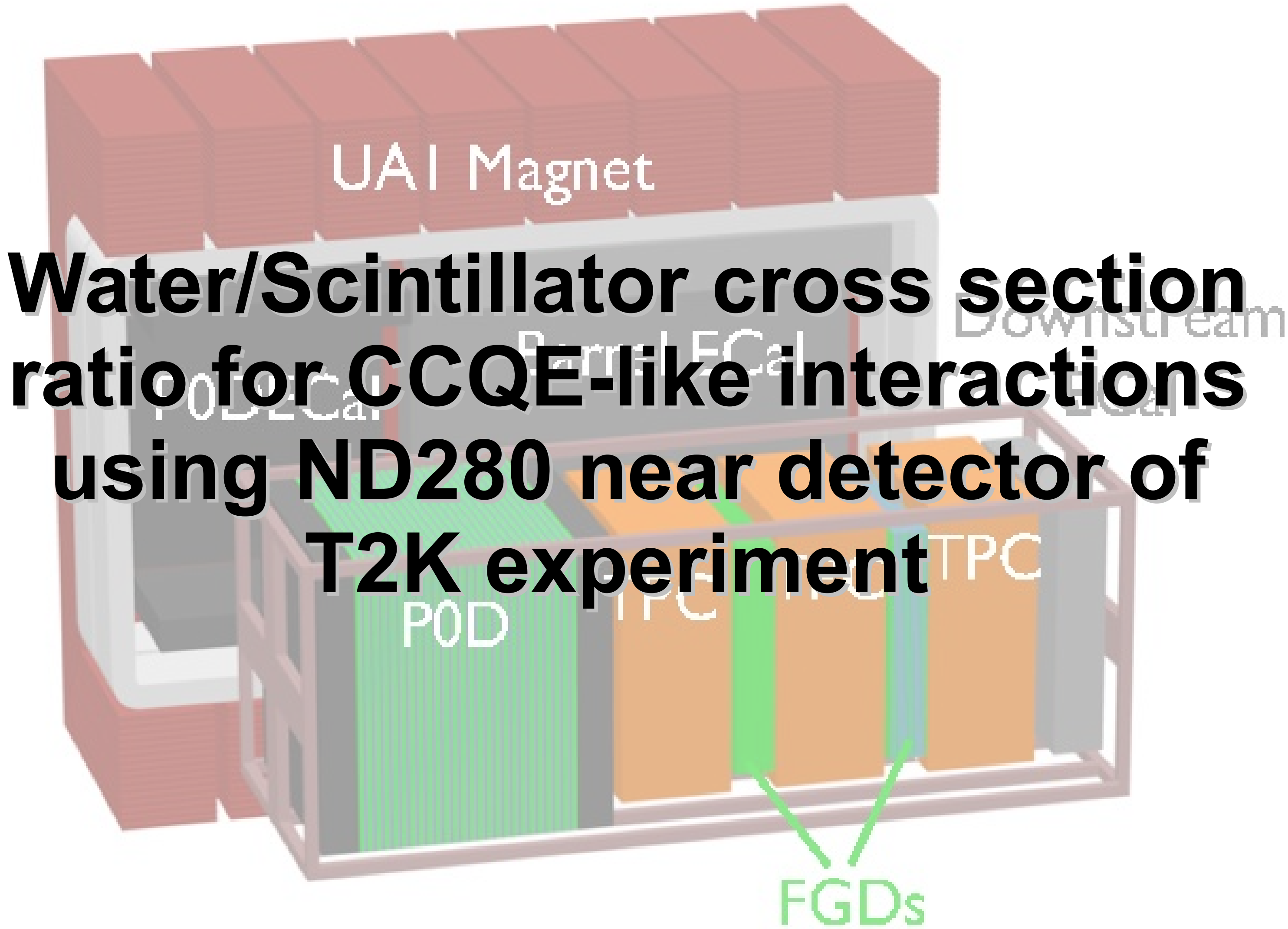
Water/Scintillator cross section ratio for CCQE-like interactions using ND280 near detector of T2K experiment



Pheniics Days 11/05/16

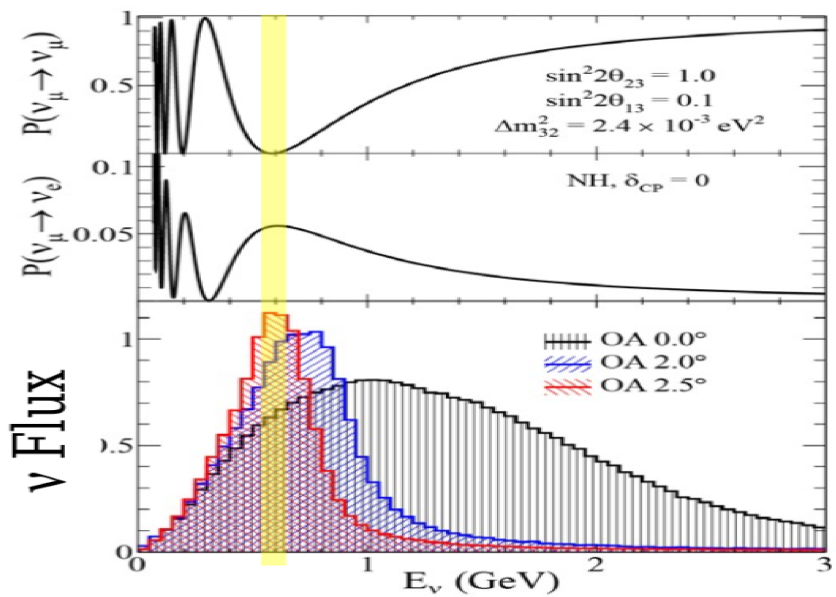
Francesco Gizzarelli IRFU/CEA Saclay

Outline

- T2K experiment
- Motivations
- MicroMegas alignment and results
- Water/Scintillator CCQE cross section ratio
- Results
- Conclusion

The T2K experiment

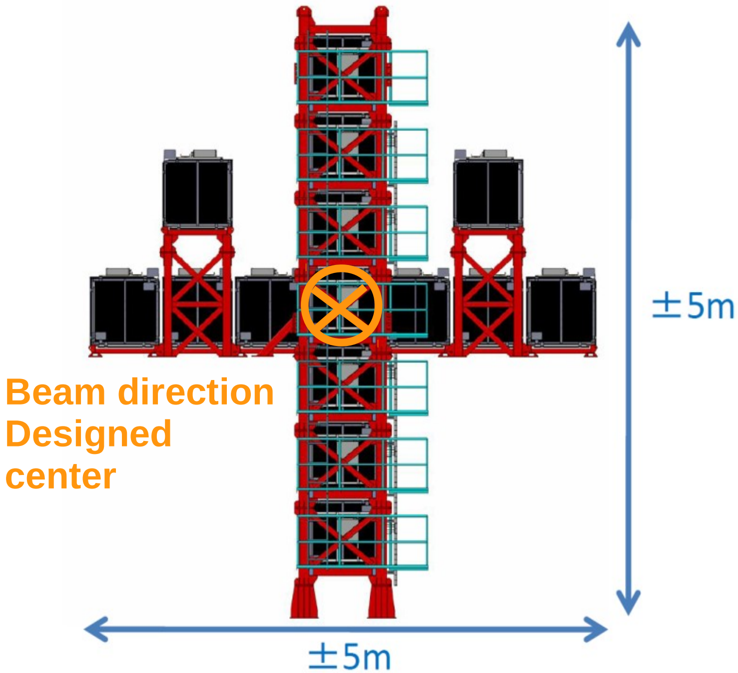
- Long baseline neutrino experiment **T**okai-**to**-**K**amioka
- **L** ~ 295 km
- Beam line and near detectors at J-Parc in **T**okai
- Far detector in **K**amioka
- ν and $\bar{\nu}$ mode
- **Off-axis** beam experiment



Physics goal

- Neutrino oscillation (Δm^2_{23}, θ_{23}, θ_{13}, δ_{CP})
  - ν_e and $\bar{\nu}_e$ appeareance ($\nu_\mu \longrightarrow \nu_e$, $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$)
  - ν_μ and $\bar{\nu}_\mu$ disappearence
- Neutrino interaction cross section
- Study of new phenomena (sterile neutrino, IV generation, new interactions)

The near detectors (280 m)

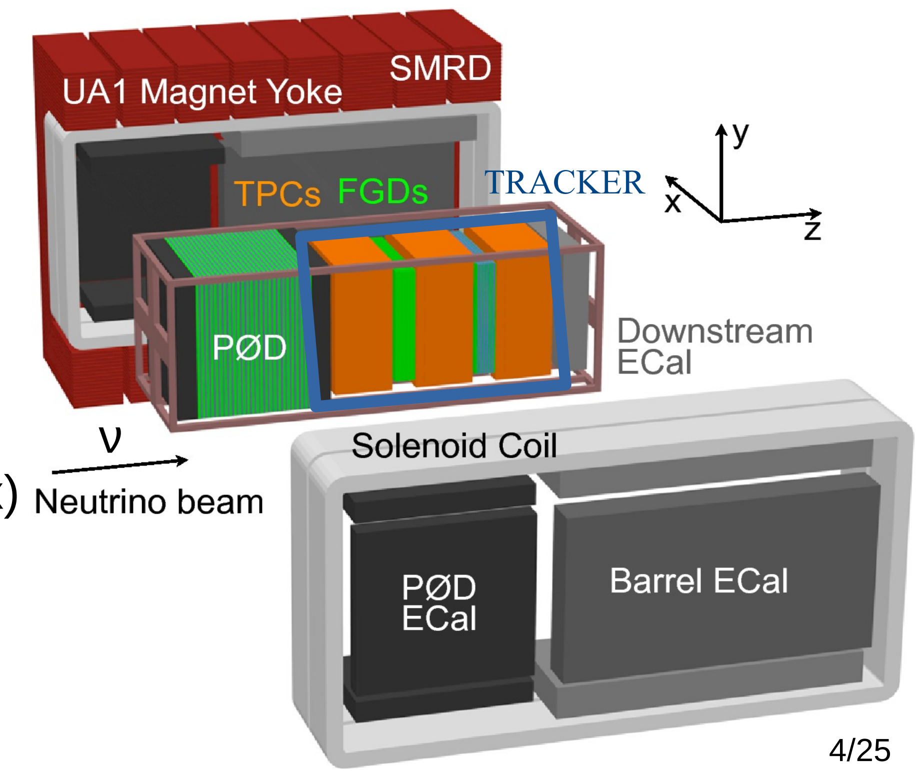


INGRID

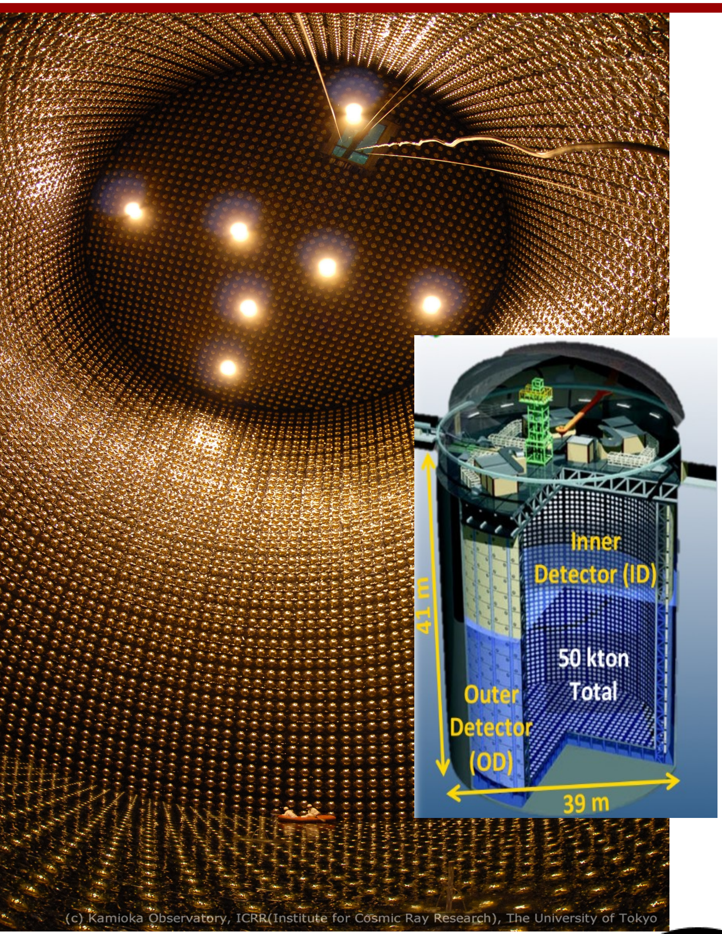
- On-axis detector
- 0°-0.9° coverage
- Iron/scintillator tracking calorimeters, 16 modules
- 1 all-scintillator proton module
- Monitors beam intensity, direction, profile and stability

ND280

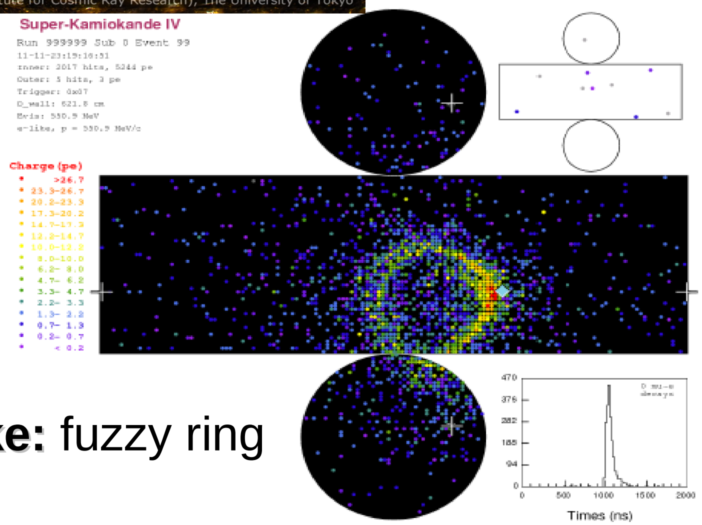
- Off-axis detector 2.5° (same SK direction)
- Sub-detectors allow a fully reconstructed event
- Fully magnetized detector B = 0.2 T
- PØD: π^0 detector
- 3 TPCs: momentum measurement, particle ID (dE/dx)
- 2 FGDs: active target mass (2*1.2 ton)
- ECal: electron, gamma identification
- SMRD: improve muon identification



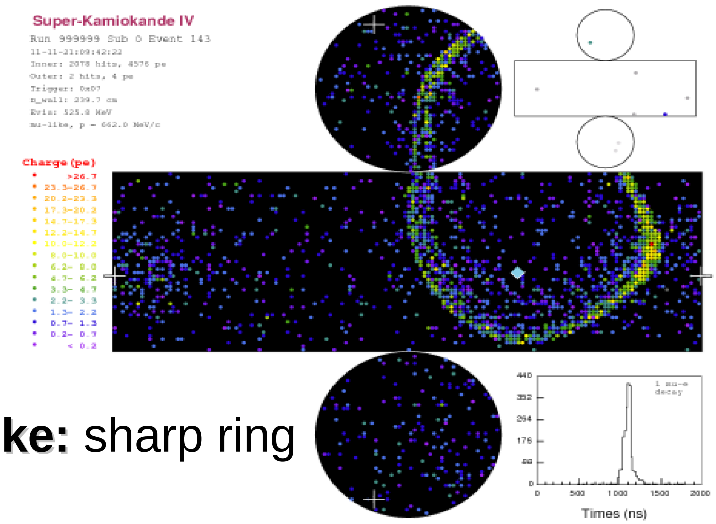
The far detector Super-K (295 km)



- 50 kton water cherenkov detector 1 km undergrond (Kamioka mine)
- 22 kton of Fiducial Volume
- ~11k PMTs in the inner detctor
- ~2k PMTs in the outer detector
- Veto entering background (cosmic rays, radioactivity) and rejects exiting events
- Excellent muon-electron separation thanks to cherenkov light ring shape
- Misidentification < 1%
- No magnetic field to distinguish particles from anti-particles



e-like: fuzzy ring



μ-like: sharp ring

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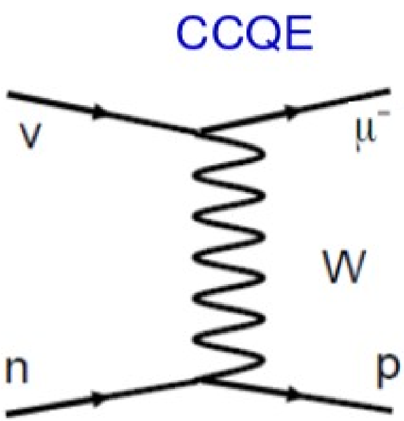
Neutrino interactions

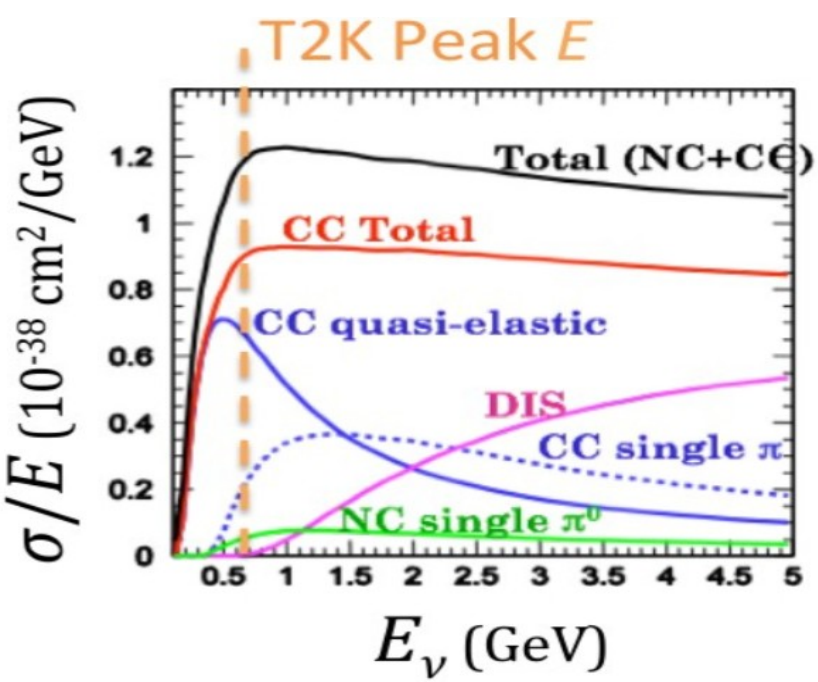
Charged-**C**urrent **Q**uasi-**E**lastic is the dominant interaction process for T2K's neutrino energy spectrum



$$E_\nu^{CCQE} = \frac{(m_n - \epsilon_B)\, E_\mu + \left(2m_n\epsilon_B - \epsilon_B^2 - m_\mu^2 + m_p^2 - m_n^2\right)/2}{m_n - \epsilon_B - E_\mu + P_\mu cos\theta_\mu}$$

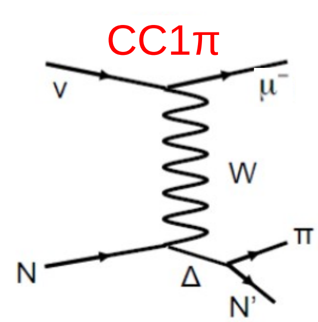
I. Fully reconstructed events allows to measure neutrino energy thanks to charge lepton kinematics

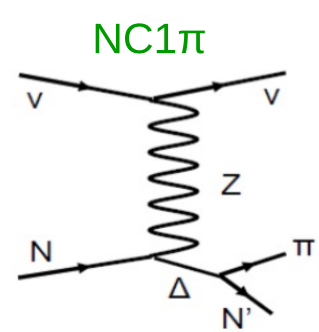
II. Nucleon target is assumed at rest

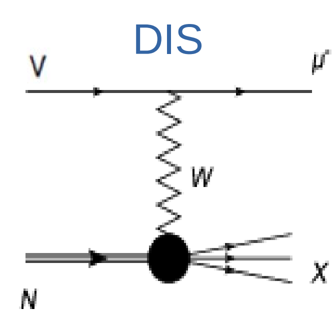


Additional processes:

- Charged current single pion production (CC1π)
- Neutral current single pion production (NC1π)
- Deep inelastic scattering (DIS)







Motivations

Why water?

- Relevance in SK and oscillation analysis:

i. Important systematics in the ND280-SK extrapolation
ii. Reduce oscillation analysis uncertanties
iii. Neutrino-nucleon scattering physics

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total	7.7%	6.8%

FGD2 filled with plastic scintillators and water modules

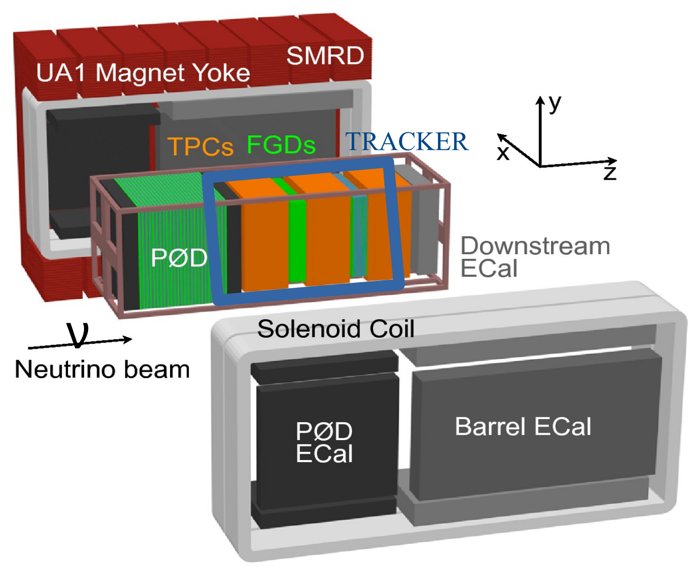
Why ND280?

