Neutrino Interactions and Future LBL experiments

H. A. Tanaka (UBC/IPP)

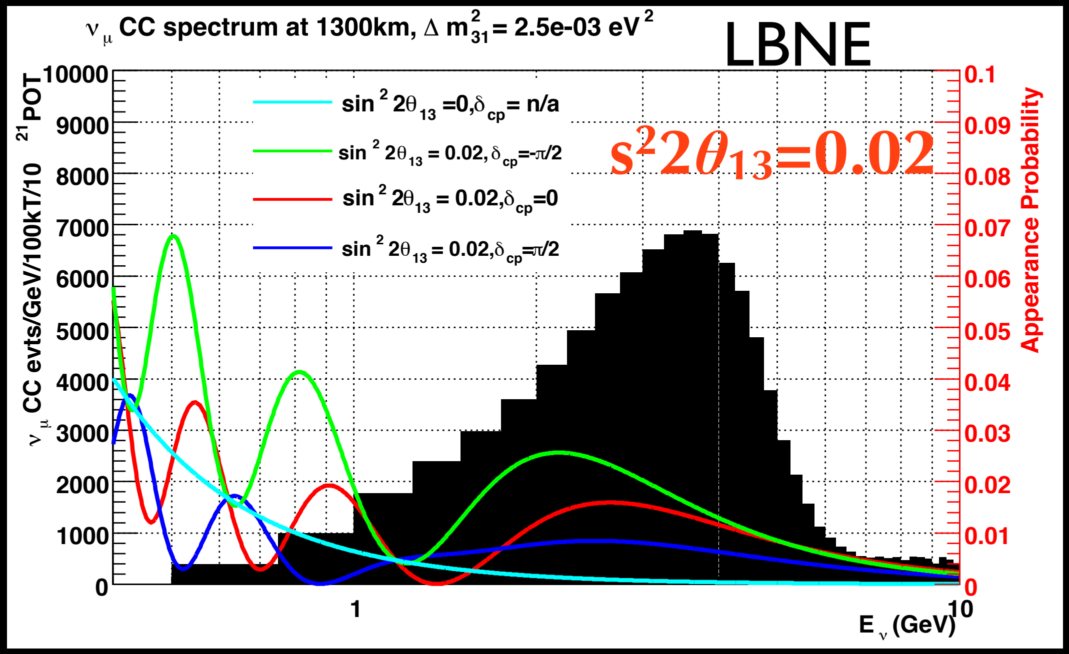
INSTITUTE OF PARTICLE PHYSICS

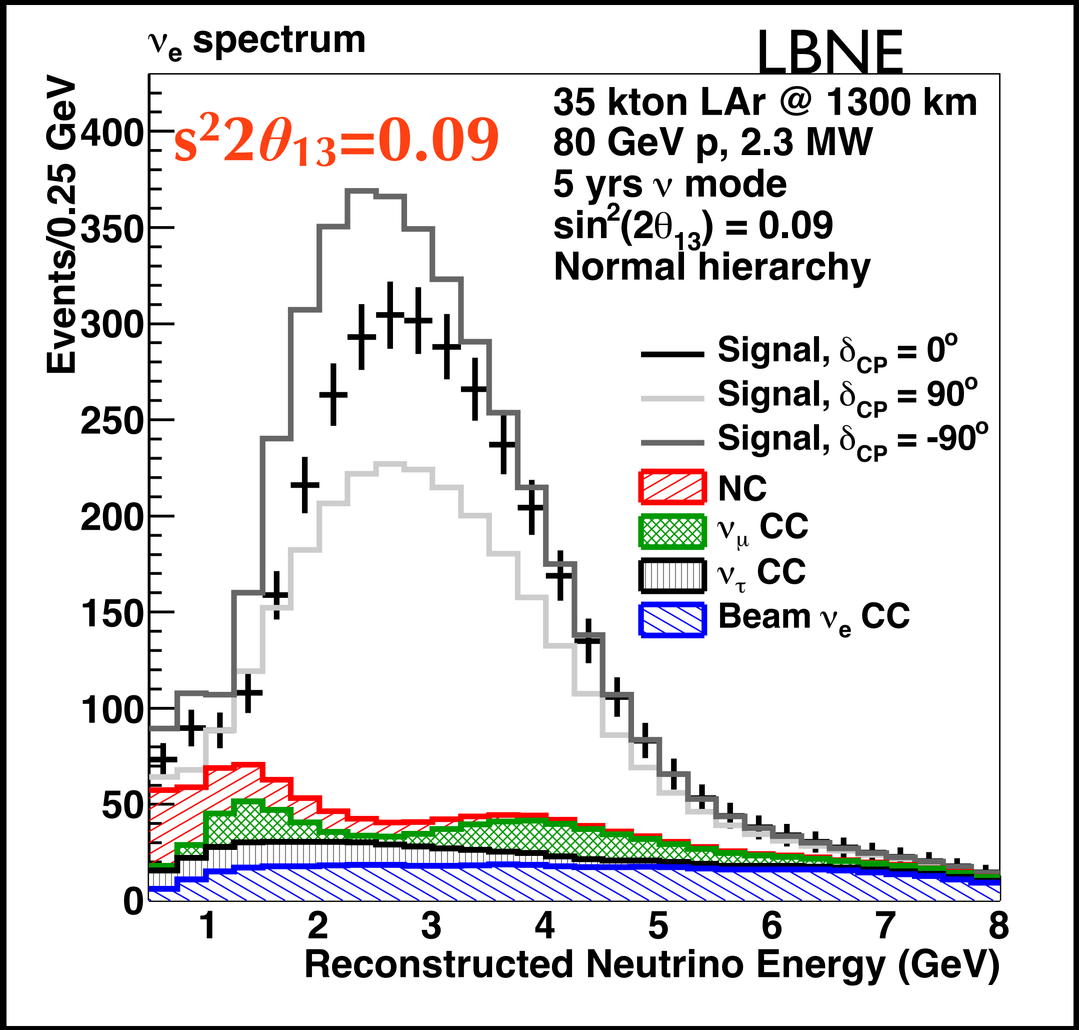
International Workshop Next-Generation Nucleon Decay and Neutrino Detectors
Kavli-IPMU, Kashiwa, Japan, 11 Nov 2013

Overview

- Some generic comments on ν-int issues for LBL experiments
  - selective examples to illustrate general issues
- Some thoughts on next-generation neutrino near detectors
  - (a new workshop series?)
  - some other interesting efforts and activities
- Some sociological commentary
  - A pitch . . . . .
- In the background: physics at the terascale . . . .
  - 1 MWatt x 1 MTon = 1 Tera Watt-ton
  - 1 G$ x 1 kPerson = 1 Tera $-Person
  - how do we ensure that we get the most out of this?

The Mixed Blessing of large θ_{13}





- CP asymmetry/variation of oscillation probability is smaller for larger θ_{13}
- small θ_{13}:
  - smaller rate/larger asymmetry
  - background systematics important
- large θ_{13}:
  - larger rate/smaller asymmetry
  - need/opportunity to exploit spectrum
  - "signal" ($\nu_{e/\mu}$ CC) systematics important

In my opinion:
Large θ_{13} is definitely a "blessing" overall

Oscillation Measurements

$$P(\nu_\mu \to \nu_e) \sim \frac{1}{2} \sin^2 2\theta_{13} \times \sin^2 \Delta$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \times \sin^2 \Delta$$

- With θ_{13} ~large and non-zero, we are in the era of full "3-flavor mixing"
  - all parameters (and their precision) matter
- Entering an era of precision where 3 flavor mixing effects matter
  - current $\sin^2\theta_{23}$ uncertainty in $\nu_\mu \to \nu_e$ appearance
  - $\sin^2\theta_{13}$ in ν_μ disappearance

N.B.
above equations are
only for illustration

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M. Freund, Phys.Rev. D64 (2001) 053003

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

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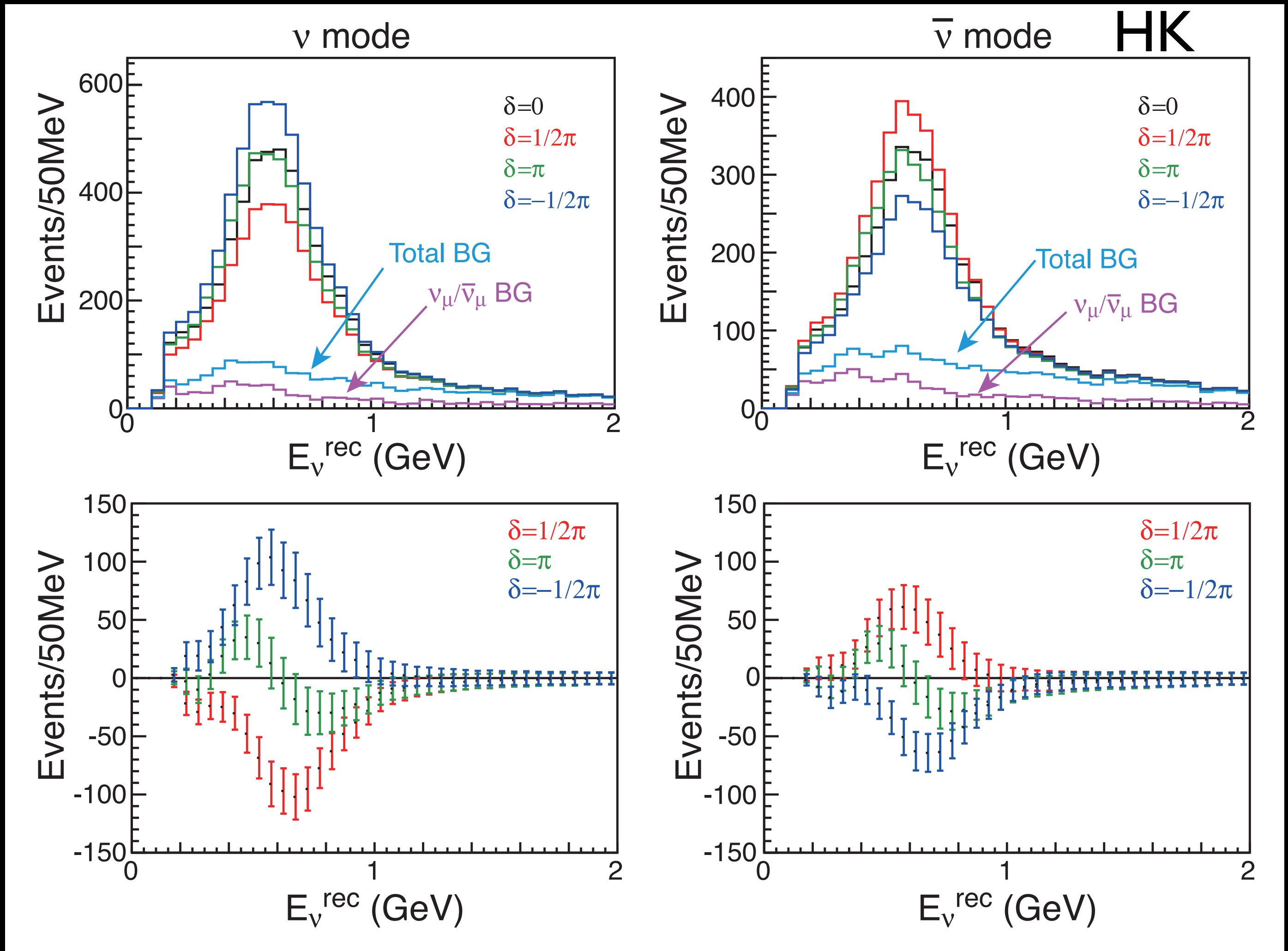
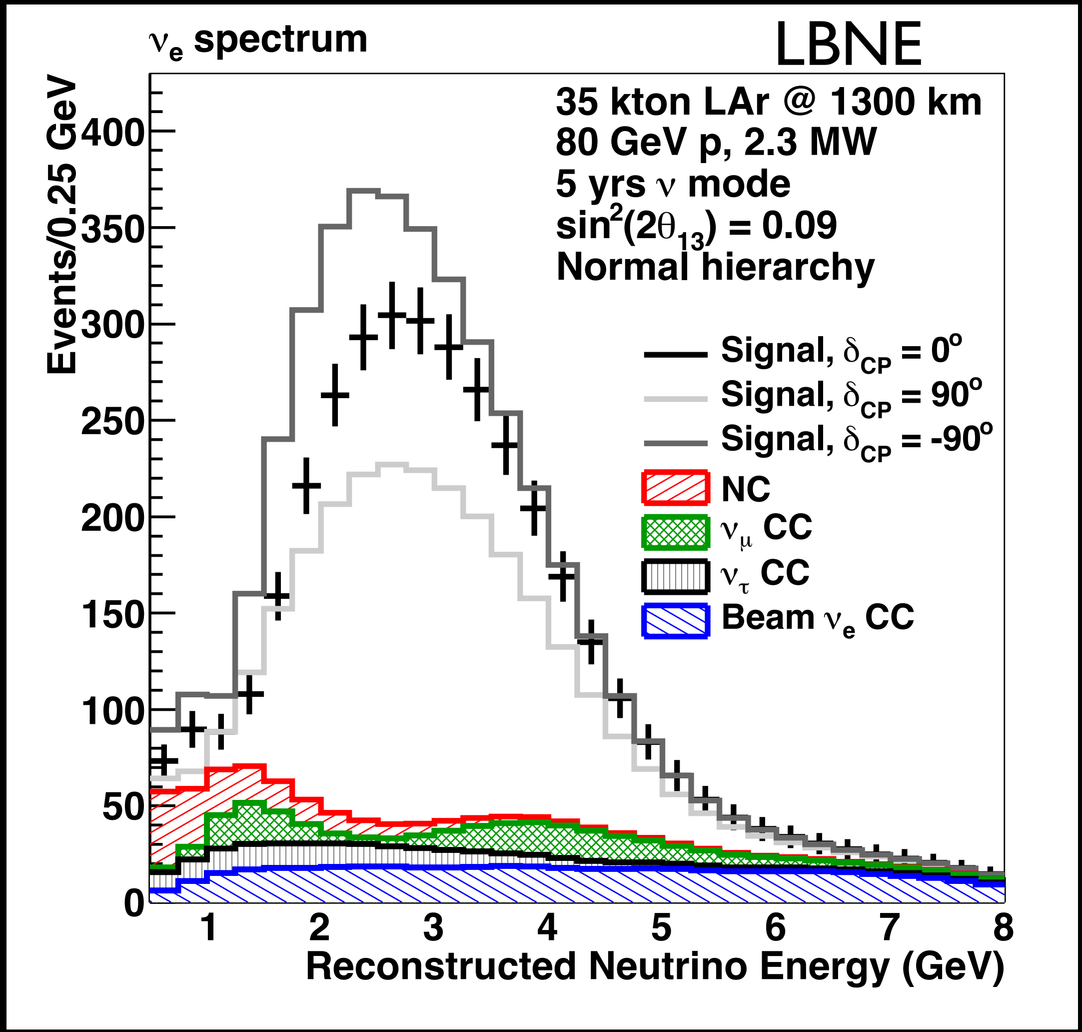
Spectrum Information

