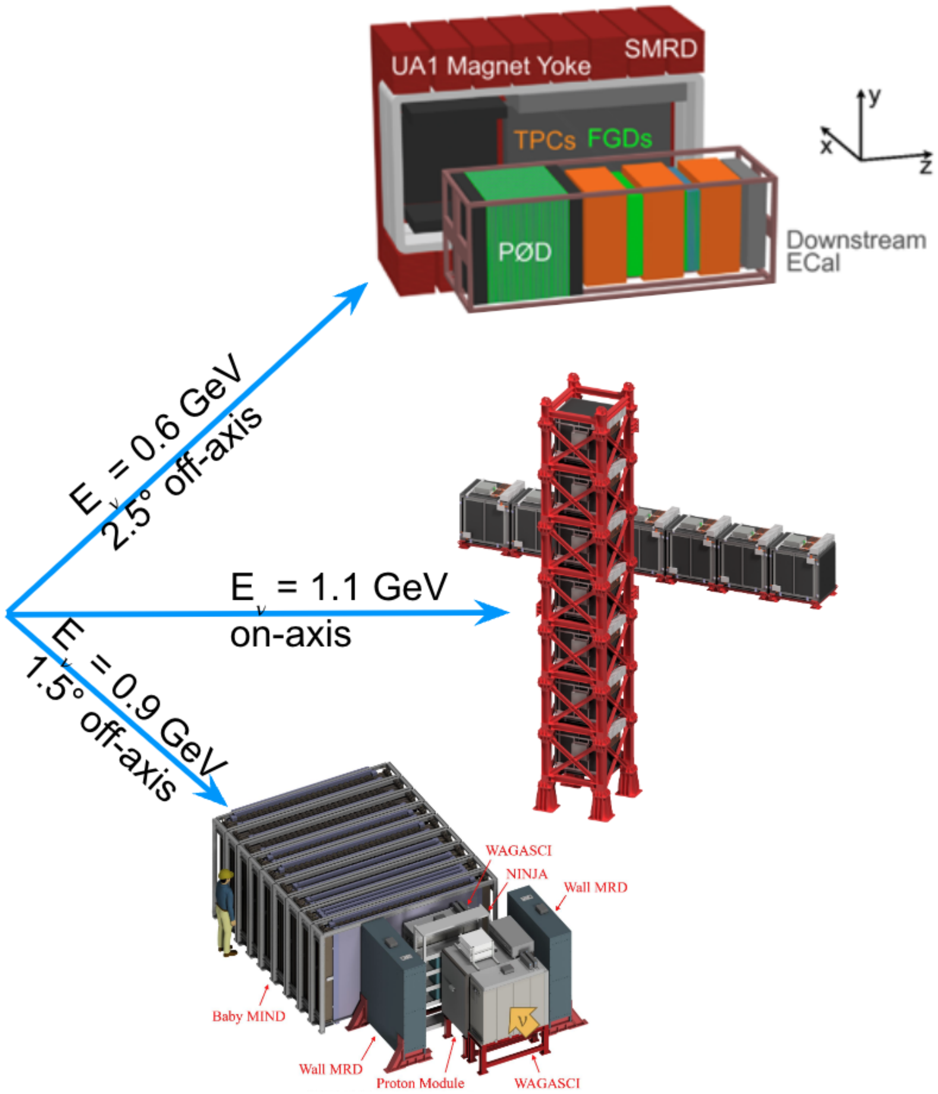
Neutrino Cross-Section Results From T2K



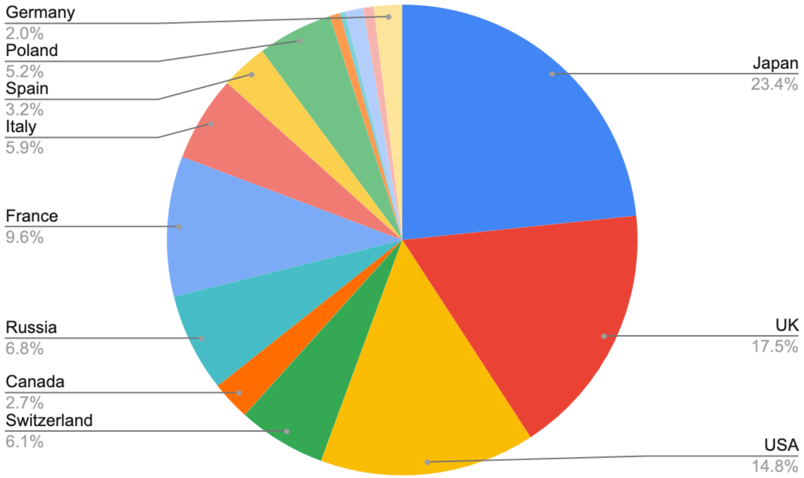
Daniel Cherdack, University of Houston
on behalf of the T2K Collaboration

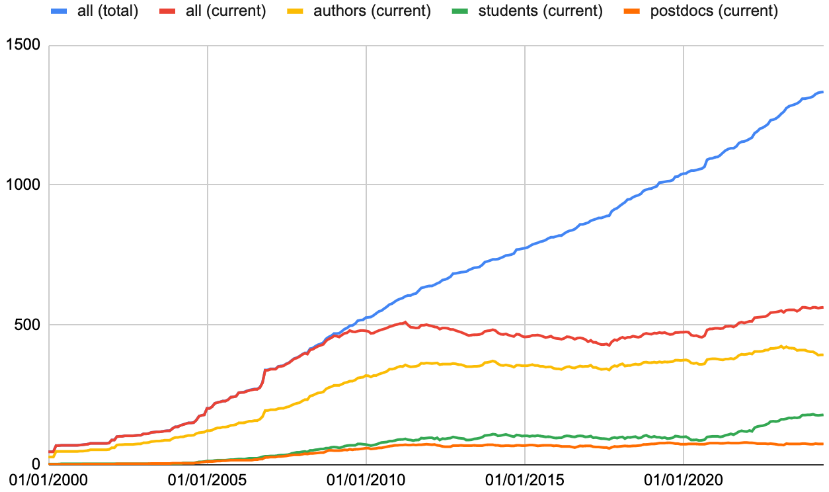
ICHEP 2024, Prague CZ, July 17 – 24, 2024

THE T2K Collaboration

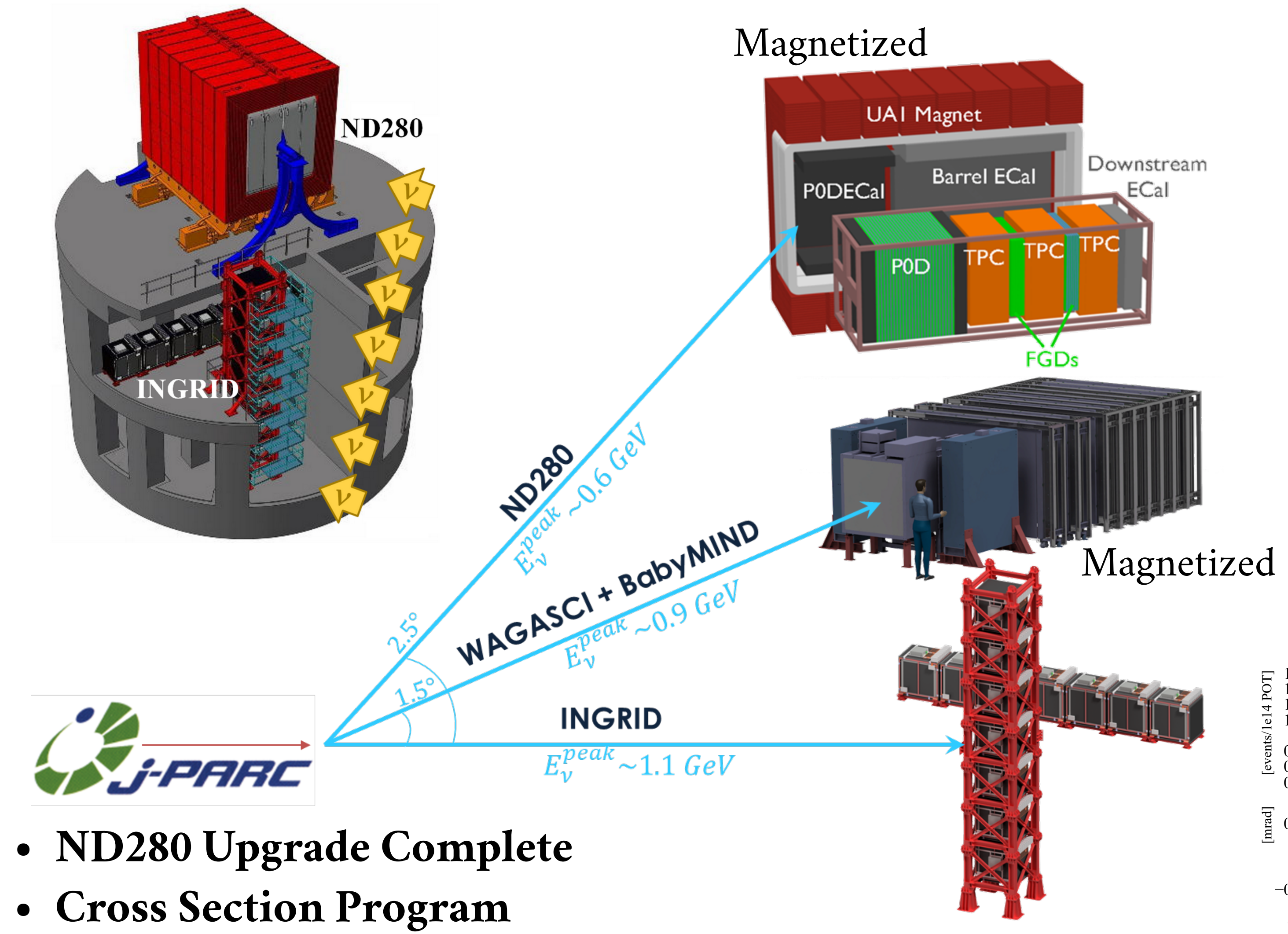
UNIVERSITY OF HOUSTON

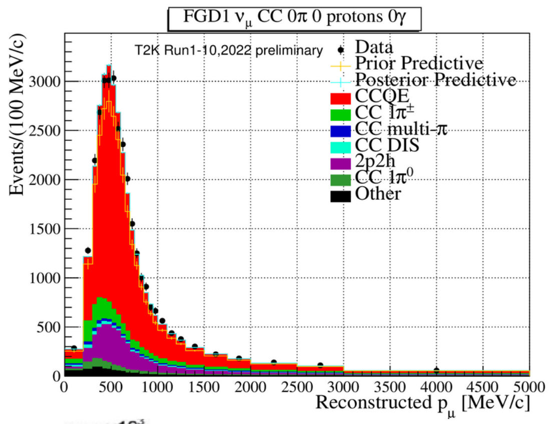
~ 500 Members, 74 Institutions, 15 countries



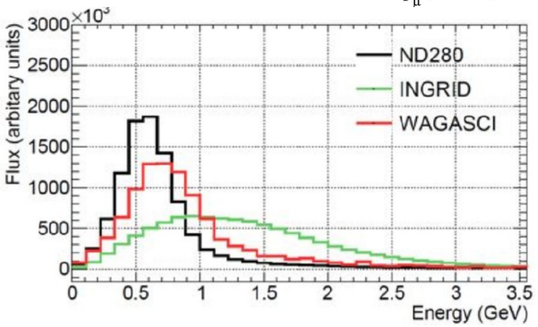


Near Detector Complex



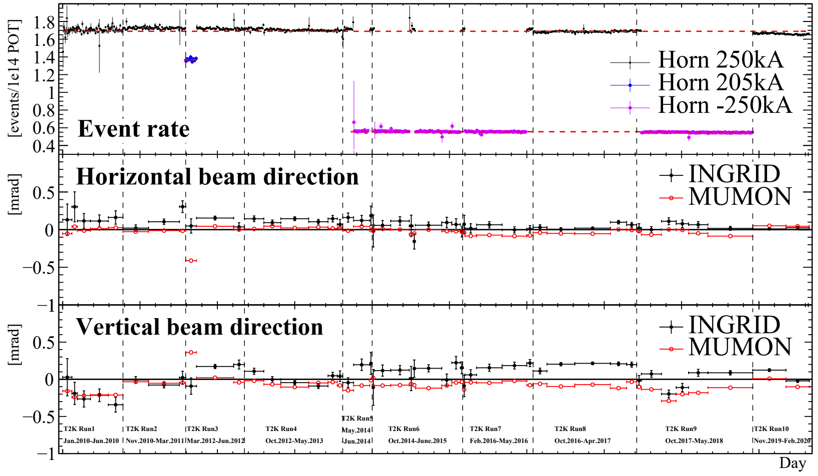


Constrain the Unoscillated SK Event Rate



Sample on & off-axis fluxes

CH and H_2O Targets

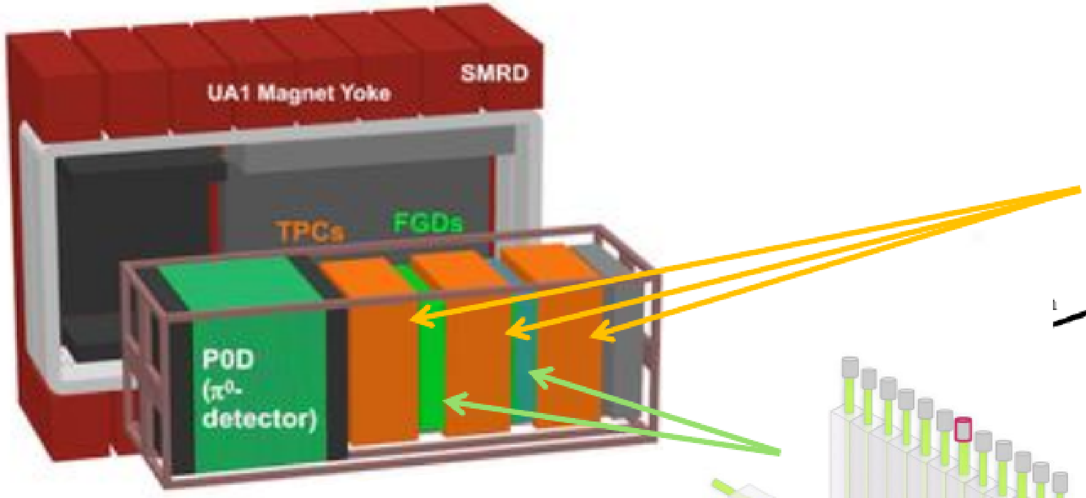


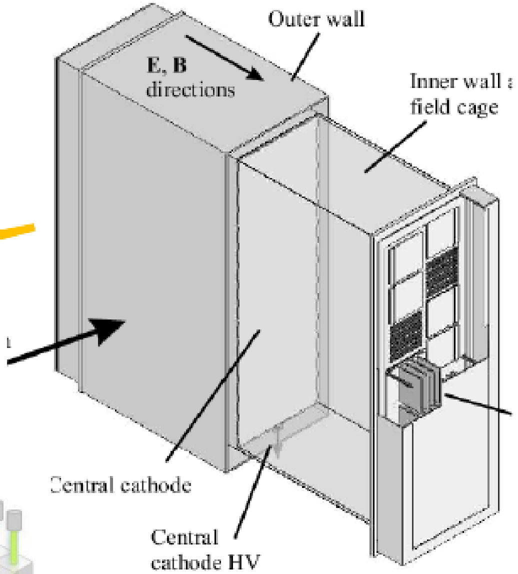
Monitor Beam Stability

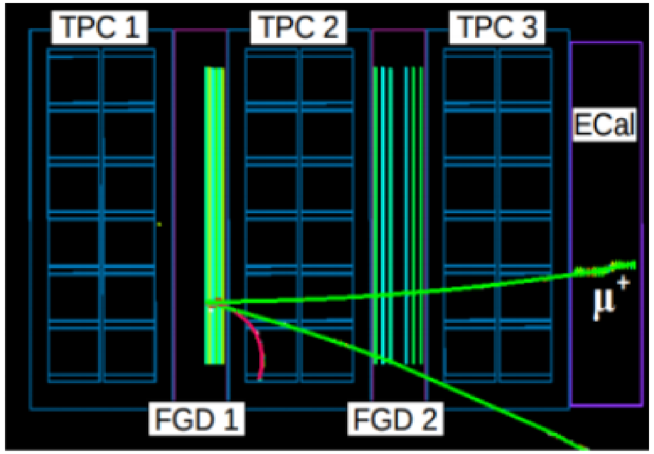
- ND280 Upgrade Complete
- Cross Section Program
- Flux and Cross Section Constraints for Oscillation Analyses

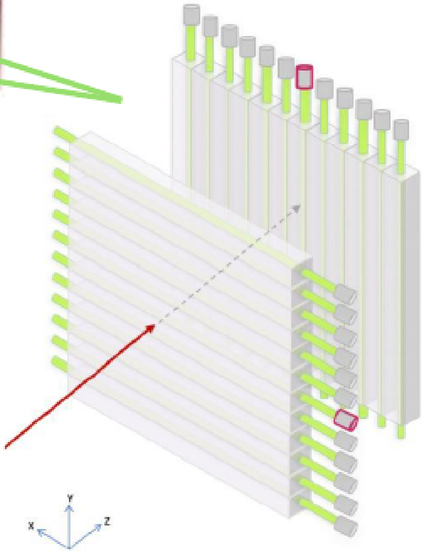
Near Detector: ND280 Design

UA1/NOMAD magnet (0.2 T field)





