

Asimov and fake data studies

3rd Workshop on Neutrino Near Detectors based on
gas TPCs

Ideas

- If it can be easy to track down current detector limits, it's harder to assess how much an upgrade of the near detector, with a different phase space, would impact the oscillation analysis.
- In order to have quantitative informations on this impact, and helping choosing a configuration for the upgrade, we use the analysis tools currently used in T2K oscillation analysis with predicted efficiencies.
- We use MC true tracks, selected relatively to those predicted efficiencies and use this as a selection of events.

What do we do with this tool ?

With the Asimov/fake data studies we want to get quantitative informations on :

1. How is the constraints on the model's parameters improved by the upgrade ?

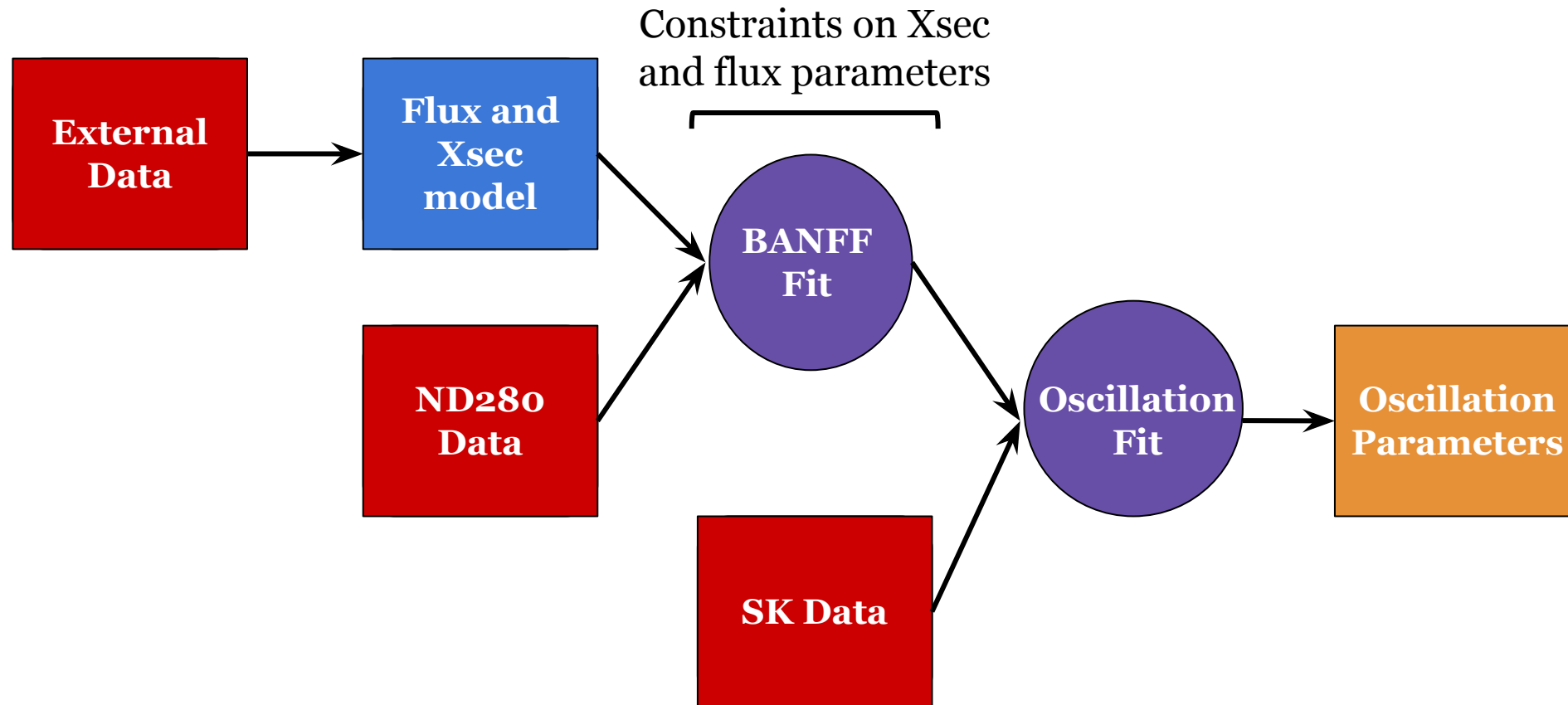
➡ **Asimov studies**

2. What is the sensitivity to the cross section model separation ? And in particular can we reduce the bias introduced by cross-section modelling ?

➡ **Fake data studies**

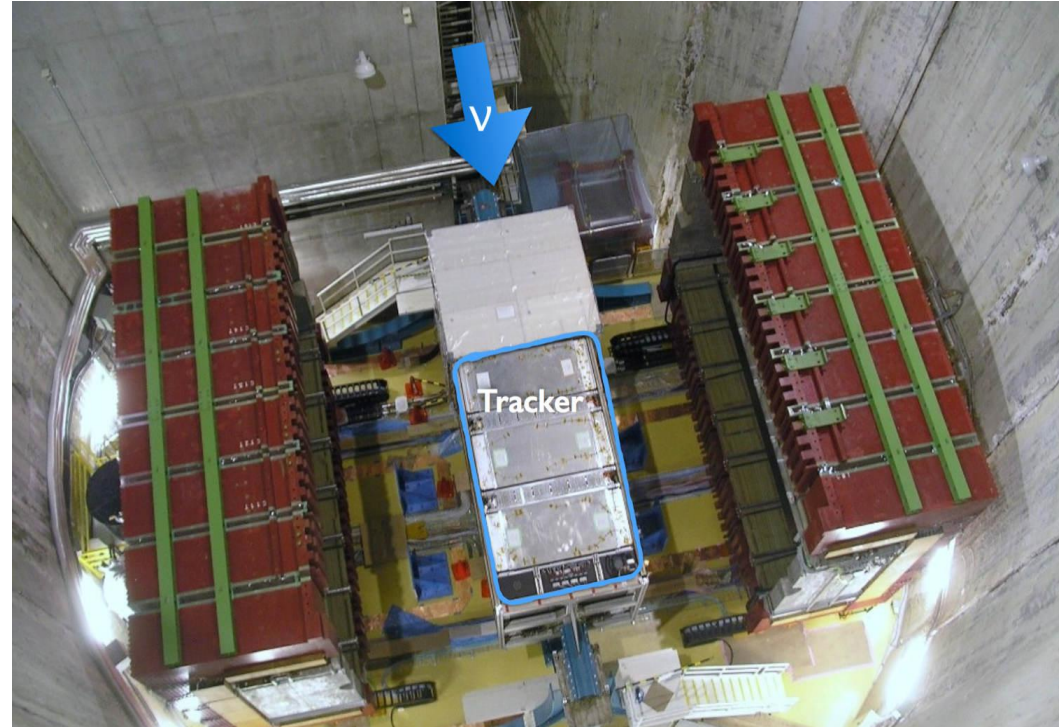
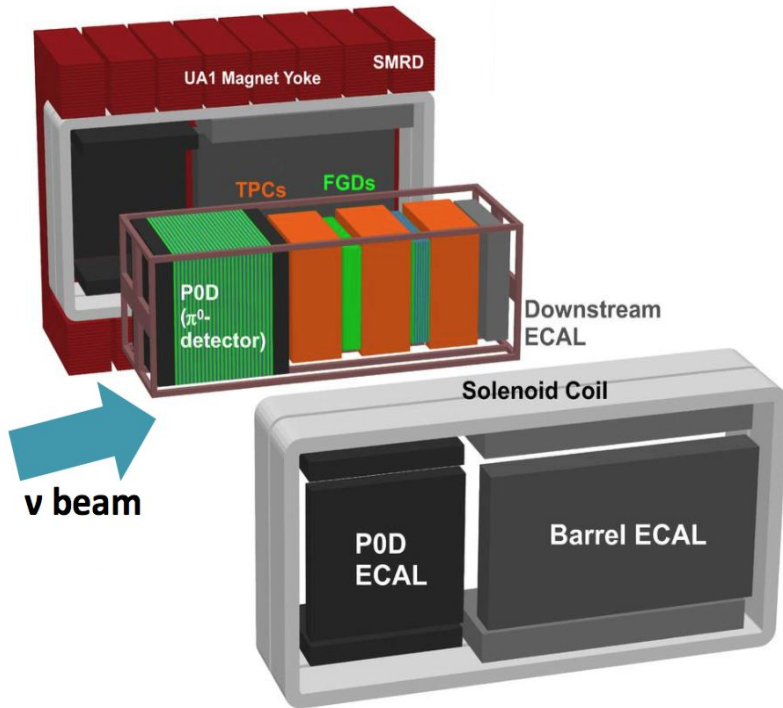
Use this selection of MC tracks as input in a fit and perform several Asimov and fake data studies to answer those questions.

T2K analysis chain



- We do a first fit (BANFF) with the near detector data in order to constrain our flux and cross-section models, to have a precise prediction of the number of events we expect at the far detector

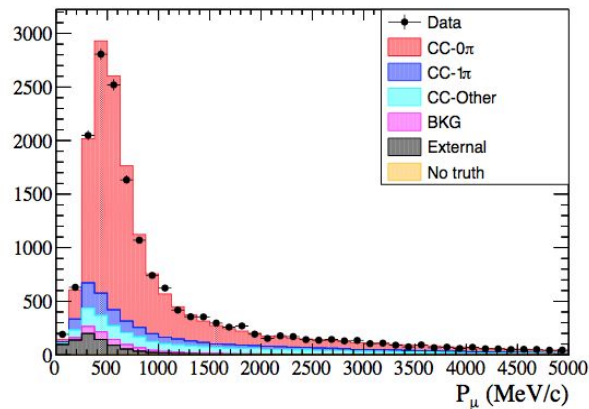
Systematics reduction with ND280



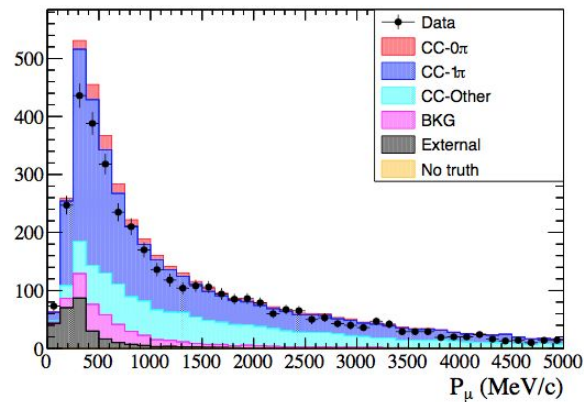
- The main systematics in the experiment are coming from neutrino flux and neutrino interaction cross-section. We use the near detector to constrain them.