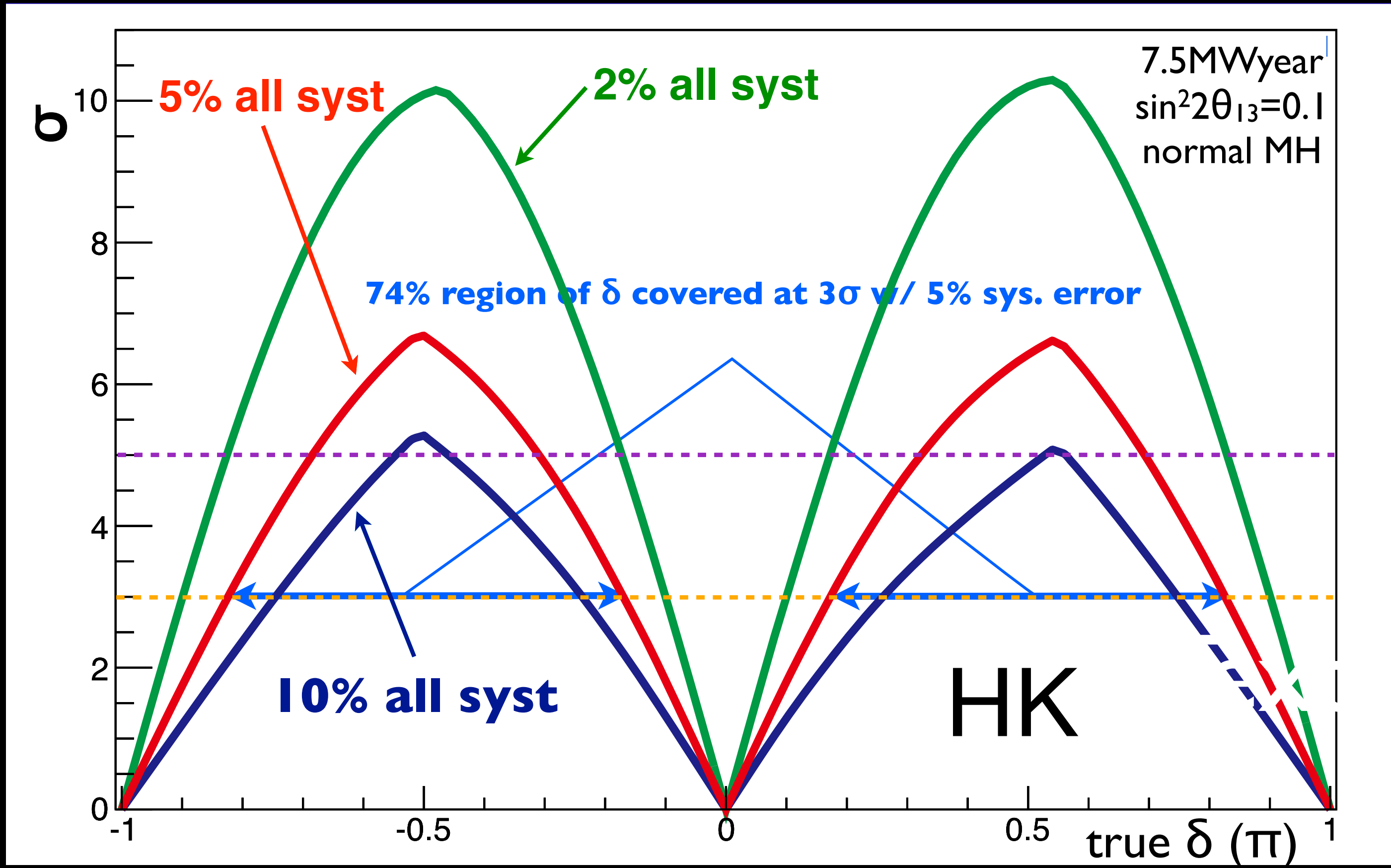




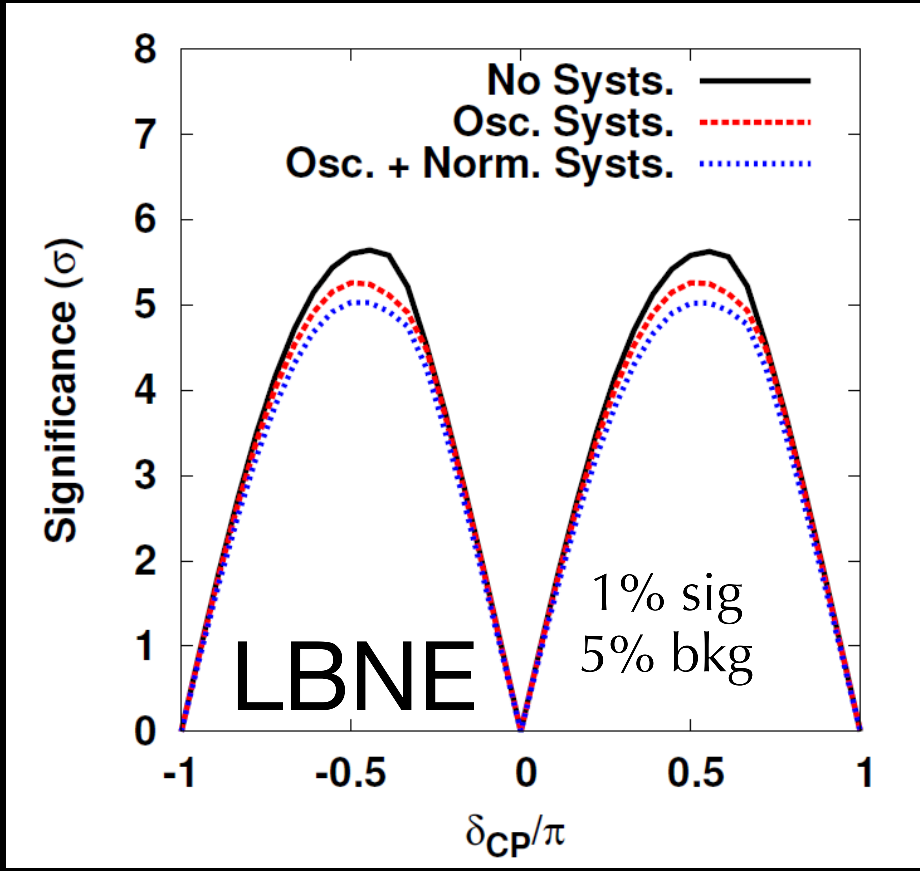
- At both HK and LBNE, spectrum information is important
- In principle, we need a thorough and precise understanding of
  - energy dependence of cross sections
  - energy reconstruction (relation between E_ν and outgoing particles).
    - "kinematic": assume underlying mechanism and use $E_\nu(p_l, \theta_l)$
    - "calorimetric": sum energy outgoing particles.

Impact of systematics

HK LOI



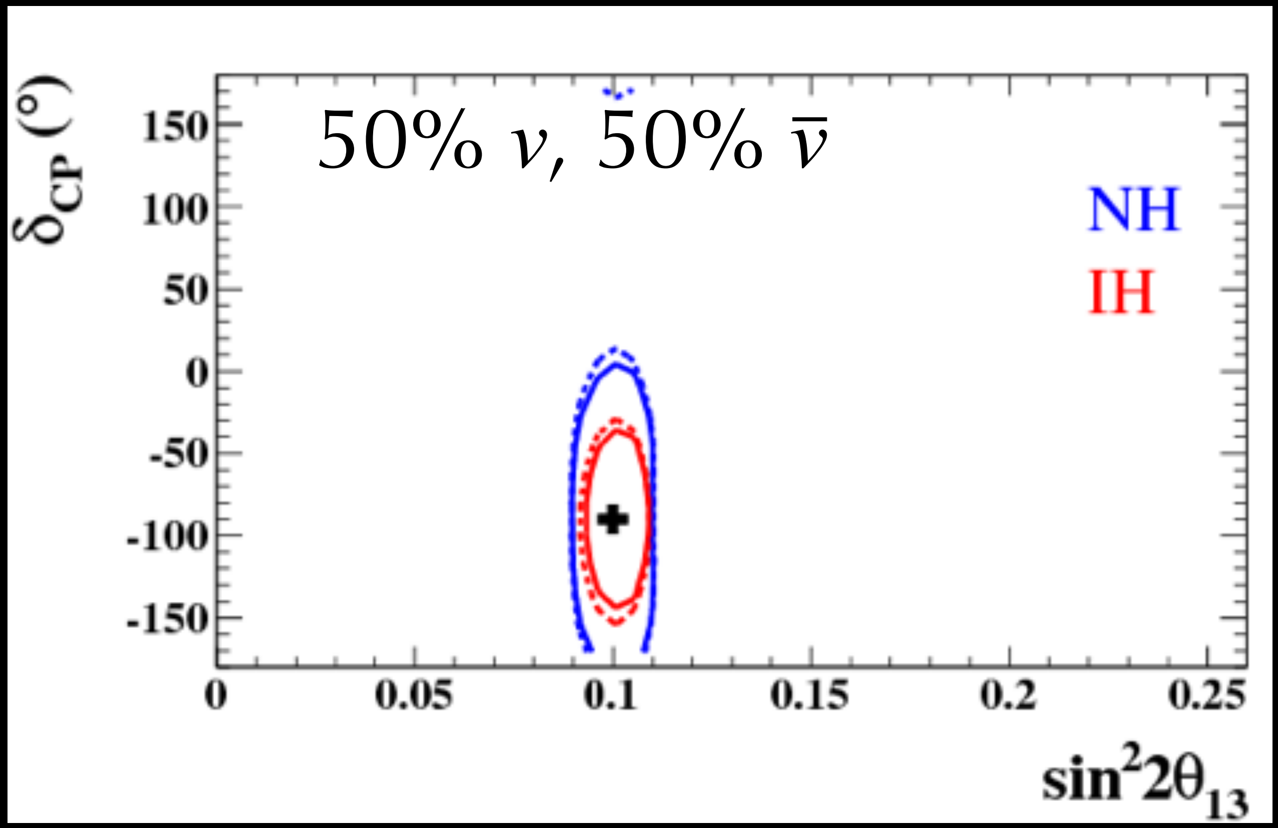
M. Bass et al.
LBNE/LBNO joint studies

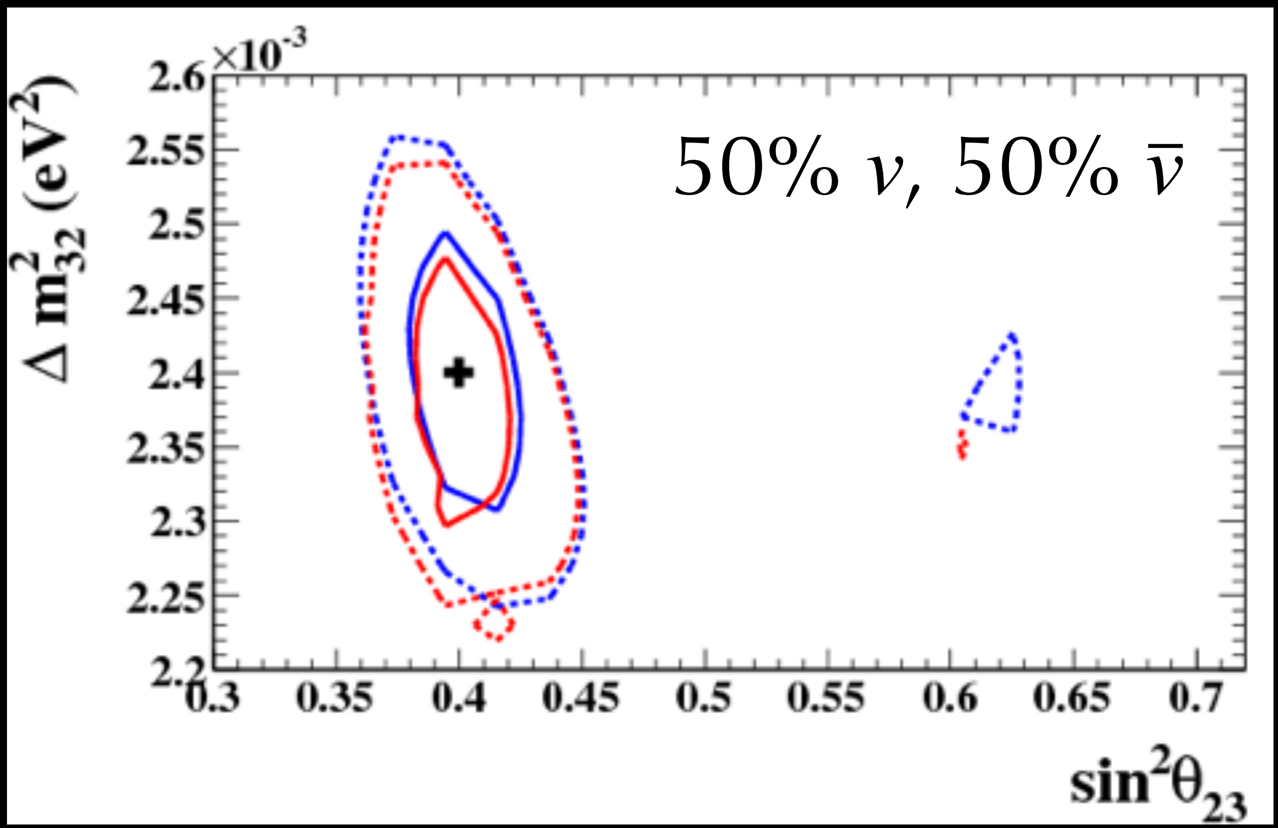


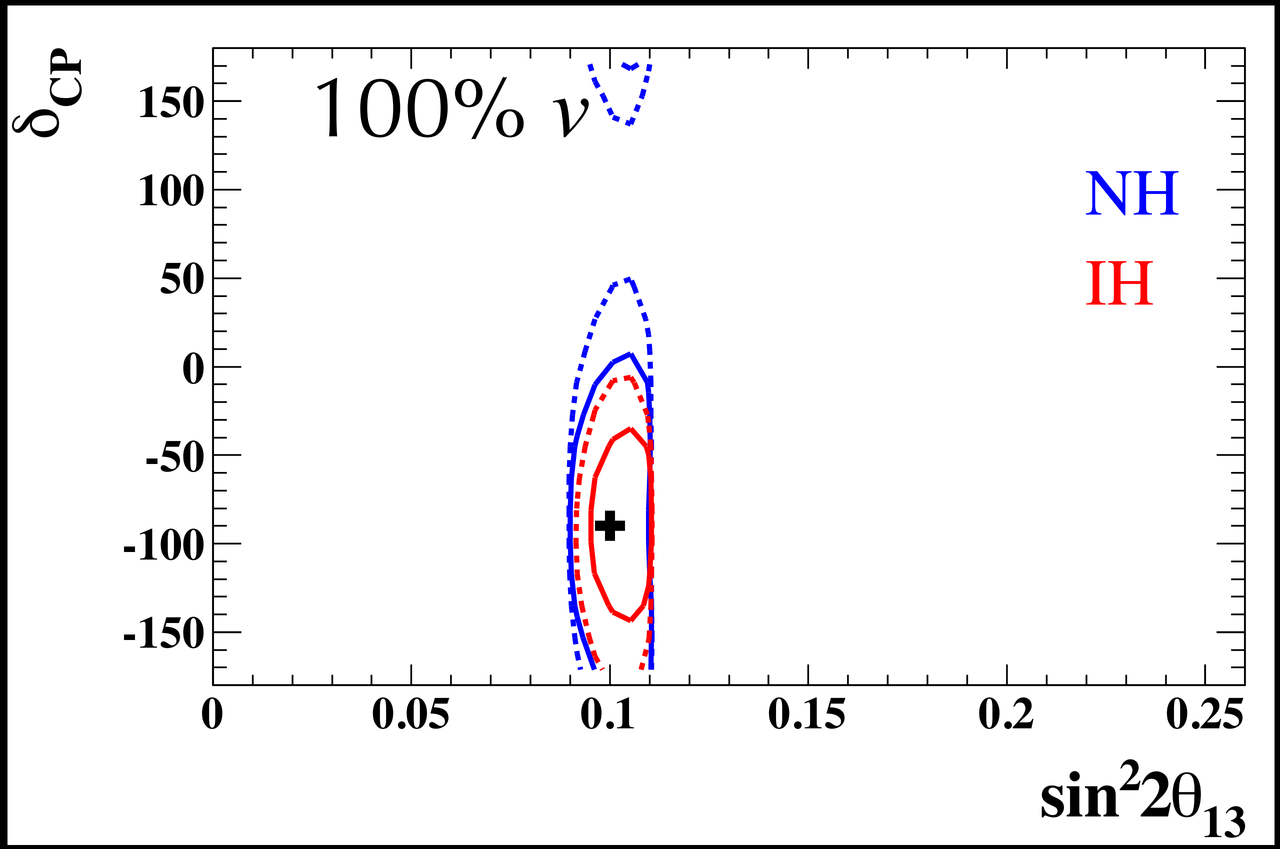
- Many studies have assumed "normalization" systematics that scale overall event yields but preserve spectrum shape.
  - doesn't capture the full picture, but still very useful
    - estimates are becoming more sophisticated
  - Even few % systematic errors can have significant impact
    - how to incorporate potential ND measurements into sensitivity

