Group meeting: Update on the integration of WAGASCI in the OA

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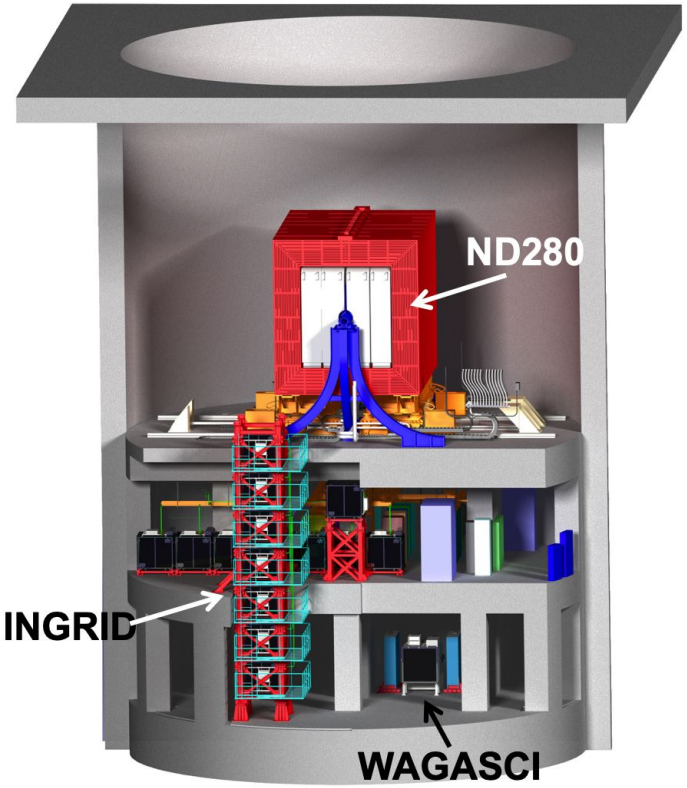
16/05/2023

RECAP

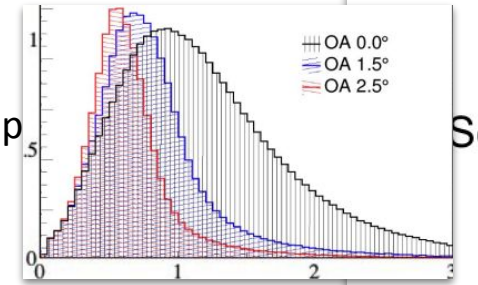
Near detector complex

REMINDER: since 2019, FGD2 is running with only 4 water bags (instead of 6)... but since 2019 we have WAGASCI/BM in place!

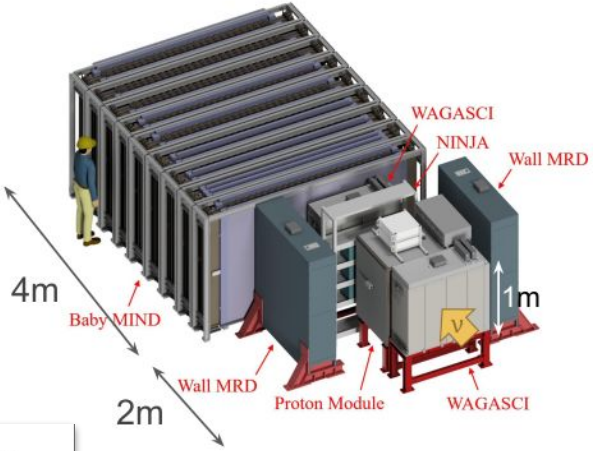


WAGASCI

- Thus far only used for **xsec measurements** (link to detailed xsec analysis below)
- Could be interesting to exploit **water content** to constrain oxygen parameters
- A different **off-axis** could potentially help constrain flux systematics and energy dependant parameters



WAGASCI, 1.5° off-axis



Recently added (2019)

Segmented cubic CH/H_2O (WAGASCI) and SMRD+BabyMIND

Magnetized detector

Made of **80% of water (~0.5t)**

https://www.t2k.org/meet/collab/CM_Oct_2022/Talks/Oct14/wagasci-babymind-xsec-plenary

MOTIVATION

- The goal of this study is to perform sensitivity studies with the WAGASCI samples to see the additional constraints we might obtain in the OA (notably on spectral function oxygen parameters)
  https://www.t2k.org/asg/meeting/2023/2023-02-02/waga

- The first part of this study was **integrating** samples from WAGASCI (courtesy of Kenji Yasutome) to the analysis framework in the same format as the ND280 samples (GUNDAM for OA)

- Ongoing study consists of comparing post fit errors as a function of POT to see the constraints of adding WAGASCI samples

First joint fit results

Current fit configuration (still running)

- Samples:
  - **FGD1/FGD2** (same rootfiles as OA2022)
  - **sFGD** (as in official sensitivity studies from Jaafar)
  - **WAGASCI** (as in Kenji's analysis, but 2D binning)

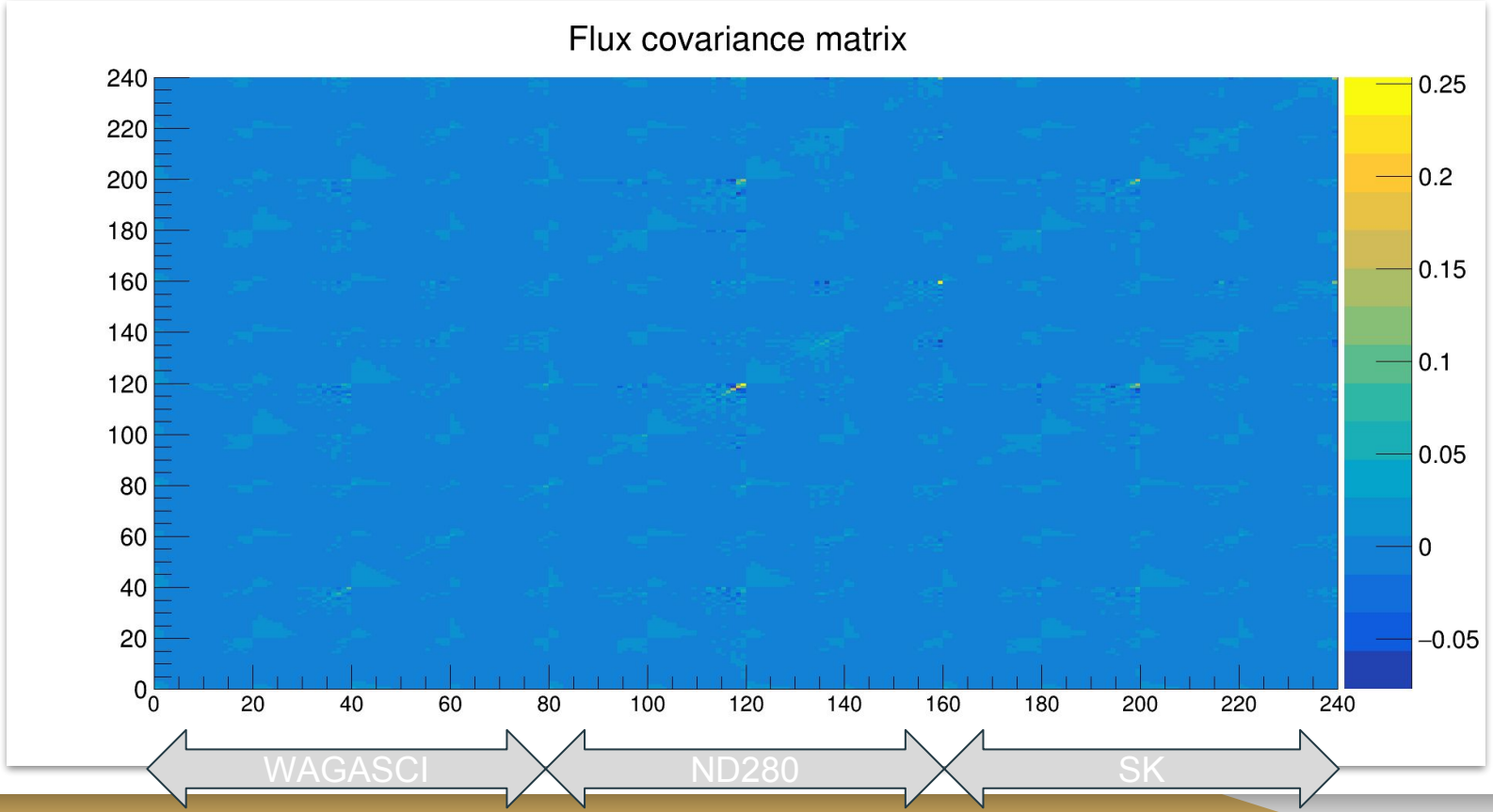
- So far, *CC 0pi* and *CC 1pi* only

- Detector smearing enabled for FGD,sFGD,WAGASCI

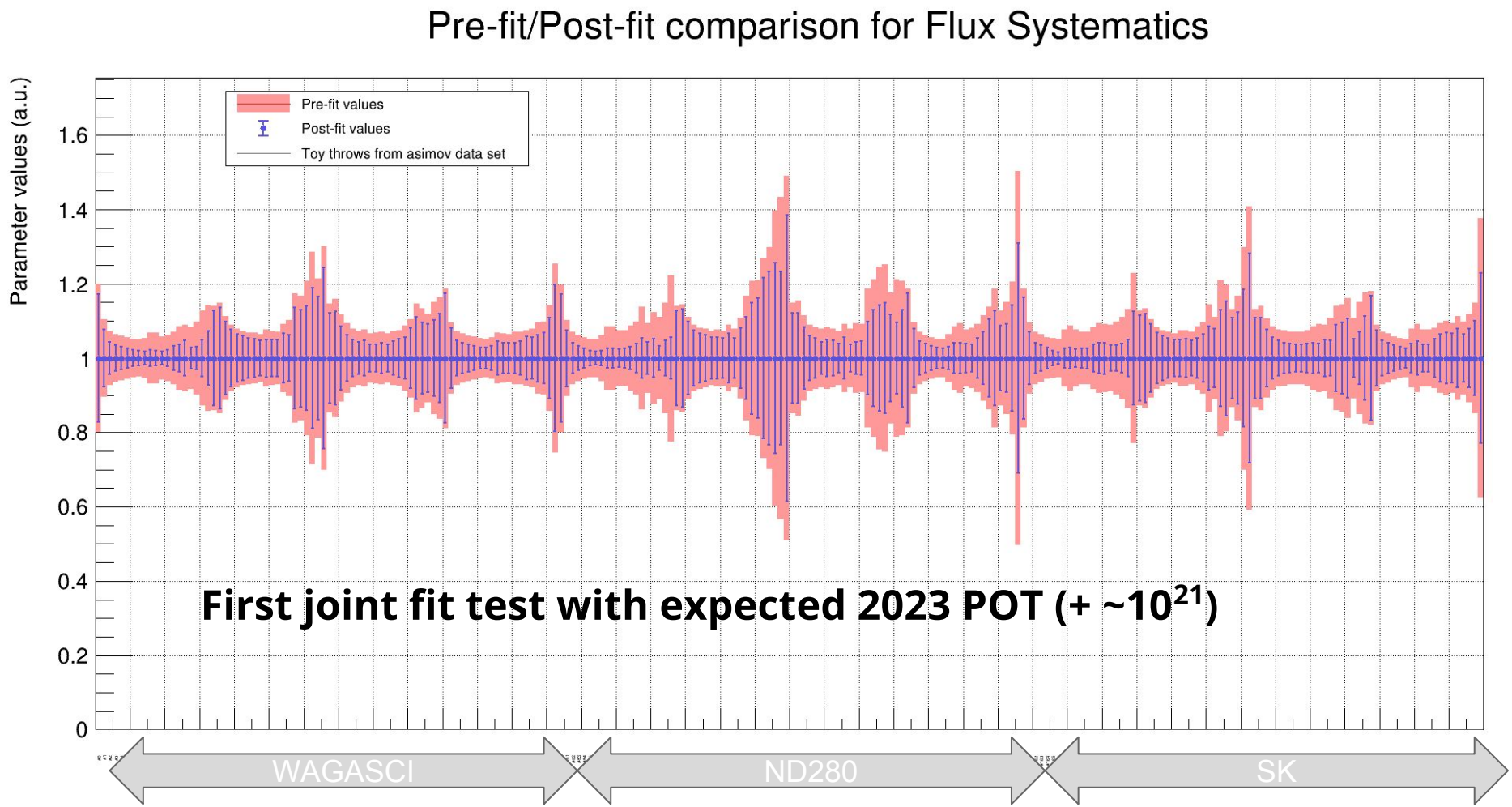
- Parameters: Flux and Cross-Sections

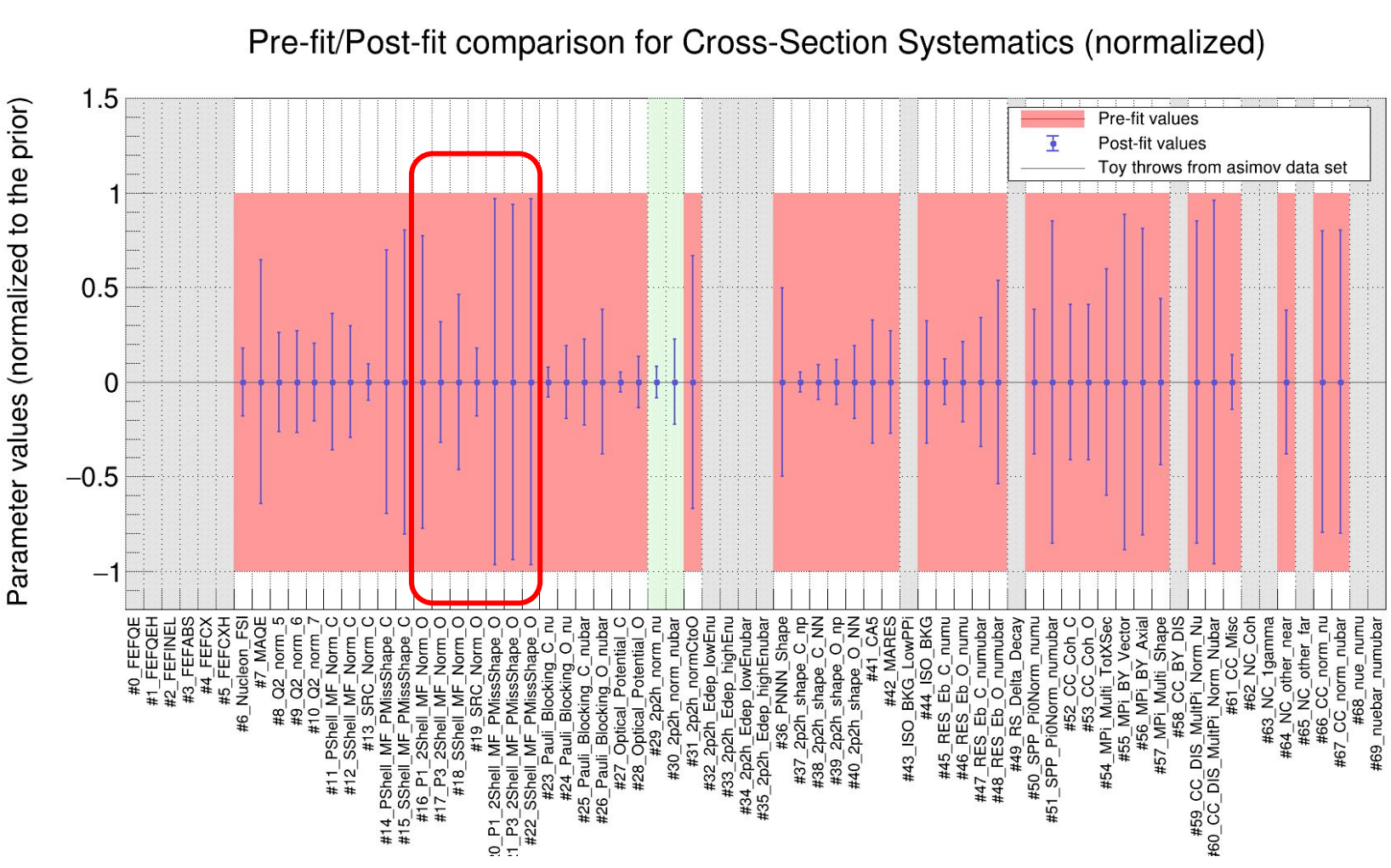
Caspar's flux matrix

Caspar (xsec analyser/convener) developed a tool in collaboration with the beam group, to provide joint covariance matrices