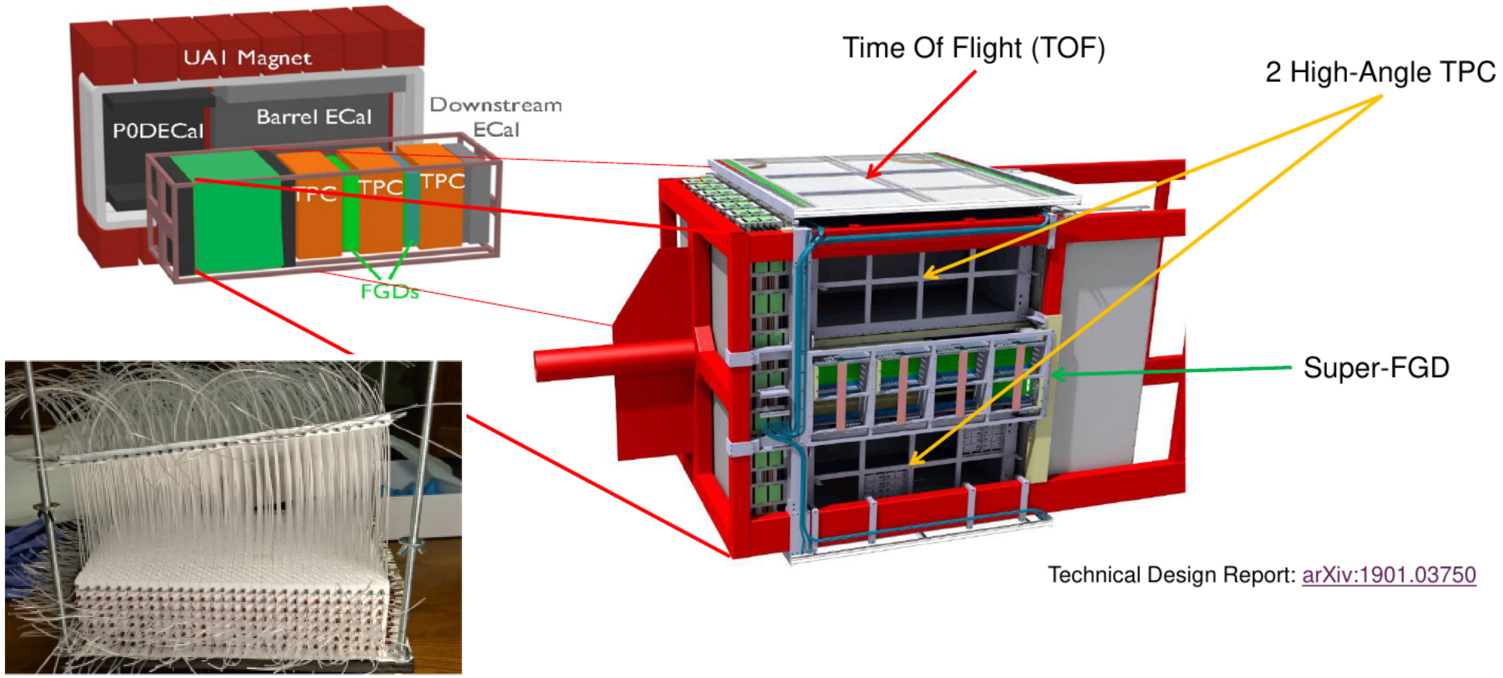




2 Fine-Grained Detectors
→ scintillating bars
→ neutrino target

3 Time Projection Chambers
→ reconstruct final state particles
→ momentum and PID

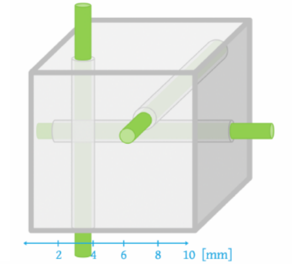
Near Detector: ND280 Upgrade

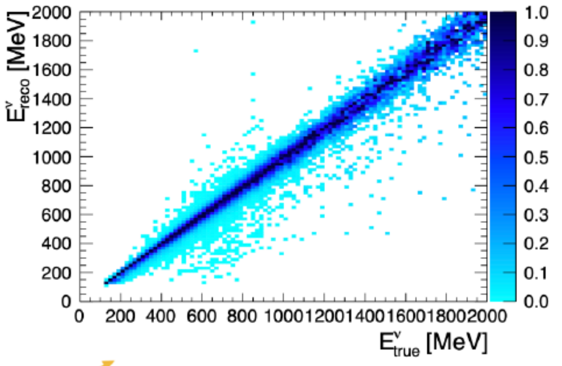


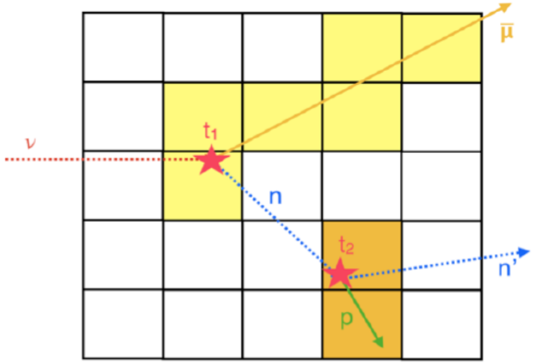
Technical Design Report: arXiv:1901.03750

~40 p.e./MIP/fiber

Nucl.Instrum.Meth.A 1041 (2022) 167219







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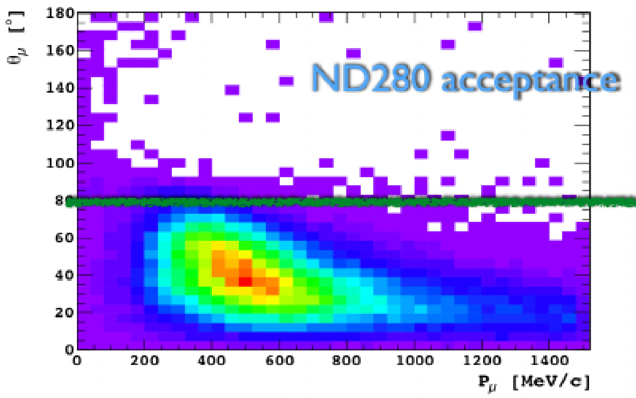
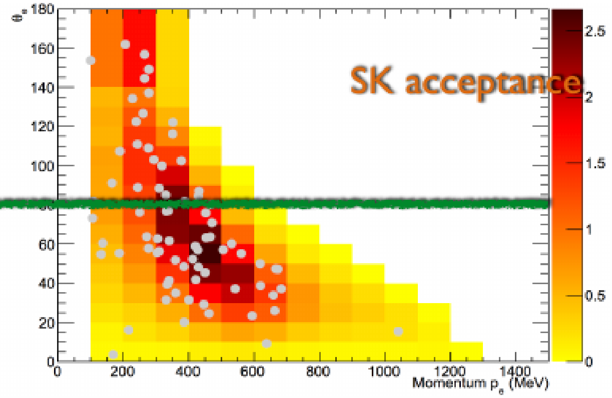
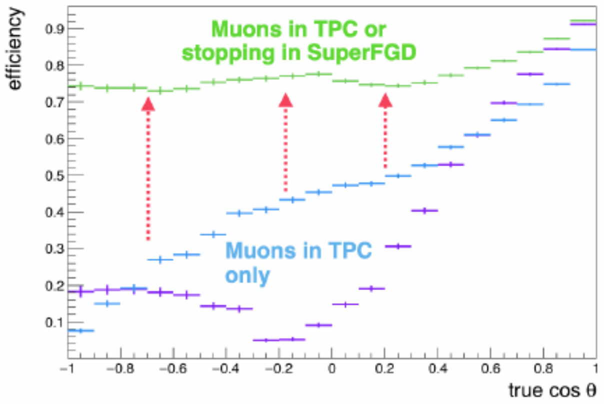
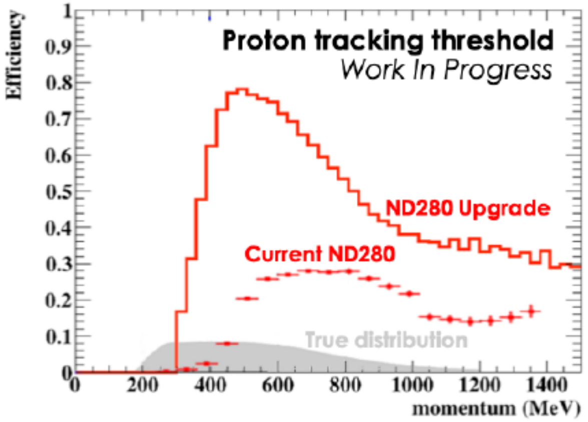
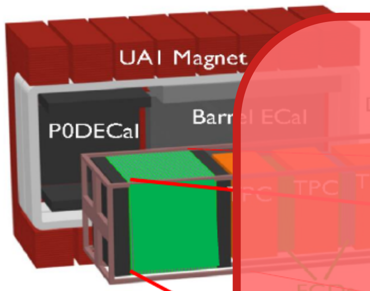


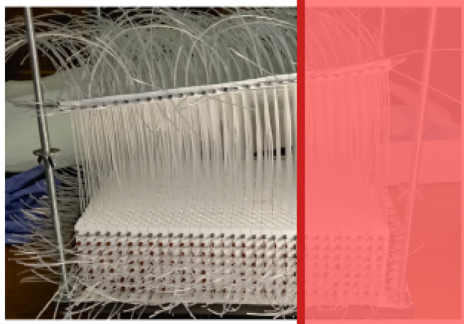


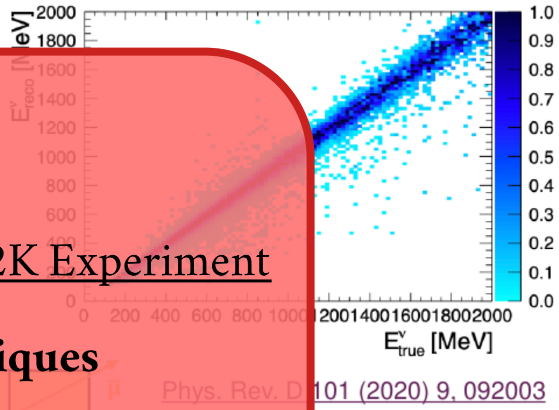


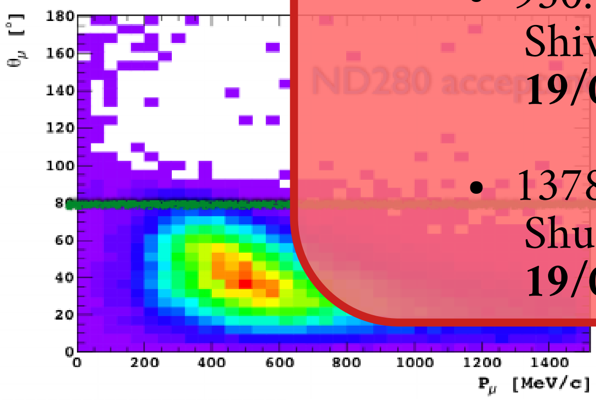


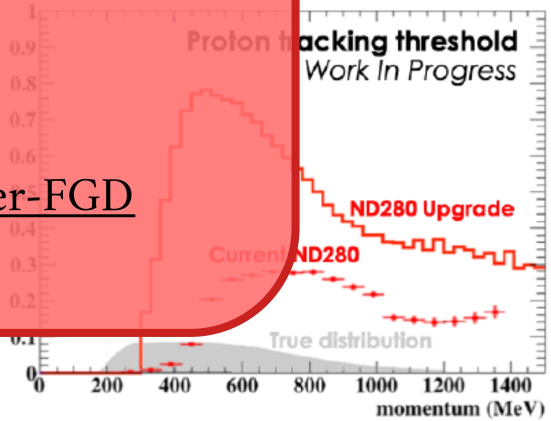
Near Detector: ND280 Upgrade











ND280 Upgrade Talks

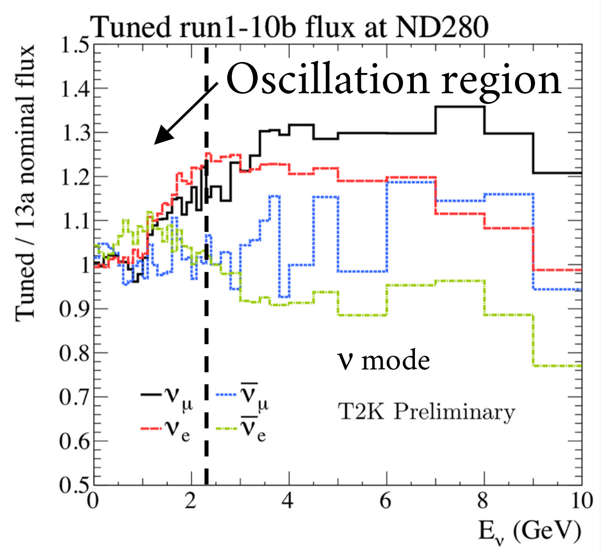
- 1062. A Novel Highly-Segmented Neutrino Detector SuperFGD for the T2K Experiment
  Thomas Jan Kutter (Louisiana State University (US))
  18/07/2024, 09:55, Detectors for Future Facilities, R&D, Novel Techniques

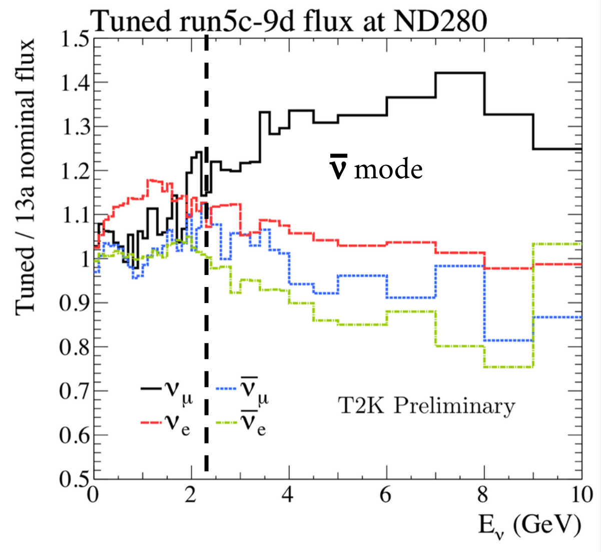
- 182. Characterization of Charge Spreading and Gain of Encapsulated Resistive Micromegas Detectors for the Upgrade of the T2K Near Detector Time Projection Chambers
  Samira Hassani (Université Paris-Saclay (FR))
  19/07/2024, 11:36, Detectors for Future Facilities, R&D, Novel Techniques

- 950. The ND280 Upgrade of the T2K Experiment
  Shivam Ashish Joshi (Université Paris-Saclay (FR))
  19/07/2024, 17:45, Neutrino Physics

- 1378. The DAQ System Development for the T2K New Near Detector Super-FGD
  Shunta Arimoto (Kyoto University)
  19/07/2024, 19:00, Poster

Flux Tuning & Uncertainty



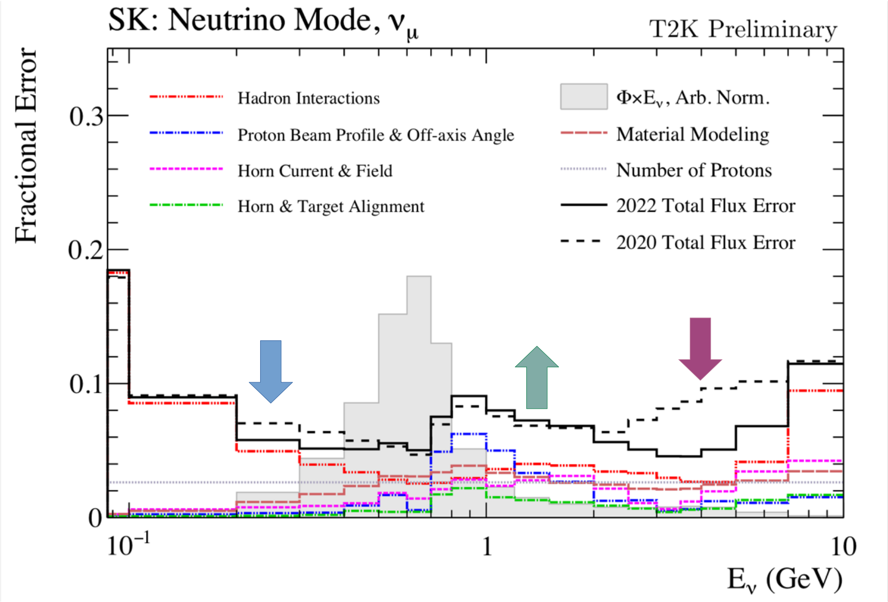


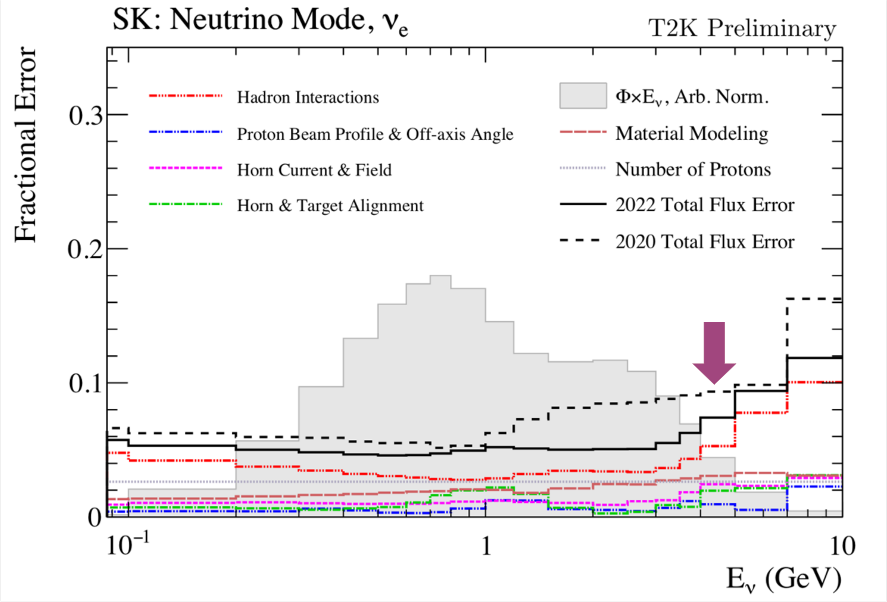
<u>Impact of flux tuning</u>

Based on replica target hadron production data from NA61/SHINE

New NA61/SHINE Replica Target Data

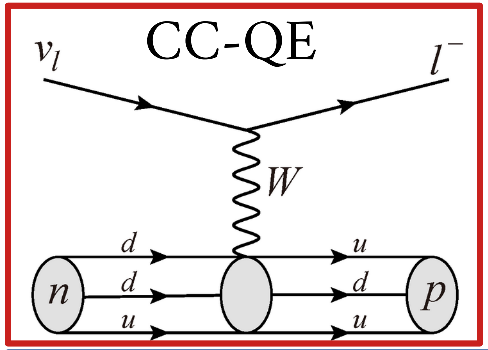
- Improved (2020 → 2022) flux uncertainties
- $\pi^\pm$ data improvements
- Cooling water
- $K^\pm$ data improvements