Recent T2K study:

more details in D. Cherdack's talk



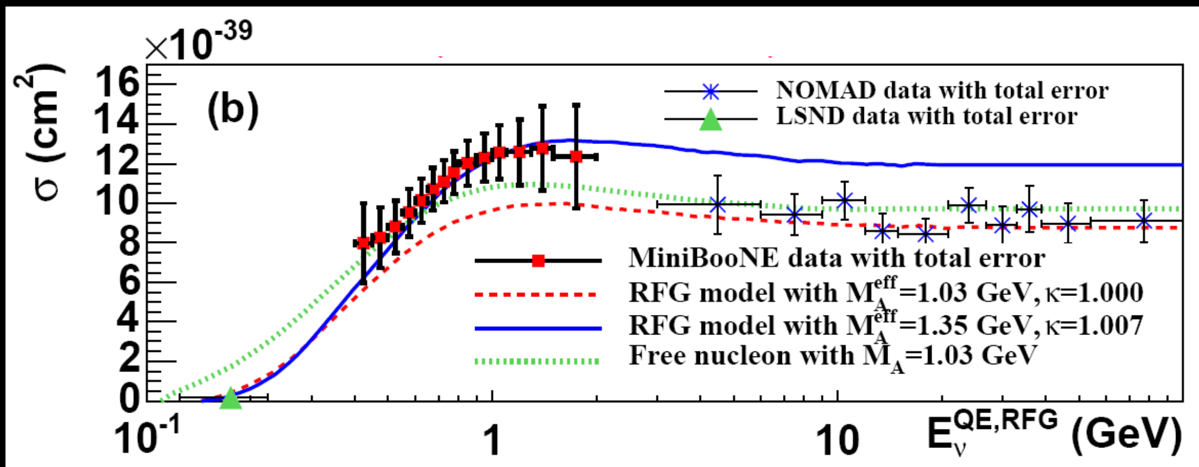


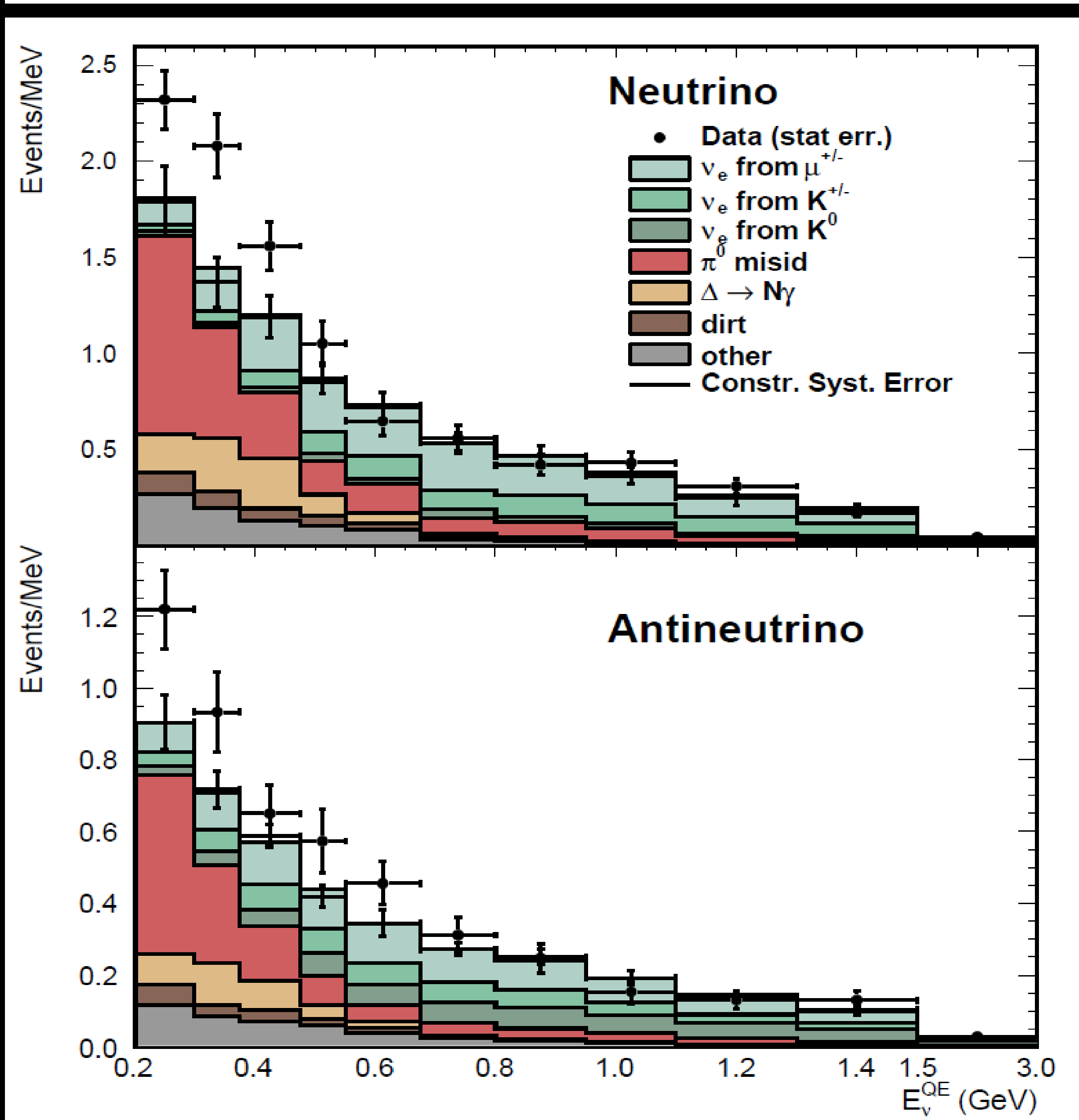


- Explore sensitivity to δ_{CP}, θ_{23} in most favorable cases
  - 90% CL contours for "full" T2K statistics (7.8×10^{21} POT)
  - $\delta = -\pi/2$, normal hierarchy
  - reactor constraint
  - systematics as of 2012

Issues

Recent issues

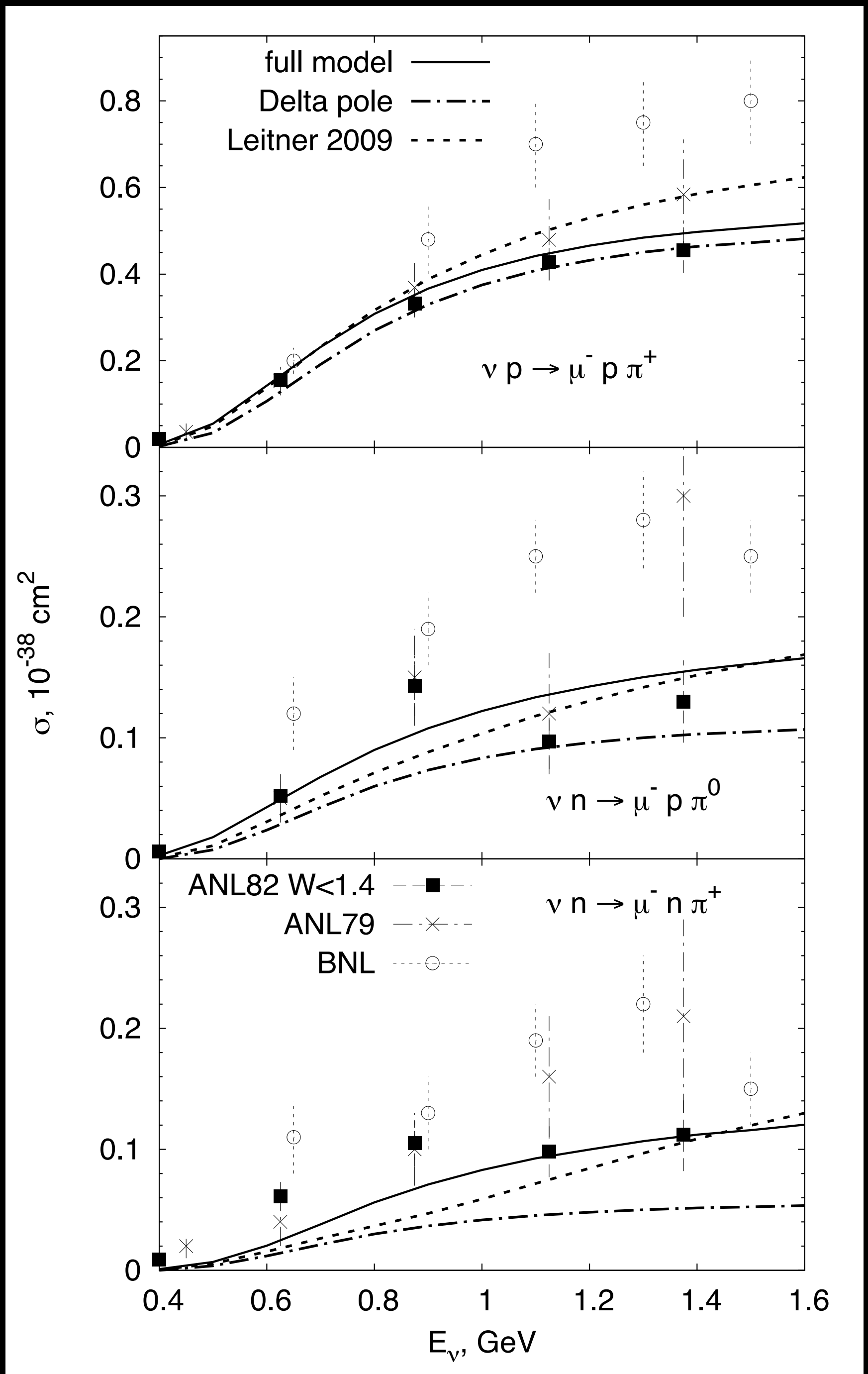




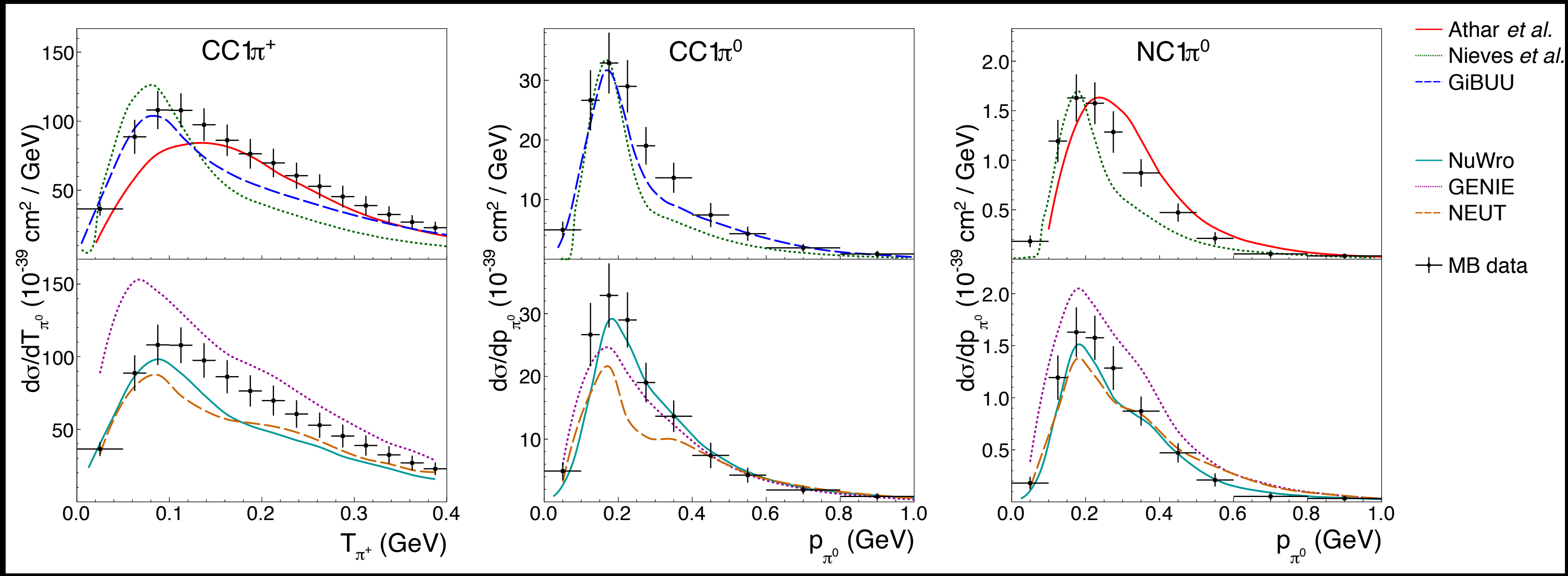
- *ab initio* ν-int uncertainties are driven to a large extent by:
  - data/model discrepancies
  - model inadequacies
- Examples:
  - MiniBooNE "CCQE" σ
  - low energy excess in ν_e
- Model inadequacy means:
  - "inflated" parameter errors
    - "if the data don't fit, you must . . "
  - explore other models to span the space of ignorance/mismodeling

