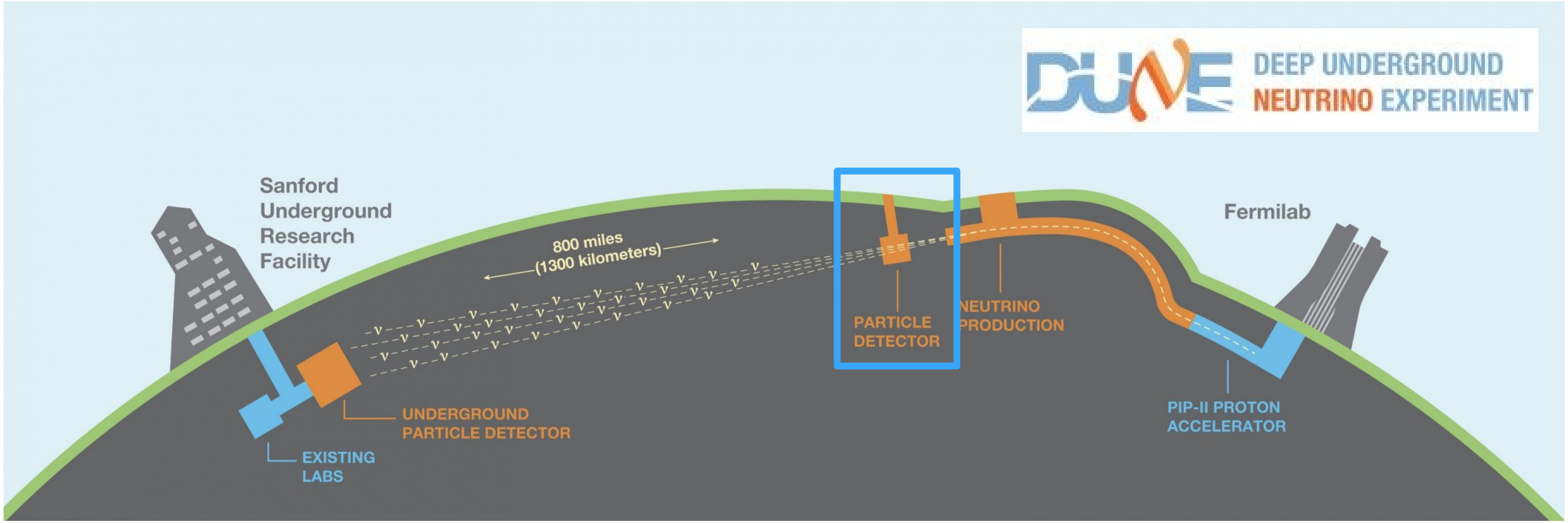


The DUNE Near Detector

Daniel Cherdack, University of Houston
on behalf of the **DUNE Collaboration**

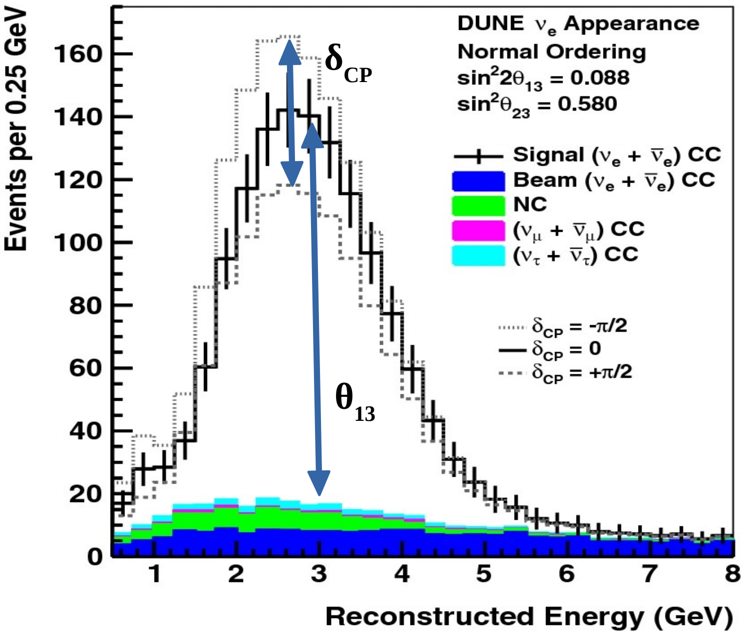
Seattle Snowmass Summer Meeting

Tuesday July 19th, 2022

UNIVERSITY of HOUSTON

Predicting the Neutrino Event Rate

DUNE TDR



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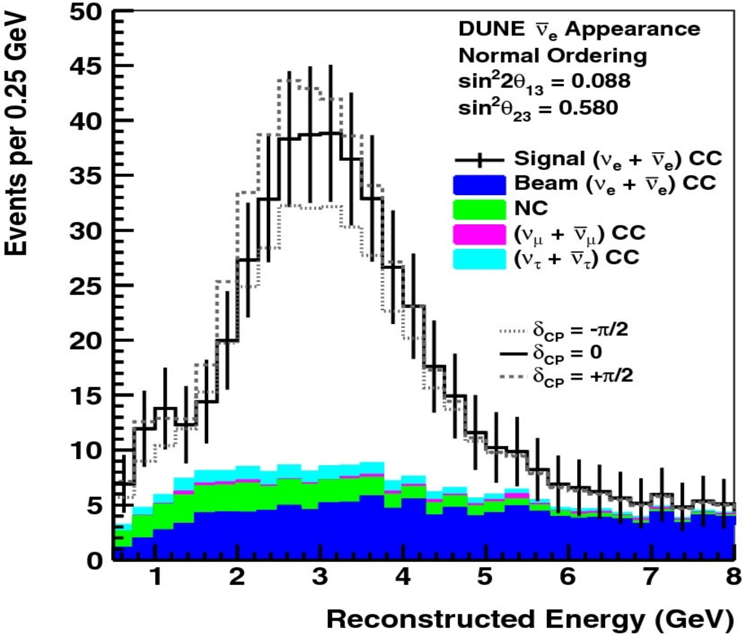
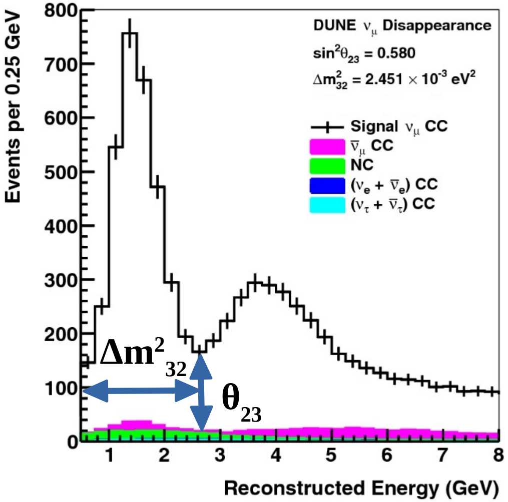
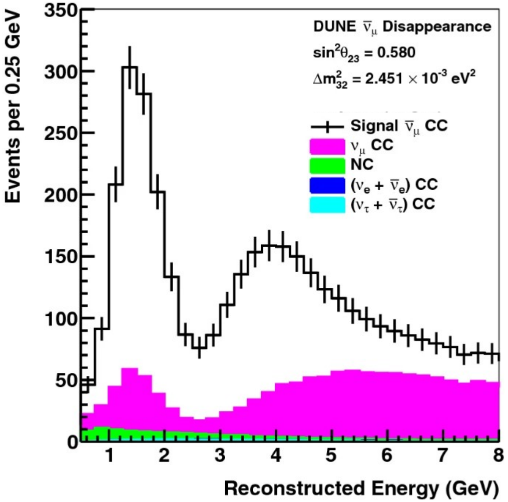




DUNE TDR



$$N_{pred}\left(E_\nu^{reco}\right) = \Phi\left(E_\nu^{true}\right)\,\sigma\left(E_\nu^{true}\right)\,P\left(\alpha\rightarrow\beta, E_\nu^{true}\right)\,\epsilon\left(E_\nu^{reco}\right)\,S\left(E_\nu^{true}, E_\nu^{reco}\right)$$

Predicting the Neutrino Event Rate

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\ \sigma(E_\nu^{true})\ P(\alpha \rightarrow \beta, E_\nu^{true})\ \epsilon(E_\nu^{reco})\ S(E_\nu^{true}, E_\nu^{reco})$$

What we measure:

- $N_{pred}(E_\nu^{reco})$ = Expected number of events

Measure with a near detector:

- $\Phi(E_\nu^{true})$ = Neutrino flux
- $\sigma(E_\nu^{true})$ = Interaction cross sections

Physics of interest:

- $P(\alpha \rightarrow \beta, E_\nu^{true})$ = Oscillation probability

Detector Effects:

- $\epsilon(E_\nu^{reco})$ = Selection efficiency
- $S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

Predicting the Neutrino Event Rate

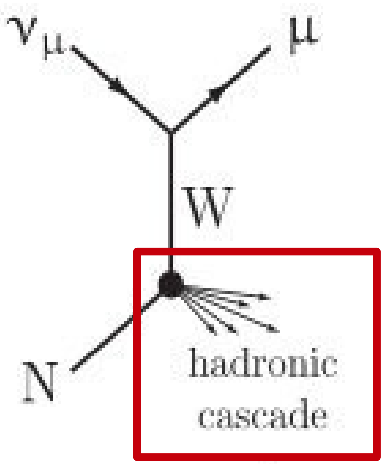
$$N_{pred}\left(E_\nu^{reco}\right) = \Phi\left(E_\nu^{true}\right)\,\sigma\left(E_\nu^{true}\right)\,P\left(\alpha \rightarrow \beta, E_\nu^{true}\right)\,\epsilon\left(E_\nu^{reco}\right)\,S\left(E_\nu^{true}, E_\nu^{reco}\right)$$

$N_{pred}\left(E_\nu^{reco}\right)$

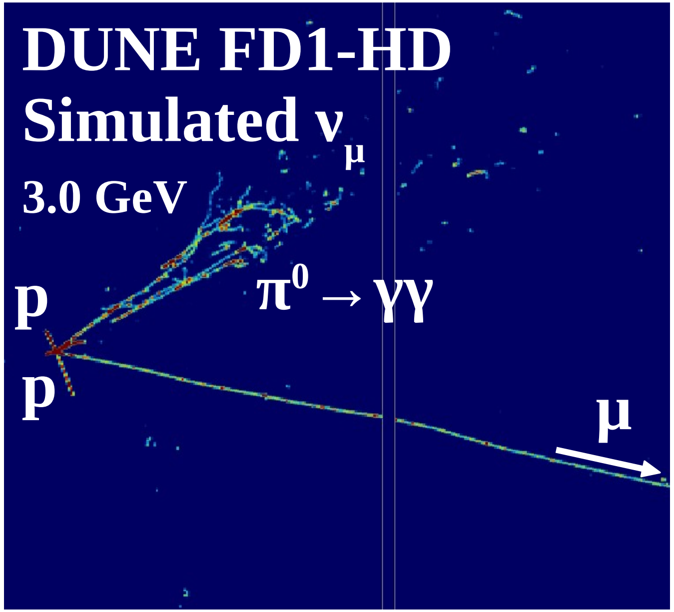
Measure with a near detector: $\Phi\left(E_\nu^{true}\right)$, $\sigma\left(E_\nu^{true}\right)$

$P\left(\alpha \rightarrow \beta, E_\nu^{true}\right)$

Highly Dependent on Hadronic System: $\epsilon\left(E_\nu^{true}\right)$, $S\left(E_\nu^{true}, E_\nu^{reco}\right)$



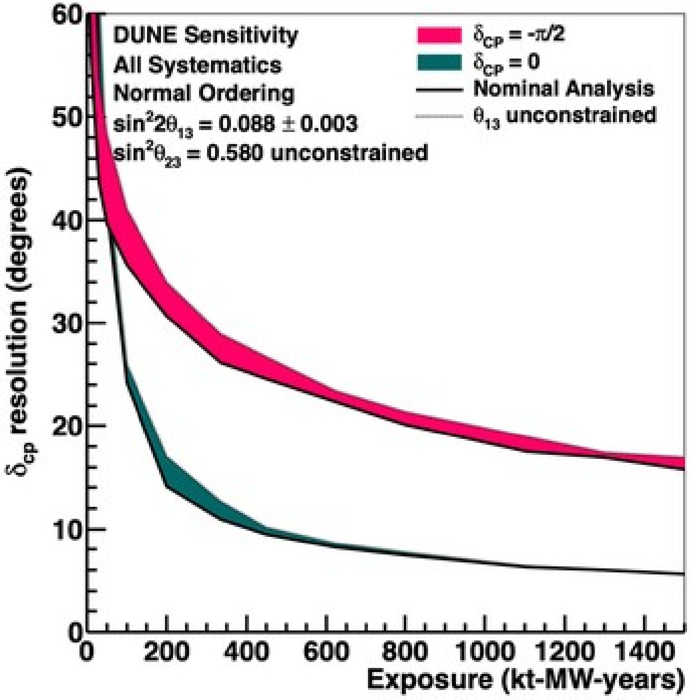
QCD!



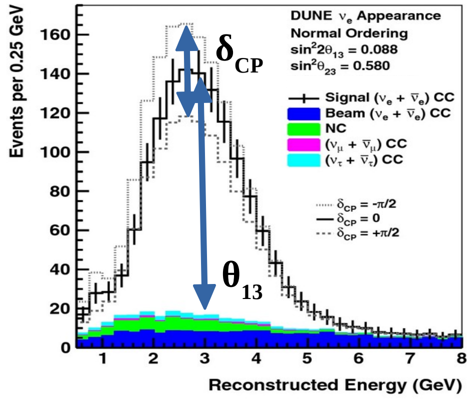
Requirements for the DUNE Near Detector

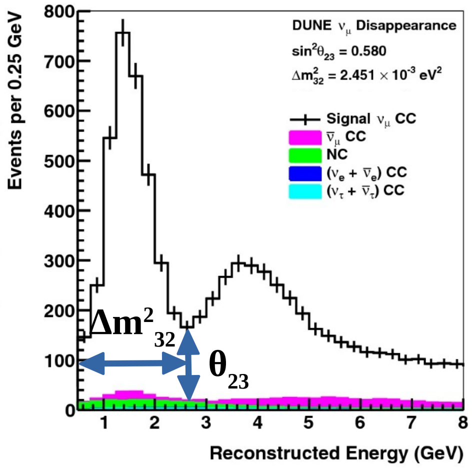
- Constrain systematic uncertainties at levels consistent with FD statistics
  - Neutrino flux
  - Neutrino-argon cross sections
  - Relationship between interaction products and neutrino energy
  - LAr TPC detector response
- Detector design consideration
  - On-axis beam monitoring
  - Event containment
    - Transverse size: hadronic system
    - Longitudinal size: downstream spectrometer
  - (Functionally) identical detector technology
    - Modifications for high rate
    - Same nucleus, same physical response
  - Ability to sample off-axis fluxes
  - Lower particle detection thresholds
  - Neutron detection

