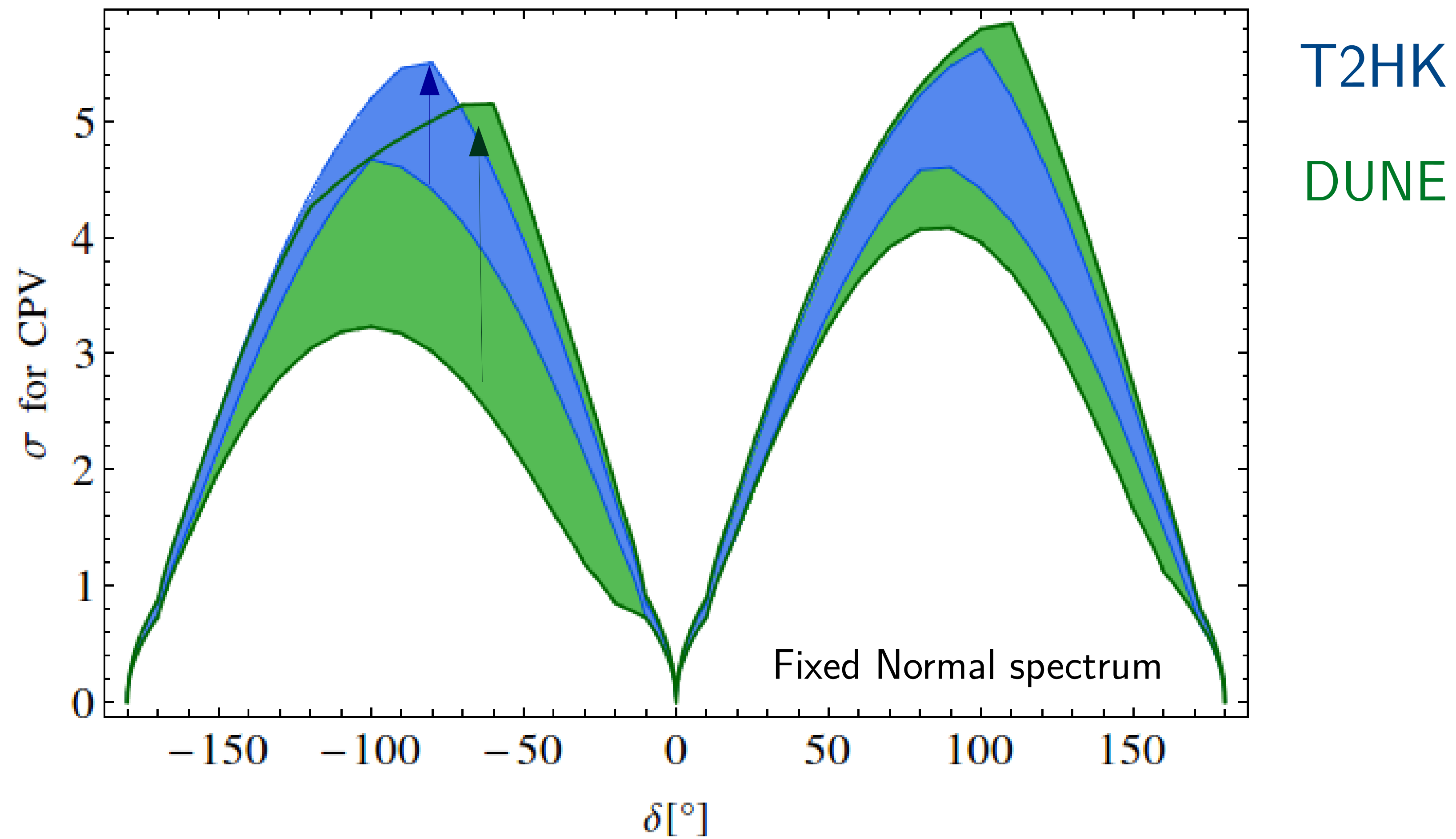
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}$$

For neutrinos, there is non-trivial energy dependence too

Wide band beams exploit this

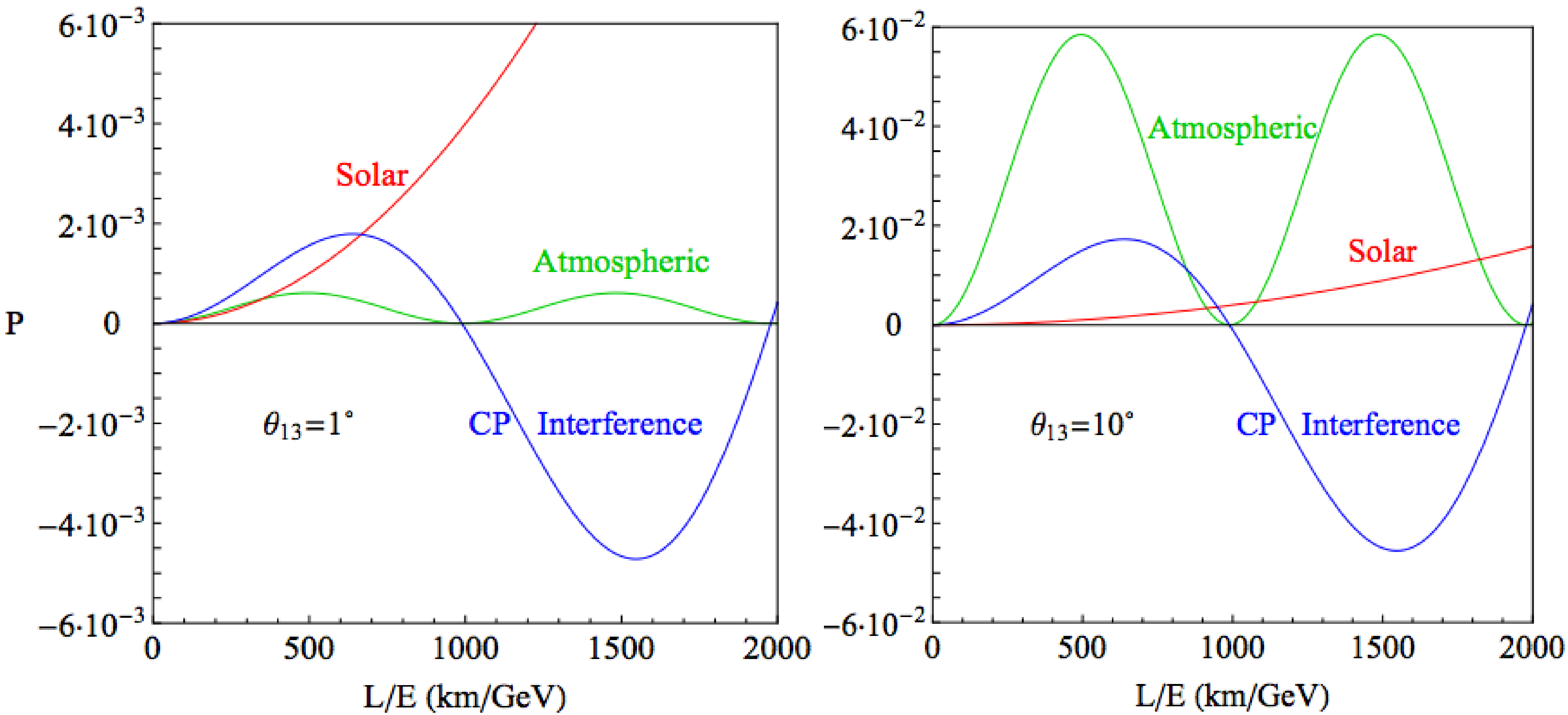
CP violation measurements

An example of relative importance of energy resolution:



Normalization uncertainties

Impact of systematics on CPV



Coloma and Fernandez-Martinez, 1110.4583 [hep-ph]

See also Marciano, hep-ph/0108181, Hagiwara et al, hep-ph/0607255 and Meregaglia, Rubbia, 0801.4035

Near/Far cancellation?

$$n_{\alpha\rightarrow\beta}(L,E) \sim \frac{1}{L^2}\epsilon_\beta(E) \times \sigma_\beta(E) \times \phi_\alpha(E) \times P_{\alpha\beta}(L,E)$$

Near/Far cancellation?

