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T2K strategy on cross-sections: a personal view

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Overview

- What is T2K?
- Global strategy T2K:
  - Fits for oscillations.
  - Improving models for oscillations beyond oscillations
- Future:
  - N280 upgrade
  - Expectations
- Recap

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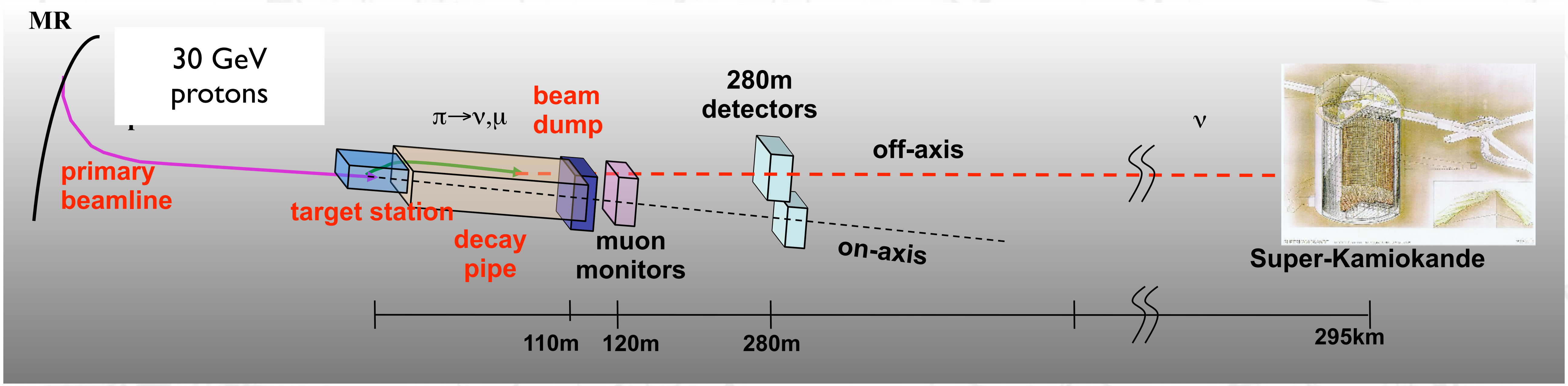
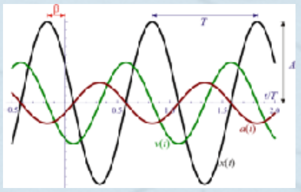
T2K experiment



Neutrinos produced in a particle accelerators or nuclear reactors.

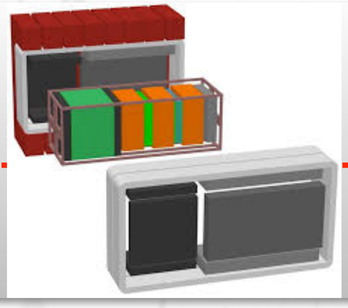
Neutrino flux properties

ν oscillations



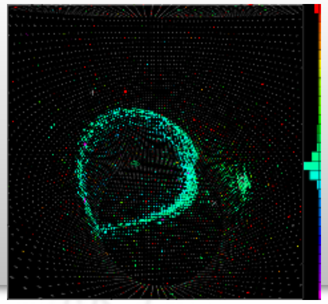
Neutrino flux & flavour

$\nu_\mu, \bar{\nu}_\mu$

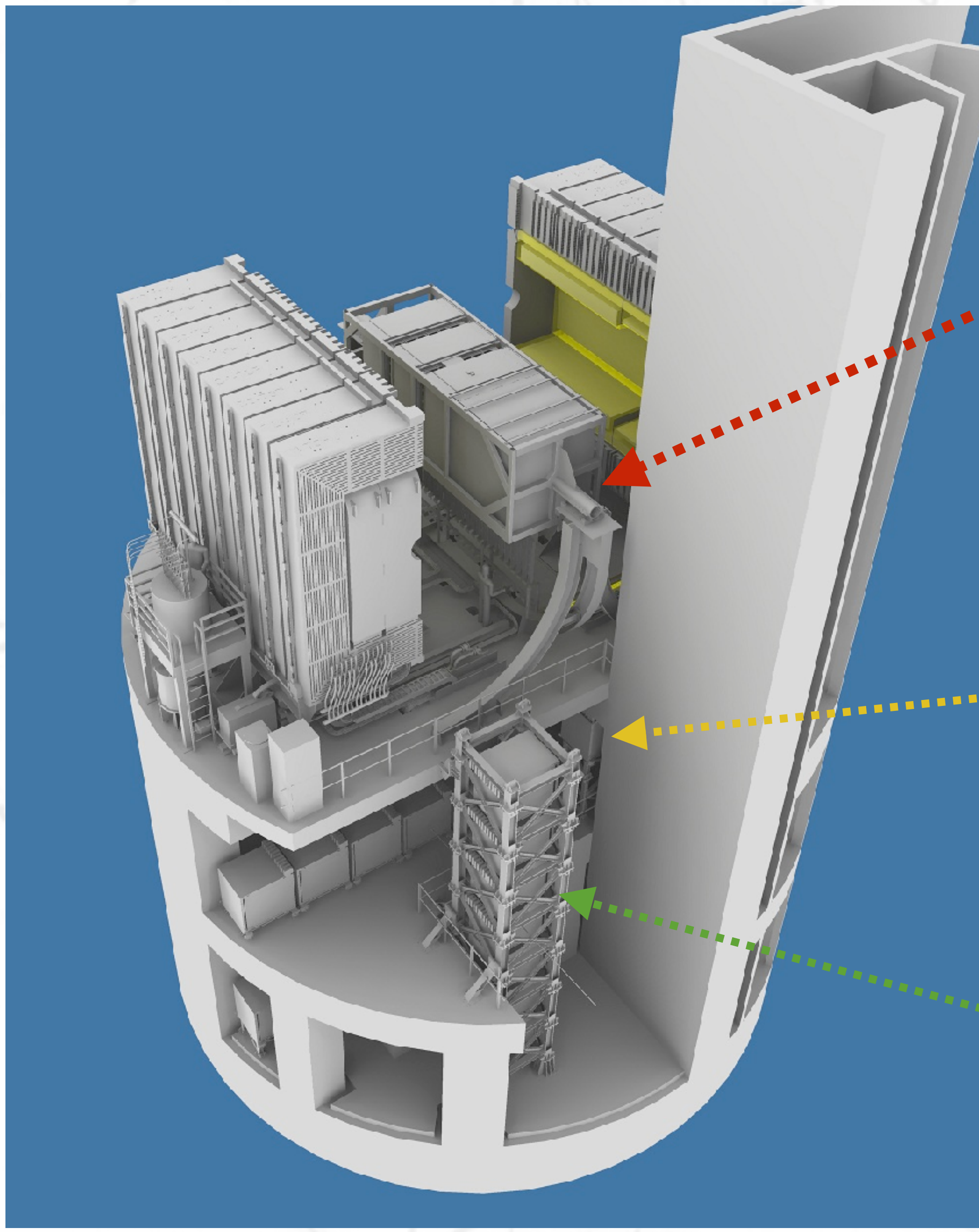


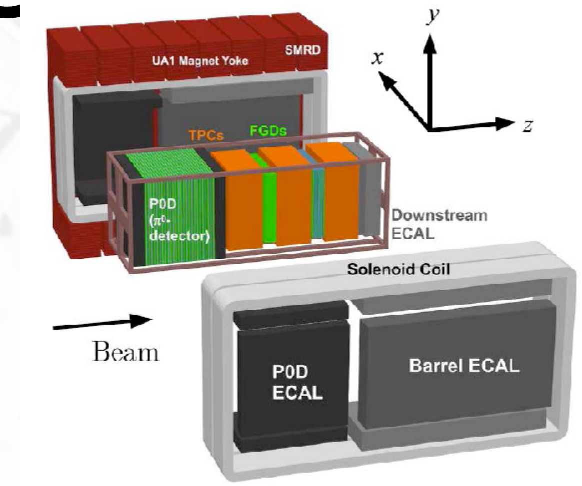
$\nu_e \bar{\nu}_e$

$\nu_\mu \bar{\nu}_\mu$

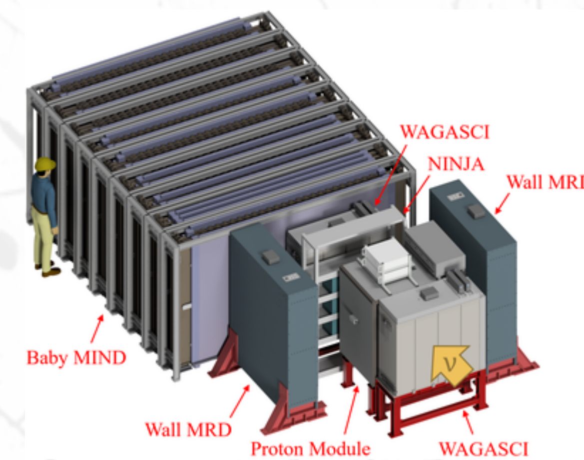


ND280

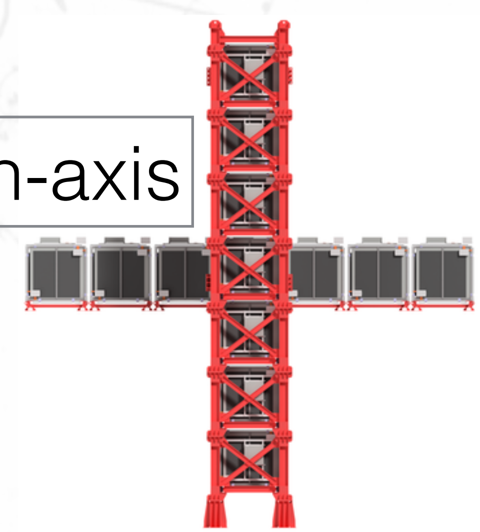




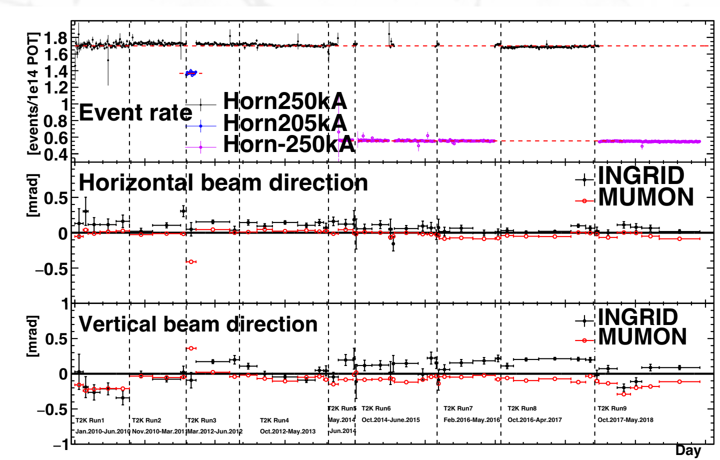
ND280: Off-axis



Wagasci/BabyMind: Off-axis



INGRID: On-axis



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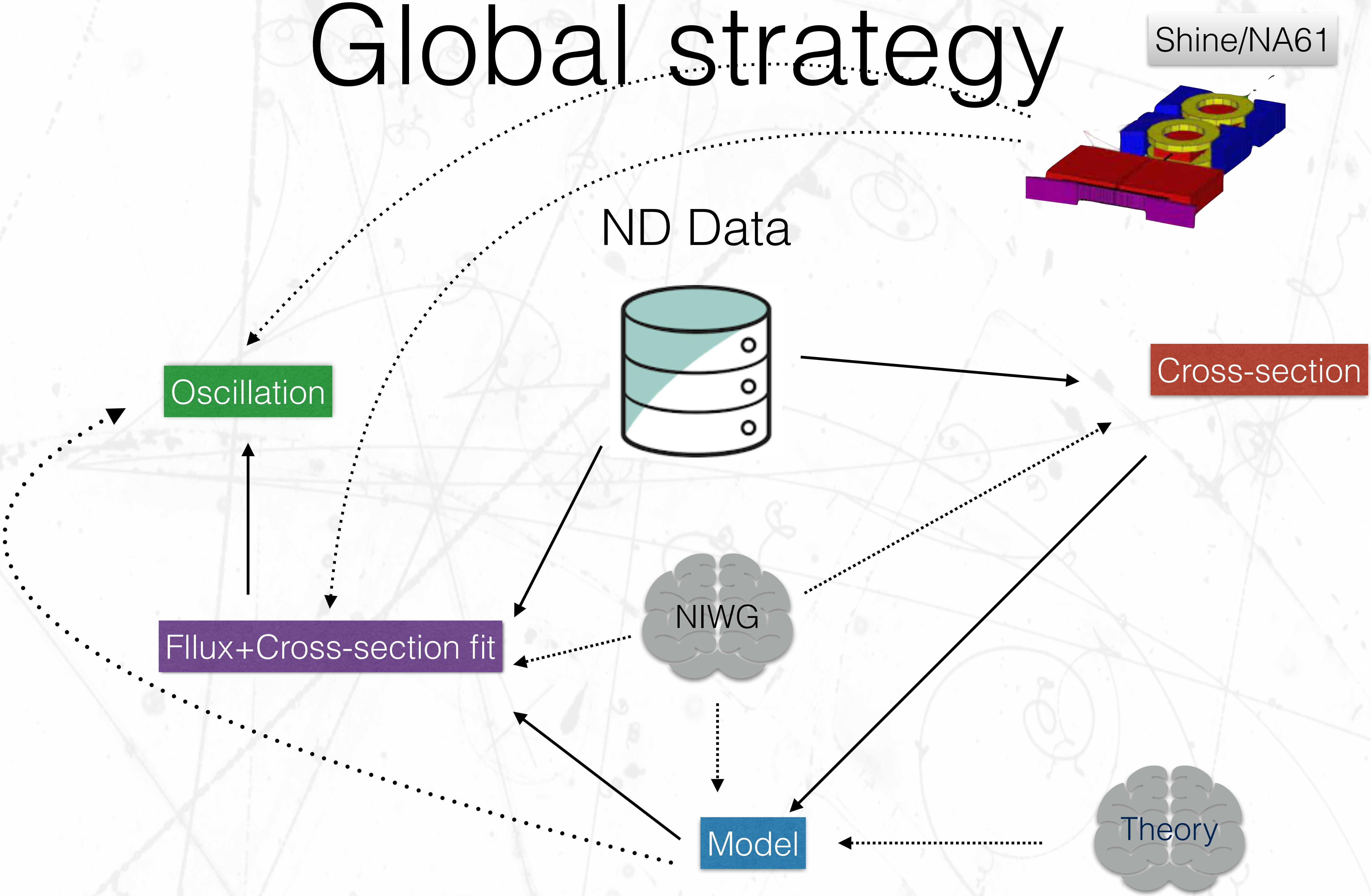
Global strategy



T2K strategy

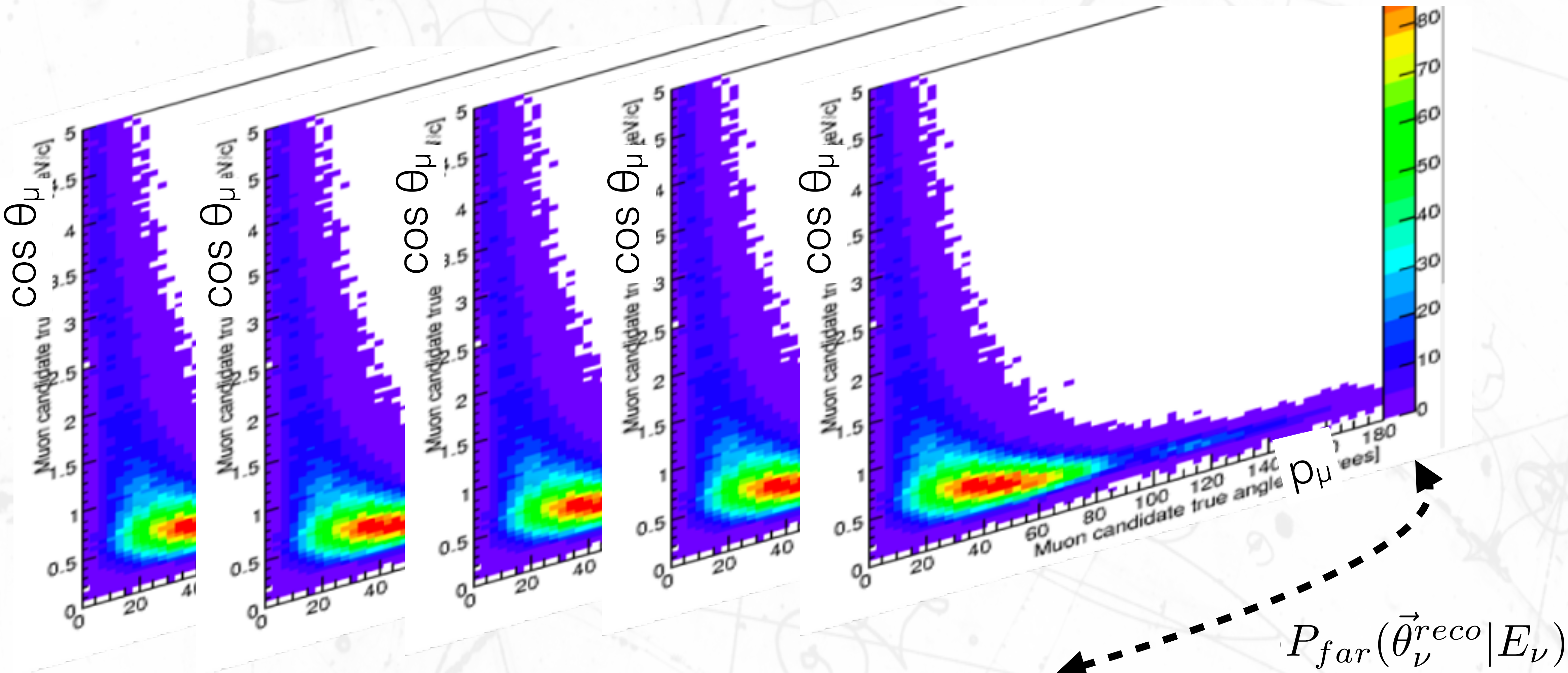
- Since the neutrino energy is not monochromatic:
  - we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

T2K Strategy

Accurate model mandatory



E1 E2 E3 E4 …. EN

$$\frac{N^{far}_{evts}(\vec{\theta}^{reco}_\nu)}{N^{near}_{evts}(\vec{\theta}^{reco}_\nu)} = \frac{\int \sigma(E_\nu)\phi^{far}(E_\nu)P_{far}(\vec{\theta}^{reco}_\nu|E_\nu)P_{osc}(E_\nu)dE_\nu + Back_{far}(\vec{\theta}^{reco})}{\int \sigma(E_\nu)\phi^{near}(E_\nu)P_{near}(\vec{\theta}^{reco}_\nu|E_\nu)dE_\nu + Back_{near}(\vec{\theta}^{reco})}$$

In the kinematical case $P_{far}(\vec{\theta}^{reco}_\nu|E_\nu)$ is given by models tuned by experiments.

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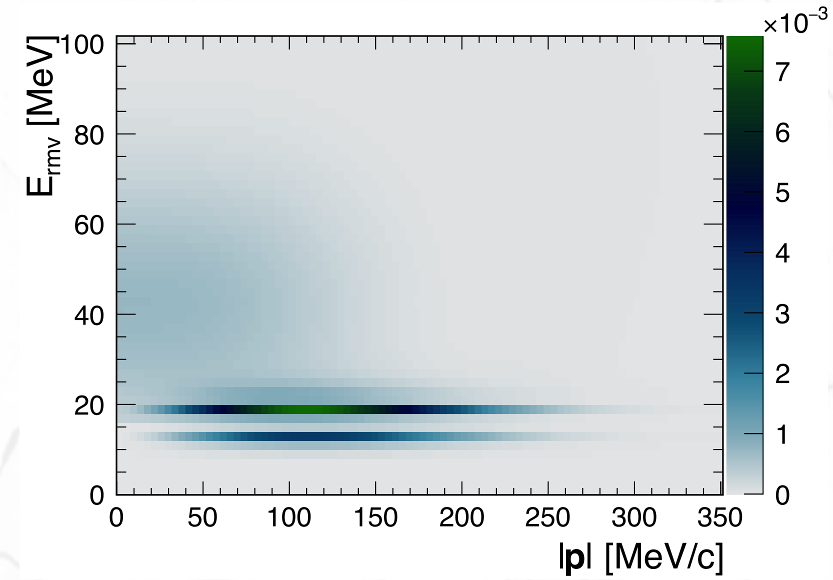
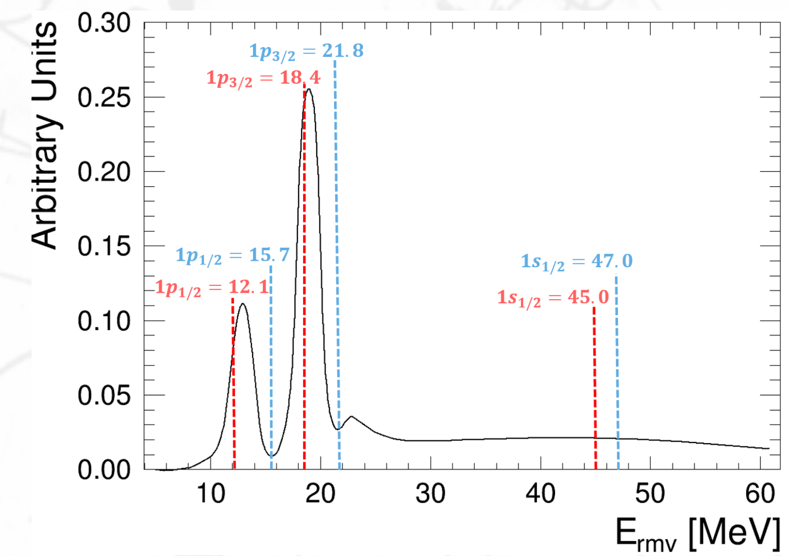
Neutrino interaction model

arXiv:2303.03222v2

- As an example on the model migration efforts the new model used in oscillations include:
  - New spectral-function based nuclear model for charged-current quasi-elastic (CCQE) interactions;
    - introducing an additional uncertainty due to nuclear effects in the four-momentum transferred to the nucleus (Q^2),
    - uncertainty for the nucleon removal energy.
  - Nuclear cascade model for pions was tuned to external data.





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Model degrees of freedom

- This is one of the most delicate issues in the oscillation fits.
- Degrees of freedom should be such that:
  - has a physical motivation.
  - can be applied as reweights to the Monte-Carlo events:
    - not always obvious when the available phase space is not covered by nominal MC: bind energy, Pauli blocking, etc…
  - are adapted to the model in use.

T2K does not consider these modified models as true models, but as a way to parametrise the cross-section to adapt to experimental results.

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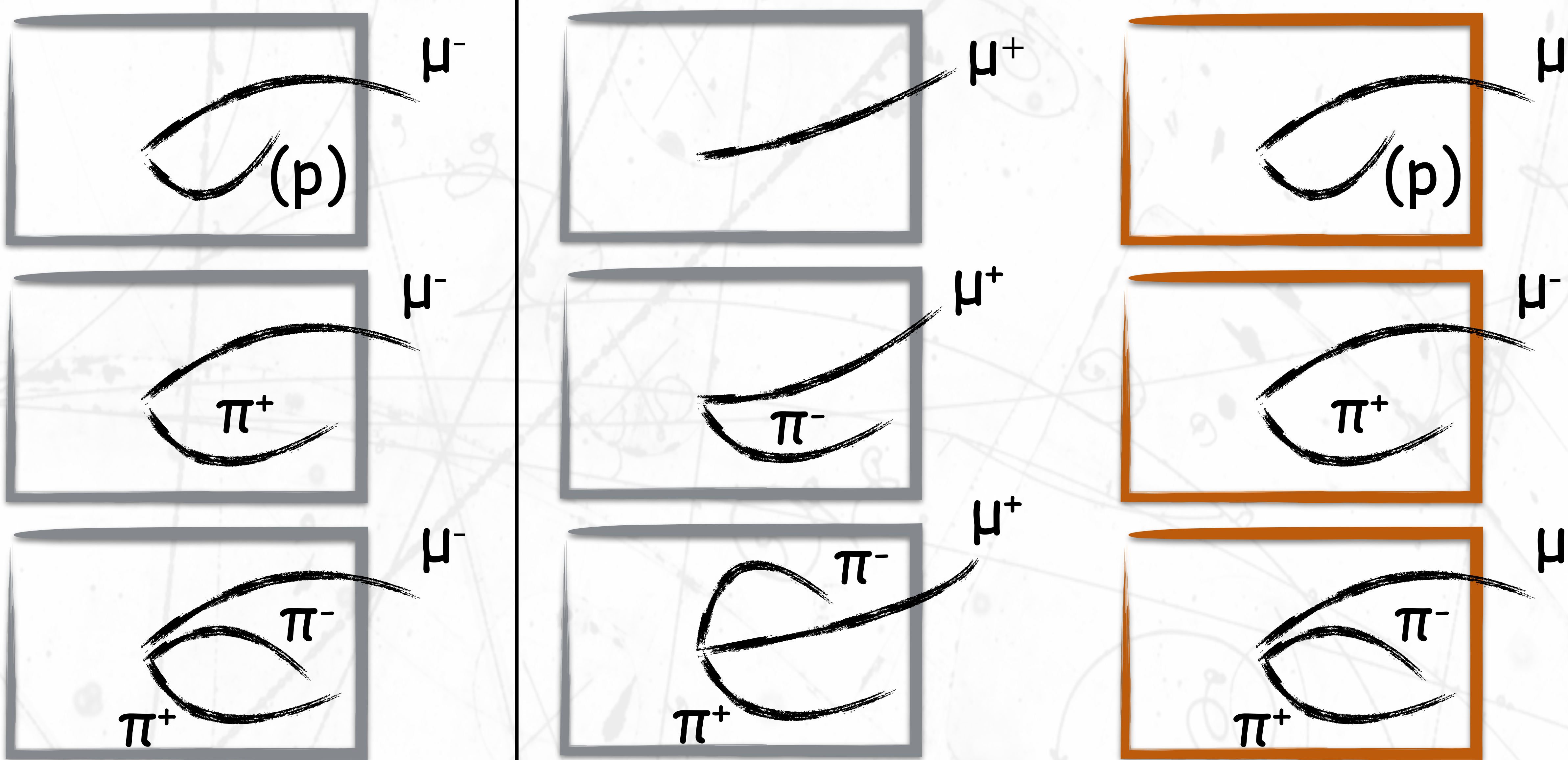
Near detector data

Forward Horn Current (FHC)

Reversed Horn Current (FHC)



ν sample

$\bar{\nu}$ sample

ν sample

All are duplicated in FGD1 (pure CH) and FGD2 (CH+O)

Near detector data fits

- Fits are done in the usual (p_μ,cosθ_μ) variables.
  - other ones are some function of them (like E_{reco} = f (p_μ,cosθ_μ)).
    - This could be useful to improve the binning of the data, but not used so far.
- The presence of protons in those samples can be seen as a 2 bin in proton momentum (< 450 MeV/c and > 450 MeV/c).
  - Proton information is not used in the fits (maybe in future with the incorporation of complex variables).