DUNE TDR



DUNE TDR





Phase I Requirements for the DUNE Near Detector

- Constrain systematic uncertainties at levels consistent with FD statistics
  - **Neutrino flux**
  - **Neutrino-argon cross sections**
  - Relationship between interaction products and neutrino energy
  - **LAr TPC detector response**
- Detector design consideration
  - **On-axis beam monitoring**
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    - Transverse size: hadronic system
    - Longitudinal size: downstream spectrometer
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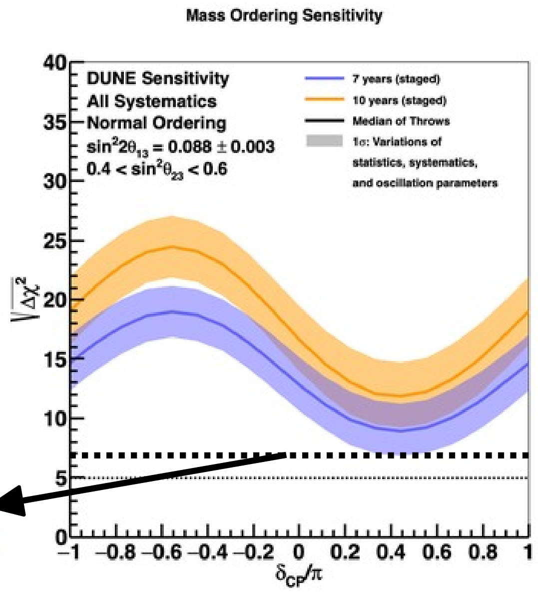
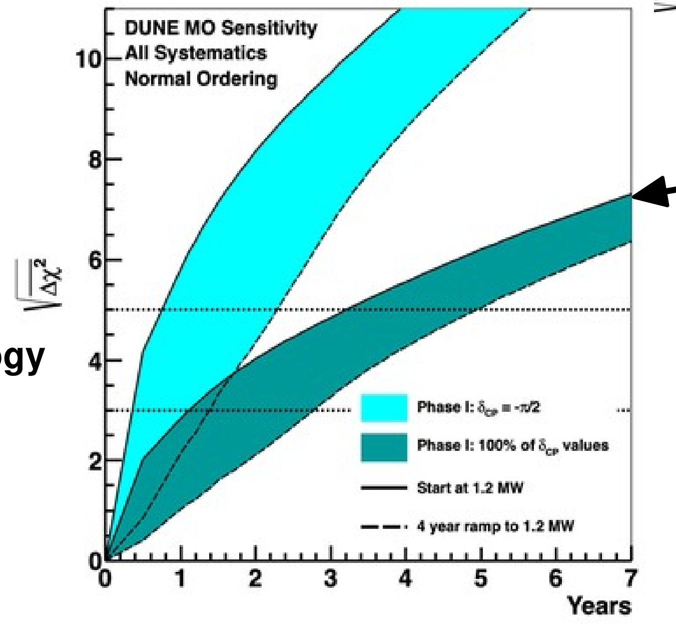
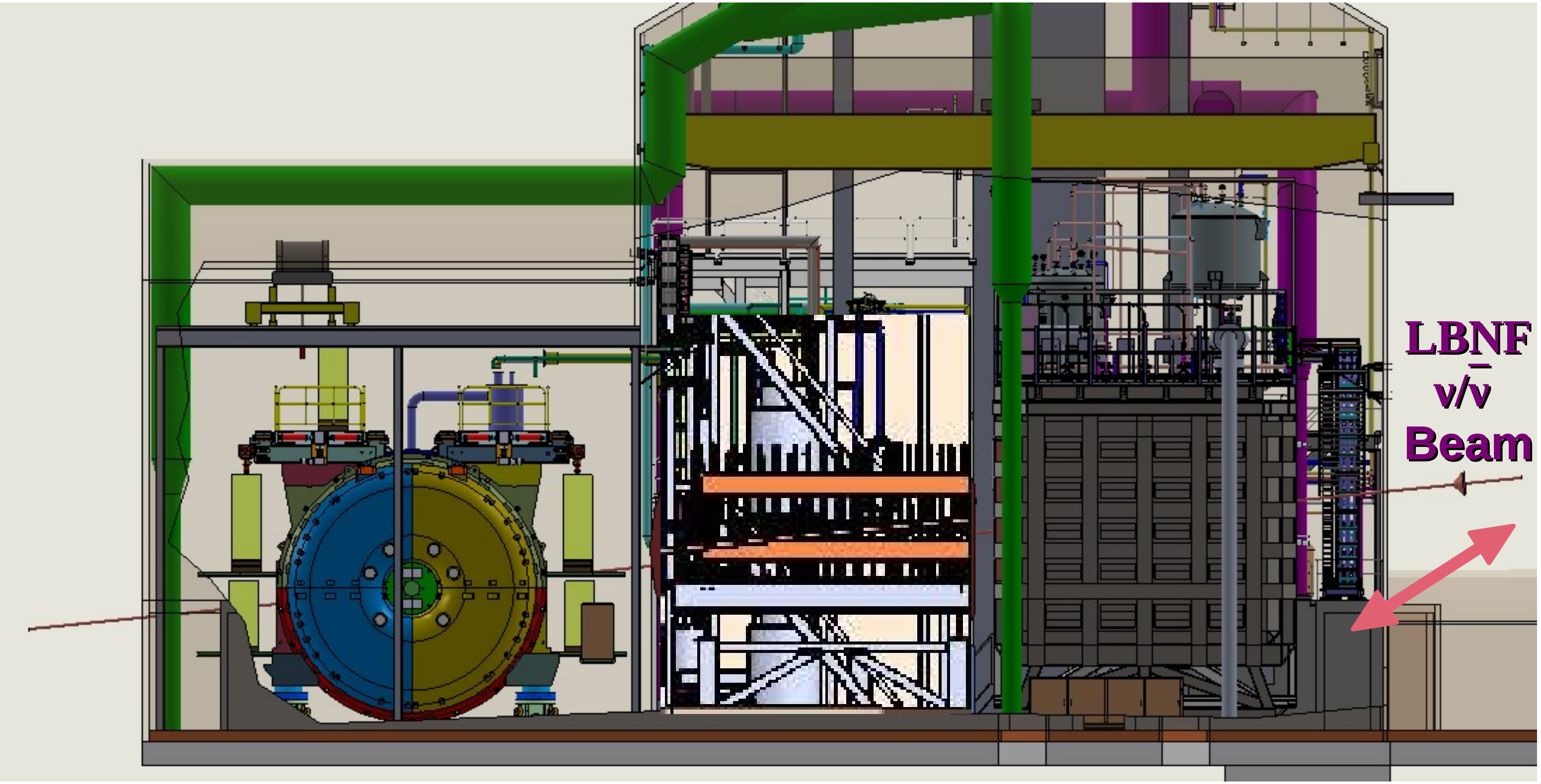
  - **Ability to sample off-axis fluxes**
  - Lower particle detection thresholds
  - Neutron detection

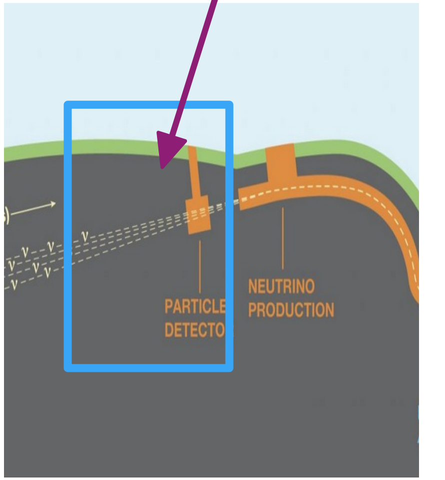




<u>Phase I</u>:
Requirements based on Mass Ordering sensitivity

The DUNE ND Complex - Phase I





SAND
System for On-Axis
Neutrino Detection

TMS
Magnetized Temporary
Muon Spectrometer

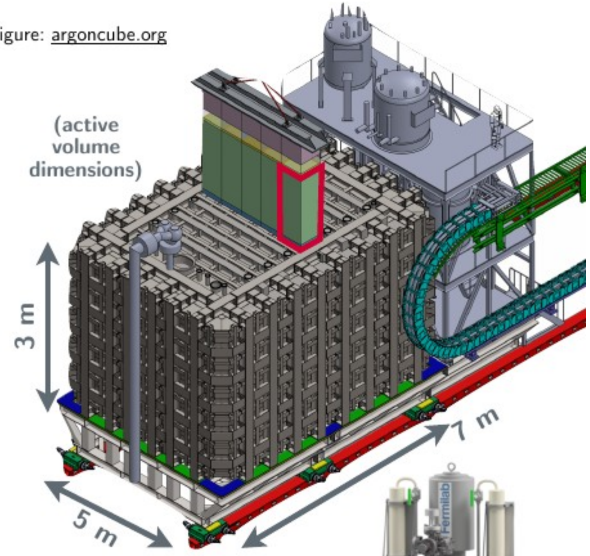
ND-LAr
Modular Liquid
Argon TPC

PRISM
30m Off-Axis Mobility for
LAr + Spectrometer

ND-LAr Modular TPC

- Design
  - Same liquid argon target as the DUNE FD
  - Modular design: 35 1×1×3 m^3 modules with two TPCs per module (50 cm drift)
  - Charge readout: LArPix pixel readout for direct-to-3D charge information
  - Light readout: High (~40%) detector coverage with ns-scale timing and cm-scale position
- Physics
  - High-statistics ν interactions in LAr TPC
  - **~30M accepted ν_μ CC events/year (FHC / ν mode, 1.2 MW beam)**
  - Constrain flux via ν+e elastic scattering
  - Precise constraints on event rates (flux × cross sections) in LAr

Figure: argoncube.org



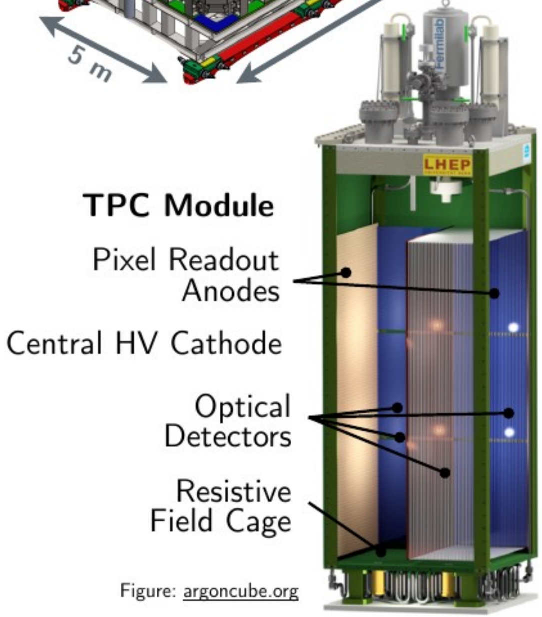


Figure: argoncube.org

ND-LAr Event Containment

- Constrain systematic uncertainties at levels consistent with FD statistics
  - Neutrino flux
  - **Neutrino-argon cross sections**
  - Relationship between interaction products and neutrino energy
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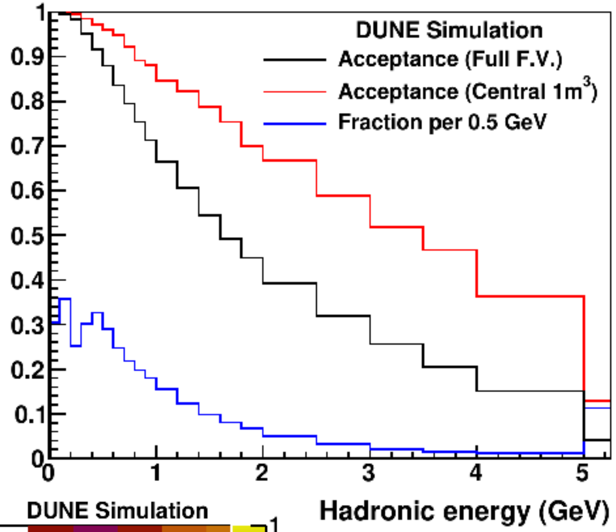
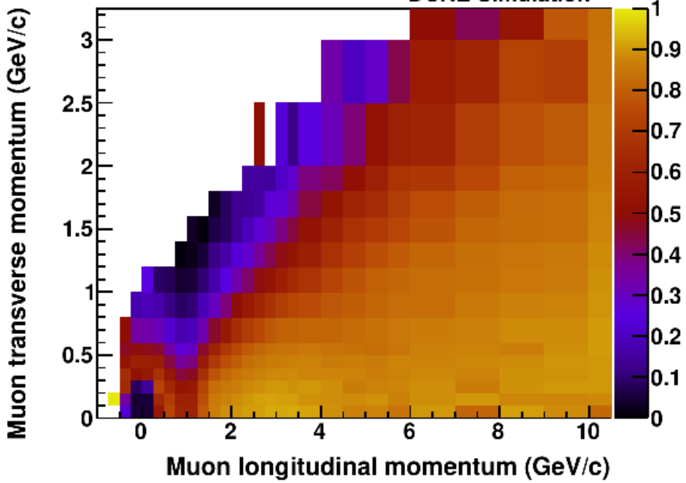


Muon Containment Efficiency



TMS extends longitudinal muon containment beyond ND-LAr length

ND-LAr CC-ν_μ Inclusive Samples

- Constrain systematic uncertainties at levels consistent with FD statistics
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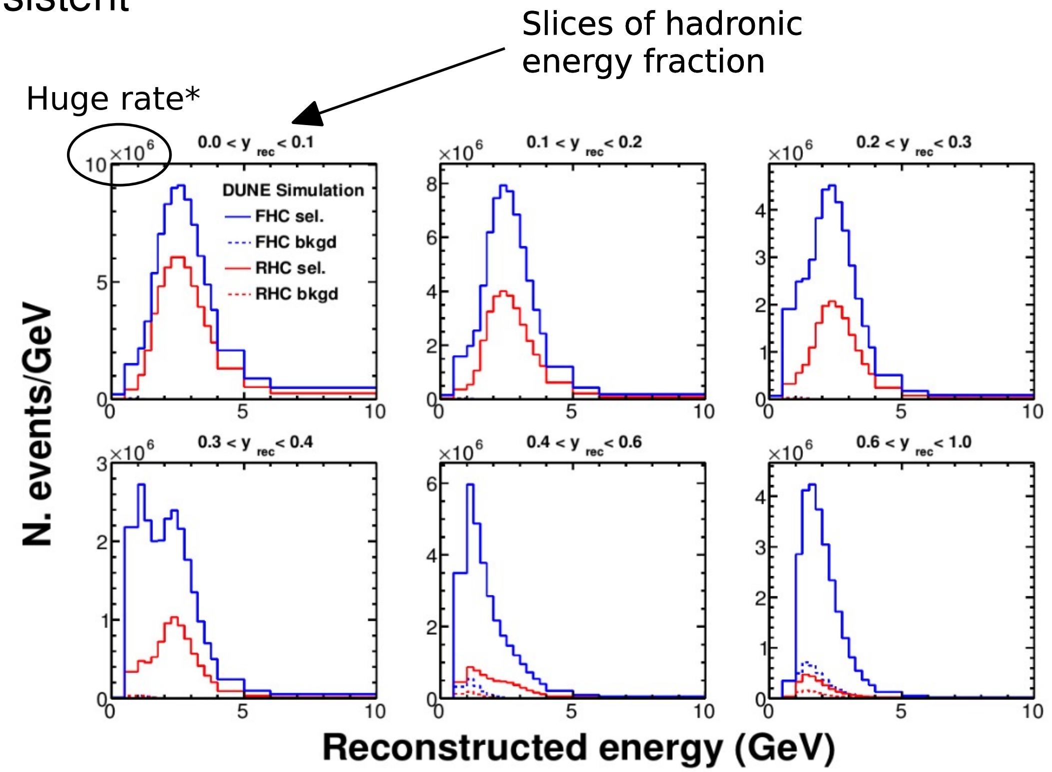

*High statistics provide opportunities to "slice" up data in informative ways.

ND-LAr Constraints (CC-ν_μ Inc.)

