Neutrino cross-section uncertainties and the ND analysis at T2K

T2K

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NuInt, Seoul, South Korea
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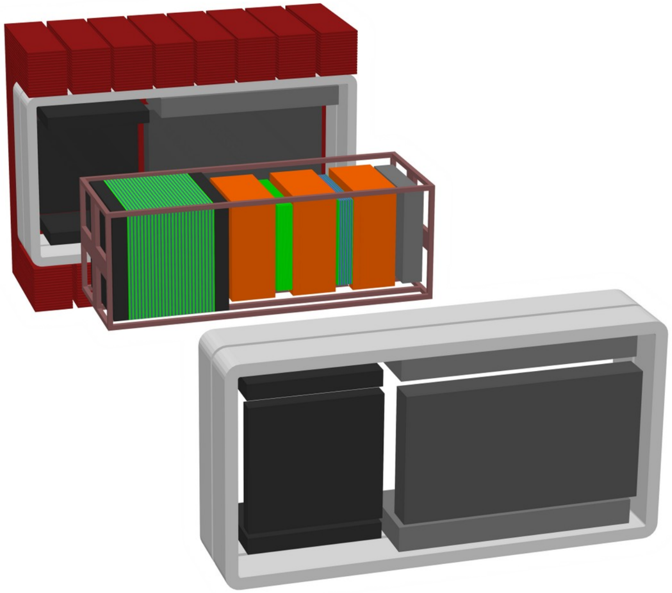
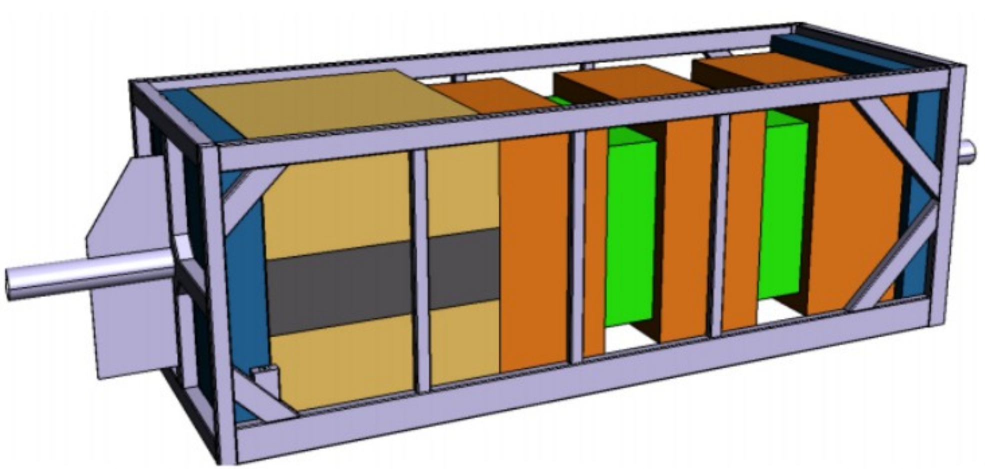
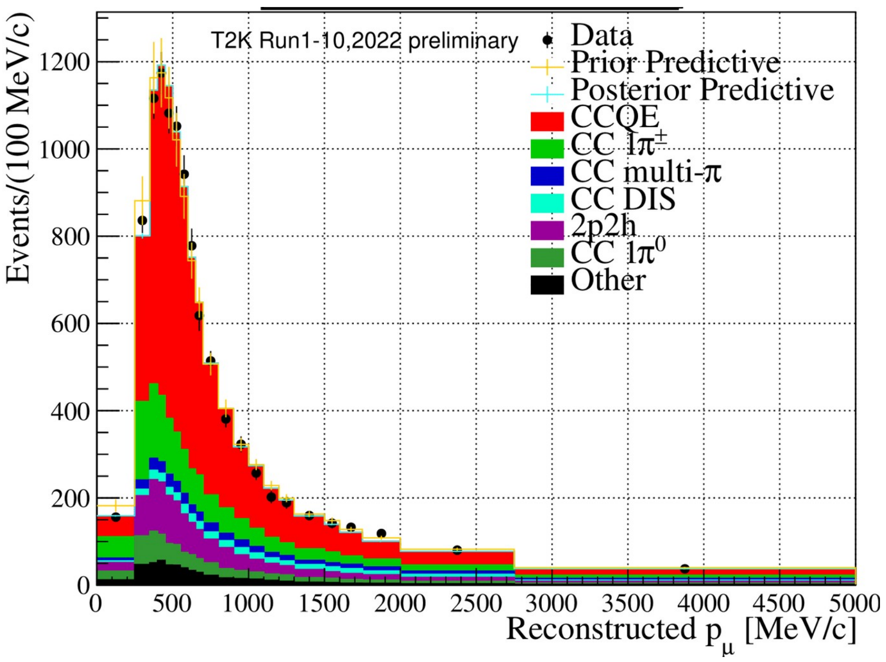
Outline

- The T2K experiment and ND280
- The ND280 selection
- Data analysis
- The future and summary



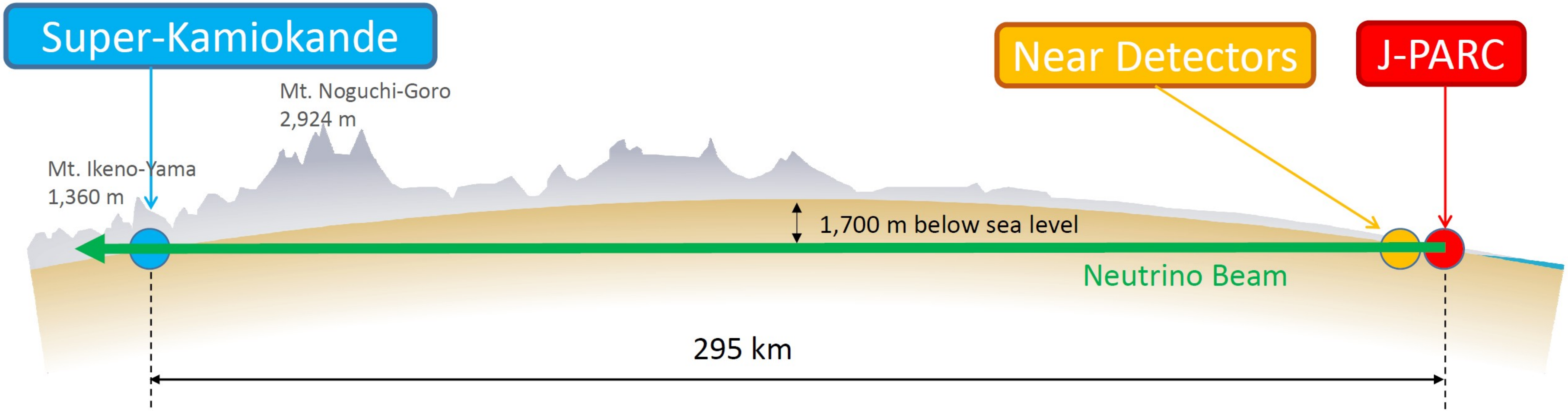




The T2K experiment

The T2K experiment

- 295 km long-baseline neutrino oscillation experiment in Japan
- Starts at J-PARC in Tokai, going towards Super-Kamiokande (SK), in Kamioka
- 30 GeV proton beam, 3-horn system, 2.5° off-axis, suite of near-detectors, Super-Kamiokande as far detector



Why a near detector?

- Characterise the neutrino beam before long-baseline oscillations

$\vec{\mathbf{x}}$ are physical observables

Near

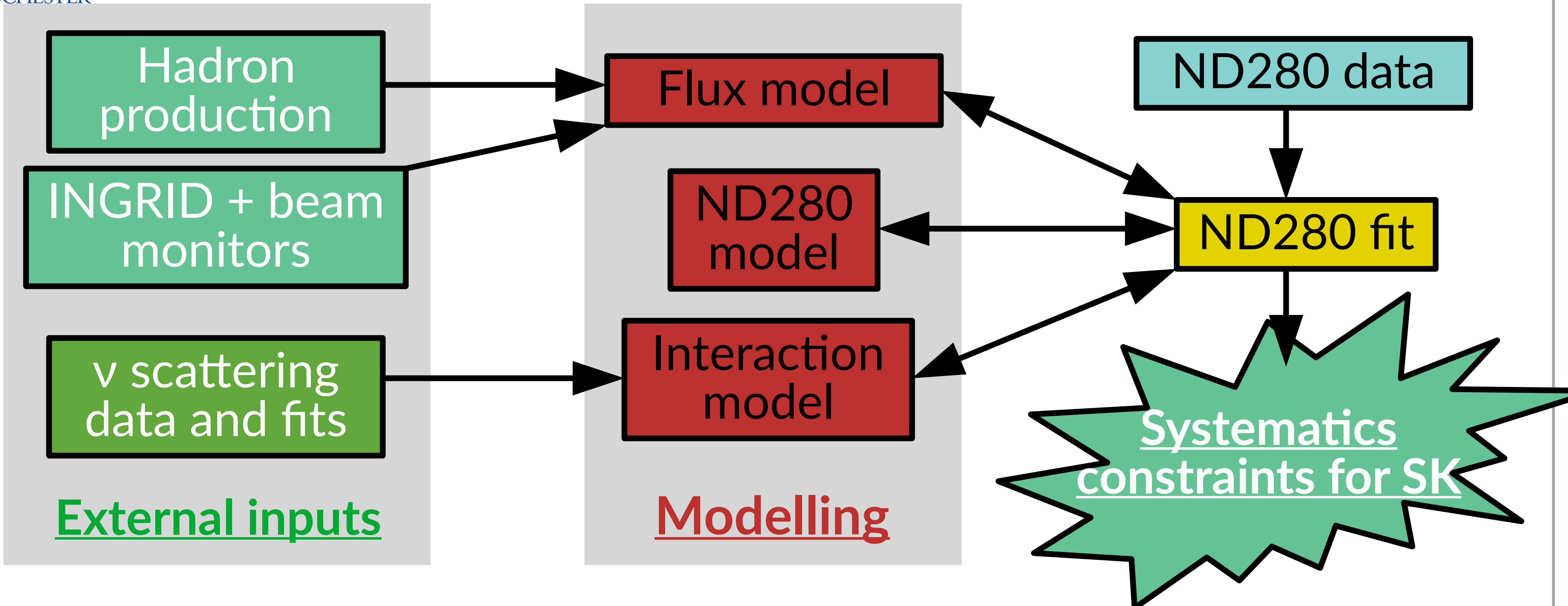
$$R(\vec{\mathbf{x}}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)$$

Events | Flux | Cross sections | Efficiency | Oscillations

Far

- Model relates observables at FD (e.g. p_μ, θ_μ) to neutrino energy (E_ν), which constrains the oscillation parameters
- The ND constrains a convolution of neutrino flux, cross sections, and detector effects
  - Can not perfectly separate them in the ND analysis
  - Cross-section effects may be absorbed as flux effects, with different energy dependency, causing bias
- Develop selections that better isolate and separate the effects, and perform bias testing with alternate models
- Use **near-detector selections that match the far detector** to constrain the major signal and background processes

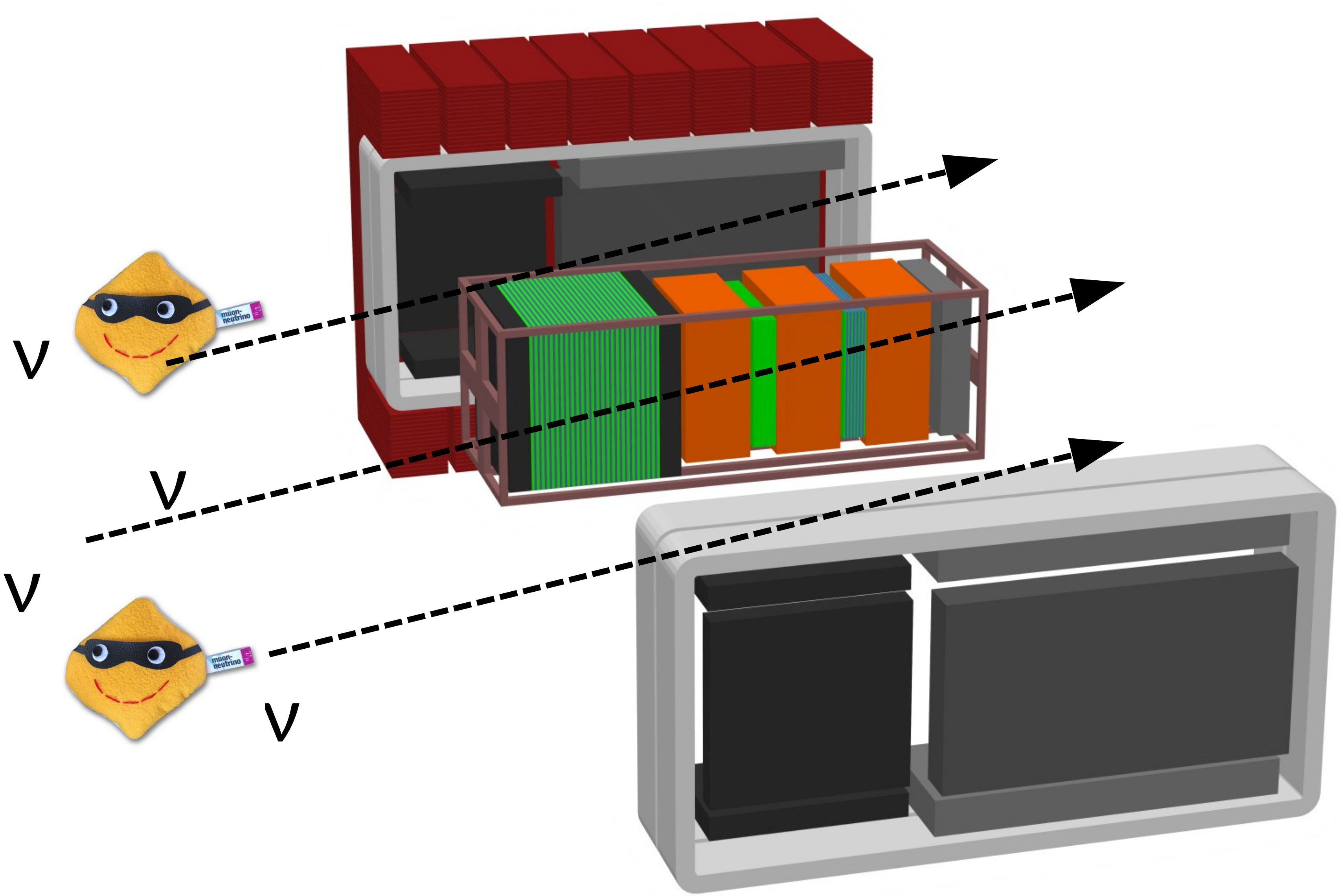
The T2K oscillation analysis



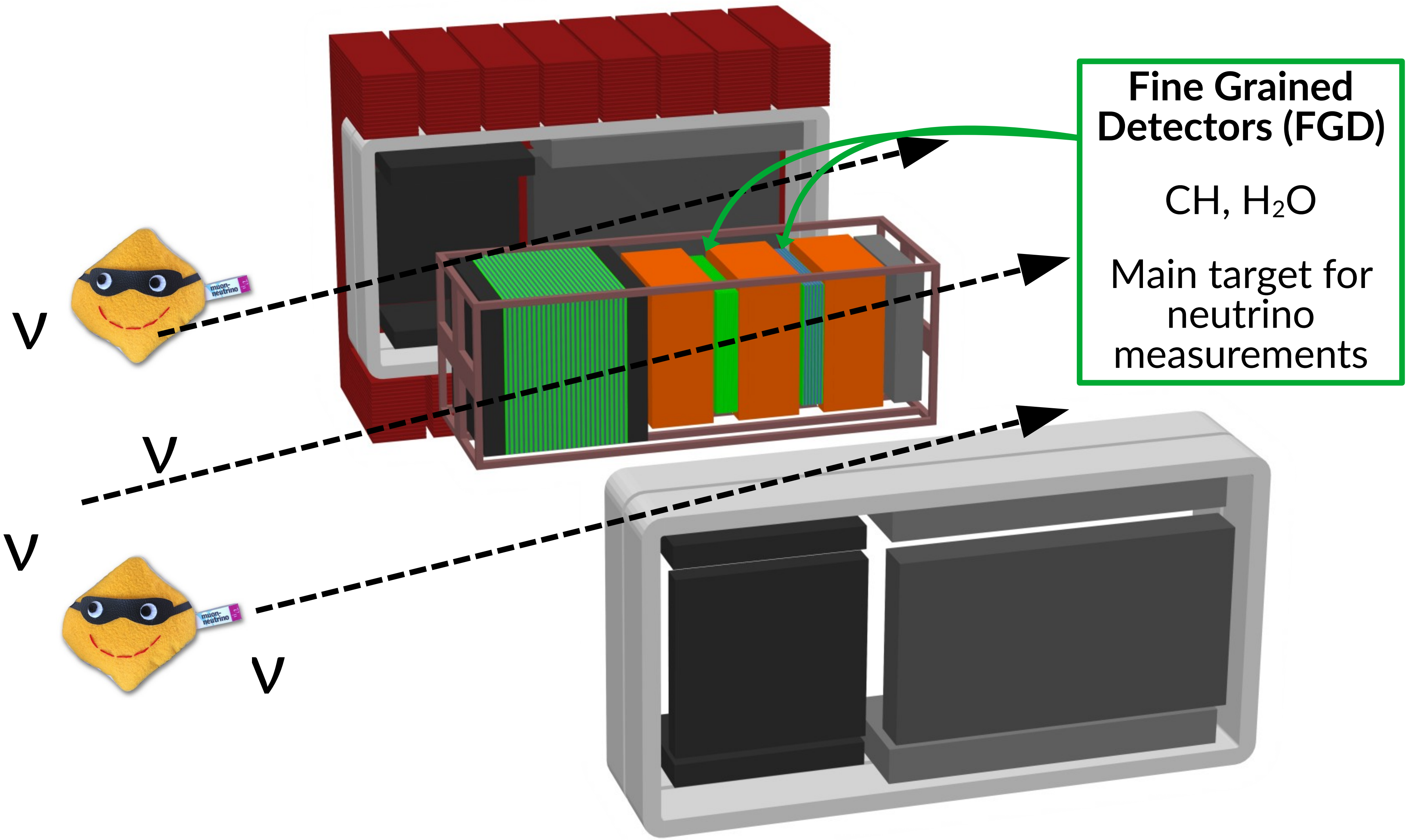
- T2K fits its systematic model to near-detector data, including external constraints, and uses that model for SK prediction
  - For details on the cross-section model, see Stephen's talk
  - For details on the flux model, see Yoshikazu's talk
- Can propagate ND constraint to FD piece-wise, or run simultaneous ND+FD fit
- Frequentist gradient-descent and Bayesian MCMC analyses

The ND280 near detector

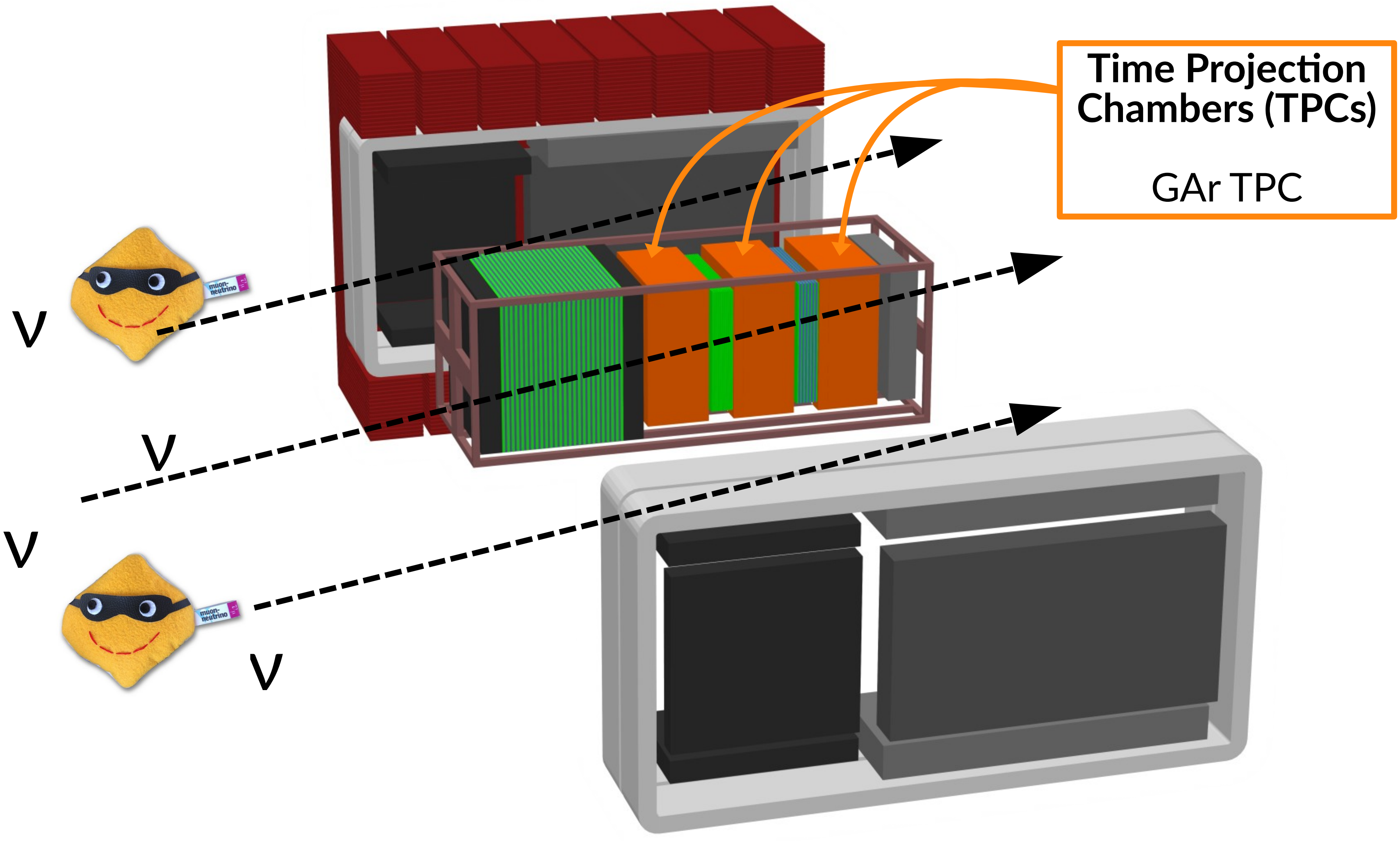
- Segmented detector with multiple sub-detectors



The ND280 near detector



The ND280 near detector



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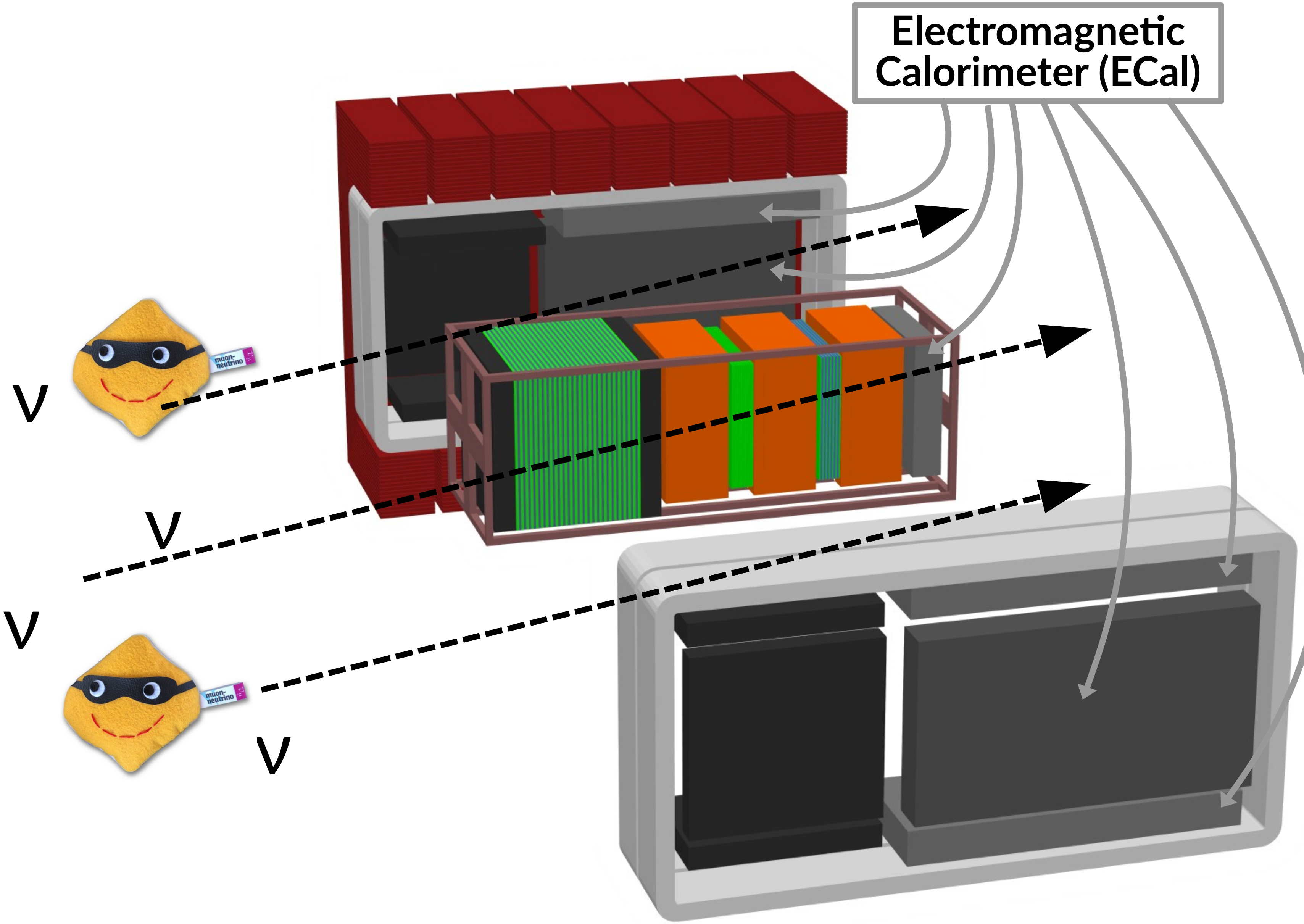