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Model degrees of freedom

arXiv:2303.03222v2

- Latest published model (2020 model) contains:

M_A

Parameter	Central Value	Uncertainty
M_A^{QE} (GeV)	1.03	0.06
$\Delta E_{rmv}^{\nu O}$ (MeV)	+4	6
$\Delta E_{rmv}^{\bar{\nu} O}$ (MeV)	0	6
$\Delta E_{rmv}^{\nu C}$ (MeV)	+2	6
$\Delta E_{rmv}^{\bar{\nu} C}$ (MeV)	0	6
$0.00 < Q^2 < 0.05$	1.00	—
$0.05 < Q^2 < 0.10$	1.00	—
$0.10 < Q^2 < 0.15$	1.00	—
$0.15 < Q^2 < 0.20$	1.00	—
$0.20 < Q^2 < 0.25$	1.00	—
$0.25 < Q^2 < 0.50$	1.00	0.11
$0.50 < Q^2 < 1.00$	1.00	0.18
$Q^2 > 1.00$	1.00	0.40

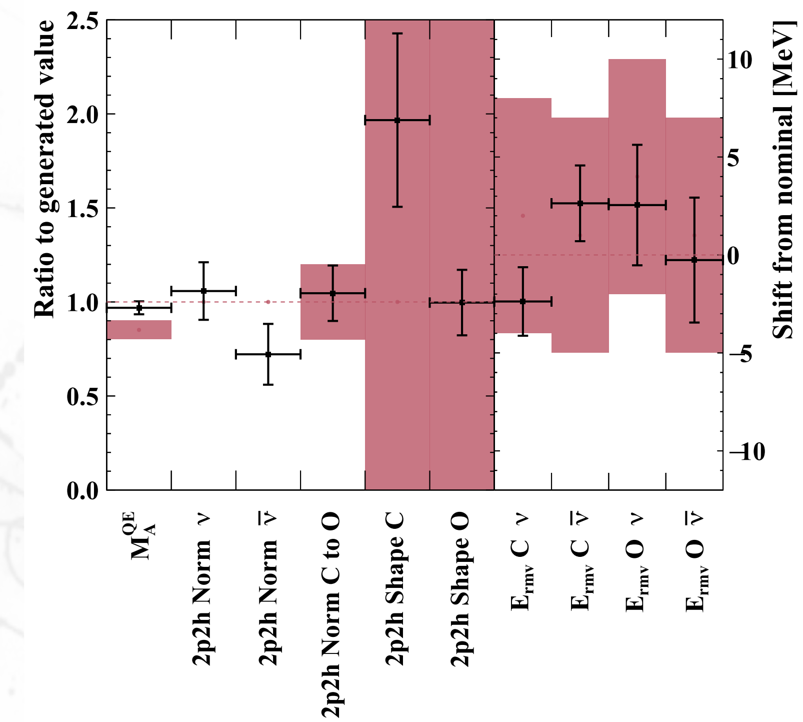
Removal Energy

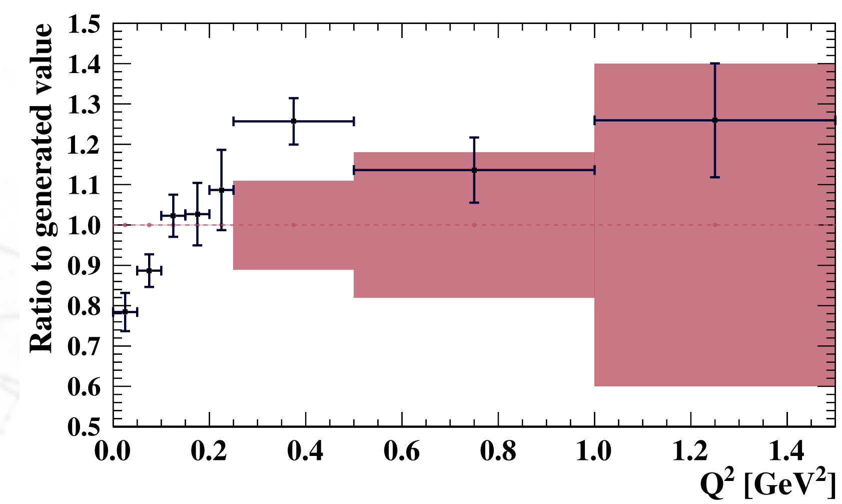
Some sort of RPA

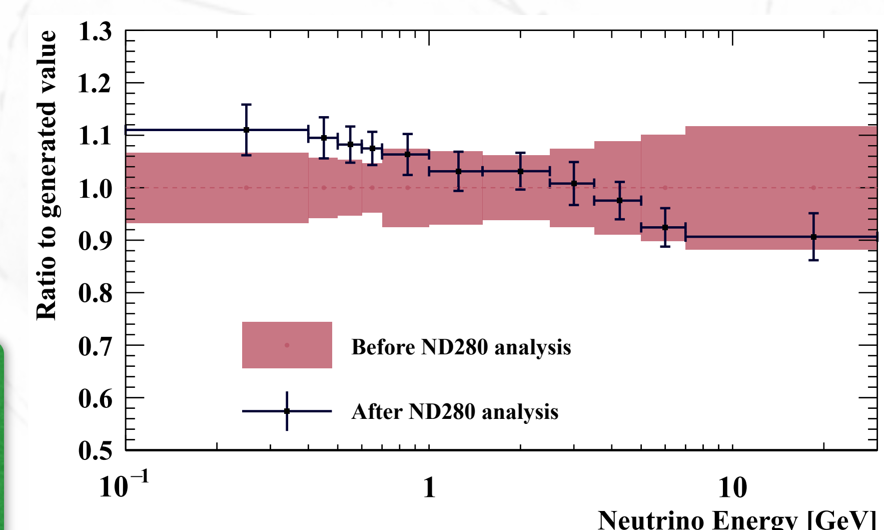
+ 2p2h normalisation for neutrinos antineutrinos and Carbon/Oxygen
+ Flux

+ newer model almost done with more physically justified -improved- parametrisation. (remove Q^2)

Requires a dedicated talk







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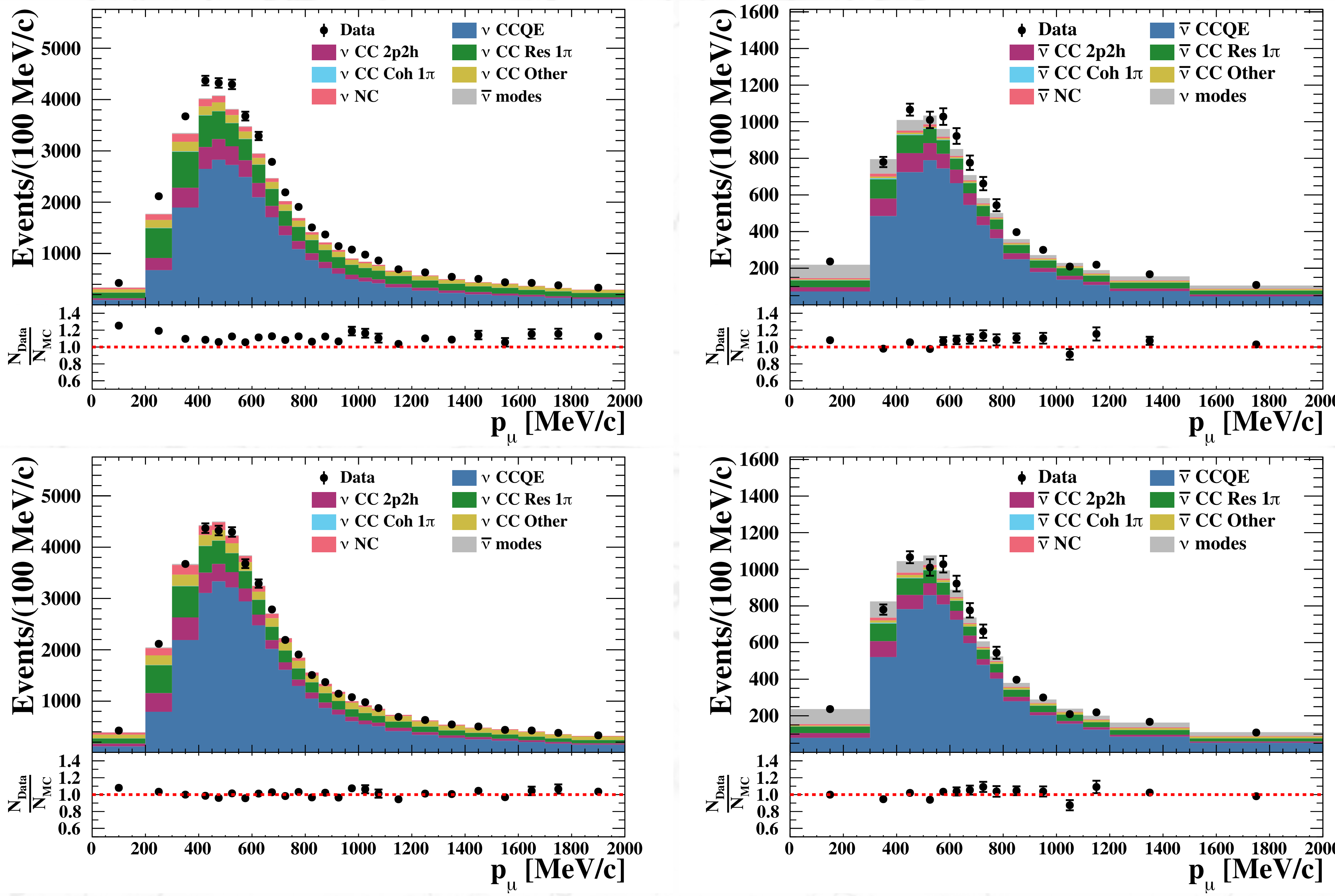
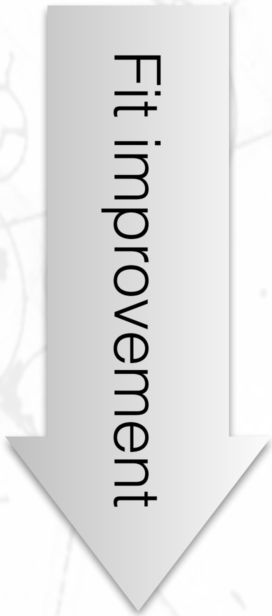
N280 fit result



(a) FGD1 ν-mode ν_μ CC0π

(b) FGD2 $\bar{\nu}$-mode $\bar{\nu}_\mu$ CC0π

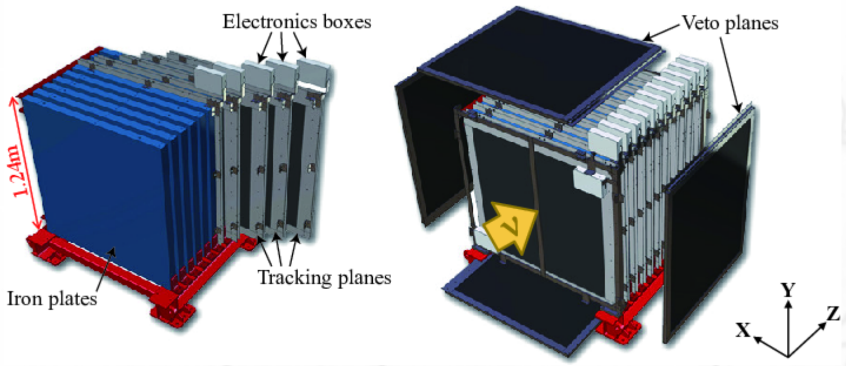


Improving models for oscillations beyond oscillation fits

- The oscillation methodology works better when the fitted model is the best.
- T2K carry out measurements to improve/constrain models.
- Several approaches:
    1. explore **inclusive distributions** for CC0π and CCNπ (point 3 and 4 should work better).
    2. explore measurements **at different off-axis** (combined modified neutrino spectrum results).
    3. explore combinations of reactions: **CC0π + CC1π** to better control backgrounds.
    4. Compare **Carbon vs Oxygen** enriched samples.
    5. Explore very sensitive parameters: normally **transverse variables**.

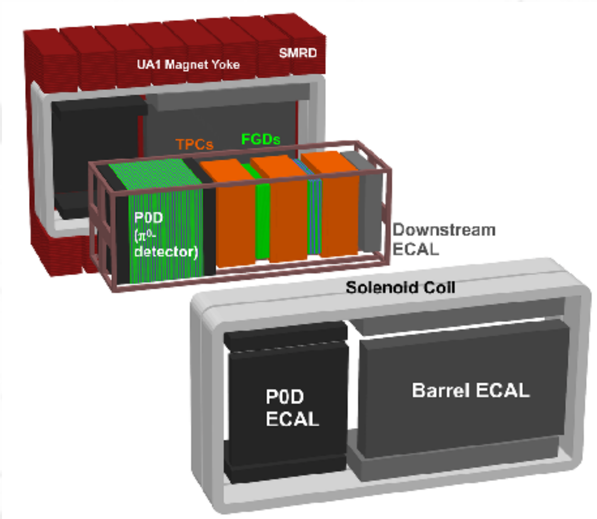
Using detectors at different locations

arXiv:2303.14228v1

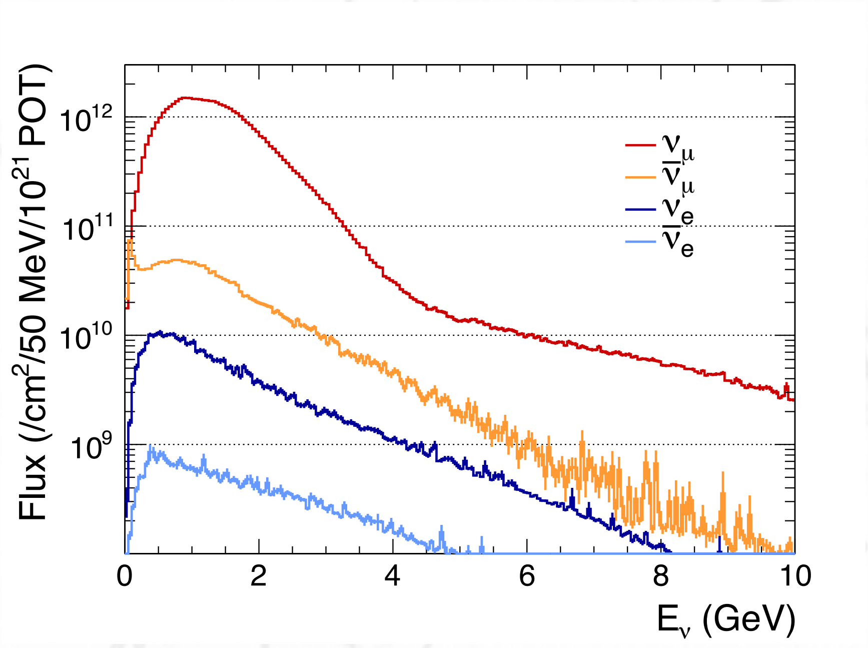


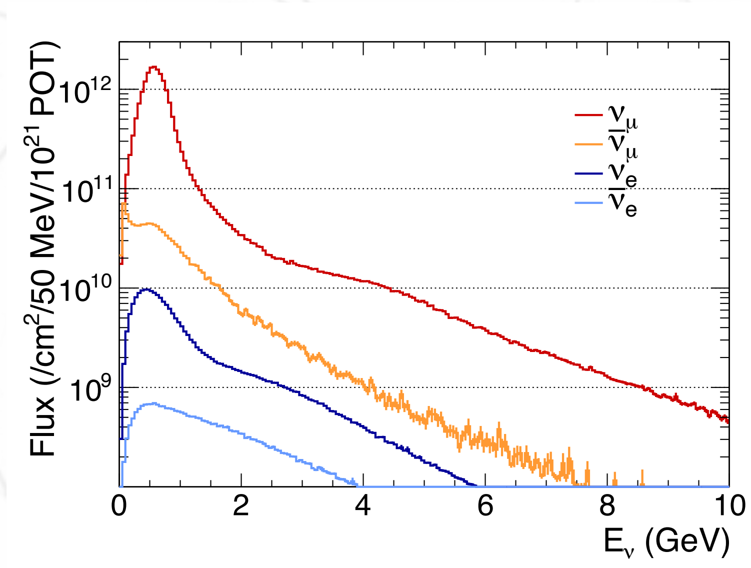
Range

- Same target CH.
- Different technology
- different flux



Magnet





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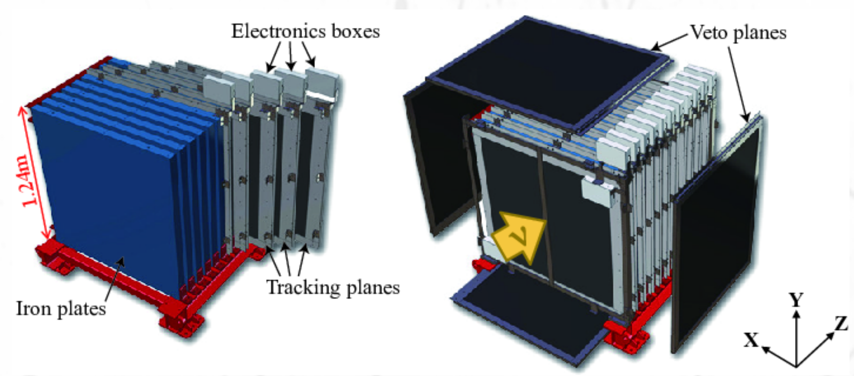
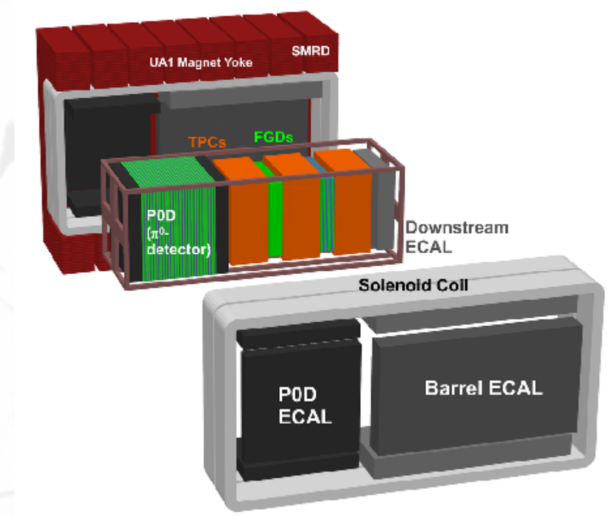
Using detectors at different locations

arXiv:2303.14228v1

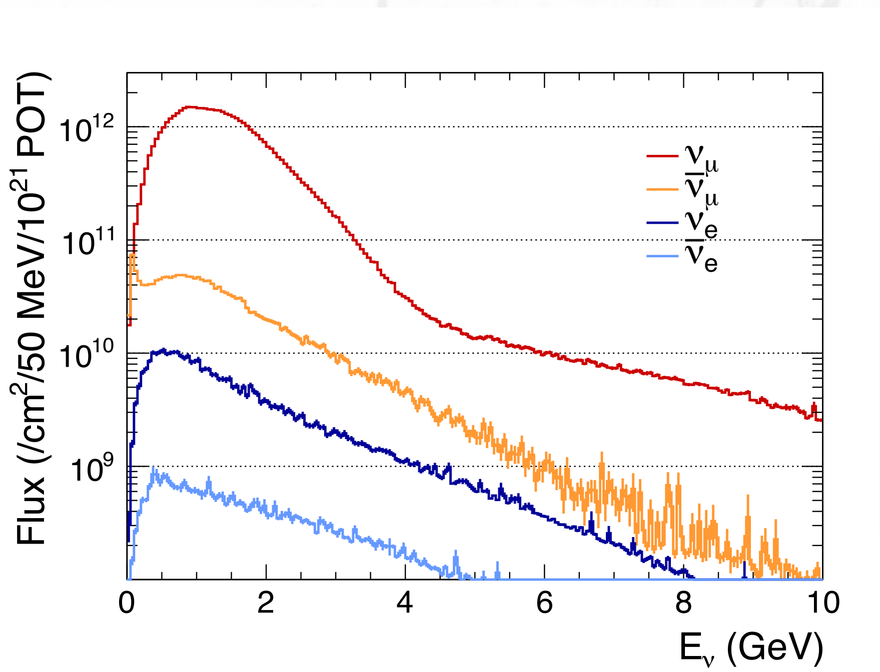


- Same target CH.
- Different technology
- different flux



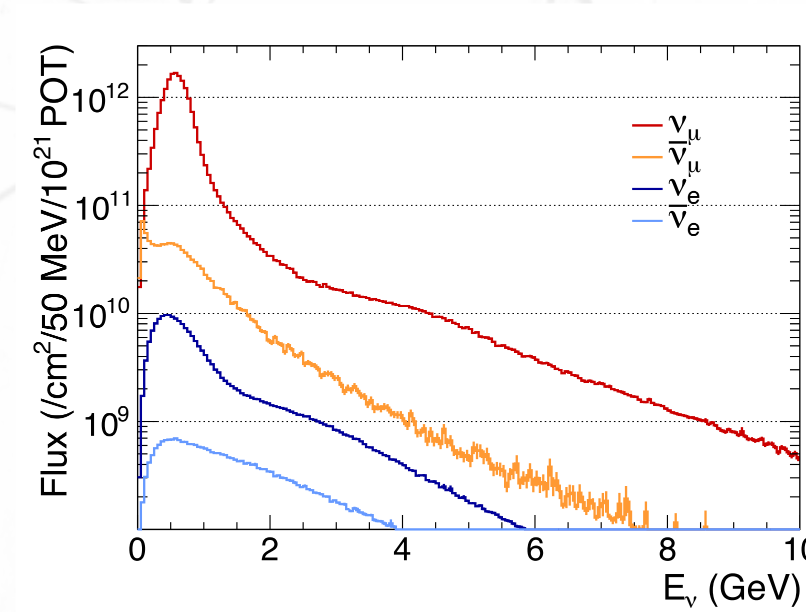
Range

Magnet



CC0π
inclusive measurement

with protons and no protons
in final state



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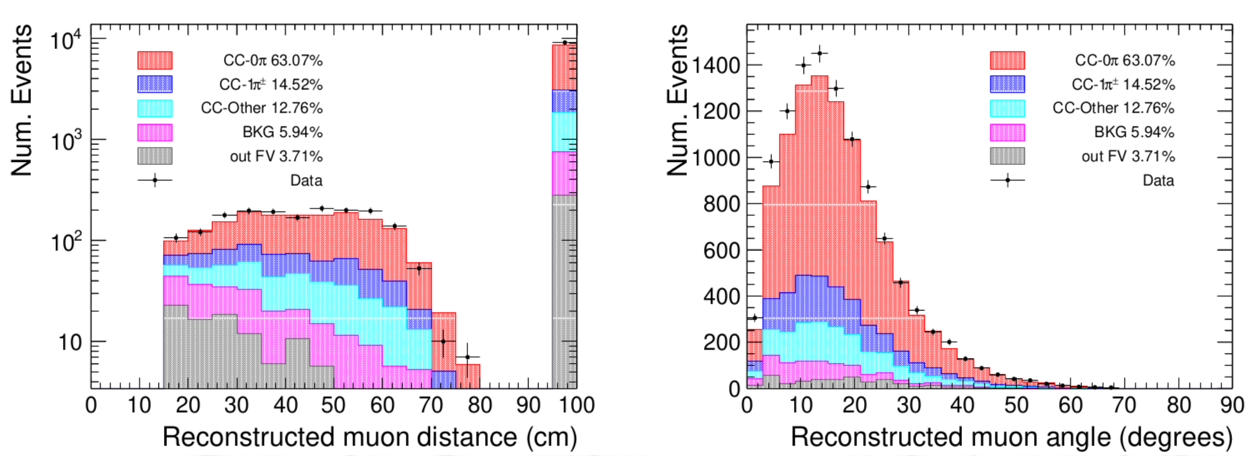
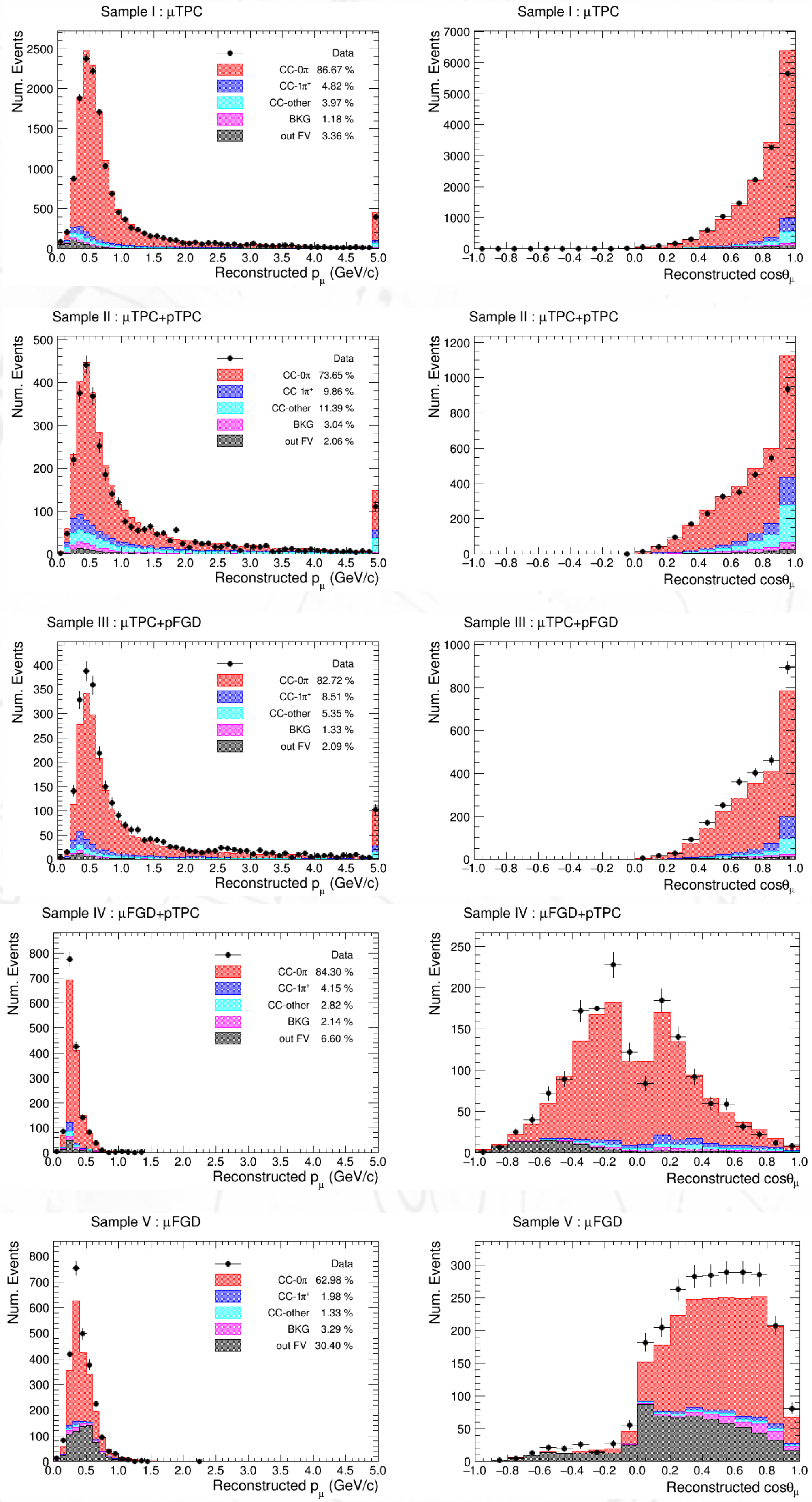
arXiv:2303.14228v1

Using detectors at different locations

on-axis



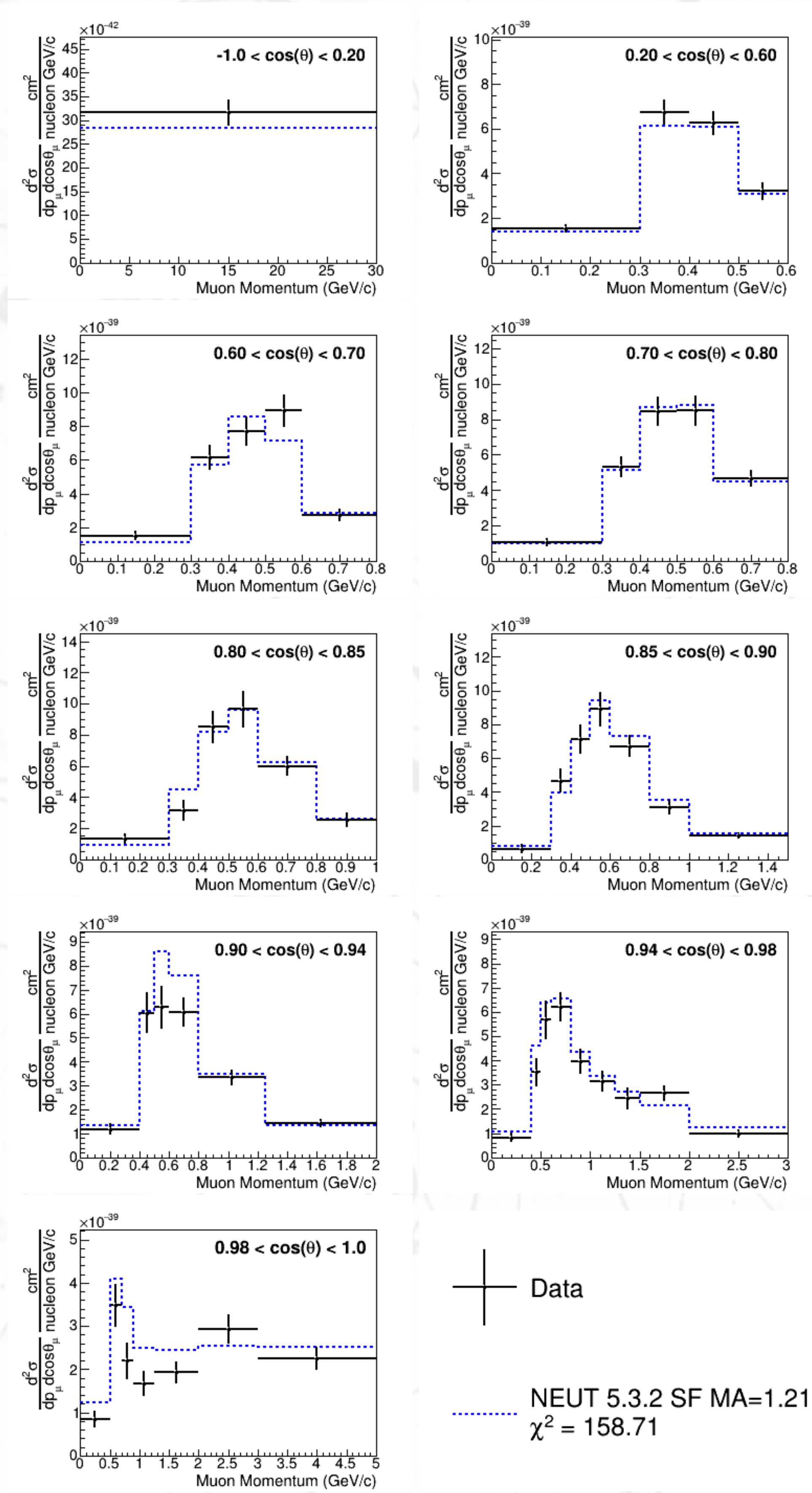
off-axis



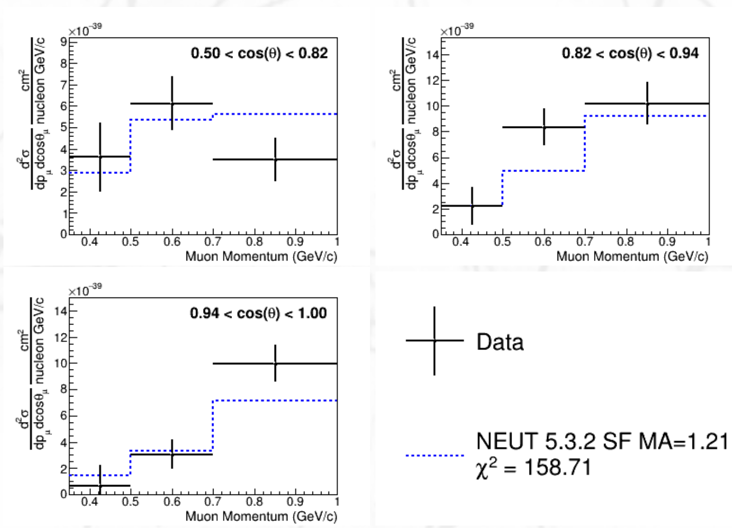
arXiv:2303.14228v1

Using detectors at different locations

off-axis



on-axis



The presence of the two ν spectra reduces the degeneracies caused by the flux

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Using detectors at different locations

arXiv:2303.14228v1

The cross-section can be compared directly with models and it is provided to the theory community

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

Difficult to extract more information:

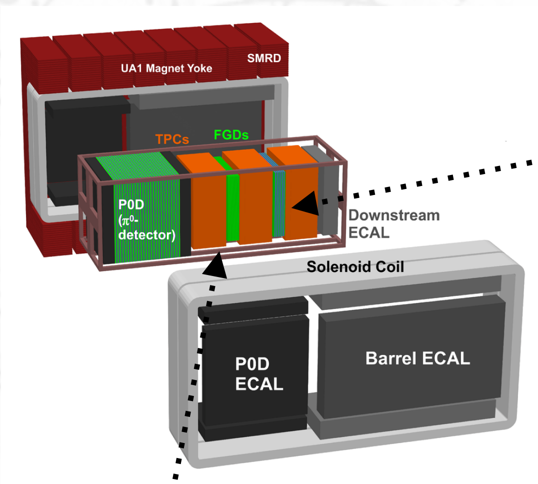
1. model comparison —> input for decisions
2. fit "a la" ocillations

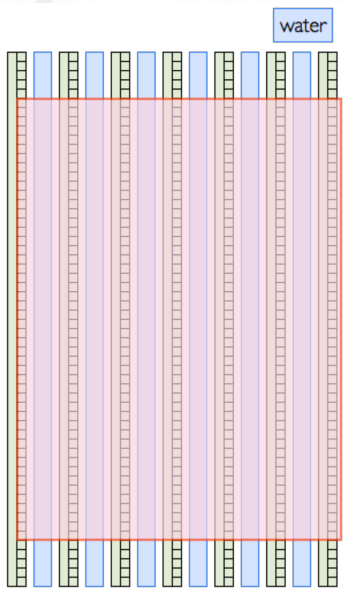
Carbon vs Oxygen

arXiv:2004.05434v2

- This is one of the “issues” with T2K.
  - ND is “mostly” Carbon target
  - Far detector is mostly Hydrogen.
- The cross-section prediction in Oxygen from Carbon has systematic uncertainties.