So far, only ν_μ and $\bar{\nu}_\mu$ are included. Caspar will add ν_e and $\bar{\nu}_e$ later and adapt the binning as for the OA

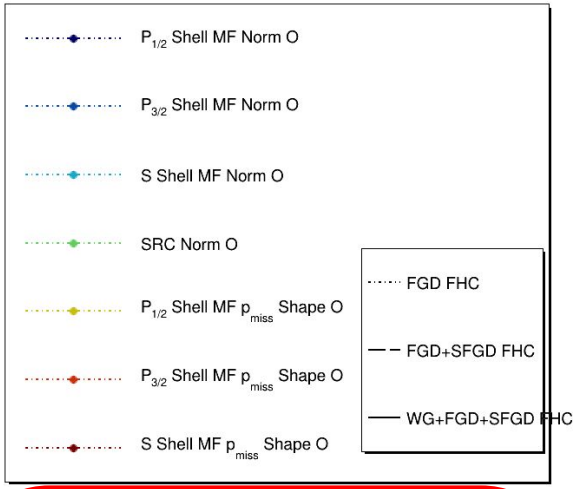

Pre-fit/Post-fit comparison for Flux Systematics
Parameter values (a.u.)
Pre-fit values
Post-fit values
Toy throws from asimov data set
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
First joint fit test with expected 2023 POT (+ ~10^21)
WAGASCI
ND280
SK

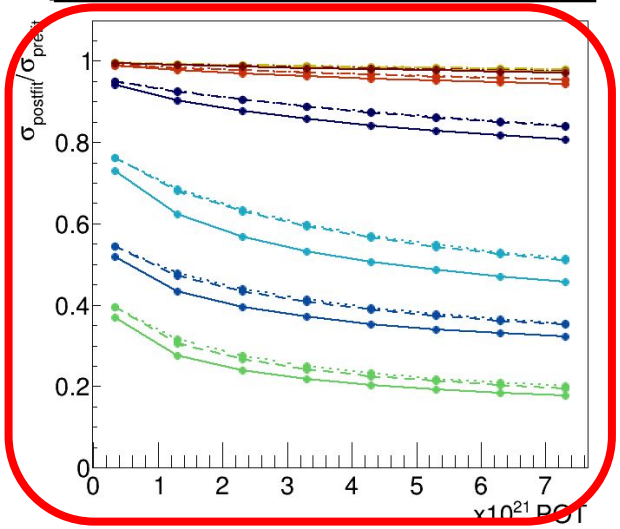

Pre-fit/Post-fit comparison for Cross-Section Systematics (normalized)
Parameter values (normalized to the prior)
1.5
1
0.5
0
−0.5
−1
Pre-fit values
Post-fit values
Toy throws from asimov data set
#0_FEFQE
#1_FEFQEH
#2_FEFINEL
#3_FEFABS
#4_FEFCX
#5_FEFCXH
#6_Nucleon_FSI
#7_MAQE
#8_Q2_norm_5
#9_Q2_norm_6
#10_Q2_norm_7
#11_PShell_MF_Norm_C
#12_SShell_MF_Norm_C
#13_SRC_Norm_C
#14_PShell_MF_PMissShape_C
#15_SShell_MF_PMissShape_C
#16_P1_2Shell_MF_Norm_O
#17_P3_2Shell_MF_Norm_O
#18_SShell_MF_Norm_O
#19_SRC_Norm_O
#20_P1_2Shell_MF_PMissShape_O
#21_P3_2Shell_MF_PMissShape_O
#22_SShell_MF_PMissShape_O
#23_Pauli_Blocking_C_nu
#24_Pauli_Blocking_O_nu
#25_Pauli_Blocking_C_nubar
#26_Pauli_Blocking_O_nubar
#27_Optical_Potential_C
#28_Optical_Potential_O
#29_2p2h_norm_nu
#30_2p2h_norm_nubar
#31_2p2h_normCtoO
#32_2p2h_Edep_lowEnu
#33_2p2h_Edep_highEnu
#34_2p2h_Edep_lowEnubar
#35_2p2h_Edep_highEnubar
#36_PNNN_Shape
#37_2p2h_shape_C_np
#38_2p2h_shape_C_NN
#39_2p2h_shape_O_np
#40_2p2h_shape_O_NN
#41_CA5
#42_MARES
#43_ISO_BKG_LowPPi
#44_ISO_BKG
#45_RES_Eb_C_numu
#46_RES_Eb_O_numu
#47_RES_Eb_C_numubar
#48_RES_Eb_O_numubar
#49_RS_Delta_Decay
#50_SPP_Pi0Norm_numu
#51_SPP_Pi0Norm_numubar
#52_CC_Coh_C
#53_CC_Coh_O
#54_MPi_Multi_TotXSec
#55_MPi_BY_Vector
#56_MPi_BY_Axial
#57_MPi_Multi_Shape
#58_CC_BY_DIS
#59_CC_DIS_MultPi_Norm_Nu
#60_CC_DIS_MultPi_Norm_Nubar
#61_CC_Misc
#62_NC_Coh
#63_NC_1gamma
#64_NC_other_near
#65_NC_other_far
#66_CC_norm_nu
#67_CC_norm_nubar
#68_nue_numu
#69_nuebar_numubar

Sensitivity studies with increasing POT

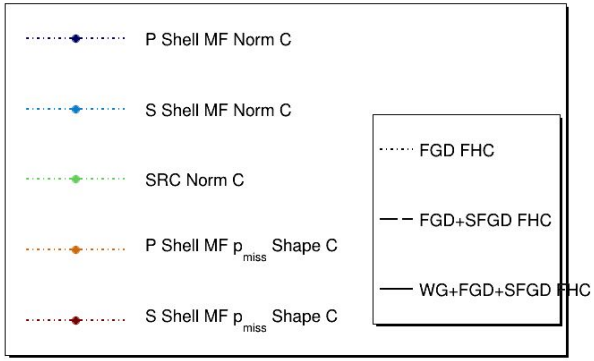
POT studies

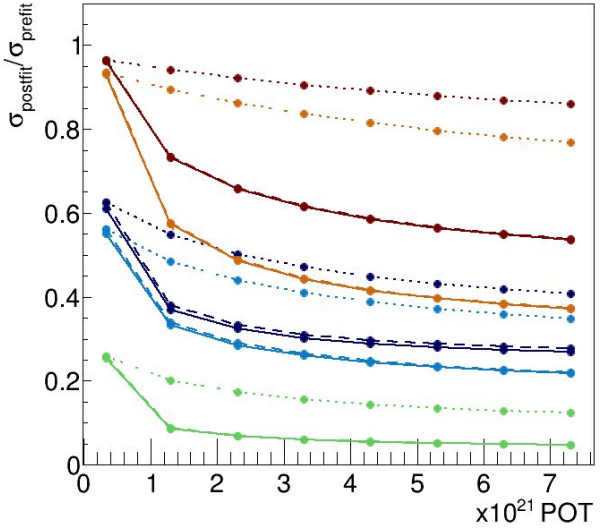
- Tested effects on Cross-Section parameters and flux parameters
- Using WAGASCI, FGD1/FGD2 and SFGD
- Detector smearing enabled for all samples
- Scaled FGD2 samples to take into account lost water content
- Only increasing POT with FHC samples (with $1x10^{21}$ steps)

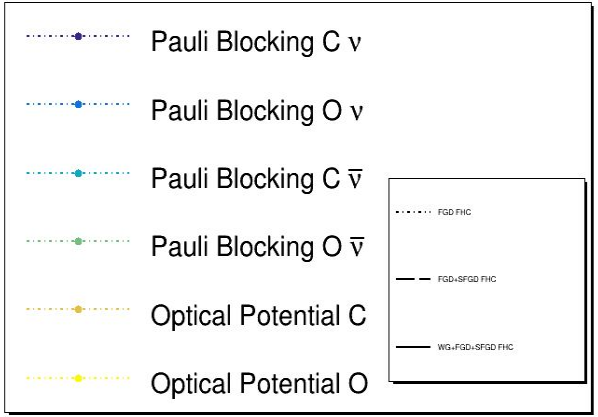


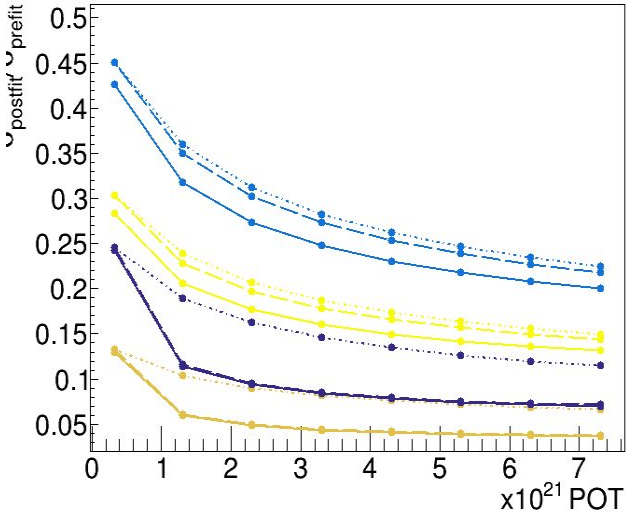


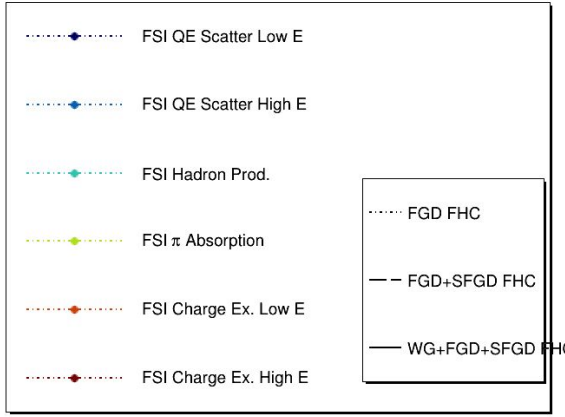
➜ WAGASCI constrains oxygen parameters, especially shell parameters!

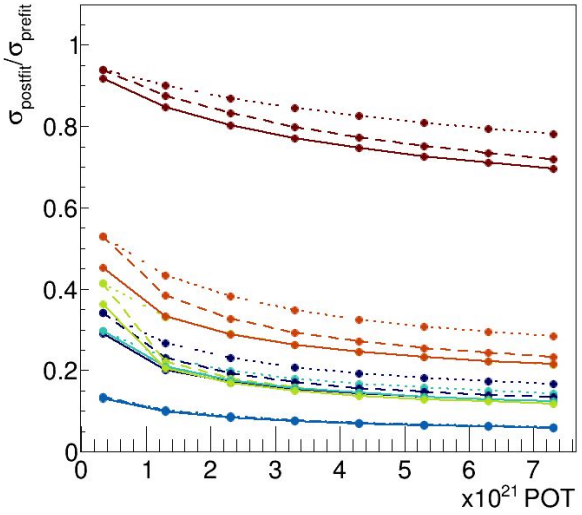


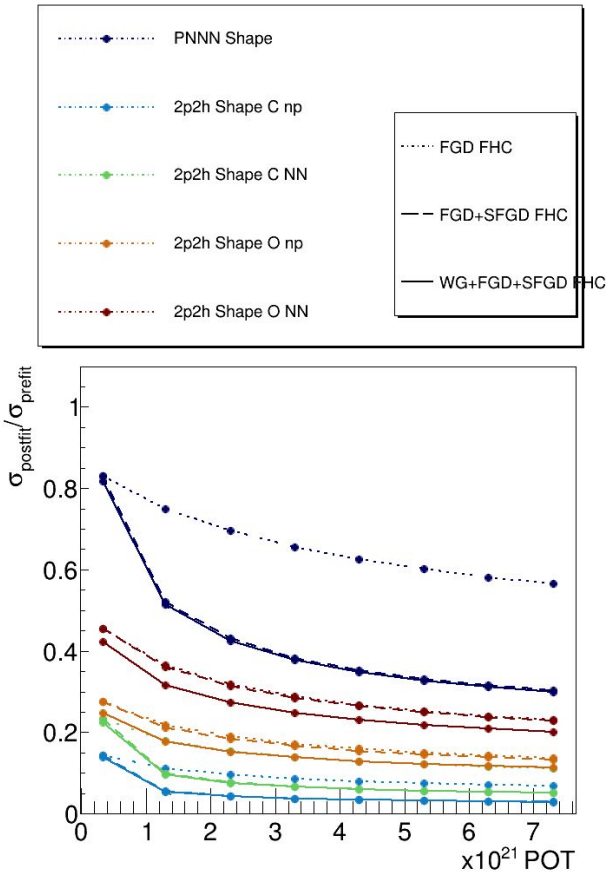


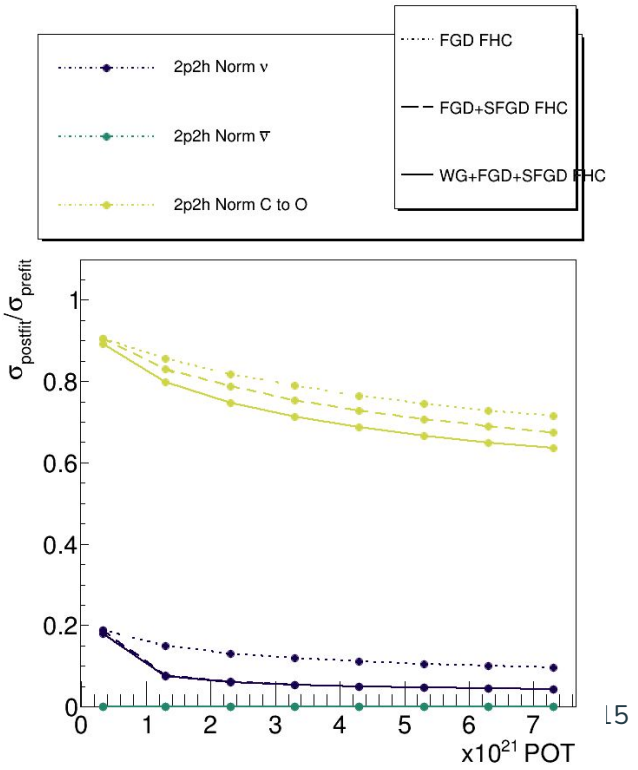

Pauli Blocking C ν
Pauli Blocking O ν
Pauli Blocking C ν̄
Pauli Blocking O ν̄
Optical Potential C
Optical Potential O
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC

