Near Detectors for Long Baseline Oscillation Experiments

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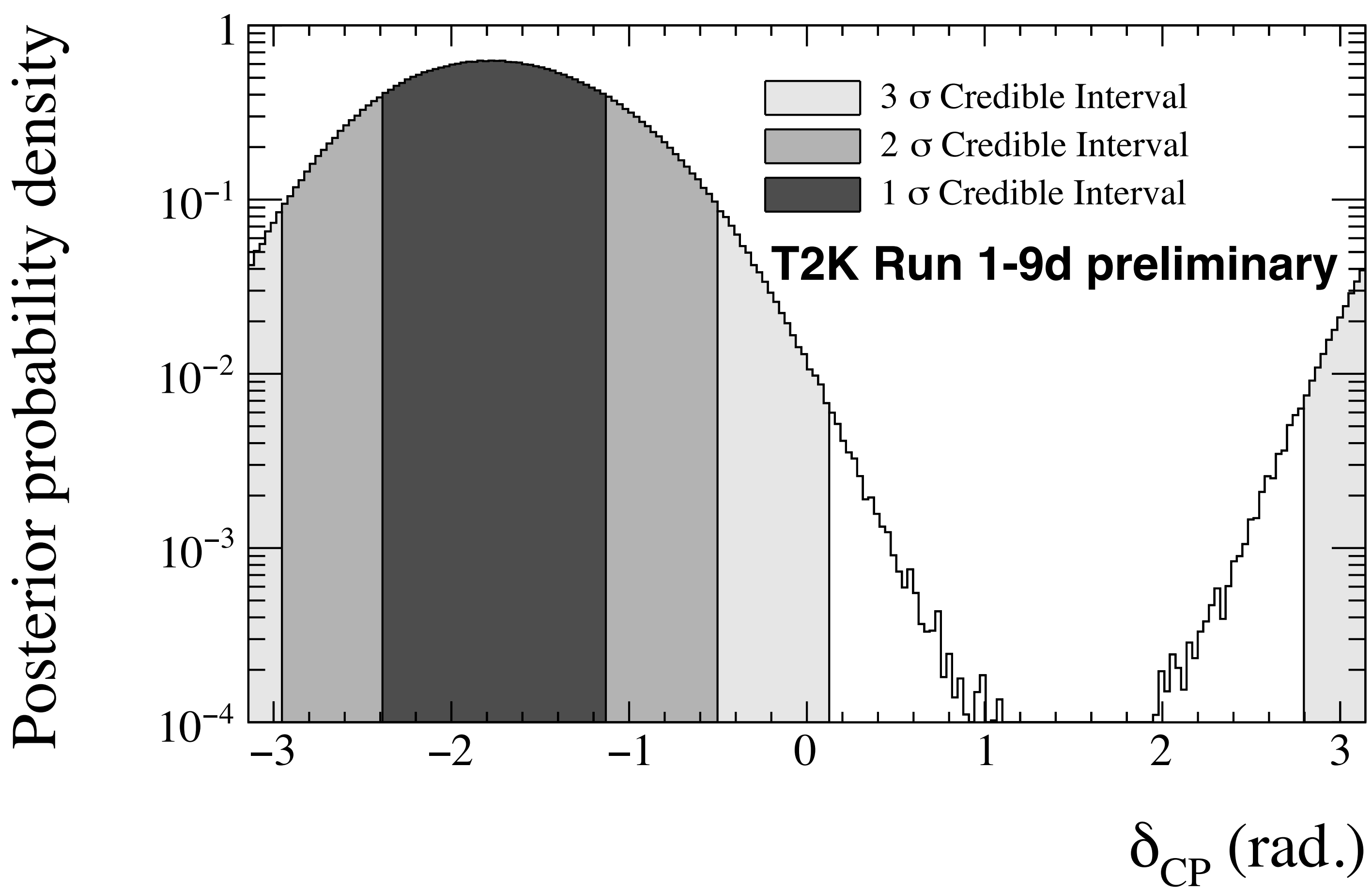
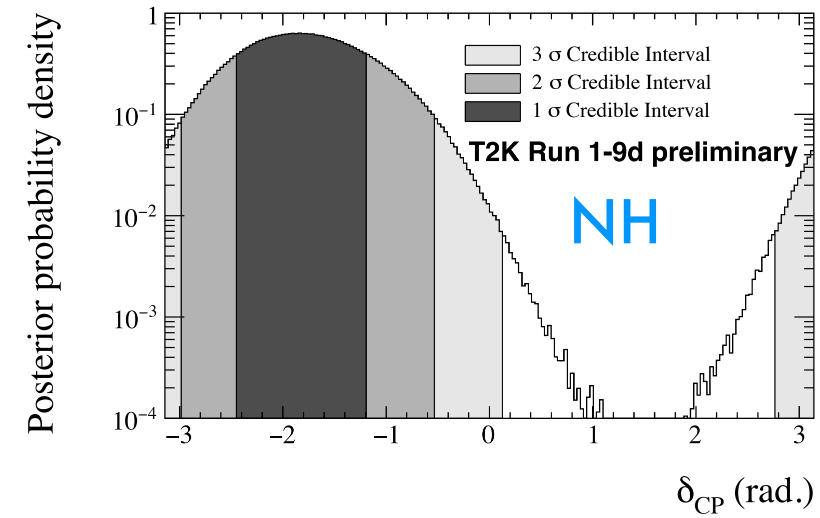
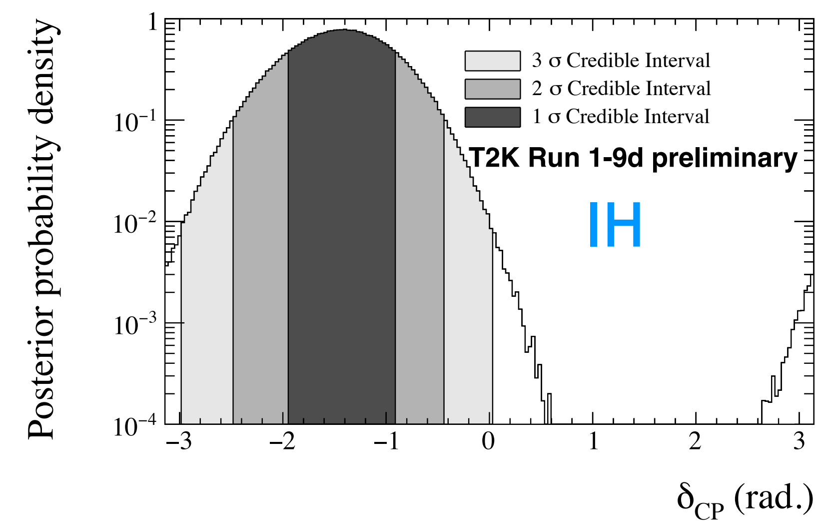
10 April 2019

CP Violation

Results shown are for with reactor constraint; T2K only in back up



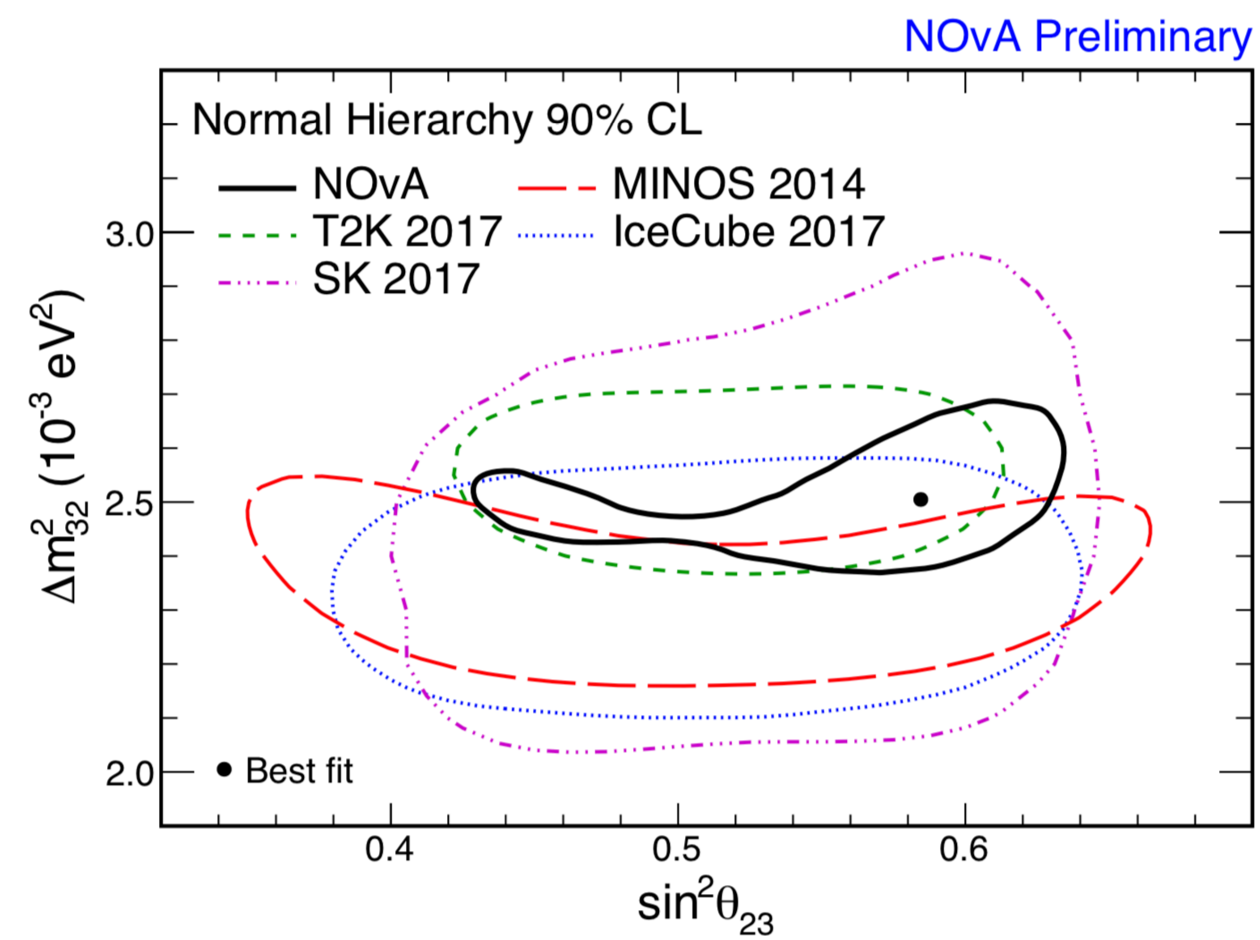




- There is a hint from T2K that δ_{CP} is not $0/\pi$
- Should we trust this result?

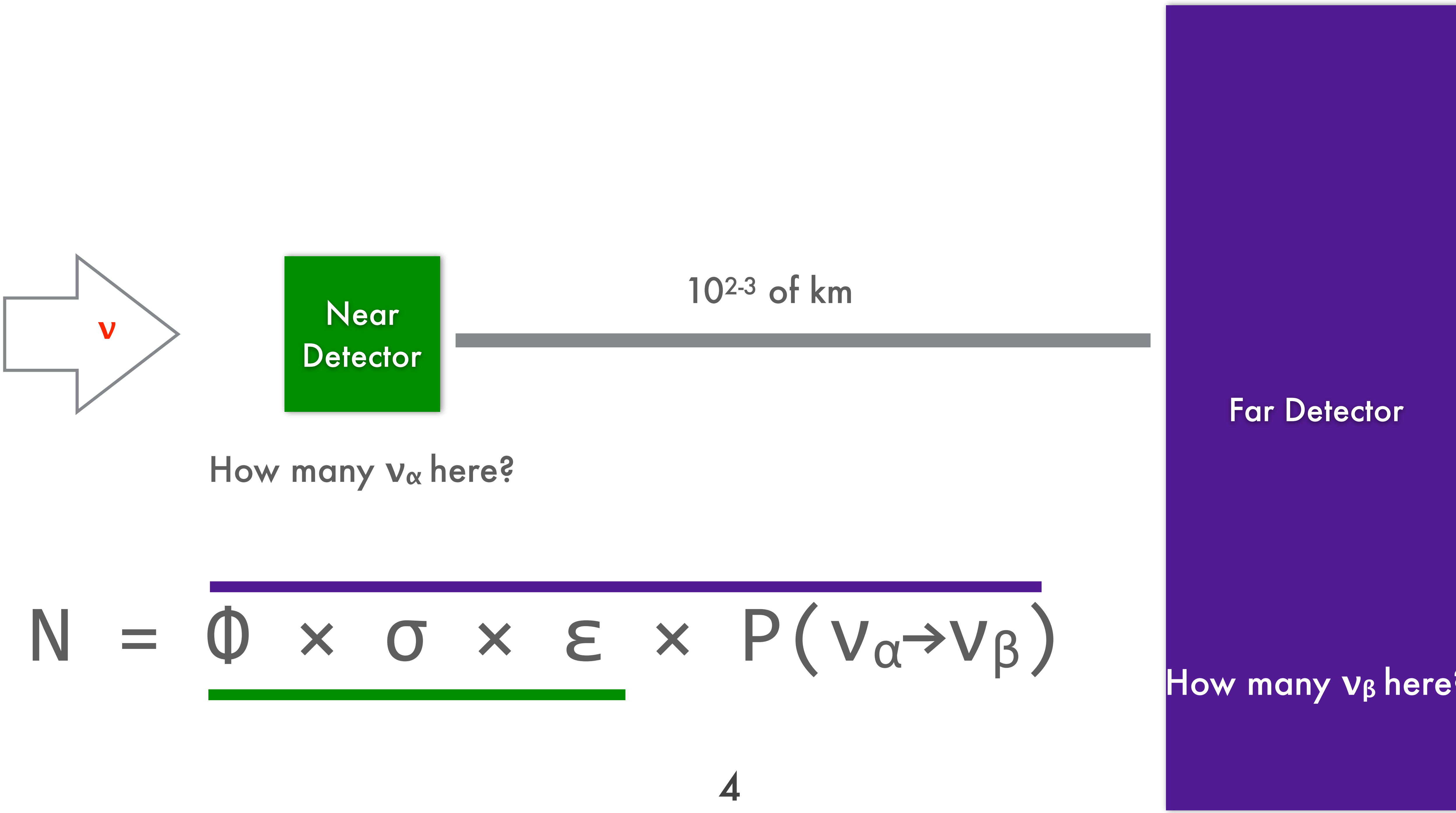
Disappearance Sector

- NOvA results prefer non-maximal mixing
- Very narrow result in Δm^2_{32}
- Should we trust this result?



Prefer NH at 1.8σ (T2K similar)

Oscillation Experiments in a Nutshell



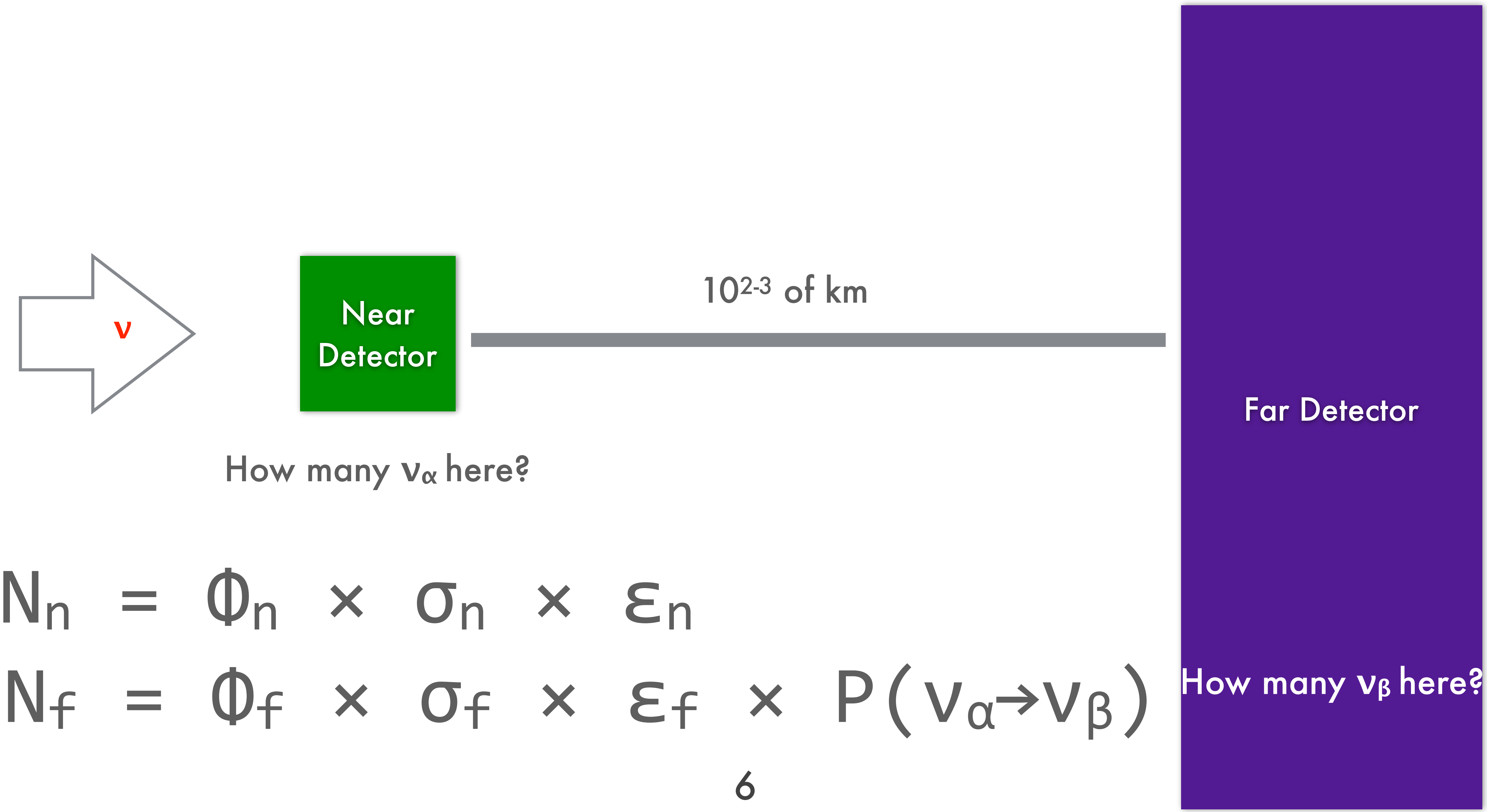
$$N = \Phi \times \sigma \times \varepsilon \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Why Is This Hard?

QCD RUINS EVERYTHING

Non-perturbative!
Ancient data!
Axial currents!
Effective parameters!
A-scaling is hard!