Other issues

P. Rodriguez
NuInt 2012



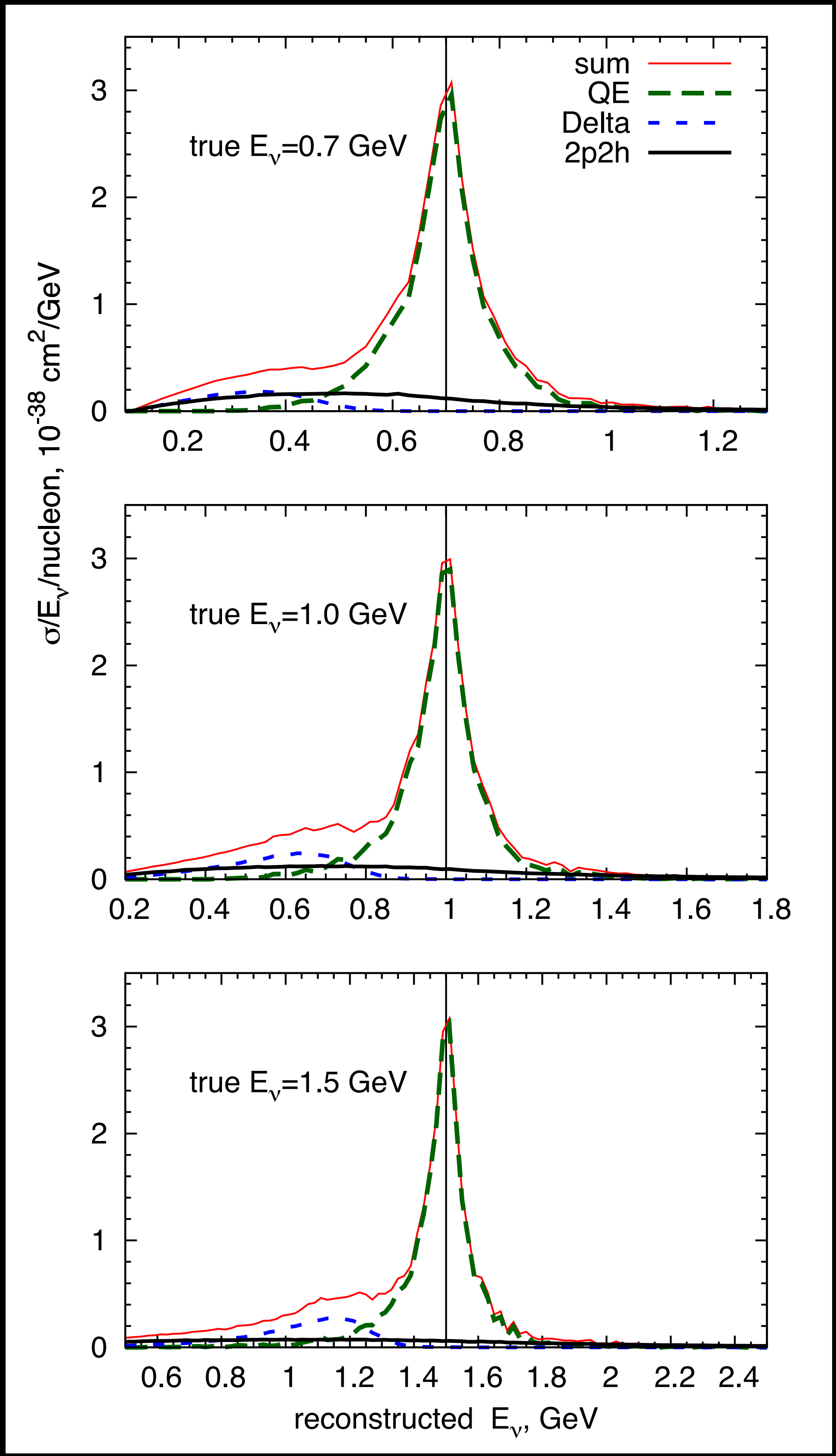
O. Lalakulich et al.
hep-ex/1007.0925v2

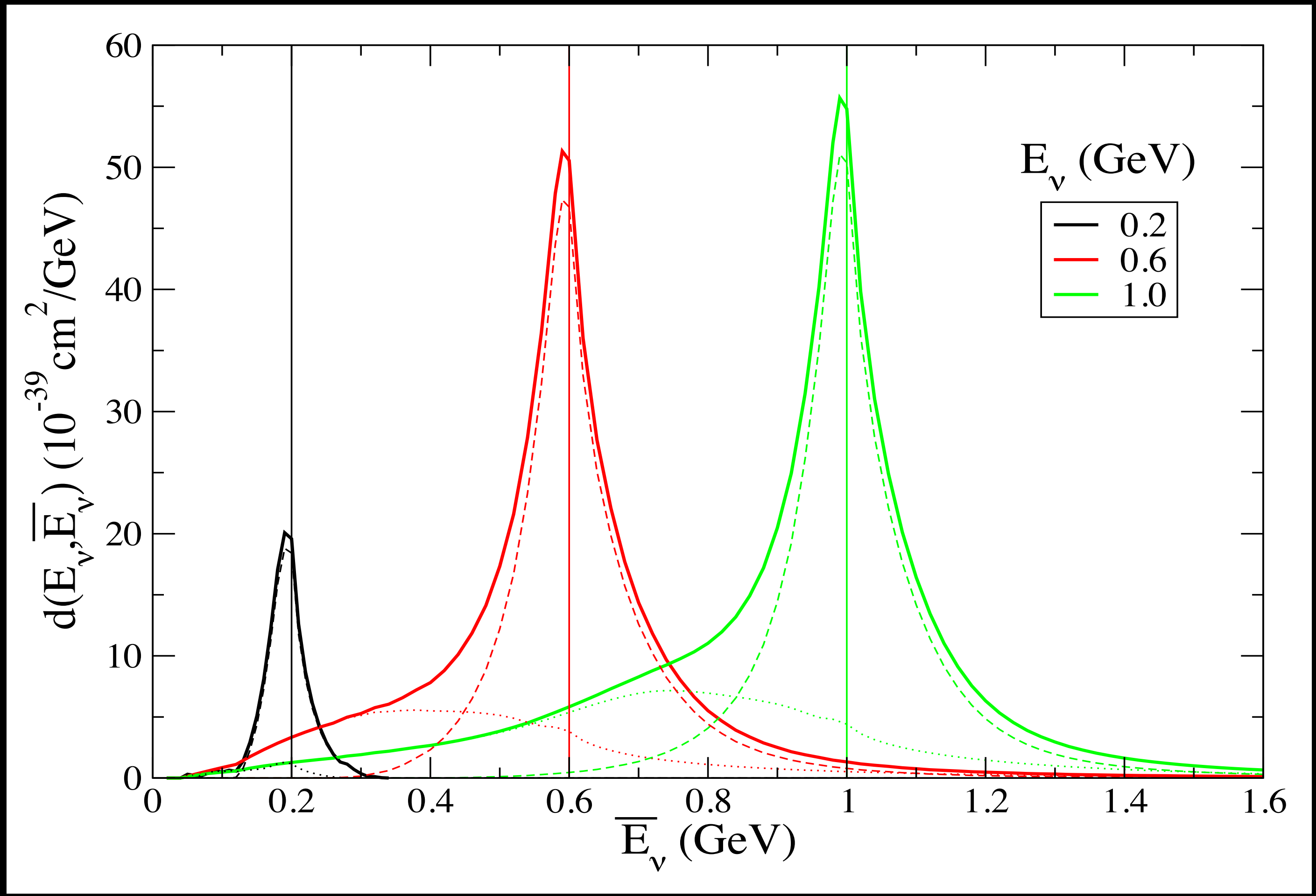


- Most model issues are with the nuclear environment
  - but even nucleon-level scattering data has serious discrepancies.
  - Revisit them?
- Need to think “differentially”
  - kinematic distributions important in addition to overall cross section
    - sometimes n-fold-differential
  - cross channel correlations
    - same physics in different *ν*-int channels

Energy reconstruction

T. Leitner, U. Mosel
Phys.Rev. C81 (2010) 064614





M. Martini et al.
Phys.Rev. D85 (2012) 093012

- To fully utilize spectral information, we have to confidence in final state kinematics
- Nuclear dynamics to a large extent determines neutrino energy reconstruction
  - not just "new" effects like MEC/multi-N but "old" stuff like π absorption, final state interactions

Near Detector

Near Detector

Far (θ_{ij}, Δm^2_{ij})
$\nu_\mu \rightarrow \nu_e$ (θ_{23} , θ_{13})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($\theta_{23,}$ Δm^2_{32})
ν_μ, ν_e backgrounds

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$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

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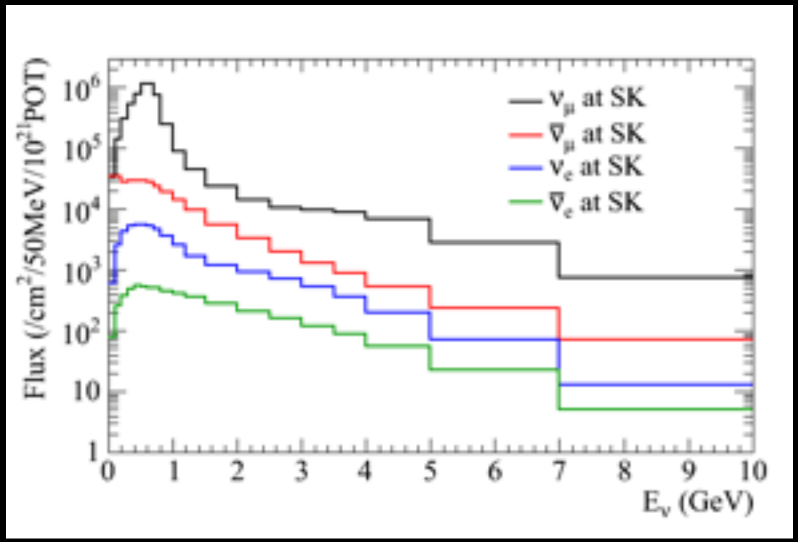
φ_ν



MC simulation of neutrino beamline tuned with external data + operational parameters

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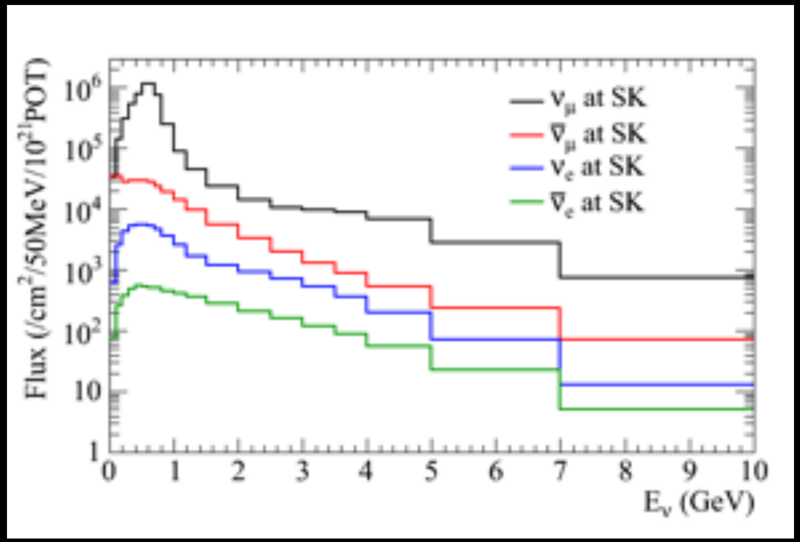

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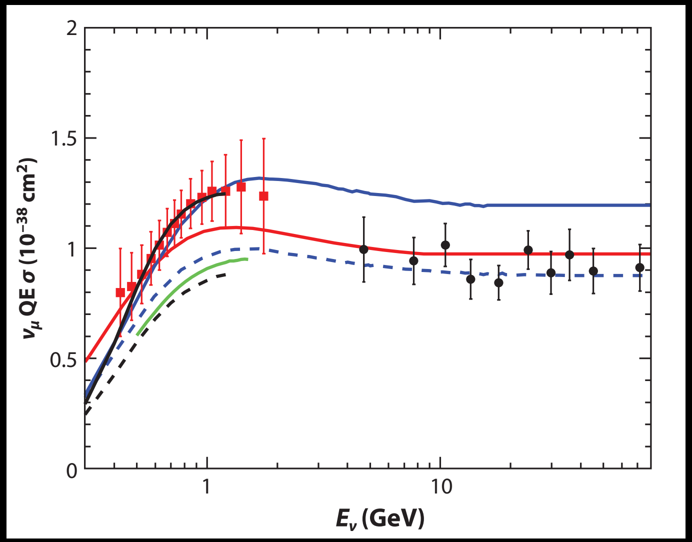
σ_ν



Neutrino cross section and interaction model tuned to external measurements

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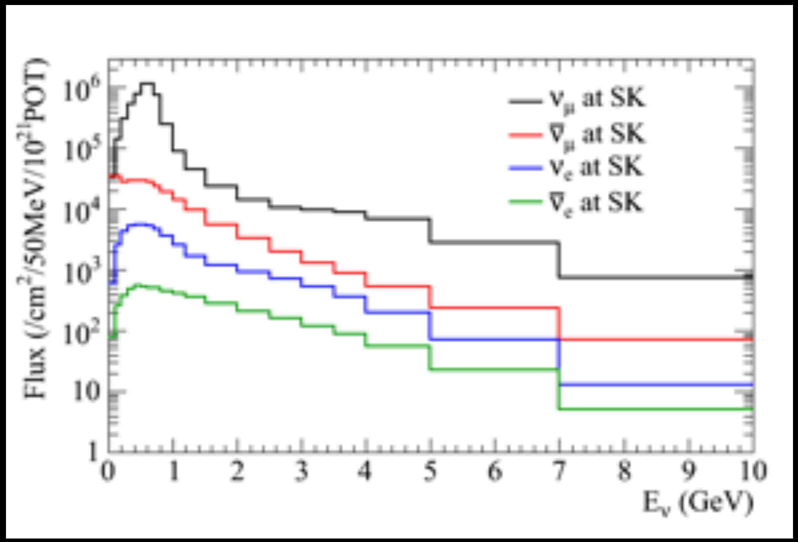

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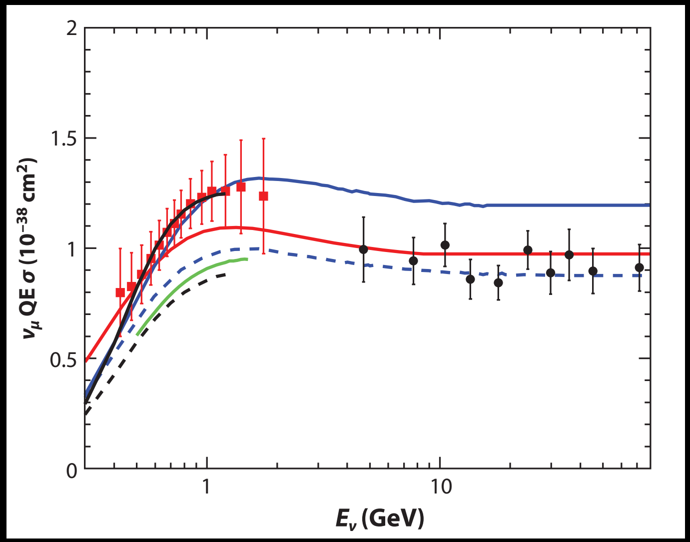

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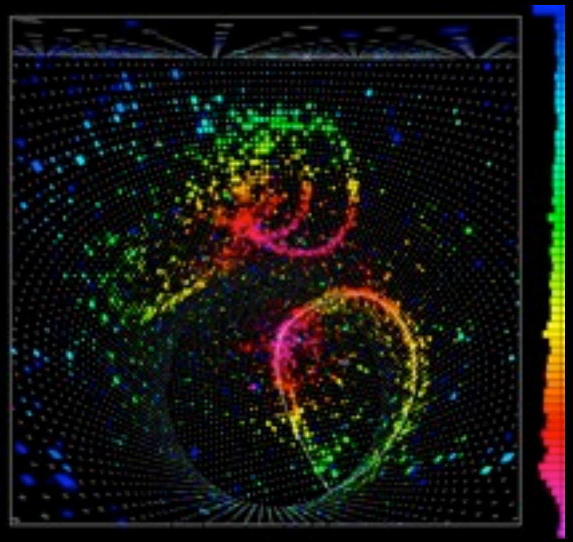

Detector simulation to determine efficiencies/ backgrounds

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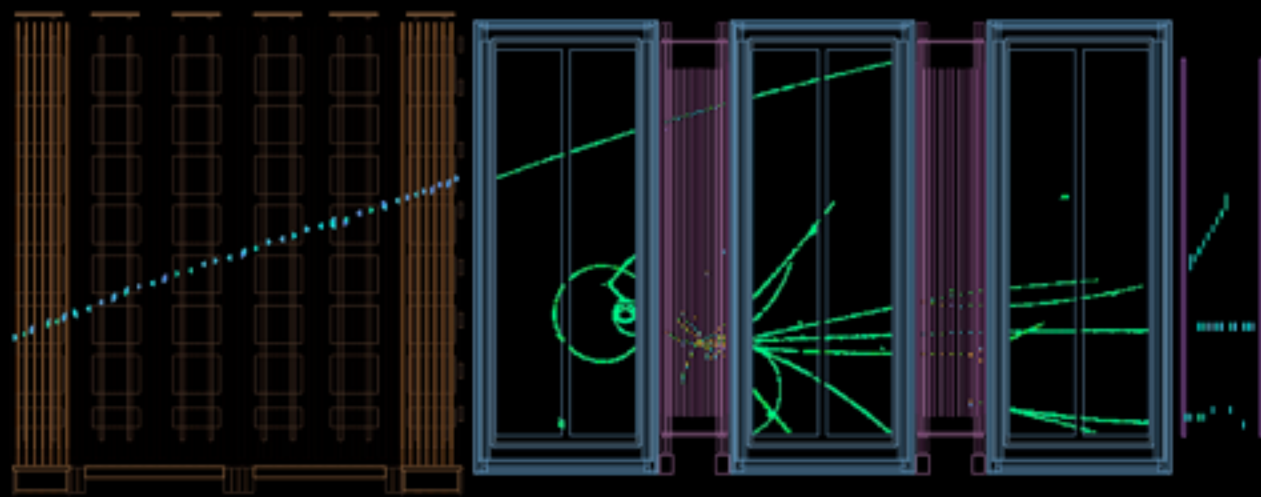