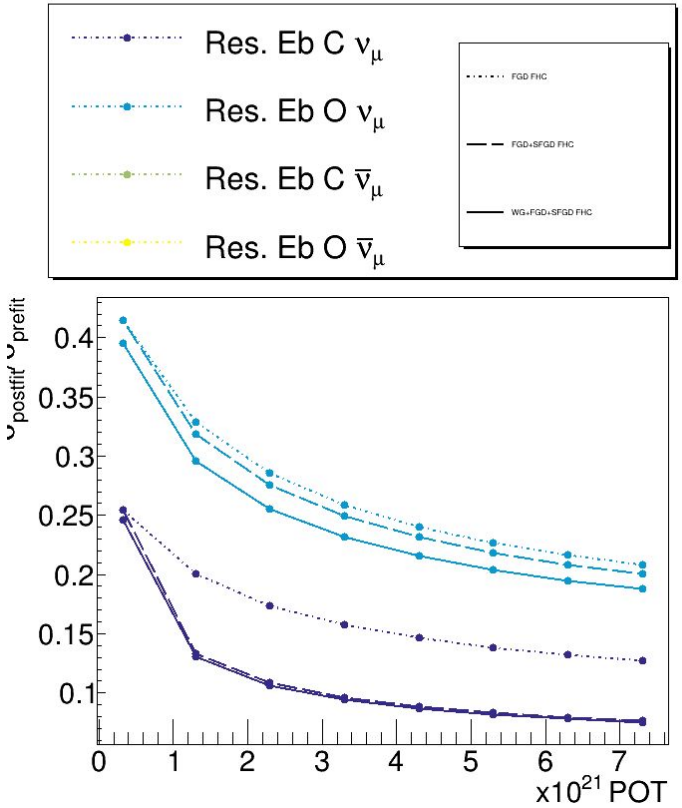

σpostfit/σprefit
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
x10^21 POT

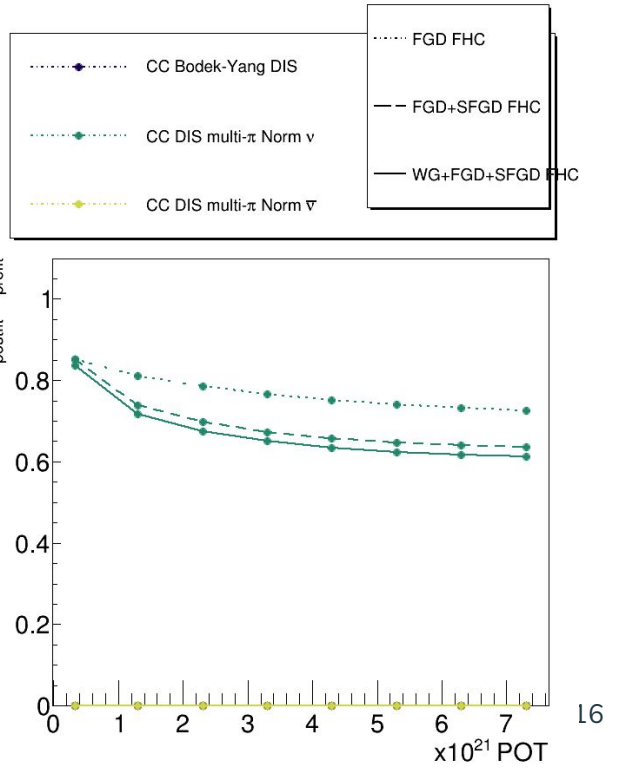

FSI QE Scatter Low E
FSI QE Scatter High E
FSI Hadron Prod.
FSI π Absorption
FSI Charge Ex. Low E
FSI Charge Ex. High E
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC


σpostfit/σprefit
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
x10^21 POT


PNNN Shape
2p2h Shape C np
2p2h Shape C NN
2p2h Shape O np
2p2h Shape O NN
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{postfit}/\sigma_{prefit}$
x10^{21} POT


2p2h Norm ν
2p2h Norm ν̄
2p2h Norm C to O
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{postfit}/\sigma_{prefit}$
x10^{21} POT

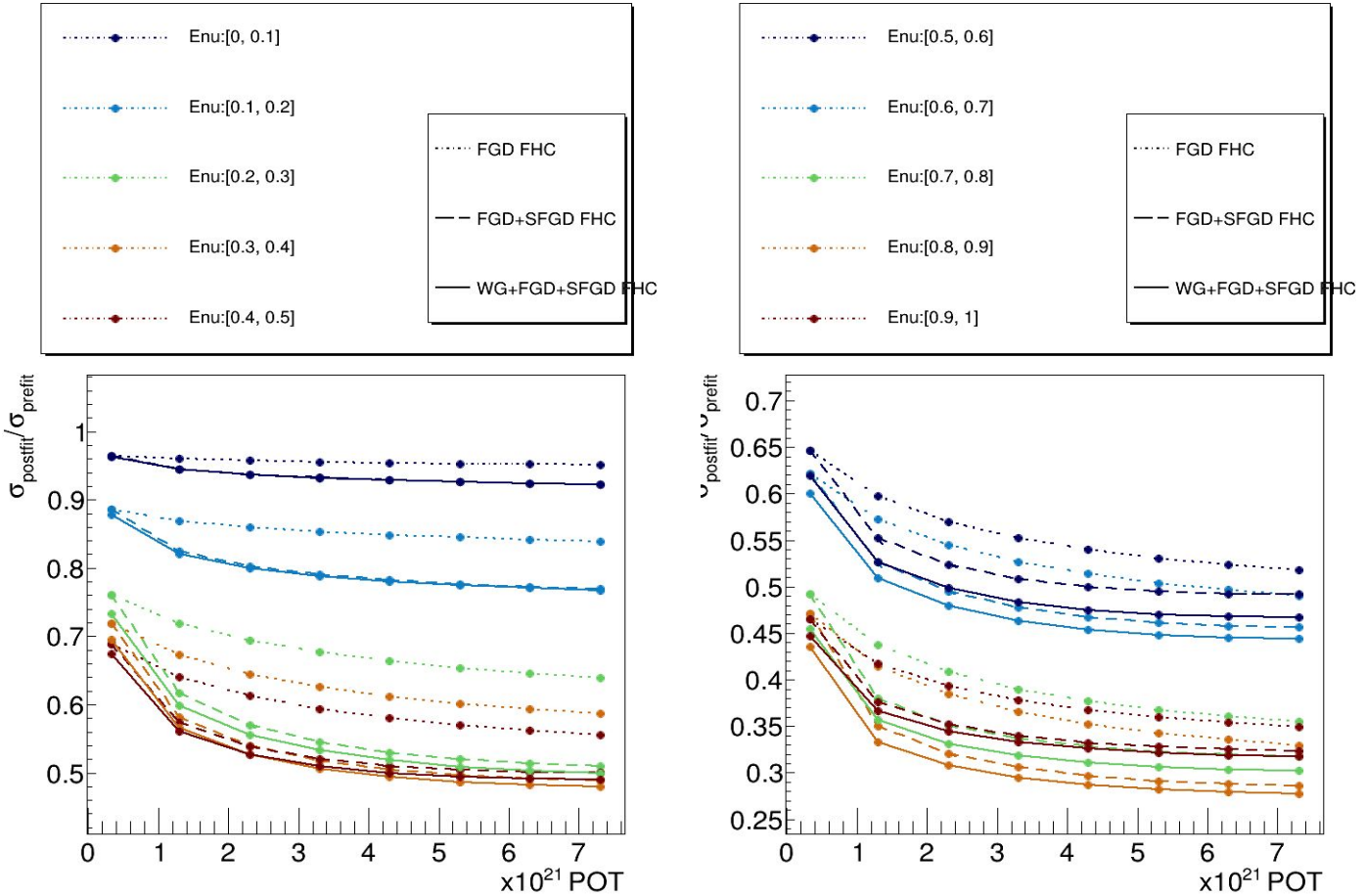

Res. Eb C ν_μ
Res. Eb O ν_μ
Res. Eb C $\bar{\nu}_\mu$
Res. Eb O $\bar{\nu}_\mu$
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{postfit}/\sigma_{prefit}$
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
1
2
3
4
5
6
7
x10^{21} POT


CC Bodek-Yang DIS
CC DIS multi-π Norm ν
CC DIS multi-π Norm $\bar{\nu}$
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{postfit}/\sigma_{prefit}$
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
x10^{21} POT

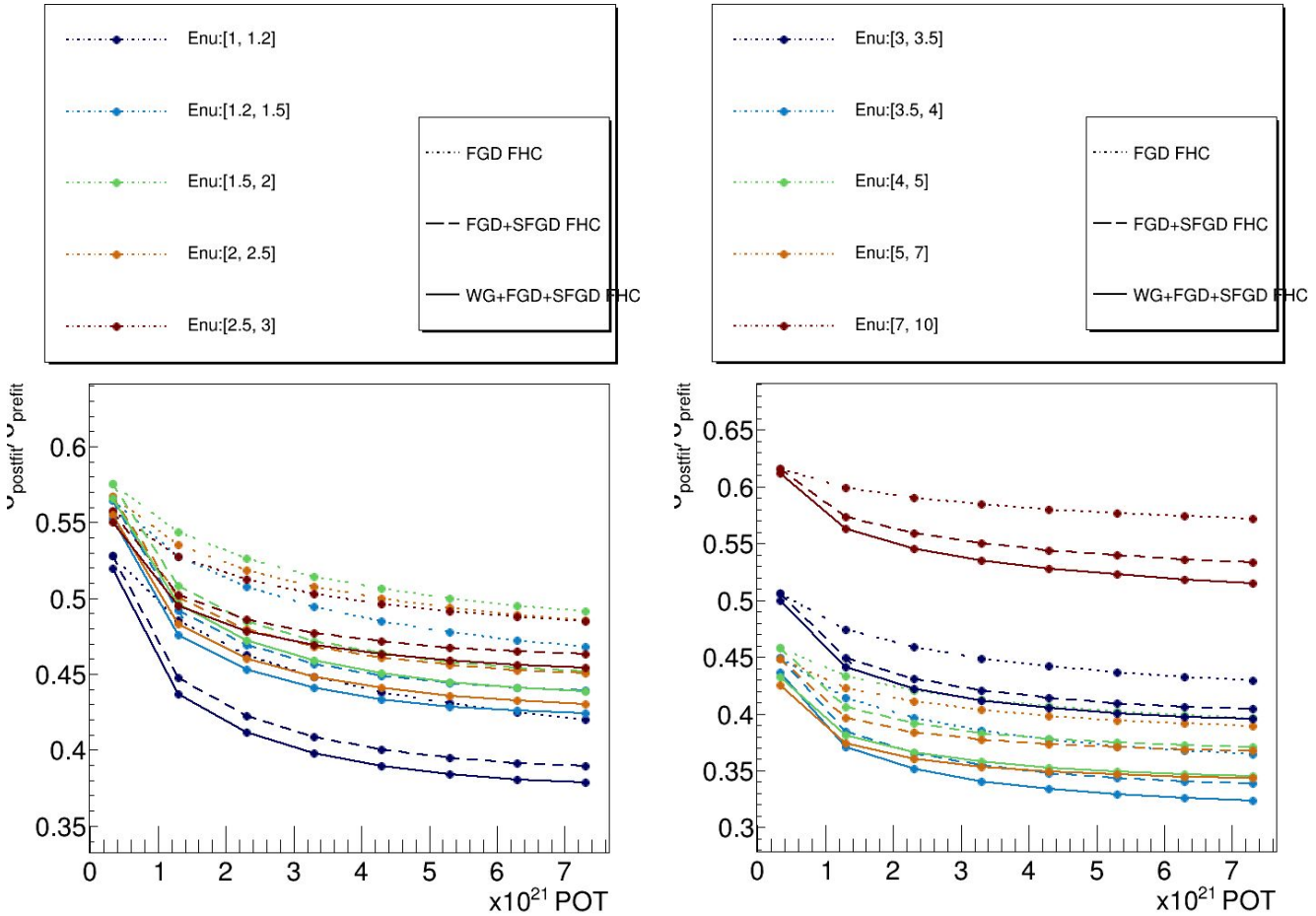
Flux

- Only kept FHC parts of flux covariance matrix
- Eigen decomposition enabled for the fit
- See if adding WAGASCI shows any further constraints

SK FHC


Enu:[0, 0.1]
Enu:[0.1, 0.2]
Enu:[0.2, 0.3]
Enu:[0.3, 0.4]
Enu:[0.4, 0.5]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
Enu:[0.5, 0.6]
Enu:[0.6, 0.7]
Enu:[0.7, 0.8]
Enu:[0.8, 0.9]
Enu:[0.9, 1]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
σpostfit/σprefit
x10^21 POT
νpostfit/νprefit
x10^21 POT

