Sujet de la thèse:

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

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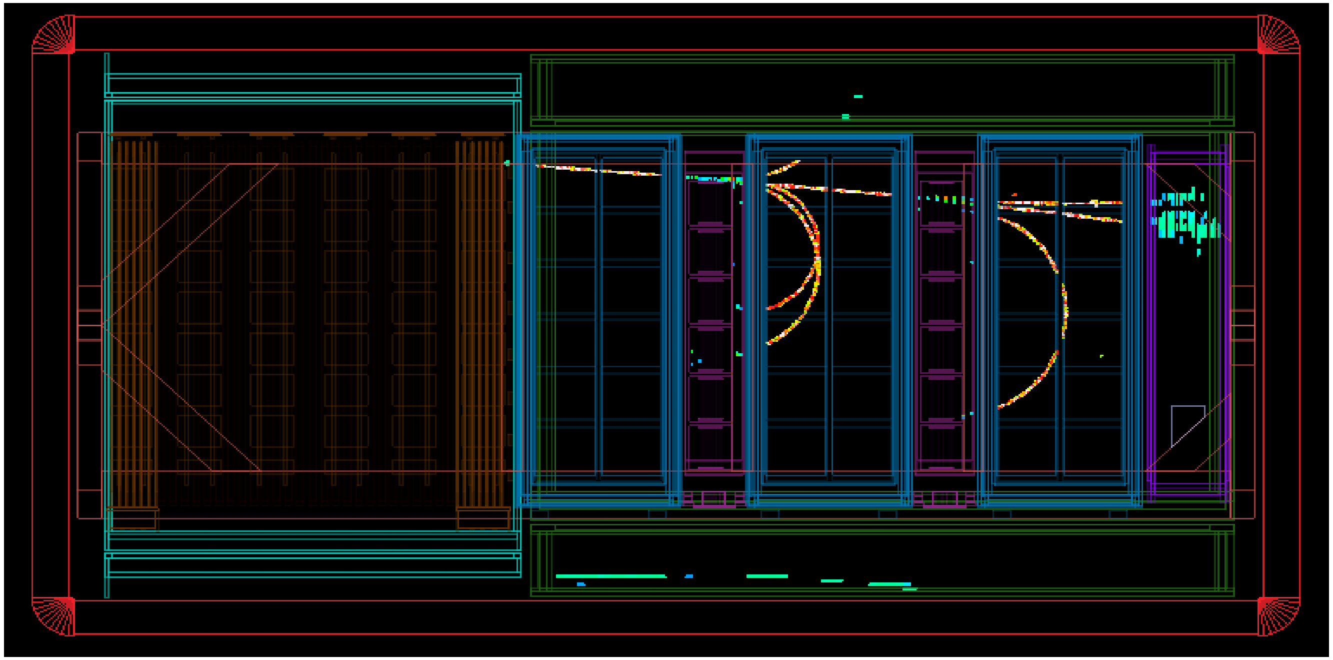


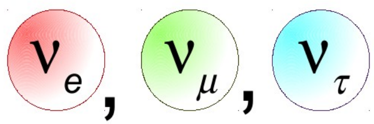
Outline:

- Introduction: ν oscillations and interactions
- CCQE Water/Scintillator ν cross section ratio
- Service task: MicroMegas alignment

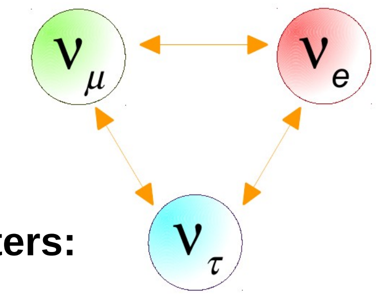
Mots clés: T2K, ND280, water, CC0π, cross section, oxygen carbon ratio, ratio

Neutrino oscillations (I)

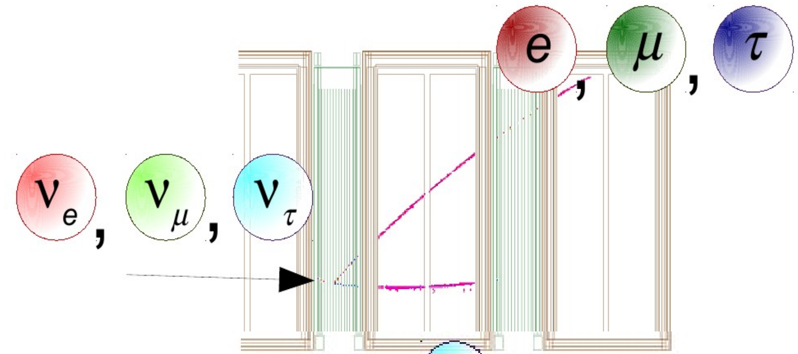
1) Production



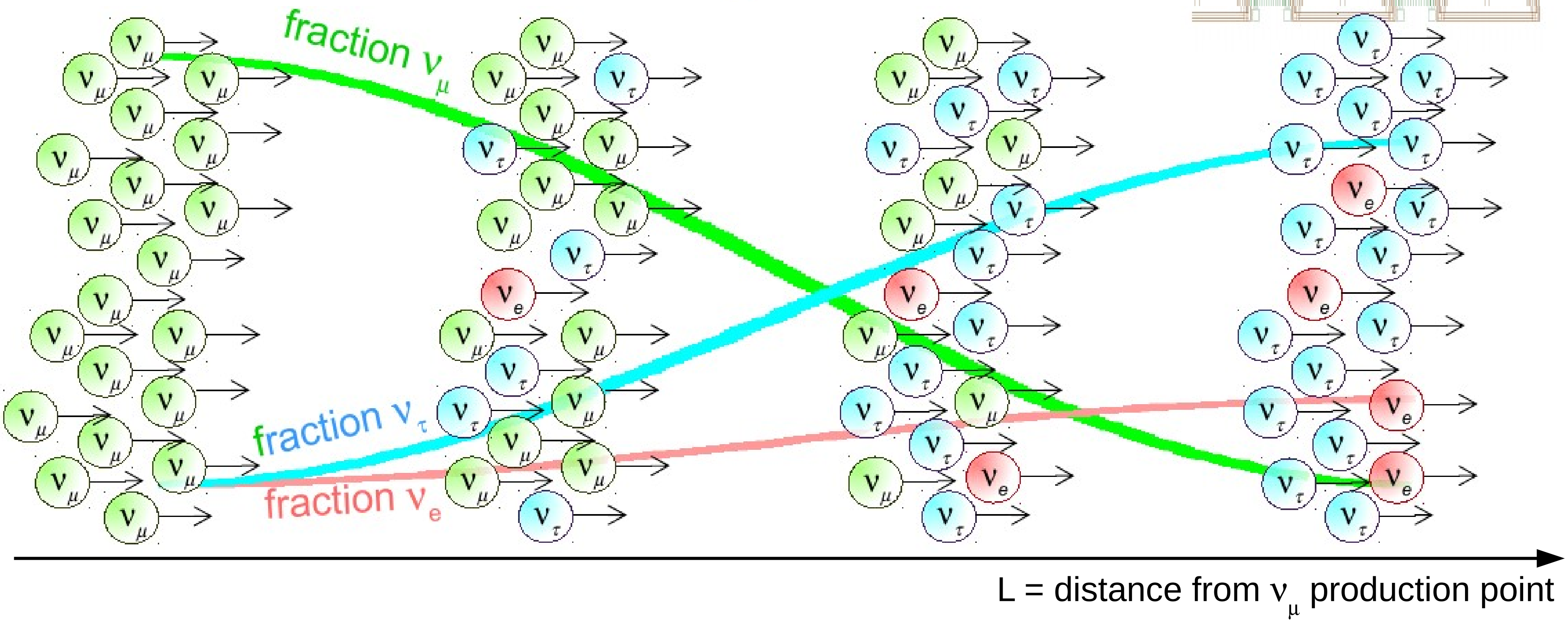
2) Oscillations



3) Detection

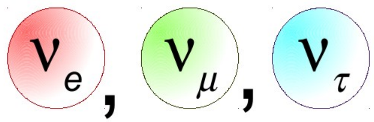


- **3 neutrino generations in the SM**
- **Oscillations described by 6 parameters:**

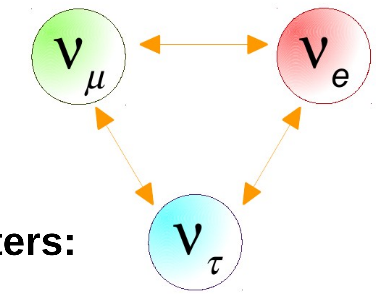


Neutrino oscillations (II)

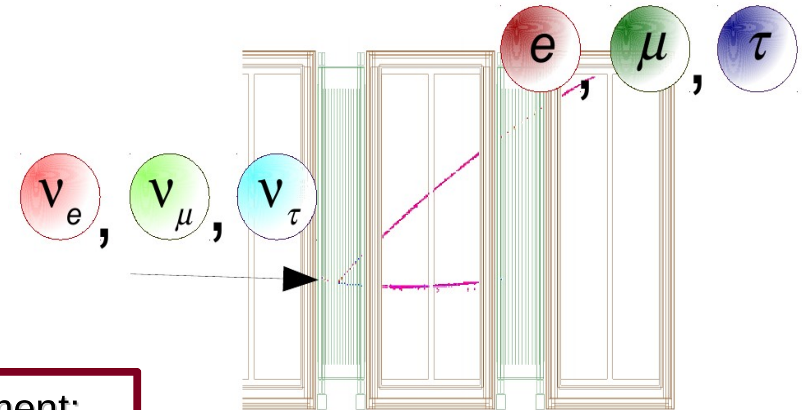
1) Production



2) Oscillations



3) Detection



- **3 neutrino generations in the SM**
- **Oscillations described by 6 parameters:**

Mass eigenstate: (ν_1, ν_2, ν_3)

Weak eigenstate: (ν_e, ν_μ, ν_τ)

Accelerator experiment:
T2K

$$|\nu_\alpha(t)>=\sum_{i=1}^{3} U_{\alpha i}|\nu_i(t)> \Rightarrow U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

U = PMNS matrix

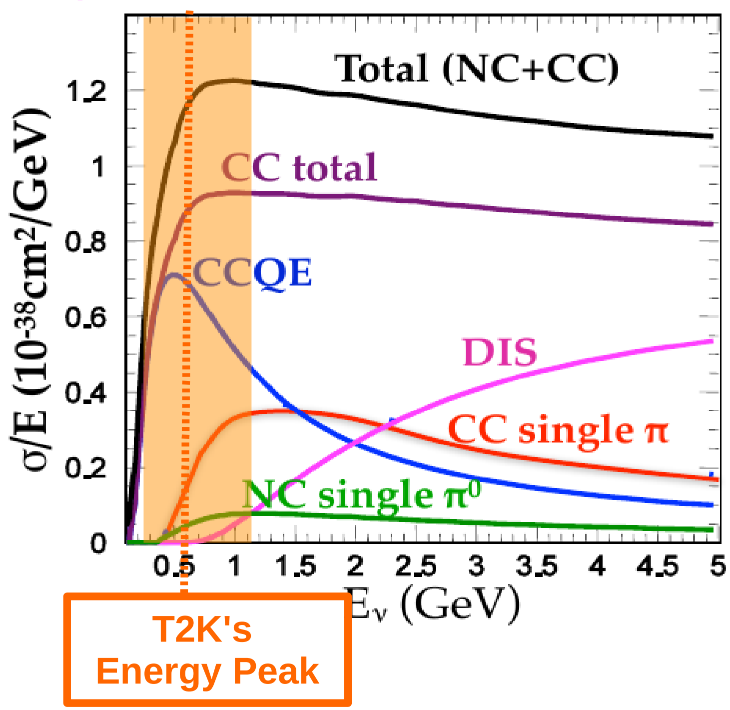
$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

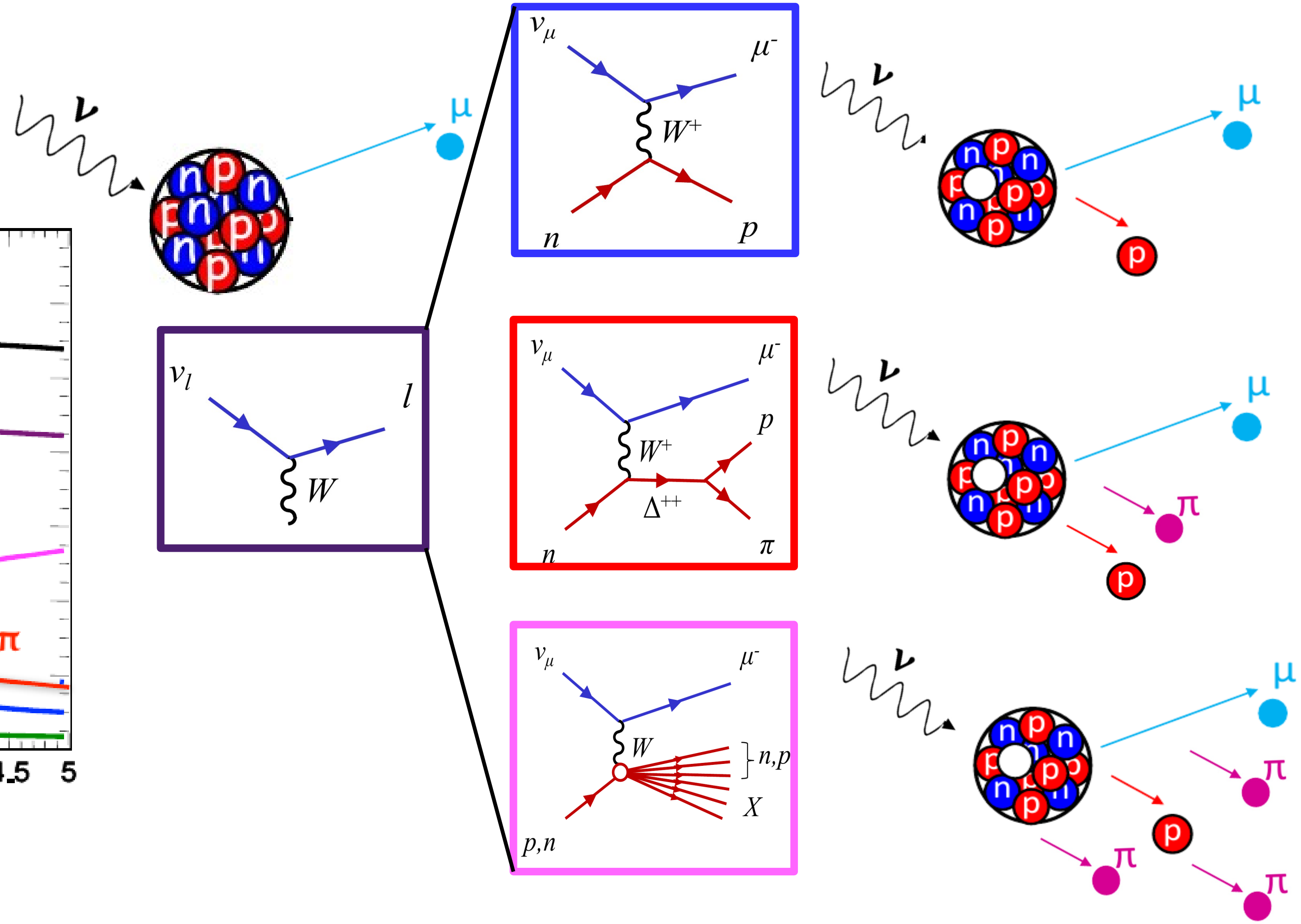
- Mixing angles θ_{12}, θ_{23}, θ_{13}
- Mass square difference Δm^2_{21}, Δm^2_{31}
- CP violation δ_{CP} (difference matter-antimatter)

- Need small uncertainties to measure precisely θ_{23}, θ_{13} and δ_{CP}
- Systematics limited by the neutrino interaction model
- Need precise measurements of neutrino interaction cross section

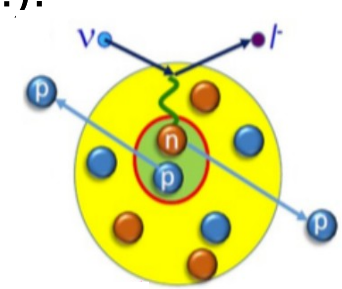
Neutrino interactions

Charge Current (CC):
- CC Quasi Elastic (CCQE)
- CC RESonance or CC 1π
- Deep Inelastic DIS





- Neutrino interaction on nuclei (not on free nucleons!):
  - Nuclear effects (correlation within nucleons)
  - Difficult kinematic reconstruction of the final state
  - Better theoretical models are needed!!!
  - Better cross section measurements in different nuclei



The T2K experiment

T2K = long baseline neutrino oscillations experiment Tokai-to-Kamioka

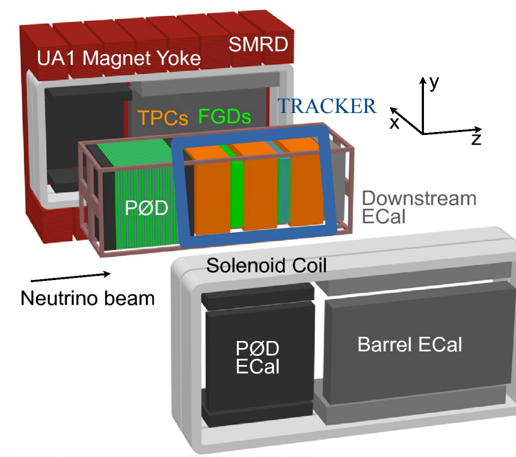
- Far detector in **K**amioka:

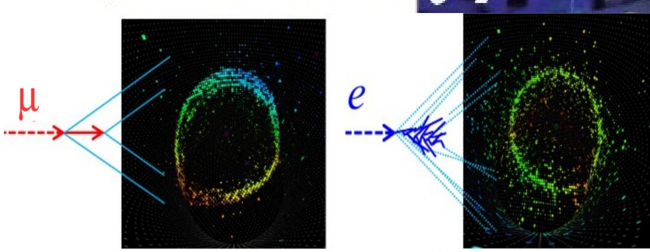
  Super-Kamiokande 50 kton **water** Cherenkov

  1 km undergrond

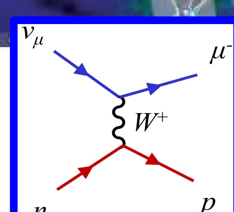
- Beam line at J-Parc in **T**okai:

  Near detector ND280 fully magnetized with B = 0.2 T



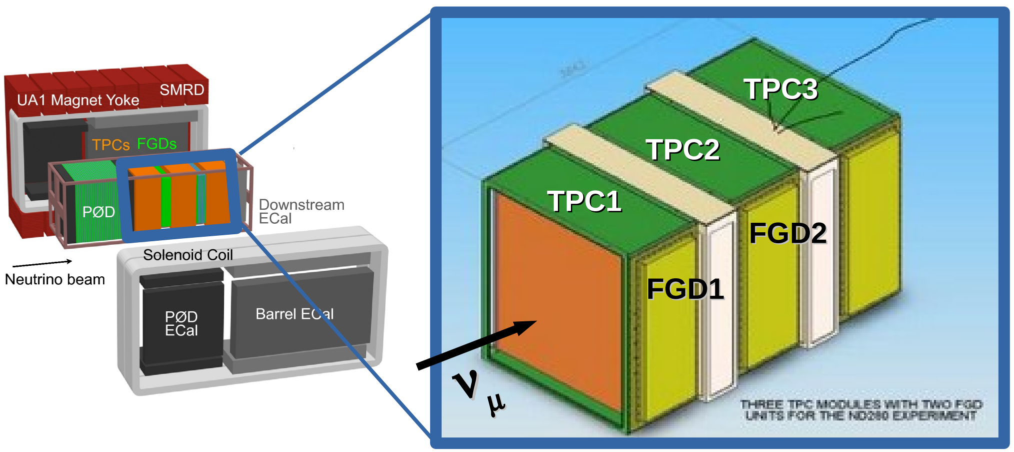


- ν_μ, ν_e detection after oscillations via **CCQE** interaction



The Near Detector: ND280

- Constrains flux, cross section and background for oscillation analysis in the un-oscillated $\nu_\mu - \nu_e$ flux
- High statistics ~ 60k ν_μ events in ~$7\text{x}10^{20}$ Protons on Target (POT) recorded so far



- Sub-detectors allow a fully reconstructed event
- **Tracker optimize to detect CC interactions:**

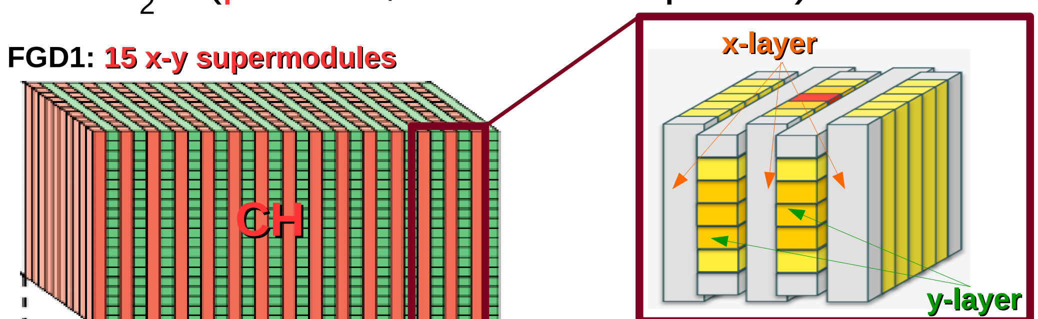
  - 3 Time Projection Chambers (TPC): gas mixture, momentum measurement, particle ID

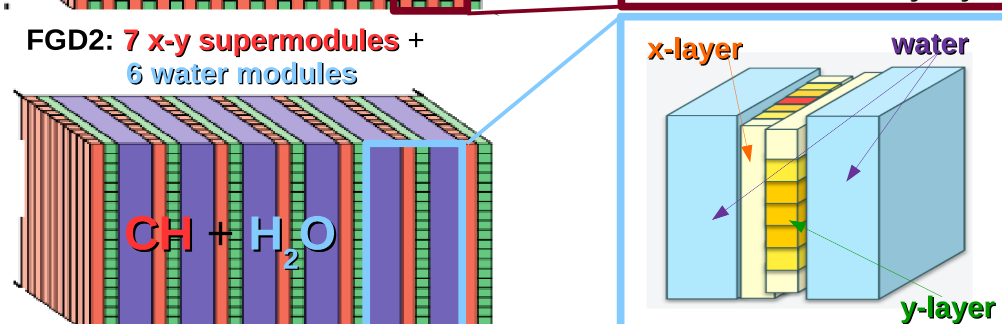
  - 2 Fine Grained Detectors: 2*1.2 ton target mass CH (active) and H_2O (passive, same as Super-K)

- Neutrino cross-section measurements:

  - **Active (FGD1 + FGD2):** CH scintillator bars arranged in alternating x-y oriented layers (supermodule)

  - **Passive (FGD2):** H_2O water modules

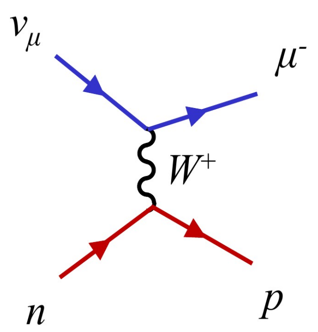


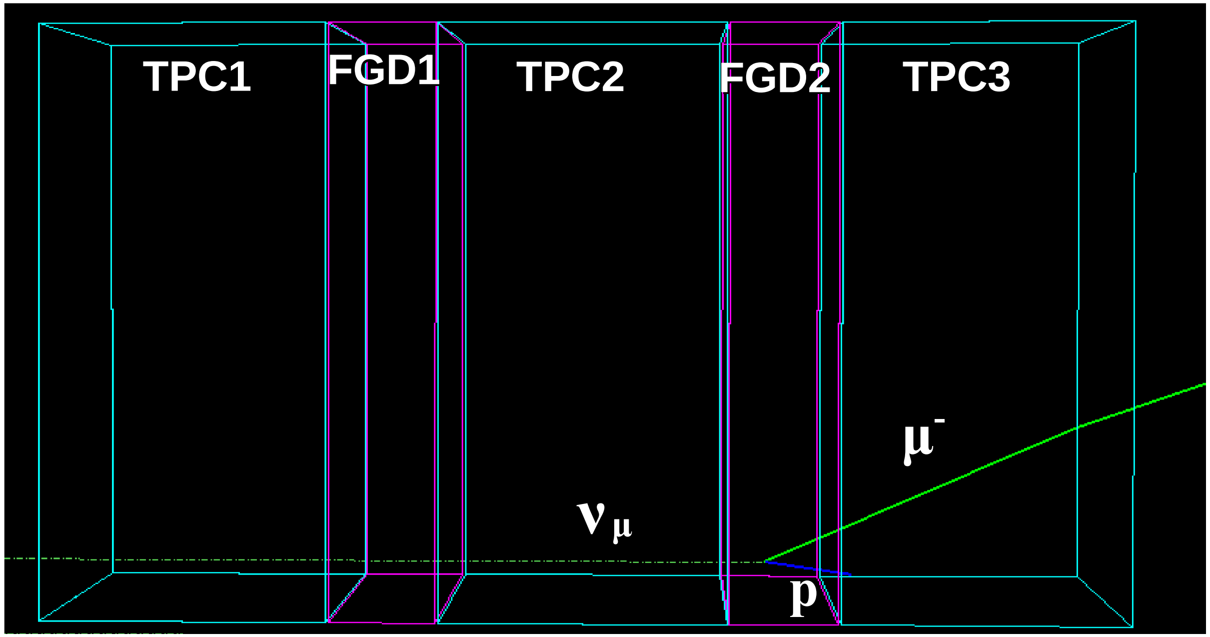


CC0π Water/Scintillator ratio

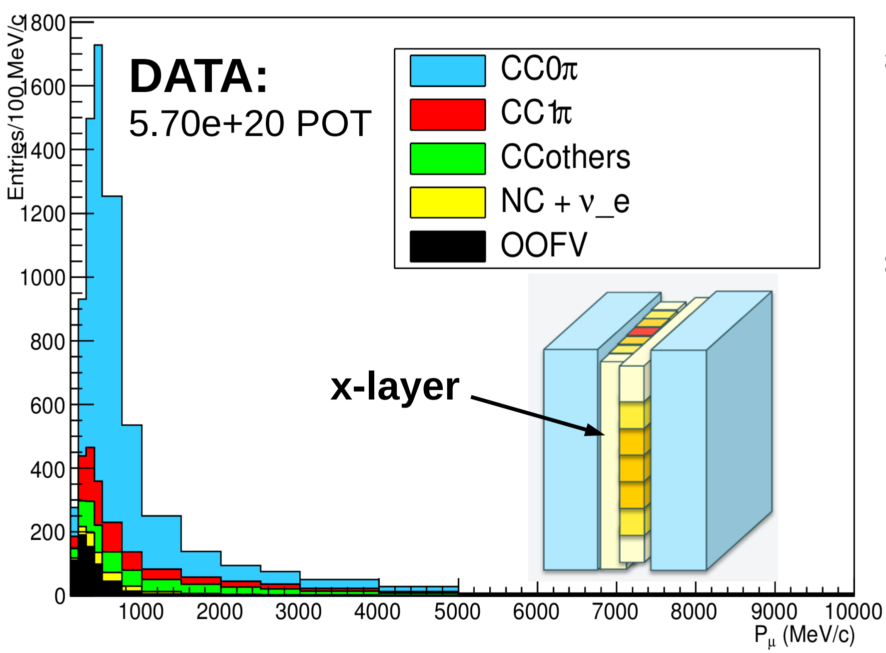
CC0π selection

- Muon produced in FGD2
- Good track quality
- Muon PID in the TPC
- No pion in the final state





Vertex = most upstream hit



	Expected events	Purity [%]	ϵ_s [%]	ϵ_w [%]
FGD2-x	12875 ± 113	68.8	47.9	49.7
FGD2-y	4390 ± 66	64.3		

$$\boxed{N_{exp.} = \Phi \cdot \varepsilon \cdot \sigma \cdot T}$$

Φ = ν flux
ε = detector response
σ = ν cross section
T = # of target

Vertex position

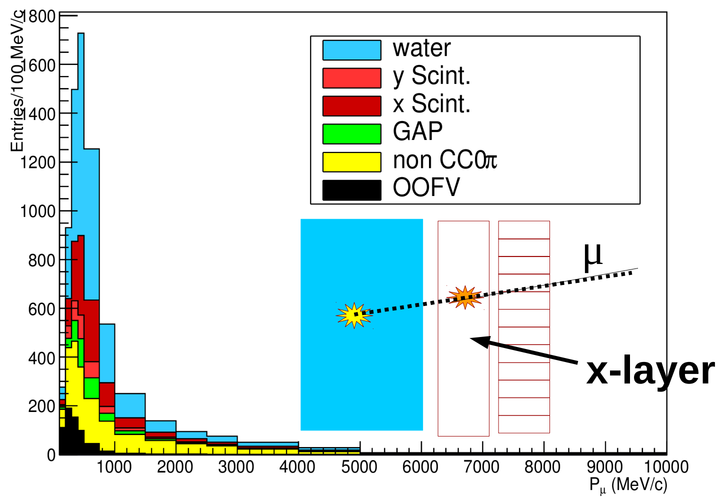
$$R_{Water/Scint.} = \frac{\sigma_{water}}{\sigma_{Scint.}} = f(\boxed{N_x}, \boxed{N_y}, \epsilon_w, \epsilon_s, T_w, T_s)$$

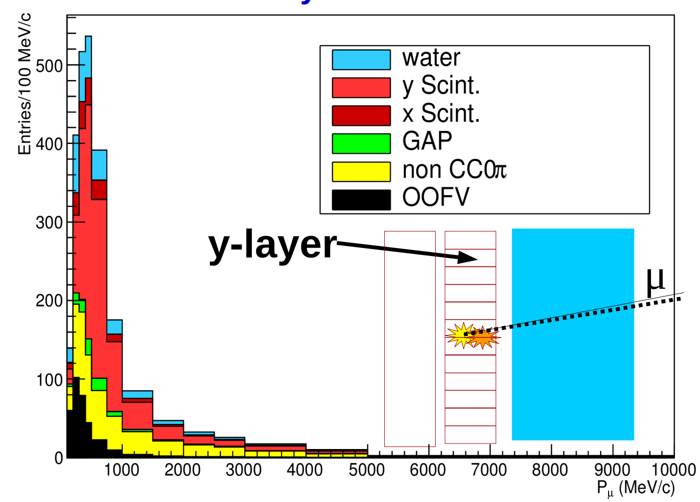
N_x = x-layer + water

N_y = y-layer

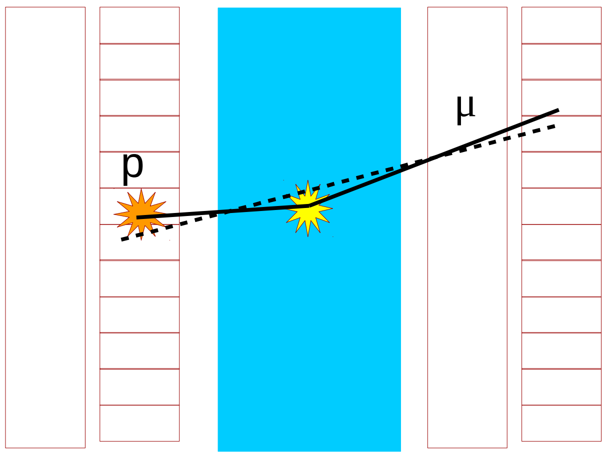
True vertex position

Track's 1[st] hit





- Migration: the neutrino interaction vertex is moved from a layer to another
  - N_x = x-layer + water + y-layer (backwards)
  - N_y = y-layer + water (backwards) + x-layer (forward)
- Backward: low energetic backward particles aligned with forward μ

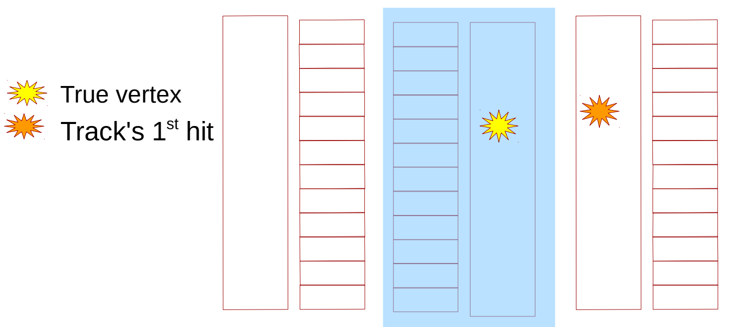


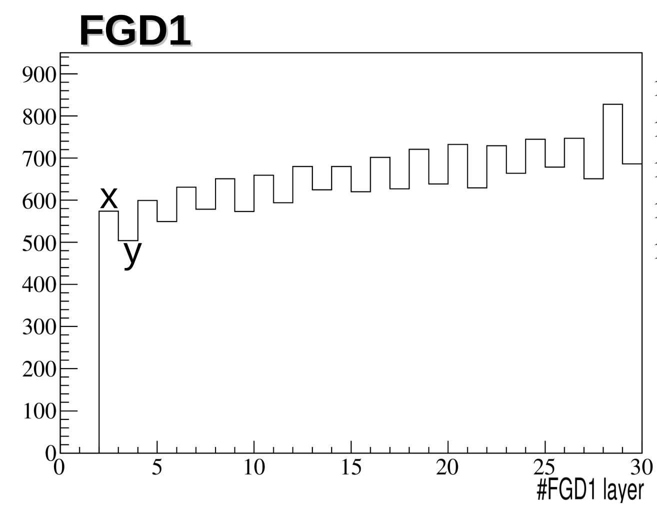
Amount of backward tracks is not well known
→ Need to constraint it from control sample in data.
Hybrid FGD1

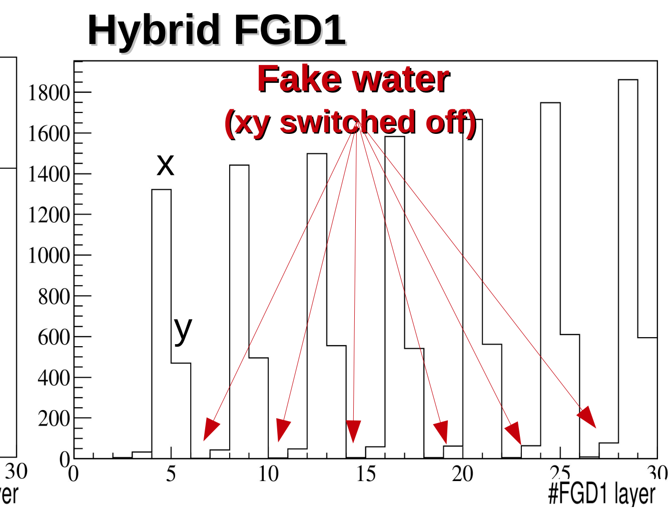
Hybrid FGD1 control sample

Masked in the FGD1 one x-y supermodule every two in order to properly simulate passive material

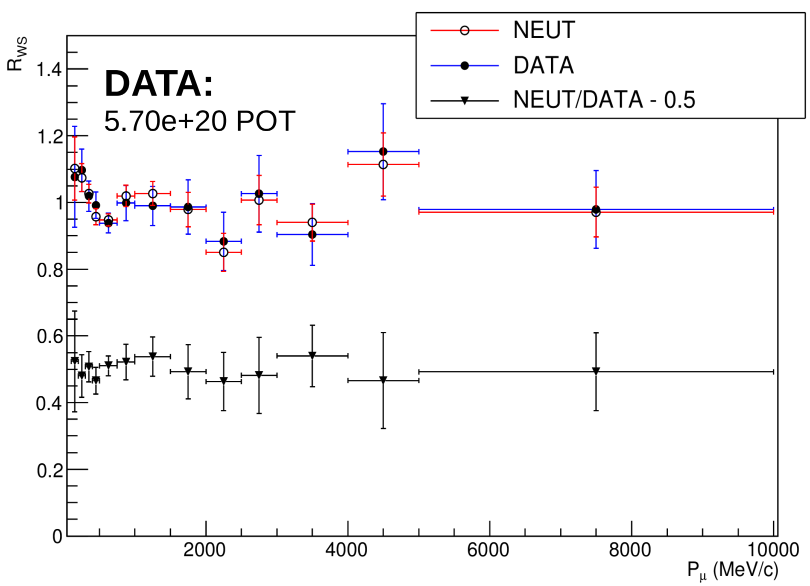
- **Scintillator:** 8 xy-supermodules
- **Fake water:** 7 xy-supermodules







$$R_{FakeWater/Scint.} = \frac{\sigma_{fakewater}}{\sigma_{Scint.}}$$ = 1 (CH/CH), any deviation is due to systematics



Integrated MC

$R_{FakeWater/Scintillator}$ **= 0.993 ± 0.015 (~1.5% MC stat.)**
± 0.009 (~0.9% det.)