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At reactor experiments, the cancellation of systematics between near/far detectors is very effective:

$$\frac{n_{ee}^{FD}}{n_{ee}^{ND}} \sim \frac{L_{ND}^2}{L_{FD}^2}\cancel{\frac{\epsilon_e\sigma_e\phi_e}{\epsilon_e\sigma_e\phi_e}}P_{ee}$$

Near/Far cancellation?

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At Daya Bay this works extremely well!

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

(Seminar given by Xin Qian at Fermilab, on Oct 15)

Near/Far cancellation?

- For CP violation searches, we need an appearance experiment
- An ideal near detector can be used to predict some backgrounds:

$$n_{\nu_e}^{FD,bg} \sim n_{\nu_e}^{ND,bg} \frac{L_{ND}^2}{L_{FD}^2} \frac{V_{FD}}{V_{ND}}$$

Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Near/Far cancellation?

- For CP violation searches, we need an appearance experiment
- An ideal near detector can be used to predict some backgrounds:

$$n_{\nu_e}^{FD,bg} \sim n_{\nu_e}^{ND,bg} \frac{L_{ND}^2}{L_{FD}^2} \frac{V_{FD}}{V_{ND}}$$

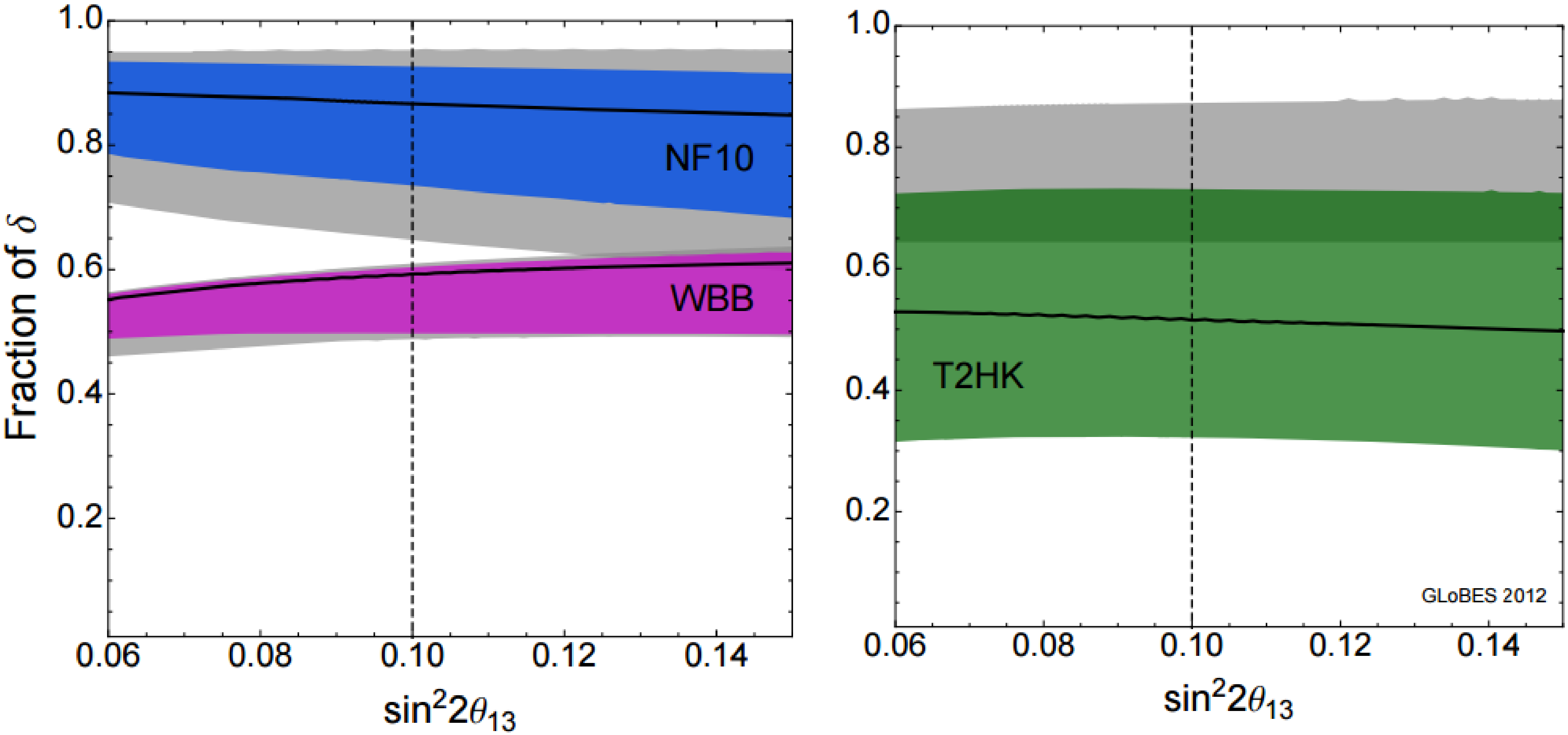
- However, a similar extrapolation for the signal will not work that well:

$$n_{\nu_e}^{FD,sig} \sim n_{\nu_\mu}^{ND,sig} \frac{L_{ND}^2}{L_{FD}^2} \frac{V_{FD}}{V_{ND}} \frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \times P(\nu_\mu \rightarrow \nu_e)$$

Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Impact of normalization uncertainties



Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]
(See also Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph])

