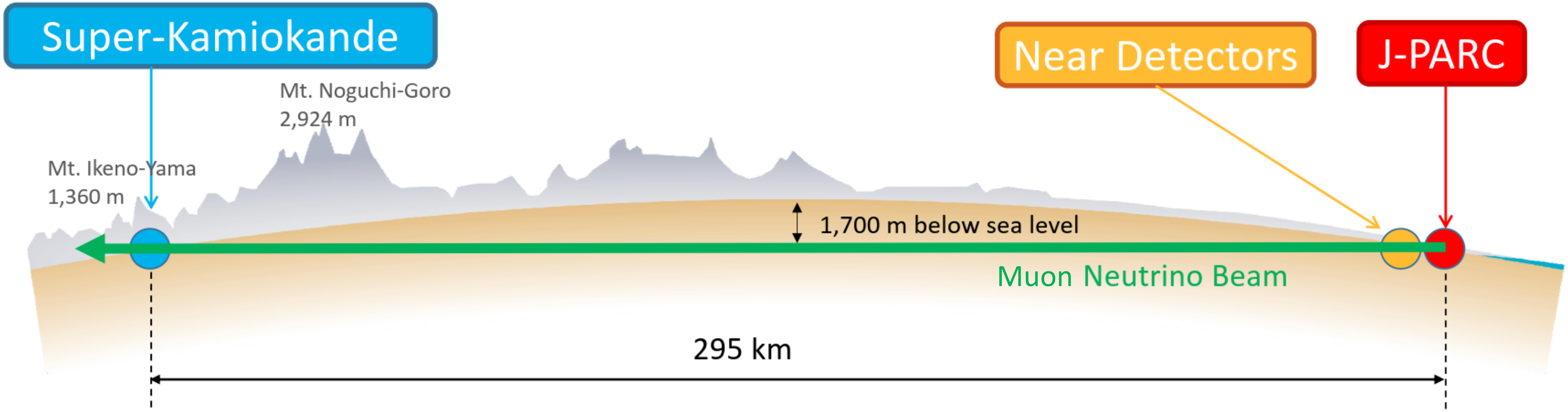
Mesonless measurements at T2K

Stephen Dolan
for the T2K Collaboration

stephen.joseph.dolan@cern.ch

The T2K Experiment

The T2K Experiment



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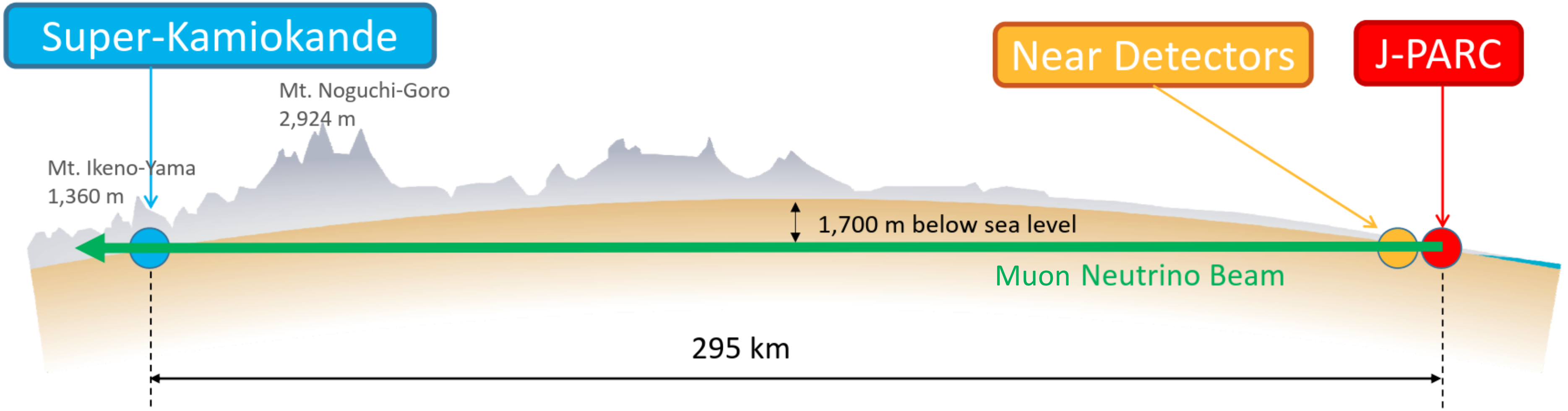

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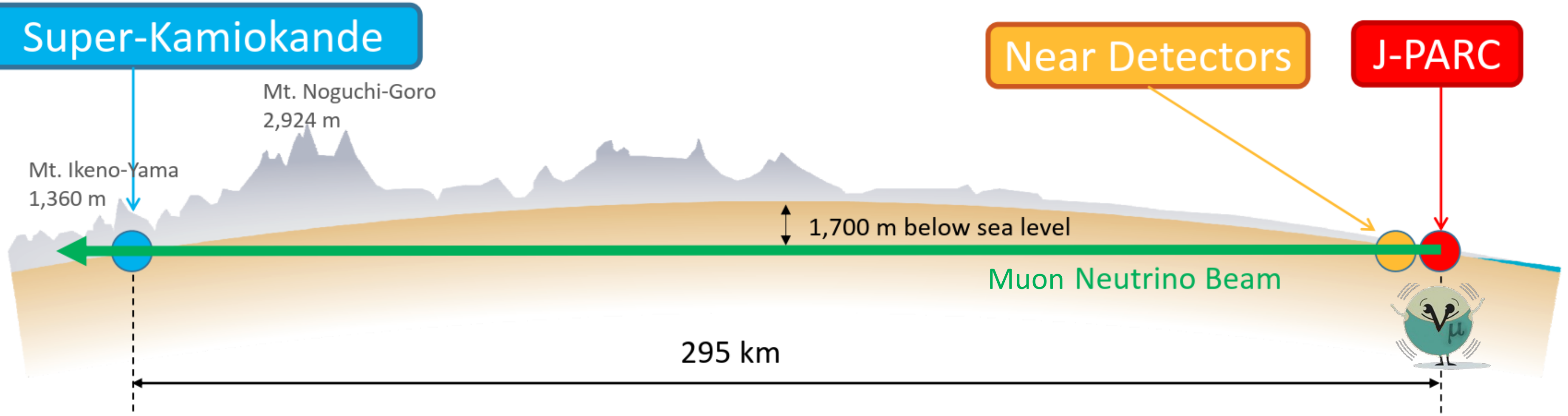
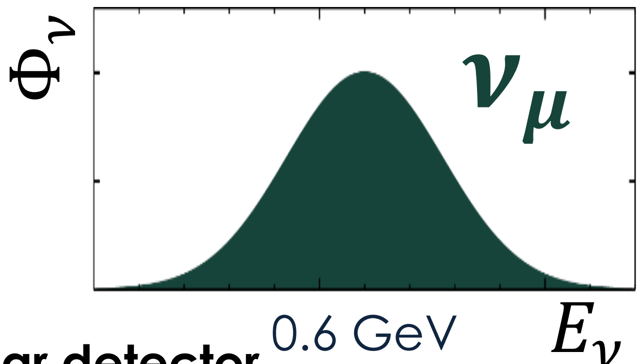




At the near detector

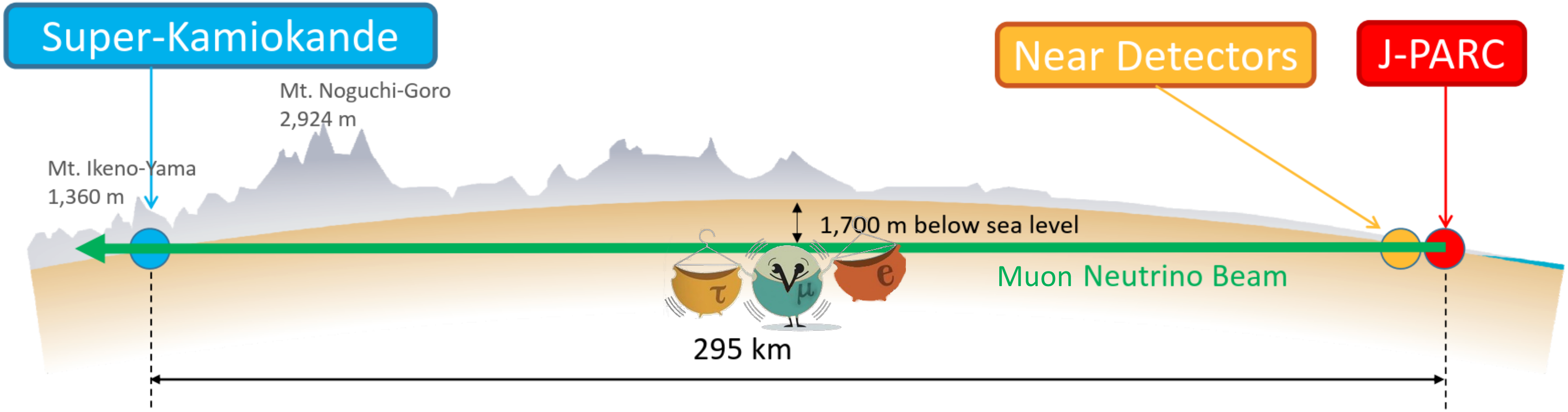
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

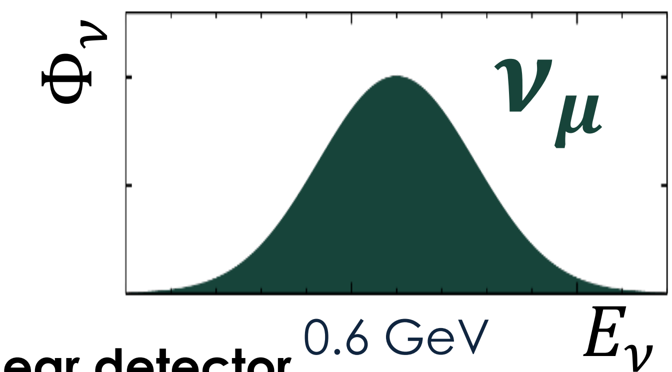
Interaction cross section

Neutrino flux

Detector effects

The T2K Experiment





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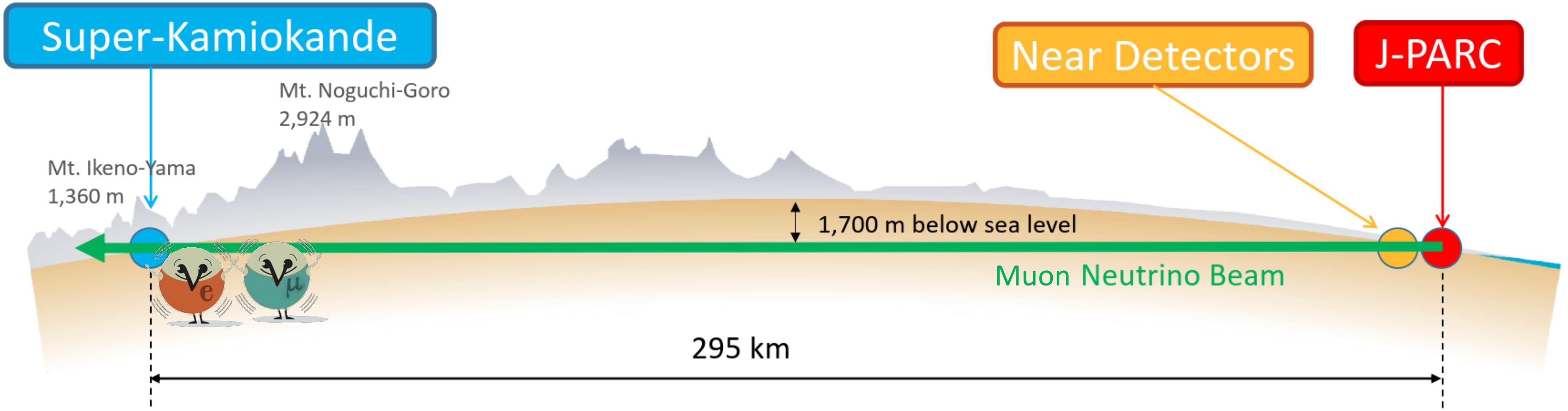

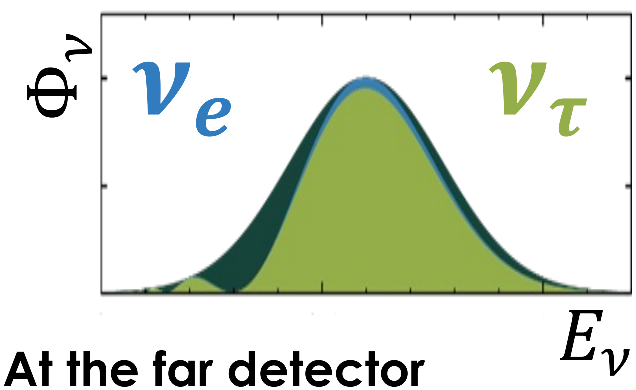

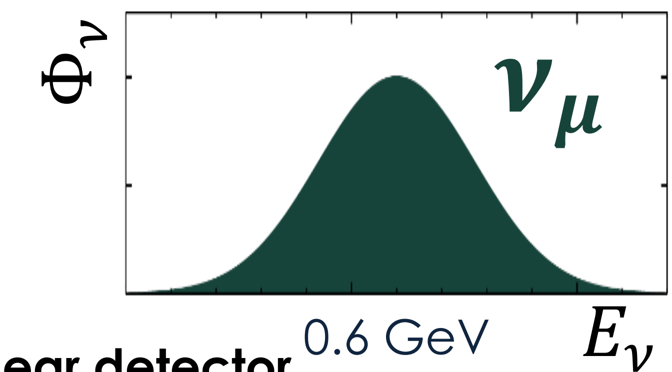

At the far detector

$$N_\mu(E_\nu) = P(\nu_\mu \rightarrow \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

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Oscillation probability

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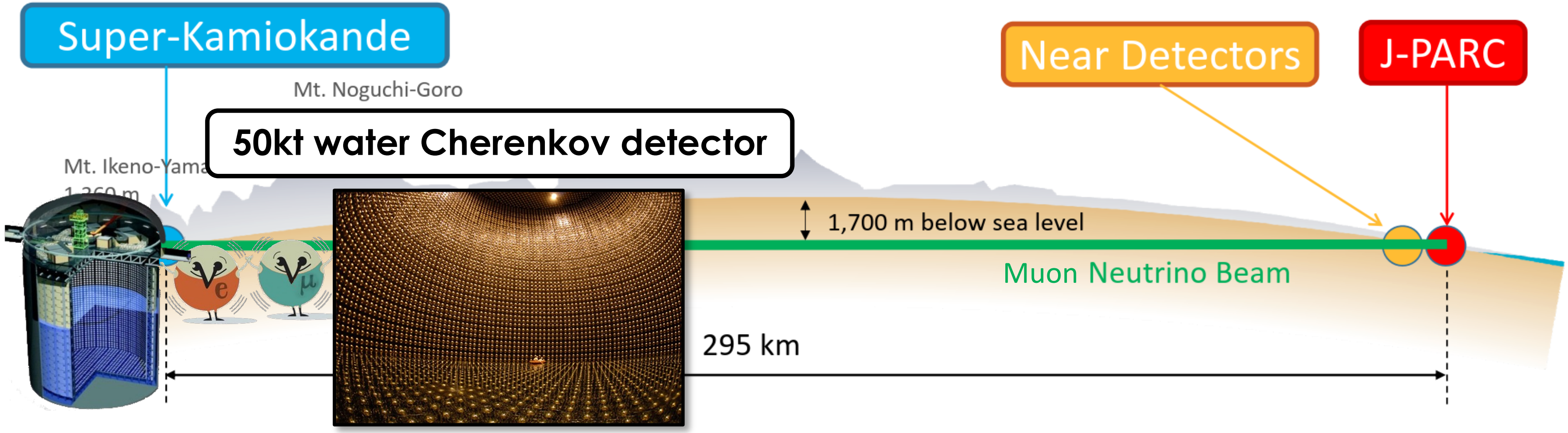

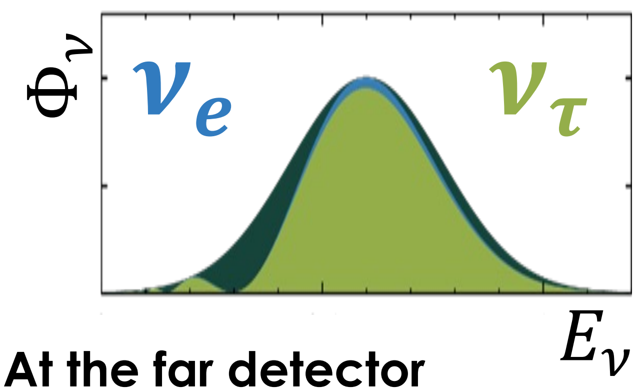

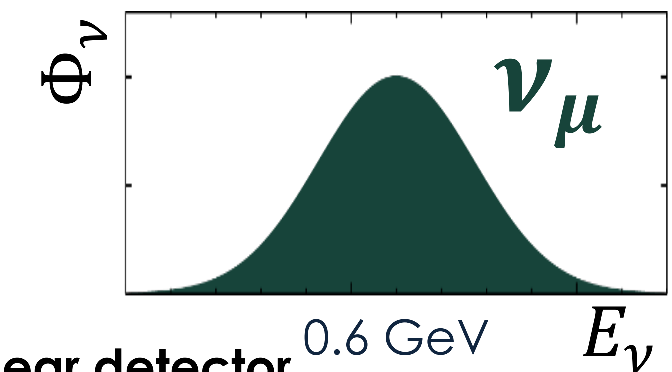

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At the near detector

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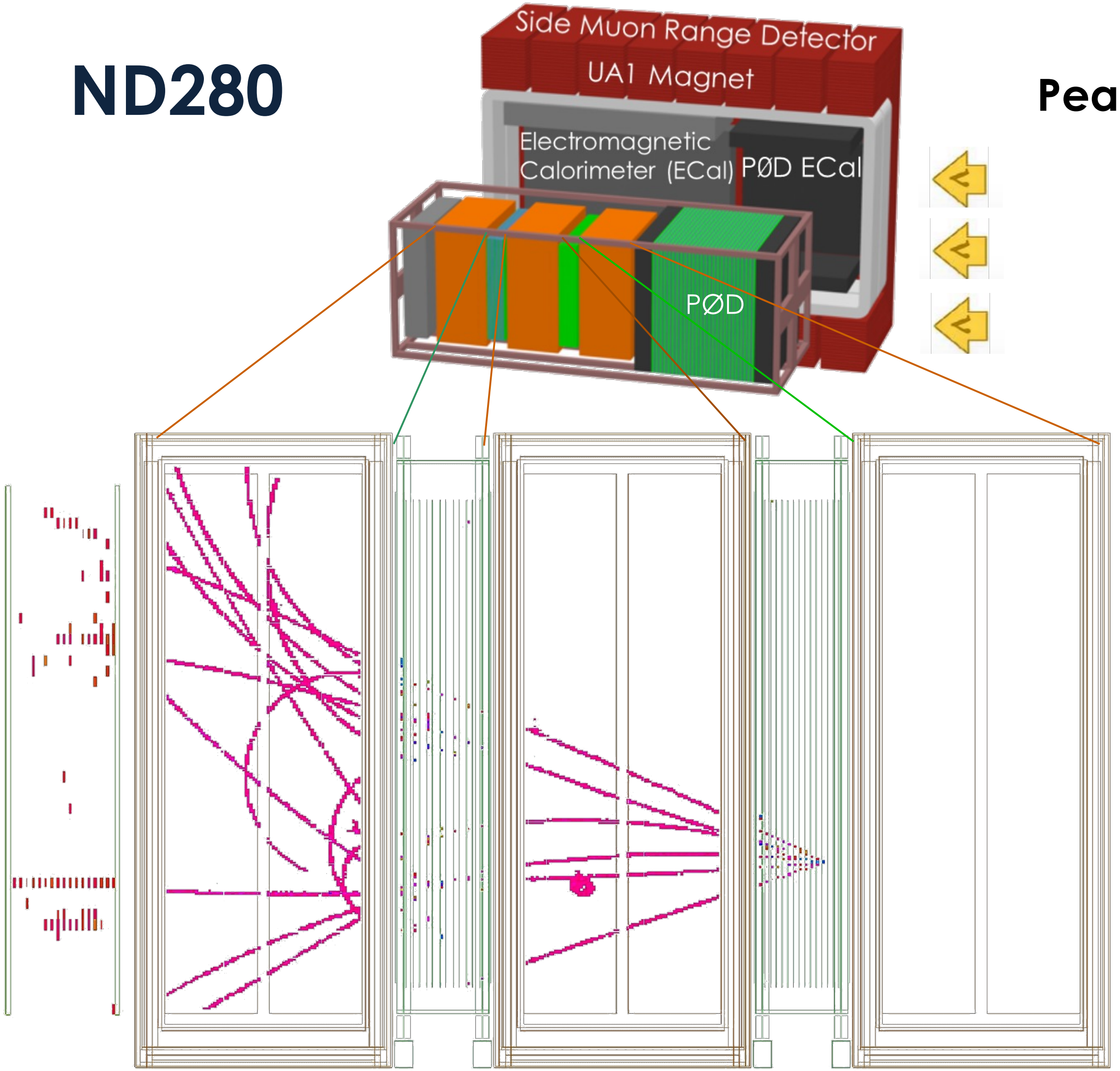
Neutrino flux