- Good performance for cross section measurement:

i. High statistics

ii. Full final state reconstruction and particle identification (μ, p, π)

iii. Several possible measurements ν_μ, $\bar{\nu}_\mu$, ν_e, C, O

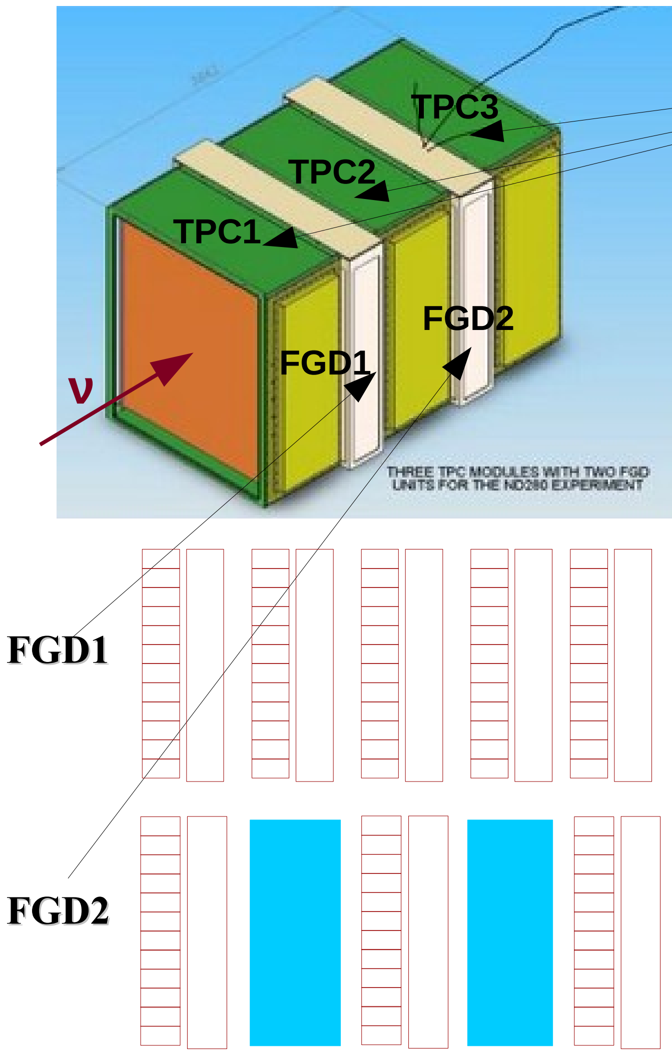


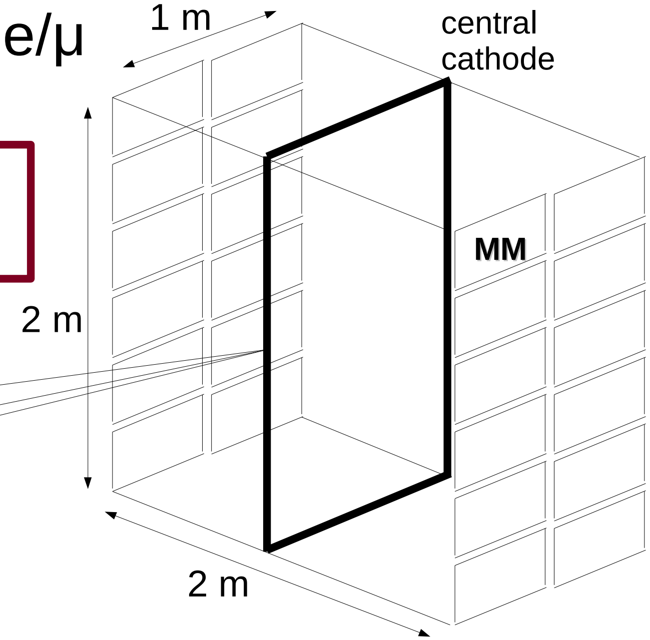
A very precise detector calibration is needed to reduce detector systematics

ND280 tracker

- Tracker = 3TPCs + 2FGDs
- dE/dx capability separate e/μ
- $\sigma(p)/p < 10\%$ @ 1 GeV/c^2

➜ **Alignment improve particle momentum resolution**





TPC

- **T**ime **P**rojection **C**hamber
- Amplification via MicroMegas modules (MM)
- MM modules arranged in a 6x2 matrix geometry
- Total MM 3X2X6x2 = 72

FGD

- **F**ine **G**rained **D**etector of 2x2x0.3 m^3
- Total mass 2x1.2 ton
- Fine segmentation to track low energy particles to tag CCQE events
- Active material: scintillator bars (1x1x200 cm^3) arranged in alternating x-y supermodules
- FGD1 = 15 x-y supermodules
- FGD2 = 7 x-y supermodules alternating with 6 water layers

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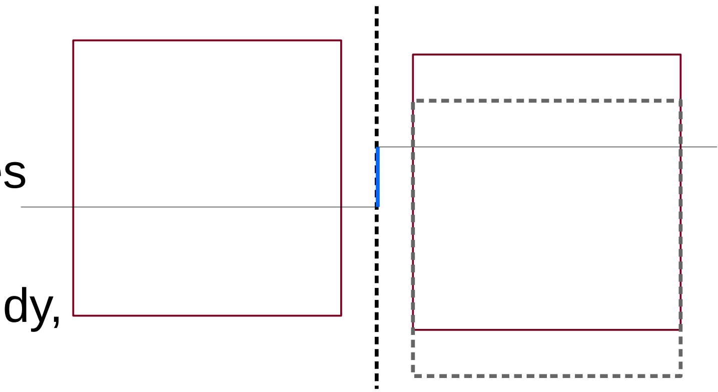
Alignment strategy

- Cosmic rays collected with magnetic field off
- Reconstruct straight track in each module separately
- Match tracks in the middle plane between adjacent MM modules and extract residuals Δy, $\Delta\varphi$
- Horizontal tracks constraint translational misalignment (vertical dy, horizontal dz) and rotation dφ
- Correction extracted via a fit to the residuals

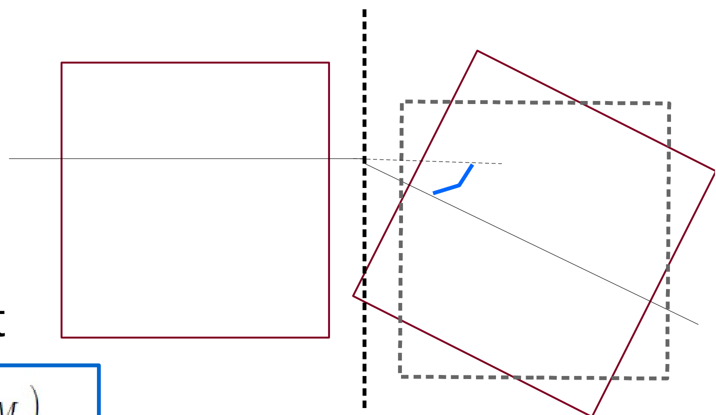


$\Delta y = y_{MMi} - y_{MMj}$

$$\chi^2 = \chi^2_{\Delta y} + \chi^2_{\Delta\phi} \qquad \chi^2_{\Delta} = \sum^{n_{tracks}} \left(\frac{\Delta + f_{\Delta}}{\sigma_{\Delta}}\right)^2$$

$$\text{residual } \Delta = \Delta y,\ \Delta\phi$$

$$\text{total correction } f_{\Delta} = traslation + rotation$$



$\Delta\varphi = \varphi_{MMi} - \varphi_{MMj}$

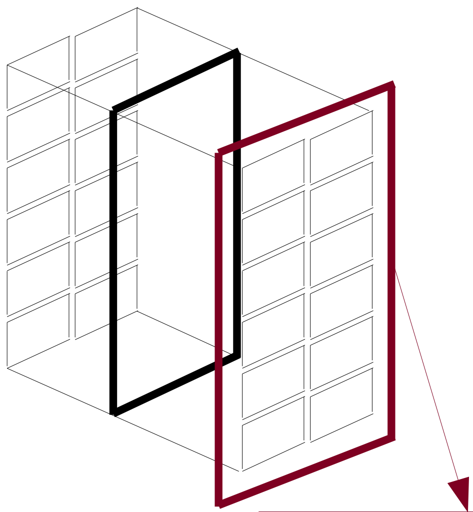
- Total correction depends on dy, dz, dφ free parameters in the fit

$$f_{\Delta y}\left(y_{MM_i}, y_{MM_j}, z_{MM_i}, z_{MM_j}, \phi_{MM_i}, \phi_{MM_j}\right) = \left(y_{MM_i} - y_{MM_j}\right) - \left(z_{MM_i} - z_{MM_j}\right) tan\left(\phi_{MM_{\cdot}}\right) - \left(\phi_{MM_i} - \phi_{MM_j}\right)\left(\frac{d+L}{2} - y_{MM_i} tan\left(\phi_{MM_{\cdot}}\right)\right)$$

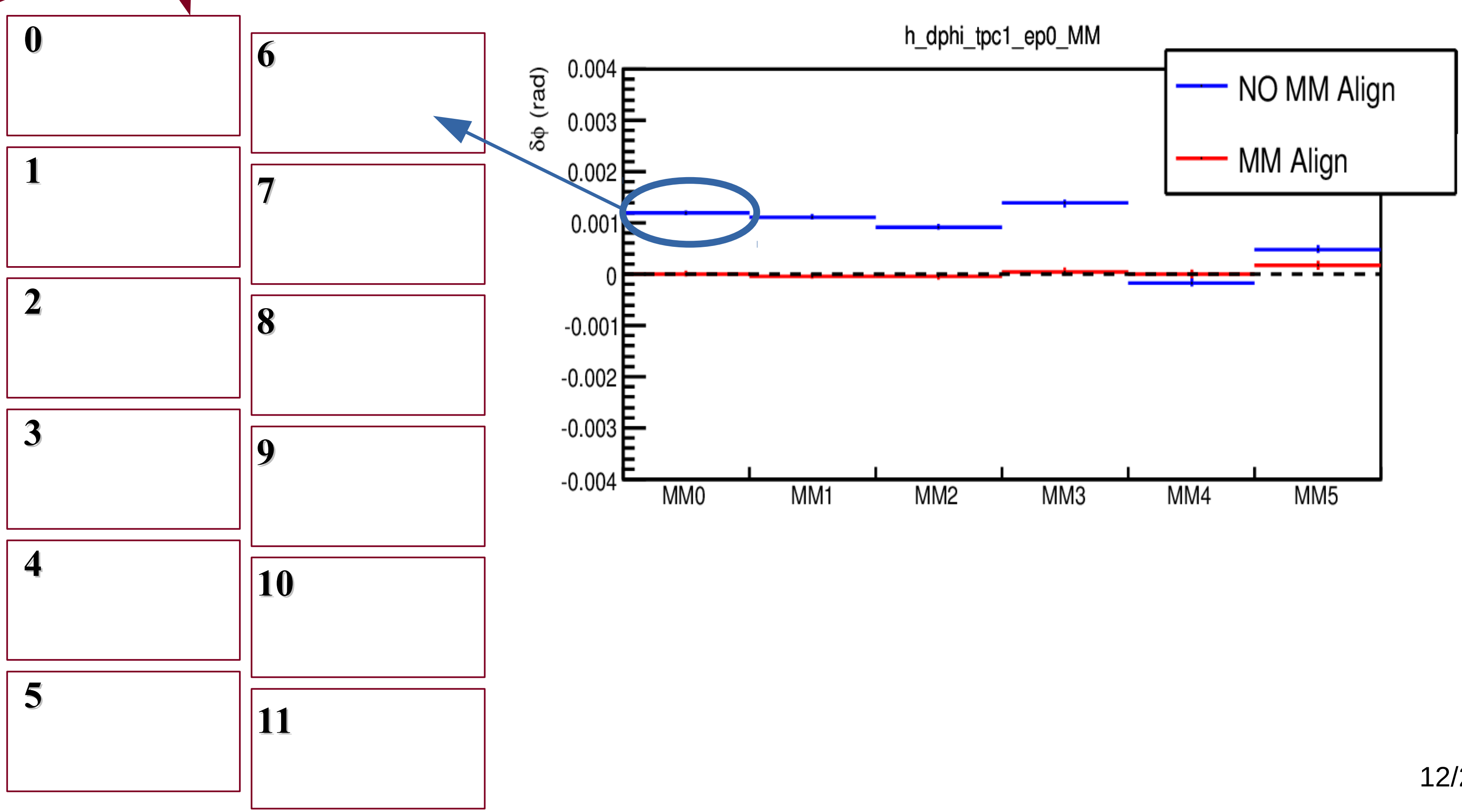
$$f_{\Delta\phi}\left(\phi_{MM_i}, \phi_{MM_j}\right) = \left(\phi_{MM_i} - \phi_{MM_j}\right)$$

- Laser monitor system gives few hundred microns in translations and few mrad for rotations
- The fit has to be very sensitive
- Generated MC test geometries to test the fit

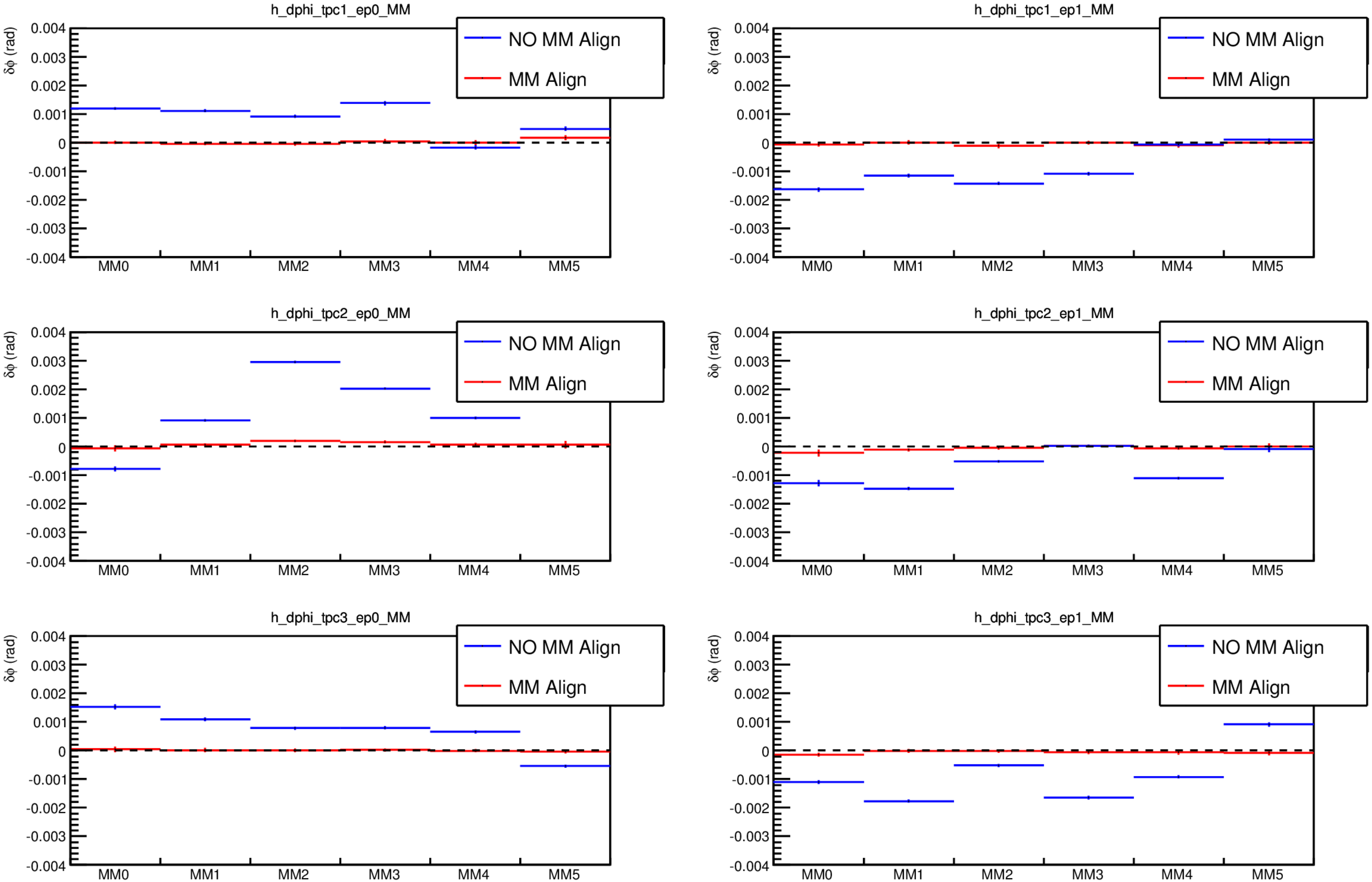
MicroMegas alignment



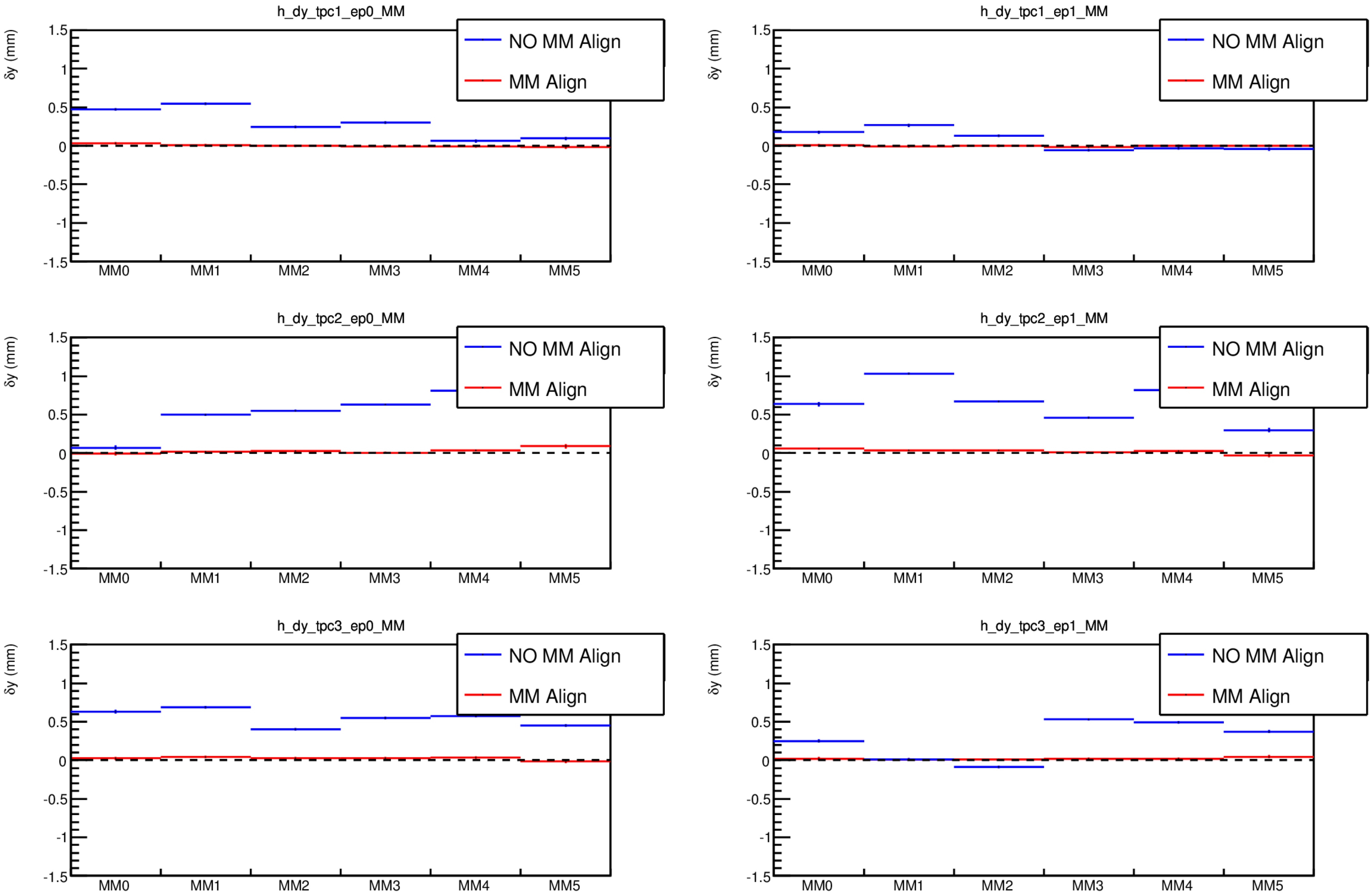
- 3 TPC with 2 read-out planes each
- MM modules arranged in a 6x2 matrix
- Total MM 3X2X6x2 = 72
- Column staggered by 5 cm
- 6 MM pair in each read-out plane
- Each point is associated to a MM couple



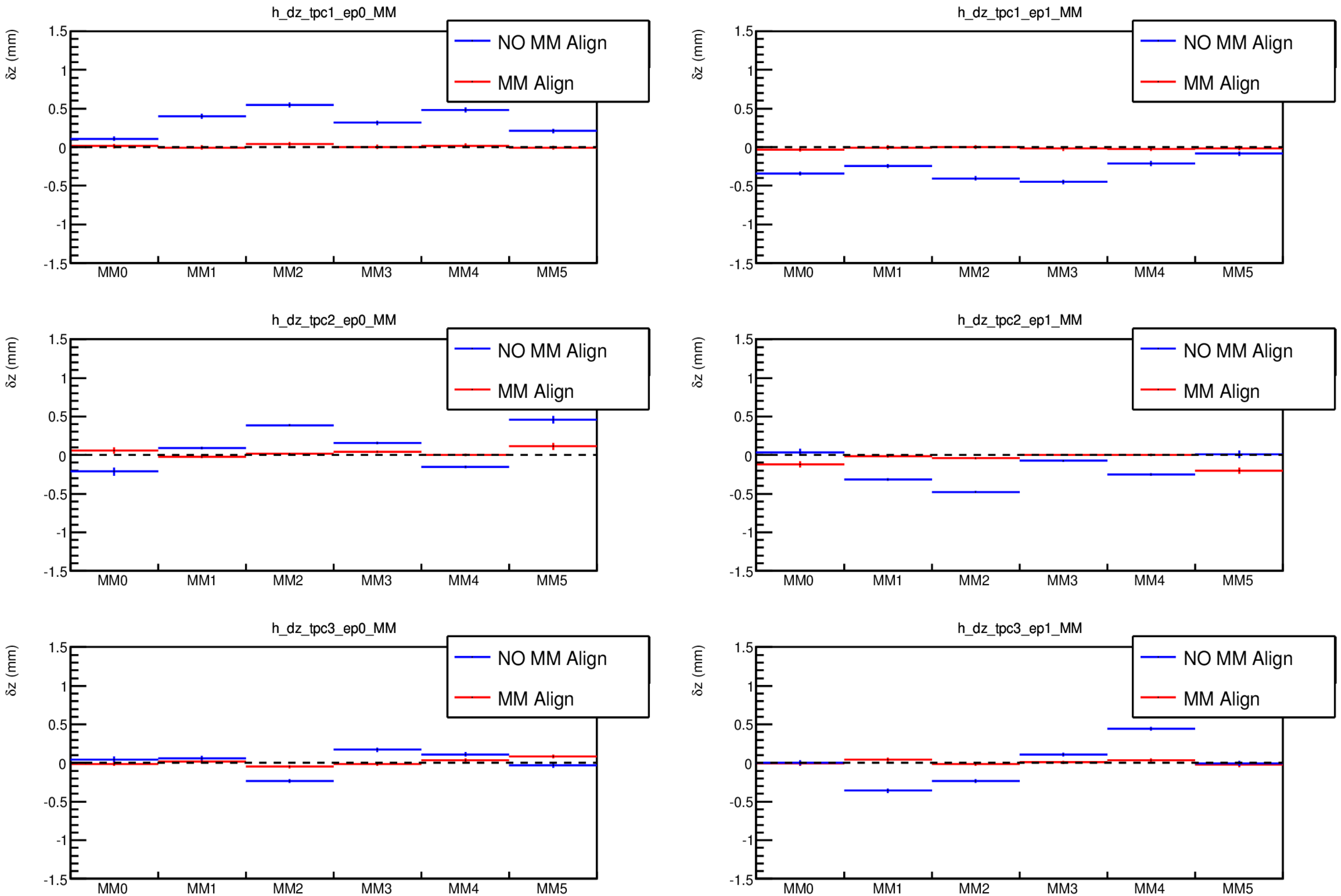
MicroMegas φ alignment



MicroMegas y alignment



MicroMegas z alignment



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Water/Scintillator ratio

$$R_{W/S} = \left(\frac{N_X f_x^{CC0\pi} f_x^{w} + N_Y f_y^{CC0\pi} f_y^{w}}{N_X f_x^{CC0\pi} f_x^{s} + N_Y f_y^{CC0\pi} f_y^{s}} \right)\Bigg|_{(P_\mu,\ \cos\theta_\mu,\ E_\nu)^{TRUE}} \frac{\varepsilon_s}{\varepsilon_w} \frac{N_n^s}{N_n^w}$$