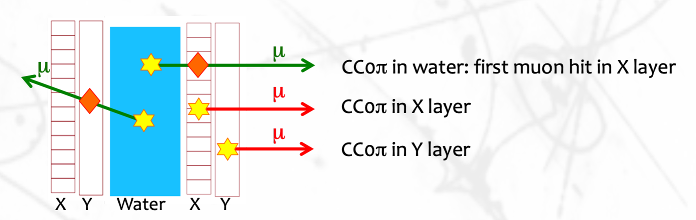
Can we control the difference?

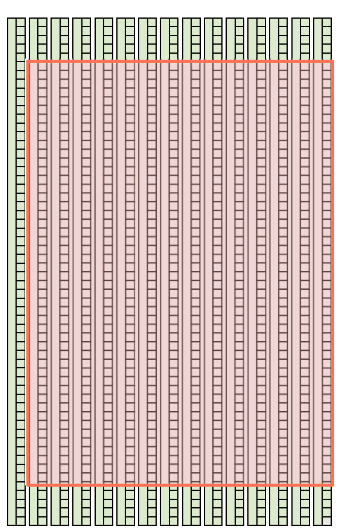




7 xy + 6 water modules
192x2 bars/layer

Some capability to separate
C and O





15 layers
192x2 bars/layer

- We can perform the measurement in the C+O detector and subtract the C measurement.
- Subtraction is inefficient statistically:

$$\sigma_O = \sigma_{C+O} - \sigma_C$$
$$\delta^2\sigma_O = \delta^2\sigma_{C+O} + \delta^2\sigma_C$$

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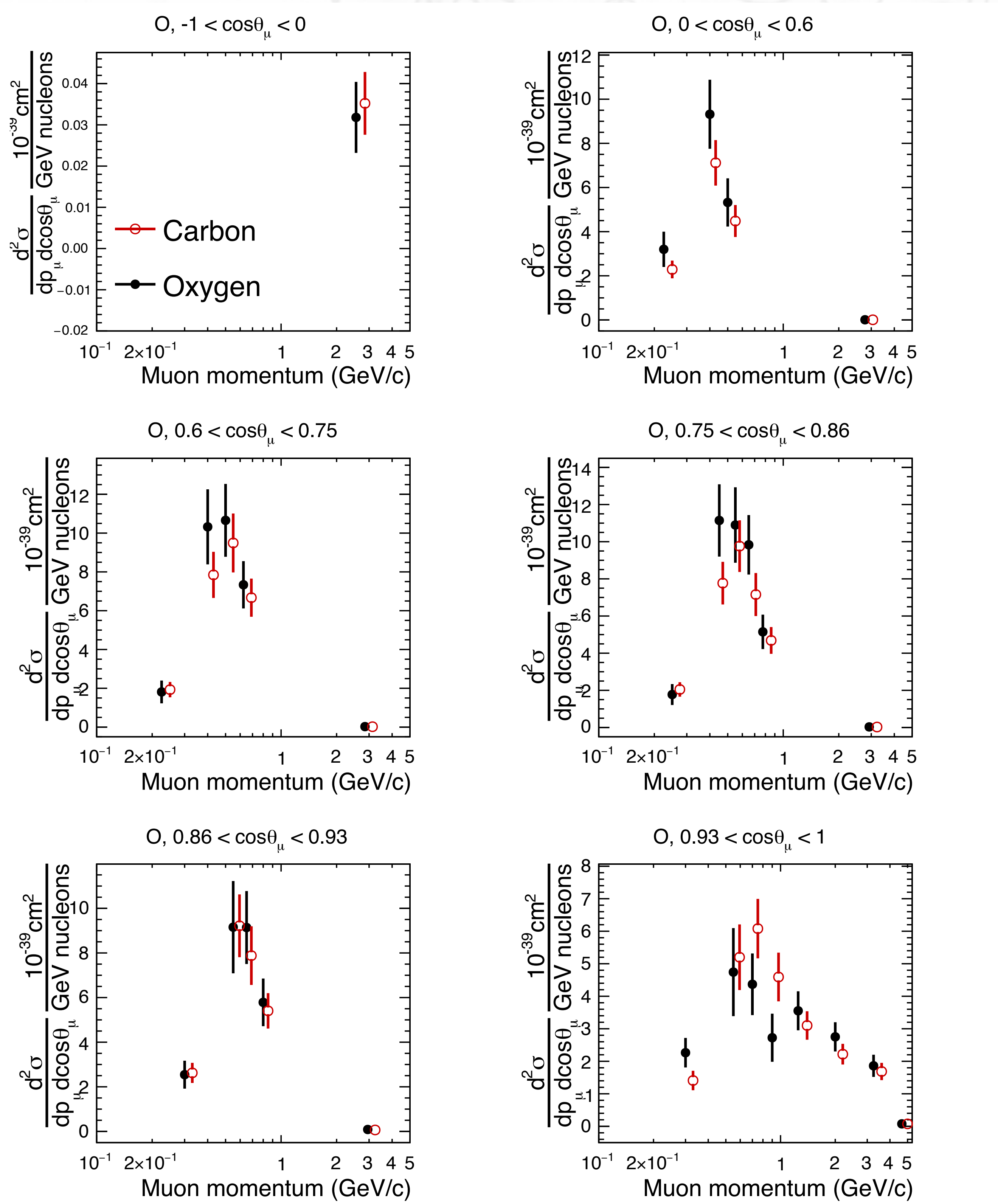
Carbon vs Oxygen

arXiv:2004.05434v2

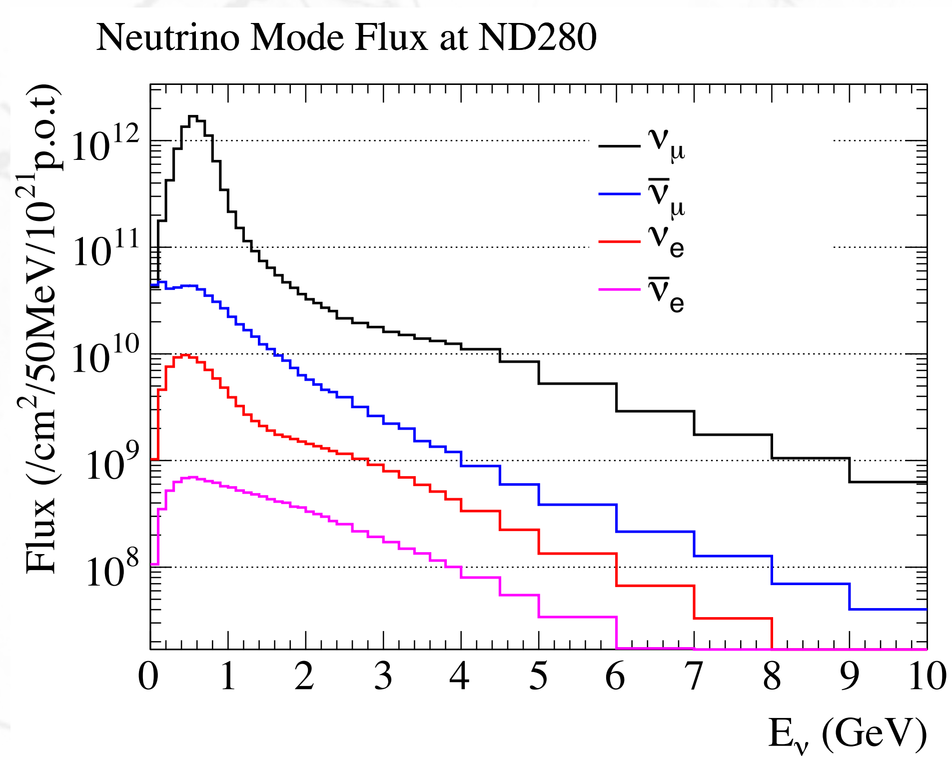


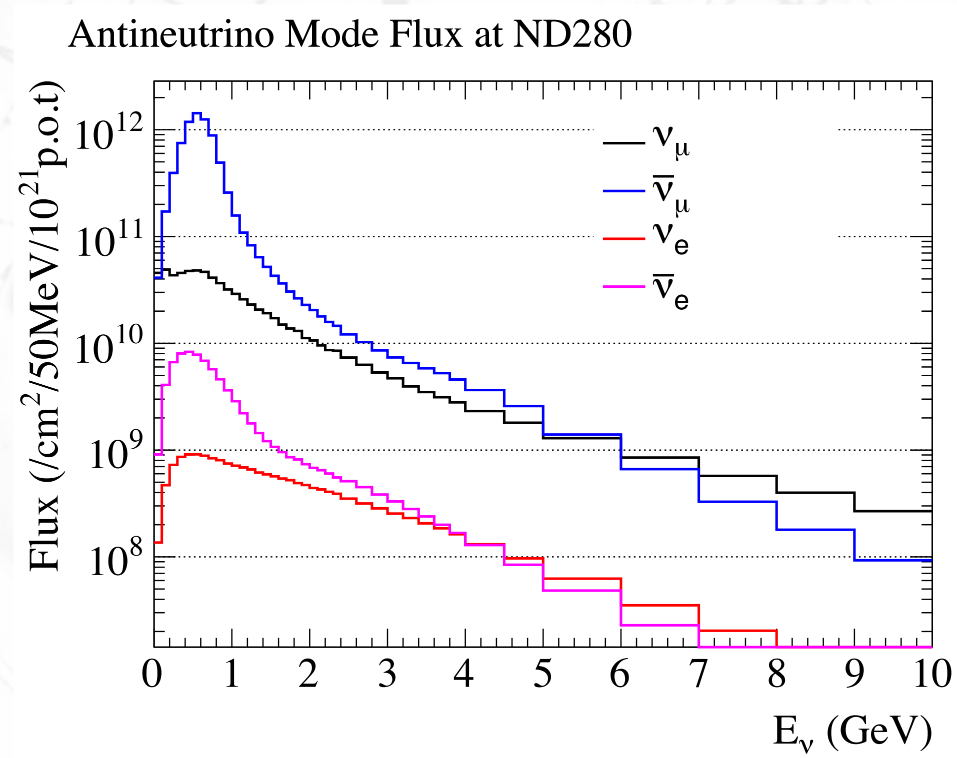
Extract the Carbon and Oxygen cross-sections per nucleon & model comparison

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

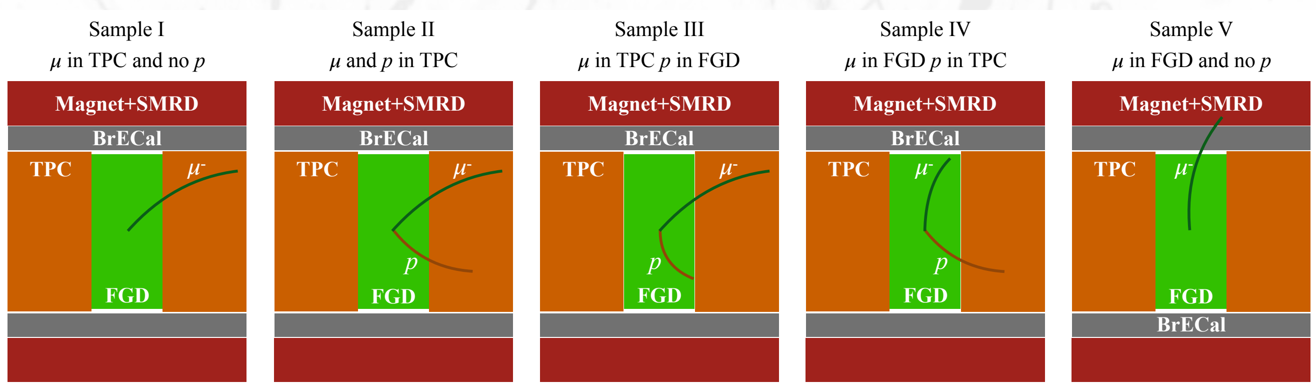
Neutrino vs antineutrinos

- Exploit magnet in ND280.
- Several advantages:
  - Neutrino is a bck on antineutrino sample —> better control.
  - Same detector —> common detector error treatment.
  - Neutrinos in FHC have different flux than in RHC (reduction of degeneracy).

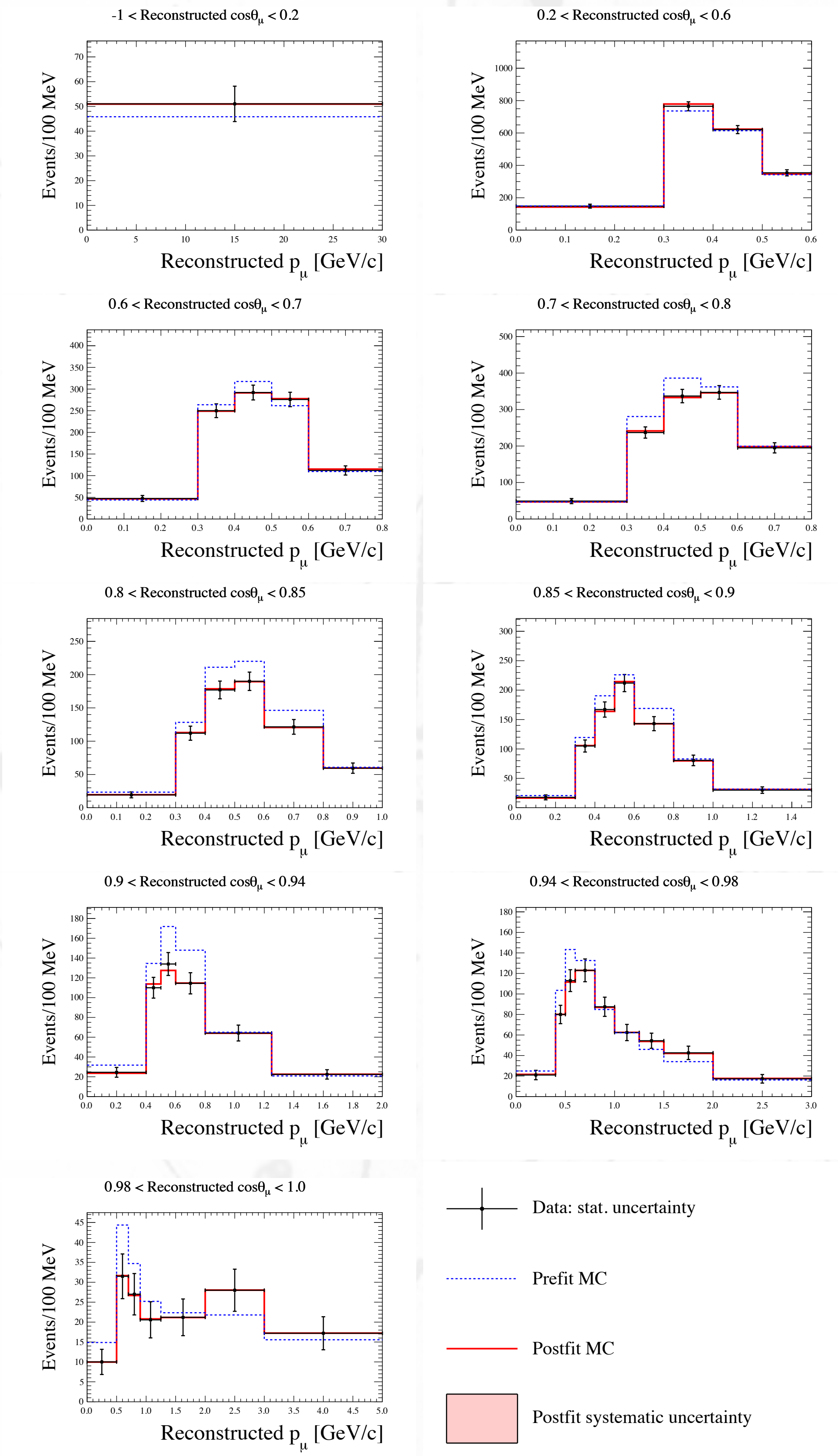




3 samples:
neutrino in FHC & RHC
antineutrino in RHC



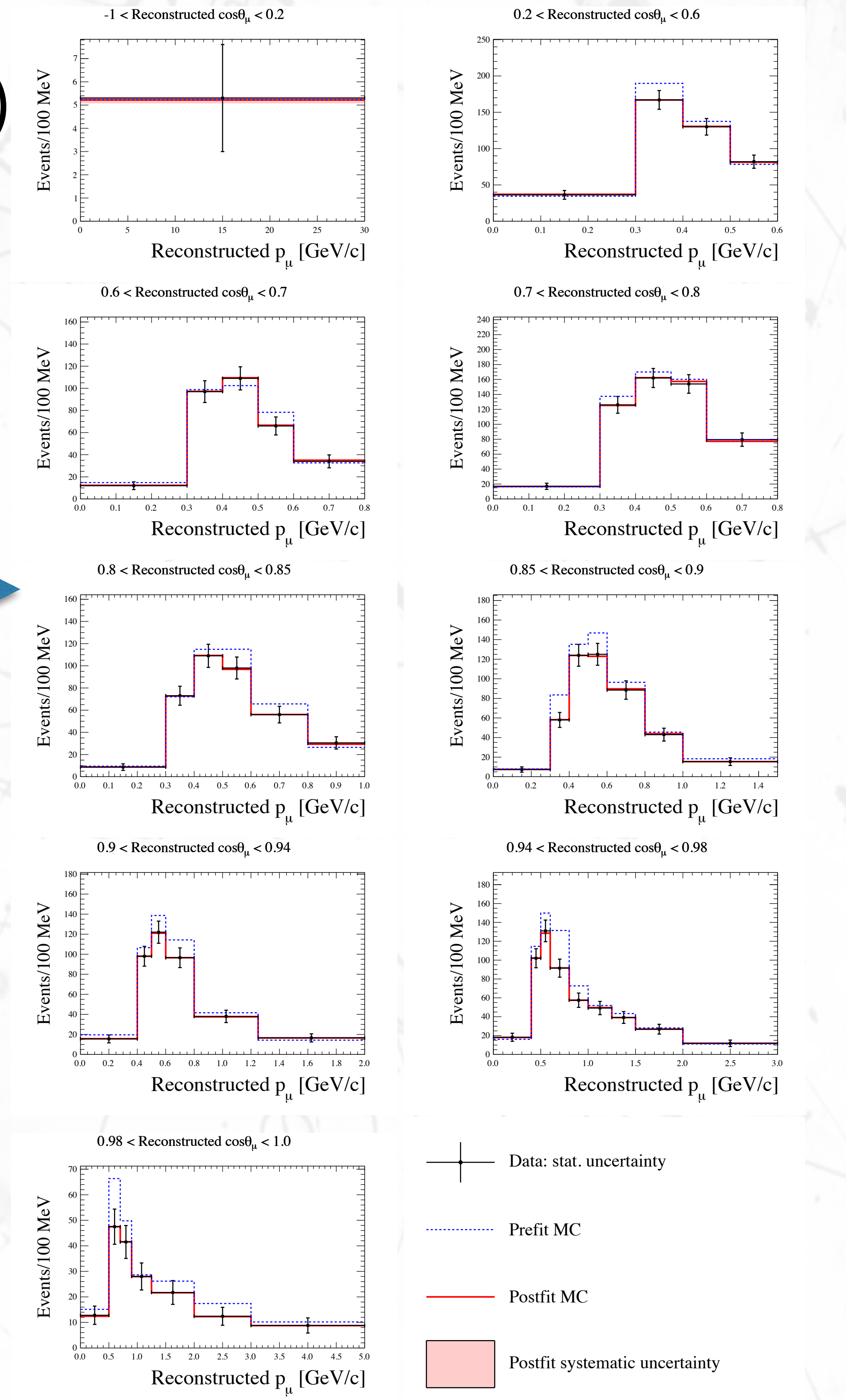
neutrino vs antineutrinos



Usual (p_μ,cosθ_μ)

neutrinos

anti-neutrinos



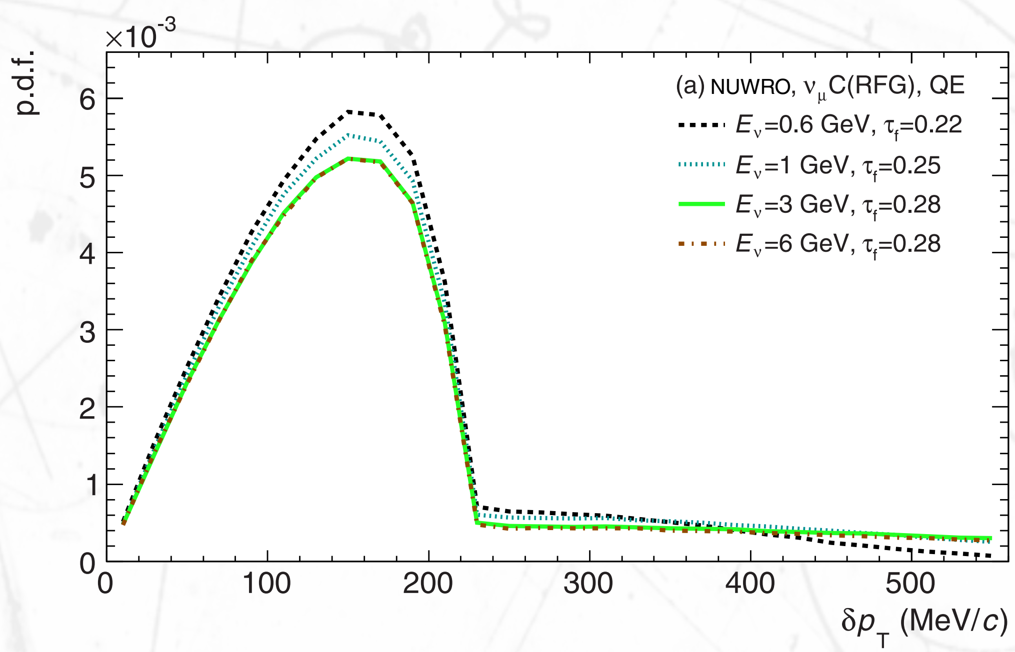
Explore sensitive parameters:TKI

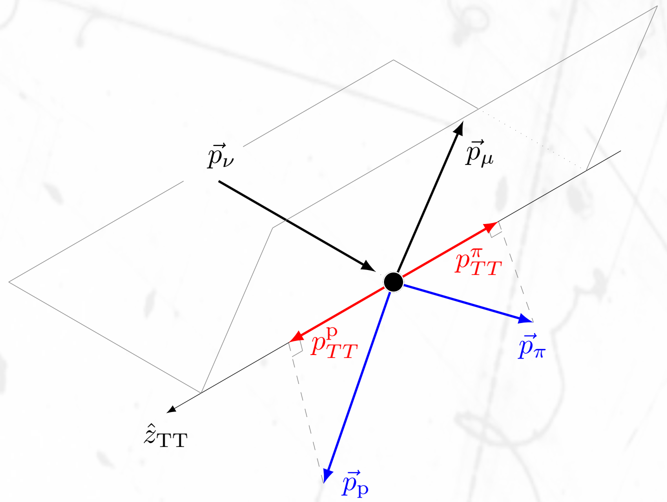
Phys. Rev. C **94**, 015503

- The problem with the previous calculations is that give us an idea of which model (and physics inputs) to use but little (indirectly) on the validity of the detailed model inputs.

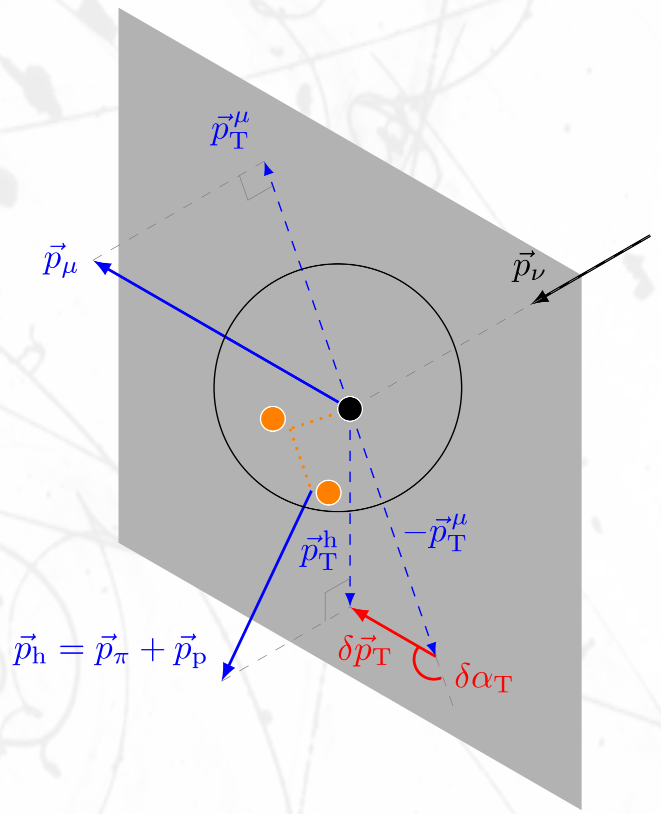
- We need to explore variables that allow us to singularise some of the physics inputs: binding energy, nuclear re-scattering, fermi model, …

- Transverse kinematic imbalance reduces the contribution of the (unknown) neutrino energy enhancing nuclear effects and sensitivity to the details.





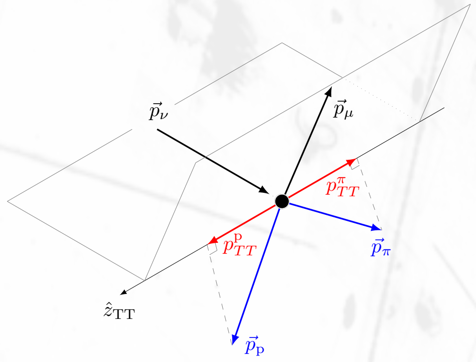
(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT}$.



(b) $\delta\vec{p}_T$ and $\delta\alpha_T$.