- Constrain systematic uncertainties at levels consistent with FD statistics
  - Neutrino flux
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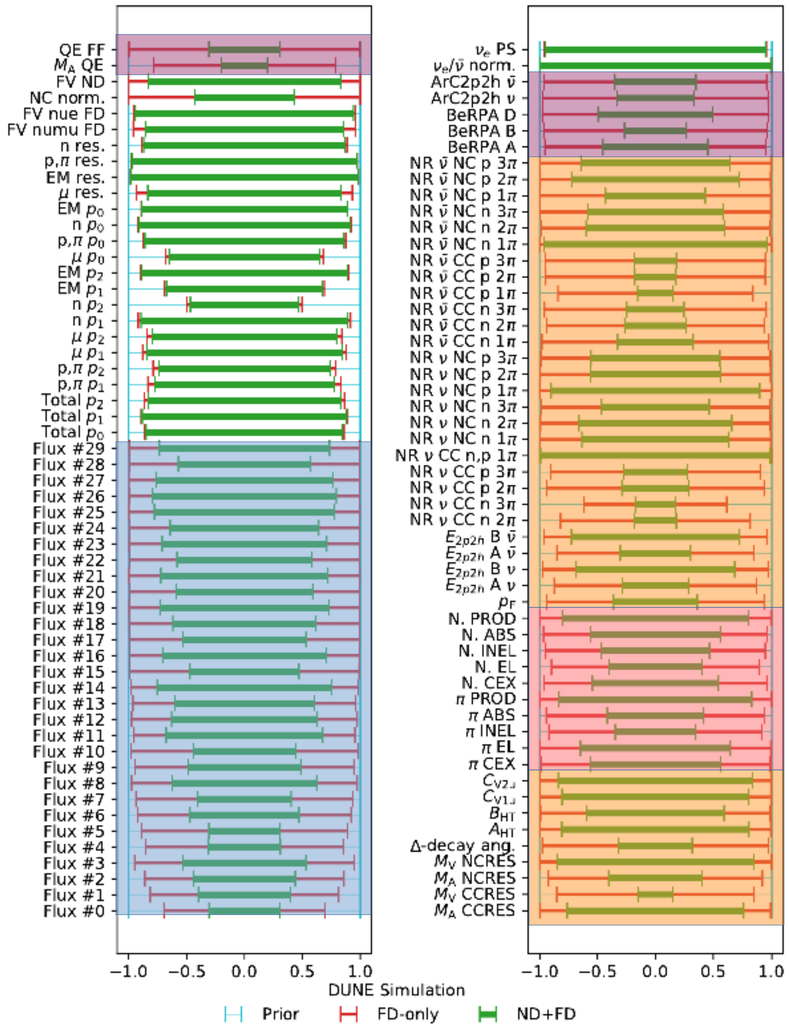
Flux
QE + 2p2h
Res + DIS
Nuclear



ND-LAr Flux Measurement (ν+e)

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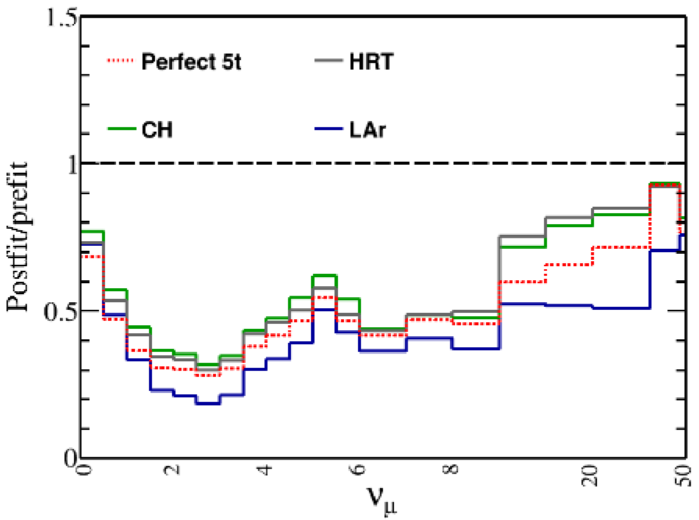

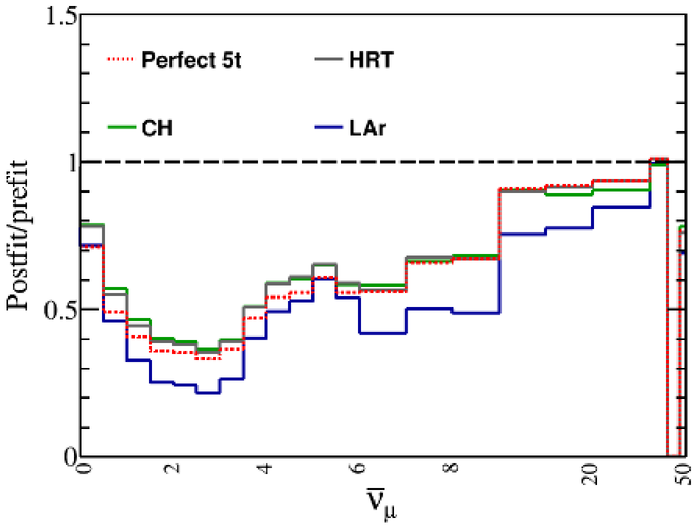

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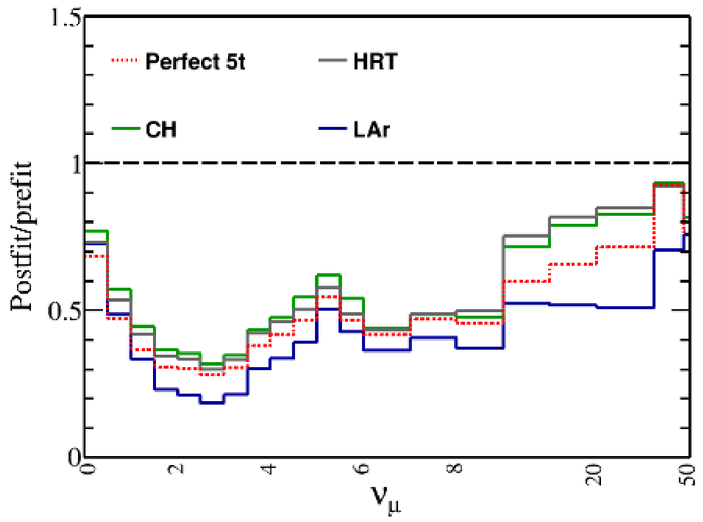
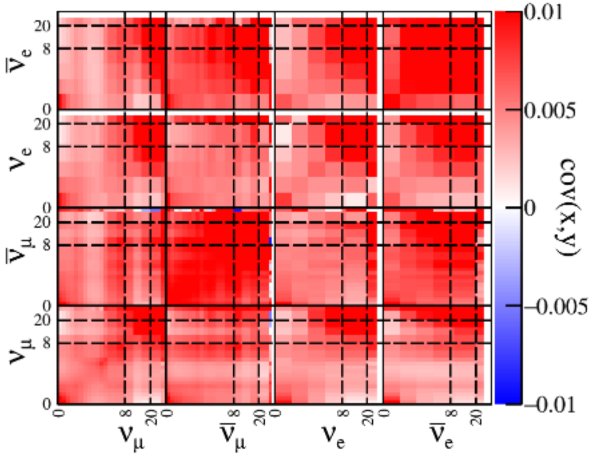
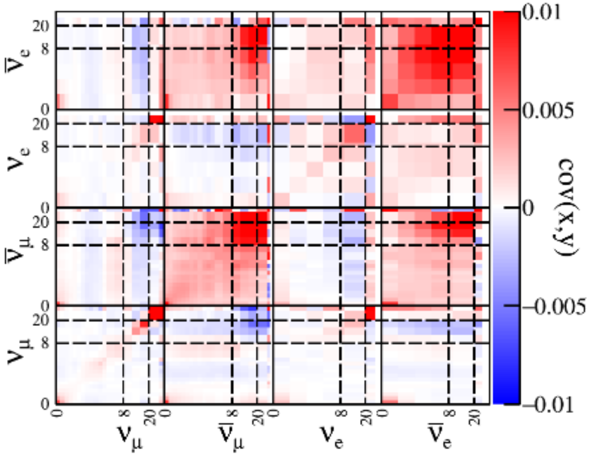


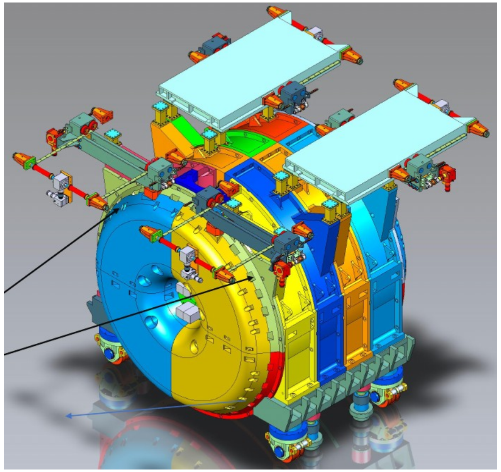


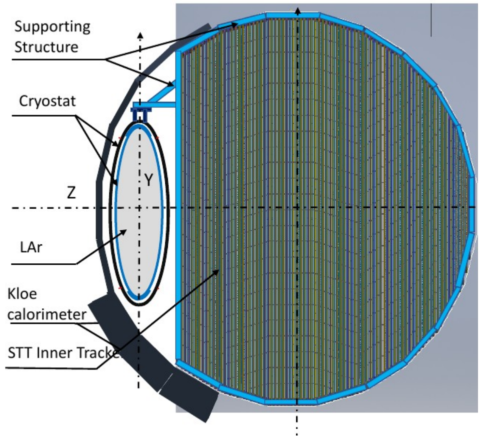


SAND: System for On-Axis Neutrino Detection

- Design
  - **Fixed on-axis position**
  - LAr Target + STT + Ecal + solenoid magnet
  - Ecal and Magnet repurposed from KLOE Experiment
- Physics
  - **Continuous monitoring of the on-axis flux:**
    - **Detailed flux stability on a weekly basis**
    - **Tune flux model as function of time**
    - **Quick response to beamline geometry changes**
  - STT provides CH and C targets for comparison with world cross section data (mostly CH) and H cross sections via subtraction
  - Broad physics program beyond neutrino oscillations:
    - Cross sections
    - Weak mixing angle
    - BSM Searches
  - Ar events provide ND-LAr cross check

SAND Consortium





SAND: System for On-Axis Neutrino Detection

SAND Consortium

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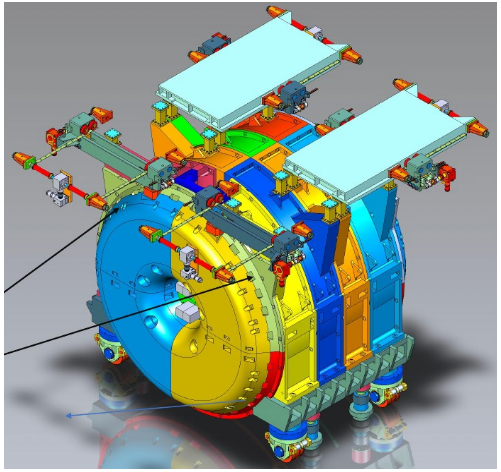
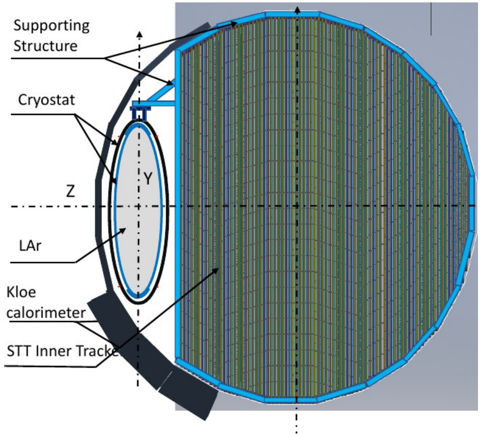
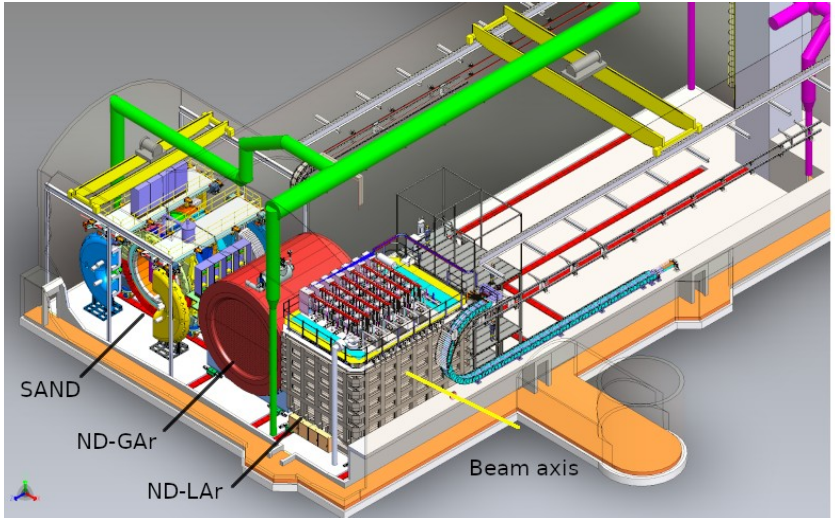
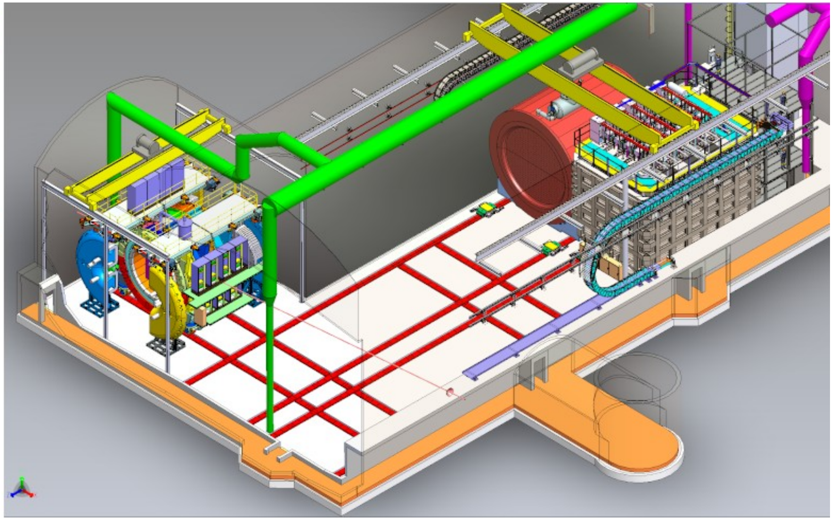




PRISM

- Design
  - System for moving the LAr TPC + tracker up to 30 m transverse to the beam direction
  - Enables scan of beam at multiple off-axis positions
- Physics
  - Beam energy spectrum changes with off-axis position
  - Peak energy is reduced; peak width narrows
  - Use statistical subtraction to measure cross sections in a narrow incoming neutrino energy range
  - Better control of hadronic physics with constrained incoming neutrino energy
  - Direct use of ND data in oscillation analysis: shifts cross section uncertainties to flux uncertainties





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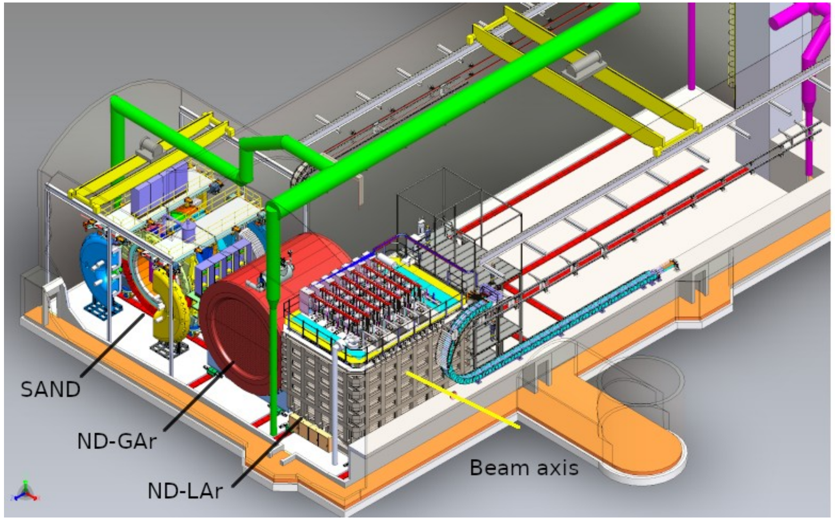

