Some considerations on carbon or water target

Uncertainty on C/O measurement

Only statistical uncertainty considered!
Compare simplified simulation of ND280 with real T2K analyses

$$\frac{\delta R_{O/C}}{R_{O/C}} = \sqrt{\frac{1}{N_C} + \frac{1}{N_O}}$$

6×10^{20} POT

Configuration	N^C_{events}	N^O_{events}	CC inclusive $\delta R/R\|_{inc}$ (%)	CC0pi $\delta R/R\|_{0\pi}$ (%)
Current (2 FGDs)	37617	10339	1.110	1.320
Current (only FGD2)	12532	10333	2.039	2.432
Baseline (1 water tgt, 2 FGDs)	54975	49019	0.621	0.755
Baseline (1 carbon tgt, 2 FGDs)	93664	10331	1.037	1.235

To be compared with present ND280 full simulation: 2.5%

When we do a real analysis (background, C<->O migrations...) the actual error is 5%(stat) + 4.5%(syst). Systematics is fully dominated by C<->O migrations.
Using also FGD1 (TN) migration irrelevant → 2% syst

CH or H_2O target in the new baseline

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Clear improvement in the upgrade: new baseline configuration considered.
2 options considered: - new horizontal target of 70% H_2O + 30% CH
- new horizontal target 100% CH
Same reconstruction capabilities assumed: only muons in TPC (clearly pessimistic for the 100% C), pion rejection also in target (5cm track with 70% good PID)

The question

It is clear that we miss a lot of precision with a water target... is it worth?

The uncertainties we are including in our OA are relatively small → **will be ever capable of measuring C/O well enough with the ND280 upgrade to be useful?**

NOTE: to answer this question we need to know what is the real C/O difference. Our ND precision TODAY is not good enough yet to measure it.
We need to use some model to estimate what is the plausible difference and what is the uncertainty on this difference!

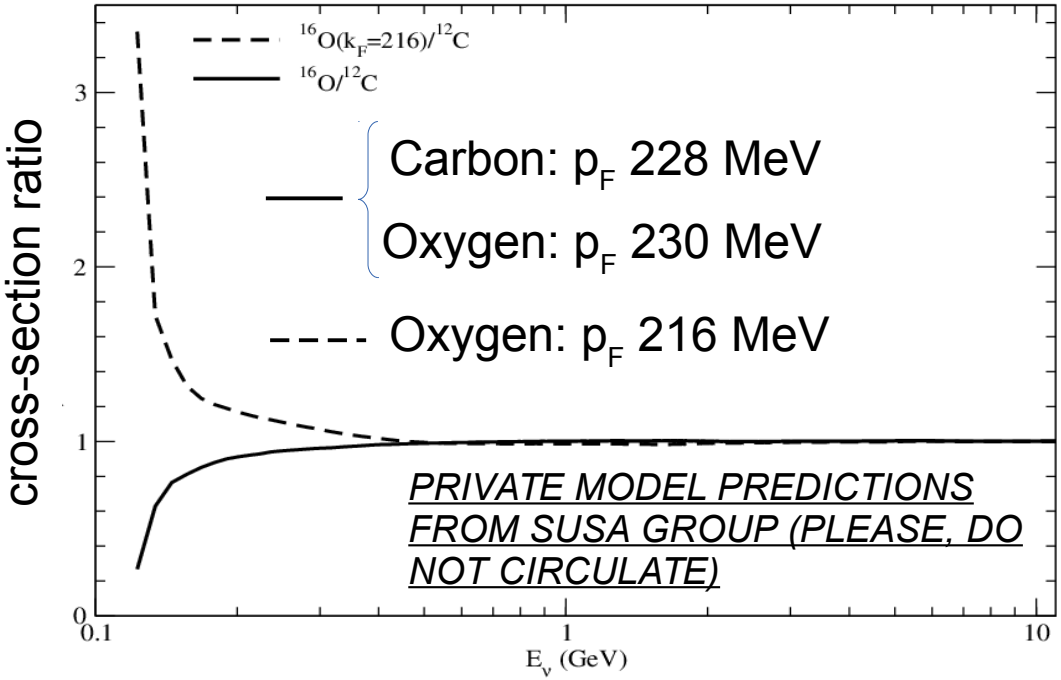
I can give my opinion but it is clear that the answer would have been different 10 years ago and it may be that something new will show up in the future...