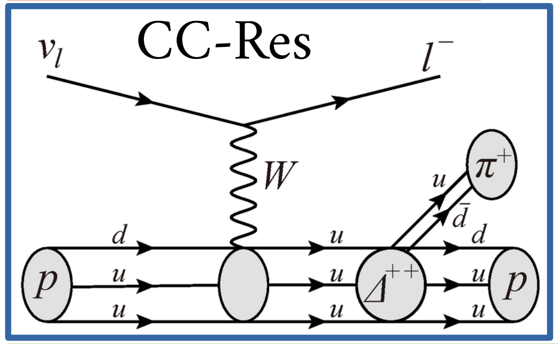


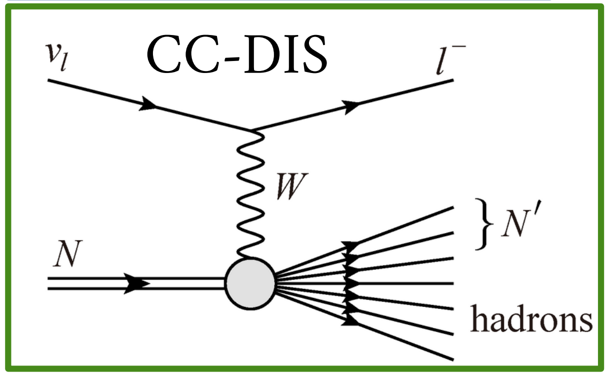


X-Section Models & Uncertainties

The NEUT MC Generator

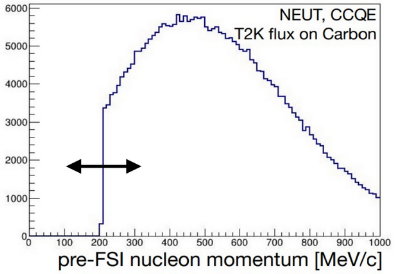


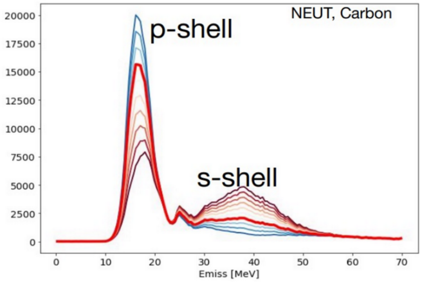




75 Cross Section Parameters

- Mostly related to QE
- Separate C & O parameters
- Fermi motion
- Binding/removal energy
- 2D Spectral Function (12 parameters)
- Pauli Blocking
- FSI: lepton kinematics
- 2p2h: nn vs np pairs
- NC/CC π production ratios



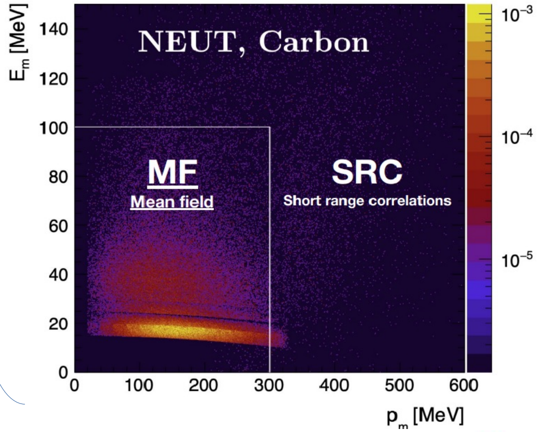


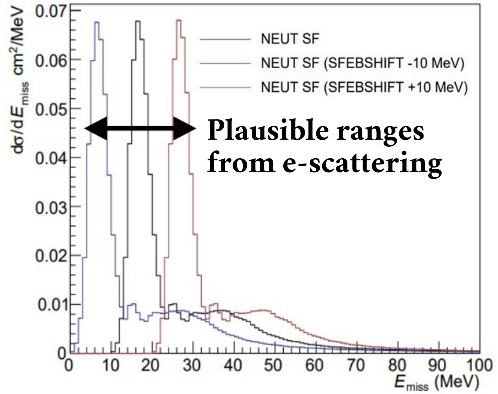
New work emphasizes E_{reco} impacts

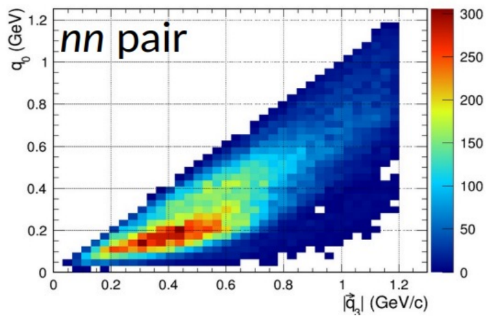
$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)dE_{\ell}'} \sim S(E_m, \boldsymbol{p}_m) L_{\mu\nu} W^{\mu\nu} \delta(\omega + M - E_m - E_{p'})$$

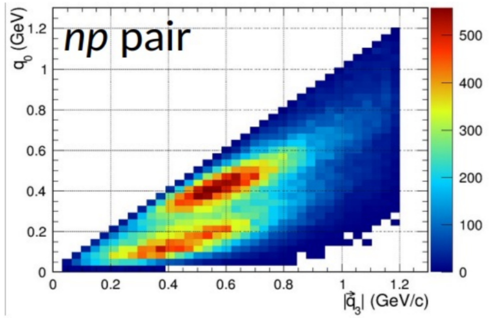
"Spectral Function"

Single nucleon tensor contraction

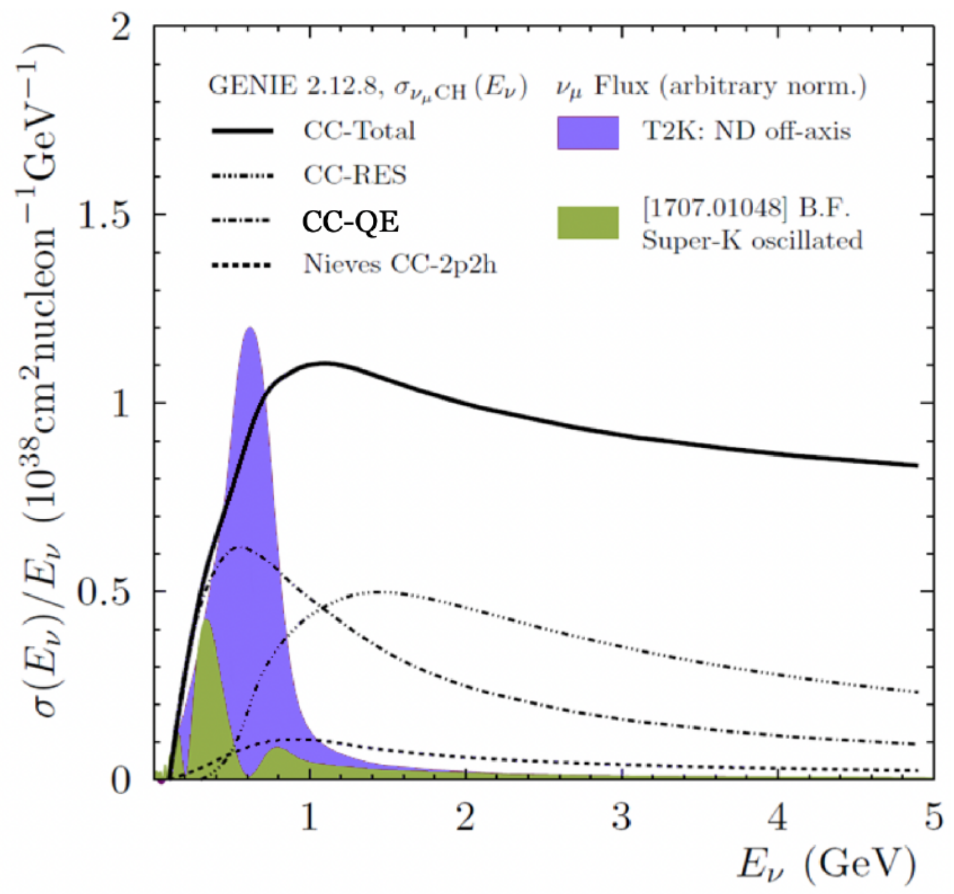








Cross Section Difficulties



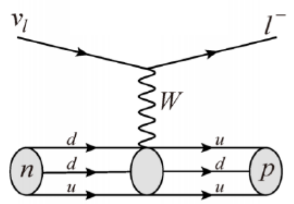
What We Model

What Keeps Us Up at Night

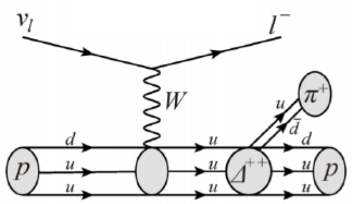
What We Measure

Nucleon -Level Physics Interaction Channels

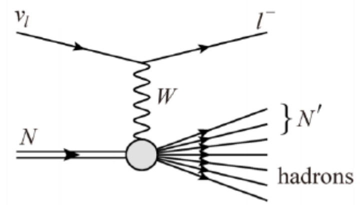
CC-QE



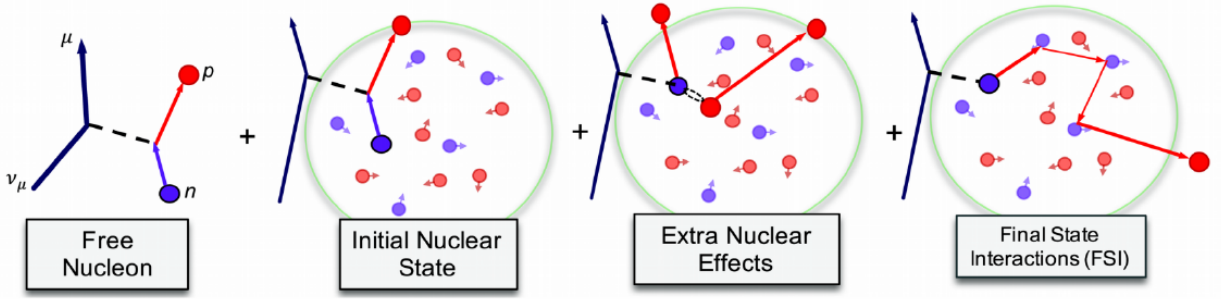
CC-RES



CC-DIS

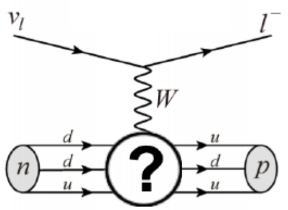


Nuclear Effects

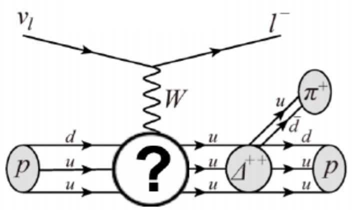


Topologically Defined Observed States

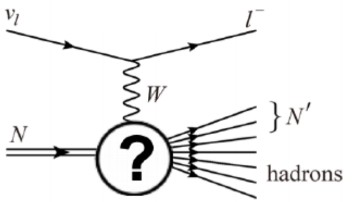
CC0π



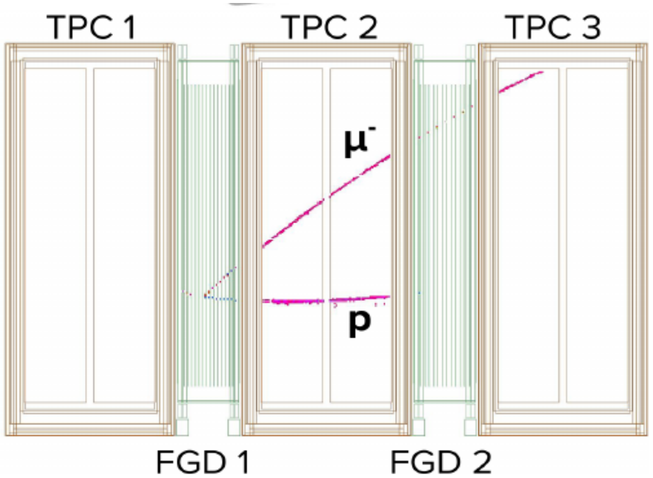
CC1π

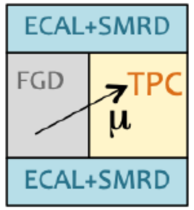
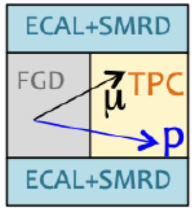
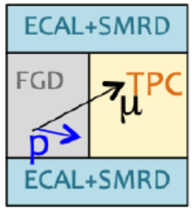
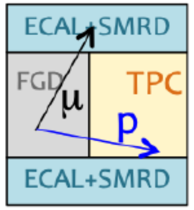
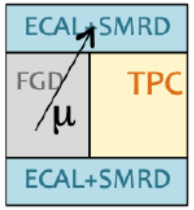


CC-Other



$CC\nu_\mu$ 0π: CH vs H_2O in μ Kinematics



	I – μTPC	II – μTPC+pTPC	III – μTPC+pFGD	IV – μFGD+pTPC	V – μFGD
Signal sample					
Description	Single μ candidate tracked in TPC	Both μ and *p* candiates are tracked in the TPC	μ tracked in the TPC and : • 1*p* tracked in the FGD • or multi *p*	μ tracked in FGD/Ecal and: • 1 *p* tracked in the TPC • or 1 *p* tracked in the TPC + multi *p* • or multi *p*	μ_{FGD} only reconstructed in the FGD/ Ecal

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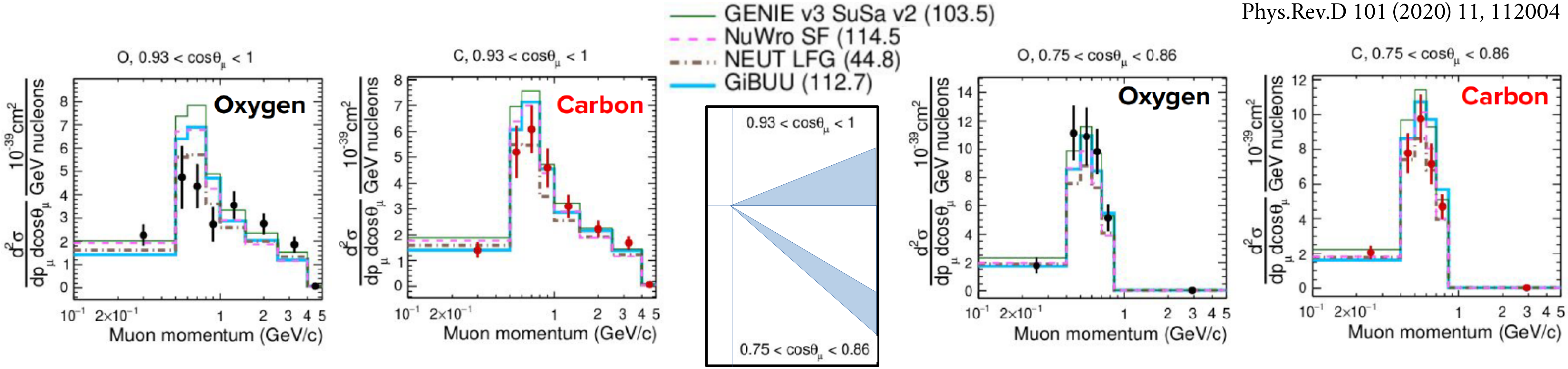
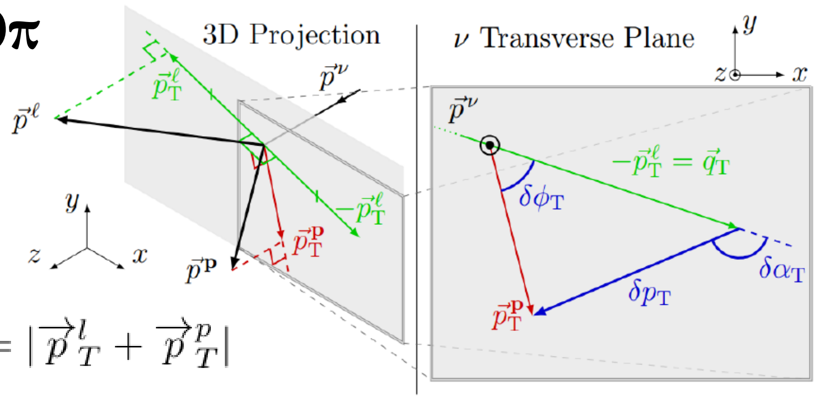