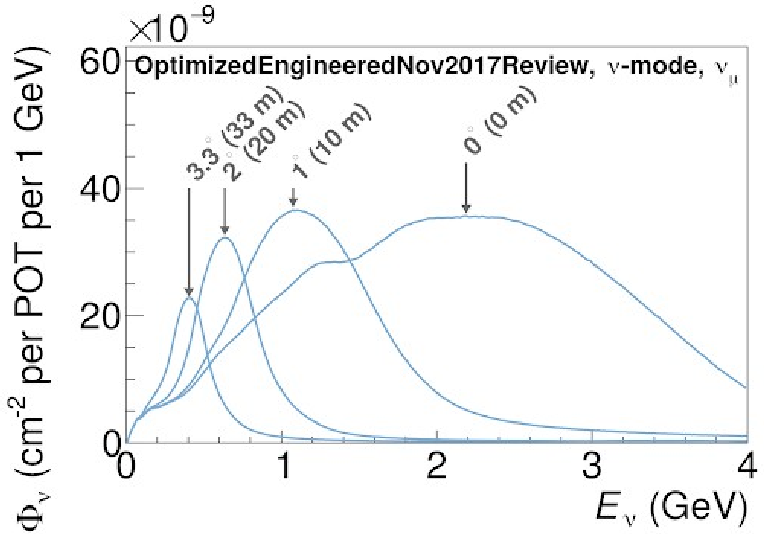

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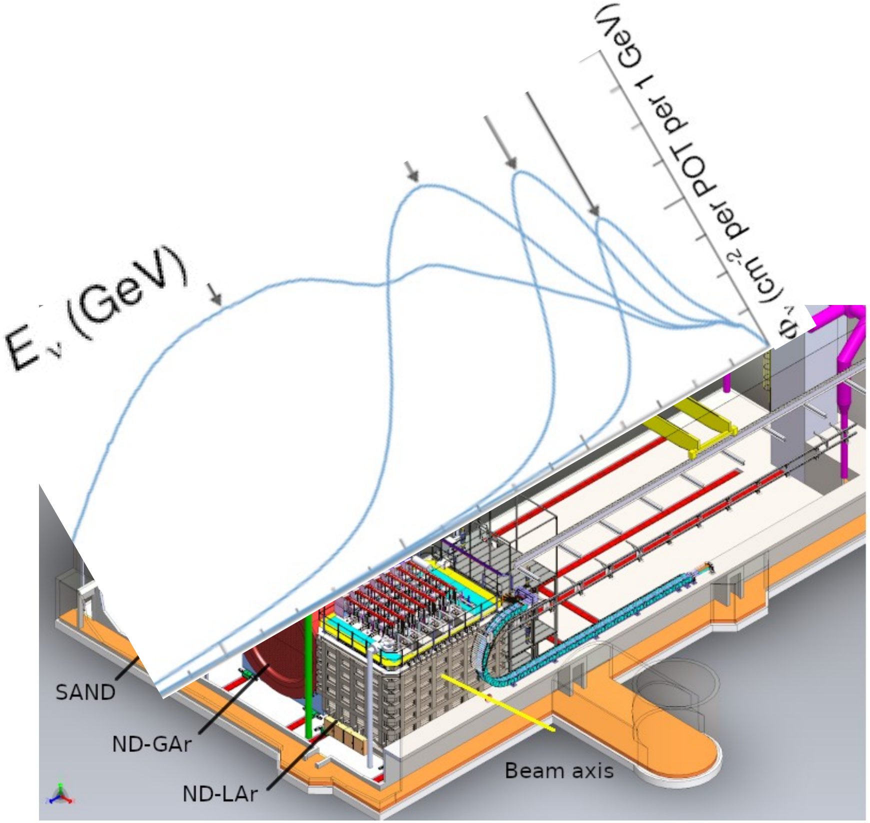

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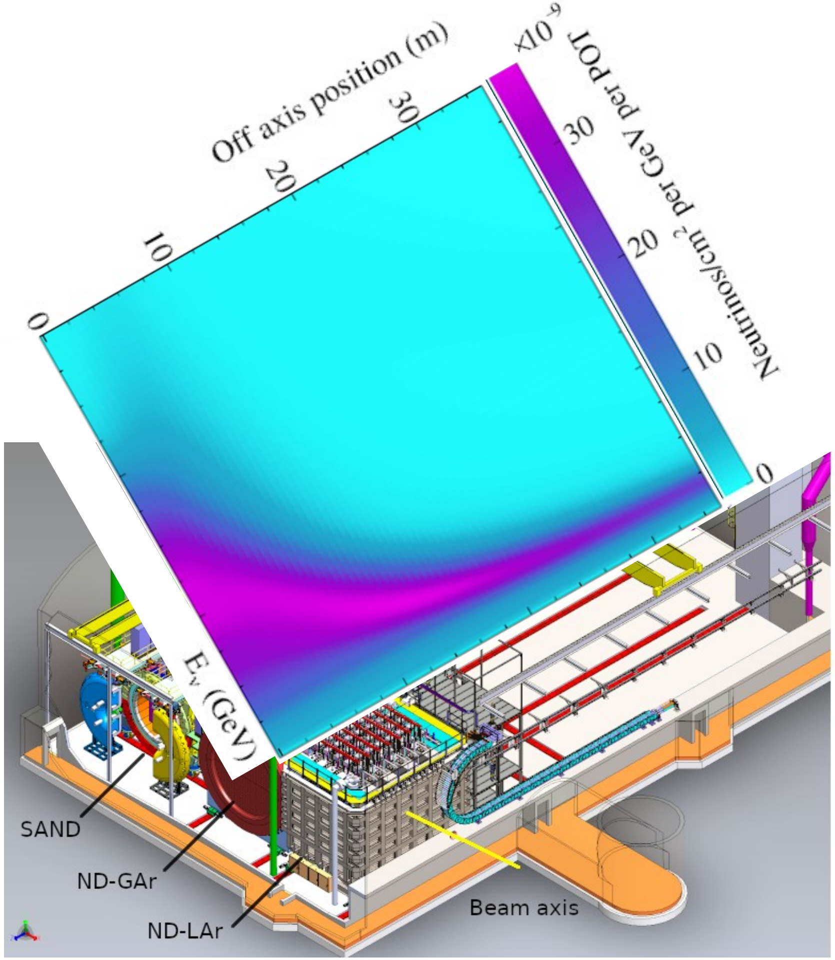
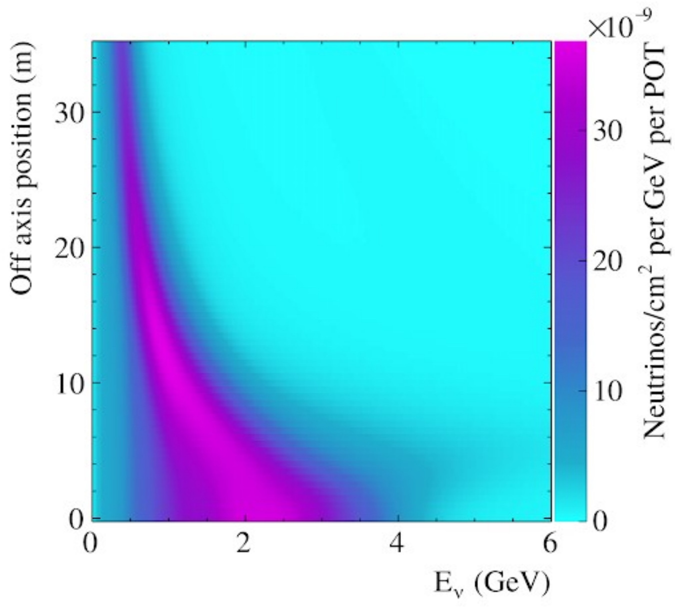
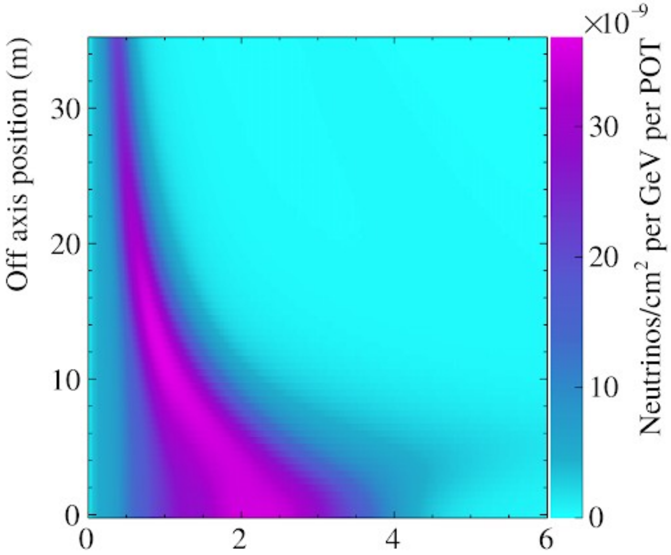


PRISM: Express Osc. Prob. as ND Flux Weights

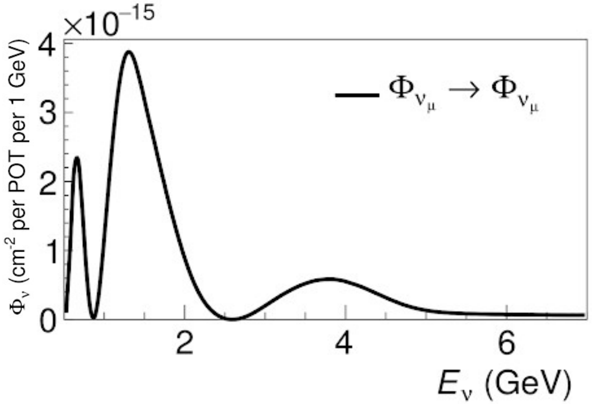


Start with:
MC ND ν_μ flux prediction at each off-axis position: $\Phi^{ND}(E_\nu, x)$

PRISM: Express Osc. Prob. as ND Flux Weights

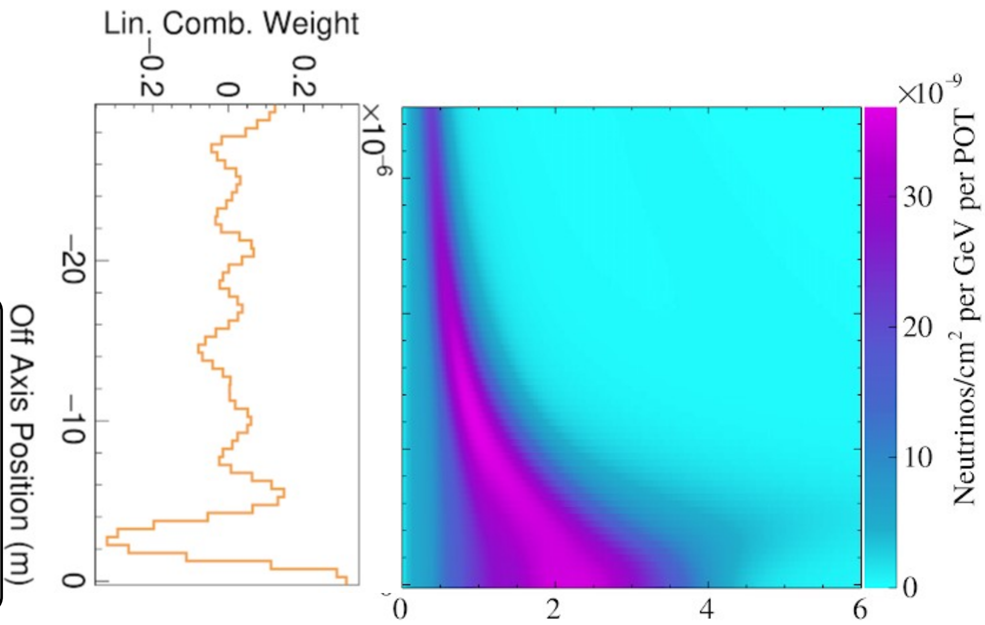


<u>Start with</u>:
MC ND ν_μ flux prediction at each off-axis position: $\boldsymbol{\Phi^{ND}(E_\nu,x)}$



<u>Step 1</u>:
Pick oscillation hypothesis to get FD ν_μ flux $\boldsymbol{\Phi^{FD}(E_\nu)}$

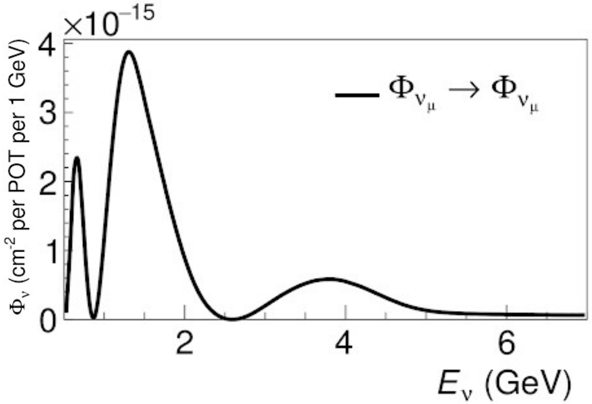
PRISM: Express Osc. Prob. as ND Flux Weights



Start with:
MC ND ν_μ flux prediction at each off-axis position: $\boldsymbol{\Phi^{ND}(E_\nu,x)}$

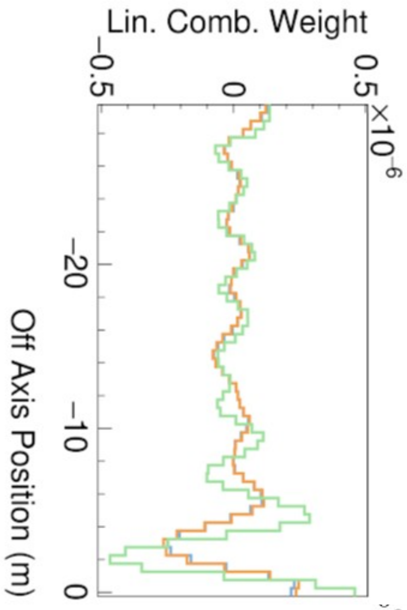
Step 2:
Find set of position weights $\mathbf{C(x)}$ such that:
$\mathbf{C(x)} \cdot \boldsymbol{\Phi^{ND}(E_\nu,x)} = \boldsymbol{\Phi(E_\nu)}$

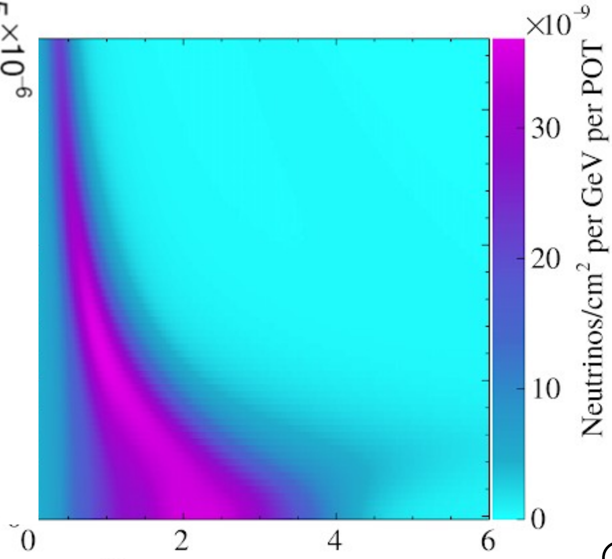
Step 1:
Pick oscillation hypothesis to get FD ν_μ flux $\boldsymbol{\Phi^{FD}(E_\nu)}$



PRISM: Express Osc. Prob. as ND Flux Weights

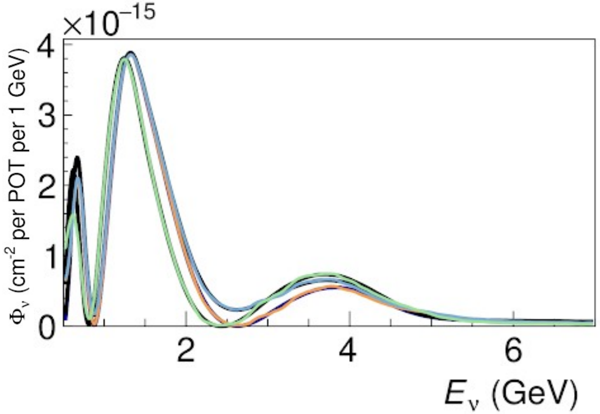
<u>Step 2</u>:
Find set of position weights $C(x)$ such that:
$\mathbf{C(x) \cdot \Phi^{ND}(E_\nu,x) = \Phi(E_\nu)}$





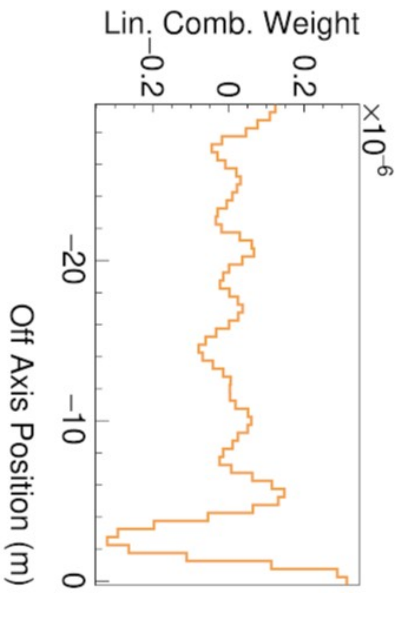
<u>Start with</u>:
MC ND ν_μ flux prediction at each off-axis position: $\Phi^{ND}(E_\nu,x)$

<u>Step 1</u>:
Pick oscillation hypothesis to get FD ν_μ flux $\Phi^{FD}(E_\nu)$



<u>Step 3</u>:
Repeat for each FD ν_μ flux $\mathbf{\Phi^{FD}(E_\nu)}$ required for osc. parameter fits

PRISM: Use Weights to Predict FD Event Spectrum



Start with:
Oscillation hypothesis, $\mathbf{P(E_\nu)}$ expressed as position weights $\mathbf{C(x)}$ such that:

$$\mathbf{C(x) \cdot \Phi^{ND}(E_\nu,x) = \Phi(E_\nu)}$$

Only uses MC flux prediction

No cross section model required!