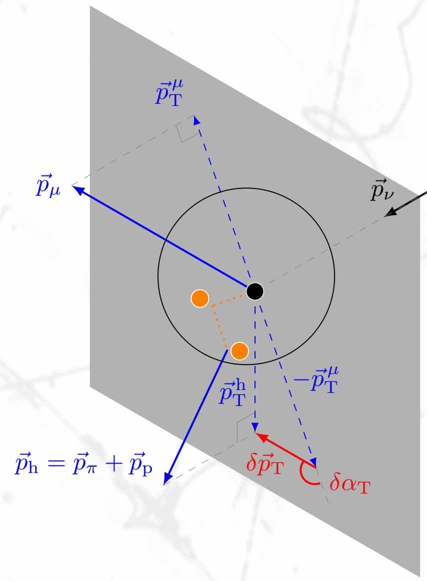
Explore sensitive parameters:TKI

Phys. Rev. C **94**, 015503

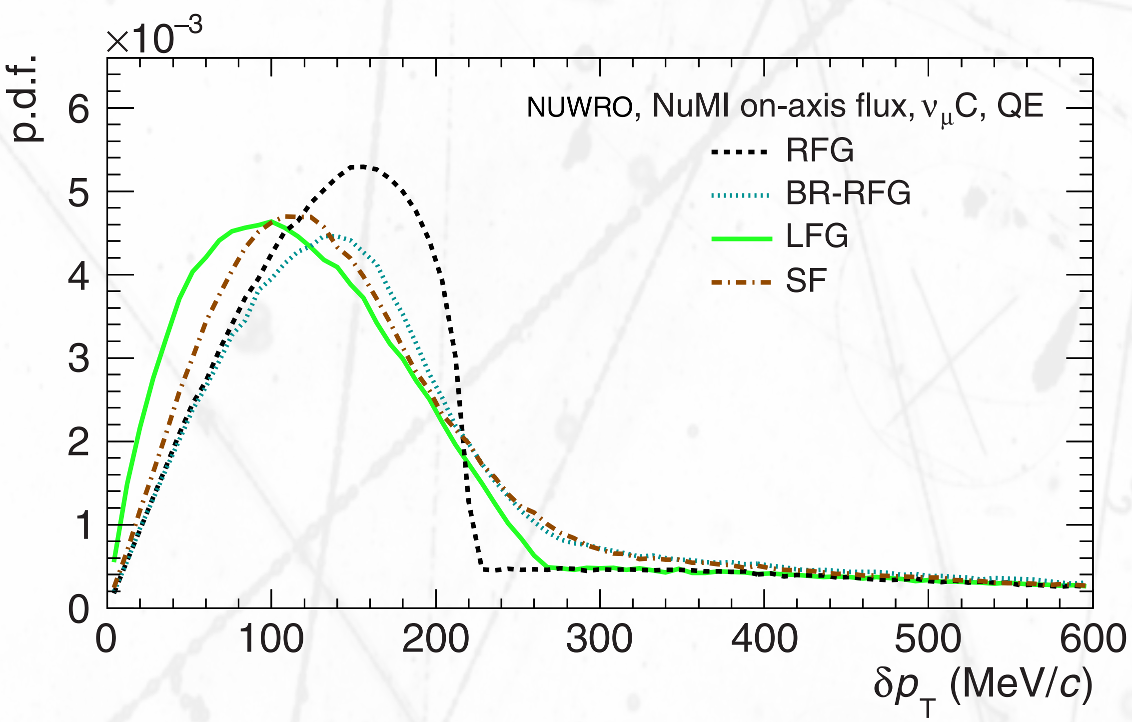


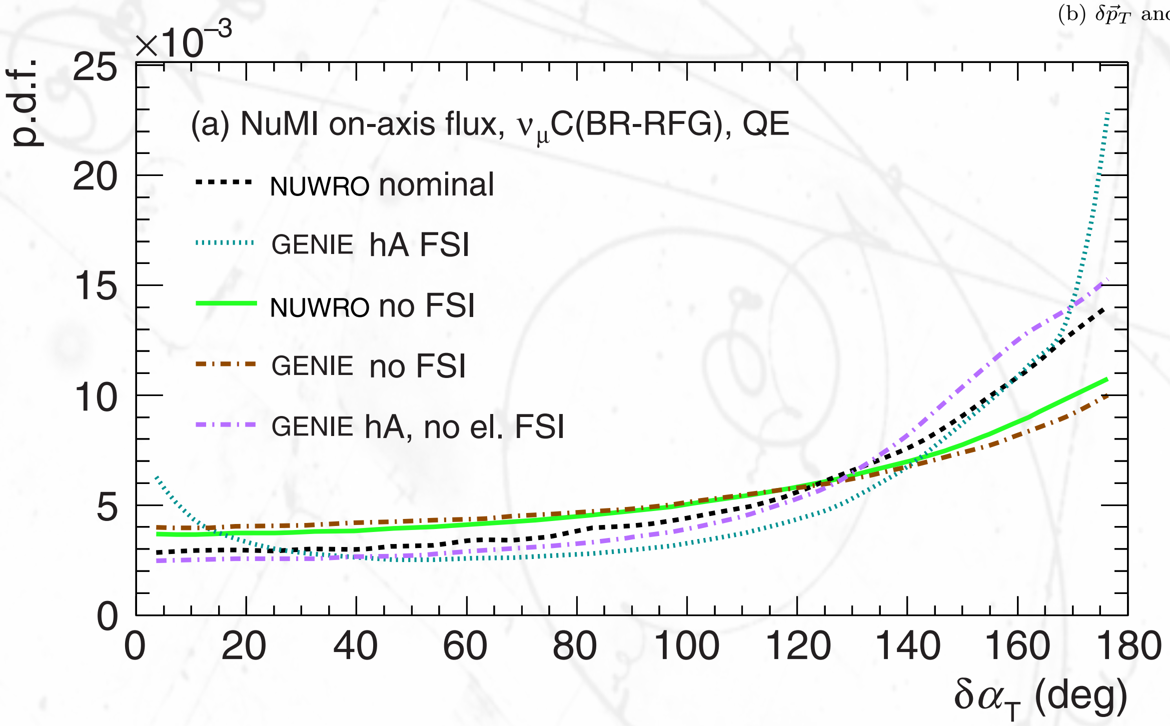
(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT}$.

- …. enhancing nuclear effects.
- also, the different observables have different dependencies with the model inputs.



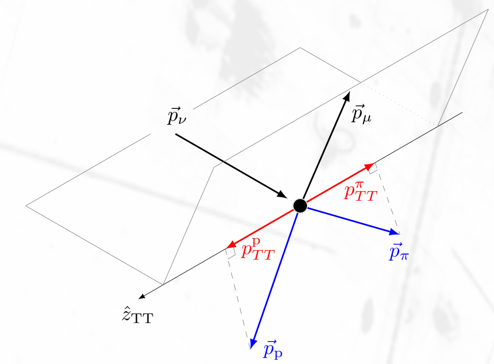
(b) $\delta \vec{p}_T$ and $\delta\alpha_T$.



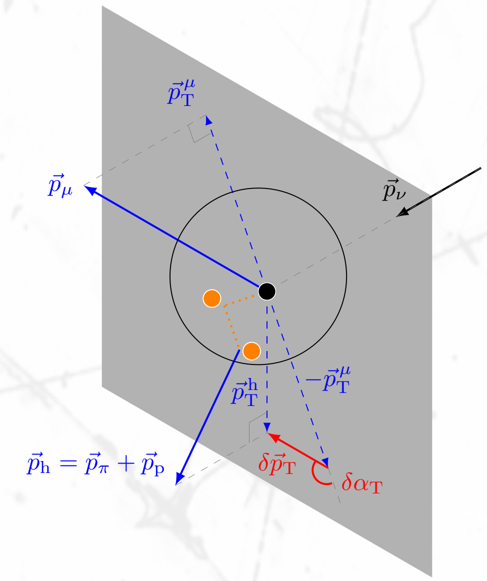


Explore sensitive parameters:TKI

Phys. Rev. C **94**, 015503



(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{\mathrm{p}}_{TT}$.



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- …. enhancing nuclear effects.
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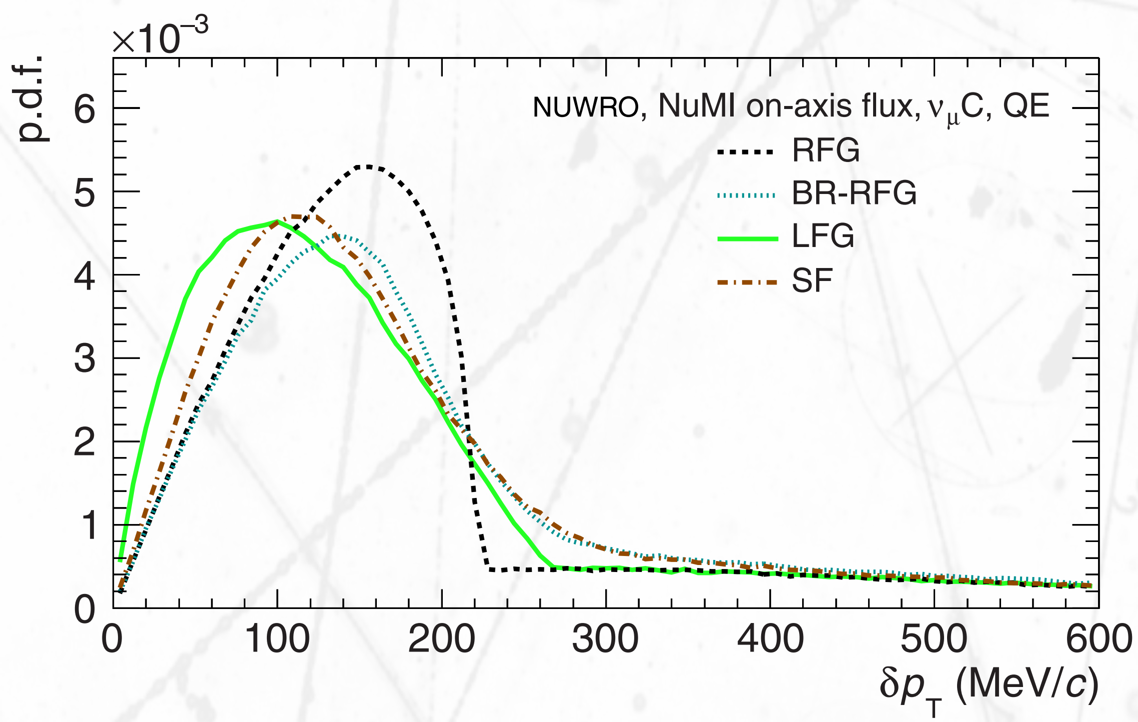

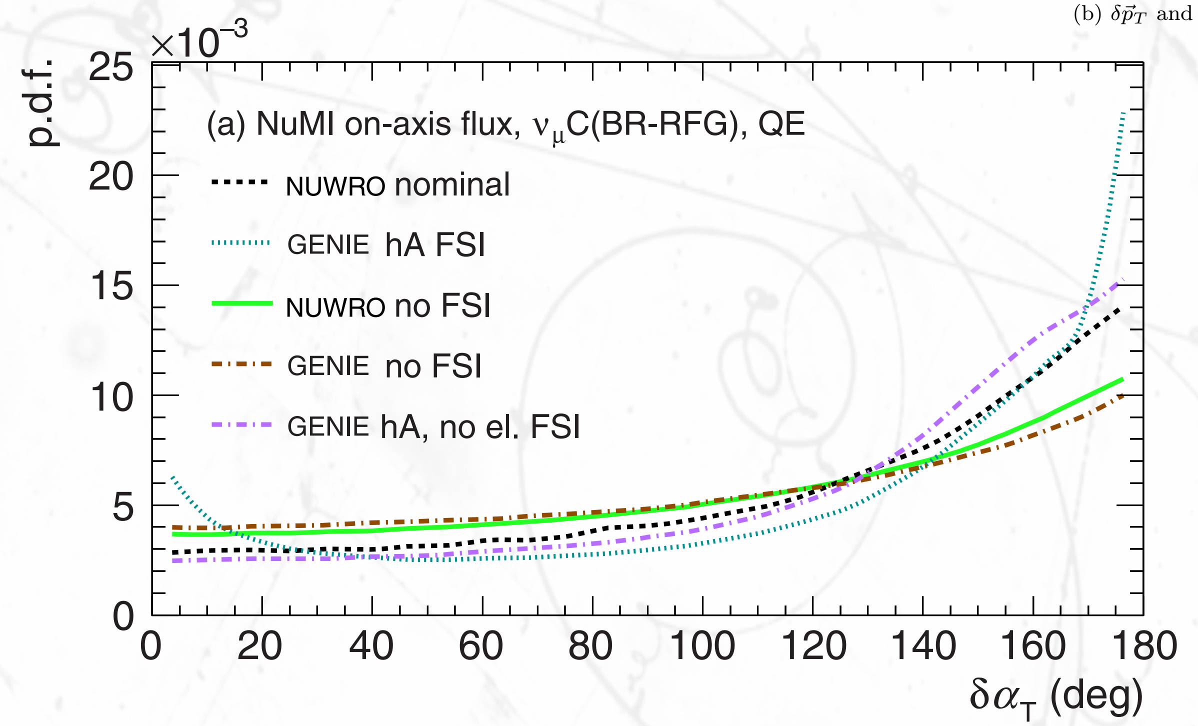

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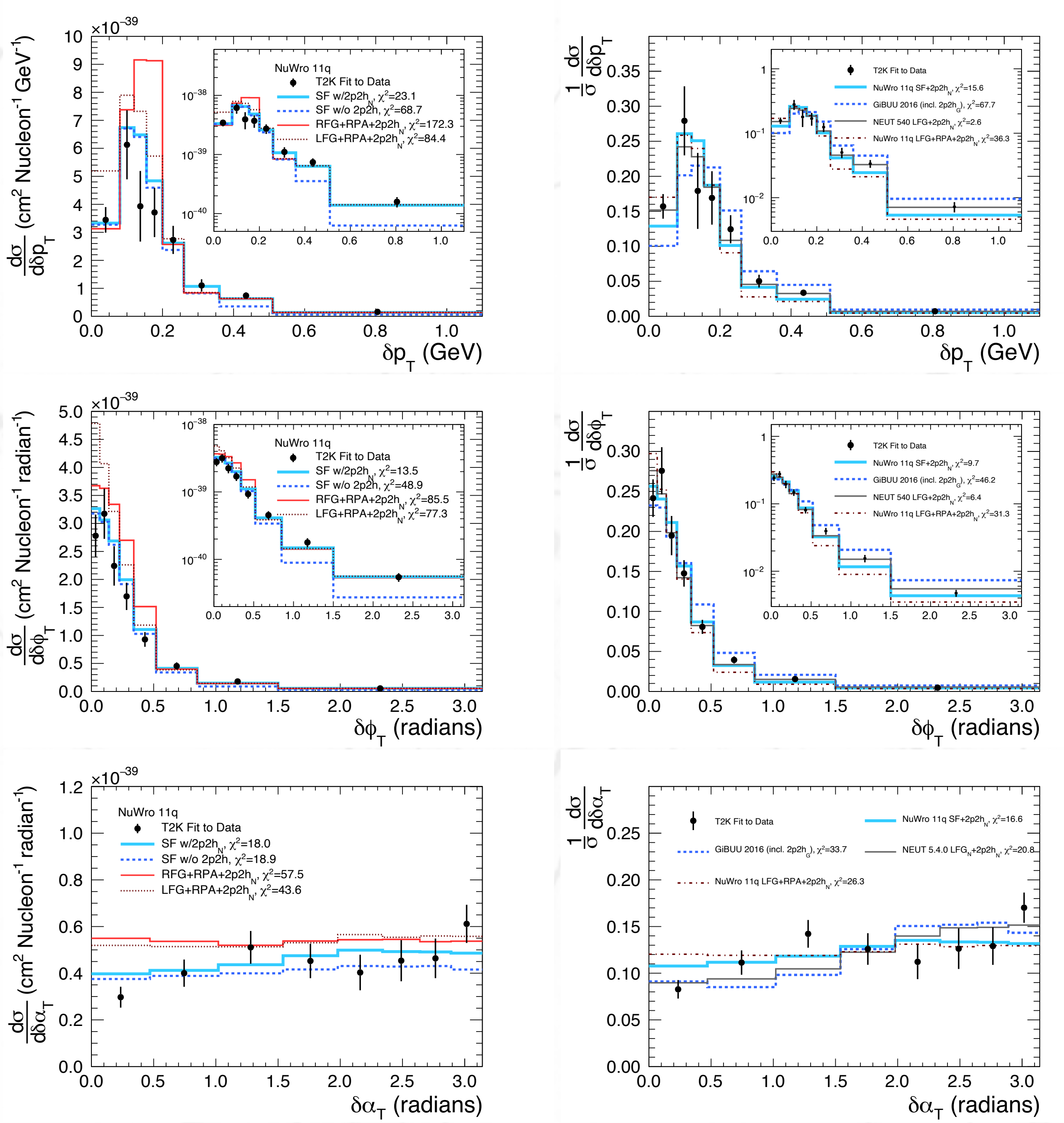
Explore sensitive parameters:TKI

Normally these variables are very sensitive to physics in models
but require an exclusive lepton-hadron model implementation in our event generators

arXiv:1802.05078v3 TKI



2D kinematical measurements:
hadron vs lepton

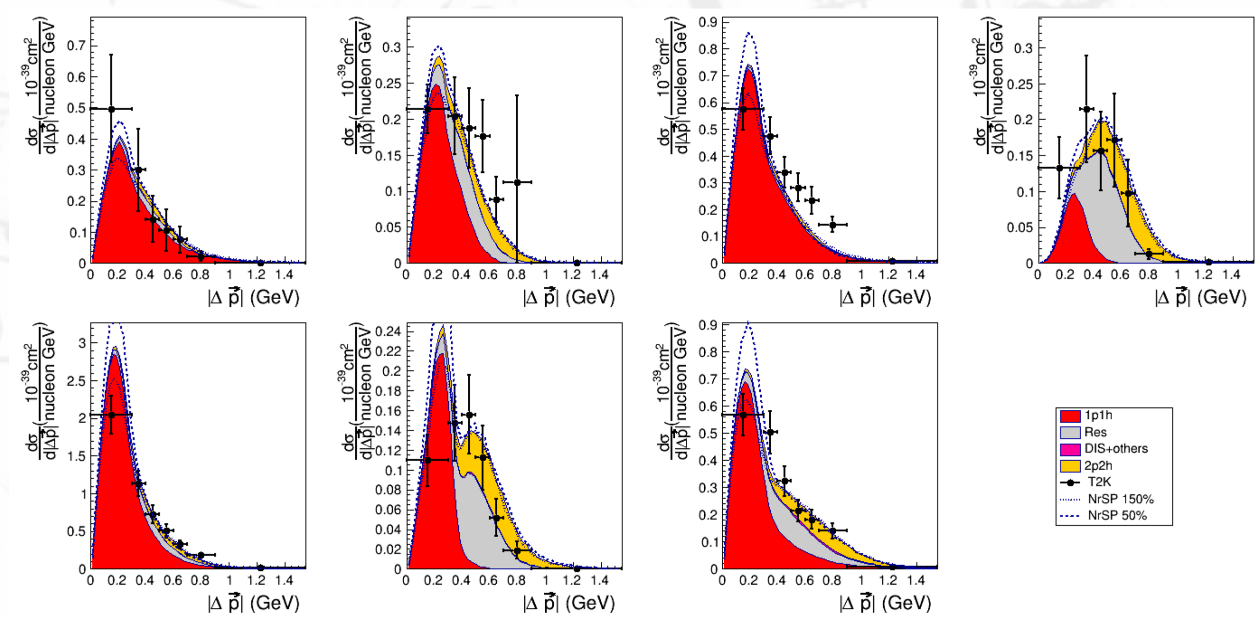
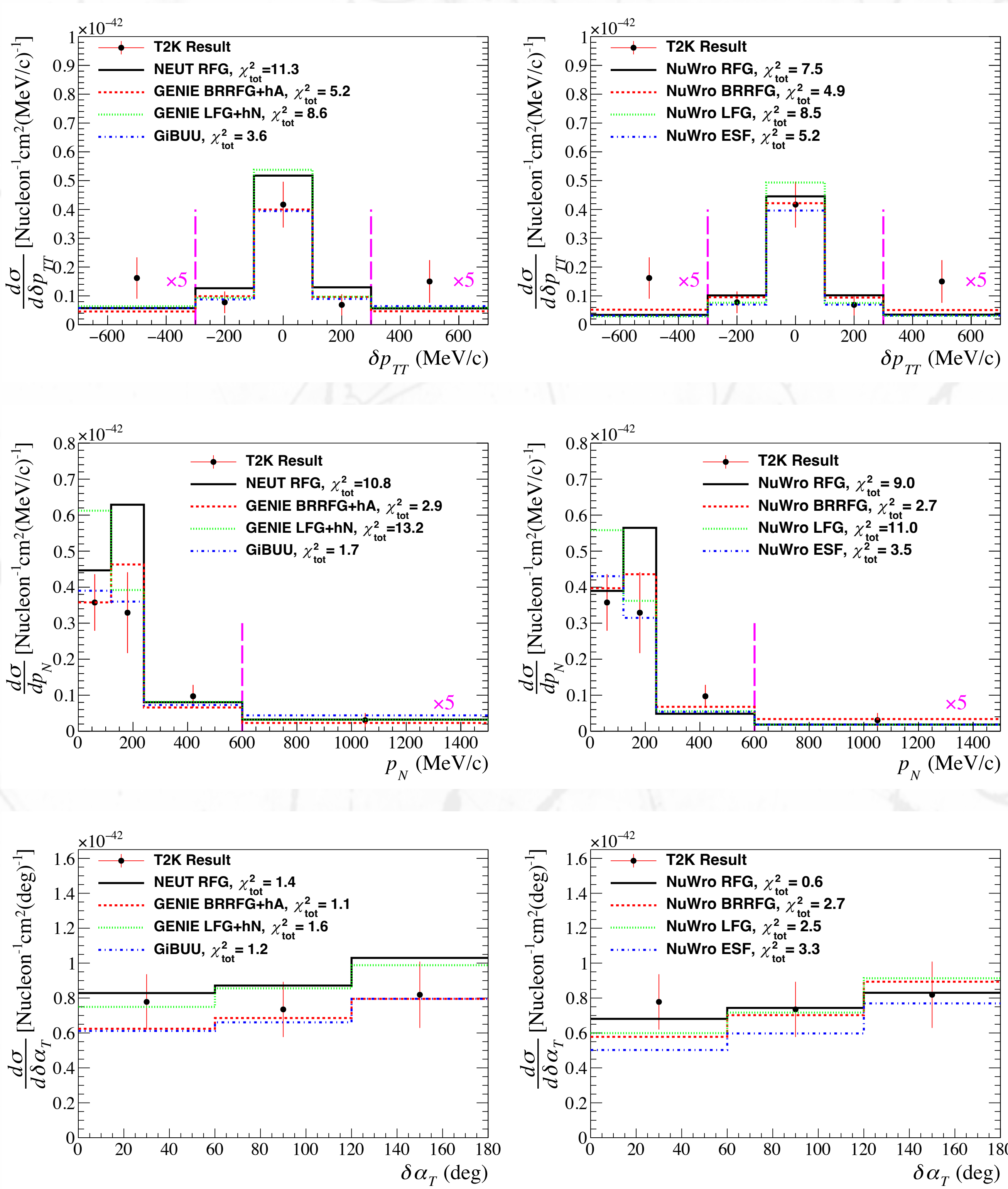


Figure 15. T2K CC0π1p $|\Delta\vec{p}|$ distribution. The panels correspond to different muon kinematic bins. From left to right and up to down: $-1 < \cos\theta_\mu < -0.6$, $-0.6 < \cos\theta_\mu < 0$ with $|\vec{p}_\mu| < 250$ MeV, $-0.6 < \cos\theta_\mu < 0$ with $|\vec{p}_\mu| > 250$ MeV, $0 < \cos\theta_\mu < 1$ with $|\vec{p}_\mu| < 250$ MeV, $0 < \cos\theta_\mu < 0.8$ with $|\vec{p}_\mu| > 250$ MeV, $0.8 < \cos\theta_\mu < 1$ with 250 MeV $< |\vec{p}_\mu| <$ 750 MeV and $0.8 < \cos\theta_\mu < 1$ with $|\vec{p}_\mu| > 750$ MeV. Data taken from Ref. [21].

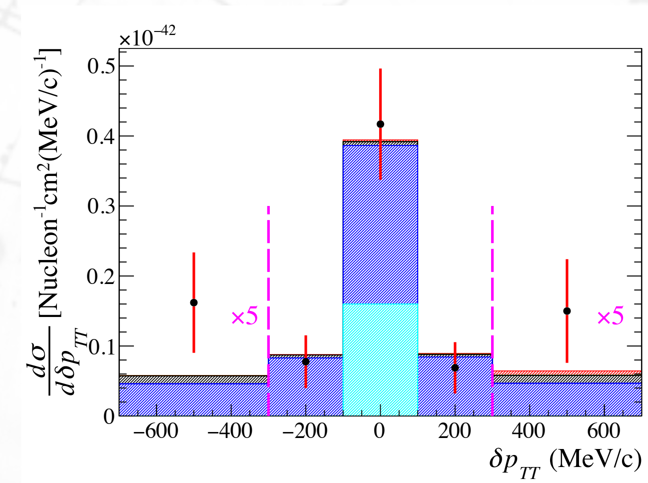
Explore sensitive parameters:TKI



- This method can be also applied to **CC1p1π** samples

statistics is low but it shows its strength

- Also it allows to isolate Hydrogen contributions.



also anti-neutrino CCQE using neutrons “a la” Minerva.

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Basic vs elaborated observables

Basic observables (p_μ,$\cos\theta_\mu$)

- simple deconvolution of detector effects is possible.
- little (self)influence of the reference model in the final cross-section.
- We can "confidently" provide cross-sections to be compared with models:
  - acceptance correction is provided and can be applied to models.
- There are still some remaining model effects: proton detectability, background rejection, …
- But, it is less sensitive to subtle model effects.

Complex observables (TKI):

- simple deconvolution of detector effects is difficult, more than one particle involved.
  - (self)influence of the reference model in the final cross-section difficult to define.
- Cross-sections to be compared with models are difficult.
  - acceptance correction is depends on the reference model (biased)
- The best solution in this case is to compare with a model in our event generators.
- It is more sensitive to model details.

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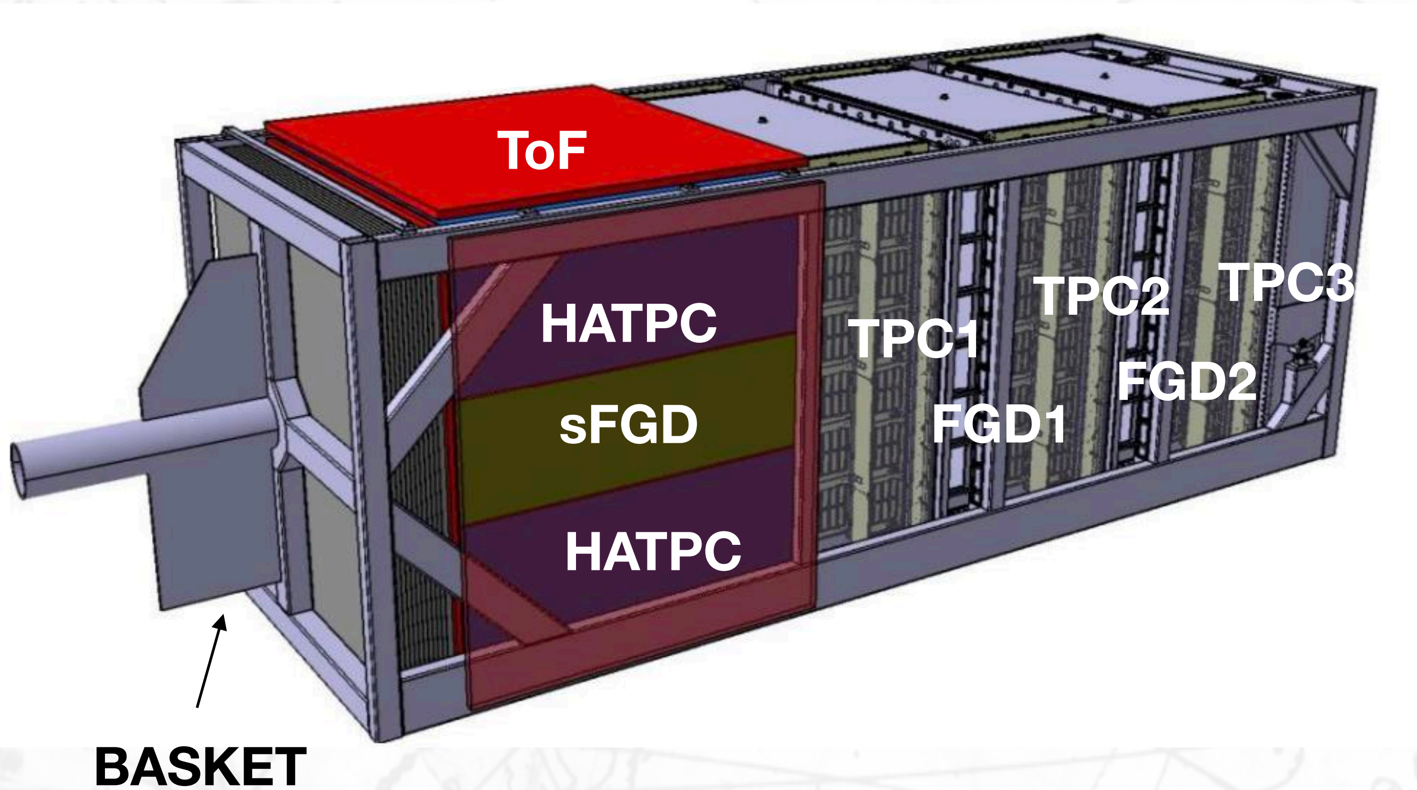
What's next

- I think there is plenty to explore.
  - Not all potential observables have been explored.
  - statistics is still low for more than 2 dimensional analyses.
  - Advanced models have been incorporated which will allow us to understand & control systematics to a better level.
- But, we now the detector we had has some limitations:
  - high angle (large Q^2) lepton detector acceptance.
  - low momentum proton threshold for optimal TKI exploration.
  - Gamma/electron separation.
  - Vertex activity control (very low energy hadronic debris)
  - No neutron detection capabilities.
  - limited Michel Electron
  - External background (wrong sign background).
  - ….