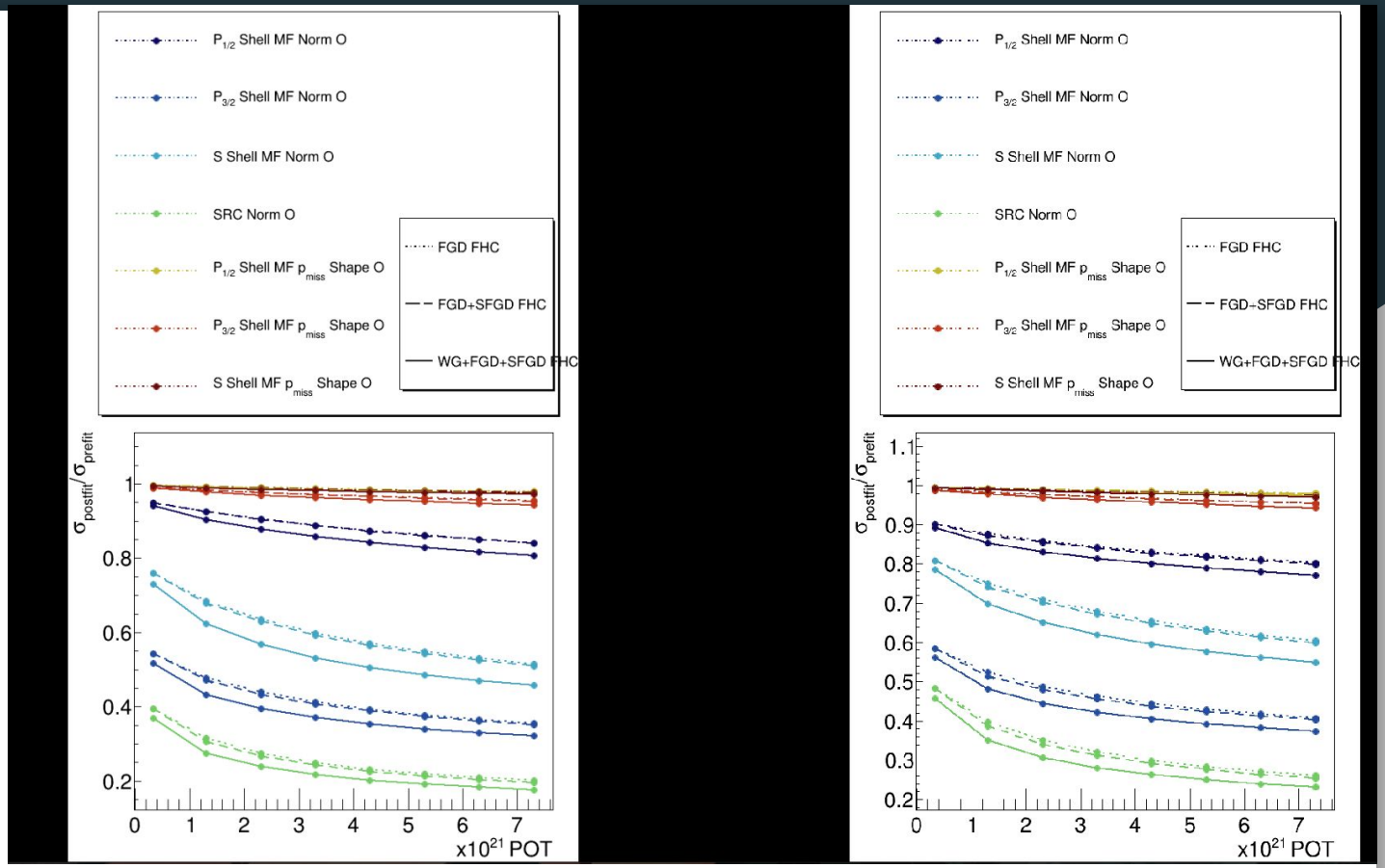
SK FHC


Enu:[1, 1.2]
Enu:[1.2, 1.5]
Enu:[1.5, 2]
Enu:[2, 2.5]
Enu:[2.5, 3]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
Enu:[3, 3.5]
Enu:[3.5, 4]
Enu:[4, 5]
Enu:[5, 7]
Enu:[7, 10]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\upsilon_{postfit}/\upsilon_{prefit}$
0.6
0.55
0.5
0.45
0.4
0.35
0
1
2
3
4
5
6
7
x10^{21} POT
$\upsilon_{postfit}/\upsilon_{prefit}$
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0
1
2
3
4
5
6
7
x10^{21} POT

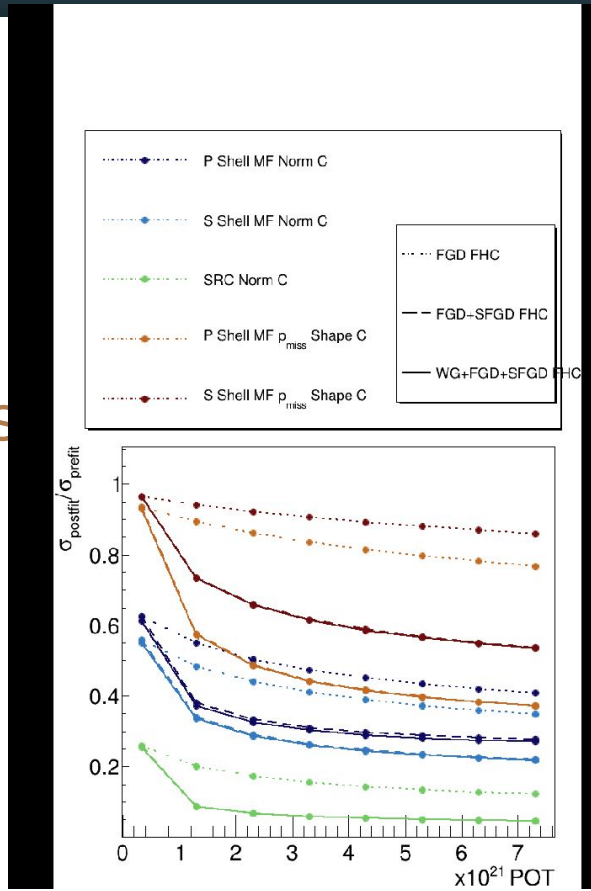
OC Correlations

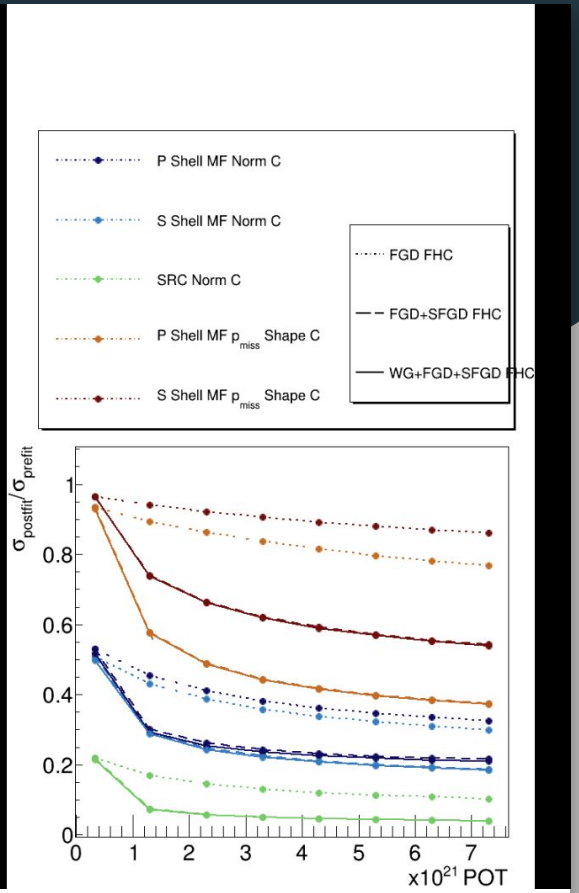
- 30% correlations between SF parameters
- For some reason carbon is more constrained in fit
- There seems to be a threshold where constraints are larger then when there are no correlations, have to further investigate