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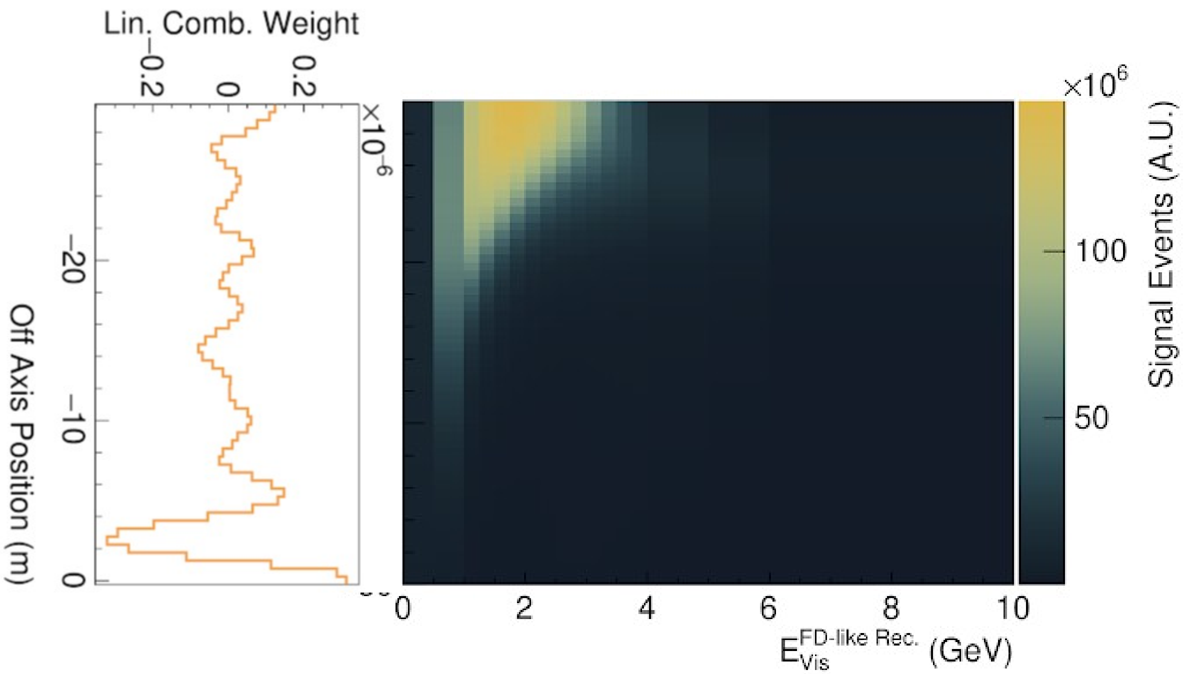
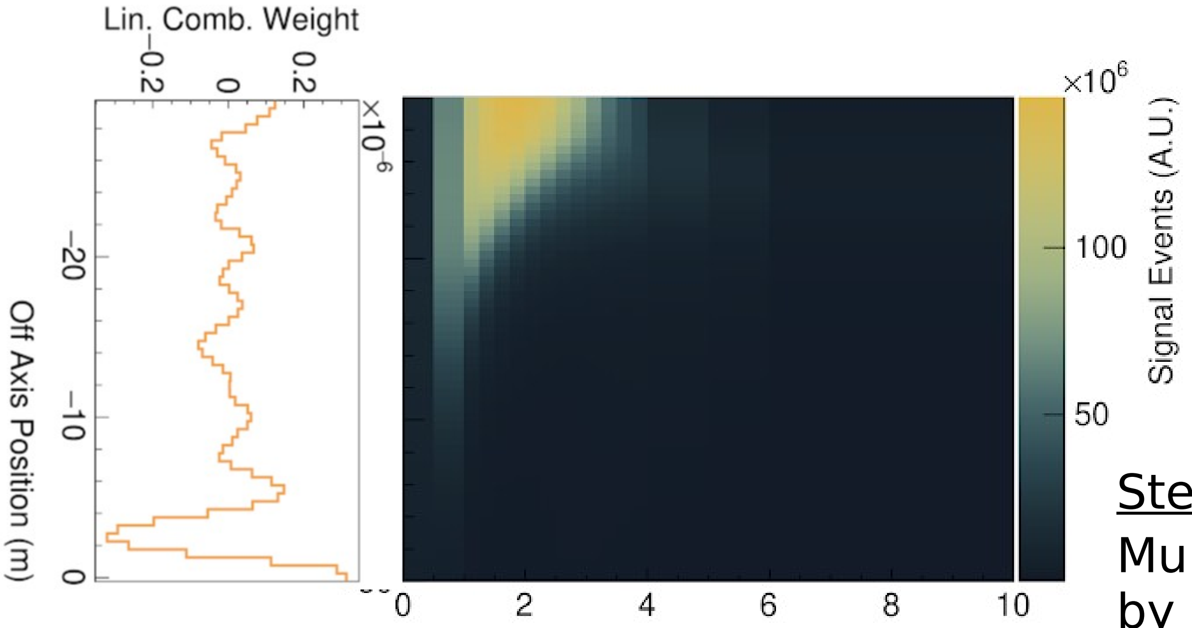


Only uses MC flux prediction & ND data

No cross section model required!

Step 1:
Multiply $C(x)$ by ND **data**, $D^{ND}(E_{rec},x)$ to get the FD event rate:
$C(x)\cdot D^{ND}(E_{rec},x) = R^{FD}(E_{rec})$

PRISM: Use Weights to Predict FD Event Spectrum



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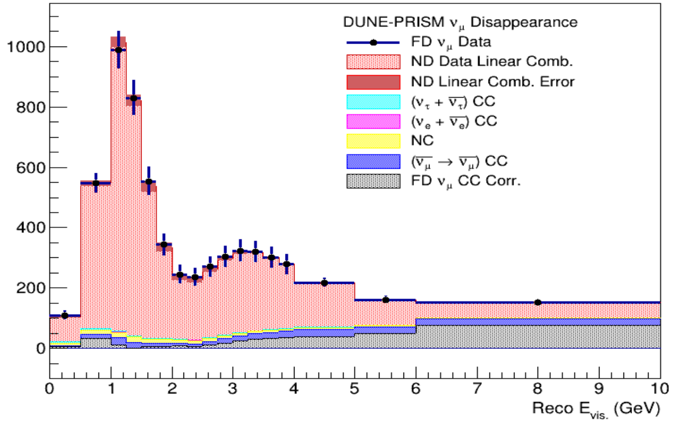
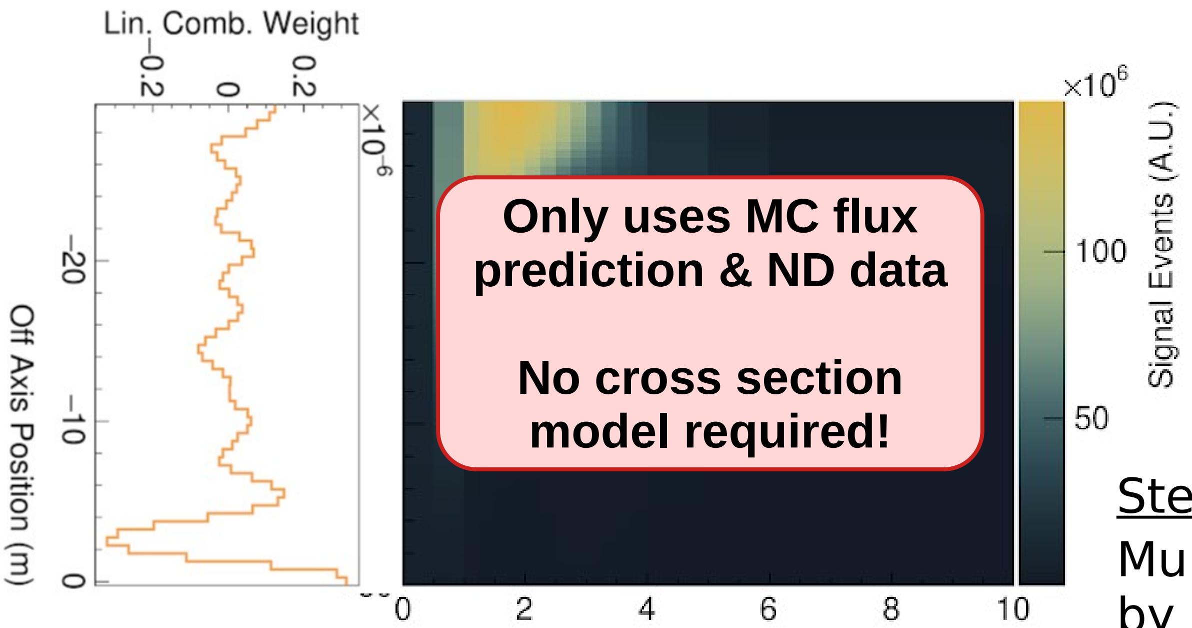


Step 2:

Compare with FD data, $\mathbf{D^{FD}(E_{rec})}$ with the prediction $\mathbf{R^{FD}(E_{rec})}$ to determine likelihood of $\mathbf{P(E_\nu)}$

PRISM: Use Weights to Predict FD Event Spectrum



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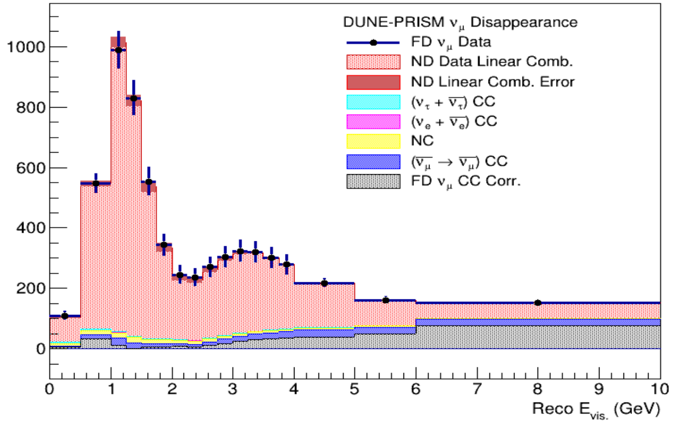
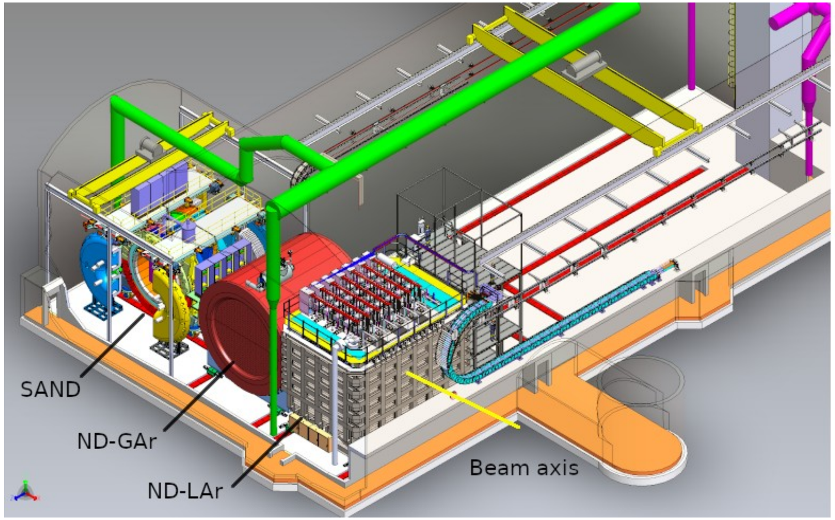
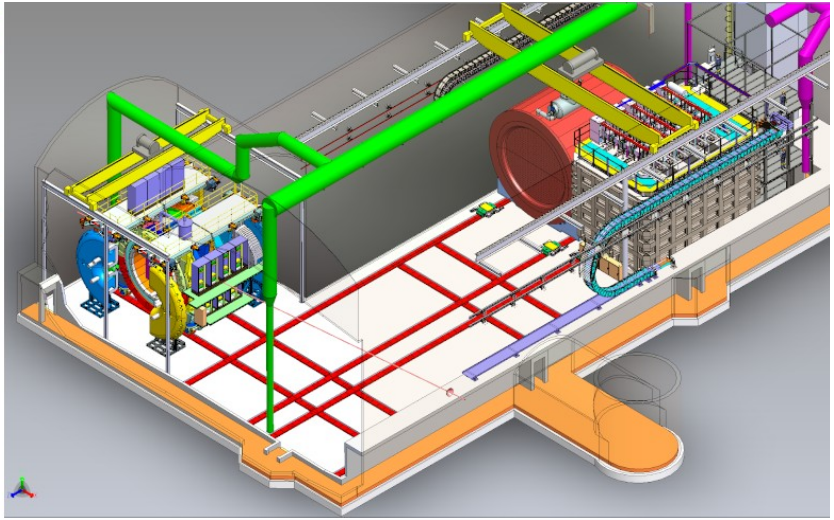


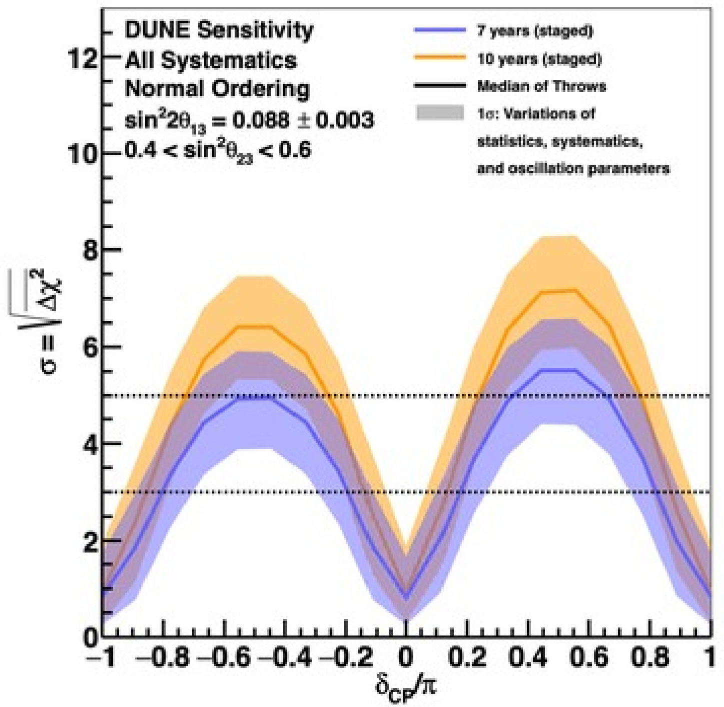
PRISM

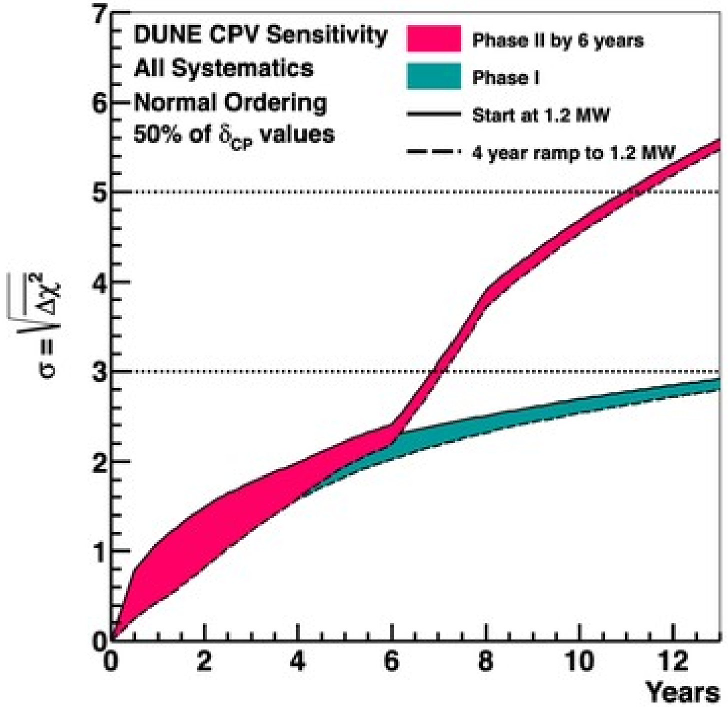
- Constrain systematic uncertainties at levels consistent with FD statistics
  - Neutrino flux
  - Neutrino-argon cross sections
  - **Relationship between interaction products and neutrino energy**
  - **LAr TPC detector response**
- Detector design consideration
  - On-axis beam monitoring
  - Event containment
    - Transverse size: hadronic system
    - Longitudinal size: downstream spectrometer
  - **(Functionally) identical detector technology**
    - Modifications for high rate
    - Same nucleus, same physical response
  - **Ability to sample off-axis fluxes**
  - Lower particle detection thresholds
  - Neutron detection