Oscillation Experiments in a Nutshell

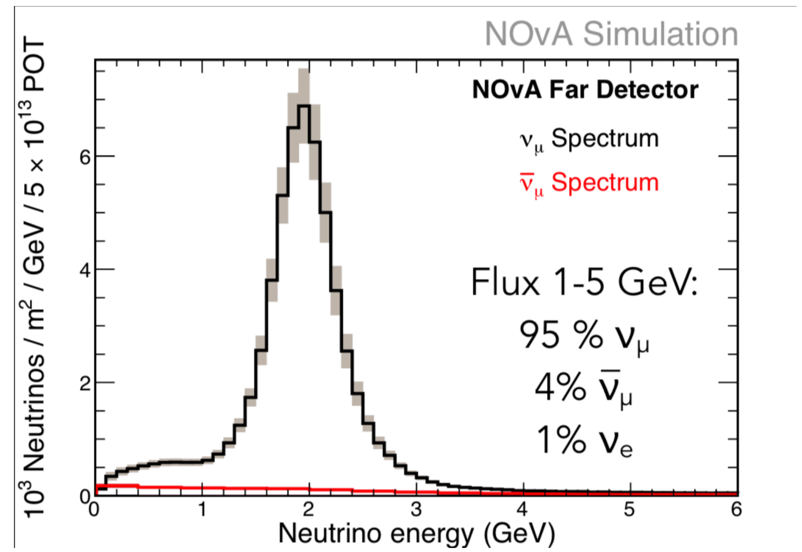


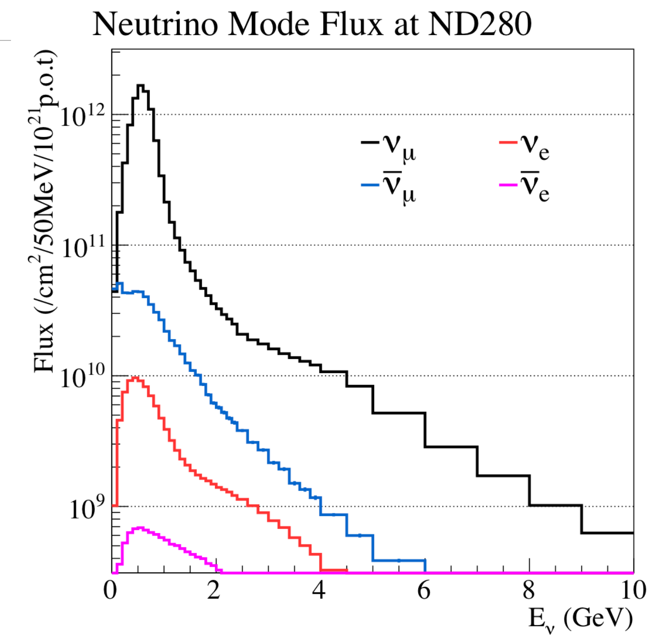
$$N_n = \Phi_n \times \sigma_n \times \varepsilon_n$$

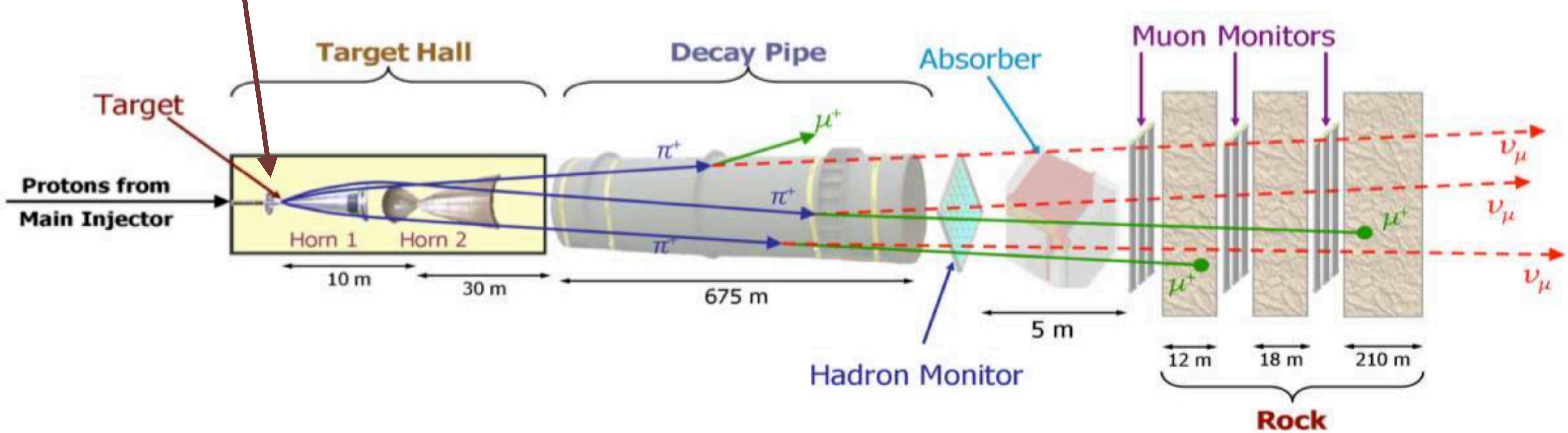
$$N_f = \Phi_f \times \sigma_f \times \varepsilon_f \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Neutrino Beam

QCD Lives Here

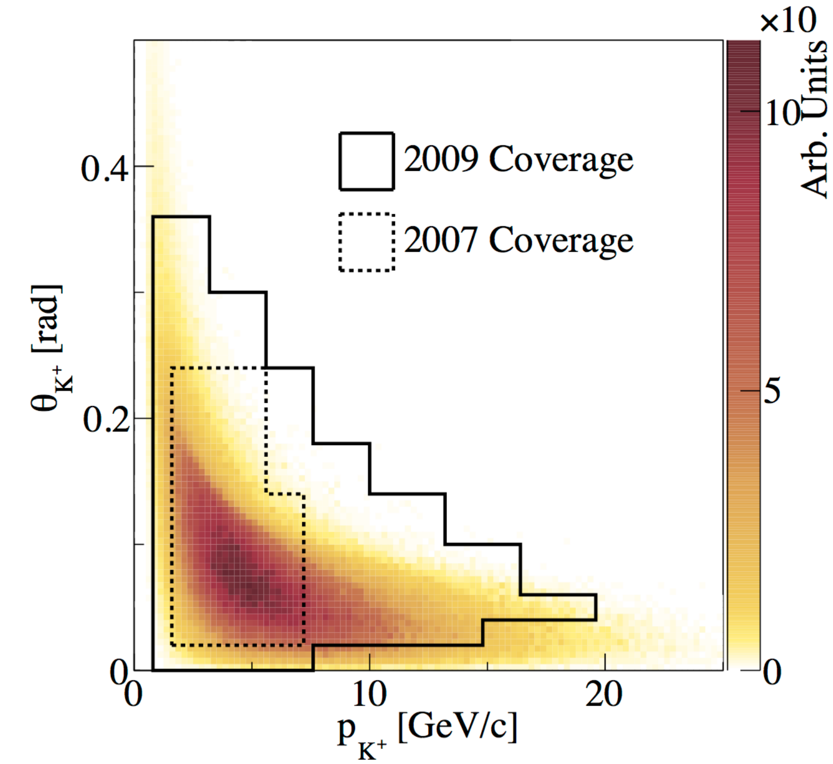


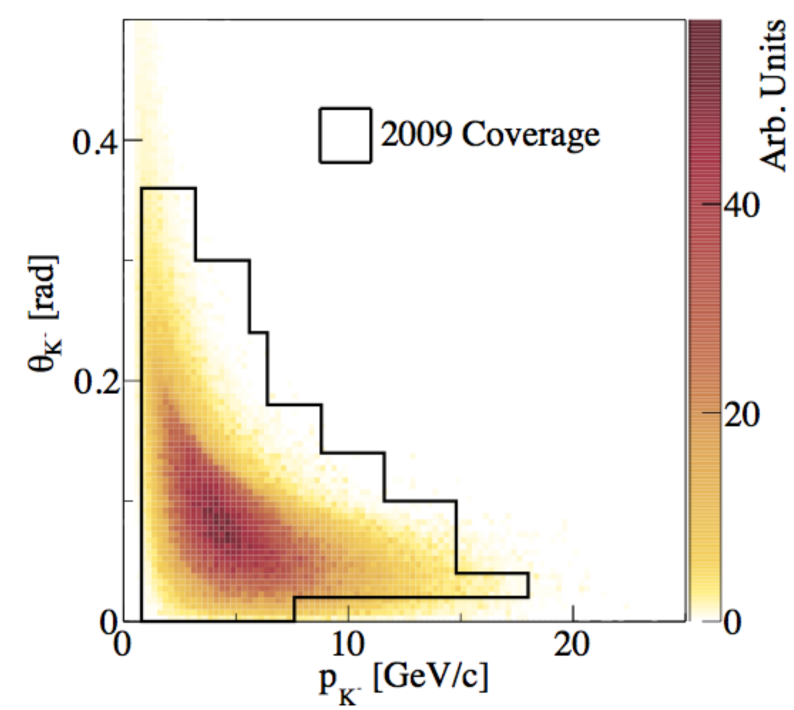




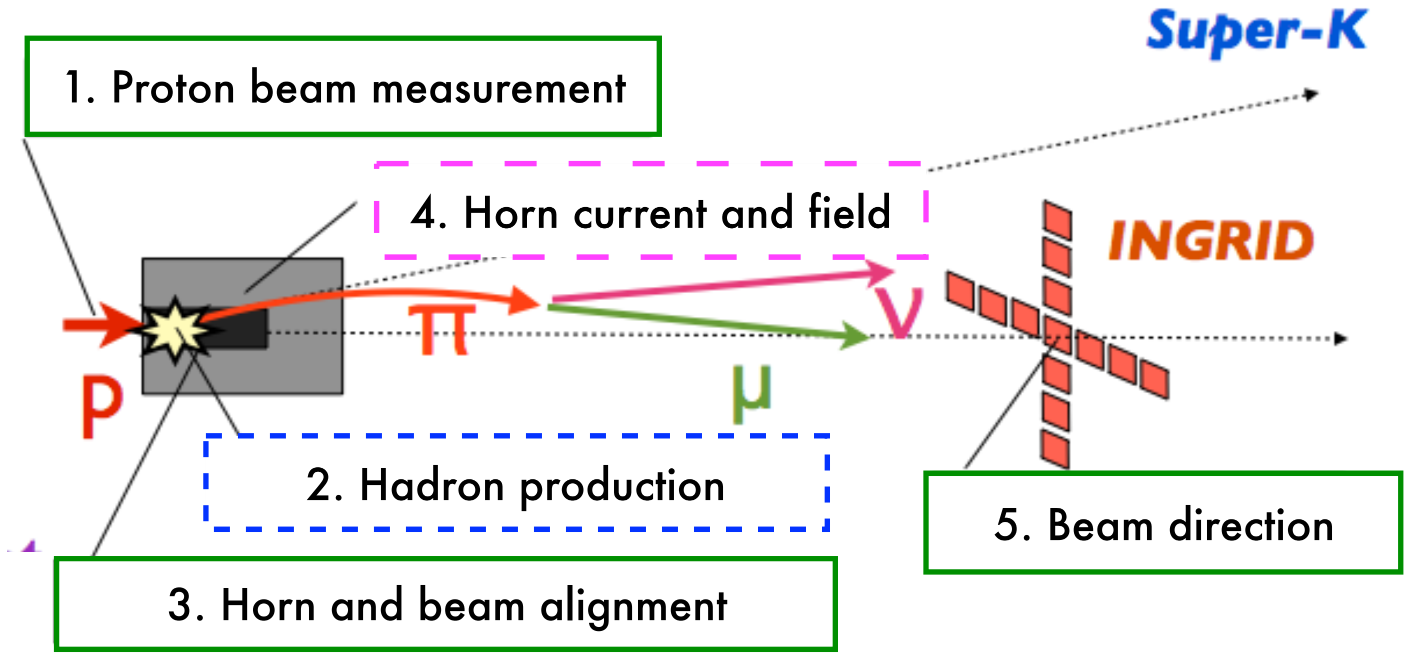
Hadronic Uncertainties

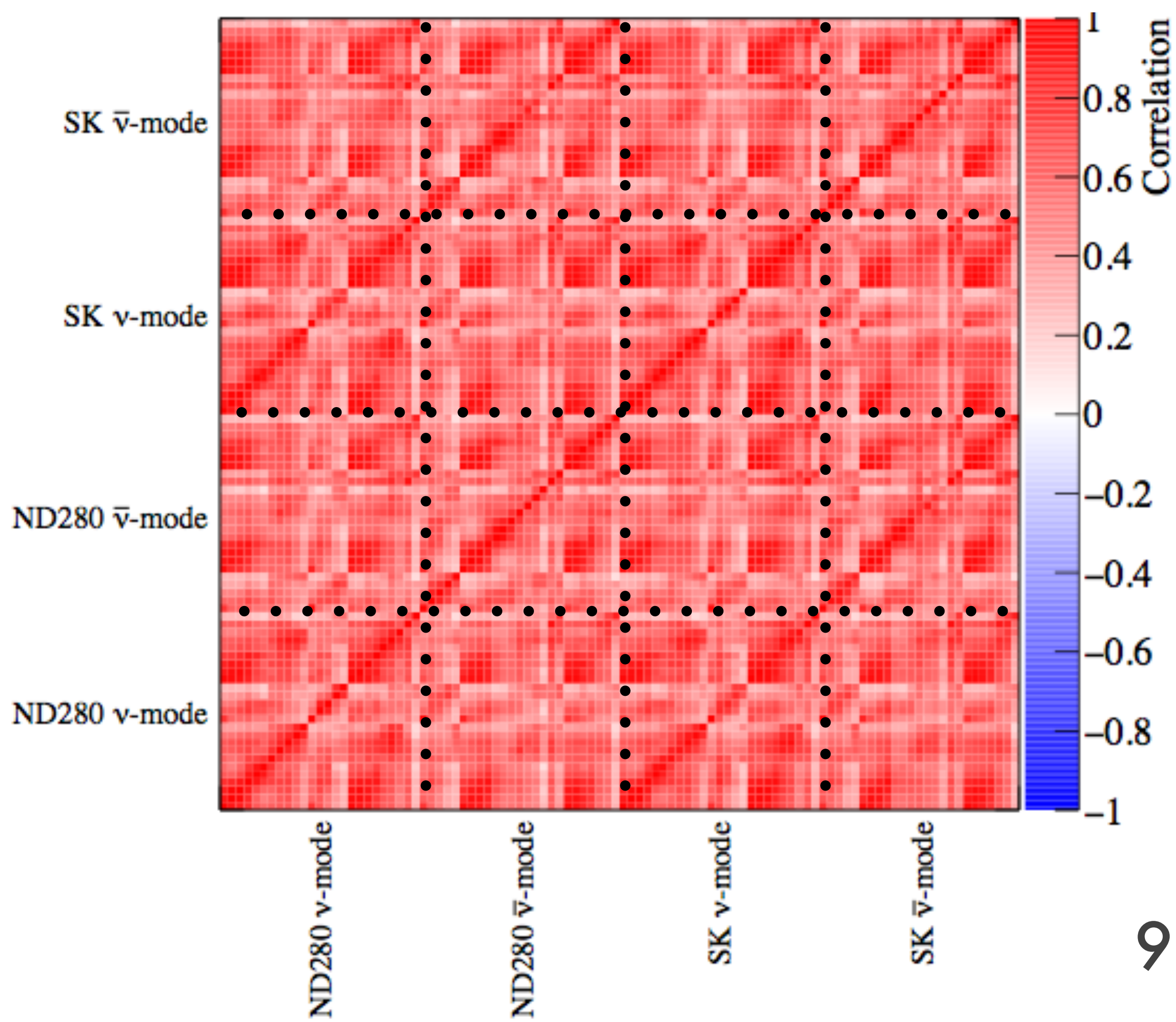
- Long baseline experiments use associated hadronic production experiments (e.g. NA61/SHINE) to constrain pion/kaon production
- Still need to extrapolate from phase space of associated experiments to full beam line