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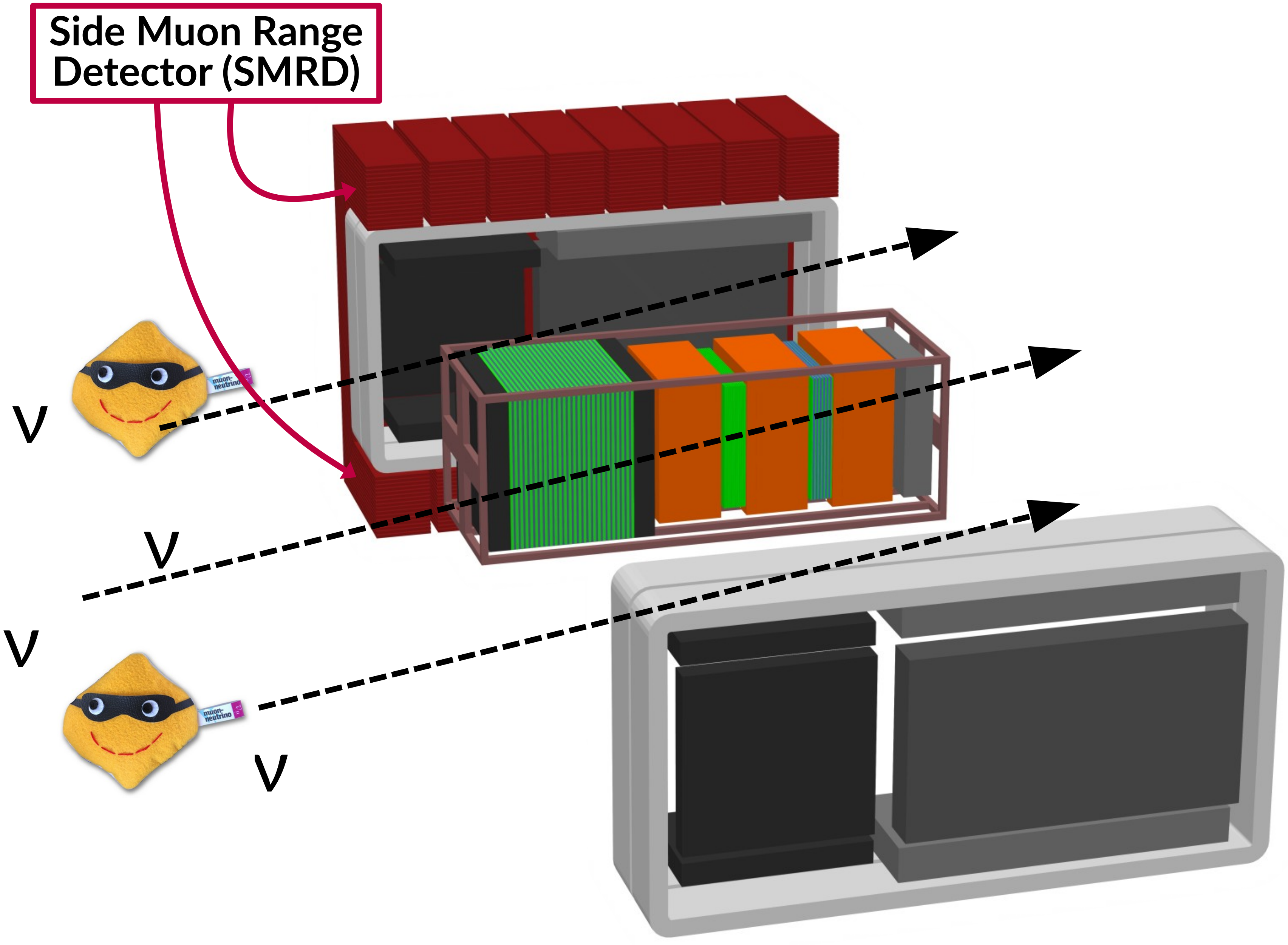

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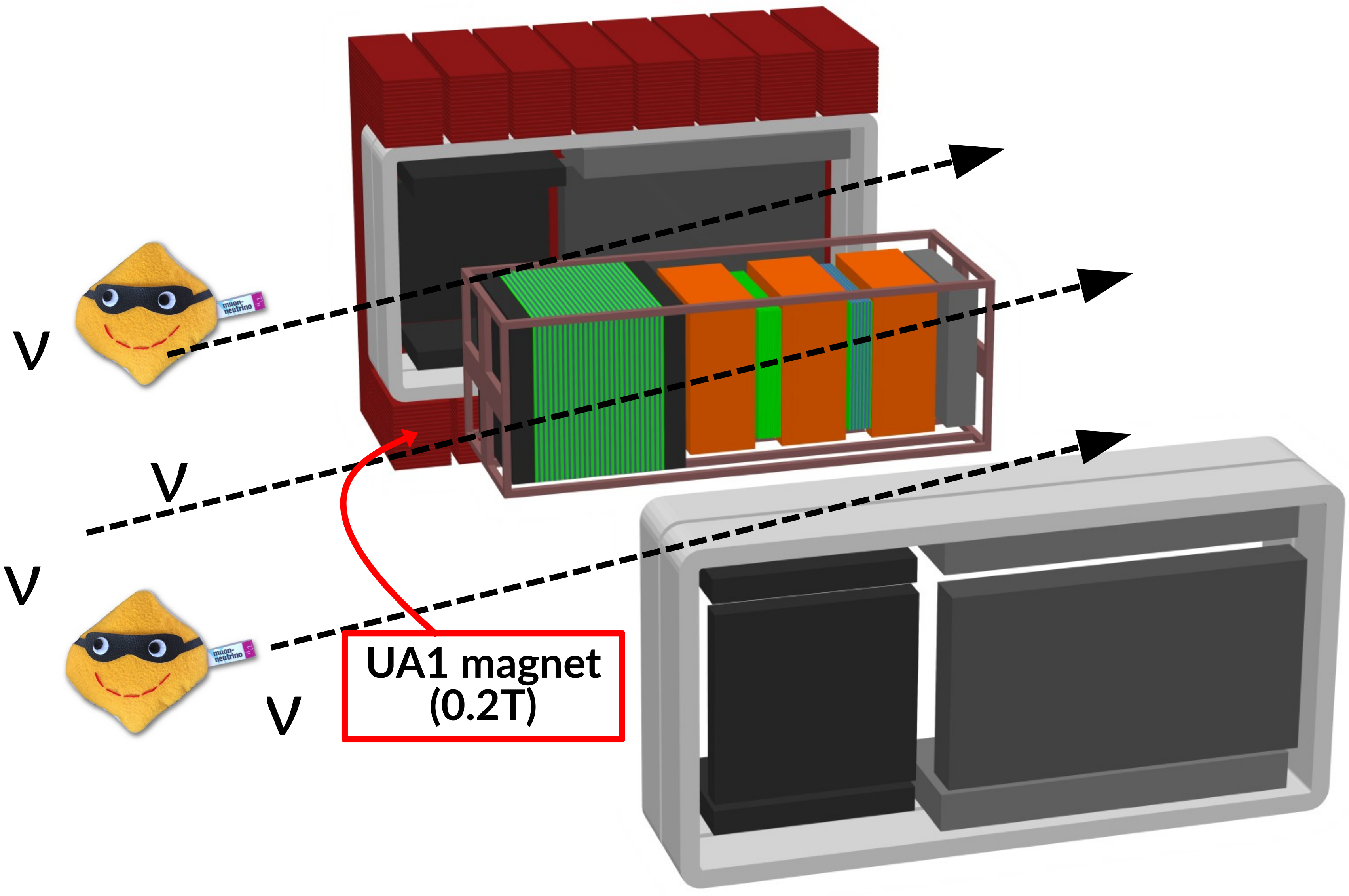

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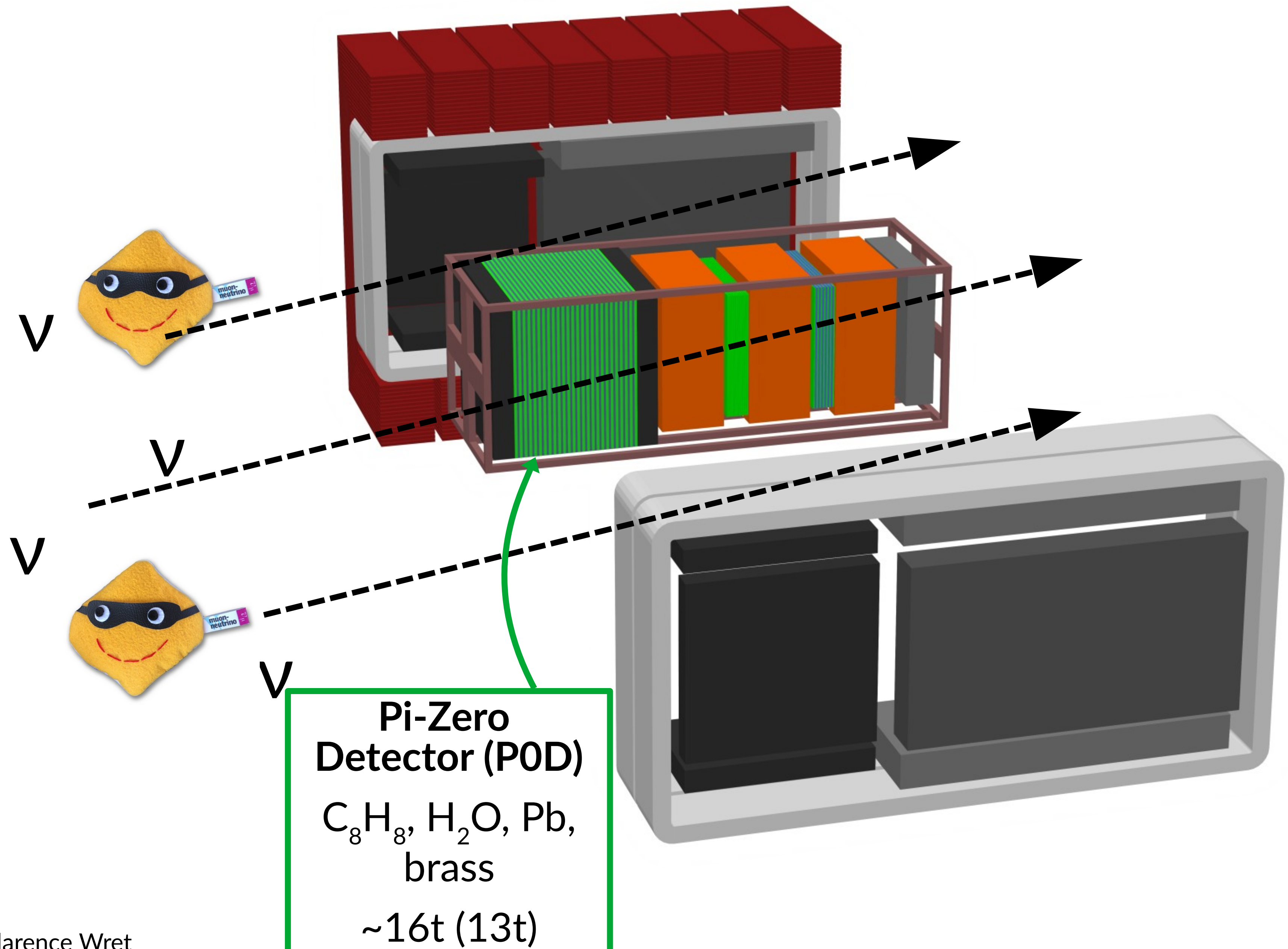
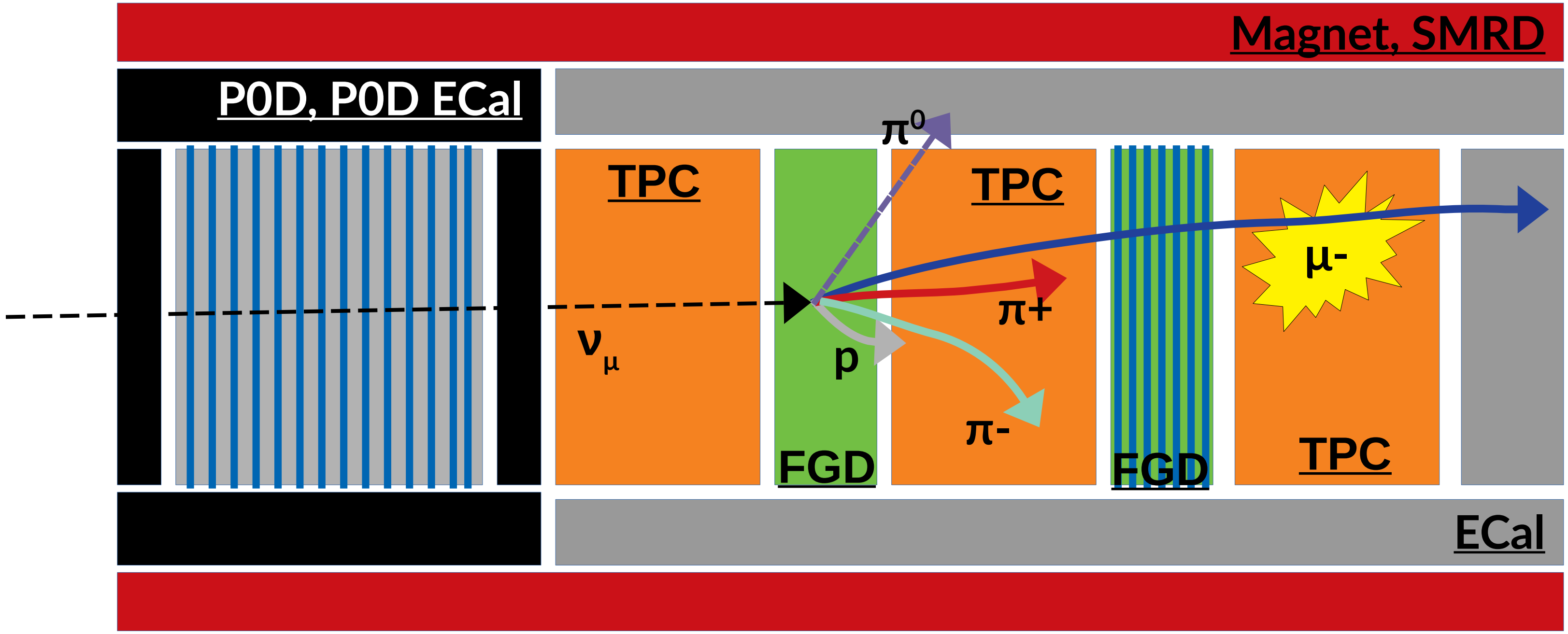


The ND280 selections

The ND280 selections

- Oscillation analysis utilises the FGD+TPC selections, and ECal for tagging escaping particles and photon candidates
  - Use FGD1 (CH) and FGD2 (CH, **H_2O**) to constrain neutrino flux and interaction cross-section
  - Water target is critically important, as it's the target in SK

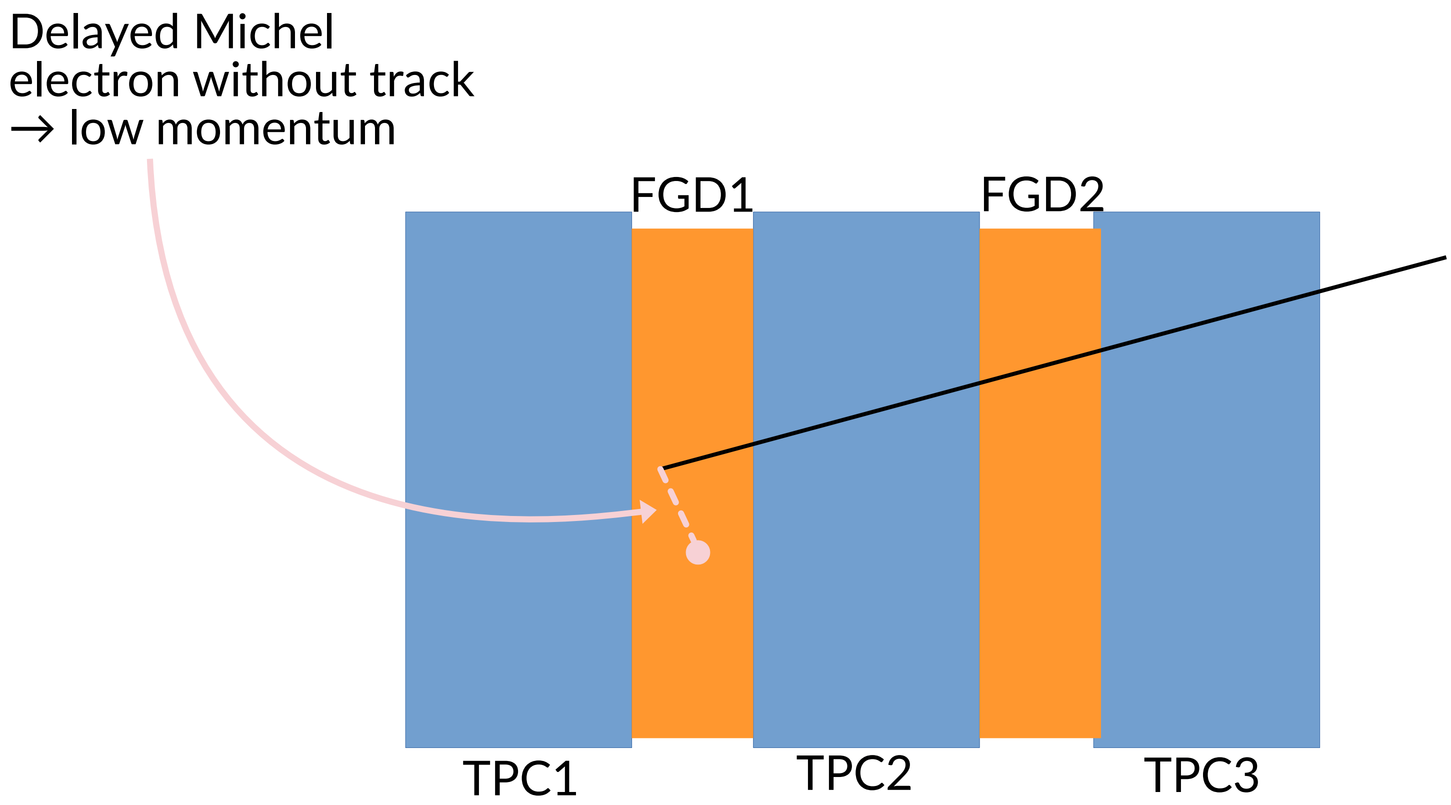
ND280 side-view



- Sign selection; ~8% MIP resolution in TPC; 0.2% μ/e confusion
  - Can constrain wrong-sign backgrounds in-situ, and momentum resolution that exceeds that of the far detector

The ND280 selections

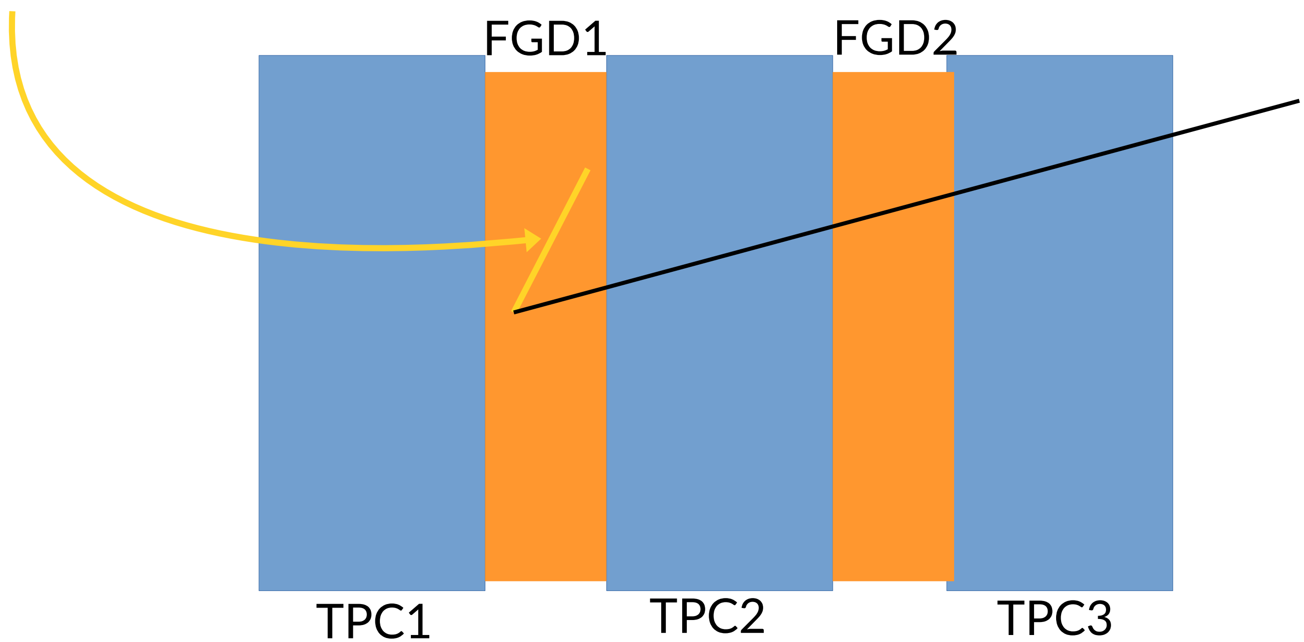
- Have three **pion** tagging methods, increasing in p_{π}
  - Michel electron
  - FGD contained
  - FGD-TPC track



The ND280 selections

- Have three **pion** tagging methods, increasing in p_π
  - Michel electron
  - FGD contained
  - FGD-TPC track

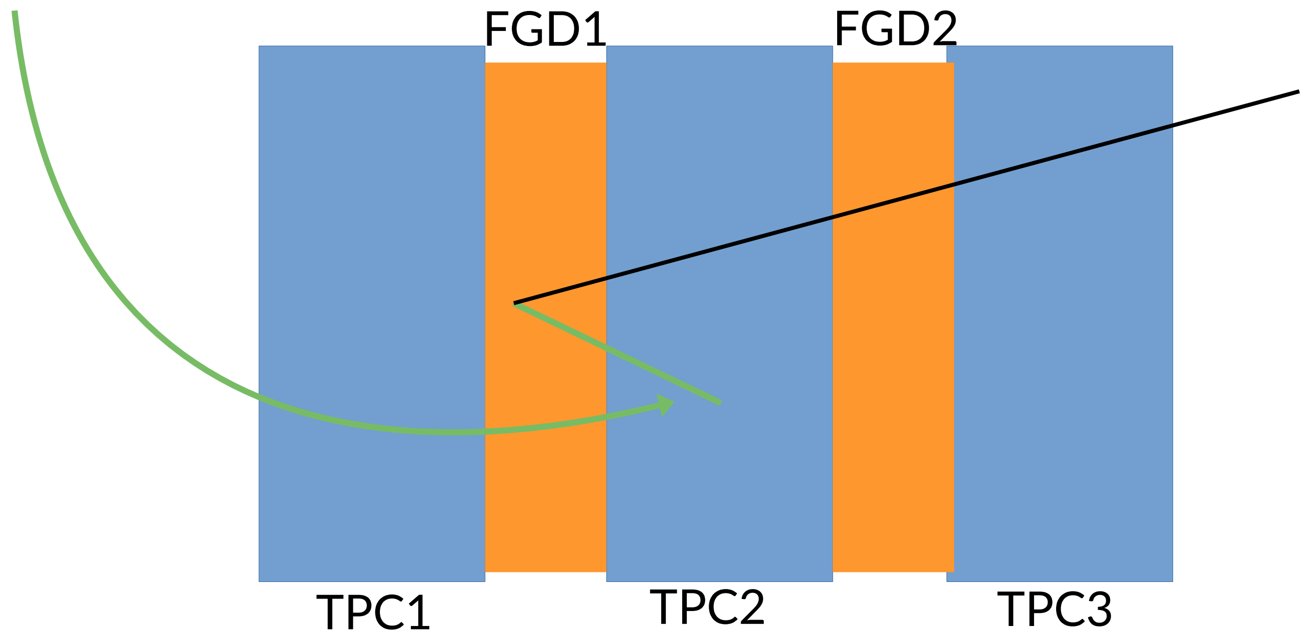
Visible track
contained in FGD
→ Somewhat low
momentum