Transverse Kinematic Imbalance

CC ν_μ 0π



$$\delta p_T = |\vec{p}^{\,l}_T + \vec{p}^{\,p}_T|$$

Sample	μTPC (1 track)	μFGD (1 track)	$\mu TPC + pTPC$	$\mu TPC + pFGD$	μTPC + multi p	$\mu FGD + pTPC$
	ECAL+SMRD, FGD, TPC, μ, ECAL+SMRD	ECAL+SMRD, FGD, TPC, μ, ECAL+SMRD	ECAL+SMRD, FGD, TPC, μ, p, ECAL+SMRD	ECAL+SMRD, FGD, TPC, μ, p, ECAL+SMRD	ECAL+SMRD, FGD, TPC, μ, p, p, ECAL+SMRD	ECAL+SMRD, FGD, TPC, μ, p, ECAL+SMRD
Description and number of measured events	• Single μ candidate tracked in TPC • **8874 events**	• Single μ candidate tracked in FGD and stopped in ECal • **1585 events**	• Both μ and p candidates are tracked in TPC • **1785 events**	• μ candidate is tracked in TPC • p candidate is tracked in FGD only • **1592 events**	• μ candidate is tracked in TPC • Multi p candidates, leading p is in TPC • **131 events**	• μ candidate is tracked in FGD only • p candidate is tracked in TPC • **1068 events**

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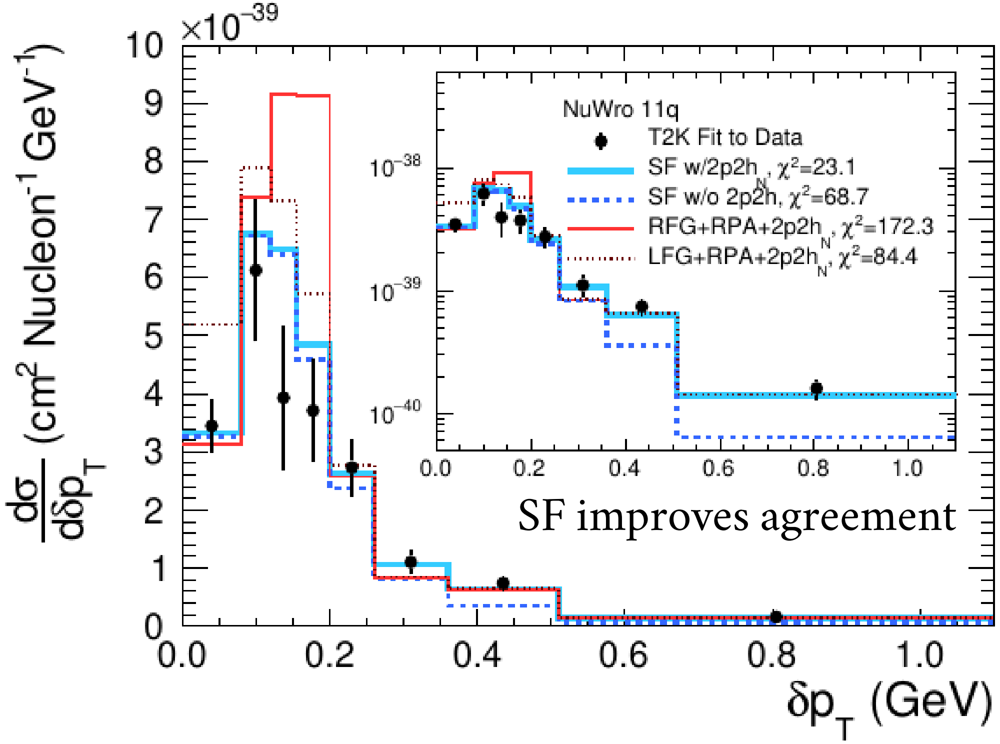
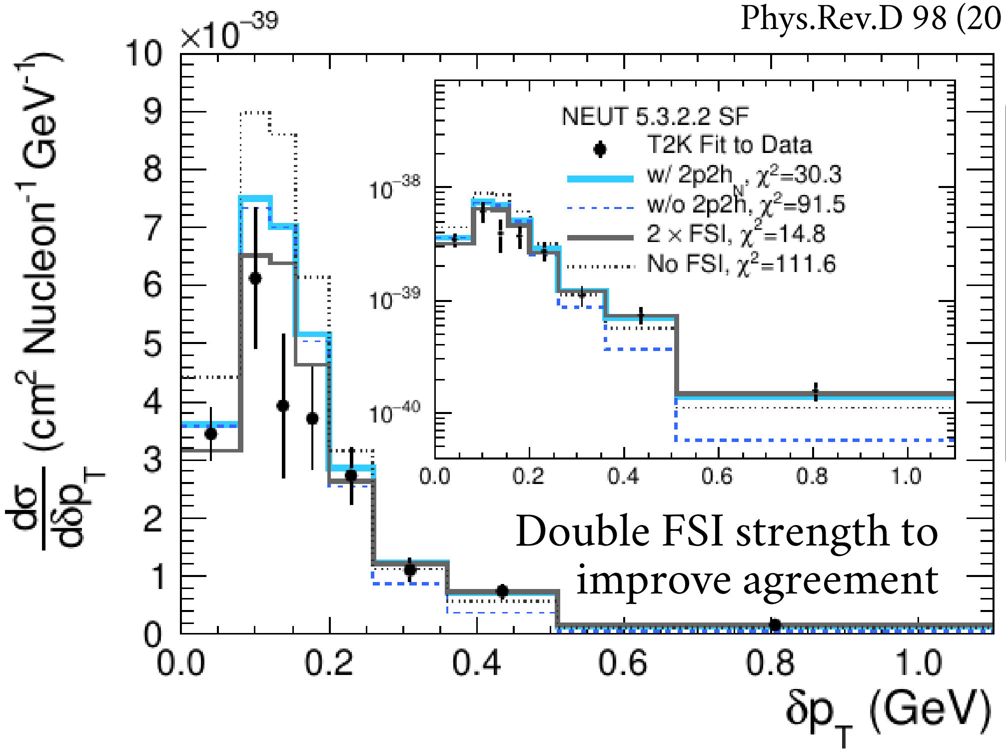
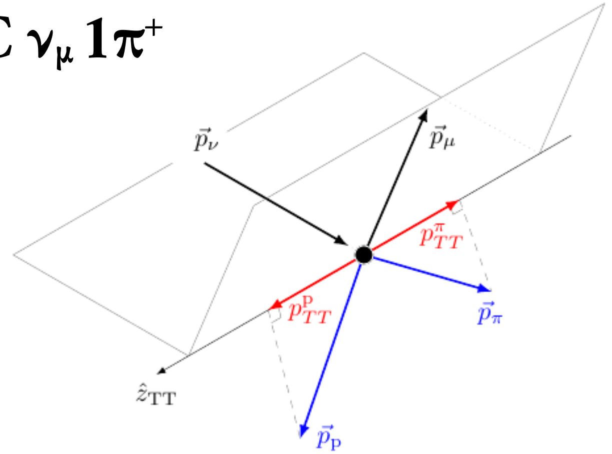




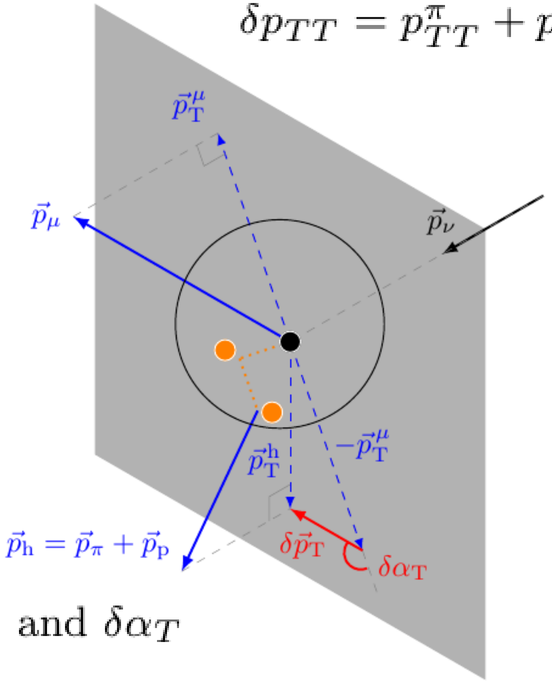
A new analysis with (almost) double POT and updated models, reconstruction, and systematics is underway.

Transverse Kinematic Imbalance

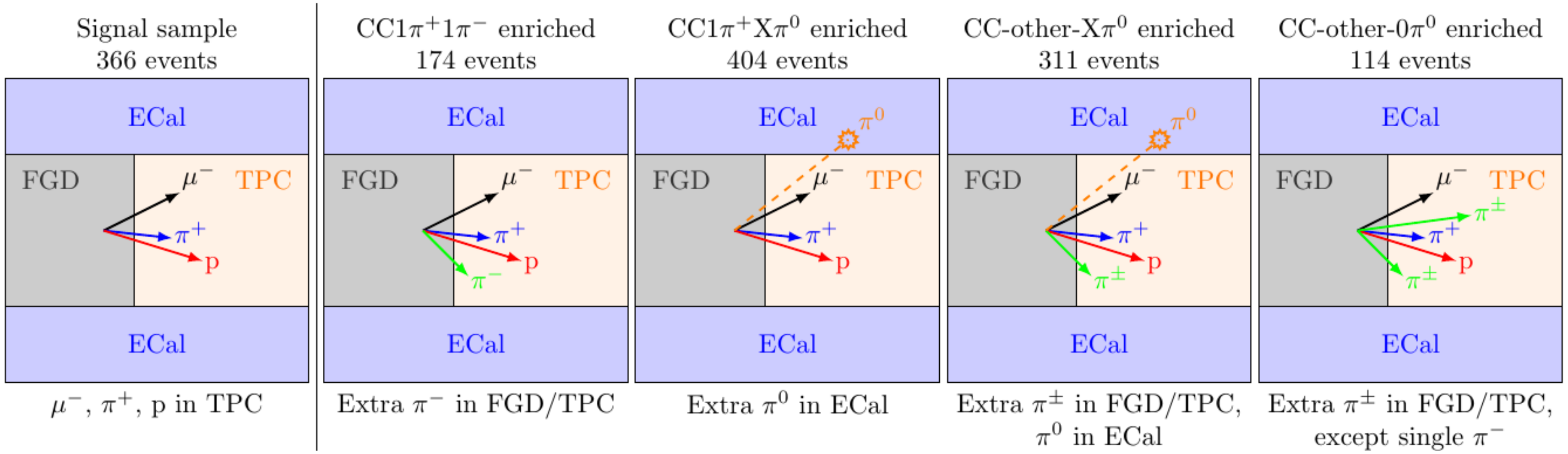
CC ν_μ $1\pi^+$



$$\delta p_{TT} = p^\pi_{TT} + p^p_{TT}$$



$\delta\vec{p}_T$ and $\delta\alpha_T$



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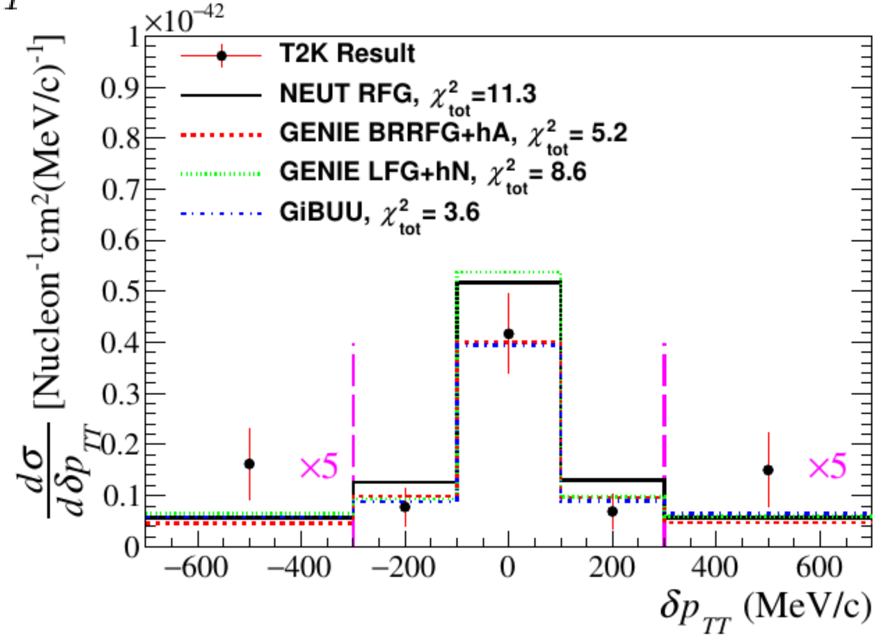
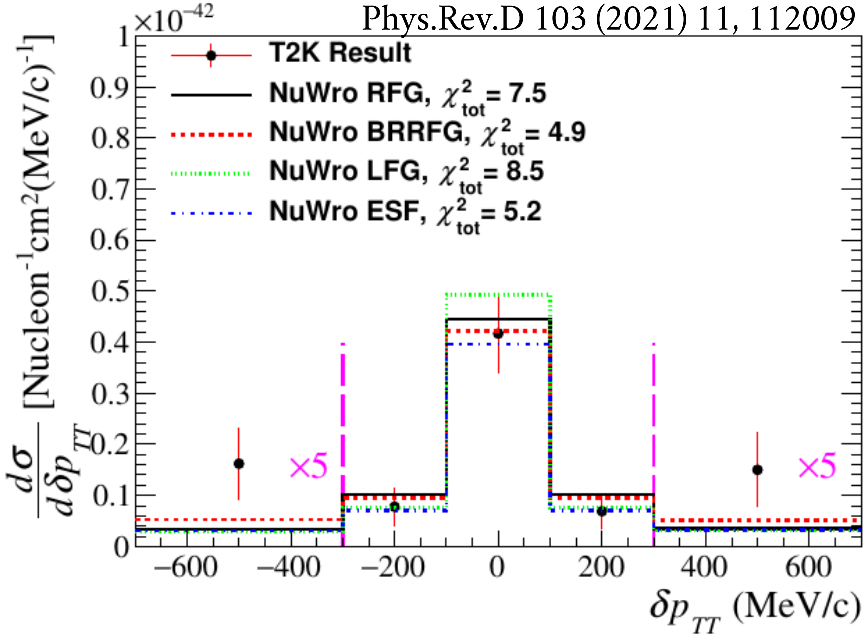
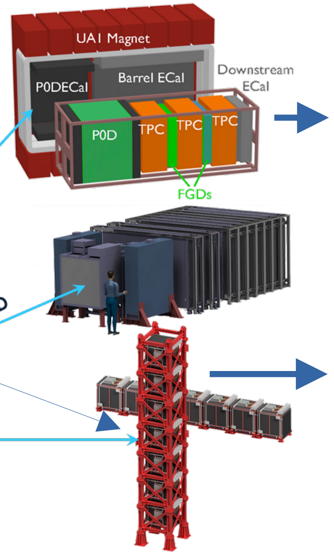
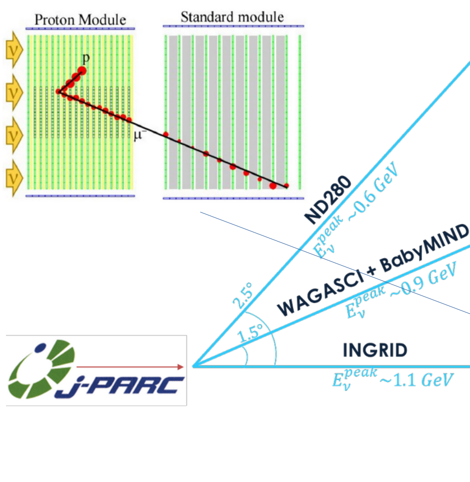


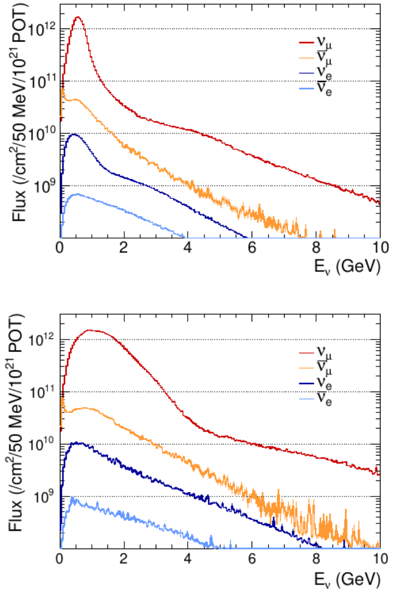


Multi-Detector Analyses

ND280 & INGRID



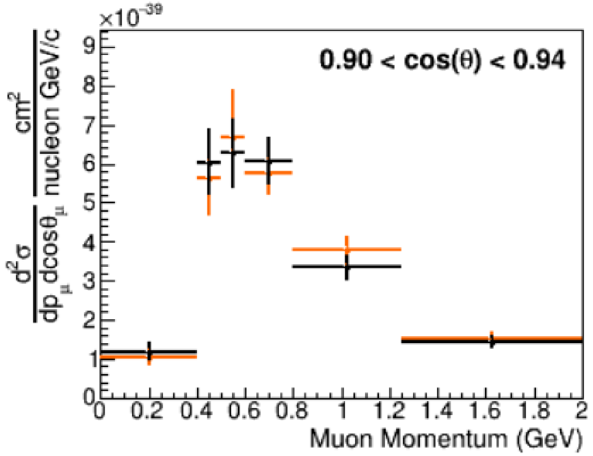


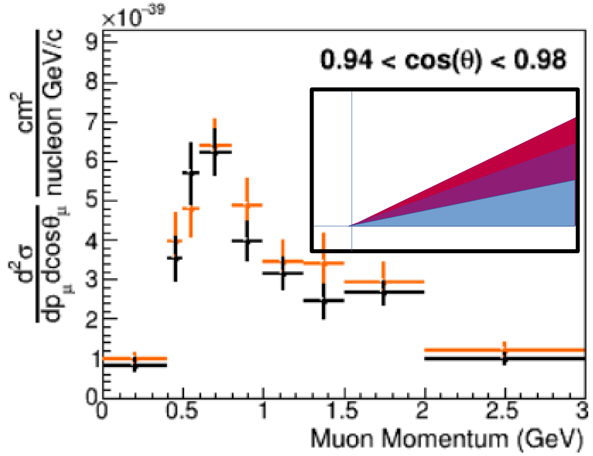


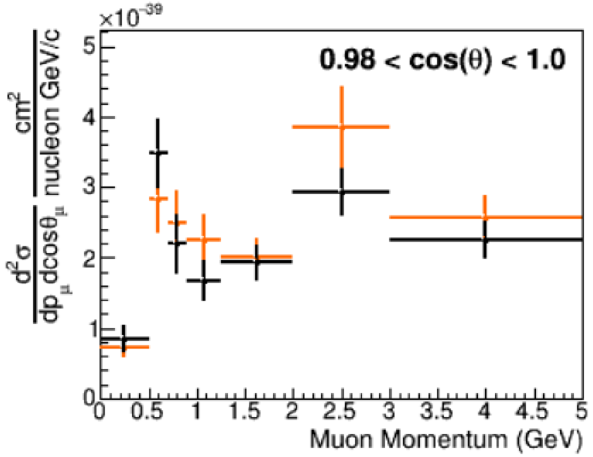
Model comparisons

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

ND280 results w/ INGRID and higher CCν_μ stats (black) vs. w/ CC$\bar{\nu}_\mu$ data included (orange)