ND280 event selection

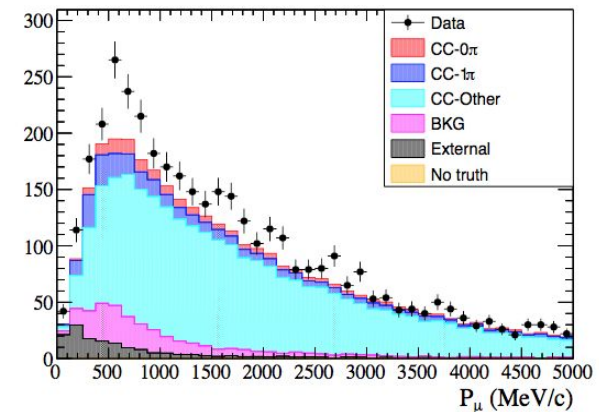
CCopi



CC1pi



CCOther



- We currently use a selection of ν_μ CC events in the tracker, using the FGD as target and the TPC to reconstruct charge and momentum.
- We separate the CC inclusive events in three topologies depending on the number of pions reconstructed (0, 1 and ≥ 2)

This selection is used as input in the fit

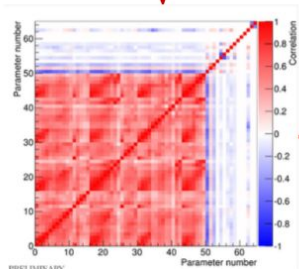
T2K Oscillation Analysis

Flux model constrained by NA61/SHINE

Cross section model constrained by other experiment (Minerva, Miniboone...)

BANFF

lepton p - θ



Constrained covariance matrix

Systematic error source	$\Delta N_{SK}/N_{SK}$ before ND fit	$\Delta N_{SK}/N_{SK}$ after ND fit
Flux	8.8%	3.2%
Cross section	7.1%	4.7%
Flux and cross section	11.4%	2.7%
Final state/secondary interactions at SK		2.5%
SK detector		2.5%
Total	11.9%	5.2%

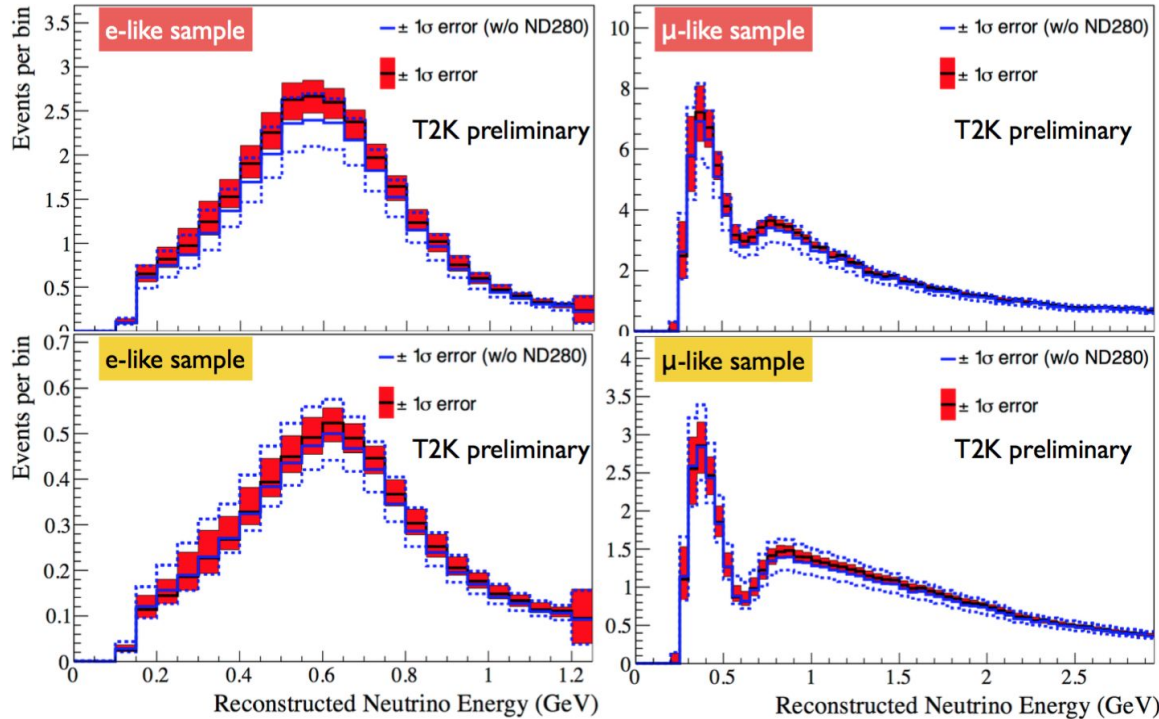
SK Fit

**Oscillation
Parameters**

The constraints

ν beam mode

$\bar{\nu}$ beam mode



➔ With the help of the near detector fit, we can reduce the uncertainties on the number of events expected at the far detector to ~5% !

	ν_{μ} sample 1R $_{\mu}$ FHC	ν_e sample 1R $_e$ FHC	$\bar{\nu}_{\mu}$ sample 1R $_{\mu}$ RHC	$\bar{\nu}_e$ sample 1R $_e$ RHC
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	5,0%	5,4%	5,2%	6,2%

An upgrade of the near detector

- As T2K data taking is ongoing, a large number of oscillated events will be collected.
- Systematics will become dominant, and need to be lowered to 2-3%
 - ➡ Hard with the current near detector currently at $\sim 5\%$
 - ➡ Indeed this detector is limited by low efficiency at high angles, backward and for low momentum hadrons
- Need to understand how an upgrade of the near detector can lower down those systematics, which phase space is important for the oscillation analysis

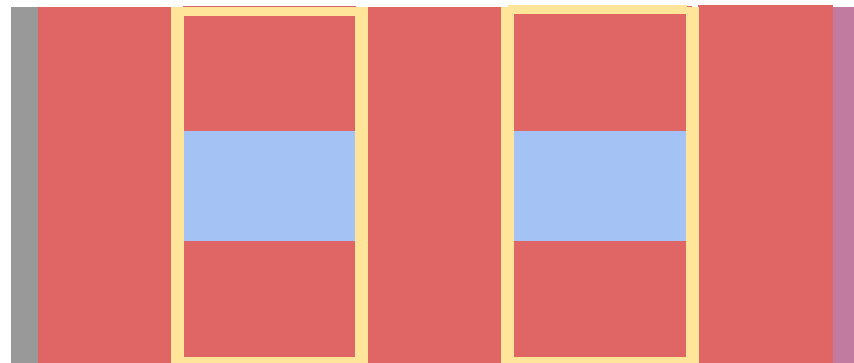
Trying to use current oscillation analysis tool (“BANFF-like”) to evaluate the impact of an upgrade

Upgrade configurations

Current



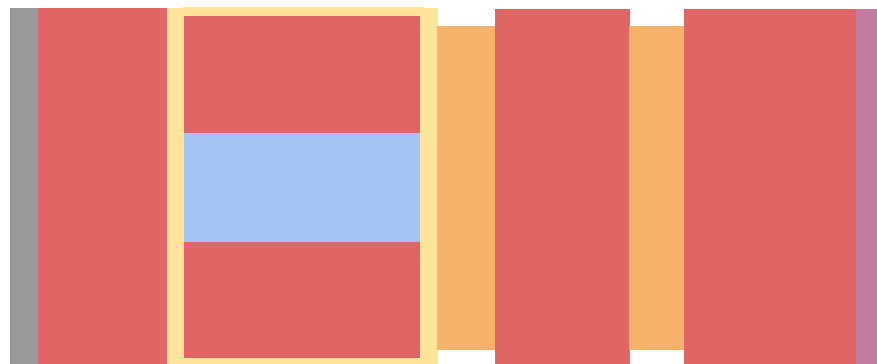
Reference



Alternative (c2)



Alternative (c3)



PoD TPCs FGDs Wagashi-like target ToF DsECal

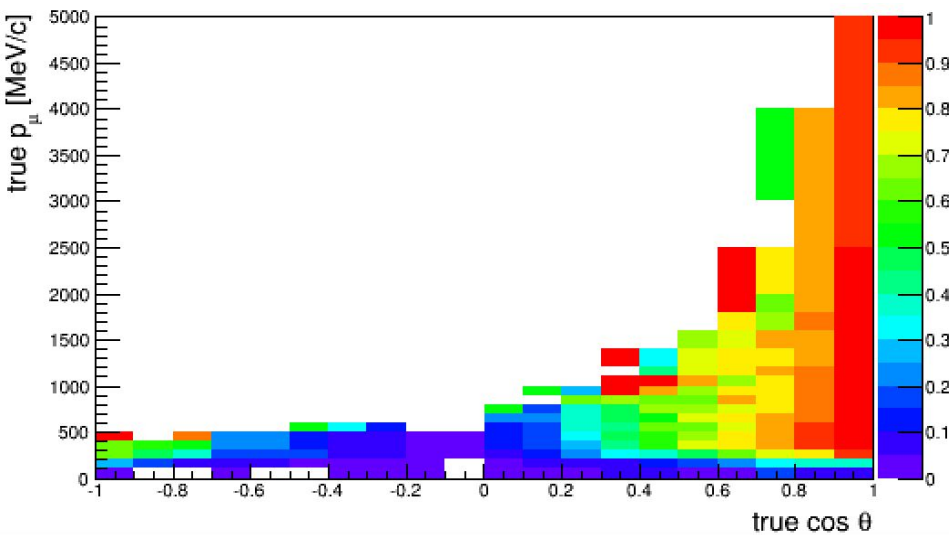
Upgrade Configurations

- 4 configurations :
 - ➔ current ND280 (FGD1-FGD2)
 - ➔ upgrade reference (target water + empty).
 - ➔ two alternative upgrade configurations (TPC-Target-FGD or Target-TPC-FGD).
- We have 12 samples ($CC0\pi$, $CC1\pi$, $CCOther$ for neutrino, antineutrino, C and O target) + 6 new samples for the alternative configurations (same samples as the others but in the Wagashi-like target).
- Mass used for the targets : reference water target is 1342kg, empty one is 416kg, and alternative configuration target is 2118kg.