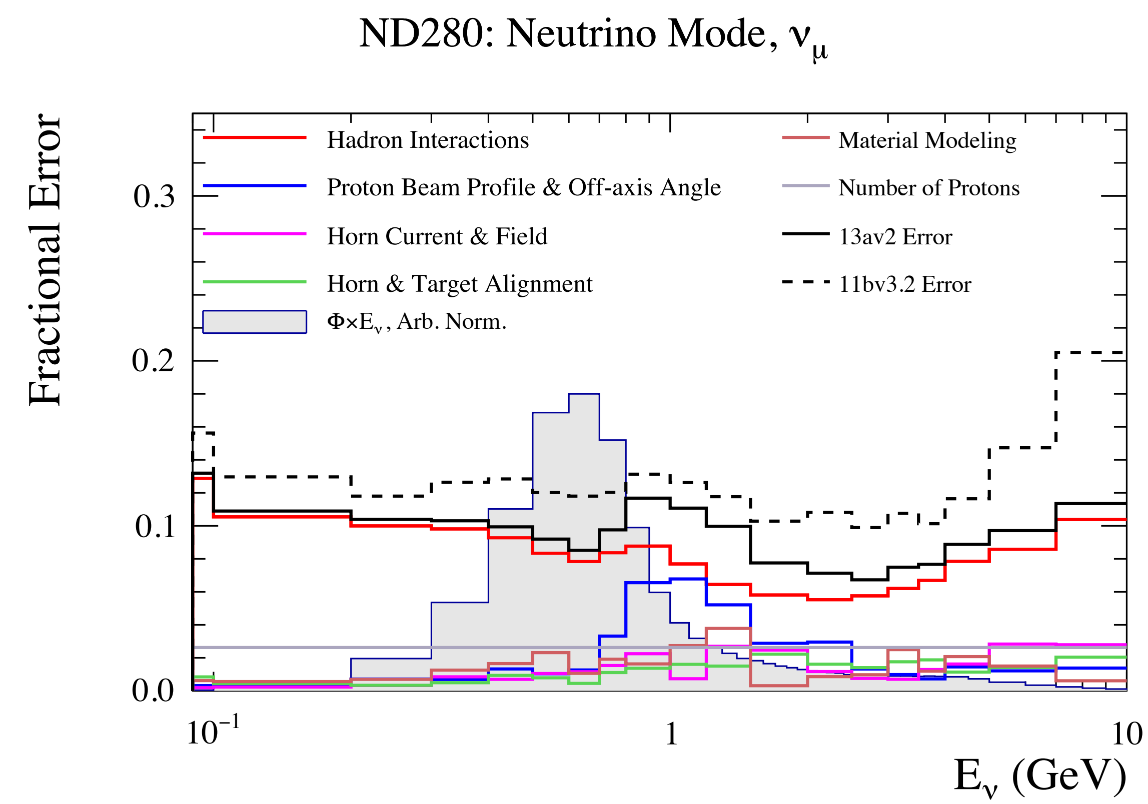


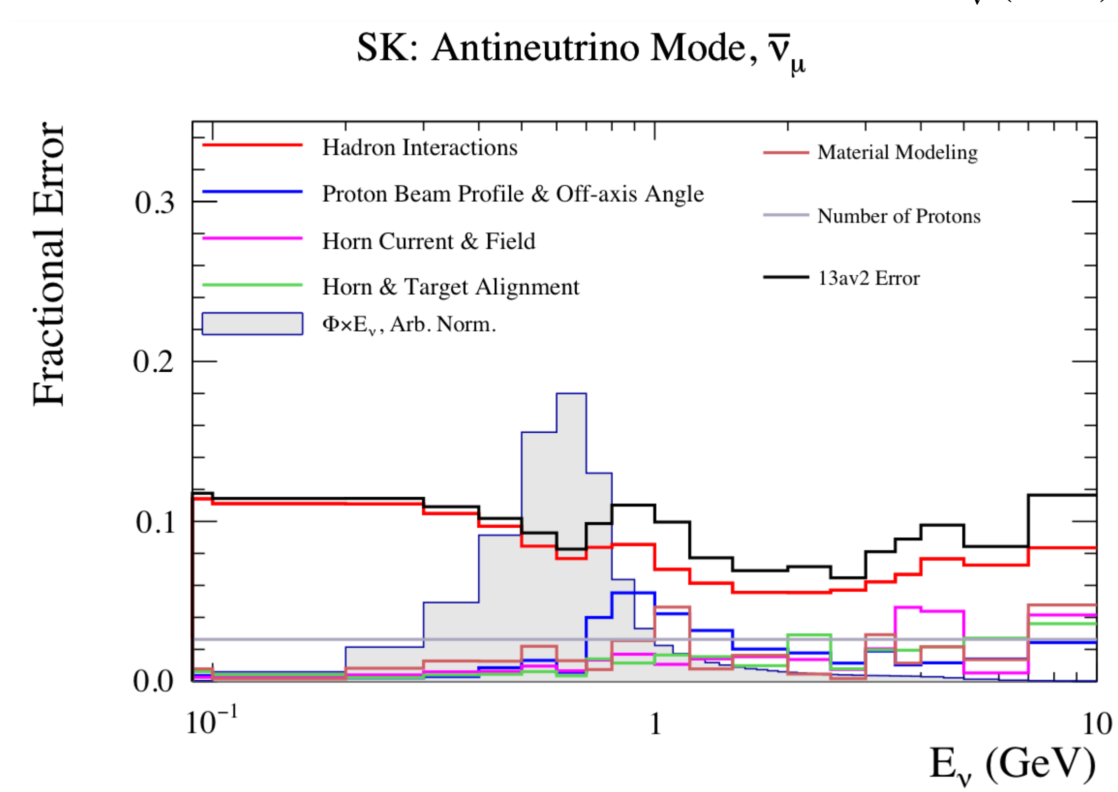


Beam Uncertainties

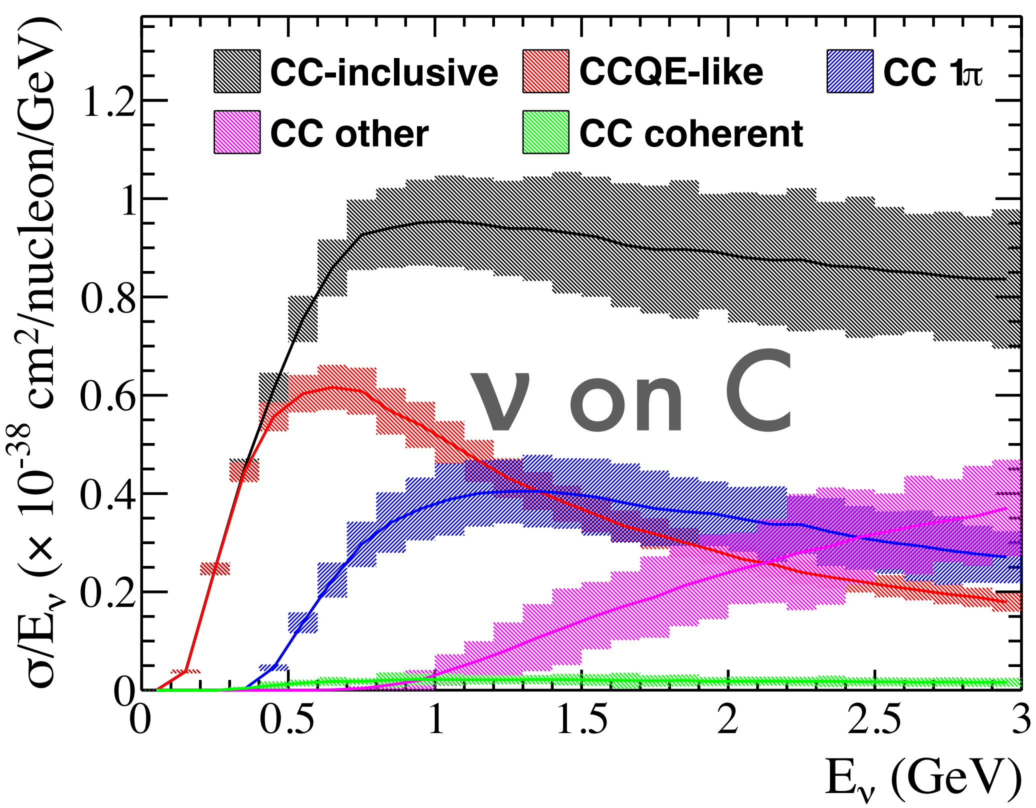


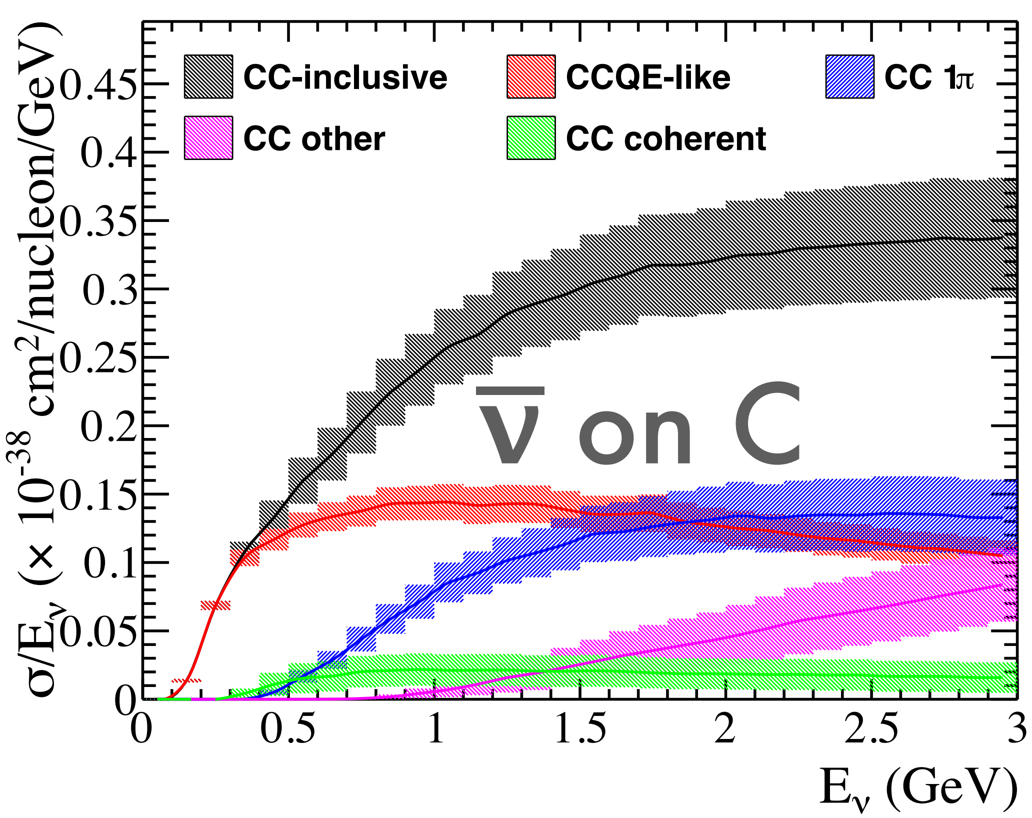






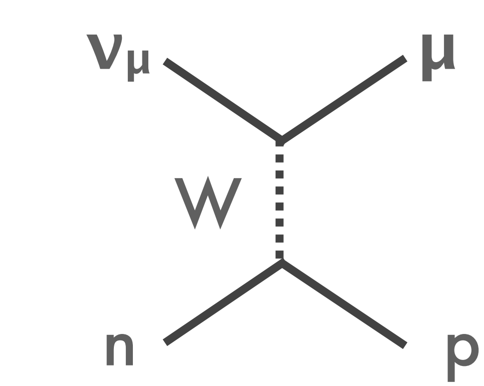
ν-N Cross Section Model



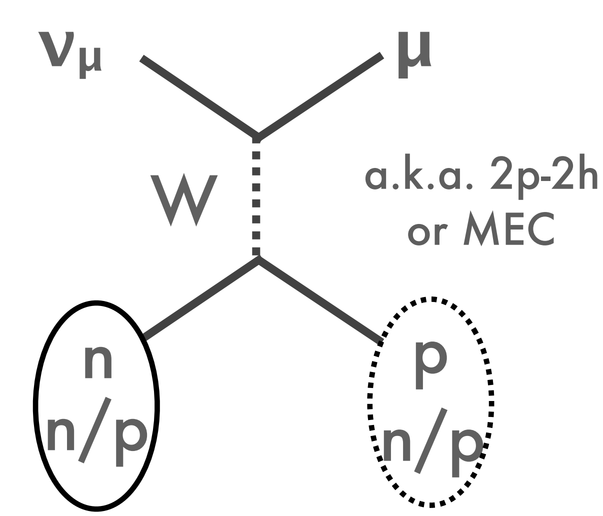


Uncertainties come from underlying model parameters and normalizations

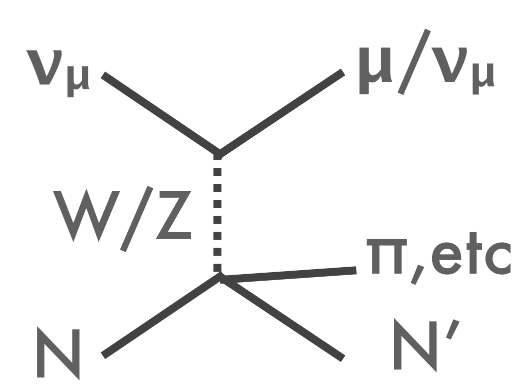
Charged current quasi-elastic



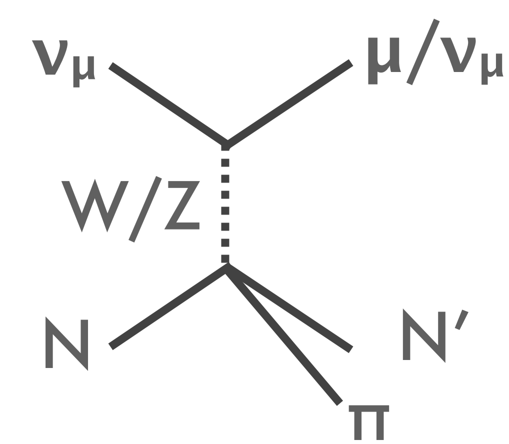
Charged current multinucleon

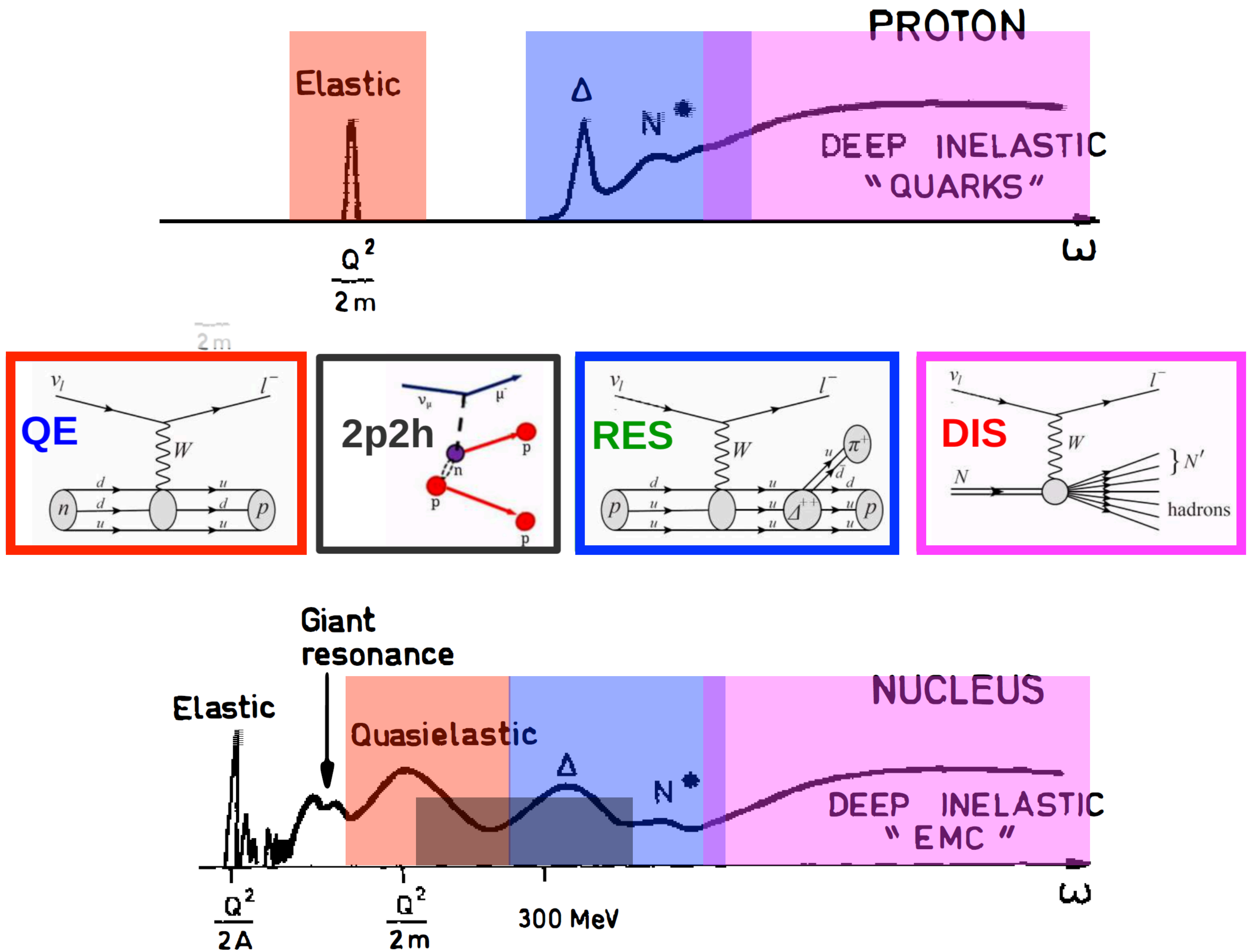


Deep Inelastic Scattering

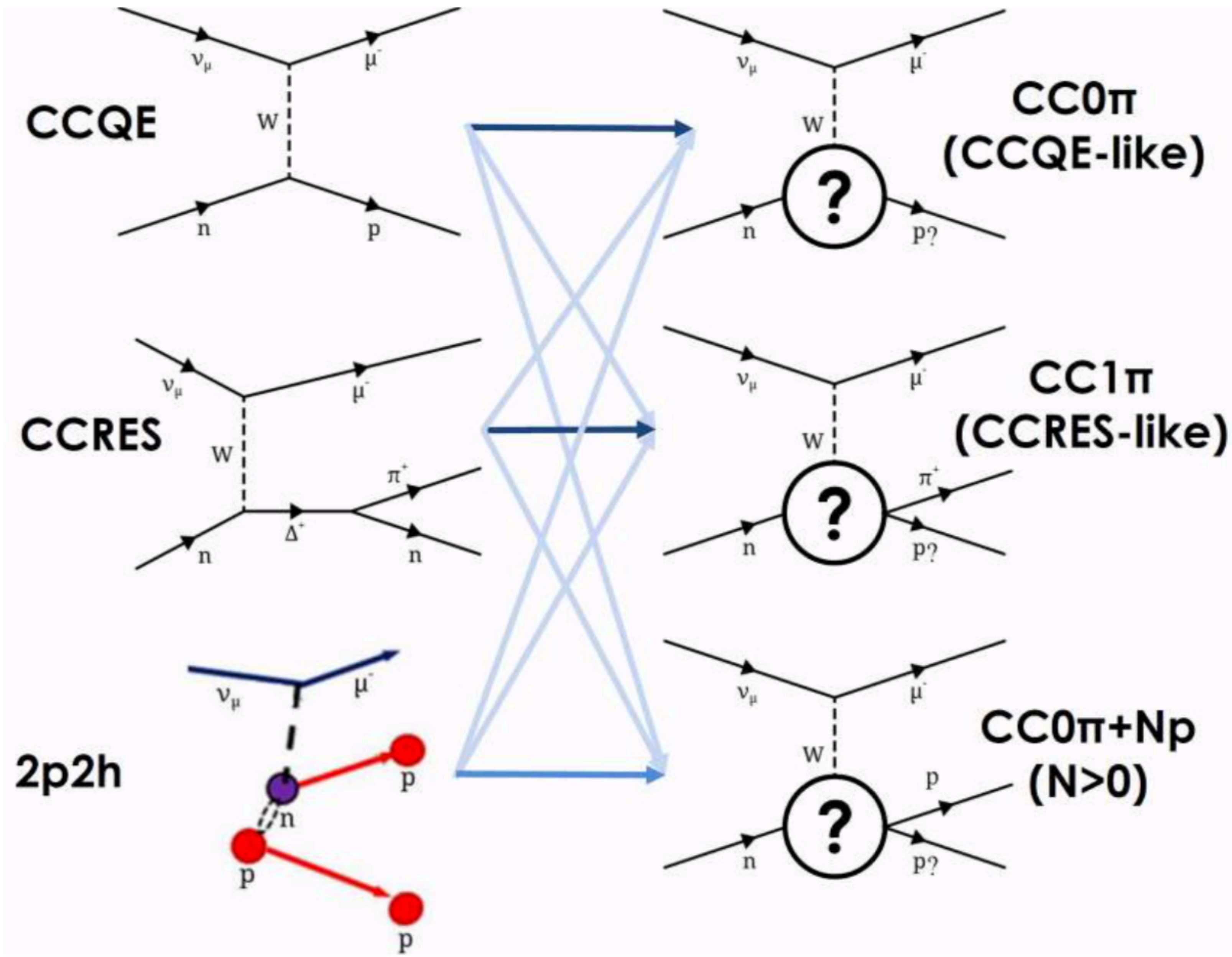


Charged Current 1π



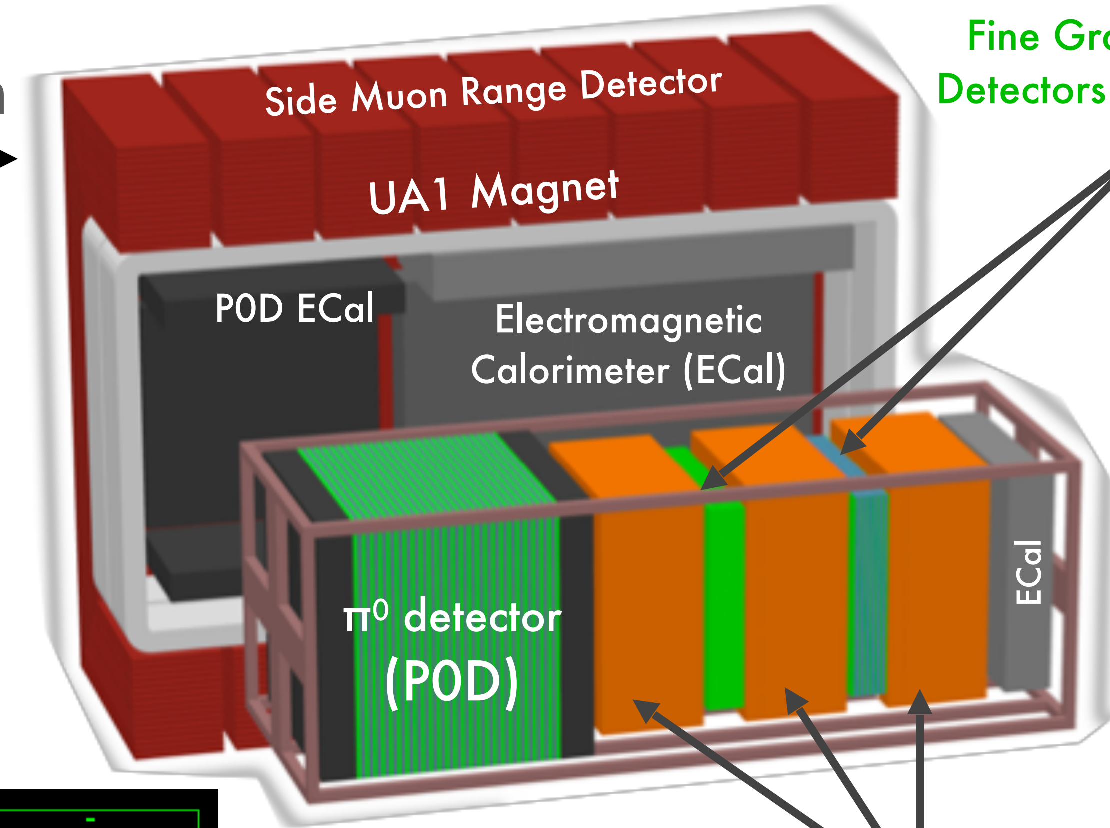

PROTON
Elastic
Δ
N*
DEEP INELASTIC
"QUARKS"
Q²/2m
ω
QE
2p2h
RES
DIS
hadrons
Giant resonance
Elastic
Quasielastic
NUCLEUS
Δ
N*
DEEP INELASTIC
"EMC"
Q²/2A
Q²/2m
300 MeV
ω

Mode vs Topology



T2K Off-Axis Near Detector

Beam →



Fine Grained Detectors (FGDs)