highest cosθ_μ bins shown

On/Off-Axis analysis

Phys.Rev.D 108 (2023) 11, 112009

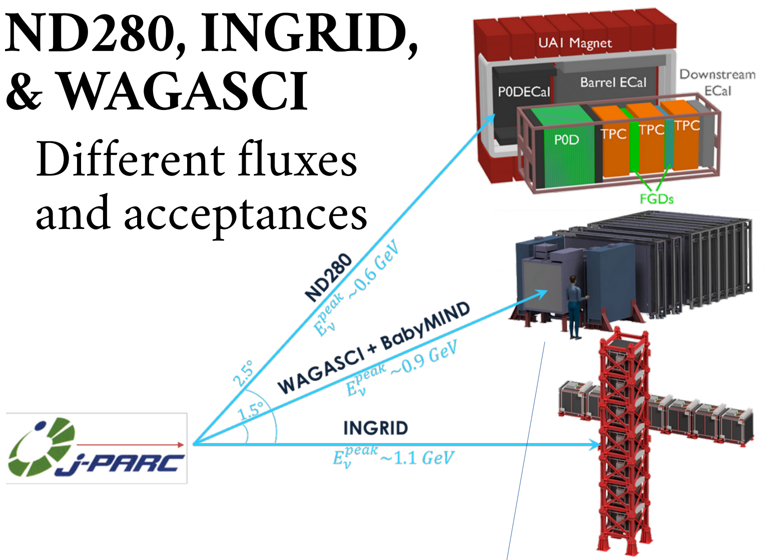
ν_μ-$\bar{\nu}_\mu$ combined analysis

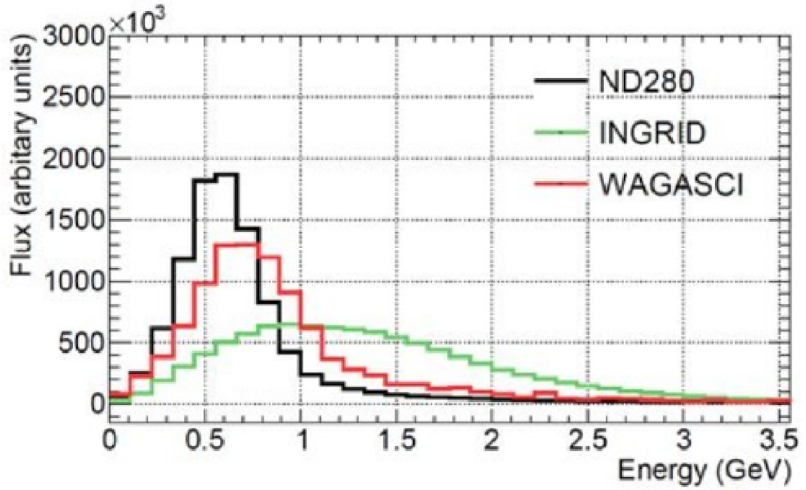
Phys. Rev. D 101, 112001 (2020)

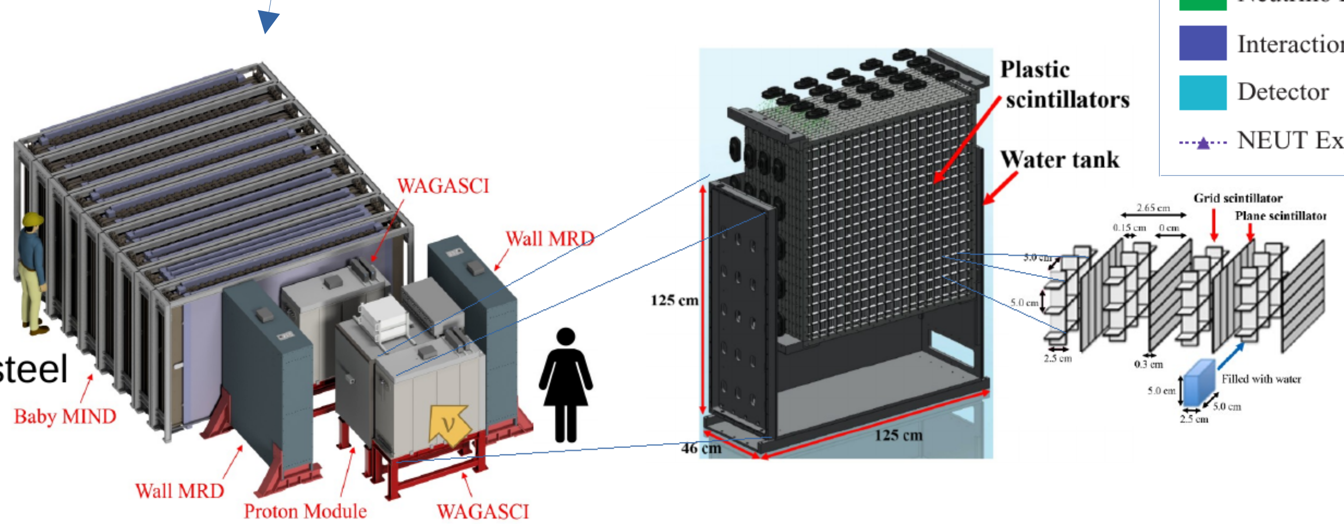
Multi-Detector Analyses

ND280, INGRID, & WAGASCI

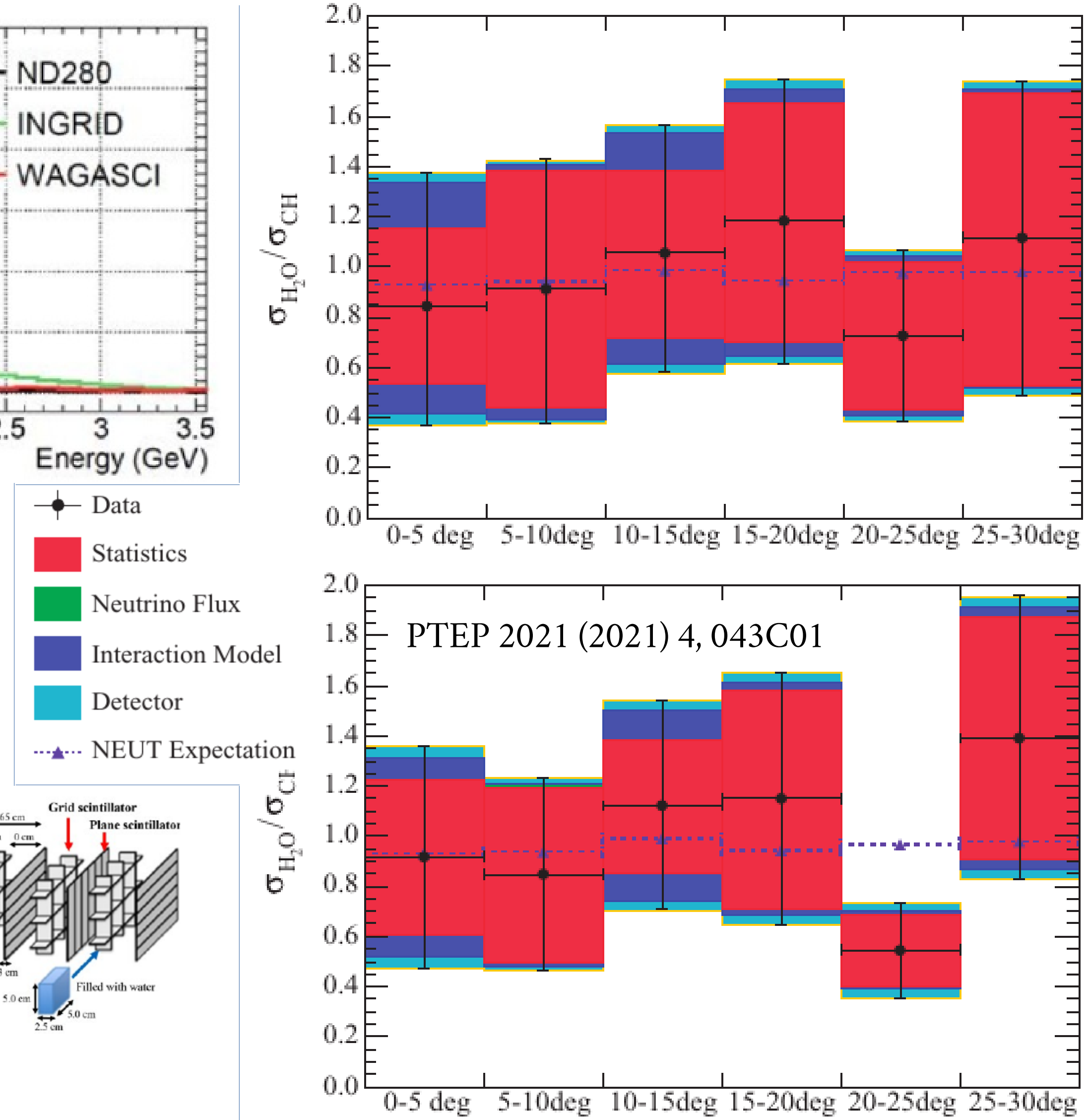
Different fluxes and acceptances





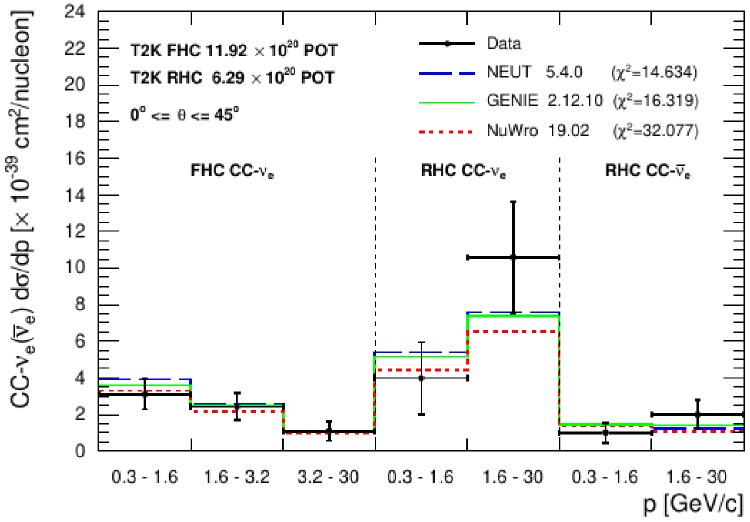


CH &
Magnetised steel



CC ν_e Inclusive and 1π^+

CC $\nu_e/\overline{\nu}_e$ Cross Section



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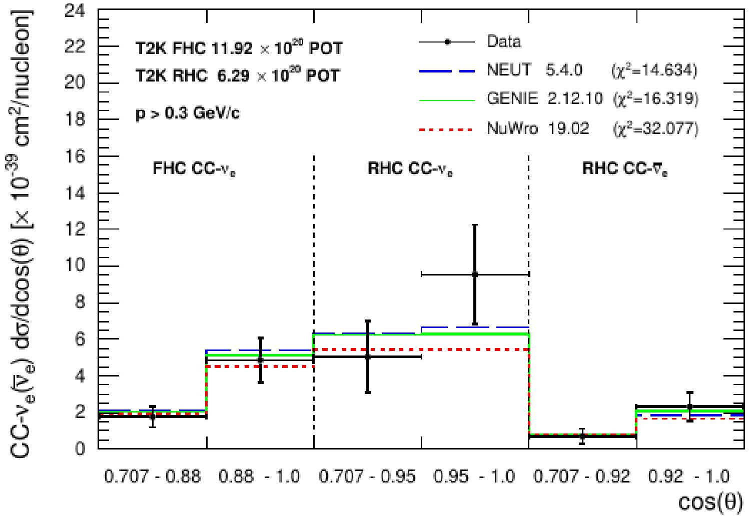
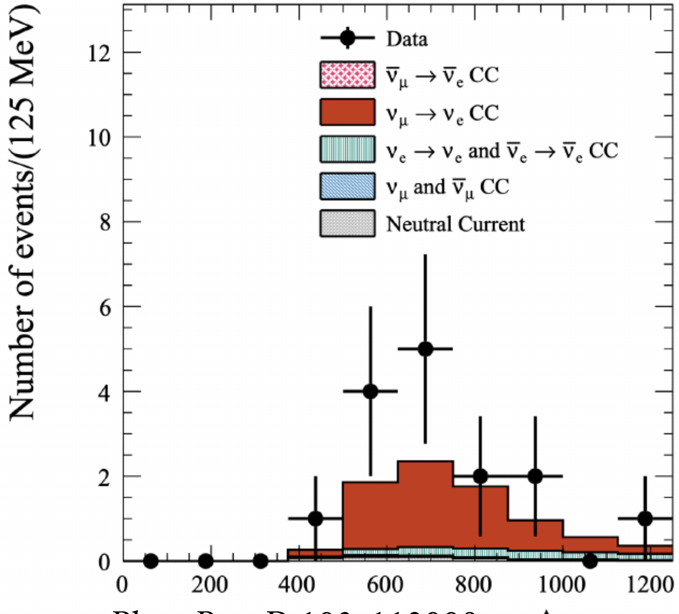


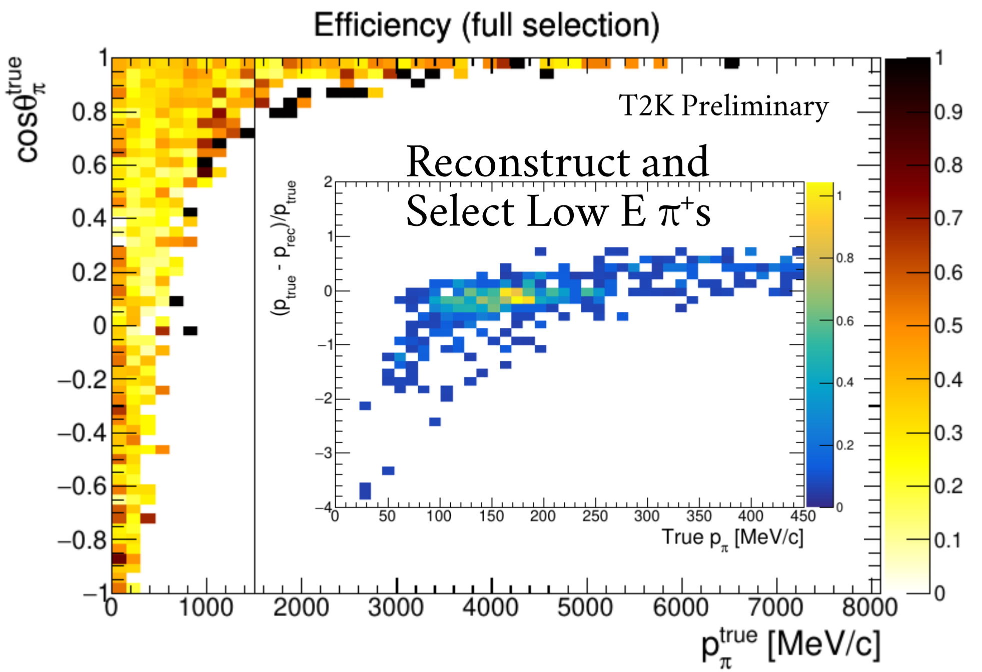
CC ν_e 1π^+ Cross Section

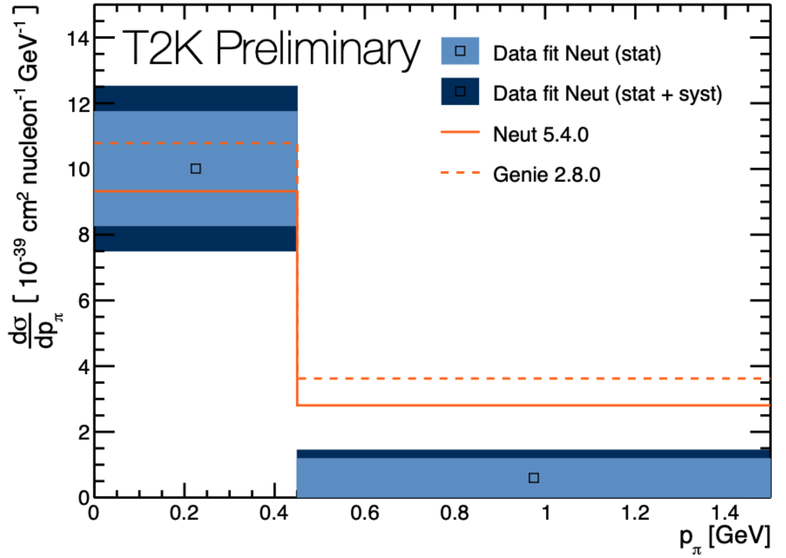


Phys. Rev. D 103, 112008

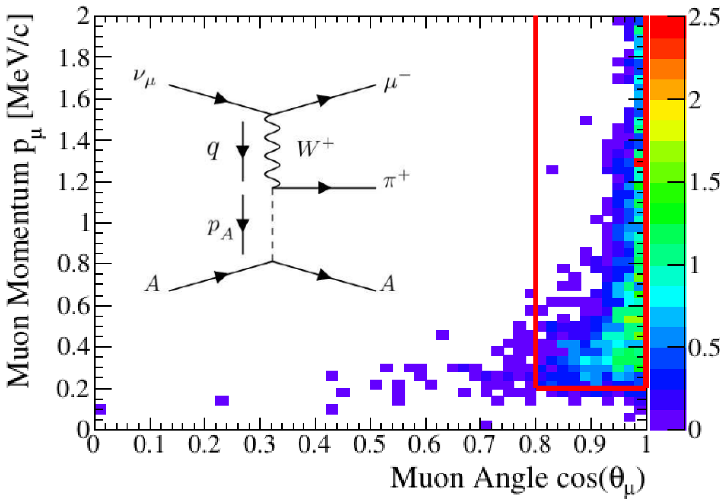
$$E^{\Delta}_{\mathrm{rec}} = \frac{2M_p E_e + M^2_{\Delta^{++}} - M^2_p - M^2_e}{2\left(M_p - E_e + p_e \cos\theta_e\right)}$$

