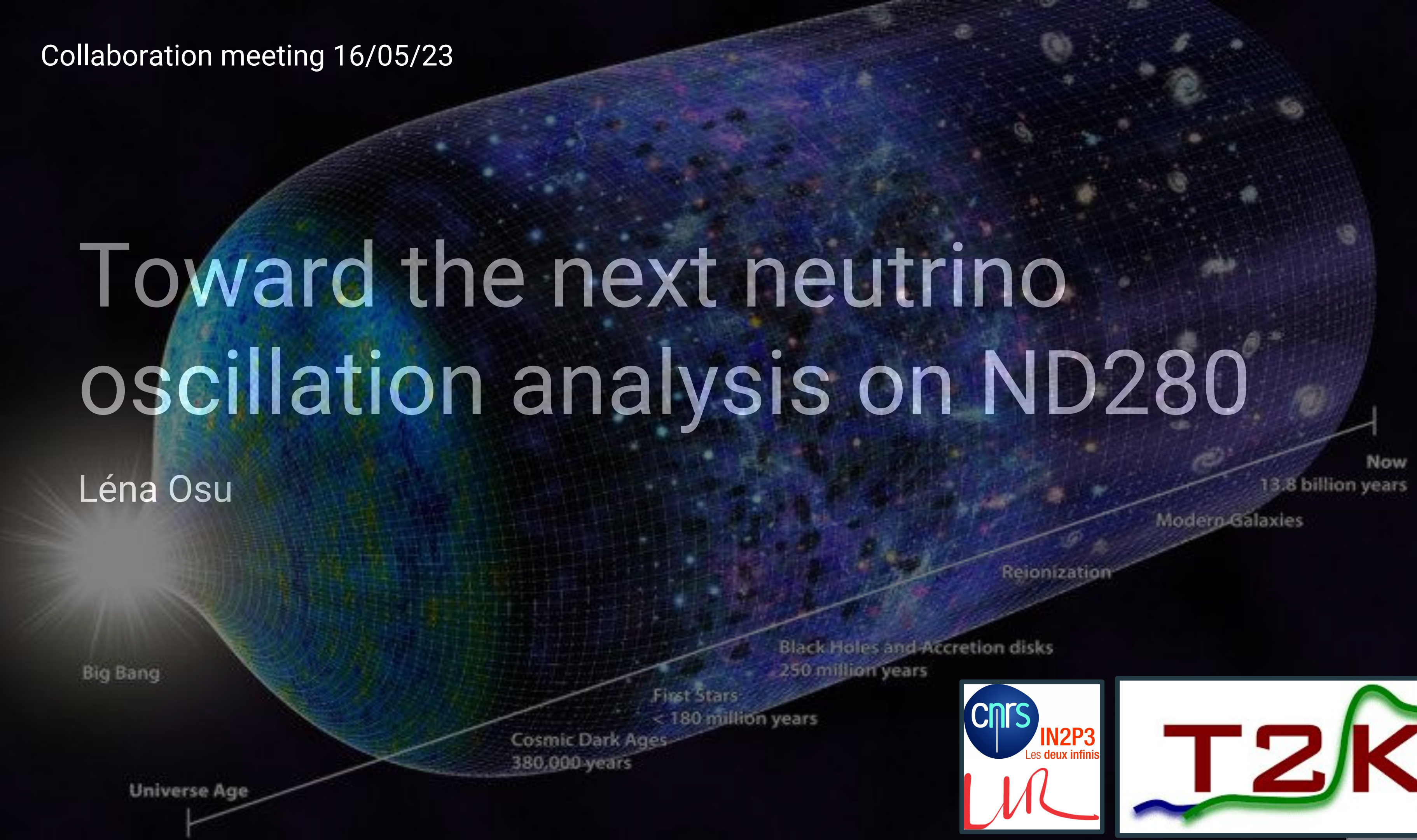
Collaboration meeting 16/05/23

Toward the next neutrino oscillation analysis on ND280

Léna Osu



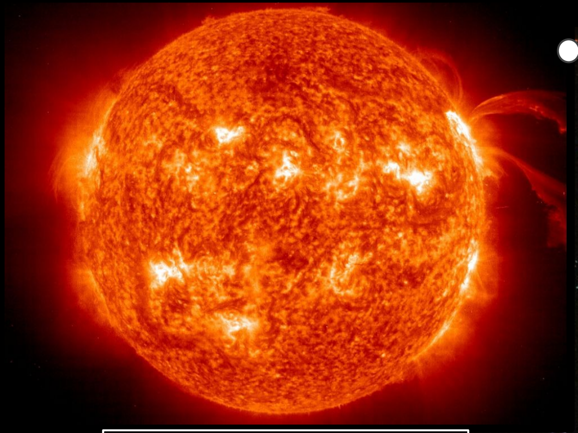
Summary

1. **T2K Experiment**
   1.1. Beam
   1.2. Flux prediction and uncertainties
   1.3. Cross-section Model
   1.4. ND280 Near Detector Fit

2. **GUNDAM Fitter**
   2.1. Some first tests with cuts on $\delta\alpha_t$
   2.2. Looking for instabilities on Hesse Minimizer (FLUX)
   2.3. Investigation to correct Hesse Flux instabilities

3. **New parameterization in GUNDAM**
   3.1. Dials types
   3.2. Likelihood comparison between GUNDAM & MaCh3
   3.3. Options for validation

4. **ND280 Upgrade and Electronic tests**
   4.1. Upgrade and FEB tests
   4.2. Conclusion



- Nuclear fusion in the Sun

$4p^{+} \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_{e}$

A major key to understand better early ages of the Universe !!

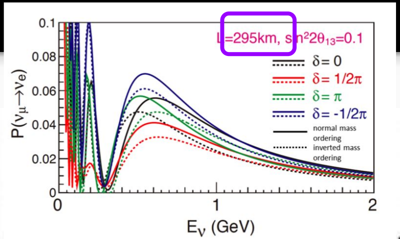
$P(\nu_{\mu} \rightarrow \nu_{\mu}) \simeq 1 - \sin^{2}(2\theta_{23})\sin^{2}(\Delta m^{2}_{32}L/4E)$

$P(\nu_{\mu} \rightarrow \nu_{e}) \simeq \sin^{2}(2\theta_{13})\sin^{2}(\theta_{23})\sin^{2}(\Delta m^{2}_{32}L/4E) \mp O(\sin\delta_{CP})$

$\pi^{+} \rightarrow \mu^{+} + \nu_{e}$
$\mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$

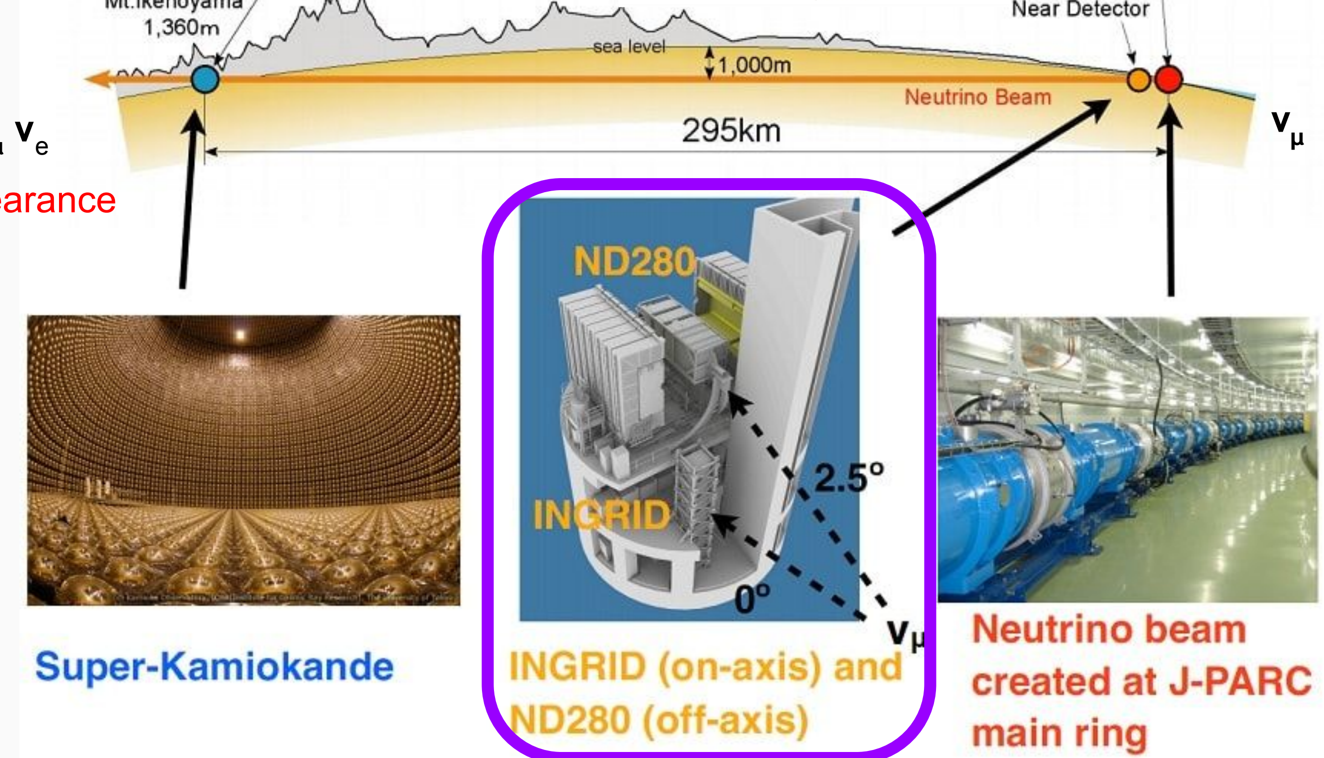
- Cosmic particles interaction with terrestrial atmosphere