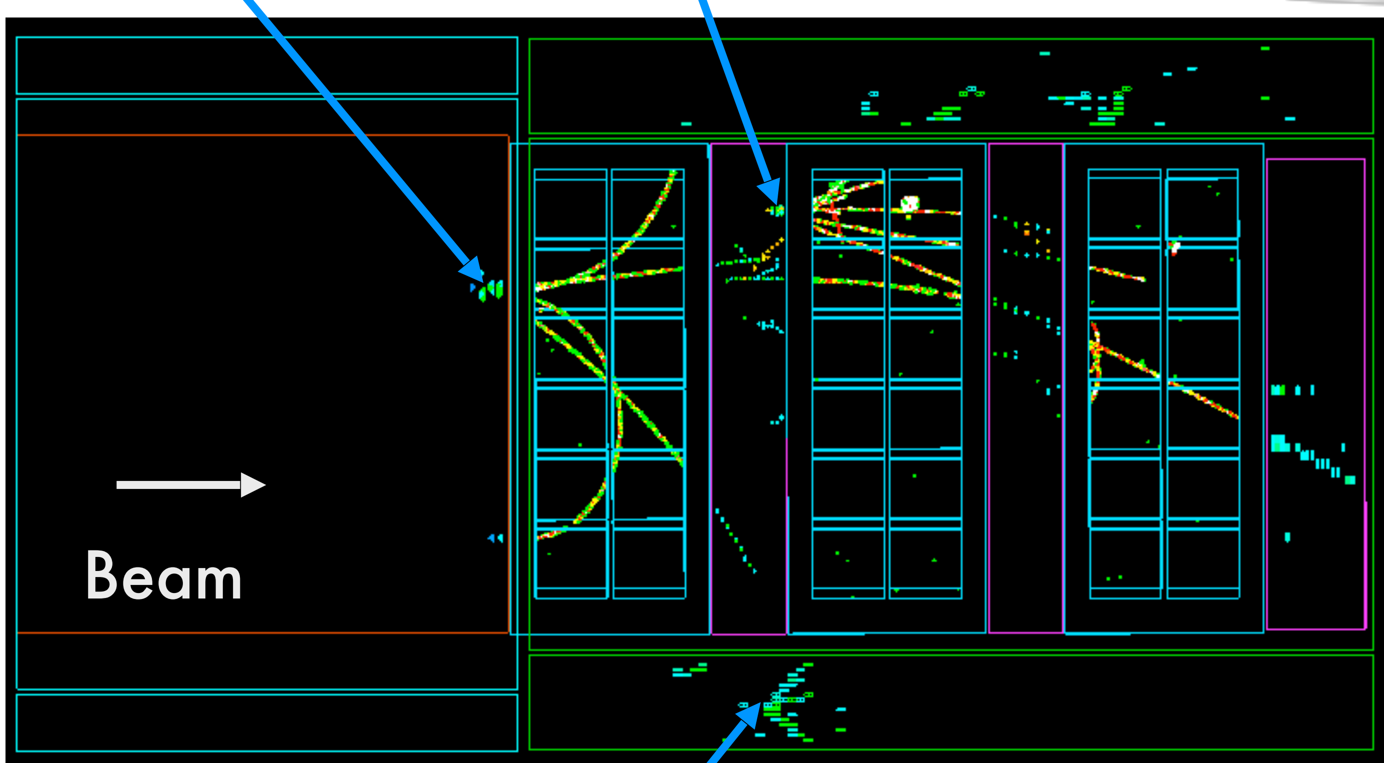
Time Projection Chambers (TPCs)

Primary Interaction Material: Carbon

Secondary Interaction Materials:
Oxygen, Lead, Brass, Argon

Interaction in P0D

Interaction in FGD1

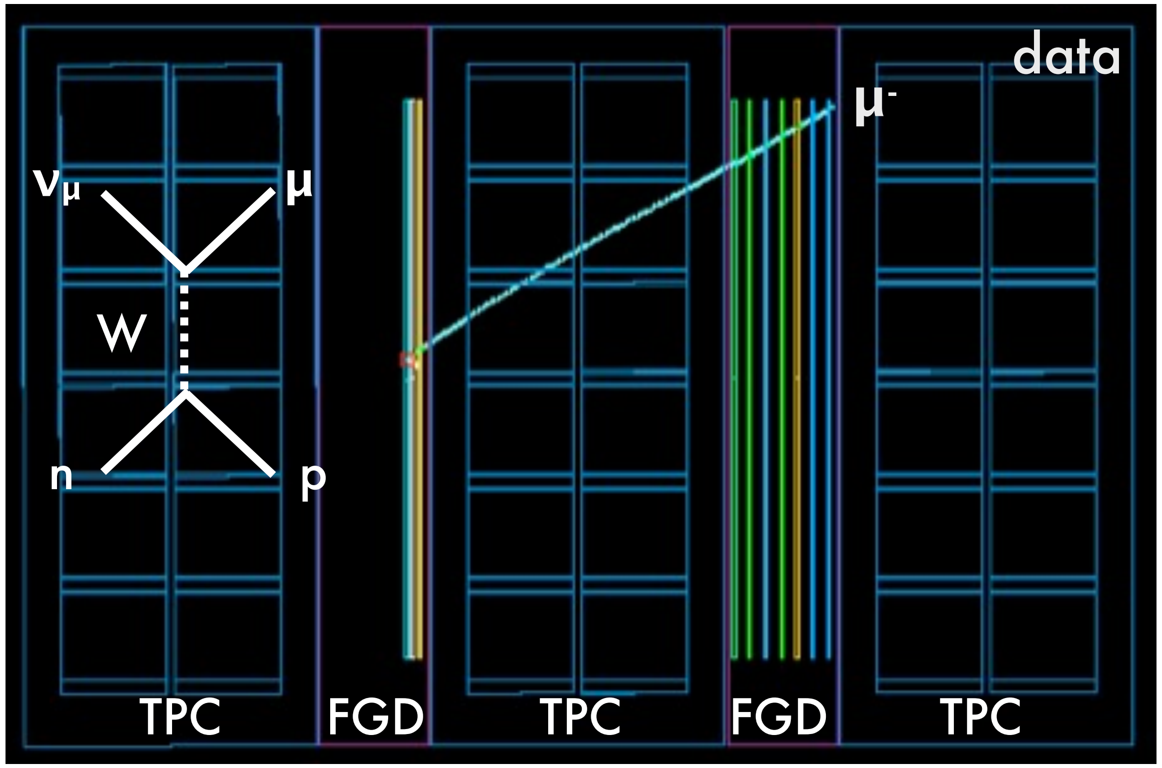


Interaction in ECal

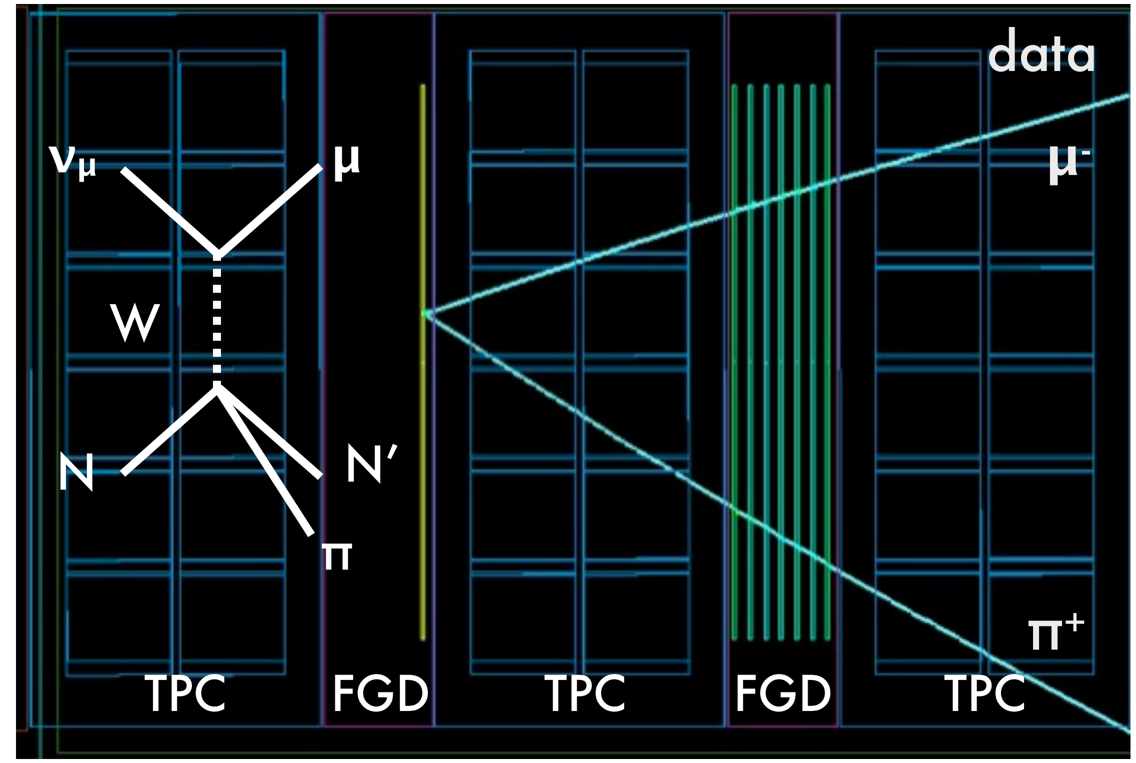
Strategy:

- Parameterize underlying models
- Select data samples to optimize constraints
- Propagate uncertainties through parameters

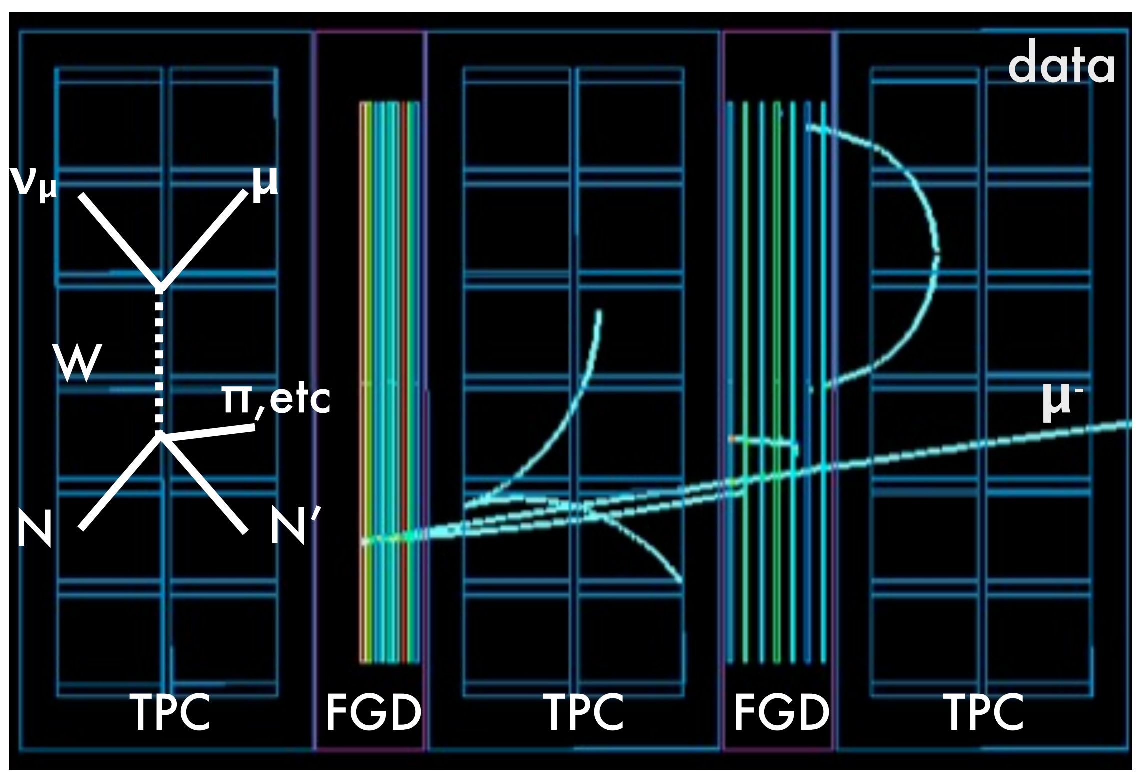
CC0π



CC1π+



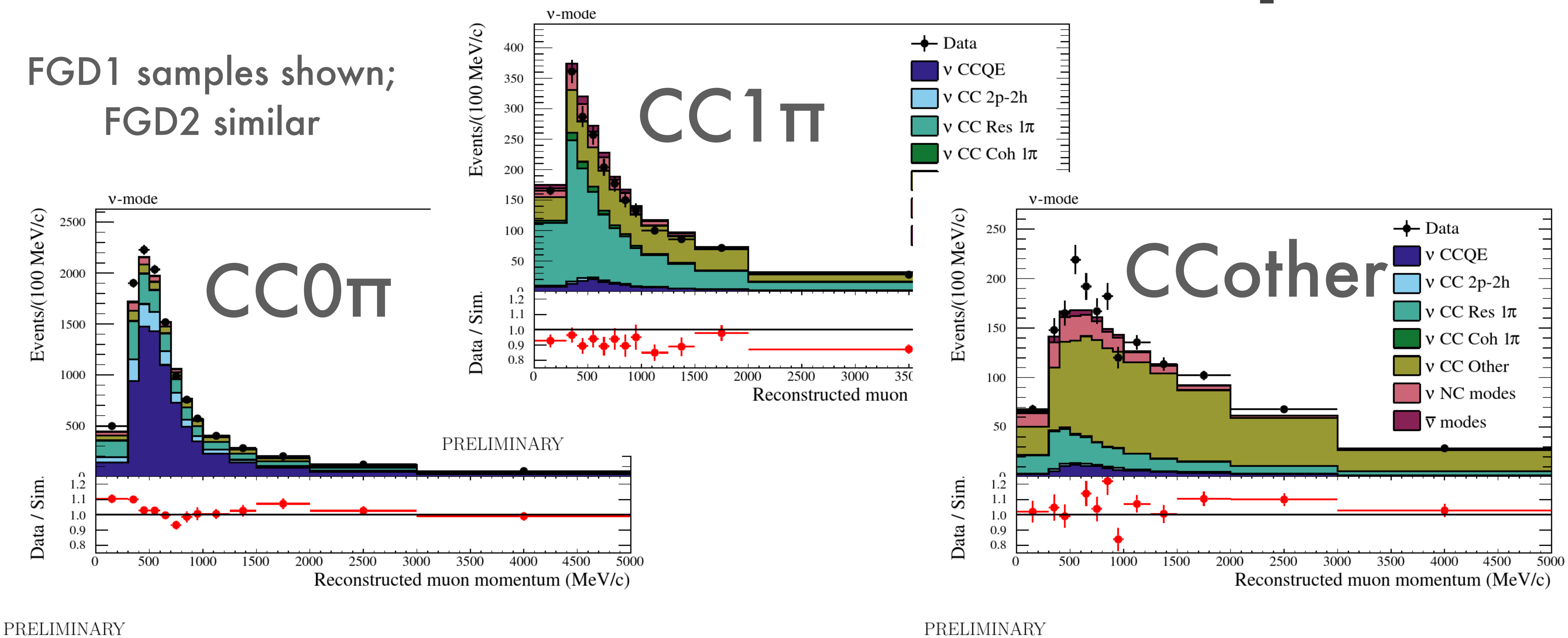
CC other



Beam

ND280 ν-mode samples

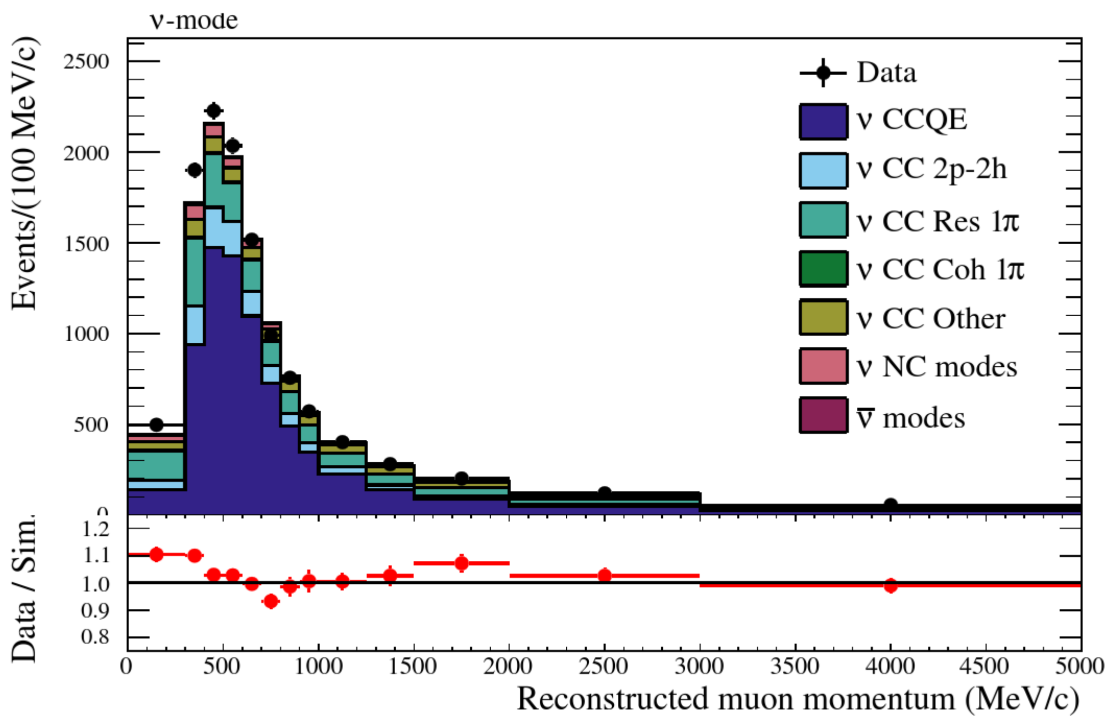
FGD1 samples shown;
FGD2 similar



- Three samples allow sensitivity to different beam energies and cross section interaction modes
- High statistics in neutrino mode provide strong constraints