Improved Systematics: Phase I → Phase II

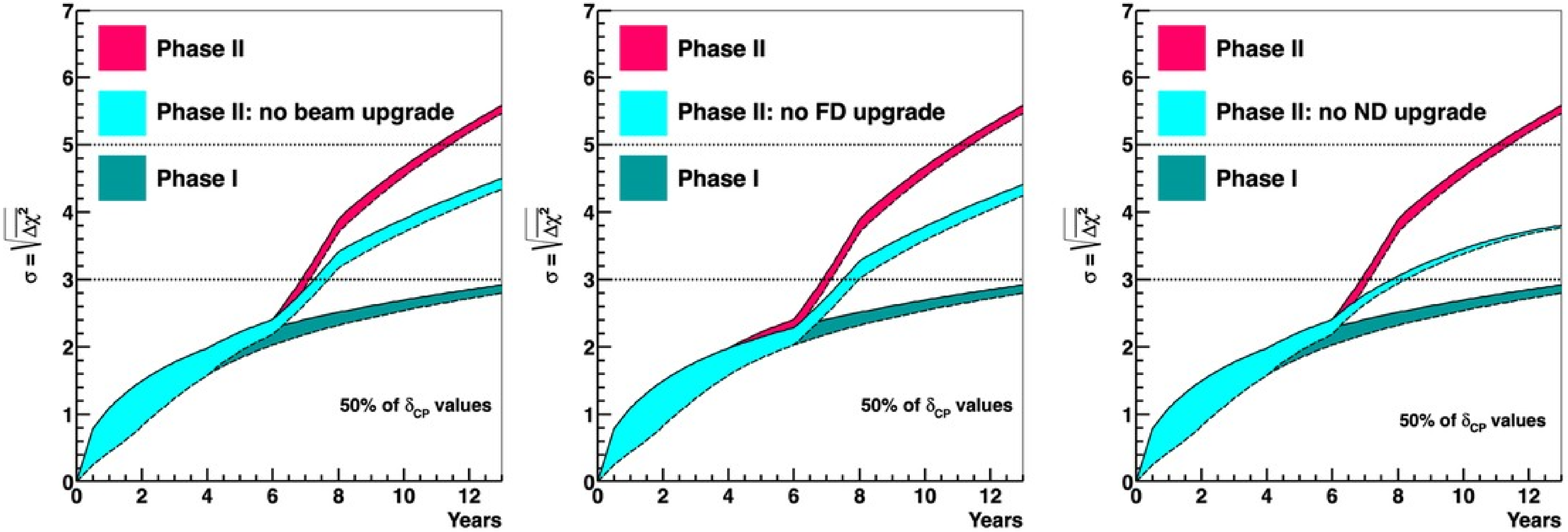




- Phase II required to push CPV sensitivity above 5σ for 50% of δ_{CP} values
- Flux and FD functionally doubled increasing FD event rate by 4

- Upgrade required to enable high-precision physics goals, especially for δ_{CP}
- ND Upgrade: Lower thresholds, higher resolution, “missing energy” detection

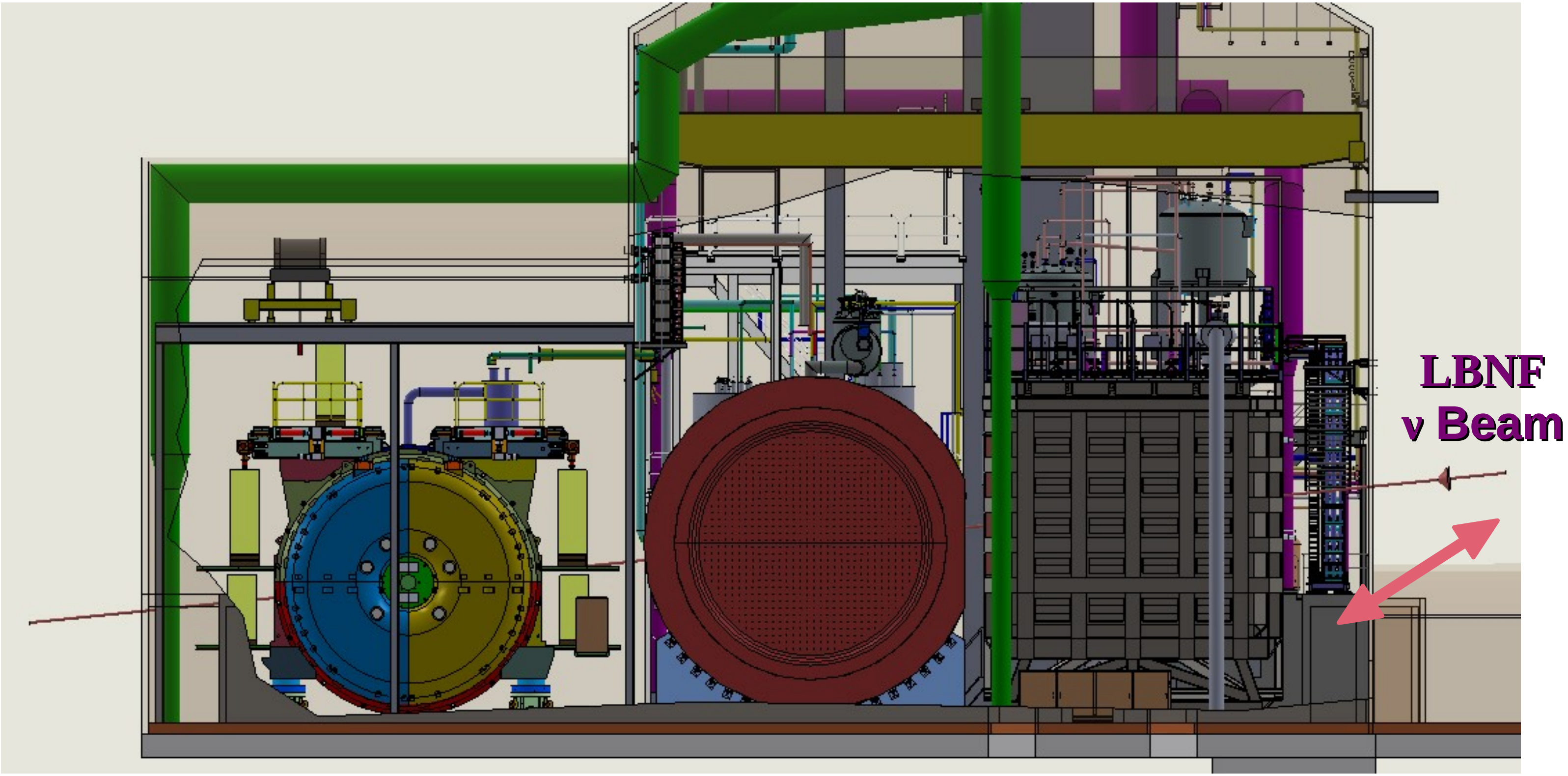
Improved Systematics: Phase I → Phase II



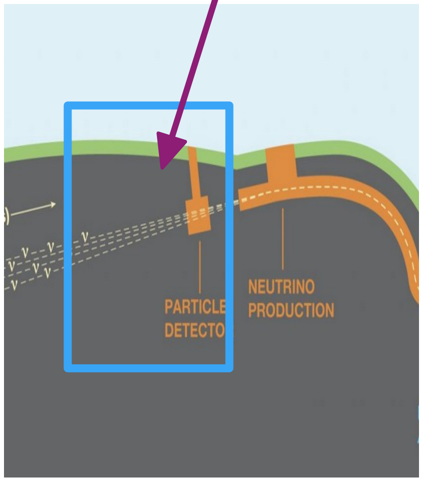
- Phase II requires 3 major upgrades
  - Double beam intensity
  - Double effective far detector mass
  - Improve ND complex to keep pace with systematics

- Upgrade required to enable high-precision physics goals, especially for δ_{CP}
- ND Upgrade: Lower thresholds, higher resolution, “missing energy” detection

The DUNE ND Complex - Phase II



60 meters underground



SAND
System for On-Axis Neutrino Detection

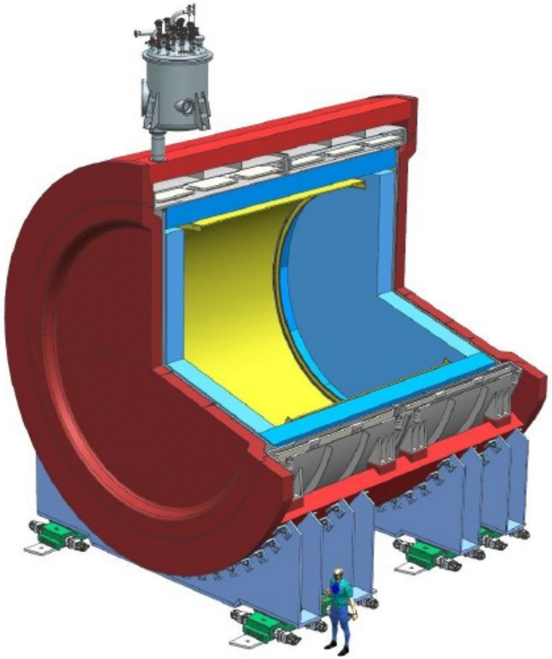
MCND
¿Magnetized Gaseous Argon TPC?

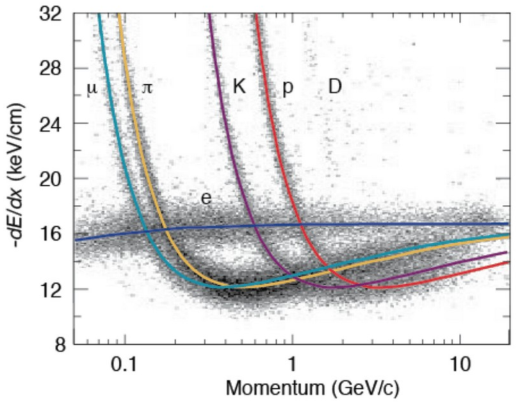
ND-LAr
Modular Liquid Argon TPC

PRISM
30m Off-Axis Mobility for LAr + Spectrometer

ND-GAr Magnetized TPC

- Design
  - Same Ar target at the DUNE FD (and ND-LAr)
  - High-pressure (10 bar)
  - TPC surrounded by EM calorimeter and superconducting magnet
  - May need to wait for Phase II; Temporary Muon Spectrometer (TMS) until then (magnetized planes of Fe & scintillator)
- Physics
  - ν-Ar interactions with low thresholds: better understand the hadronic system details
  - Excellent particle ID: study details of exclusive final states
  - Fine tuning of cross section systematic errors
  - Spectrometer for tracks that exit ND-LAr: track sign and momentum (Adequate replacement for TMS)





ND-GAr Magnatized TPC

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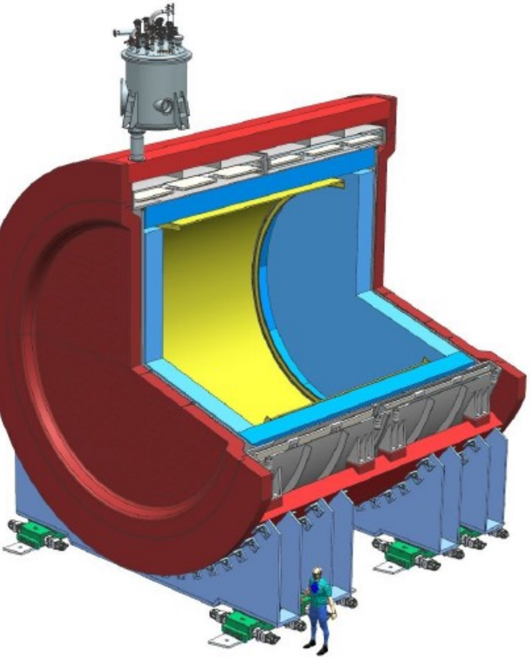
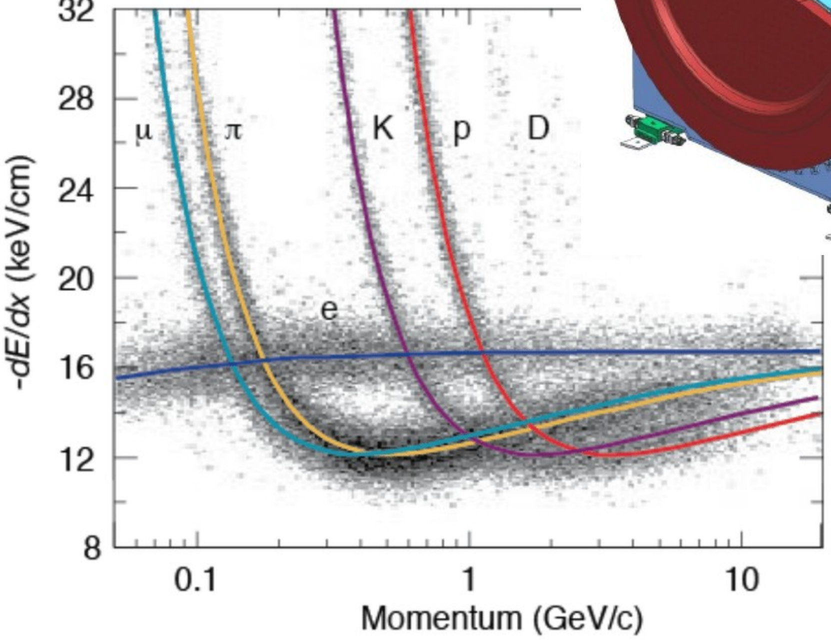
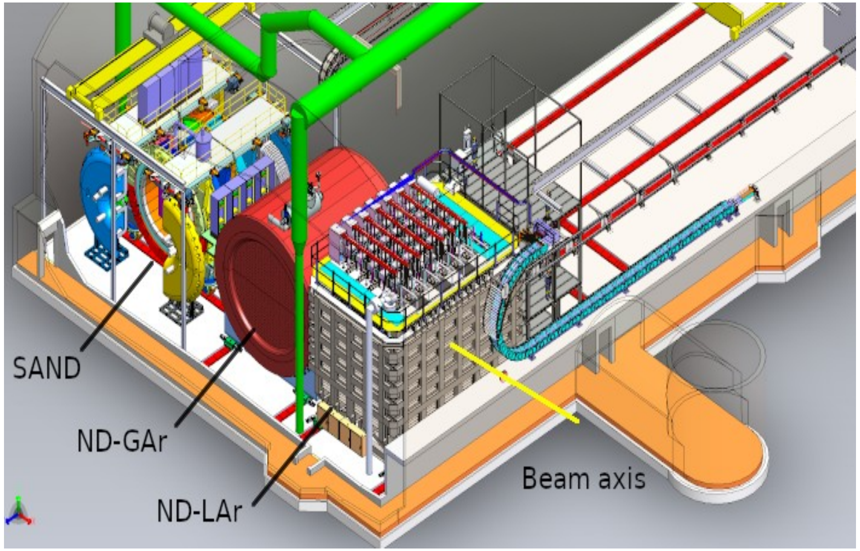