In 2018 T2K decided to upgrade the near detector.

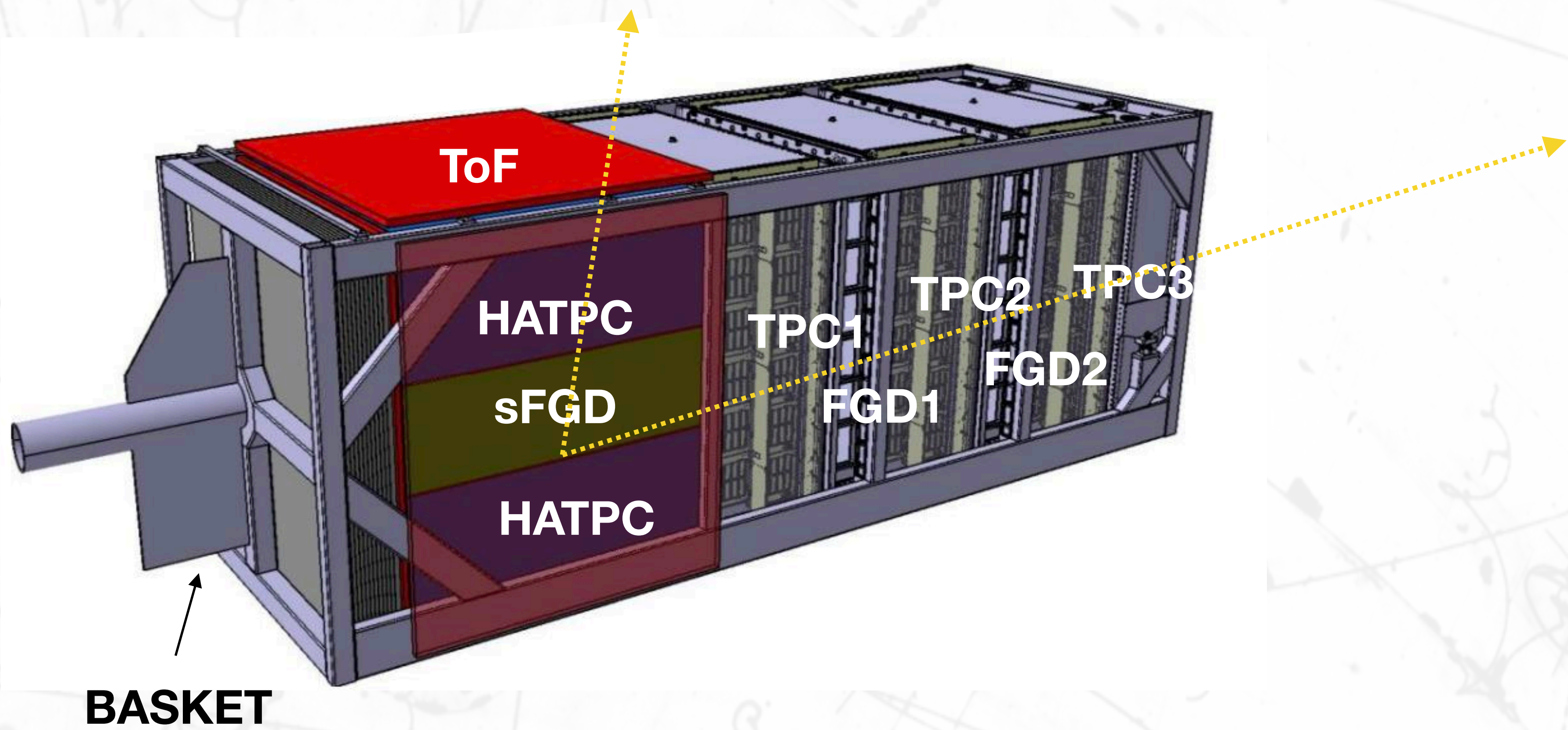
Construction is almost finished, first data by the end of the year.

The ND280 upgrade

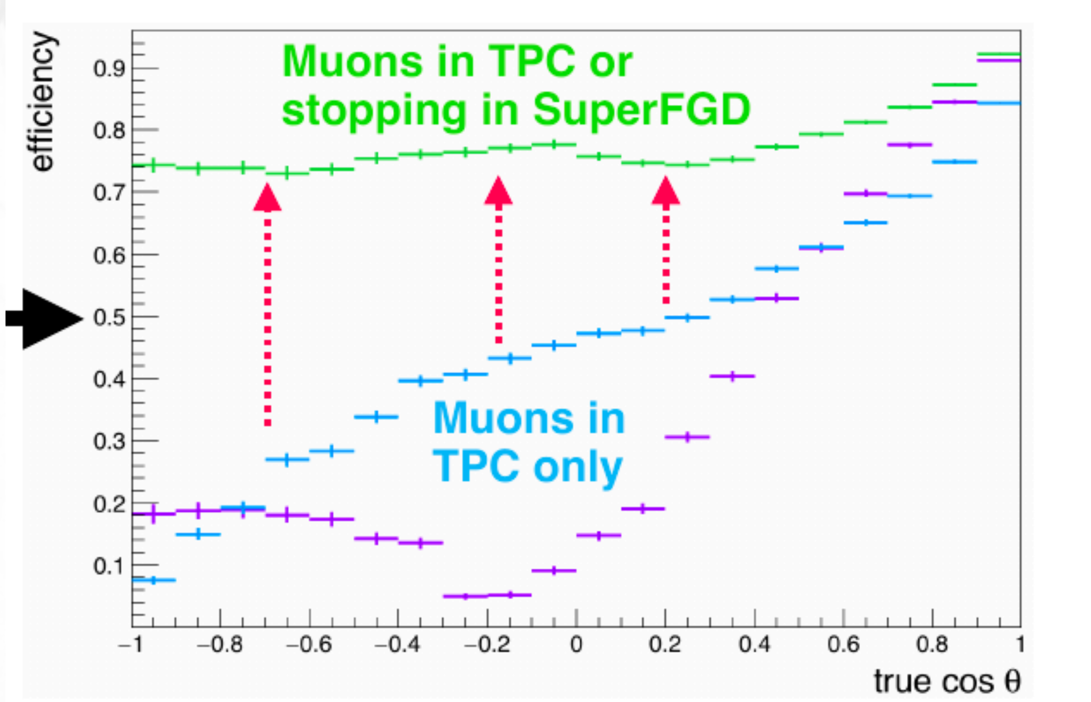


- **sFGD:** quasi-3D imaging.
  - Improved target tracking.
  - Improved proton detection threshold.
  - Neutron detection capabilities & kinematics reconstruction in final state
- **High Angle TPC's:**
  - Improved high angle acceptance:
- **Time of Flight**
  - Reduction of background from magnet interactions.

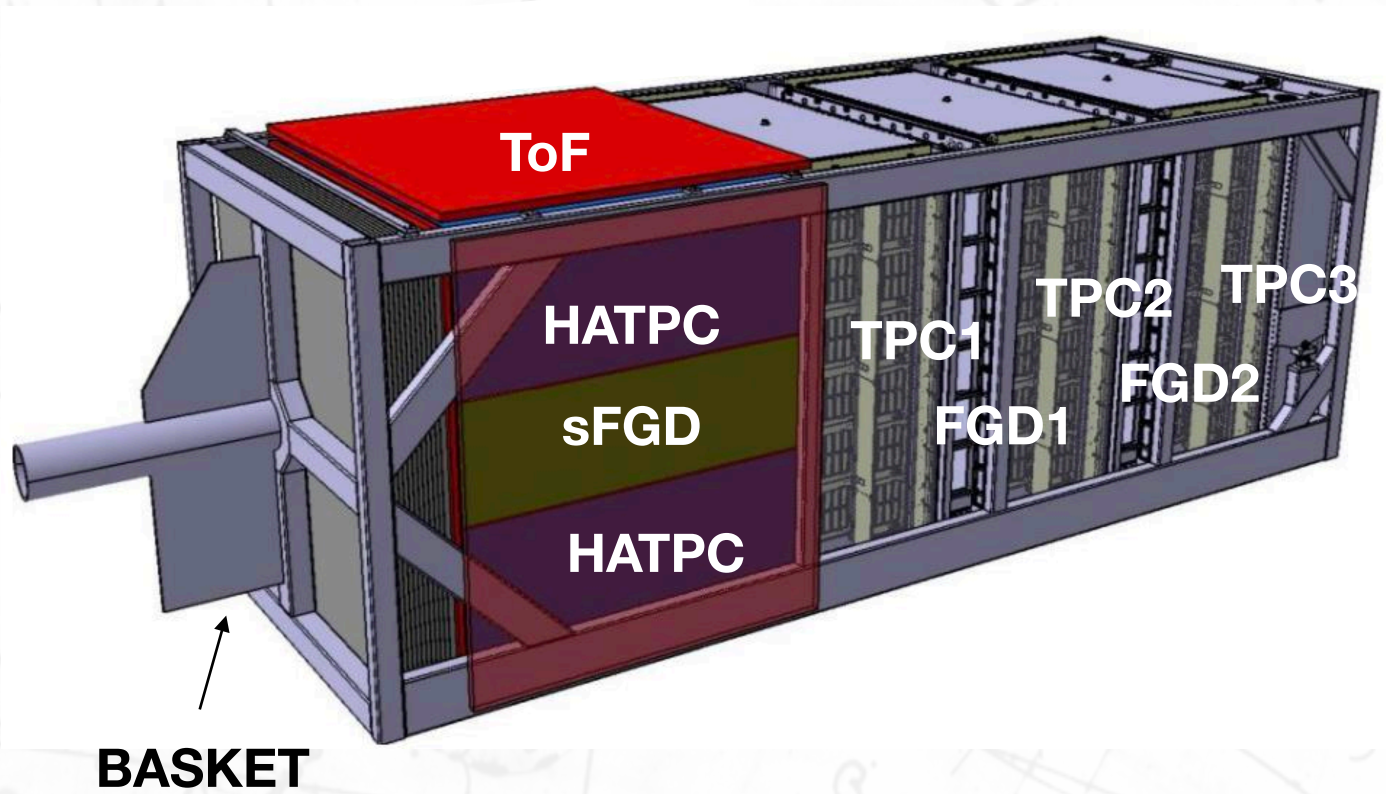
The ND280 upgrade

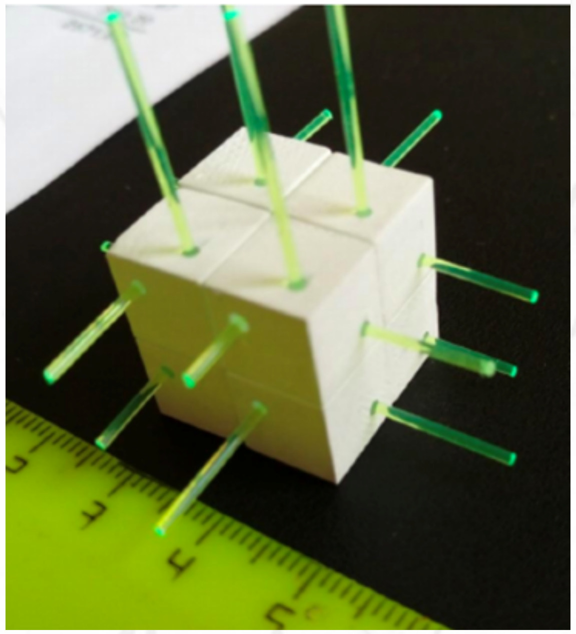


High angle acceptance



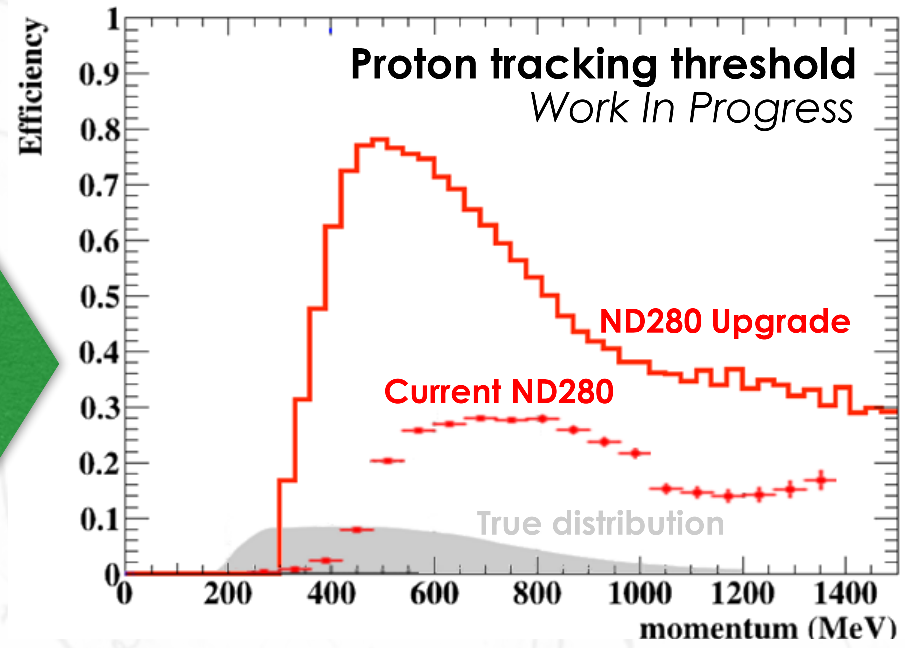
The ND280 upgrade



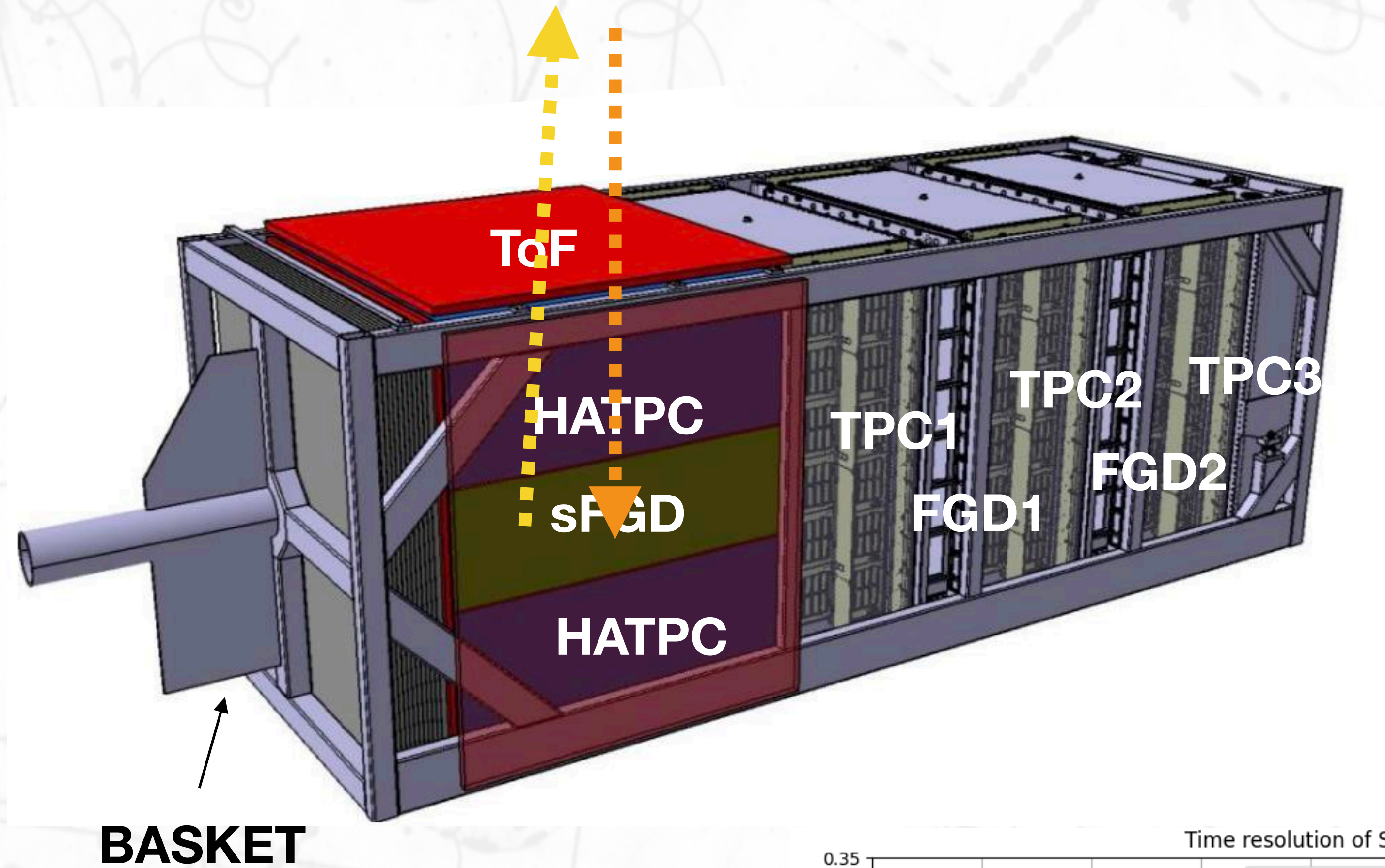


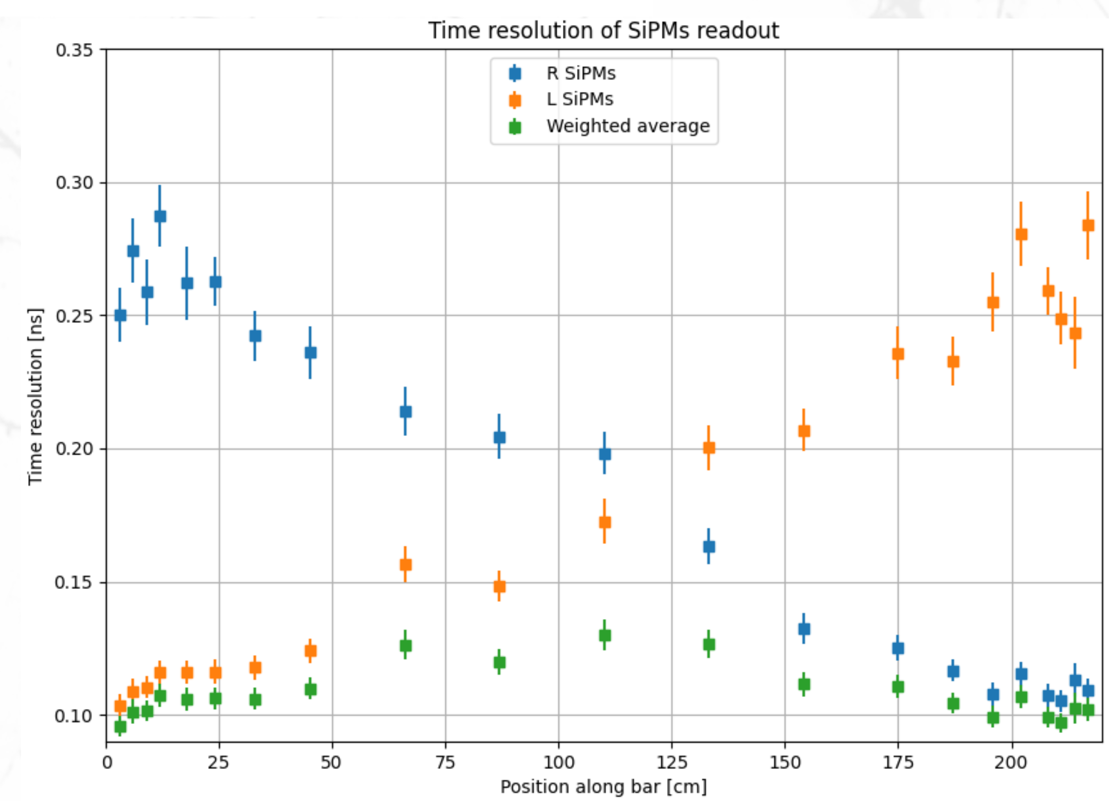
Finner quasi-3D tracker:

Old detector we needed 3 x + 3 y planes = 6
New detector we need 3xy planes = 3



The ND280 upgrade





With ~150 ps time resolution we can determine if the particle was produced outside the detector (background) or inside (signal)

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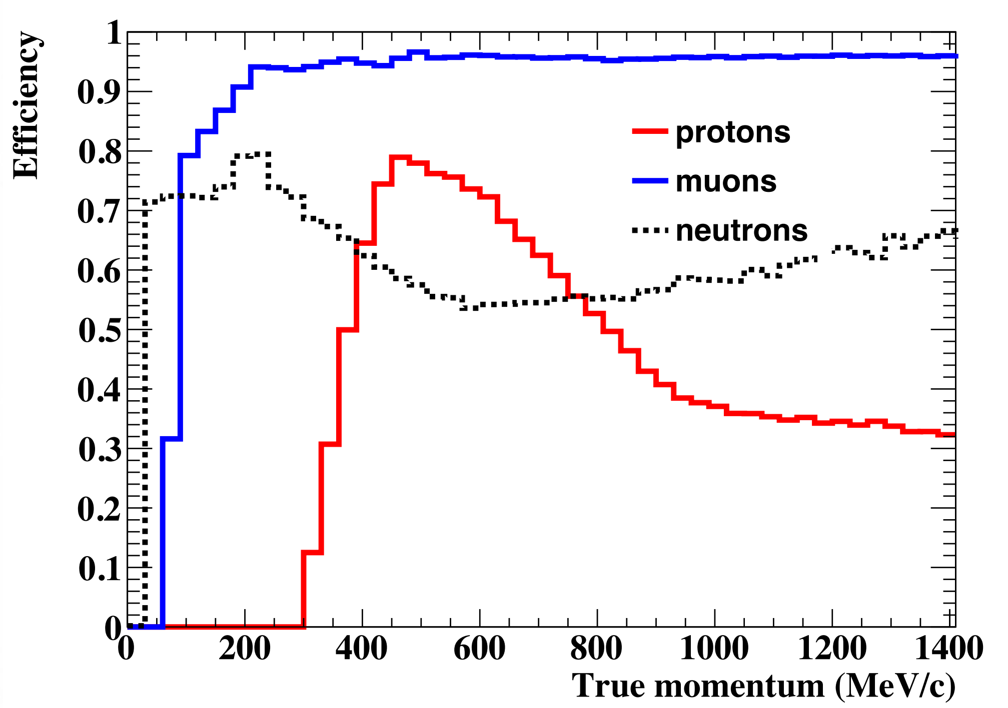
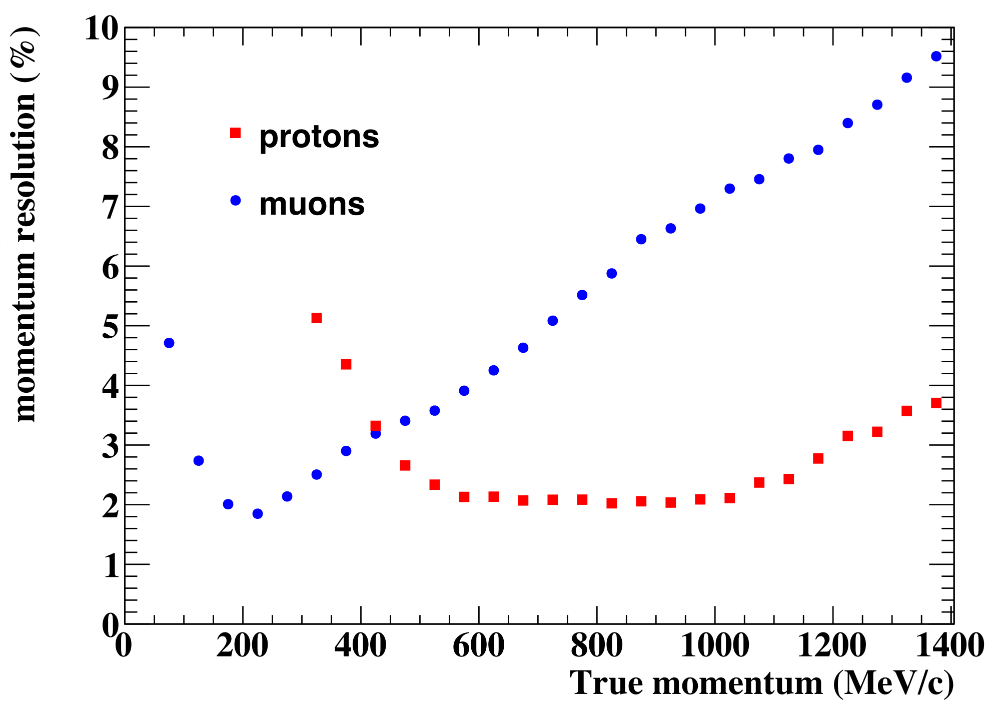
What can T2K do with the new detector ?

arXiv:2108.11779v2



New detector has:
low proton threshold detection (200 MeV/c)
and high efficiency (~ 95%)



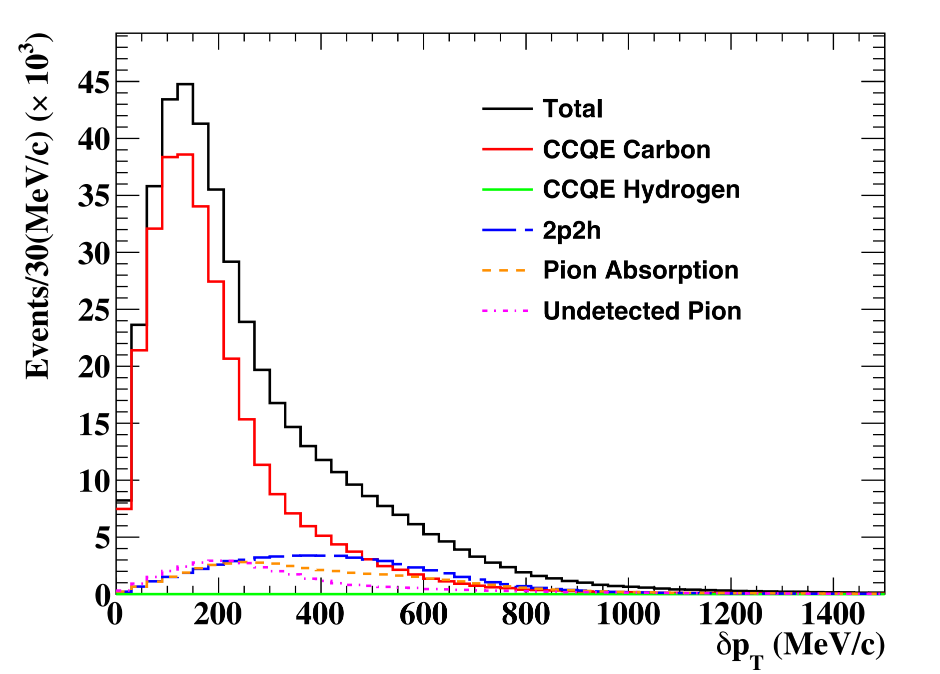
Momentum resolution is also excellent (< 10%)

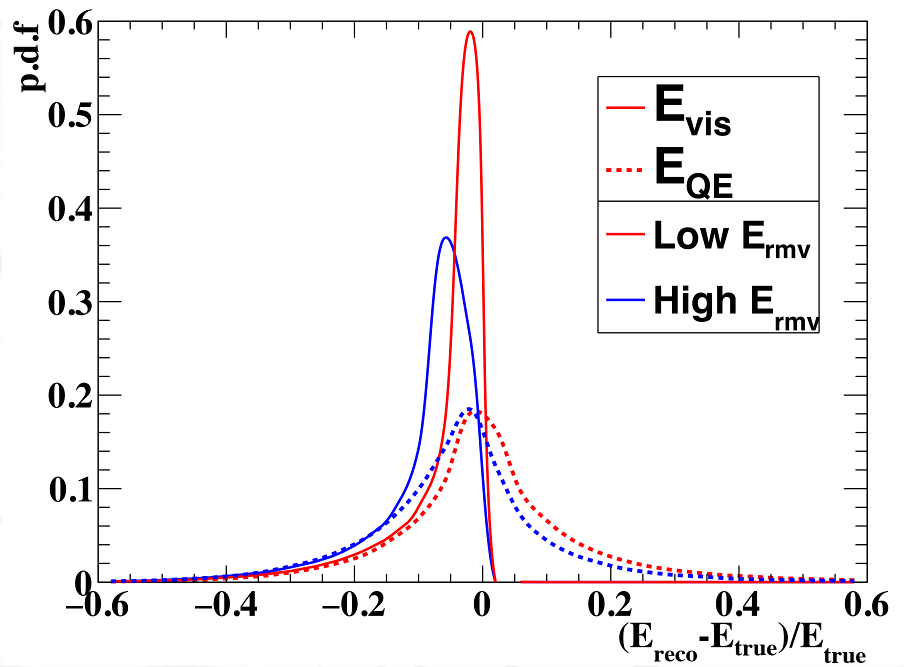
TKI variables will profit from both improvements significantly