Oxygen/Carbon

- The C/O uncertainty is due to different nuclear structure/size → most of the effect at very low transferred energy to the nucleus (ω)

  Typically parametrized as a function of Fermi momentum (p_F) and binding energy

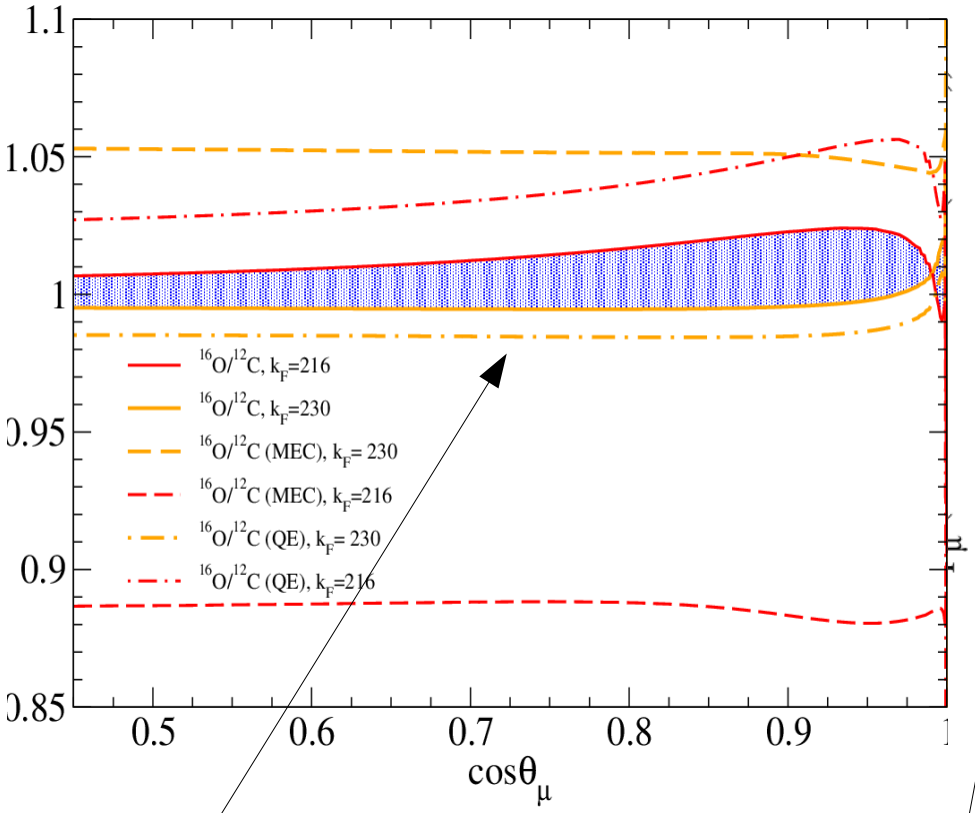
- The best way I found to estimate this uncertainty is to use the latest CCQE+2p2h model from SuSa which tuned the A-dependency from electron scattering data