N_X , N_Y : the numbers of observed events in data after transfer to MC

$f_x^{CC0\pi}$, $f_y^{CC0\pi}$: purities in x and y layers from MC

ε_w , ε_s : efficiency × acceptance for water and scintillator from MC

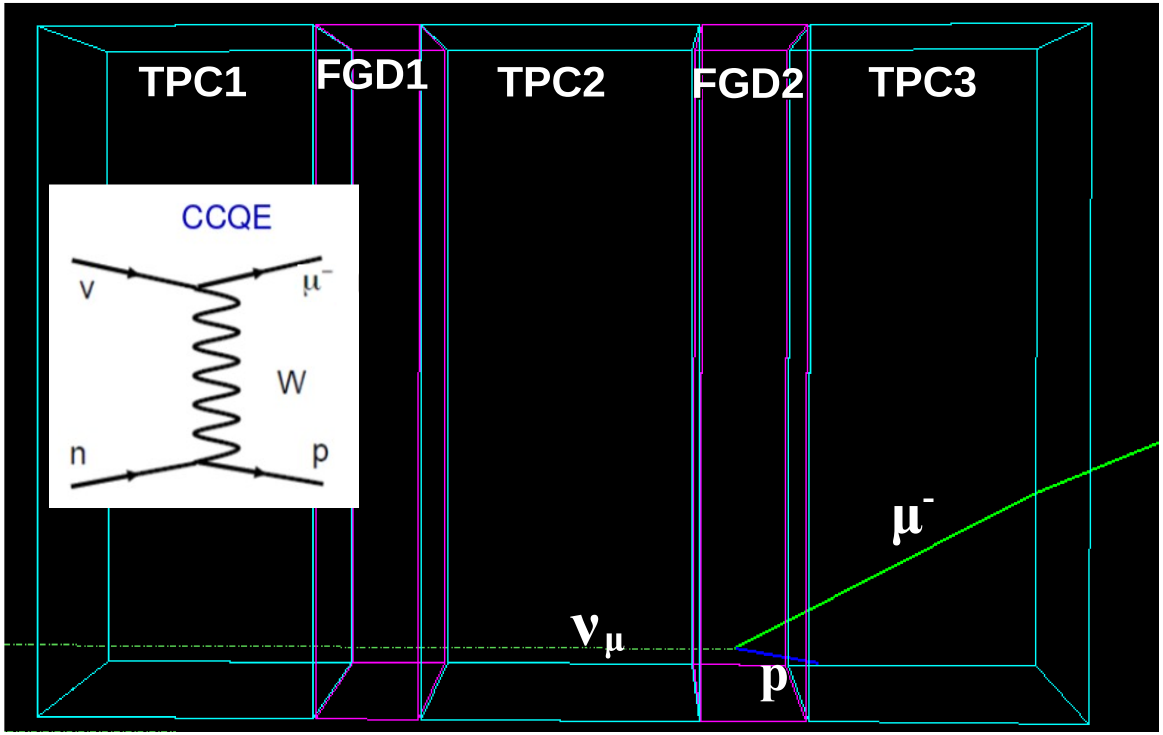
$f_{x,y}^{\ s,w}$: scintillator, water events fractions from MC for each x,y layer

$N_n^{\ s,w}$: number of neutron targets in the Fiducial Volume for scintillator and water

Signal definition

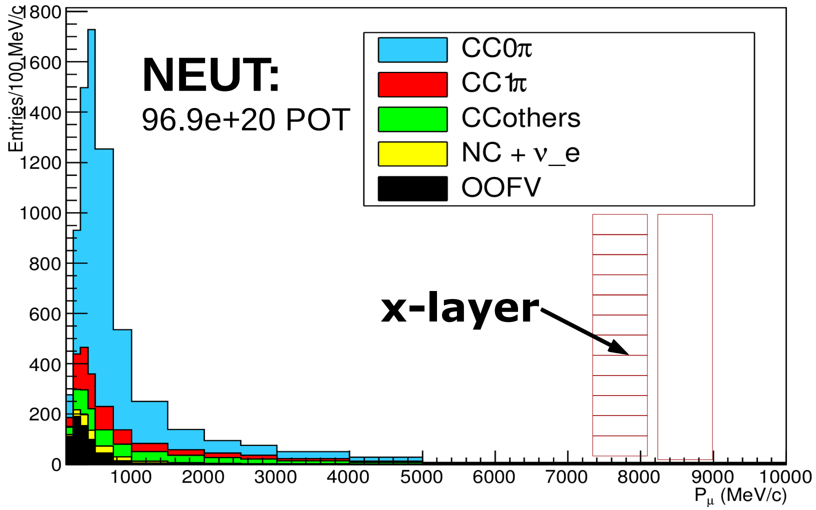
- Standard T2K quality event (good spill, good detector)
- Detector acceptance and tag

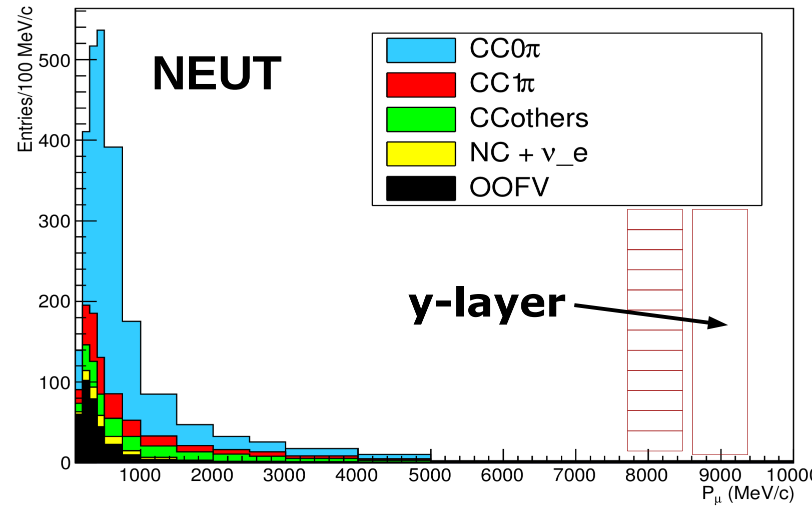
1. HNMT in FGD2 Fiducial Volume (FV)
2. Tracks quality in TPC
3. External veto cut on FGD2
4. Muon PID in the TPC
5. No pion in the final state



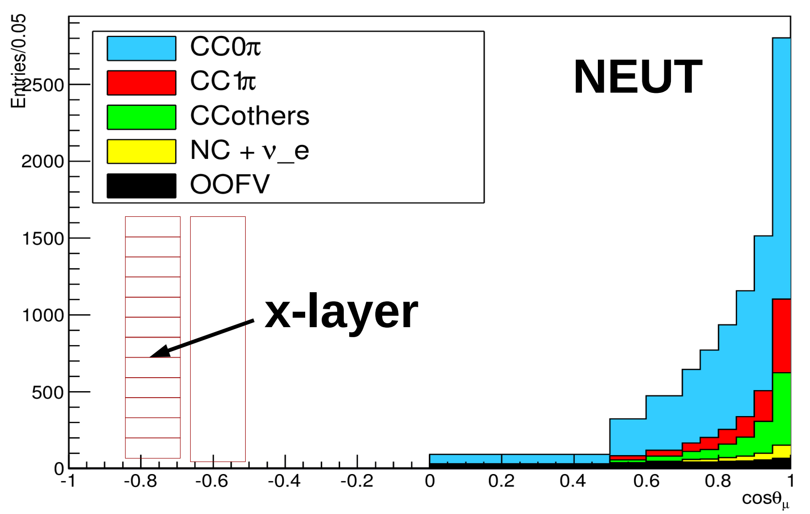
CC0π sample

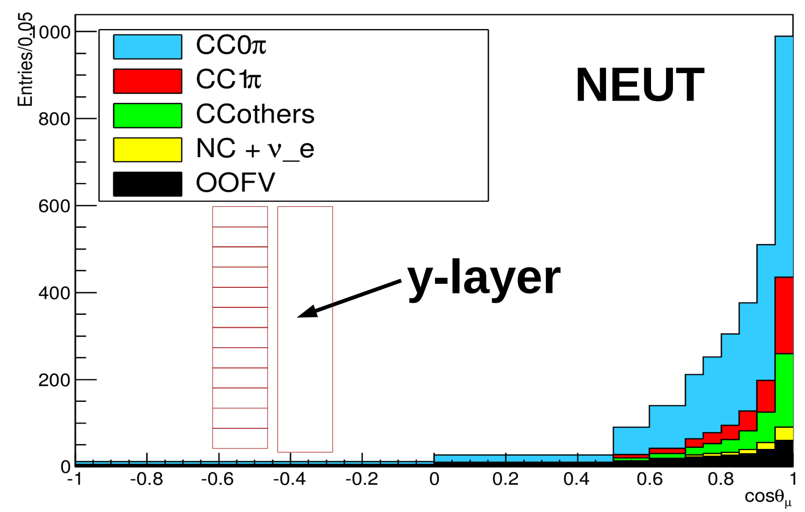
Momentum





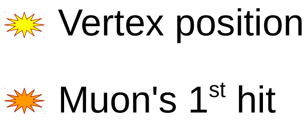
Direction





	NEUT	$CC\ 0\pi$ [%]	$CC\ 1\pi$[%]	$CC\ others$ [%]	$NC\ +\ \nu_e$ [%]	$OOFV$ [%]	ϵ_s [%]	ϵ_w [%]
FGD2-x	12875 ± 29	68.8	11.7	11.0	2.43	6.01	47.85	49.65
FGD2-y	4390 ± 17	64.3	11.2	11.4	2.52	9.70		
	GENIE	$CC\ 0\pi$ [%]	$CC\ 1\pi$[%]	$CC\ others$ [%]	$NC\ +\ \nu_e$ [%]	$OOFV$ [%]	ϵ_s [%]	ϵ_w [%]
FGD2-x	12131 ± 26	66.4	13.9	9.54	3.24	6.34	47.52	50.26
FGD2-y	4035 ± 15	62.4	14.3	9.79	3.43	9.51		

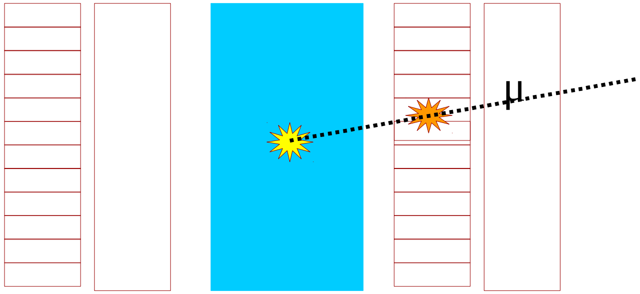
Vertex position



Critical is the capacity of dividing water and scintillators interactions

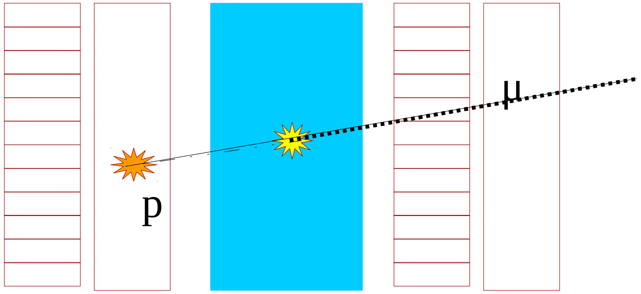
Background from carbon

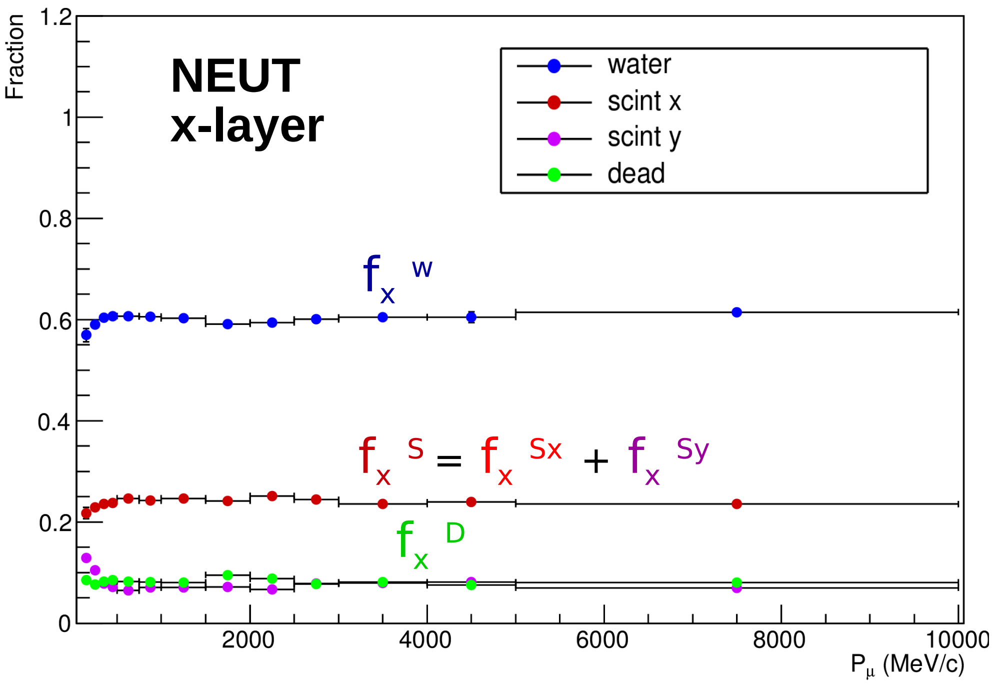
Vertex = 1st hit in active layer →
Layer x enhanced with water (~60%) + ~30% C →
C and O cross-section need to be measured together

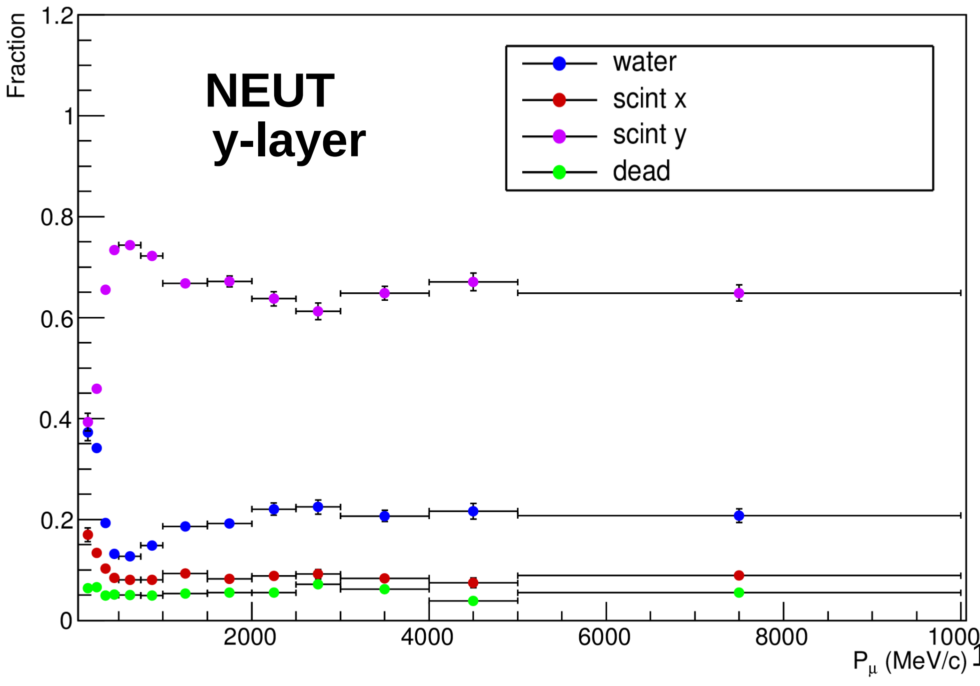


Migration between layers

Low energetic backward particles aligned with forward μ could be reconstructed as a single μ track with vertex in previous layer



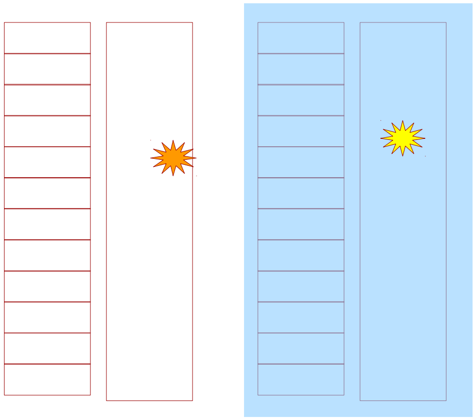


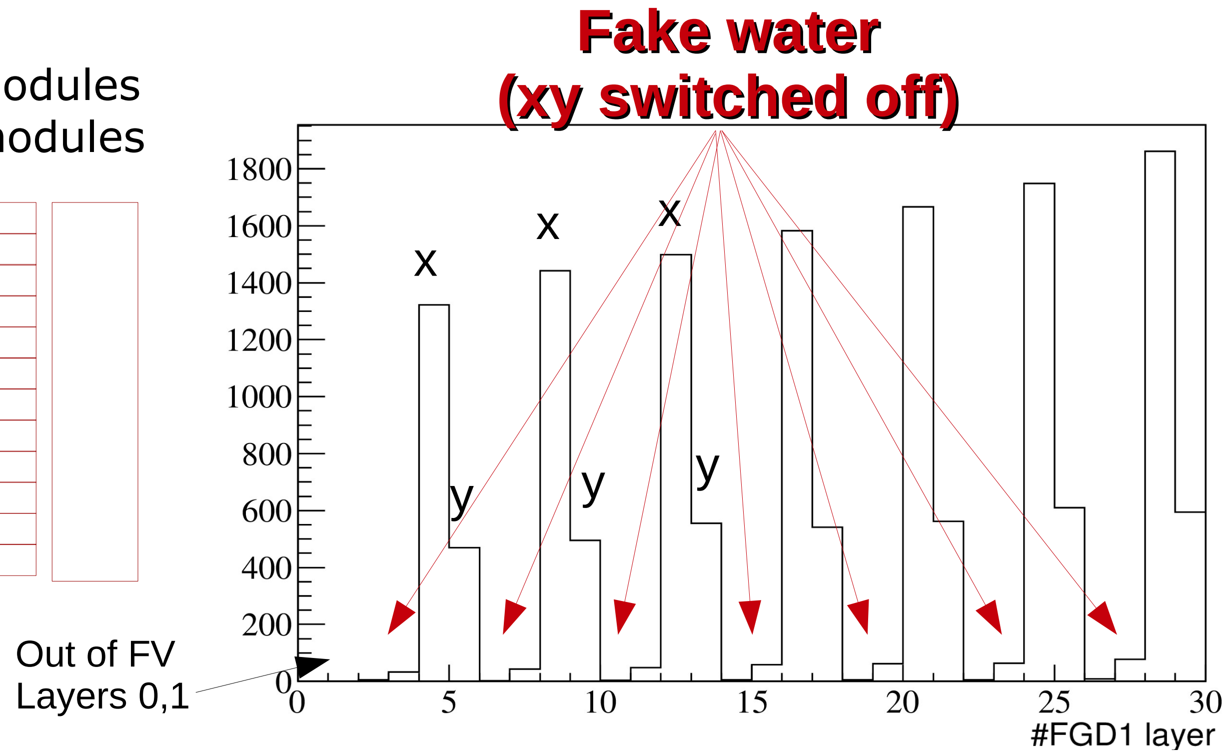


Hybrid FGD1 control sample

True vertex layer
Reco vertex layer

- Scintillator: 8 xy-supermodules
- Fake water: 7 xy-supermodules





Fake water/Scintillator

$$R_{FW/S} = \left(\frac{N_X f_x^{CC0\pi} f_x^{fw} + N_Y f_y^{CC0\pi} f_y^{fw}}{N_X f_x^{CC0\pi} f_x^{s} + N_Y f_y^{CC0\pi} f_y^{s}} \right) \Bigg| \; P_\mu, \cos\theta_\mu, E_\nu^{TRUE} \quad \frac{\varepsilon_s}{\varepsilon_{fw}} \quad \frac{N_n^S}{N_n^W}$$