Detector effects

The ND280 Near Detectors

ND280



Peak E_ν
On Axis ~ 1.1 GeV
Off Axis ~ 0.6 GeV

The ND280 Near Detectors

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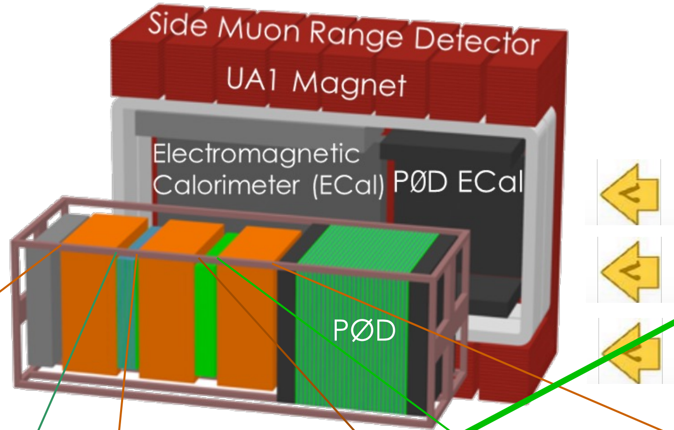


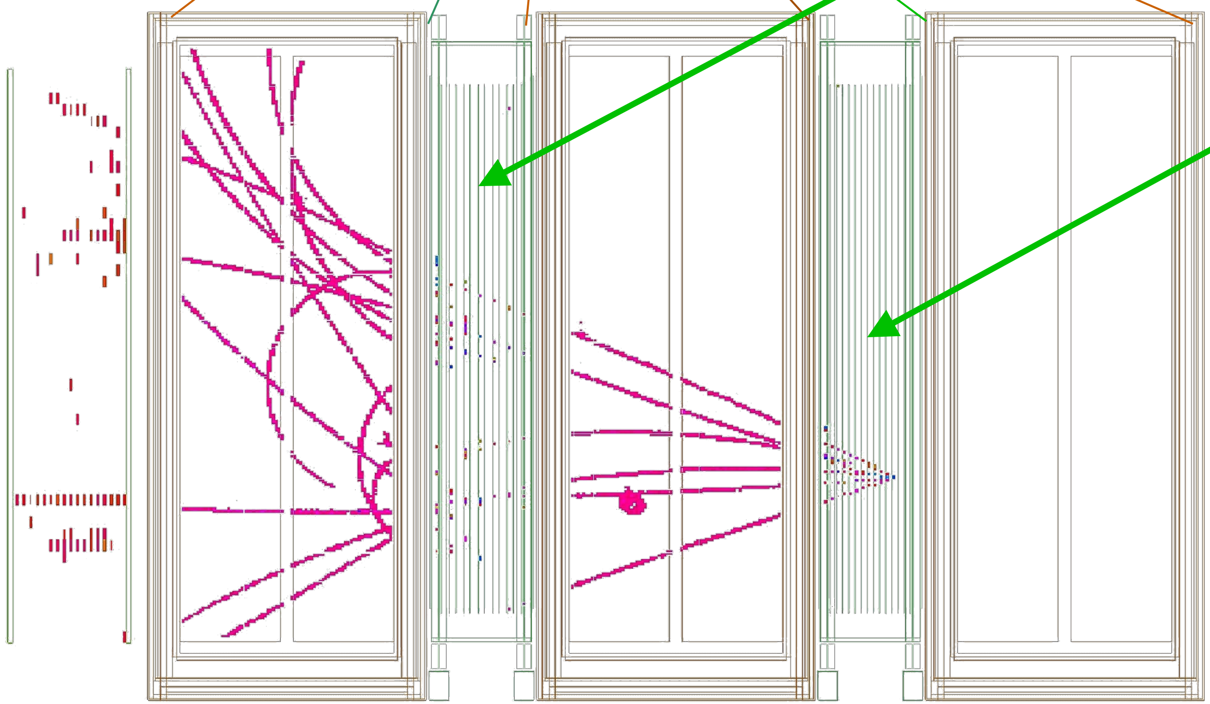
On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water



The ND280 Near Detectors

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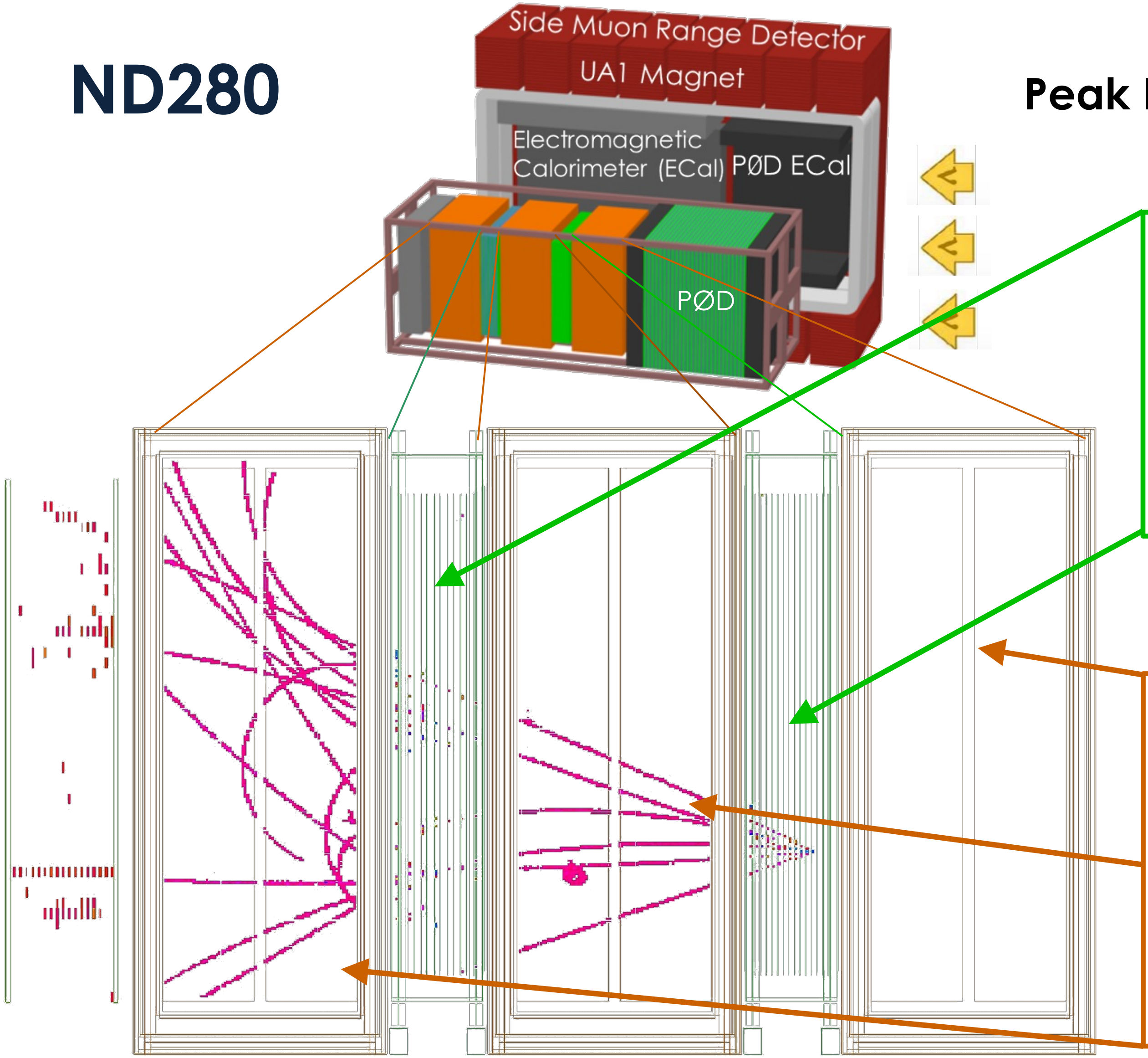


Peak E_ν
- On Axis ~ 1.1 GeV
- **Off Axis ~ 0.6 GeV**

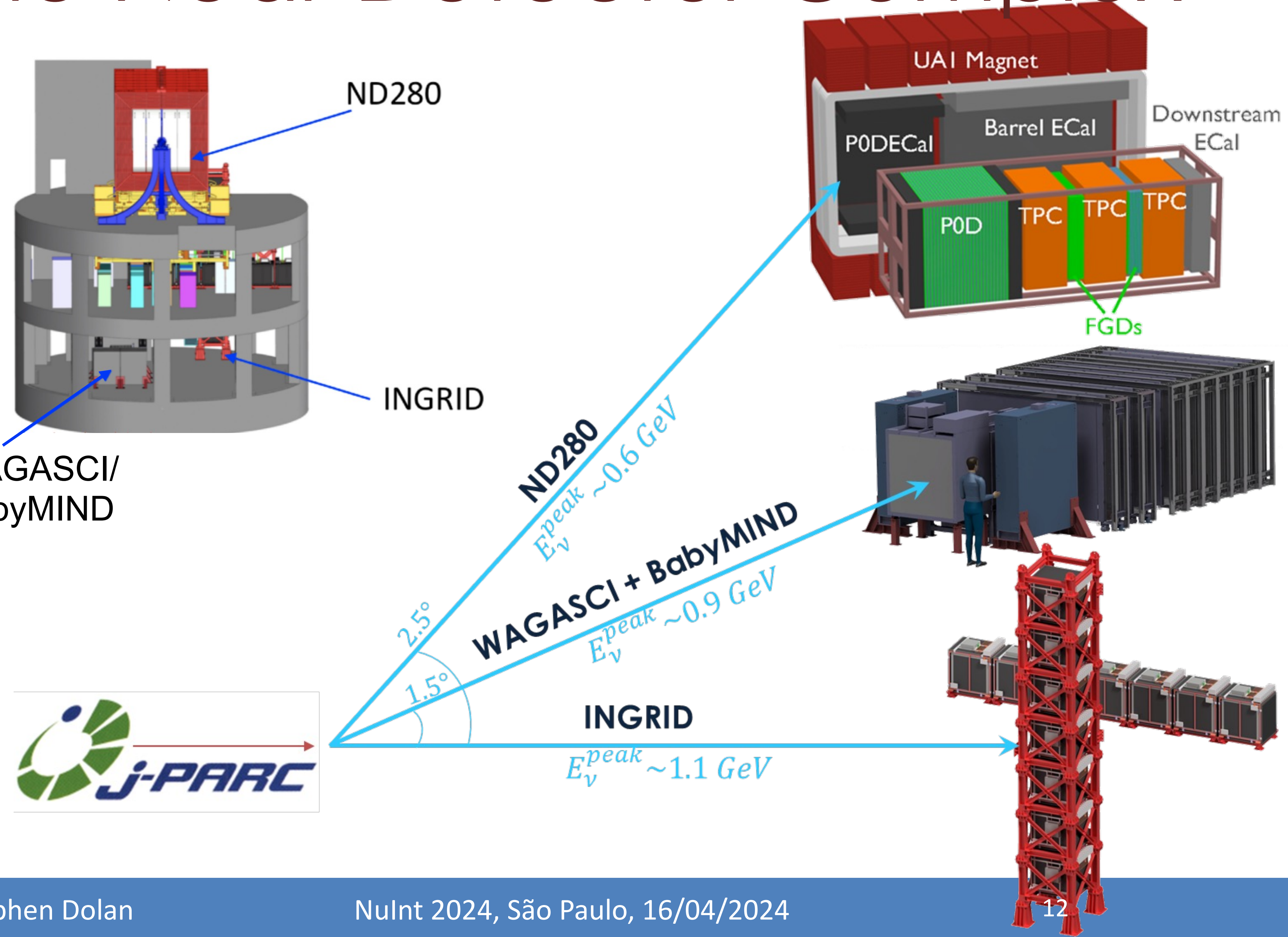
Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

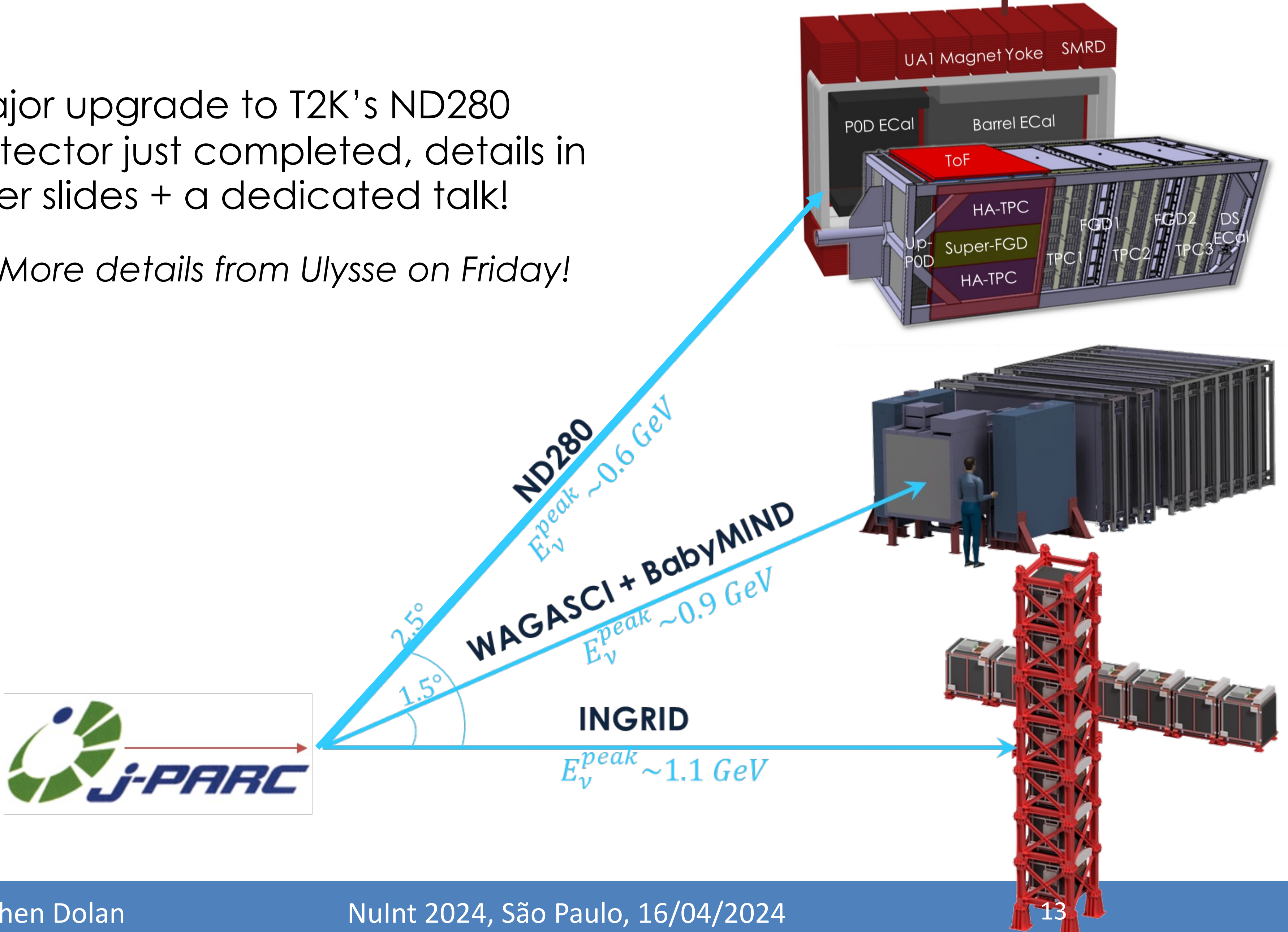
The Near Detector Complex



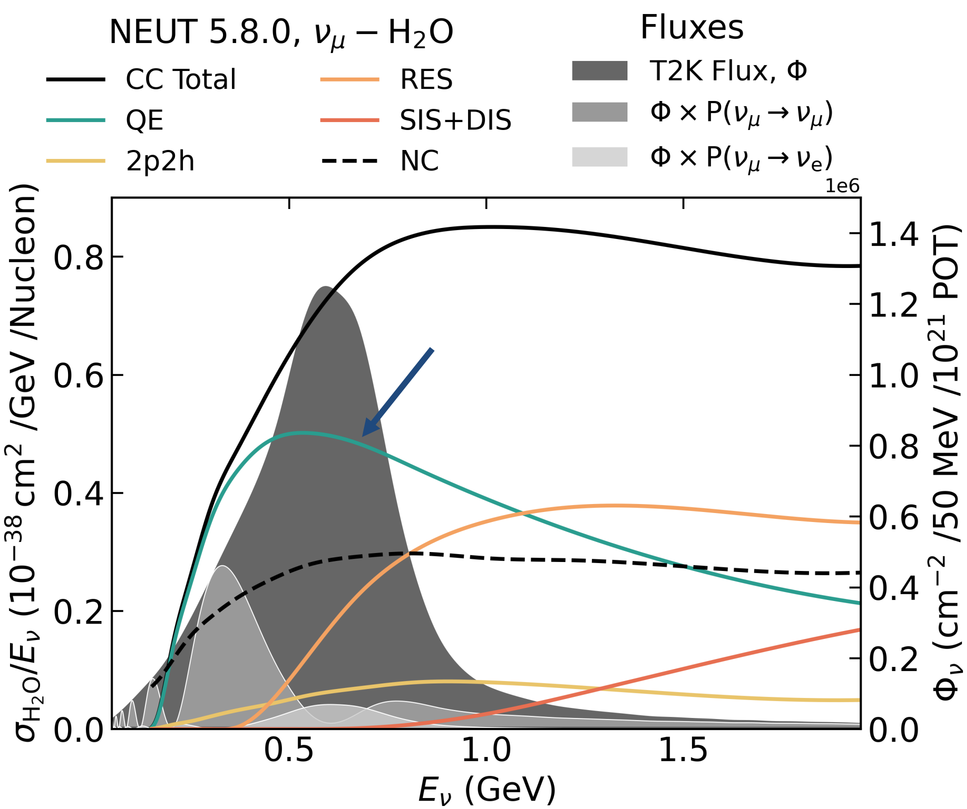
The Near Detector Complex

Major upgrade to T2K's ND280 detector just completed, details in later slides + a dedicated talk!

More details from Ulysse on Friday!