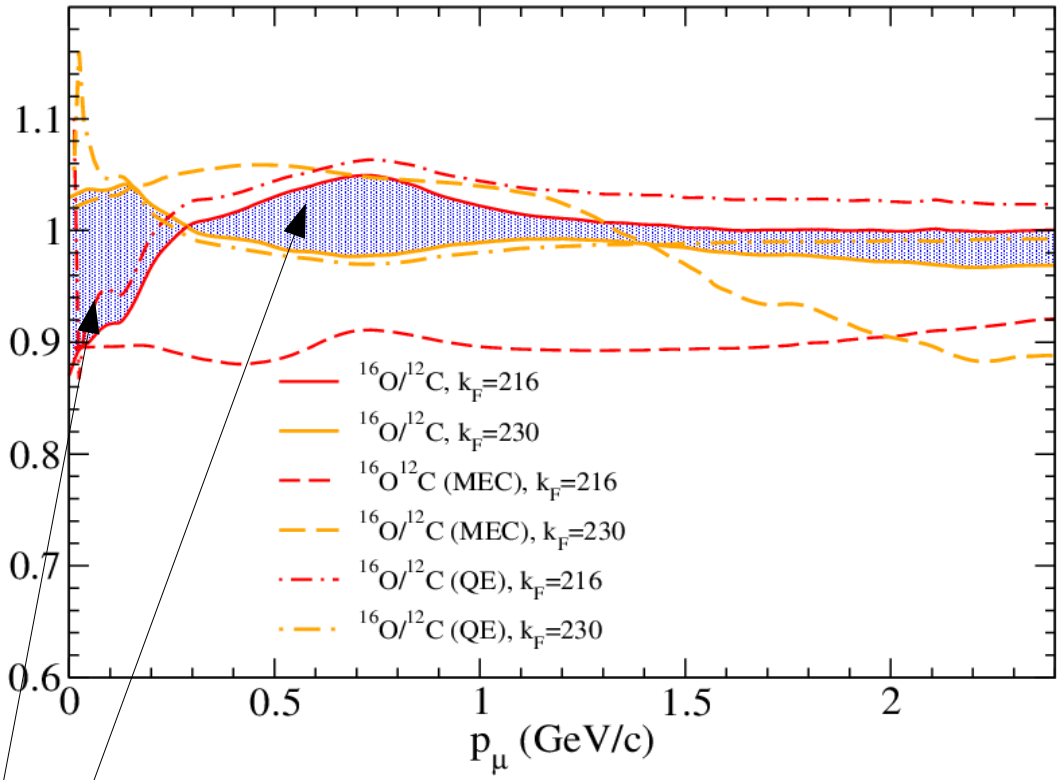


T2K uses:
Carbon p_F 223 MeV
Oxygen p_F 225 MeV

Looking into more details

PRIVATE MODEL PREDICTIONS FROM SUSA GROUP (PLEASE, DO NOT CIRCULATE)



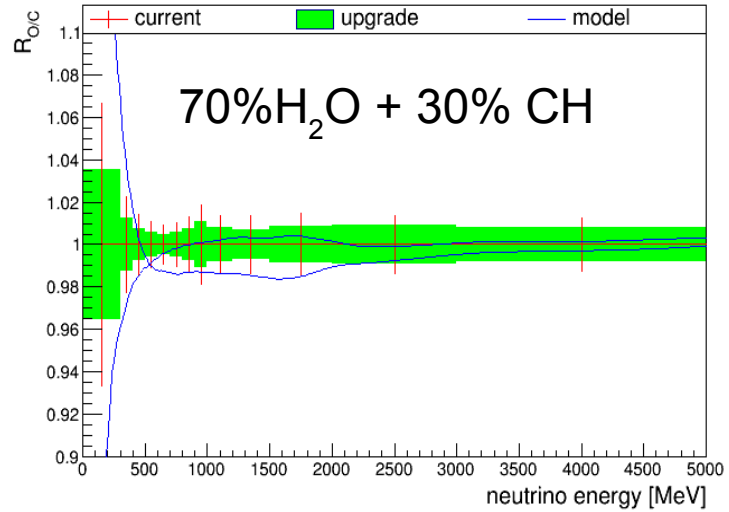


- 2p2h and CCQE have opposite C/O behavior! ← 2p2h ~ $A*p_F^2$, CCQE ~ A/p_F

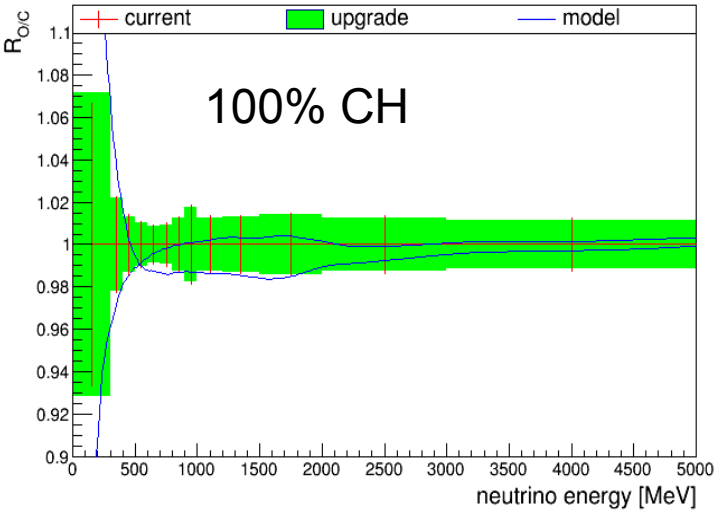
  Some cancellation: C/O difference 5% goes down to ~1-2%

- Most of the effect in the very low muon momentum region (very difficult to measure muons in water at ~100MeV)

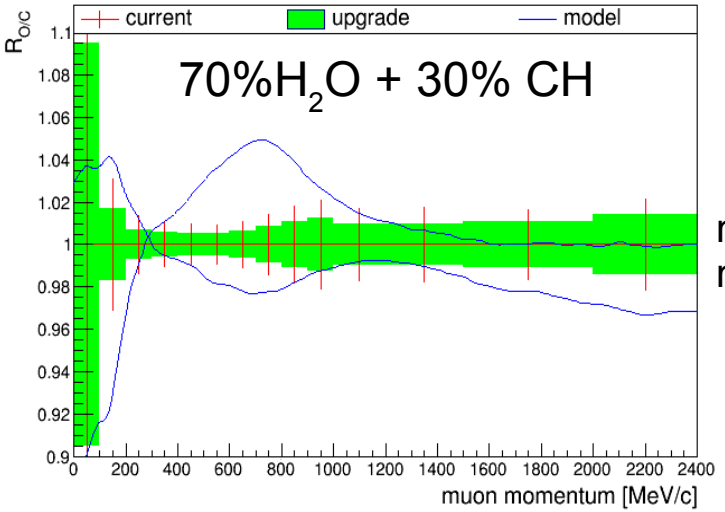
- A large effect also at p_μ~600 GeV but this is due to change in 2p2h/CCQE ratio → quite model dependent effect...