What can T2K do with the new detector

TKI variables & energy reconstruction (E_μ+E_p)

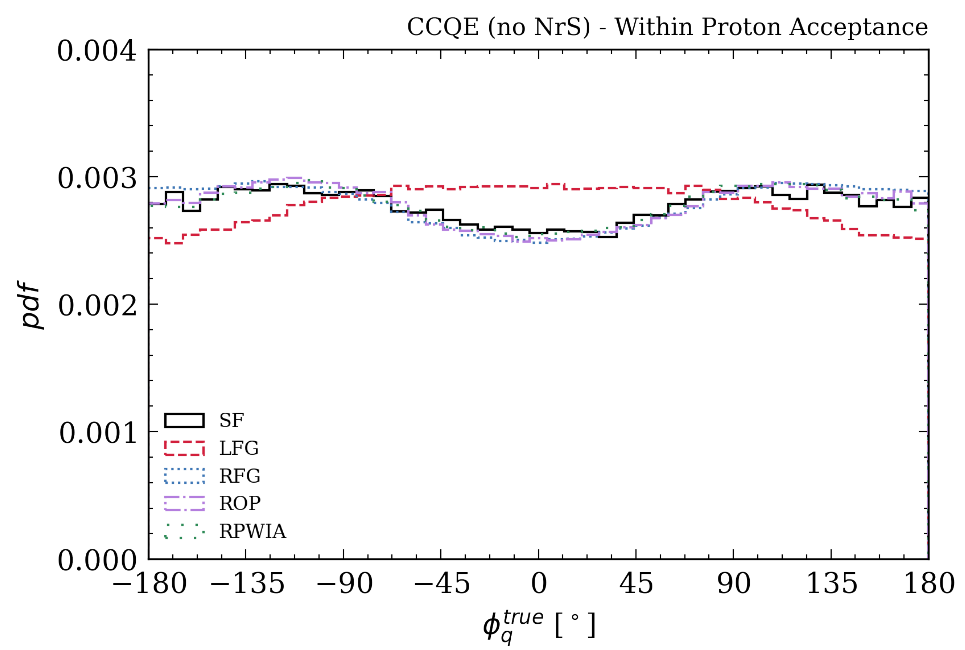
arXiv:2108.11779v2

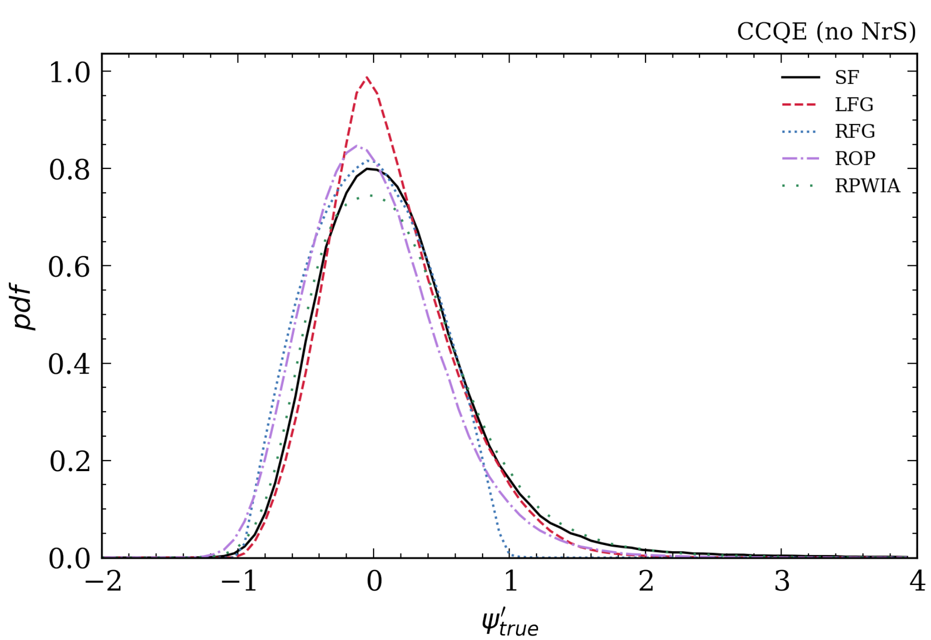




New variables can be explored

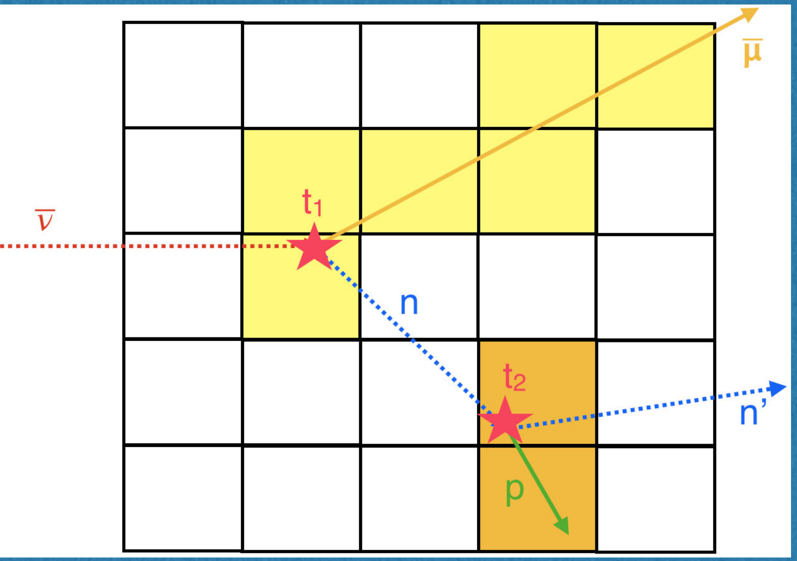
Publication in preparation



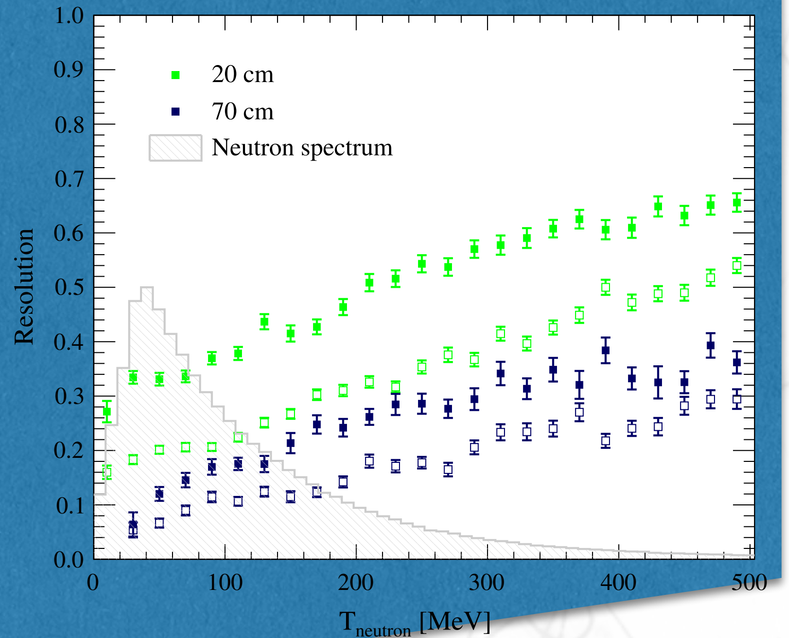


But also neutrons

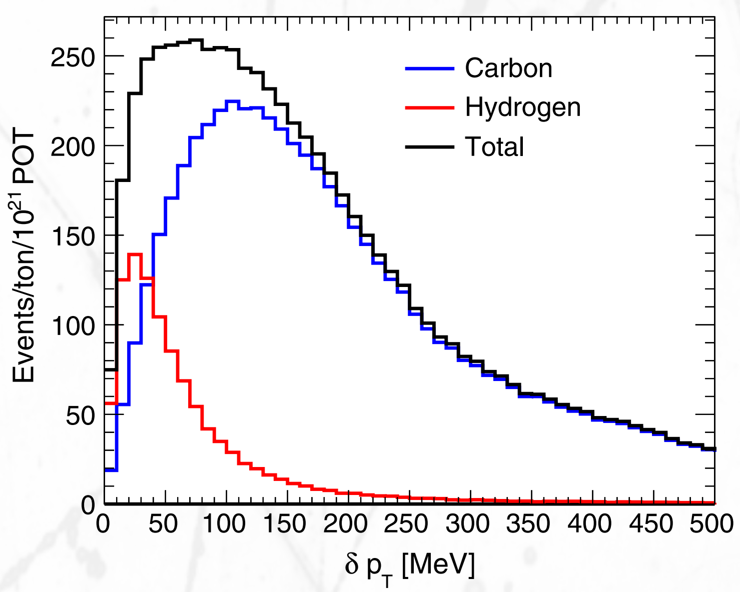
PHYSICAL REVIEW D 101, 092003 (2020)



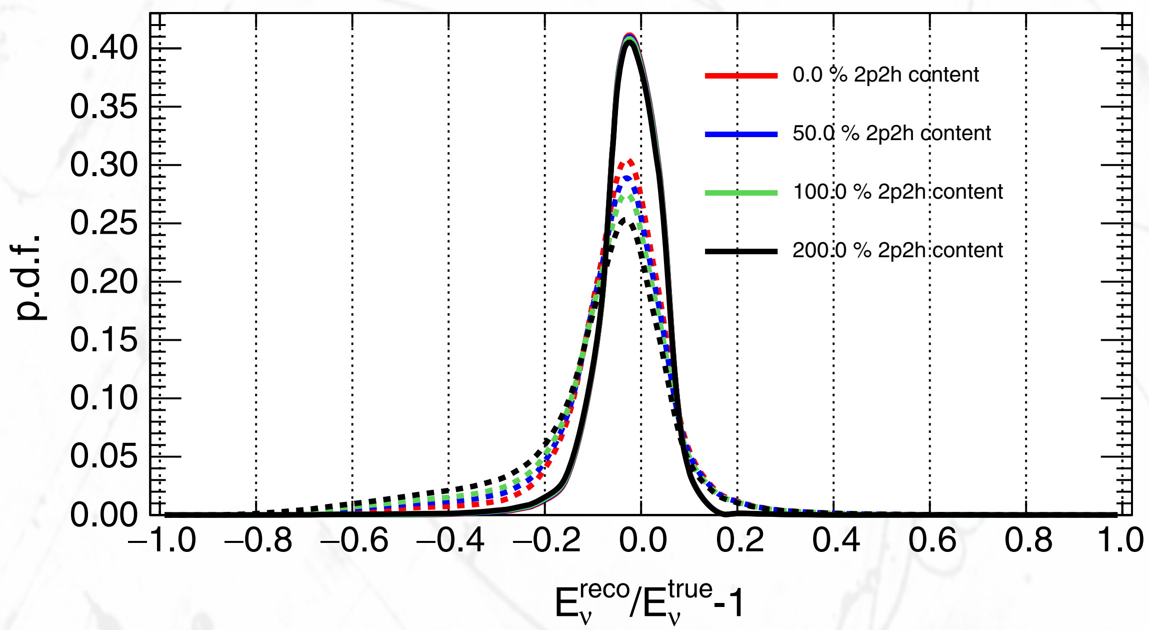
Quasi-3D sFGD geometry facilitates the neutron tagging and kinematic reconstruction through time of flight.



Hydrogen tagging



anti-ν Energy reconstruction



T2K and HK

- The near detector will be transferred together with all the experience to HK.
    - this will increase the amount of neutrinos available and open the possibility to explore for example > 2 dimensional cross-sections.
- HK-ND280 is already starting to think about possible improvements of the ND:
    - reduced proton threshold.
    - increase statistics.
    - improve Oxygen vs Carbon
    - improve electron neutrino measurements.

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Remarks

- T2K approach to cross-section is multidirectional with a mixture of theoretical and experimental approaches.
- Clear distinction between cross-section for oscillations and cross-section measurements.
  - They have two different time impacts on the oscillations.
- Exploring both the off-axis configuration and the capabilities of the detector.
- We pay attention to the “validity” of our results trying to avoid biases from our model assumptions.
- T2K is improving the experimental setup to improve their control on the cross-sections.
- Probably not the last, Hyper-K will need an additional upgrade to constrain even further the cross-section uncertainties.
- The strong relation between theory and experiment inside T2K is critical to the success of this program: active theory-T2K relations, model implementation in MC’s, ….

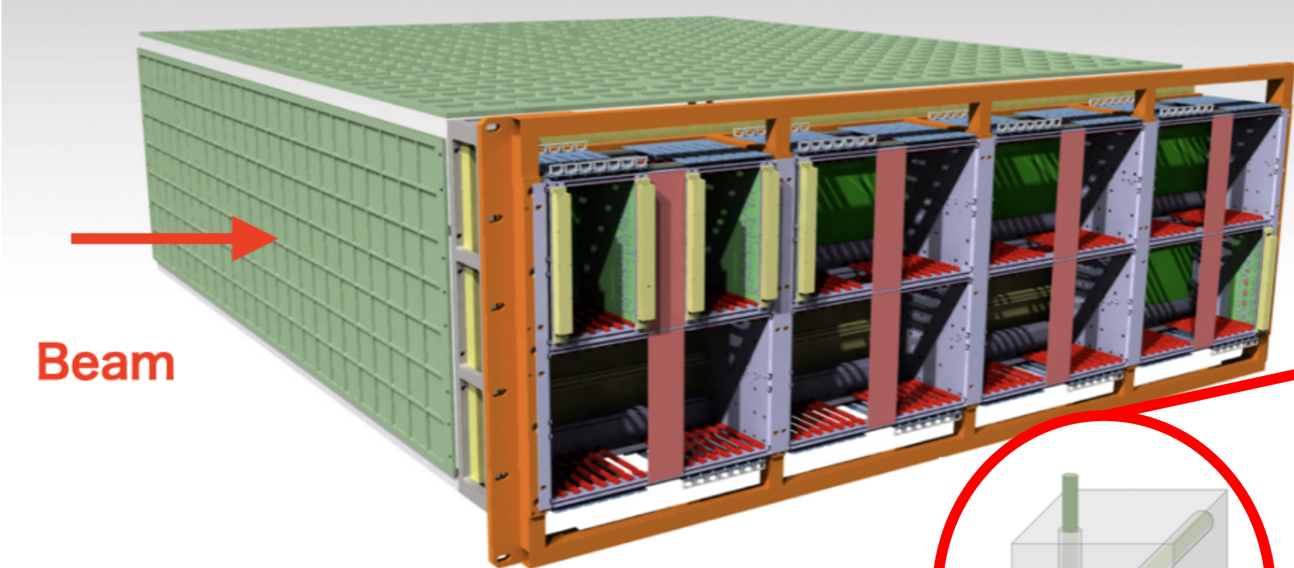
Stay tuned

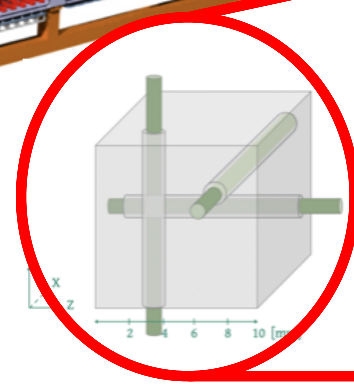
Plenty of new exciting results expected from T2K during next years.

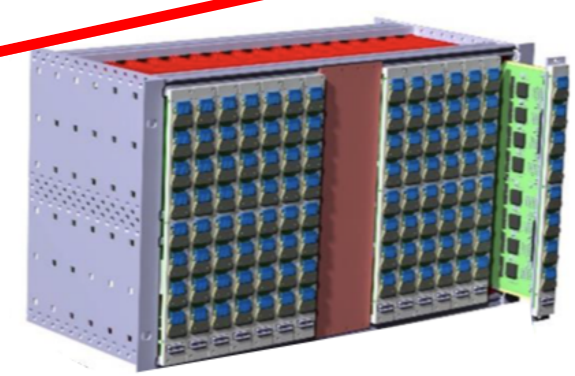
Support slides

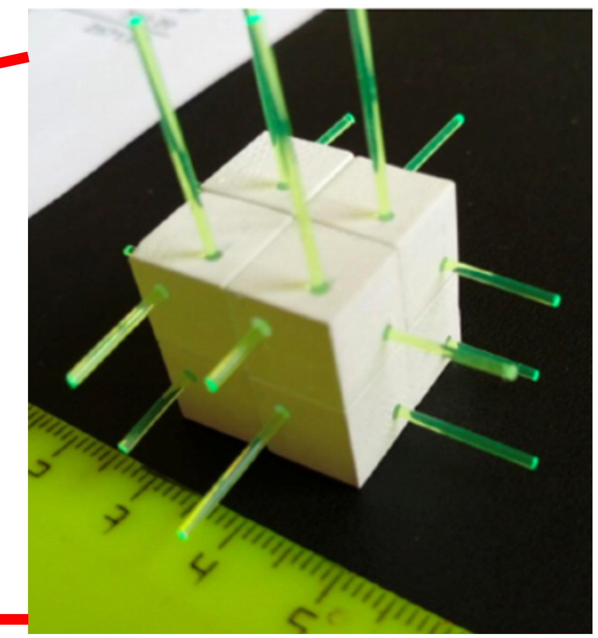
SFGD

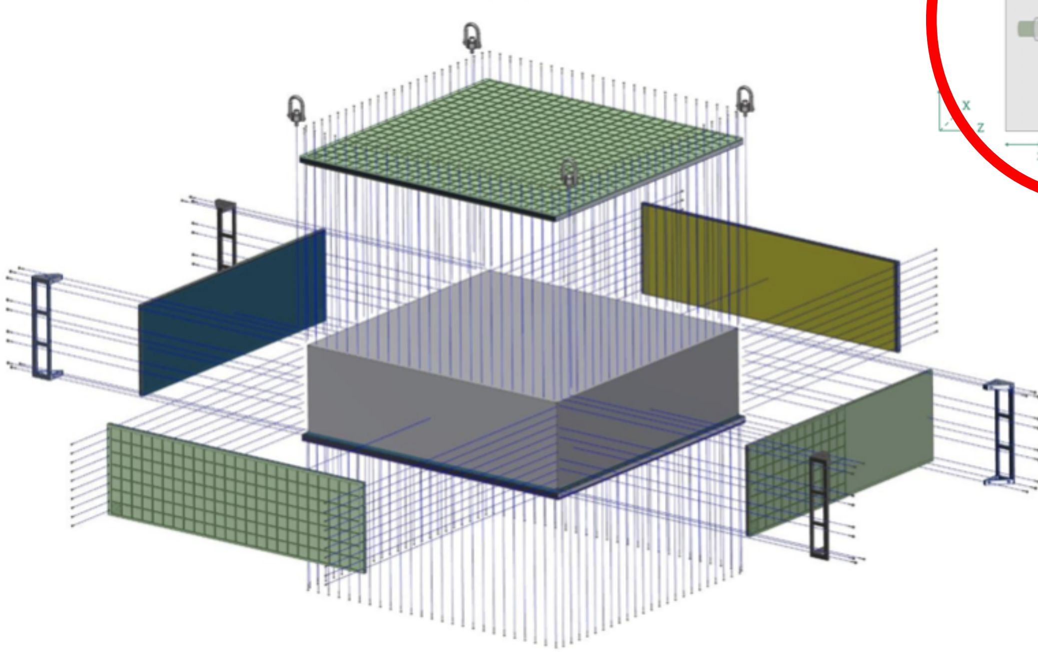
- 192 x 182 x 56 cubes
- Mechanical box for ~2t
- ~56k fiber/MPPCs
- ~56k readout channels