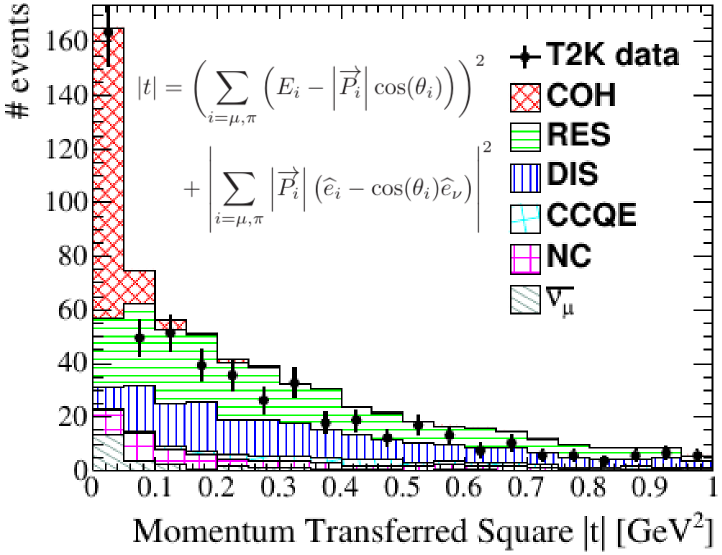
CC ν_e 1π^+ Excess in SK

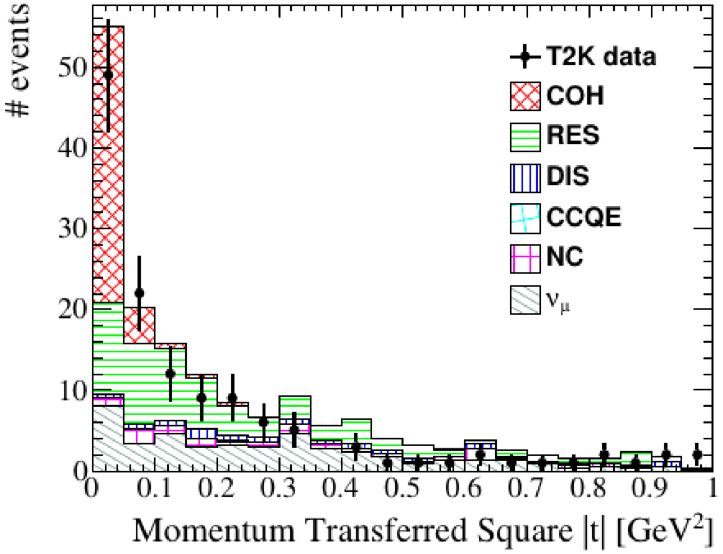


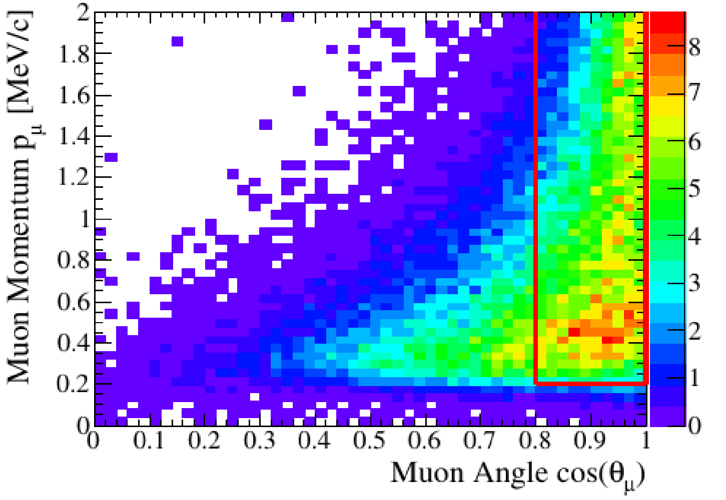


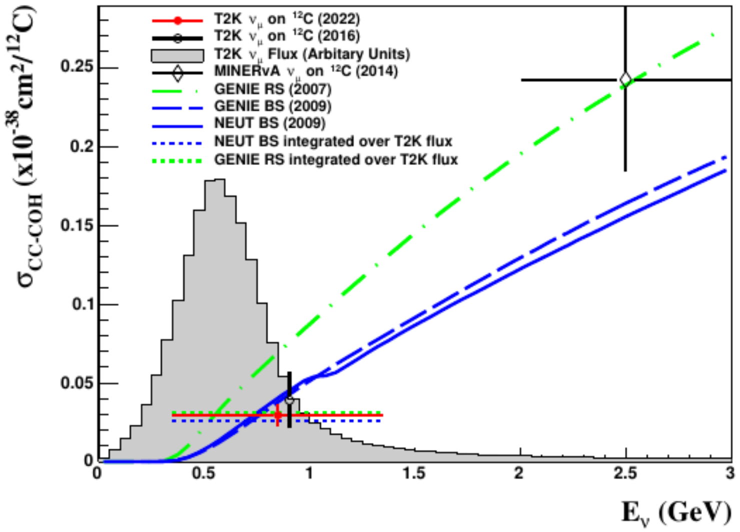
Coherent Pion production

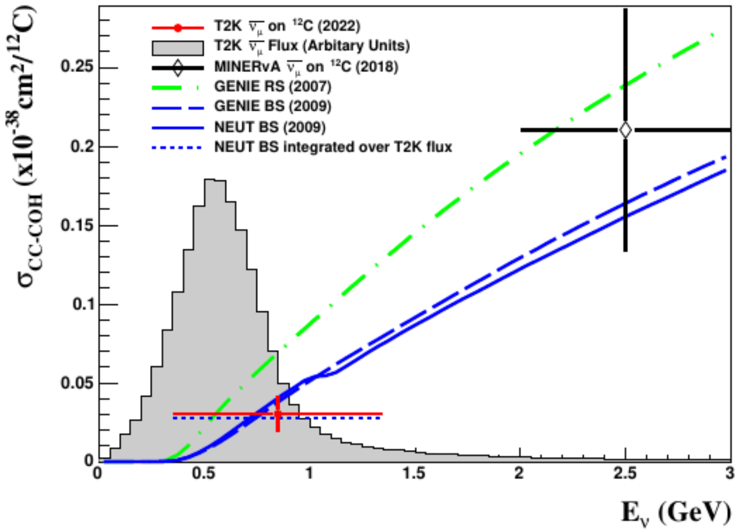




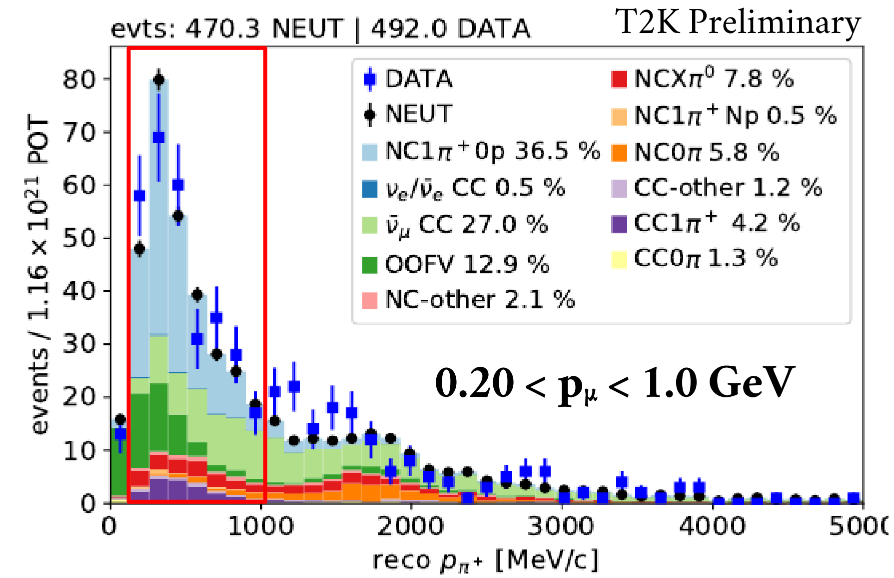


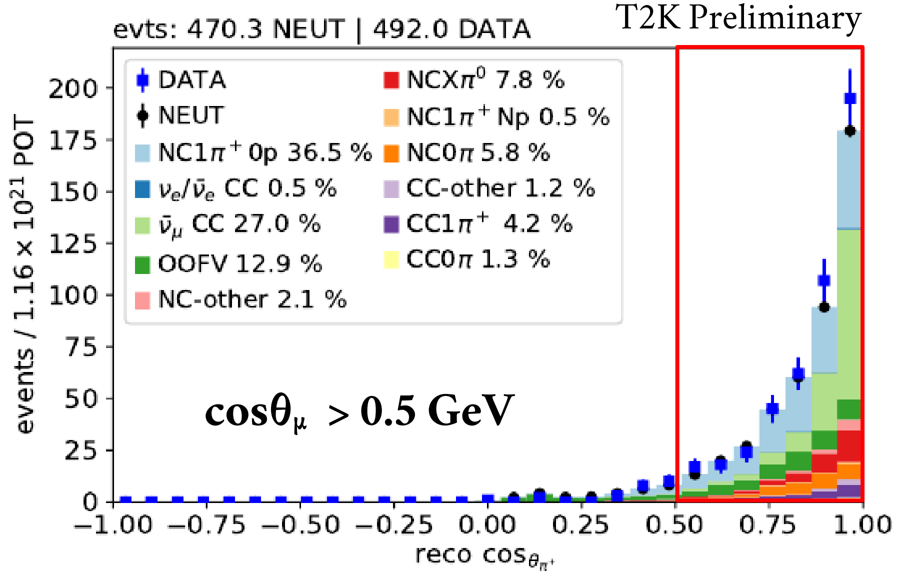


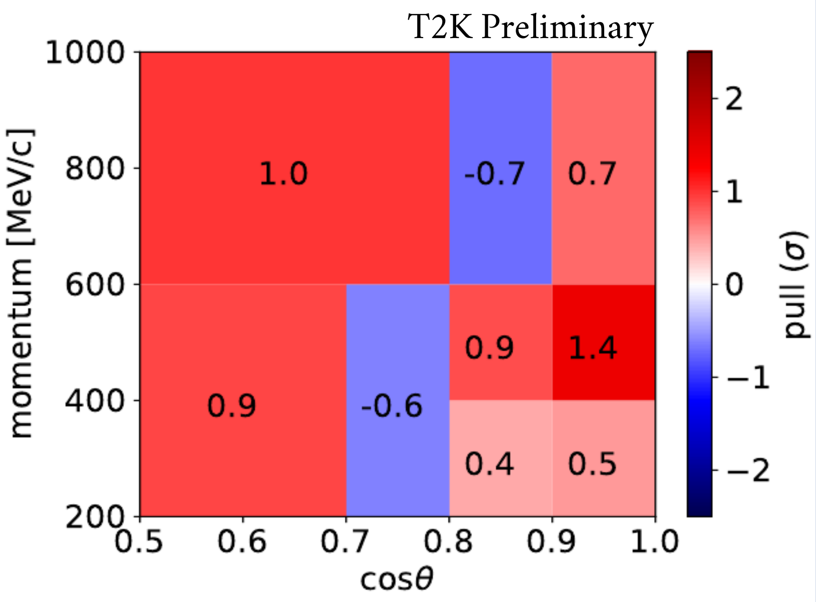


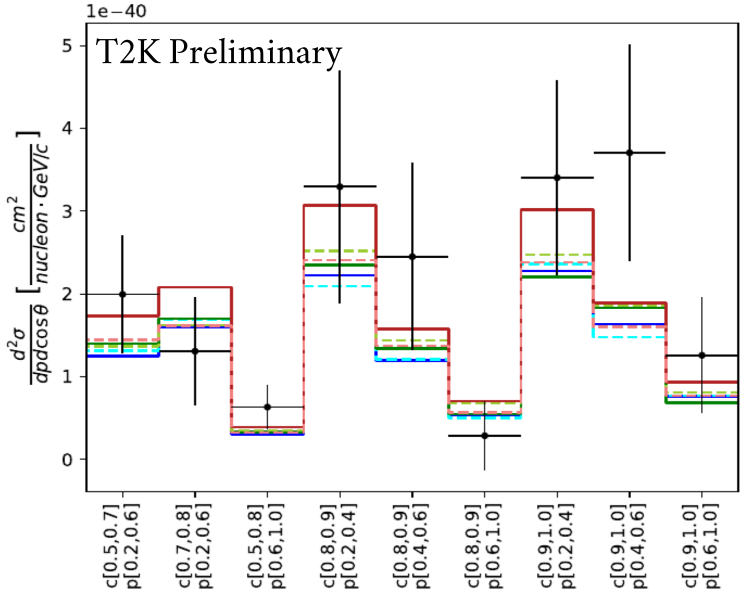


Most Recent Result: NC 1π^+



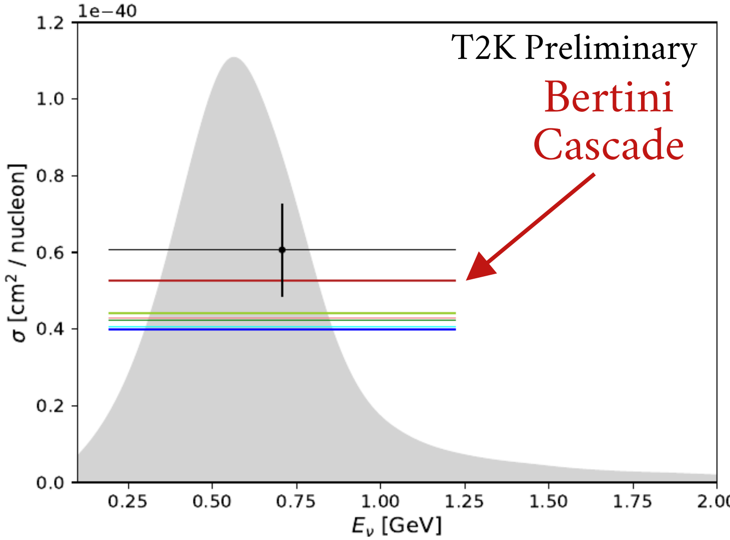






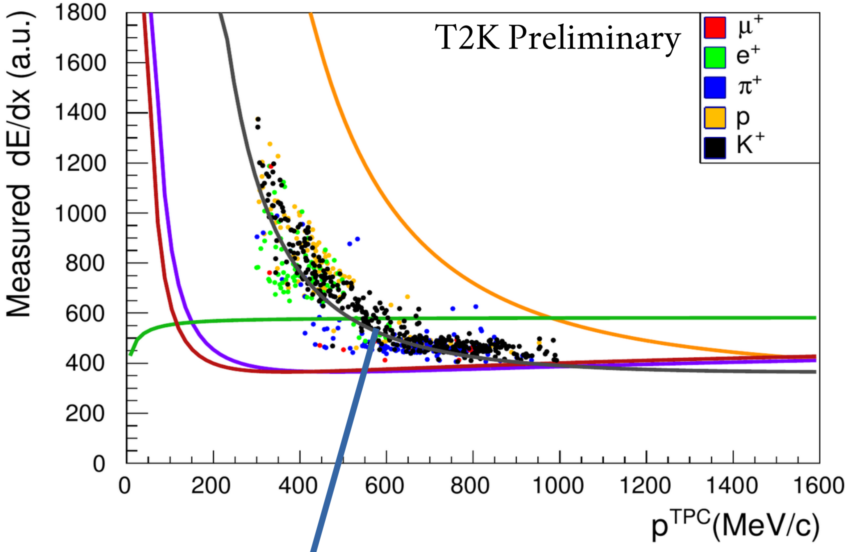
G18_10X_00_000 χ^2=2.90	G18_10d_00_000 χ^2=0.44
G18_10a_00_000 χ^2=2.70	G21_11a_00_000 χ^2=2.14
G18_10b_00_000 χ^2=2.26	Data
G18_10c_00_000 χ^2=1.83	

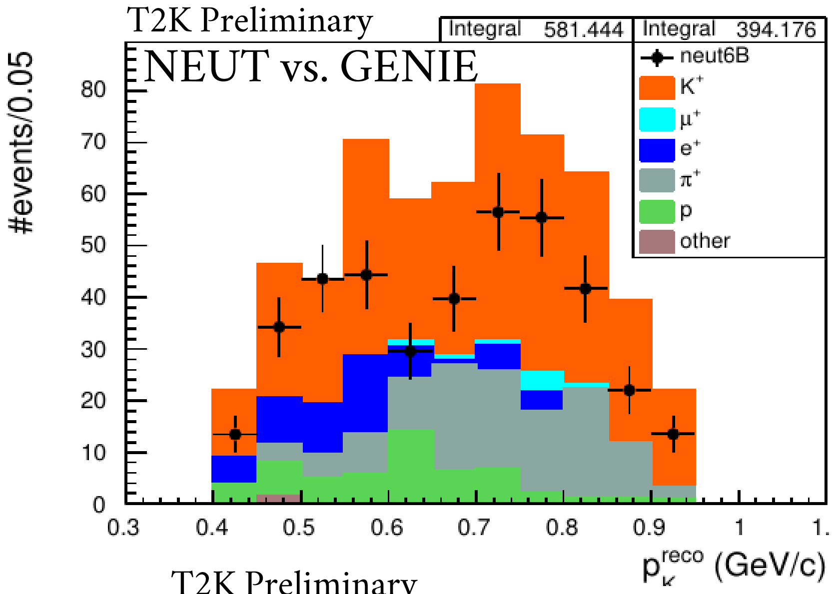
G18_10X_00_000: Has no FSI.
G18_10a_00_000: Uses hA Nuclear Cascade.
G18_10b_00_000: Uses hN Nuclear Cascade.
G18_10c_00_000: Uses Intra-Nuclear Cascade of Liège (INCL).
G18_10d_00_000: Uses Bertini Cascade.
G21_11a_00_000: Uses SuSAv2 for 1p1h and 2p2h.