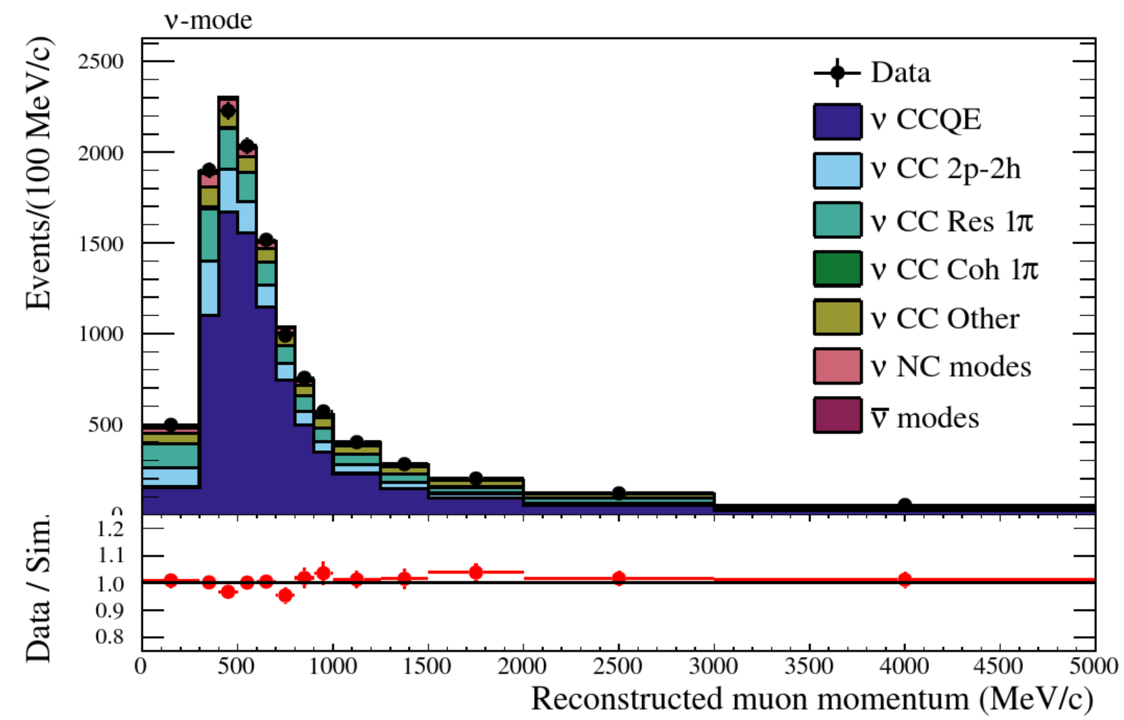
CC0π Samples

Before analysis



PRELIMINARY

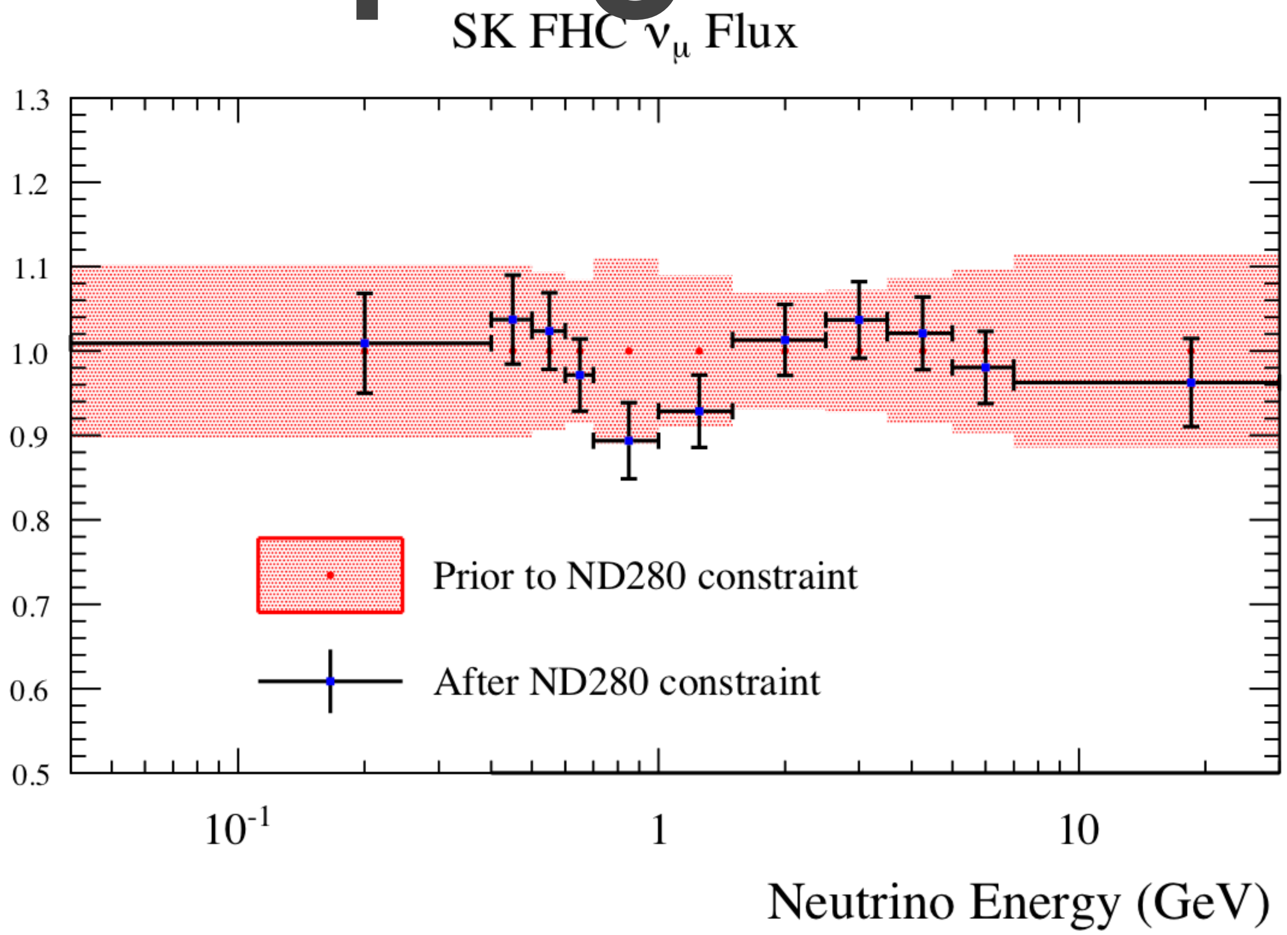
After analysis

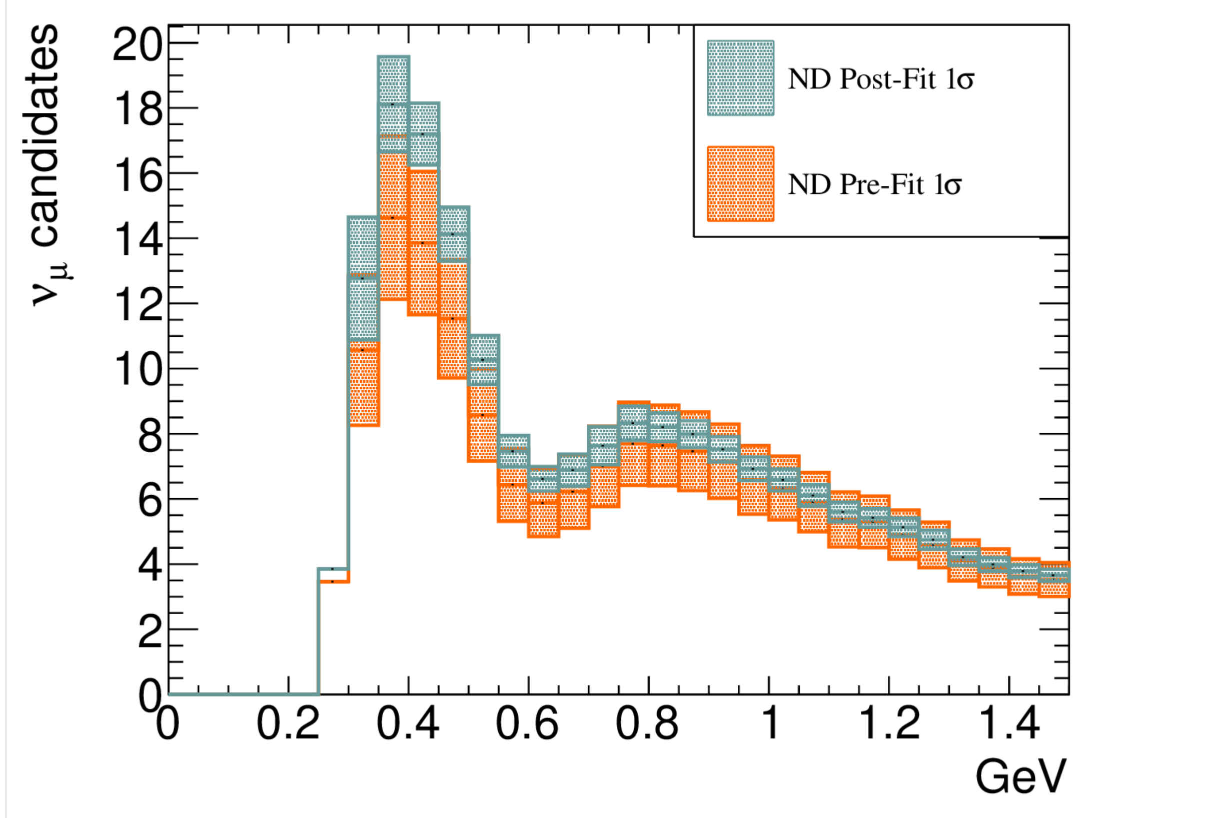


PRELIMINARY

- Clear that data is in better agreement after the analysis
- Adjustment comes through all the modes
- T2K is no longer statistically limited at the near detector!

Propagation of Uncertainty

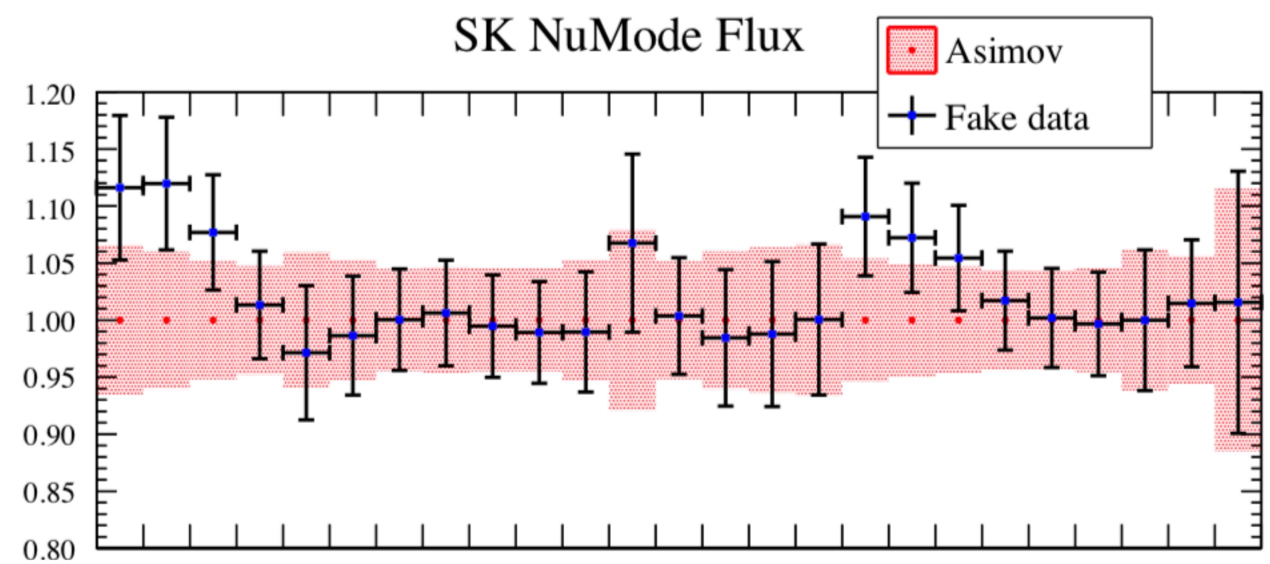


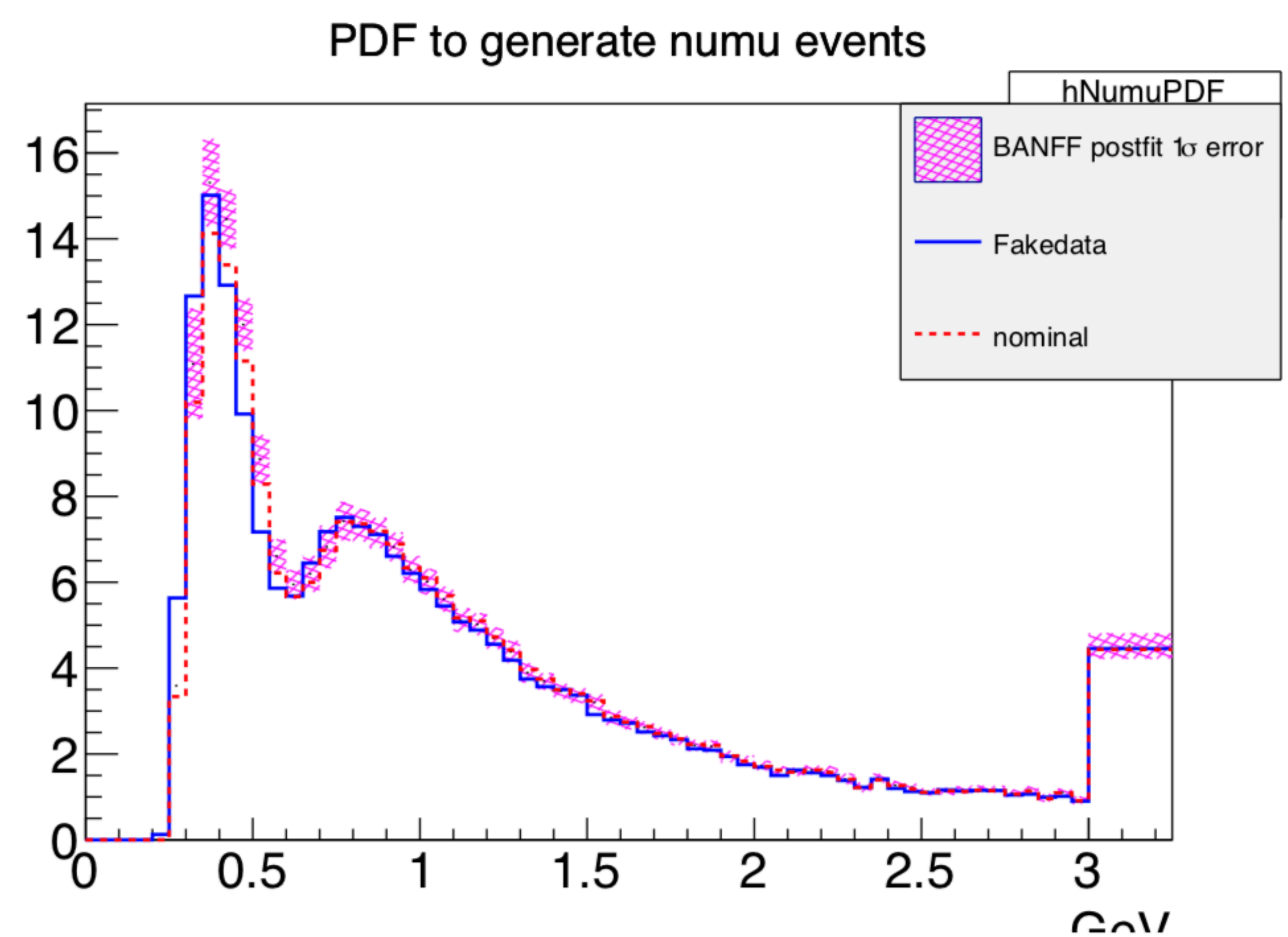


	1-Ring μ		1-Ring e		
Error source	FHC	RHC	FHC	RHC	FHC CC1π
Beam	4.3%	4.1%	4.4%	4.2%	4.4%
Cross-section (constr. by ND280)	4.7%	4.0%	4.8%	4.1%	4.1%
Cross-section (all)	5.6%	4.4%	8.4%	6.2%	5.6%
Beam + Cross-section (constr. by ND280)	3.3%	3.3%	3.3%	3.1%	4.0%
Beam + Cross-section (all)	4.4%	2.9%	7.7%	5.7%	5.6%
New E_b fake data parameter	3.2%	1.3%	7.2%	4.1%	2.8%
SK+FSI+SI	3.3%	2.9%	4.1%	4.3%	16.6%
Total	5.5%	4.4%	8.8%	7.3%	17.8%

'Fake Data' Analyses

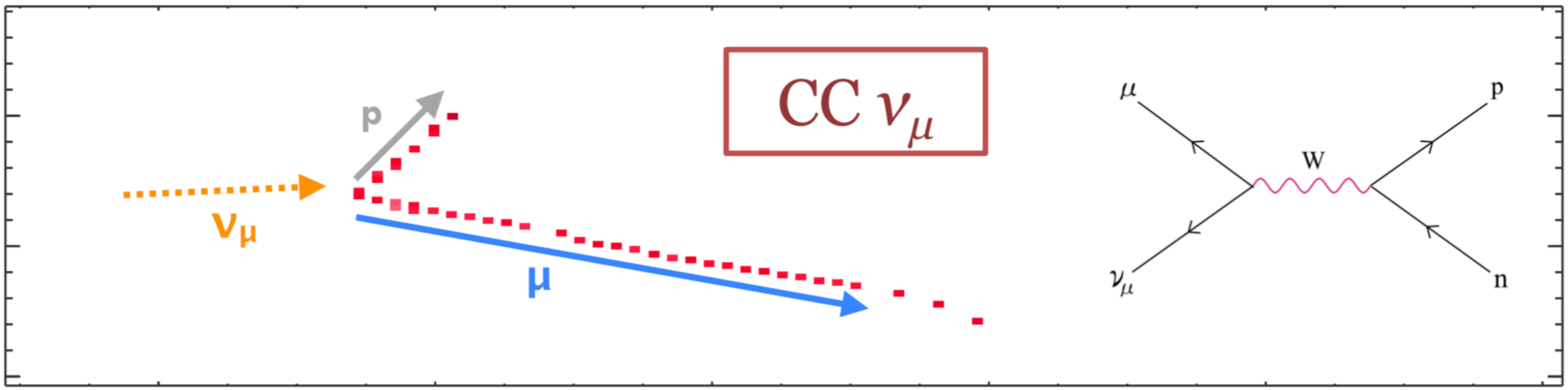
- Generate 'fake data' from alternative models
- Perform full analysis
- Example: Binding energy in nuclei
- Check if the analysis is sensitive to this