T2K Experiment



ν_μ ν_e

ν_e appearance



ν_μ

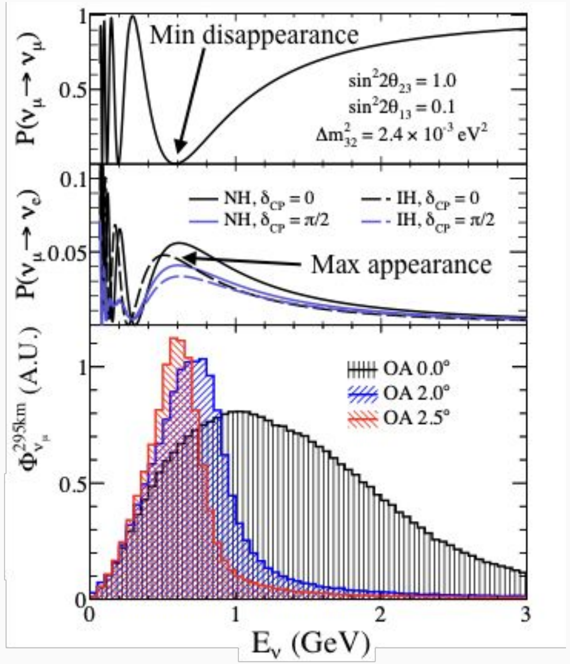
Beam

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x})\otimes\Phi(E_\nu)\otimes D^{far}(\vec{x})\otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x})\otimes\Phi(E_\nu)\otimes D^{near}(\vec{x})}$$

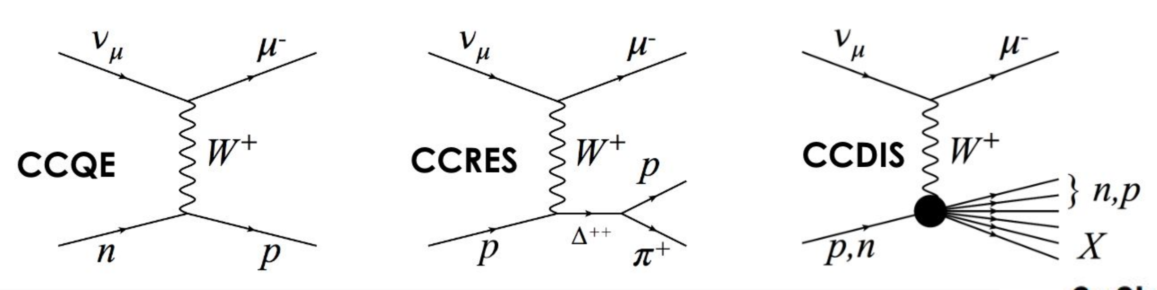
30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)

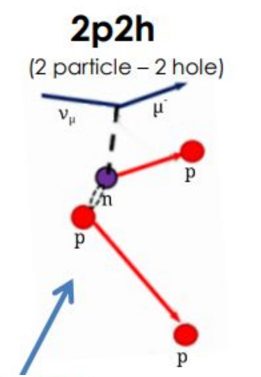
Hadrons are focused and selected in charge by 3 electromagnetic horns: **ν_μ beam created by π^+ and $\bar{\nu}_\mu$ beam by π^- decay**

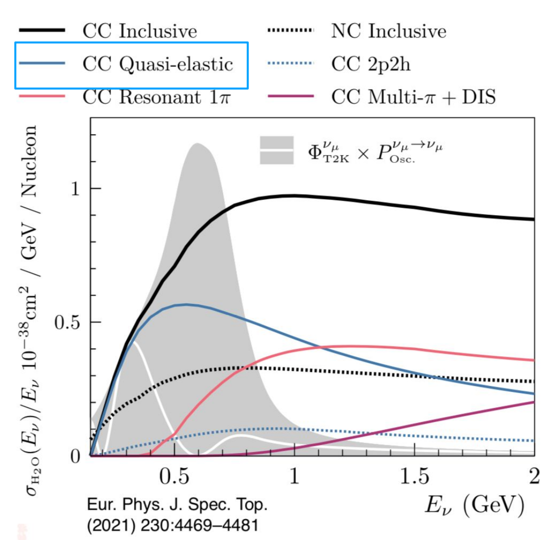
Detectors 2.5° off the direction of the beam centered around 0.6 GeV. **Off-axis method** reduce high energy tail and maximize oscillation detection probabilities



Cross-section model







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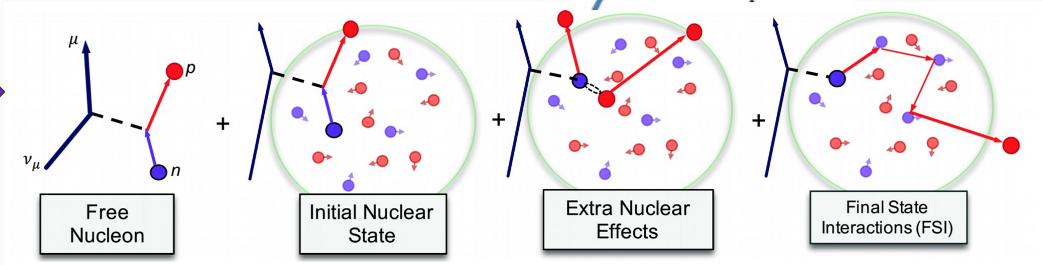
CCQE interactions are the dominant one at T2K energies.
Neutrino energy reconstruction is based on the CCQE assumption.
Ideally we want to select CCQE events, but nuclear effect play an important role