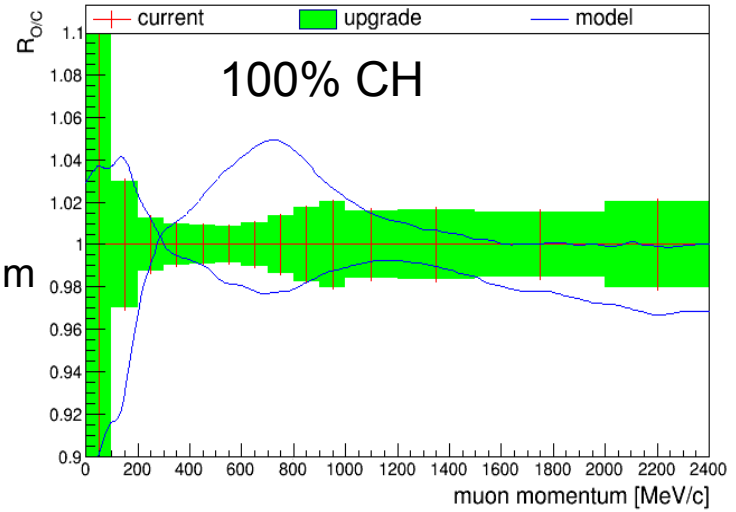
neutrino energy



Plots from M.Lamoureux

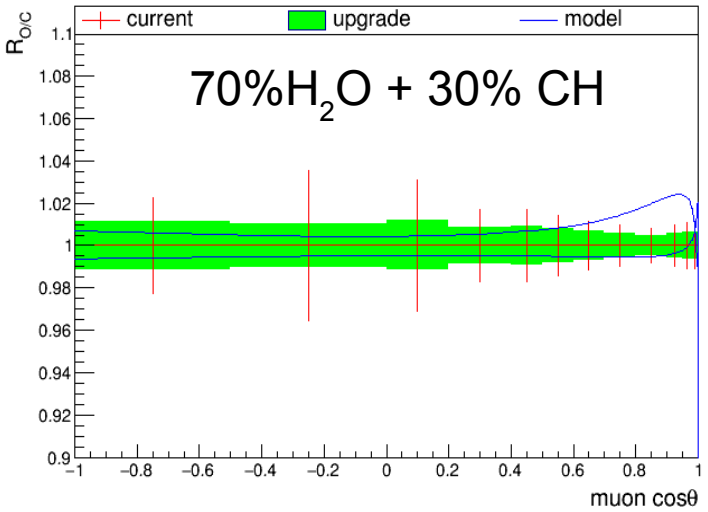


muon momentum

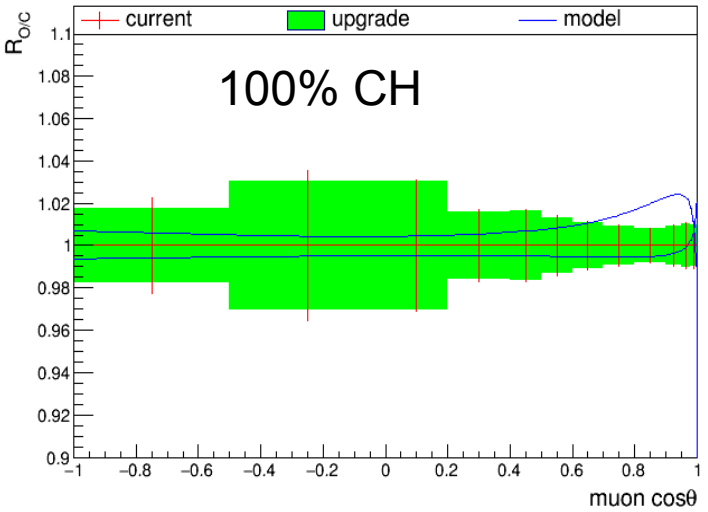


Results:

precision with new baseline upgrade design (8×10^{21} POT)