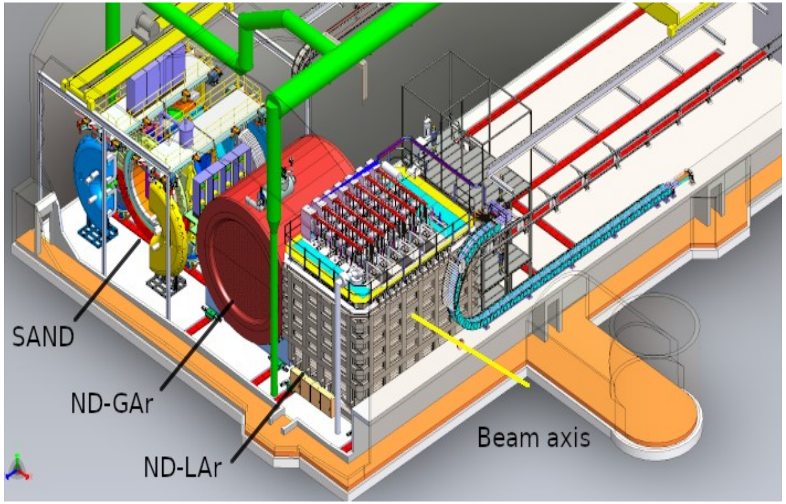
DUNE ND Complex Summary

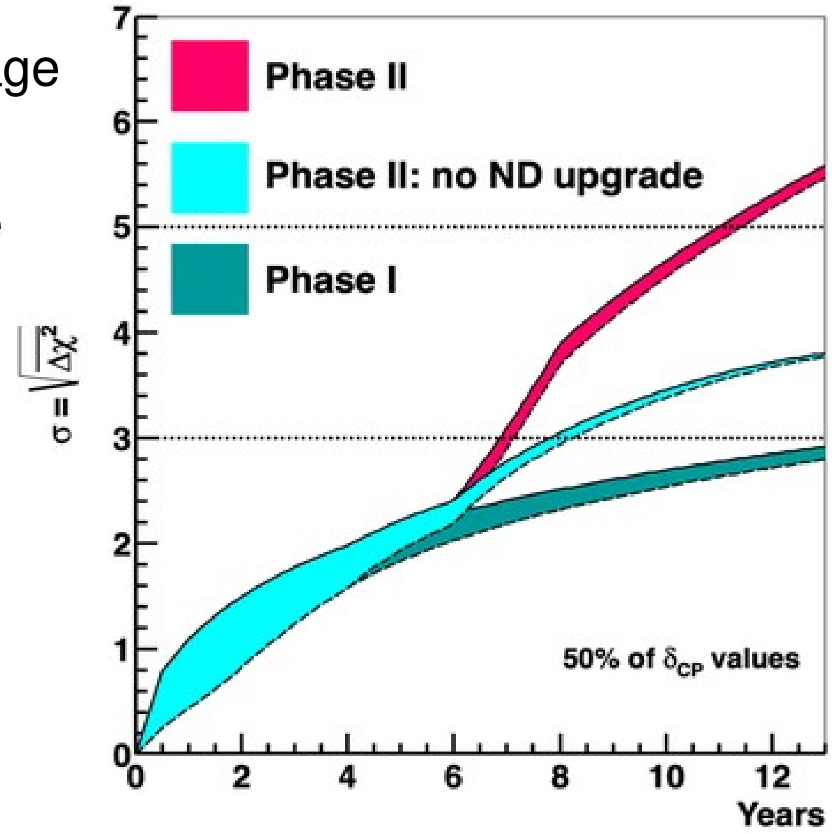
- Multi-detector design
- Liquid Argon TPC
  - Similar technology to the FD
  - Design changes to handle high rates
- Downstream Spectrometer
  - Measures momentum and charge of exiting tracks
  - Will eventually be a GAr TPC able to measure hadronic shower details
- On-axis beam monitor
  - Ensure stable beam operations
  - Contribute physics measurements and crosschecks
- Off-axis measurements from PRISM
  - Enables statistical constraints of incoming neutrino energy
  - Paradigm shifting oscillation measurement technique



Take Home Message

- DUNE has the ability to push neutrino oscillation (lepton weak mixing) physics into the precision age
- A highly capable ND complex is crucial to exploiting the high statistics data provided by the beam and FD





Thank You

Questions?

Backup Slides

Weak Mixing Physics with DUNE: Structure and Precision

Quarks

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td}	V_{ts}	V_{tb}

Precision: Sub-percent   CPV: confirmed

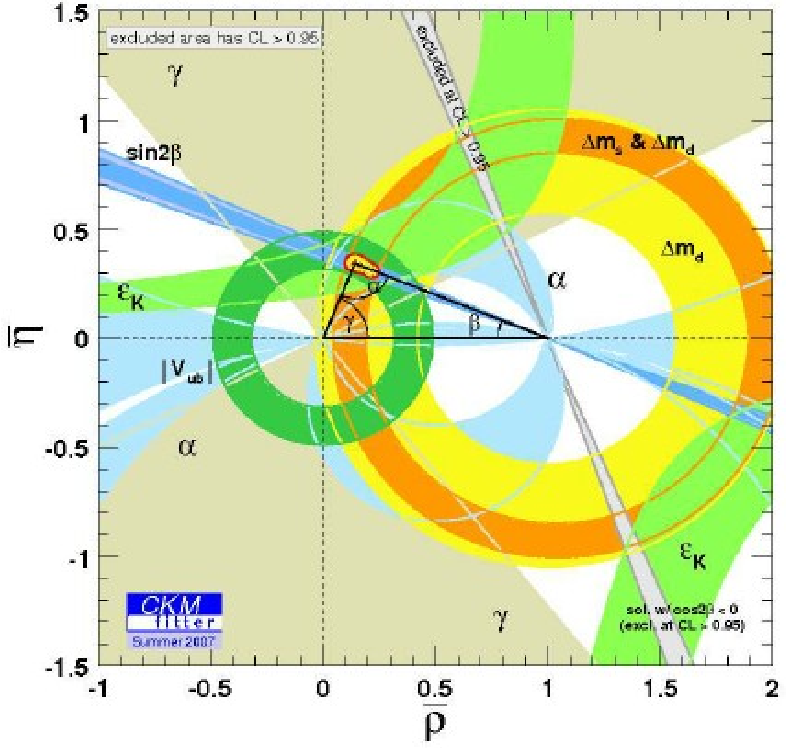
Leptons

U_{e1}	U_{e2}	U_{e3}
$U_{\mu1}$	$U_{\mu2}$	$U_{\mu3}$
$U_{\tau1}$	$U_{\tau2}$	$U_{\tau3}$

Precision: Few-percent   CPV: unconfirmed

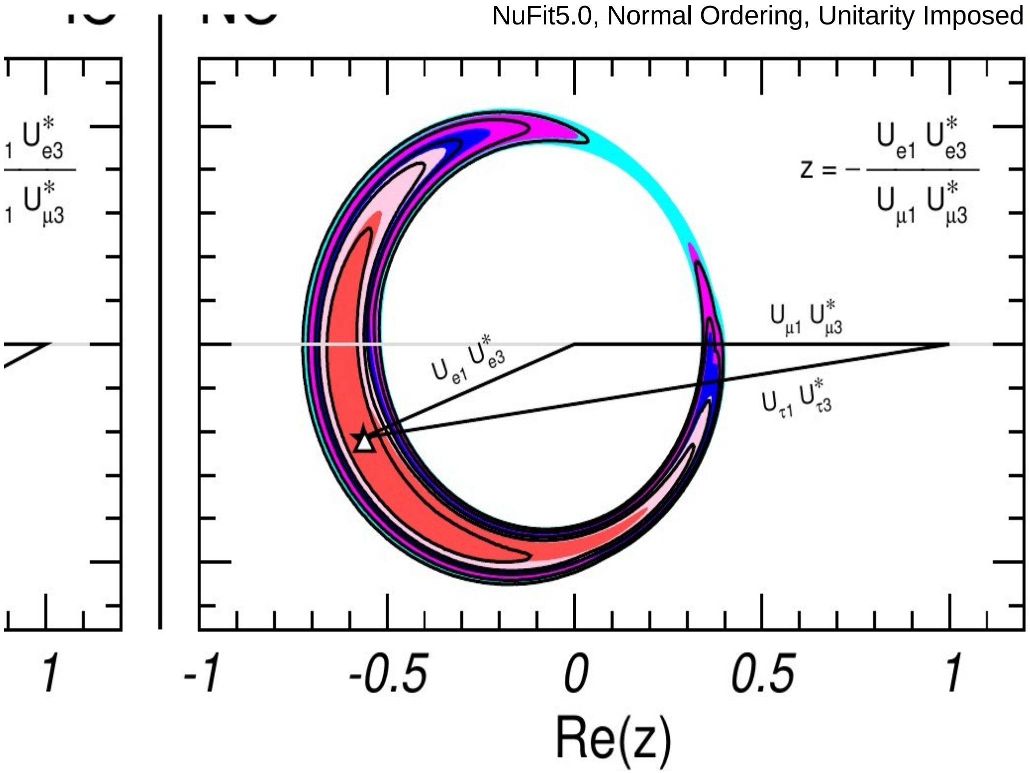
Weak Mixing Physics with DUNE: Unitarity and CP-Violation

Quarks

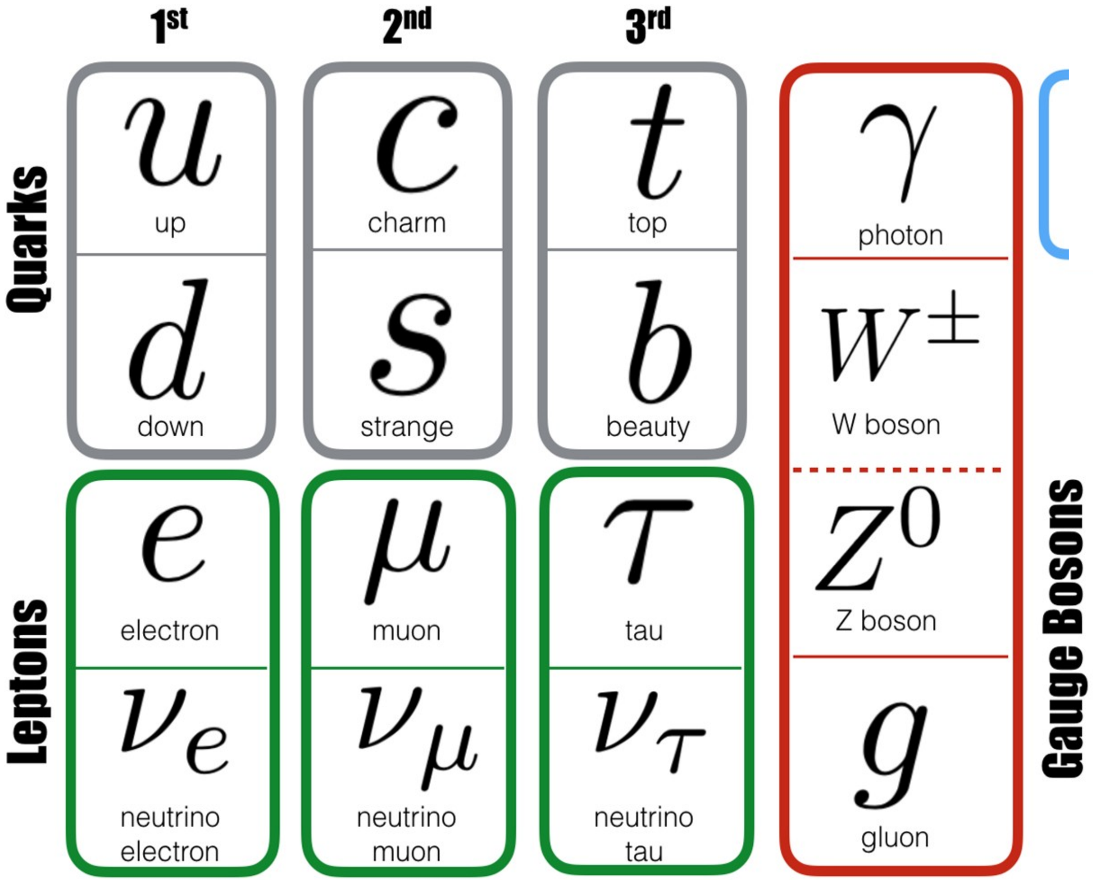


Leptons

NuFit5.0, Normal Ordering, Unitarity Imposed



Mixing Between Weak Flavor and Mass Eigenstates



- For most interactions the incoming and outgoing particles are the same flavor
  - Gravitational
  - Electromagnetic
  - Strong
- For Weak interactions the incoming and outgoing particles are weak isospin pairs
- Differences between Weak Flavor and Mass eigenstates also allow for apparent mixing between isospin pair families
- This mixing is described by the:
  - CKM Matrix (quarks)
  - PMNS Matrix (leptons)

The Mixing Matrices

The CKM Matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_J = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_M$$

The PMNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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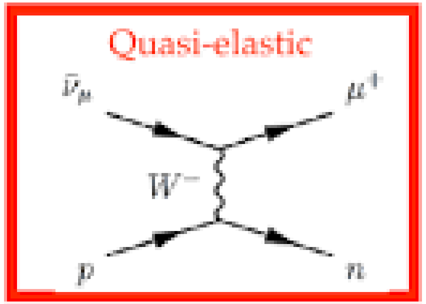
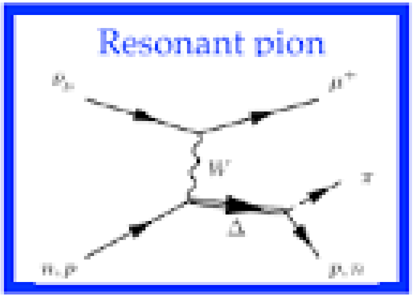
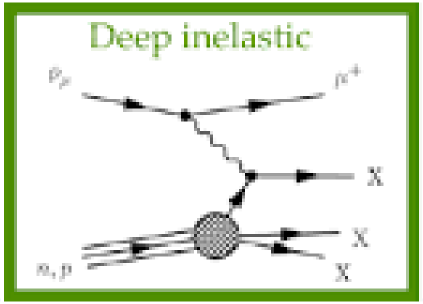
Understanding ν Cross Sections