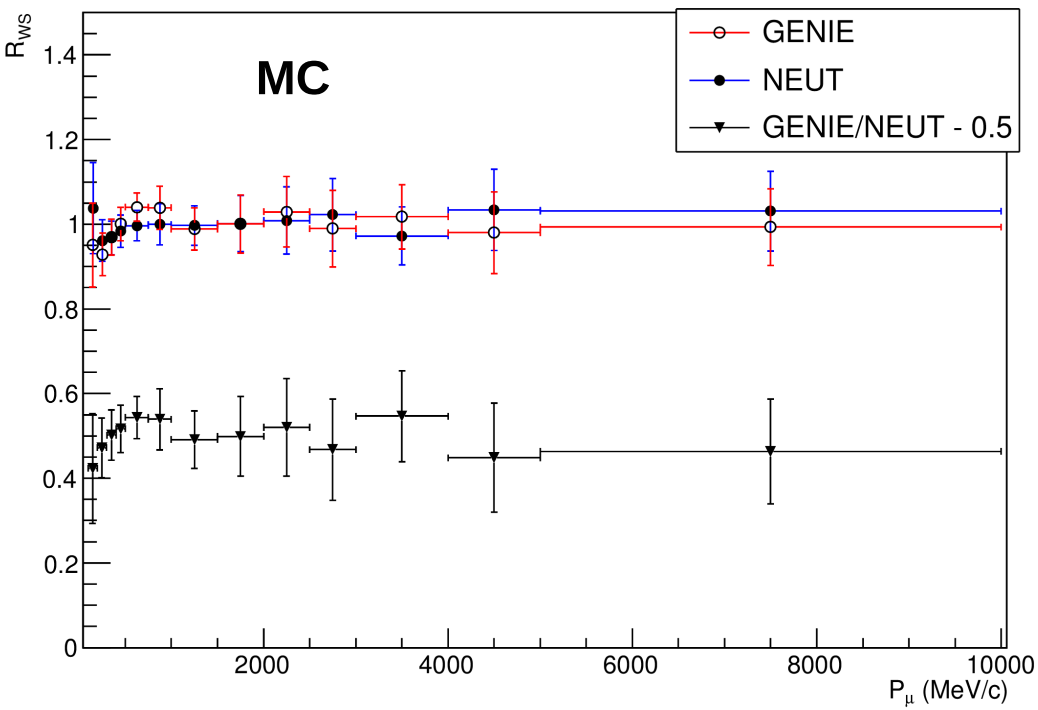
Integrated DATA

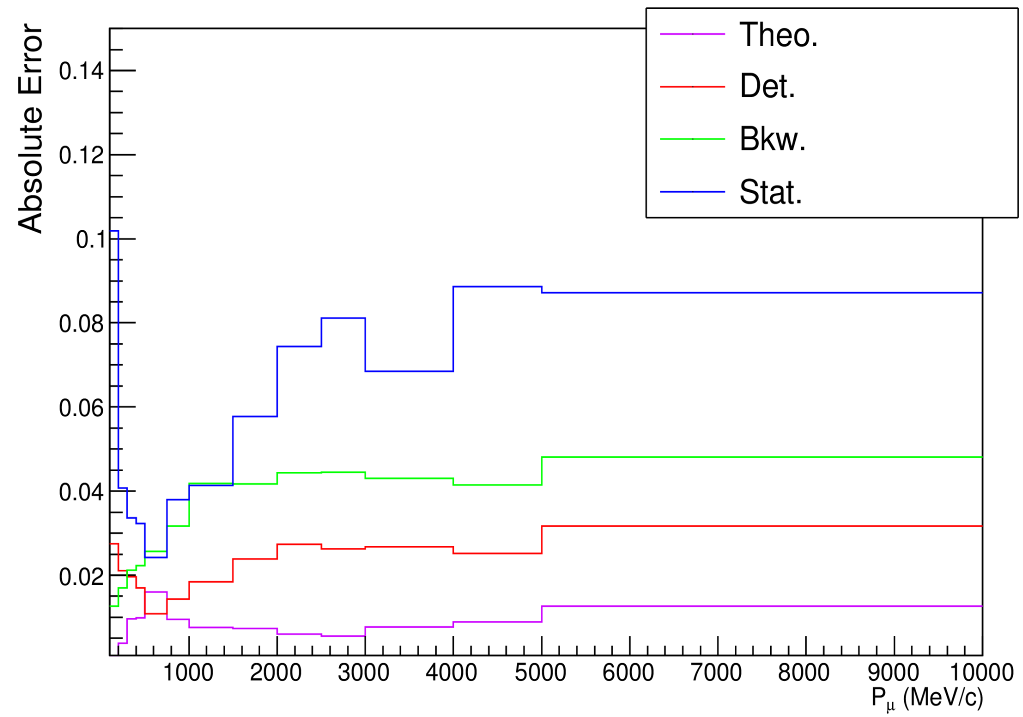
$R_{FakeWater/Scintillator}$ **= 0.995 ± 0.021 (~2.1% stat.)**
± 0.009 (~0.9% det.)

Successful test $R_{FW/S}$ ~ 1
with a total uncertainty ~ 2%

Results FGD2

- Full assessment of detector and theoretical systematics
- Analysis still at MC level in FGD2 (blind analysis)





Integrated MC

$R_{w/s}$ (NEUT) = 0.996 ± 0.015(~1.5% MC stat.) ± 0.009(~0.9% det.) ± 0.007(~0.7% mass.) ± 0.017(~1.7% bkw.) ± 0.009(~0.9% theo.)

$R_{w/s}$ (GENIE) = 0.994 ± 0.016(~1.6% MC stat.) ± 0.012(~1.2% det.) ± 0.007(~0.7% mass.) ± 0.016(~1.6% bkw.)

Next step...

- Precise knowledge of σ_ν is crucial for present and future oscillation experiments
- **What can be further improved in T2K?**

I) Reduce the statistical errors –---> Take more DATA!!!

II) Bring the total uncertainty on the oscillation analysis at 3% -----> Cross section measurement

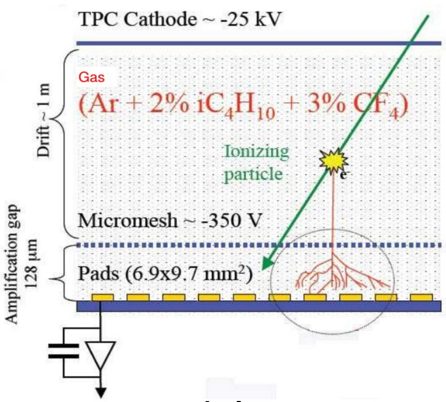
Systematics	w/o ND280 constraint	w/ ND280 constraint
Flux	7.7%	3.1%
Cross section	7.6%	3.8%
Flux and cross section	10.9%	2.5%
Final state/Secondary interaction at Super-K	1.8%	1.8%
Super-K detector	4.6%	4.6%
Total	12.1%	4.9%

III) Improve P_μ resolution and reduce detector systematics –---> MicroMegas Alignment

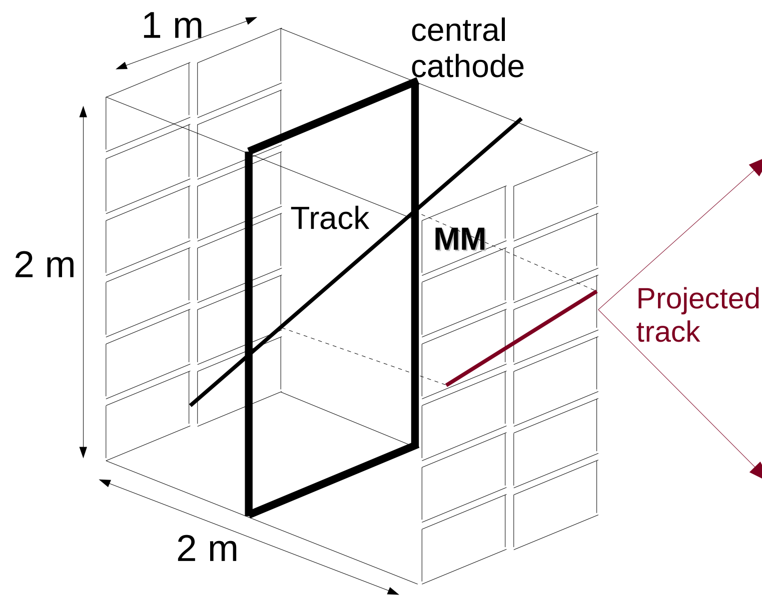
MicroMegas Alignment

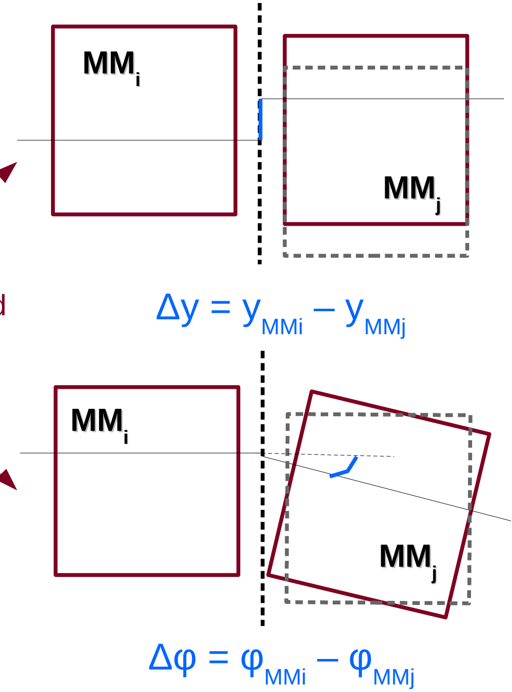
TPC

- **T**ime **P**rojection **C**hamber
- Amplification via MicroMegas



- Gaseous ionization detector
- High electron collection efficiency (~100%)
- High gain (~10^3)
- Fast signal





- MM modules arranged in a 6x2 matrix

- Mechanical precision:

Translation ~100 μm y(z)

Rotation ~0.5 mrad (φ)

- Cosmic rays collected with magnetic field off
- Match straight tracks in the middle plane between adjacent MM modules and extract residuals **Δy, Δφ**
- Fit to the the residuals to extract corrections

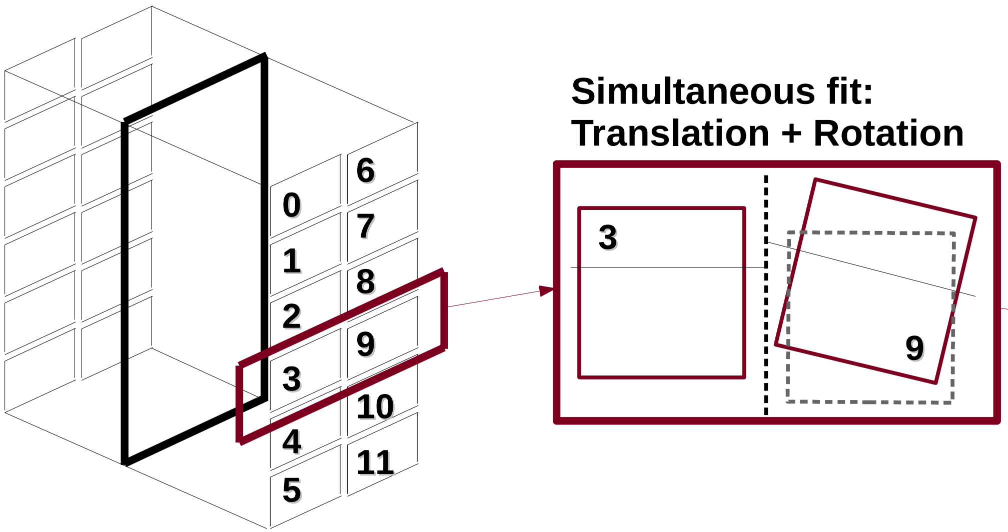
$$\chi^2_\Delta = \sum^{n_{tracks}} \left(\frac{\Delta + f_\Delta}{\sigma_\Delta} \right)^2$$

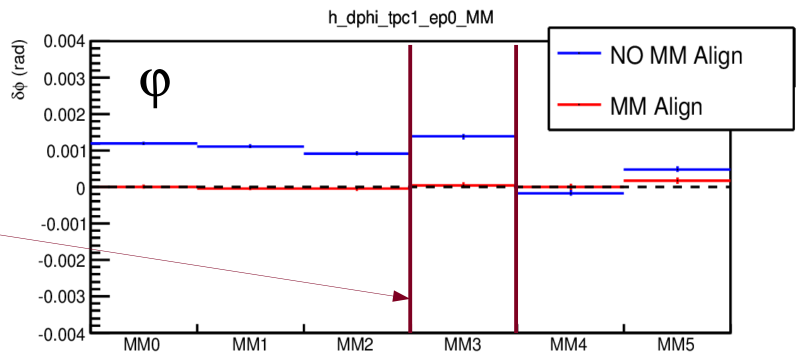
Δ = measured residual

f_Δ= f(δy, δz, δφ) free parameters in the fit

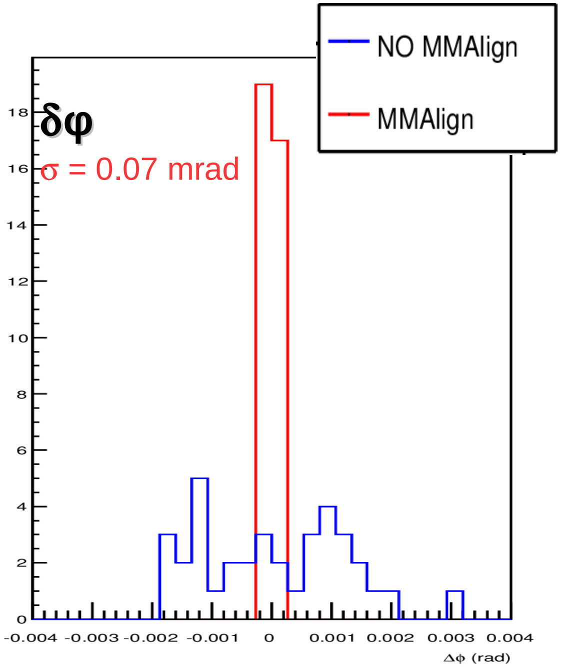
δy, δz, δφ = alignment corrections

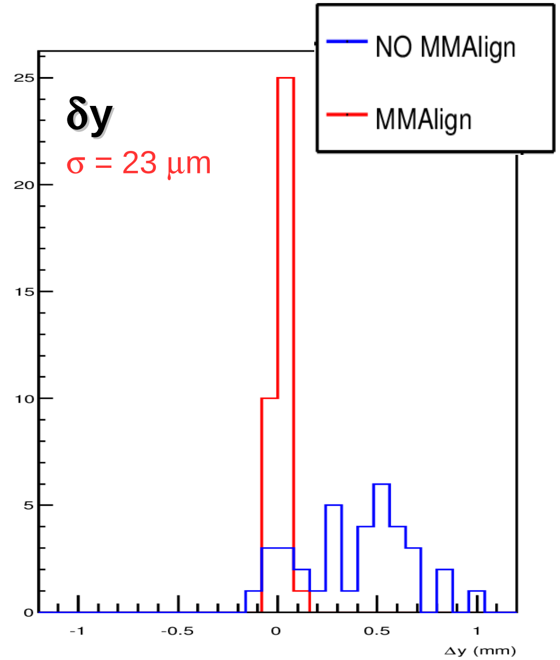
MM alignment results

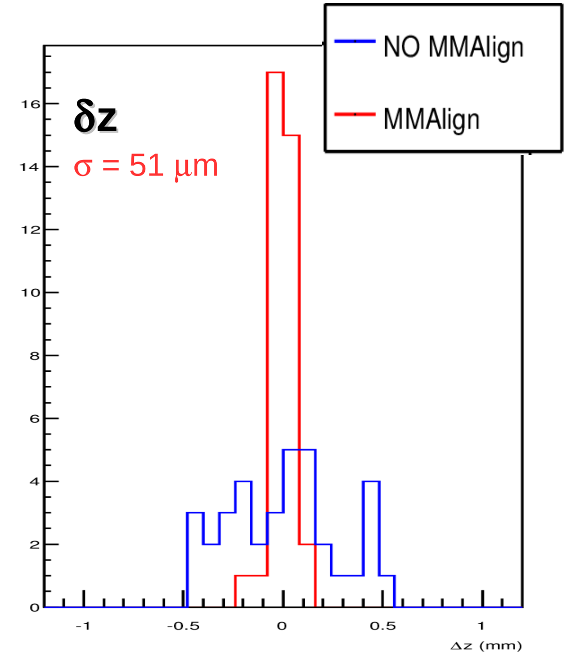




6 MM pairs for each TPC read-out plane = 36 corrections for all the TPCs







Conclusion

- ND280 is essential to reduces the systematic uncertainties in the predicted event rate at Super-K