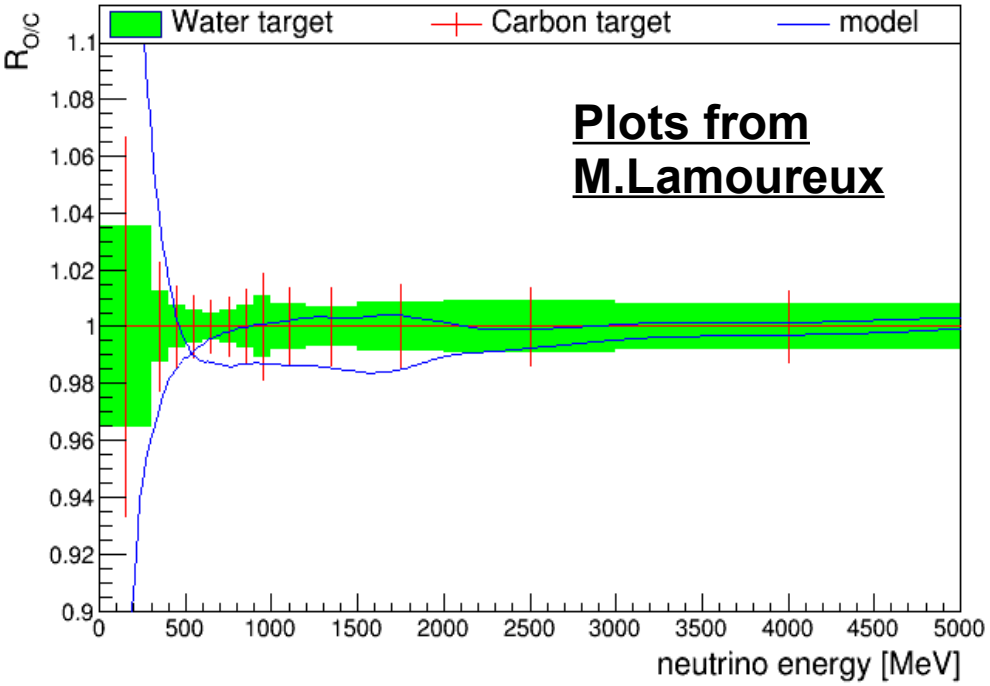
muon angle

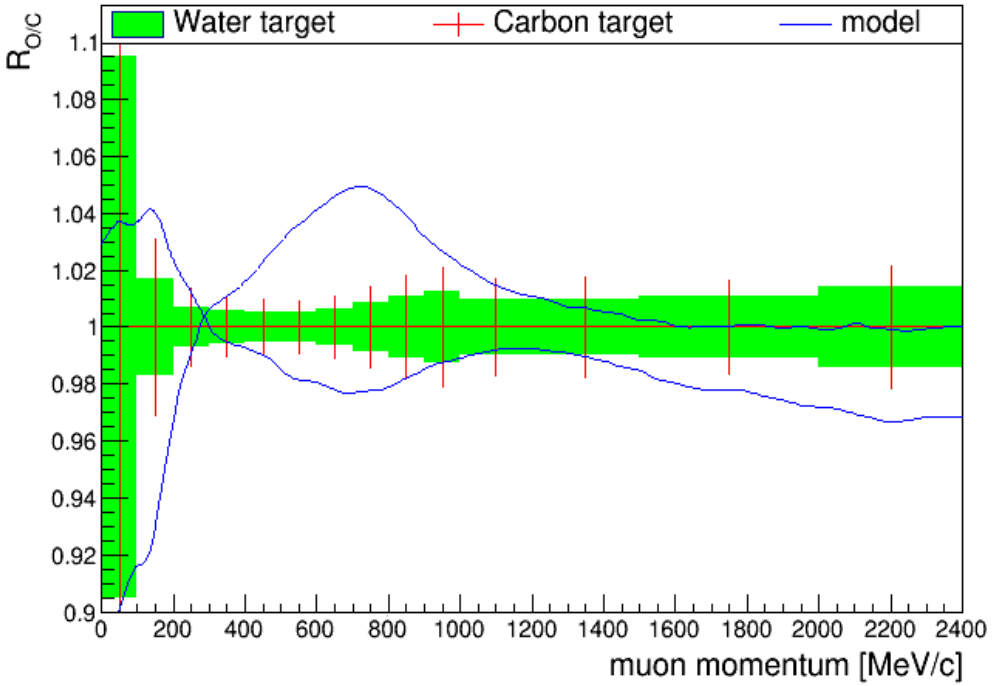


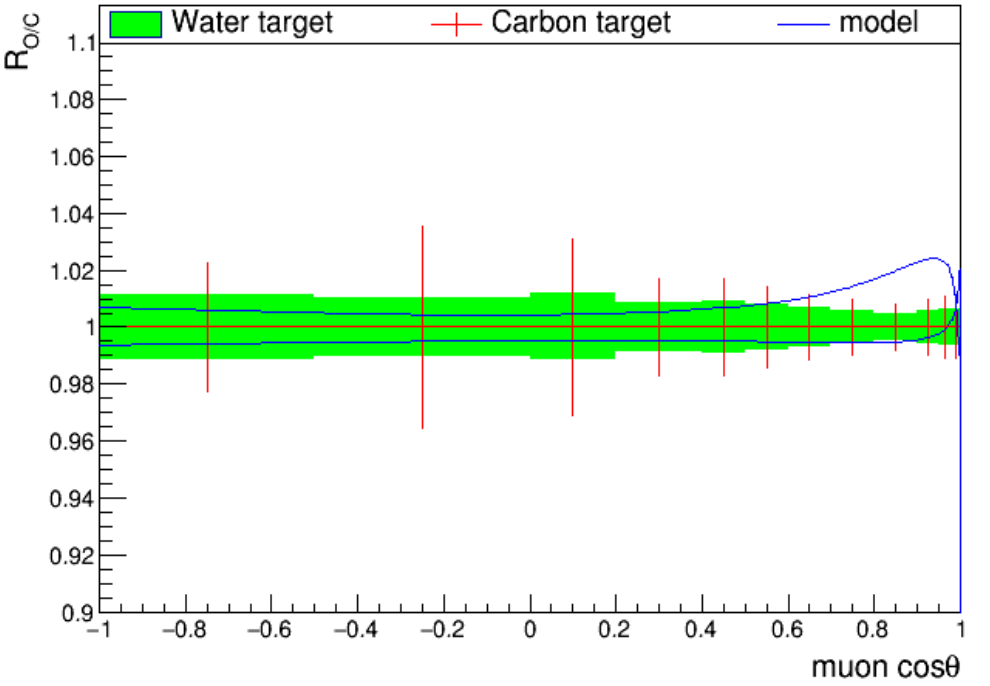
Results

Precision with new baseline upgrade design (8x10^{21} POT)

Same plots as before but comparing directly the two targets: 100% CH vs 70%H_2O







My personal conclusions

If we consider that **in a real analysis the statistical uncertainty shown in the previous plots have to be multiplied by 2 (+ >2% systematics).** I do not think that putting water in the ND280 new target is really worth.

In order to measure C/O xsec a VERY large statistics is needed: it is much more useful to put a water target on-axis where the statistics is much larger!
If we compare today analyses of WAGASCI prototype with respect to the ND280 FGD1+FGD2 analysis, for the ~same POTs we get ~half of the statistical error

BTW: another C/O systematics which I didn't mentioned here is the **pion FSI/SI difference between C and O** (see backup for details).
This should be even more difficult to measure: it needs very large statistics of pion scattering on C and O with well known pion momentum →
WAGASCI module on a pion beam? (need low energy beam)

Back-up

Pion FSI in C and O

- We constrain the probability of pion rescattering in the nucleus from π-N scattering data
  → uncertainty from data +
  → large uncertainty extrapolation from nucleus surface to inside the nucleus fully based on (not well known) nuclear physics model

- **The correlation between C and O FSI uncertainty is actually very large (for what we know)**

  - ND280 fit use fully correlated FSI uncertainty between C and O

- In any case measuring **low momentum pions in water target is not feasible...**

  - not much an issue of ND design, more useful to have external data on π-nucleus scattering measured on O