Near detector observes the same neutrinos prior to neutrino oscillations

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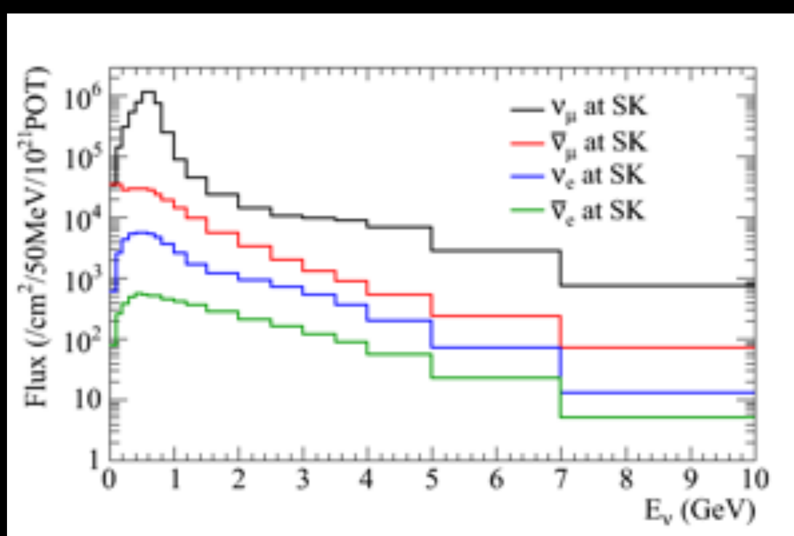

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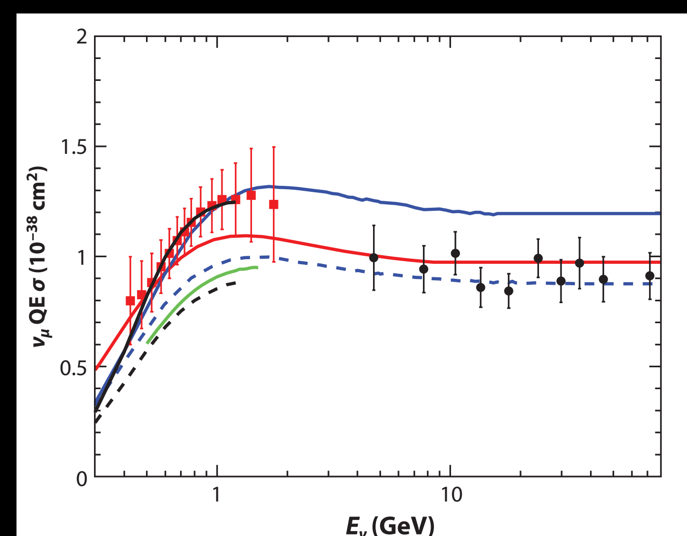

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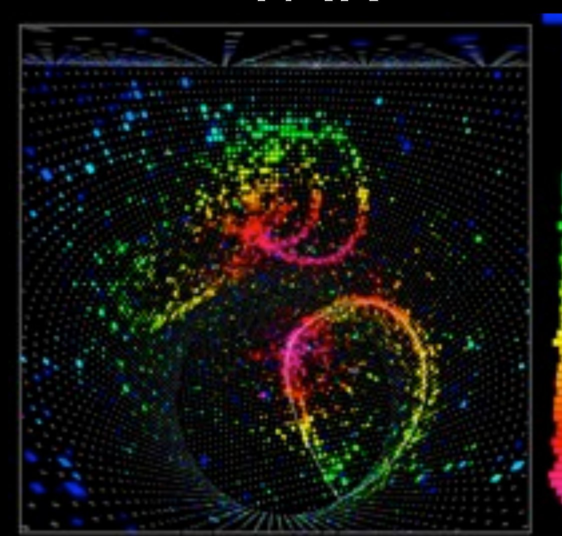

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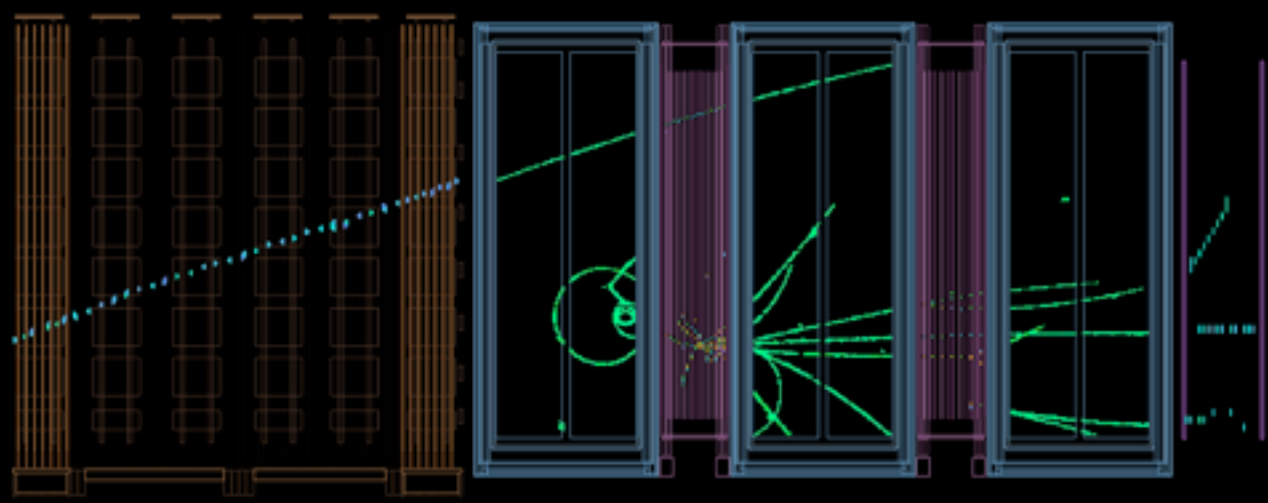

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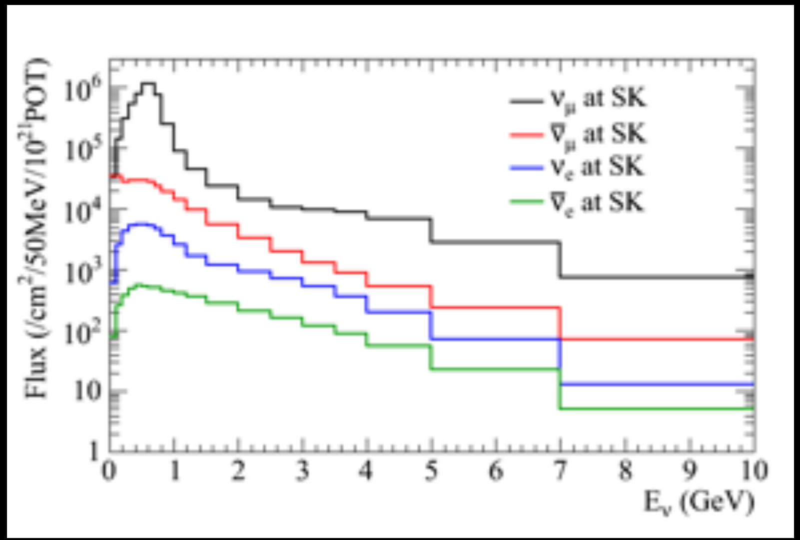
φ_ν



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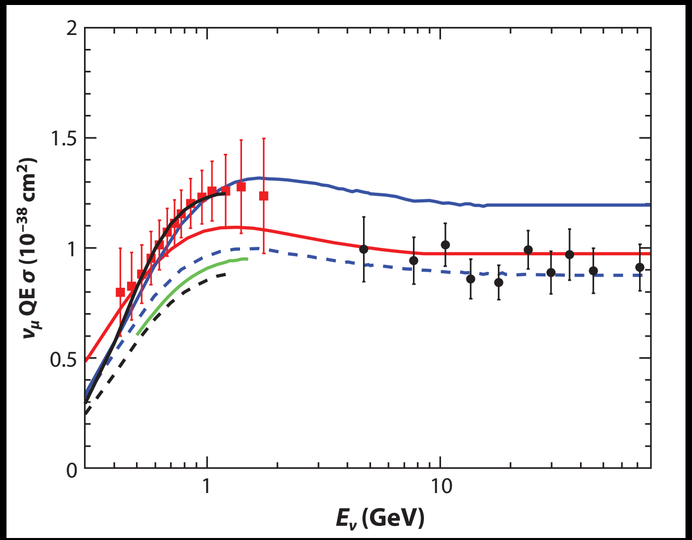

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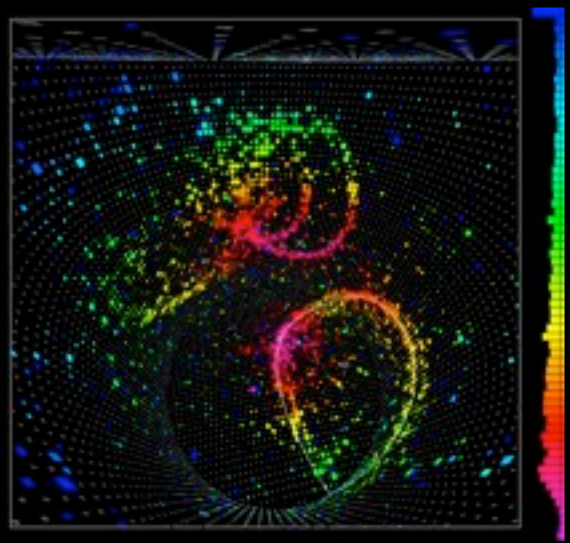

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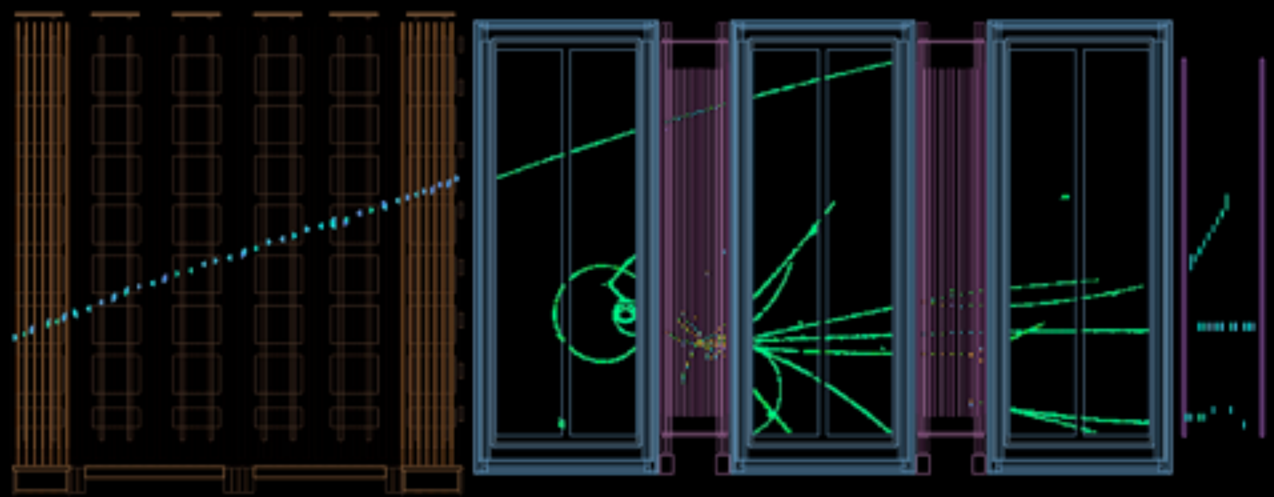

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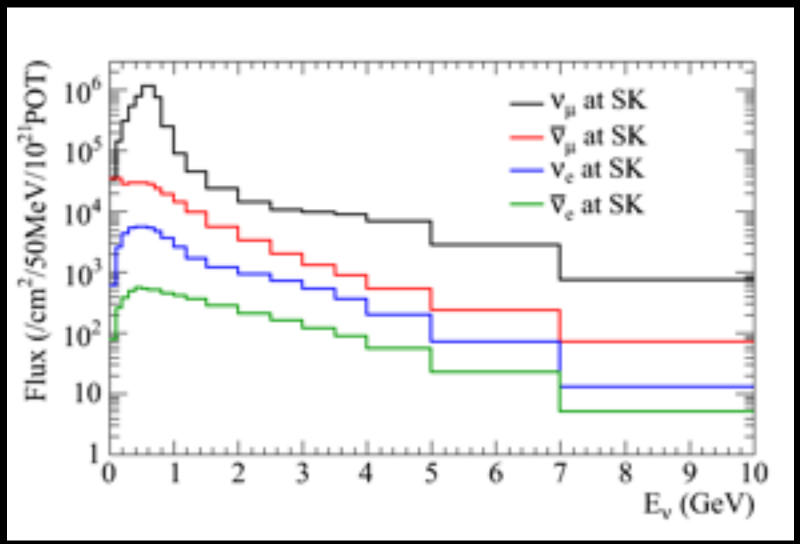

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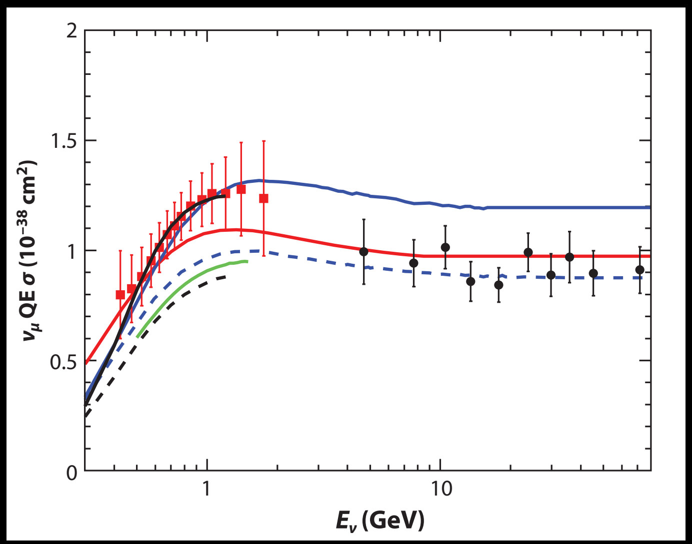