Neutrino interactions at T2K

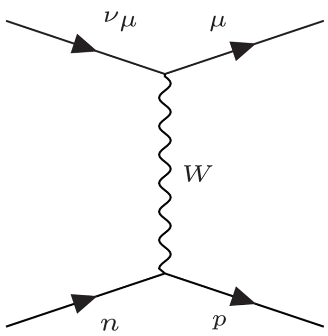


Plot from L. Pickering

[Hayato, Y., Pickering, L. *Eur. Phys. J. Spec. Top.* **230**, 4469–4481 (2021)]

CC-QE

(Quasi-elastic)



ND: ~58%
FD: ~53%

Percentages show contribution to ν_μCC interactions at the near (before oscillation) and far (after oscillation) detector sites for $E_\nu < 2$ GeV simulated with NuWro

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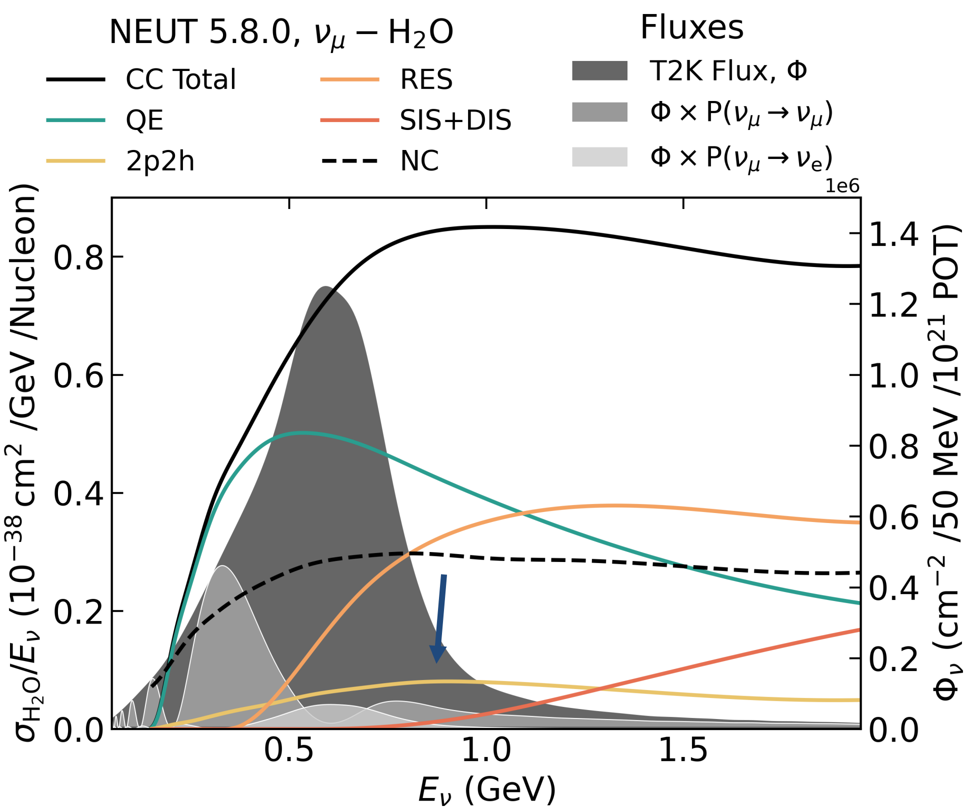

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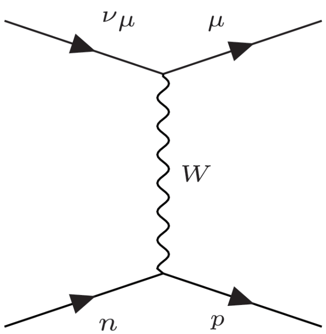
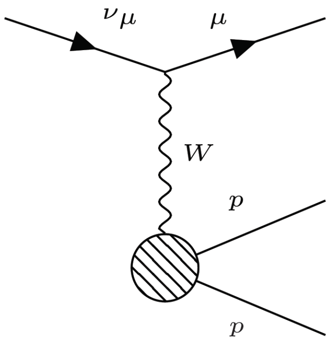


ND: ~58%
FD: ~53%

CC-2p2h
(Two-Particle-Two-Hole)



ND: ~10%
FD: ~9%

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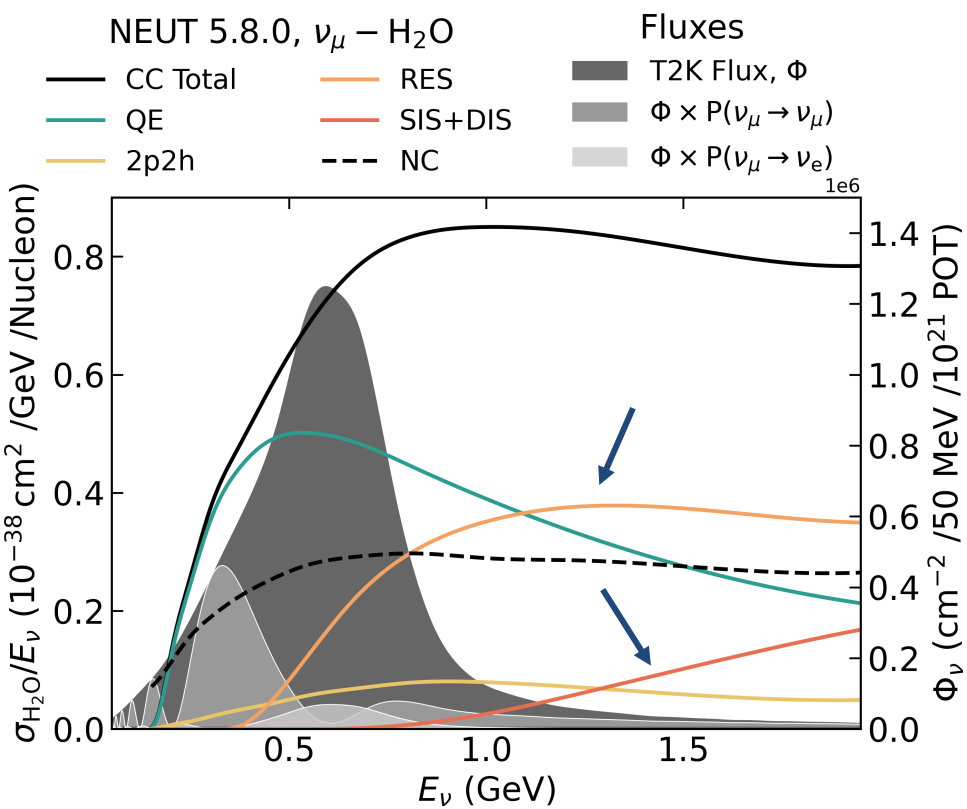
Neutrino interactions at T2K



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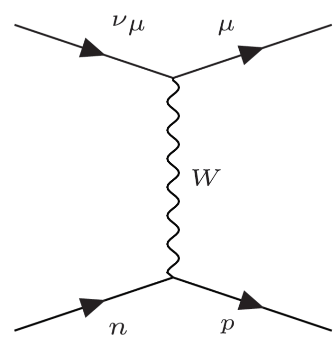

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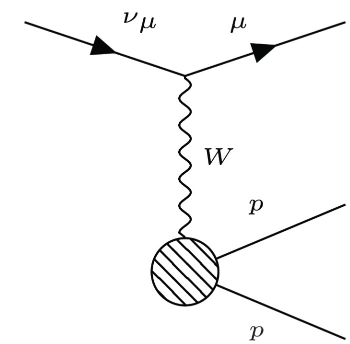

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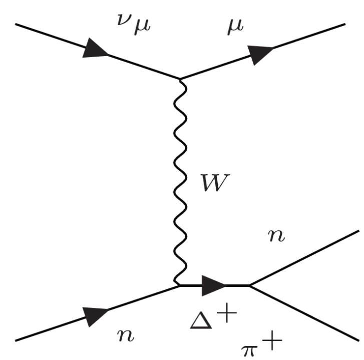
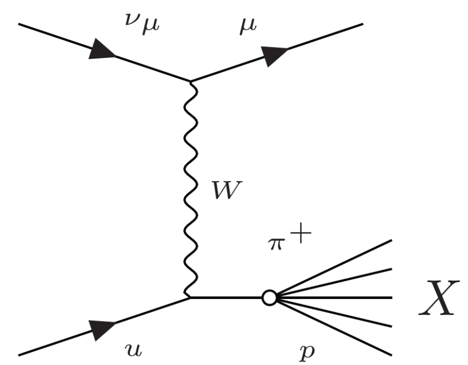
CC-Resonant 1π



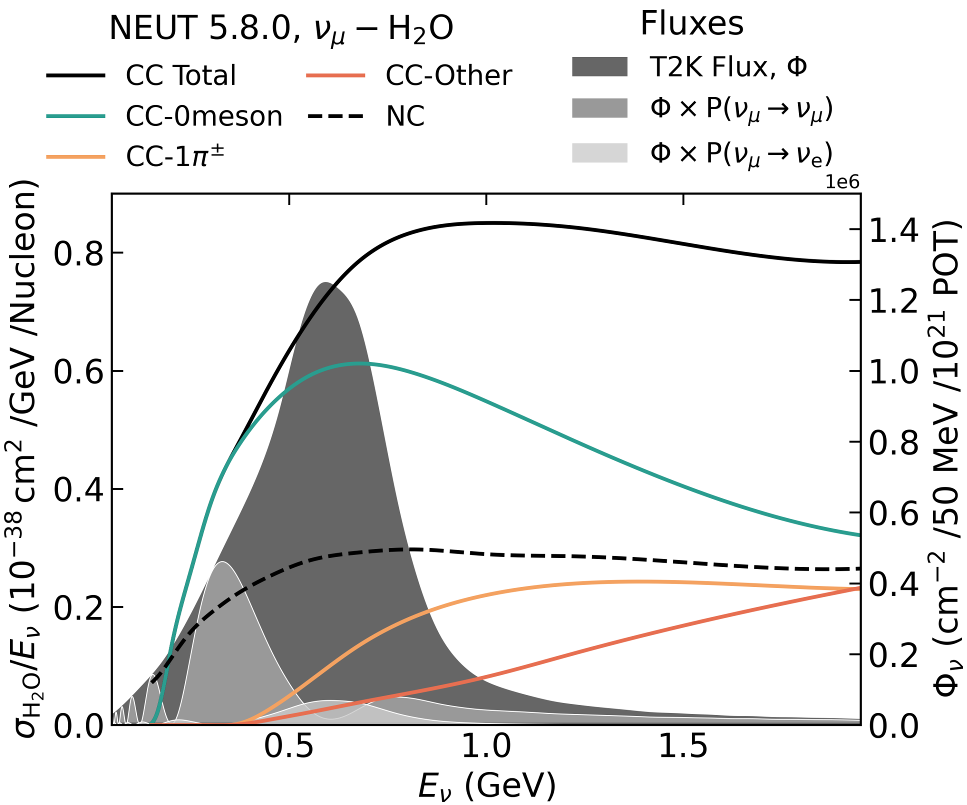
ND: ~30%
FD: ~32%

CC-DIS
(Deep Inelastic Scattering)



ND: ~2%
FD: ~5%

Neutrino interactions at T2K



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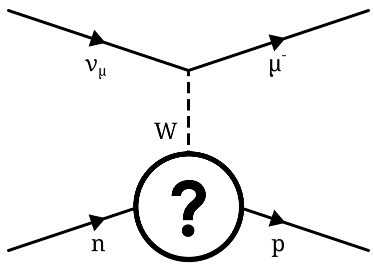
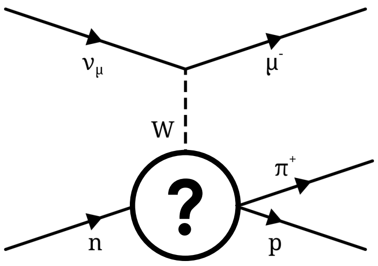
CC-0π



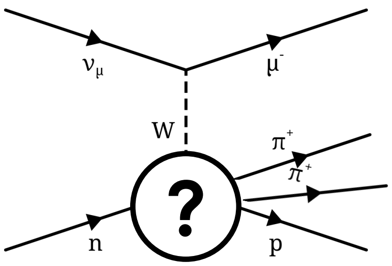
ND: ~72%
FD: ~67%

CC-1$\pi^{+/-}$



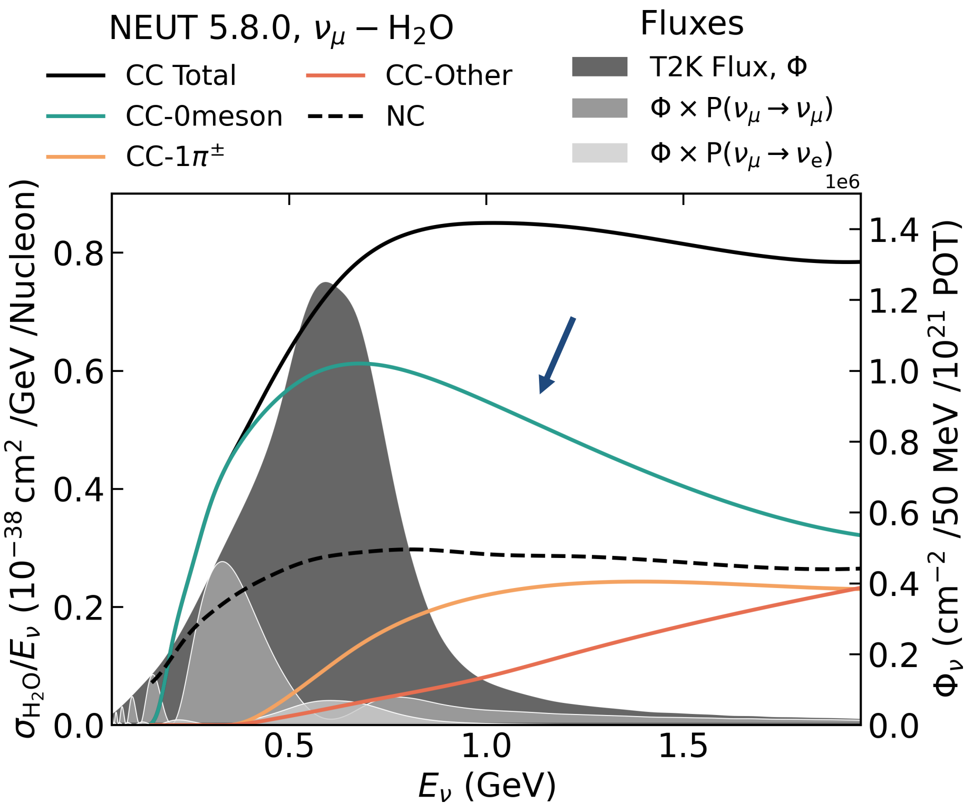
ND: ~21%
FD: ~24%

CC-Other



ND: ~7%
FD: ~9%

Neutrino interactions at T2K



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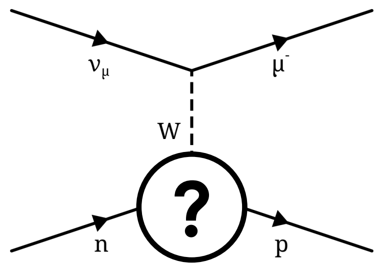

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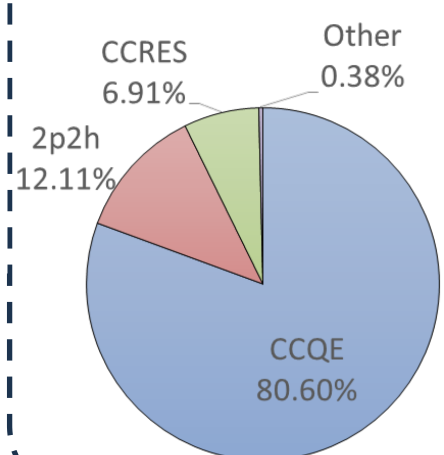

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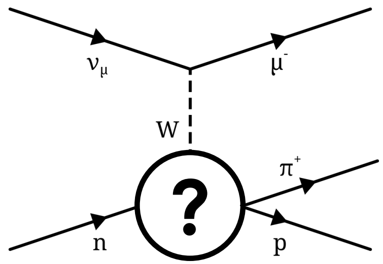

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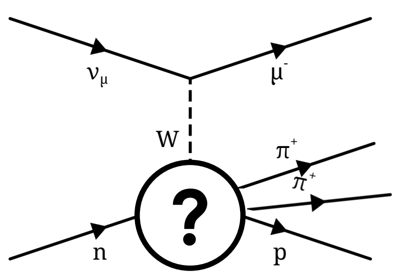

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Five things we need to know

See Monday's talks from Laura and Clarence

(a non exhaustive list)

1. Relative CC0π contribution of CCQE and other processes
   - *So we know how often we mis-reconstruct* E_{ν}

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   - *So we know how wide (and biased) our CCQE* E_ν *reconstruction is*

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3. Neutrino energy dependence of cross sections and their differences on Carbon and Oxygen
   - *So we know how to extrapolate from our ND to our FD*

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4. Differences in $\nu/\bar{\nu}$ cross sections
   - *So we know when* $\nu/\bar{\nu}$ *differences imply CP-violation*

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4. Differences in $\nu/\bar{\nu}$ cross sections
   - *So we know when $\nu/\bar{\nu}$ differences imply CP-violation*
5. Physics beyond the plane-wave impulse approximation
   - *To confront the largest uncertainties in current analyses*
   - *So we know how to use our ND constraints on ν_μ in ν_e app. analyses*


KEEP CALM
AND
MEASURE dσ/dx

What we measure when we measure σ

Top priority: avoid input model dependence

T2K Cross Section Measurements

$$\left.\frac{d\sigma}{dx}\right|_i = \frac{N_i^{sig}}{\epsilon_i \, \Phi \, N_{tgts}} \frac{1}{(\Delta x)_i}$$

Incoming ν_μ flux

Number of targets (nucleons)

Bin width

Top priority: avoid input model dependence

T2K Cross Section Measurements

Number of signal events, background subtracted + corrected for detector smearing

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Top priority: avoid input model dependence

- **Free normalisation parameters** controlling N_i^{sig} are fit alongside those describing the flux, background and detector response to **signal and control region** data: *background model directly constrained by data.*
- Cross-section extracted with **no explicit regularisation** are provided: *minimal input model bias from unfolding.*

T2K Cross Section Measurements

Detector efficiency

Number of signal events, background subtracted + corrected for detector smearing

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- **Efficiency correction** made, where possible, **in all relevant model dependent observables** that can affect detector response: *minimise model bias.*

T2K Cross Section Measurements

Detector efficiency

Number of signal events, background subtracted + corrected for detector smearing

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- **Fre**[…] **parameters** controlling N_i^{sig} are fit alongside those de[…]d and detector response to **signal and control regi**[…]nstrained by data.
- Cross-section extrac[…]vided: *minimal input model bias from unfolding.*
- **Efficiency correction** made, where possible, **in di**[…]**pendent observables** that can affect detector response: *minimise mode*[…]*s.*

For lots more details see Sam's or Margherita's talks at NuXtract and Andrew's CEWG talk

T2K Cross Section Measurements

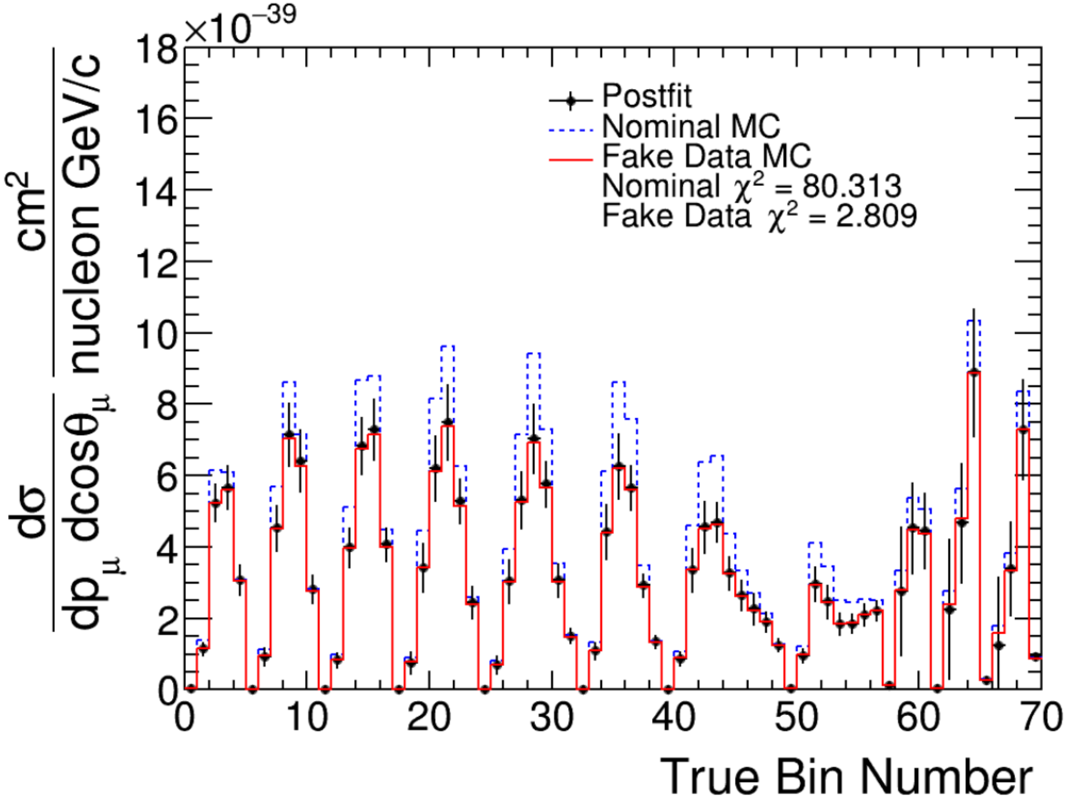
Top priority: avoid input model dependence

- T2K makes extensive use of ”mock data studies” to test analysis robustness:

Example from our latest analysis:

Phys. Rev. D **108**, 112009

- Extract the cross-section from mock data built using a different signal model
- Verify that any bias is very small relative to other uncertainties
  - Check bin by bin and globally (using p-values)



Past measurements

T2K CC0π highlights: a history

2016

First steps

- Double differential in muon kinematics on CH (2016) Phys. Rev. D **93**, 112012
- First measurement on water (2017) Phys. Rev. D **97**, 012001

Youthful optimism

- Measuring muon-proton correlations (2018) Phys. Rev. D **98**, 032003

Mature joint fit measurements

- C vs O, ν vs $\bar{\nu}$ (2020) Phys. Rev. D **101**, 112001, Phys. Rev. D **101**, 112004
- First measurement with WAGASCI (2021) PTEP **2021**, 043C01
- ***Correlated energy spectra (2024)*** Phys. Rev. D **108**, 112009

2024

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Phys. Rev. D **93**, 112012
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Final generation pre-upgrade analysis

2024

- Second generation WAGASCI analysis (<1 year)
- Multi differential T/GKI on C+O, exploring Omnifold (~1 year)
- CC0π + CC1π joint analysis

First ND280 upgrade analyses arXiv:1901.03750

- Low proton tracking thresholds and 4π angular acceptance
- Calorimetric analysis a la MINERvA
- Neutrons! Phys. Rev. D **101**, 092003

Next NuInt?