N_X , N_Y : the numbers of observed events in data

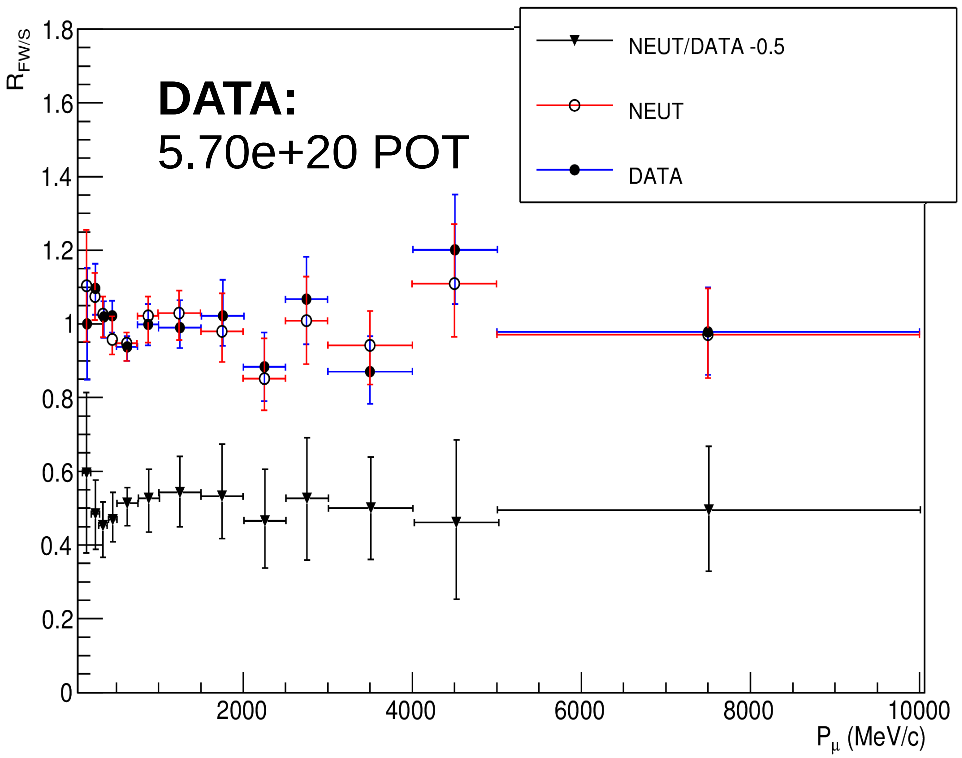
$f_x^{CC0\pi}$, $f_y^{CC0\pi}$: purities from MC in x and y layers

ε_w , ε_s : efficiency $\times$ acceptance for water and scintillator targets from MC

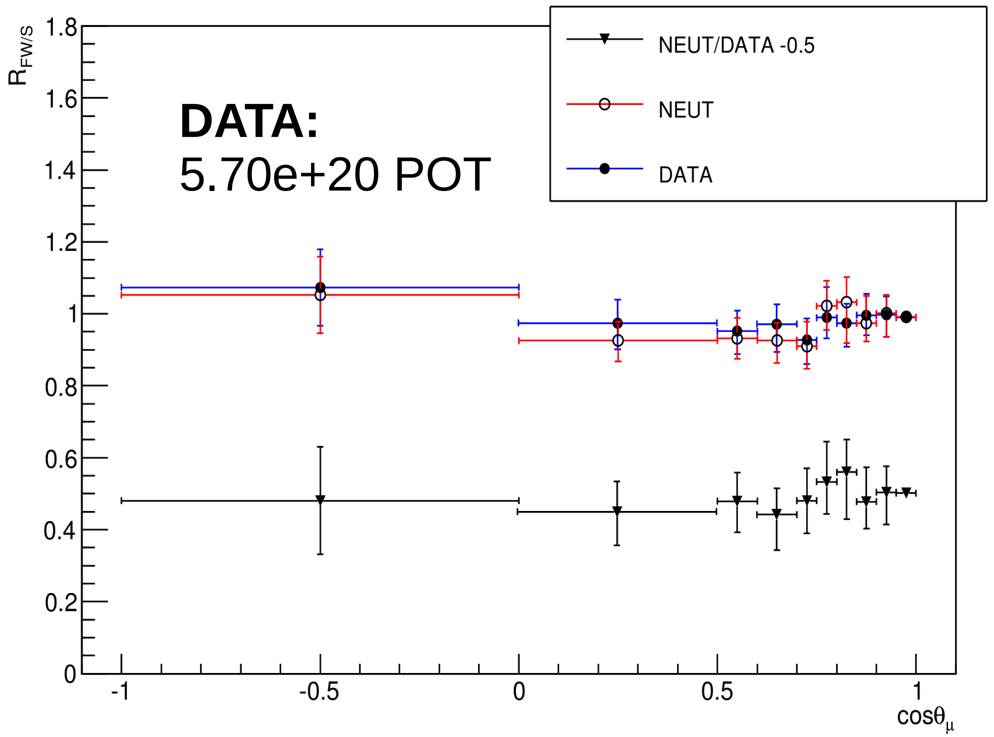
$f_{x,y}^{s,w,fw}$: scintillator, (fake-)water events fractions from MC
xy supermodule off = fake water (fw)
xy supermodule on = scintillator (s)

Results Hybrid FGD1

Momentum



Direction



Integrated

$R_{FW/S}$ (DATA) = 0.995 ± 0.021 (~2.1% stat.) ± 0.021 (~2.1% bkw.) ± 0.009 (~0.9% syst.)

$R_{FW/S}$ (MC) = 0.993 ± 0.021 (~2.1% stat.) ± 0.021 (~2.1% bkw.) ± 0.009 (~0.9% syst.)

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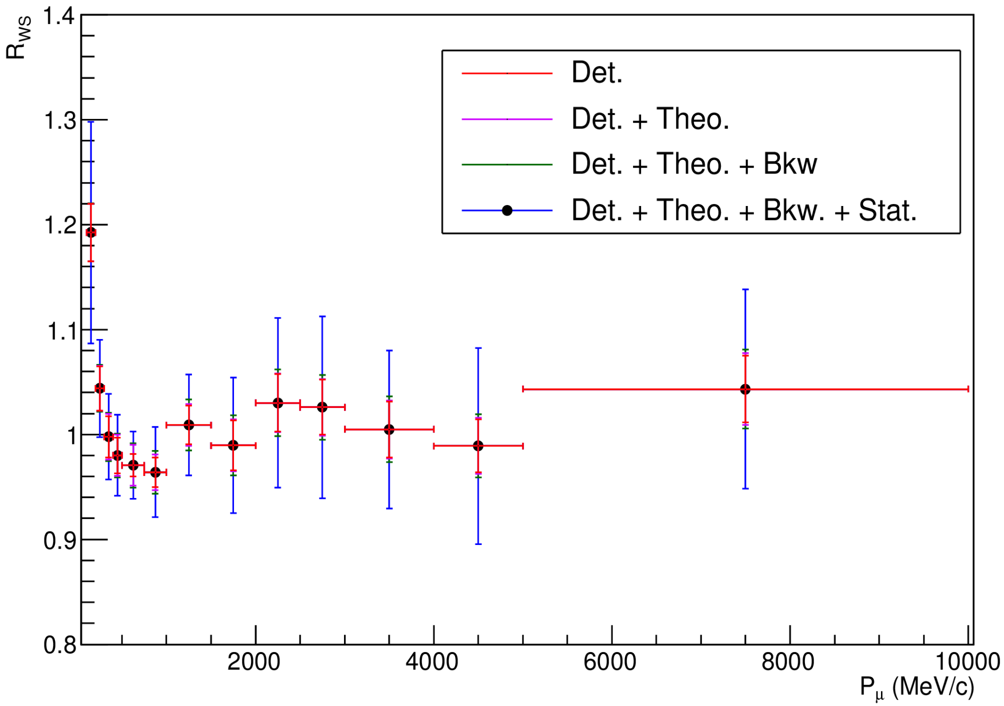
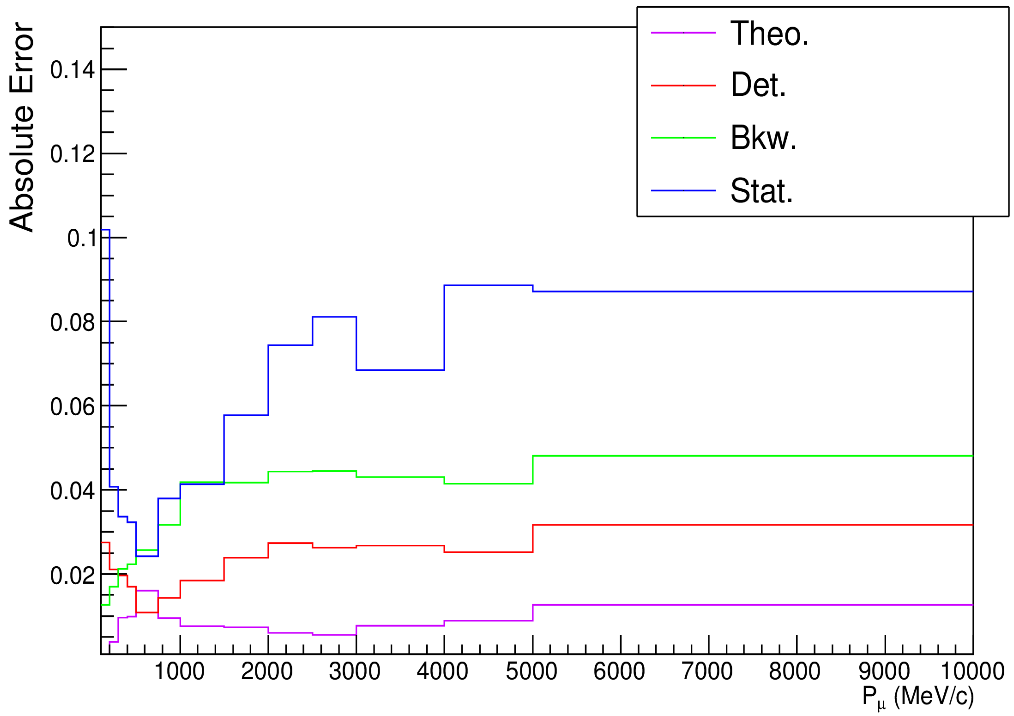
Total error FGD2

Analysis still blind in FGD2





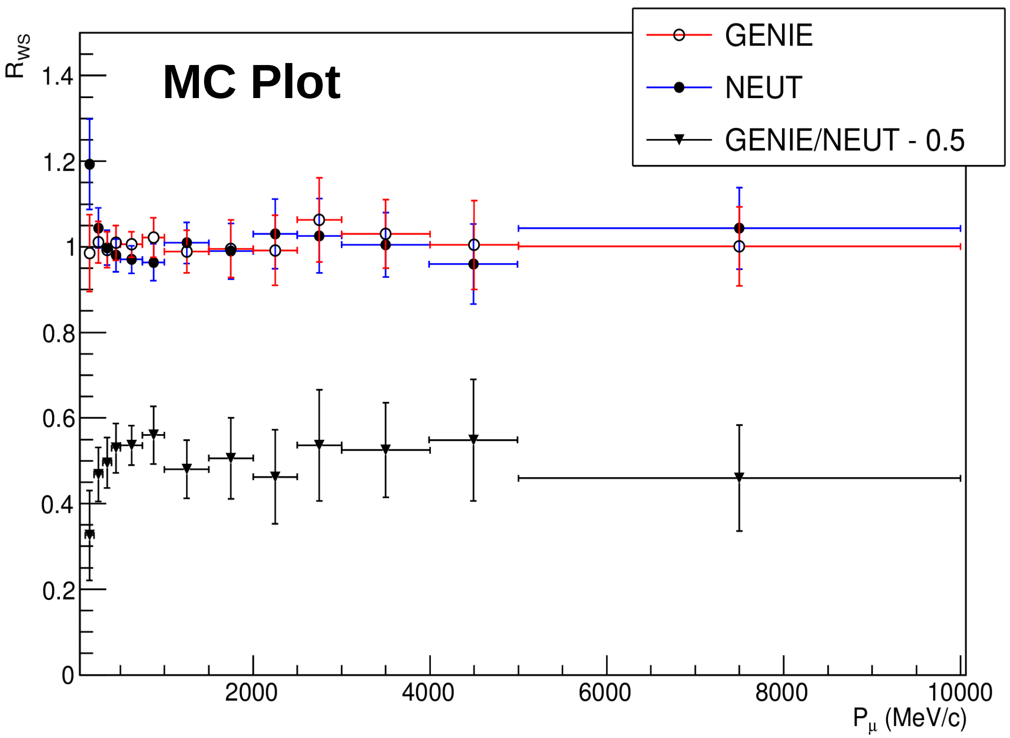
(~2.3% stat.)(~0.9% det.)(~0.9% theo.)(~1.7% bkw.)

Total uncertainty on the integrated value ~3%

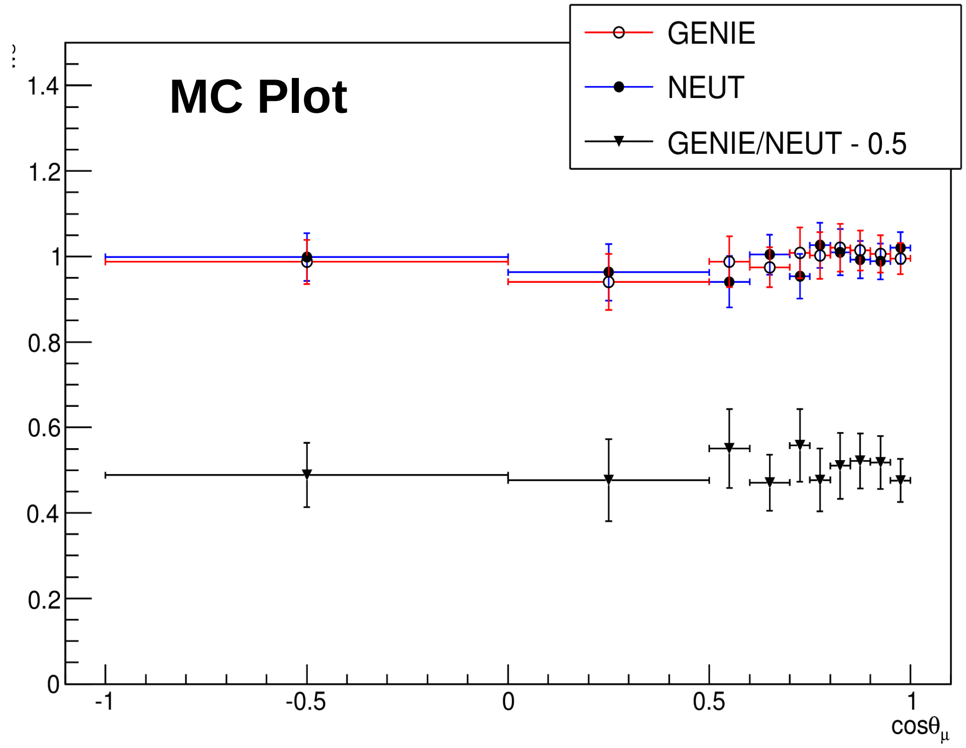
Results FGD2

Analysis still blind in FGD2

Momentum



Direction



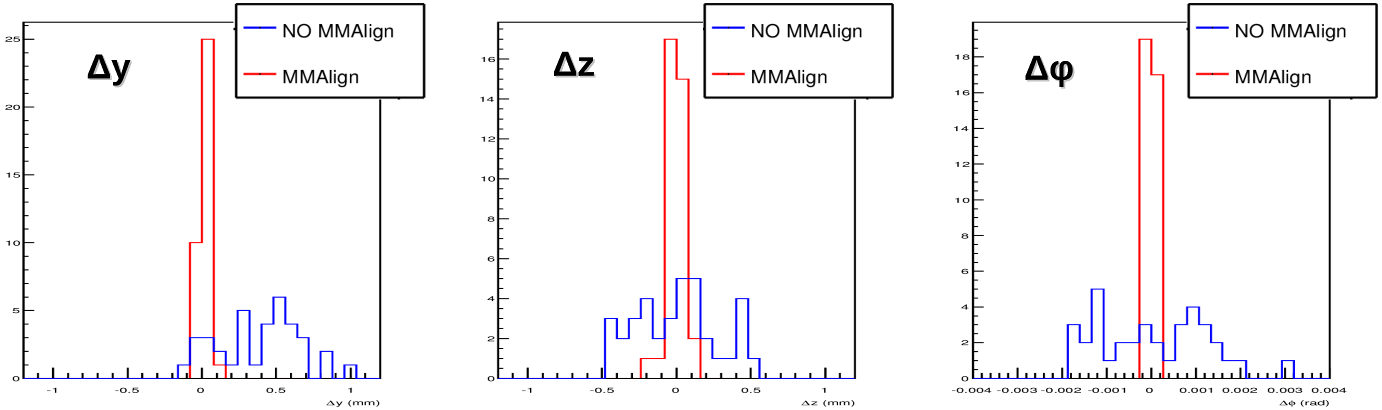
Integrated MC

$R_{W/S}$ (NEUT) = 0.996 ± 0.023(~2.3% stat.) ± 0.009(~0.9% det.) ± 0.009(~0.9% theo.) ± 0.017(~1.7% bkw.)

$R_{W/S}$ (GENIE) = 0.994 ± 0.023(~2.3% stat.) ± 0.012(~1.2% det.) ± 0.016(~1.6% bkw.)

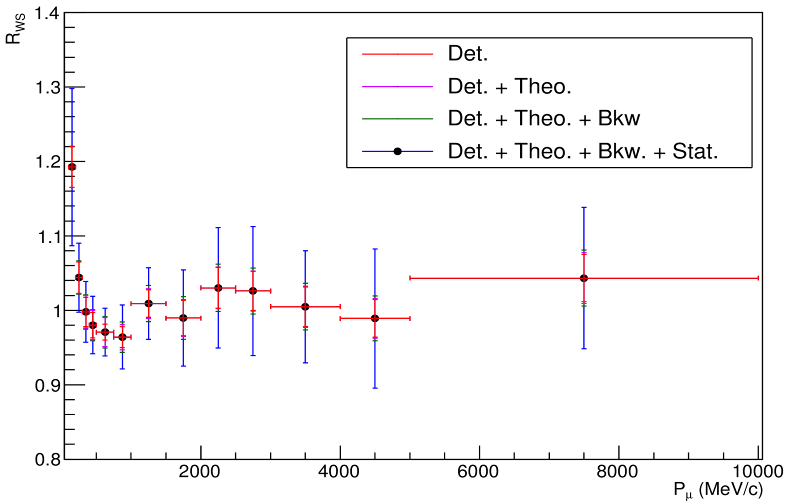
Conclusion

- **T2K** a world leading experiment about neutrino oscillation, new results will come: **stay tuned!**
- MM alignment to improve momentum resolution and **reduce systematics**
- Minuit fit shows a **very good precision** in the corrections extraction



- Water/Scintillator **CCQE-like** cross section ratio
- Results vs kinematics dominated by **statistics**
- Integrated results dominated by **systematics**

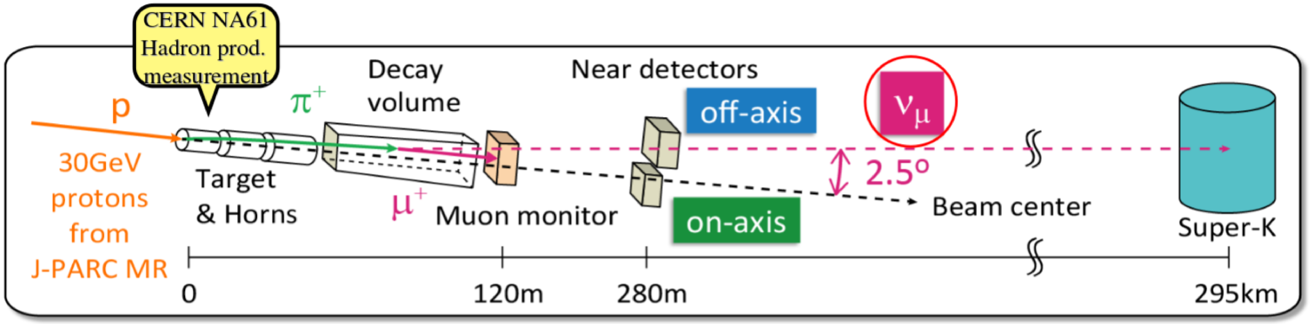
$R_{W/S}$ (NEUT) = 0.996 ± 0.023(~2.3% stat.) ± 0.009(~0.9% det.) ± 0.009(~0.9% theo.) ± 0.017(~1.7% bkw.)