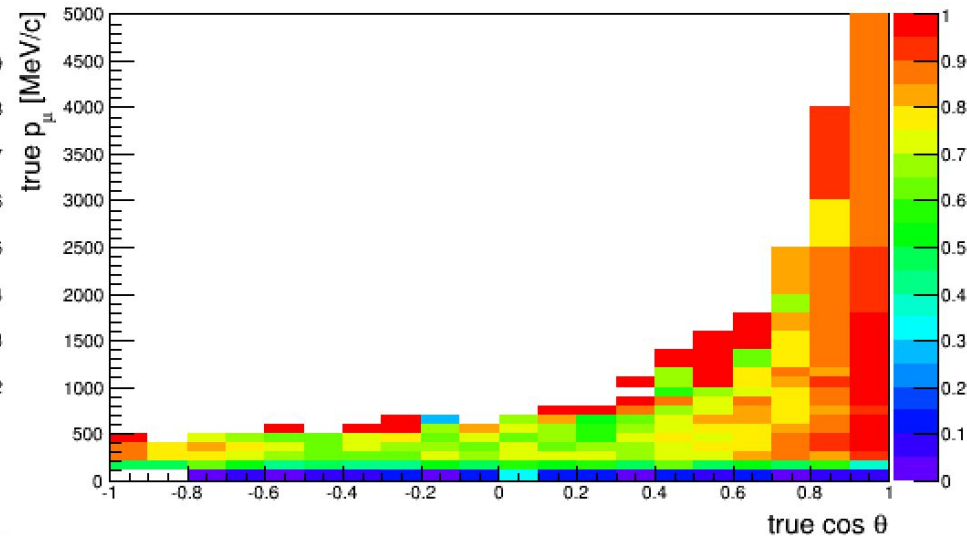
Inputs of the tool

- A first study is made, using GEANT4 and current ND280 software, to get predicted efficiencies for the different configurations of an upgrade.

4π selection efficiency in current ND280

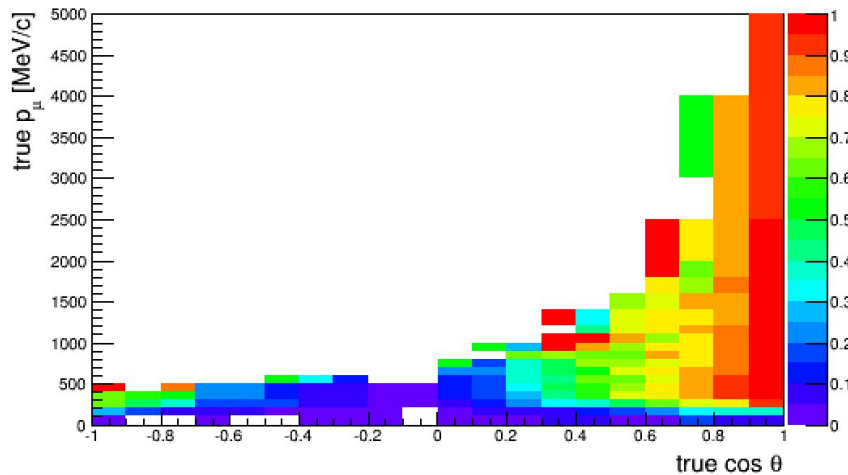


GEANT4 predicted efficiency of reference

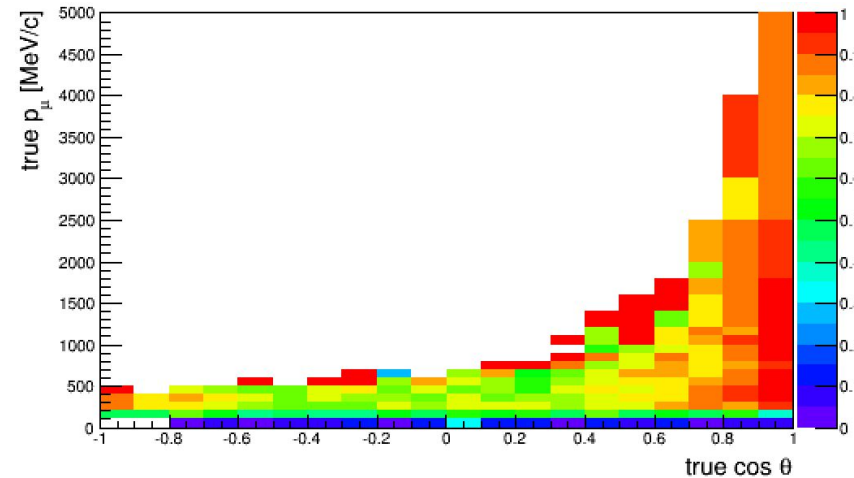


Efficiencies for water target

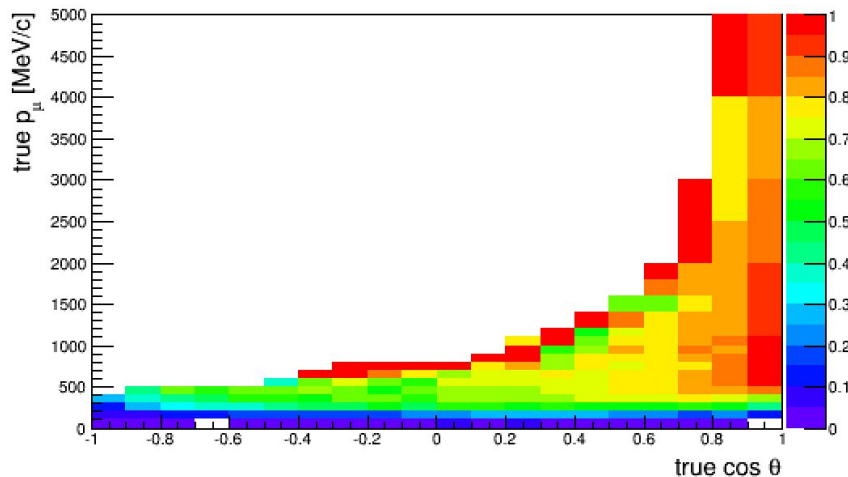
Current



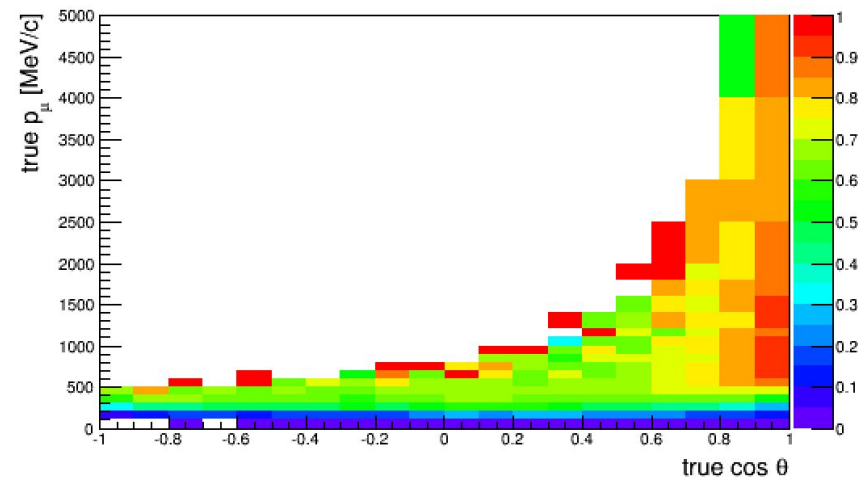
Reference



Alternative (c2)



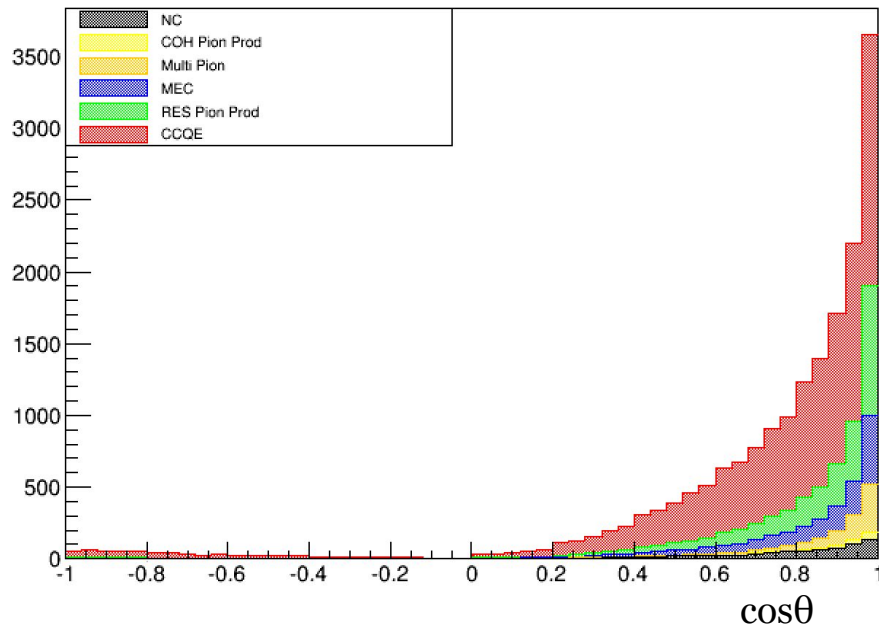
Alternative (c3)