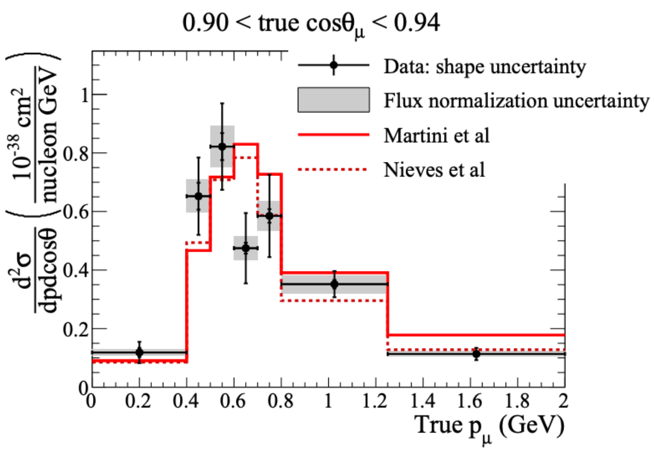
First inclusive CC0π measurement

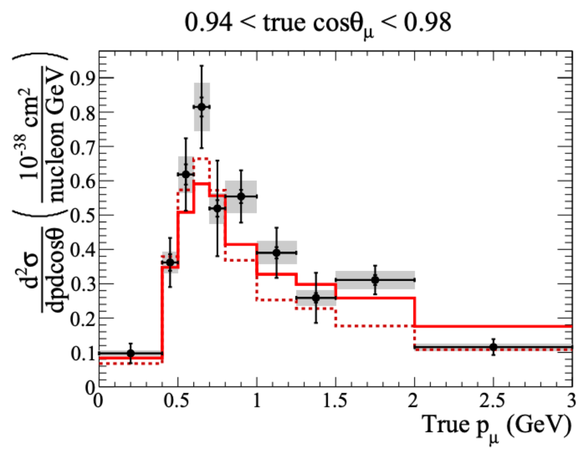
First steps

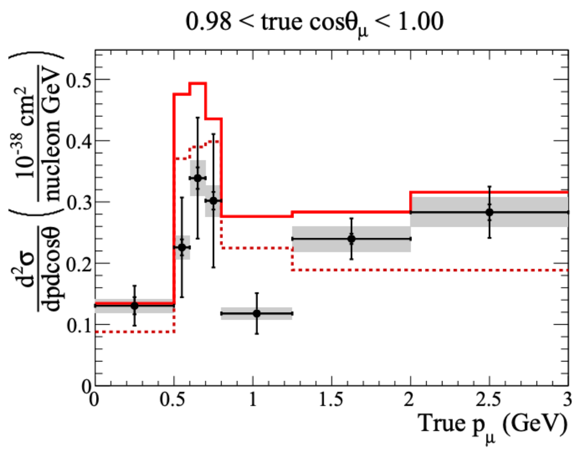
- Double differential in muon kinematics on CH (2016)
- First measurement on water (2017)

Phys. Rev. D **93**, 112012

Phys. Rev. D **97**, 012001







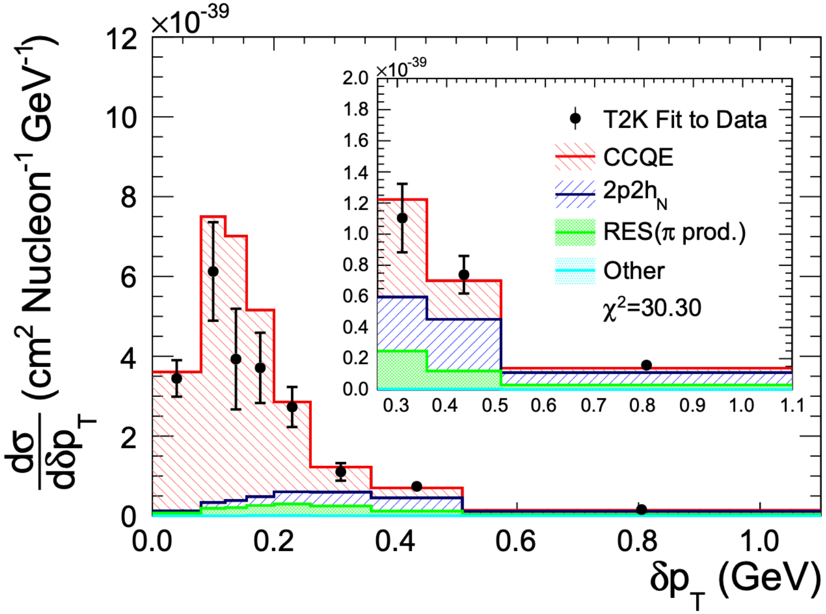
What we've learnt

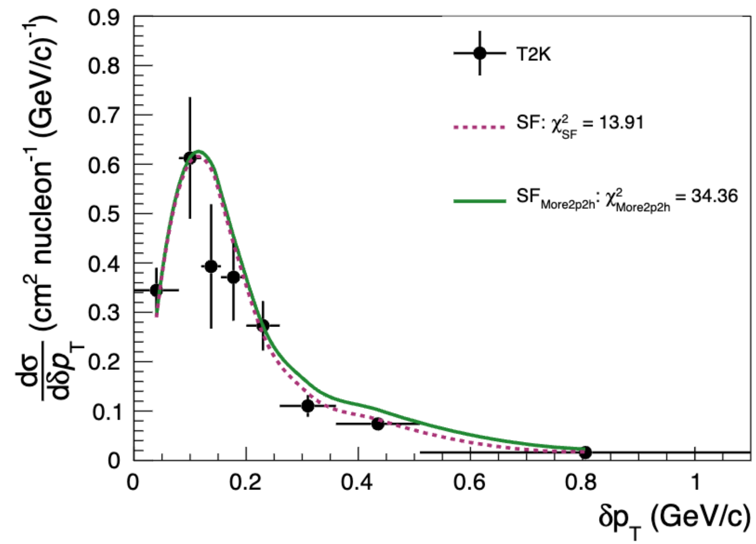
- Preference for important 2p2h contribution
- Clear need for suppression of the cross section at forward angles w.r.t. PWIA models
- Qualitative reasonable agreement, but most models rejected quantitatively (even after fits)

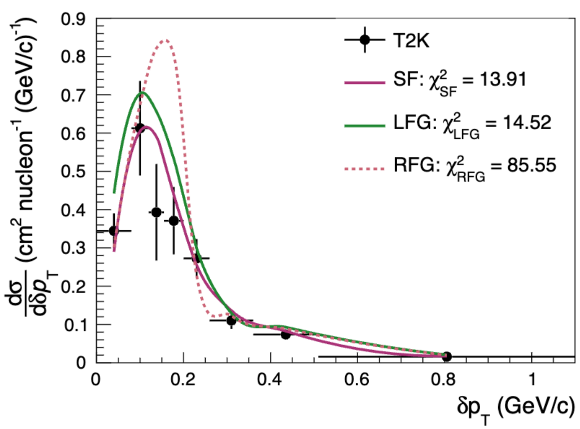
Measuring muon+proton kinematics

Youthful optimism

- Measuring muon-proton correlations (2018) Phys. Rev. D **98**, 032003





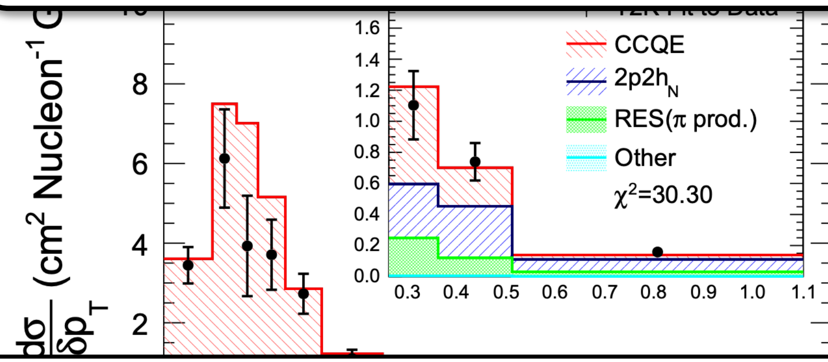


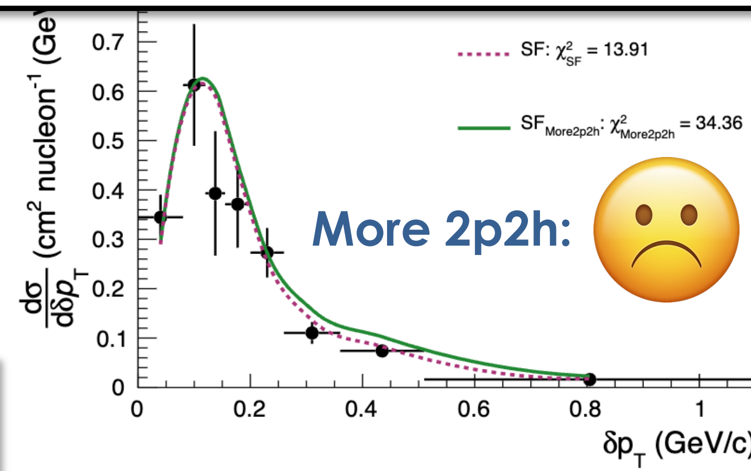
What we've learnt

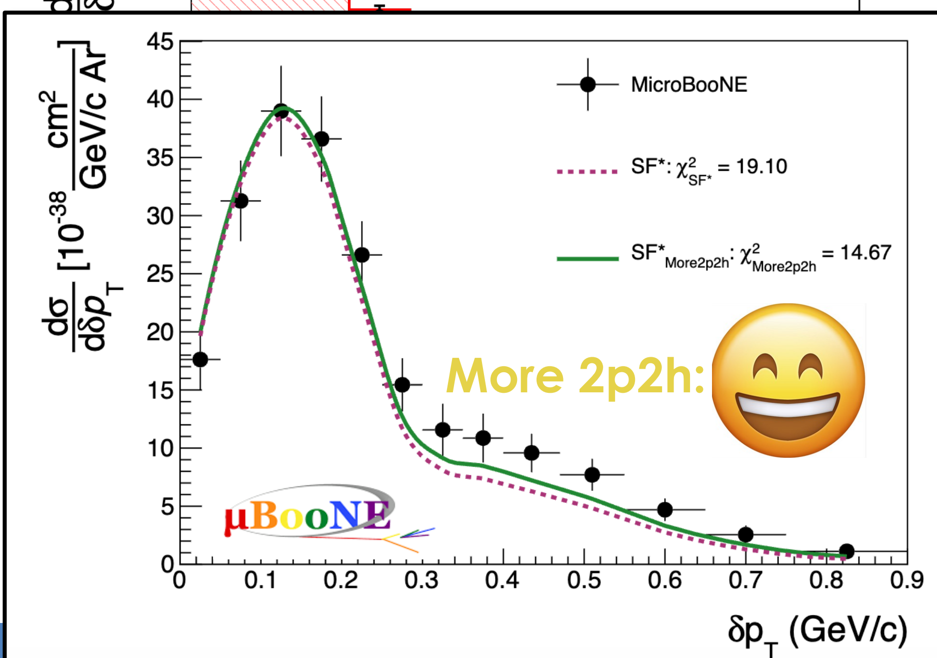
- No model quantitatively describes measurements
- RFG models clearly rejected
- Robust estimation of QE vs non-QE in CC0π+Np
- Clear requirement for 2p2h+π abs not much scope to alter one without changing the other

Measuring muon+proton kinematics

Lots more to learn when considering T2K TKI measurements alongside those from MINERvA and MicroBooNE
(W. Filali et. al. + NuSTEC white paper update: papers in preparation)







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Joint Measurements

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- ✓ Neutrino scattering predictions carefully constructed from nuclear theory.
- ✓ Precisely validated with electron scattering data
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  - Limited predictive power for hadron kinematics
  - Only valid for one process (e.g. only CCQE)
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Event generators

- Inputs to our oscillation measurements
- Stitch together available models however we can
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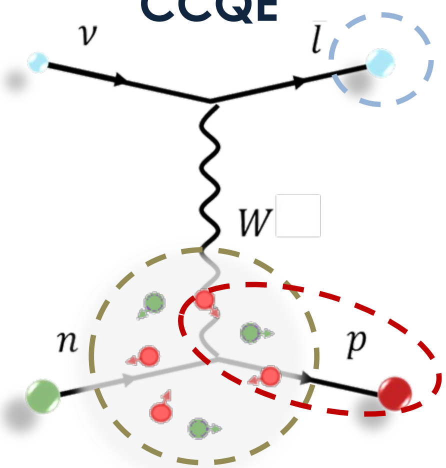
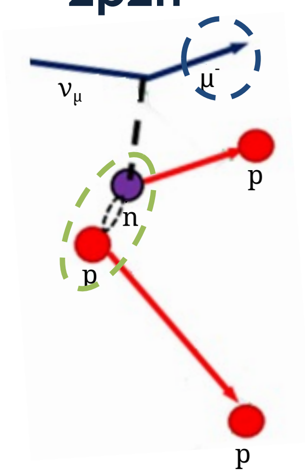
CCQE



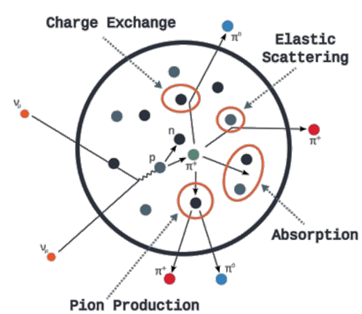
+

2p2h



+ … +

Final State Interactions



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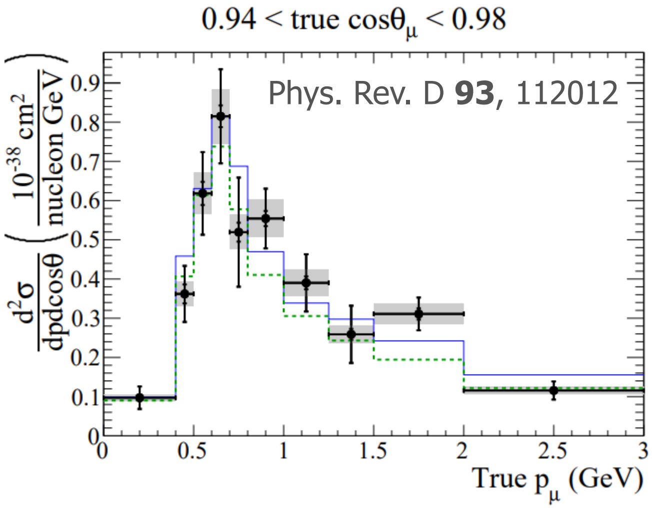
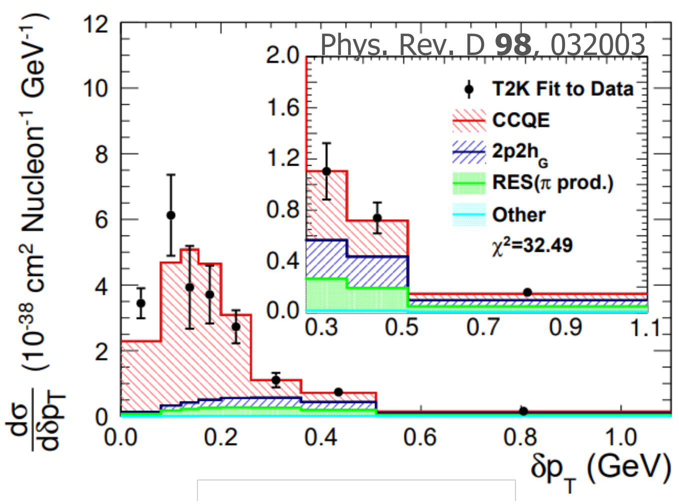
Produce results which directly probe key physics for oscillation measurements





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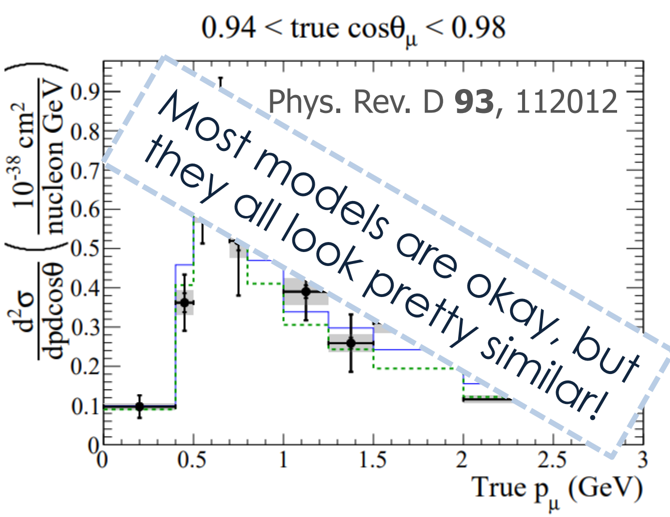

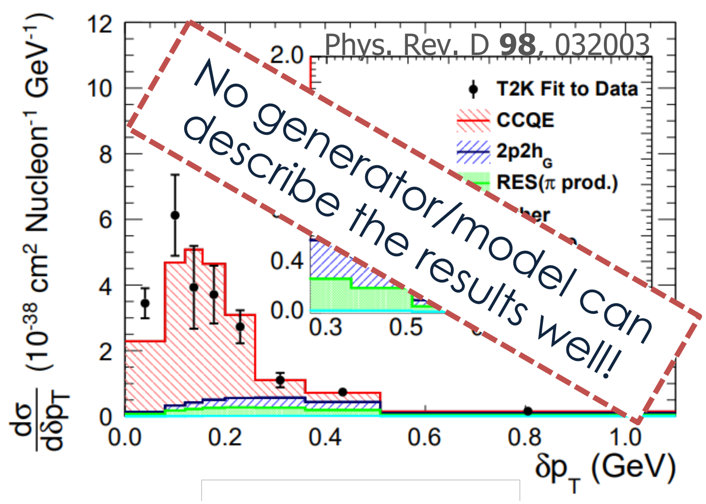

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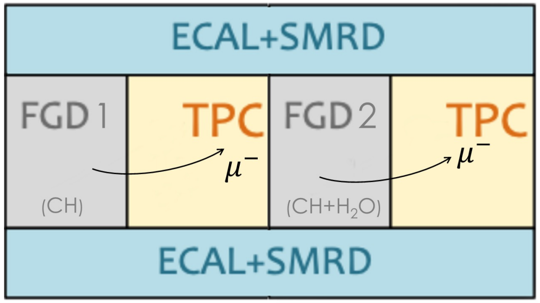
Carbon + Oxygen