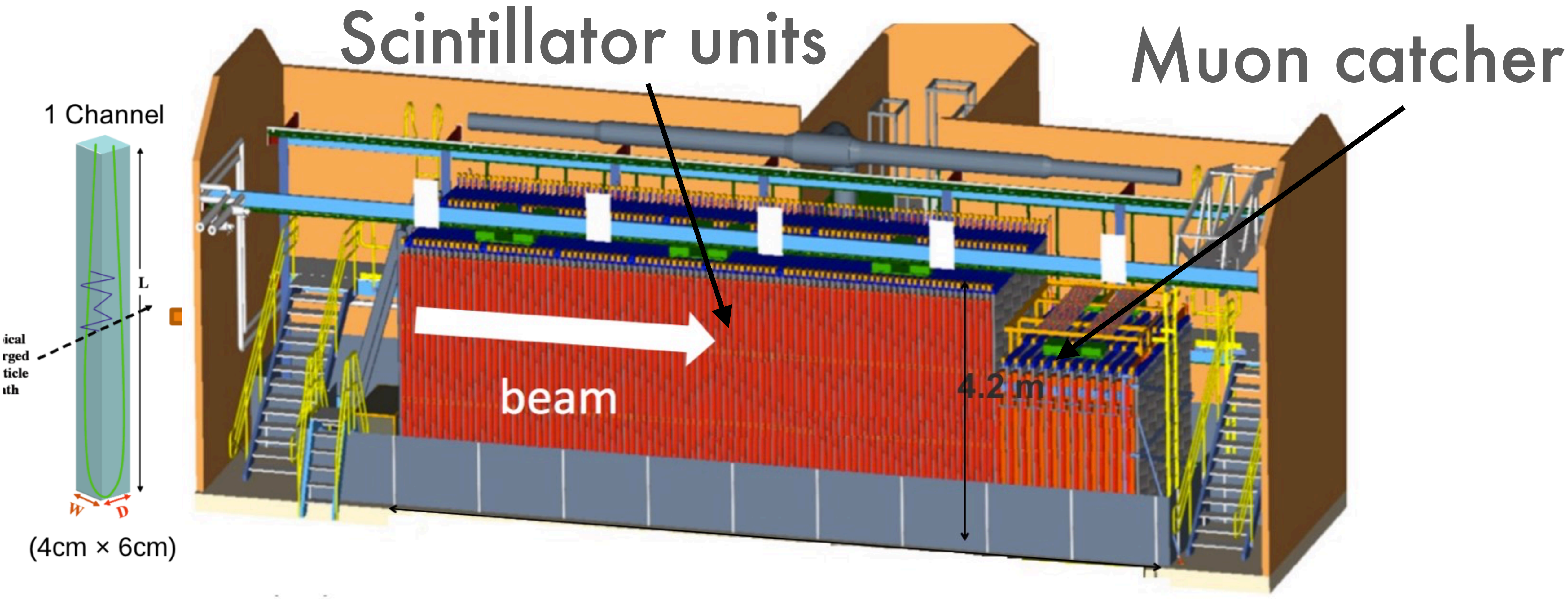




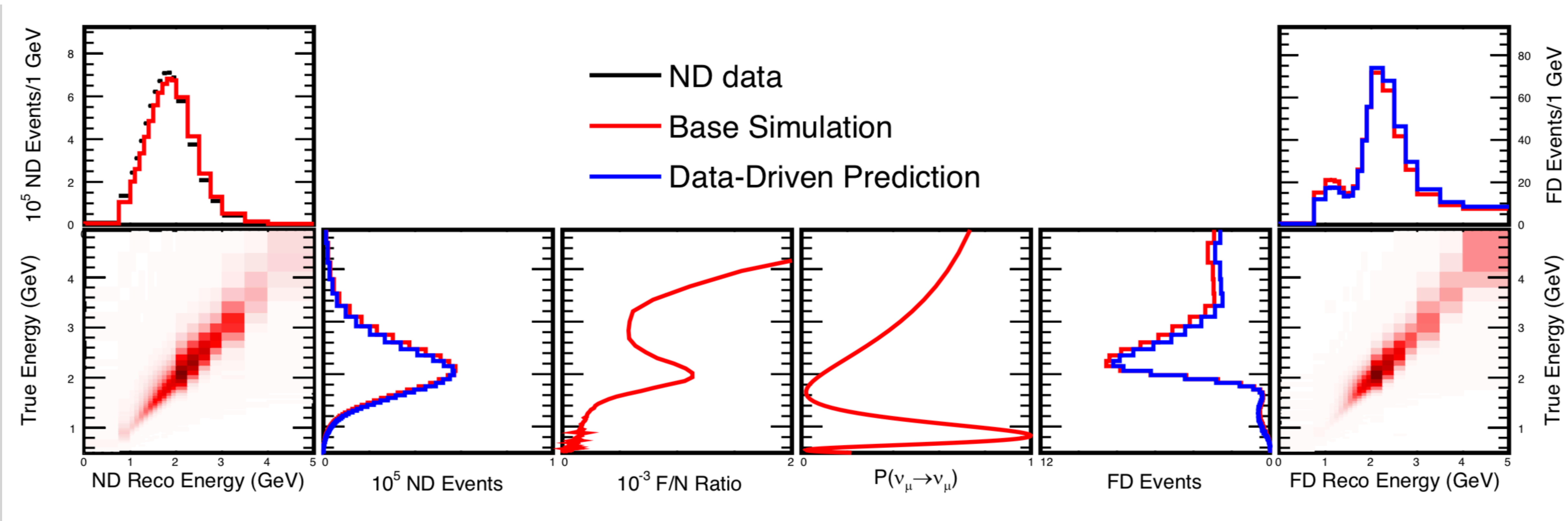
NOvA ND

Primary Interaction Material: Carbon





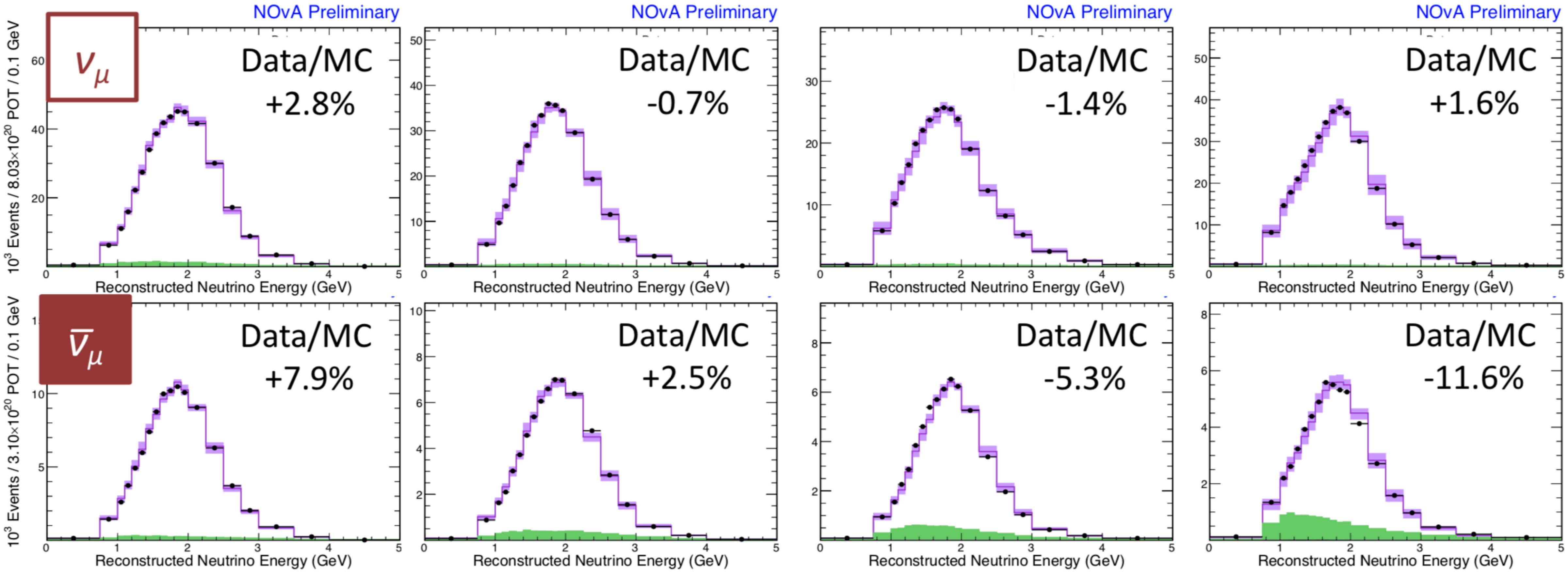
NOvA ND

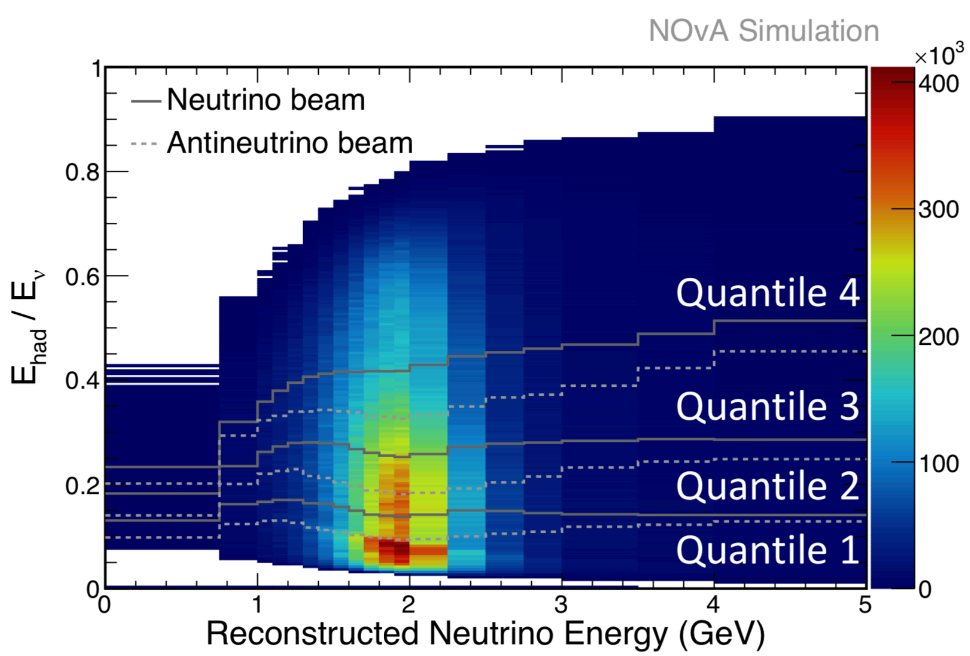


Strategy:

- Unfold ND data to predict true energy spectrum
- Apply Far/Near ratio and oscillations
- Fold back to reconstructed energy
- Systematics are applied as variations on the true-reconstructed matrices

NOvA ND

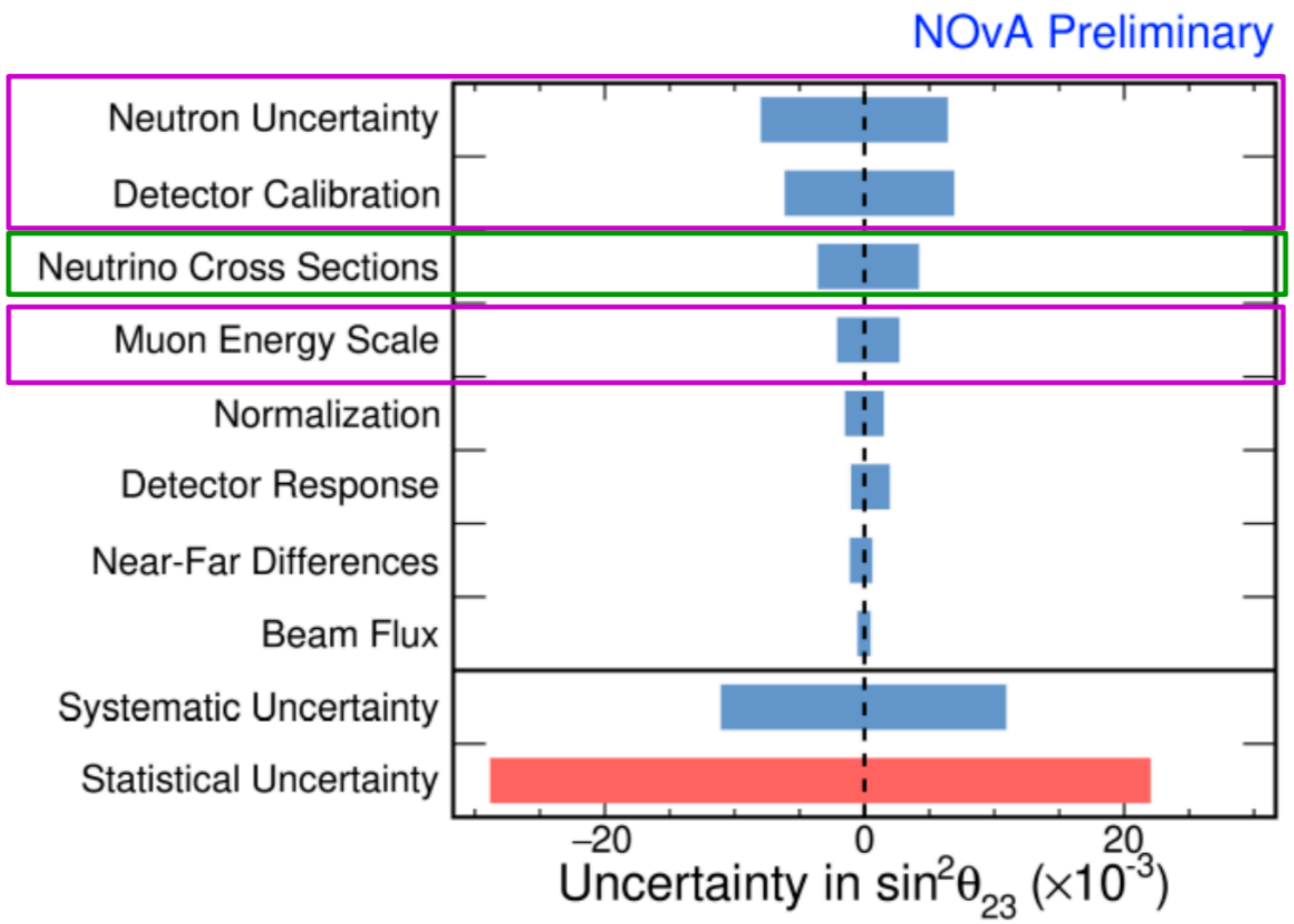




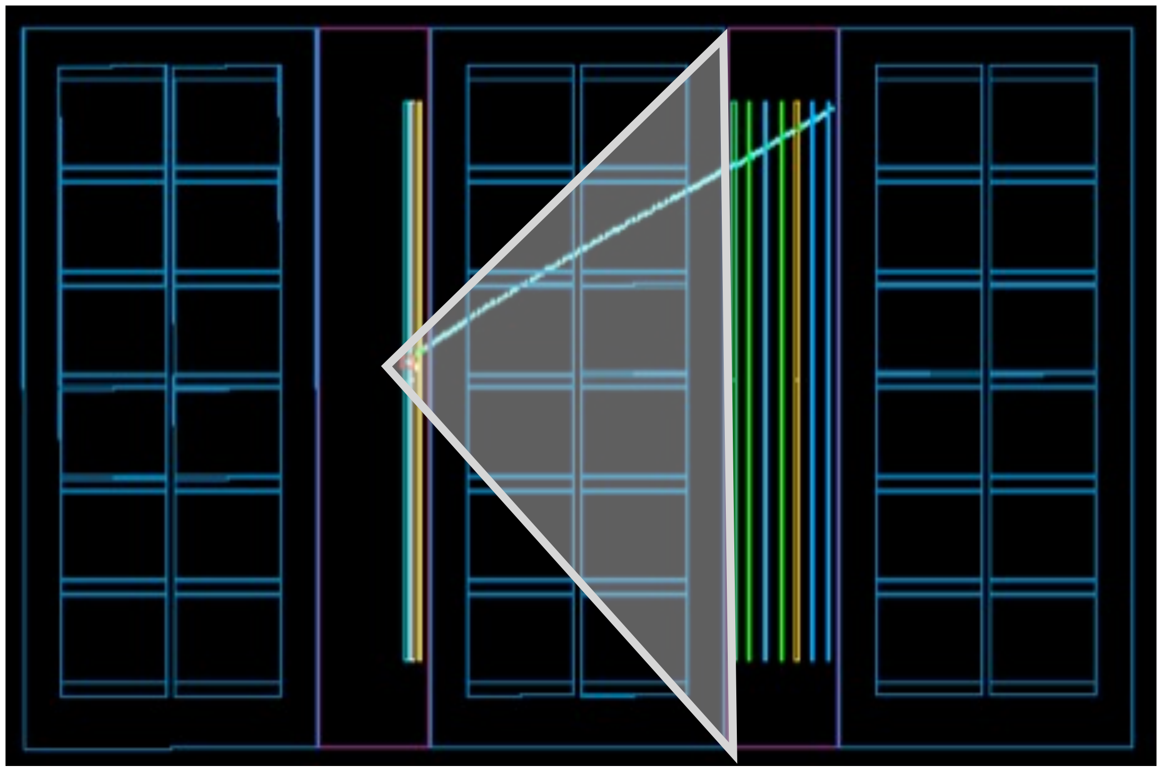
- Split into bins of hadronic energy
- This reflects different energy resolutions

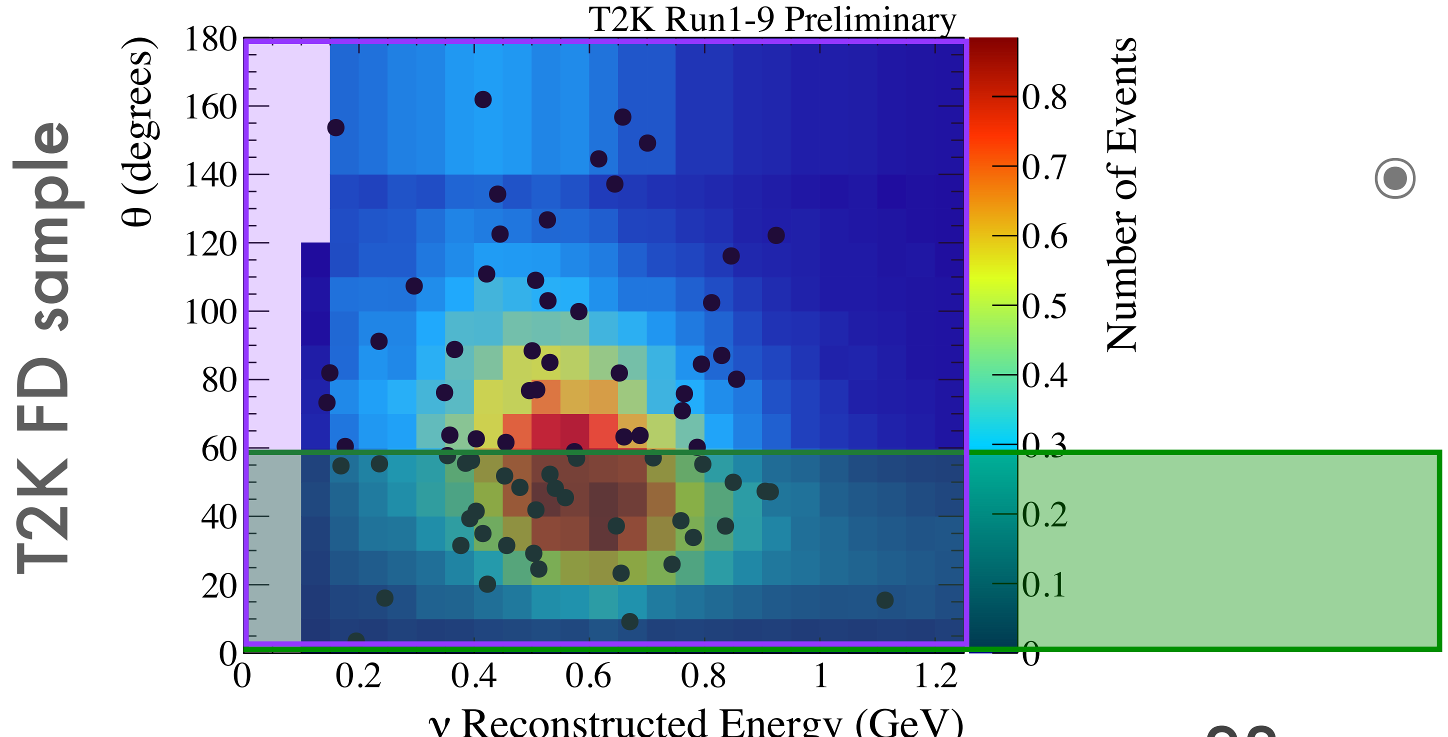
Propagation of Uncertainty

- Statistical uncertainty still dominates for NOvA
- Nevertheless, as datasets increase, this will become increasingly important