Frankenstein model

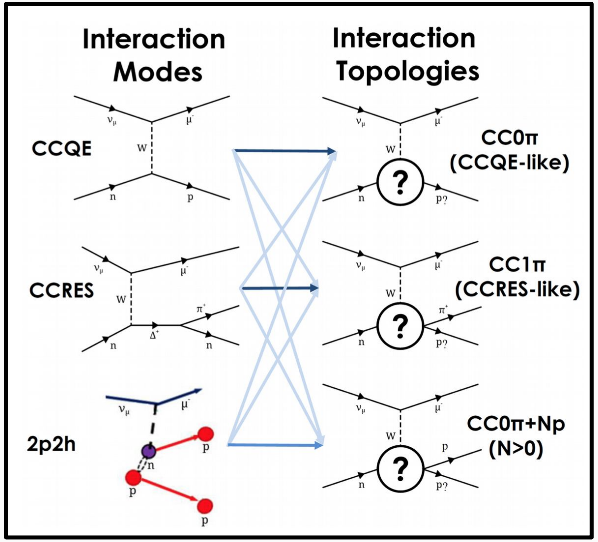
NUCLEAR EFFECTS



Cross-section model - Event selection

- Event selection based on the final state topology → limit model dependence

- CC0π mostly composed by CCQE, 2p2h, CCRes and Deep Inelastic Scattering events

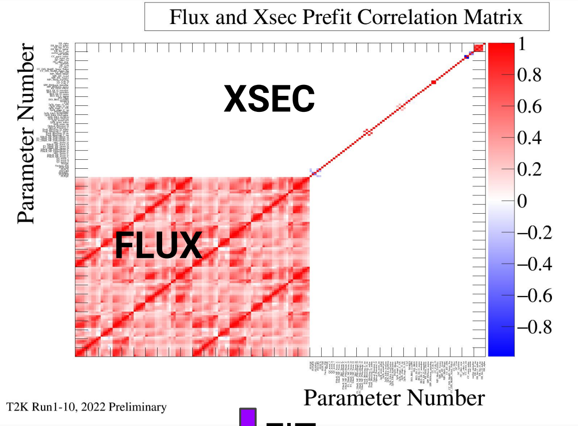


in CC0π

CCQE	2p2h	Res	DIS
80%	12%	8%	< 1%

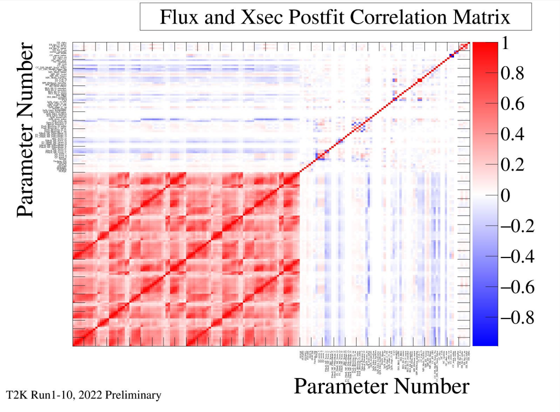
ND280 Near Detector fit

prefit

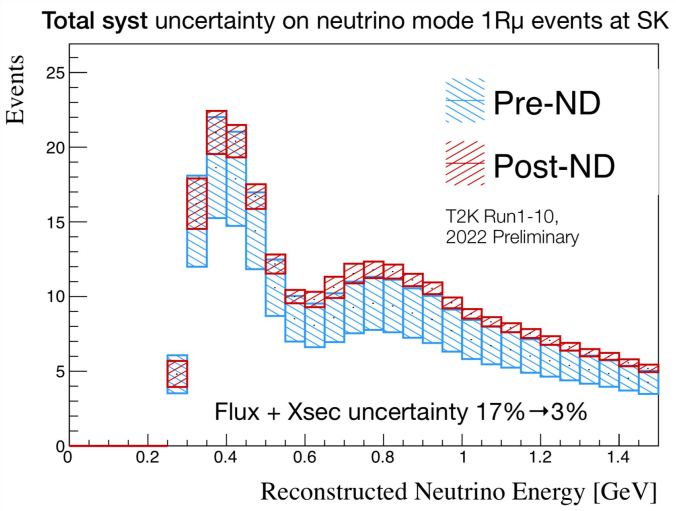


FIT

postfit



Prediction at Super-Kamiokande



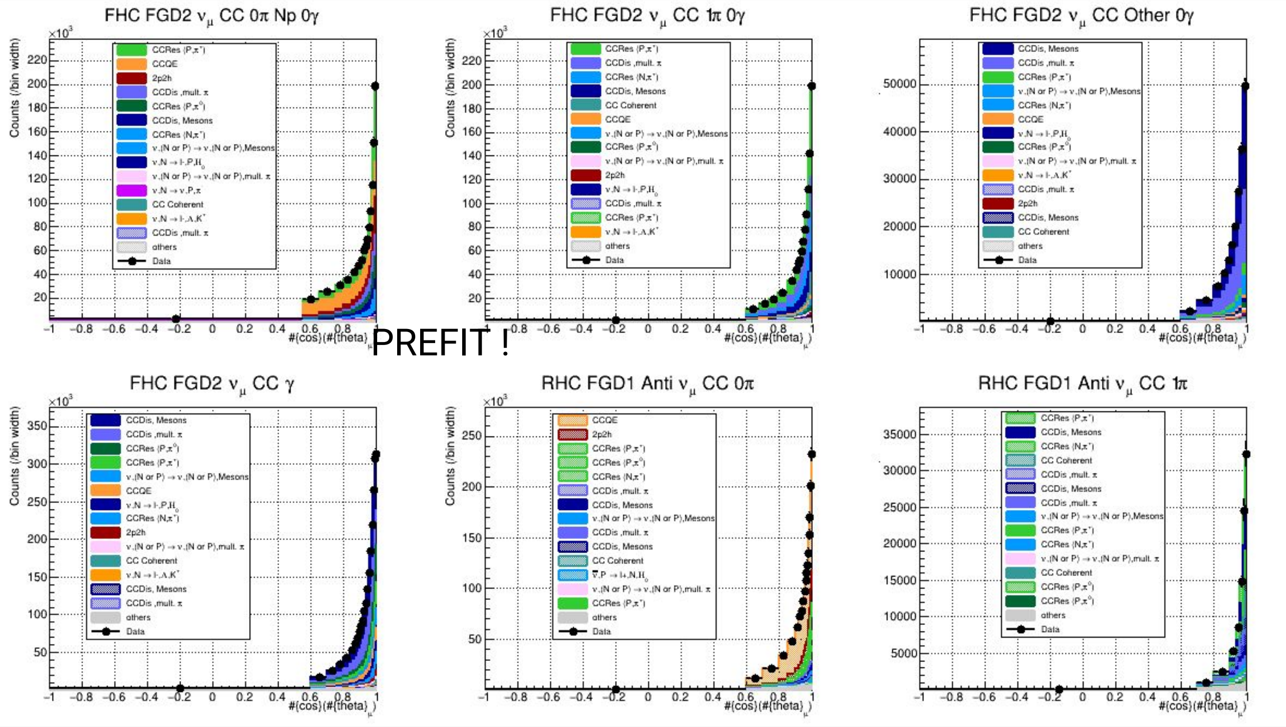
Flux & Xsec uncorrelated
Propagation of ND fits errors to SK

Flux and xsec uncertainties reduced from 17% to 3% !

ND280 Near Detector fit

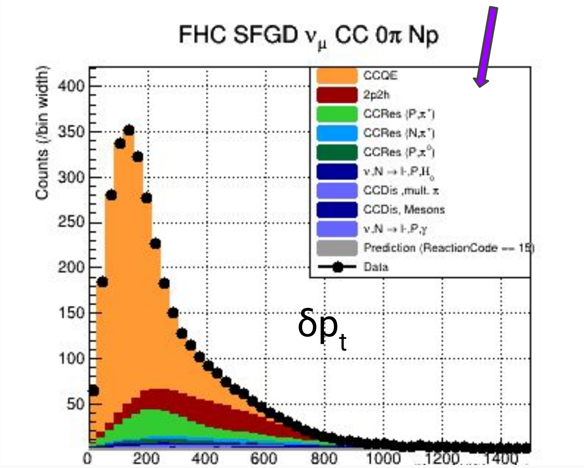
$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

22 samples right now (FGD1/FGD2), more to come



PREFIT !