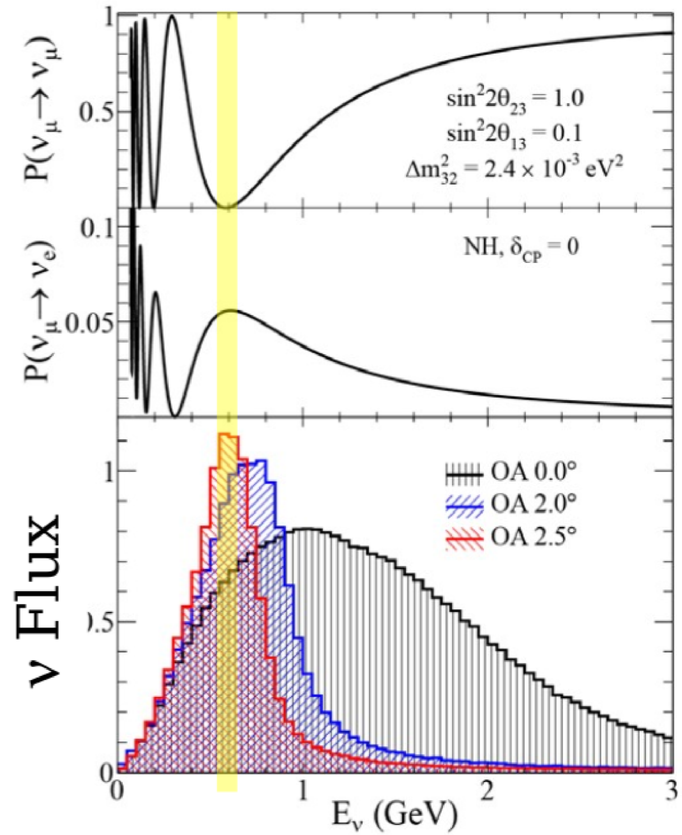


- Data control sample needed to constraint backward track systematic
- Analysis blind -> FGD1 control sample gives successful **closure test at 1% level**

BACKUP

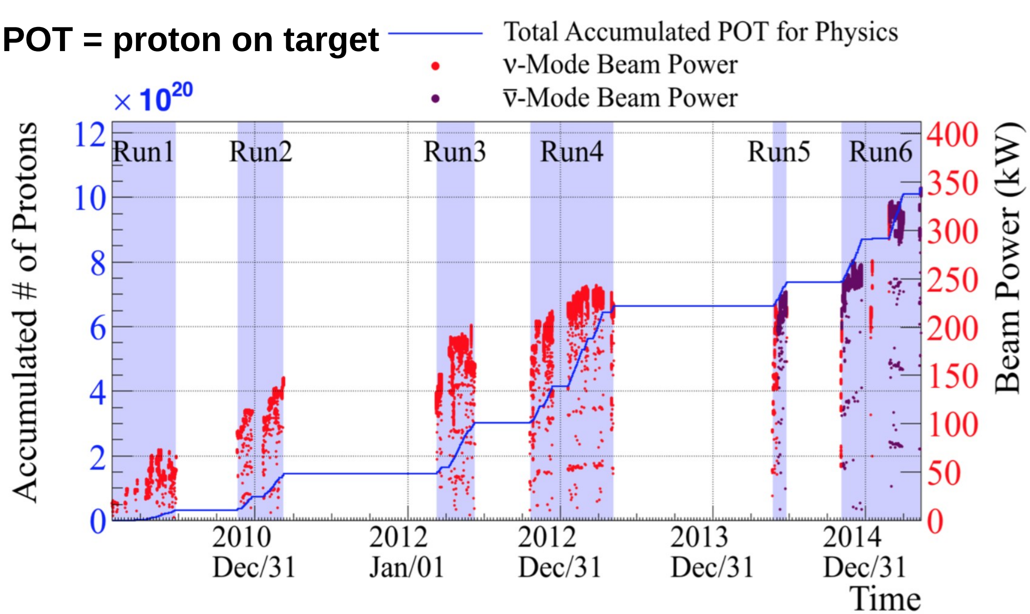
Beam line





- π, K production at target measured by NA61 experiment at CERN (see Matej talk)
- Beam direction stability < 1 mrad
- ν and $\overline{\nu}$ mode changing horn current
- Off-axis beam allows a narrow peak in E_ν to maximize oscillation probability and reduce high energy background

DATA taking Run1-6



Stable operation at ~345kW achieved!

Integrated POT up to 1st June 2015:

- Neutrino mode: 7.0×10^{20} POT
- Antineutrino mode: 4.0×10^{20} POT

T2K goal is 78×10^{20} POT

Analysis strategy

Neutrino Flux

Beam line simulation

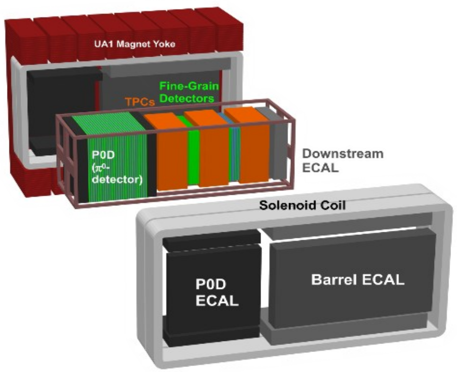
External Hadron production data
NA61/SHINE

Beam monitor measurement
INGRID

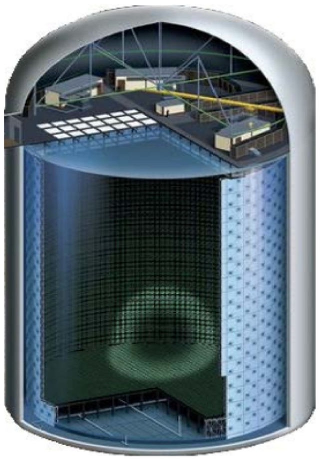
Neutrino Interactions

Interaction model tuned
NEUT

Constrained using external data
MiniBooNe & Minerva



ND280 prediction



ND280 measurement

Measure ν interaction

Fit to ND280 data to reduce the flux and cross section uncertainties

Super-K prediction

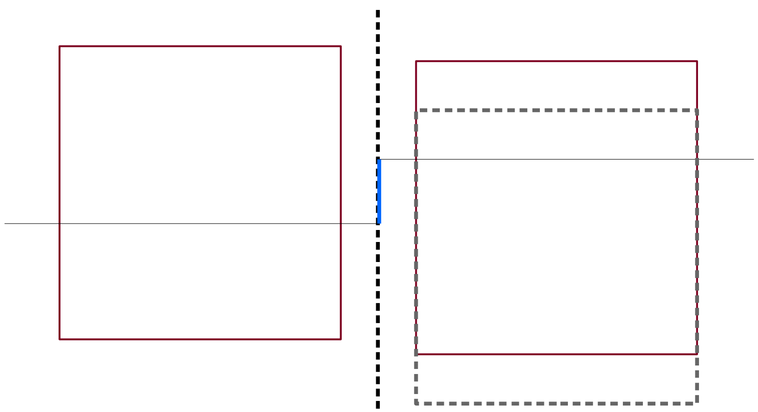
Oscillation fit

Super-K data

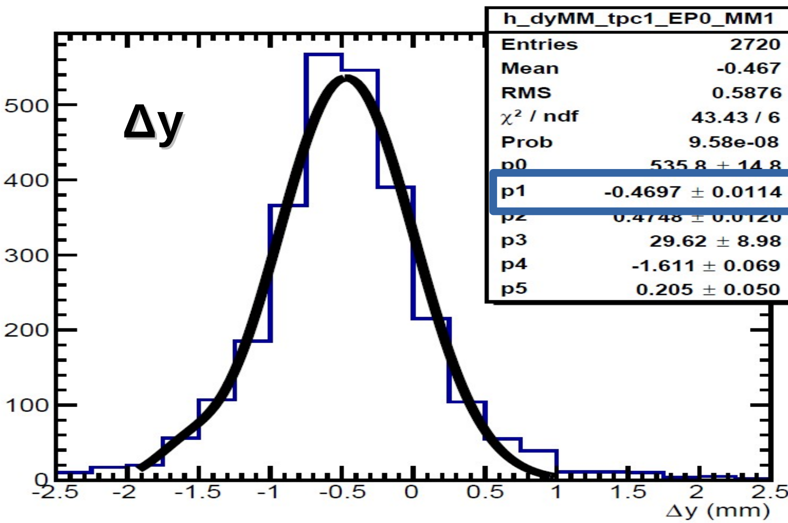
ν_μ and ν_e candidates

Strategy I

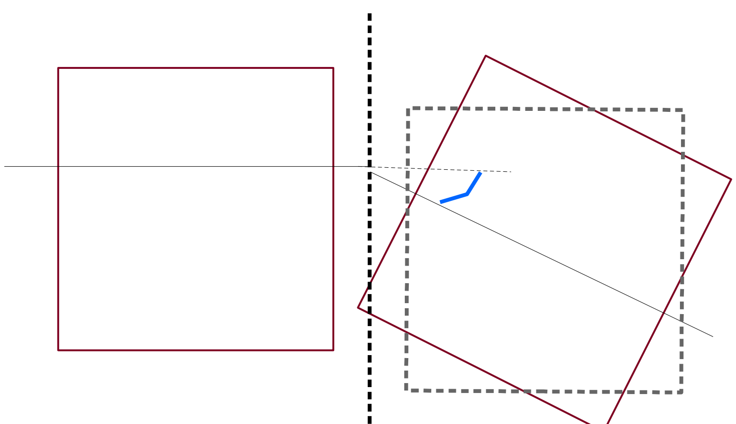
- Cosmic rays collected with magnetic field off
- Reconstruct straight track in each module separately
- Match tracks in the middle plane between adjacent MM modules and extract residuals Δy, Δφ
- Horizontal tracks constraint translational misalignment (vertical dy, horizontal dz) and rotation dφ



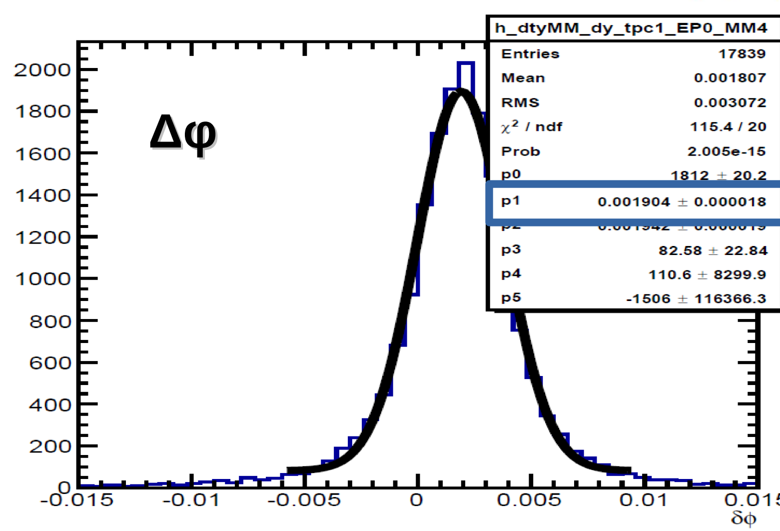
$\Delta y = y_{MMi} - y_{MMj}$



-0.470 μm



$\Delta\varphi = \varphi_{MMi} - \varphi_{MMj}$

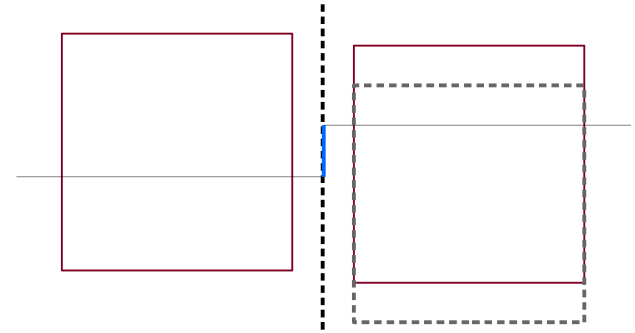


1.904 mrad

Strategy II

- Correction extracted via a fit to the residuals

$$\chi^2 = \chi^2_{\Delta y} + \chi^2_{\Delta\phi} \qquad \chi^2_\Delta = \sum^{n_{tracks}} \left(\frac{\Delta + f_\Delta}{\sigma_\Delta}\right)^2$$

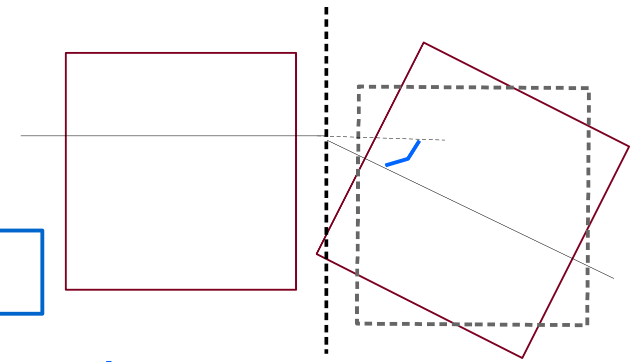


$\Delta y = y_{MMi} - y_{MMj}$

- Minimize χ^2 function who depends from:

$$\text{residual } \Delta = \Delta y,\ \Delta\phi$$
$$\text{total correction } f_\Delta = traslation + rotation$$

- Total correction depends on dy, dz, dφ



$\Delta\varphi = \varphi_{MMi} - \varphi_{MMj}$

$$f_{\Delta y}\left(y_{MM_i}, y_{MM_j}, z_{MM_i}, z_{MM_j}, \phi_{MM_i}, \phi_{MM_j}\right) = \left(y_{MM_i} - y_{MM_j}\right) - \left(z_{MM_i} - z_{MM_j}\right) tan\left(\phi_{MM}\right) - \left(\phi_{MM_i} - \phi_{MM_j}\right)\left(\frac{d+L}{2} - y_{MM_i} tan\left(\phi_{MM}\right)\right)$$

$$f_{\Delta\phi}\left(\phi_{MM_i}, \phi_{MM_j}\right) = \left(\phi_{MM_i} - \phi_{MM_j}\right)$$

- Rotations and translations could be corrected separately running the minuit fit in two steps:

First step:

a) Rotation corrections extraction $\qquad \chi^2 = \cancel{\chi^2_{\Delta y}} + \chi^2_{\Delta\phi}$

Second step:

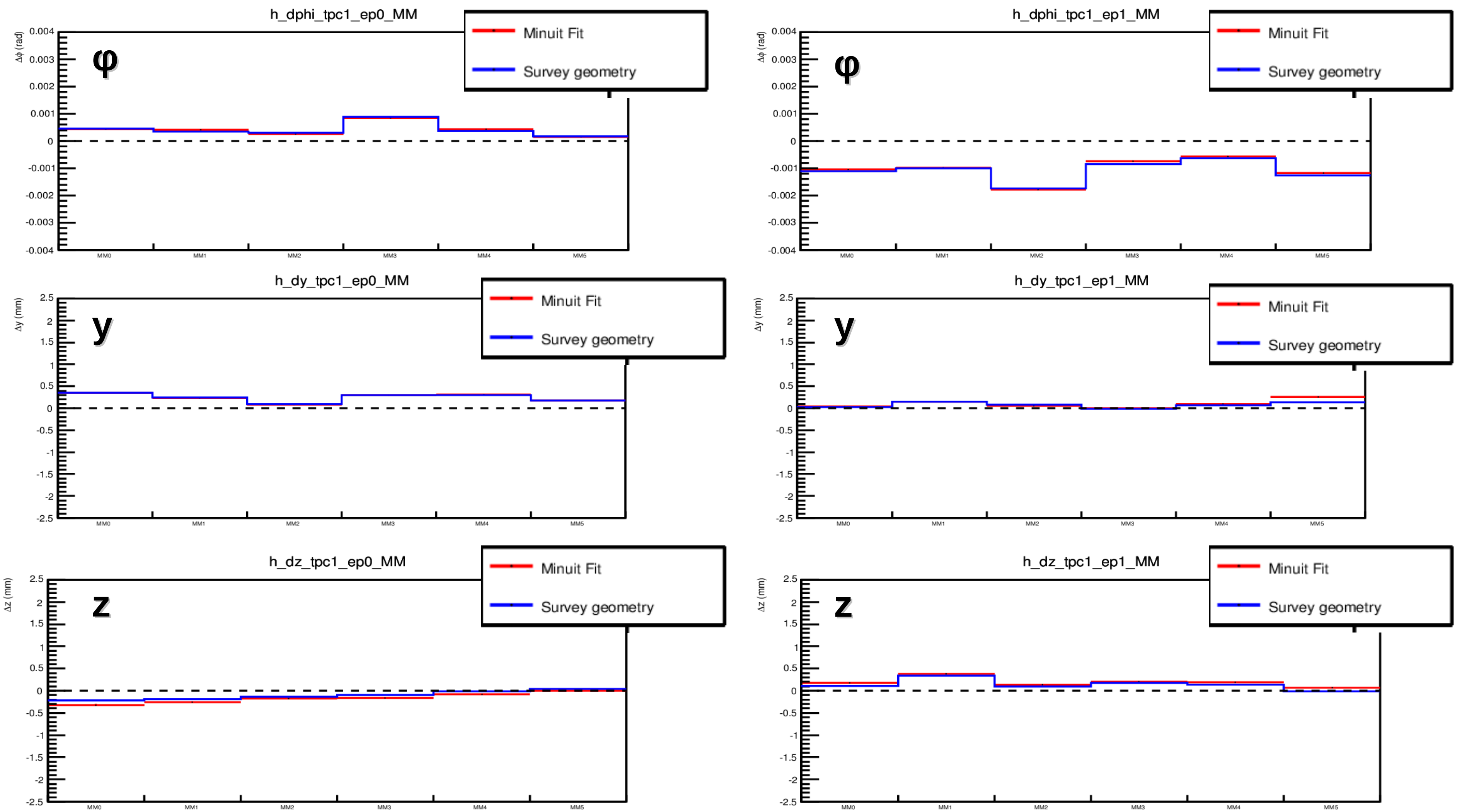
a) Translational corrections extraction, Once rotational ones are applied

b) Put together translational and rotational corrections and apply to the sample $\qquad \chi^2 = \chi^2_{\Delta y} + \chi^2_{\Delta\phi}$

MC test geometry

- Few hundred microns in y and z direction and few mrad for rotation from laser monitor system (survey)
- Minuit fit has to be very sensitive
- Survey like geometry generation to test the fit

EP0 **EP1**



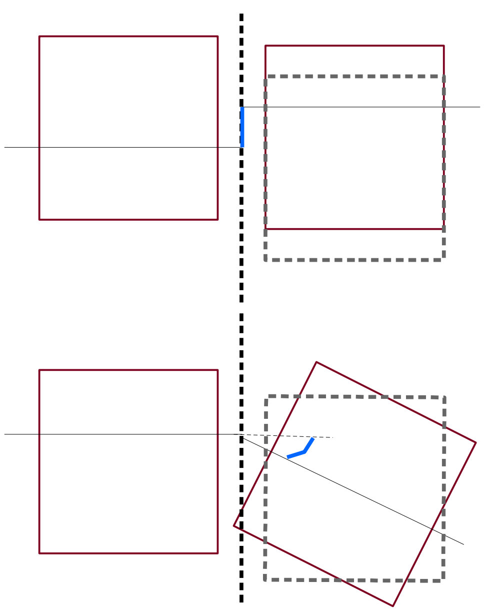
DATA Run2-4

Global Run2	run number	sub-run
Track ~ 33k	00006606	0000-0038
	00006646	0000-0017
	00007714	0000-0102

Global Run3	run number	sub-run
Track ~ 37k	00008215	0000-0111
	00008306	0000-0097
	00008465	0000-0071
	00008520	0000-0040
	00008765	0000-0016
	00008783	0000-0044

Global Run4	run number	sub-run
Track ~ 18k	00009730	0000-0017
	00009731	0000-0025
	00009732	0000-0005
	00009738	0000-0002
	00009739	0000-0038
	00009748	0000-0038

Cuts



Track quality

Tracks

$10^{-5} < \chi^2/ndf < 0.5$

$20 < \#hits < 50$

$\Delta y = y_{MMi} - y_{MMj}$

$\Delta \varphi = \varphi_{MMi} - \varphi_{MMj}$

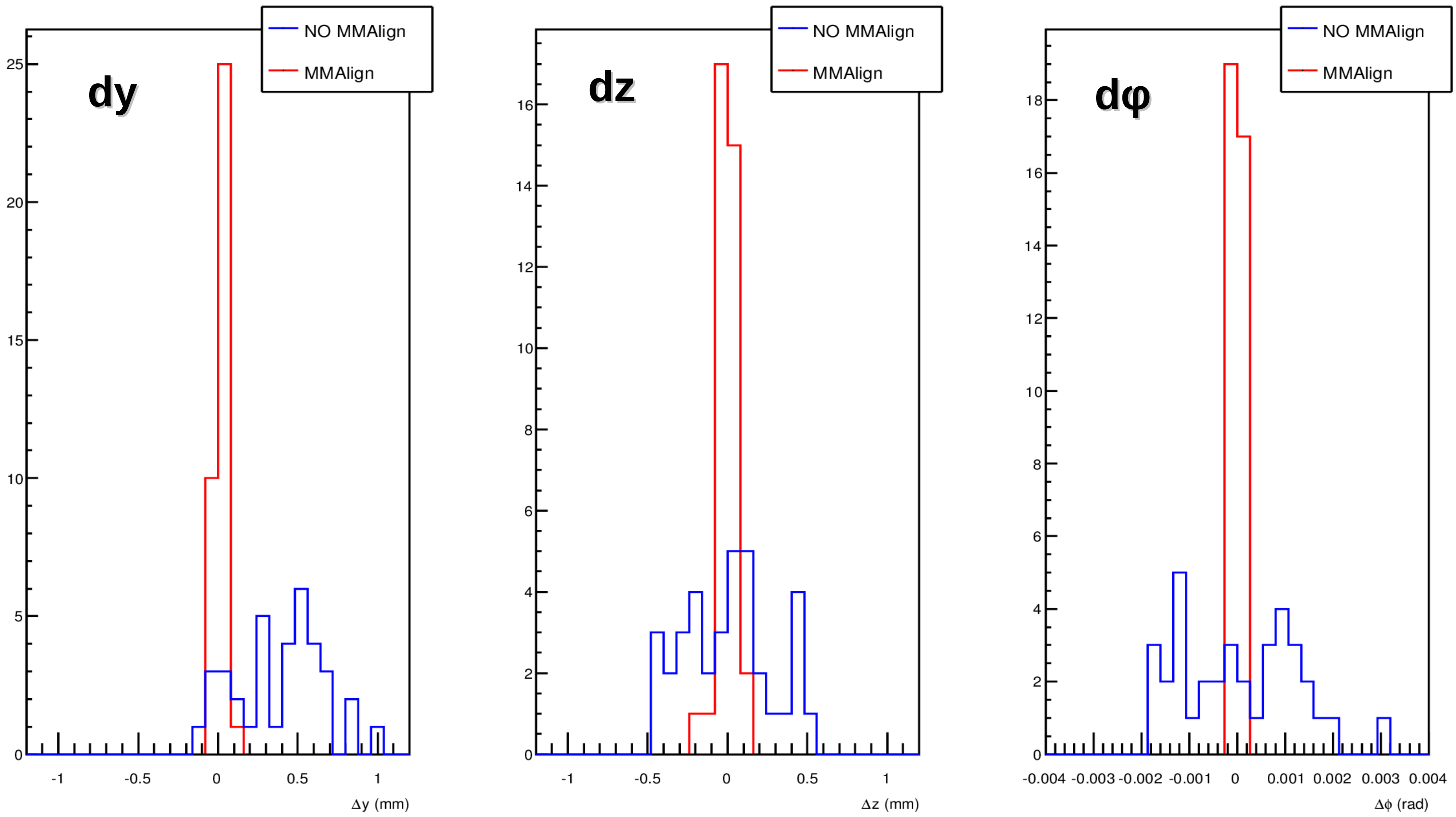
Cuts

$|\varphi| < 1.$ rad

$|\Delta\varphi| < 0.015$ rad

$|\Delta y| < 2.5$ mm

Before/After Alignment



Good precision in corrections extraction
Narrow misalignment distributions after corrections