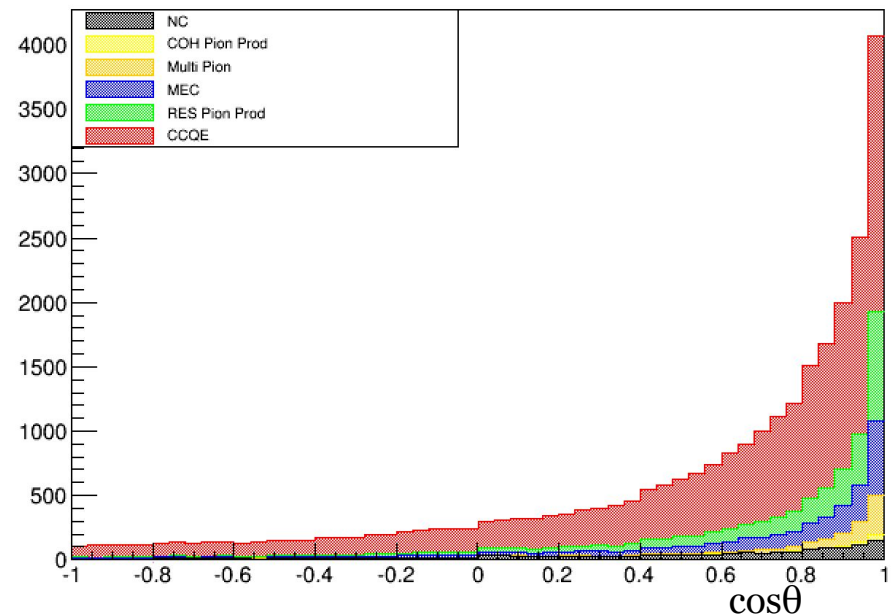
Distributions

- We use those efficiencies to select true MC tracks.
- This selection can be considered as a simulation of a selection done in a configuration of the upgrade.
- This selection is used as input in the tool, as we do in the oscillation analysis.