Test extrapolation from ND to FD

Sensitive to nuclear effects via C/O ratio



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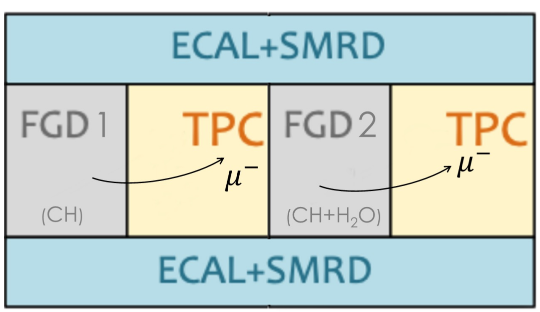
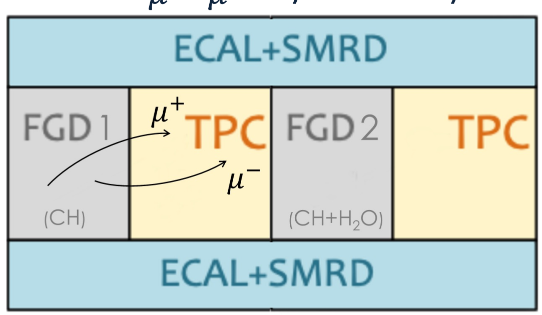


Neutrino + Antineutrino

Characterise $\nu_\mu/\bar{\nu}_\mu$, critical for δ_{CP} sensitivity

Sensitive to nuclear effects via $\nu_\mu/\bar{\nu}_\mu$ asymmetry



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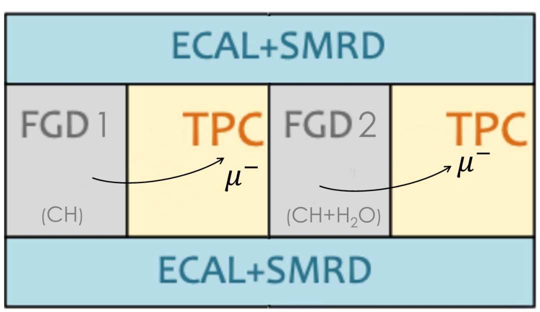

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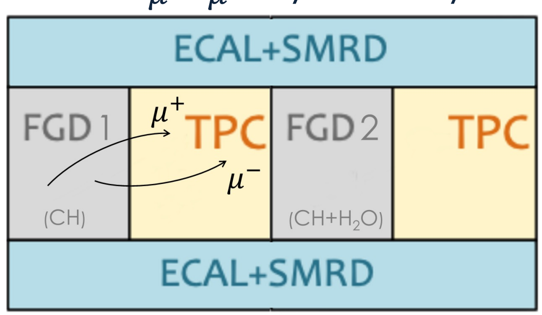
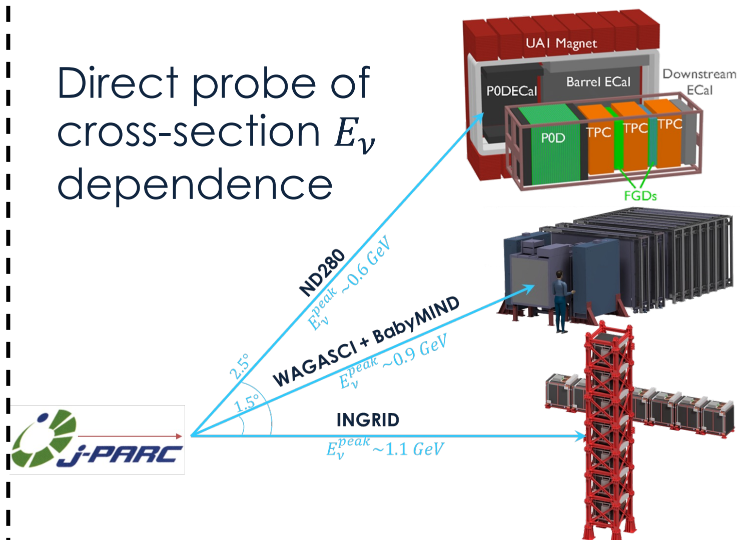


On+Off axis

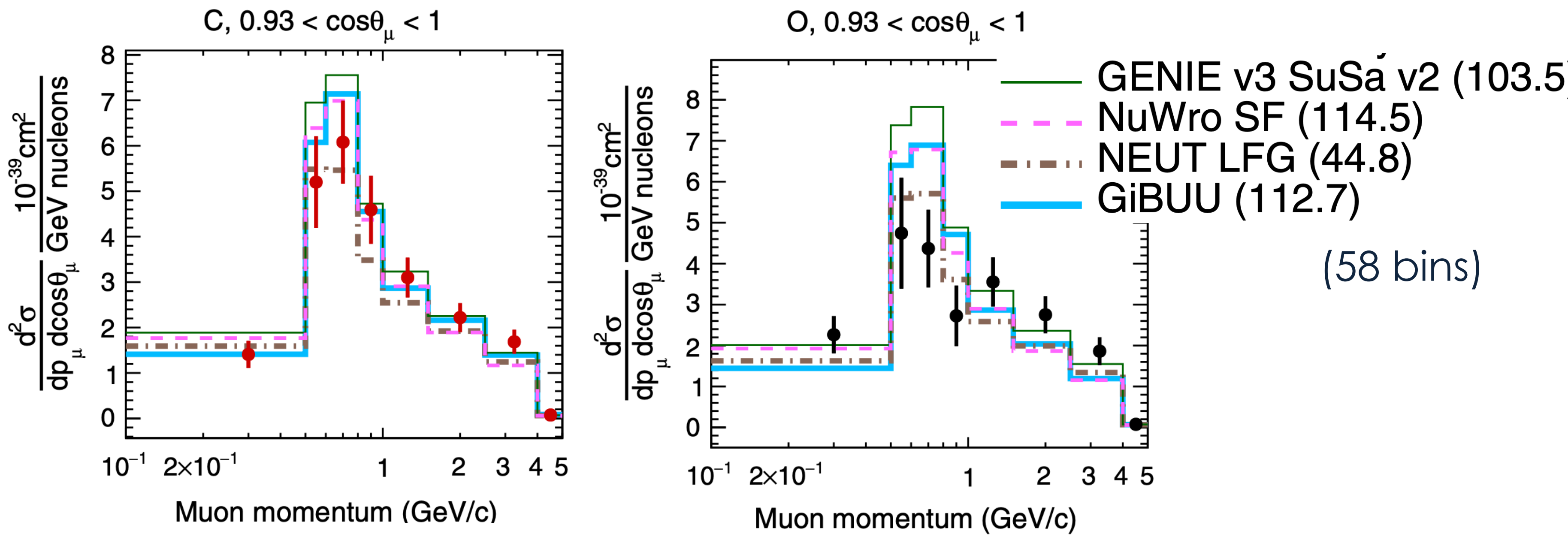
Direct probe of cross-section E_ν dependence



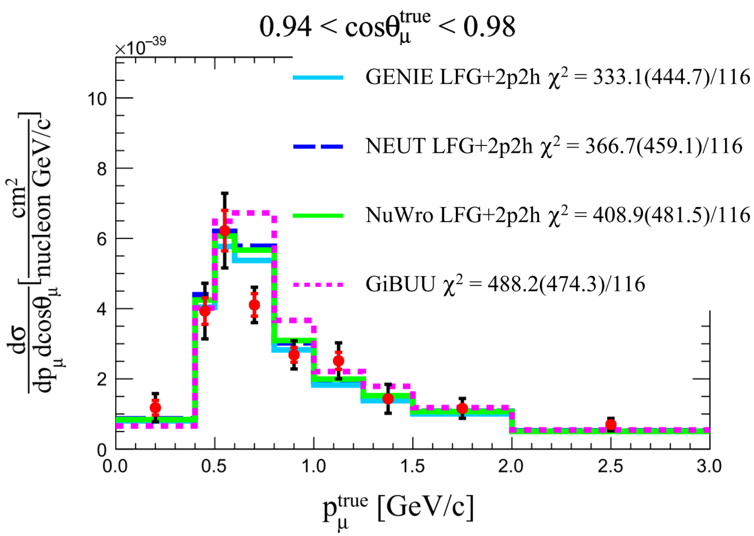
What we've learnt from joint measurements

Mature joint fit measurements

- C vs O, ν vs $\bar{\nu}$ (2020) Phys. Rev. D **101**, 112001, Phys. Rev. D **101**, 112004



(58 bins)



What we've learnt

- Suppression at forward angles w.r.t. PWIA models is different for C/O and $\nu/\bar{\nu}$
- Valencia RPA model gives a quantitatively good description of the C vs O measurement
- No model describes ν vs $\bar{\nu}$ measurement

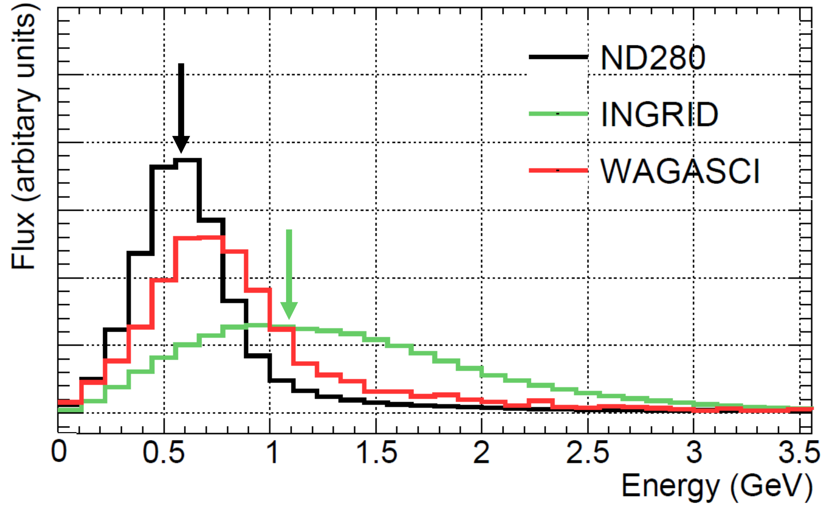
Our latest result

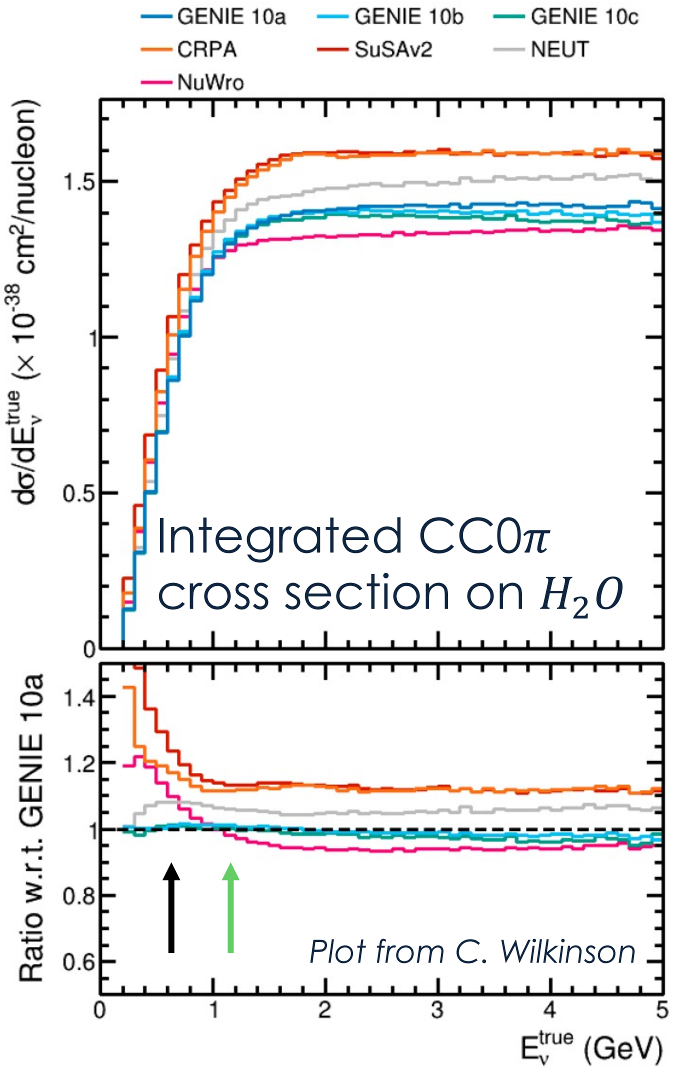
Mature joint fit measurements

- ***Correlated energy spectra (2024)*** Phys. Rev. D **108**, 112009

Out latest CC0π analysis:

- Measure cross-section at two detectors **at different off-axis angles**
- Comparison of measurements **probes cross-section energy dependence**
- Uncertainties are highly correlated: effective cancellation when making comparisons





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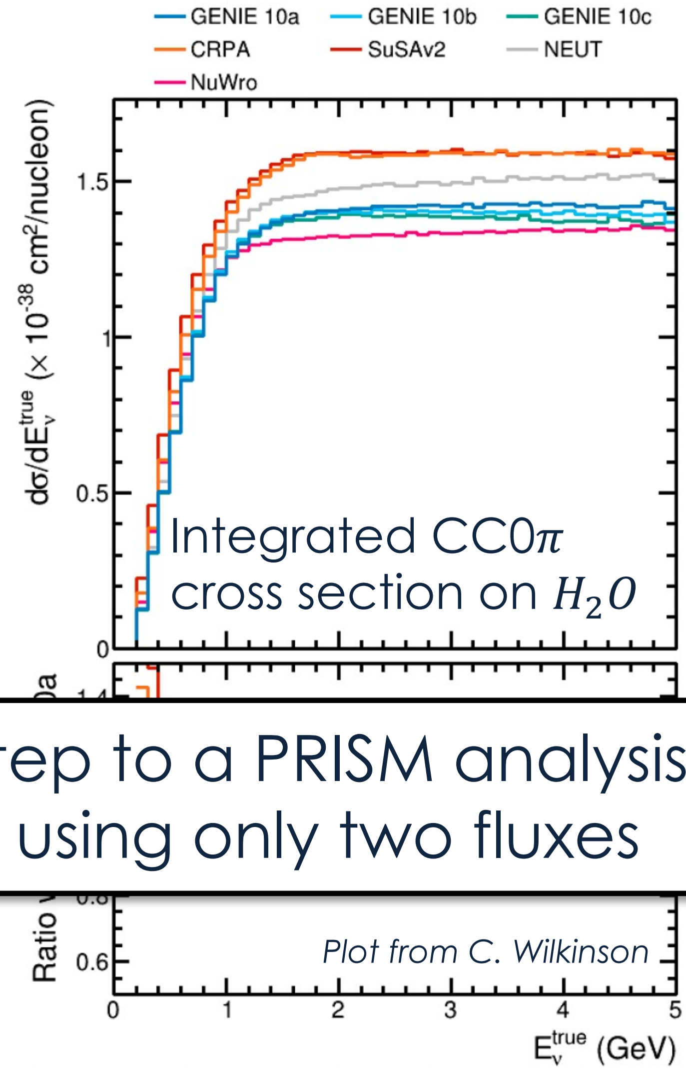

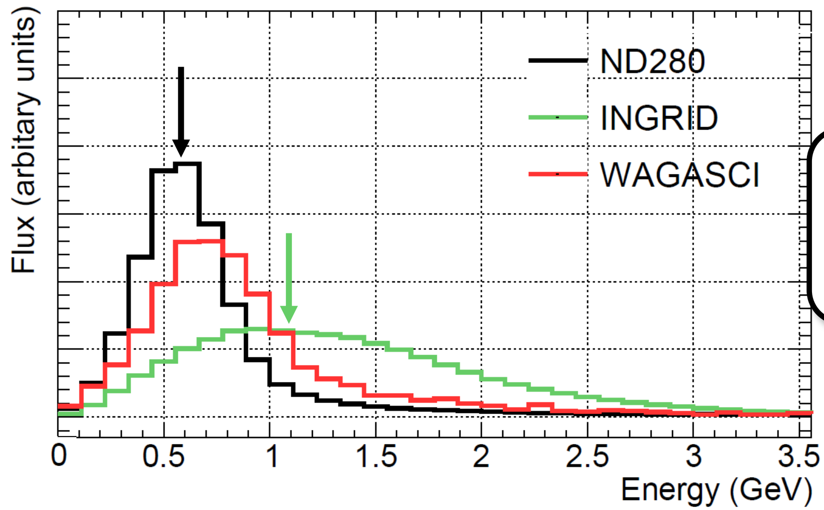

First step to a PRISM analysis, just using only two fluxes

Our latest result

Mature joint fit measurements

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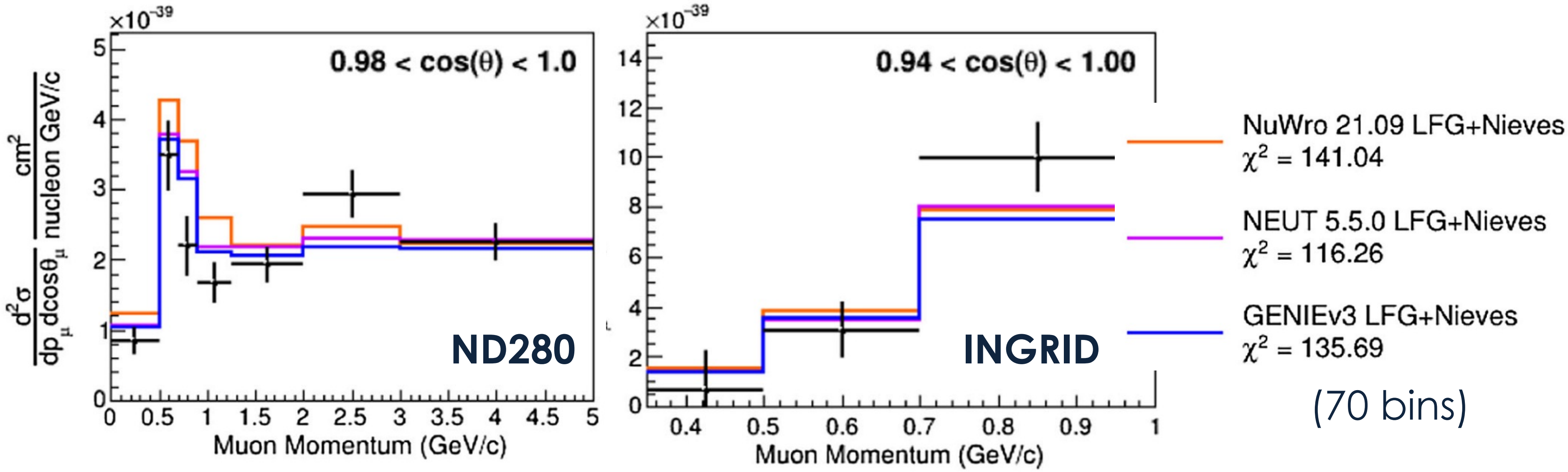

- Overestimation of models at forward angles for ND280 but not for INGRID
  - Issue with energy dependence of low ω suppression (RPA)?
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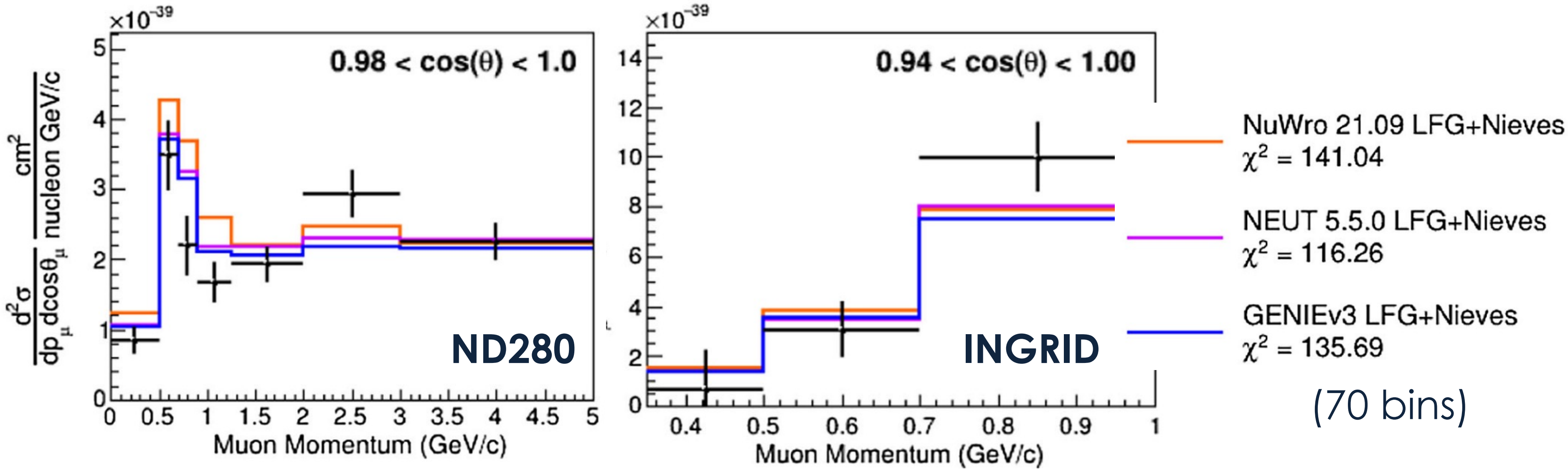