TPC1

TPC1 EP0	NoMMAlign Δ z	MMAlign Δ z	NoMMAlign Δ y	MMAlign Δ y	NoMMAlign Δ ϕ	MMAlign Δ ϕ
MM0	0.108851 $\pm$ 0.028290	0.013258 $\pm$ 0.025922	0.471934 $\pm$ 0.018374	0.033625 $\pm$ 0.016748	0.001197 $\pm$ 0.000053	0.000047 $\pm$ 0.000053
MM1	0.401032 $\pm$ 0.030078	-0.005274 $\pm$ 0.027099	0.545960 $\pm$ 0.018301	0.006058 $\pm$ 0.016448	0.001112 $\pm$ 0.000056	-0.000042 $\pm$ 0.000056
MM2	0.547888 $\pm$ 0.030224	0.042317 $\pm$ 0.027193	0.242179 $\pm$ 0.016668	-0.002953 $\pm$ 0.014986	0.000924 $\pm$ 0.000058	-0.000014 $\pm$ 0.000059
MM3	0.316078 $\pm$ 0.030495	0.001781 $\pm$ 0.027695	0.302285 $\pm$ 0.017420	-0.005421 $\pm$ 0.015790	0.001383 $\pm$ 0.000067	0.000019 $\pm$ 0.000068
MM4	0.479952 $\pm$ 0.030484	0.019580 $\pm$ 0.027308	0.064669 $\pm$ 0.019617	-0.008037 $\pm$ 0.017809	-0.000164 $\pm$ 0.000074	0.000004 $\pm$ 0.000075
MM5	0.210816 $\pm$ 0.028250	-0.011415 $\pm$ 0.024955	0.095145 $\pm$ 0.020878	-0.018755 $\pm$ 0.018585	0.000485 $\pm$ 0.000078	0.000064 $\pm$ 0.000079
TPC1 EP1	NoMMAlign Δ z	MMAlign Δ z	NoMMAlign Δ y	MMAlign Δ y	NoMMAlign Δ ϕ	MMAlign Δ ϕ
MM0	-0.342023 $\pm$ 0.026703	-0.031210 $\pm$ 0.023957	0.177166 $\pm$ 0.018812	0.005355 $\pm$ 0.017203	-0.001636 $\pm$ 0.000071	-0.000044 $\pm$ 0.000071
MM1	-0.244080 $\pm$ 0.027923	-0.004994 $\pm$ 0.025799	0.267061 $\pm$ 0.018586	-0.009839 $\pm$ 0.017001	-0.001149 $\pm$ 0.000069	-0.000044 $\pm$ 0.000070
MM2	-0.405215 $\pm$ 0.029646	0.000280 $\pm$ 0.026630	0.128533 $\pm$ 0.017096	0.000886 $\pm$ 0.015358	-0.001424 $\pm$ 0.000064	-0.000077 $\pm$ 0.000065
MM3	-0.449940 $\pm$ 0.028758	-0.019226 $\pm$ 0.025903	-0.059783 $\pm$ 0.016741	-0.012044 $\pm$ 0.015113	-0.001085 $\pm$ 0.000062	-0.000052 $\pm$ 0.000063
MM4	-0.213977 $\pm$ 0.030862	-0.023390 $\pm$ 0.026935	-0.032553 $\pm$ 0.019126	-0.003539 $\pm$ 0.016991	-0.000070 $\pm$ 0.000061	-0.000008 $\pm$ 0.000062
MM5	-0.084176 $\pm$ 0.028273	-0.012269 $\pm$ 0.025101	-0.043332 $\pm$ 0.019750	0.001860 $\pm$ 0.017711	0.000102 $\pm$ 0.000061	-0.000008 $\pm$ 0.000062

TPC2

TPC2 EP0	NoMMAlign Δ z	MMAlign Δ z	NoMMAlign Δ y	MMAlign Δ y	NoMMAlign Δ ϕ	MMAlign Δ ϕ
MM0	-0.213742 ± 0.049601	0.058309 ± 0.043866	0.069002 ± 0.027548	-0.005827 ± 0.024703	-0.000779 ± 0.000096	-0.000045 ± 0.000097
MM1	0.090344 ± 0.016270	-0.023209 ± 0.014632	0.495794 ± 0.011548	0.015968 ± 0.010403	0.000915 ± 0.000042	0.000026 ± 0.000043
MM2	0.388374 ± 0.014382	0.016060 ± 0.013136	0.551791 ± 0.011019	0.026125 ± 0.009986	0.002965 ± 0.000040	0.000173 ± 0.000041
MM3	0.158108 ± 0.014737	0.041912 ± 0.013365	0.630022 ± 0.011338	0.005742 ± 0.010238	0.002037 ± 0.000041	0.000127 ± 0.000042
MM4	-0.154447 ± 0.016657	-0.000655 ± 0.015052	0.809814 ± 0.012028	0.034705 ± 0.010883	0.001004 ± 0.000045	0.000041 ± 0.000045
MM5	0.455568 ± 0.049552	0.114960 ± 0.045038	0.646293 ± 0.031072	0.087457 ± 0.028057	0.001741 ± 0.000119	0.000190 ± 0.000120
TPC2 EP1	NoMMAlign Δ z	MMAlign Δ z	NoMMAlign Δ y	MMAlign Δ y	NoMMAlign Δ ϕ	MMAlign Δ ϕ
MM0	0.037891 ± 0.044514	-0.121204 ± 0.039750	0.635492 ± 0.028215	0.055316 ± 0.015136	-0.001277 ± 0.000108	-0.000141 ± 0.000065
MM1	-0.315297 ± 0.015802	-0.016037 ± 0.013794	1.029977 ± 0.011912	0.034237 ± 0.005781	-0.001464 ± 0.000045	-0.000122 ± 0.000025
MM2	-0.476553 ± 0.013745	-0.039681 ± 0.011864	0.671667 ± 0.010973	0.032891 ± 0.008311	-0.000524 ± 0.000041	-0.000023 ± 0.000035
MM3	-0.073700 ± 0.014041	0.002017 ± 0.011697	0.461854 ± 0.011306	0.007611 ± 0.006411	0.000024 ± 0.000042	0.000018 ± 0.000027
MM4	-0.247972 ± 0.015987	0.001915 ± 0.013625	0.818187 ± 0.012021	0.025973 ± 0.006624	-0.001100 ± 0.000045	-0.000054 ± 0.000028
MM5	0.009271 ± 0.046078	-0.205203 ± 0.040922	0.297103 ± 0.029229	-0.029225 ± 0.026166	-0.000079 ± 0.000102	-0.000078 ± 0.000103

TPC3

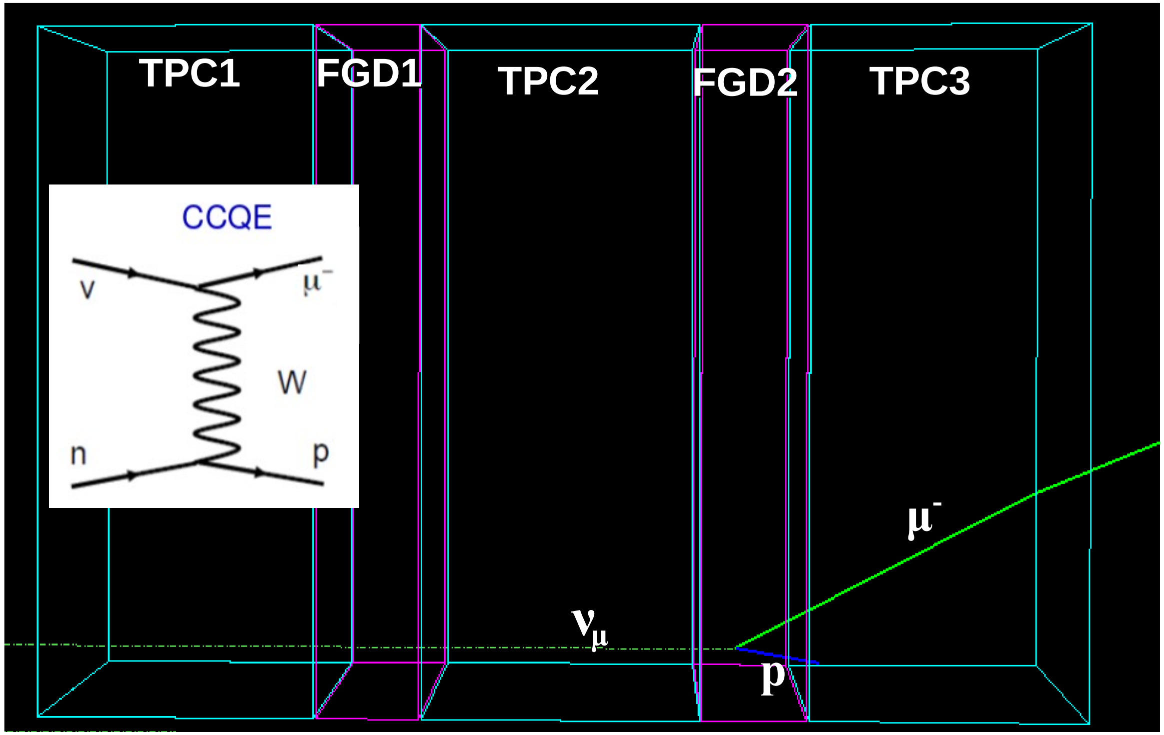
TPC3 EP0	NoMMAlign Δ z	MMAlign Δ z	NoMMAlign Δ y	MMAlign Δ y	NoMMAlign Δ ϕ	MMAlign Δ ϕ
MM0	0.046701 ± 0.034330	-0.009194 ± 0.031032	0.631050 ± 0.022440	0.024914 ± 0.020403	0.001532 ± 0.000083	0.000028 ± 0.000083
MM1	0.062381 ± 0.027536	0.016352 ± 0.025056	0.685843 ± 0.017622	0.040823 ± 0.015901	0.001092 ± 0.000066	0.000052 ± 0.000067
MM2	-0.236283 ± 0.025157	-0.048363 ± 0.022655	0.401804 ± 0.015300	0.030880 ± 0.013843	0.000783 ± 0.000058	0.000029 ± 0.000059
MM3	0.171373 ± 0.025557	-0.011475 ± 0.023135	0.550933 ± 0.015141	0.026979 ± 0.013669	0.000796 ± 0.000052	0.000056 ± 0.000053
MM4	0.111380 ± 0.029336	0.032260 ± 0.026613	0.575856 ± 0.017078	0.038456 ± 0.015408	0.000654 ± 0.000050	0.000038 ± 0.000051
MM5	-0.033039 ± 0.031528	0.084718 ± 0.027800	0.451536 ± 0.019901	-0.015796 ± 0.017658	-0.000539 ± 0.000054	-0.000053 ± 0.000054
TPC3 EP1	NoMMAlign Δ z	MMAlign Δ z	NoMMAlign Δ y	MMAlign Δ y	NoMMAlign Δ ϕ	MMAlign Δ ϕ
MM0	0.005043 ± 0.032974	-0.008223 ± 0.029772	0.251739 ± 0.021743	0.022991 ± 0.019495	-0.001106 ± 0.000061	-0.000020 ± 0.000062
MM1	-0.358676 ± 0.027346	0.040629 ± 0.024748	0.012976 ± 0.016813	0.009350 ± 0.015285	-0.001771 ± 0.000056	-0.000049 ± 0.000056
MM2	-0.231898 ± 0.023562	-0.016213 ± 0.021267	-0.086447 ± 0.014855	0.010104 ± 0.013498	-0.000520 ± 0.000055	0.000017 ± 0.000056
MM3	0.112635 ± 0.023953	0.009396 ± 0.021526	0.529915 ± 0.015362	0.023620 ± 0.013875	-0.001641 ± 0.000059	-0.000035 ± 0.000059
MM4	0.443388 ± 0.027404	0.034965 ± 0.025312	0.490555 ± 0.017327	0.020379 ± 0.015847	-0.000916 ± 0.000063	-0.000055 ± 0.000064
MM5	-0.007251 ± 0.033780	-0.018268 ± 0.031476	0.372092 ± 0.020586	0.045809 ± 0.019005	0.000917 ± 0.000074	0.000069 ± 0.000074

Signal definition

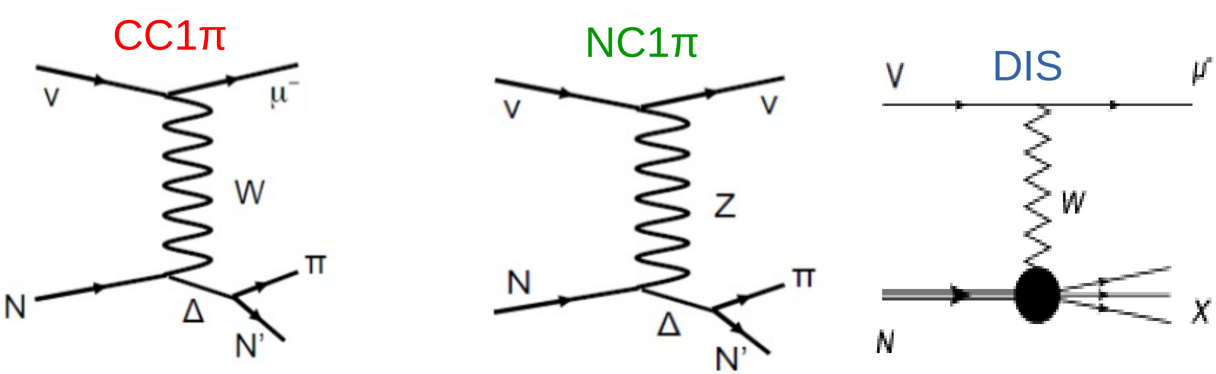
- Standard T2K quality event (good spill, good detector)
- Detector acceptance and tag
  1. HNMT in FGD2 Fiducial Volume (FV)
  2. Tracks quality in TPC
  3. External veto cut on FGD2
  4. Muon PID

$$L_{MIP} = \frac{L_\mu + L_\pi}{1 - L_p} > 0.8 \qquad L_\mu > 0.05$$

  5. No pion in the final state



Backgrounds:
- Charged current single pion production (CC1π)
- Neutral current single pion production (NC1π)
- Deep inelastic scattering (DIS)
- Out of fiducial volume interaction (OOFV)



Backward systematic

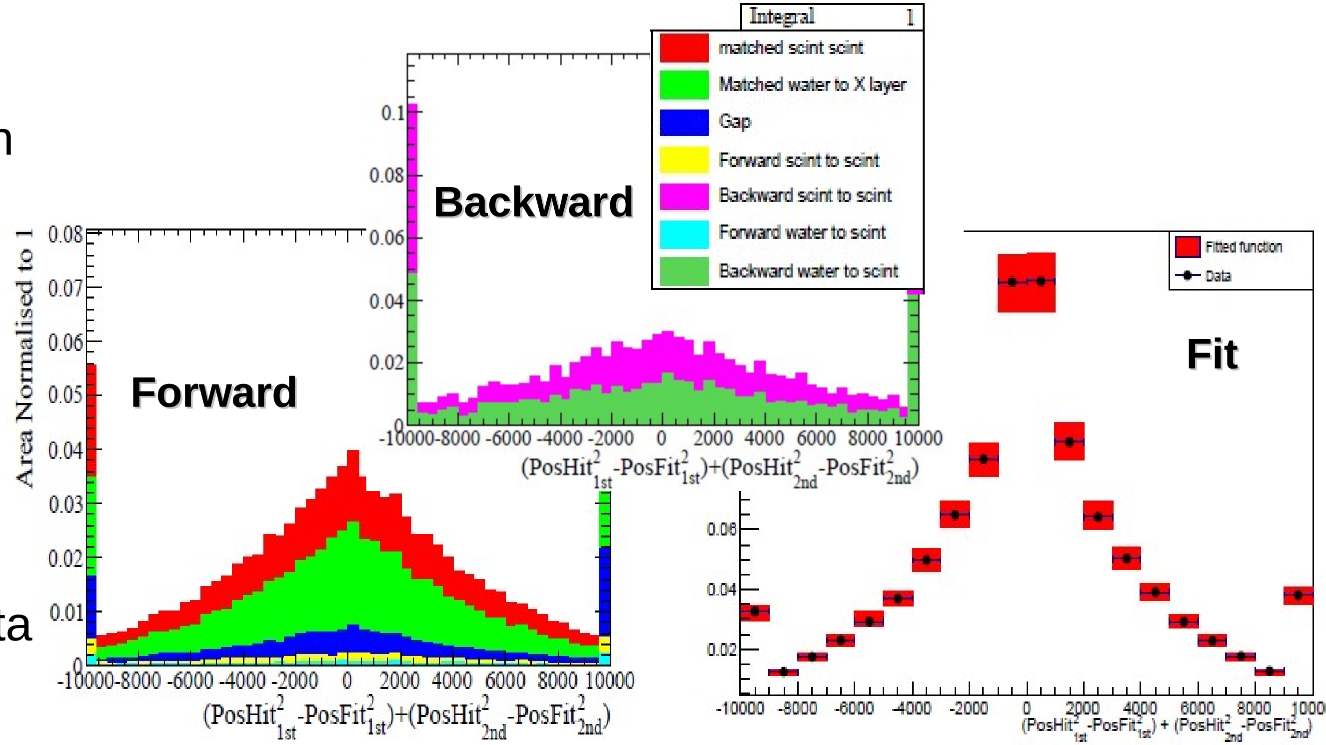
Strategy

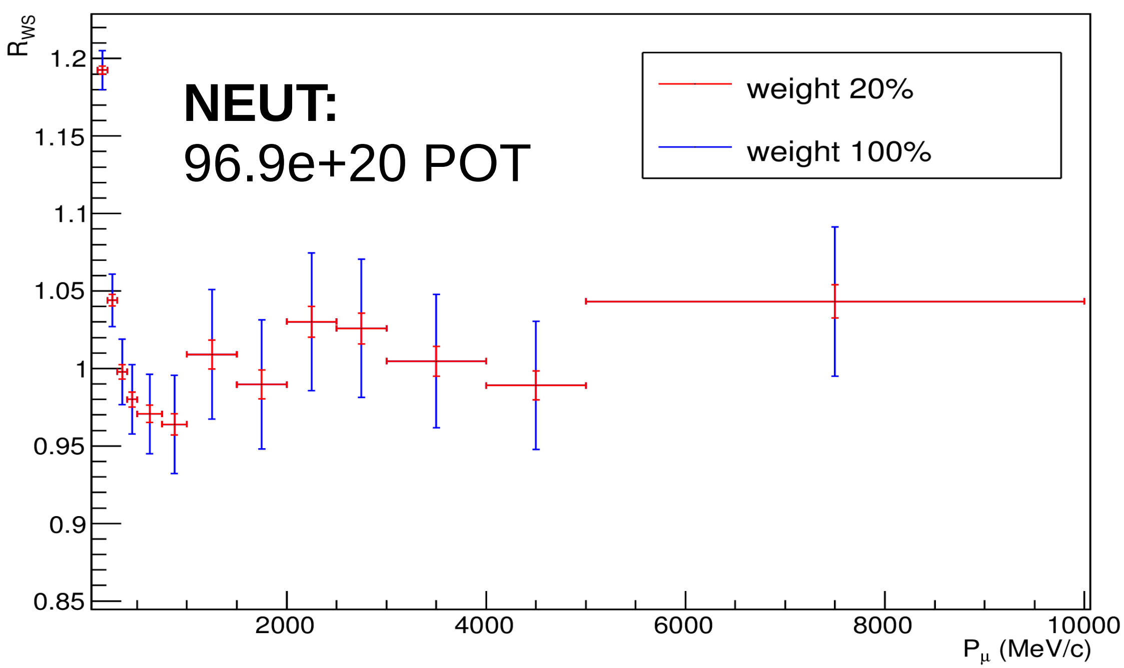
- In backward tracks first hit position and fitted tracks are offset
- Migrated and not migrated events have a different 1st hit distritbution

$$f_{MC}(X)^{\text{non migrated}} + \beta \times f_{MC}(X)^{\text{migrated}}$$

$$\beta_4 = 0.1068 \pm 0.0222(20.8\,\%)$$

- reweight backward events
- ± 20% from fit on CC-inclusive data
- ± 100% extreme hypothesis





NEUT

±20%: ~0.7 %

±100%: ~3.5 %

Amount of backward tracks is basically unknown, it need to constraint it from control sample in data.