SF O: before After correlations 30%

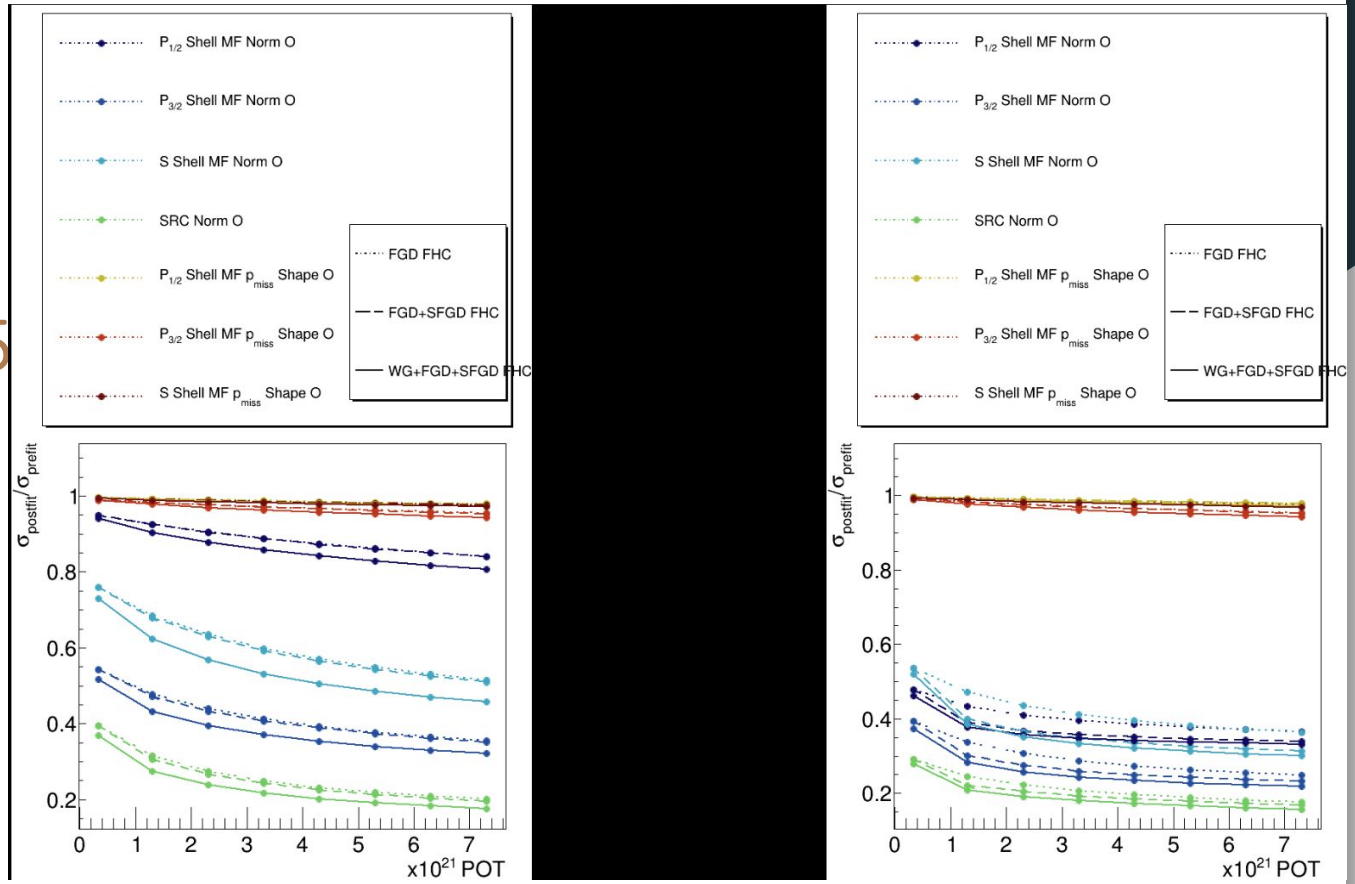


SF C: before after Correlations 30%

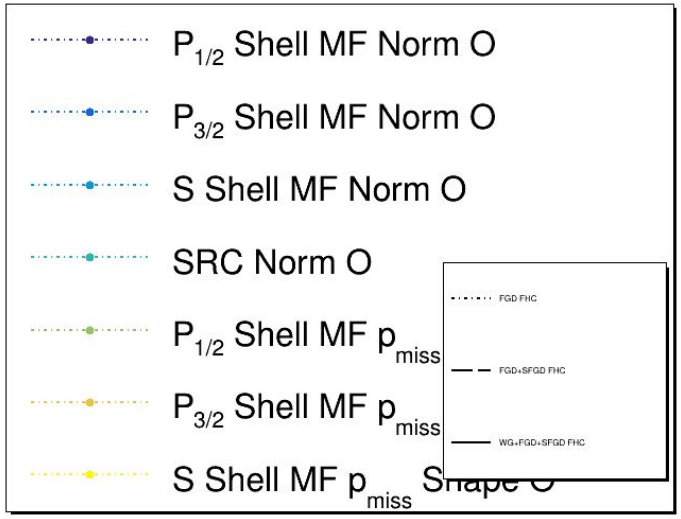


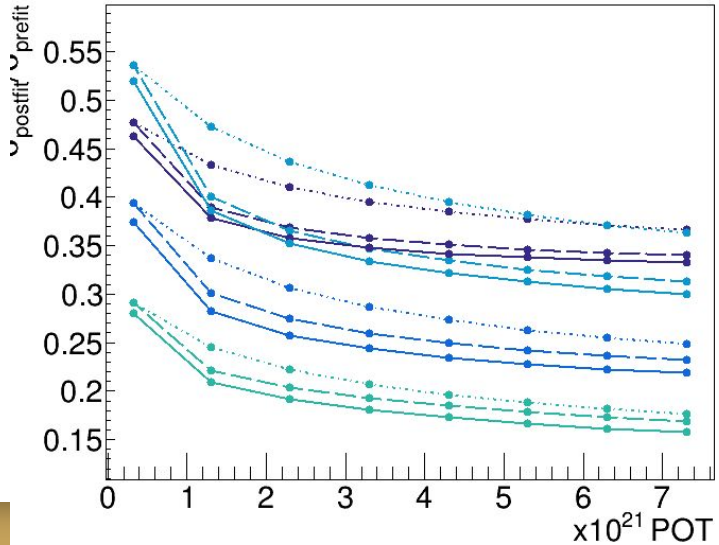


SF O: before after correlations 95

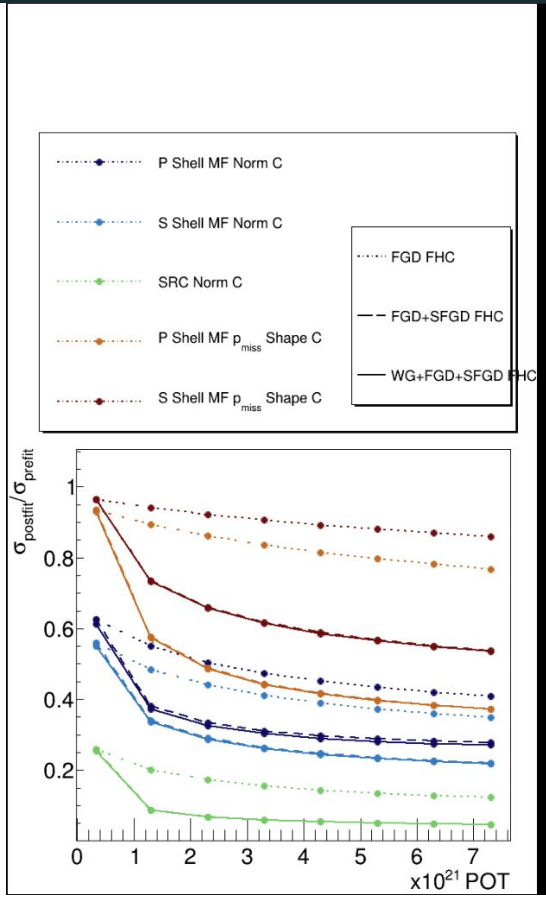


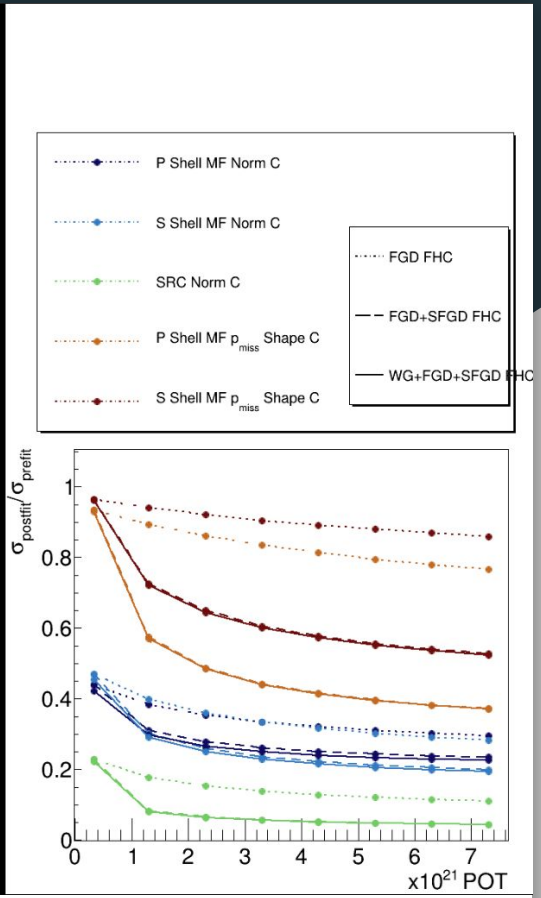
ZOOM

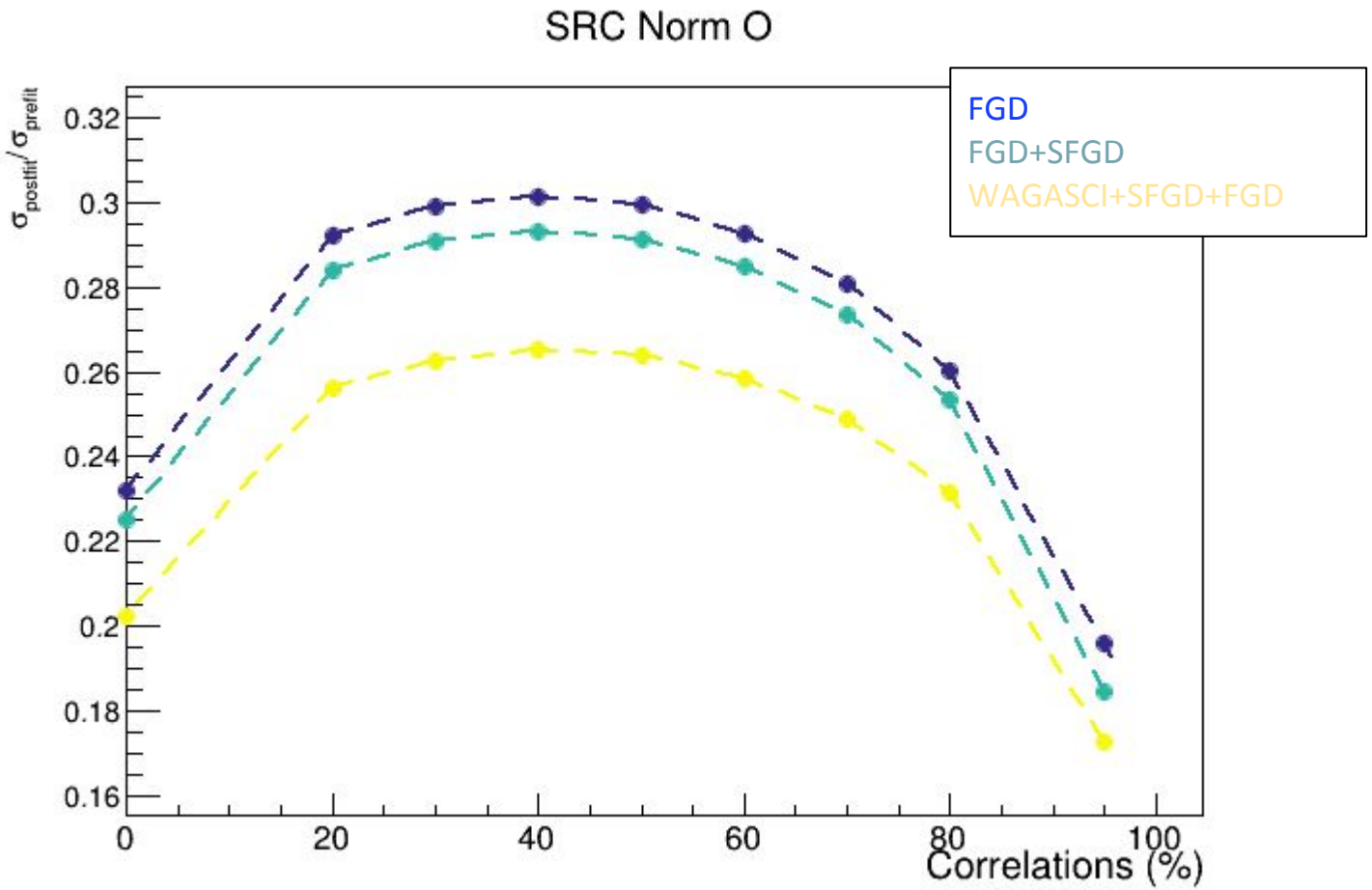

$P_{1/2}$ Shell MF Norm O
$P_{3/2}$ Shell MF Norm O
S Shell MF Norm O
SRC Norm O
$P_{1/2}$ Shell MF p_{miss}
$P_{3/2}$ Shell MF p_{miss}
S Shell MF p_{miss} Shape O
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC

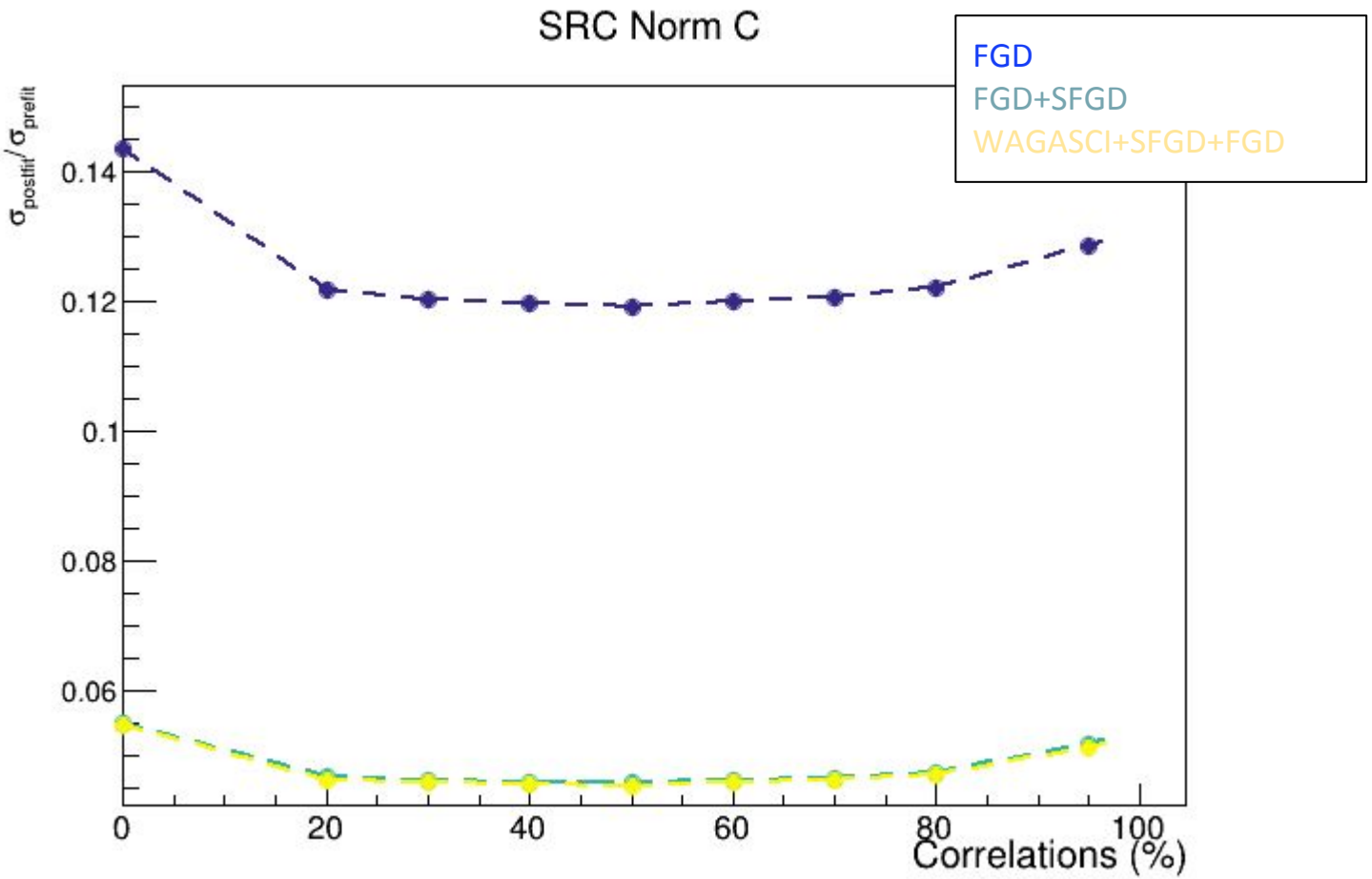

$\nu_{postfit}/\nu_{prefit}$
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0
1
2
3
4
5
6
7
$x10^{21}$ POT

SF C: before after correlations 95%






SRC Norm O
FGD
FGD+SFGD
WAGASCI+SFGD+FGD
$\sigma_{postfit}/\sigma_{prefit}$
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0
20
40
60
80
100
Correlations (%)


SRC Norm C
FGD
FGD+SFGD
WAGASCI+SFGD+FGD
$\sigma_{postfit}/\sigma_{prefit}$
0.14
0.12
0.1
0.08
0.06
0
20
40
60
80
100
Correlations (%)

Conclusion

- The addition of WAGASCI in OA is definitely achievable: Inputs for sensitivity study ready and working
- Further work on the selection could give more promising results
- **Goal:** show ~complete results (with current selection) by next CM to motivate additional work around WAGASCI implementation in Highland and reconstruction/selection improvements

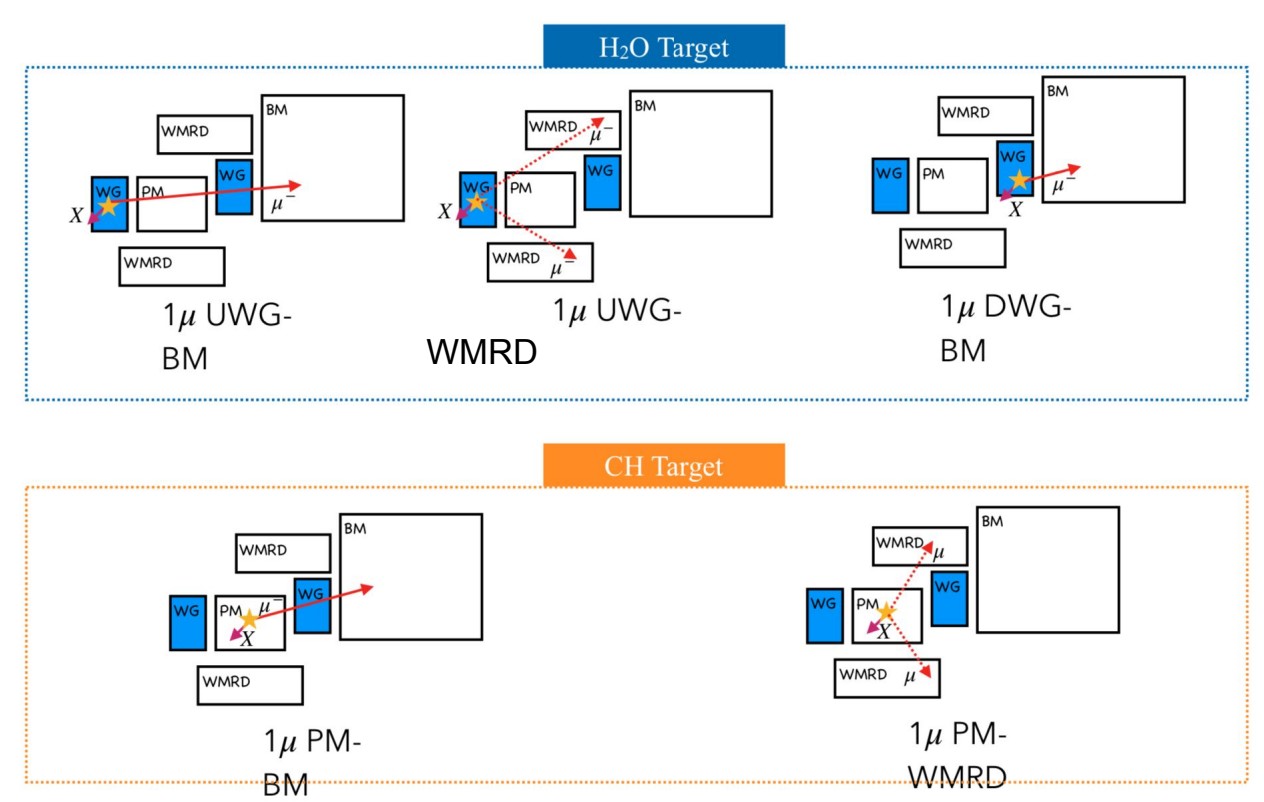
What's next?