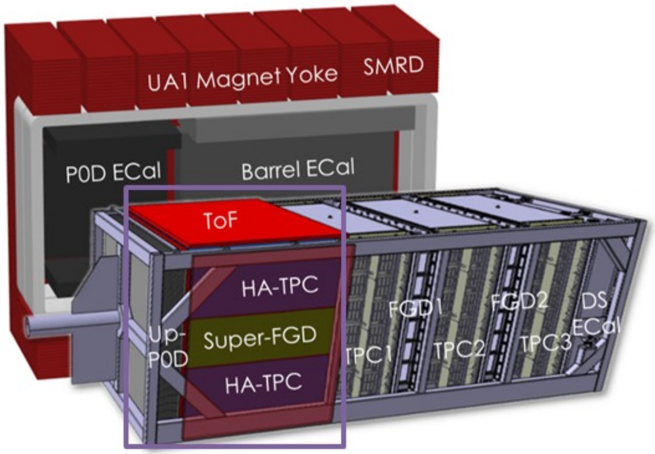
- Overestimation of models at forward angles for ND280 but not for INGRID
  - Issue with energy dependence of low ω suppression (RPA)?
  - Or with non-QE contributions?
- All tested models excluded by the measurement

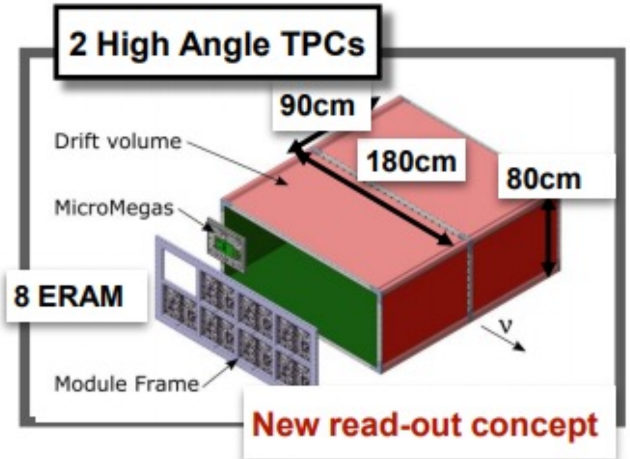
Model	ND280	INGRID	Joint
Nominal MC (NEUT)	136.34	18.21	158.71
NEUT LFG + Nieves	106.46	11.46	116.26
NEUT SF + Nieves $M_A = 1.03$	194.88	14.36	209.18
NEUT SF + Nieves $M_A = 1.21$	158.71	9.98	170.93
NuWro SF + Nieves	122.74	15.68	137.02
NuWro LFG + Nieves	125.88	12.75	141.04
NuWro LFG + SuSAv2	121.57	11.13	135.38
NuWro LFG + Martini	138.86	12.46	155.68
GENIE BRRFG + EmpMEC	141.40	12.80	156.05
GENIE LFG + Nieves	125.50	14.45	135.69

Cross-sections with an upgraded near detector

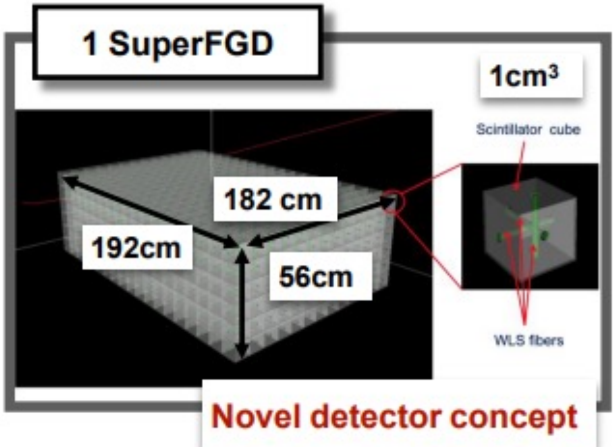
Near detector upgrade

arXiv:1901.03750

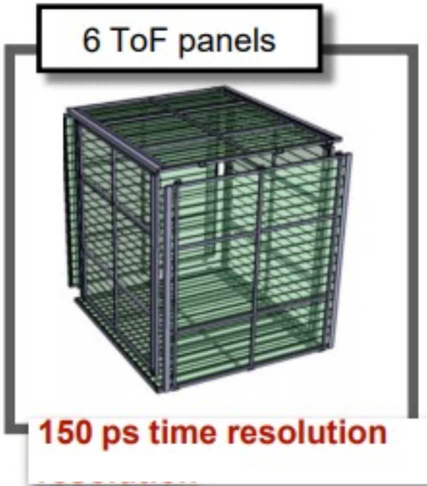




NIM A 957 163286 (2020)



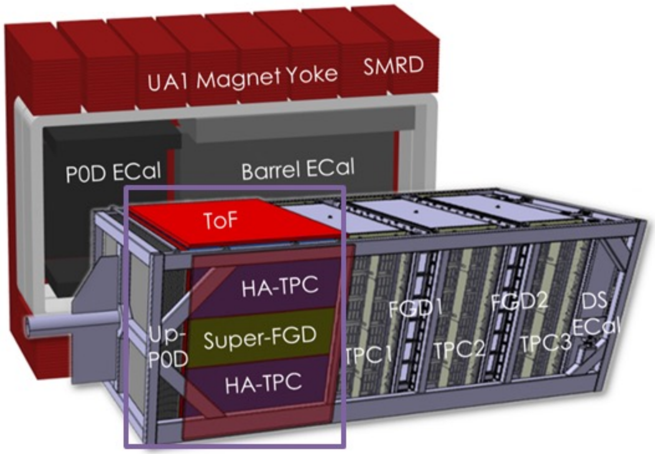
JINST 13, P02006 (2018)
JINST 15 P12003 (2020)



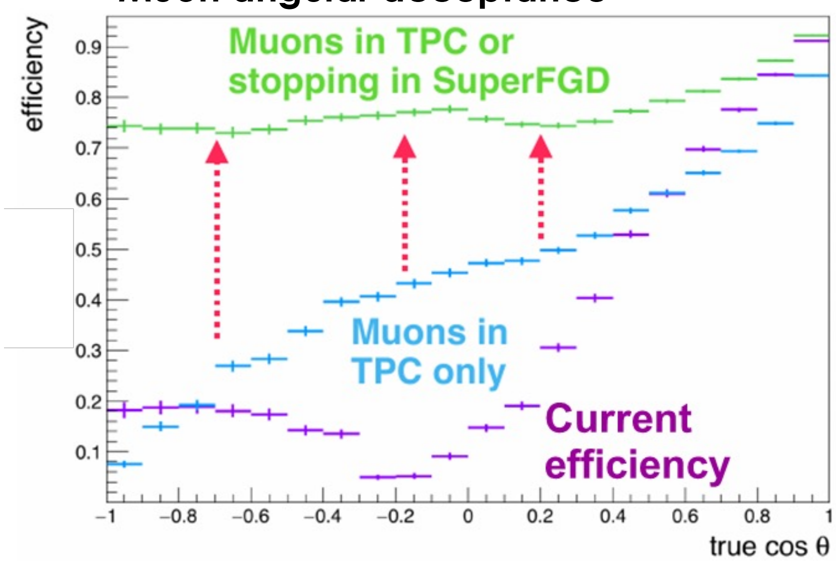
JPS Conf. Proc. 27, 011005 (2019)

Near detector upgrade

- 4π angular acceptance



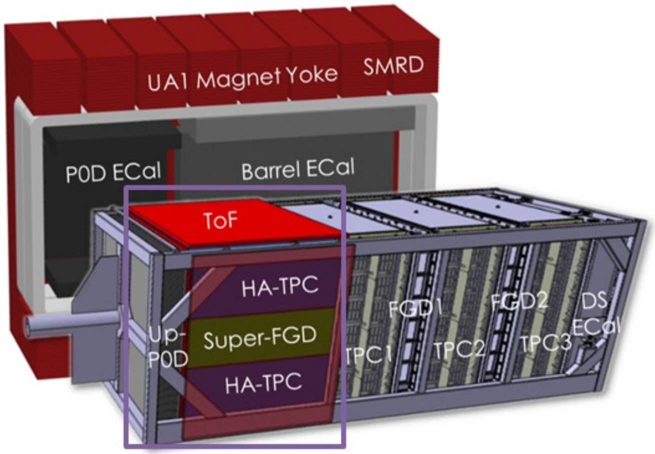
Muon angular acceptance

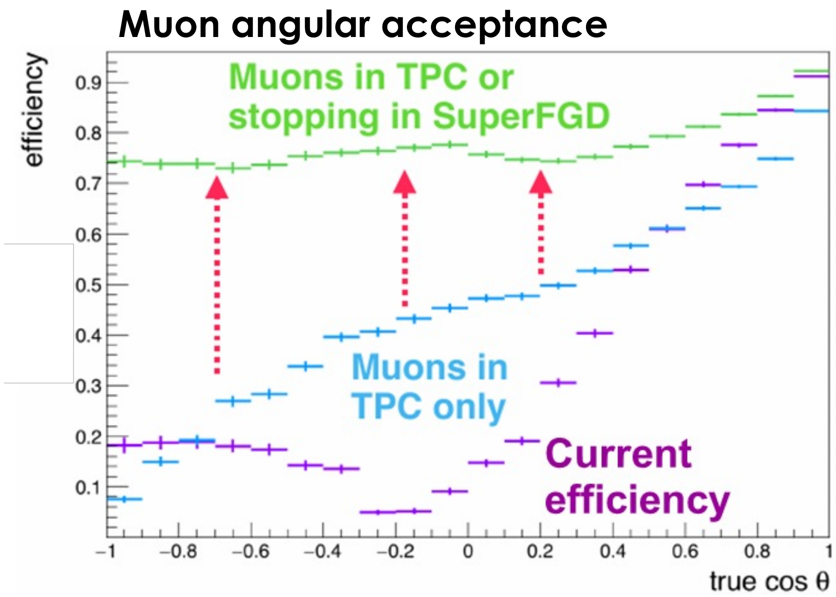


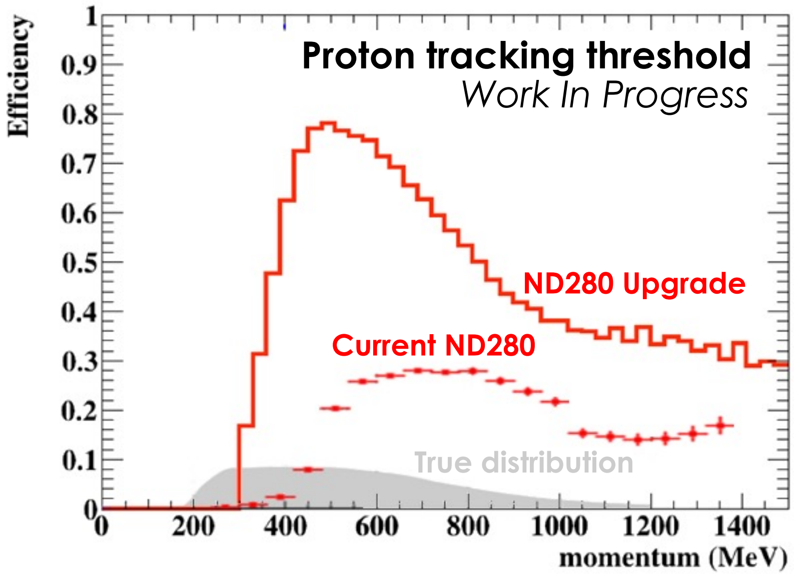
Near detector upgrade

arXiv:1901.03750

- 4π angular acceptance
- Lower tracking thresholds $p_p^{thresh} \sim 300\ MeV/c$, $p_\mu^{thresh} < 100\ MeV/c$







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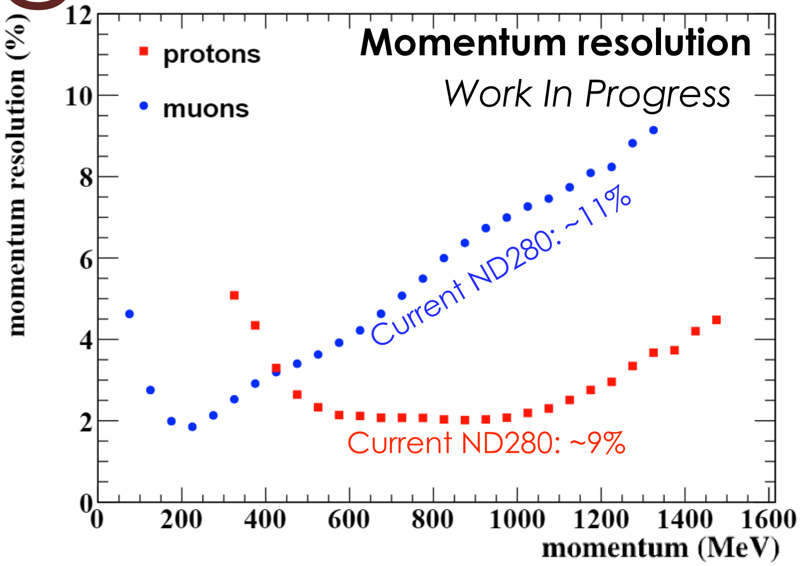
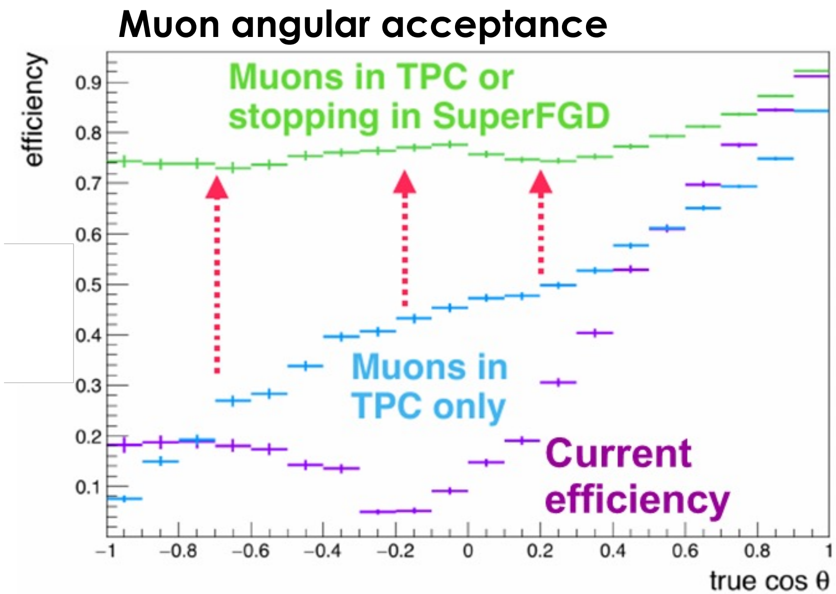
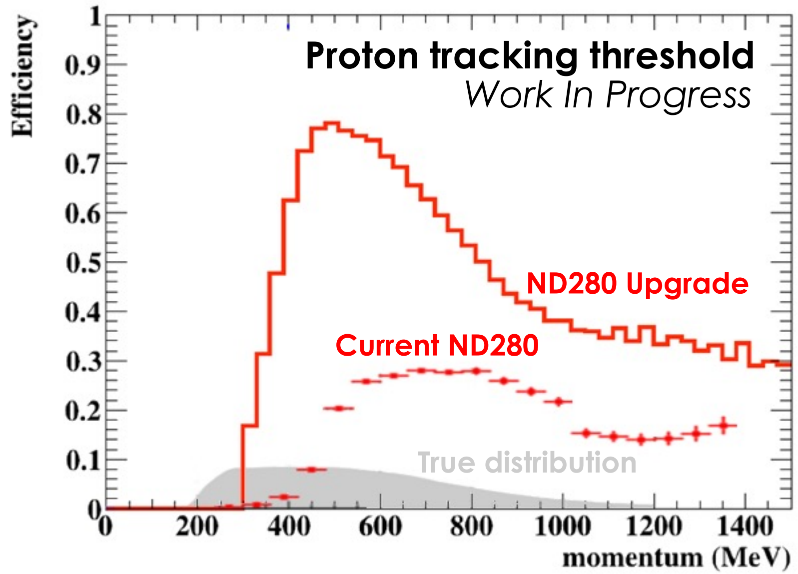
Phys. Rev. D **105**, 032010







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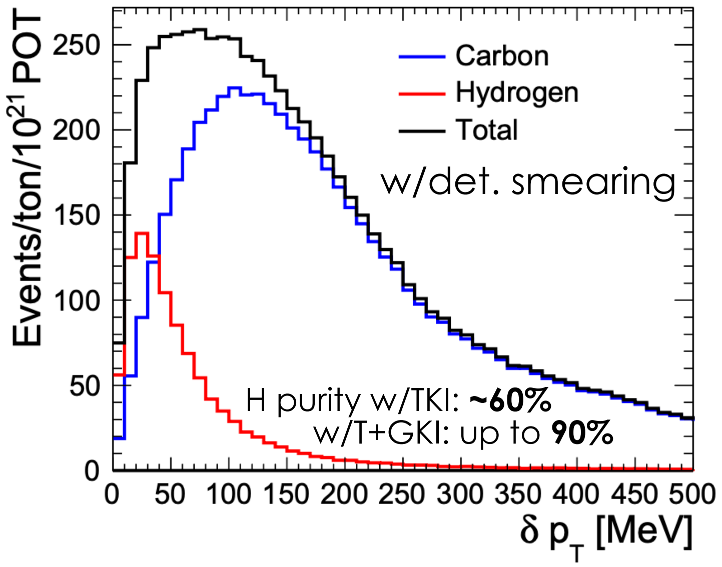
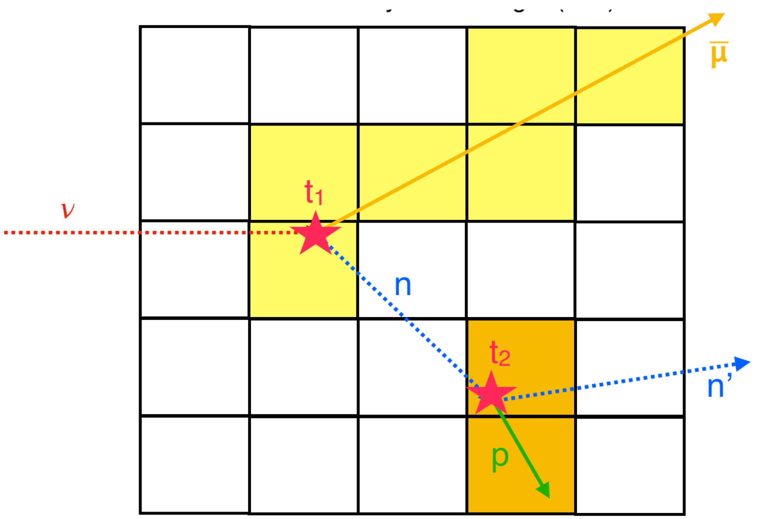
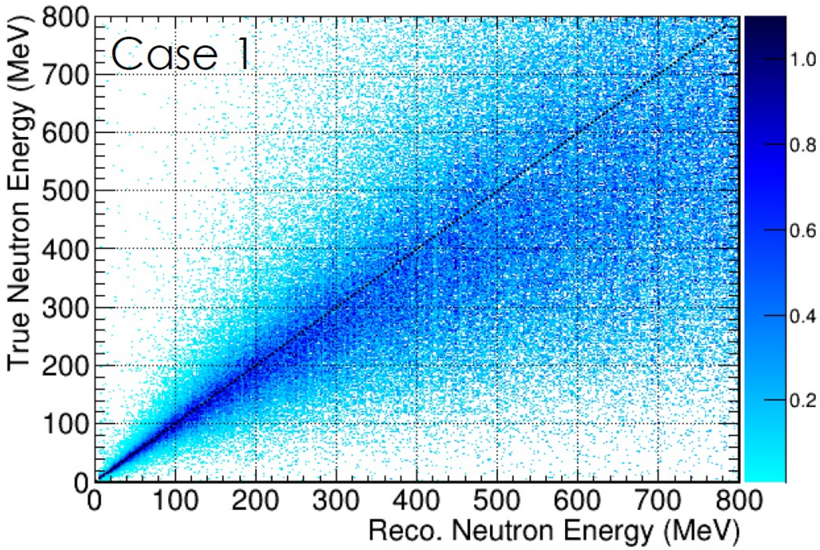
- Better timing resolution enables neutron energy measurements! $\Delta p_n/p_n < 30\%$
  Phys. Rev. D **101**, 092003
  arXiv:2310.15633