Reaction Code



Gundam Fitter

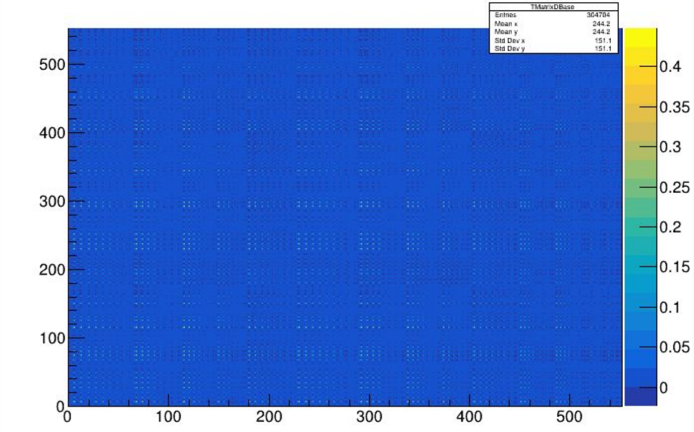
- GUNDAM = Generic fitter for Upgraded Near Detector Analysis Methods

take ND280 data and constraint Flux, Cross-section & Detector systematics

→ enable to evaluate post-fit errors on Flux, Cross-section and Detector systematics according POT year (until 2027)

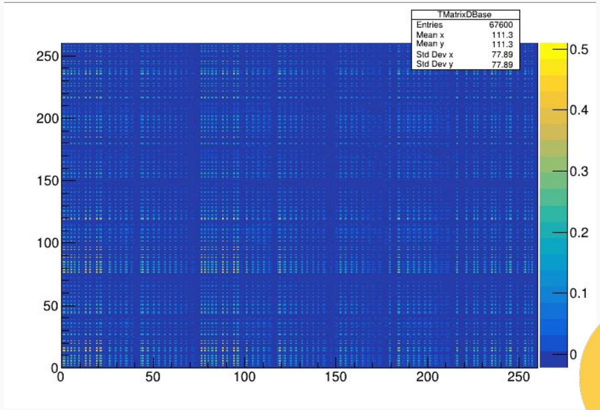
→ New parameterization of splined detector parameters (BANFF → GUNDAM // MaCh3 → GUNDAM)

Old Covariance detector matrix



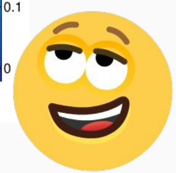
552 bins (too big !!)

New Covariance detector matrix

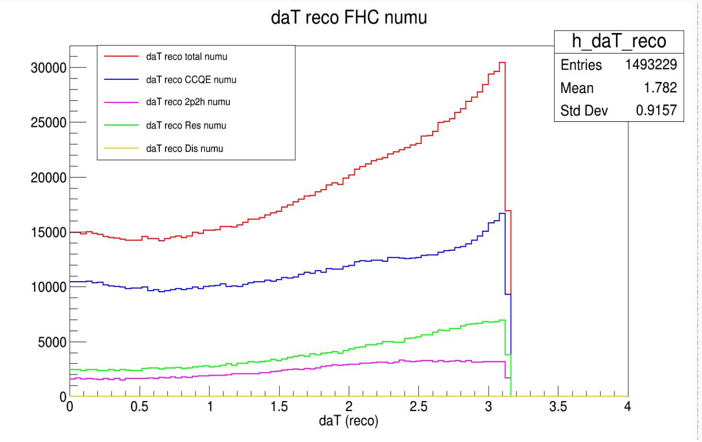


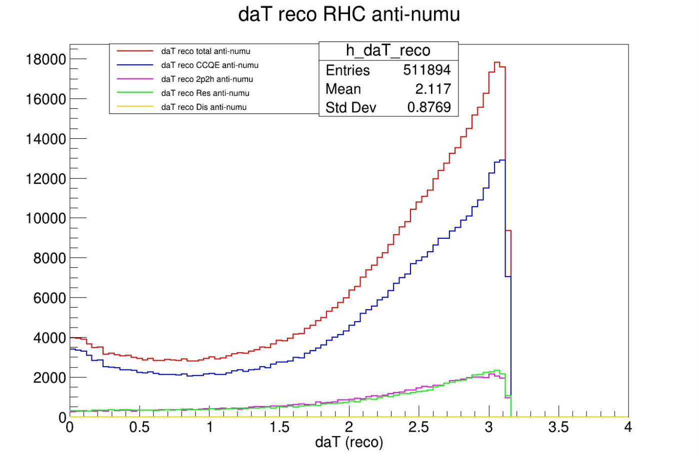
260 bins

+ 80 splined detector parameters for 2022 selections



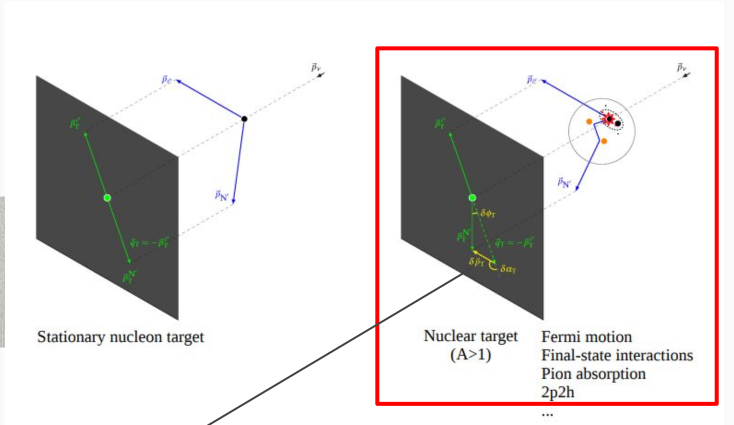
Some first tests with cuts on $\delta\alpha_t$

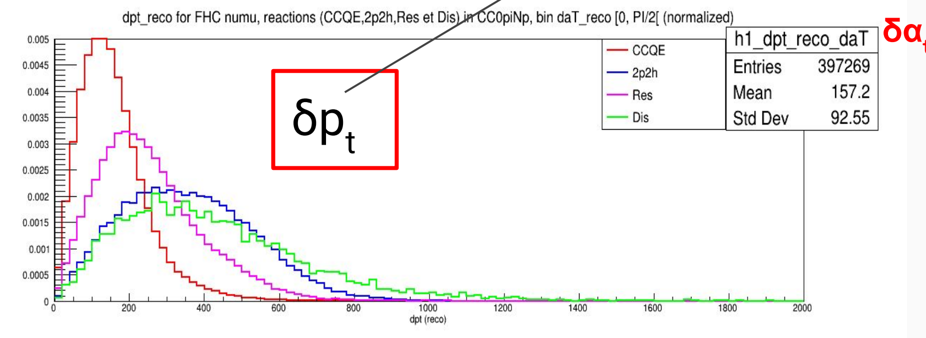




$$\delta p_T = |\vec{p}^{\,l}_T + \vec{p}^{\,p}_T|,$$

$$\delta\alpha_T = \arccos\frac{-\vec{p}^{\,l}_T \cdot \delta\vec{p}_T}{p^l_T\,\delta p_T},$$

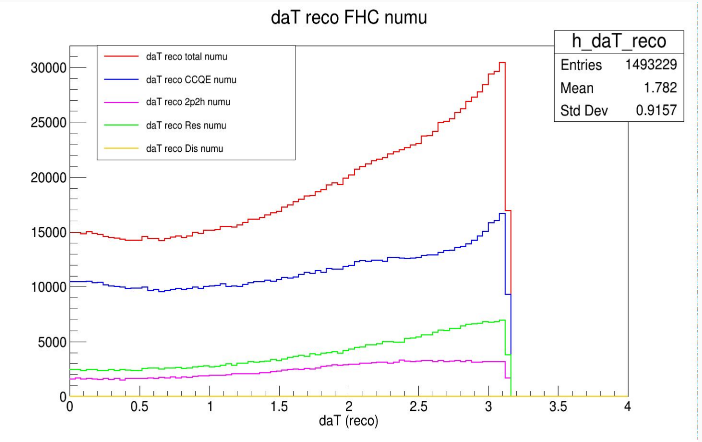


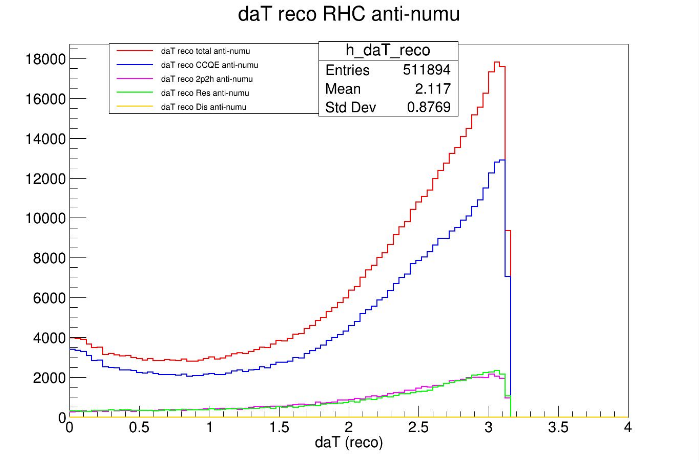


δp_t

$\delta\alpha_t$ = [0, π/2]