Currently

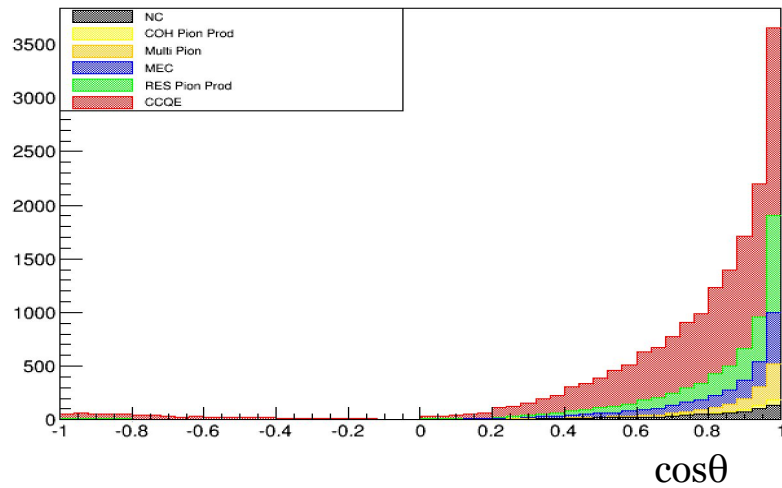


Upgrade

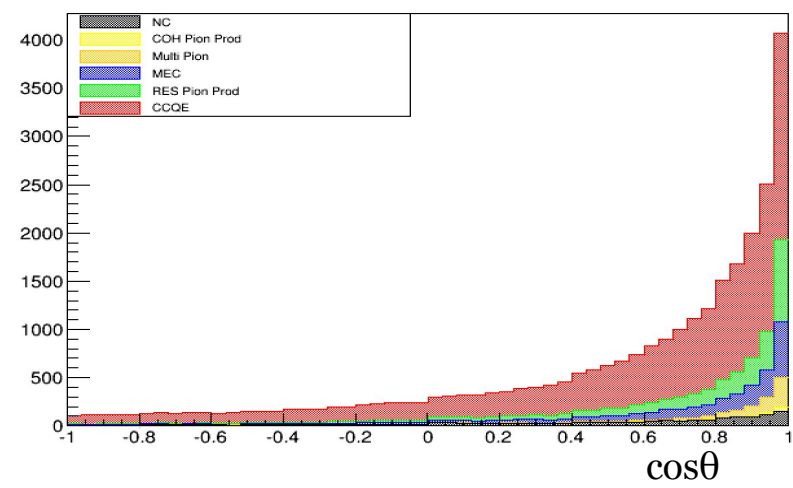


Distributions of $\text{C}\text{Co}\pi$ in the water target

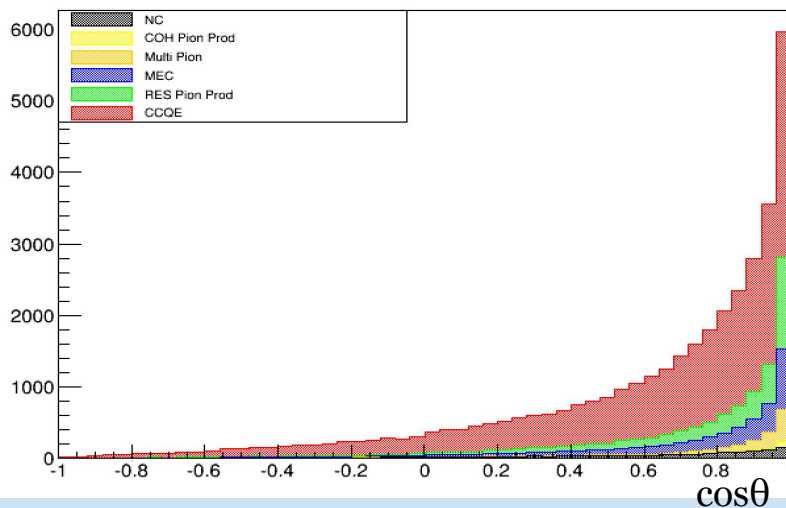
Current



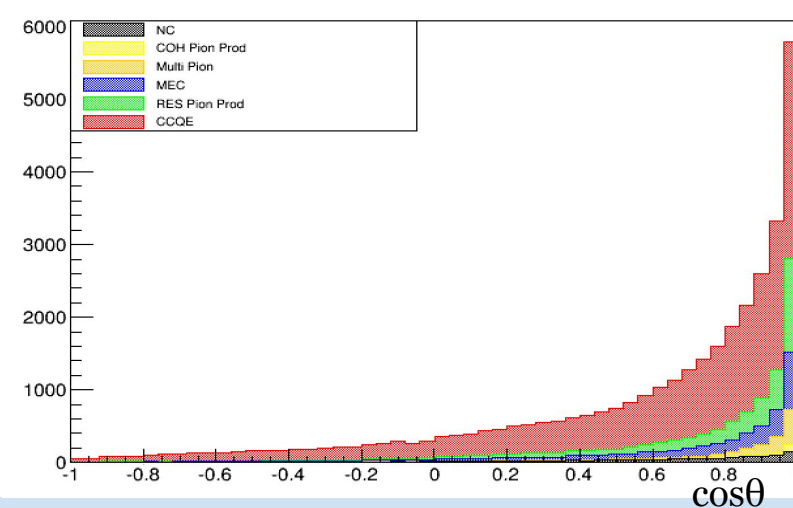
Reference



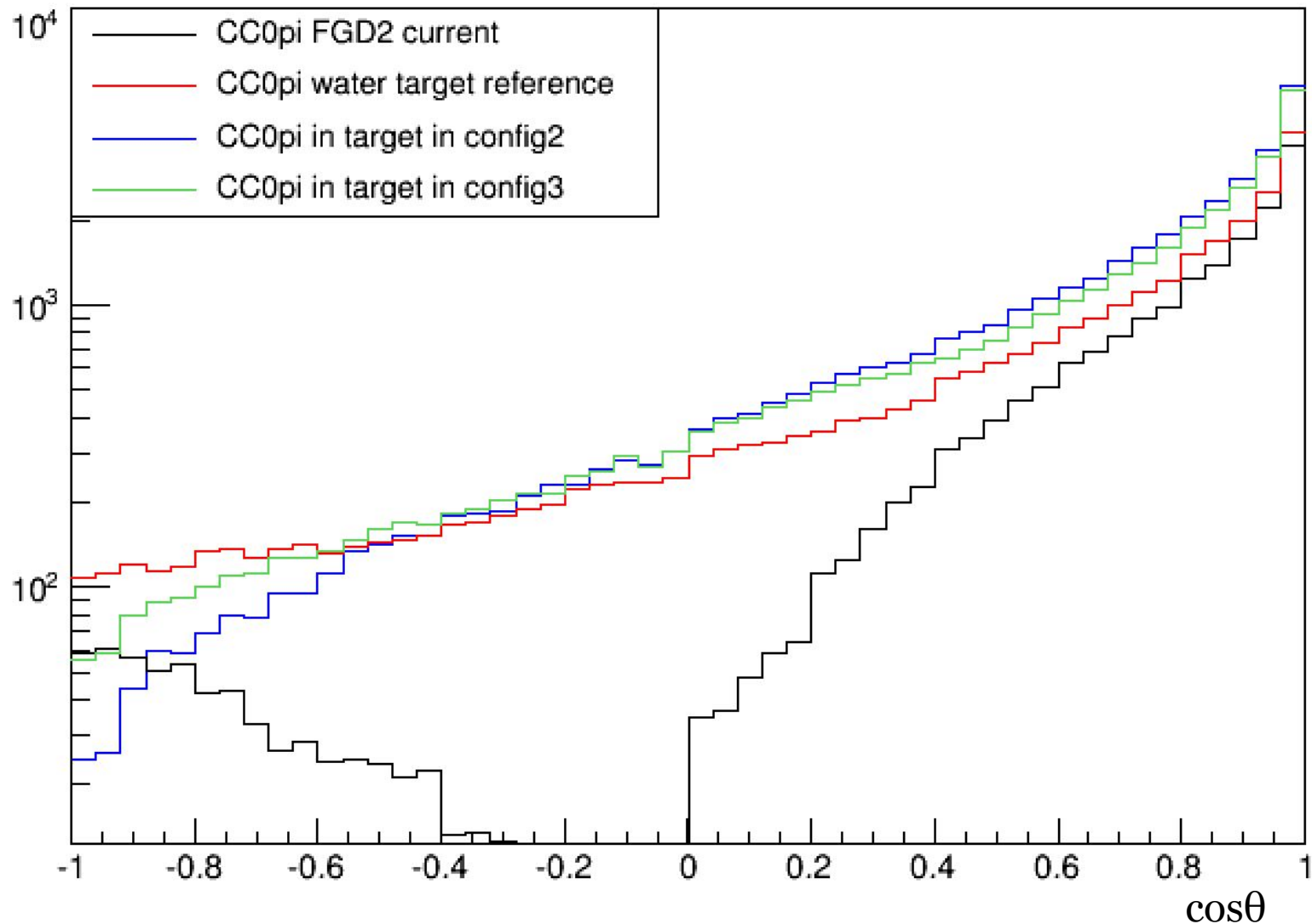
Alternative (c2)



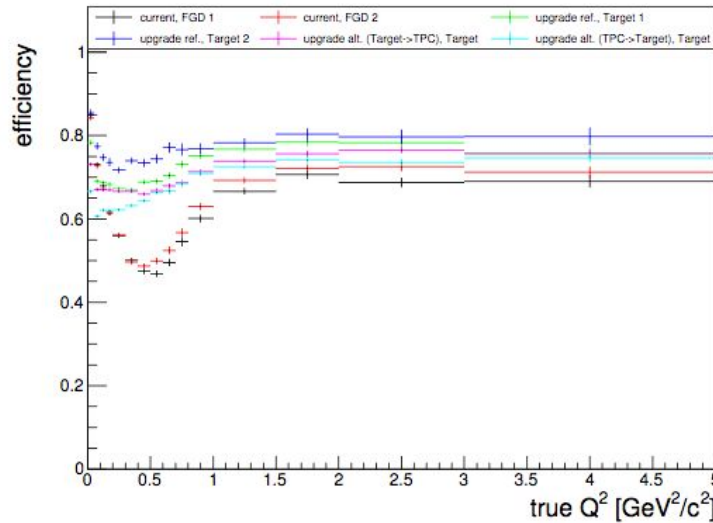
Alternative (c3)



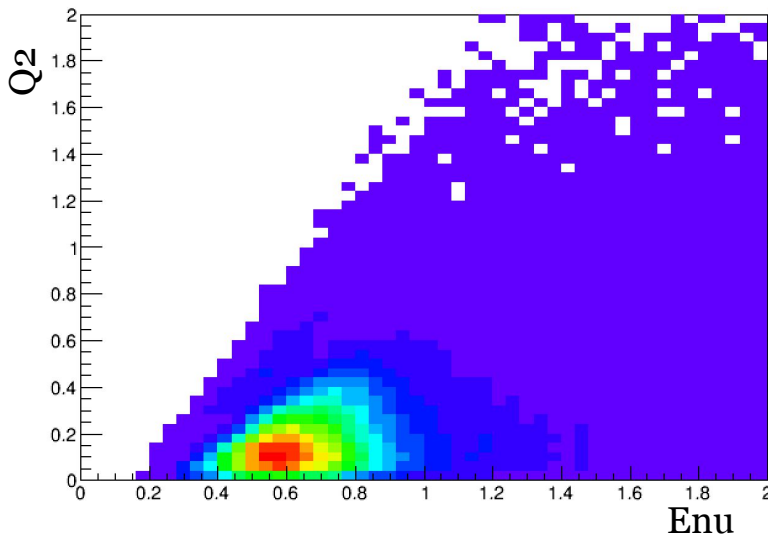
Distributions of $\text{CC}\pi$ in the water target



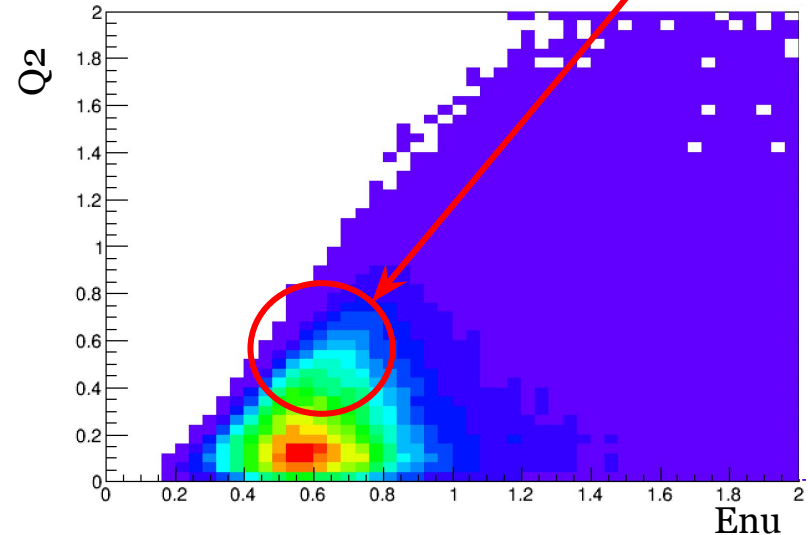
Distributions : a better Q2 sensitivity



Current



Reference upgrade



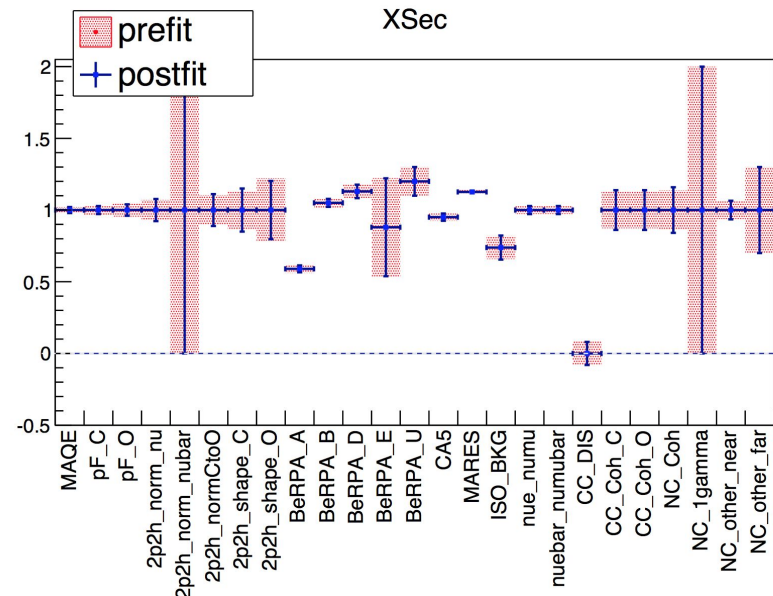
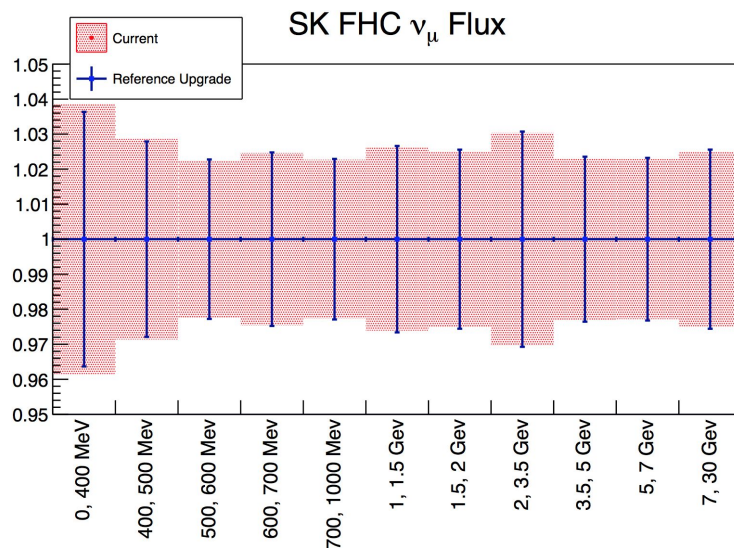
**Region of interest of
T2K**

Status

- Worked with Mathieu and Davide to modify the selection of true MC to better use information coming from their efficiency studies.
- Added the alternative configurations, now the tool can give information about what is the impact of the upgrade but also helps to compare configurations.
- Moved to the a new cross-section parametrization (the one used in current T2K oscillation analysis)
 - ➡ Larger Q^2 dependence, needed in our case to understand better the differences between current, and the different upgrade configurations.
- Made first Asimov with the 4 configurations (current, ref, c2 and c3).
- Currently producing first fake data to study cross-section model sensitivity.