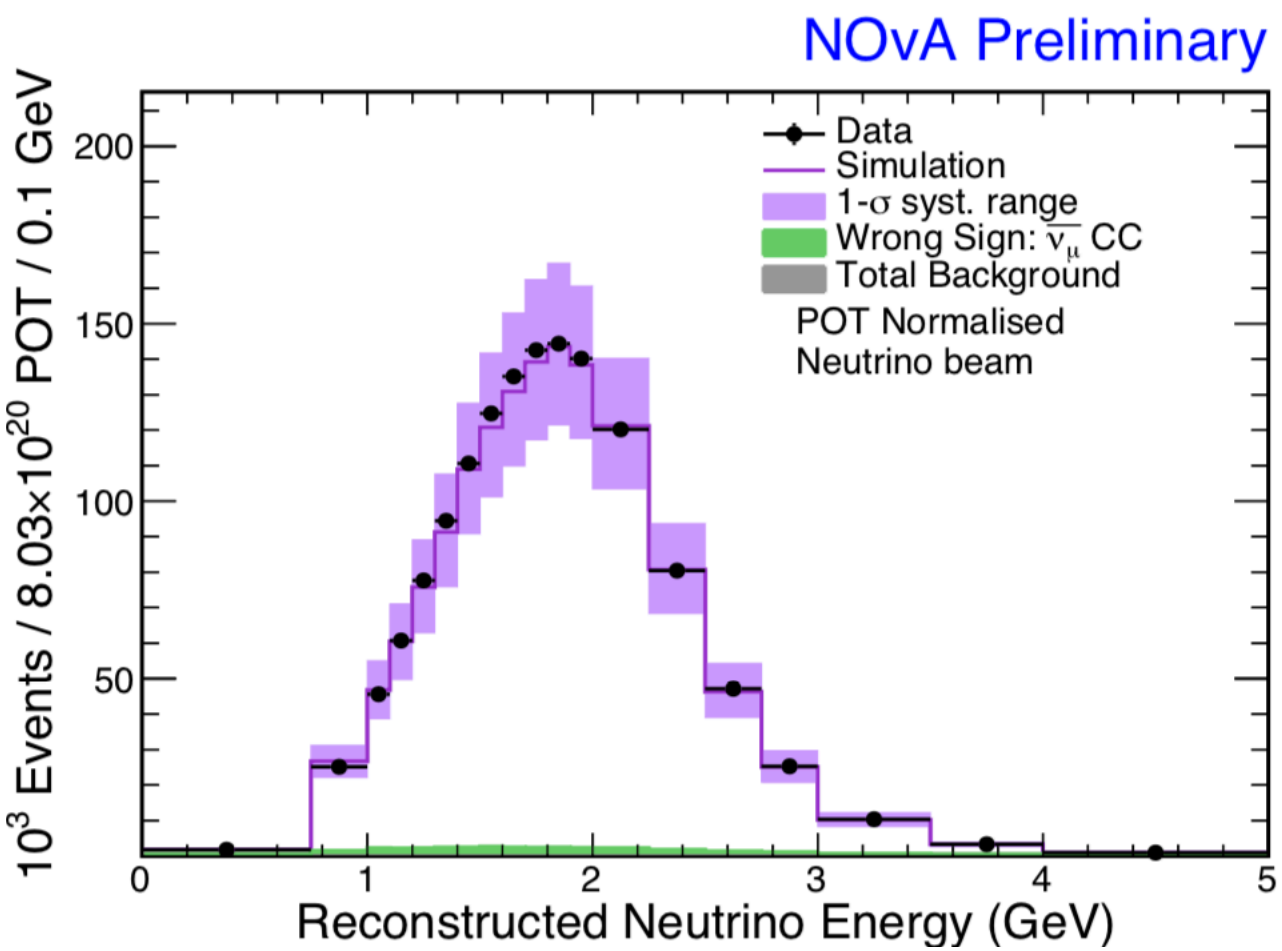
Problems: Phase Space

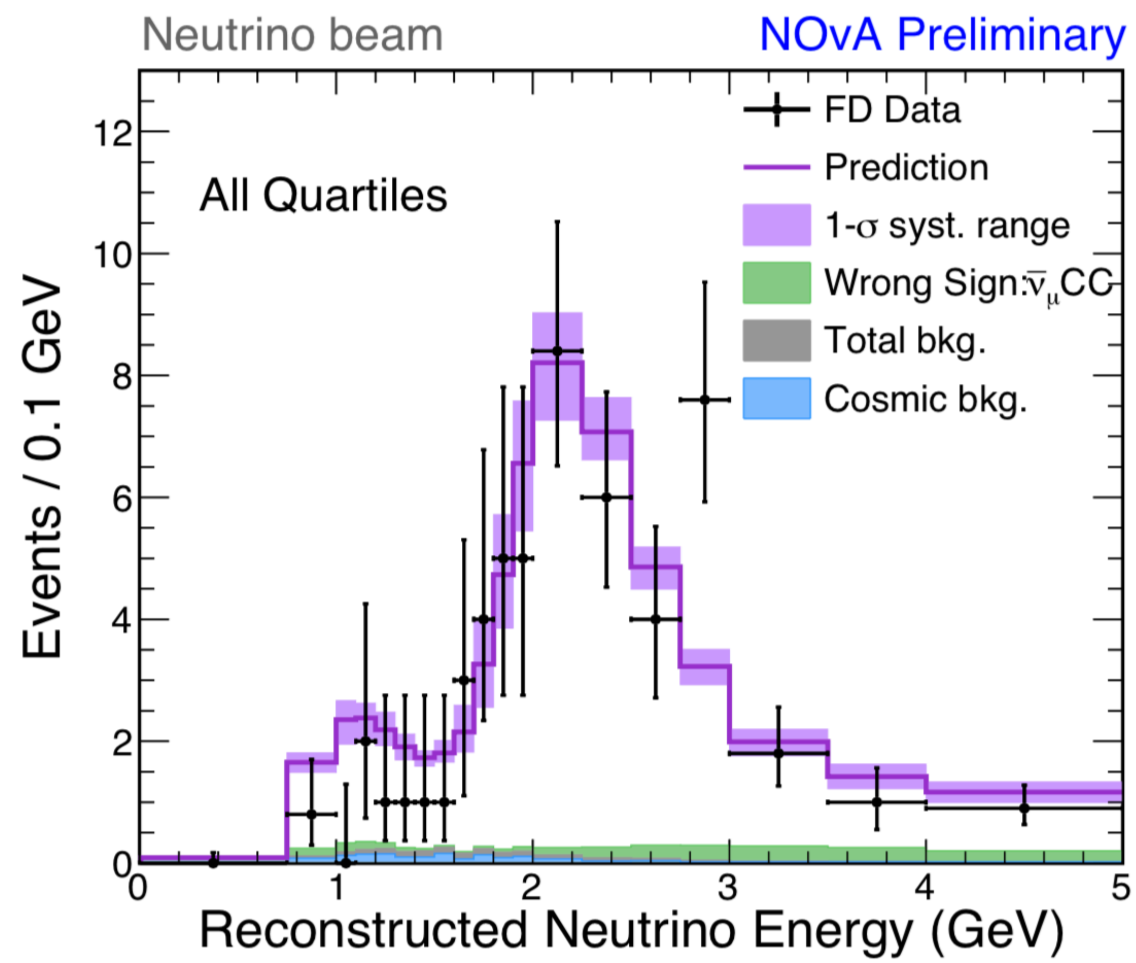




- Near detectors typically have a restricted phase space relative to their far detectors
- Uncertainties in Q^2 can badly affect this!

Problems: Energy Spectrum

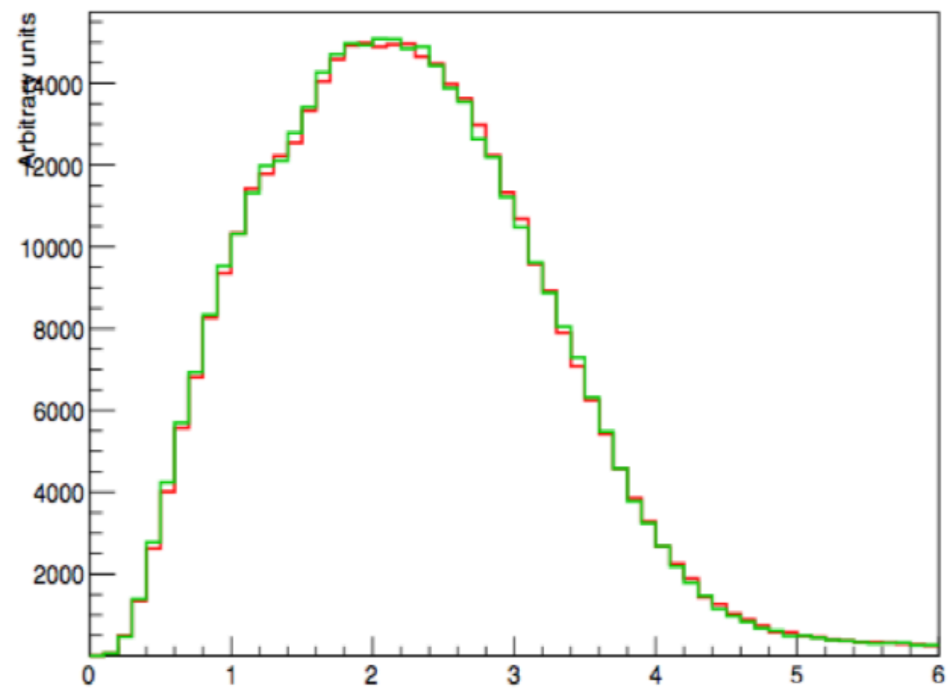




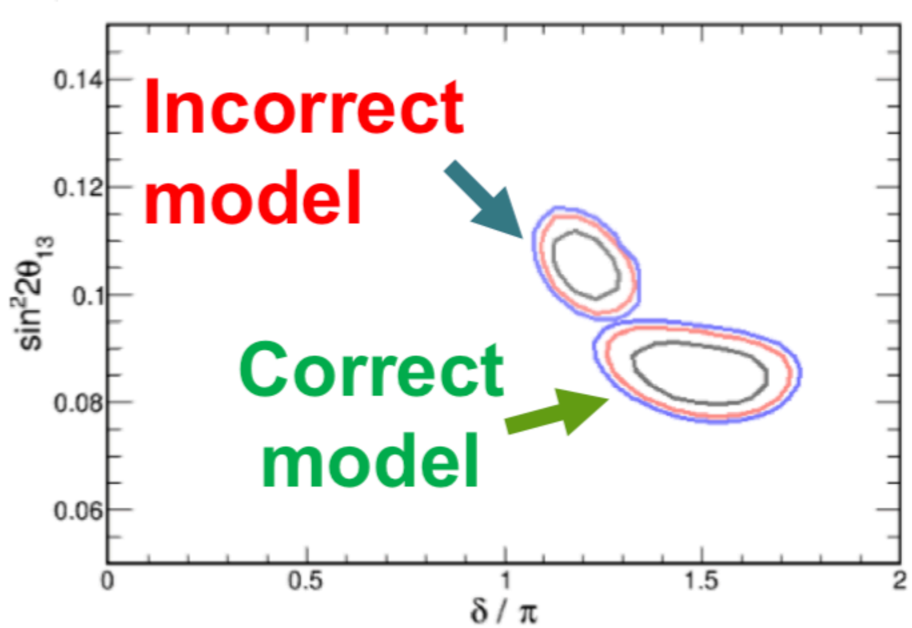
- Near and far do not see identical fluxes
- Different modes have different energy resolution/biases
- If this is wrong—can produce biases in osc. parameters

Problem: Model Degeneracy

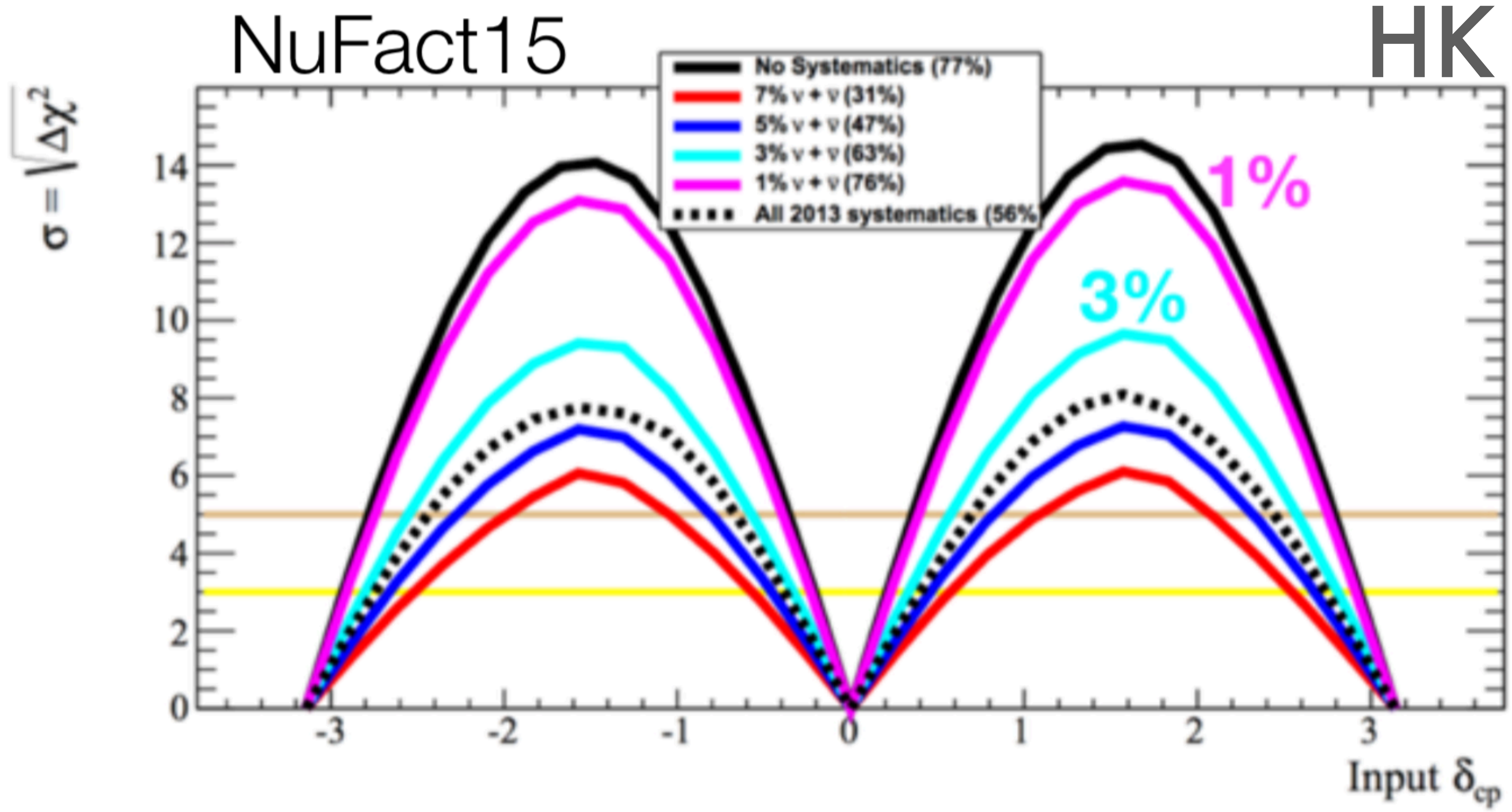
- Example: can shift energy from protons to neutrons and the ND spectrum looks fine via other model compensations
- Impact on oscillation contours is large



ND E_{reco} on-axis

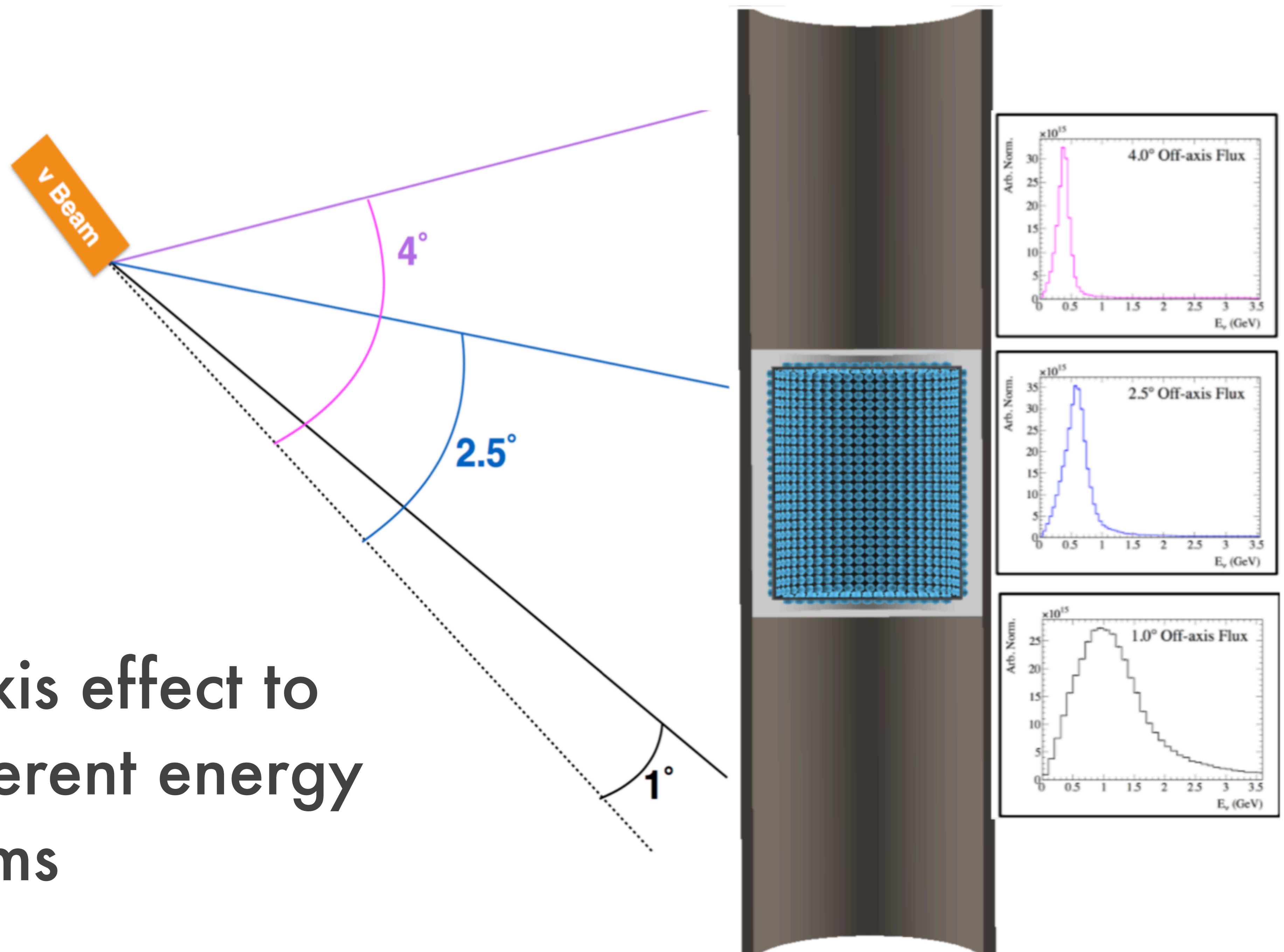


Next Generation



- Systematic uncertainties have a huge effect on the sensitivity of future LBL experiments
- We have to do much better!

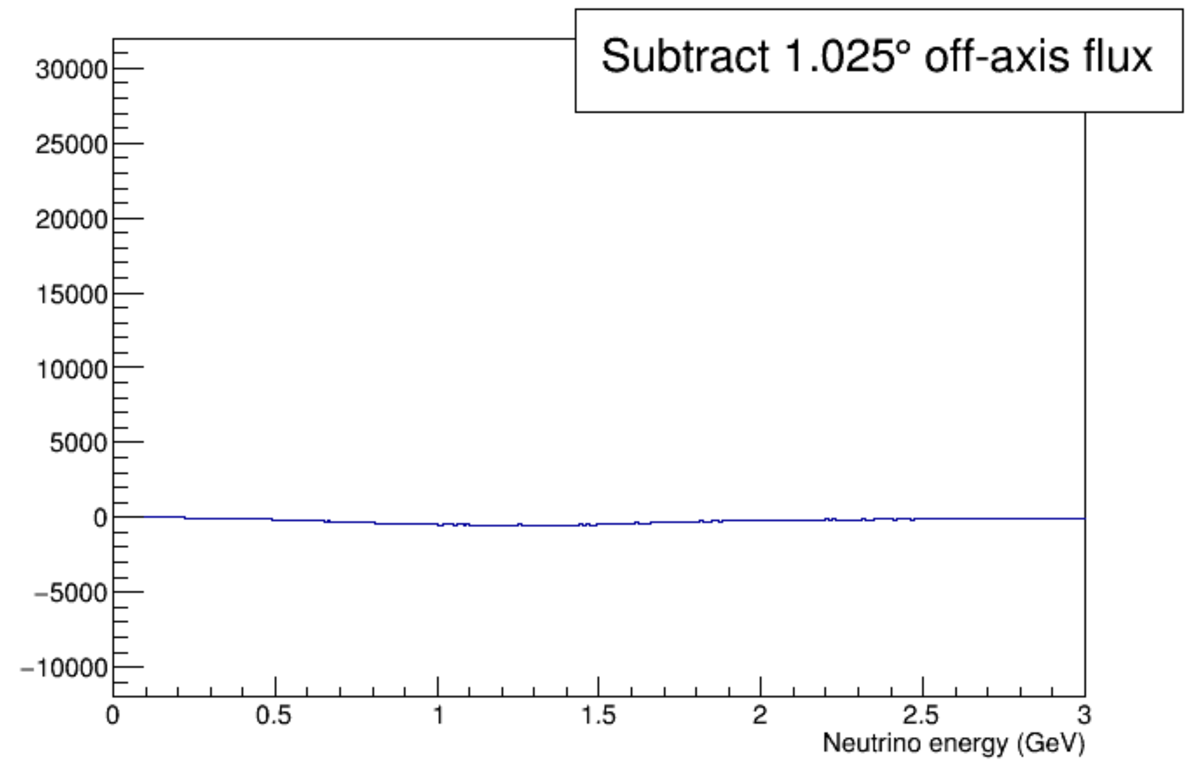
New Concepts: PRISM

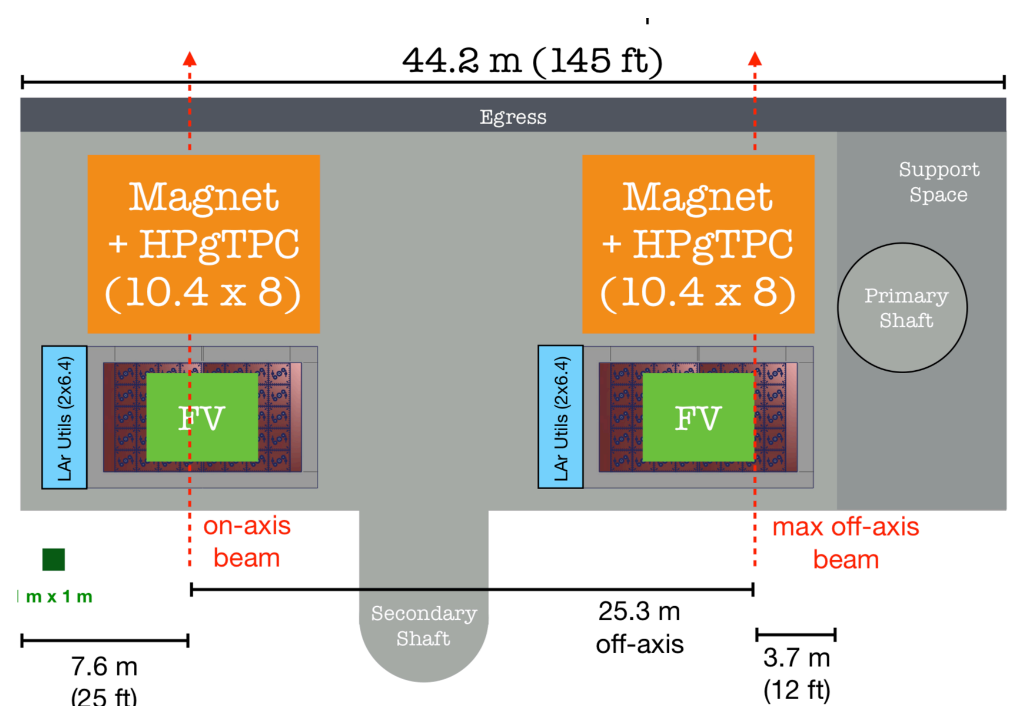


- Use the off-axis effect to generate different energy neutrino beams
- Systematics are low 'bin-to-bin'