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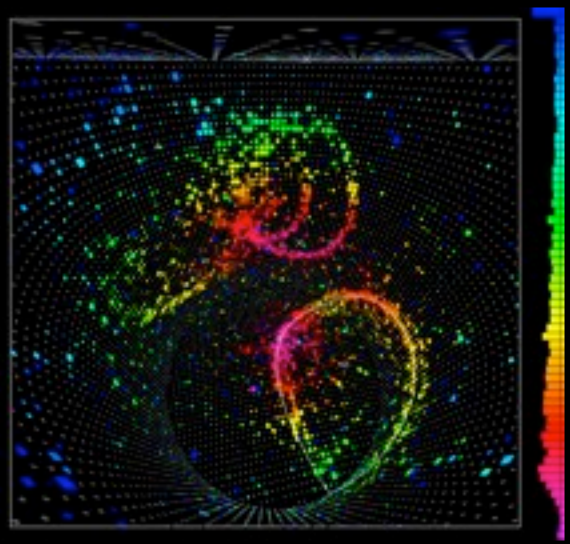
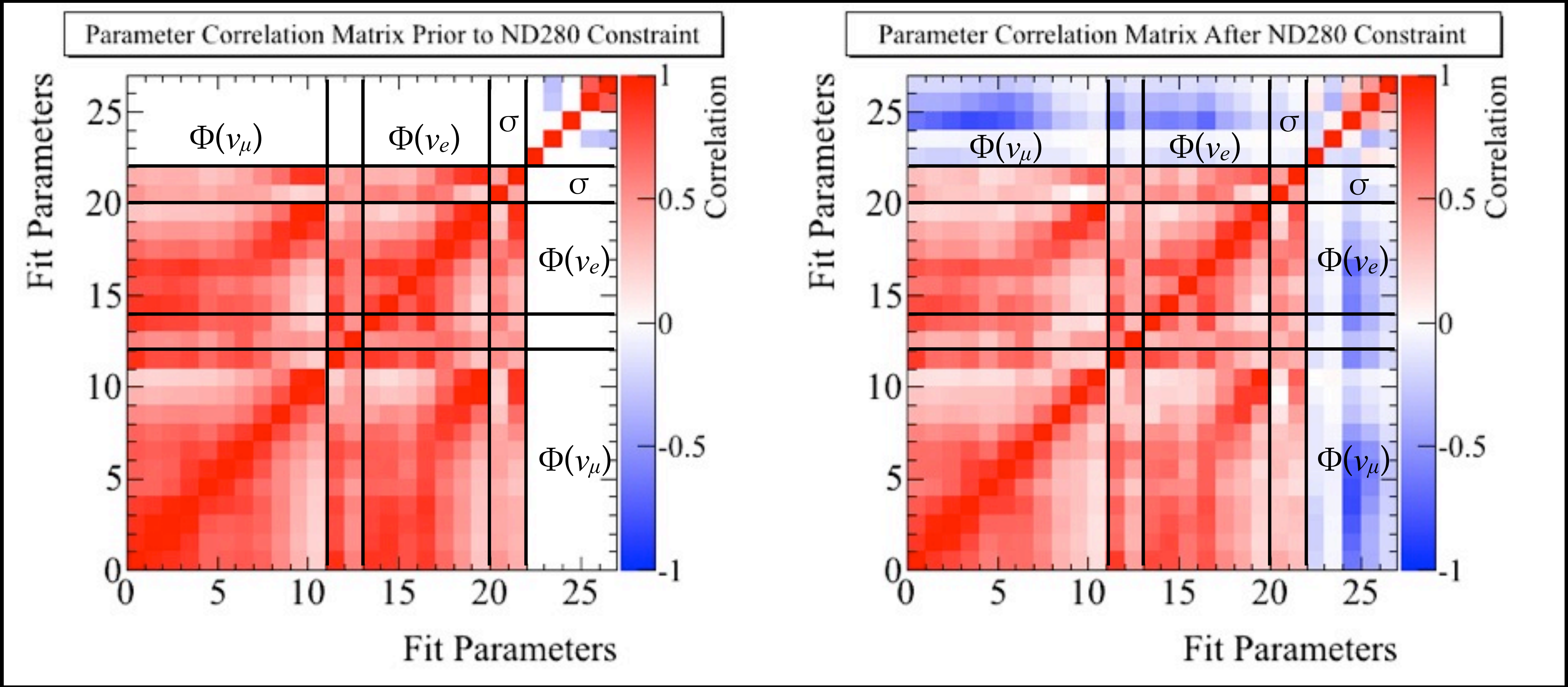


Detector simulation to determine efficiencies/ backgrounds

T2K ND fit

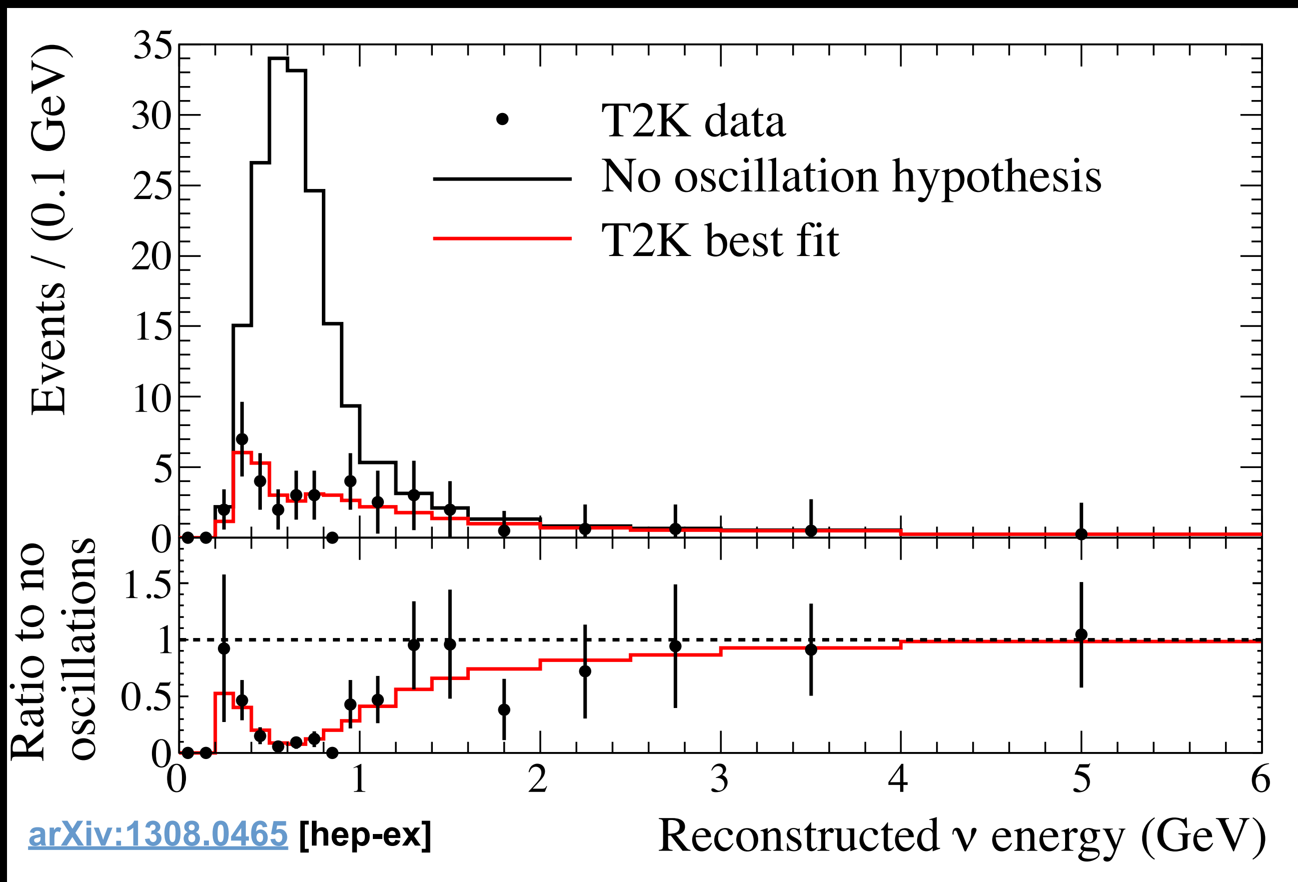
more details in D. Cherdack's talk

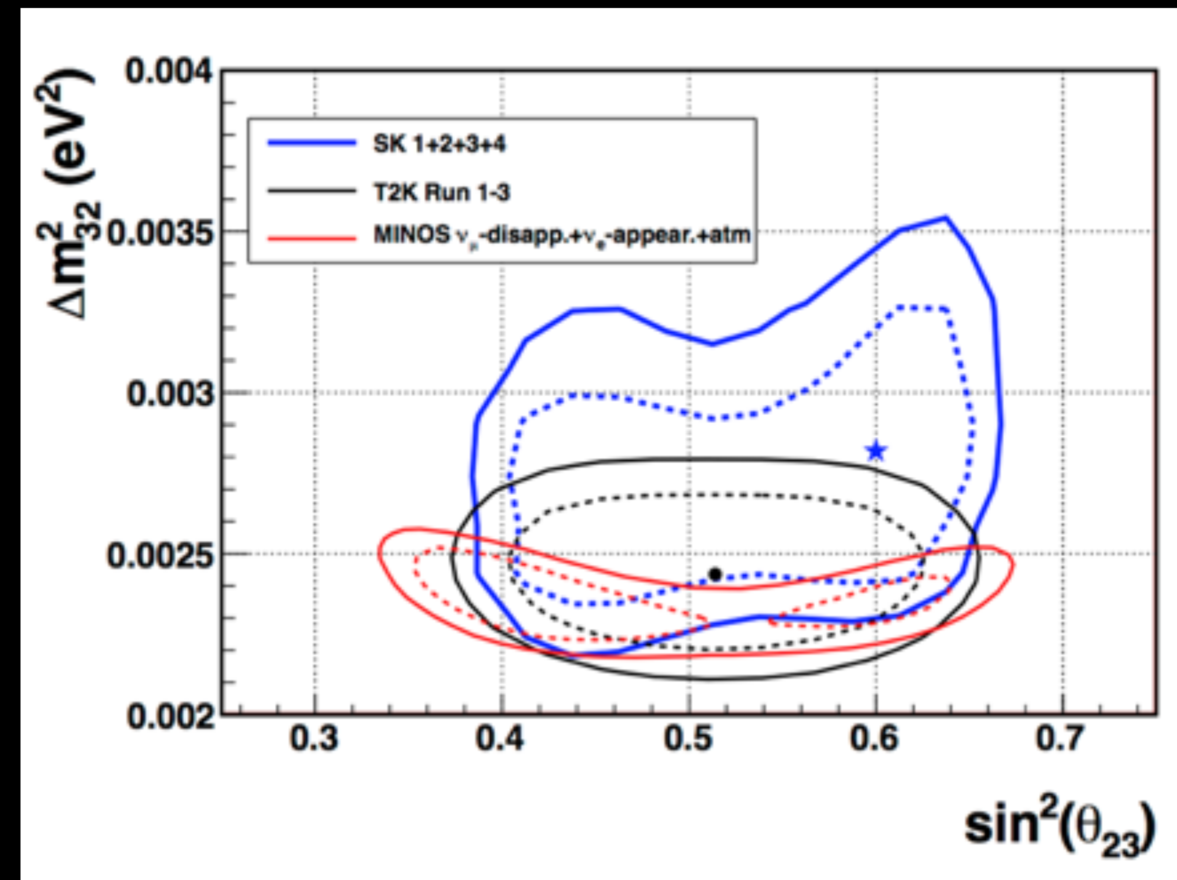


- Fit to ND data introduces anti-correlations between flux normalization (Φ) and ν cross section (σ) parameters
- partial cancellation in predicted rate from ~28% to ~9%
  - ~3% due to parameters directly constrained by the ND data
  - question of "dominant" uncertainties is non-trivial

ν_μ disappearance

more details in D. Cherdack's talk





$$P(\nu_\mu \to \nu_\mu) \quad = 1 \quad - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Delta m^2_{31}\frac{L}{4E}$$

- High precision means we must consider higher order terms
  - θ_{13}: now known to be not so small . . . . $\sin^2\theta_{13} \sim 0.03$
- Precision ν_μ disappearance will be a testing ground for latest developments in ν-int theory/modeling and associated systematics

Near Detector

Top/down

- Design near detector to
  - maximize near/far cancellation
  - minimize ν-int model dependence
- Advantages:
  - go directly to the issue without dealing with detailed ν-int physics
  - usually calls for similar/same near/far detector, simplifies analysis.
- Disadvantages:
  - there will always be some model dependence
  - data may not enlighten us on how to improve model (TLI)
    - how to estimate systematics with model you don't believe

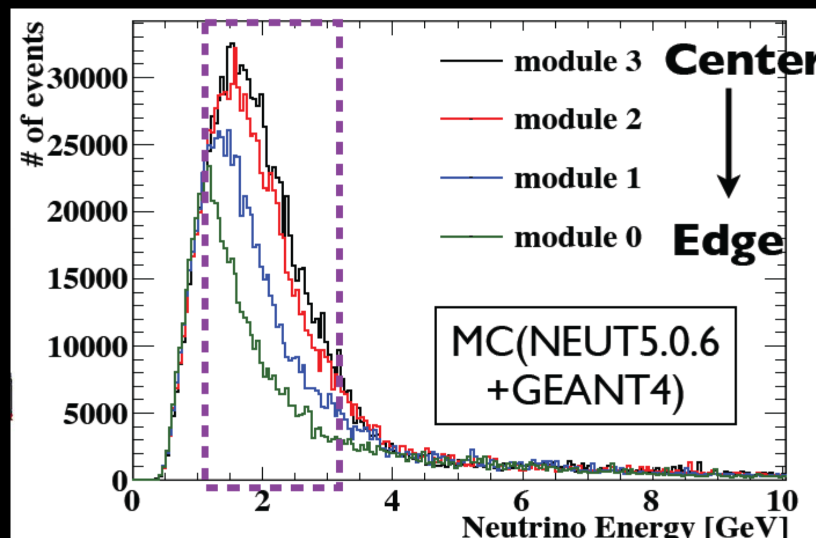
Bottom/up

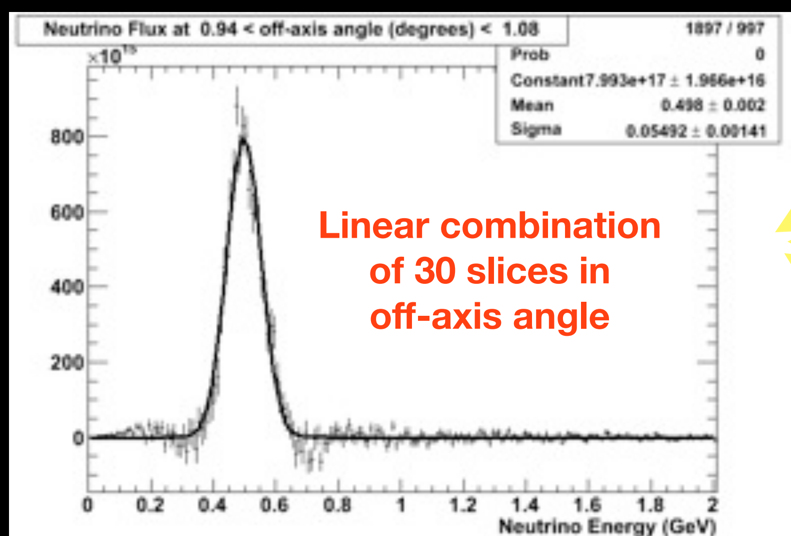
- Design near detector to
  - study details of ν-int interactions
  - advance theory and modeling
- Advantages
  - more freedom to design detector to optimize "information"
  - more information to understand and verify ν-int model
- Disadvantages:
  - may not tell you what you need to impact osc. physics immediately
  - detector/analysis may be more complicated (TMI), substantially different from far detector