The ND280 selections

- Have three **pion** tagging methods, increasing in p_π
  - Michel electron
  - FGD contained
  - FGD-TPC track

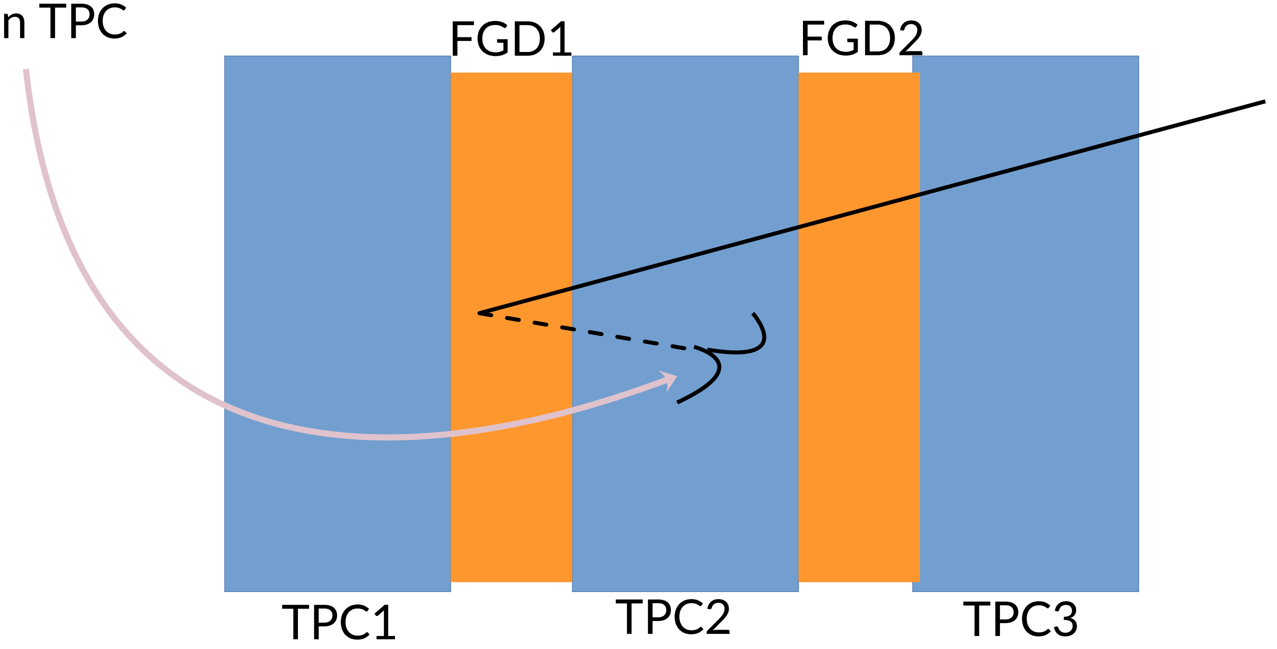
TPC track matched to FGD and vertex → higher momentum



The ND280 selections

- Have two **photon** tagging methods
  - TPC-tagged electron candidates
  - ECal photon cluster

At least one electron
tagged in TPC



The ND280 selections

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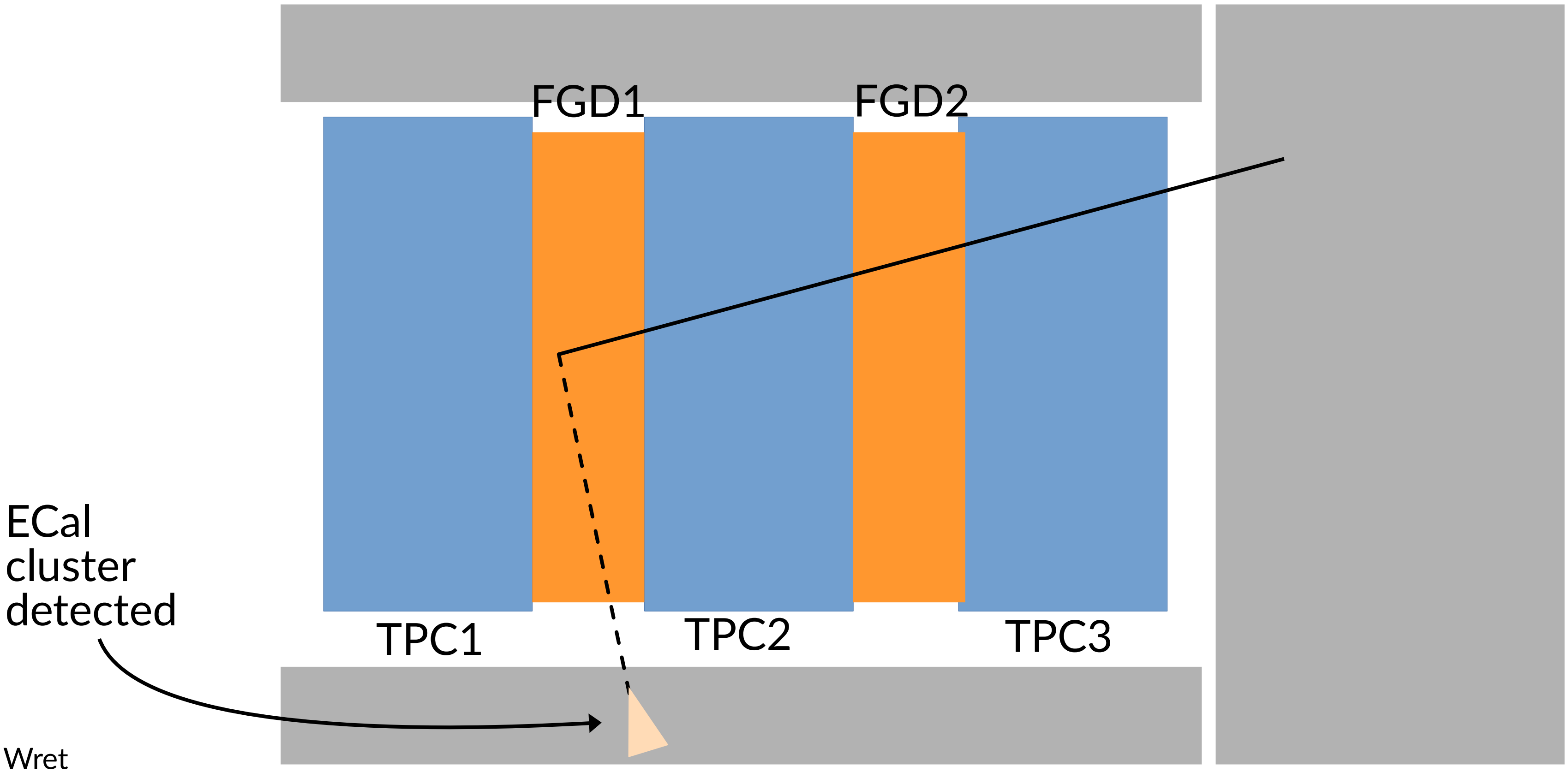
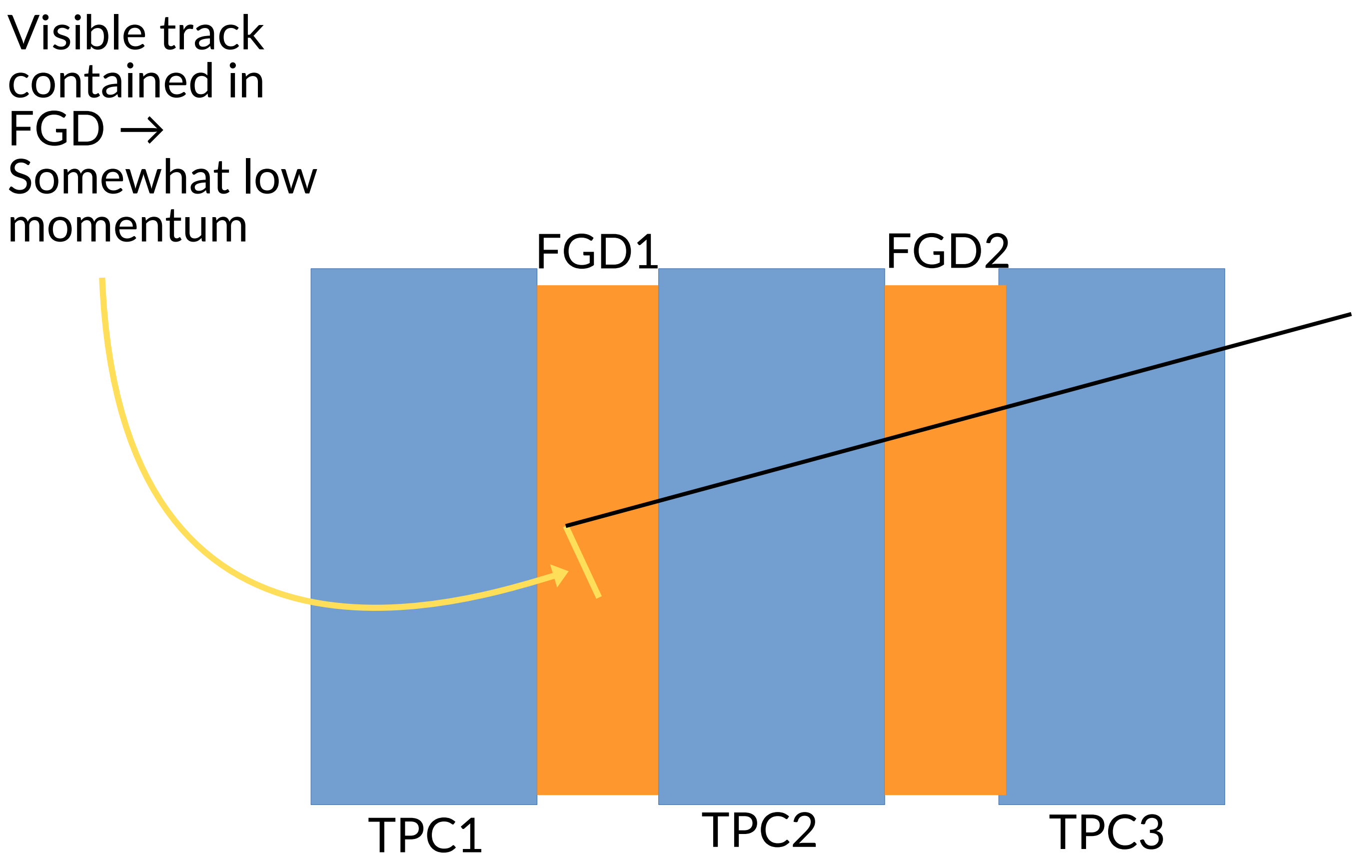


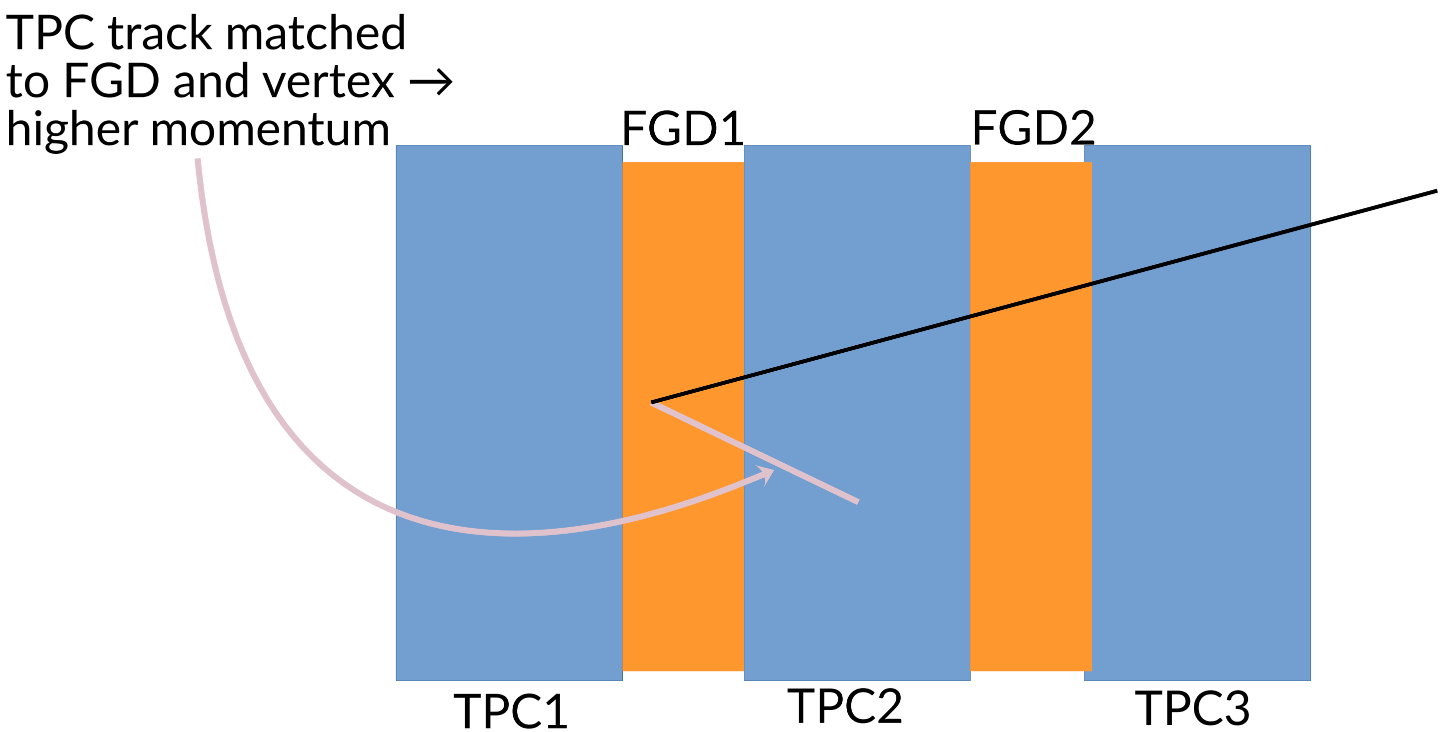
The ND280 selections

- Have two **proton** tagging methods, increasing in p_p
  - FGD contained
  - FGD-TPC track



The ND280 selections

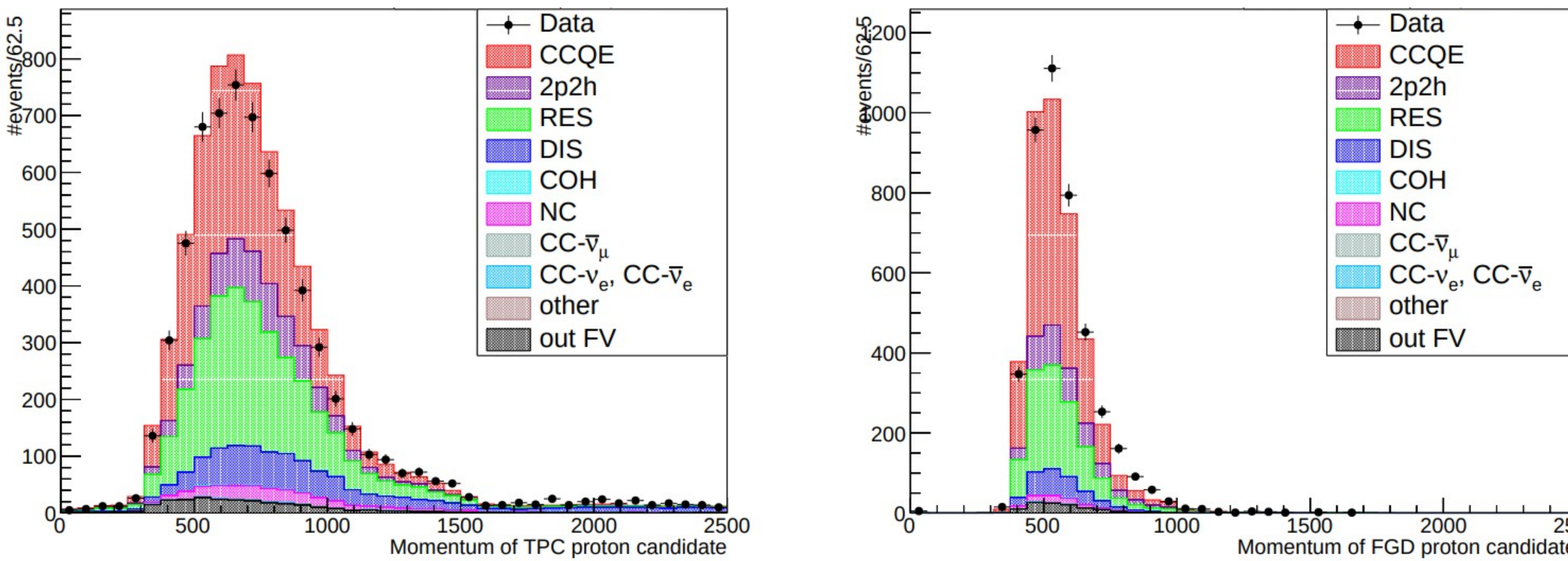
- Have two **proton** tagging methods, increasing in p_p
  - FGD contained
  - FGD-TPC track



The ND280 selections

- Have two **proton** tagging methods, increasing in p_p
  - FGD co
  - FGD-TP

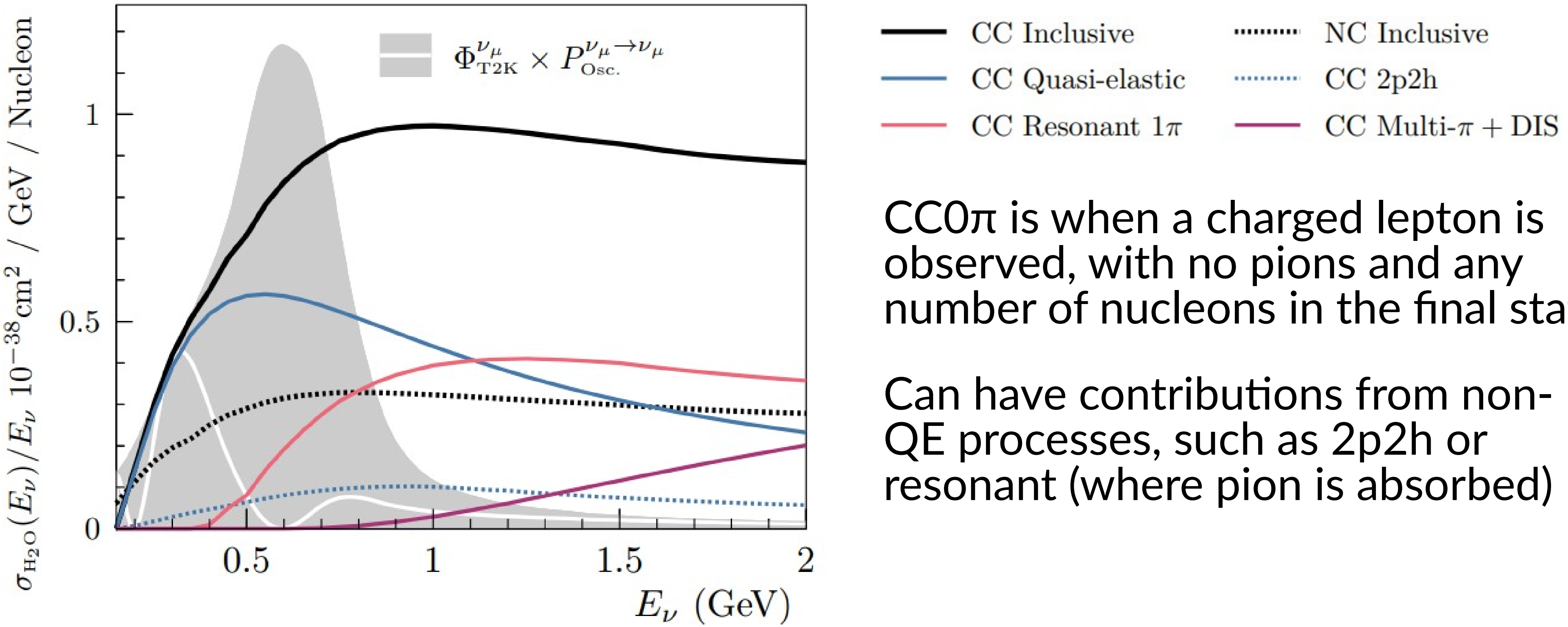
Proton threshold in ND280 is ~450 MeV/c → Not very sensitive to nuclear effects on proton (e.g. Pauli blocking)



(a) TPC matched (b) isoFGD

The ND280 selections

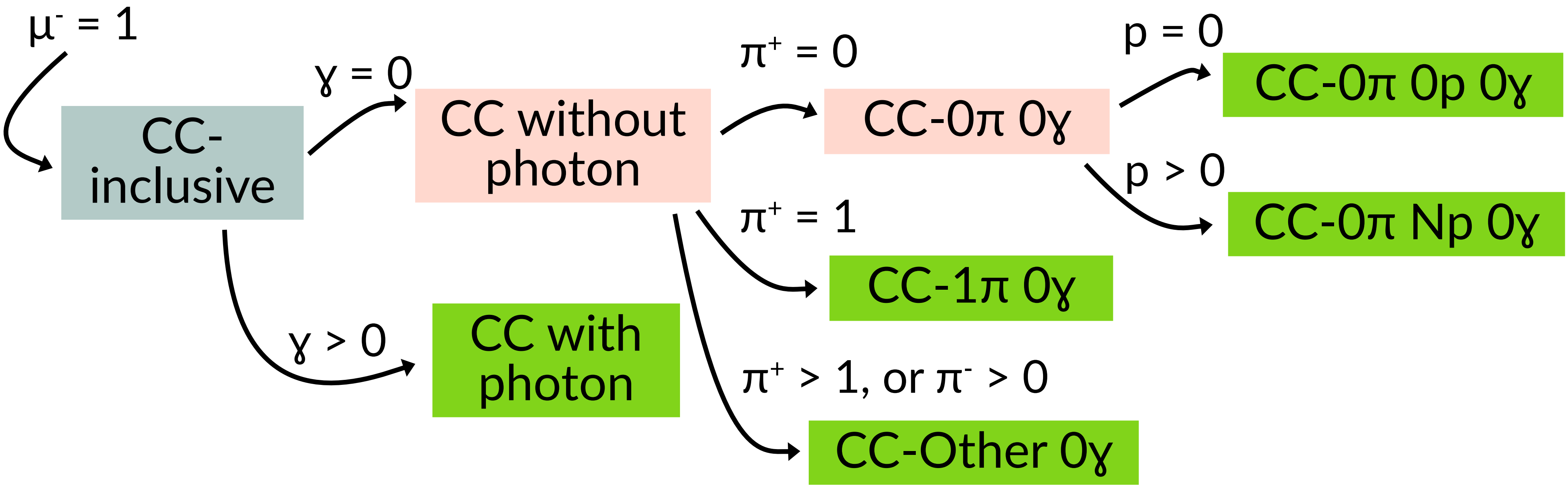
- Separate selections into
  - Beam mode: Forward Horn Current (FHC, ν_μ dominated) or Reverse Horn Current (RHC, anti-ν_μ dominated) including wrong-sign background for RHC
  - Vertex location: FGD1 and FGD2
- FHC and RHC selections differ due to statistics and final states
- Dominated by CCQE interaction → Lots of CC0π events



CC0π is when a charged lepton is observed, with no pions and any number of nucleons in the final state

Can have contributions from non-QE processes, such as 2p2h or resonant (where pion is absorbed)