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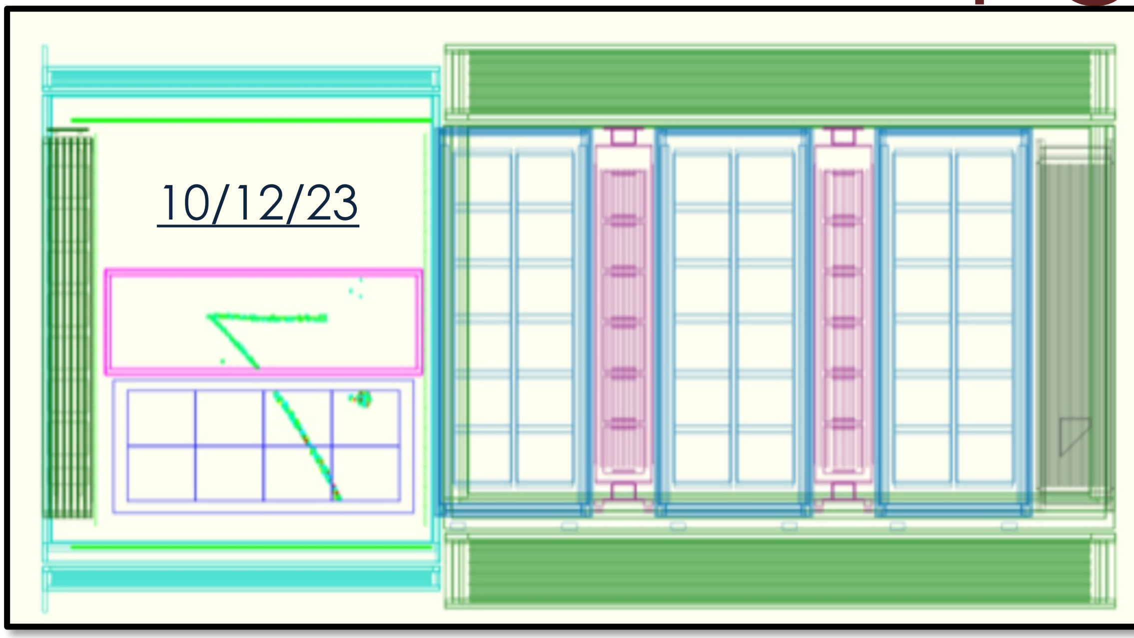
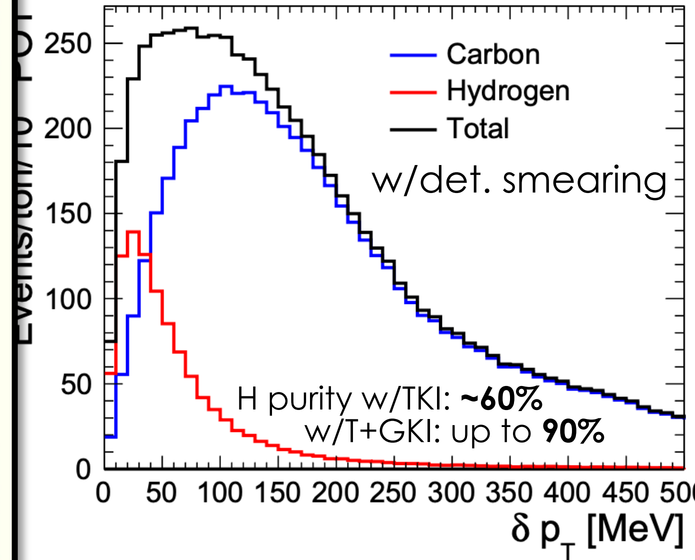
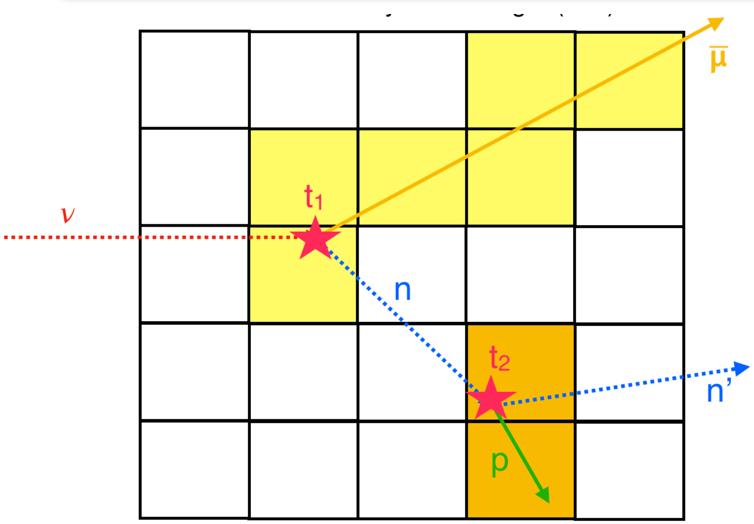
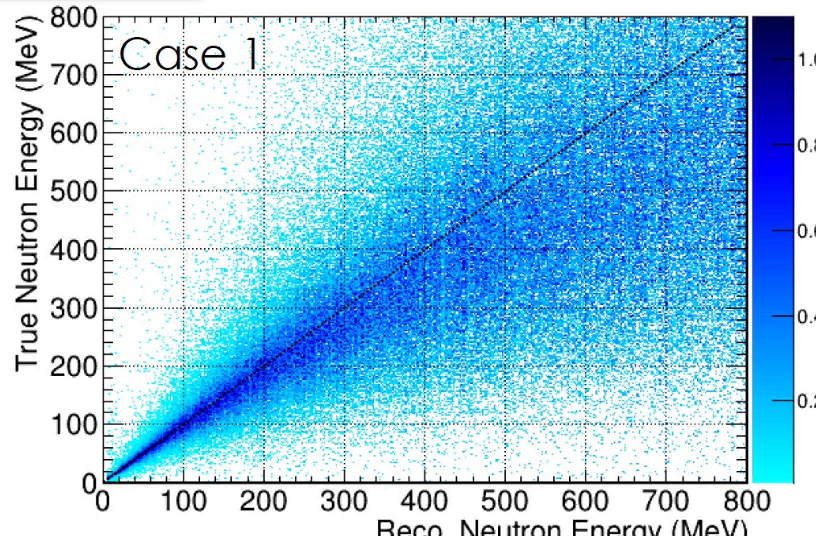




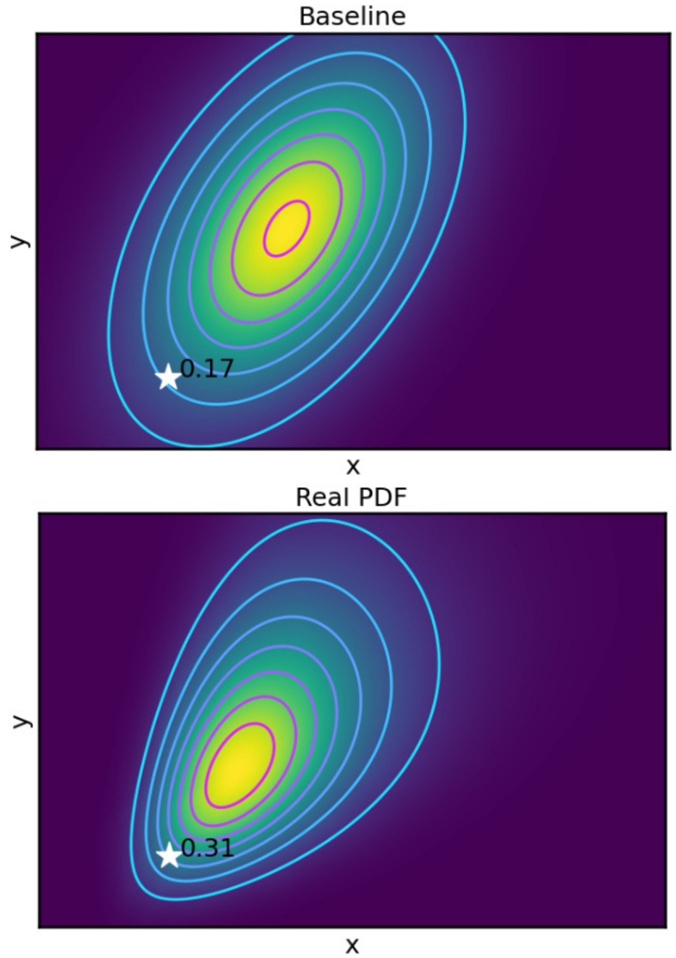




Considerations for our future high-stats analyses

Uncertain about Gaussian Uncertainties

- We always release our results with an accompanying covariance matrix
  - Approximation: uncertainties are Gaussian
  - ***But are they?***



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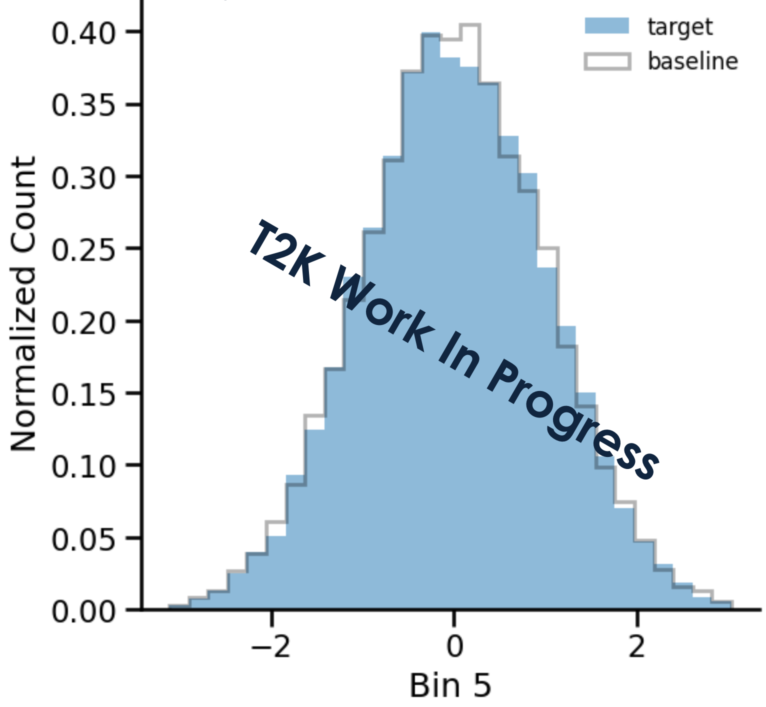
Analysis from R. Radev



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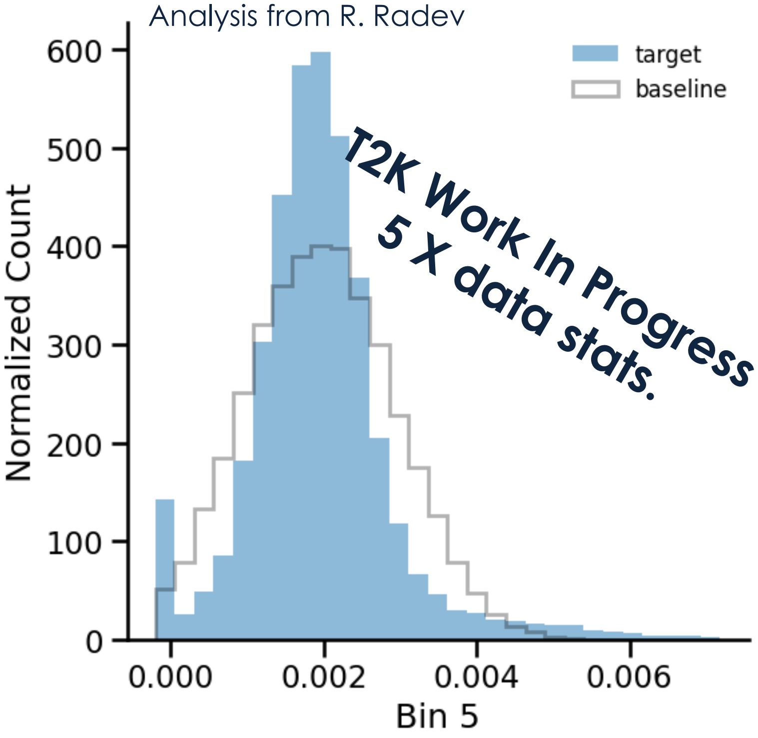
- **Example:** toy T2K analysis with 5x more stats



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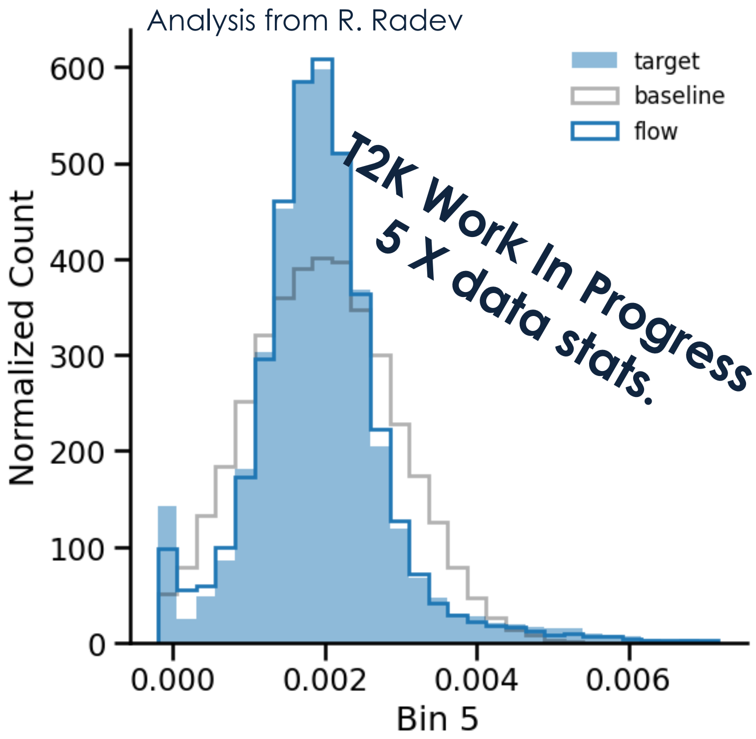
- But this isn't true if we simulate analyses with higher statistics, as we'll have with the upgrade
- **Example:** toy T2K analysis with 5x more stats
- **Potential solution:** use ML methods to learn the real p.d.f., seems to work well!



Uncertain about Gaussian Uncertainties

- We always release our results with an accompanying covariance matrix
  - Approximation: uncertainties are Gaussian
  - ***But are they?***

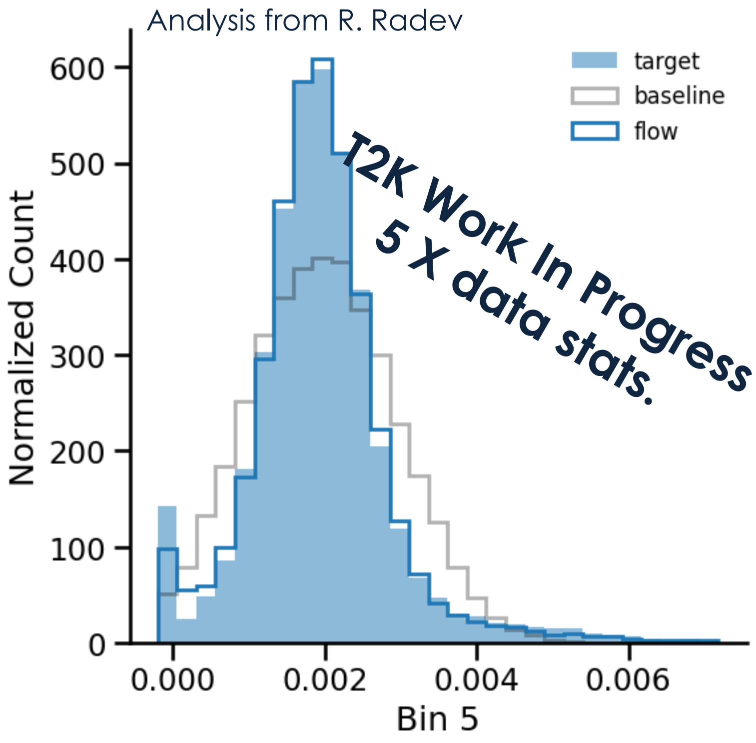
- With current statistics, T2K uncertainties do seem to be mostly Gaussian
  - We test this for each analysis

- But this isn't true if we simulate analyses with higher statistics, as we'll have with the upgrade

- **Example:** toy T2K analysis with 5x more stats

- **Potential solution:** use ML methods to learn the real p.d.f., seems to work well!

- Requirement from experiments: provide the "universes" that went into building our covariance matrices: T2K plans to do this.