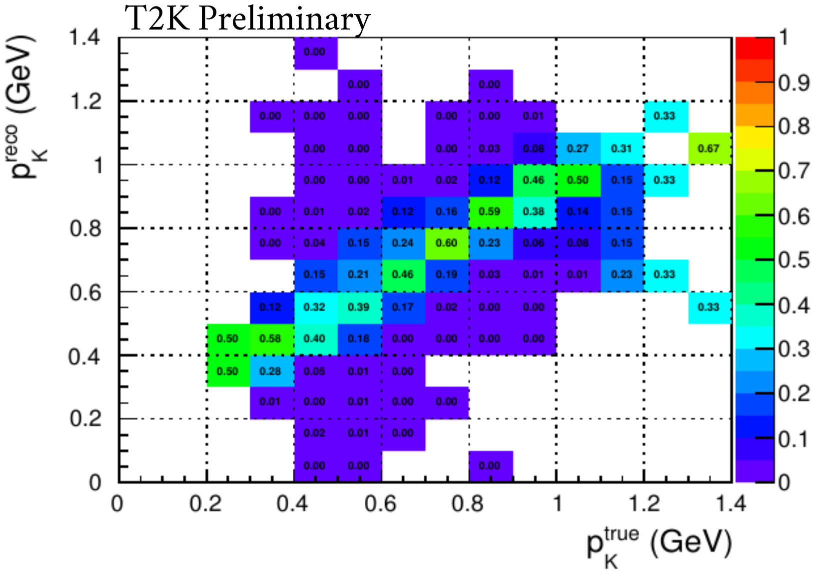


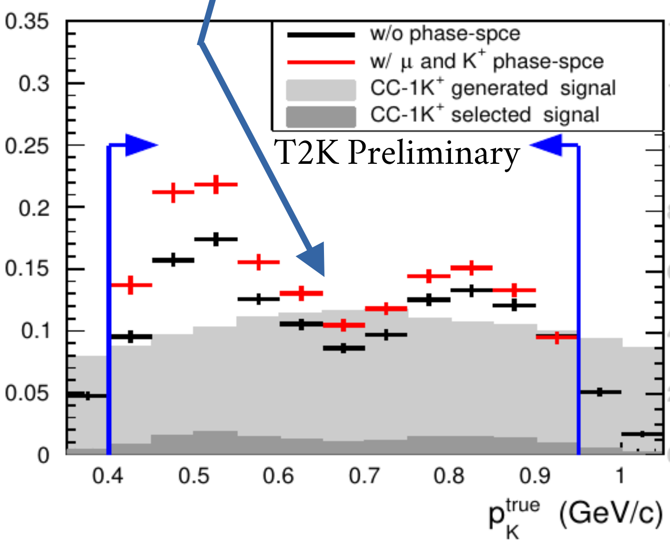
Coming Soon: CC ν_μ 1K^+

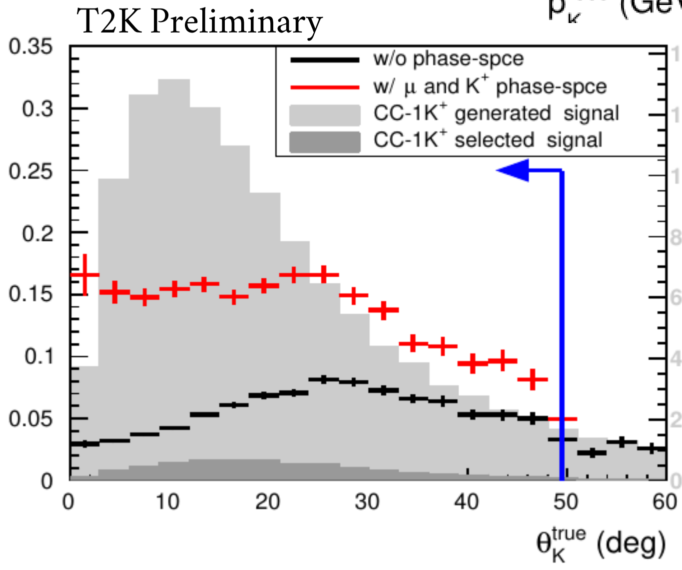
UNIVERSITY OF HOUSTON











Phase Space Restrictions

- $p_\mu > 0.25$ GeV
- $\cos\theta_\mu > 0.6$ ($\theta_\mu < 53°$)
- $0.4 < p_K < 0.95$ GeV
- $\cos\theta_K > 0.65$ ($\theta_K < 49°$)

Flat efficiencies in μ kin.

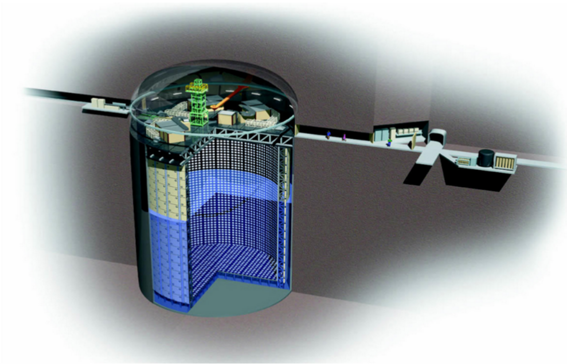
Conclusions

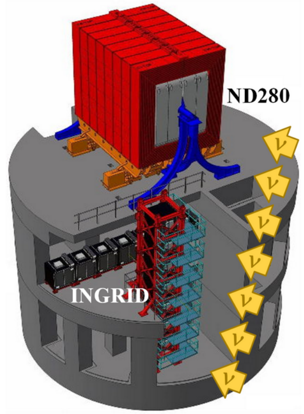
- The primary physics mission is the measurement of ν_e-appearance and ν_μ-disappearance in the Super-Kamiokande detector to constrain the parameters of the PMNS matrix.
- A robust program of systematic uncertainty estimation and constraint is performed using a Near Detector complex.
- The Near Detector complex also has a rich physics program of ν cross section physics.
- This program supports model and systematic development in T2K and other experiments.
- A set of T2K cross section physics measurements was presented:
  - Measurements of μ kinematics on CH and H_20 for CC ν_μ 0π interactions.
  - Explorations of the hadronic system using Transverse Kinematic Imbalance (CC ν_μ 0π and $1\pi^+$)
  - The use of multiple detector exposed to different fluxes to elucidate energy dependence.
  - The CC ν_e inclusive and $1\pi^+$ cross sections.
  - The CC $\nu_\mu/\bar{\nu}_\mu$ coherent $1\pi^+$ cross section.
  - The NC $1\pi^+$ cross section.
  - The CC ν_μ $1K^+$ cross section.
- We continue to make progress on understanding the nuclear effects and their impacts energy reconstruction.

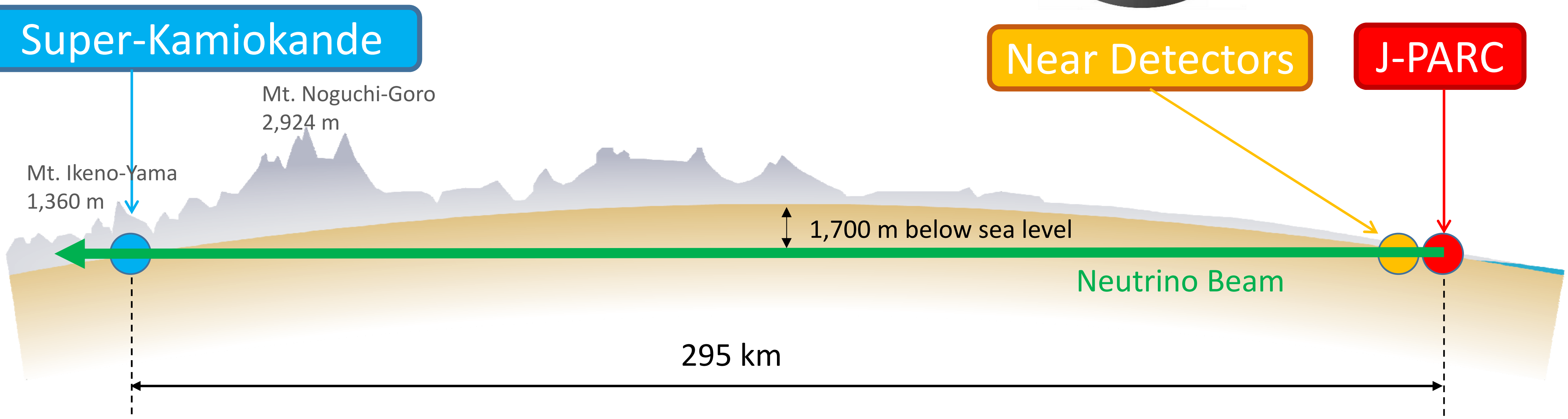
Thank you for your attention.

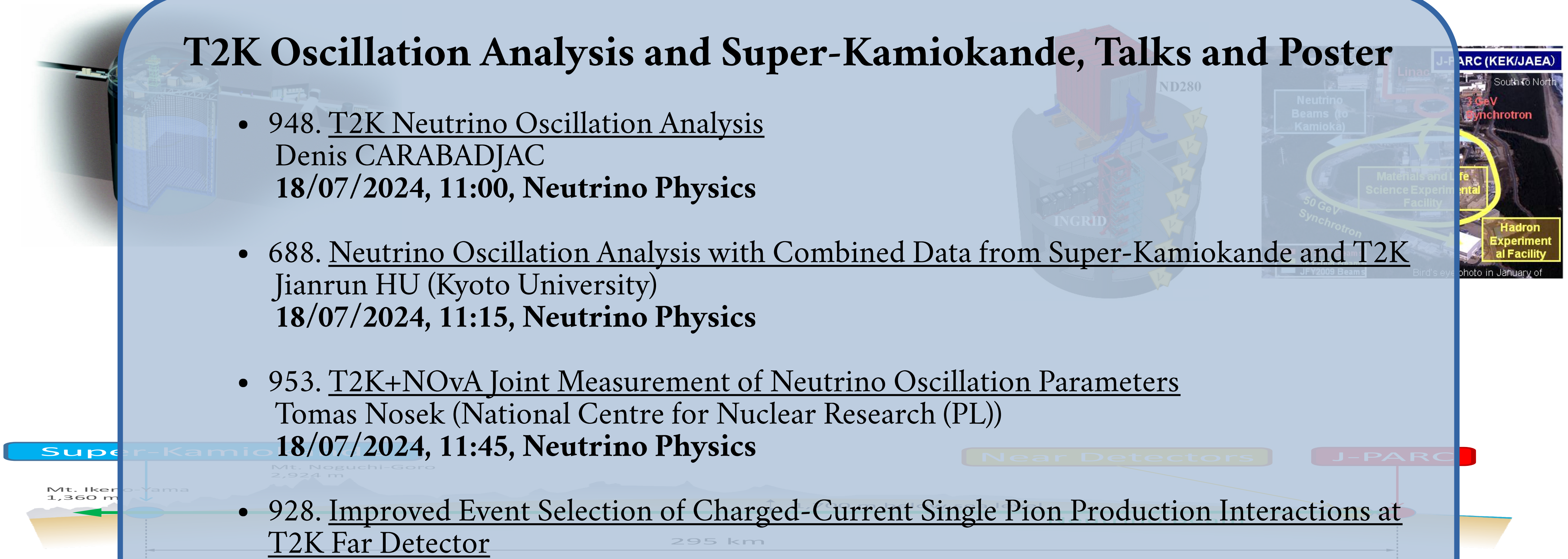
Backup Slides

The T2K Experiment









T2K Oscillation Analysis and Super-Kamiokande, Talks and Poster

- 948. T2K Neutrino Oscillation Analysis
  Denis CARABADJAC
  18/07/2024, 11:00, Neutrino Physics

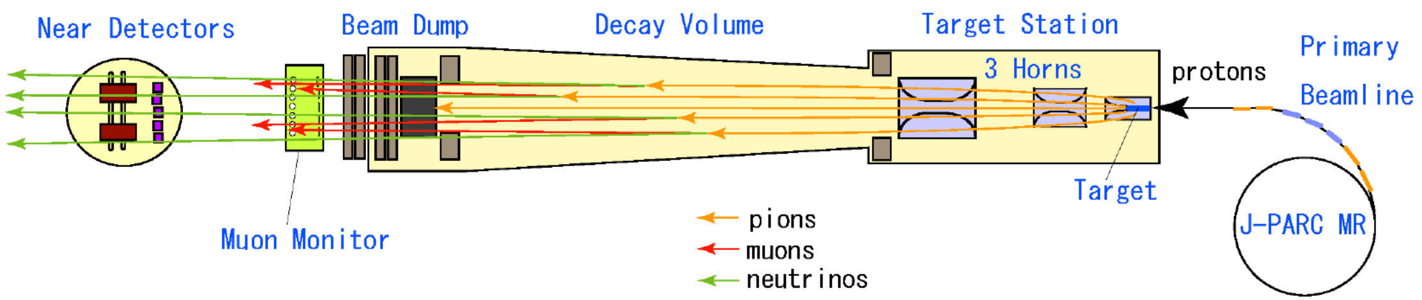
- 688. Neutrino Oscillation Analysis with Combined Data from Super-Kamiokande and T2K
  Jianrun HU (Kyoto University)
  18/07/2024, 11:15, Neutrino Physics

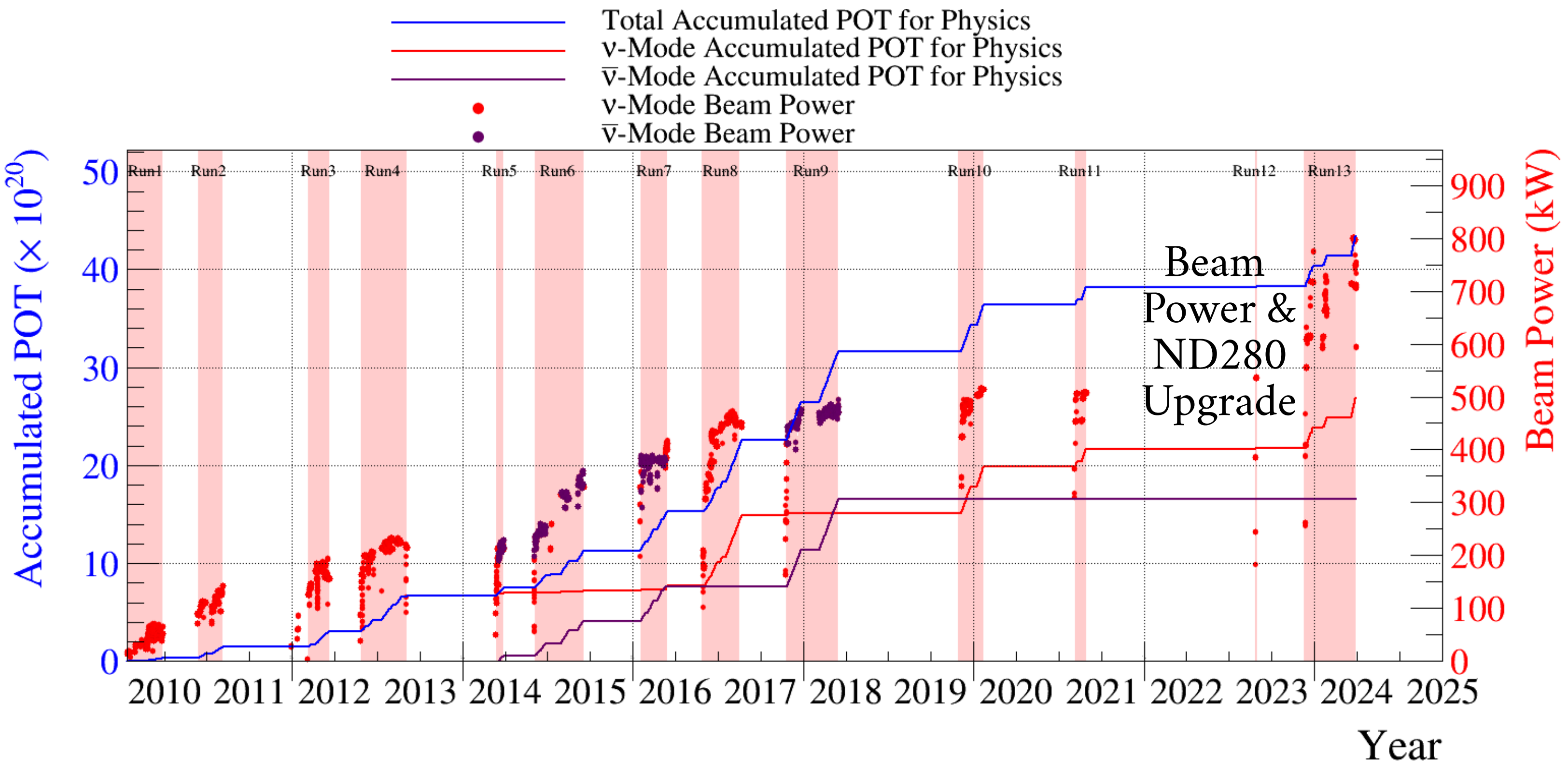
- 953. T2K+NOvA Joint Measurement of Neutrino Oscillation Parameters
  Tomas Nosek (National Centre for Nuclear Research (PL))
  18/07/2024, 11:45, Neutrino Physics