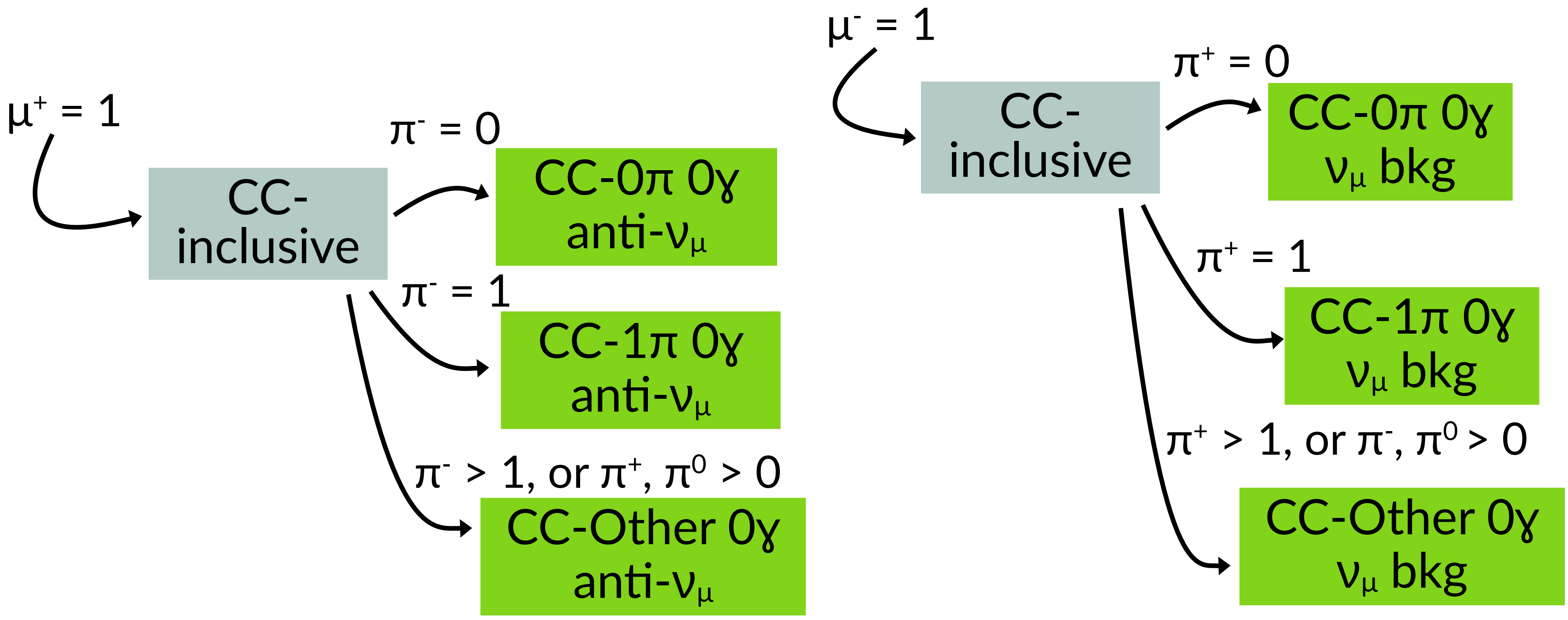
The ND280 FHC selections



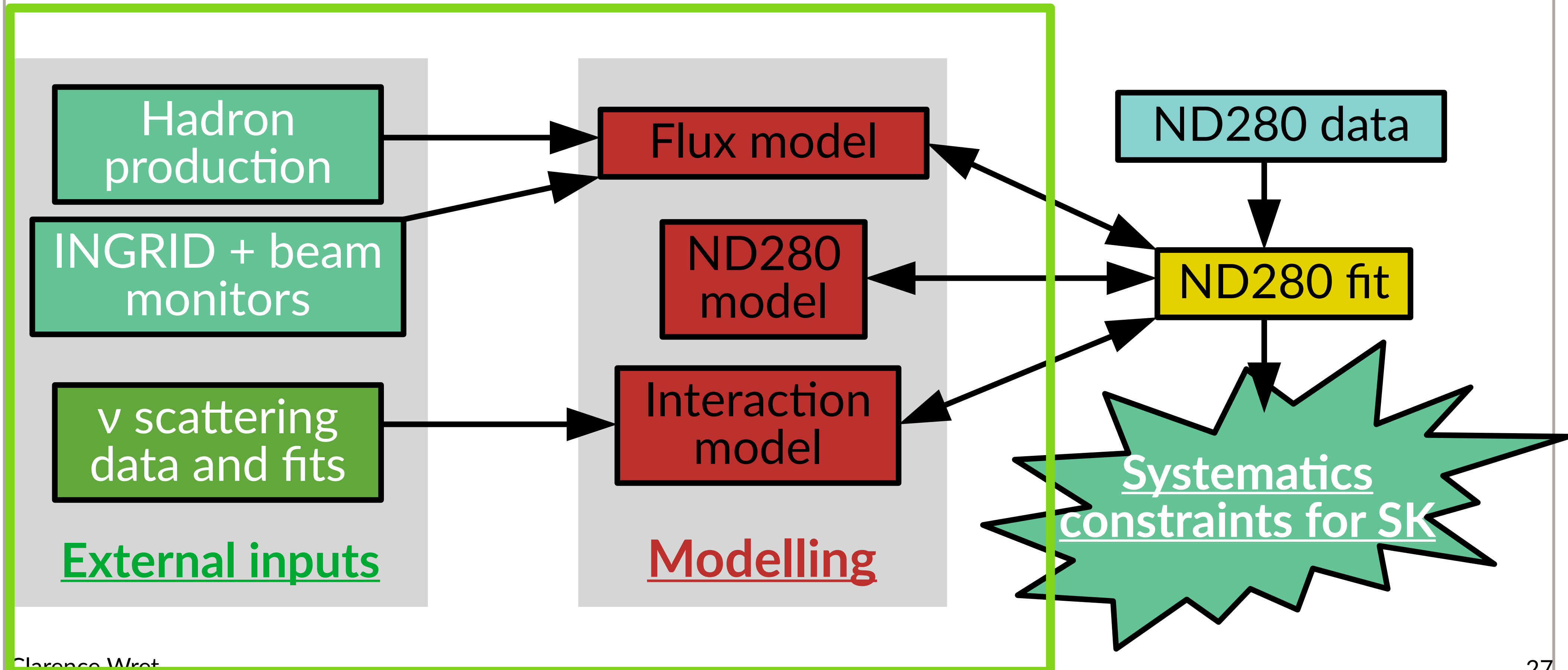
- Select on photon, charged pion and proton multiplicity
- Proton multiplicity in CC0π separates CCQE and 2p2h processes, and low and high Q^2
- Pion multiplicity separates neutrino interaction modes
  - CC0π is CCQE, 2p2h and resonant+FSI
  - CC1π is predominantly resonant
  - CC Other is SIS/DIS, and CC photon is mixture

The ND280 RHC selections

- Start with $\mu^{+/-}$ identification
  - μ^+ candidate → right-sign; μ^- candidate → wrong-sign
  - Charged pion needs to be opposite sign to muon candidate
- No proton or photon tagging
- 12 RHC selections, 10 FHC selections

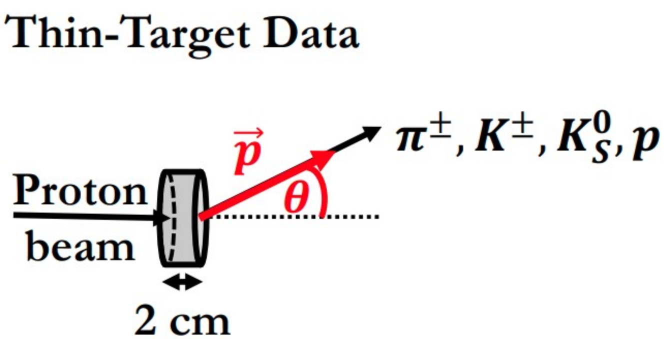


The uncertainty model

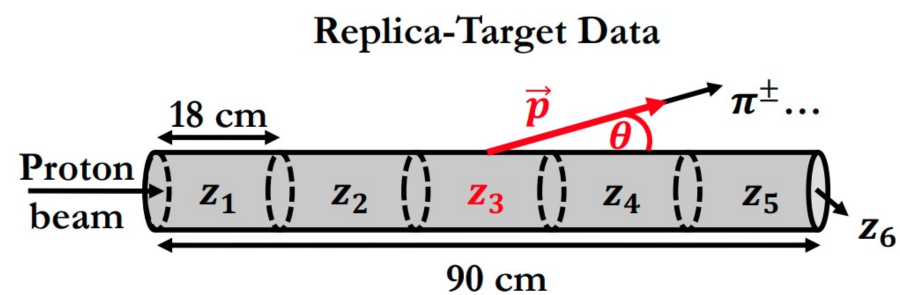


Neutrino flux uncertainties

- NA61/SHINE hadron production experiment at CERN SPS
- Dedicated T2K data at p=31 GeV/c, with thin and replica target

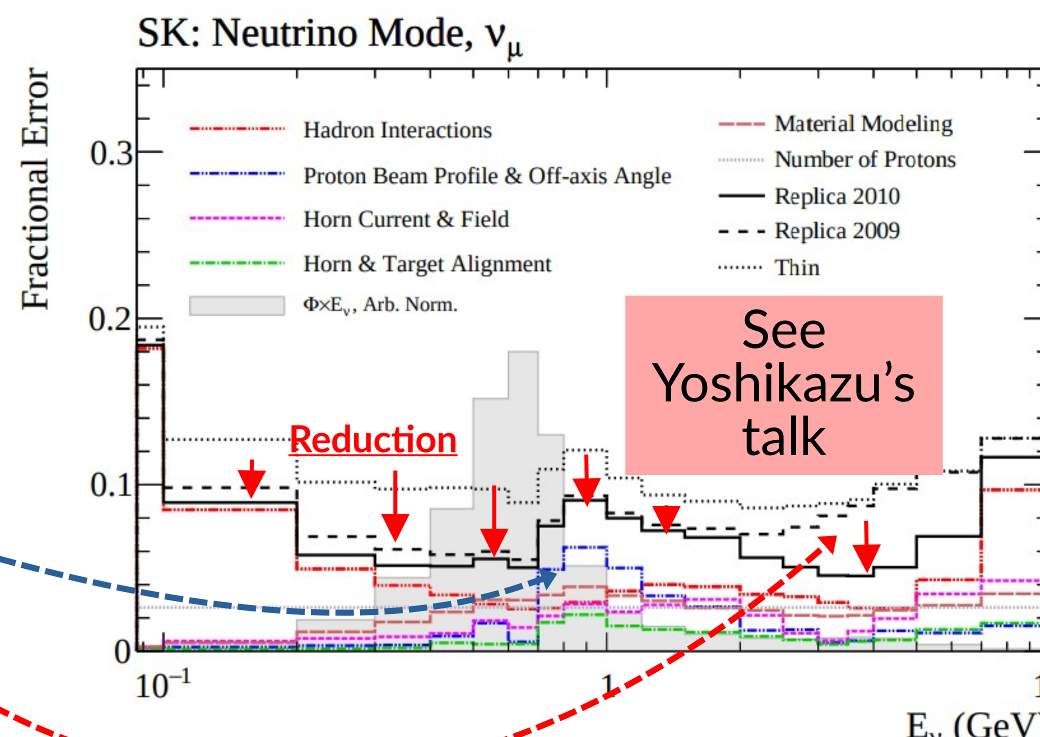


Eur. Phys. J., C76(2):84, 2016



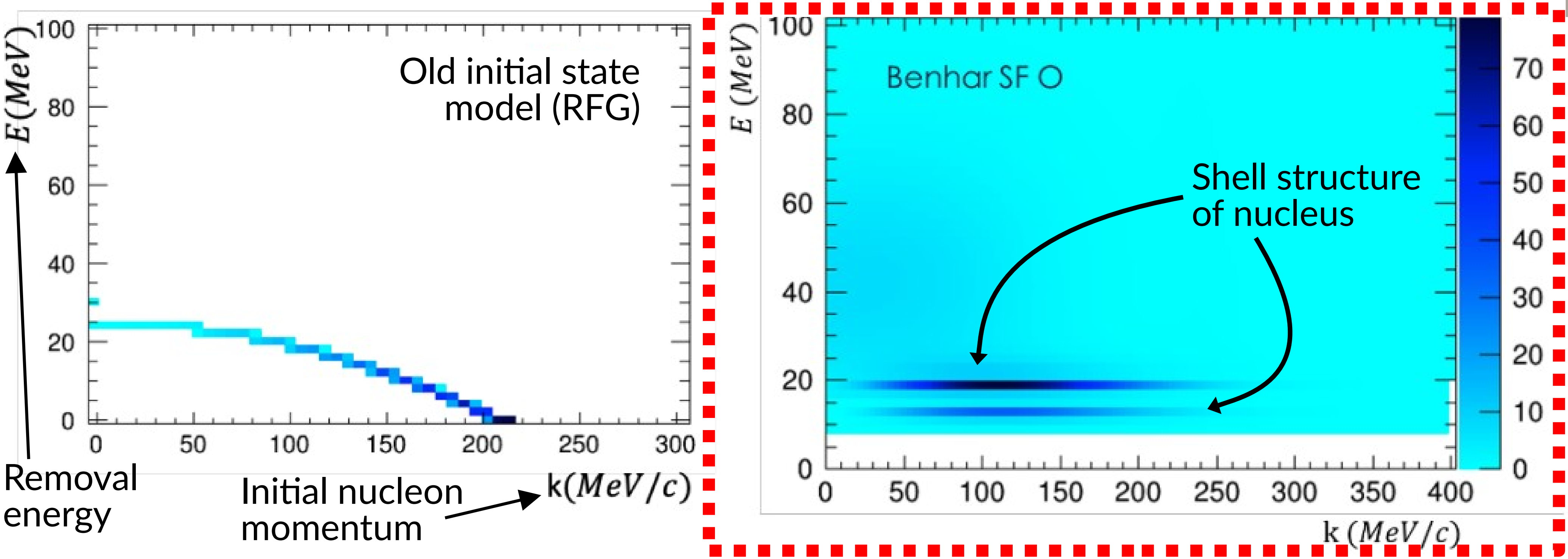
Eur. Phys. J., C76(11):617, 2016

- Replica target data decreases flux uncertainty from ~10% to ~5% in E_ν peak
  - Increases nominal ν_μ and ν_e fluxes
  - Largest remaining uncertainty is proton beam related
- NA61/SHINE 2010 data includes kaon and proton yields (improves high E_ν ν_μ and ν_e)



Neutrino interaction uncertainties

- Benhar Spectral Function model for nuclear structure
  - CCQE nucleon interaction tuned to bubble chamber data



- Removal energy treatment developed for spectral function
- CCQE and 2p2h model hugely benefitted from collaborations with the ND280 Upgrade

See Stephen's talk

  - optical potential, Pauli blocking, 2p2h shape, short-range correlated vs MF pairs, etc

ND280 detector uncertainties

- Dedicated detector systematics for
  - mis-ID probabilities in TPCs and FGD, magnetic field distortions, momentum resolution and scale, cluster efficiencies, tracking and track matching, Michel tagging efficiency, pile-up, FGD mass, out-of-fiducial volume, and sand muon backgrounds
- Use dedicated control samples for specific systematics
  - e.g. through-going muons for FGD-TPC matching, stopping cosmic muons for Michel e tagging efficiency
- For pion selections, pion secondary interactions (SI) is the largest systematic
- For proton selections, proton SI is the largest systematic
- Future data from EMPHATIC and other hadron scattering experiments, and models from e.g. INCL, will help in the global tuning effort
  - Nailing down the secondary interaction systematics will also be imperative to next-generation experiments and neutron tagging

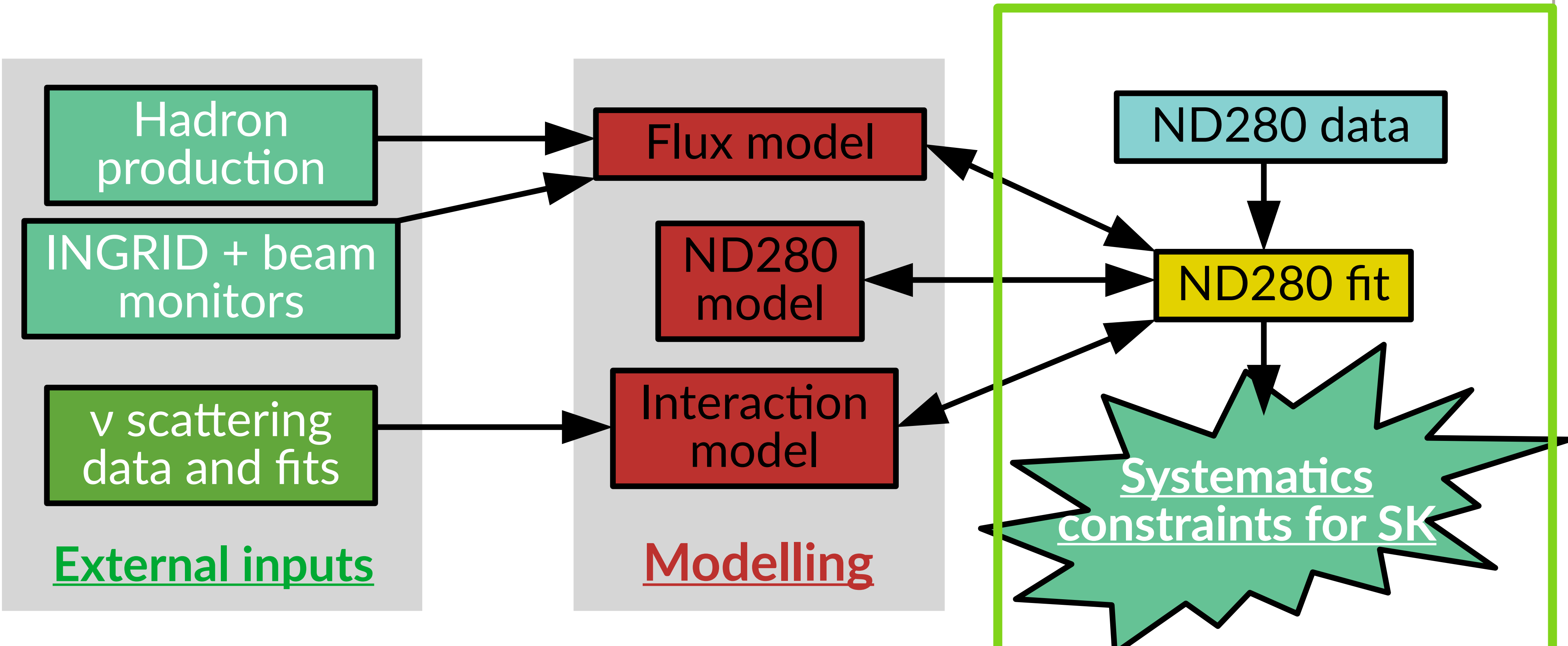
The ND280 selections

- With these selections, the T2K ND280 analysis can expose mismodelling of
  - Neutrino vs anti-neutrino
  - Carbon vs Oxygen
  - Specific interactions (CC0π, CC1π, …)
- Separate and correlate neutrino interaction model within reason
  - e.g. completely separating M_A^{QE} for carbon and oxygen interactions is not motivated

See Stephen's talk

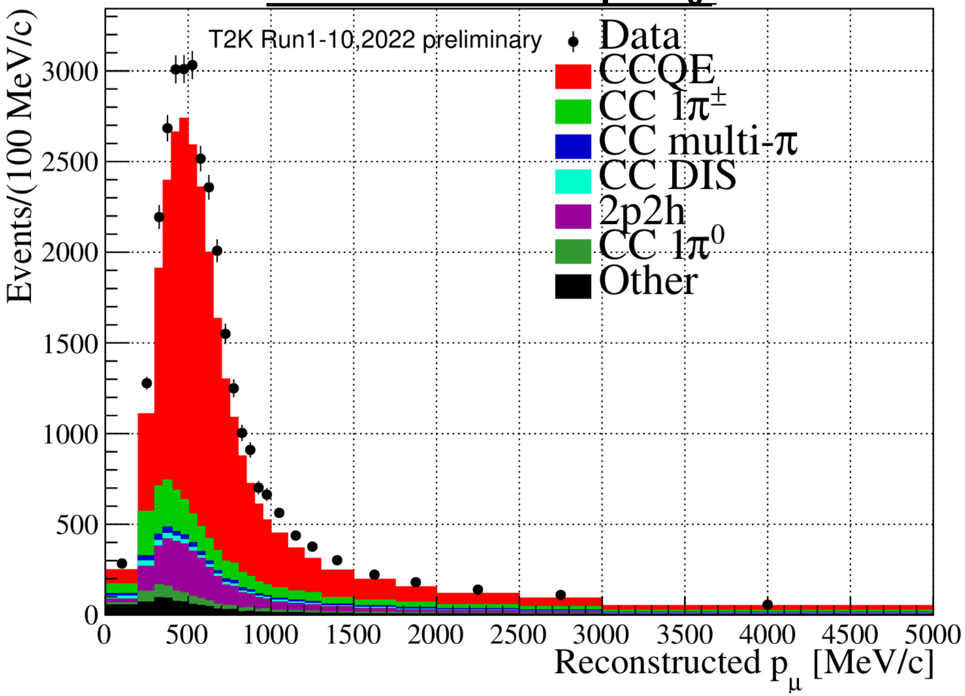
  - Different cross-section of 2p2h in (q_0, $\mathbf{q_3}$) for nn/np seems reasonable from theory calculations
- Analysis in p_μ $\cos\theta_\mu$ in **reconstructed space**, with cross-checks on proton and pion kinematics
  - The pion and proton tagging methods with different efficiency provide an implicit sensitivity to pion and proton kinematics
- Stir until convergence!

The analysis

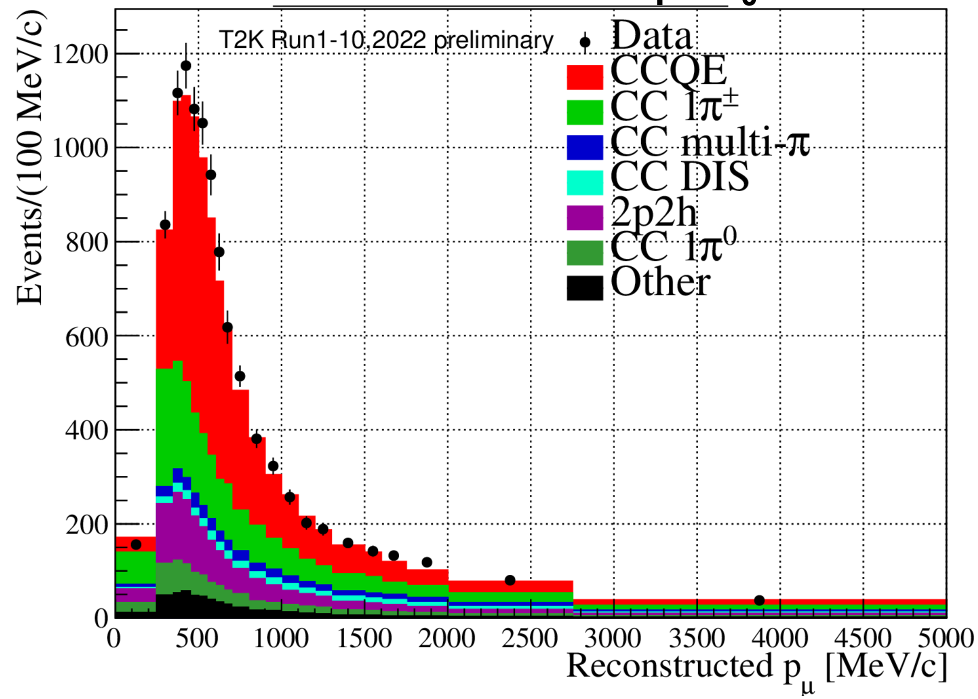


Before the ND280 analysis

FGD1 CC0π 0p 0γ



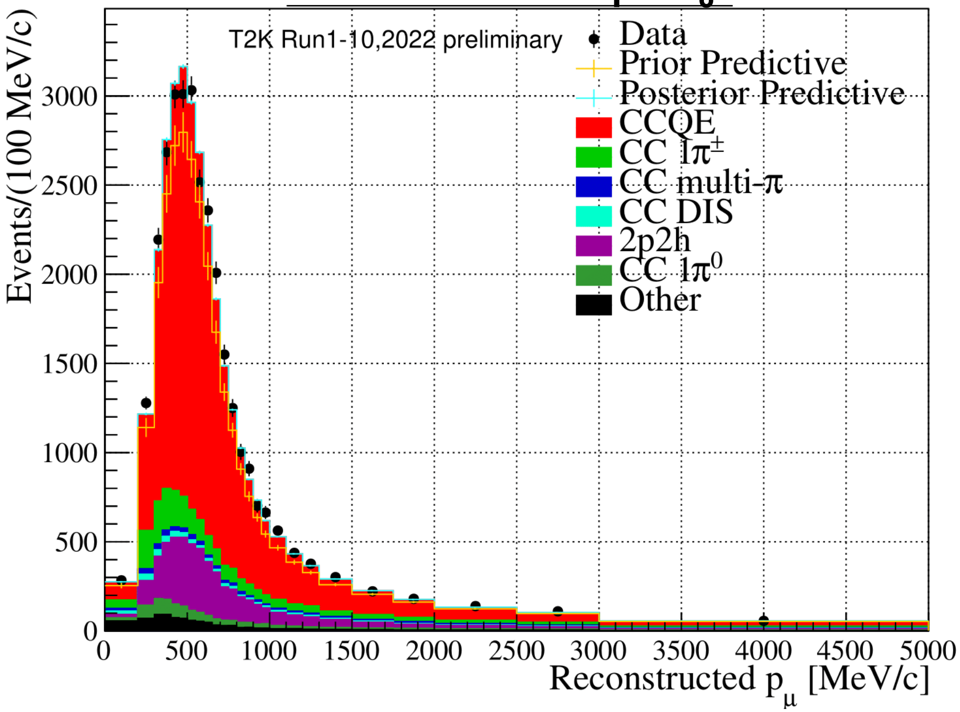
FGD1 CC0π Np 0γ



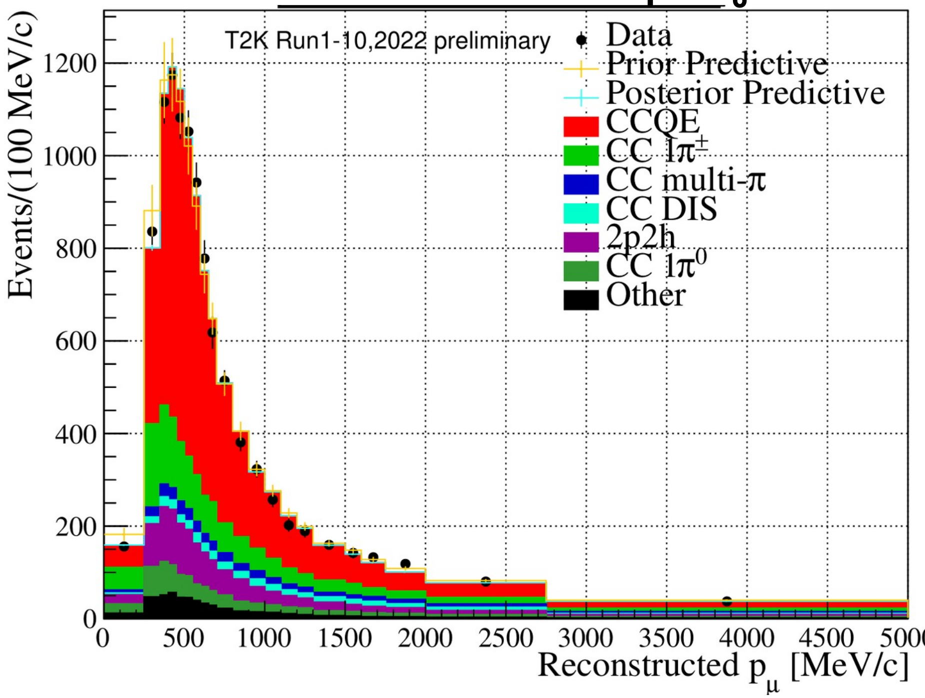
- ν_μ CC0π Np selection has significantly larger fraction of true CC1π events than 0p selection
- ν_μ CC0π 0p selection clearly underpredicted, Np selection is well predicted