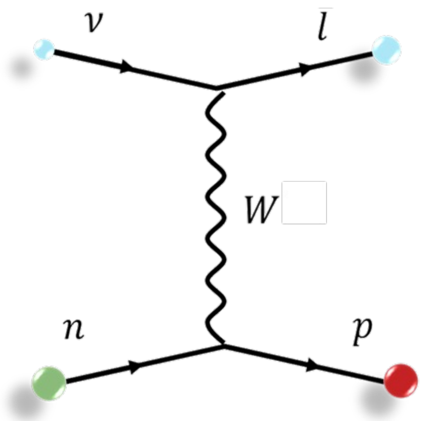
Summary

- **CC0π is the dominant channel** for T2K oscillation analyses
  - T2K cross-section measurements **hone in on the physics that drives our oscillation analysis' systematic uncertainties**
  - Recent **focus on joint measurements**
  - **Long history** of measurements with some clear conclusions:
    - Importance of forward-angle suppression
    - Constraints on C vs O and ν vs $\bar{\nu}$ (need guidance parameterising this)
    - Proportion of QE vs non-QE
    - All models are unable to describe all our measurements!
- Strong focus on **ensuring model-independence**
- Latest analysis: **measurements on/off axis simultaneously**
  - A **model-independent probe of σ energy evolution**
- A very exciting future ahead of us with ND280's upgrade

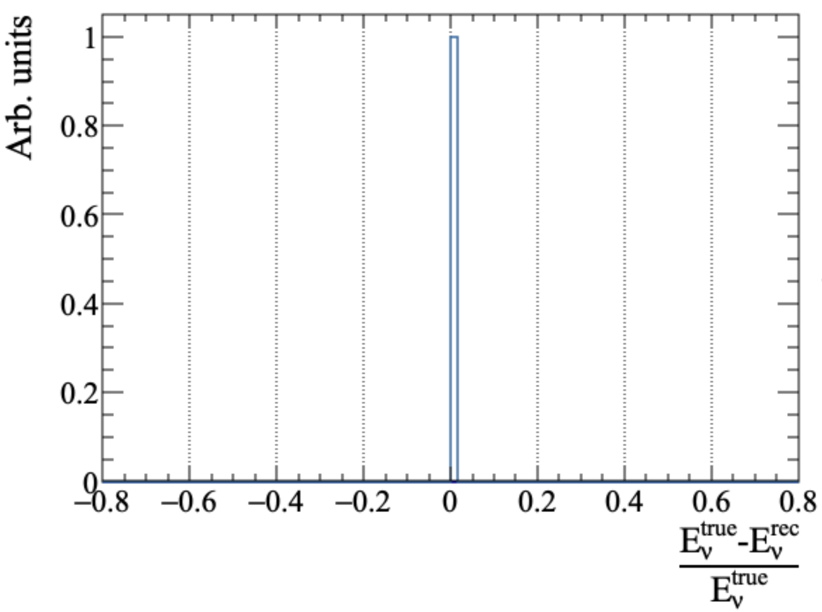
Backups

Neutrino energy reconstruction

CCQE (1p1h)



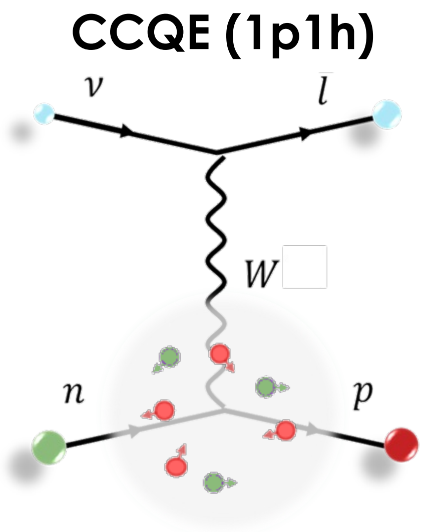
- T2K is dominated by CC0π interactions
- These are dominated by CCQE
- We are well suited to applying **kinematic neutrino energy reconstruction** to CC0π event selections

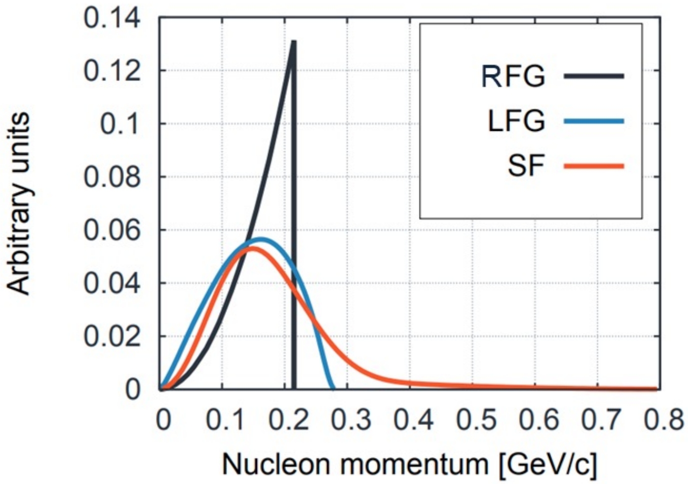


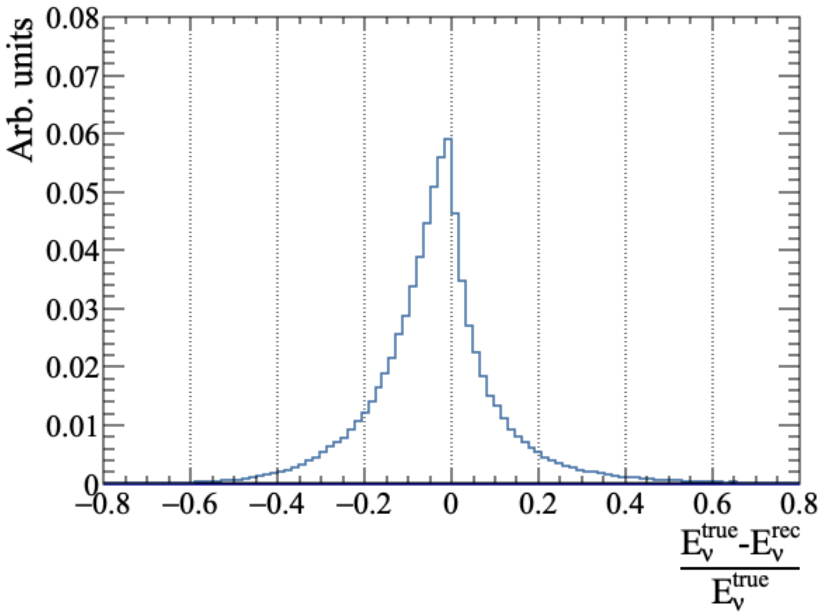
$$E_\nu = \frac{m_p^2 - (m_n - E_B)^2 - m_\ell^2 + 2E_\ell(m_n - E_B)}{2(m_n - E_B - E_\ell + p_\ell \cos\theta_\ell)}$$

Proxy for E_ν from lepton kinematics is exact only for **CCQE elastic scattering** off a **stationary nucleon**

Neutrino energy reconstruction







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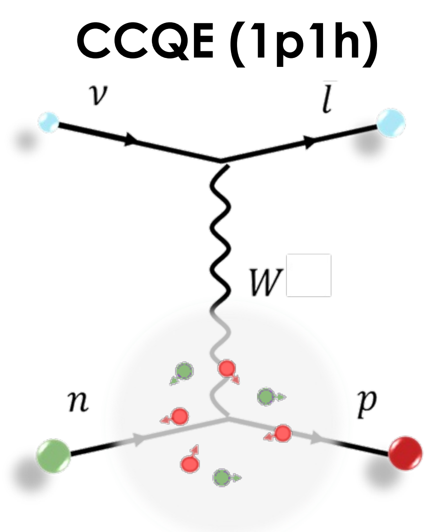
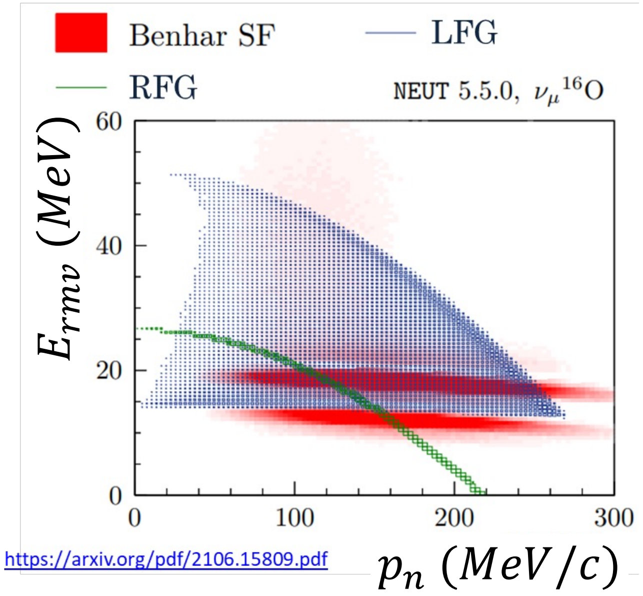
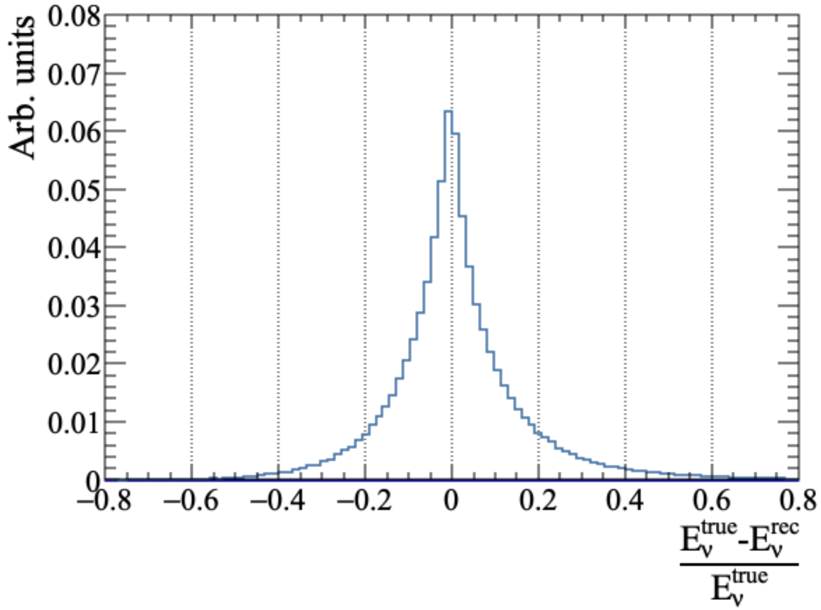
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

Neutrino energy reconstruction





https://arxiv.org/pdf/2106.15809.pdf



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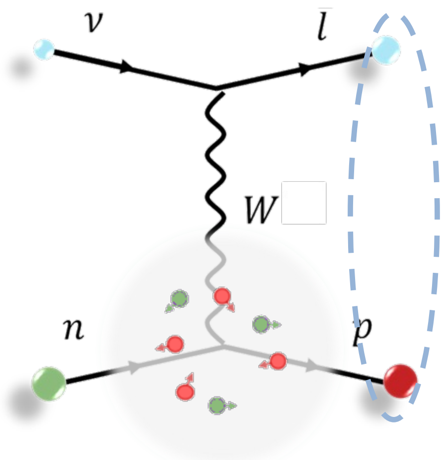
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

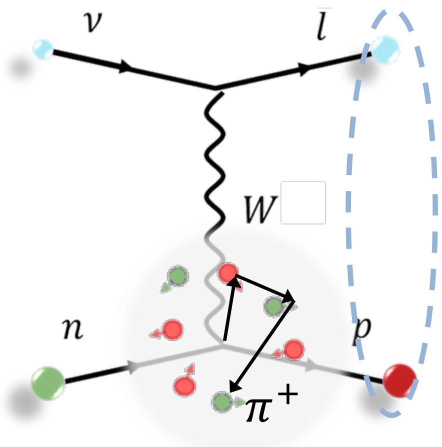
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Neutrino energy reconstruction

CCQE (1p1h)

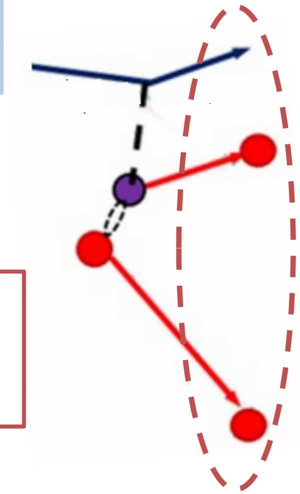


CCRES

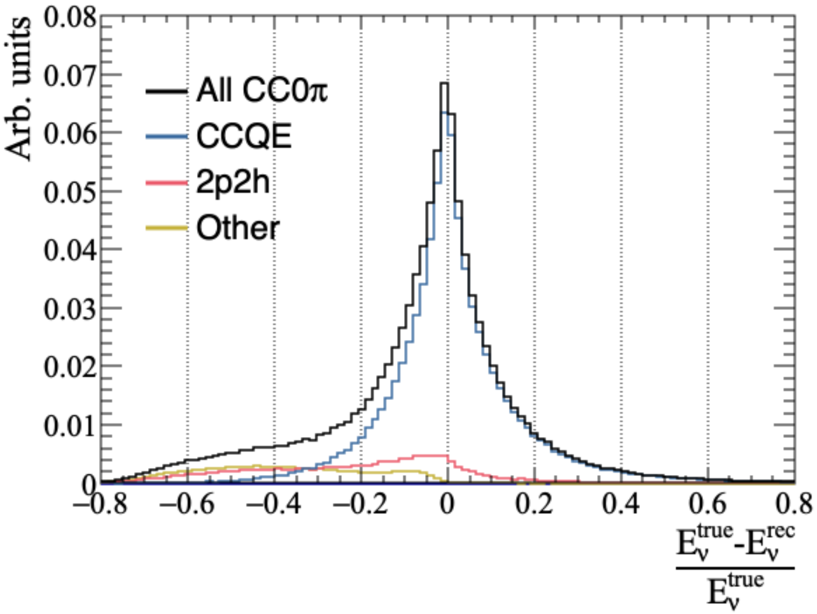


Final state interactions (FSI) can cause different interaction modes to have the same final state

2p2h



Interactions off a bound state of two nucleons can result in **2p2h** final states



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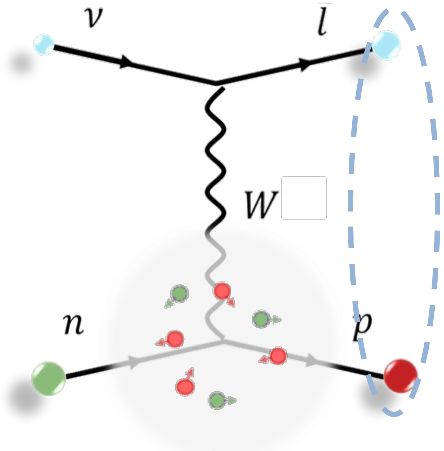
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Not a good proxy for non-CCQE events: 2p2h and CC1π with pion abs. FSI

Neutrino energy reconstruction

CCQE (1p1h)



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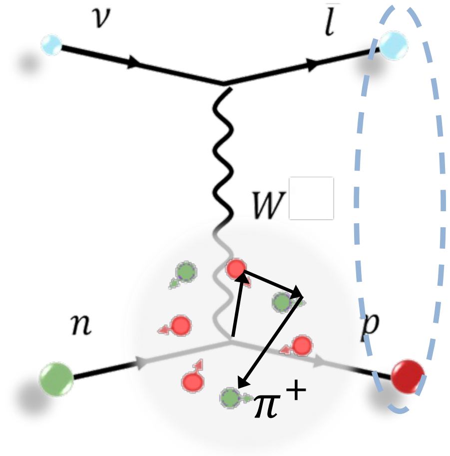
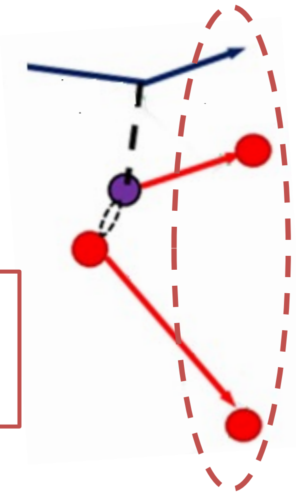
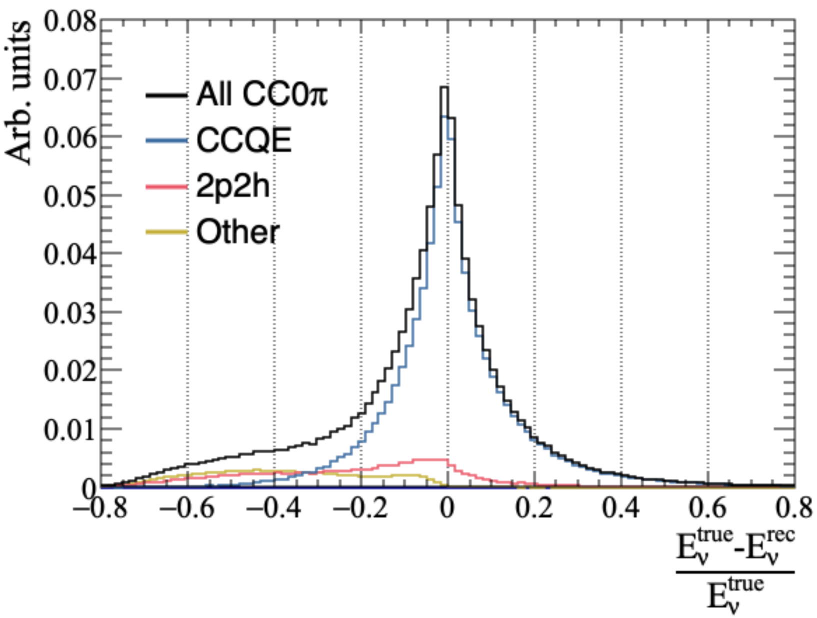


Final state interactions (FSI) can cause different interaction modes to have the same final state

2p2h



Interactions off a bound state of two nucleons can result in **2p2h** final states



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First-order effects

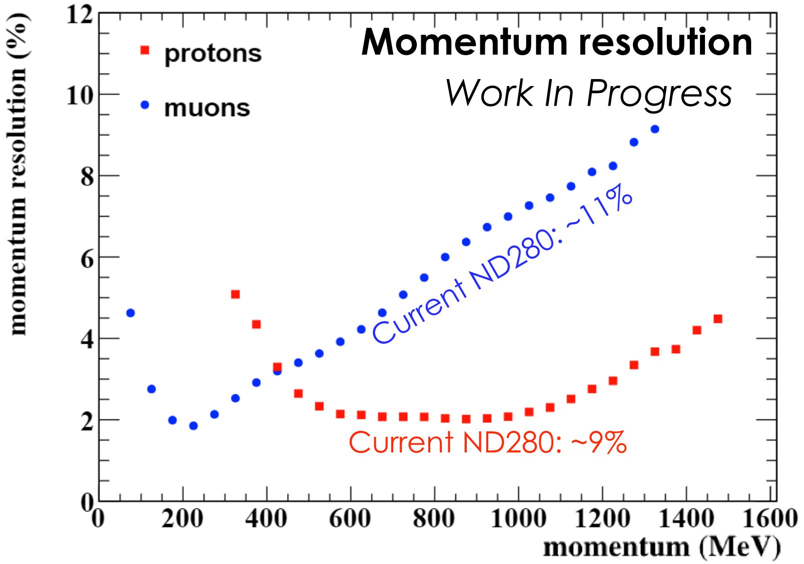
Fermi motion causes a **smearing** on E_ν^{QE}

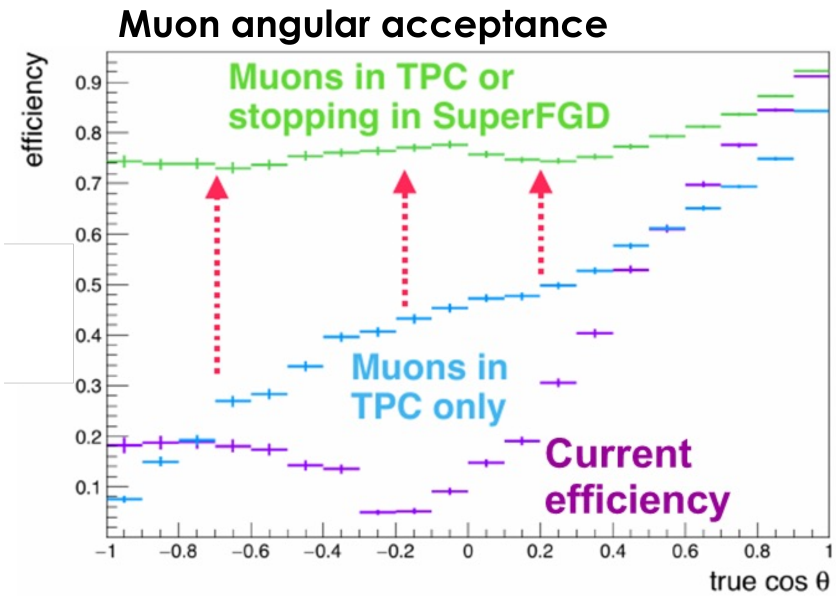
Nuclear removal energy effects introduce a **bias**

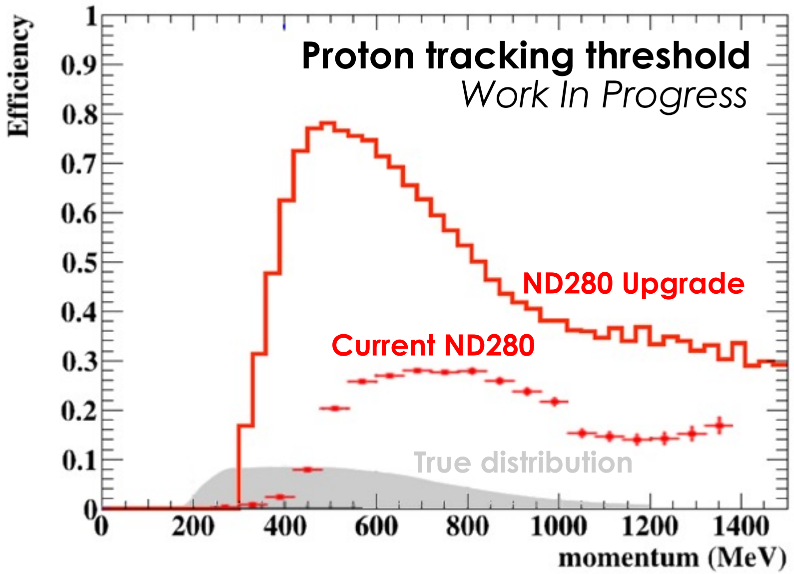
2p2h and pion abs. *FSI* cause further **bias**

Upgrade detector performance

- Dramatically improved angular acceptance
- Much lower tracking thresholds
- Substantially improved resolutions
- Better timing resolution enables neutron energy measurements!







Updated flux prediction

- Uses **NA61/SHINE** 2010 T2K replica target data for hadron production
  - Adds more stat to $\pi^{\pm}$ production
  - Also adds $K^{\pm}$ and proton data
- Overall **reduction of flux error** compared to 2009 replica target data (**by ~6%**)