- We will need a new flux covariance matrix with the same format as OA
- Ideally we would also like to propagate this to **SK** (ptheta)
- I'm planning to join the effort (Kenji, Cesar, John, Honjo-san,...) to improve current *WAGASCI reconstruction* (proton? Mom. by curvature?) and *selection*

BACK UP

Integrating WAGASCI samples for the OA

WAGASCI Samples



- Using samples defined by Kenji for his CC0pi xsec analysis (see his slides for more details)
- WAGASCI: 3 CC0pi + 1 CC1pi
- Proton module: 2 CC0pi + 1 CC1pi

https://www.t2k.org/nd280/physics/xsec/subgroup/mse-fdmc/2022/lsameeting_oct31/wagasci-babymind-lsa

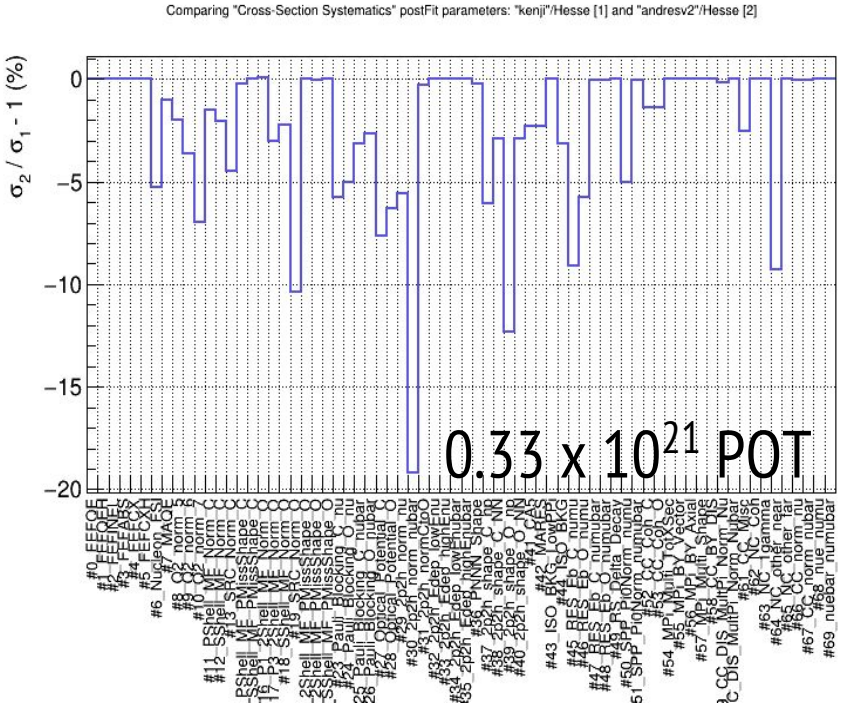
Generic fitter for Upgraded Near Detector Analysis Methods (GUNDAM)

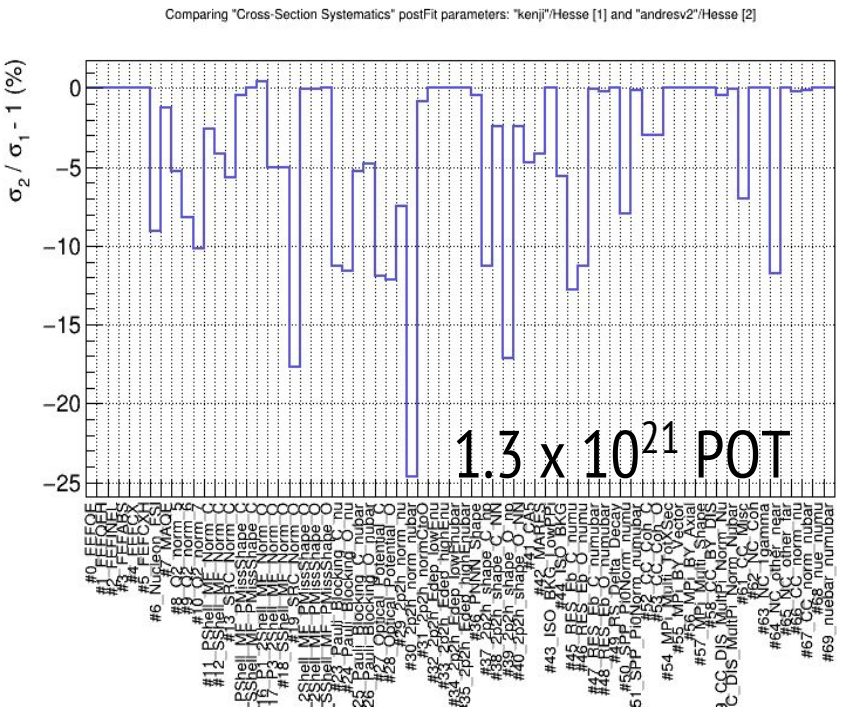
- Fitter framework for the next statistical analysis of T2K
  - Suite of applications for statistical analysis developed for ND280 upgrade
  - Is becoming the official fitter for ND fit (OA) and cross section analyses
- Framework designed to host multiple analysis using JSON/YAML configuration file for better traceability and validation of output ⟶ inputs easily shared
- Open source (LGPL) C++ code based on ROOT publicly available on GitHub
- First part was integrating WAGASCI samples into GUNDAM
- Development of readable inputs (from Kenji's xsec inputs)

New binning scheme

- Kenji's binning scheme adapted to his *Cross Section analysis*, only 1D in Pmu or Costhetamu
- Decided on a 2D binning that is more suitable to constrain systematic parameters
- **Idea**: make binnings where each bin has at least ~10 events per bin while taking into account detector resolution et reconstruction efficiency, see Kenji's TN https://www.t2k.org/nd280/physics/xsec/xsecreviews/T2K-TN-455/review_for_fitter_method_fake_data_study/version_0_1_4/view

Hesse post fit XSEC error ratio: 1D vs 2D binning





σ_1 = Kenji's 1D binning
σ_2 = My 2D binning

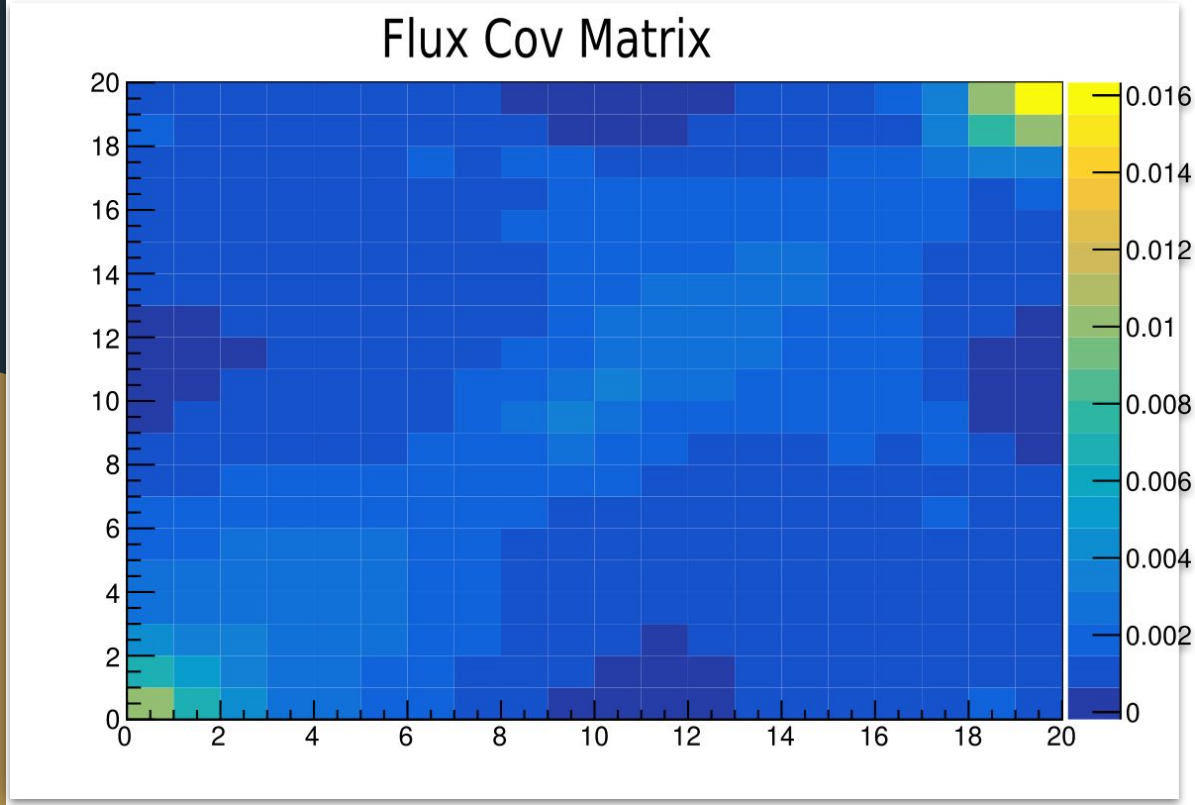
Better constraint with the new (2D) binning!

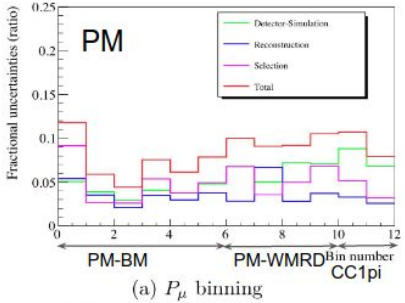
First fits with WAGASCI samples with GUNDAM

WAGASCI fit

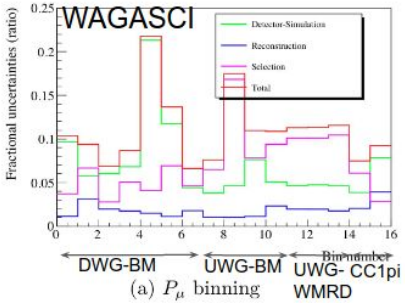
- Using Kenji's flux matrix (used in his xsec analysis)
- Cross-Section parameters same as in OA2022 (spline via WAGASCIReweight)
- Selected could be better adapted to current studies
- Detector smearing implemented directly in likelihood calculations (using detector performances in Kenji's TN https://www.t2k.org/nd280/physics/xsec/xsecreviews/T2K-TN-455/review_for_fitter_method_fake_data_study/version_0_1_4/view)
- Integration in GUNDAM complete and ready for future analysis

WAGASCI fit





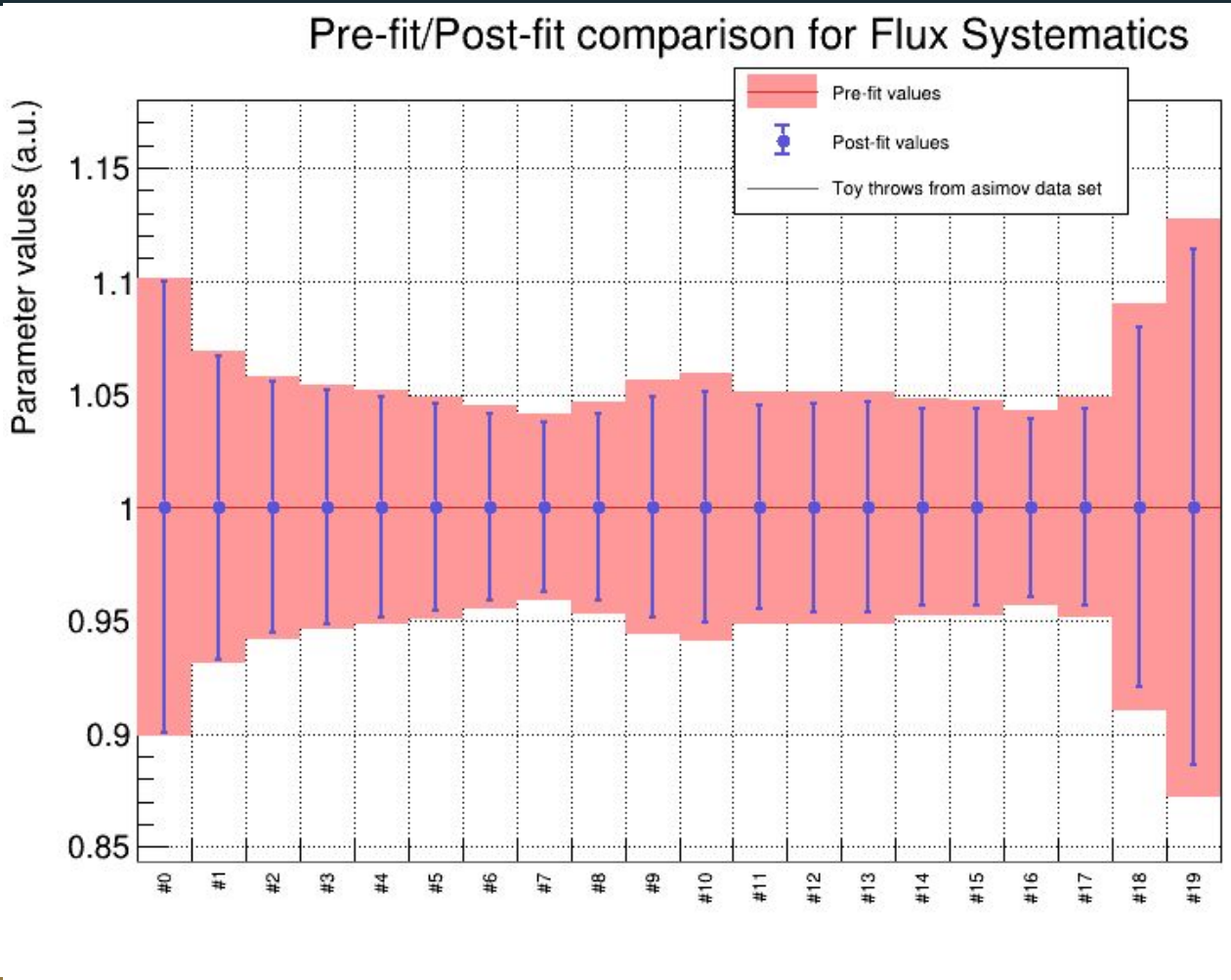
(a) P_μ binning



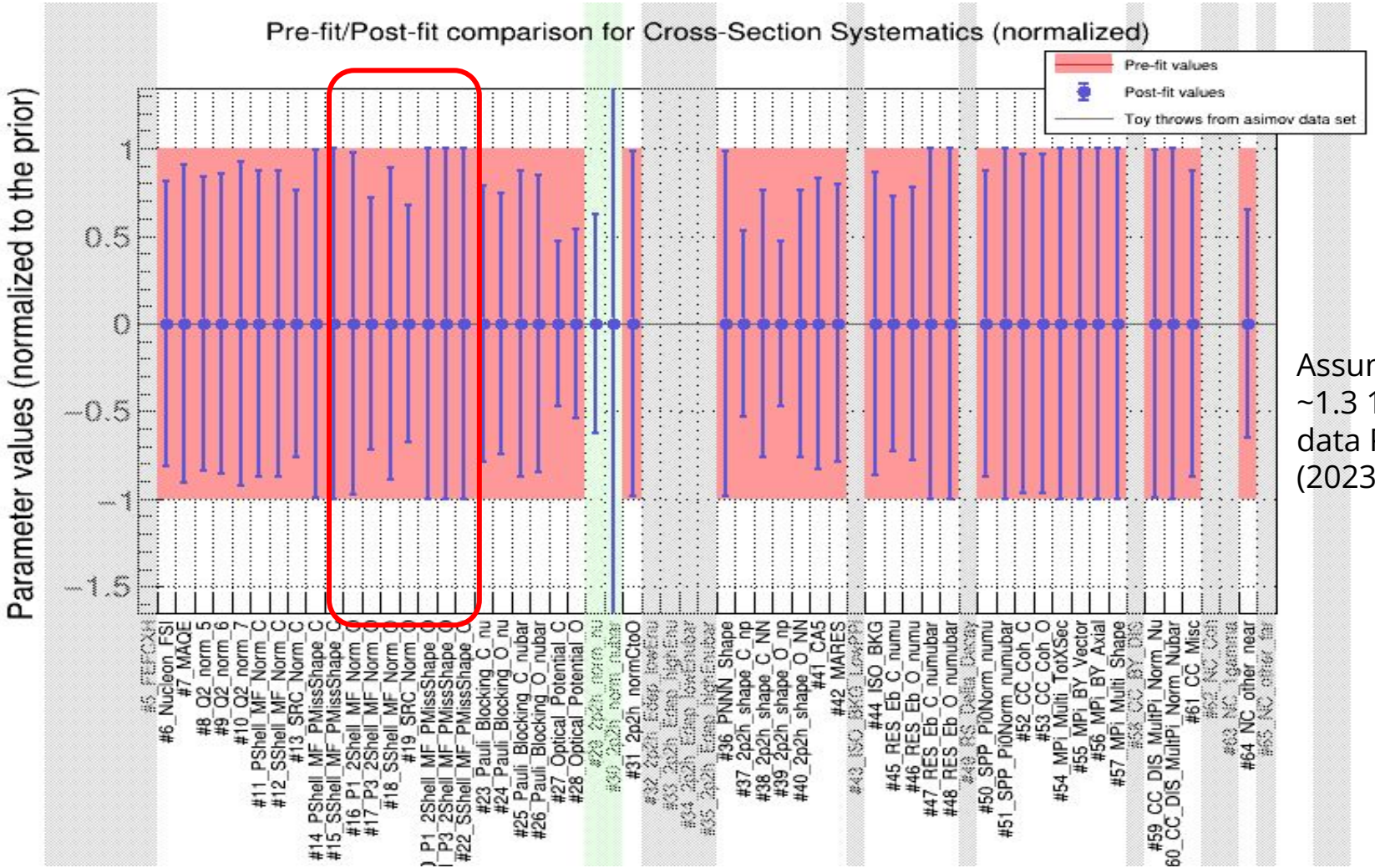
(a) P_μ binning

For sensitivity studies we can start by applying a *~10% smearing factor* on WAGASCI and PM samples