After the ND280 analysis

FGD1 CC0π 0p 0γ



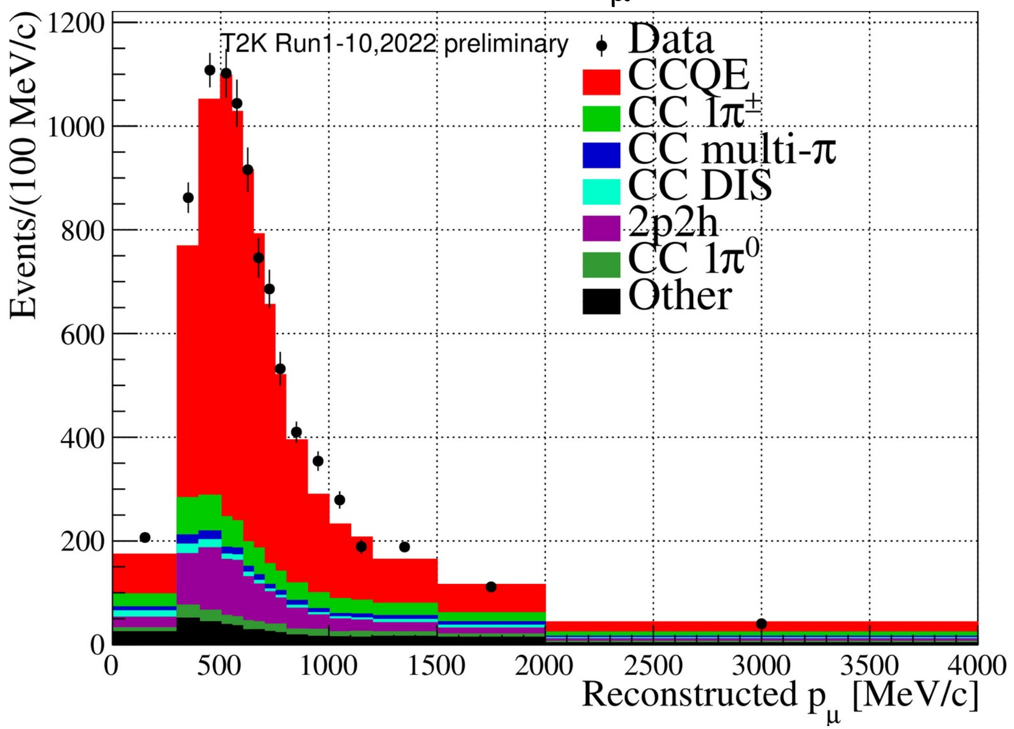
FGD1 CC0π Np 0γ



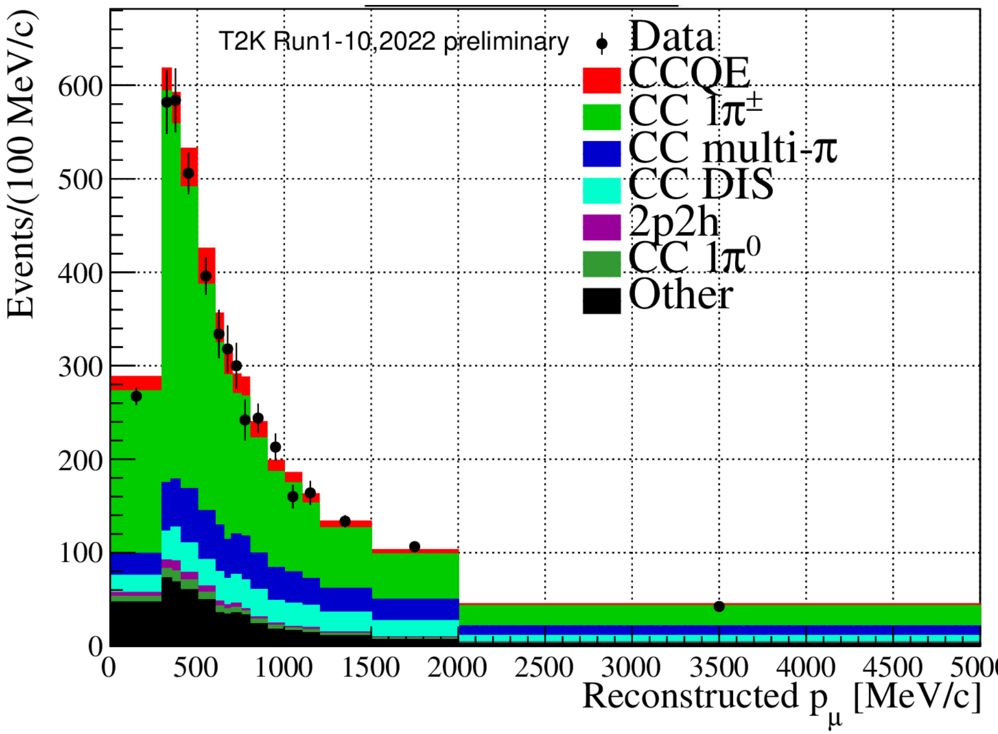
- CCQE fraction increases
- 2p2h fraction increases
- 2p2h shape changes
- CC1π+ contributions decreases

Before the ND280 analysis

FGD1 anti-ν_μ CC0π



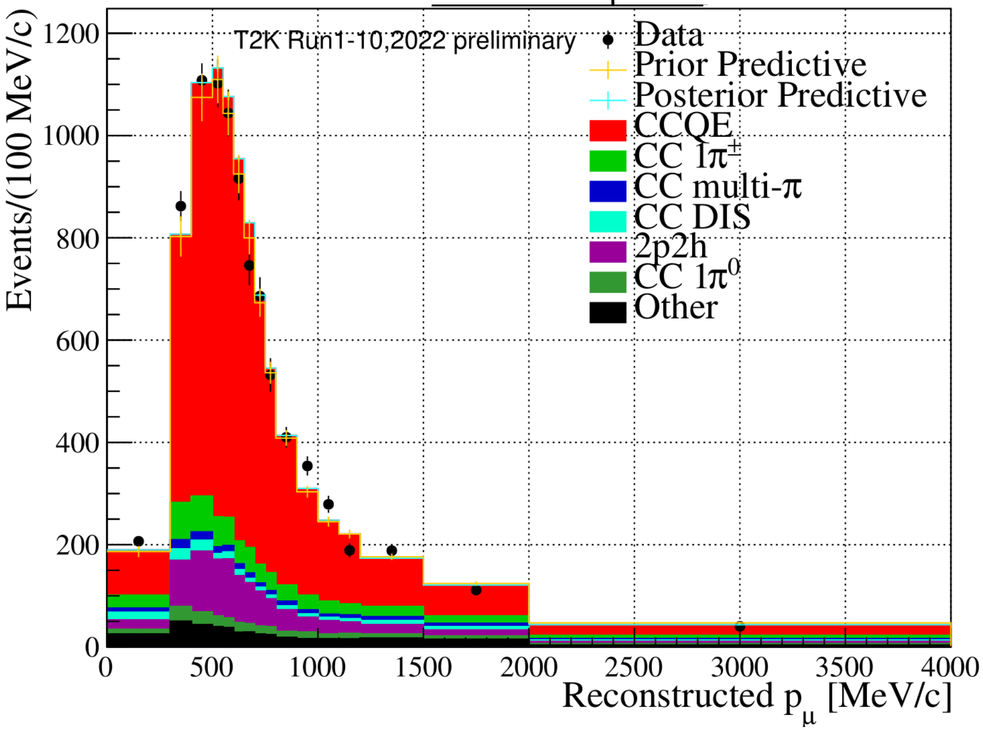
FGD1 CC1π



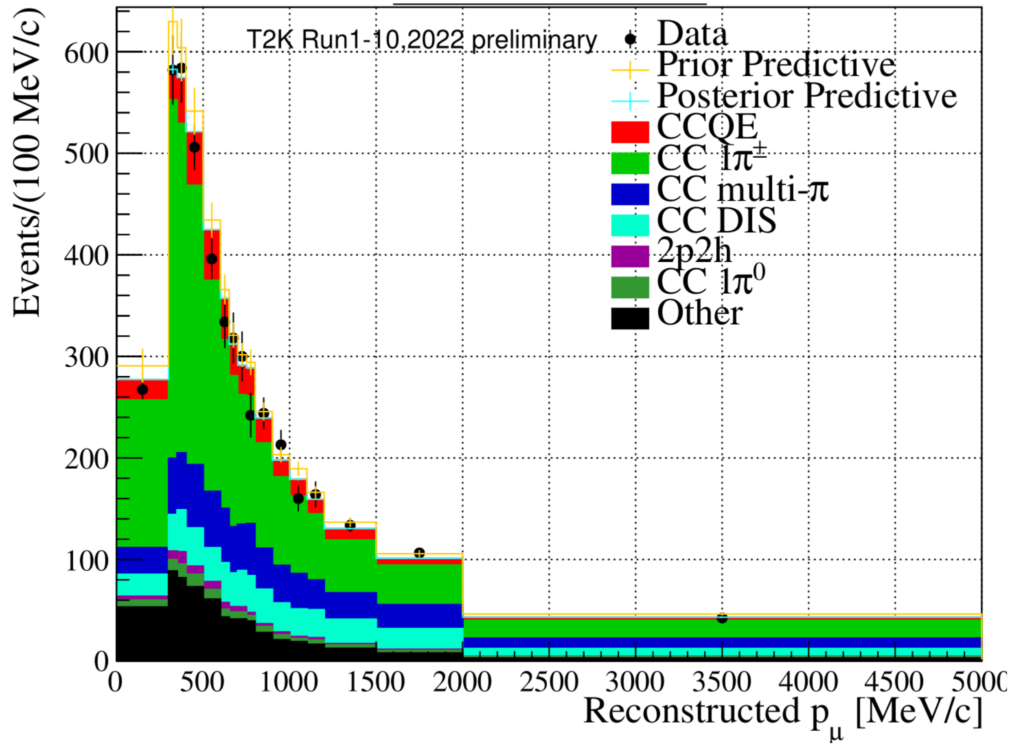
- Anti-ν_μ CC0π selection also relatively well-predicted
- ν_μ CC1π selection slightly overestimated

After the ND280 analysis

FGD1 anti-ν_μ CC0π



FGD1 CC1π

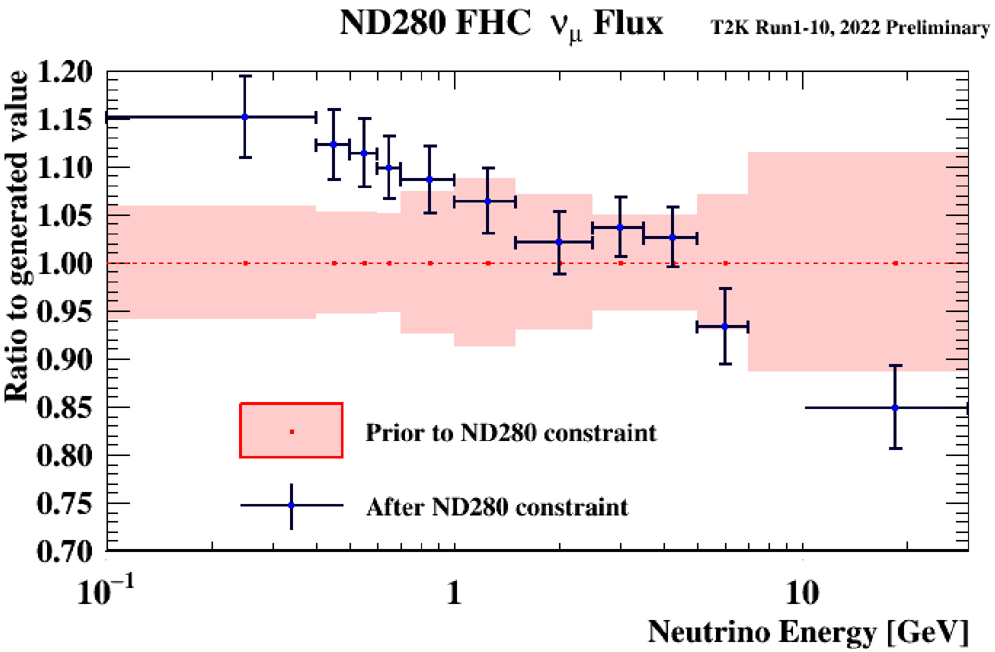


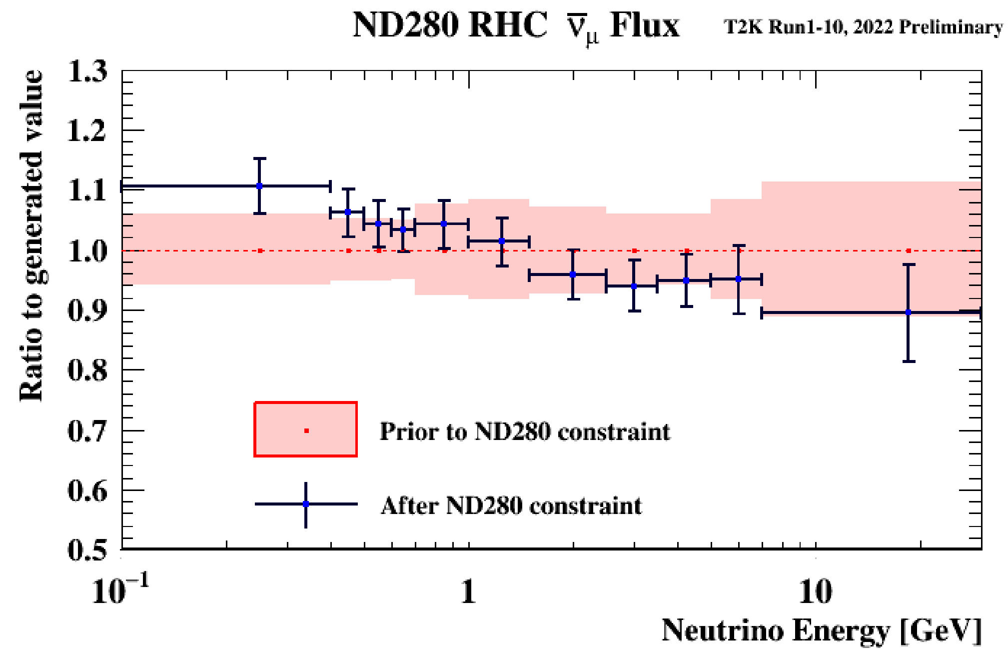
- CCQE fraction increases
- 2p2h and CC1π fractions stay the same
- CC1π fraction decreases
- CC multi-π and DIS fractions increase

The general results

- CC0π0p final states are underestimated, whereas CC0πNp and anti-ν_μ CC0π are predicted within statistical uncertainty
- CC1π samples are largely well-described
- Parameters pulled to compensate
  - Increased 2p2h cross-section
  - Increased CCQE cross-section
  - Decreased CC1π cross-section
  - Visible shape changes, even in muon momentum

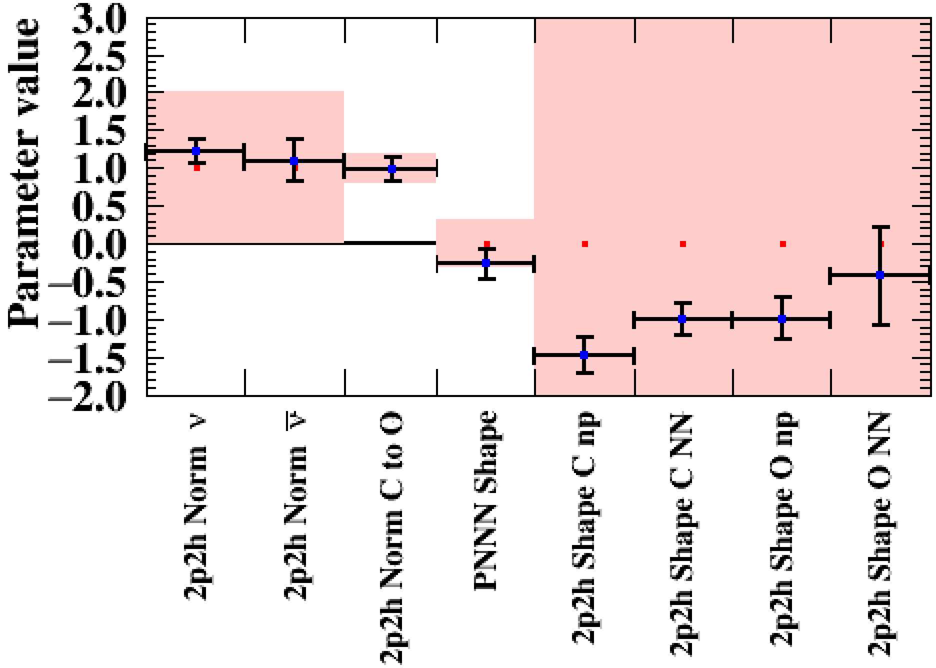
The flux parameters

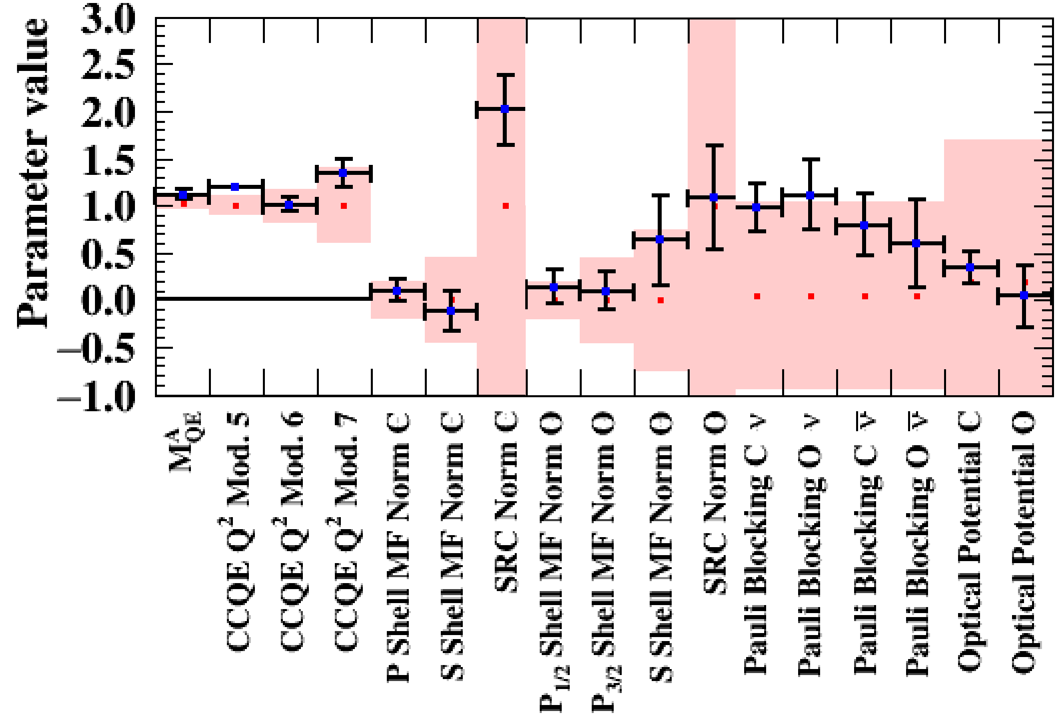




- Neutrino flux parameters significantly increase at low energies for both ν_μ and anti-ν_μ
- At 0.6 GeV (flux peak), see 10% increase in ν_μ and ~7% increase in anti-ν_μ
- Although chi-by-eye looks large, this spectrum distortion incurs a χ^2~60 penalty for 100 neutrino flux parameters
  - Not much tension with input prior from neutrino flux group

The 2p2h and CCQE parameters

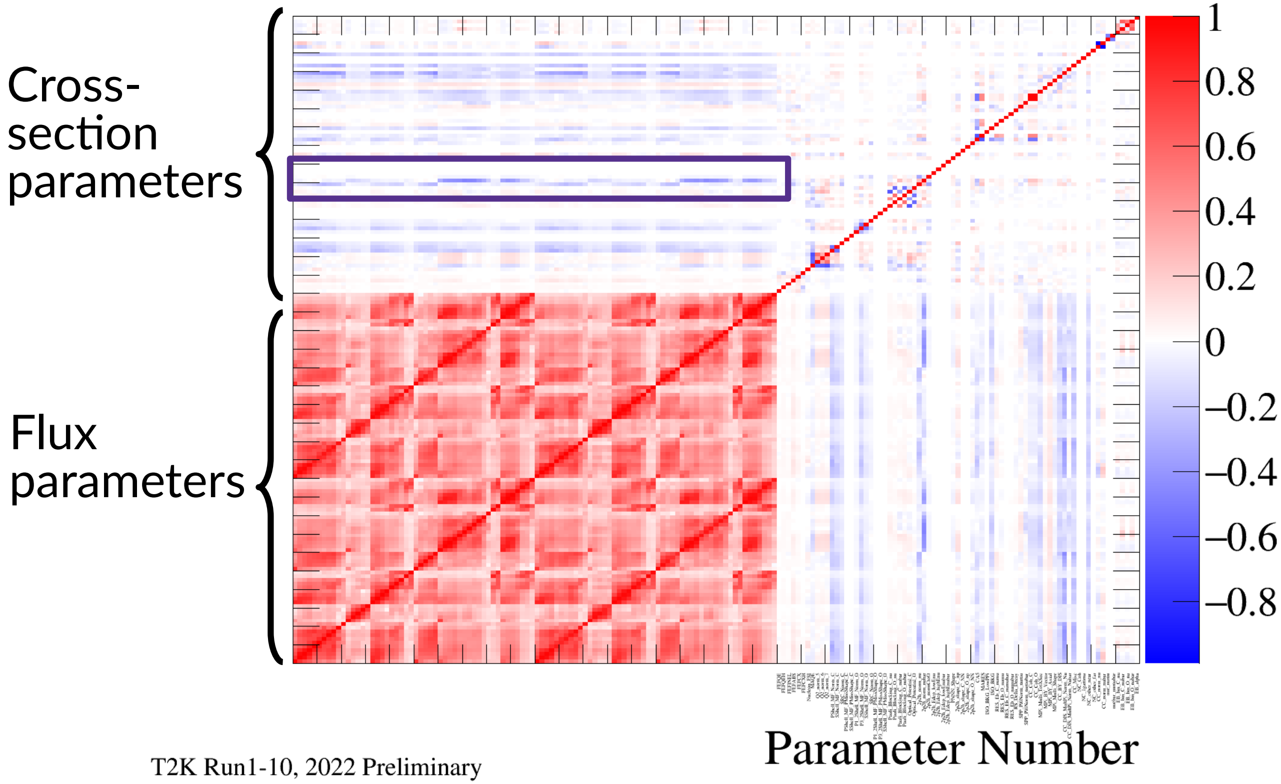




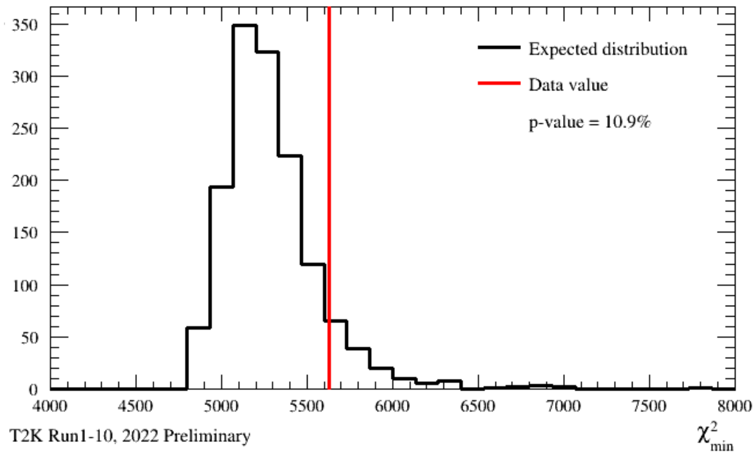
- 2p2h normalisation parameters are both increased
  - Neutrino and anti-neutrinos slightly different (~1.2 vs ~1.05)
- 2p2h shapes consistently pulled towards non-Δ region (shift 2p2h towards low q_0), for C/O and nn/np separated parameters
- M_A^{QE} increased above input prior, norm. of SF SRC pairs increased, CCQE high Q^2 cross-section increased
- Amount of Pauli blocking increased: changes low Q^2 region of CC0π 0p with little effect on CC0π Np events