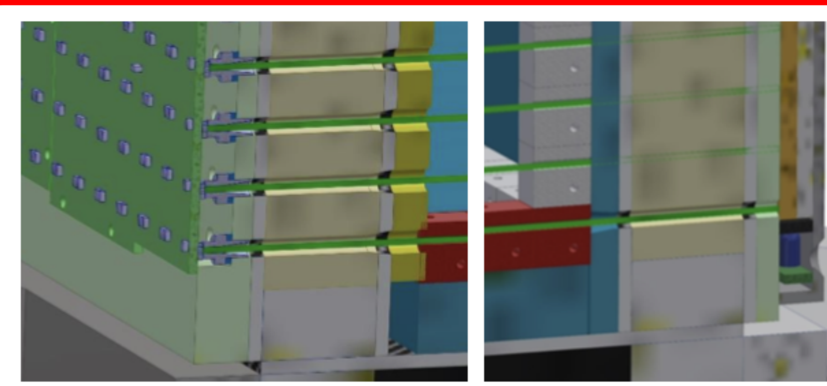












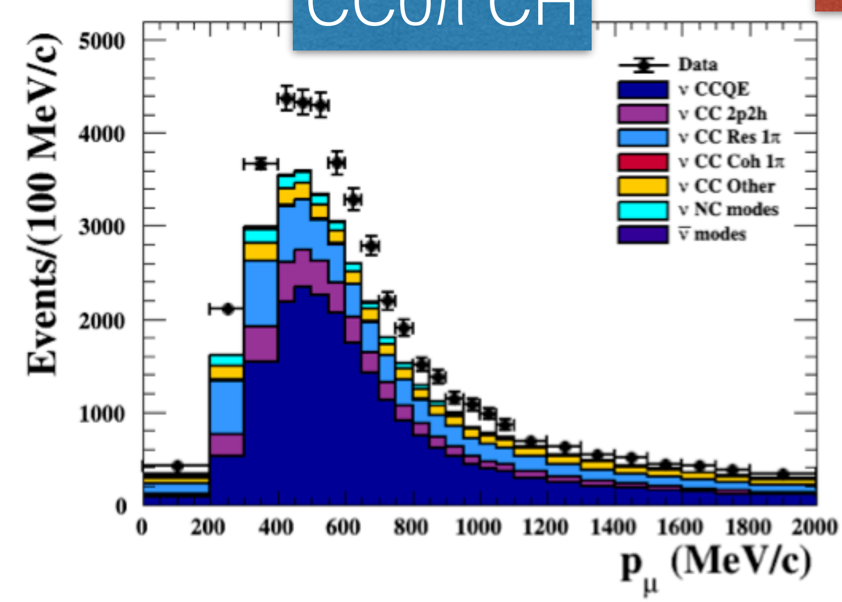
All ND data samples pre- and post-fit

FHC is ν-mode
RHC is $\bar{\nu}$-mode

FHC

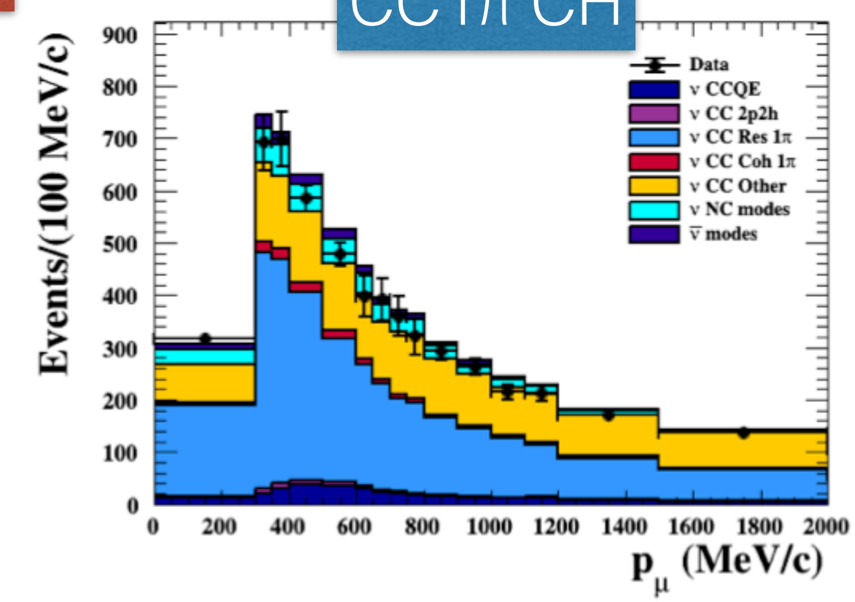
Pre-fit

CC0π CH



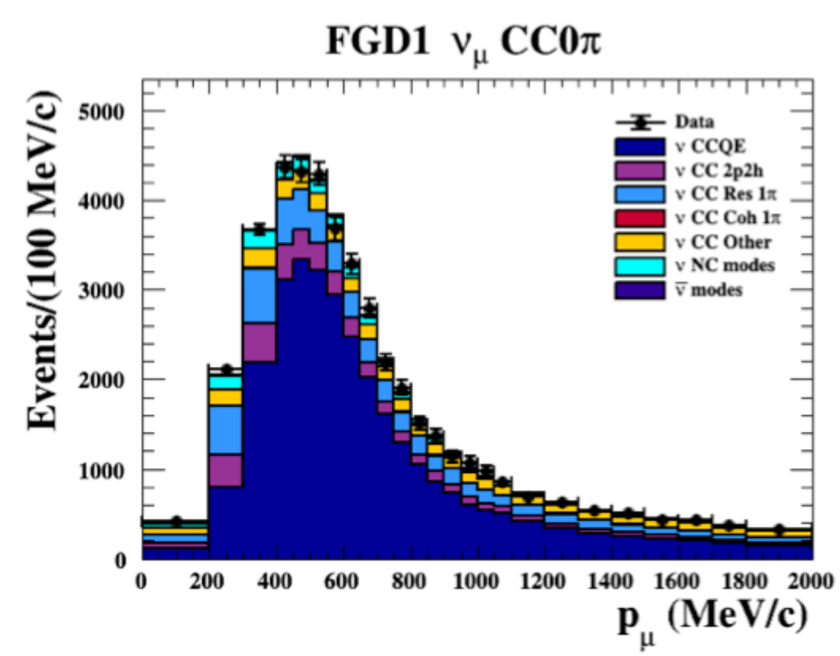
(a) FGD1 FHC ν_μ 0π

CC1π CH

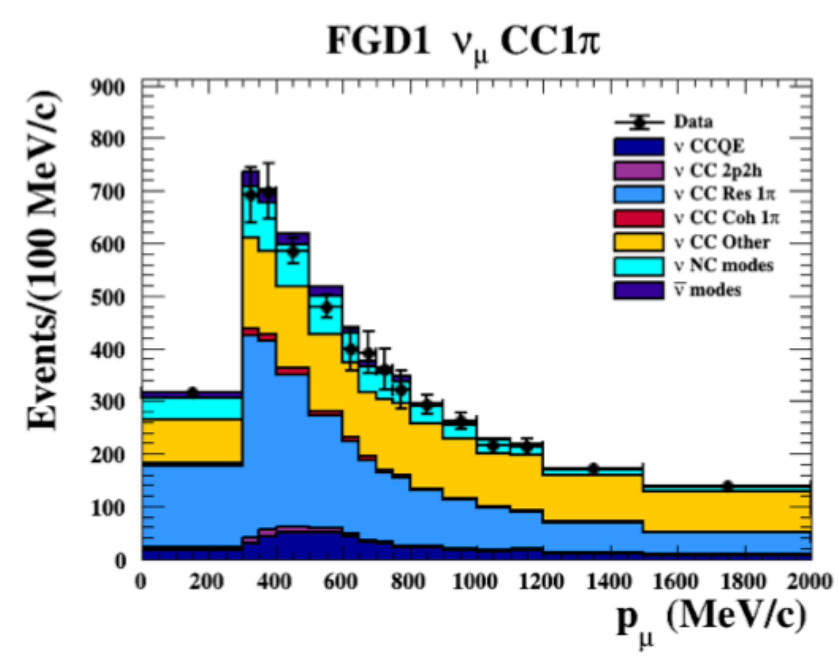


(b) FGD1 FHC ν_μ 1π

Post-fit



(a) FGD1 FHC ν_μ 0π



(b) FGD1 FHC ν_μ 1π

All ND data samples pre- and post-fit

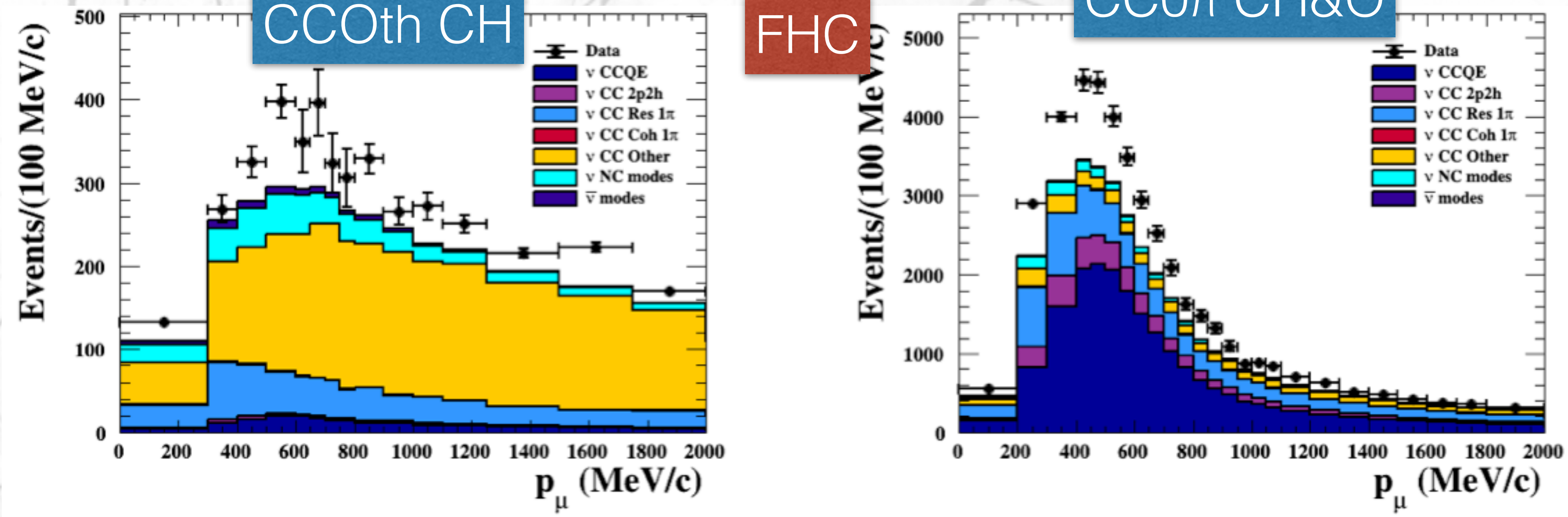
FHC is ν-mode
RHC is $\bar{\nu}$-mode

CCOth CH

FHC

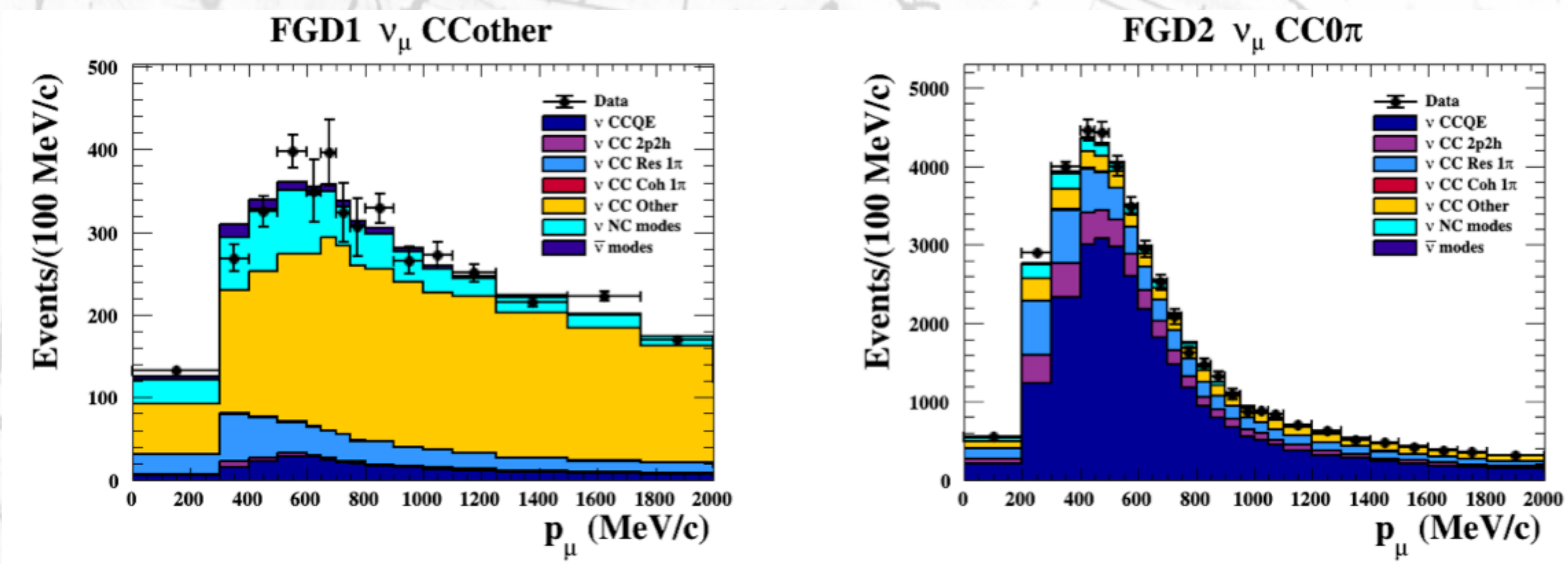
CC0π CH&O

Pre-fit



(c) FGD1 FHC ν_μ Other   (d) FGD2 FHC ν_μ 0π

Post-fit



(c) FGD1 FHC ν_μ Other   (d) FGD2 FHC ν_μ 0π

All ND data samples pre- and post-fit

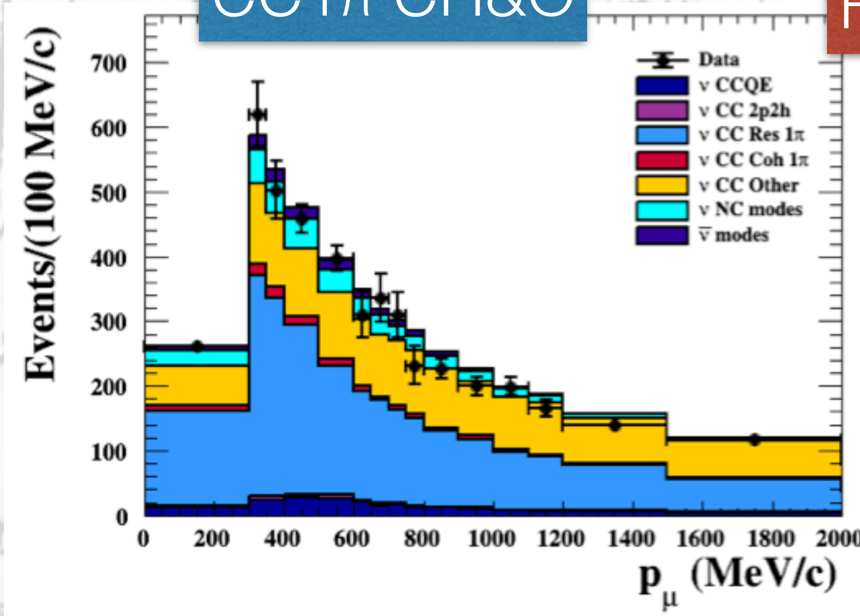
FHC is ν-mode
RHC is $\bar{\nu}$-mode

CC1π CH&O

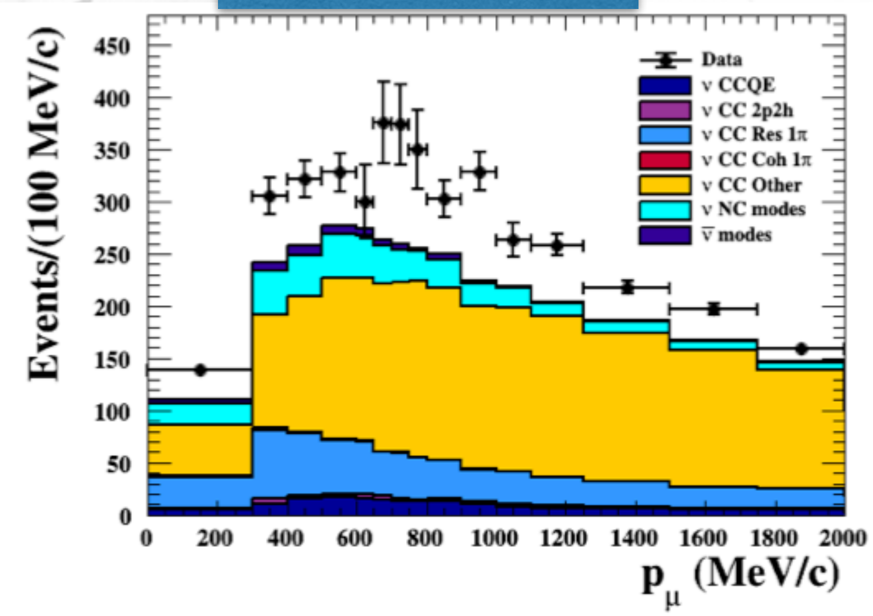
FHC

CCOth CH&O

Pre-fit

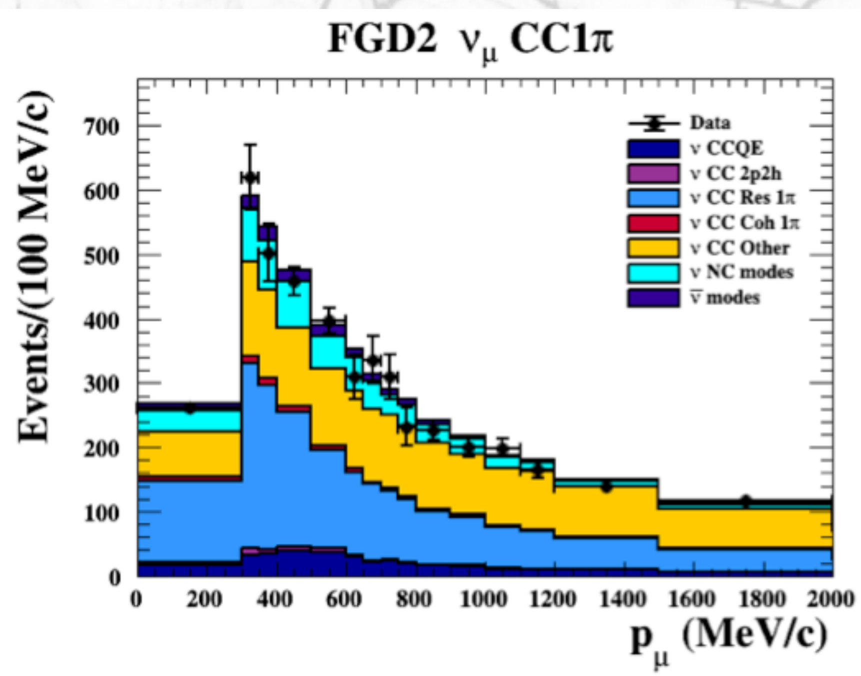


(e) FGD2 FHC ν_μ 1π

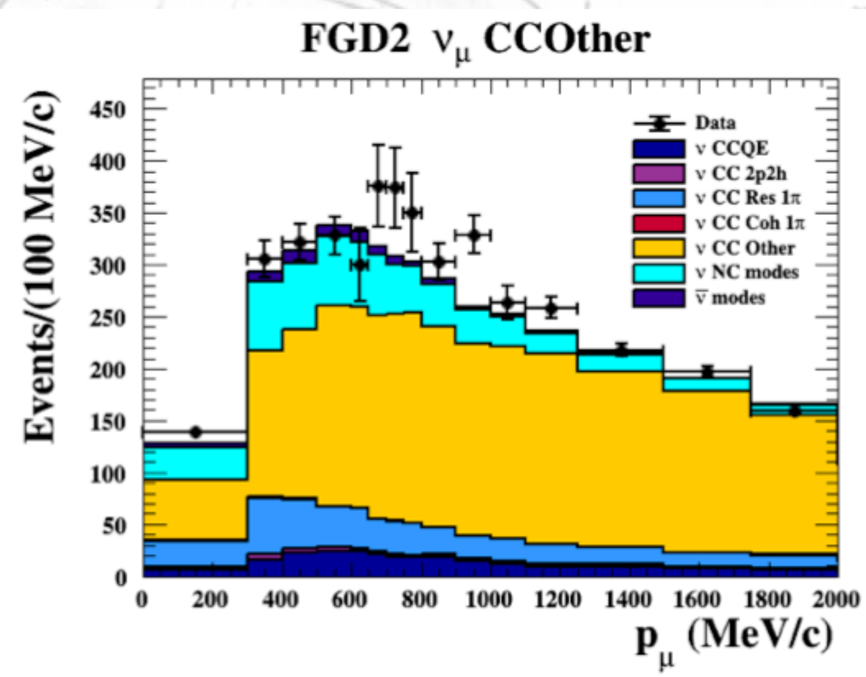


(f) FGD2 FHC ν_μ Other

Post-fit



(e) FGD2 FHC ν_μ 1π



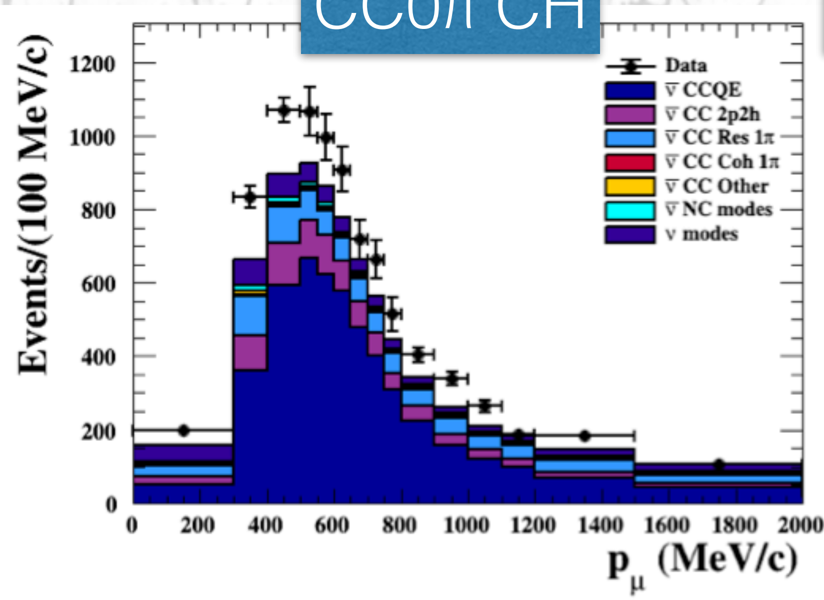
(f) FGD2 FHC ν_μ Other

All ND data samples pre- and post-fit

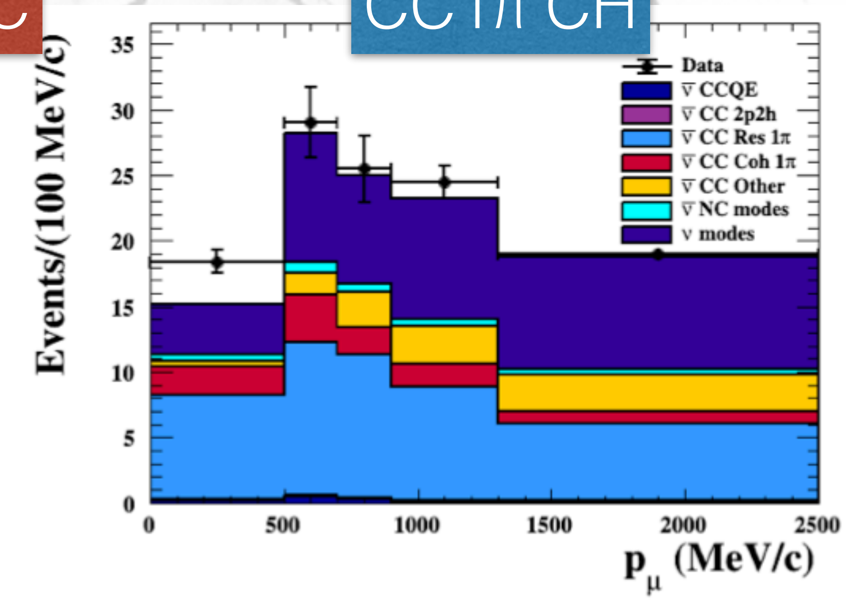
FHC is ν-mode
RHC is $\bar{\nu}$-mode

CC0π CH | RHC | CC1π CH

Pre-fit

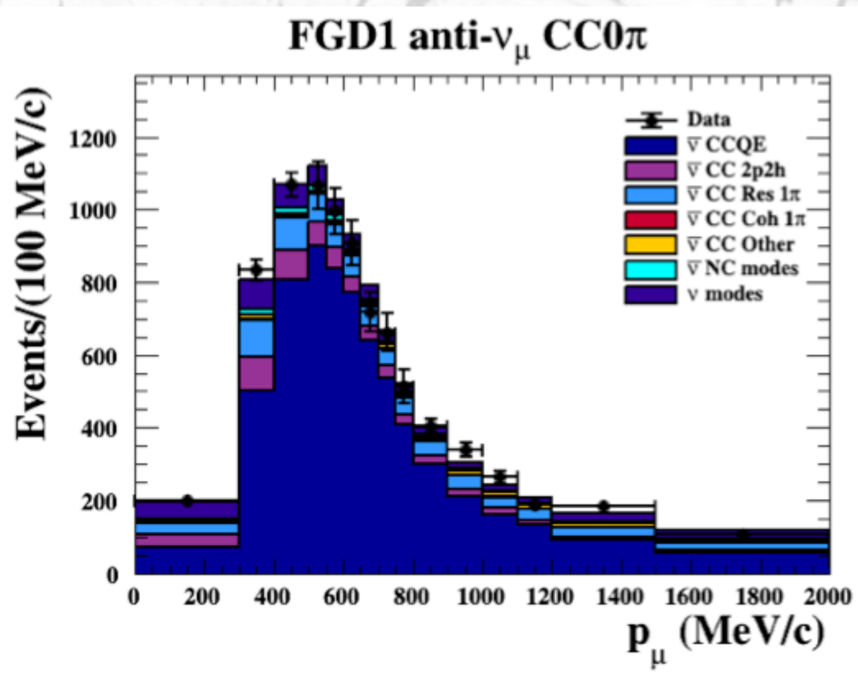


(a) FGD1 RHC $\bar{\nu_\mu}$ 0π

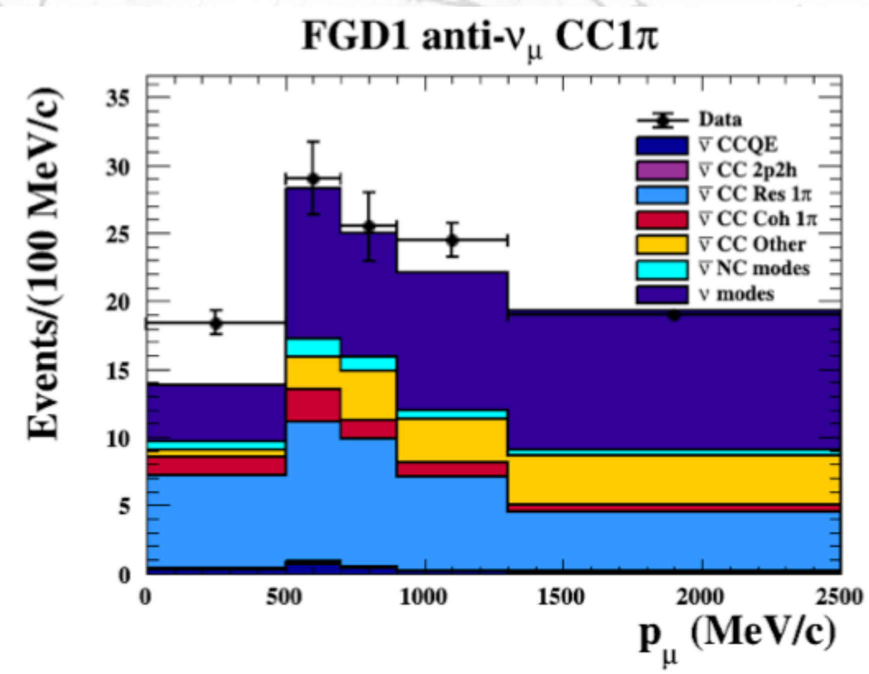


(b) FGD1 RHC $\bar{\nu_\mu}$ 1π

Post-fit



(a) FGD1 RHC $\bar{\nu_\mu}$ 0π



(b) FGD1 RHC $\bar{\nu_\mu}$ 1π

All ND data samples pre- and post-fit

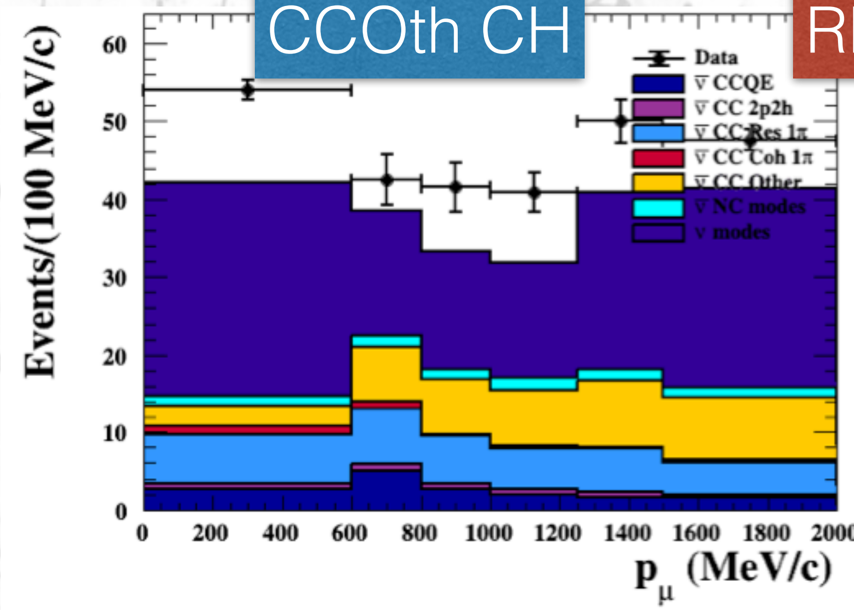
FHC is ν-mode
RHC is $\bar{\nu}$-mode

CCOth CH

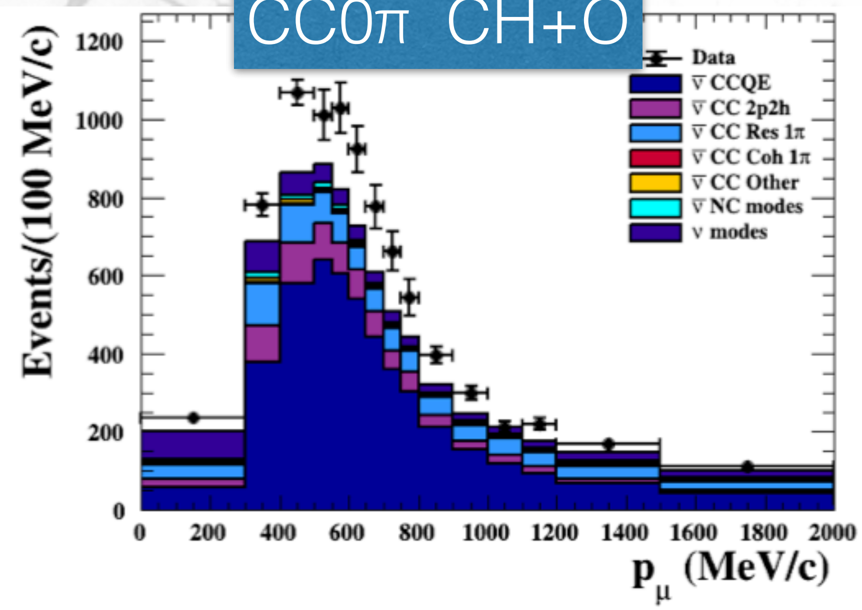
RHC

CC0π CH+O

Pre-fit

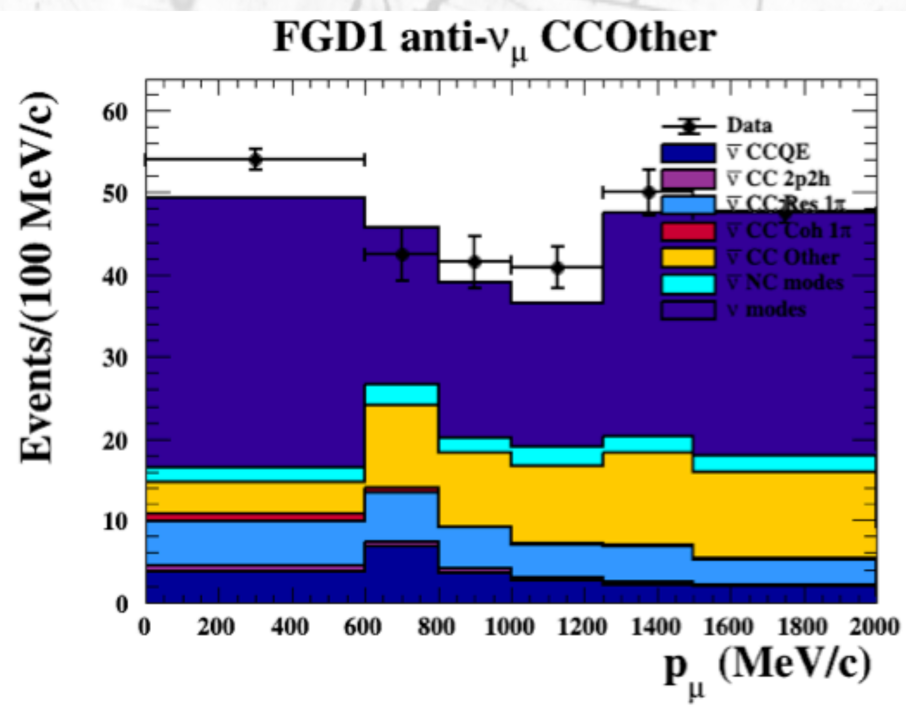