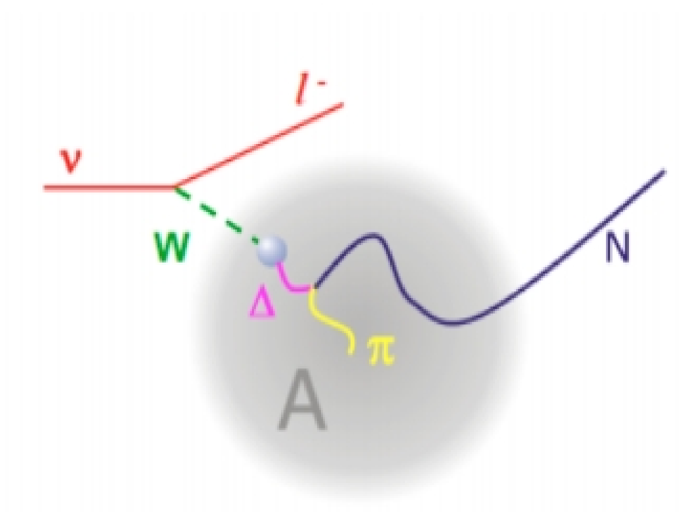
Possible ways out

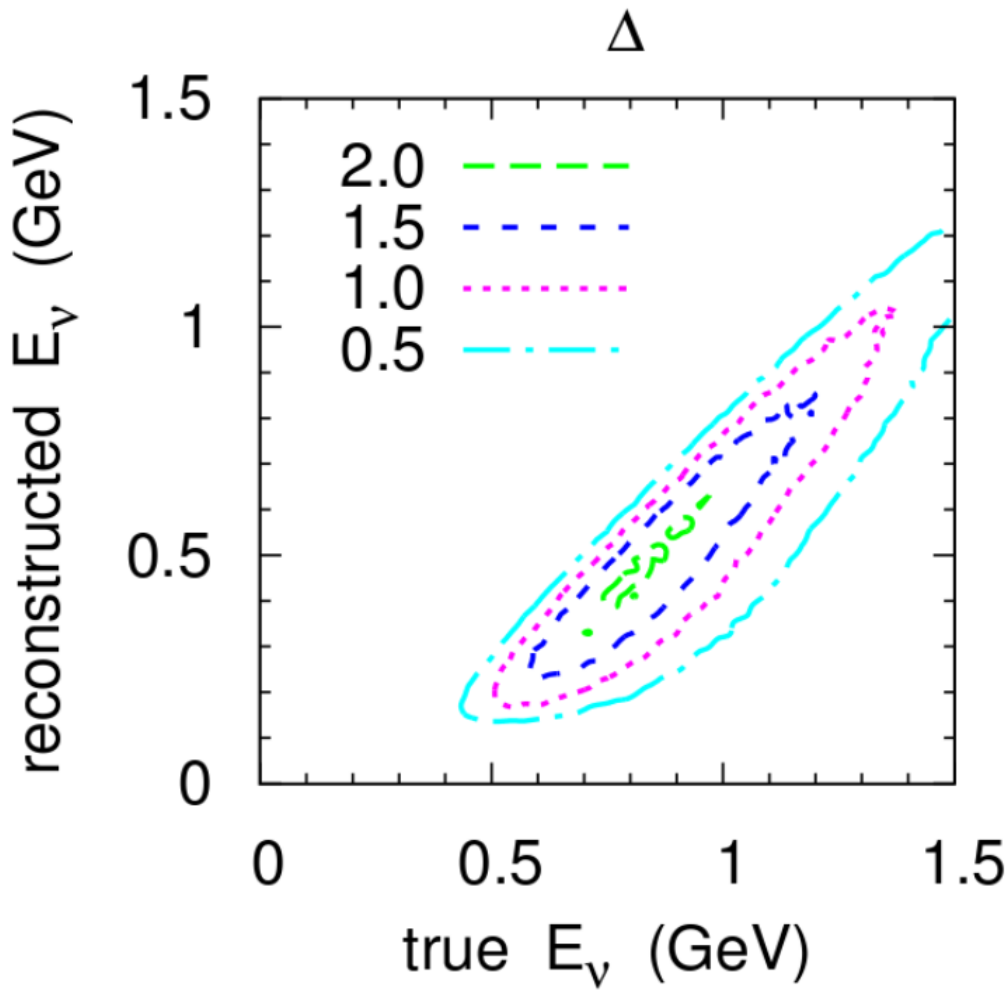
- Correlations can help to reduce impact of systematics:
  - the far detector can act as a "near detector"
- Possible ways to reduce the effect of <u>normalization uncertainties</u>:
  - measure final flavor cross sections at a near detector (intrinsic contamination).
  - put theoretical constraints on ratios between cross sections for different flavors
- Caveats: near/far flux extrapolation is tricky; near/far detectors may not be identical, etc

Shape uncertainties

Energy reconstruction effects

These effects can be parametrized as migration matrices from true to reconstructed energy:

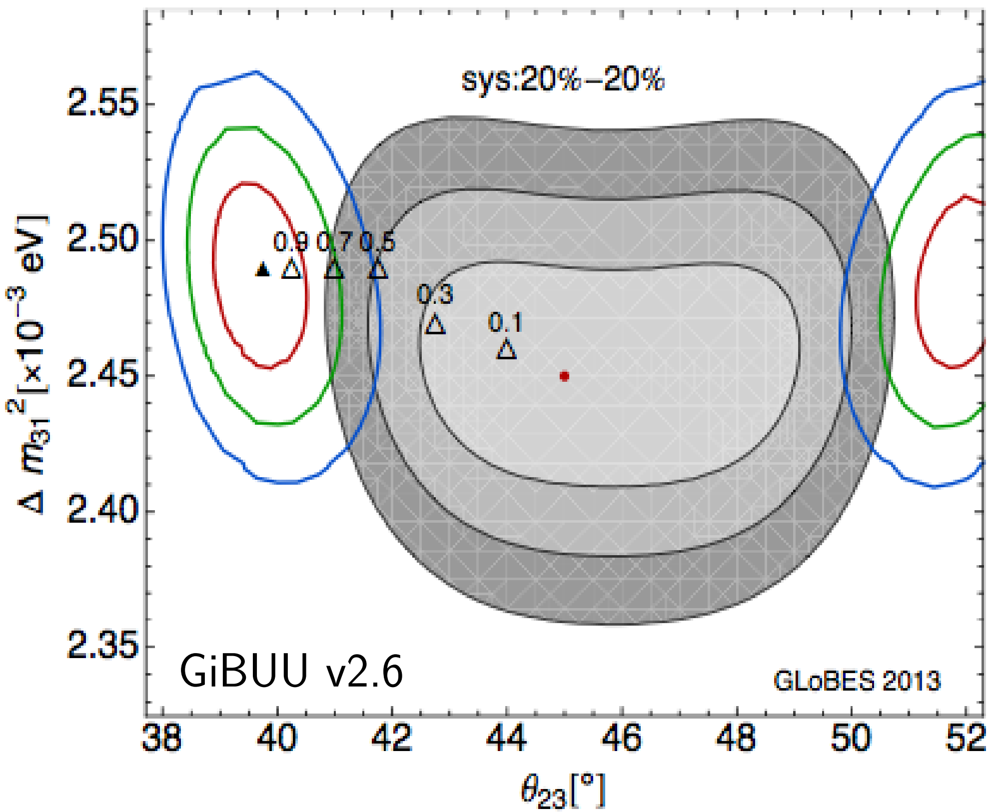


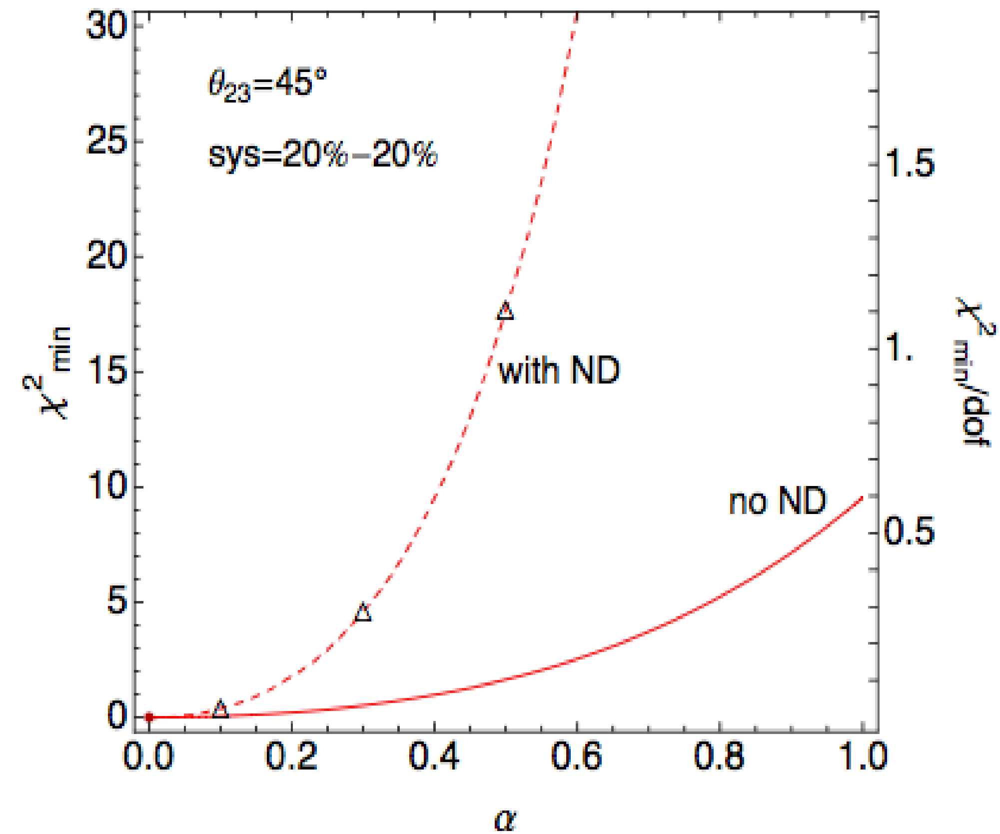


Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]

Toy model

$$N_i^{\text{test}}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$$

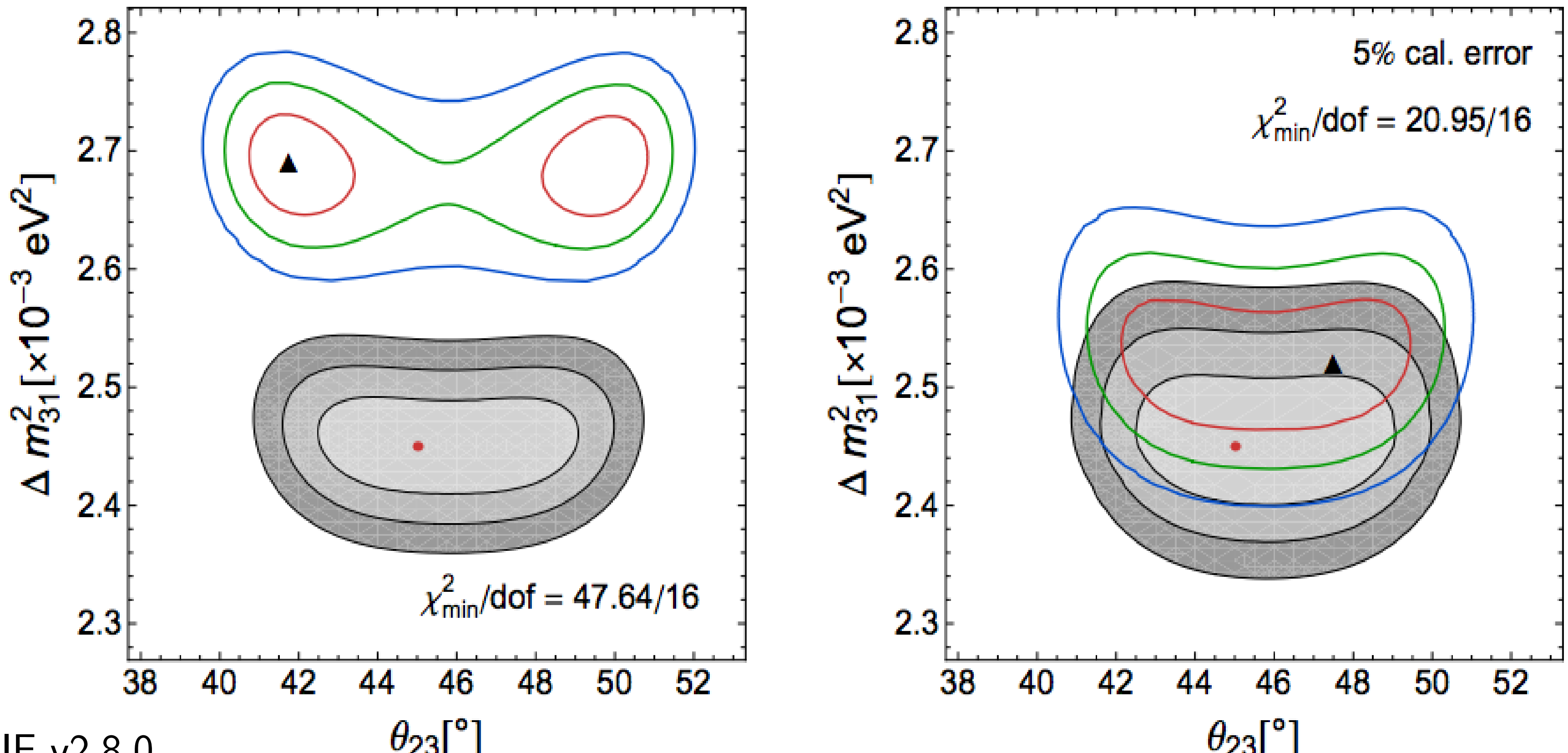




Coloma and Huber, 1307.1243 [hep-ph]

Impact of nuclear model

How large can these effects be?



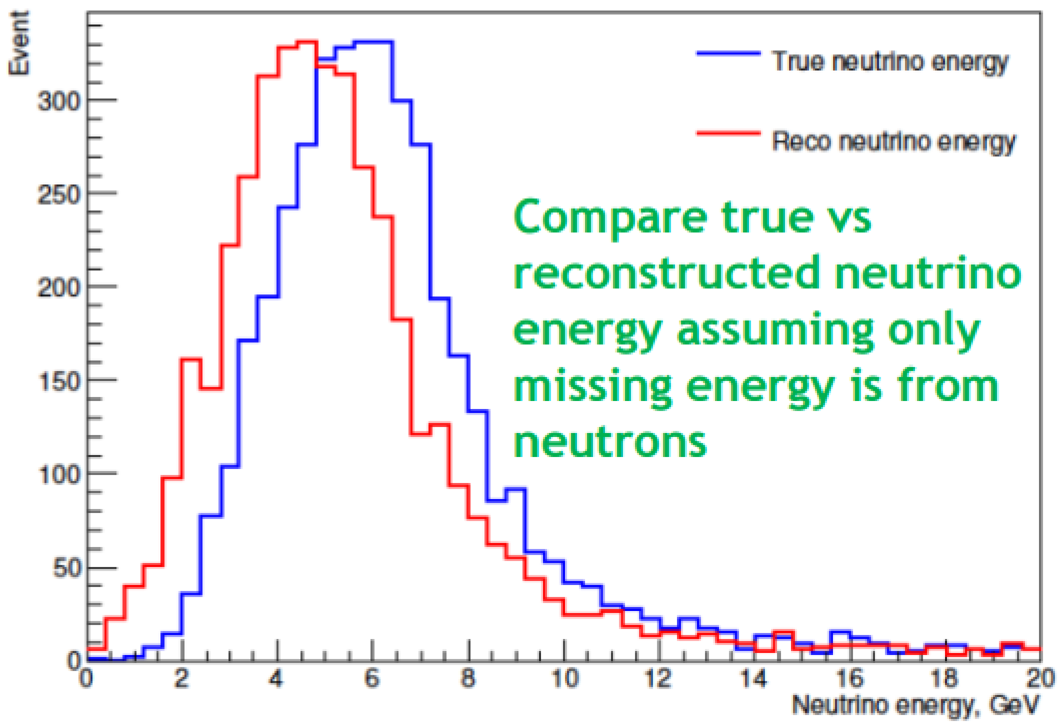
GENIE v2.8.0

GiBUU v2.6

Coloma, Huber, Mariani and Jen, 1311.4506 [hep-ph]

Does this improve with calorimetry?