FGD1

FGD1 control sample

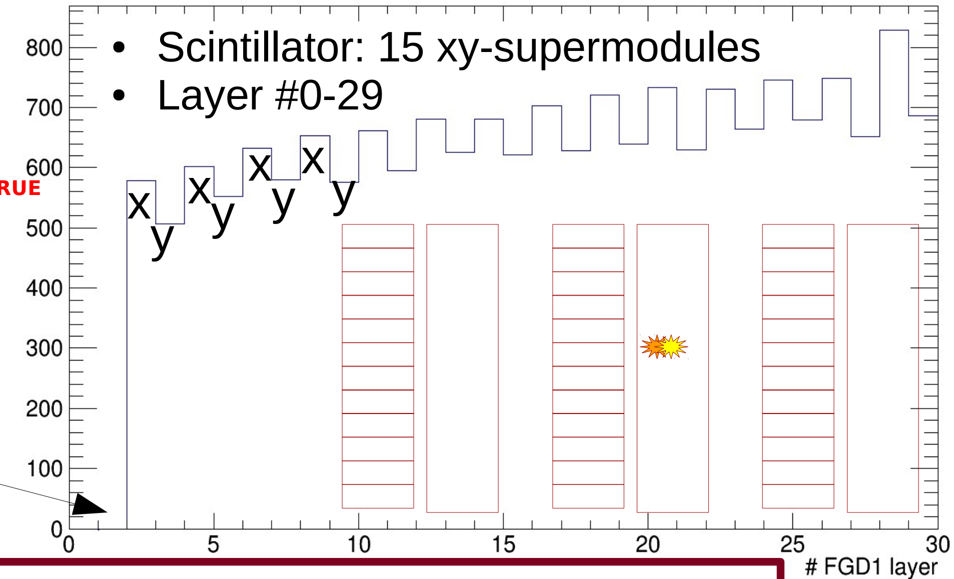
True vertex layer
Reco vertex layer

Ratio x-layer/y-layer

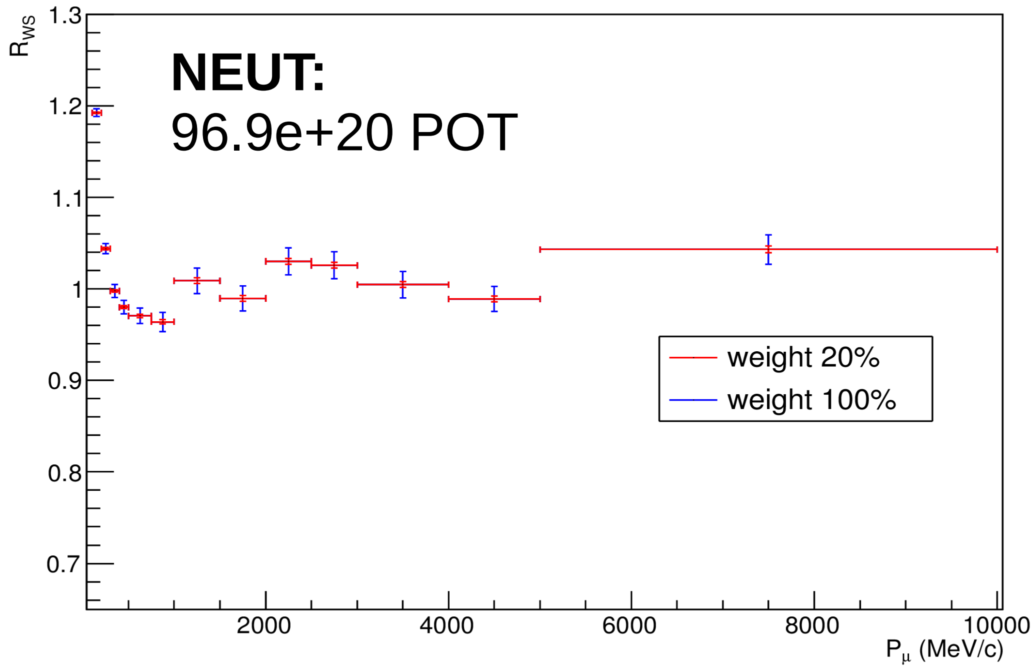
Ratio in FGD1 must be 1 (CH/CH)

$$R_{x/y} = \left(\frac{N_X f_x^{CC0\pi} f_x^{x} + N_Y f_y^{CC0\pi} f_y^{x}}{N_X f_x^{CC0\pi} f_x^{y} + N_Y f_y^{CC0\pi} f_y^{y}} \right) \Bigg|_{(P_\mu,\, \cos\theta_\mu,\, E_\nu)^{TRUE}} \frac{\varepsilon_s}{\varepsilon_w} \frac{N_n^s}{N_n^w}$$

Out of FV
Layers 0,1



Any difference from 1 can be used to constraint the systematics



FGD1

±20%: ~0.3% on the ratio $R_{x/y}$

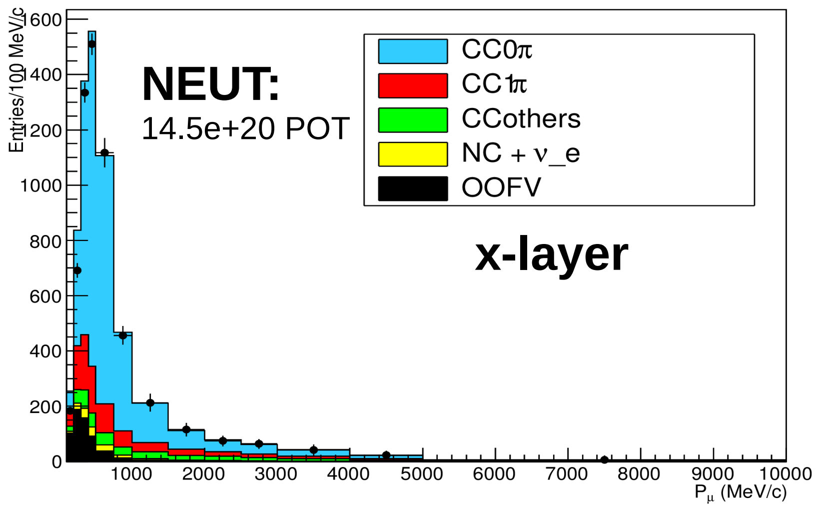
±100%: ~1.5% on the ratio $R_{x/y}$

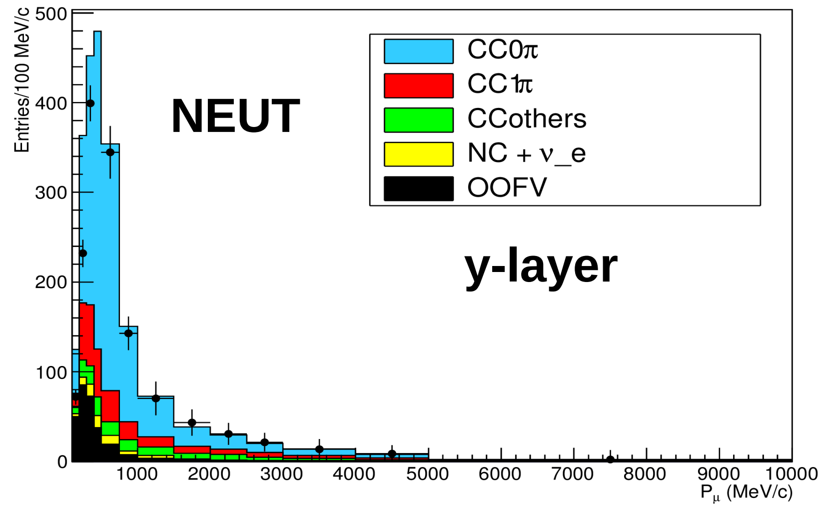
Switch off one xy-supermodule in succession every two in FGD1 to properly simulate reconstruction effect.

Hybrid FGD1

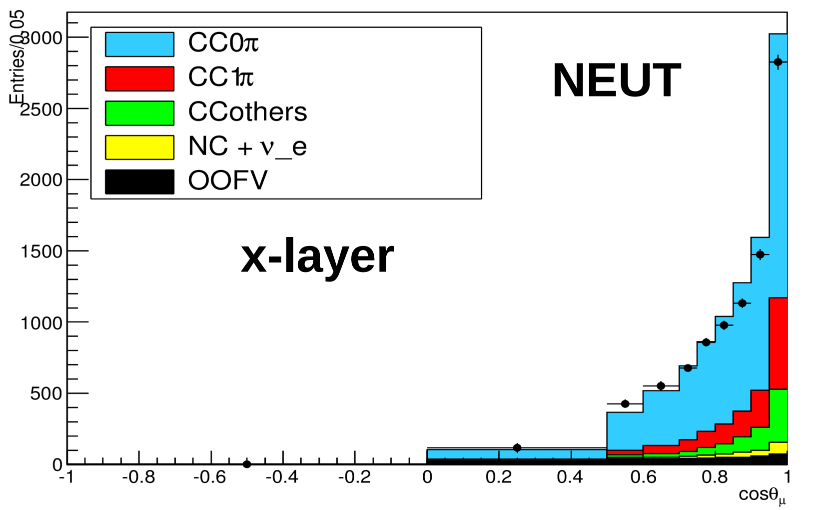
CC0π Hybrid FGD1 sample

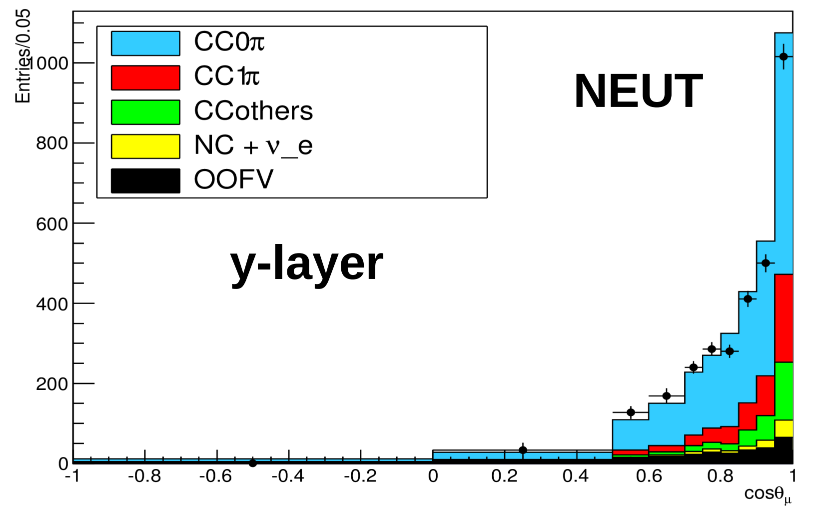
Momentum





Direction



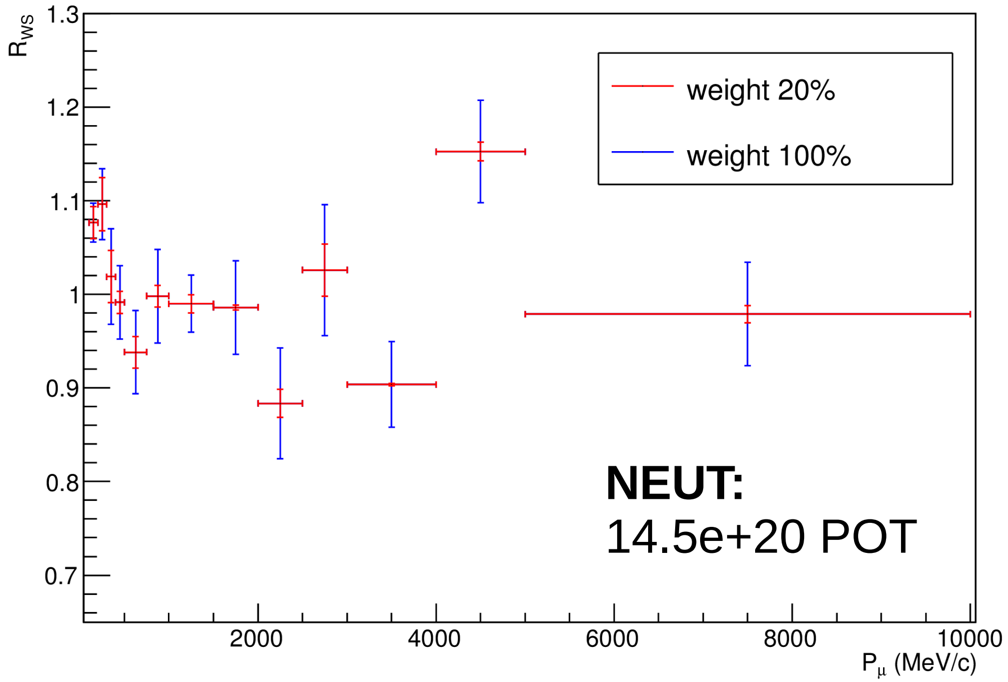


NEUT	Water	Scintx	Scinty	Dead
Hybrid FGD1-x	51.9	26.6	6.18	15.4
Hybrid FGD1-y	13.4	4.51	70.1	12.0
FGD1-x		68.9	15.1	16.0
FGD1-y		13.5	73.2	13.3

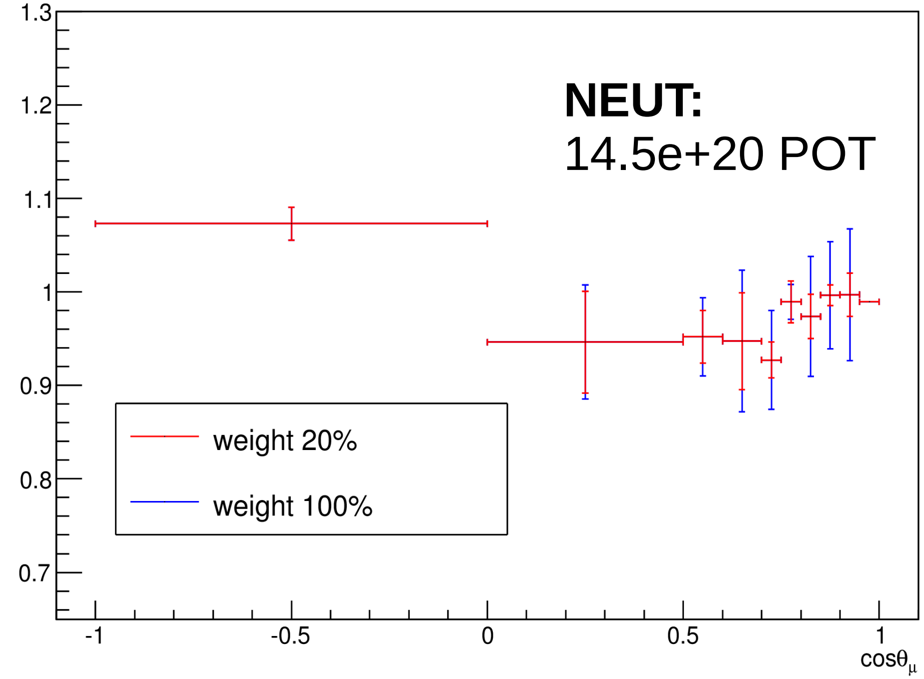
In Hybrid FGD1 x,y-layer enhanced by "water"

Backward systematics

Momentum



Direction



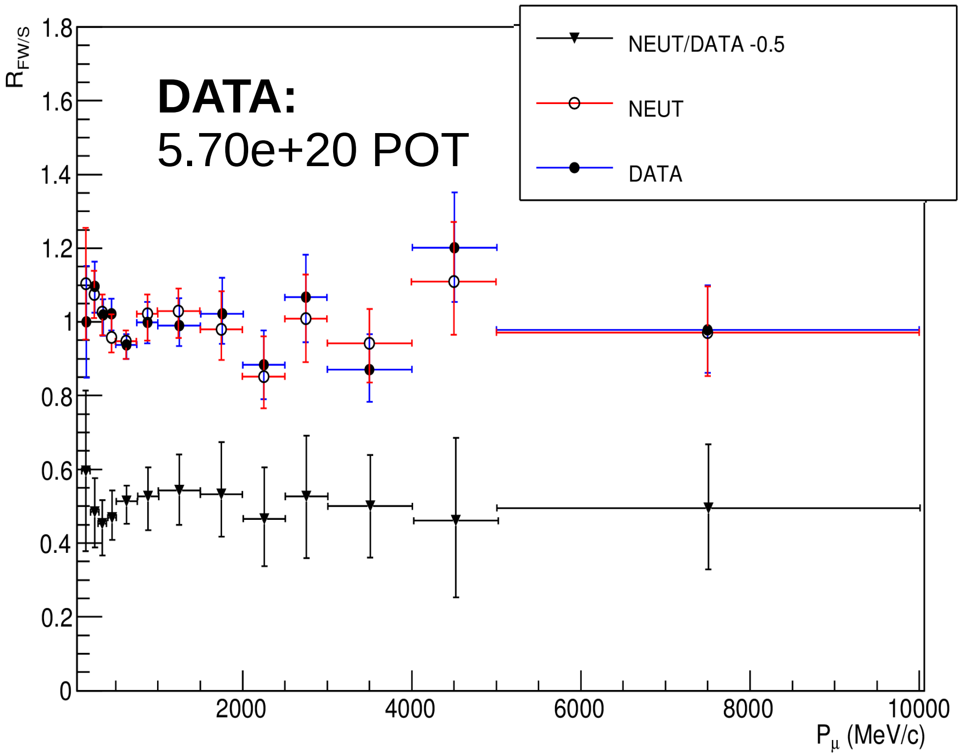
	FGD1	Hybrid FGD1	FGD2	
±20%:	~0.3%	~1.0%	~0.6%	on the ratio $R_{x/y}$
±50%:		~2.1%	~1.7%	on the ratio $R_{x/y}$
±100%:	~1.5%	~ 3.9%	~ 3.5%	on the ratio $R_{x/y}$

Hack the FGD1 brings similar results as in FGD2 on backward systematics.

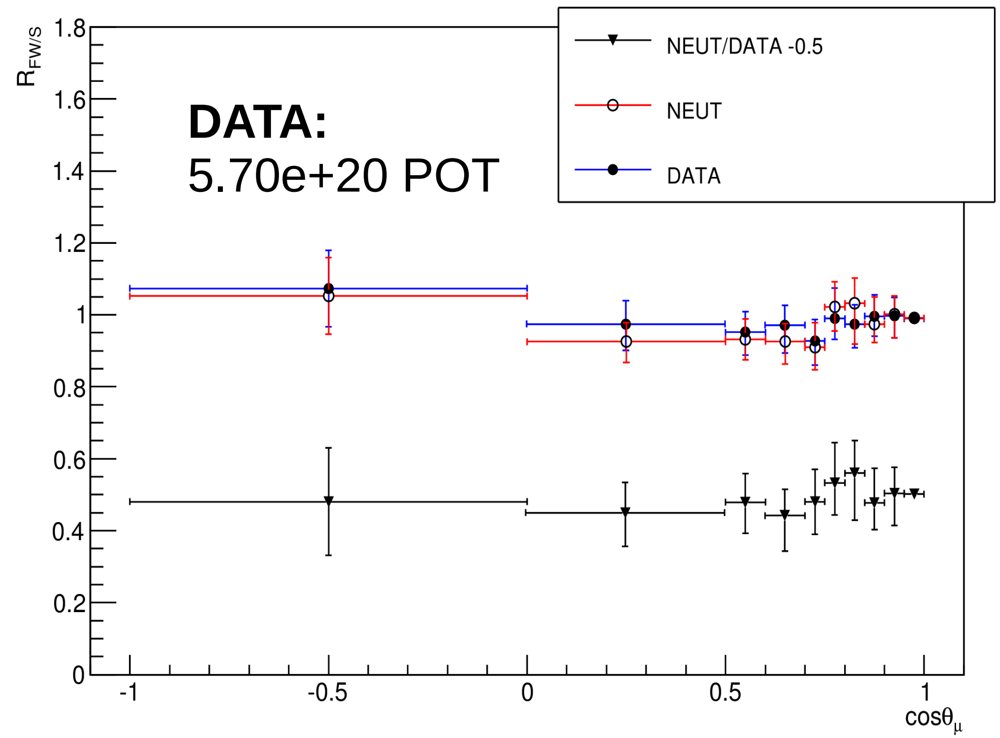
Results Hybrid FGD1

	FGD1	Hybrid FGD1	FGD2	
±20%:	~0.3%	~1.0%	~0.6%	on the ratio $R_{x/y}$
±50%:		~2.1%	~1.7%	on the ratio $R_{x/y}$
±100%:	~1.5%	~ 3.9%	~ 3.5%	on the ratio $R_{x/y}$

Momentum



Direction



Integrated

$R_{FW/S}$ (DATA) = 0.995 ± 0.021 (~2.1% stat.) ± 0.021 (~2.1% bkw.) ± 0.009 (~0.9% syst.)

$R_{FW/S}$ (MC) = 0.993 ± 0.021 (~2.1% stat.) ± 0.021 (~2.1% bkw.) ± 0.009 (~0.9% syst.)

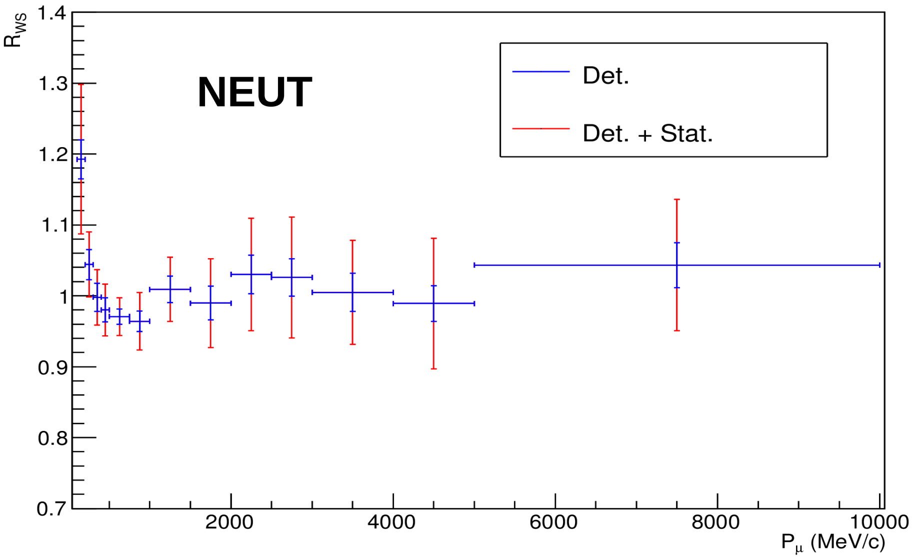
Detector systematics

	FGD2(NEUT) [%]	FGD2(GENIE) [%]	Hybrid FGD1(NEUT) [%]
BFiled	0.003	0.007	0.002
MomResolution	0.082	0.103	0.264
MomScale	0.008	0.005	0.005
TPCPID	0.453	0.514	0.496
TPCClusterEff	$> 10^{-6}$	$> 10^{-6}$	$> 10^{-6}$
TPCTrackEff	0.121	0.140	0.134
TPCFGDMatchEff	0.029	0.020	0.028
ChargeID	0.351	0.408	0.302
Michelelectron	0.002	0.003	0.003
OOFV	0.258	0.394	0.384
PileUp	0.004	0.003	0.006
πSI	0.109	0.179	0.187
FGDMass	Estimated from the number of neutron in the FV		
allsyst	0.88	1.22	0.94

Integrated

NEUT: ~2.3 % stat.
~0.9% syst.
GENIE: ~2.3% stat.
~1.2% syst.