- **First** T2K analysis of water/scintillator CCQE ν cross section ratio

  $R_{W/S} = \sigma_{water}/\sigma_{Scint.}$ with a total uncertainty of ~3%

$$\mathbf{R_{W/S}\ (NEUT) = 0.996 \pm 0.015(\sim 1.5\%\ MC.\ stat.) \pm 0.009(\sim 0.9\%\ det.)}$$
$$\mathbf{\pm 0.007(\sim 0.7\%\ mass.) \pm 0.017(\sim 1.7\%\ bkw.)}$$
$$\mathbf{\pm 0.009(\sim 0.9\%\ theo.)}$$

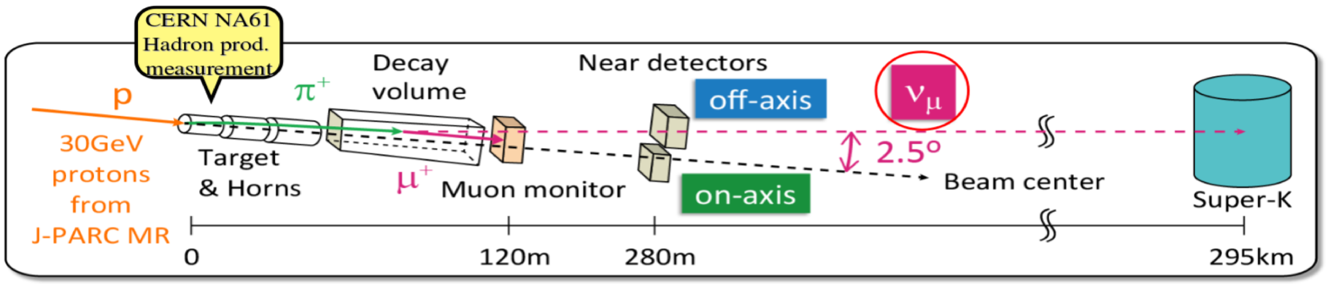
- MM alignment performed with a precision of

  i) **~20(50) µm** for y(z) translation

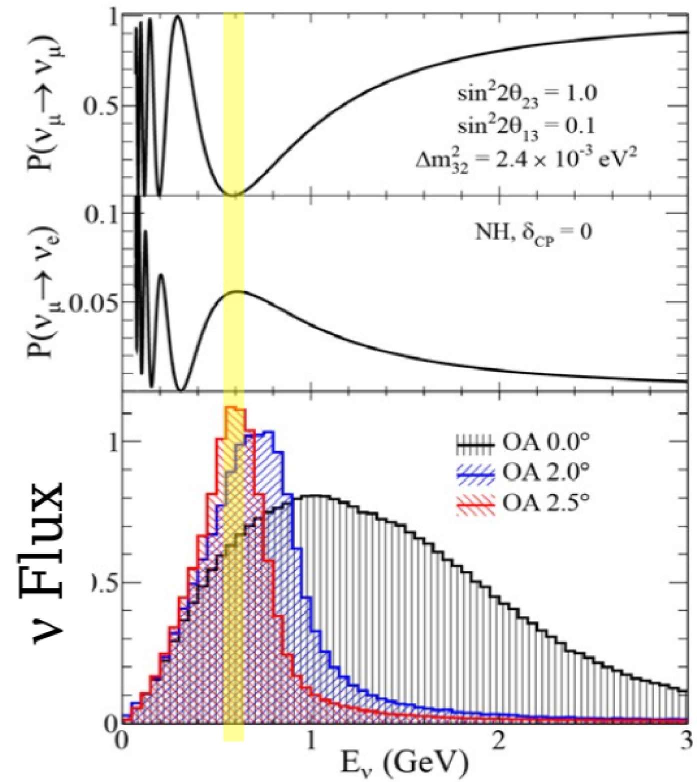
  ii) **~0.1 mrad** for rotations

BACKUP

Beam line

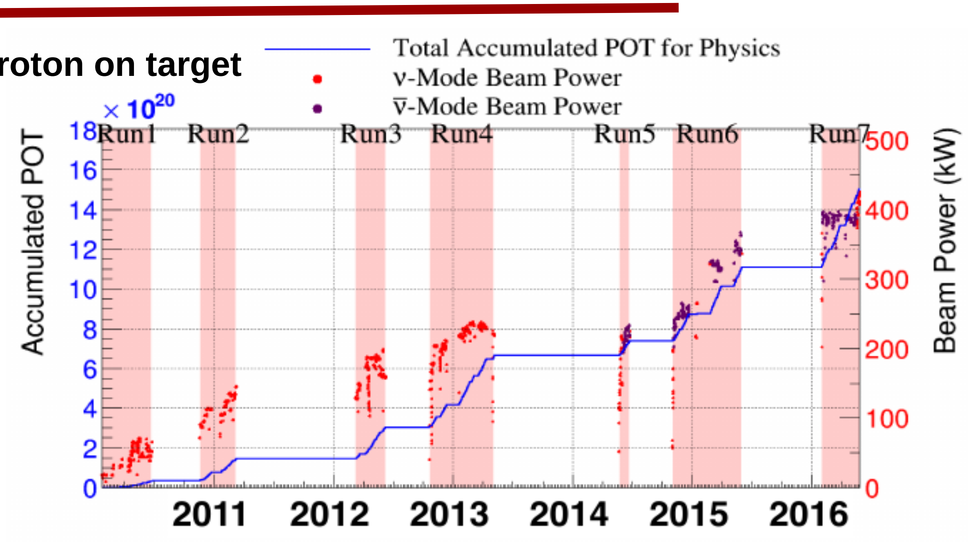


- π, K production at target measured by NA61 experiment at CERN (see Matej talk)
- Beam direction stability < 1 mrad
- ν and $\bar{\nu}$ mode changing horn current
- Off-axis beam allows a narrow peak in E_ν to maximize oscillation probability and reduce high energy background



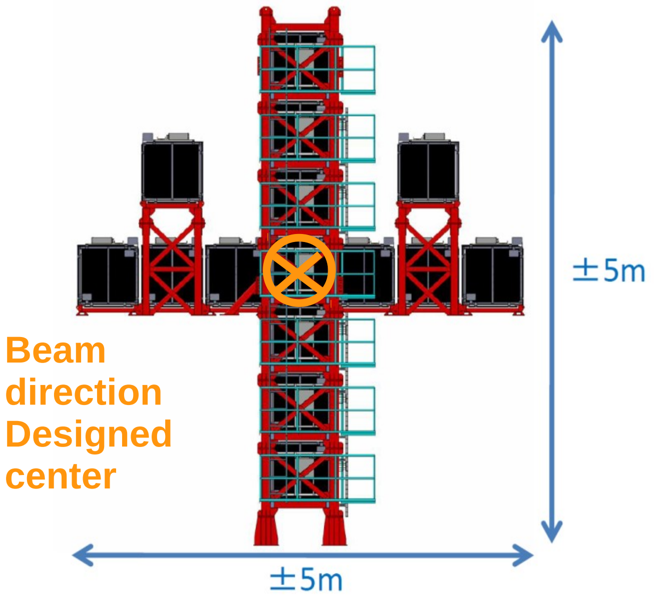
DATA taking Run1-7

POT = proton on target



- Stable operation at ~420W achieved!
- Integrated POT up to 27th May 2016:
  - ➢ Neutrino mode: 7.57×10^{20} POT
  - ➢ Antineutrino mode: 7.53×10^{20} POT
- T2K goal is 78×10^{20} POT

The near detectors (280 m)

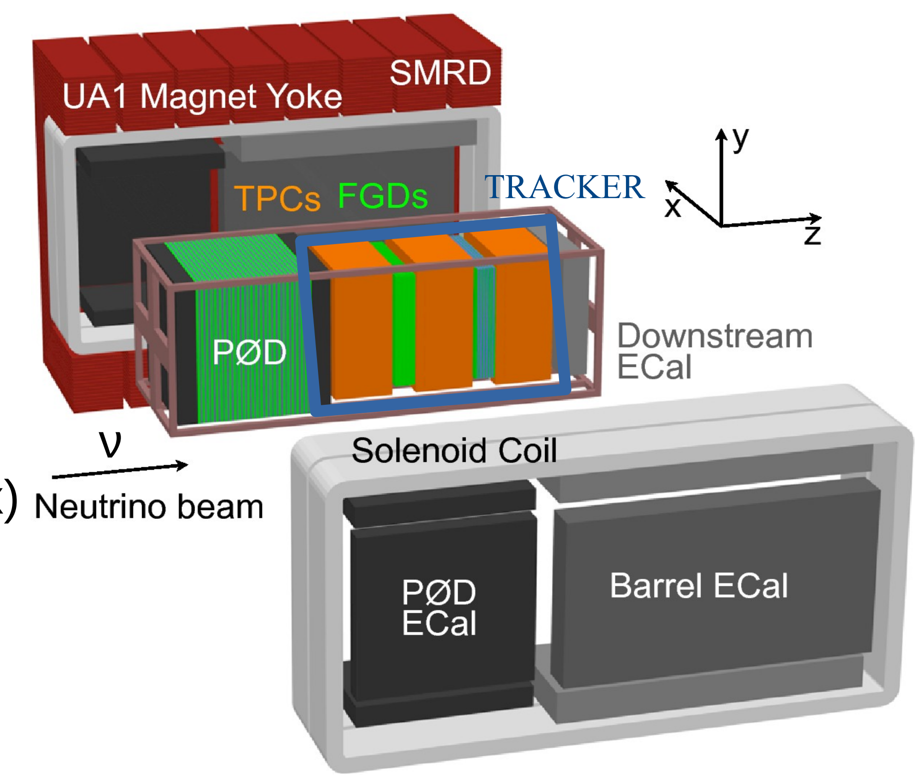


INGRID

- 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

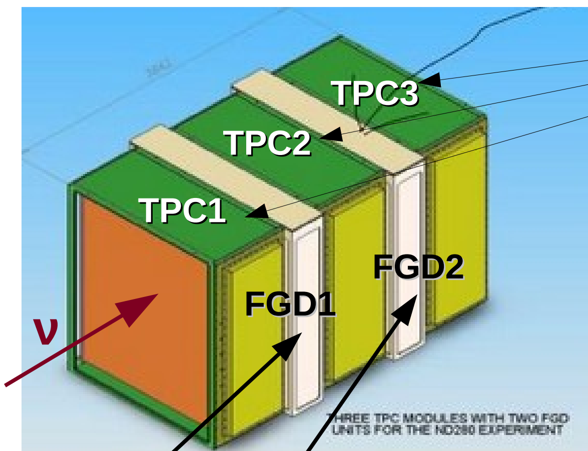
- Off-axis detector 2.5° (same SK direction)
- Sub-detectors allow a fully reconstructed event
- Fully magnetized detector B = 0.2 T
- PØD: π^0 detector
- 3 TPCs: momentum measurement, particle ID (dE/dx)
- 2 FGDs: active target mass (2*1.2 ton)
- ECal: electron, gamma identification
- SMRD: improve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

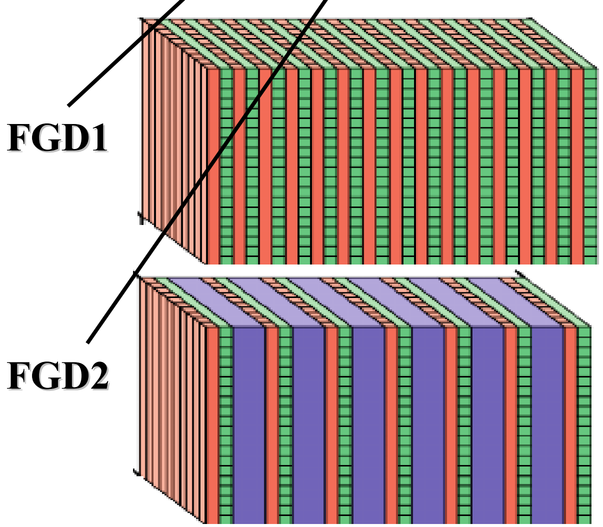


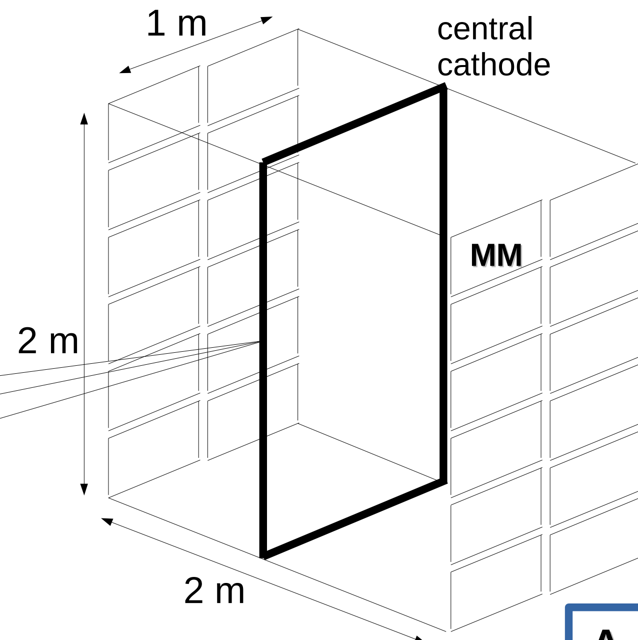
ND280 tracker

- 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
- Argon filled ~95%
- 2 Read-out Planes (RP)
- Amplification via MicroMegas modules (MM)
- Column staggered by 5 cm
- MM modules arranged in a 6x2 matrix geometry
- Total MM 3X2X6x2 = 72

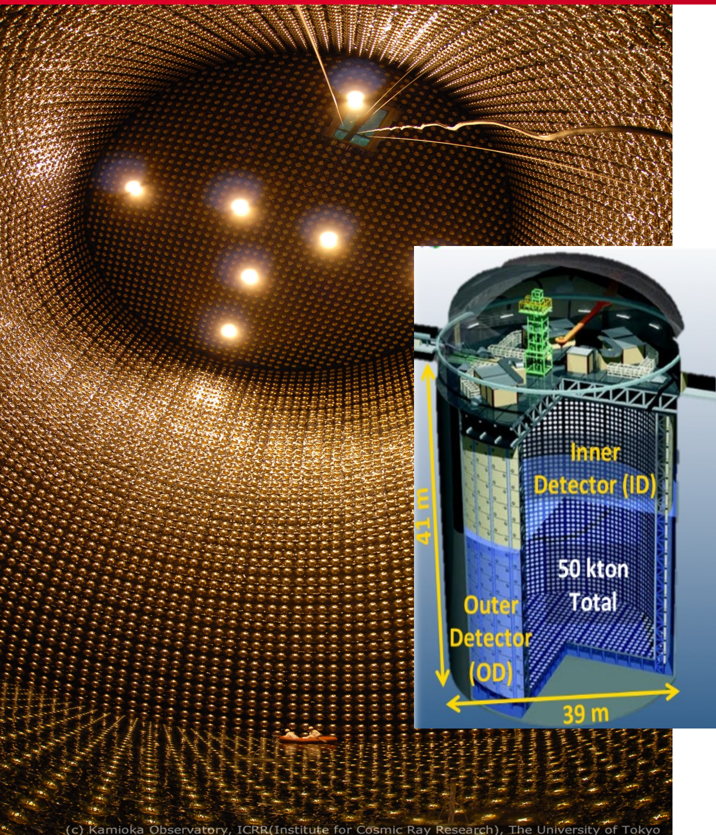
A very precise detector calibration is needed to reduce detector systematics