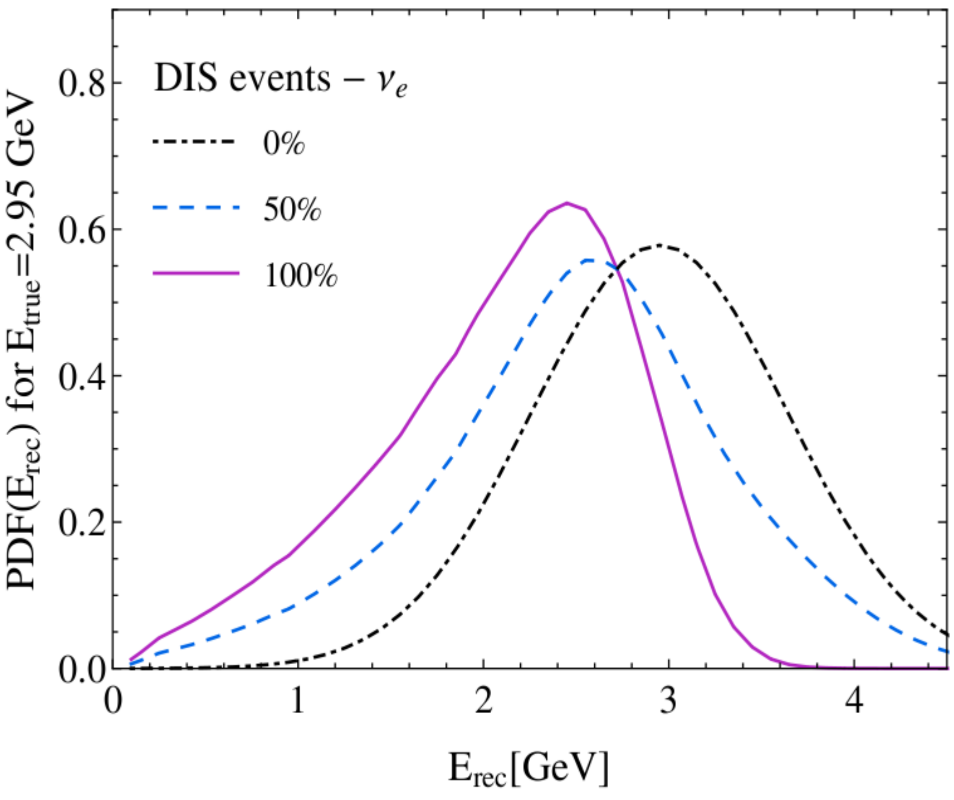
Calorimetry relies on observing all particles produced in the interaction



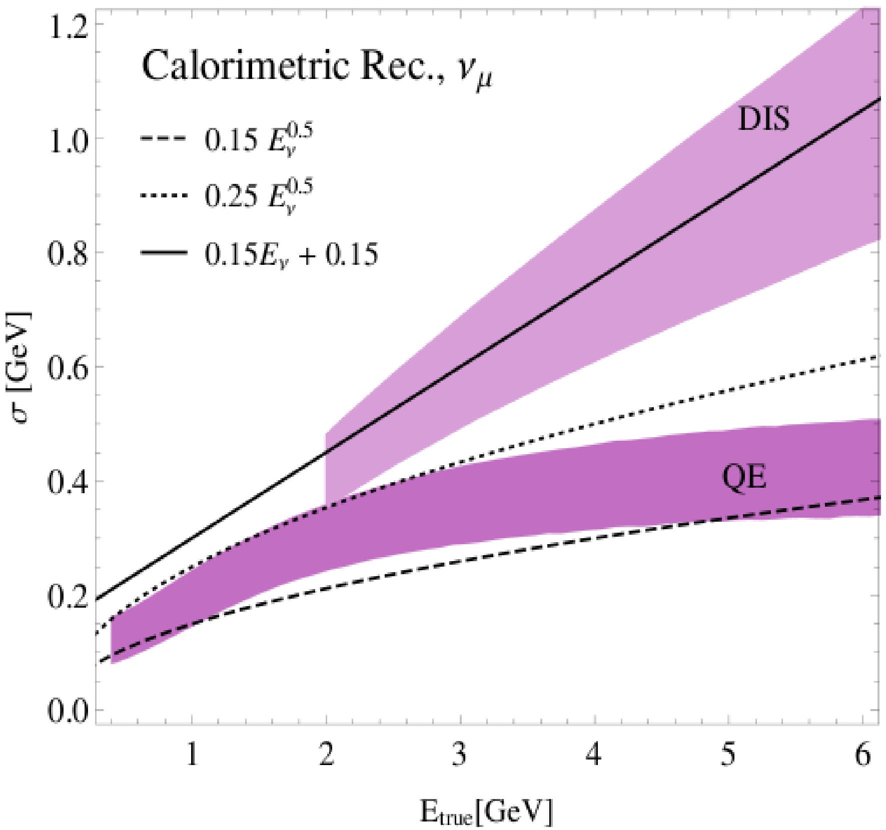
Simulation studies using NuMI medium-energy flux and GENIE (Q. Liu)

Taken from L. Whitehead's talk here at NNN

Does this improve with calorimetry?