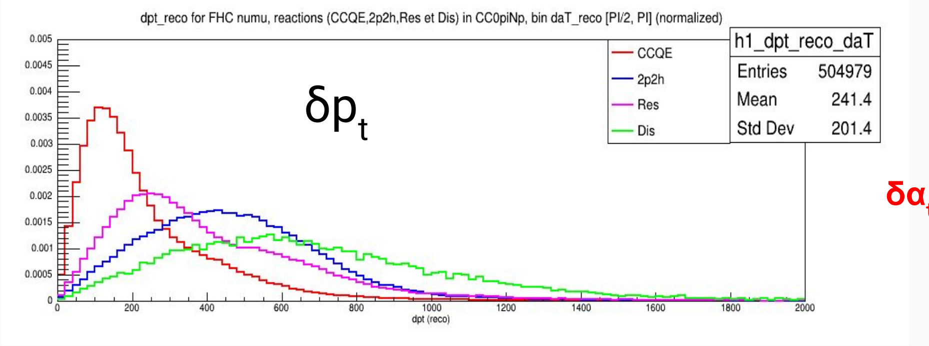
Some first tests with cuts on $\delta\alpha_t$





With High FSI when $\delta\alpha_t \rightarrow \pi$, $\Delta\delta p_t > 0$ & $\Delta E_{vis} < 0$

Simple cut on $\delta\alpha_t$ clearly impact δp_t & E_{vis}

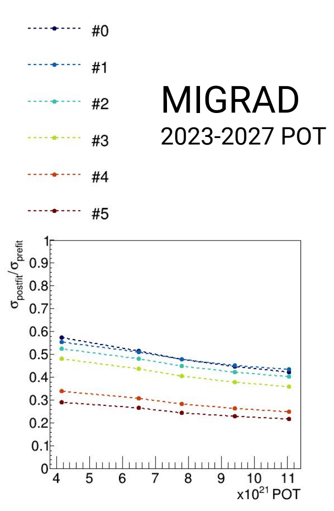


$\delta\alpha_t$ = [π/2, π]

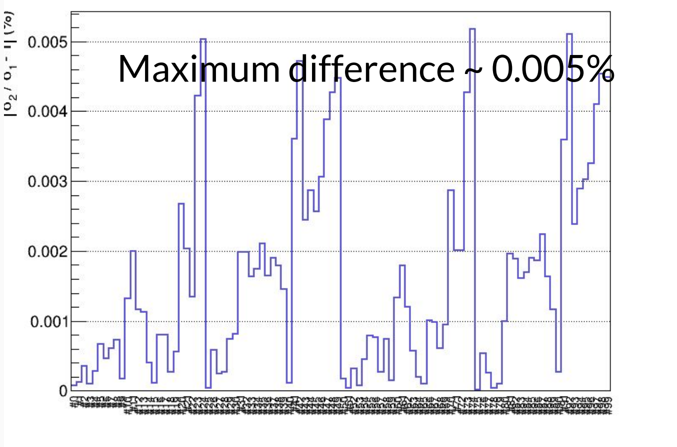
Looking for instabilities on Hesse Minimizer (FLUX)

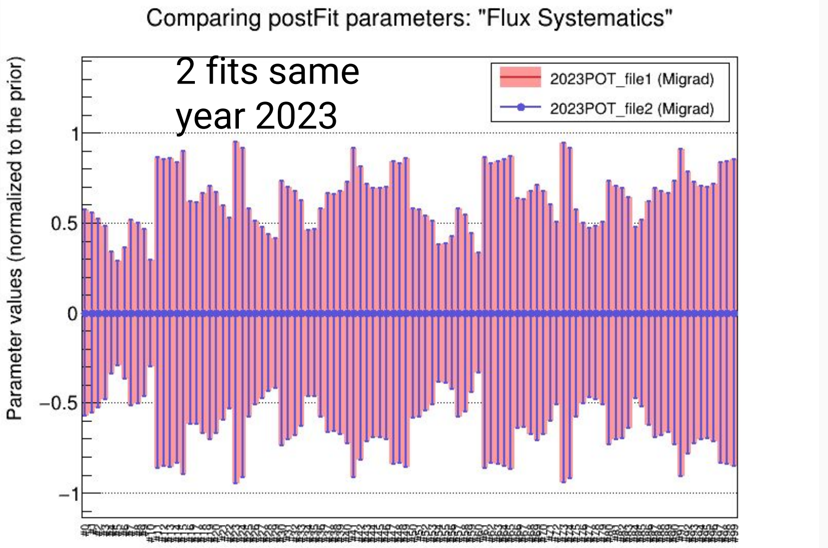
	2022 (OA2022)	2023 (+1.08 FHC)	2024 (+1.18 RHC)	2025 (+1.32 FHC)	2026 (+1.65 RHC)	2027 (+1.75 FHC)
SFGD FHC	-	1.08×10^{21}	1.08×10^{21}	2.4×10^{21}	2.4×10^{21}	4.15×10^{21}
SFGD RHC	-	-	1.18×10^{21}	1.18×10^{21}	2.83×10^{21}	2.83×10^{21}
FGD1/2 FHC	1.15×10^{21}	2.23×10^{21}	2.23×10^{21}	3.55×10^{21}	3.55×10^{21}	5.3×10^{21}
FGD1/2 RHC	0.83×10^{21}	0.83×10^{21}	2.01×10^{21}	2.01×10^{21}	3.66×10^{21}	3.66×10^{21}

#5 Flux parameters



absolute error ratio between 2 fits for 2023



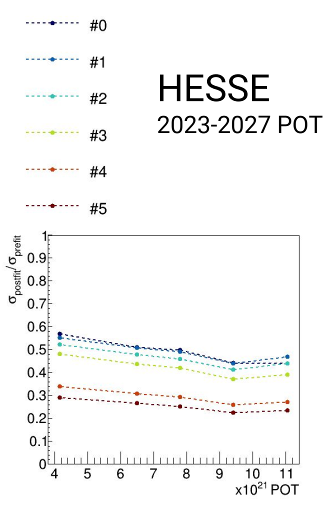


Constraints on Flux parameters

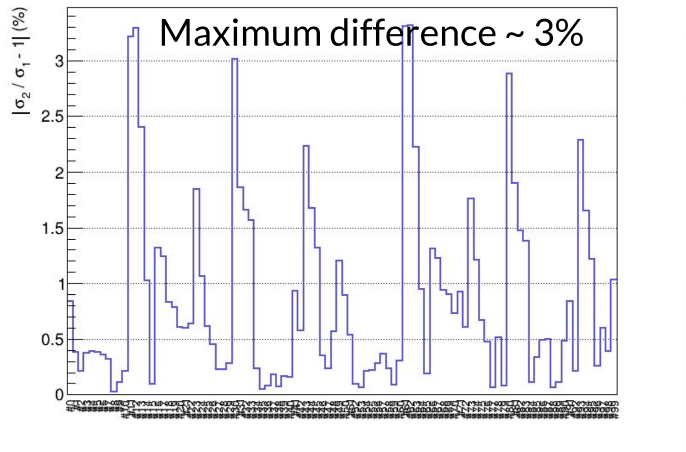
Looking for instabilities on Hesse Minimizer (FLUX)