FGD

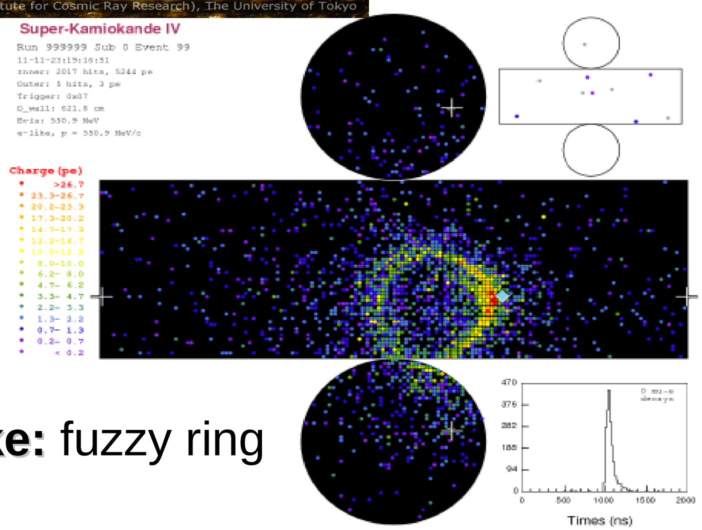
- **F**ine **G**rained **D**etector of 2x2x0.3 m^3
- Total mass 2x1.2 ton
- Fine segmentation to track low energy particles and tag CCQE events
- Active material: scintillator bars (1x1x200 cm^3) arranged in alternating x-y oriented scintillator layers (supermodule)
- FGD1 = 15 x-y supermodules
- FGD2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

FGD2 filled with plastic scintillators and water modules

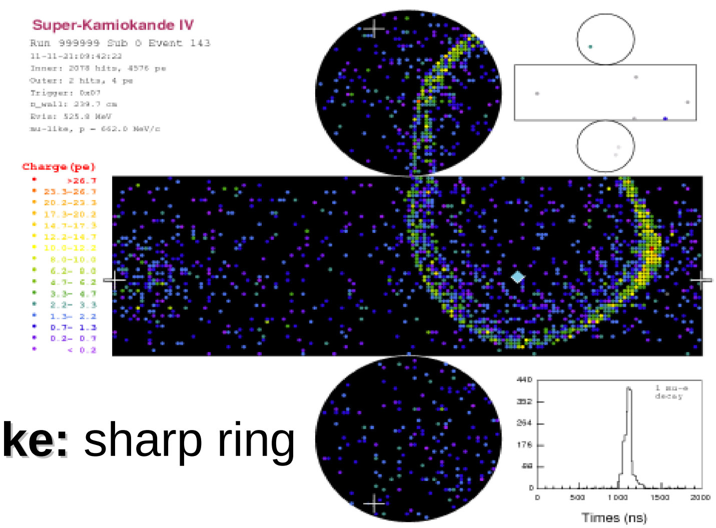
The far detector Super-K (295 km)



- 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

Analysis strategy

Neutrino Flux

Beam line simulation

External Hadron production data
NA61/SHINE

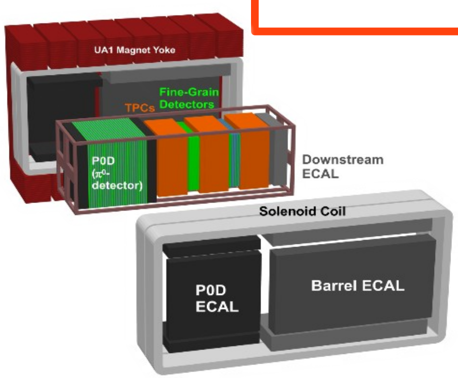
Beam monitor measurement
INGRID

Neutrino Interactions

Interaction model tuned
NEUT

Constrained using external data
MiniBooNe & Minerva

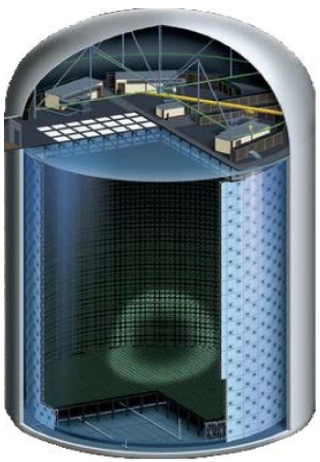
ND280 prediction



ND280 measurement

Measure ν interaction

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



Super-K prediction

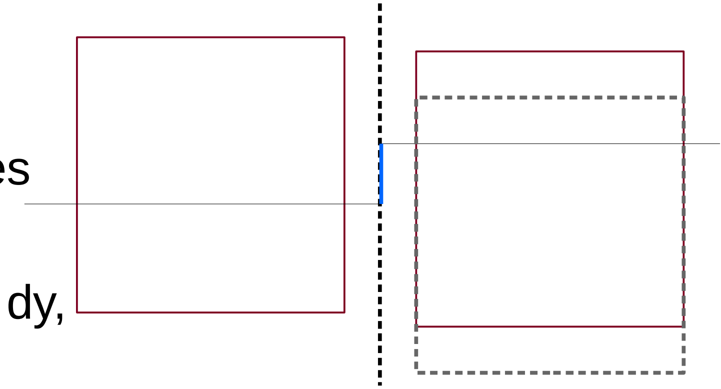
Oscillation fit

Super-K data

ν_μ and ν_e candidates

MM alignment 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
- Correction constants extracted via a fit to the residuals



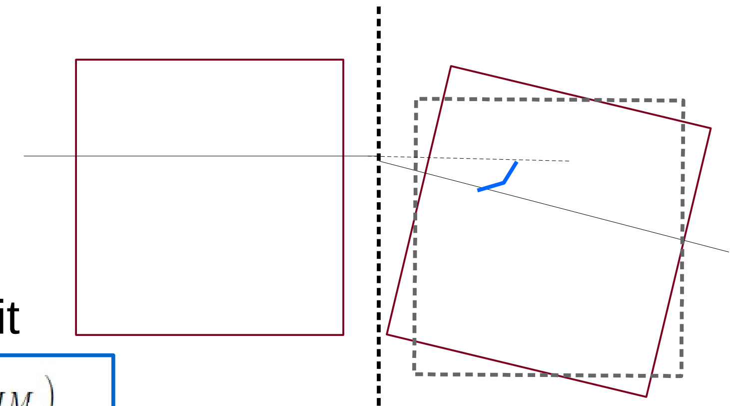
$\Delta y = y_{MMi} - y_{MMj}$

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

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

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

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



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

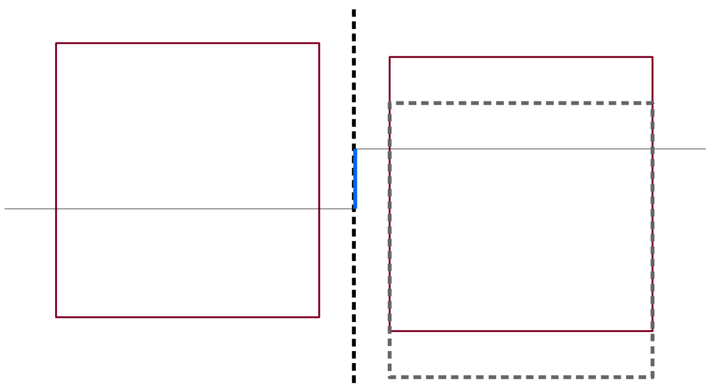
$$f_{\Delta y}\left(y_{MM_i}, y_{MM_j}, z_{MM_i}, z_{MM_j}, \phi_{MM_i}, \phi_{MM_j}\right) = \boxed{\left(y_{MM_i} - y_{MM_j}\right)} - \boxed{\left(z_{MM_i} - z_{MM_j}\right)\tan\left(\phi_{MM}\right)} - \boxed{\left(\phi_{MM_i} - \phi_{MM_j}\right)\left(\frac{d+L}{2} - y_{MM_i}\tan\left(\phi_{MM}\right)\right)}$$

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

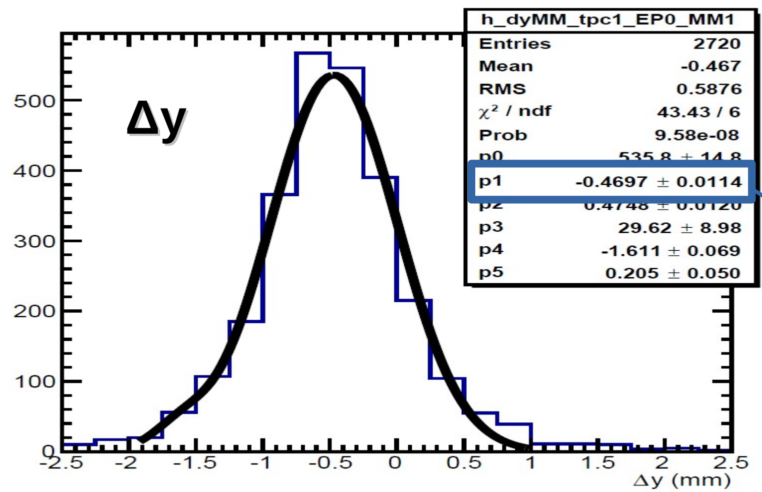
- Laser monitor system gives few hundred microns in translations and few mrad for rotations
- The fit has to be very sensitive
- Generated MC test geometries to test the fit

MM alignment strategy (II)

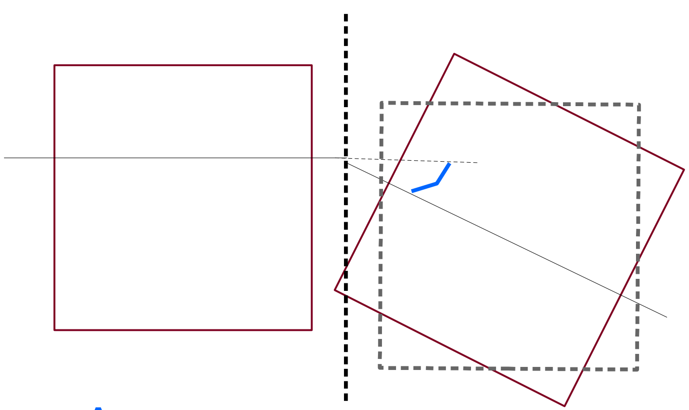
- Cosmic rays collected with magnetic field off
- Reconstruct straight track in each module separately
- Match tracks in the middle plane between adjacent MM modules and extract residuals Δy, Δφ
- Horizontal tracks constraint translational misalignment (vertical dy, horizontal dz) and rotation dφ



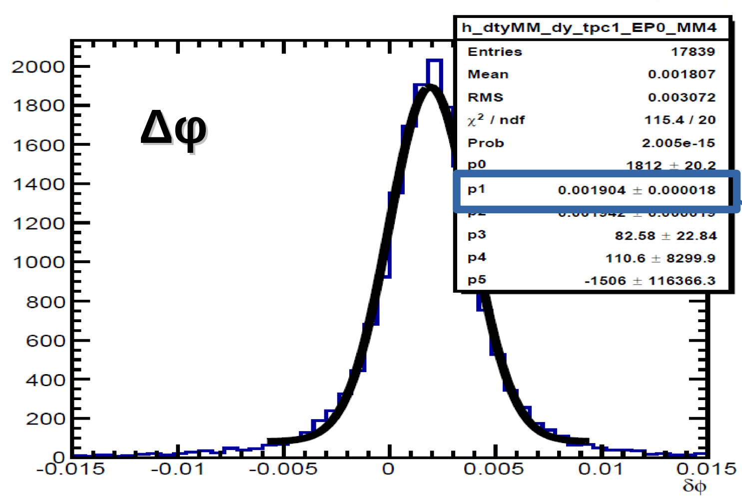
$\Delta y = y_{MMi} - y_{MMj}$



-0.470 μm



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

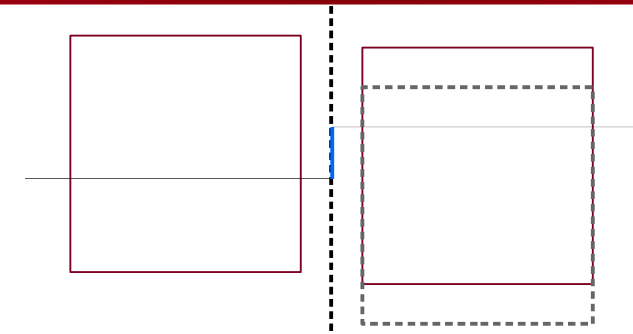


1.904 mrad

MM alignment strategy (III)

- Correction extracted via a fit to the residuals

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



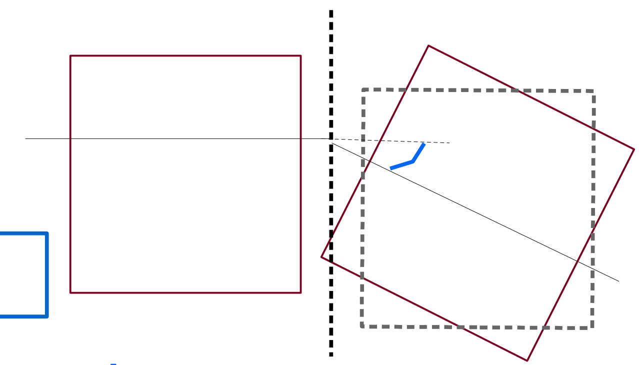
- Minimize χ^2 function who depends from:

$$\begin{aligned} \text{residual } \Delta &= \Delta y,\ \Delta\phi \\ \text{total correction } f_{\Delta} &= \mathit{traslation} + \mathit{rotation} \end{aligned}$$

- Total correction depends on dy, dz, dφ

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

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



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

First step:

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

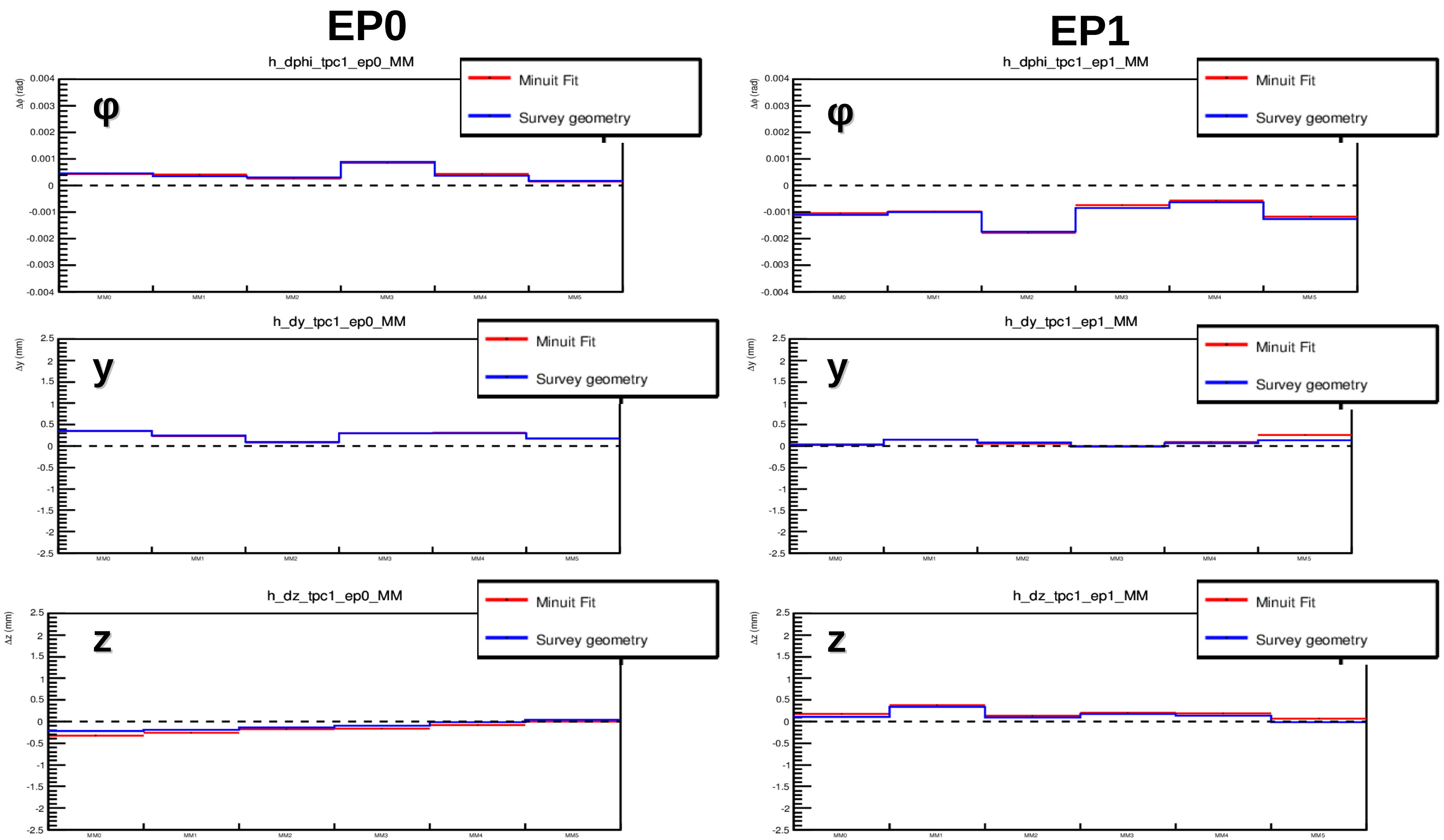
Second step:

a) Translational corrections extraction, Once rotational ones are applied

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

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



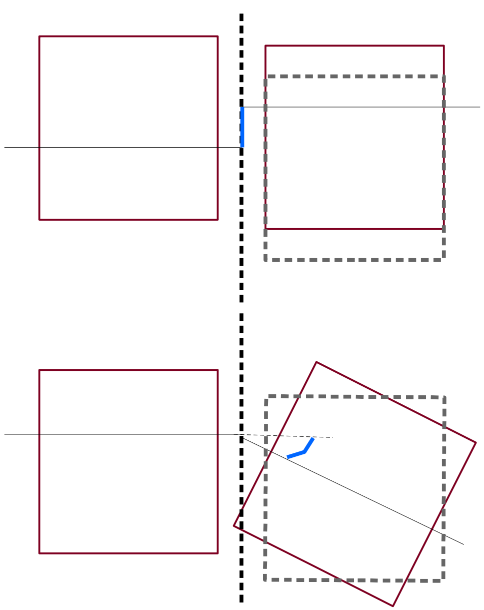
Cosmic rays Data Run2-4

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 $\Rightarrow$

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

$20 < \#hits < 50$

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

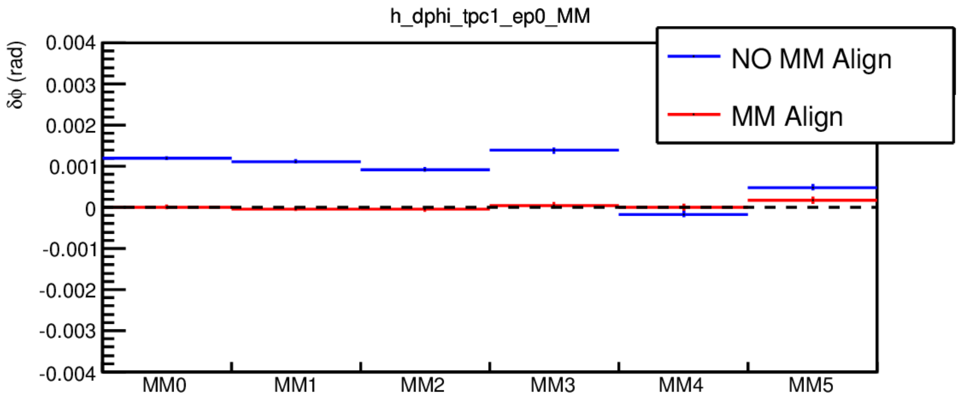
Cuts $\Rightarrow$

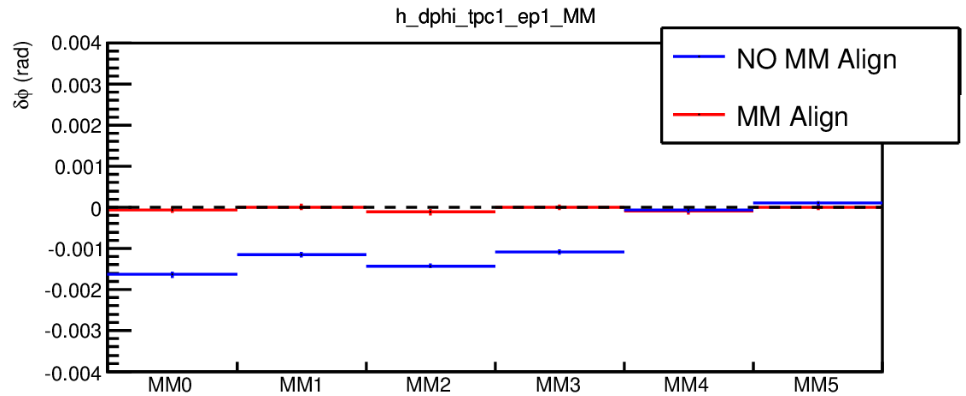
$|\varphi| < 1.$ rad

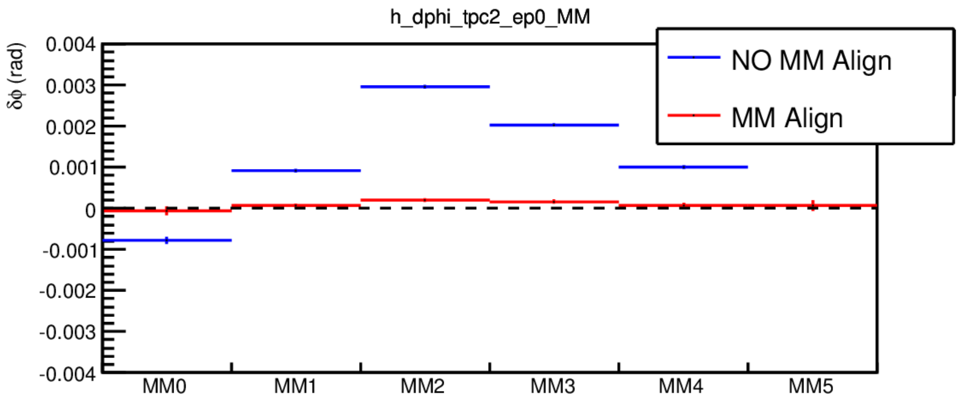
$|\Delta\varphi| < 0.015$ rad

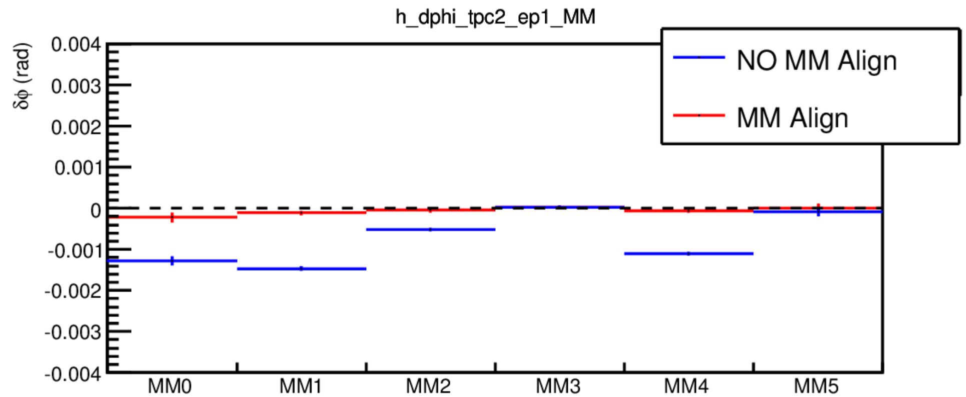
$|\Delta y| < 2.5$ mm

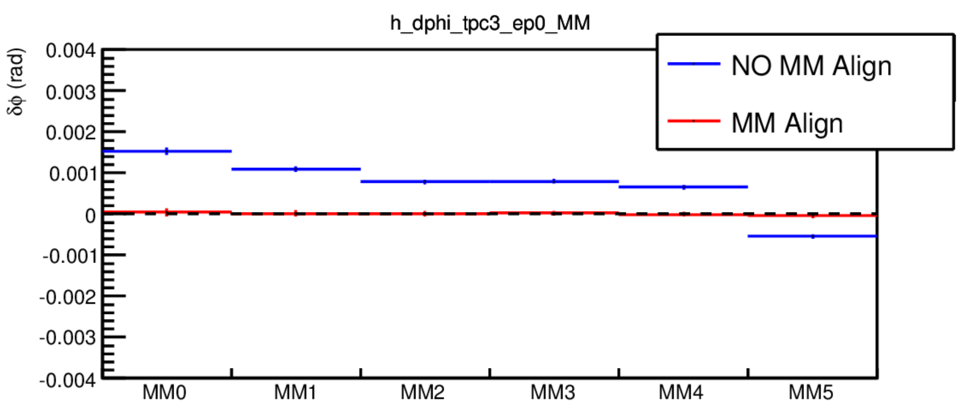
MicroMegas φ alignment

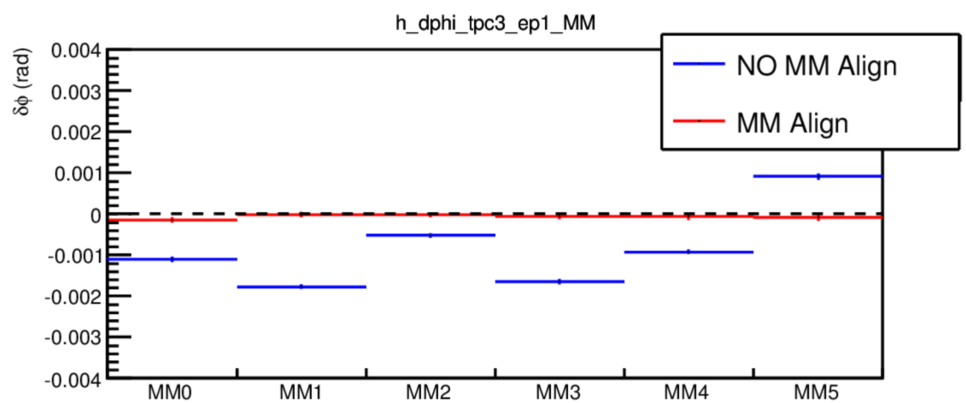




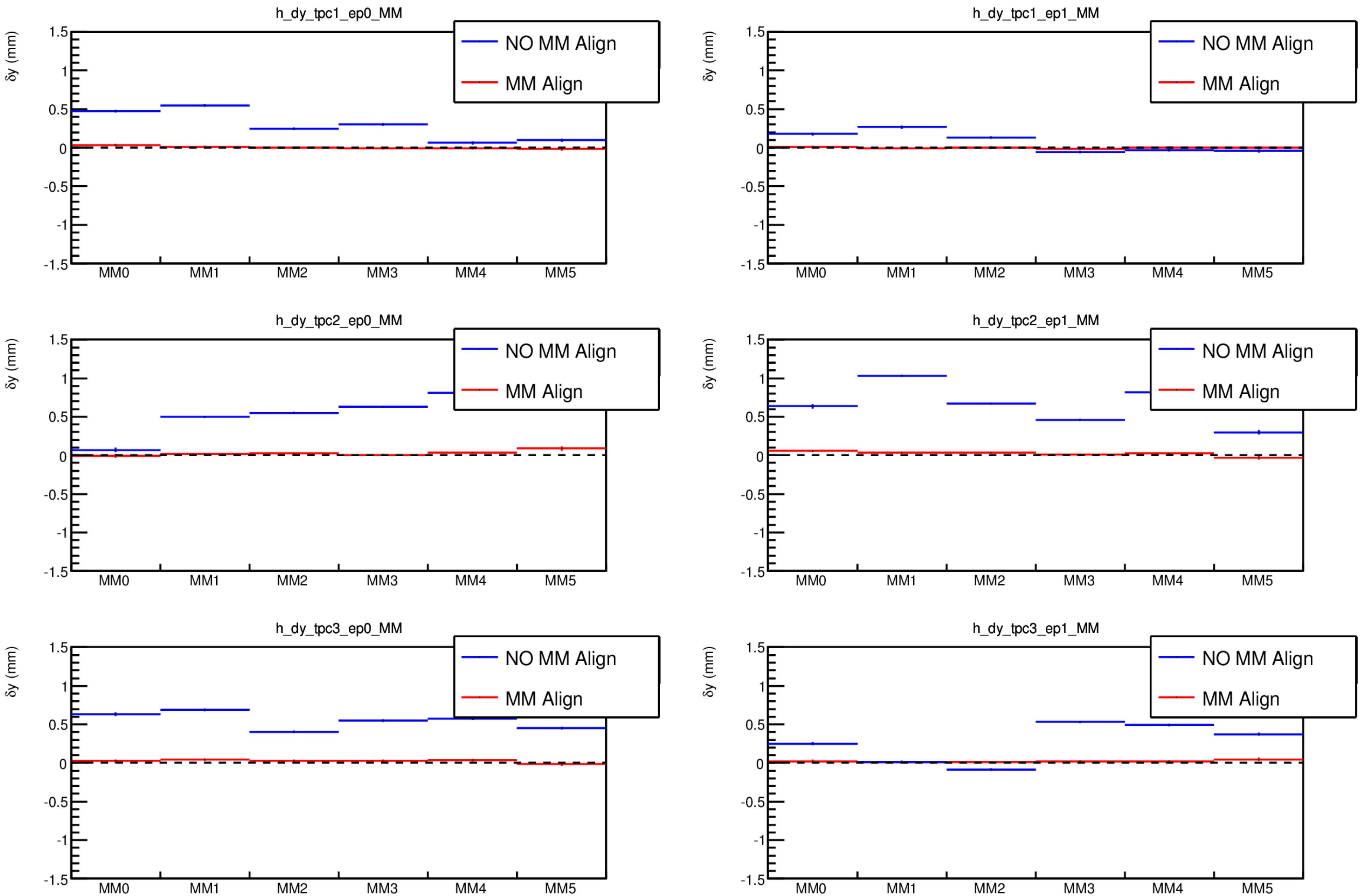




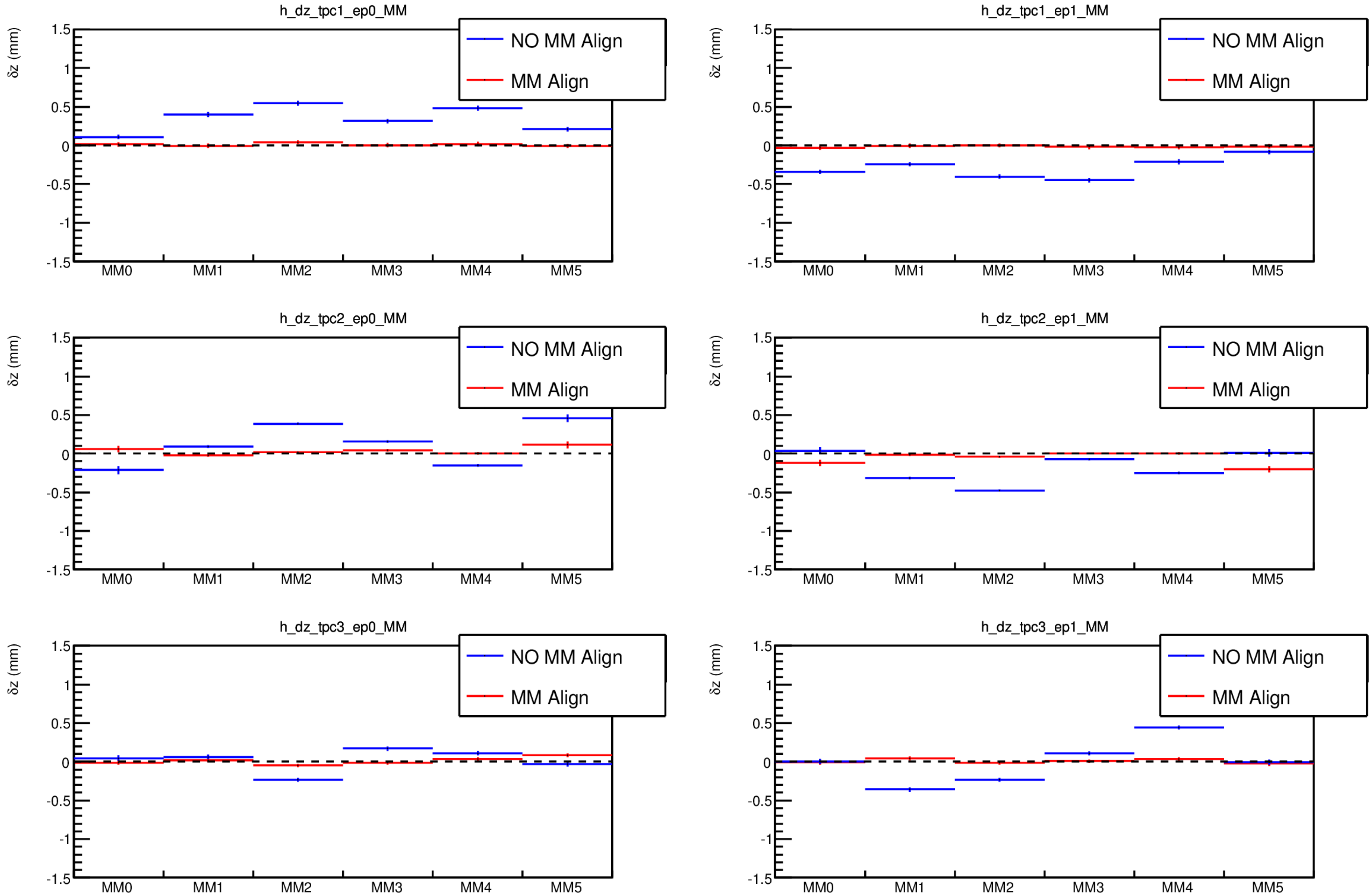




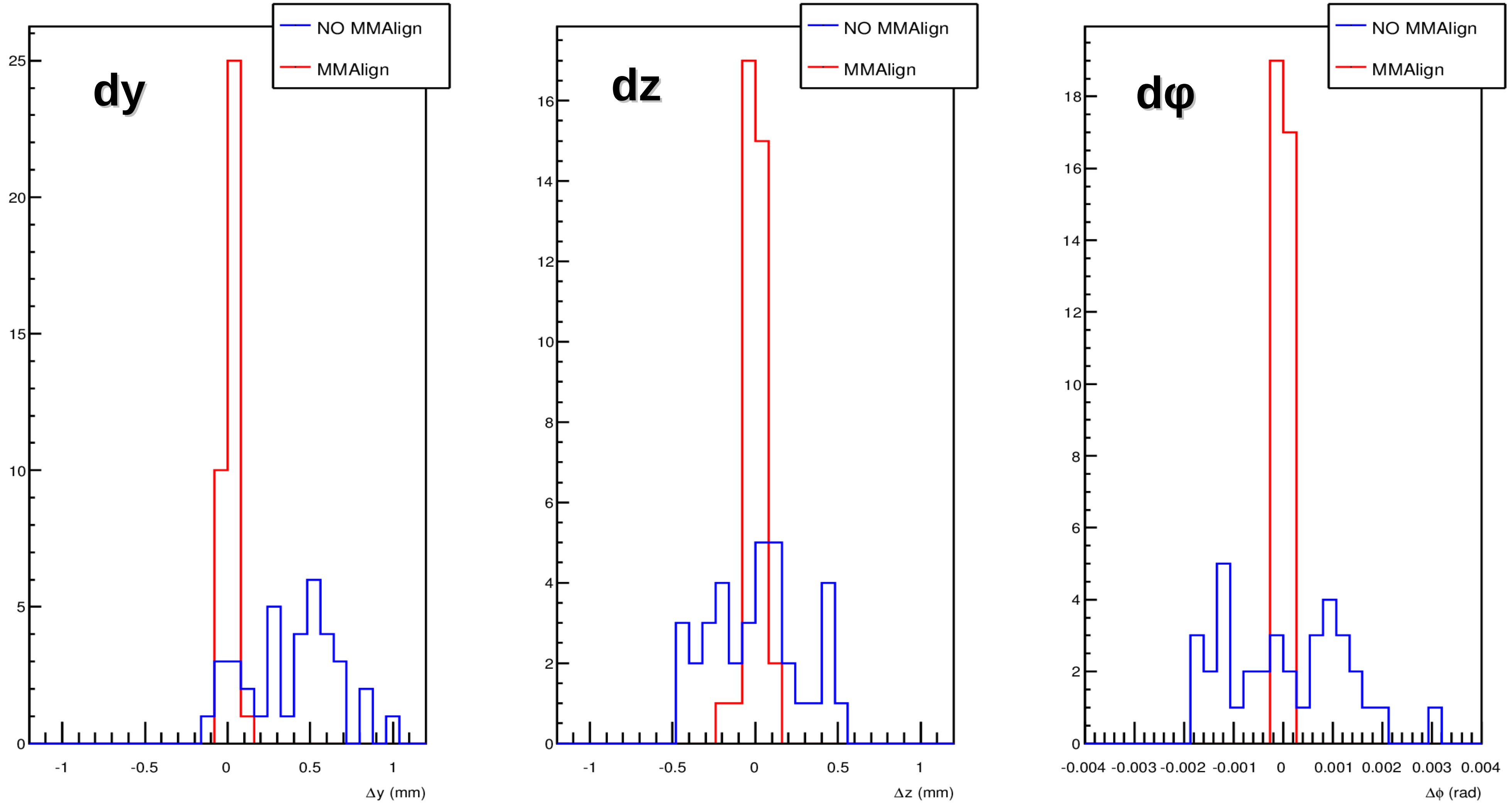
MicroMegas y alignment



MicroMegas z alignment



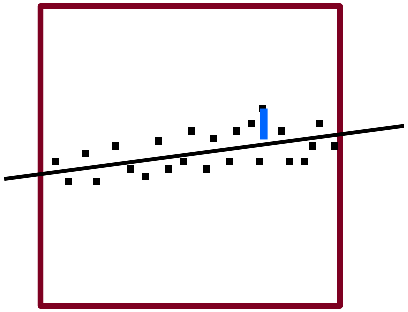
Before/After Alignment

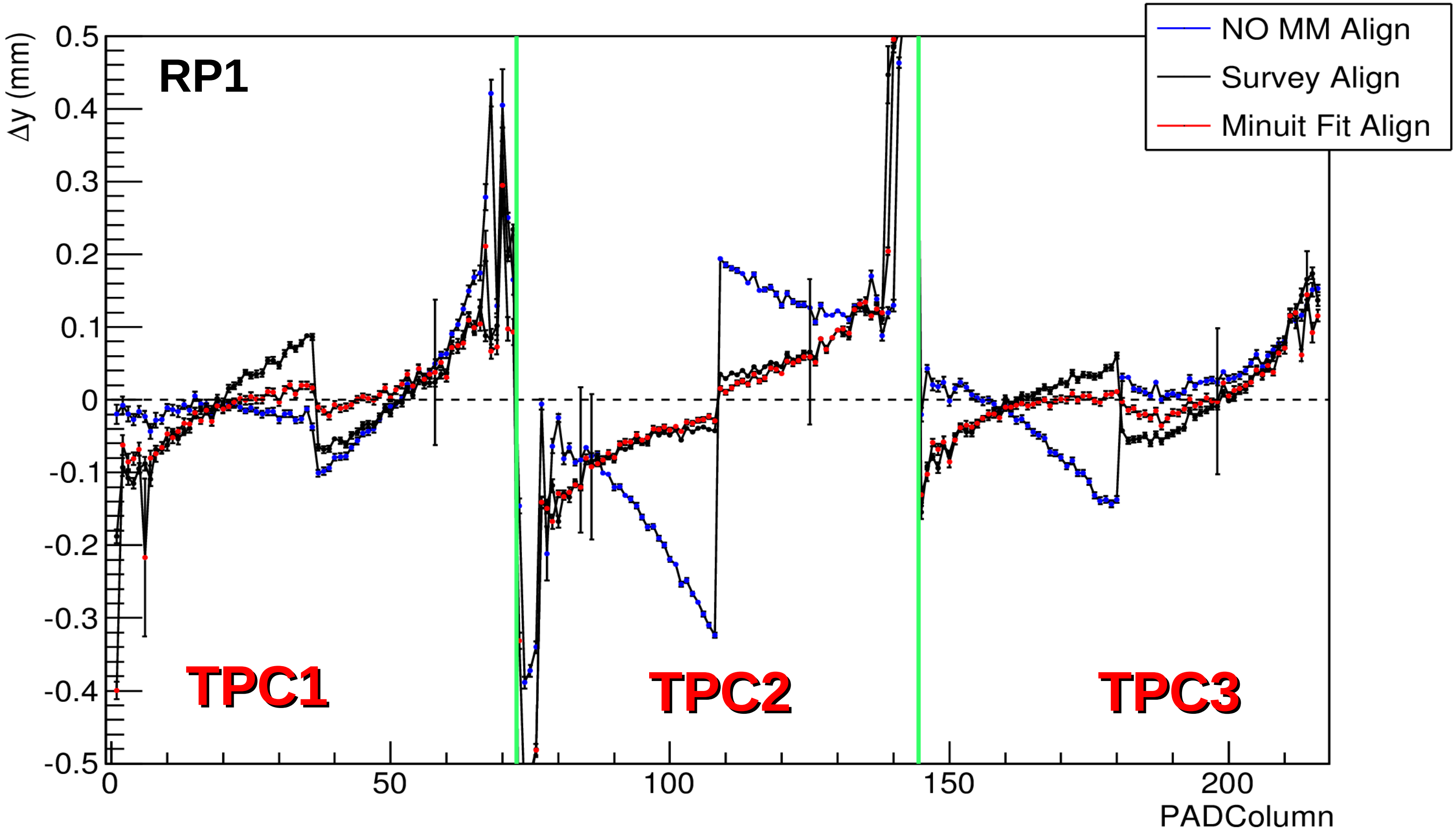


Good precision in corrections extraction

Alignment validation

- Fit alignment validation comparing 3 different samples:
  1) NO MM Alignment
  2) Survey Alignment
  3) Fit Alignment
- Residuals btw track hits and fitted track $\Delta y = y_{track} - y_{hit}$
- Residuals extracted via bi-gaussian fit to Δy distribution





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

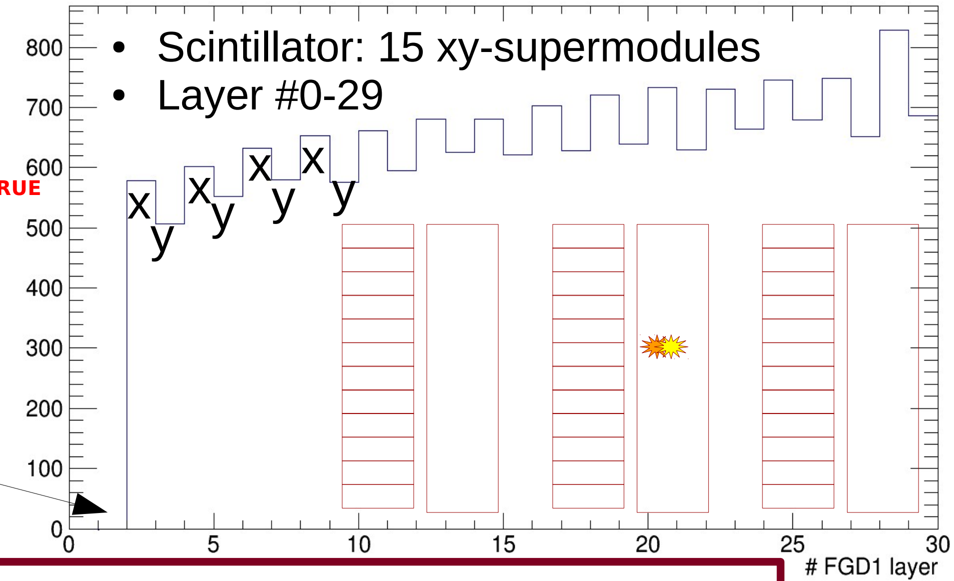
TPC3

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

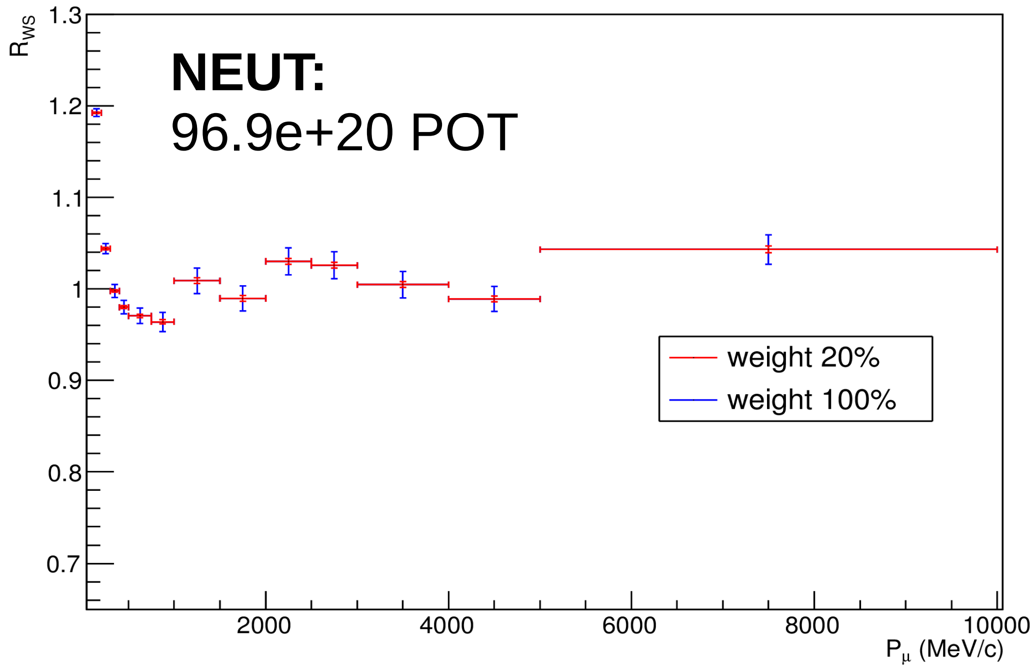
FGD1 control sample

Ratio in FGD1 must be 1 (CH/CH)

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



Any difference from 1 can be used to constraint the systematics



FGD1

±20%: ~0.3% on the ratio $R_{x/y}$

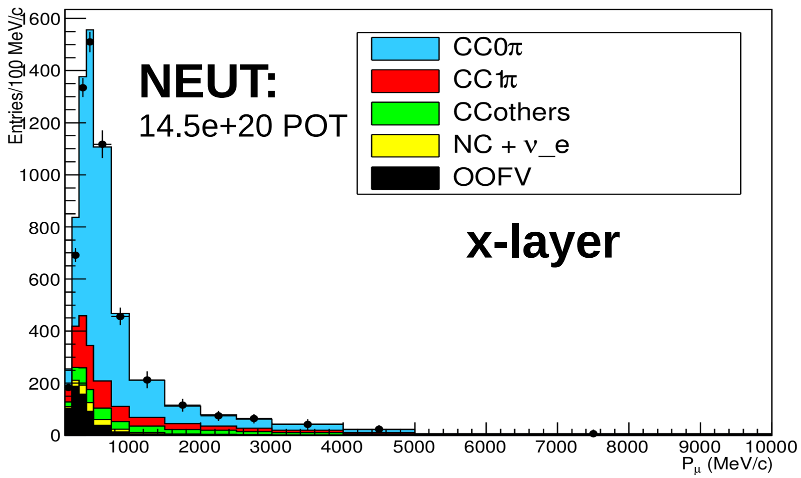
±100%: ~1.5% on the ratio $R_{x/y}$

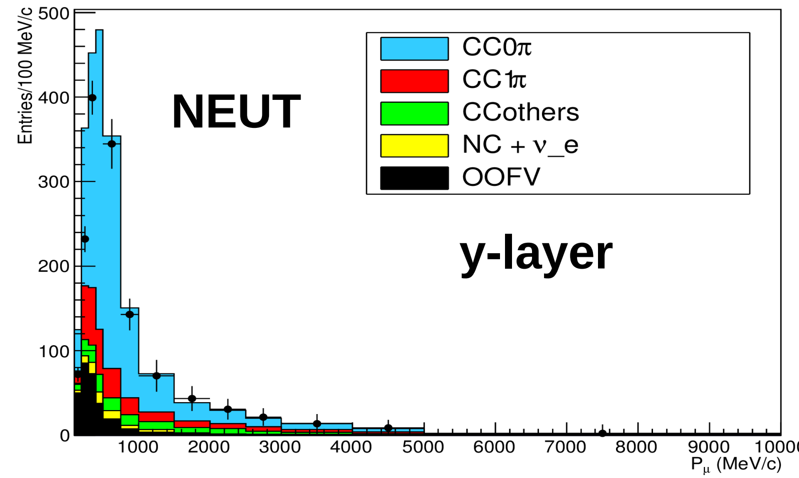
Switch off one xy-supermodule in succession every two in FGD1 to properly simulate reconstruction effect.

Hybrid FGD1

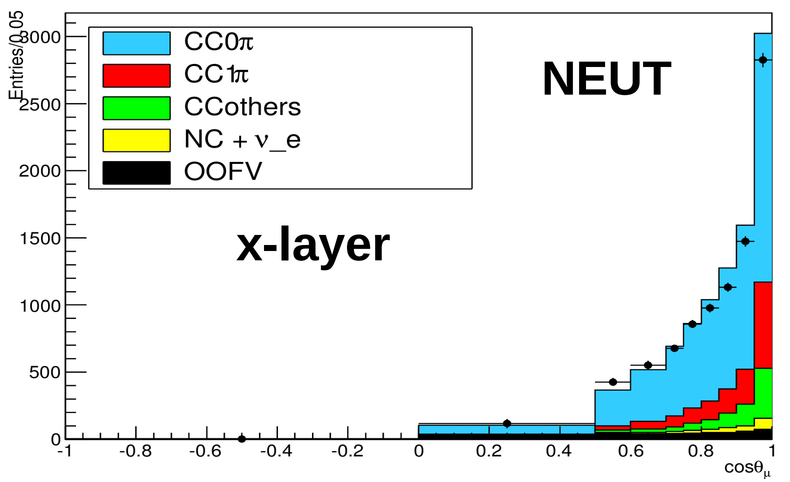
CC0π Hybrid FGD1 sample

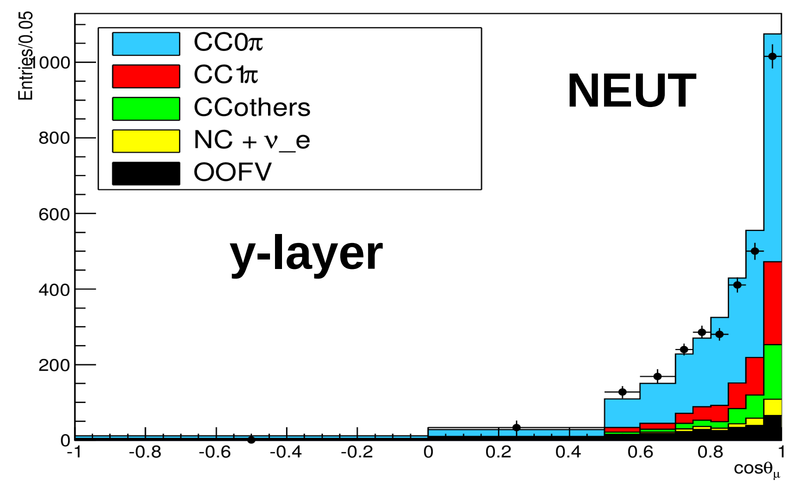
Momentum





Direction



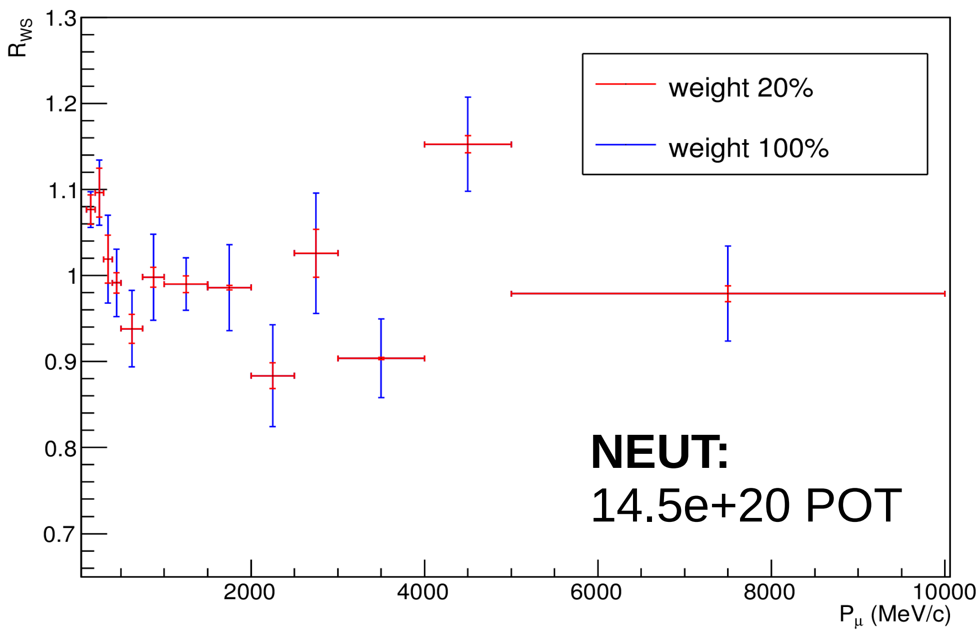


NEUT	Water	Scintx	Scinty	Dead
Hybrid FGD1-x	51.9	26.6	6.18	15.4
Hybrid FGD1-y	13.4	4.51	70.1	12.0
FGD1-x		68.9	15.1	16.0
FGD1-y		13.5	73.2	13.3