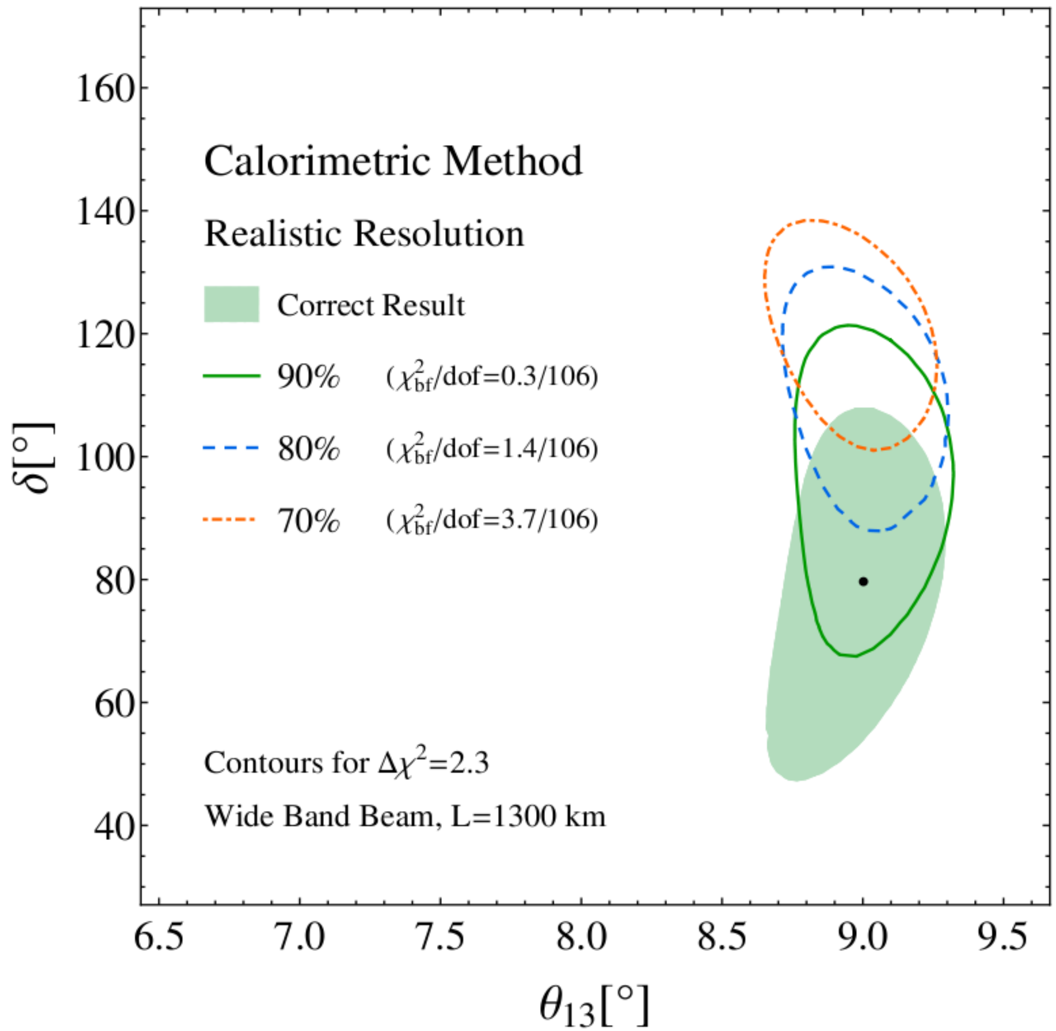


Ankowski et al, 1507.08561 [hep-ph]



Ankowski et al, 1507.08560 [hep-ph]

Does this improve with calorimetry?



Ankowski et al, 1507.08561 [hep-ph]

Summary (I/II)

- The most relevant systematics for appearance experiments are those related to cross sections. Challenges:
  - Unavailability of final flavor at the near detector
  - near-far detector extrapolation
- Systematic effects may be kept under control under several assumptions:
  - no flux shape uncertainties
  - no cross section shape uncertainties
  - disappearance data can be used to reduce uncertainties in appearance

Challenging!

Summary (II/II)

- Shape uncertainties are more dangerous. We find:
  - Large impact on the determination of the disappearance parameters for kinematic reconstruction due to non-QE contamination of the QE sample
  - Significant bias for deltaCP from missing energy in calorimetric detectors, if not accurately calibrated
- Failure to include nuclear effects properly may induce significant bias on the oscillation parameters

Thanks!

Matrix generation details

Detection thresholds: 20 MeV for mesons and 40 MeV for protons

Detection efficiencies: 60% for pi0, 80% for other mesons, 50% for protons

Resolution details assumed:

$$\sigma(|\mathbf{k}_\mu|) = 0.02|\mathbf{k}_\mu| \quad \text{and} \quad \sigma(\theta) = 0.7^\circ,$$

$$\sigma(E_e) = 0.10 E_e \quad \text{and} \quad \sigma(\theta) = 2.8^\circ$$

$$\frac{\sigma(E_{\pi^0})}{E_{\pi^0}} = \max\left\{\frac{a_{\pi^0}}{\sqrt{E_{\pi^0}}}, \frac{b_{\pi^0}}{E_{\pi^0}}\right\} \qquad \frac{\sigma(E_h)}{E_h} = \max\left\{\frac{a_h}{\sqrt{E_h}}, b_h\right\}$$

$a_{\pi^0} = 0.107$ and $b_{\pi^0} = 0.02$. $\qquad a_h = 0.145$ and $b_h = 0.067$.

(Neutrons assumed to exit undetected)

Matrix generation details

Calorimetric reconstruction:

$$E_\nu^{\text{cal}} = \epsilon_n + E_\ell + \sum_i (E_{\mathbf{p}'_i} - M) + \sum_j E_{\mathbf{h}'_j}$$

Energy of nucleons knocked-out

Energy of mesons produced

Kinematic reconstruction:

$$E_\nu^{\text{kin}} = \frac{2(nM - \epsilon_n)E_\ell + W^2 - (nM - \epsilon_n)^2 - m_\ell^2}{2(nM - \epsilon_n - E_\ell + |\mathbf{k}_\ell| \cos\theta)}$$

Number of nucleons knocked out of the nucleus

Invariant hadronic mass squared.
(For single-nucleon knock-out, $W^2 = M^2$)

Single nucleon separation energy

Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs $\times$ eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

(Theoretical constraint)

Toy model

- Neglecting all FSI and multinucleon contributions, we can compute the number of events as:

$$N_i^{QE} = \sigma_{QE}(E_i)\phi(E_i)P_{\mu\mu}(E_i)$$

- However, in practice we will observe a different distribution at the detector, given by:

$$N_i^{QE-like} = \sum_j M_{ij}^{QE} N_j^{QE} + \sum_{non-QE} \sum_j M_{ij}^{non-QE} N_j^{non-QE}$$

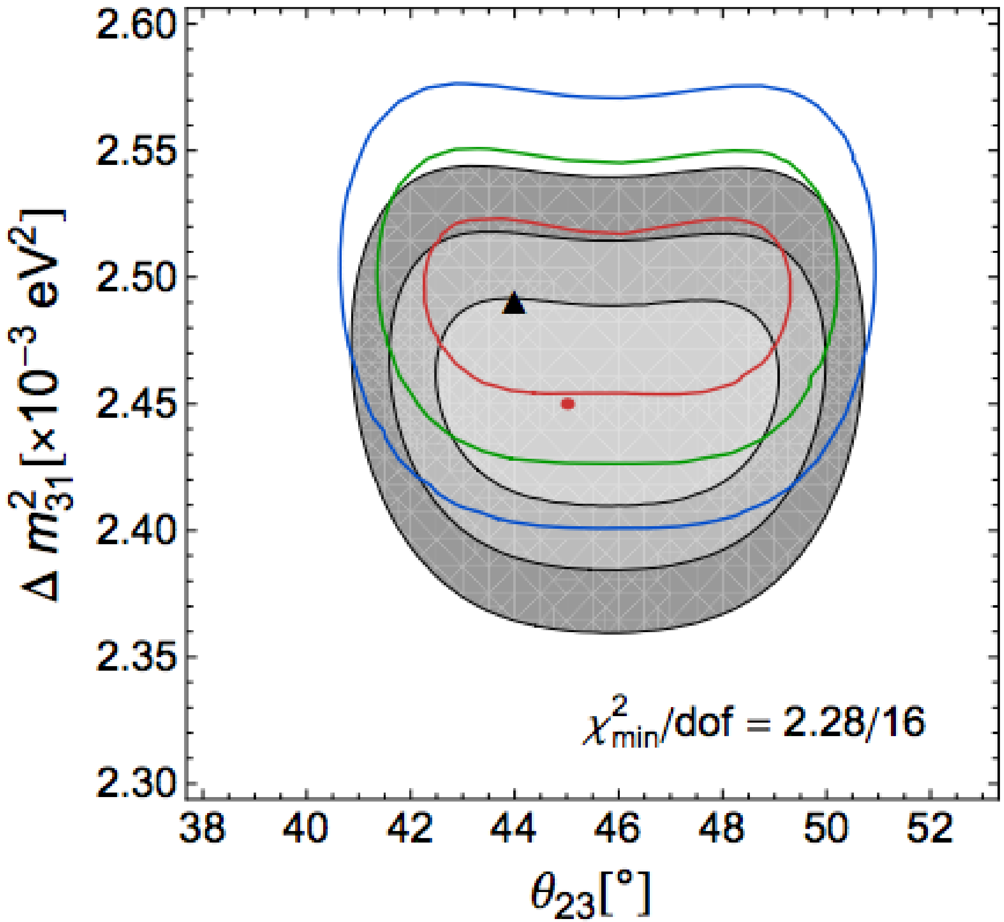
- An intermediate situation would most likely take place:

$$N_i^{test}(\alpha) = \alpha N_i^{QE} + (1-\alpha) N_i^{QE-like}$$

Coloma and Huber, 1307.1243 [hep-ph]