The general results

- Neutrino flux and cross-section parameters correlate between each other due to degenerate effects
  - e.g. norm of 2p2h has roughly similar effect to a number of flux parameters



- Finally also perform a p-value test of observed fit to data compared to the model before the fit
  - 10.9% using the total χ^2



Inspecting the ND280 constraint

- Cross-section systematics are the largest uncertainties before fitting to ND280 data
- After the fit to ND280 data, cross-section and flux systematics are the largest contributors, between 2.5-3.5% effects
- ND280 detector uncertainties are between 1-2% effects with the current selections

Sample	$\delta N/N (\%)$					
	Flux		Xsec		ND280	
	pri.	post.	pri.	post.	pri.	post.
FGD1 FHC CC0π-0p-0γ	5.0	2.7	11.8	2.8	1.8	1.2
FGD1 FHC CC0π-Np-0γ	5.5	2.8	11.7	3.2	3.5	2.2
FGD1 FHC CC1π-0γ	5.2	2.7	9.1	2.7	3.0	1.4
FGD1 FHC CC-Other-0γ	5.4	2.8	8.0	2.8	5.2	2.3
FGD1 FHC CC-Photon	5.5	2.8	8.5	2.8	2.8	1.8
FGD1 RHC CC0π	4.9	3.2	11.3	3.2	1.9	1.2
FGD1 RHC CC1π	4.6	3.1	10.3	3.0	4.2	2.6
FGD1 RHC CC-Other	4.5	2.9	9.3	3.0	3.5	2.0

Propagating the ND280 constraint

- Before the ND280 constraint, impact at SK is similar to ND280: dominated by cross-section uncertainties

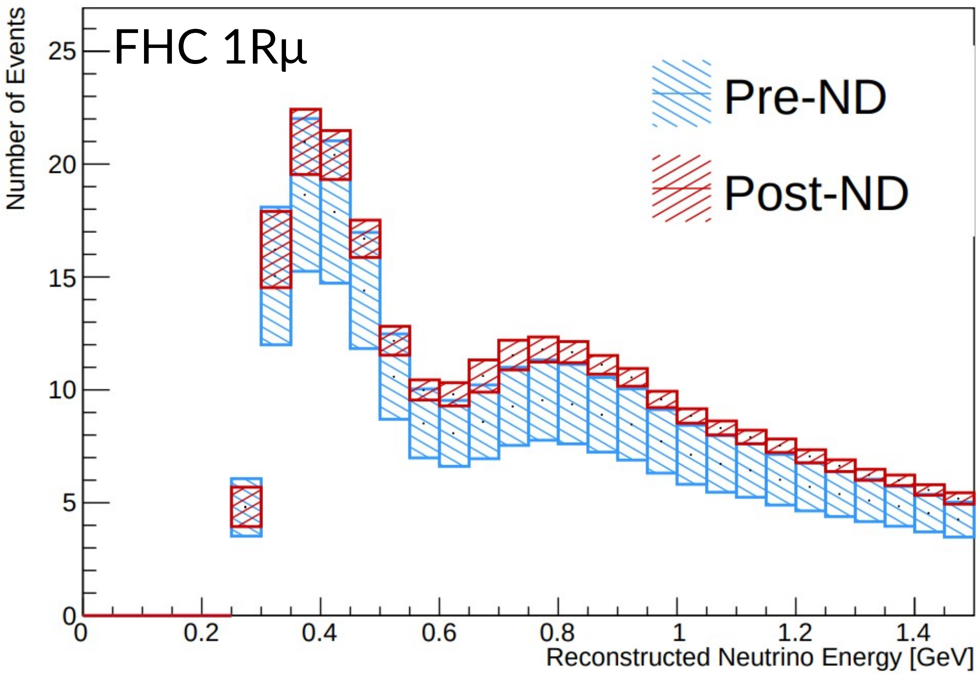
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total	16.7	14.6	12.5	17.3	14.4	20.9	11.6

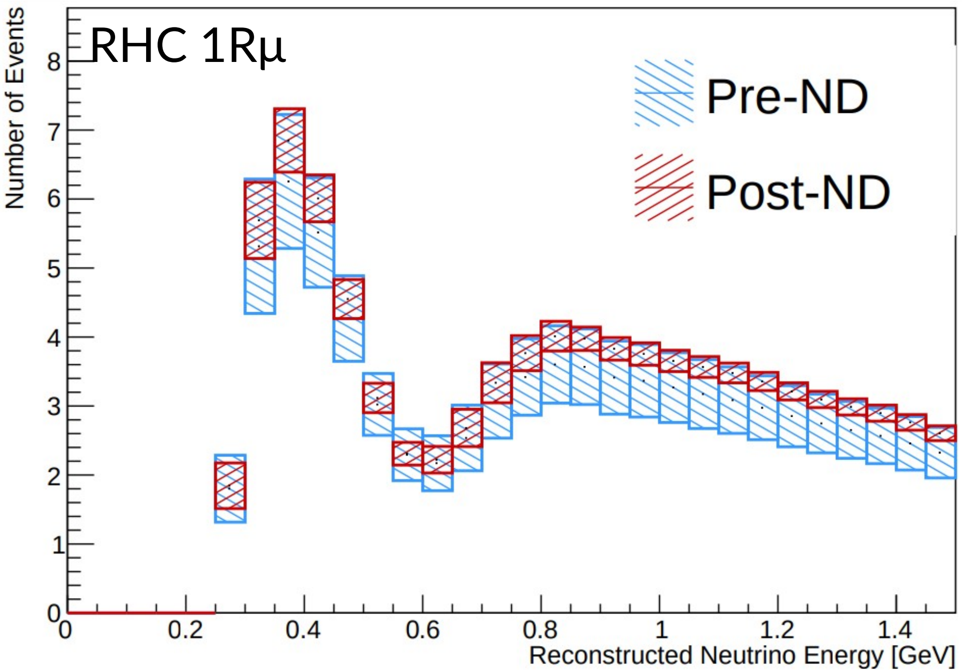
- After the ND280 analysis and correlating the flux and cross-section systematics, the flux+cross-section uncertainties are often smaller than SK det uncertainties

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total	3.4	3.9	4.9	5.2	5.8	14.3	4.5

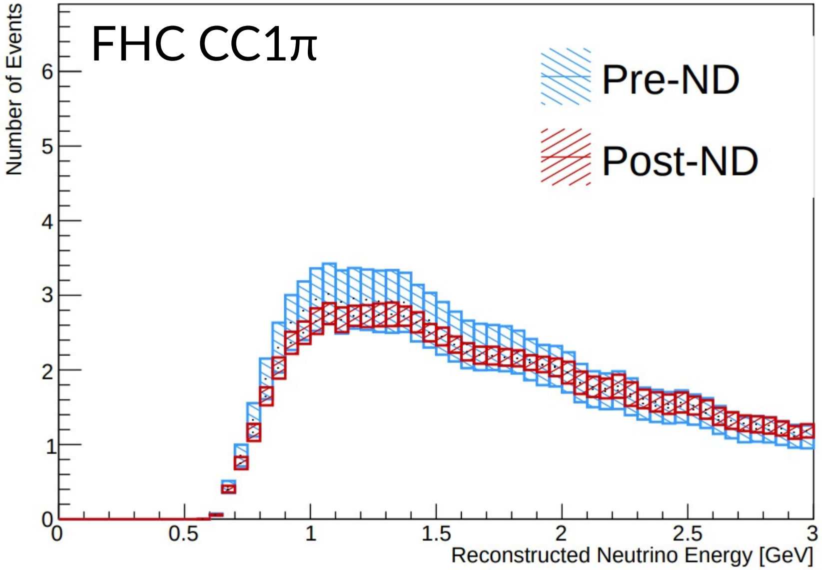
Propagating the ND280 constraint

- The ND280 analysis also changes the prediction at SK



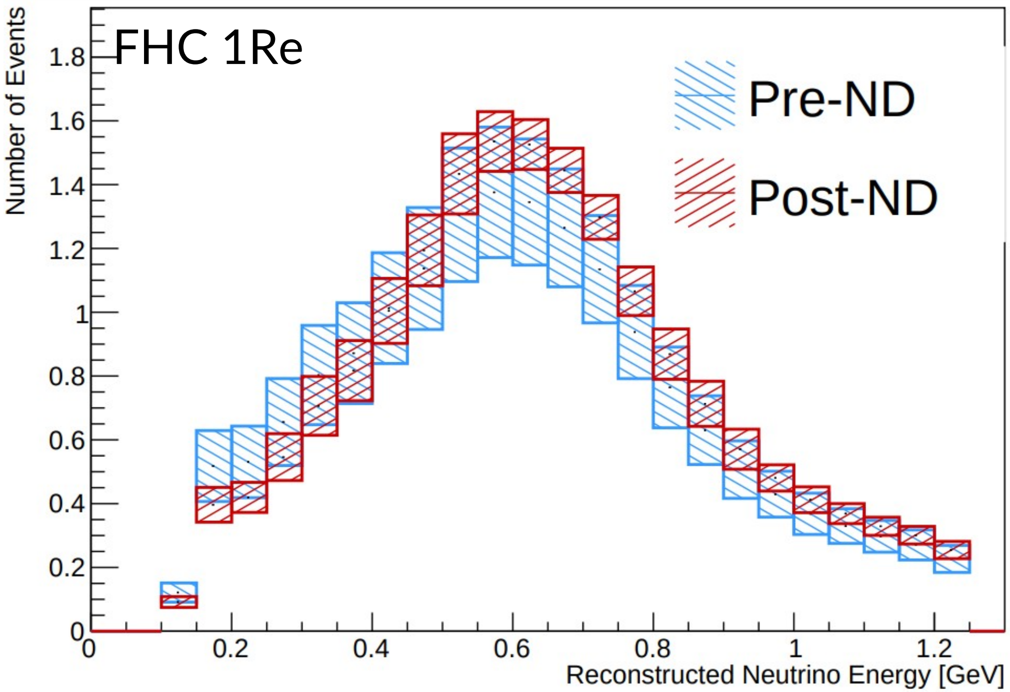


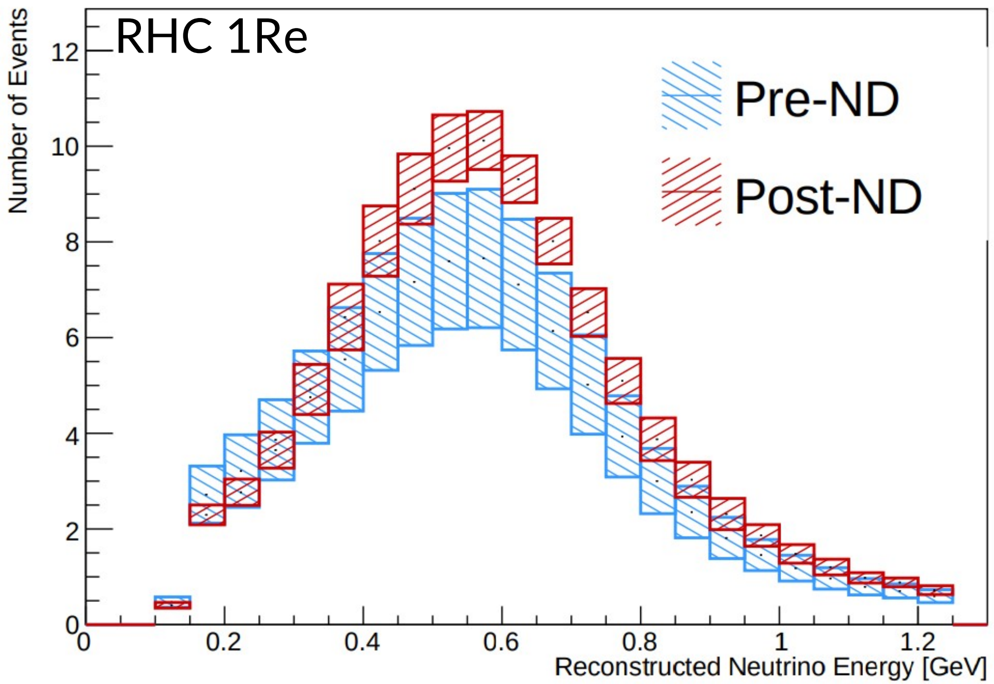
- Increases the single-ring muon selections
  - Equivalent to CC0π
- Decreases the new CC1π muon selection
  - Large fraction of CC1π events



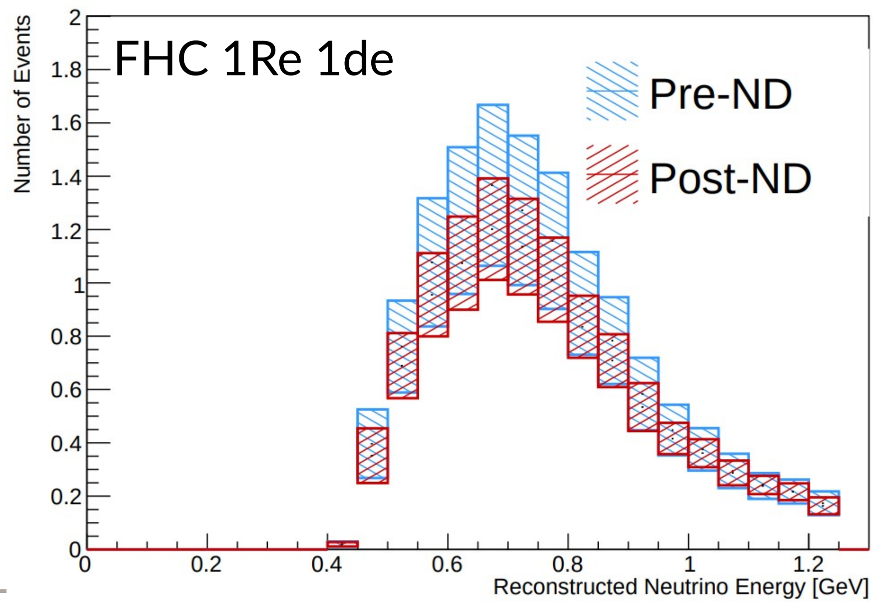
Propagating the ND280 constraint

- Similar applies to the electron neutrino selections at SK





- General increase in CC0π and decrease in CC1π cross-section reflected in samples at SK



The future and summary

Future plans

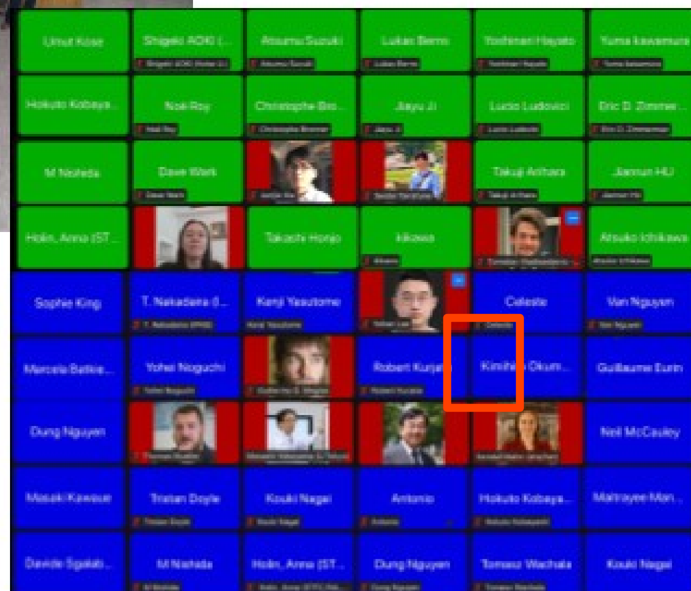
- Analysis in proton and pion kinematics, possibility of single transverse variables
  - Proton tagging in CC1π mode better separates resonant channels and SIS/DIS
  - **Pion and proton kinematics will require significant interaction model development**
- Full kinematic coverage selections with backward-going muons
  - Higher Q^2 events will enter analysis
  - See Danaisis' talk for one of the cross-section measurements and status
- ND280 Upgrade will significantly improve particle thresholds and resolution, geometric acceptance, neutron tagging
  - See more in Laura's talk
- Significantly more data to be collected, allowing for further refinement of our selections (e.g. proton tagging in anti-ν_μ)

Summary

- Near-detector analysis on T2K starts with a CC-inclusive selection
  - Splits into 22 selections and performs a fit to expose weaknesses in model for oscillation analysis; both signal and background
- Complementary tool to dedicated cross-section analyses
  - With a focus on impact on oscillation results
  - Entire analysis in reconstructed space
- Impact of analysis on cross-section uncertainties at SK go from 10-15% to 3-4%
- Can also change the central value prediction at SK
  - This analysis increases CCQE and 2p2h cross section
  - Decreases CC1π cross section
  - Generally consistent with previous T2K ND280 analyses
- Hoping to write up analysis into dedicated publication on interaction model and near-detector analysis

Thanks!

Tokai



Online

T2K May 2022 hybrid meeting

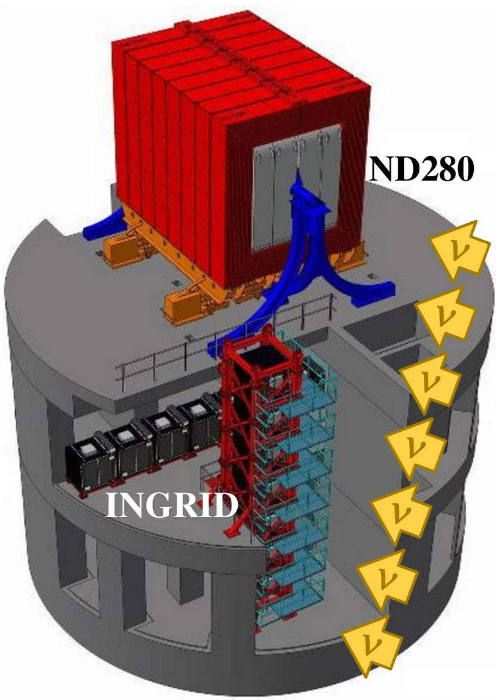
CERN

Questions or comments? c.wret@rochester.edu

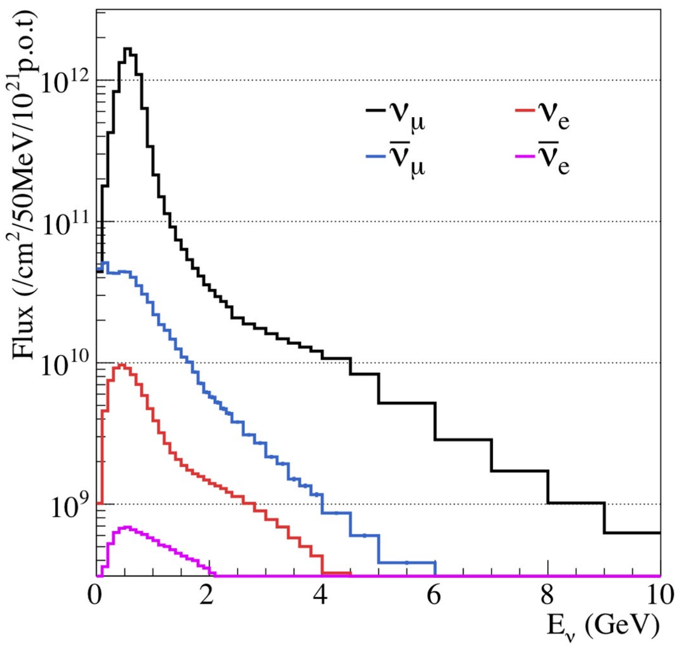
Backups

The T2K near detectors

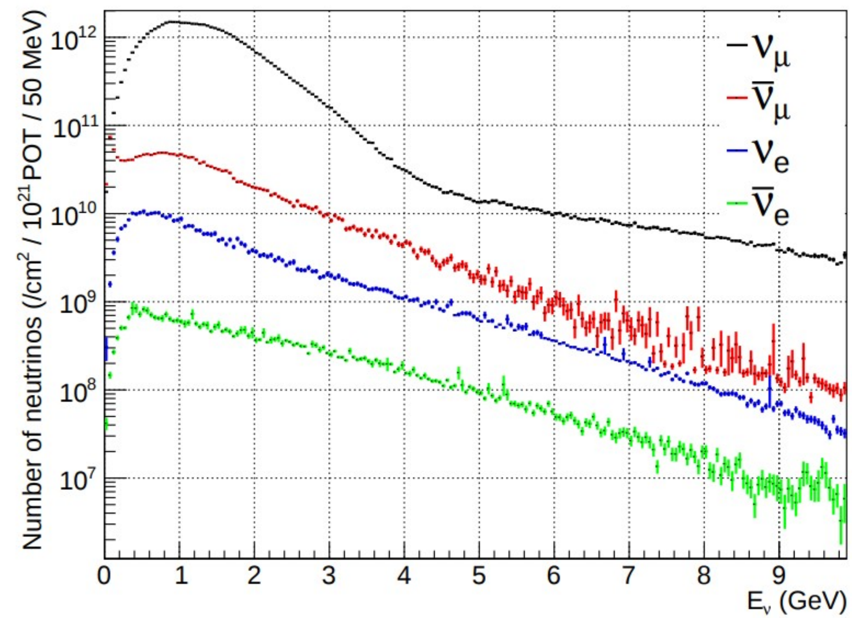
- Fluxes: ν_μ and anti-ν_μ dominated with different E_ν
  - ND280: 2.5° off-axis, 0.6 GeV narrow band – used in OA
  - INGRID: on-axis, 1.3 GeV wide band – used for monitoring



ND280 flux (off-axis)



INGRID flux (on-axis)

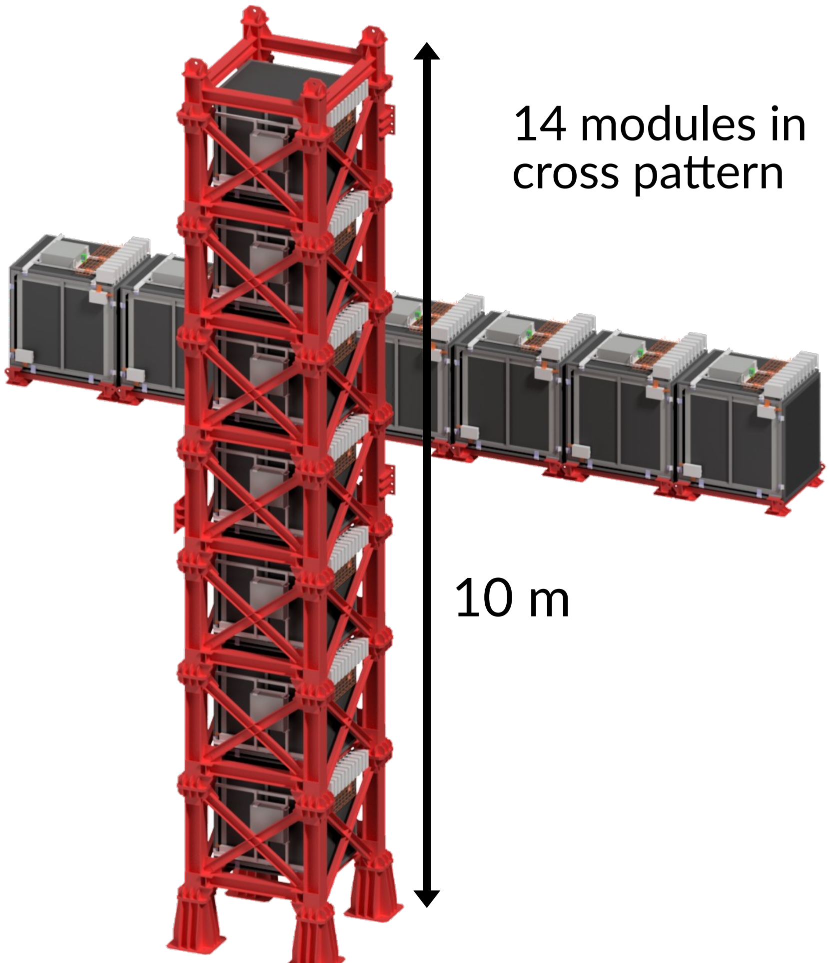


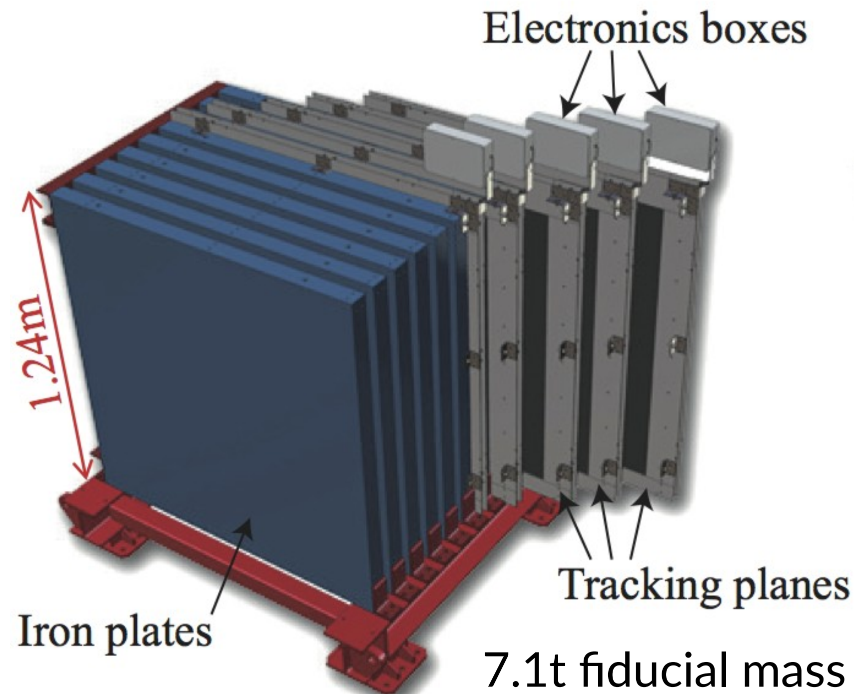
- Multiple targets in INGRID and ND280: C_8H_8, H_2O, Ar, Pb, Fe
- More detectors rolling into the ND280 pit, e.g. WAGASCI/BabyMIND, NINJA, proton and water modules