- 928. Improved Event Selection of Charged-Current Single Pion Production Interactions at T2K Far Detector
  Yashwanth Sanjeev Prabhu (National Centre for Nuclear Research (PL))
  18/07/2024, 19:00, Poster Session

T2K Beamline and POT

- Relatively pure ν_μ / $\bar{\nu}_\mu$ beam
  - Intrinsic ν_e / $\bar{\nu}_e$ < 1%
  - $\nu_\mu \rightarrow \bar{\nu}_\mu$: invert horn current
  - FHC: ν_μ dominant
  - RHC: $\bar{\nu}_\mu$ dominant
- Beam closely monitored
- NA61/SHINE Hadron production measurement program
- Recent power upgrade

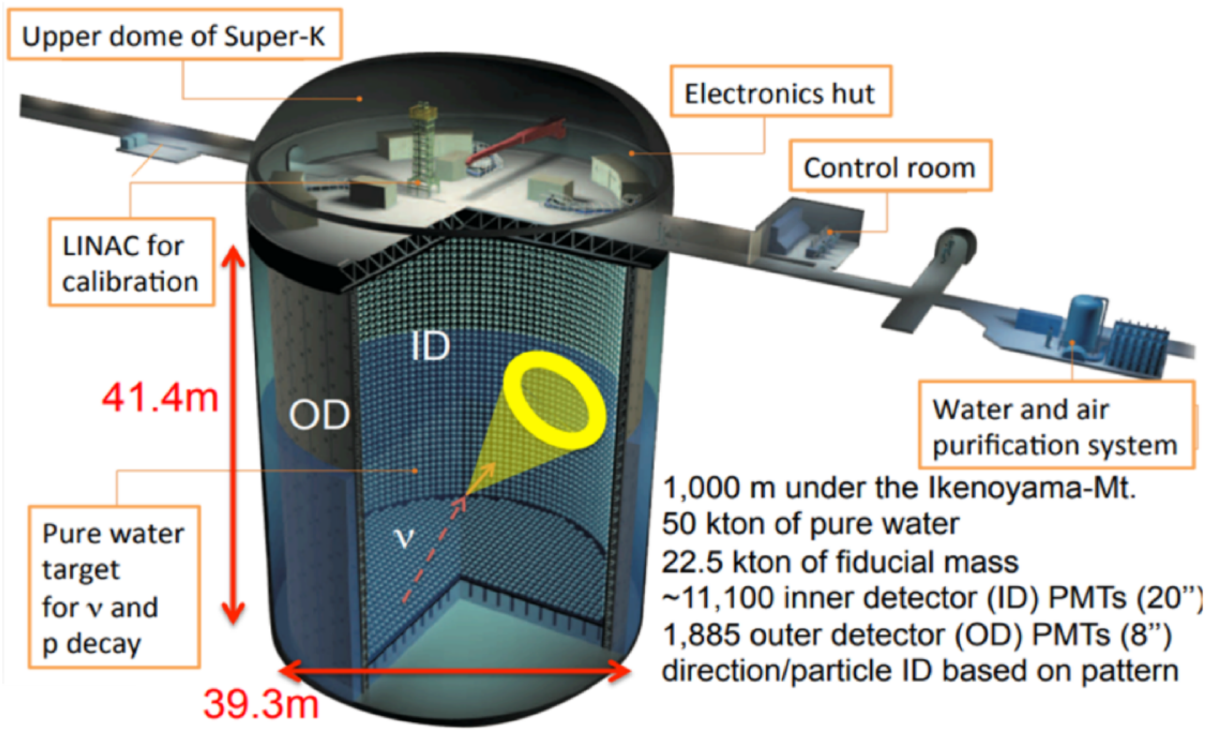


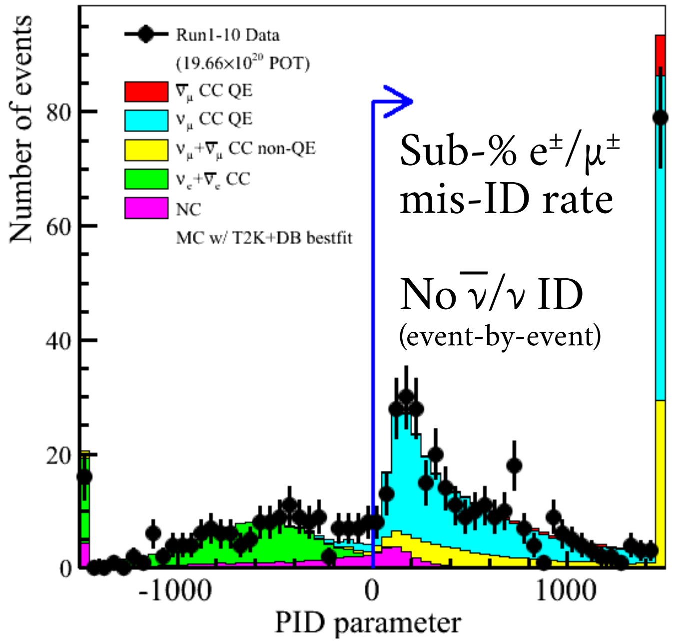


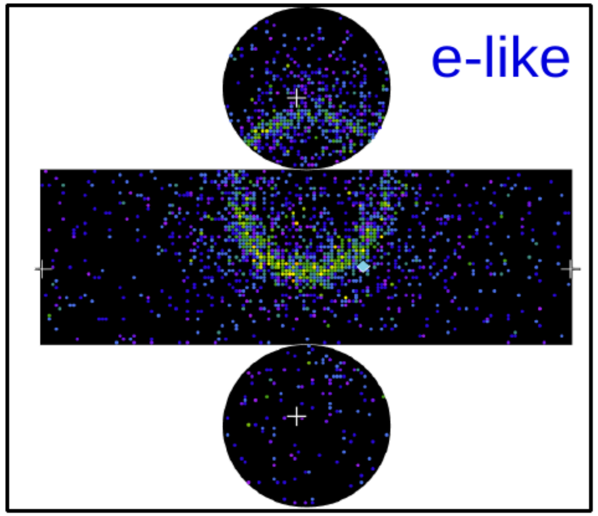
Far Detector: Super-Kamiokande

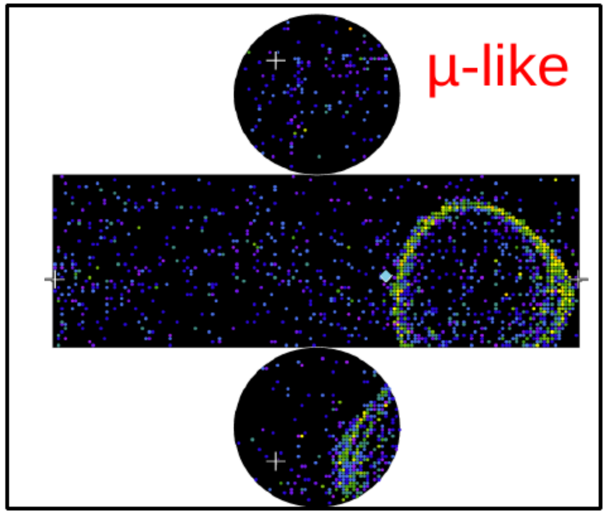
- Particle detection above Cherenkov threshold
  - Wide angular acceptance
  - Relatively high energy threshold
- Measure E_ν from charge lepton kinematics

Motivation for original ND280 design

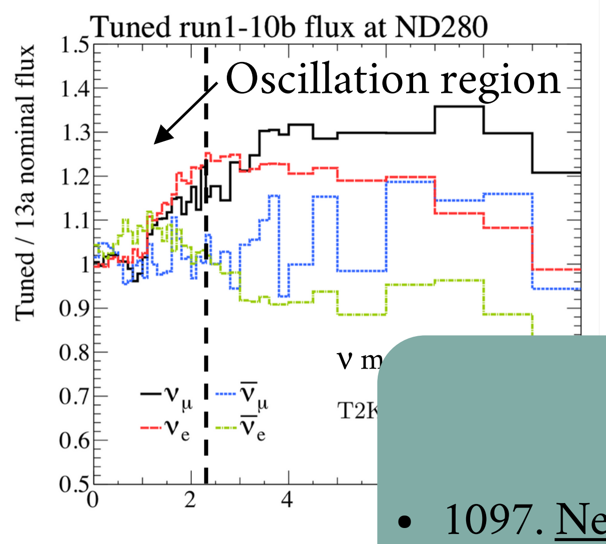


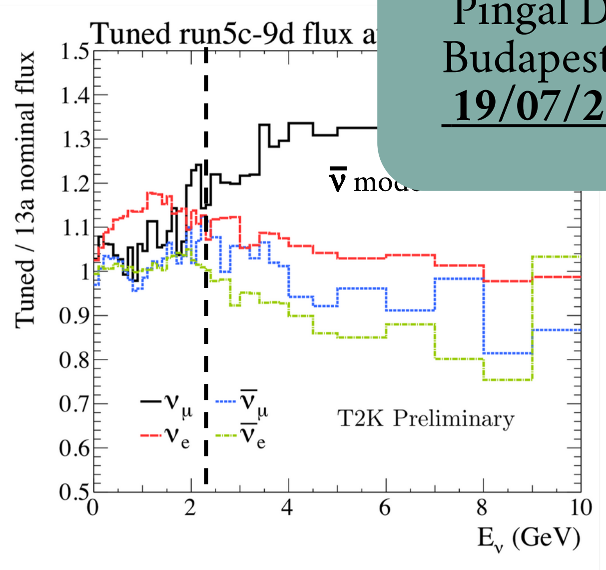






Flux Tuning & Uncertainty



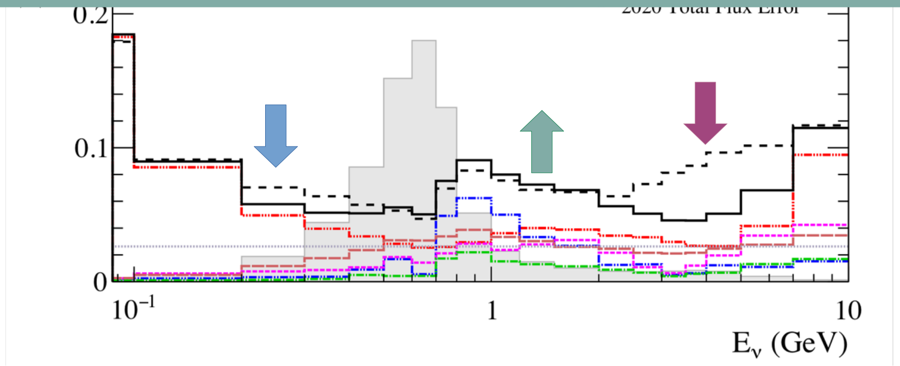


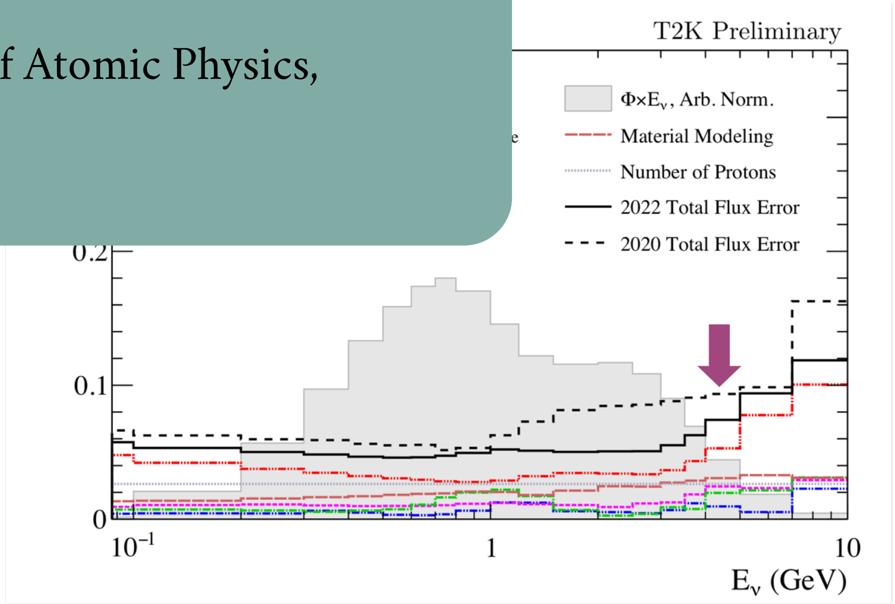
Impact of flux tuning

Based on replica target hadron production data

New NA61/SHINE Replica Target Data

- Improved (2020 → 2022) flux uncertainties
- $\pi^\pm$ data improvements
- ts

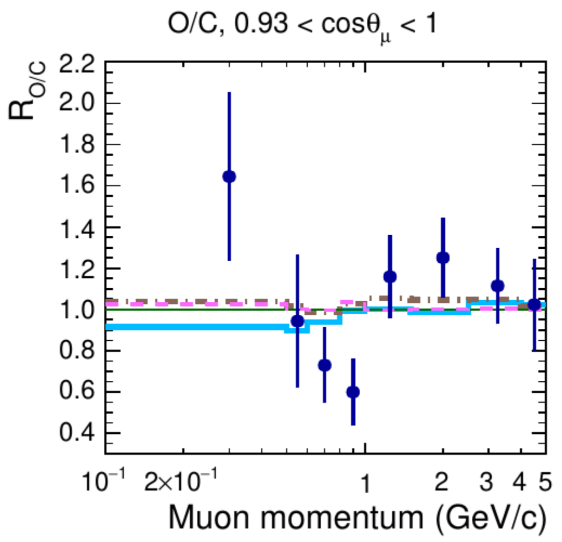


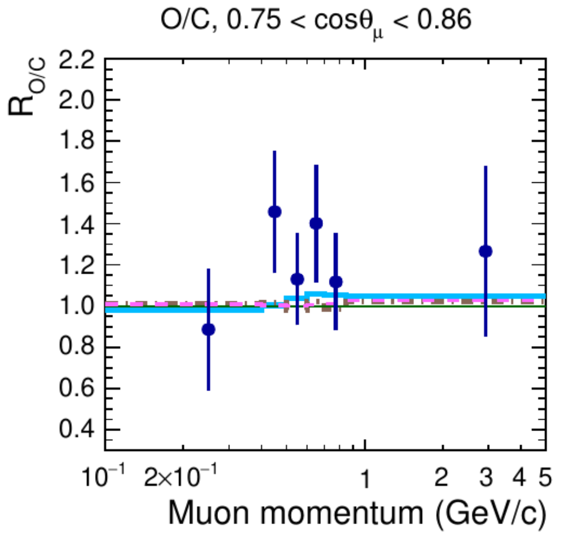


Flux Systematics

- 1097. Neutrino Flux Simulation for T2K Using GEANT4
  Pingal Dasgupta (Eötvös Loránd University, Department of Atomic Physics, Budapest, Hungary)
  19/07/2024, 19:00, Poster

CC0π: CH vs H_2O in μ Kinematics





Generator	result	Total χ^2 (shape only) (ndof = 58)	χ^2 w/o last $\cos\theta_\mu$ bin (ndof = 50)	only O χ^2 (ndof = 29)	only C χ^2 (ndof = 29)	O/C ratio χ^2 (ndof = 29)
NEUT 5.4.1 LFG	reg.	44.8 (58.6)	17.9 (21.1)	26.0 (34.5)	15.2 (20.1)	30.8
	unreg.	44.4 (62.3)	17.3 (22.5)	26.4 (39.1)	14.0 (19.4)	30.6
NEUT 5.4.0 SF	reg.	111.0 (156.8)	45.3 (69.0)	50.0 (77.6)	40.1 (58.3)	31.7
	unreg.	116.8 (166.7)	45.1 (70.1)	53.7 (86.5)	38.6 (56.2)	32.2
NuWro 18.2 LFG	reg.	64.7 (83.7)	21.0 (30.5)	31.9 (45.0)	23.5 (31.5)	33.1
	unreg.	66.8 (88.7)	21.1 (32.1)	32.9 (49.9)	22.6 (30.6)	33.5
NuWro 18.2 SF	reg.	114.5 (180.1)	50.2 (80.9)	50.1 (86.1)	44.8 (70.3)	34.2
	unreg.	119.2 (189.0)	48.7 (80.9)	52.7 (94.8)	42.6 (67.4)	33.9
Genie 3 LFG hN	reg.	48.9 (58.5)	22.3 (24.6)	24.9 (32.1)	18.4 (22.3)	33.5
	unreg.	46.6 (60.0)	20.1 (23.8)	24.7 (35.6)	16.3 (20.4)	34.0
Genie 3 LFG hA	reg.	55.4 (62.0)	22.9 (25.5)	27.8 (34.3)	19.8 (22.3)	32.3
	unreg.	52.9 (62.0)	21.0 (24.5)	27.7 (37.0)	17.7 (20.4)	32.6
Genie 3 SuSAv2	reg.	103.5 (105.4)	39.0 (44.7)	50.6 (57.3)	35.8 (36.8)	29.8
	unreg.	110.3 (111.3)	40.3 (45.6)	55.4 (62.8)	35.1 (35.5)	30.1
RMF (1p1h)	reg.	90.6 (97.5)	48.2 (60.5)	31.4 (37.8)	43.9 (51.3)	31.3
+ SuSAv2 (2p2h)	unreg.	95.8 (102.2)	49.3 (60.7)	34.0 (42.1)	41.9 (48.1)	30.7
GiBUU	reg.	112.7 (117.0)	47.2 (50.6)	46.8 (58.0)	46.6 (46.1)	39.3
	unreg.	107.5 (112.2)	41.7 (46.8)	43.5 (56.0)	41.0 (41.2)	37.0

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