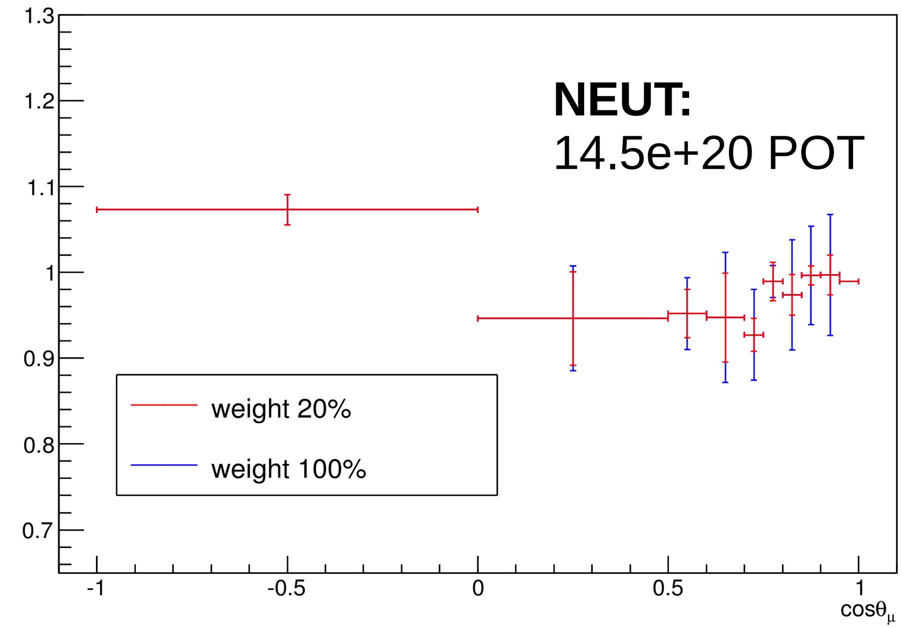
In Hybrid FGD1 x,y-layer enhanced by "water"

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 $R_{x/y}$

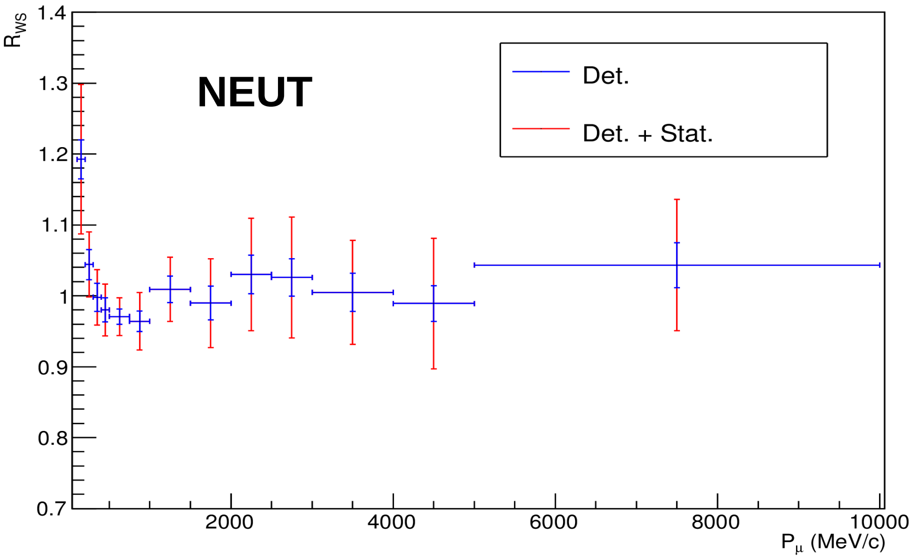
Hack the FGD1 brings similar results as in FGD2 on backward systematics.

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.



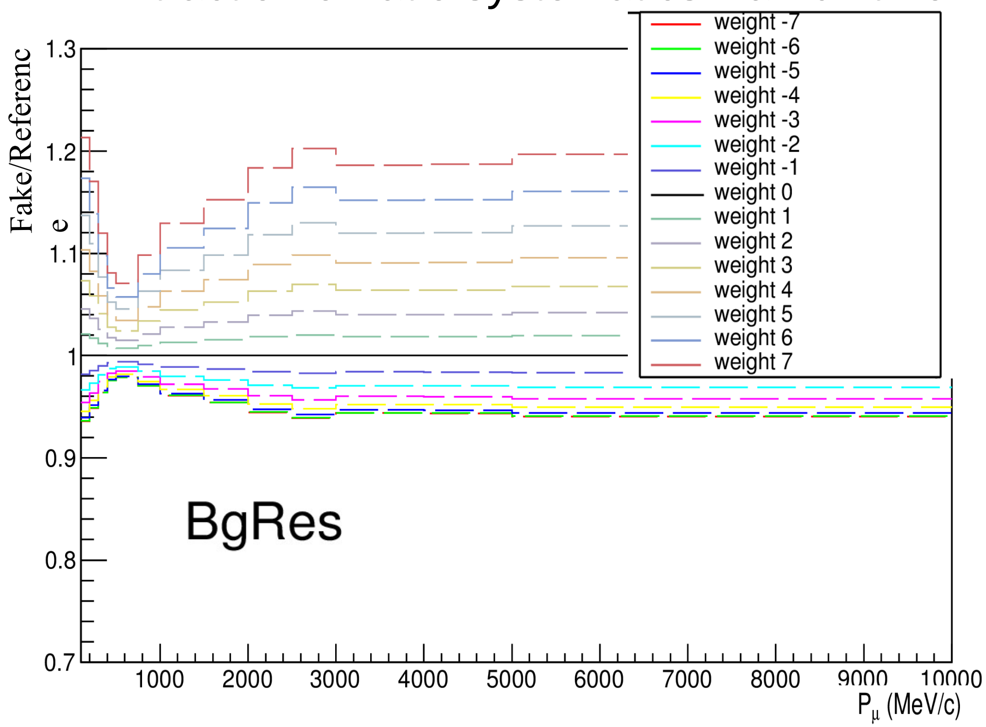
Systematic error: order of percent in each bin and less than 1% integrated

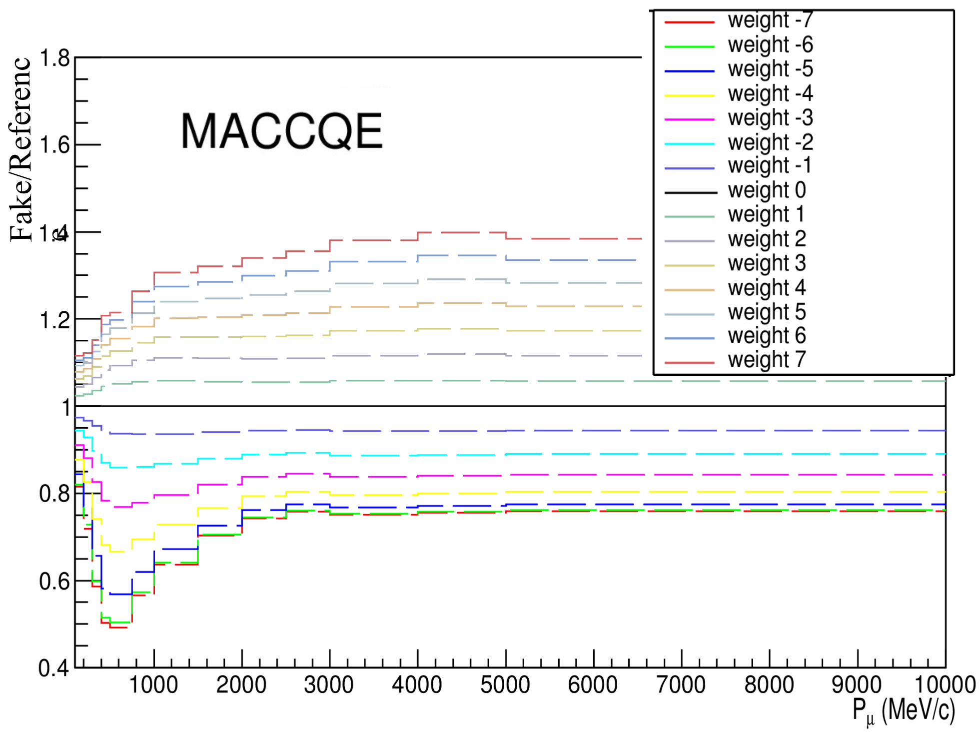
Theoretical systematics (I)

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

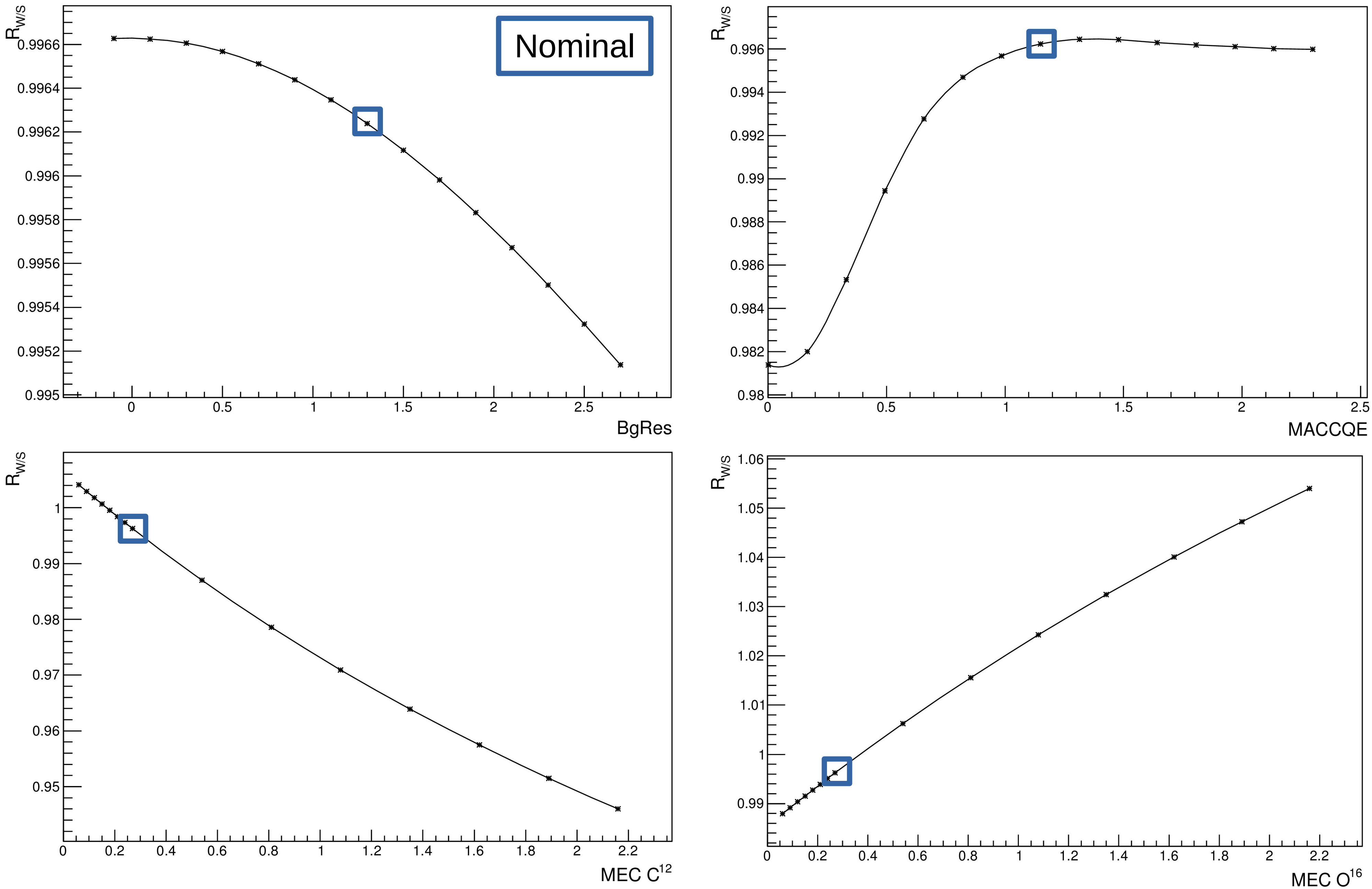
Reference sample: NEUT
Fake dataset: reweighted NEUT

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



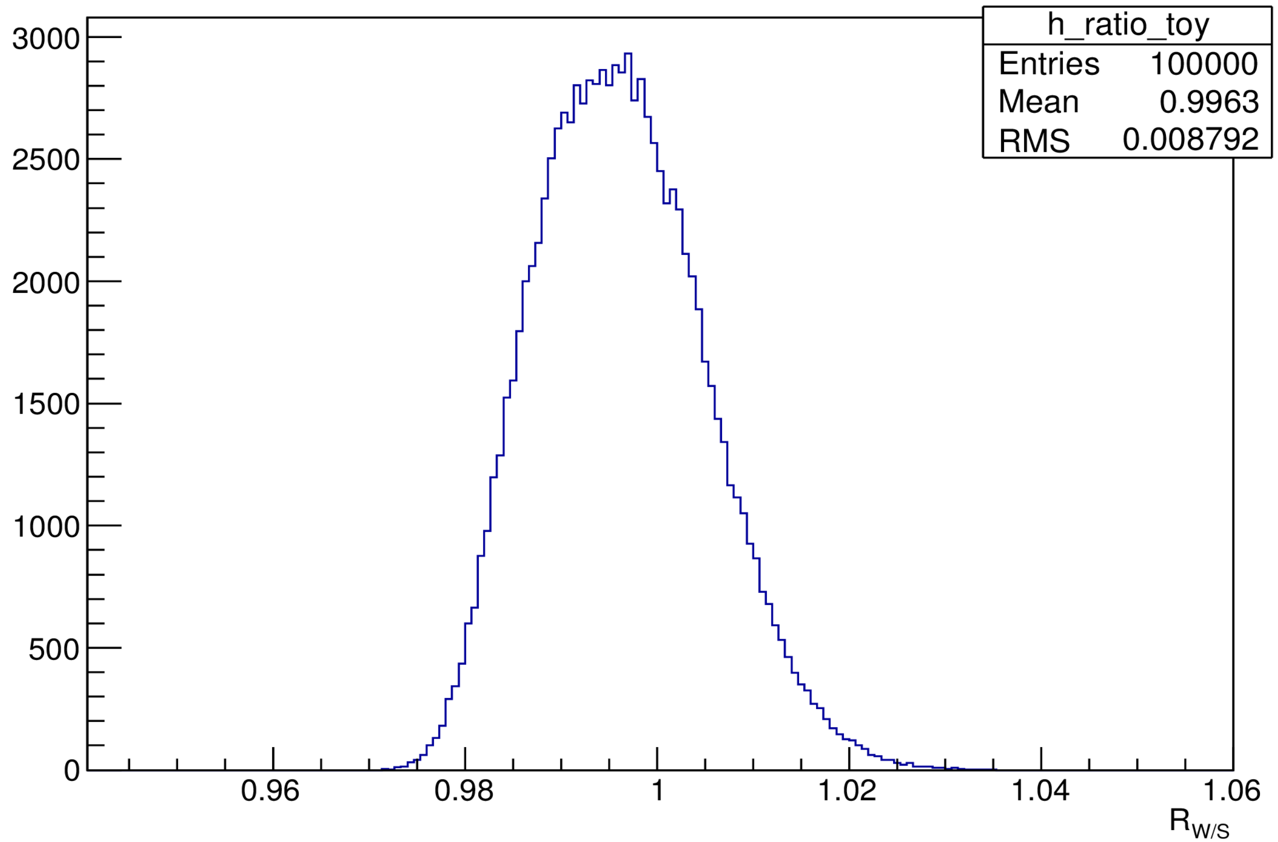


Response functions



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%