JINST 12 (2017) PTEP 2021 4 (2021) Phys. Rev. D 102, 072006 (2020)

The INGRID near detector

- Arranged in cross pattern for beam direction measurements
  - INGRID monitors ν direction and rate spill-by-spill



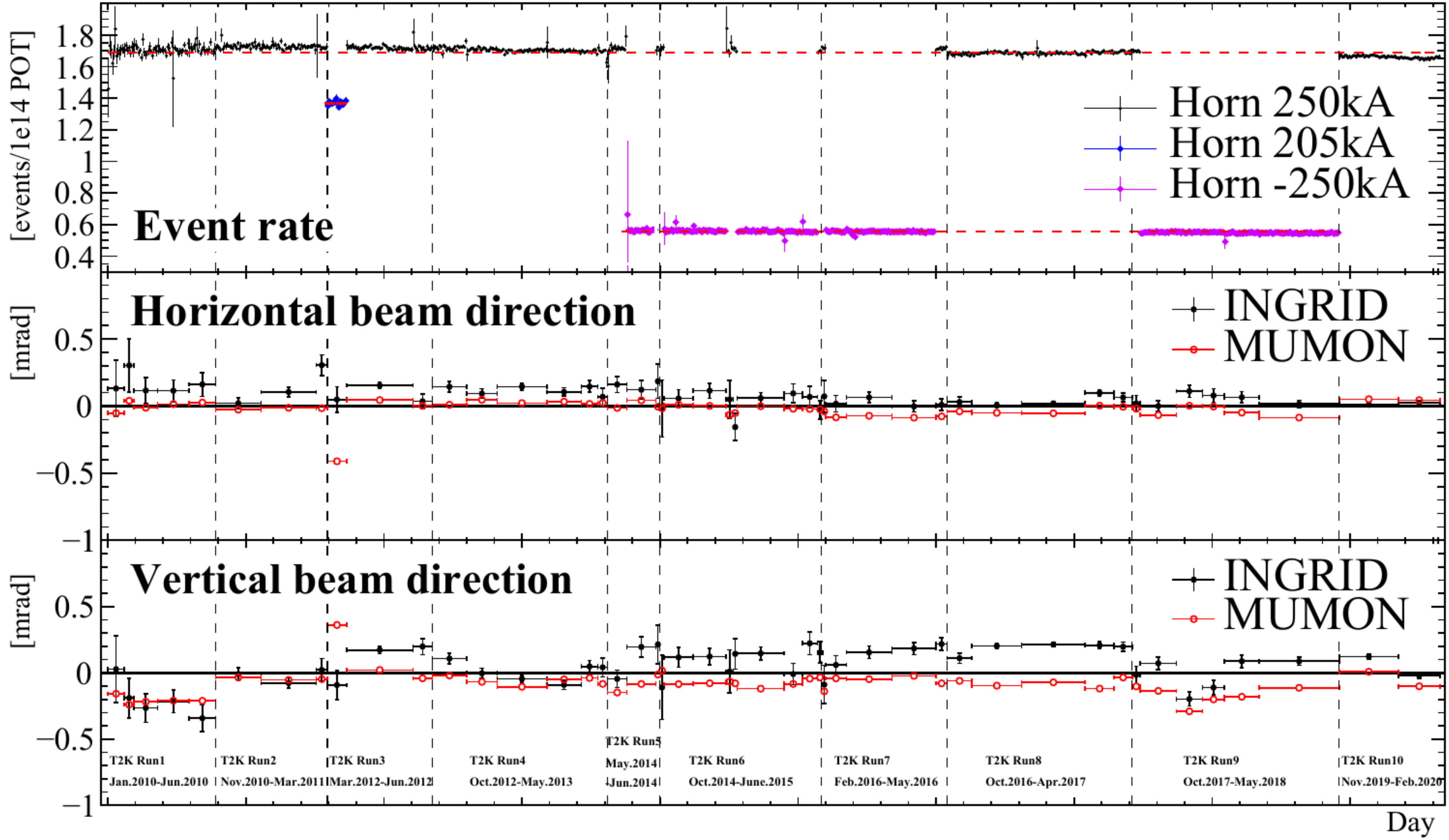


7.1t fiducial mass
per module

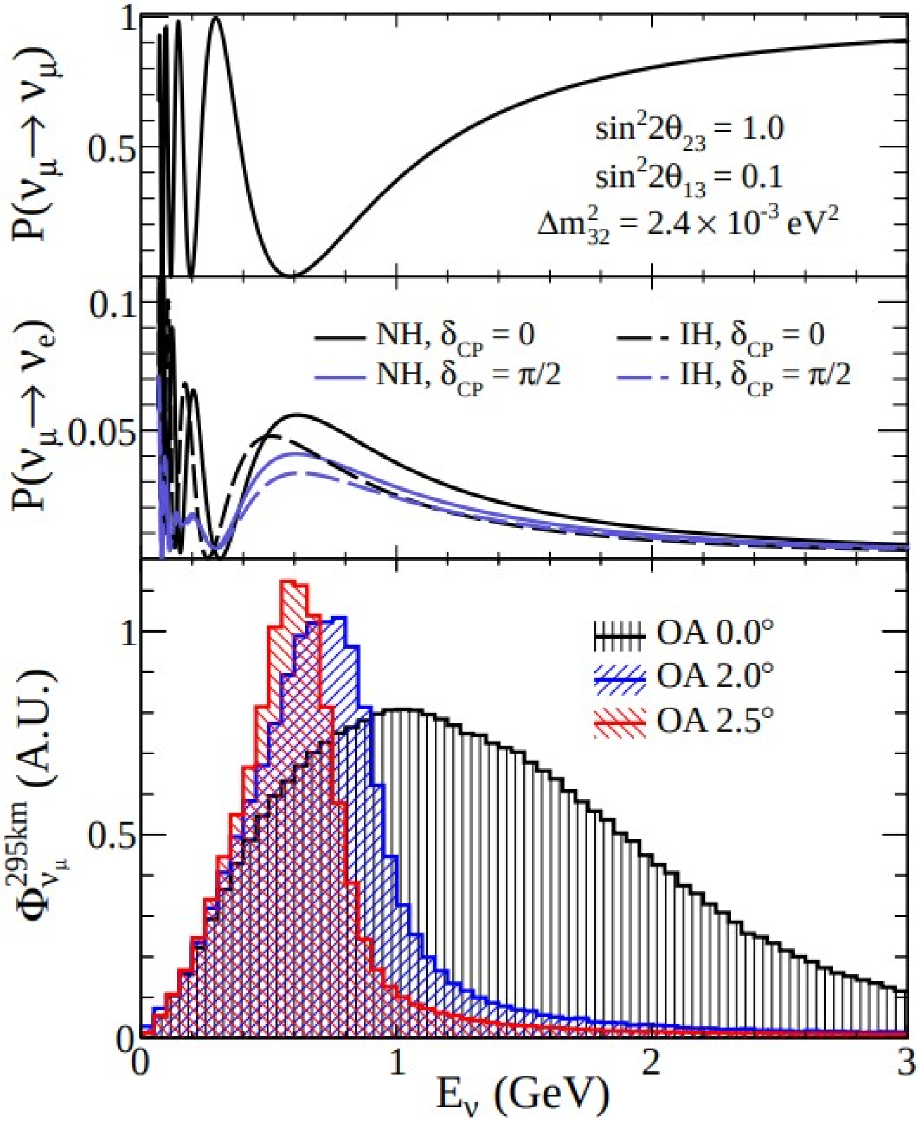
- Proton module for dedicated cross section measurements
  - No iron plates: fully plastic scintillator

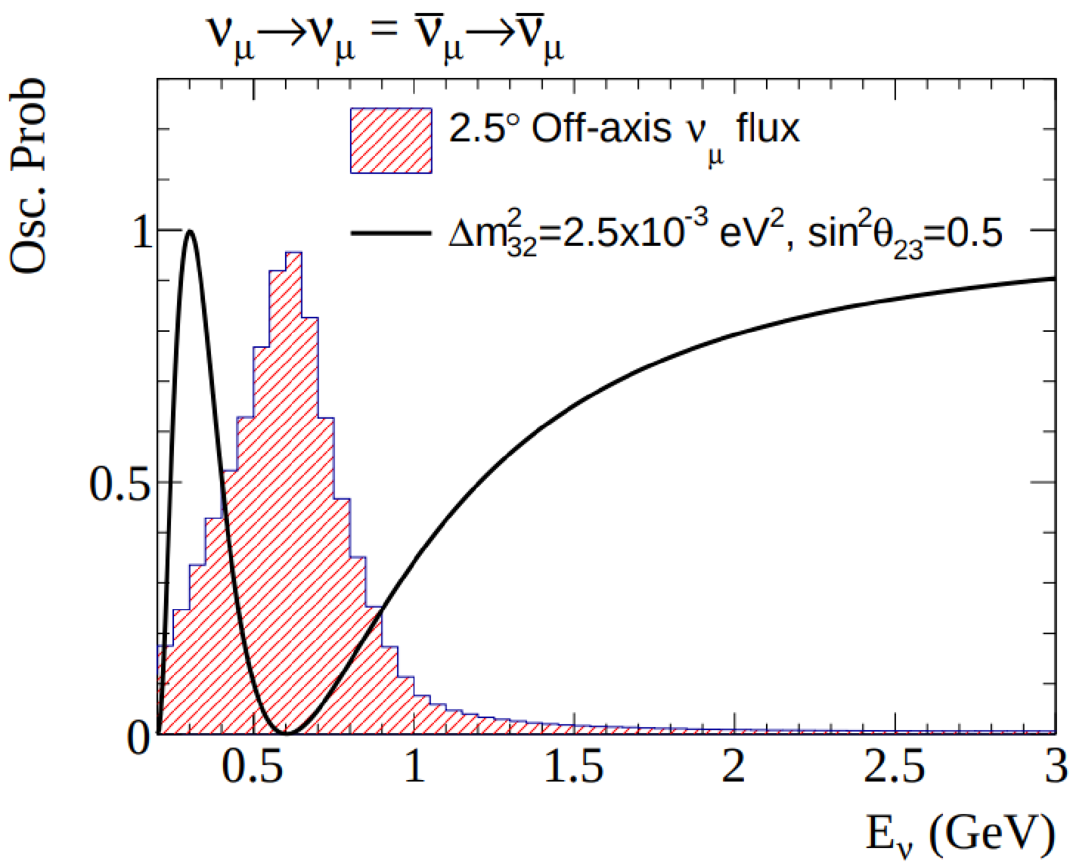
INGRID monitoring

- Good neutrino beam stability observed in INGRID
- Well within ±1 mrad tolerance on beam direction

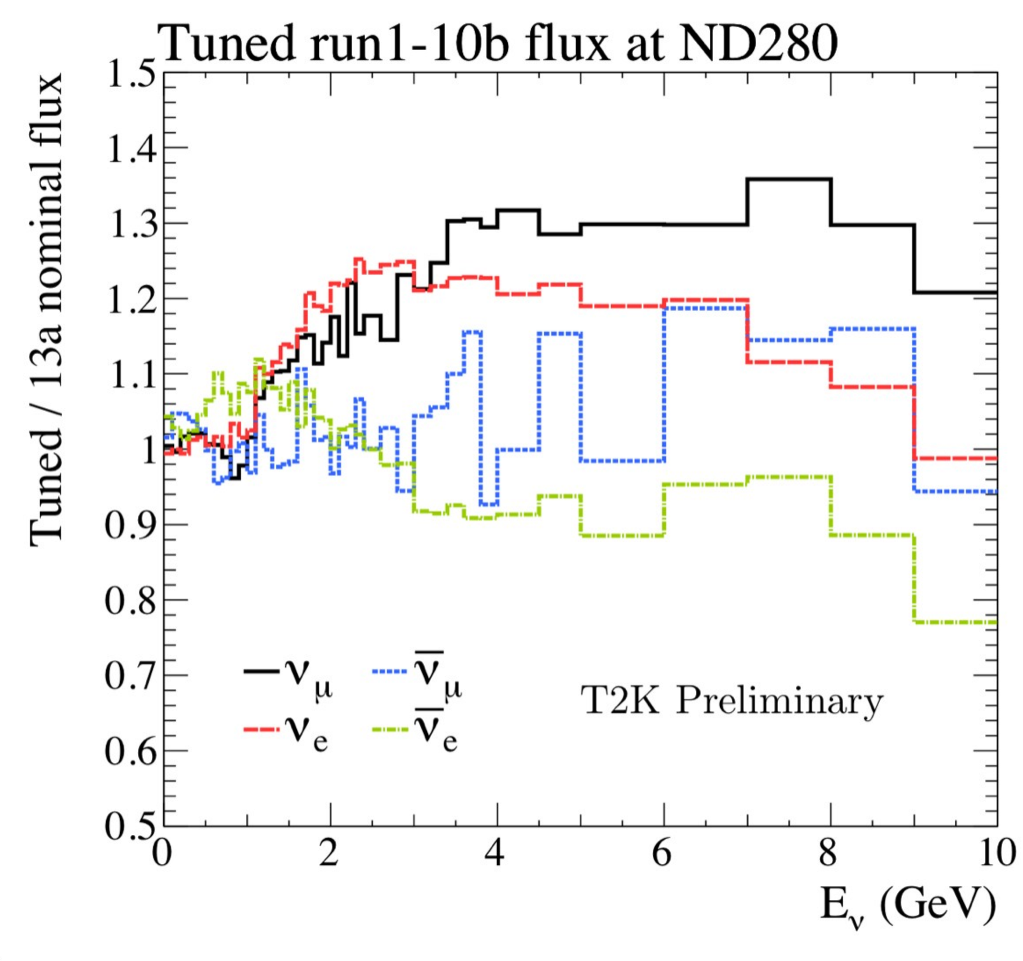


Off-axis effect

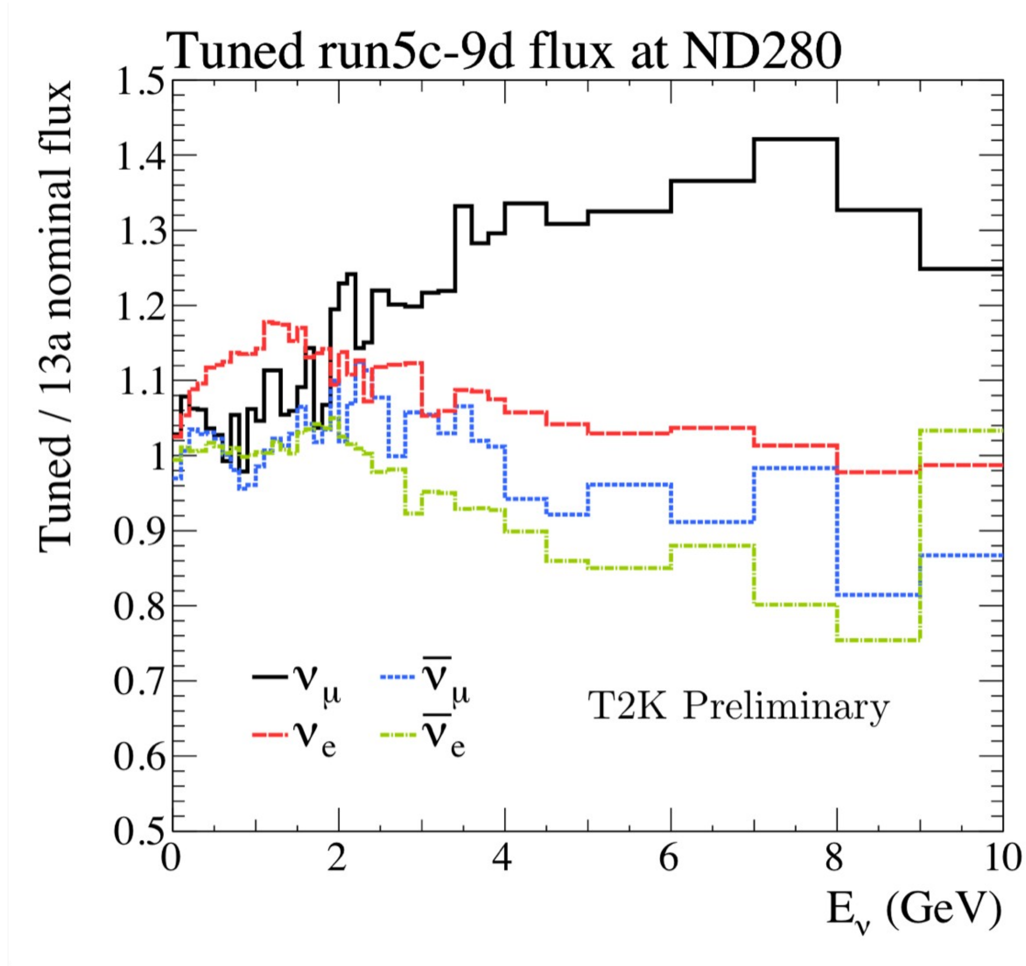




Flux tune

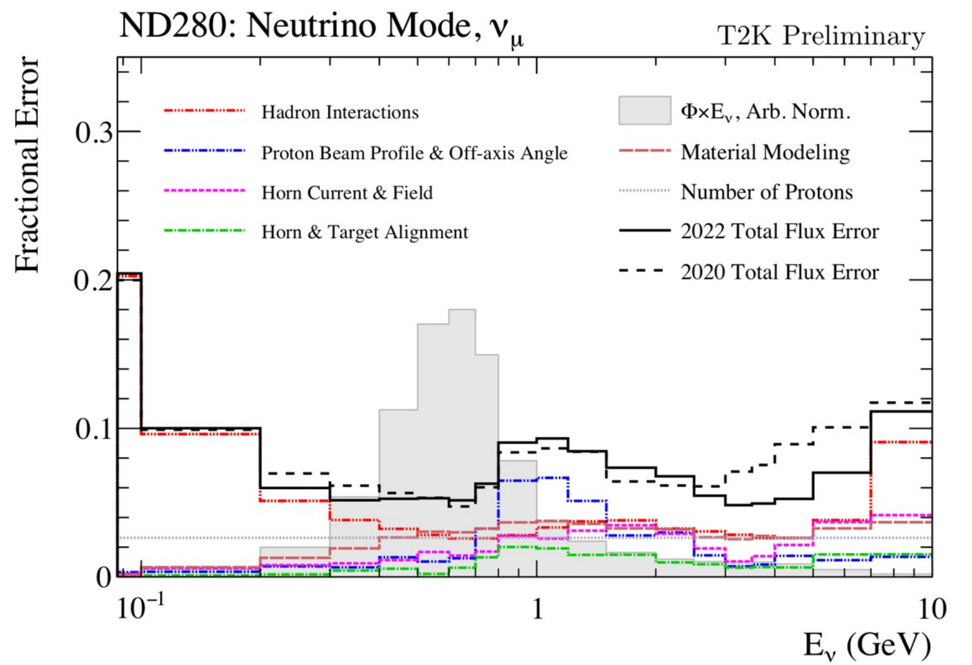


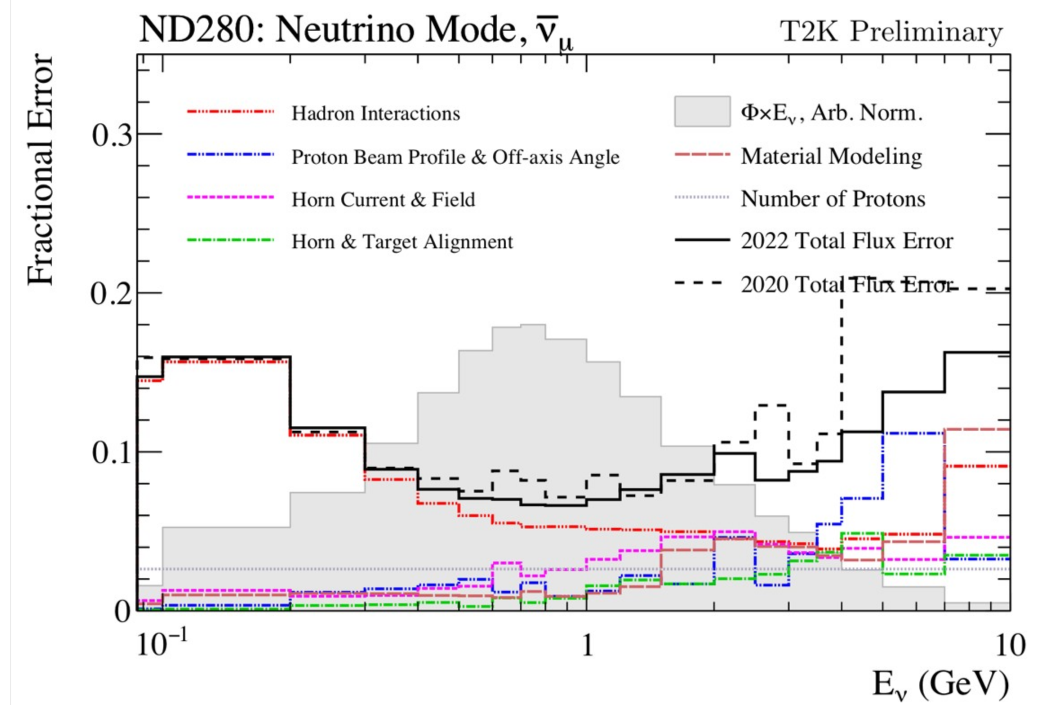
Tuned run1-10b flux at ND280
Tuned / 13a nominal flux
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0
2
4
6
8
10
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
T2K Preliminary

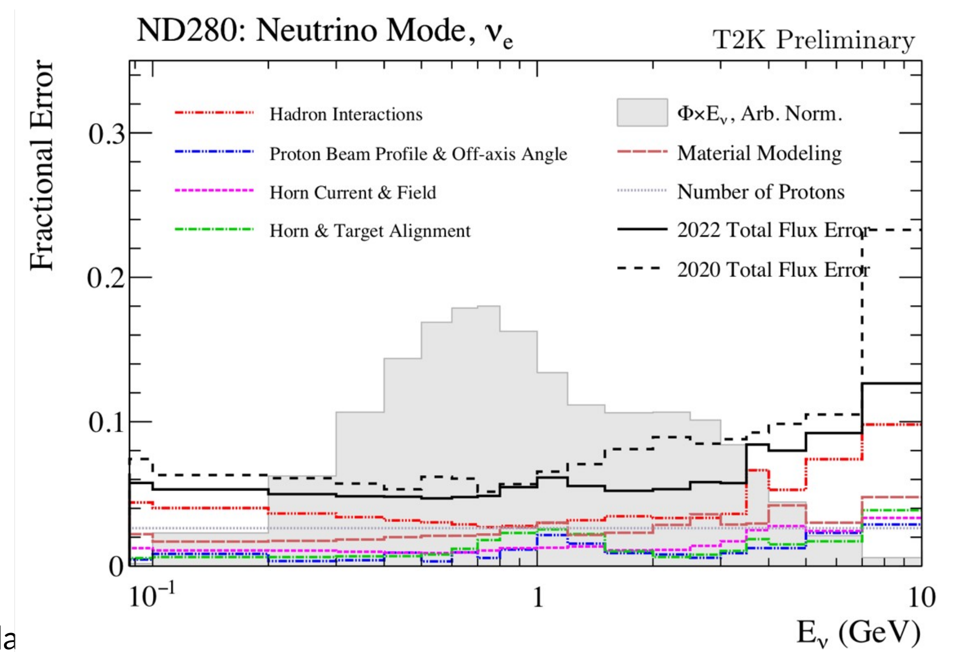


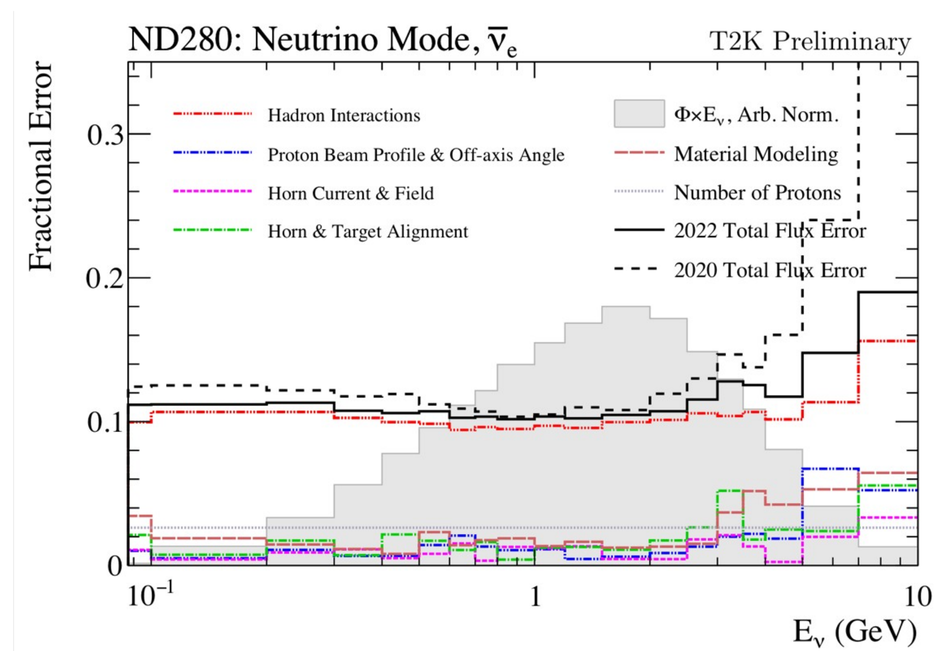
Tuned run5c-9d flux at ND280
Tuned / 13a nominal flux
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0
2
4
6
8
10
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
T2K Preliminary