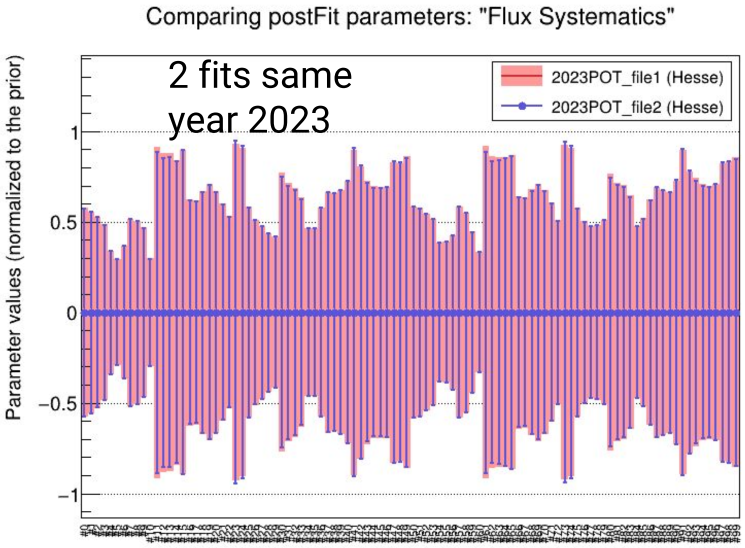
	2022 (OA2022)	2023 (+1.08 FHC)	2024 (+1.18 RHC)	2025 (+1.32 FHC)	2026 (+1.65 RHC)	2027 (+1.75 FHC)
SFGD FHC	-	$1.08\text{x}10^{21}$	$1.08\text{x}10^{21}$	$2.4\text{x}10^{21}$	$2.4\text{x}10^{21}$	$4.15\text{x}10^{21}$
SFGD RHC	-	-	$1.18\text{x}10^{21}$	$1.18\text{x}10^{21}$	$2.83\text{x}10^{21}$	$2.83\text{x}10^{21}$
FGD1/2 FHC	$1.15\text{x}10^{21}$	$2.23\text{x}10^{21}$	$2.23\text{x}10^{21}$	$3.55\text{x}10^{21}$	$3.55\text{x}10^{21}$	$5.3\text{x}10^{21}$
FGD1/2 RHC	$0.83\text{x}10^{21}$	$0.83\text{x}10^{21}$	$2.01\text{x}10^{21}$	$2.01\text{x}10^{21}$	$3.66\text{x}10^{21}$	$3.66\text{x}10^{21}$

#5 Flux parameters



absolute error ratio between 2 fits for 2023

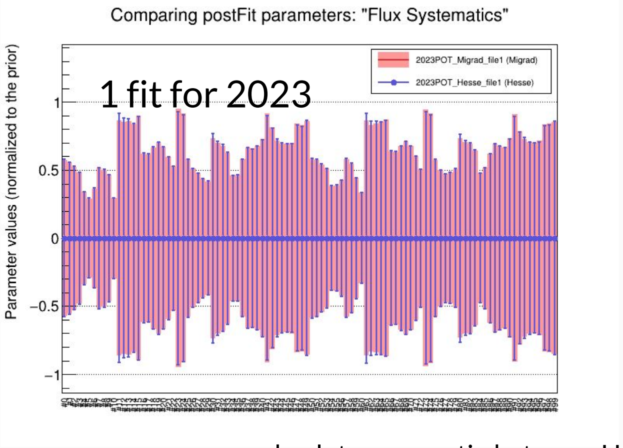




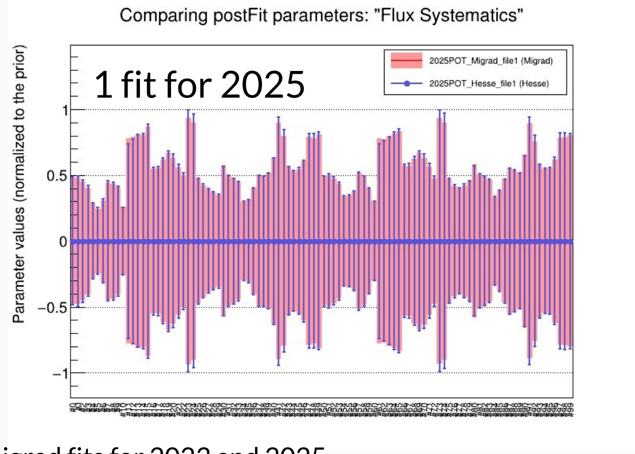
Constraints on Flux parameters

Looking for instabilities on Hesse Minimizer (FLUX)

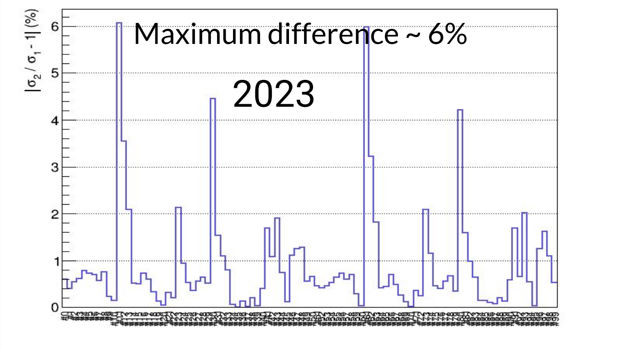
Hesse vs Migrad for 2023
same fit

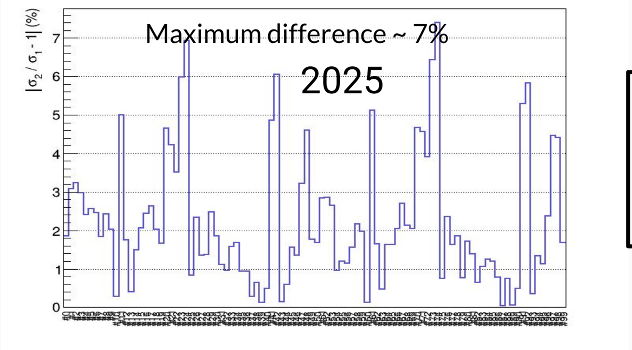


Hesse vs Migrad for 2025
same fit



absolute error ratio between Hesse & Migrad fits for 2023 and 2025





Instabilities with Hesse increase with POT !

Investigation to correct Hesse Flux instabilities

Margherita & Andrés suspect the number of threads used during the fit

→ when the event loading is made with multi threads, we must reorder events always with the same way, otherwise weights are randomly accumulated = give differents inputs

Running Gundam means to use several threads

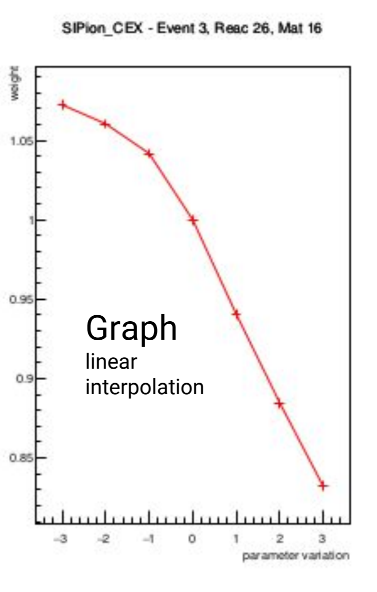
→ could be the cause of these instabilities, but not tested yet

Nonetheless, It was added in the latest version of Gundam !

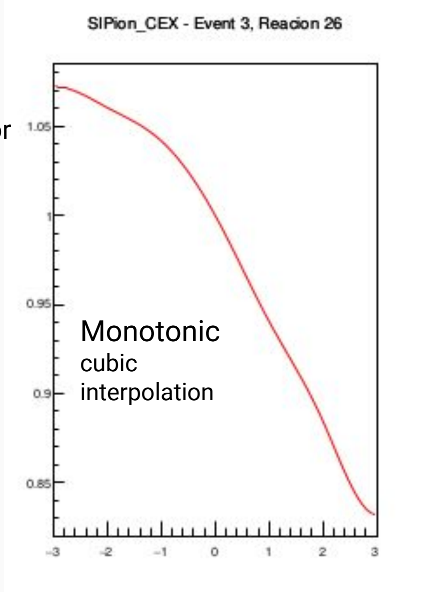
Dials types

- Spline : mathematical smooth curve used to interpolate data with a continuous way
  → x = value of the systematic parameter, y(x) = weight associated to this value

- Using new spline interpolation method on Gundam called “catmull-rom, monotonic” for detector splines (event by event splines)
  → Monotonicity means that the curve does not have abrupt changes in direction or inflection points. It maintains a consistent progression in a single direction, either strictly increasing or strictly decreasing.