(c) FGD1 RHC $\bar{\nu_\mu}$ Other

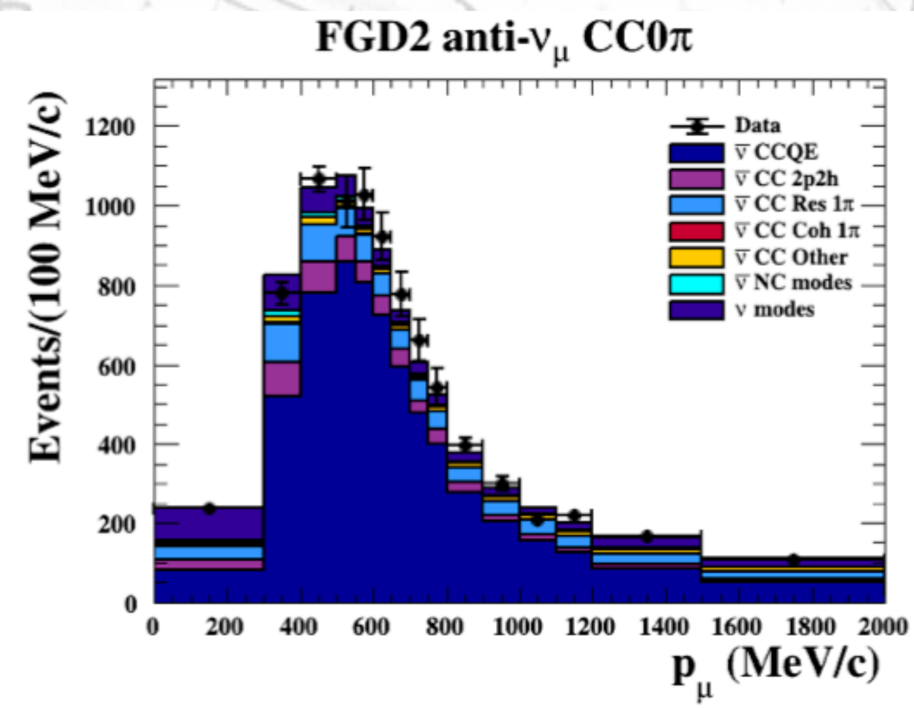


(d) FGD2 RHC $\bar{\nu_\mu}$ 0π

Post-fit



(c) FGD1 RHC $\bar{\nu_\mu}$ Other



(d) FGD2 RHC $\bar{\nu_\mu}$ 0π

All ND data samples pre- and post-fit

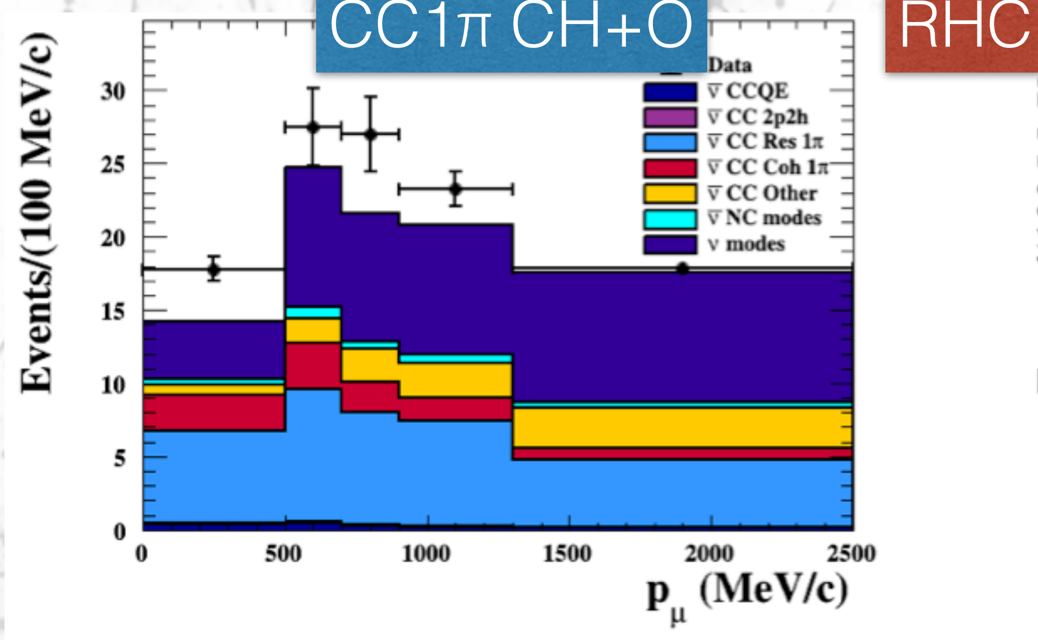
FHC is ν-mode
RHC is $\bar{\nu}$-mode

CC1π CH+O

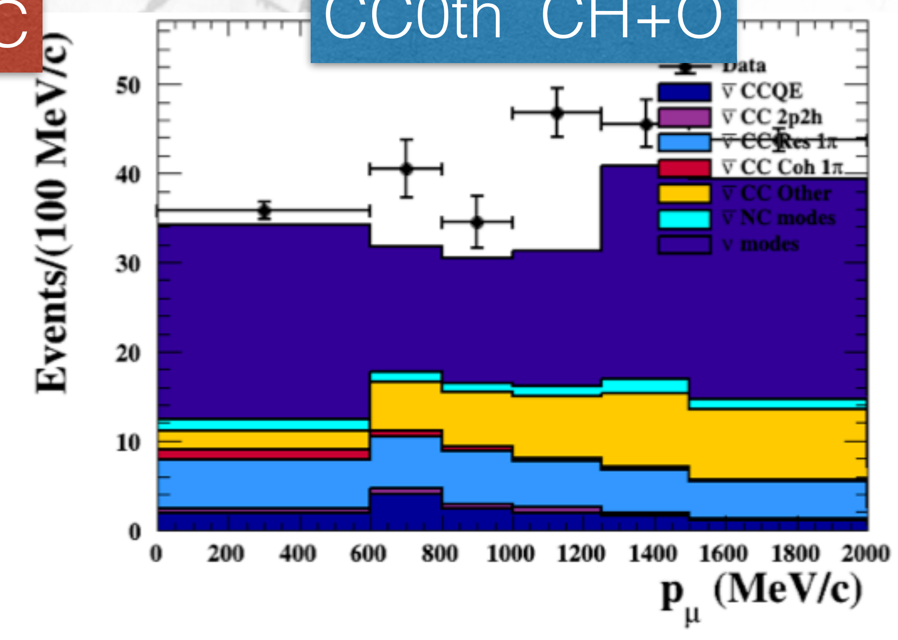
RHC

CC0th CH+O

Pre-fit

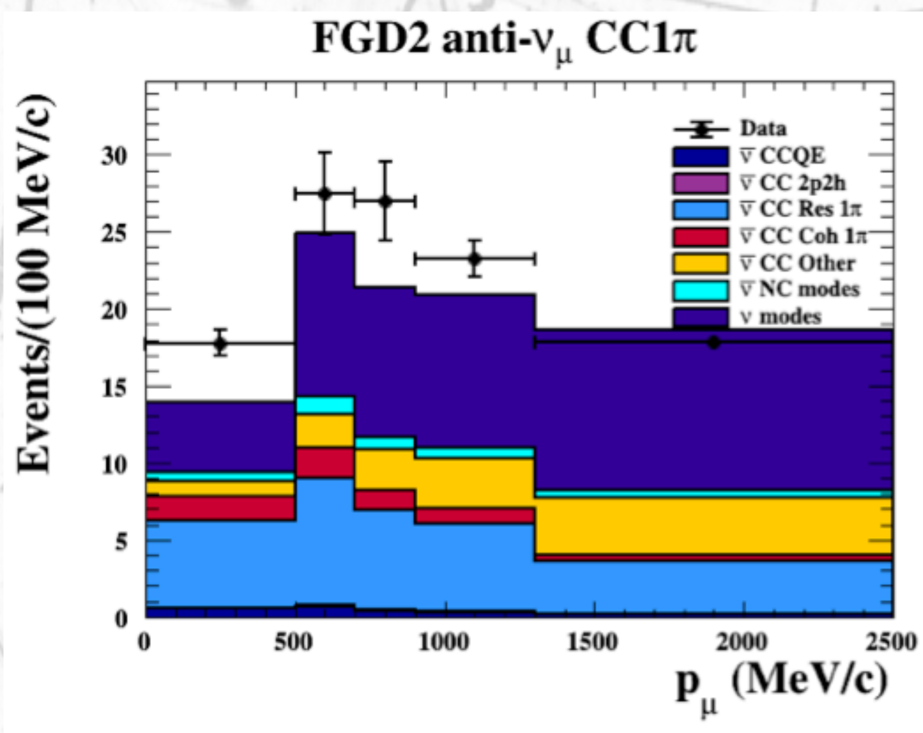


(e) FGD2 RHC $\bar{\nu}_\mu$ 1π

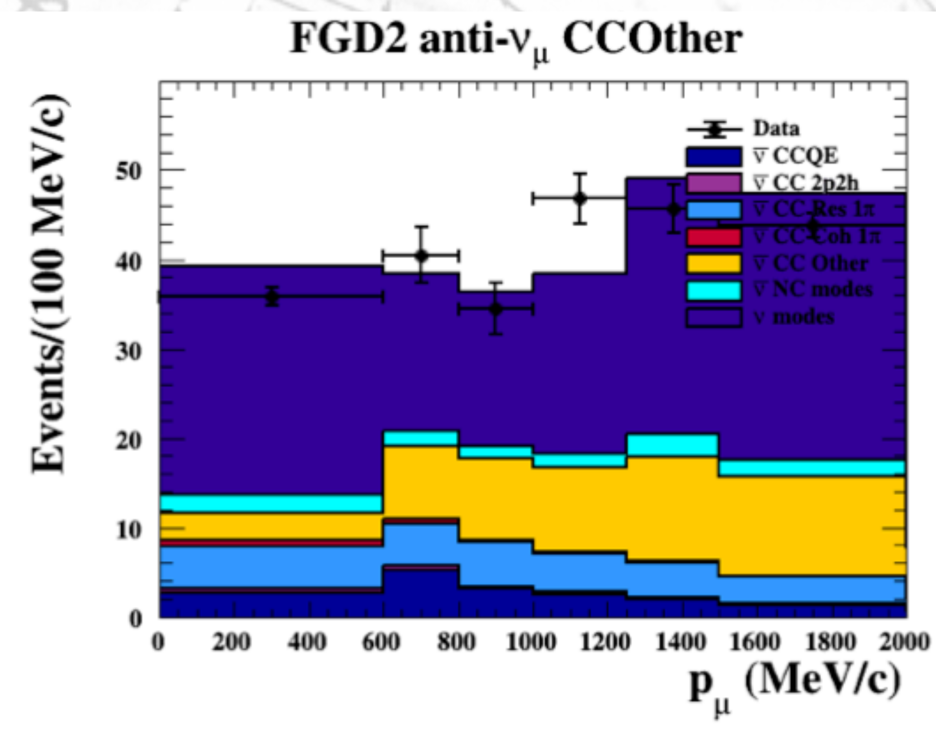


(f) FGD2 RHC $\bar{\nu}_\mu$ Other

Post-fit



(e) FGD2 RHC $\bar{\nu}_\mu$ 1π



(f) FGD2 RHC $\bar{\nu}_\mu$ Other

All ND data samples pre- and post-fit

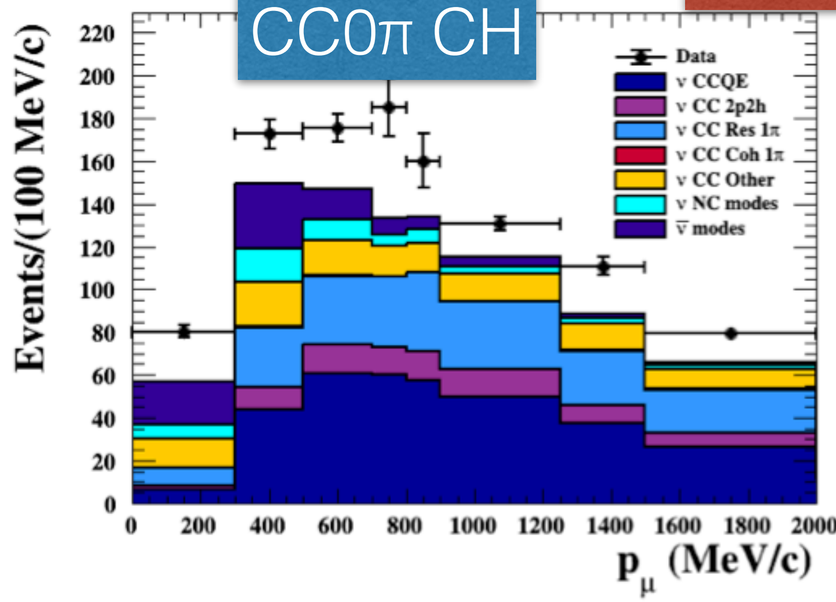
FHC is ν-mode
RHC is $\bar{\nu}$-mode

neutrinos in RHC

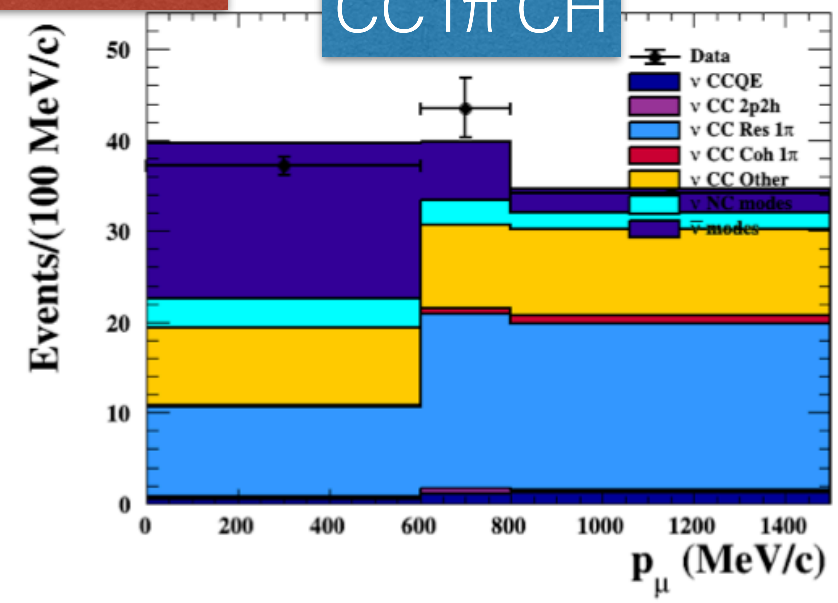
CC0π CH

CC1π CH

Pre-fit

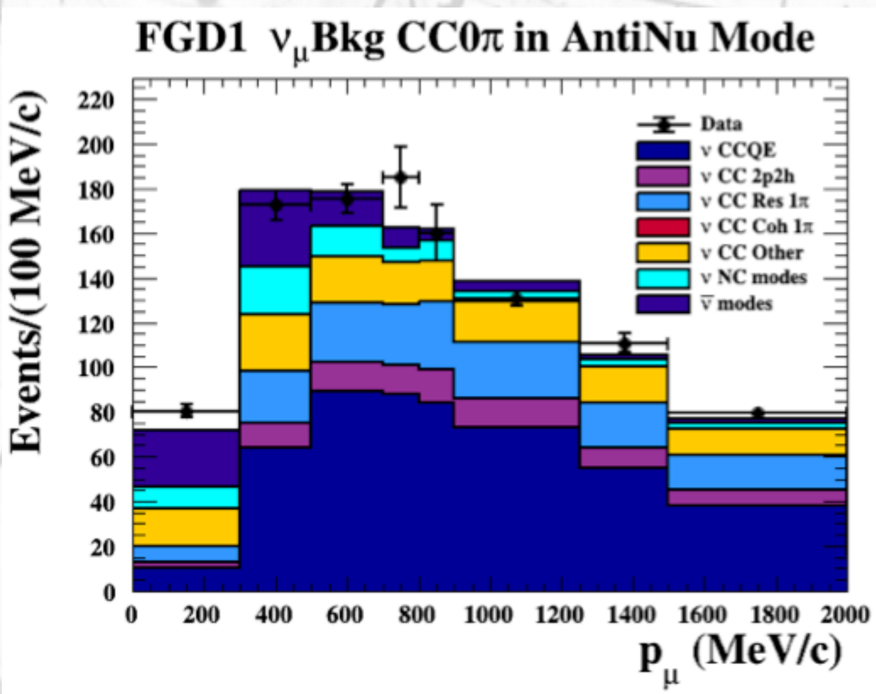


(a) FGD1 RHC ν_μ 0π

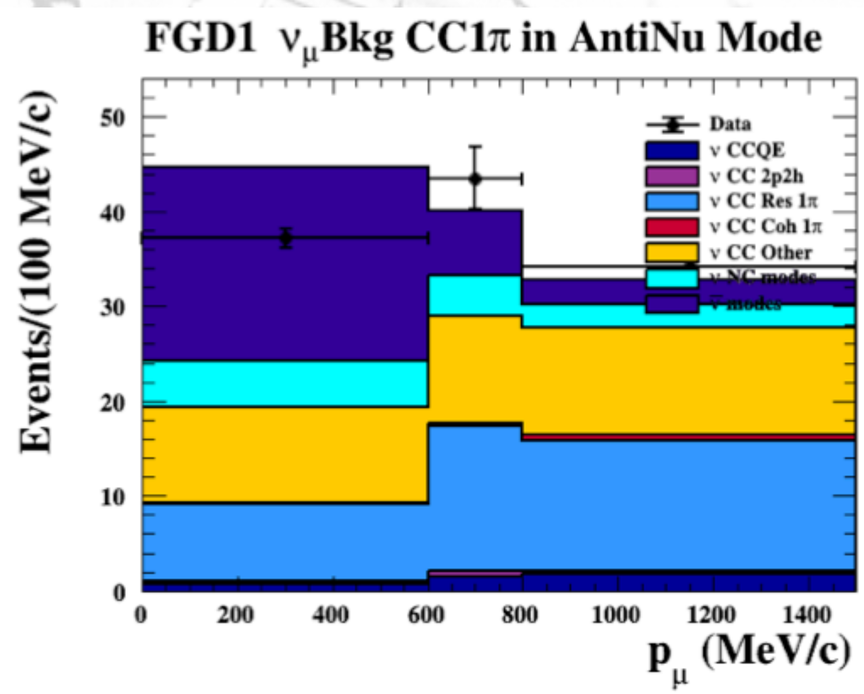


(b) FGD1 RHC ν_μ 1π

Post-fit



(a) FGD1 RHC ν_μ 0π



(b) FGD1 RHC ν_μ 1π

All ND data samples pre- and post-fit

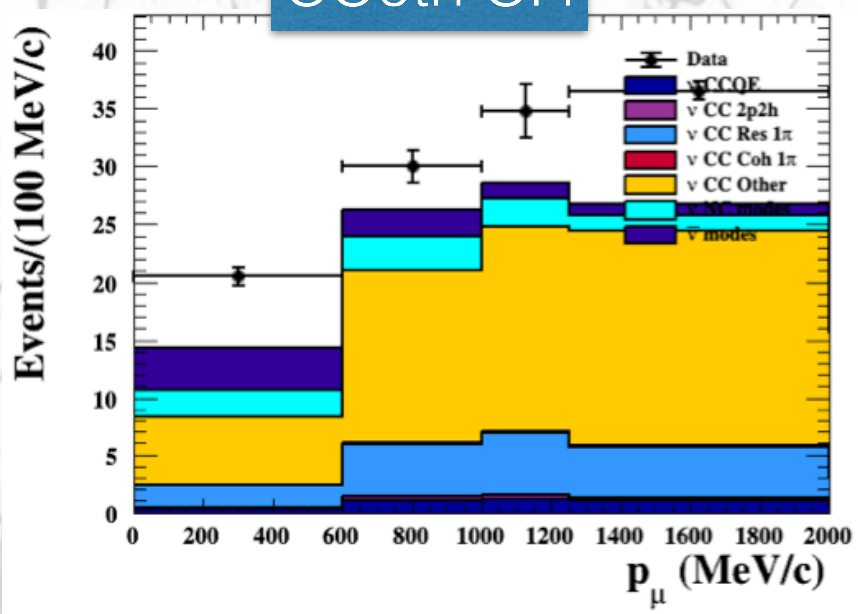
FHC is ν-mode
RHC is $\bar{\nu}$-mode

neutrinos in RHC

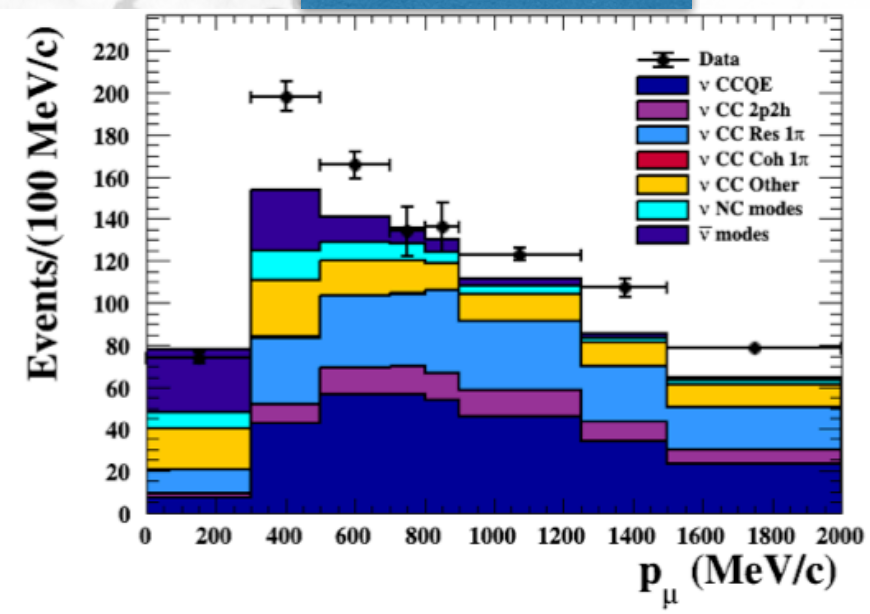
CC0th CH

CC0π CH&O

Pre-fit

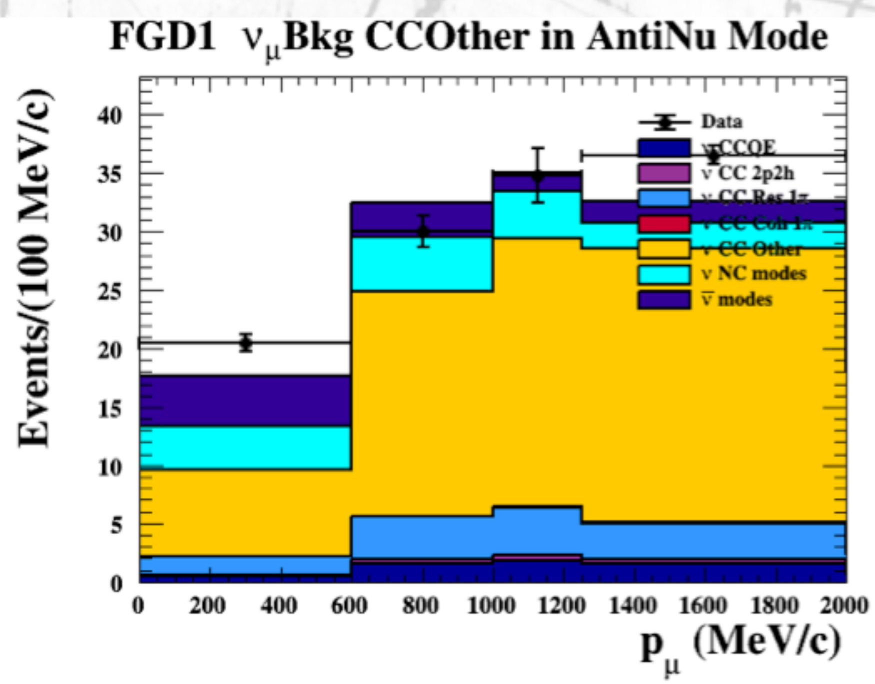


(c) FGD1 RHC ν_μ Other

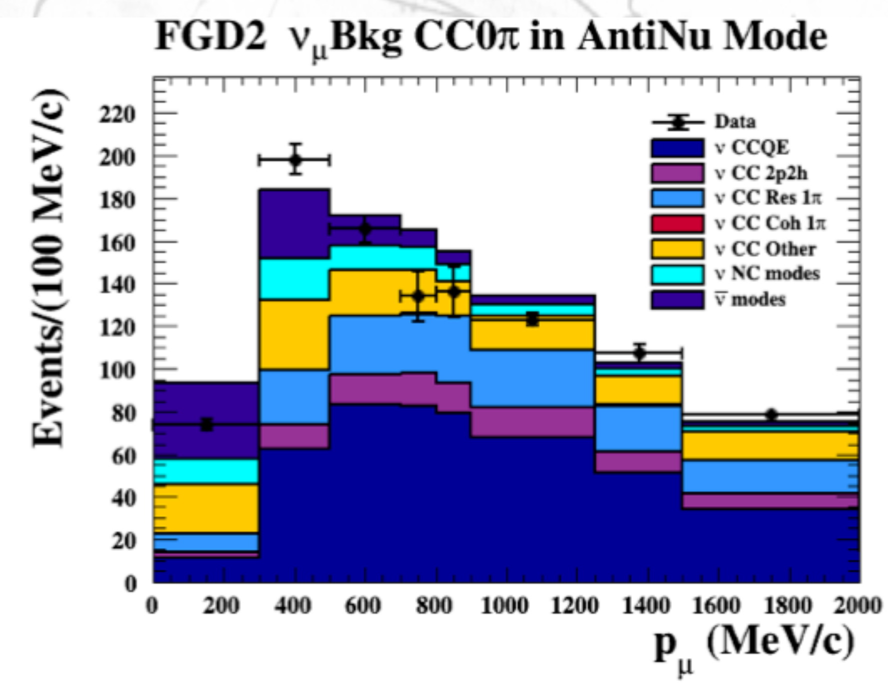


(d) FGD2 RHC ν_μ 0π

Post-fit



(c) FGD1 RHC ν_μ Other



(d) FGD2 RHC ν_μ 0π

All ND data samples pre- and post-fit

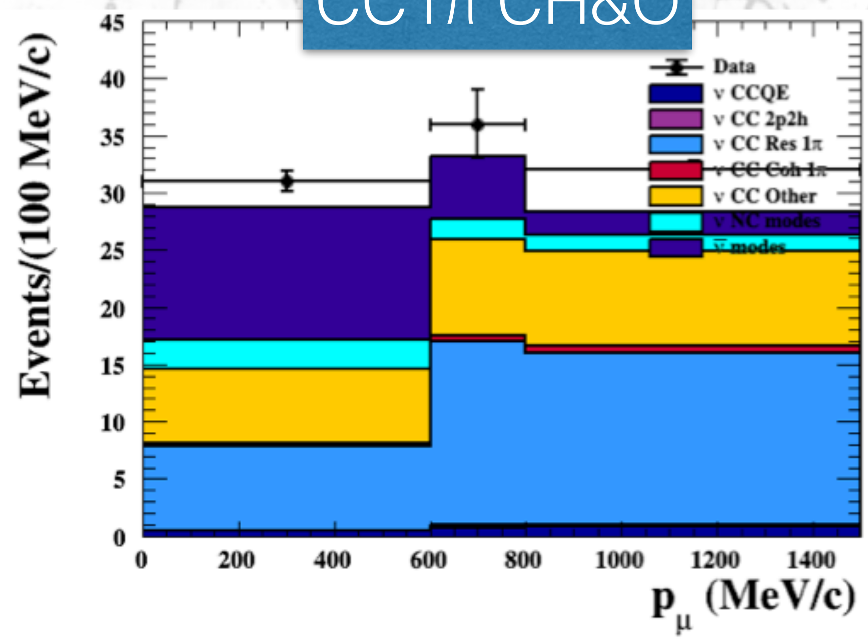
FHC is ν-mode
RHC is $\bar{\nu}$-mode

neutrinos in RHC

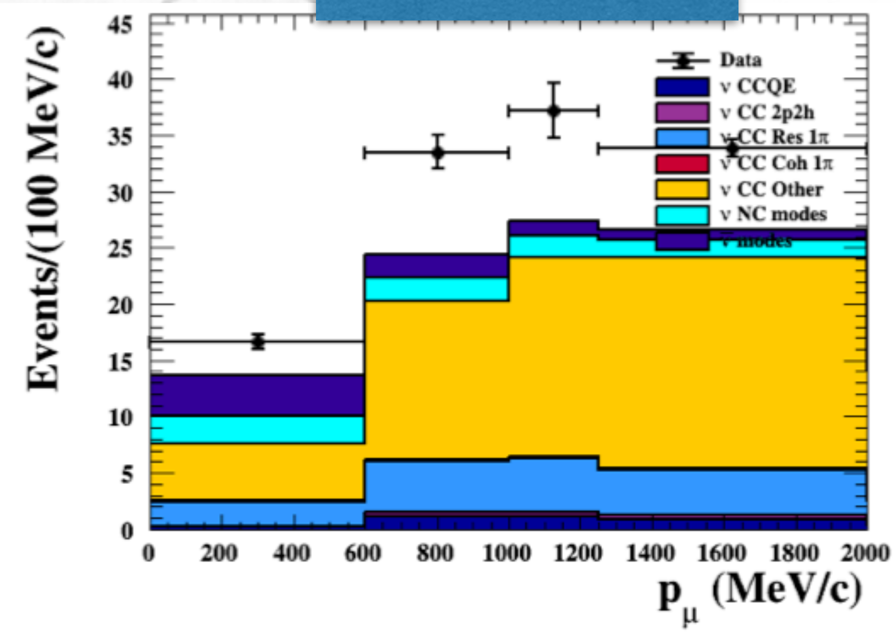
CC1π CH&O

CCOth CH&O

Pre-fit

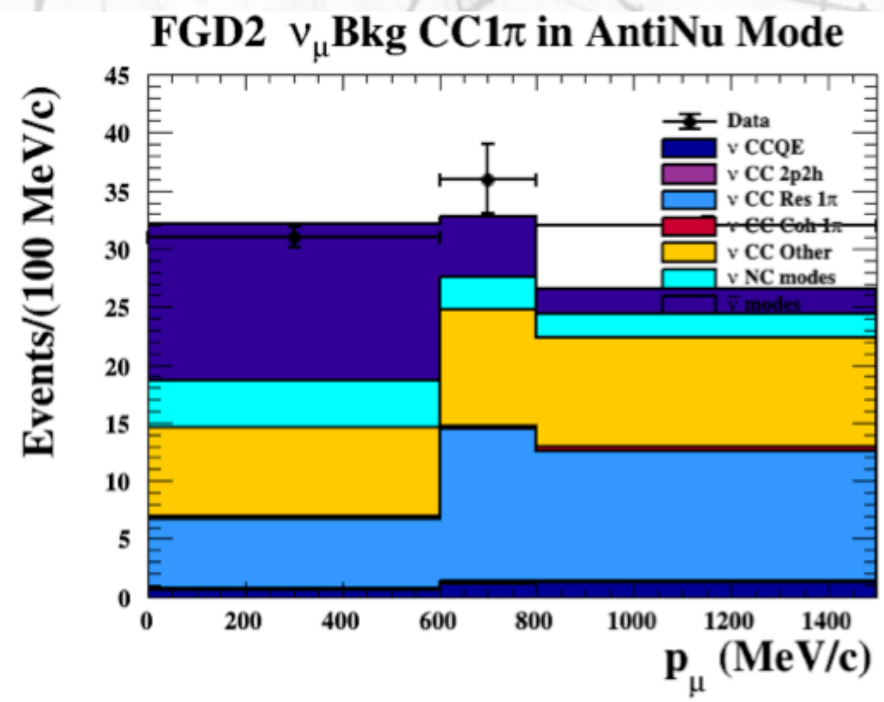


(e) FGD2 RHC ν_μ 1π

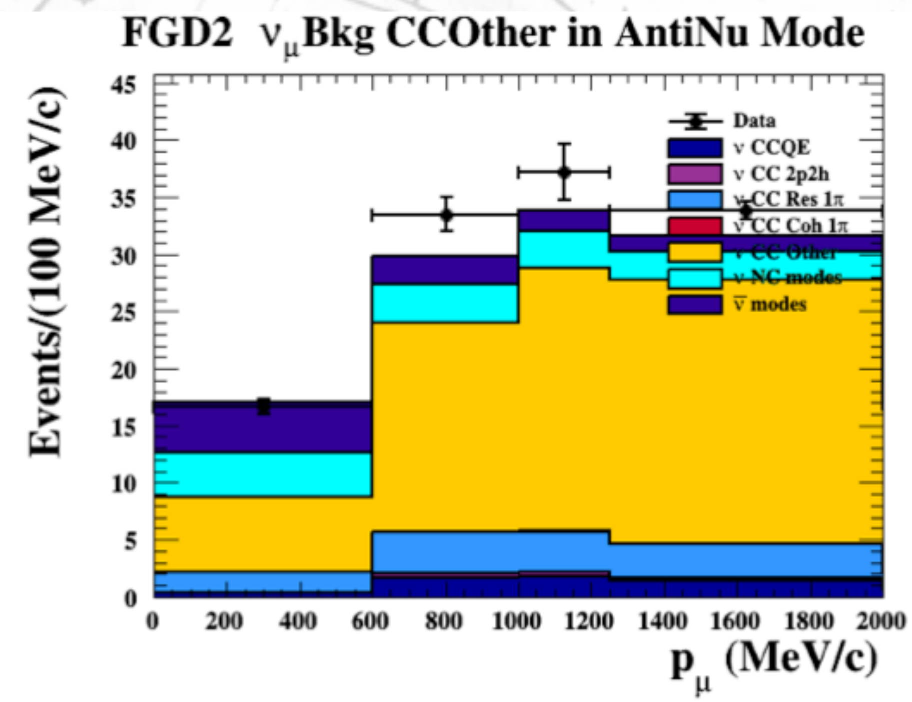


(f) FGD2 RHC ν_μ Other

Post-fit



(e) FGD2 RHC ν_μ 1π



(f) FGD2 RHC ν_μ Other