Impact of target nucleus

Oxygen vs Carbon:

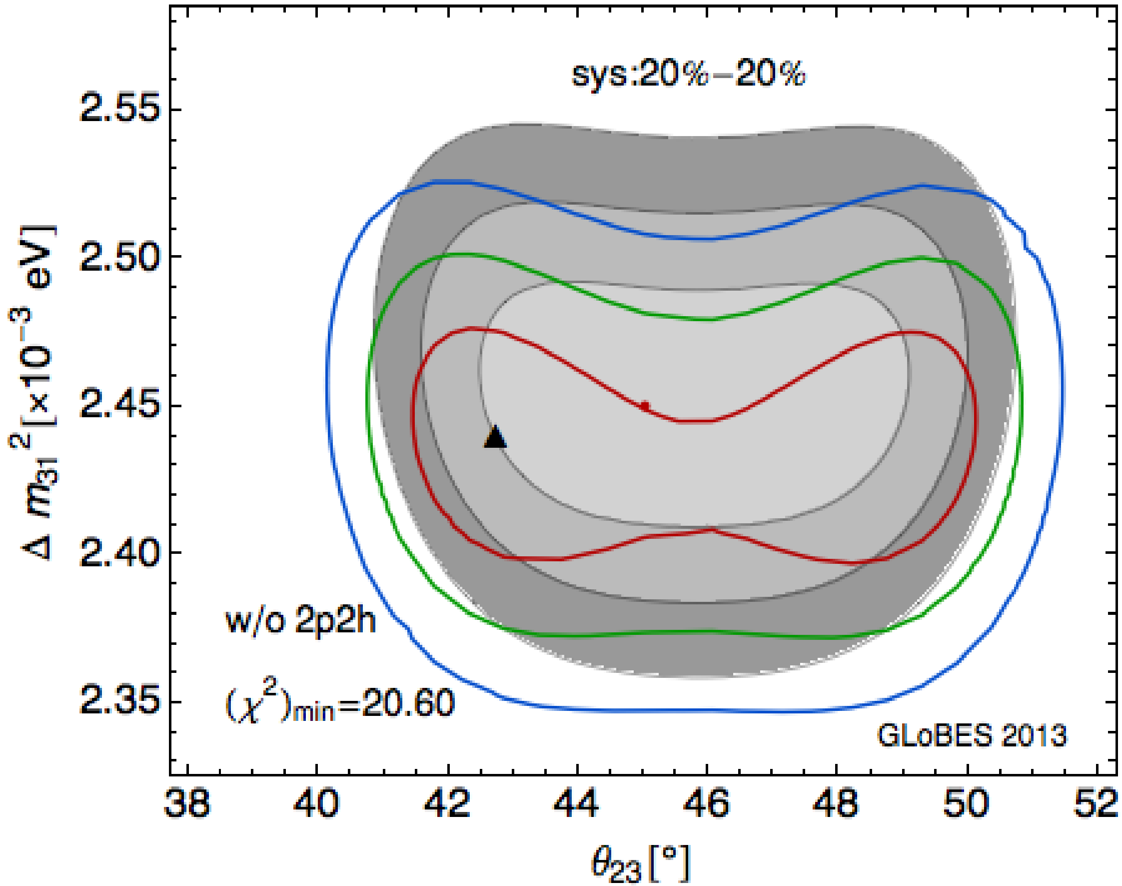


GENIE v2.8.0

Coloma, Huber, Mariani and Jen, 1311.4506 [hep-ph]

Impact of 2p2h

Even if we get all contributions right except 2p2h...