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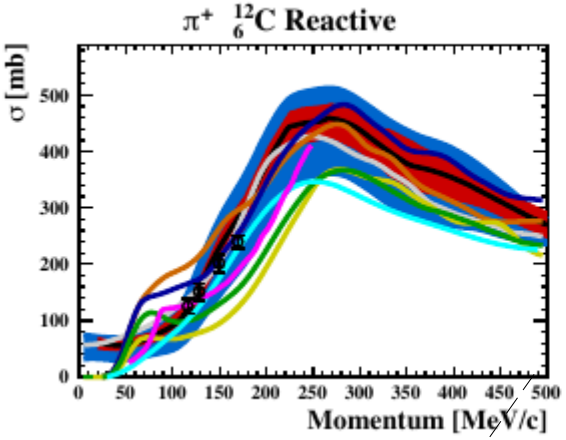
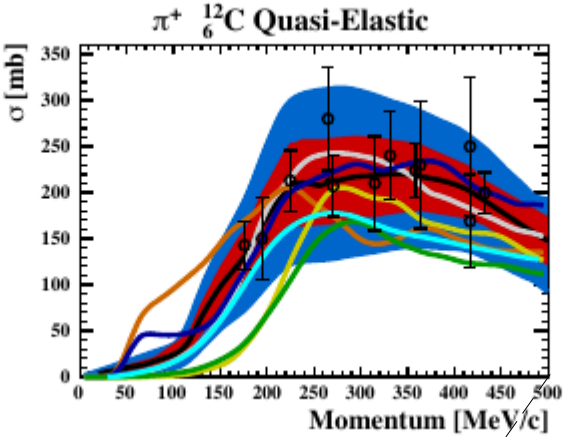
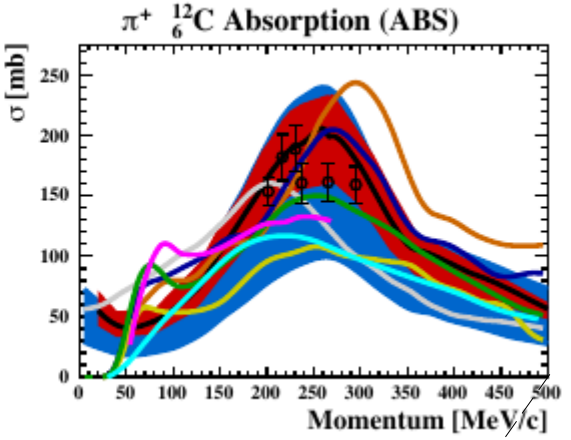
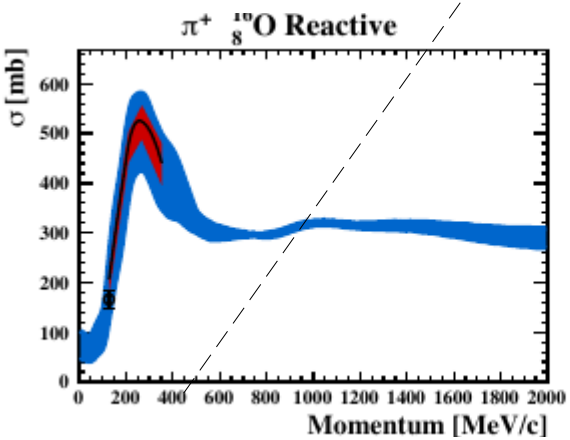
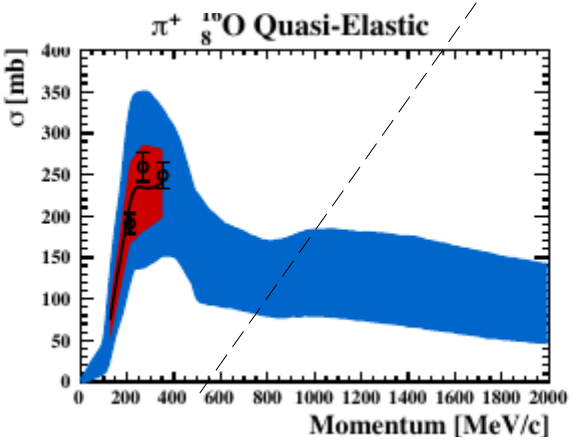
Pion scattering on C,O, Cu