Asimov Study

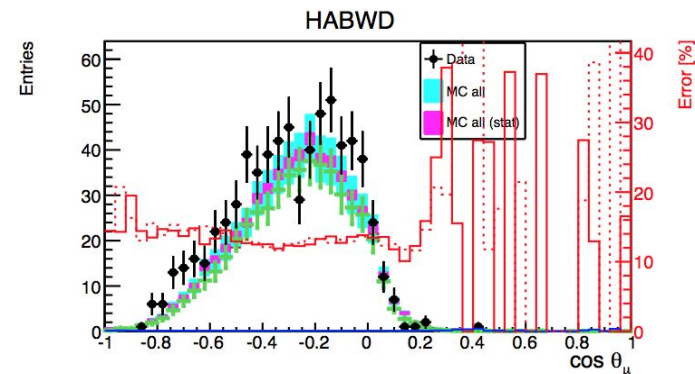
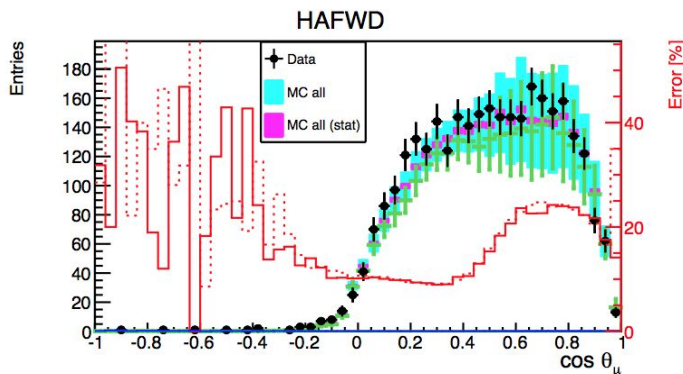
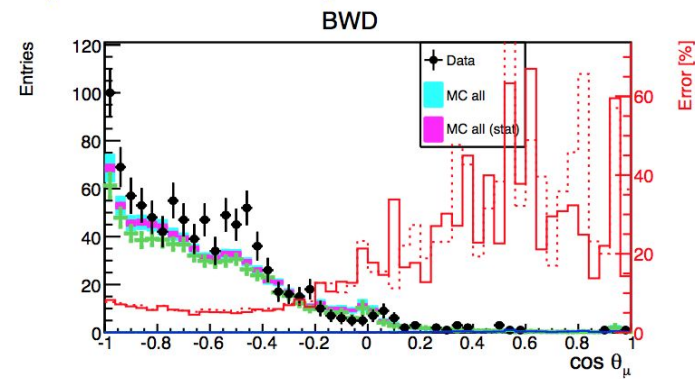
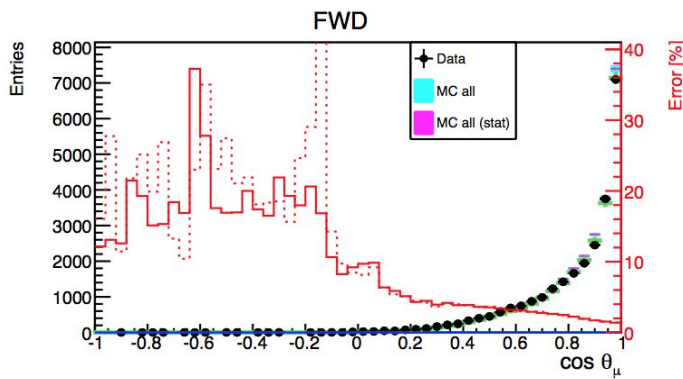
- The first point is to do Asimov fit (fitting the nominal MC) with both the current ND280 efficiency and the different predicted upgrade configuration efficiencies.
- We do this fit without considering detector systematics, and with full T2K statistics (7.8e21POT).
- This gives information on how the constraint on model's parameters evolve. And in particular how the constraint on the spectrum of neutrino events at SK evolve.



Detector systematics

- Please keep in mind that we don't use any detector systematics for all the configurations.
- In current ND280 the systematic error is quite large at high angle, while we can expect it to be as for the forward in the upgrade (added TPCs) !

Alfonso's CC
inclusive 4π xsec



Number of events in each sample

Sample	Current	Reference	Target - TPC configuration	TPC - Target configuration
fgd1cc0pi	154692.30	63915.04	166772.93	163581.29
fgd1cc1pi	42847.67	18525.89	45804.47	44097.94
fgd1ccOth	53555.62	23734.13	57400.81	53575.99
fgd1anucc0pi	9987.06	3728.46	10331.59	11527.38
fgd1anucc1pi	2193.62	1072.94	2240.50	2649.81
fgd1anuccnpi	5703.42	2519.78	5873.54	6196.27
fgd2cc0pi	146100.66	221831.12	153124.44	146785.91
fgd2cc1pi	44619.16	71699.29	47457.76	45309.21
fgd2ccOth	49715.56	69145.87	51881.89	49519.28
fgd2anucc0pi	9191.25	12392.91	9353.71	10382.33
fgd2anucc1pi	2116.96	3147.41	2254.49	2463.16
fgd2anuccnpi	5353.43	6835.26	5360.99	5816.05

Sample	Target - TPC configuration	TPC - Target configuration
tarcc0pi	287637.80	244042.81
tarcc1pi	87204.96	72536.77
tarccOth	96944.50	77563.56
taranucc0pi	16635.92	17827.21
taranucc1pi	4940.94	5556.99
taranuccnpi	10567.44	10818.68

Keep in mind that we have different statistics due to different detector masses !

Asimov Study

Parameter	Prefit	Current	Reference Upgrade	Target - TPC configuration	TPC - Target configuration
FSI_INEL_LO	0.0 ± 0.41	0.0 ± 0.038318	0.0 ± 0.041211	$2.9007\text{e-}10 \pm 0.020053$	0.0 ± 0.019902
FSI_INEL_HI	0.0 ± 0.34	0.0 ± 0.059136	0.0 ± 0.061012	$-2.1185\text{e-}10 \pm 0.032933$	0.0 ± 0.033151
FSI_PI_PROD	0.0 ± 0.5	0.0 ± 0.084381	0.0 ± 0.087048	$6.448\text{e-}11 \pm 0.047842$	0.0 ± 0.048829
FSI_PI_ABS	0.0 ± 0.41	0.0 ± 0.055106	0.0 ± 0.053212	$4.1973\text{e-}10 \pm 0.02907$	0.0 ± 0.029177
FSI_CEX_LO	0.0 ± 0.57	0.0 ± 0.090781	0.0 ± 0.096714	$9.2367\text{e-}10 \pm 0.047107$	0.0 ± 0.047773
FSI_CEX_HI	0.0 ± 0.28	0.0 ± 0.047254	0.0 ± 0.048747	$3.6109\text{e-}11 \pm 0.026792$	0.0 ± 0.027344
MAQE(GeV/c ²)	1.2 ± 0.03	1.2 ± 0.025811	1.2 ± 0.025406	1.2 ± 0.018469	1.2 ± 0.019202
pF_C(MeV/c)	217.0 ± 13.0	217.0 ± 7.3538	217.0 ± 6.1089	217.0 ± 4.0303	217.0 ± 4.248
pF_0(MeV/c)	225.0 ± 13.0	225.0 ± 10.403	225.0 ± 8.9281	225.0 ± 6.6859	225.0 ± 6.3913
2p2h_norm_nu	1.0 ± 1.0	1.0 ± 0.071063	1.0 ± 0.077261	1.0 ± 0.050152	1.0 ± 0.05098
2p2h_norm_nubar	1.0 ± 1.0	1.0 ± 0.089249	1.0 ± 0.092842	1.0 ± 0.061294	1.0 ± 0.061128
2p2h_normCto0	1.0 ± 0.2	1.0 ± 0.10425	1.0 ± 0.11125	1.0 ± 0.074339	1.0 ± 0.076636
2p2h_shape_C(%)	100.0 ± 300.0	100.0 ± 13.37	100.0 ± 15.024	100.0 ± 9.3971	100.0 ± 9.4364
2p2h_shape_0(%)	100.0 ± 300.0	100.0 ± 22.084	100.0 ± 20.312	100.0 ± 12.997	100.0 ± 13.681
BeRPA_A	0.59 ± 0.118	0.59 ± 0.028613	0.59 ± 0.024124	0.59 ± 0.017375	0.59 ± 0.017569
BeRPA_B	1.05 ± 0.21	1.05 ± 0.032499	1.05 ± 0.027909	1.05 ± 0.02167	1.05 ± 0.021766
BeRPA_D	1.13 ± 0.1695	1.13 ± 0.049104	1.13 ± 0.047013	1.13 ± 0.035204	1.13 ± 0.036317
BeRPA_E	0.88 ± 0.352	0.88 ± 0.34233	0.88 ± 0.34138	0.88 ± 0.33061	0.88 ± 0.33133
BeRPA_U	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1
CA5	0.96 ± 0.15	0.96 ± 0.02557	0.96 ± 0.025628	0.96 ± 0.016472	0.96 ± 0.017137
MARES(GeV/c ²)	1.07 ± 0.15	1.07 ± 0.013453	1.07 ± 0.012932	1.07 ± 0.0086614	1.07 ± 0.0090553
ISO_BKG	0.96 ± 0.4	0.96 ± 0.10445	0.96 ± 0.10895	0.96 ± 0.061857	0.96 ± 0.06379
nue_numu	1.0 ± 0.028284	1.0 ± 0.028284	1.0 ± 0.028284	1.0 ± 0.028284	1.0 ± 0.028284
nuebar_numubar	1.0 ± 0.028284	1.0 ± 0.028284	1.0 ± 0.028284	1.0 ± 0.028284	1.0 ± 0.028284
CC_DIS	0.0 ± 0.4	0.0 ± 0.082438	0.0 ± 0.08044	$8.7311\text{e-}11 \pm 0.05471$	0.0 ± 0.056956
CC_Coh_C	1.0 ± 0.3	1.0 ± 0.12741	1.0 ± 0.13861	1.0 ± 0.090045	1.0 ± 0.09314
CC_Coh_0	1.0 ± 0.3	1.0 ± 0.12744	1.0 ± 0.13862	1.0 ± 0.090073	1.0 ± 0.09317
NC_Coh	1.0 ± 0.3	1.0 ± 0.13719	1.0 ± 0.15904	1.0 ± 0.1054	1.0 ± 0.10533
NC_1gamma	1.0 ± 1.0	1.0 ± 1.0	1.0 ± 1.0	1.0 ± 1.0	1.0 ± 1.0
NC_other_near	1.0 ± 0.3	1.0 ± 0.062654	1.0 ± 0.064896	1.0 ± 0.040518	1.0 ± 0.041572
NC_other_far	1.0 ± 0.3	1.0 ± 0.3	1.0 ± 0.3	1.0 ± 0.3	1.0 ± 0.3