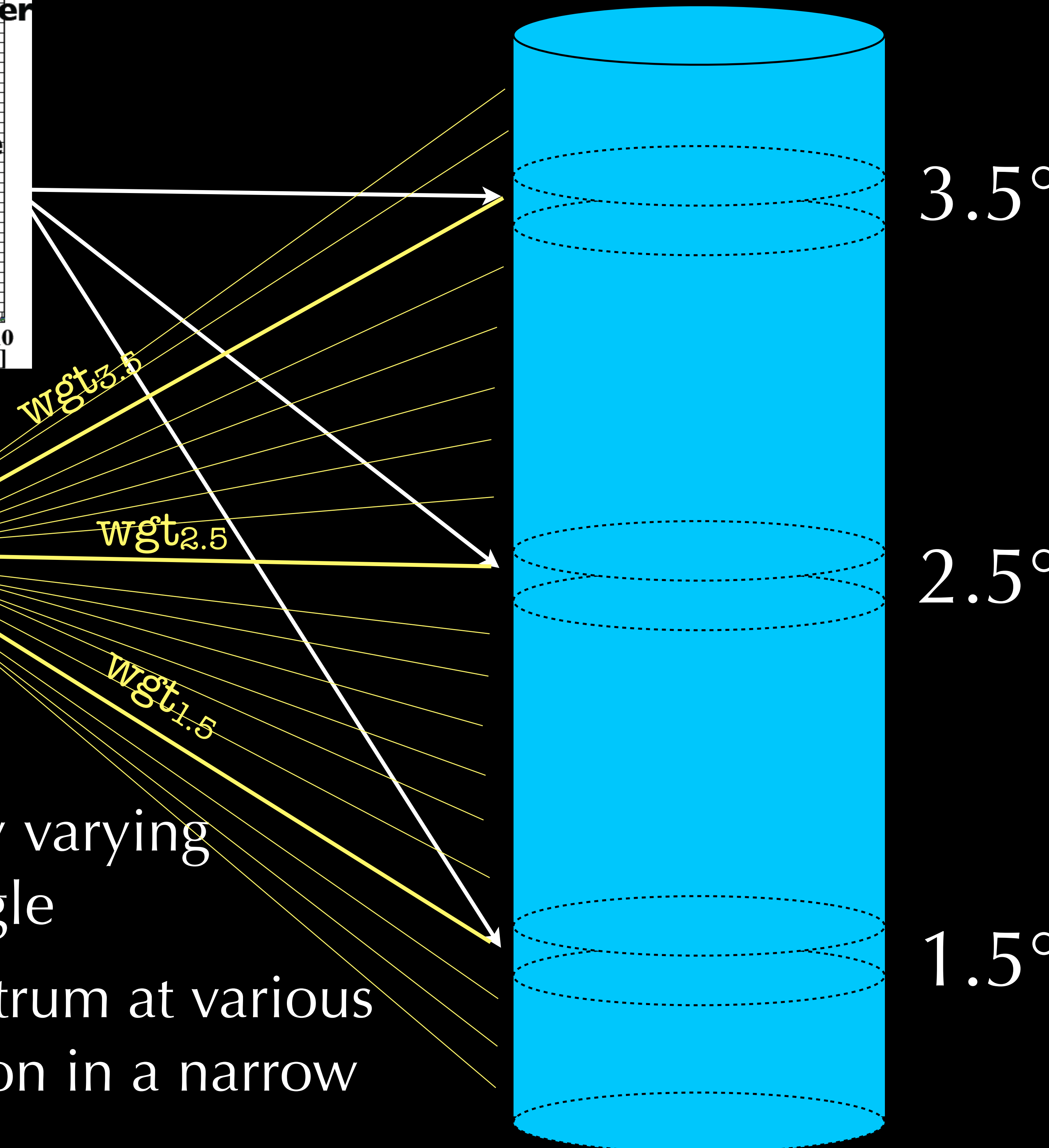
- Which is better? "both" (and not exclusive)

Neutrino Prism:

see poster by M. Hartz, M. Wilking for more details

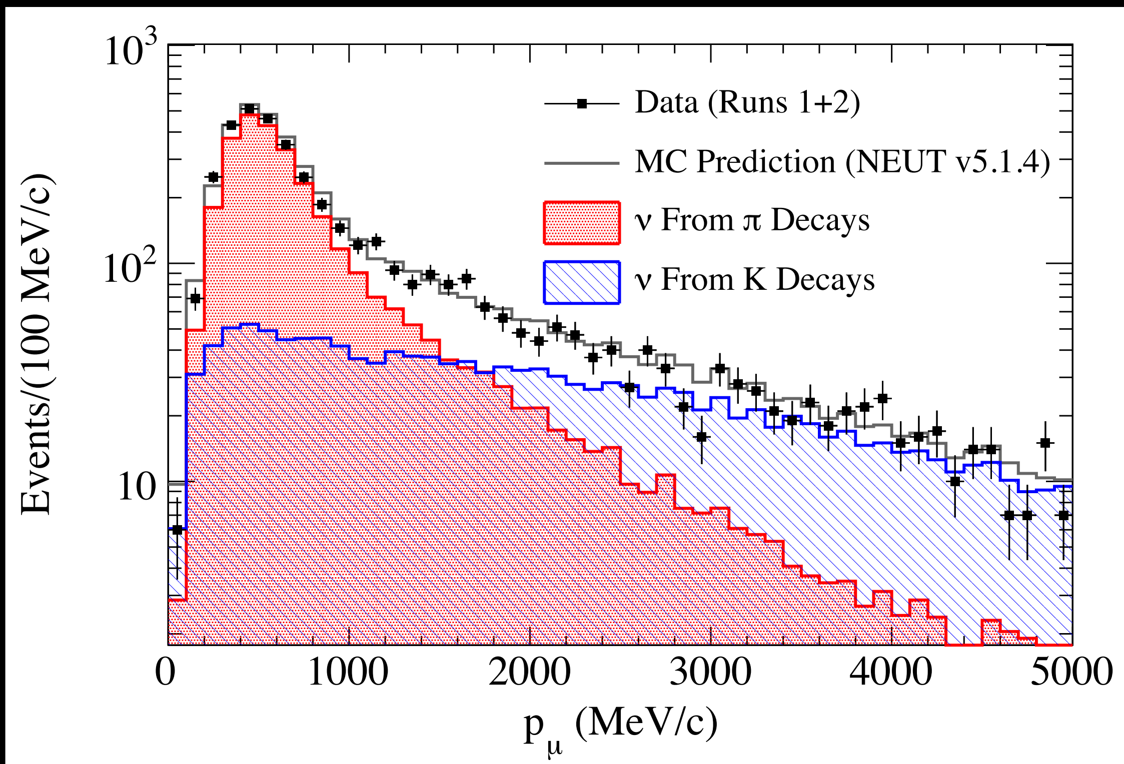


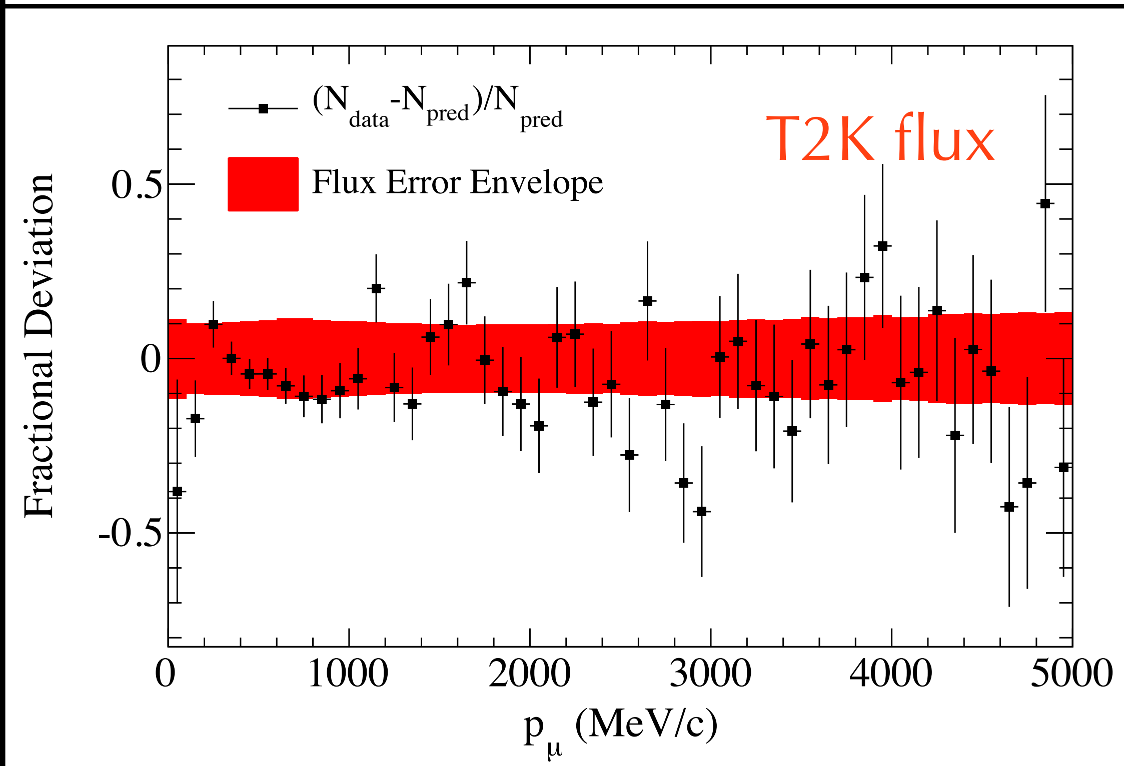


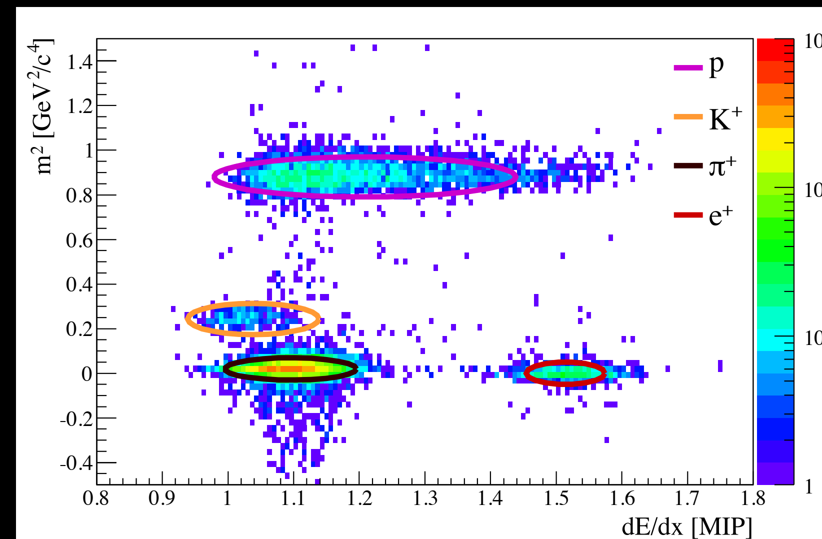


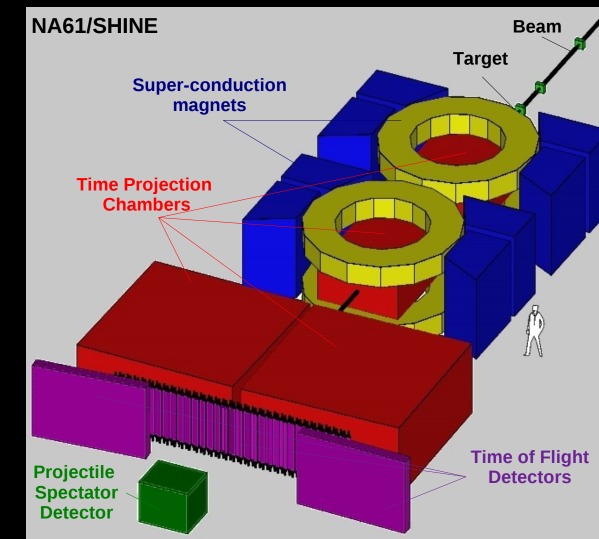
- Off-axis effect gives continuously varying neutrino energy spectrum vs. angle
- Linear combinations of flux spectrum at various angles maps kinematic distribution in a narrow neutrino energy band
- “Model independent” measurement