SIPion_CEX
(new splined detector parameter)



Mat = Target (16 → Oxygène)

Reac = Reaction (26 → CCDis)

- MaCh3 is using monotonic, so we should be able to reproduce same LLH scans with Gundam

Likelihood comparison between GUNDAM vs MaCh3

New inputs = splined detector parameters (Highland2 version 2.84 + Psyche version 3.81) made with

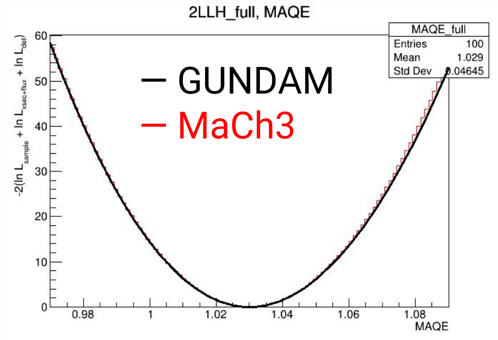
→ **OAGenWeightsApps** : *ND280GenWeights* →to generate xsec splines (config ND280_OA2021_Config_NoMirroring.toml
for each file with xsec splines : Use *makeND280SystSplines* → to generate detector splines (config ND_Syst_Merge_Def.toml)

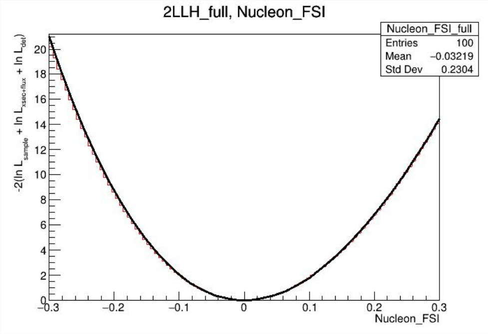
Checking with Ewan Miller (MaCh3 another fitter) if our files with new inputs are similar looking LLH scans and Splines shapes

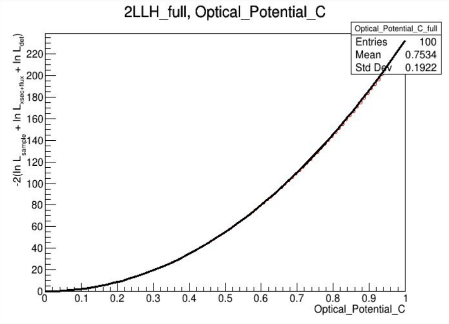
Some examples (fits with all run files 1-10) :

$$-2\log\mathcal{L}_{\text{stat}} = 2\sum_{i}^{\text{bins}}\left[\left(N_i^{\text{MC}}(\vec{\lambda}) - N_i^{\text{data}} + N_i^{\text{data}}\log\frac{N_i^{\text{data}}}{N_i^{\text{MC}}(\vec{\lambda})}\right) + \frac{(\beta_i - 1)^2}{2\sigma_{\beta_i}^2}\right].$$

$$-2\ln(\mathrm{L}^{\mathrm{syst}}) = \sum_{\mathrm{p}} (\vec{\mathrm{p}} - \vec{\mathrm{p}}_{\mathrm{prior}})\,(\mathrm{V}_{\mathrm{cov}}^{\mathrm{syst}})^{-1}\,(\vec{\mathrm{p}} - \vec{\mathrm{p}}_{\mathrm{prior}})$$



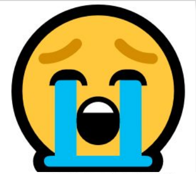


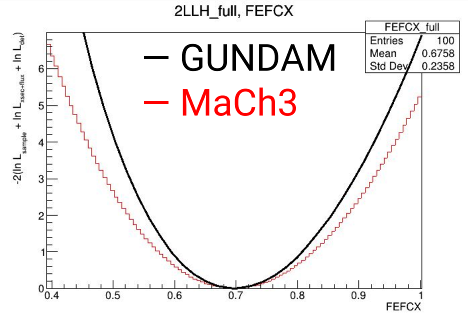


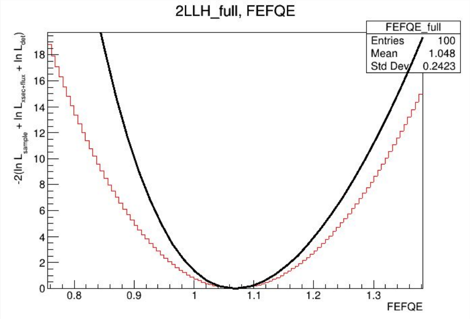
Most of Cross-section parameters are perfectly matching with Mach3 !

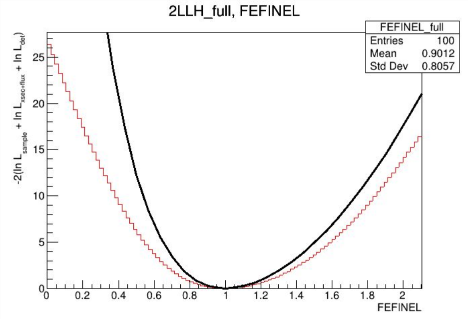
Likelihood comparison between GUNDAM vs MaCh3

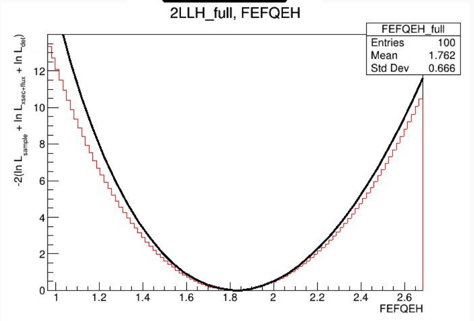
Unfortunately, some new detector splined & cross-section parameters are not matching with MaCh3
→ Cross-section FSI & SIPion splined detector parameters

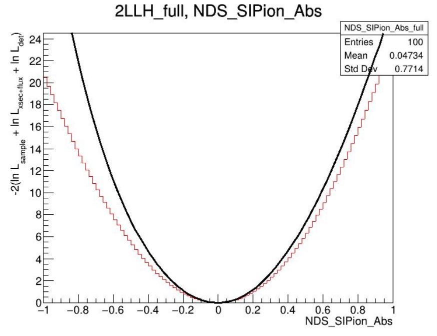


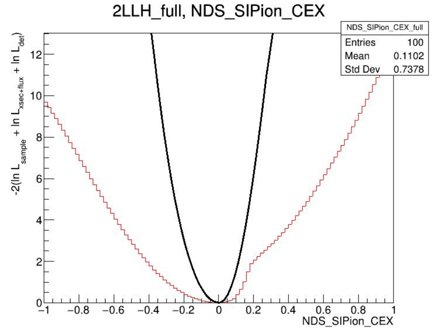


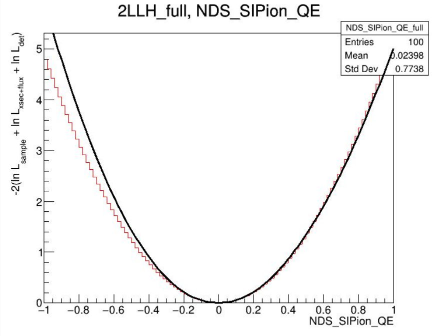












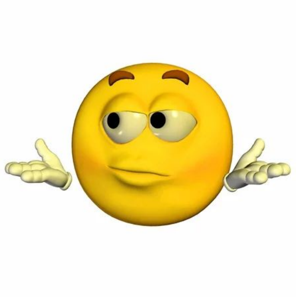
Options

- Check the event rates according the input weight (POT weight only, Cross-section nominal weight, Flux nominal weight..)

- Compare different spline type shapes

- New spline implementations in GUNDAM
  → Does the interpolation spline method is similar in GUNDAM and MaCh3 ?
  Ewan says our monotonic splines seem to be equivalent

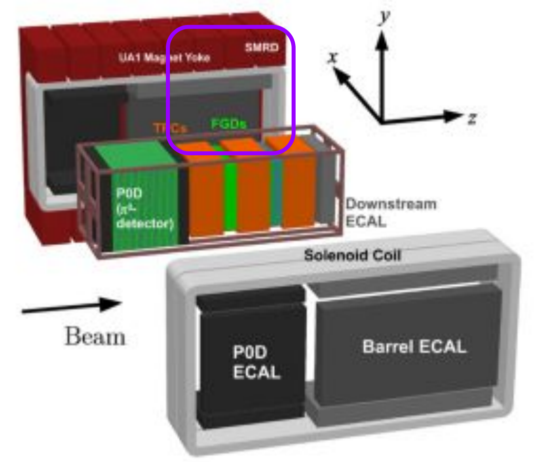
- something must be different
  in our inputs, but what ???