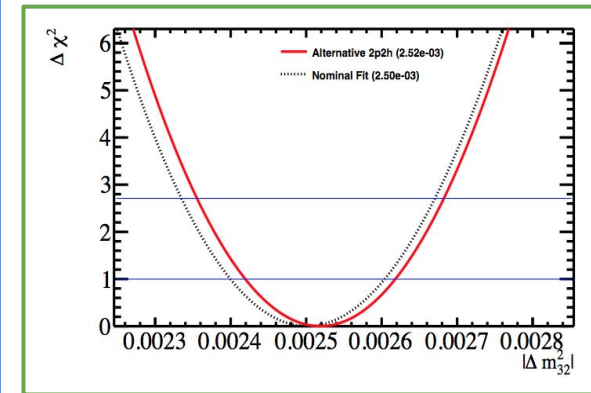
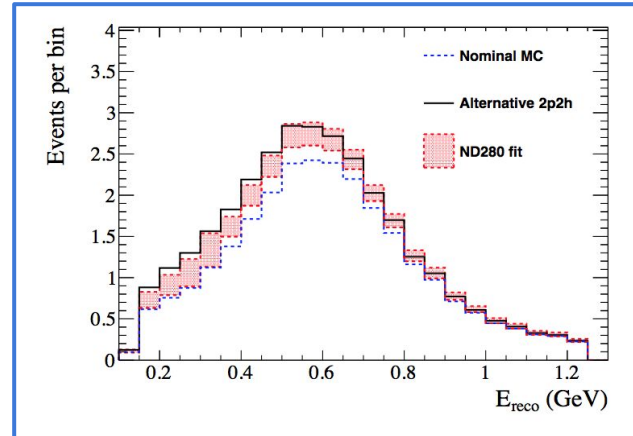
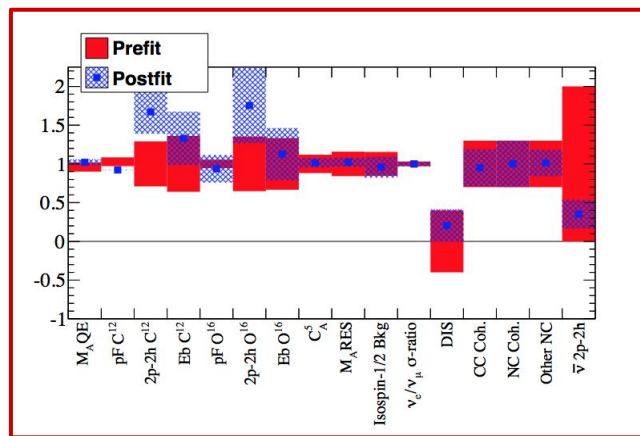
Asimov Study

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BeRPA_D	1.13 ± 0.1695	1.13 ± 0.049104	1.13 ± 0.047013	1.13 ± 0.035204	1.13 ± 0.036317
BeRPA_E	0.88 ± 0.352	0.88 ± 0.34233	0.88 ± 0.34138	0.88 ± 0.33061	0.88 ± 0.33133
BeRPA_U	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1

- Reference and current are very close on most of the parameter constraints.
 - ➡ Statistic is lower in the reference due to the empty wagashi-like target.
 - ➡ Once again we don't use any detector systematic.
- But we can see some larger difference in the Q2 dependent parameters as expected where reference is doing better than current !
- On the other side the two alternative configurations have much more statistic, explaining the tighter constraints, slightly better for configuration with Target before the TPC.

Fake data chain of study in T2K oscillation analysis

- We produce some fake data set (example here alternative 2p2h model) that we **fit to ND280 data**.
- This fit results is used to adjust **SK predicted spectra**.
- We produce and fit SK fake data set, with the fit to ND280 data as input, to obtain **the bias on the oscillation parameters**.



Alternative model	Maximum bias on parameter (σ)		
	Δm_{23}^2	$\sin^2 \theta_{23}$	$\sin^2 \theta_{13}$
Alternative <i>2p-2h</i>	0.20	0.21	0.18

Fake data studies

- The bias observed is, for now, small when compared to the overall error.
- As the statistic is growing we can expect this bias to become significant.
 - ➡ We need to evaluate how an upgrade of the near detector can reduce this bias.
- The same chain of study is used for the upgrade fake data studies.
- We are now testing several fake data sets, in particular in the new framework with more Q^2 dependence, that will soon be ready.

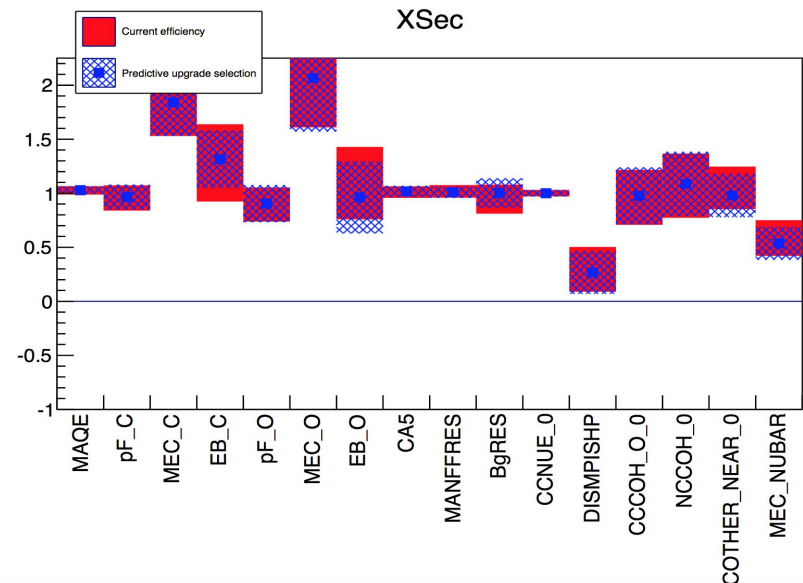
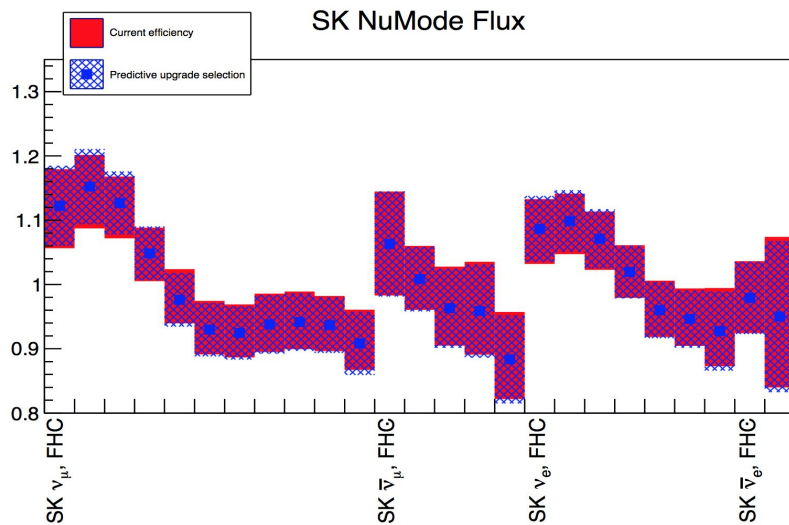
Fake datasets planned

➤ **BANFF/OA fake datasets** (ordered by priority) :

- ➔ **BeRPA** $+1\sigma$ implemented
- ➔ alternative **Form Factor** (3 component model $+1\sigma$)
- ➔ **2p2h** :
 - ➔ **Martini** fake datasets ➔ most important change on $\nu/\bar{\nu}$ implemented
 - ➔ **Delta and NotDelta** fake datasets ➔ change $p_\mu \cos\theta_\mu$ shape at ND and the reconstructed energy at SK implemented
- ➔ Other important fake datasets : **SF**, **Nieves**
- ➔ In the future ? : Eb-only, pion kinematics

Fake data studies

- Still working on several fake data sets, but here is an example for alternative 2p2h.
- Hard to see discrepancies between the fitted values for current ND280 and upgrade but interesting to notice that the fit χ^2 is worse for the upgrade (75 against 45).