New Concepts: PRISM

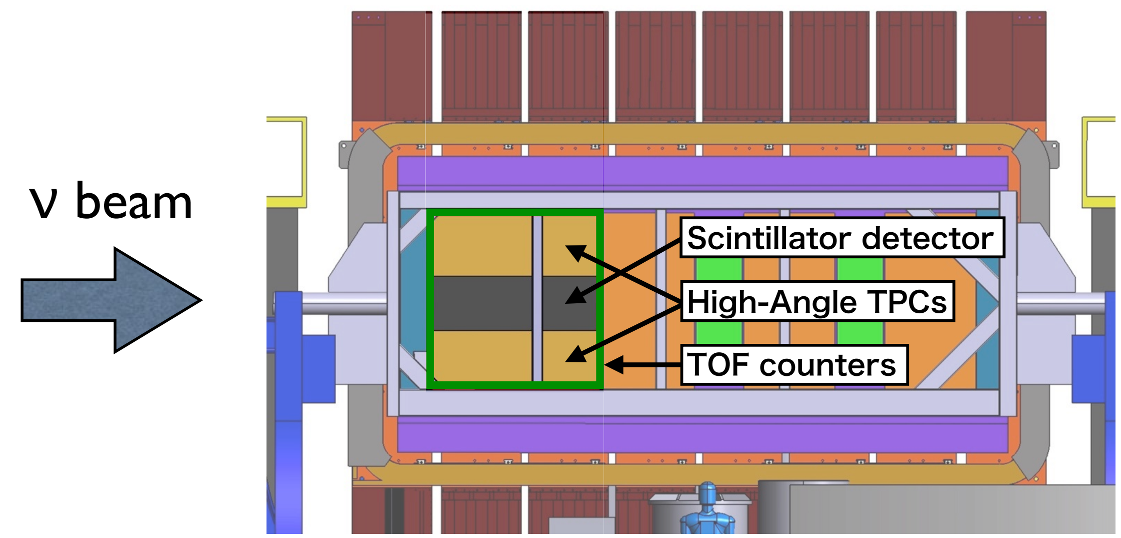
- Can construct 'monoenergetic' beams
- Can construct 'pre-oscillated' beams
- Both HK and DUNE have plans for a PRISM detector



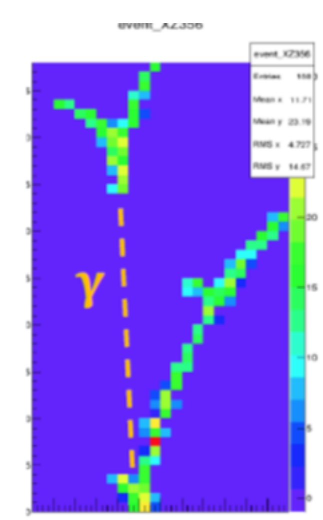


New Concepts: Low Threshold

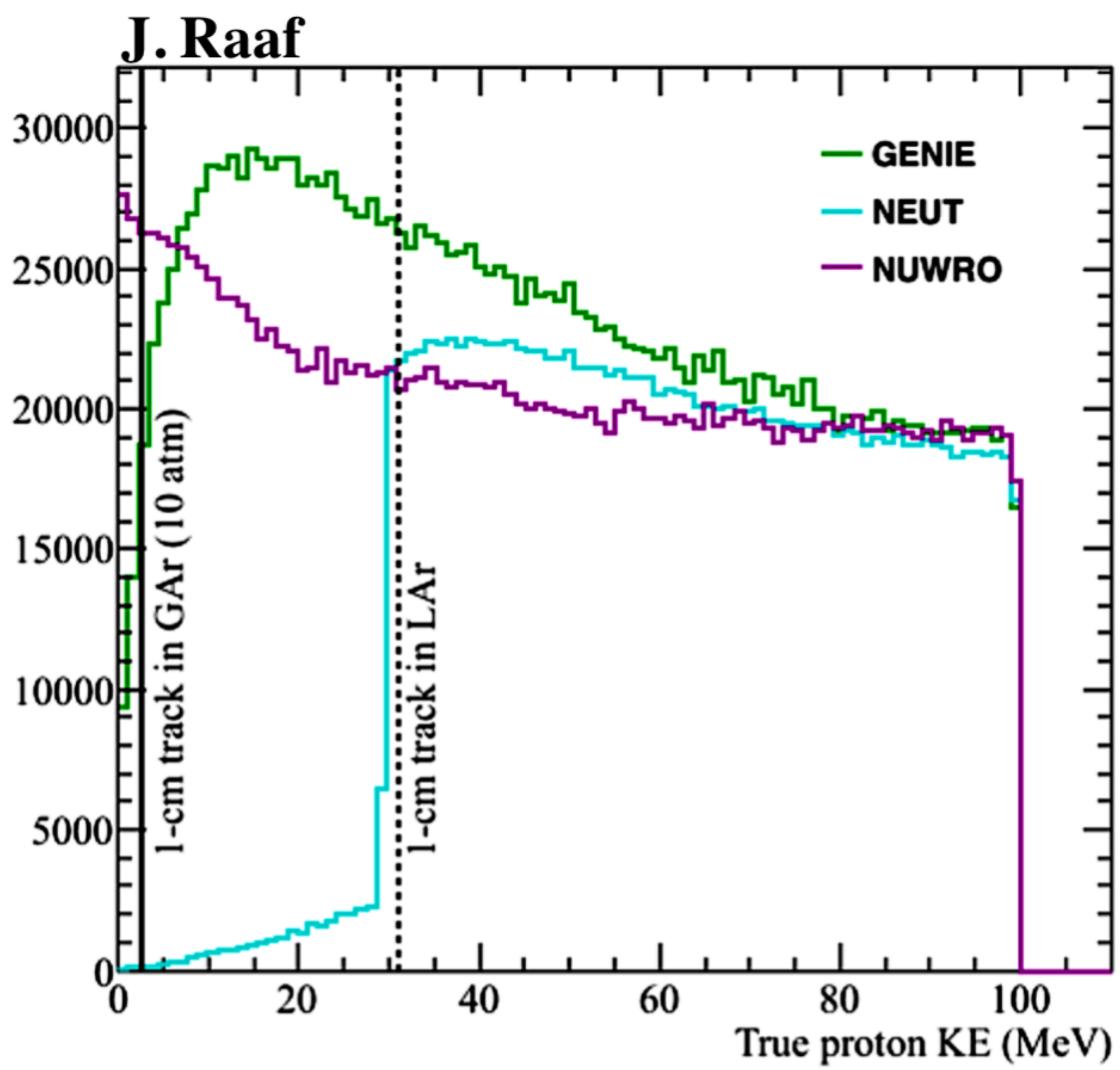
- Upgrade to T2K ND280 to increase efficiency at high angles
- New detector target with much finer granularity



- Replace (most of) P0D with **Scintillator Detector** + **2 High-Angle TPCs** + **TOF**
  - Improve acceptance for large angle tracks
- Keep current "tracker" [2 FGDs + 3 TPCs] (& upstream part of P0D) as well as ECal, magnet & SMRD

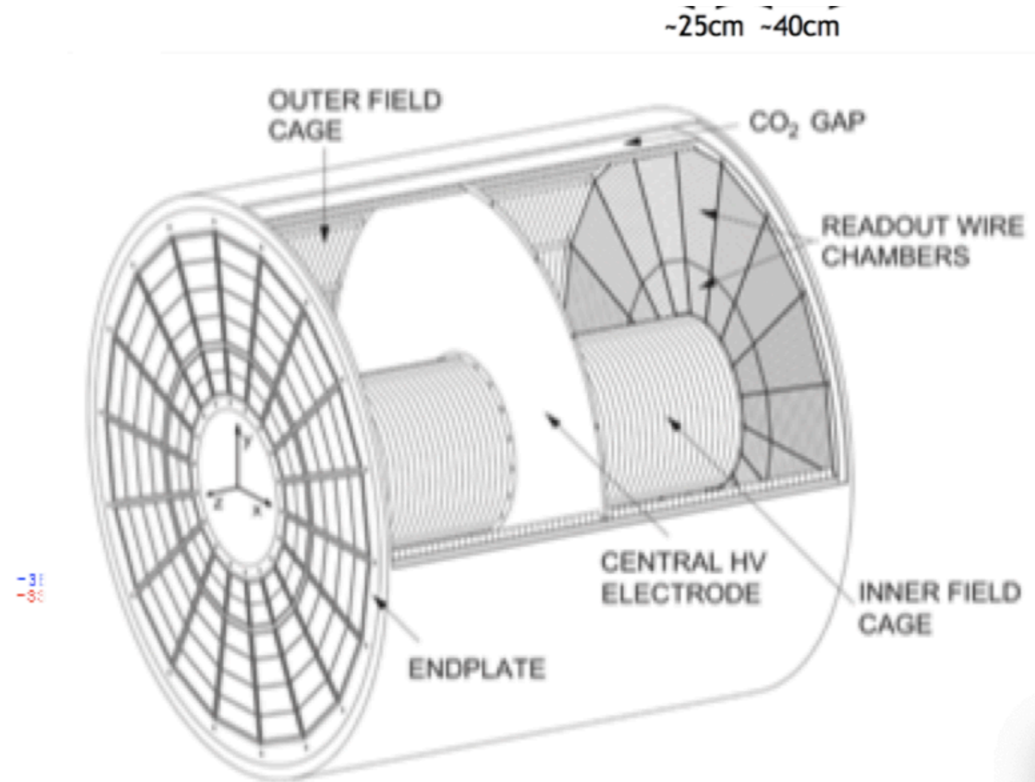


New Concepts: Low Threshold

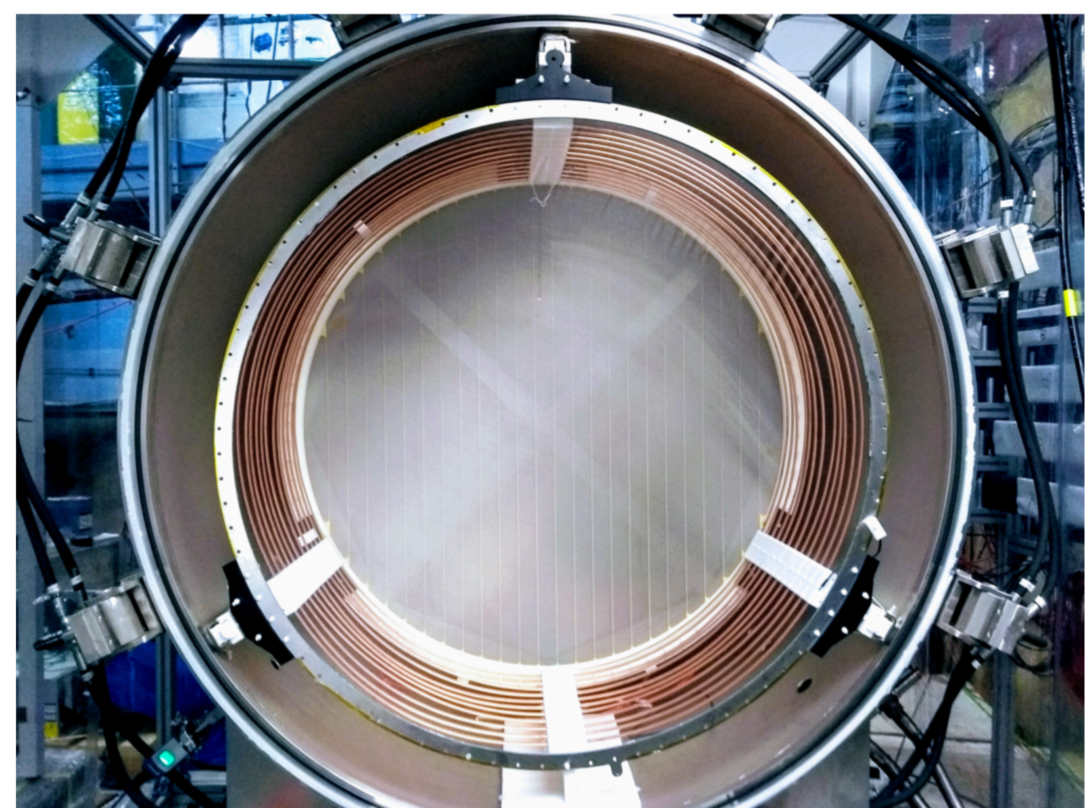


- Resolution only gets us so far—to do better, need lower density
- Proposal: High pressure gas TPC
- Begin to distinguish low energy hadrons—better mode determination, model constraint

New Concepts: Low Threshold

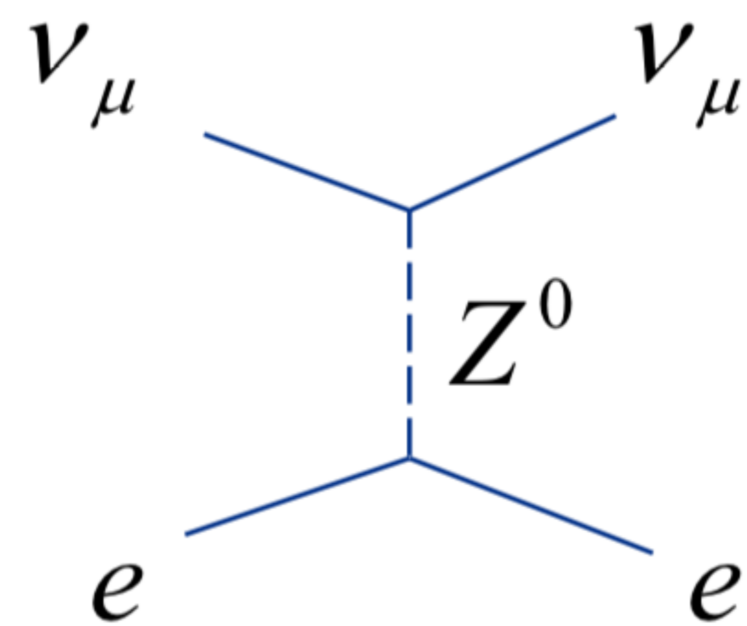


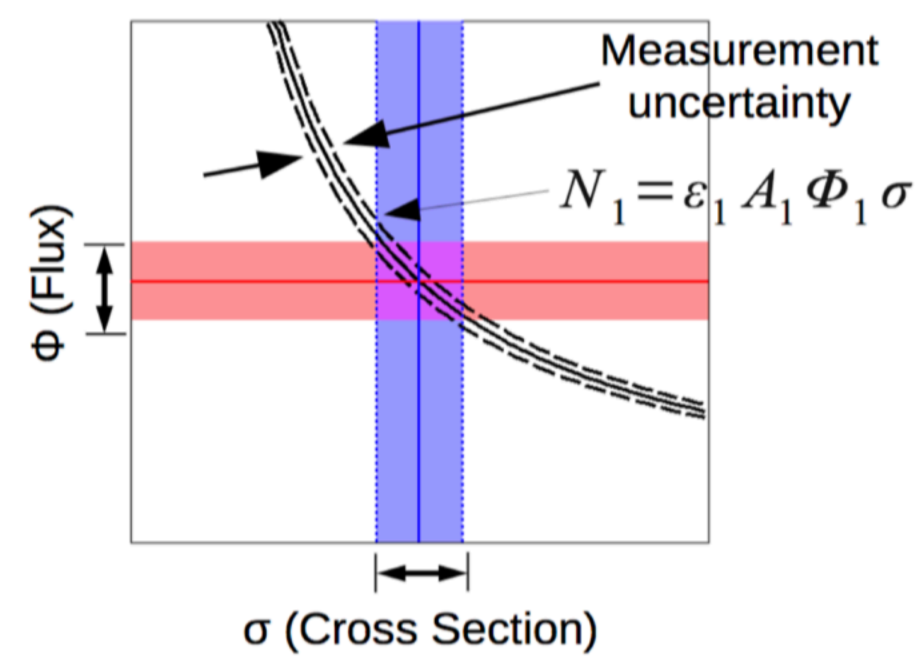
- DUNE plans to build a HPgTPC a part of the near detector complex
- Prototype detectors are underway both at FNAL and RHUL



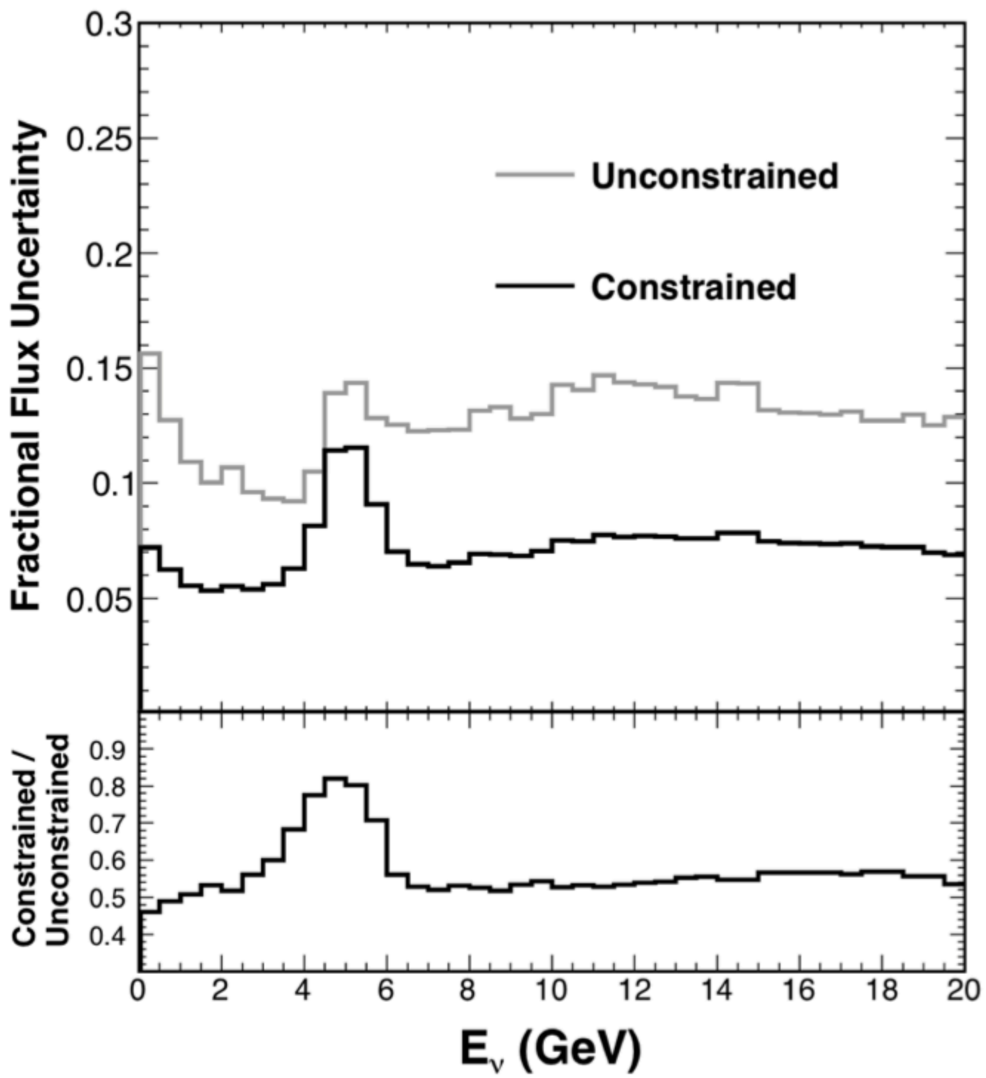
New Concepts: Beam

- Major problem is the fact that near detectors measure flux times cross section
- Separation of the two is desirable!
- Enter electron scattering!





New Concepts: Beam



- MINERvA has show a proof-of-concept analysis of this technique
- Difficulty lies in separating events from intrinsic beam nue, tiny cross section
- Future experiments thinking about ways to include this measurement in NDs

Conclusions

- The difficulty of QCD modeling produces complex challenges for neutrino physics
- The current generation of near detectors do a great job for their experiments
- Novel techniques and analyses are needed to drive the next generation of experiments