NA61



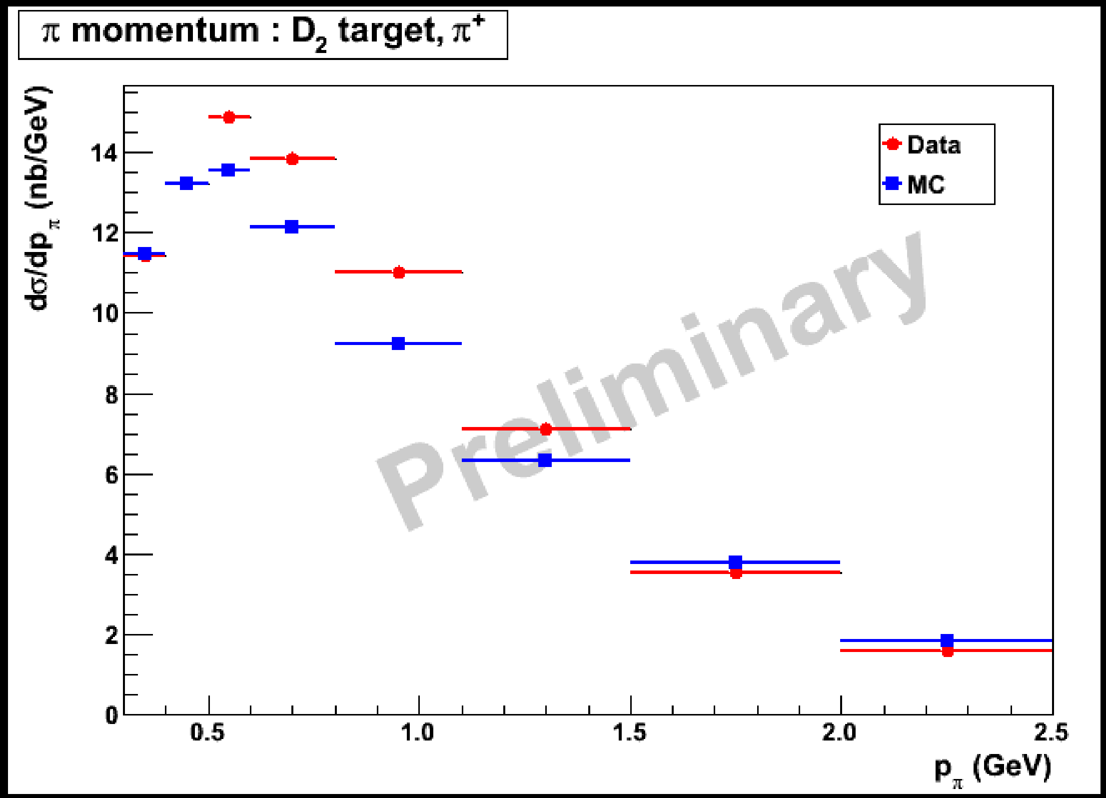


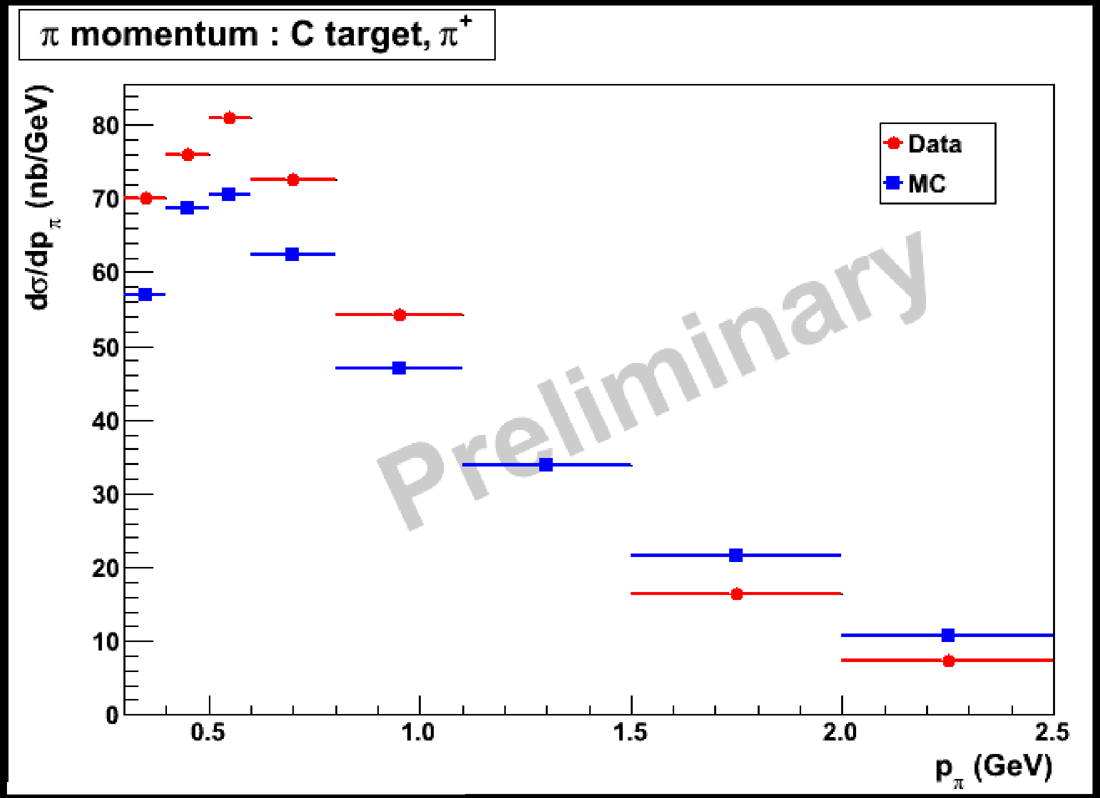




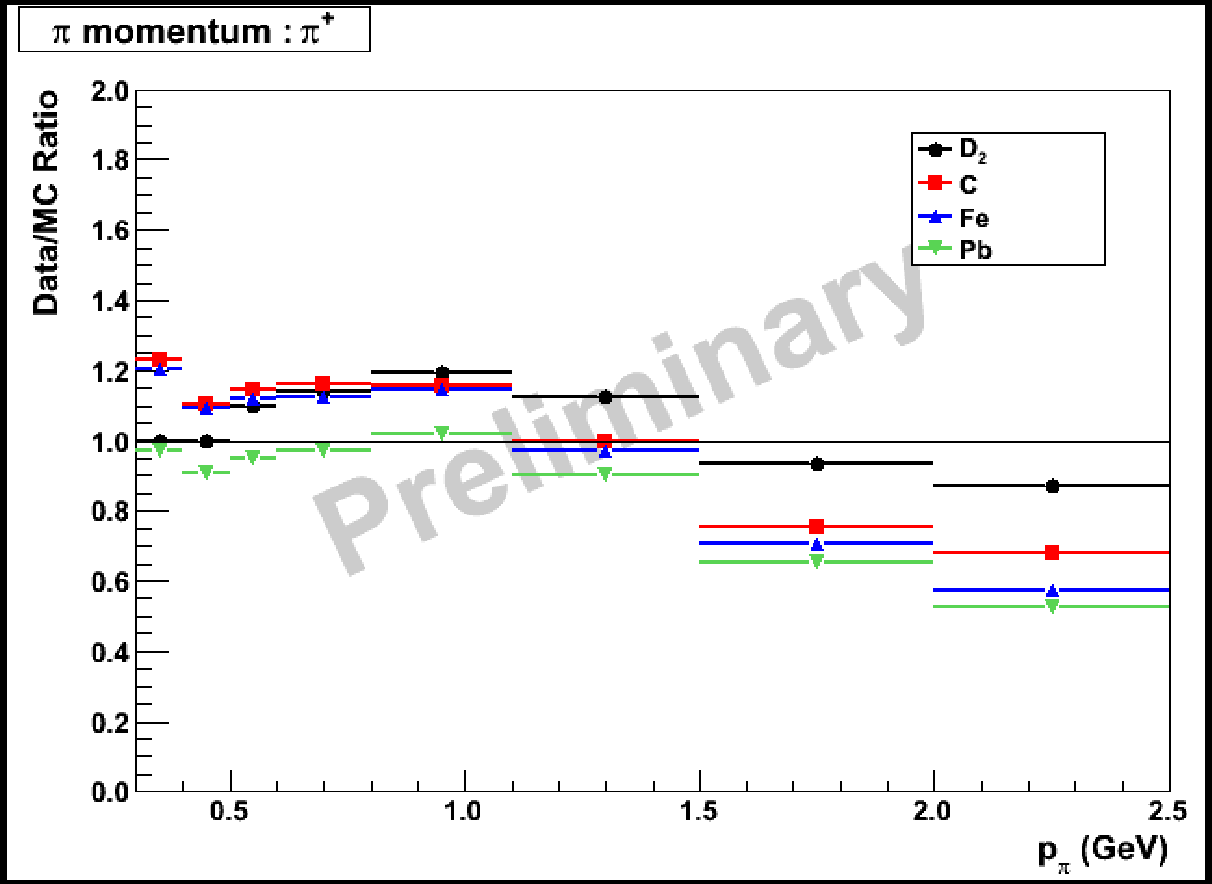
- Flux predictions will continue(?) to be a fundamental pillar for neutrino cross section/interaction physics
- Hadron production experiment(s) are essential for accurate predictions
- Can we make NA61 the ultimate hadron production experiment?
  - Are there other measurements needed/possible to reduce errors?
  - (pion scattering/absorption . .)
  - test beams for detector performance.

e-A scattering and νSTORM





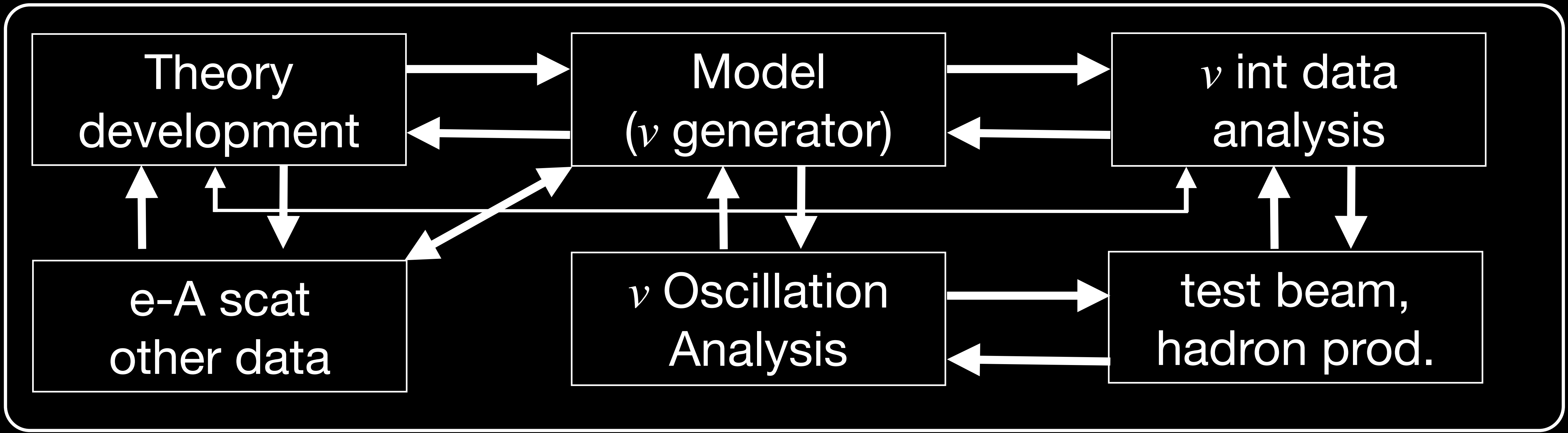
S. Manly
NuFact 2013
comparison to
Genie e-A scat.



- e-A scattering data may be a fruitful testing ground of FSI models
  - data over large range of target nuclei
  - first results from CLAS
    - an enormous effort to understand CLAS analysis tools
- Potential of μSR-based neutrino sources for ν-int should be further explored

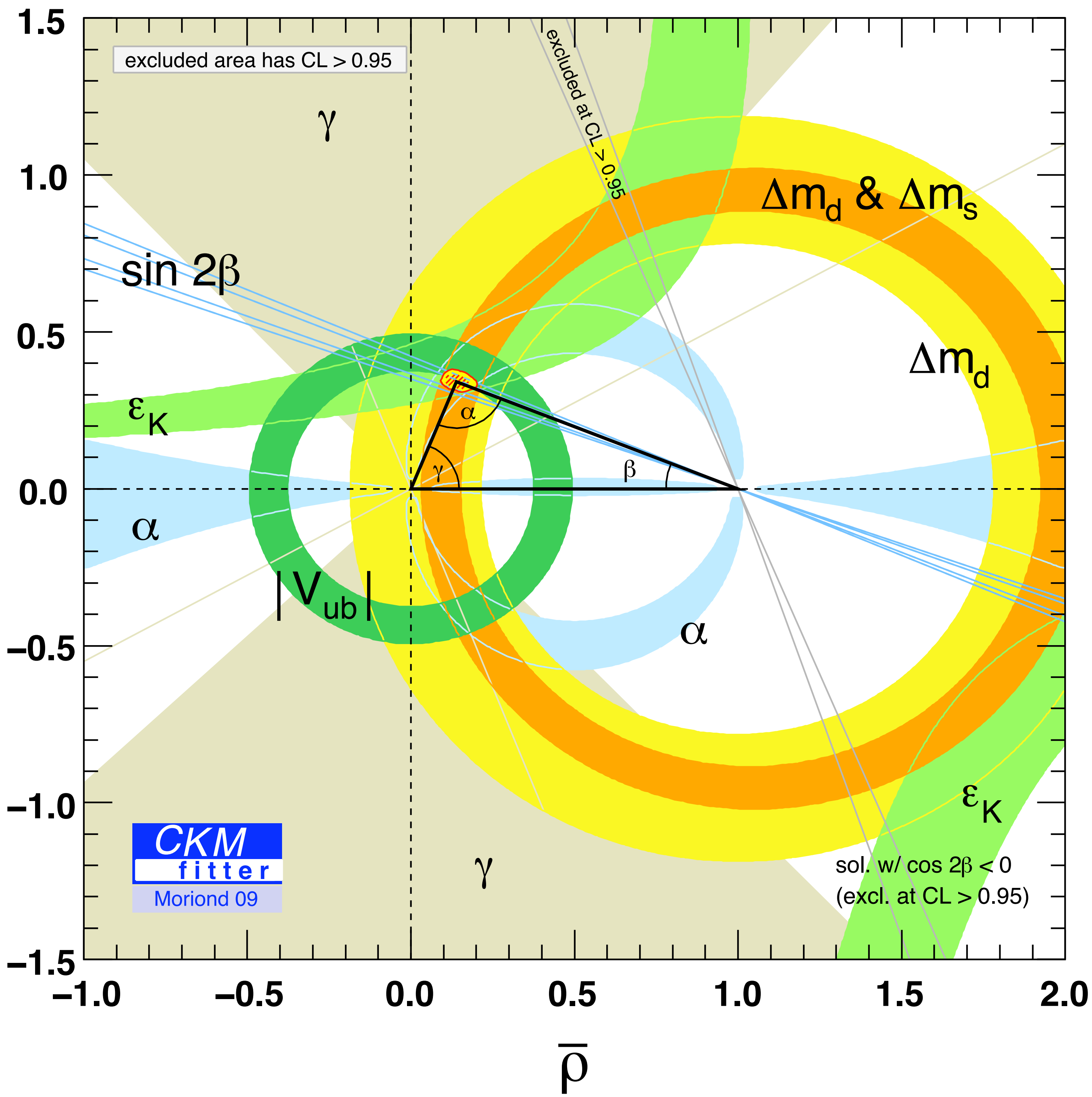
Synthesis

adapted from D. Schmitz (FNAL W&C)



- better theory may not immediately result in "improvement"
  - worse model may "effectively" better reproduce the data
  - better theory may improve certain parts, but leave out other issues
    - example: spectral function?
- as a community we need to improve the flow. . . .
  - smoother/porous interface at theory/generator interface
  - lots of progress recently, but we need to continue to improve and support

Looking ahead:



We need to do this in the lepton sector!

A. Gouvêa ISOUPS 2013

“this” = “overconstrain” the mixing matrix
find/rule out new physics

Theory

- To look for "new" physics, we need know the "old" physics.
  - a few "golden modes" (e.g. B→ψK) with minimal theoretical issues
  - beyond that, QCD corrections were often very complicated and difficult
    - even "silver" modes like b→sγ required extremely complicated calculations to predict (beyond-)SM branching fractions
- Enormous effort invested into developing the necessary theoretical tools
  - lattice QCD (masses, form factors)
  - heavy quark effective theory and other factorization schemes
  - sum rules, etc.
  - other "work arounds" like ratios, isospin decomposition, etc.

circa 2002	$B^0 \to K^{*0}\gamma$	$B^+ \to K^{*+}\gamma$	$B^0 \to \rho^0\gamma$	$B^+ \to \rho^+\gamma$
Theory	7.1 ± 2.5	7.5 ± 2.5		0.16 ± 0.05
	7.9 ± 3.5	7.9 ± 3.5		
	7.2 ± 2.7	7.2 ± 2.7	0.049 ± 0.017	0.085 ± 0.30
Experiment	$4.55^{+0.72}_{-0.68} \pm 0.34$	$3.76^{+0.89}_{-0.83} \pm 0.28$	< 1.7	< 1.3
	$4.96 \pm 0.67 \pm 0.45$	$3.89 \pm 0.93 \pm 0.41$	< 1.06	< 0.99

Quarks and Leptons

- LBL experiments should make a similar investment into fundamental neutrino interaction physics to deliver on our promises
- The quark sector has a few advantages:
  - QCD is "particle physics".
    - Much of ν-int physics is separated by particle/nuclear divide
    - cultural/social/funding/hosting issues
  - To a large extent, theory/experimental effort factorized
    - i.e. detailed theory wasn't needed to make the measurement
    - we are heavily dependent on the theory (via generators) to tell us what to measure, estimate systematic errors, etc.
- Where there is a clear opportunity, theory has delivered
  - fully embrace and support the theory we need, articulate the scientific opportunities, and push for it!

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We need to do <u>this</u> in the lepton sector!

Conclusions

- Many exciting upcoming opportunities in neutrino physics
  - CP violation, mass hierarchy, θ_{23} octant . . . and beyond?
  - Our detailed understanding of O(1 GeV) neutrino interactions will play a crucial role in getting at the "particle" physics
    - can we ensure that we will not be hampered by ν-int uncertainties?
    - Good news is that T2K/NOvA give us regular "check-ups" on progress
- Exciting opportunity to make fundamental advances in ν-int
  - can we actually reach a denouement on some of the issues?
  - forge /cultivate long-term/continuous collaboration with nuclear theory
  - ensure related/necessary measurements/analyses are carried through
    - hadron production, νSTORM?
    - test beams, electron/photoproduction data?
    - explore broadly new near detector concepts
      - start now . . . ?

T2K ν_e events

	$\sin^2 2\theta_{13}=0.1$		$\sin^2 2\theta_{13}=0$	
	ν_e Prediction (Events)	Error from Constrained Parameters	ν_e Prediction (Events)	Error from Constrained Parameters
No ND280 Constraint	22.6	26.5%	5.3	22.0%
ND280 Constraint (2012, Runs 1-3)	21.6	4.7%	5.1	6.1%
ND280 Constraint (this analysis)	20.4	3.0%	4.6	4.9%
Total error (all sources)		8.8%		11.1%

- Near detector constrain can significantly reduce overall rate uncertainty
- Uncertainties now dominated by:
  - uncorrelated/unpropagated ν interaction uncertainties
  - detector uncertainties
  - final state/secondary interactions uncertainties
- “Work in progress”: will continue to improve, but where do we bottom out?

T2K error budget

Black: 2013
Blue: 2012

	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
Beam only	10.6 10.8	7.3 7.5	11.6 11.9	7.5 8.1
M_A^{QE}	15.6 9.5	2.4 4.0	21.5 16.3	3.2 6.7
M_A^{RES}	7.2 4.5	2.1 3.9	3.3 2.0	0.9 1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1 4.9	4.8 3.8	9.3 7.9	6.3 6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9 5.1	2.4 3.5	4.2 5.2	2.0 3.5
NC1π^0 norm.	2.7 7.9	1.9 7.3	0.6 2.3	0.4 2.2
CC other shape	0.3 0.2	0.3 0.2	0.1 0.1	0.1 0.1
Spectral Function	4.7 3.3	4.8 3.3	6.0 5.7	6.0 5.7
p_F	0.1 0.3	0.1 0.3	0.1 0.0	0.1 0.0
CC coh. norm.	0.3 0.2	0.3 0.2	0.3 0.2	0.2 0.2
NC coh. norm.	1.1 2.1	1.1 2.0	0.3 0.6	0.2 0.6
NC other norm.	2.3 2.6	2.2 2.6	0.5 0.8	0.5 0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4 1.8	2.4 1.8	2.9 2.6	2.9 2.6
W shape	1.0 1.9	1.0 1.9	0.2 0.8	0.2 0.8
pion-less Δ decay	3.3 0.5	3.1 0.5	3.7 3.2	3.5 3.2
SK detector eff.	5.7	5.6	2.4	2.4
FSI	3.0	3.0	2.3	2.3
PN	3.6	3.5	0.8	0.8
SK momentum scale	1.5	1.5	0.6	0.6
Total	24.5	11.1	28.1	8.8