Summary

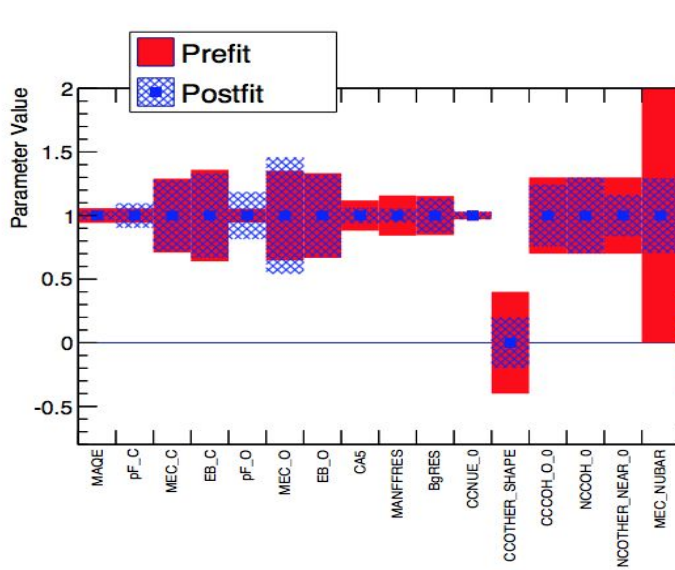
- Several progress were made :
 - ➡ Better use of the simulation studies output.
 - ➡ New cross-section parametrization.
 - ➡ Alternative configurations implemented.

- The Asimov are quite encouraging, will propagate to SK very soon to get the error on the expected number of event at SK.

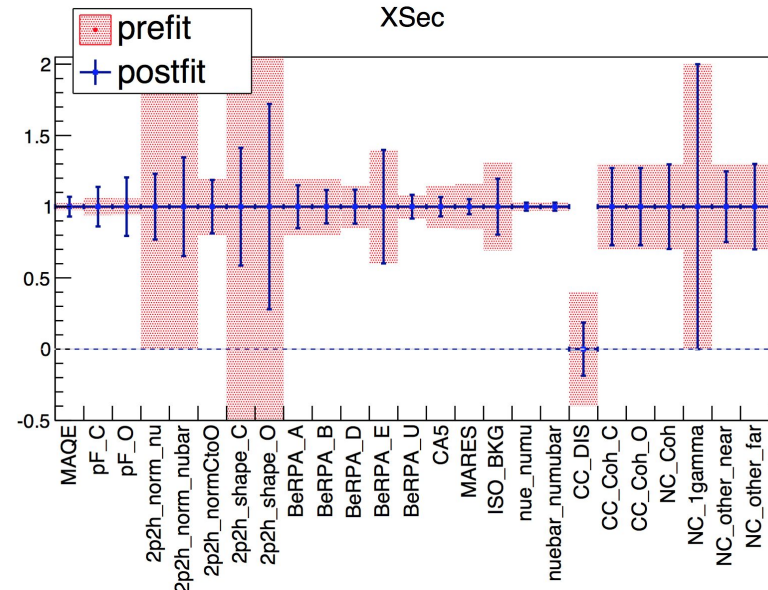
- Fake data studies are ongoing, most of the fake data sets are ready to be fitted and propagated to SK.

BACKUP

Cross-section model update



2015 cross-section parametrization

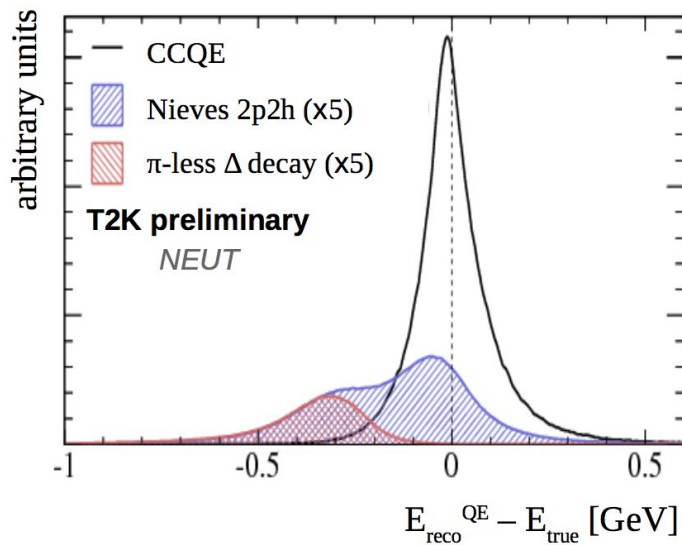
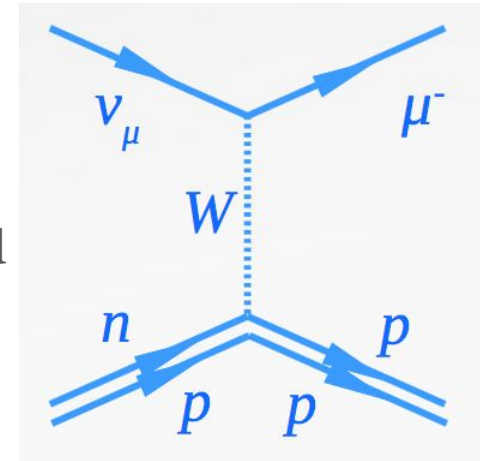


New cross-section parameterization

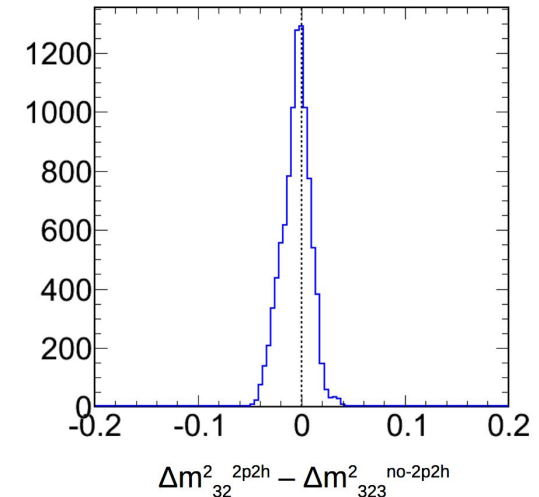
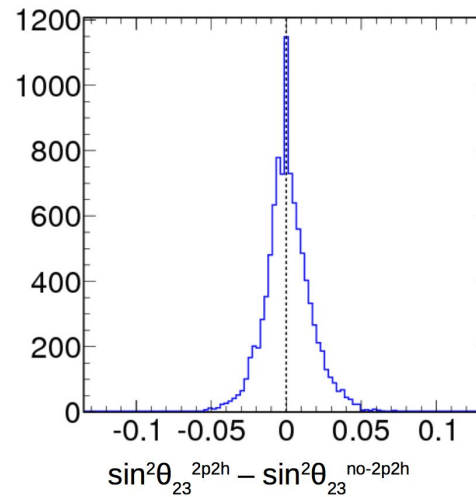
The new cross section parametrization has more freedom for the 2p2h interactions, and new BeRPA parameters, depending on Q^2 .

2p2h

If you develop the total CC cross-section, the first order expansion gives the CCQE process, the second order gives additional nucleon or Δ resonances. This process is often called a multi-nucleon interaction or 2-Particle-2-Holes (2p2h).



Effect on oscillations



1) The parameter's constraints

ASIMOV STUDY

- Make BANFF Asimov fit with the nominal (current) efficiency, and with improved efficiency
- Propagate the results to the far detector

Just an asimov fit, does not require toys, therefore easy to get.

2) Bias study : a) bias on oscillation parameters

ASIMOV STUDY

- Do BANFF fake data fits for nominal and improved efficiencies for different fake data sets :
 - ➡ Martini/Nieves
 - ➡ 1p1h NEUT/Nieves
 - ➡ Try if possible some other fake data sets to be as much model independant as possible (extreme cases)

- Propagate to the far detector and check the bias on the parameters

2) Bias study : b) bias on ND280 syst params

ASIMOV STUDY

Perform a pull study for all the systematic parameters.

Make BANFF fake data fit for nominal and improved efficiencies and look at the parameter's pull mean.

- If you increase high angle efficiency you expect larger discrepancies if models depend on that phase space.
- If the fitted xsec parameters are pulled in the right direction when increasing the efficiency, it probably means the update is going in the right direction.

⇒ **Difficult to quantify as a sensitivity**

Maybe we could also have informations on the possibility to reduce flux, xsec and detector systematics degeneracy.

3) Model sensitivity : a) Goodness of fit

TOY STUDY

- Goodness of fit test for different fake data sets (i.e. different models).
- Assume one model, make many toys, fit with nominal model (current BANFF) and get best fit χ^2 distributions.
- Then calculate the g.o.f. as p-value using nominal Asimov fit.
- Same procedure used for the run 1-6 data set BANFF fit.
- Do it for different models and get two χ^2 distributions and g.o.f.
- Follow the procedure above for the nominal and improved efficiencies : expect larger distance between χ^2 distributions and worse g.o.f. for improved efficiency if the additional phase space improve model separation.

⇒ **Difficult to quantify as a sensitivity**

3) Model sensitivity : b) Likelihood ratio

TOY STUDY

- Make one BANFF fake data fit for one fake data set (e.g. Martini) and fit it with two hypotheses :
 - ➡ nominal MC = Nieves $\Rightarrow \chi^2_{Nieves}$
 - ➡ nominal MC = Martini $\Rightarrow \chi^2_{Martini}$
- Analogue to the beta parameter in nue bar appearance analysis
- Get $\Delta\chi^2 = \chi^2_{Nieves} - \chi^2_{Martini}$ and obtain a significance from it.
(See mass hierarchy paper, also discrete and non-nested
<https://arxiv.org/pdf/1305.5150v4.pdf>)
- Do it for the two sets of efficiencies, nominal ($\Delta\chi^2_{NOM}$) and improved ($\Delta\chi^2_{UP}$), and compare them.
- If efficiency improvement is good we expect : $\Delta\chi^2_{UP} > \Delta\chi^2_{NOM}$
- Do first asimov fit (approximation, but still useful to get an idea), and eventually with many toys.

No need for new parameters in the framework