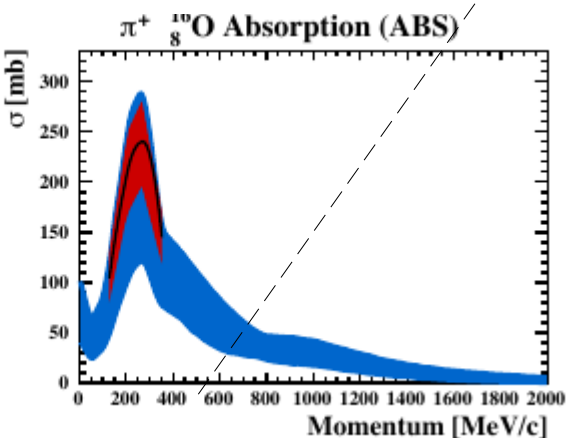


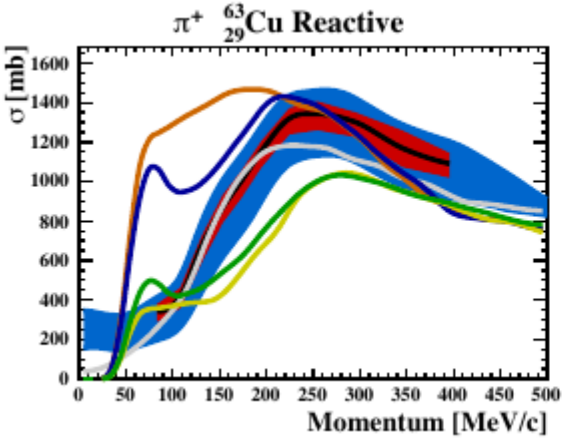


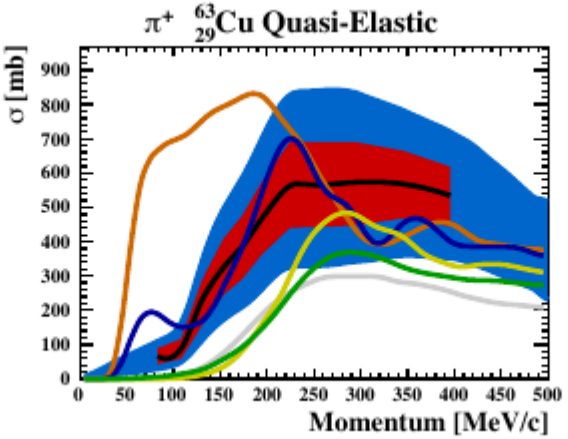


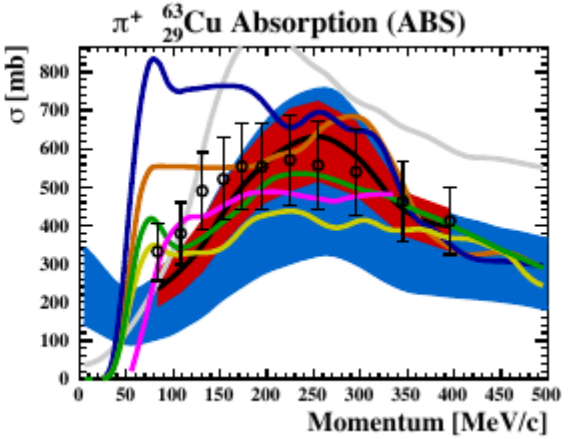




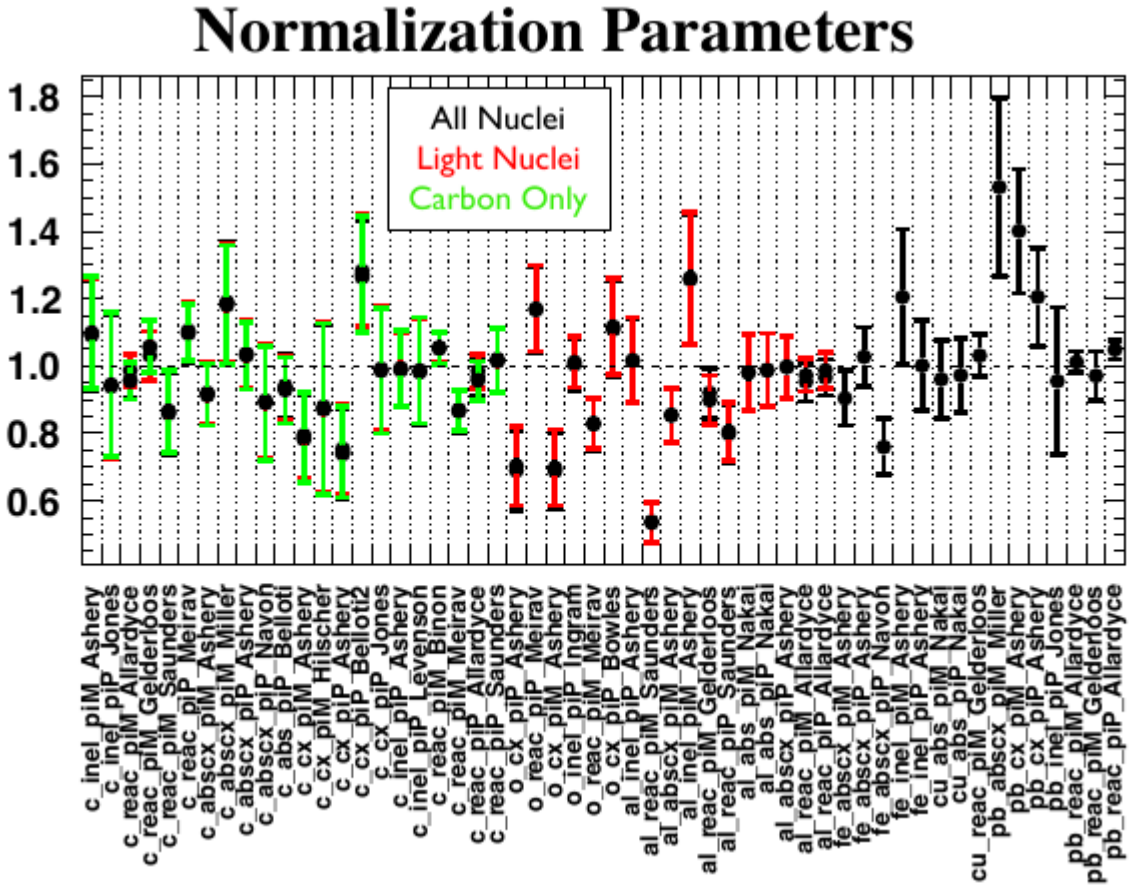








Pion FSI fit results



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