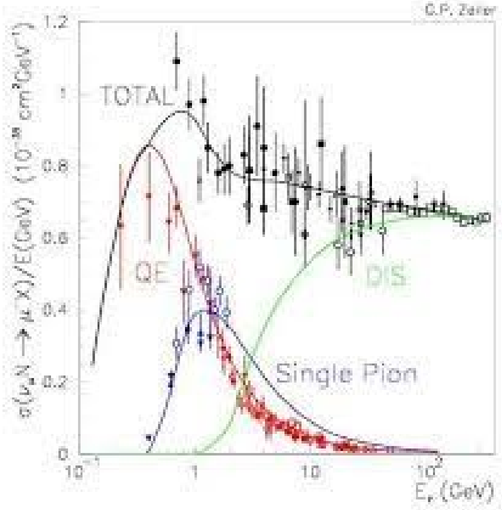
QE

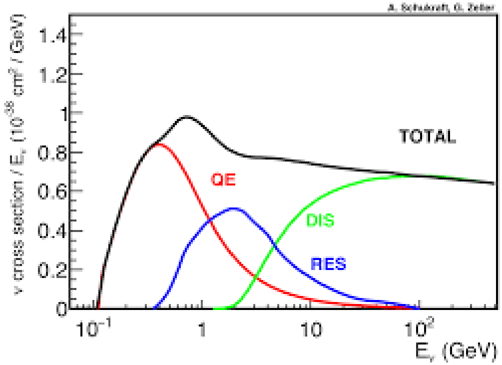


RES



DIS





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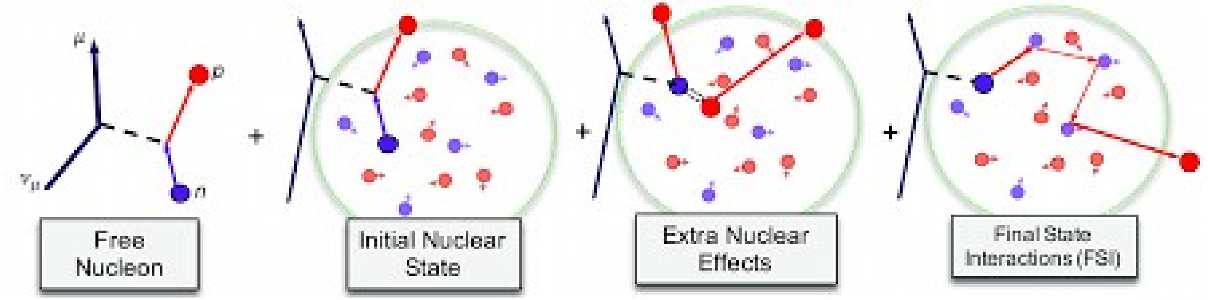
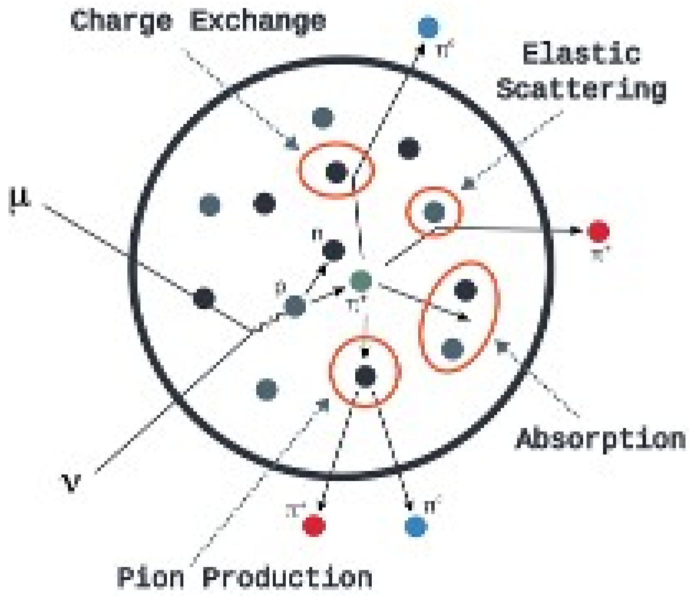
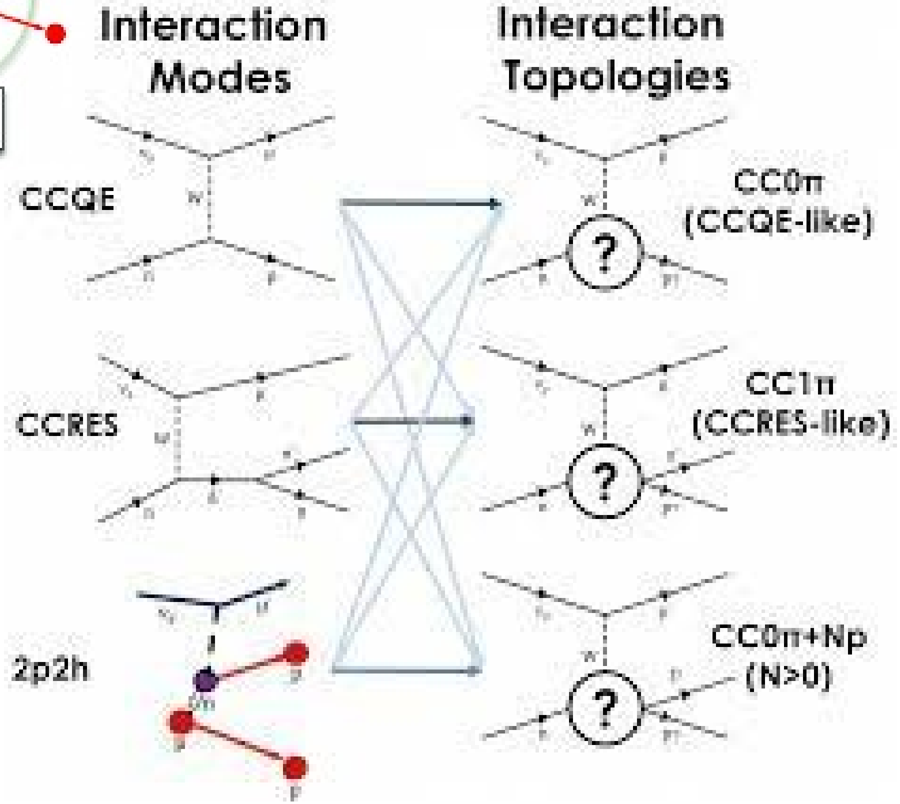






Predicting the Neutrino Event Rate

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\ \sigma(E_\nu^{true})\ P(\alpha \rightarrow \beta, E_\nu^{true})\ \epsilon(E_\nu^{reco})\ S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$

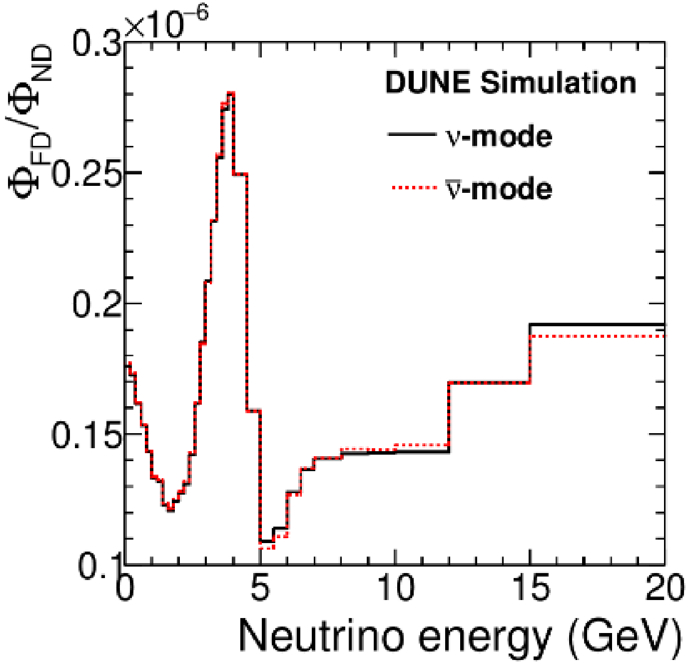
Measure with a near detector:

- $\Phi(E_\nu^{true})$
- $\sigma(E_\nu^{true})$

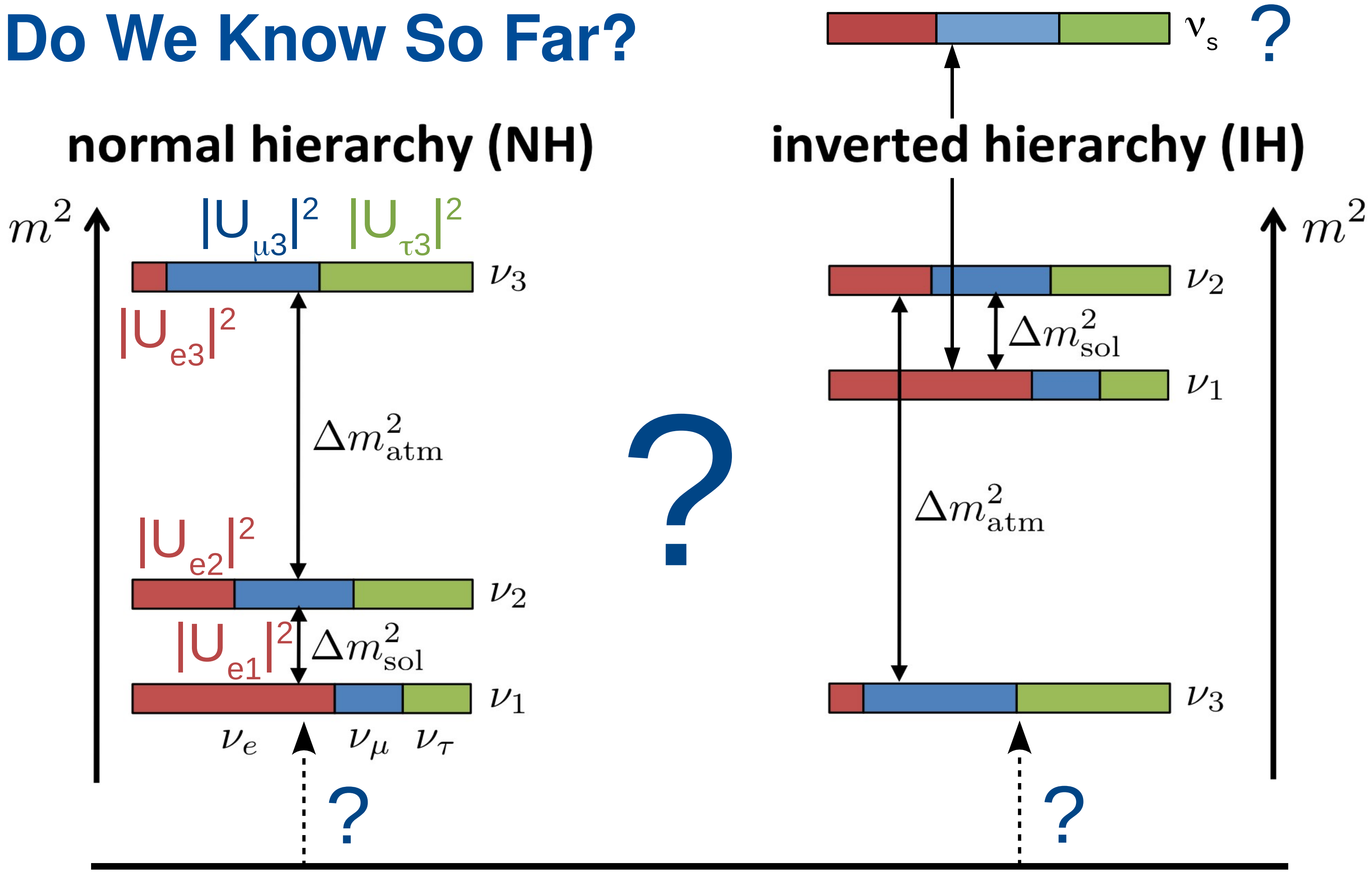
$P(\alpha \rightarrow \beta, E_\nu^{true})$

Highly Dependent on Hadronic System:

- $\epsilon(E_\nu^{true})$
- $S(E_\nu^{true}, E_\nu^{reco})$



What Do We Know So Far?



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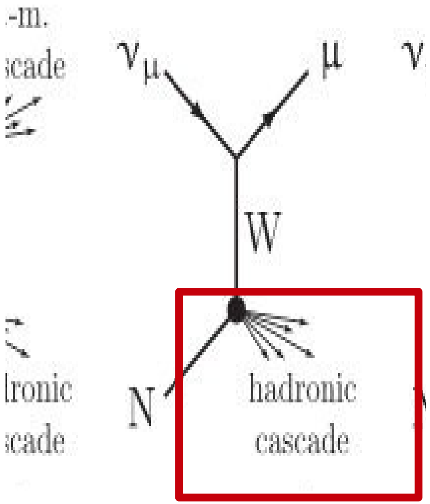
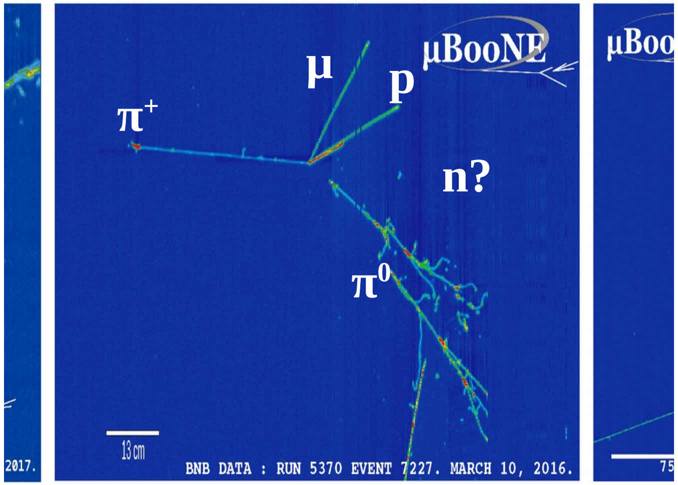


QCD!



Shamelessly stolen from A. Mastbaum

DUNE ND R&D

ND-LAr

- Tested ~70% scale module
- 2×2 ν beam test @ FNAL
- Full-scale tests to follow

Module-0 @ Bern

ND-GAr

- R&D gas TPCs @ FNAL (IROC) and RHUL (OROC)
- Gas, HV tests underway in dedicated HPgTPCs

HPgTPC @ FNAL

ALICE IROC

SAND

- 3DST beam tests @ CERN
- US-Japan joint prototyping efforts underway

US-Japan prototypes

CERN tests

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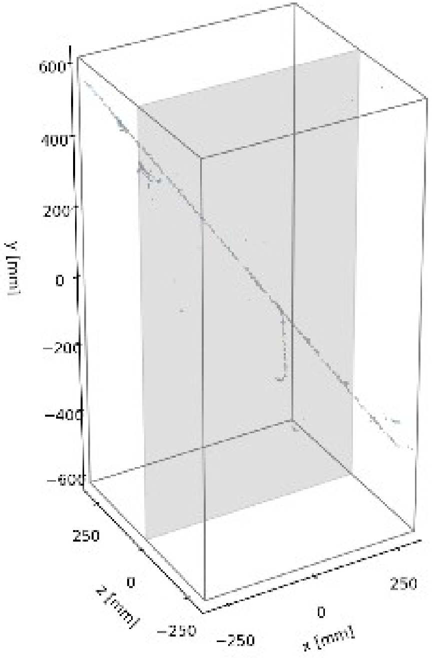

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HPgTPC @ FNAL

ALICE IROC

SAND

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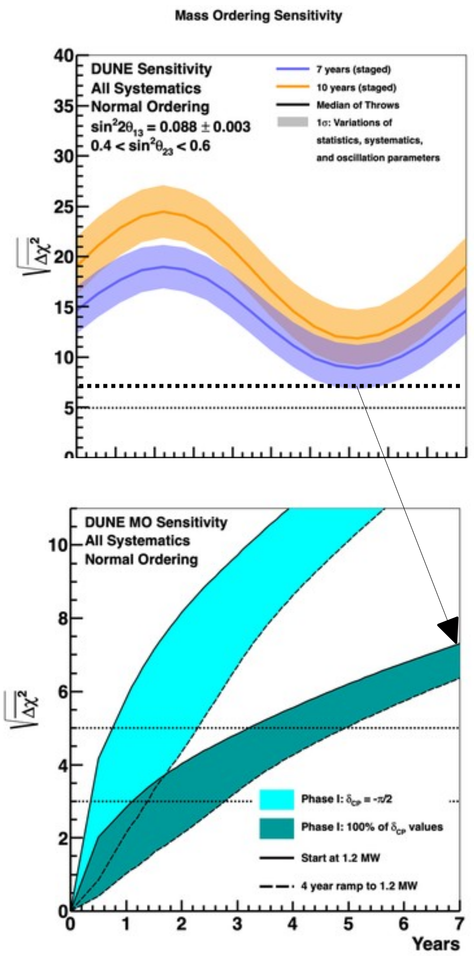
US-Japan prototypes

CERN tests

Phase I Physics Goals and ND Requirements

- Unambiguously measures the MO at greater that 5σ
- Confirm CPV at 3σ near $\delta_{CP} = \pm\pi/2$
- Confirm and/or constrain measurements on θ_{13}, θ_{23}, and Δm^2_{31}
- Phase I challenges:
  - Operating full detecor suire
  - Reconstruction algorithms



Phase I Requirements for the DUNE Near Detector

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