Flux

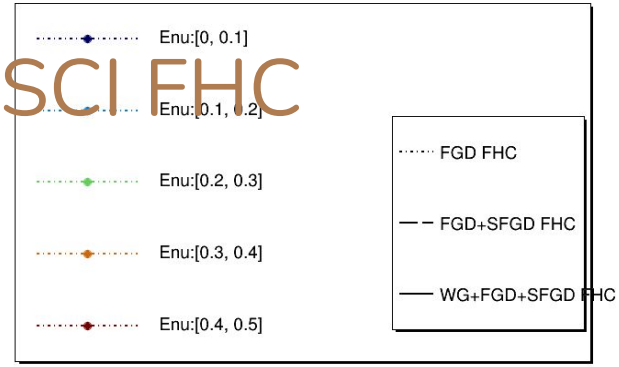


Assuming ~1.3 10^{21} data POT (2023 stat)



Assuming ~1.3 10^{21} data POT (2023 stat)

WAGASCI FHC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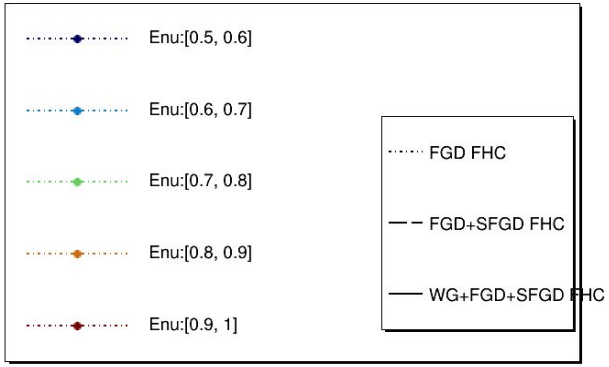
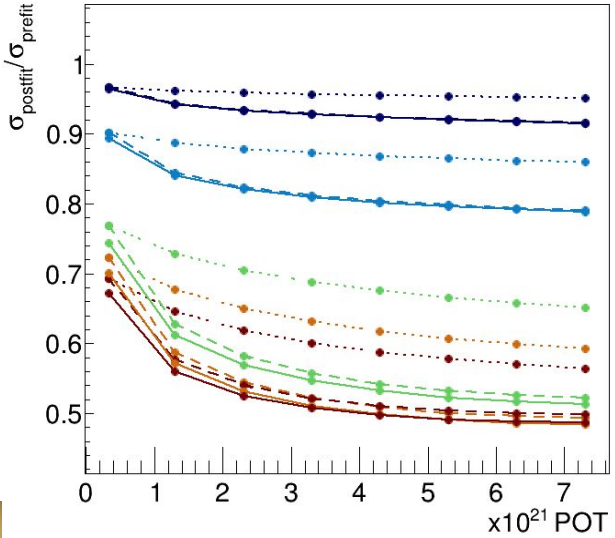
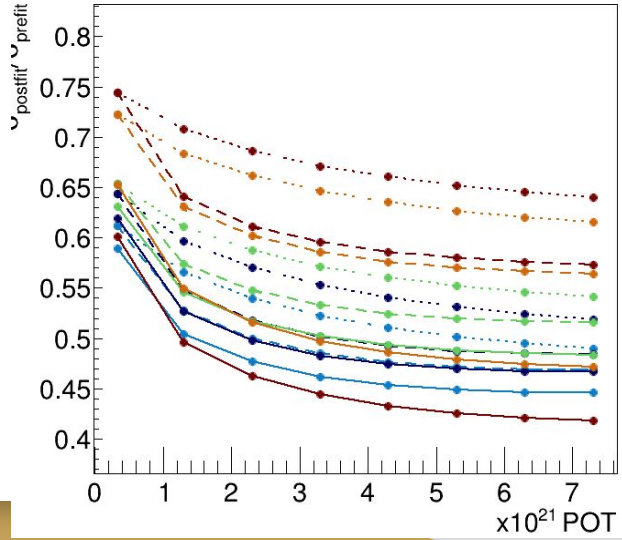
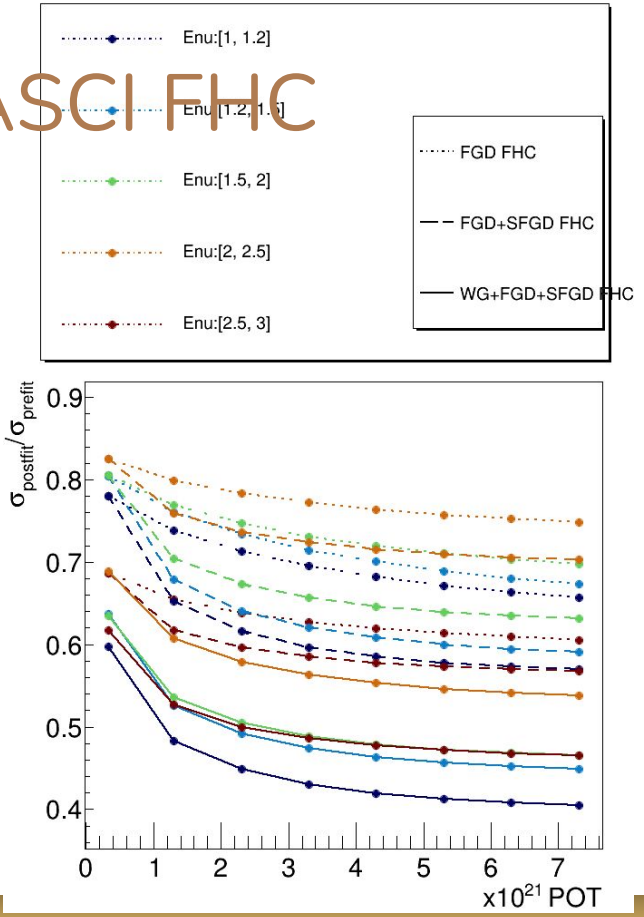
Enu:[0.1, 0.2]
Enu:[0.2, 0.3]
Enu:[0.3, 0.4]
Enu:[0.4, 0.5]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC

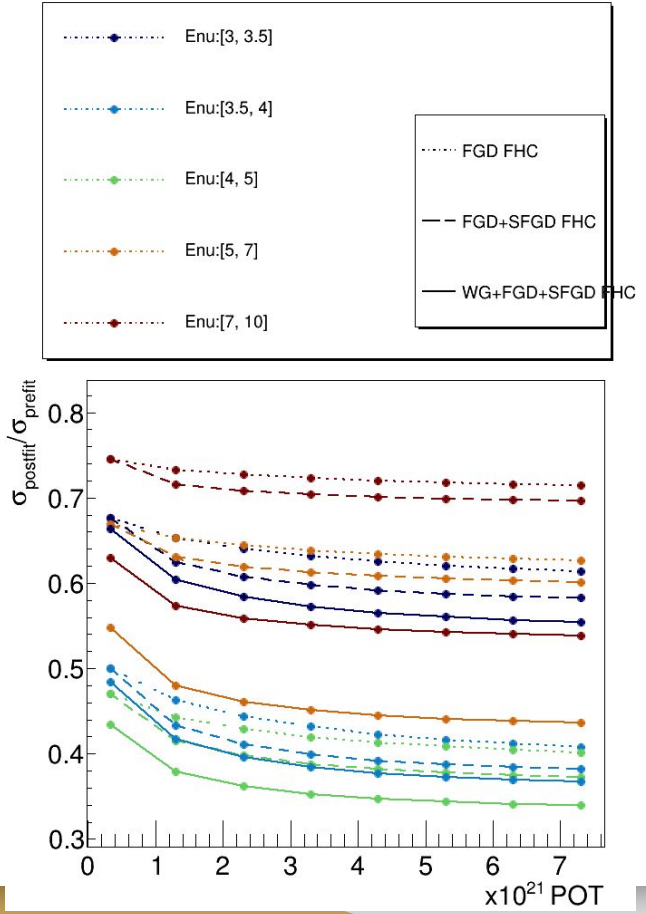

Enu:[0.5, 0.6]
Enu:[0.6, 0.7]
Enu:[0.7, 0.8]
Enu:[0.8, 0.9]
Enu:[0.9, 1]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC


σpostfit/σprefit
1
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
5
6
7
x10^21 POT

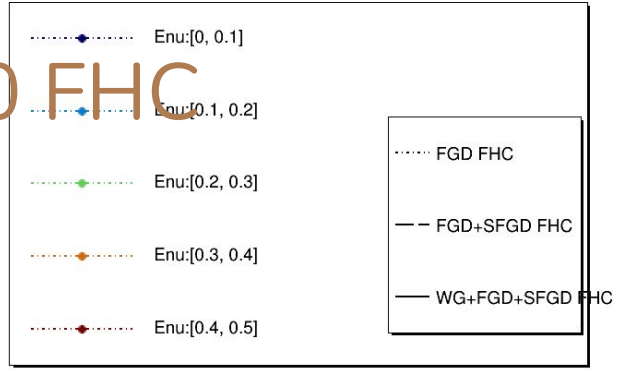

υpostfit/υprefit
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0
1
2
3
4
5
6
7
x10^21 POT

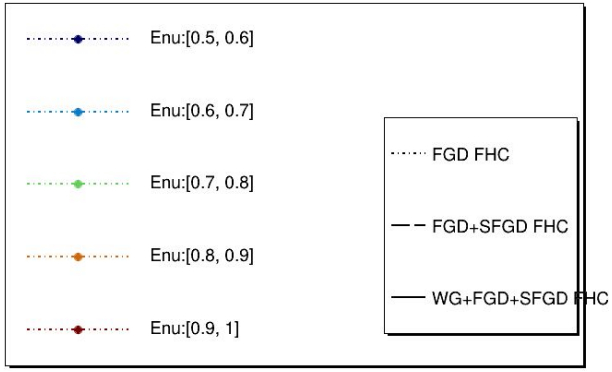
WAGASCI FHC

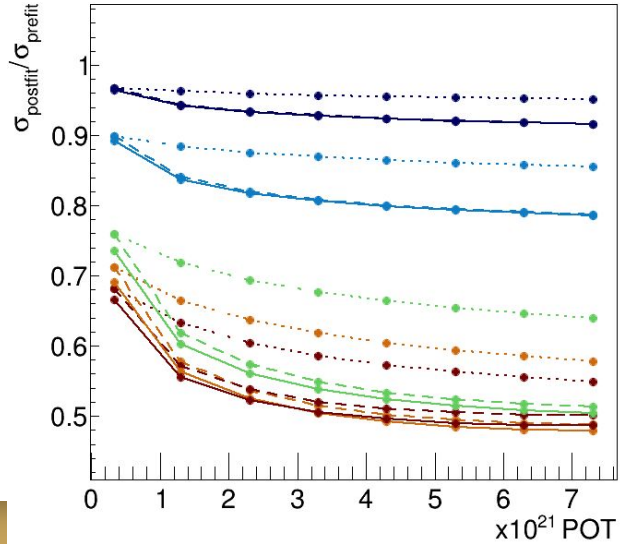

Enu:[1, 1.2]
Enu:[1.2, 1.5]
Enu:[1.5, 2]
Enu:[2, 2.5]
Enu:[2.5, 3]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{postfit}/\sigma_{prefit}$
0.9
0.8
0.7
0.6
0.5
0.4
0
1
2
3
4
5
6
7
x10^{21} POT

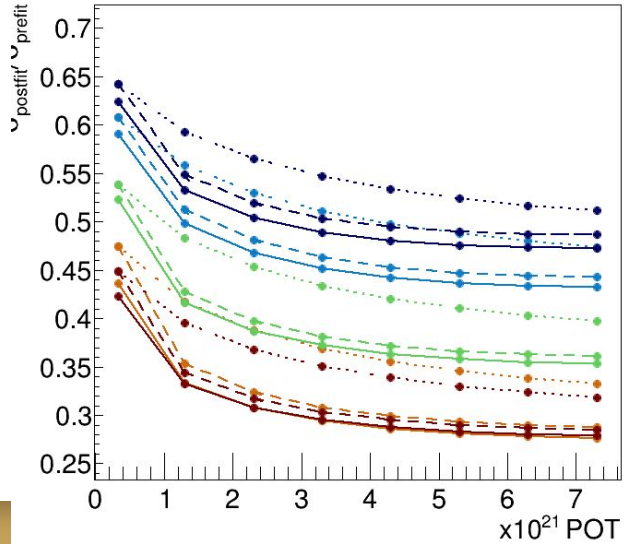

Enu:[3, 3.5]
Enu:[3.5, 4]
Enu:[4, 5]
Enu:[5, 7]
Enu:[7, 10]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{postfit}/\sigma_{prefit}$
0.8
0.7
0.6
0.5
0.4
0.3
0
1
2
3
4
5
6
7
x10^{21} POT