All weights Event rate

Sample	BANFF	GUNDAM	MACH3	(B-G)/B
FHC FGD1 ν_μ CC$0\pi0p0\gamma$	18312.5	18533.2	18372.5	0.0119119
FHC FGD1 ν_μ CC$0\pi Np0\gamma$	9027.02	9911.04	9036.49	0.0891960
FHC FGD1 ν_μ CC$1\pi0\gamma$	6491.09	6767.39	6430.31	0.0408278
FHC FGD1 ν_μ CCOther0γ	1621.02	1649.7	1617.12	0.0173860
FHC FGD1 ν_μ CCγ	10521.1	11570.9	10508.5	0.0907278
FHC FGD2 ν_μ CC$0\pi0p0\gamma$	19406.4	20315.8	19519.4	0.0447593
FHC FGD2 ν_μ CC$0\pi Np0\gamma$	7403.13	7474.48	7395.87	0.0095462
FHC FGD2 ν_μ CC$1\pi0\gamma$	5311.48	5503.45	5301.13	0.0348821
FHC FGD2 ν_μ CCOther0γ	1560.34	1570.84	1559.59	0.0066869
FHC FGD2 ν_μ CC γ	9537.12	9837.29	9526.96	0.0305134
RHC FGD1 $\bar{\nu}_\mu$ CC0π	8172.58	8354.51	8228.21	0.0217762
RHC FGD1 $\bar{\nu}_\mu$ CC1π	699.839	750.284	697.996	0.0672347
RHC FGD1 $\bar{\nu}_\mu$ CCOther	1370.95	1433.54	1345.91	0.0436585
RHC FGD2 $\bar{\nu}_\mu$ CC0π	7815.33	7946.82	7869.53	0.0165463
RHC FGD2 $\bar{\nu}_\mu$ CC1π	654.468	657.978	652.623	0.0053340
RHC FGD2 $\bar{\nu}_\mu$ CCOther	1230.61	1272.97	1228.68	0.0332805
RHC FGD1 ν_μ (bkg) CC0π	3444.8	3435.42	3420.33	-0.002730
RHC FGD1 ν_μ (bkg) CC1π	1212.63	1717.24	1204.96	0.2938490
RHC FGD1 ν_μ (bkg) CCOther	1164.15	1174.66	1161.01	0.0089470
RHC FGD2 ν_μ (bkg) CC0π	3361.06	3419.5	3356	0.0170905
RHC FGD2 ν_μ (bkg) CC1π	974.841	1021.36	975.62	0.0455450
RHC FGD2 ν_μ (bkg) CCOther	1101.66	1144.96	1099.05	0.0378199

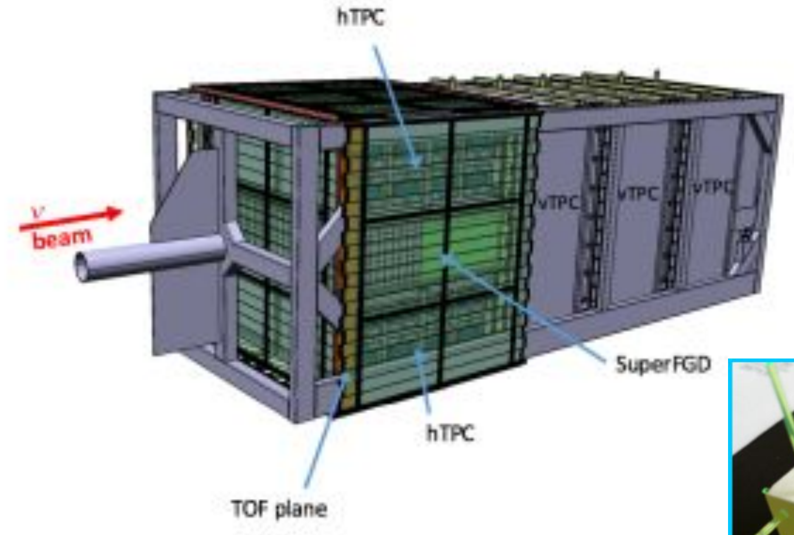
T2K ND280 near detector & SFGD upgrade



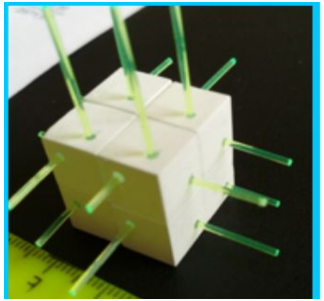
Study neutrino oscillation cross-section
3 TPCs and 2 FGDs (used for OA2022)
→limited momentum threshold (450 Mev/c)
→limited angular acceptance (for HA and BW muons)

UPGRADE

I will help for the setup in Japan !!



Two High Angle TPCs
Time of Flight detector around new tracker
Momentum threshold reduced
Expect total uncertainty systematics < 4%



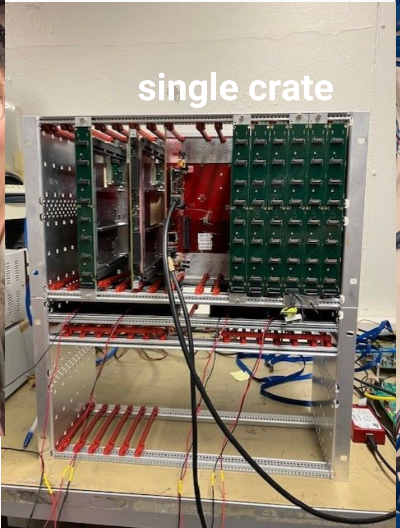
Polystirene-based Plastic scintillator
1x1x1 cm^3 cubes (~ $2x10^6$ in SFGD)

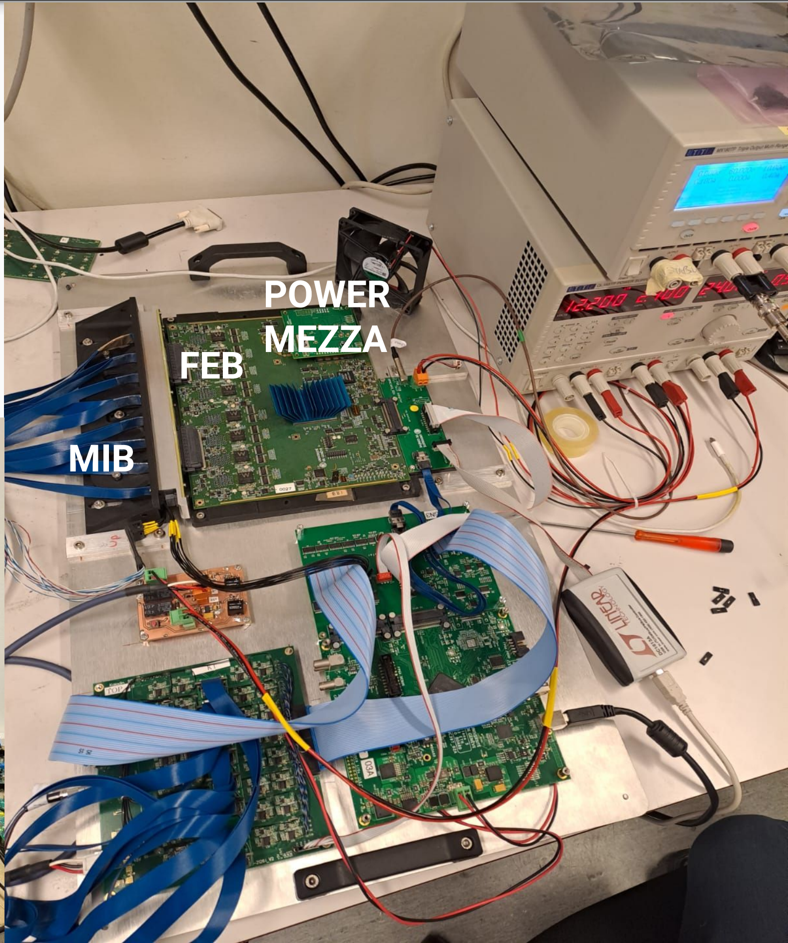
Electronic tests at Geneva University

2 banches setup tests
8 CITIROC, 32 channels each

1. FEB configuration
2. Functional test
   (housekeeping tests)

only 13% of FEB fail now !





Single crate : 14 FEBs + 1 OCB + Backplane

Conclusion

- Main goal of Gundam fitter is to be as or even more efficient than MaCh3 or BANFF
  → lot of verifications on going to lead to the validation between Gundam & MaCh3

- Validation for OA 2022 and then OA 2024 with new 4π selection

- More electronic tests to come on FEB with cold-crate mid June

- Upgrade of ND280 in Japan in July

THE END ..