Systematic error: order of percent in each bin and less than 1% integrated

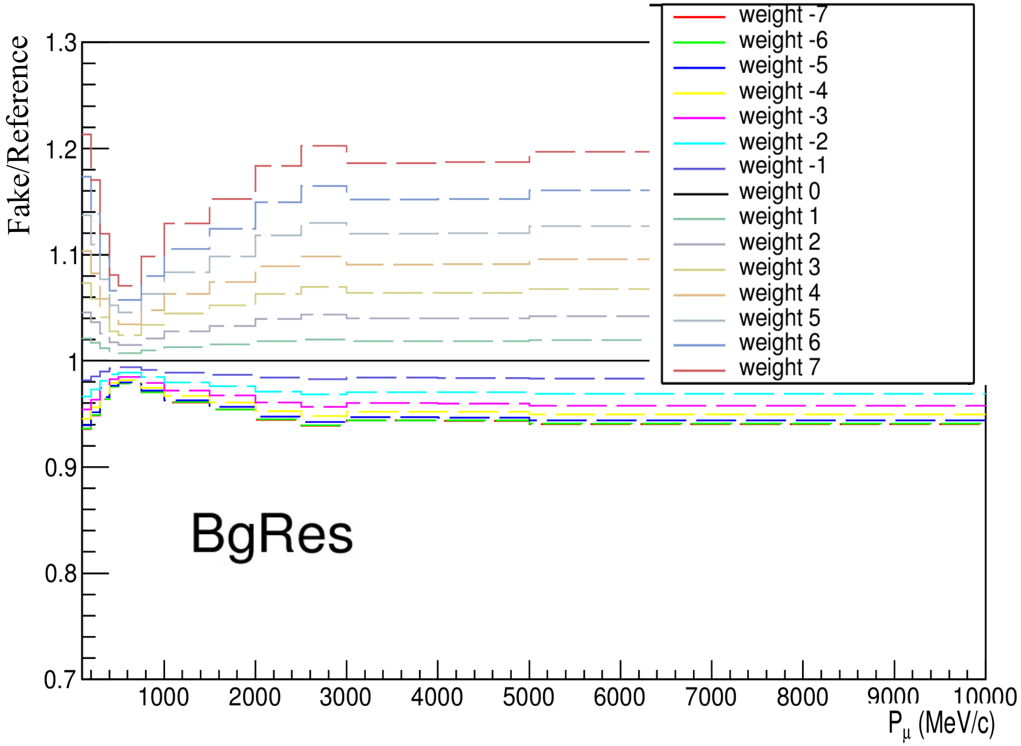


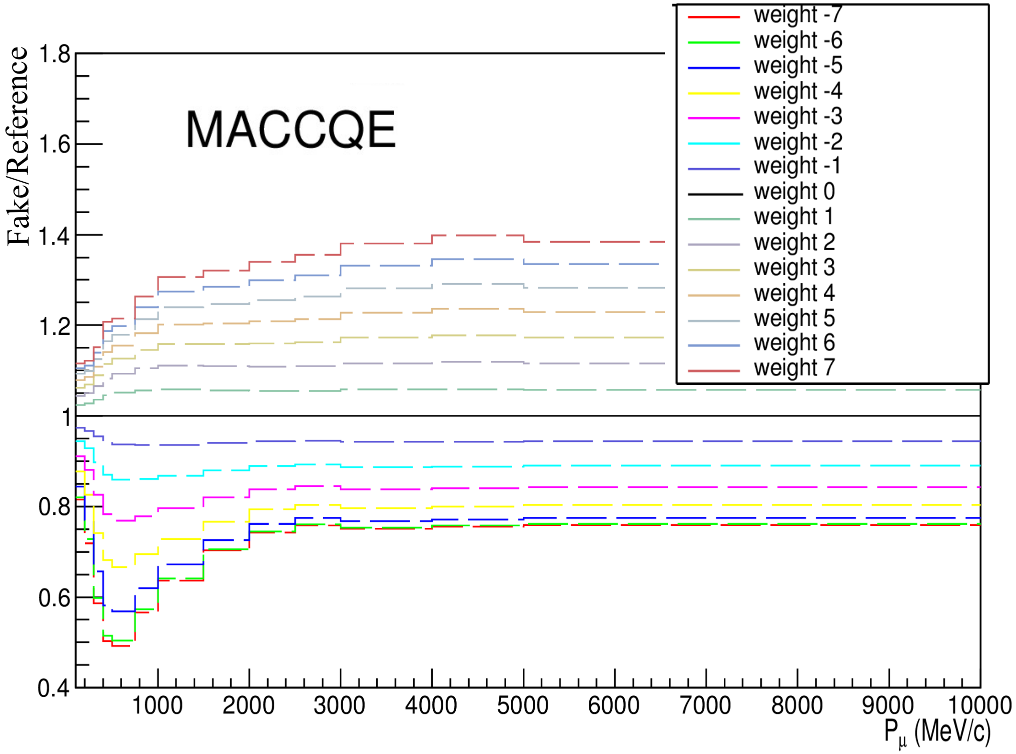
Theoretical systematics (I)

- Taken into account theoretical parameters in BANFF 2015
- Splitted parameters for C and O
- Reweighted sample to estimate the systematics

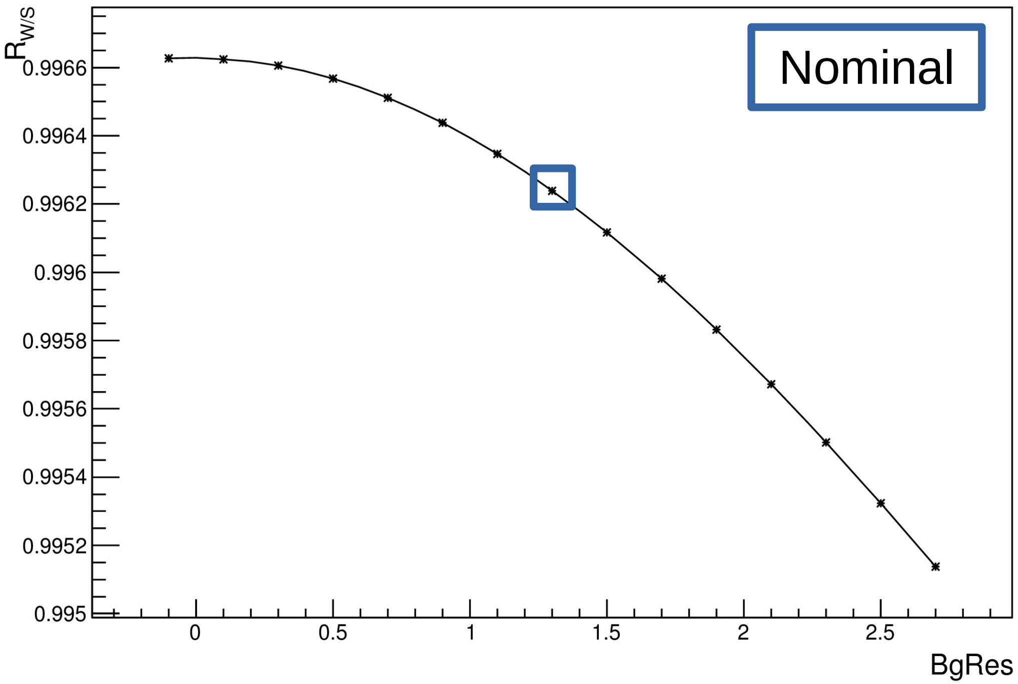
Reference sample: NEUT
Fake dataset: reweighted NEUT

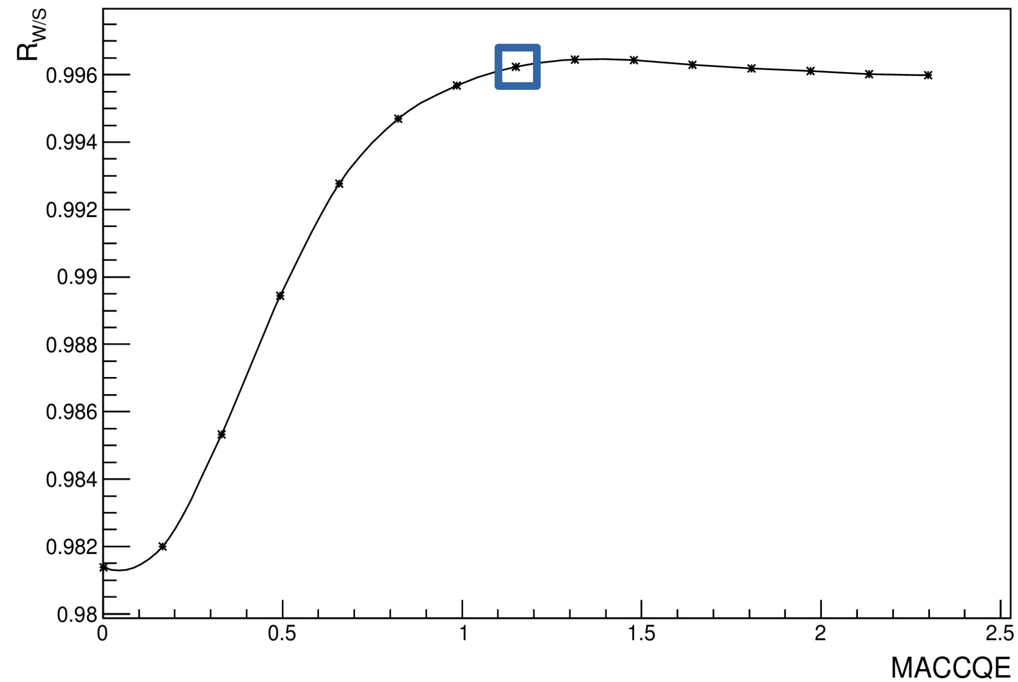
- 14 variation for each parameter around the nominal value and within its validity range
- Response functions
- Extraction of ratio systematics via 10k throws

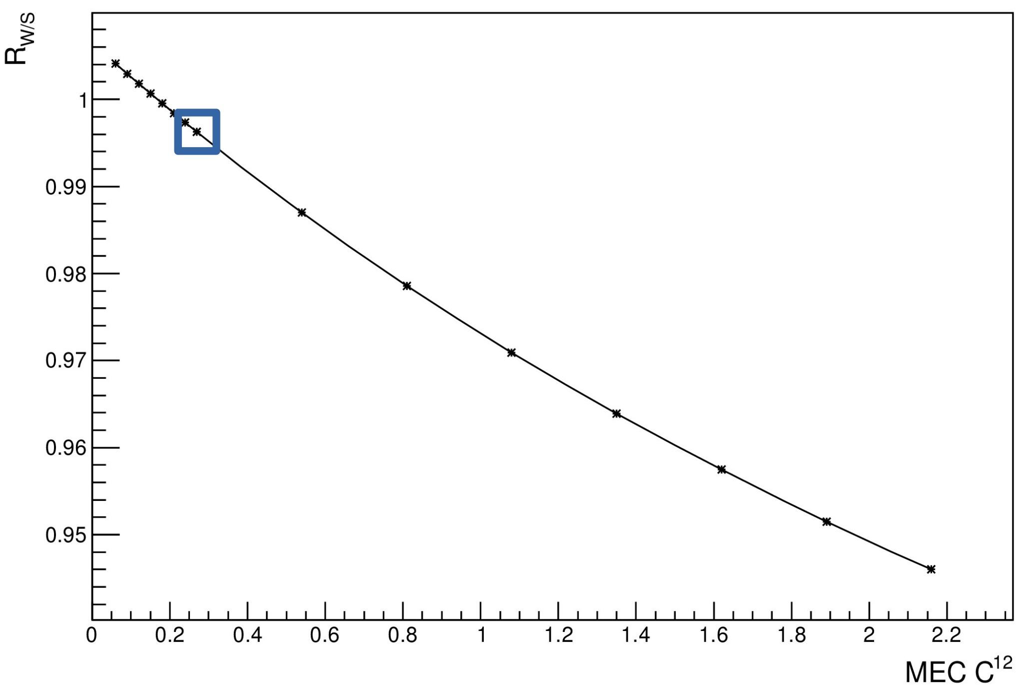


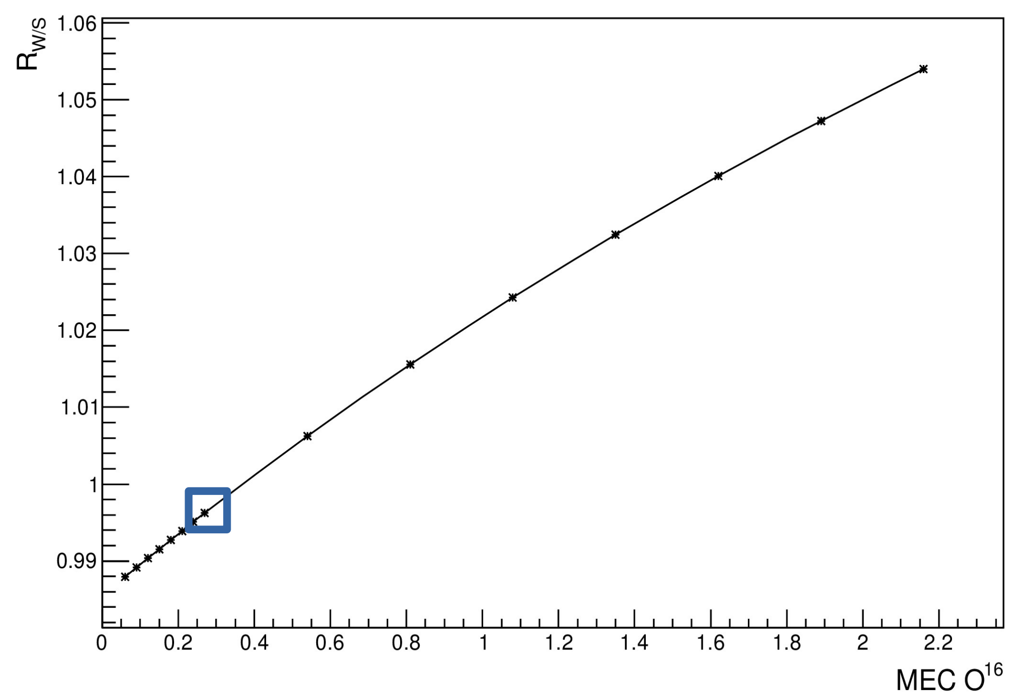


Response functions



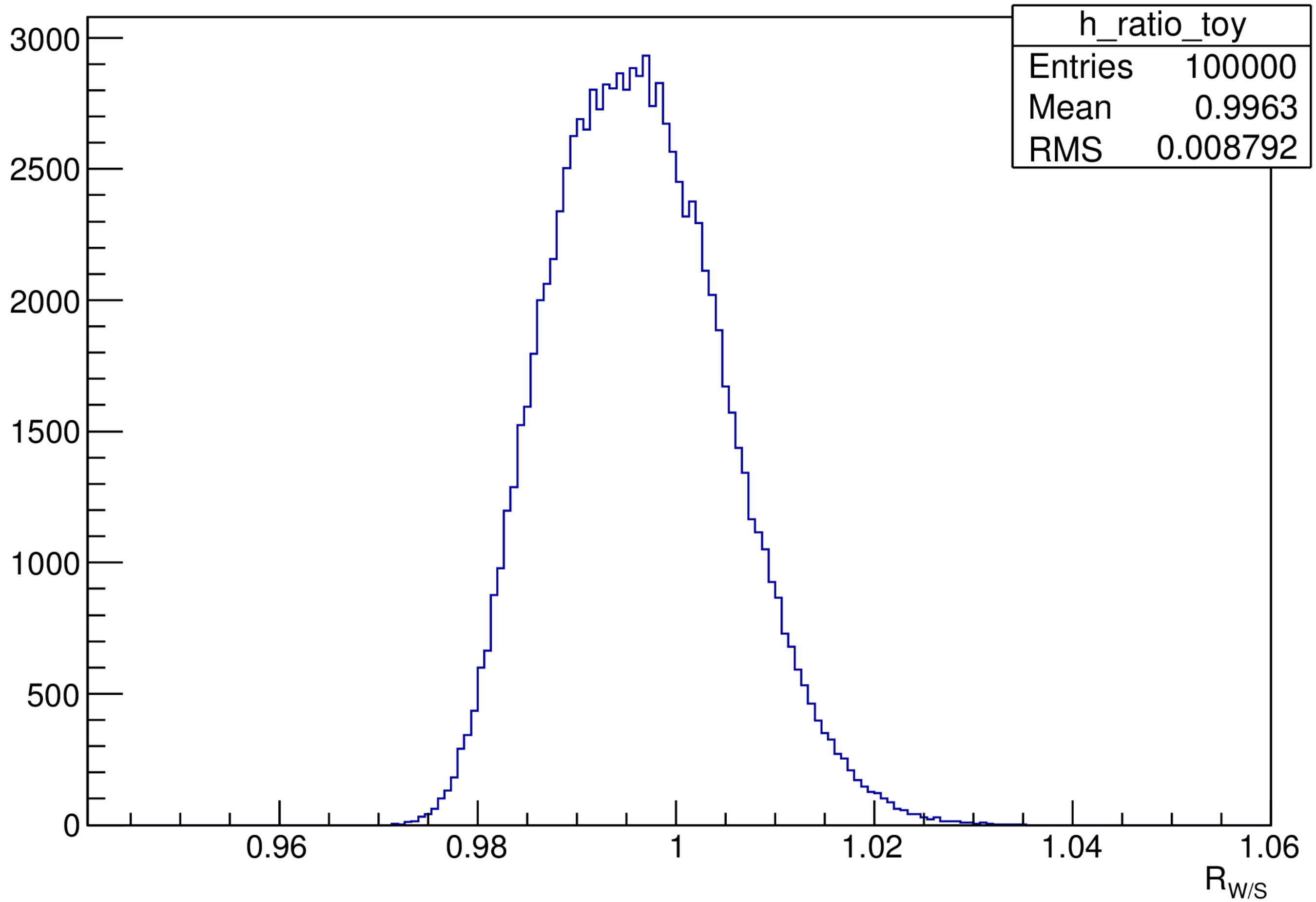






Theoretical systematics (II)

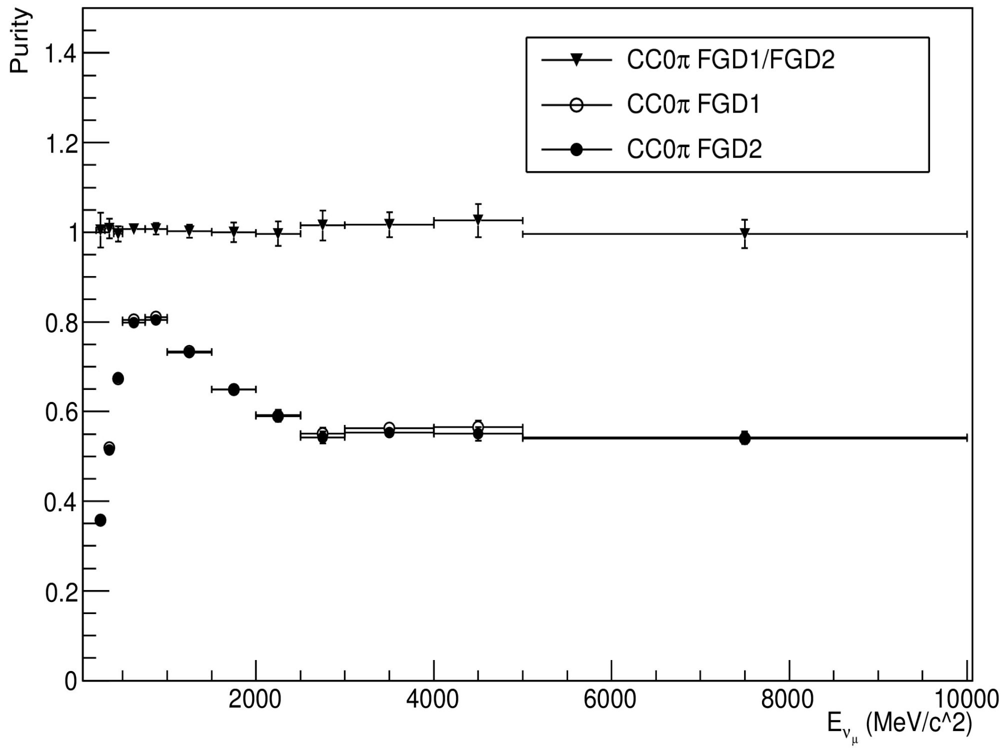
- 10k throws with proper correlation btw parameters
- Evaluation of R(W/S,Throw) from the response functions



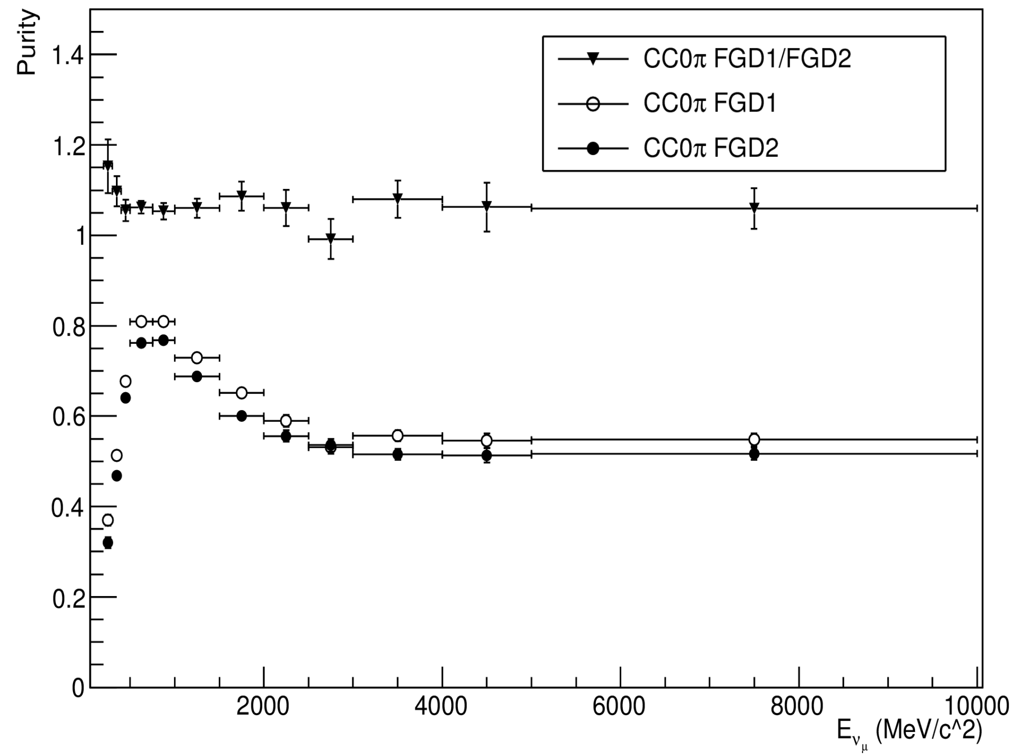
Uncertainty on the integrated value < 1%

Purity FGD1/FGD2

x-layer



y-layer



NEUT	$CC0\pi$ [%]	$CC1\pi$[%]	$CCothers$ [%]	$NC + \nu_e$ [%]	$OOFV$ [%]
FGD2-x	68.8	14.6	7.78	2.32	6.47
FGD2-y	64.2	15.0	8.17	2.52	10.1

NEUT	$CC0\pi$ [%]	$CC1\pi$[%]	$CCothers$ [%]	$NC + \nu_e$ [%]	$OOFV$ [%]
FGD1-x	69.4	15.3	7.91	2.28	5.12
FGD1-y	69.3	15.1	7.99	2.32	5.27