ND280 FHC

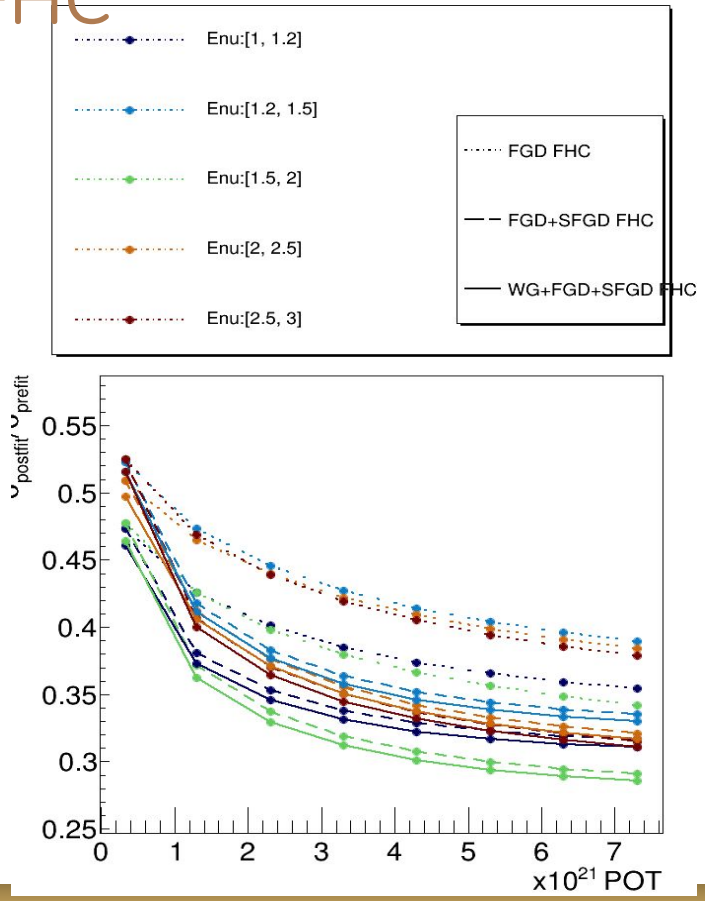

Enu:[0, 0.1]
Enu:[0.1, 0.2]
Enu:[0.2, 0.3]
Enu:[0.3, 0.4]
Enu:[0.4, 0.5]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC

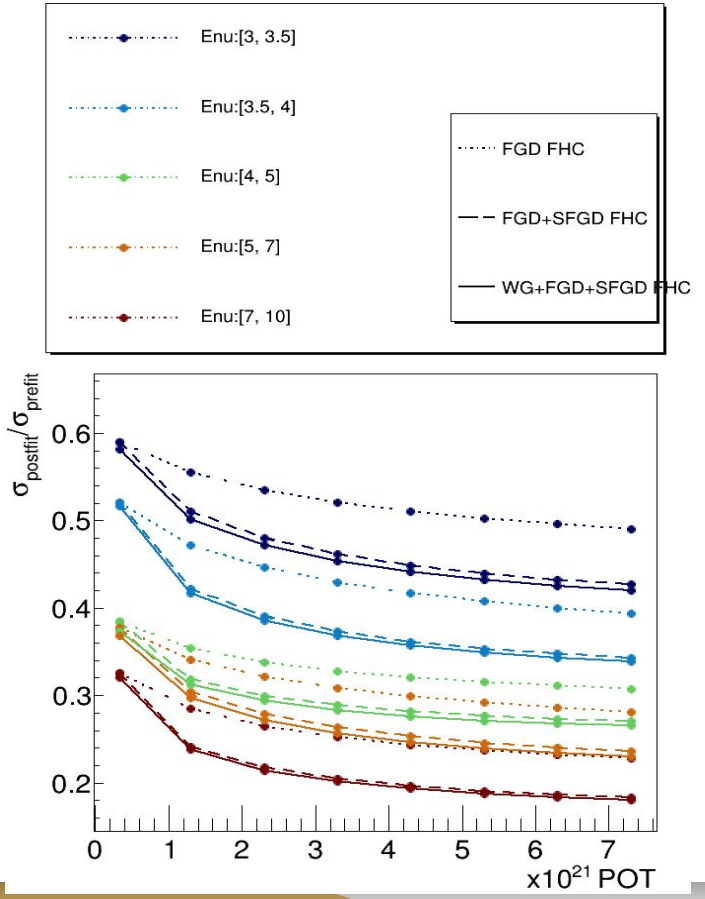

Enu:[0.5, 0.6]
Enu:[0.6, 0.7]
Enu:[0.7, 0.8]
Enu:[0.8, 0.9]
Enu:[0.9, 1]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC


σposttit/σprefit
1
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
5
6
7
x10^21 POT


υposttit/υprefit
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0
1
2
3
4
5
6
7
x10^21 POT

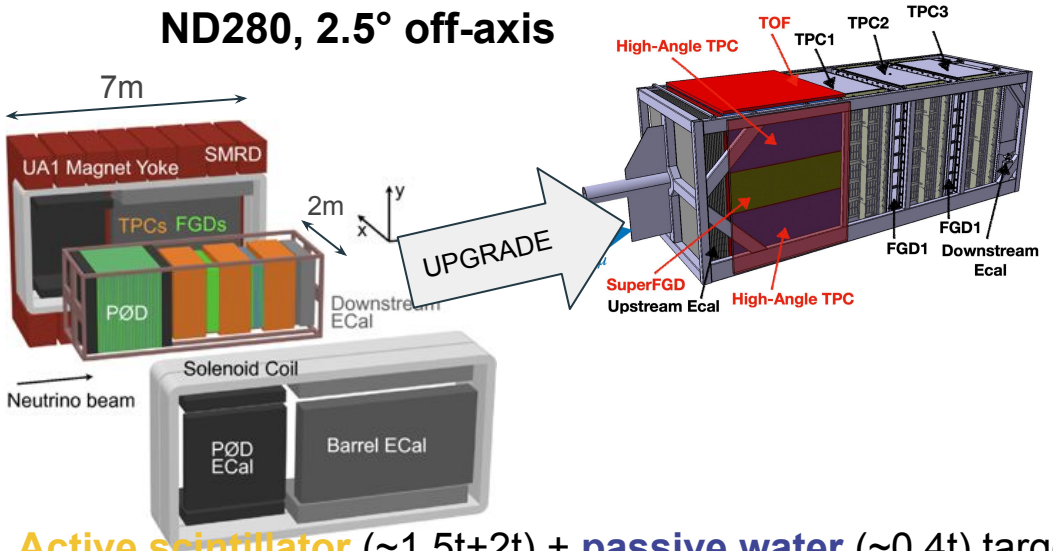
ND280 FHC


Enu:[1, 1.2]
Enu:[1.2, 1.5]
Enu:[1.5, 2]
Enu:[2, 2.5]
Enu:[2.5, 3]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\nu_{posttit}/\nu_{prefit}$
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0
1
2
3
4
5
6
7
x10^21 POT


Enu:[3, 3.5]
Enu:[3.5, 4]
Enu:[4, 5]
Enu:[5, 7]
Enu:[7, 10]
FGD FHC
FGD+SFGD FHC
WG+FGD+SFGD FHC
$\sigma_{posttit}/\sigma_{prefit}$
0.6
0.5
0.4
0.3
0.2
0
1
2
3
4
5
6
7
x10^21 POT

REMINDER: T2K off-axis near detectors

ND280, 2.5° off-axis



Active scintillator (~1.5t+2t) + **passive water** (~0.4t) targets

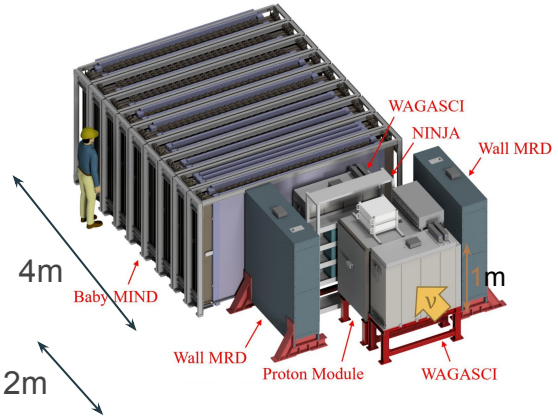
Tracking with 3 **TPC**

Magnetized for charge and momentum measurements

Ecal to distinguish tracks from showers

Used for OA and xsec measurements

WAGASCI, 1.5° off-axis



Recently added (2019)

Segmented cubic CH/H_2O (WAGASCI) and SMRD+BabyMIND

Magnetized detector

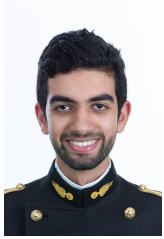
Made **of ~0.2t-1t water** and ~0.5t of CH target

Sensitivity at the ND

FGD1+2 : Current ND fit, no additional samples

SFGD+FGD1+2 μ only : Add to current ND fit SFGD samples binned in lepton kinematics

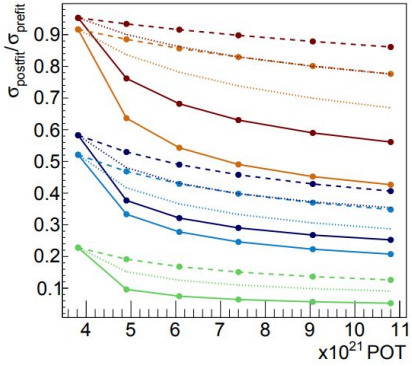
SFGD+FGD1+2 μ+N : Add to current ND fit SFGD samples binned in (Evis, δp_T)



J. Chakrani

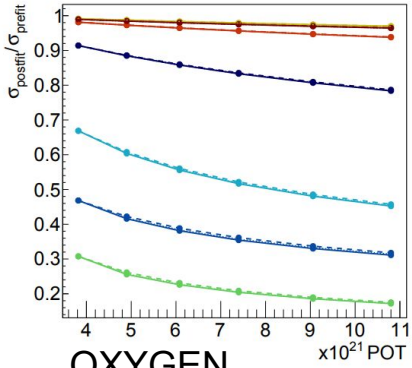
CCQE parameters,
no O/C correlation

- P Shell MF Norm C
- S Shell MF Norm C
- SRC Norm C
- P Shell MF p_{miss} Shape C
- S Shell MF p_{miss} Shape C



CARBON

- $P_{1/2}$ Shell MF Norm O
- $P_{3/2}$ Shell MF Norm O
- S Shell MF Norm O
- SRC Norm O
- $P_{1/2}$ Shell MF p_{miss} Shape O
- $P_{3/2}$ Shell MF p_{miss} Shape O
- S Shell MF p_{miss} Shape O



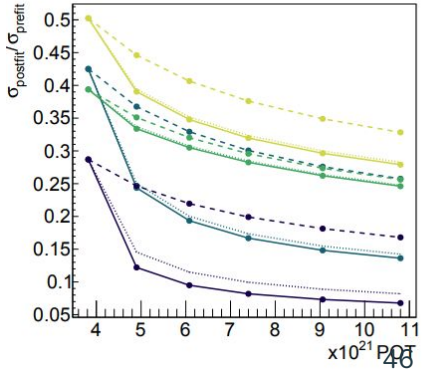
OXYGEN

The sensitivity to oxygen xsec systematics depends on the assumed O/C correlation

Adding SuperFGD (CH) events helps constraining oxygen systematics ONLY IF a prior correlation between O/C is known

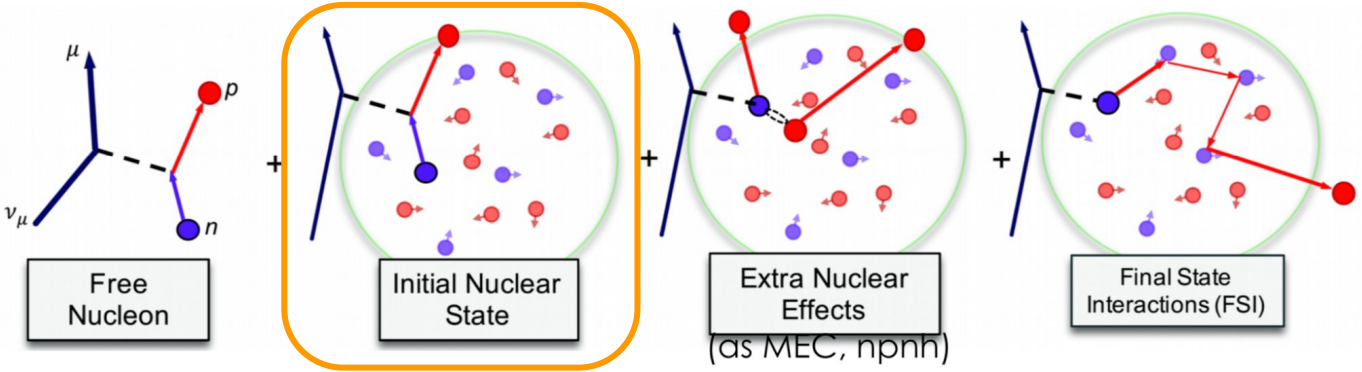
CCQE parameters,
O/C correlation (~70%)

- E_b C ν
- E_b C $\bar{\nu}$
- E_b O ν
- E_b O $\bar{\nu}$



Parametrized estimation of uncertainties for exclusive predictions of neutrino-nucleus scattering: Initial Nuclear State

Jaafar

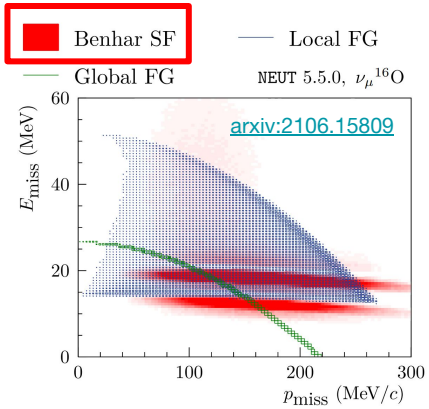


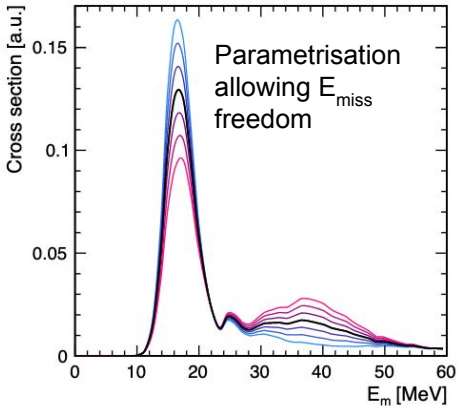
Parameterisation validated against existing xsec data

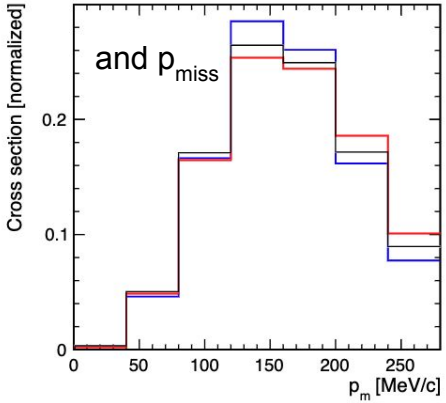
Used already in T2K OA 2022 and in Phys. Rev. D **105**, 032010 (2022)

Paper in preparation, expected in 2023

based on electron scattering data







Pauli blocking "threshold" variation