Flux uncertainties, FHC

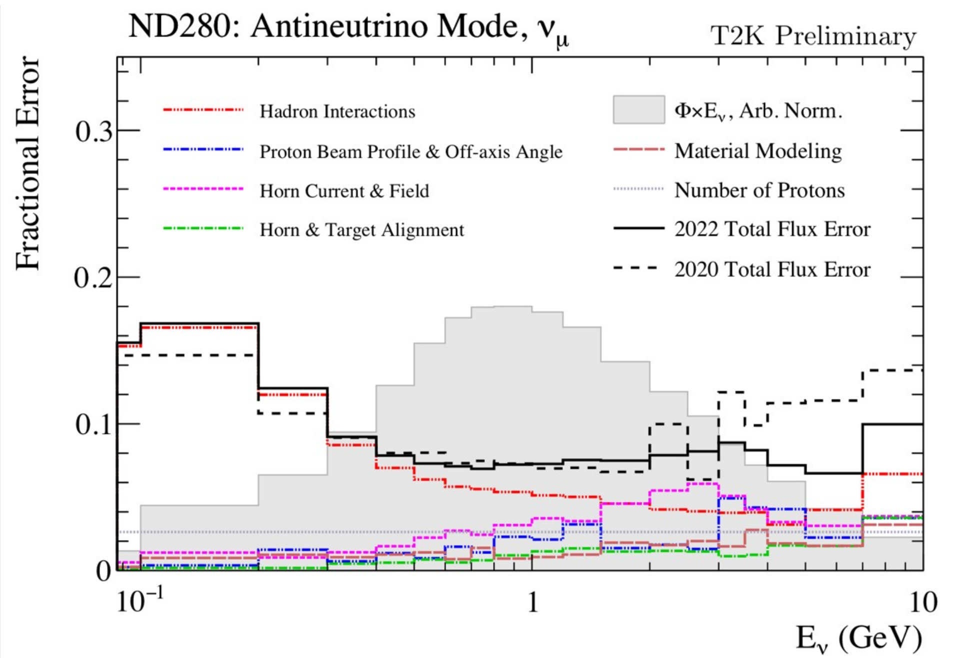


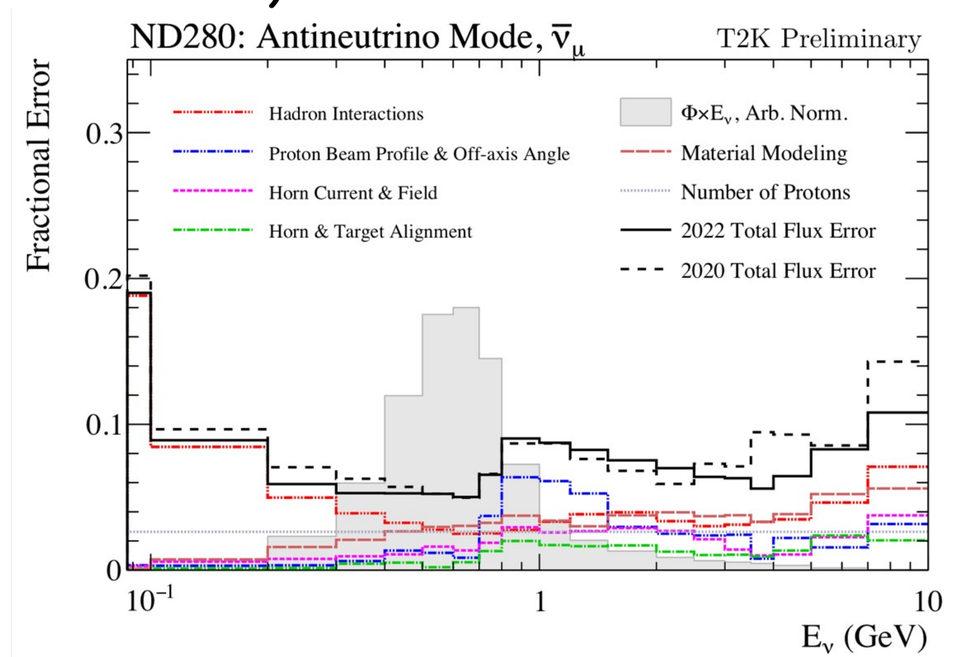


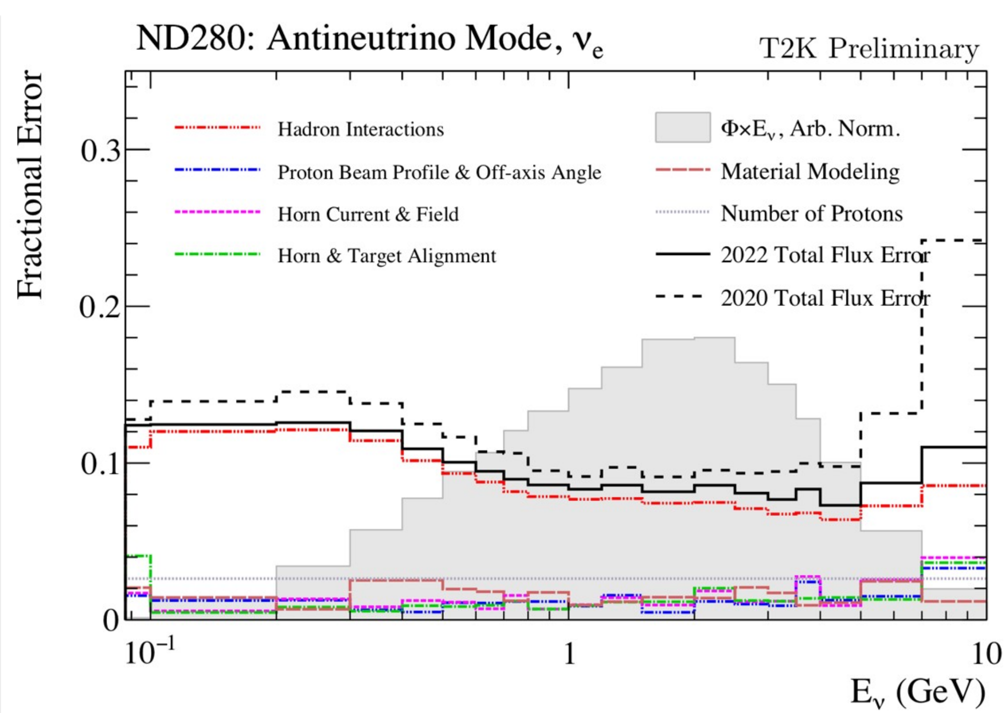


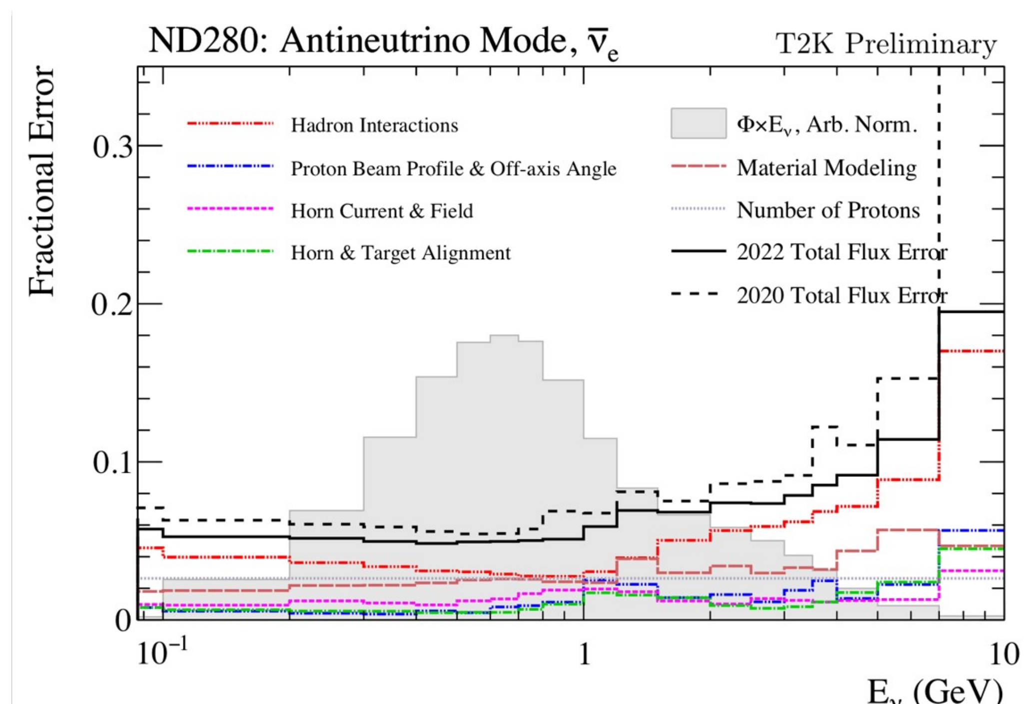


Flux uncertainties, RHC



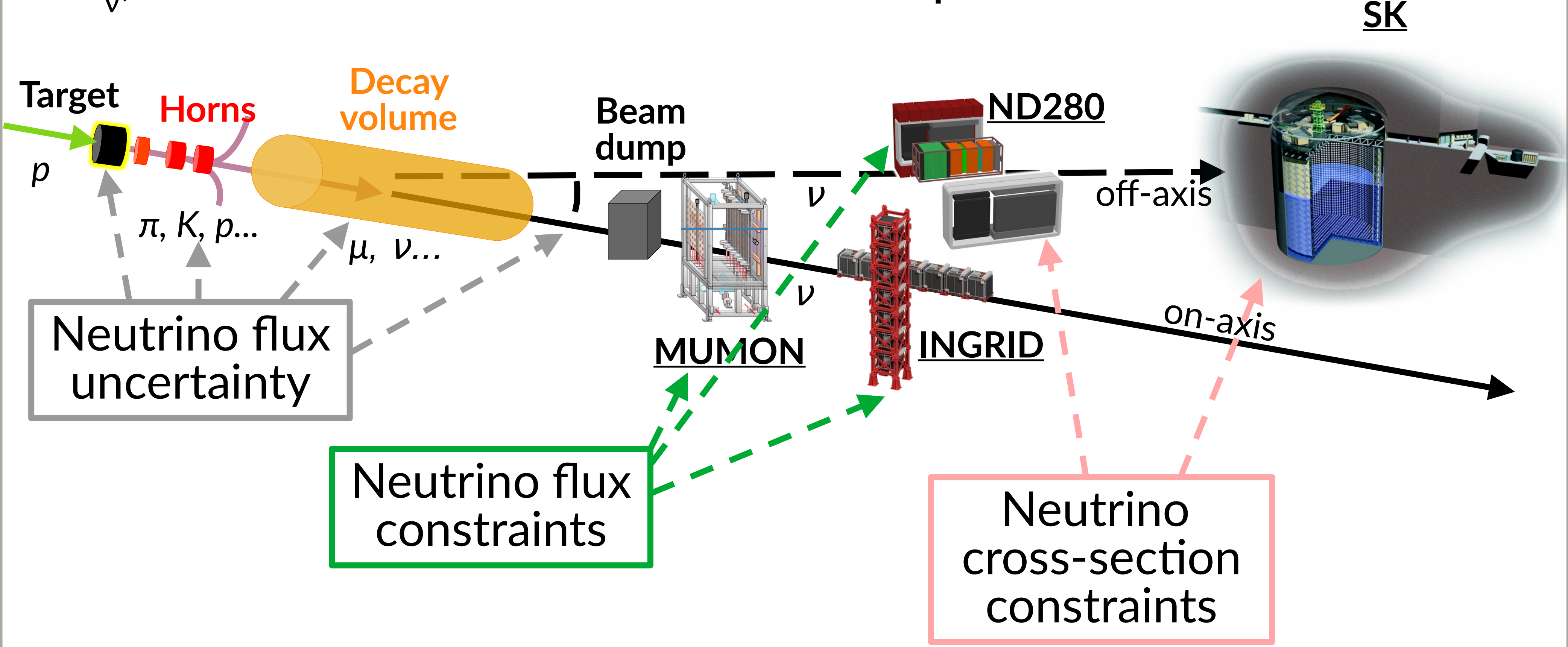






The T2K uncertainty sources

- Modelling relates observables (e.g. p_μ θ_μ) to neutrino energy, E_ν, which constrains the oscillation parameters



- MUMON monitors muons, INGRID monitors neutrinos
- ND280 and SK used directly in analysis, constraining the systematics and oscillation parameters

The T2K uncertainty sources

- Neutrino interaction is an important shared systematic for ~GeV scale neutrino oscillation experiments

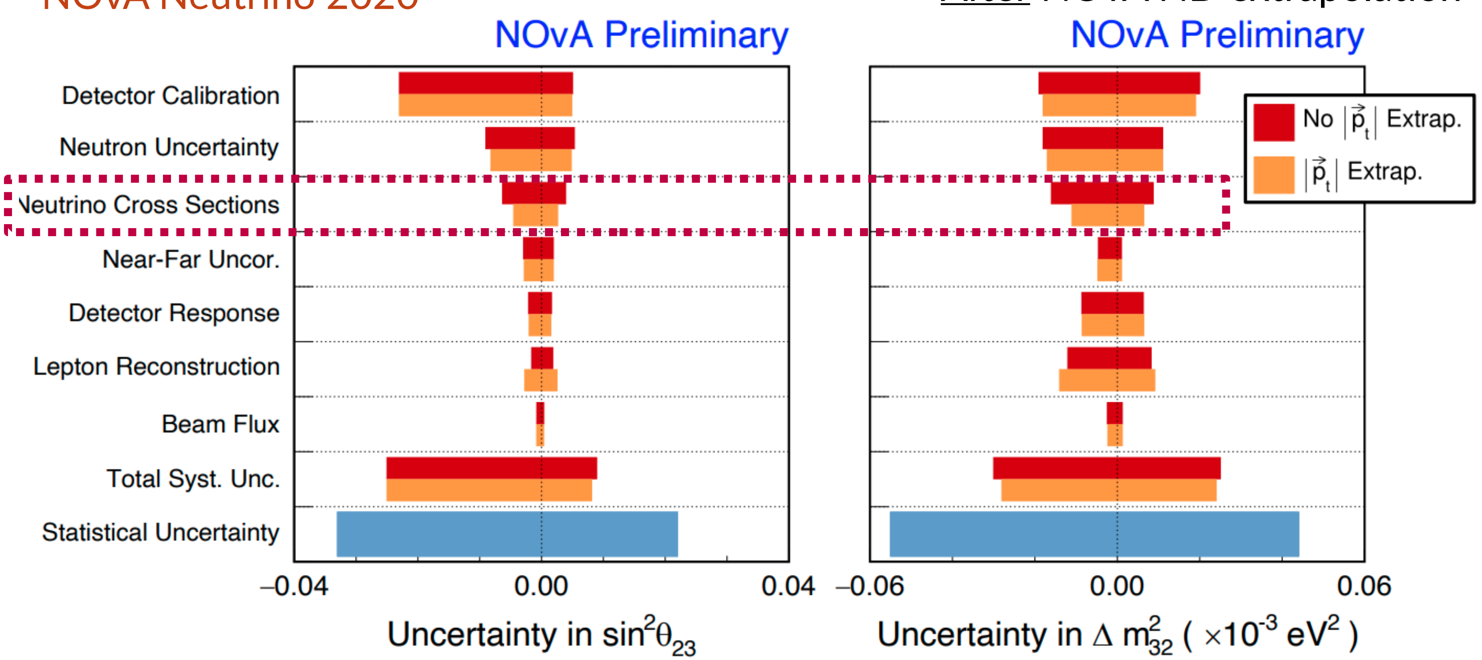
T2K Neutrino 2020

Before fit to T2K ND data

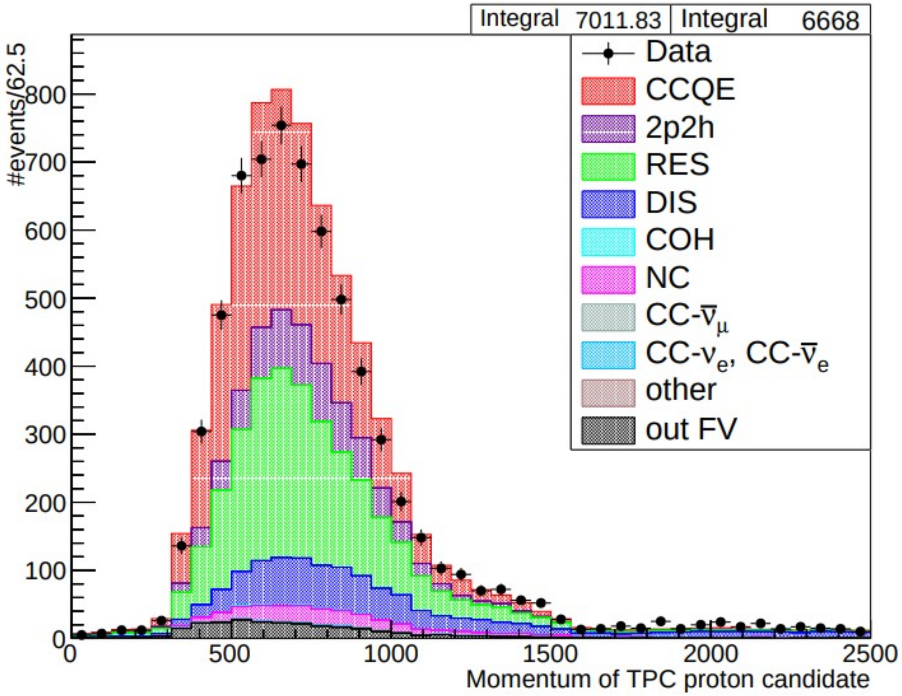
Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+
Flux	5.1%	4.7%	4.8%	4.7%	4.9%
Cross-section (all)	10.1%	10.1%	11.9%	10.3%	12.0%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%

NOvA Neutrino 2020

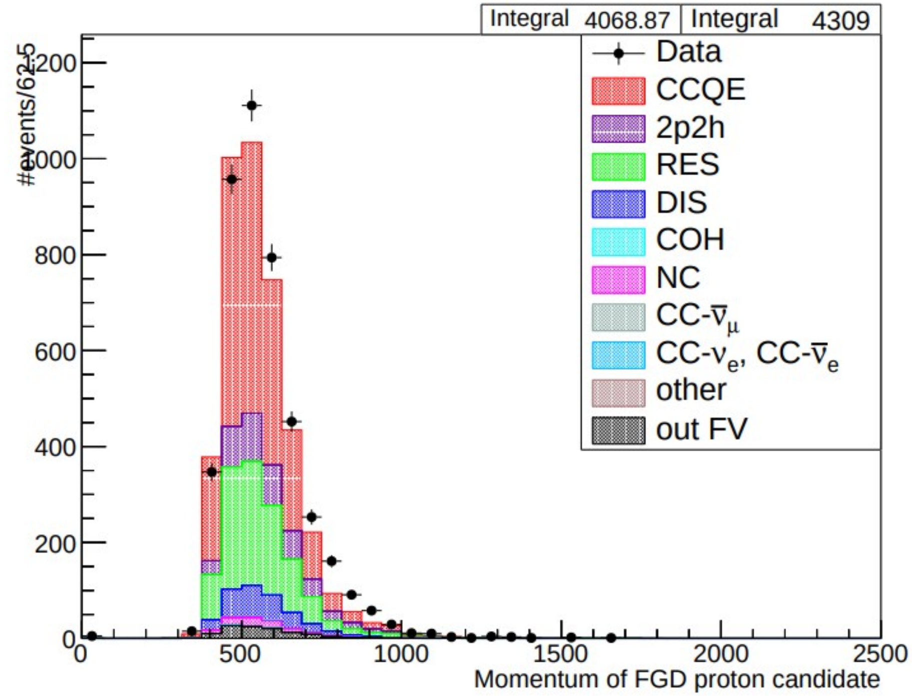
After NOvA ND extrapolation



Proton tagging in ND280



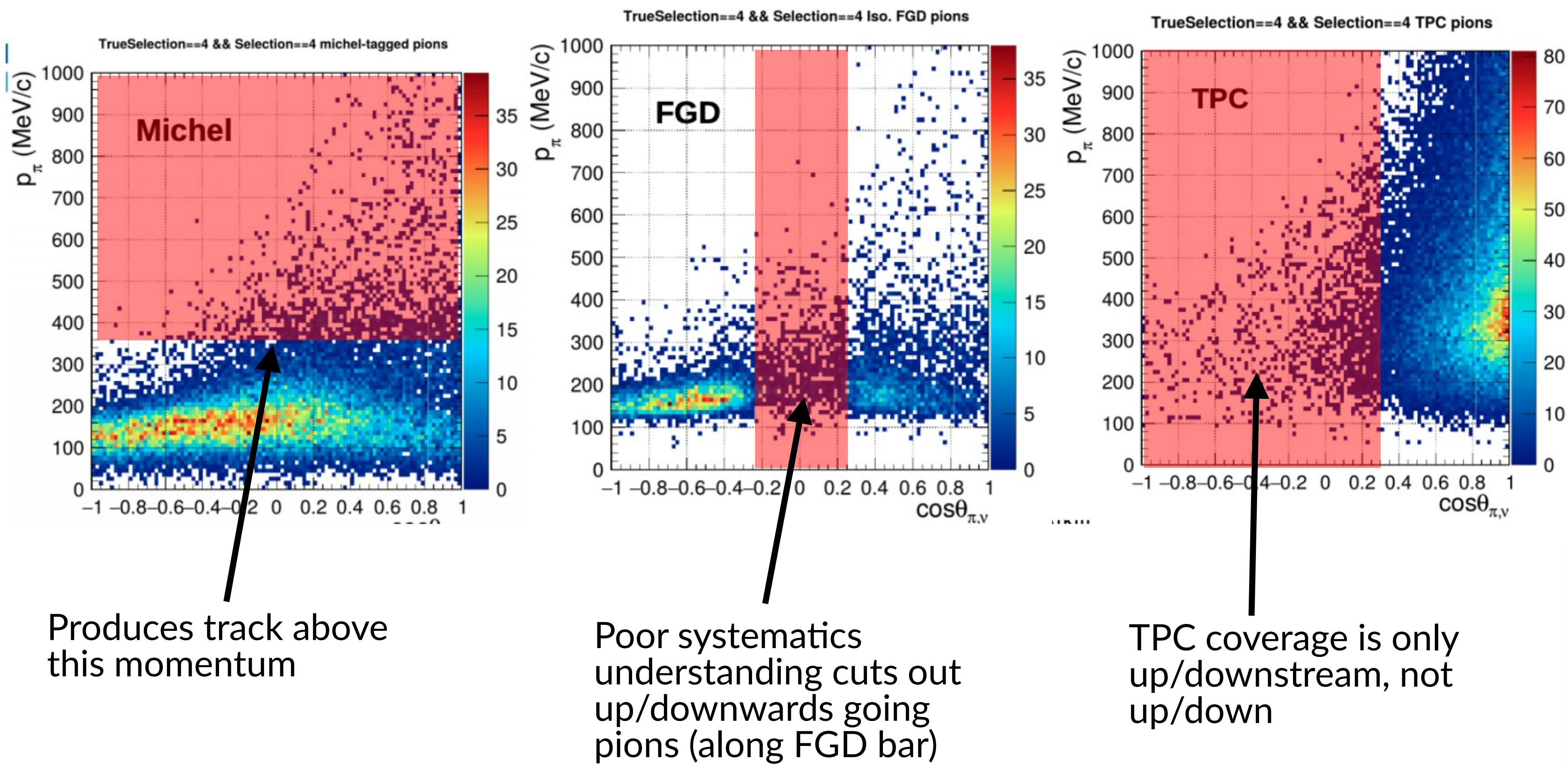
(a) TPC matched



(b) isoFGD

Pion kinematics dependence

- Relevant ND280 selection: FHC ν_μ FGD1/2 CC1π^+
- Each tag sculpted by pion kinematics; momentum and angle



Efficiencies

- Relevant ND280 selection: FHC ν_μ FGD1/2 CC1π^+
- Look at where true FGD1/2 CC1π^+ events end up