<u>Events</u>

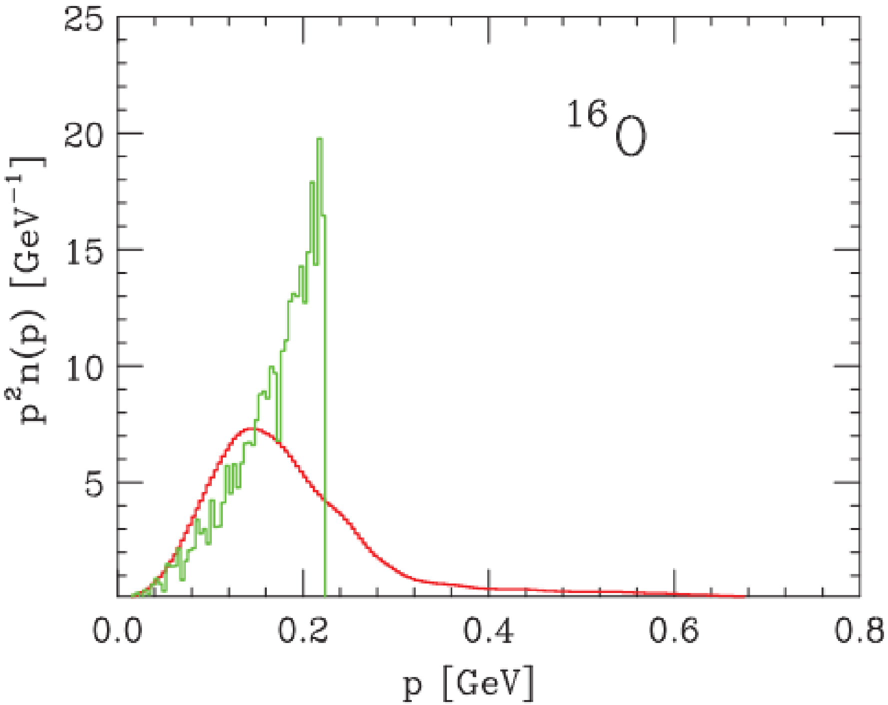
QE	2p2h	QE-like
∼870	∼215	∼1270

GiBUU v2.6

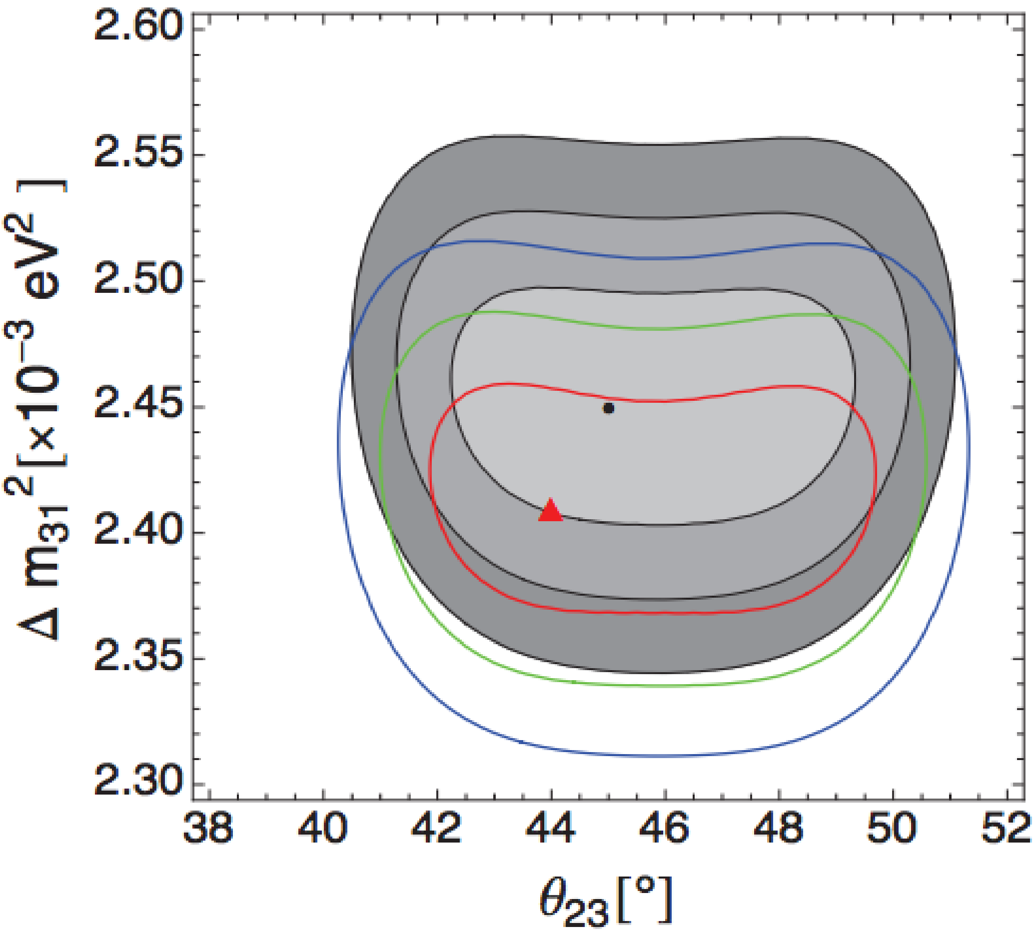
Coloma and Huber, 1307.1243 [hep-ph]

Other factors: RFGM vs SF

Nucleon momentum distribution:



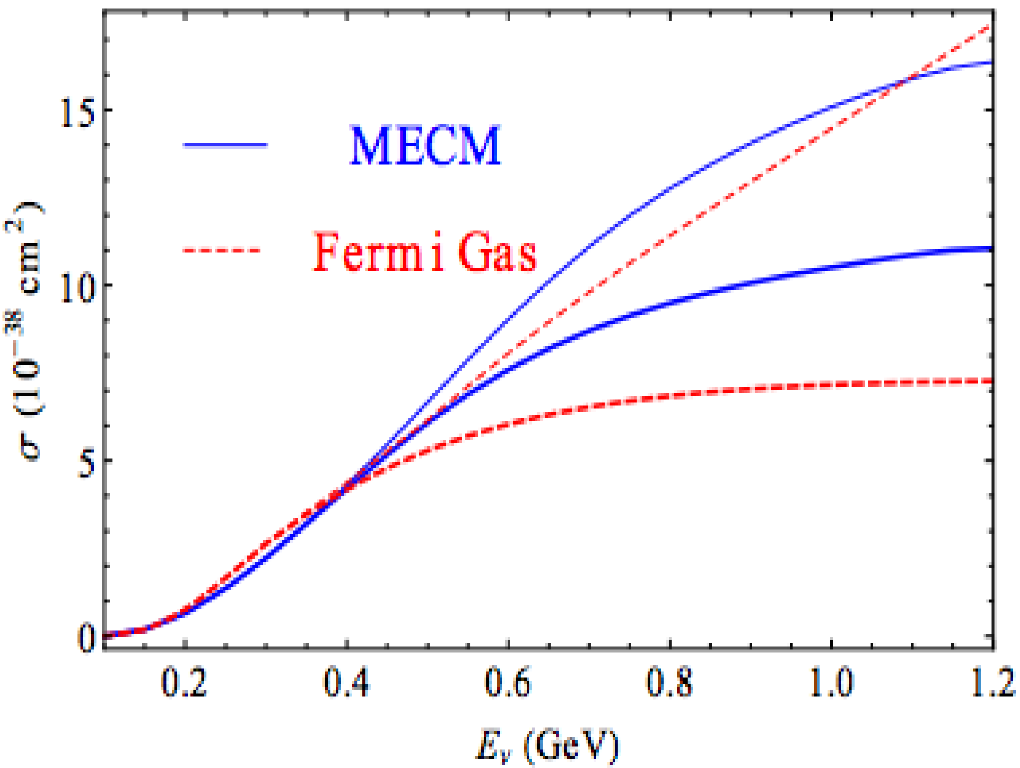
Jen et al, 1402.6651 [hep-ex]

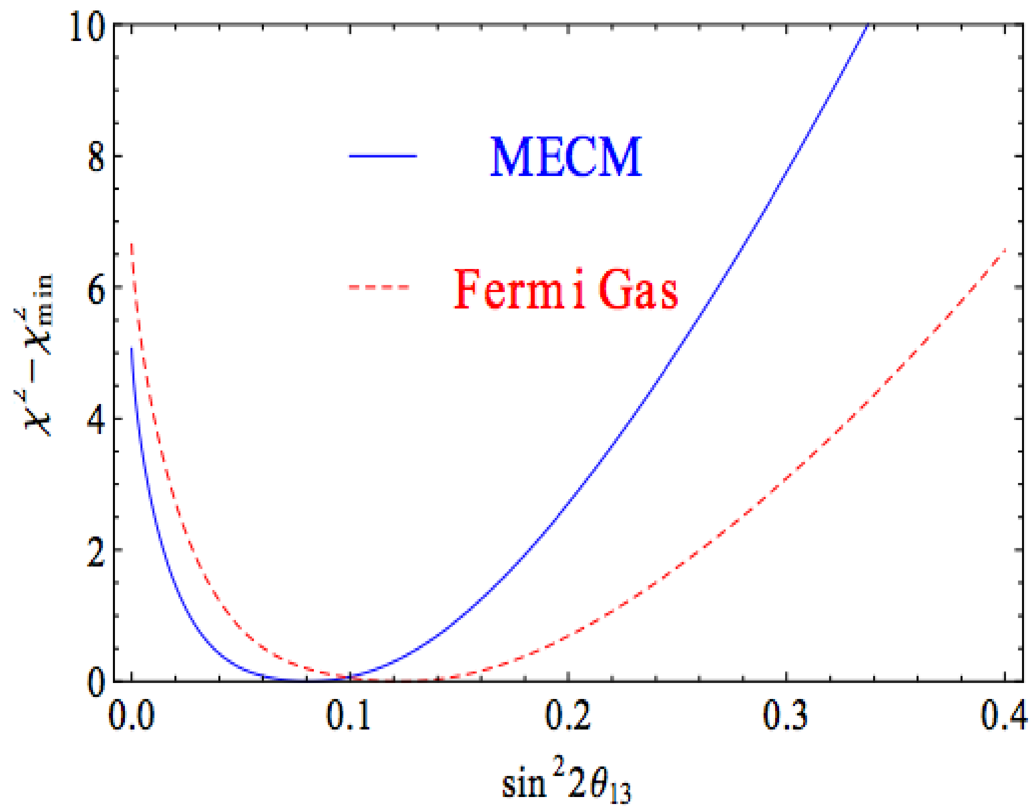


GENIE v2.8.0 - modified

Cross section models

Impact on an analysis which reproduces T2K results in 1106.2822 [hep-ex]





Martini, Meloni, 1203.3335 [hep-ph]

MECM = model from Martini, Ericson, Chanfray, Marteau, 0910.2622 [nucl-th]