Towards the measurement of neutrino cross section on water in the 1 GeV region using the WAGASCI detector of the T2K experiment.

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On behalf of the T2K collaboration

WAGASCI / Baby MIND experiment

Current Physics goal

Aim to measure the double differential cross-section on CC0π0p samples at ~10% precision for each bin with the H2O and CH target

Reduce the systematic error on cross-section on the far detector by a better understanding of neutrino interaction models.

Target Detectors

2 X WAGASCI

- interaction target : **H_2O (80%)** + CH (20%)
- directly detectable particles : μ, $\pi^{\pm}$, p, e

Proton Module

- interaction target : CH (100%)
- directly detectable particles : μ, $\pi^{\pm}$, p, e

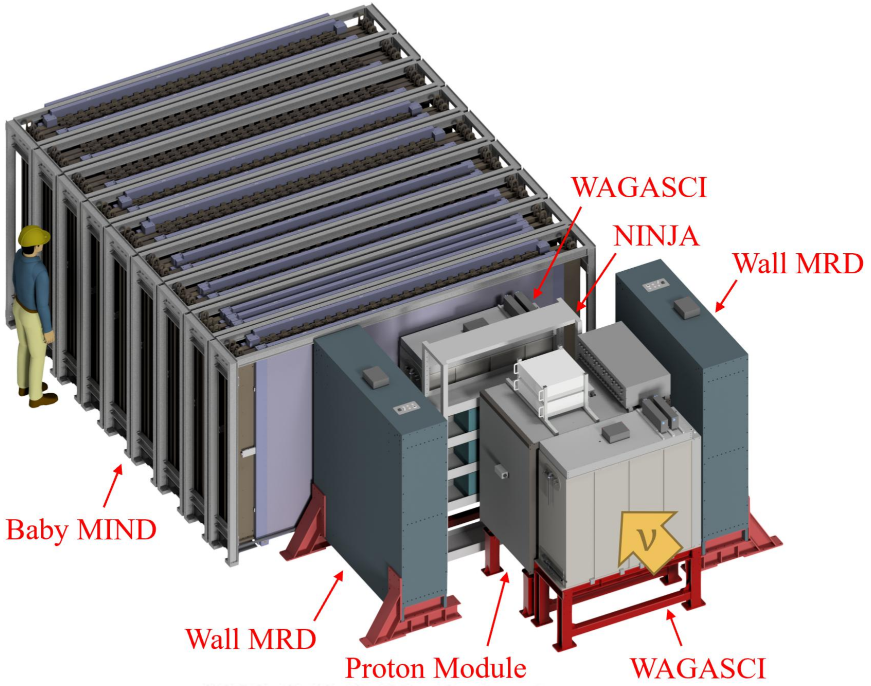
Muon range detectors

2 x Wall MRD (iron + scintillator)

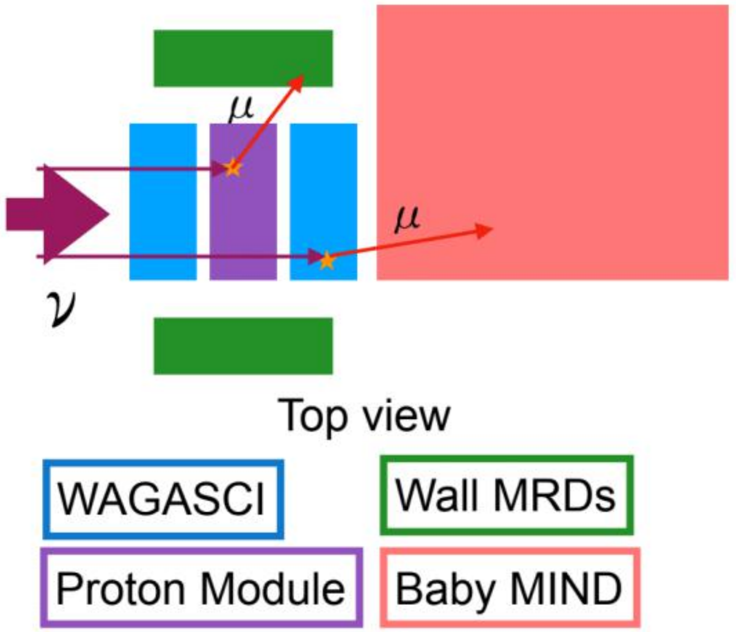
- directly detectable particles : mainly μ
- can measure momentum by energy loss

Baby MIND (magnetized iron + scintillators)

- directly detectable particles : mainly μ
- can measure momentum by energy loss and curvature
- is capable of particle change identification



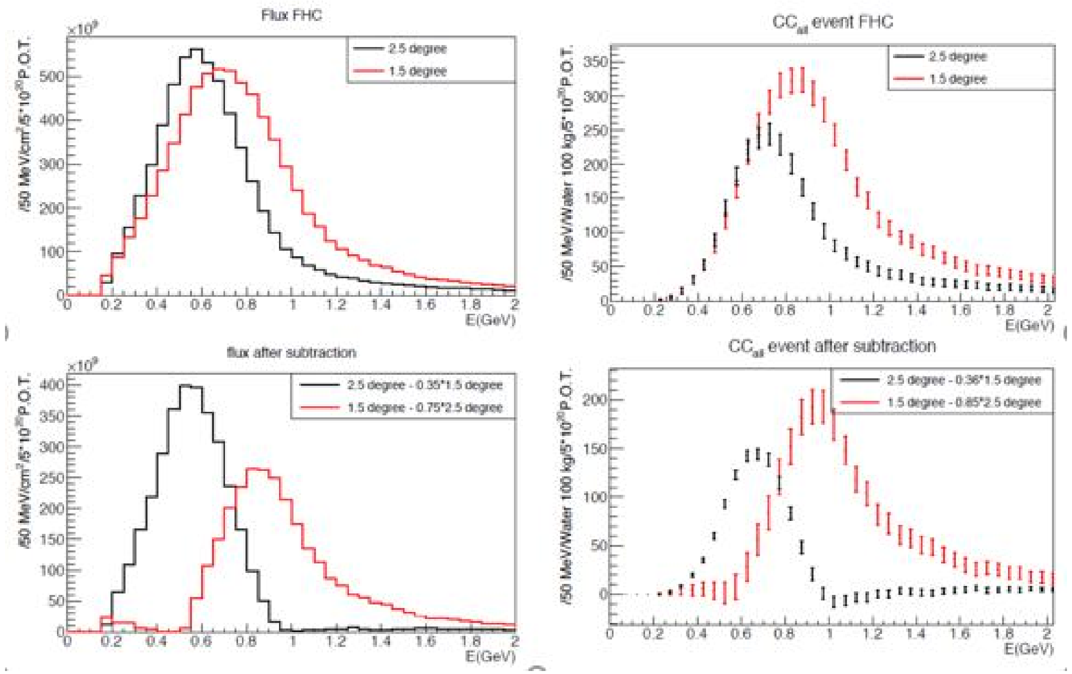
WAGASCI detectors



Top view

WAGASCI / Baby MIND experiment

	Current ND280	WAGASCI
volume ratio	The ND280 FGD2 target is half carbon, half water while the SK target is pure water (Water:CH ~ 50:50)	The WAGASCI target is **prevalently water (Water:CH ~ 80:20)**
Angular acceptance	ND280 has limited sensitivity to side and backwards escaping muons	WAGASCI has good sensitivity to **side-going muons** thanks to the two SideMRDs
Individual contribution	It is a big detector so the individual contribution is very specialized and can be "lost/not recognizable"	It is a relatively small detector so the **individial contribution is huge** and immediately recognizable



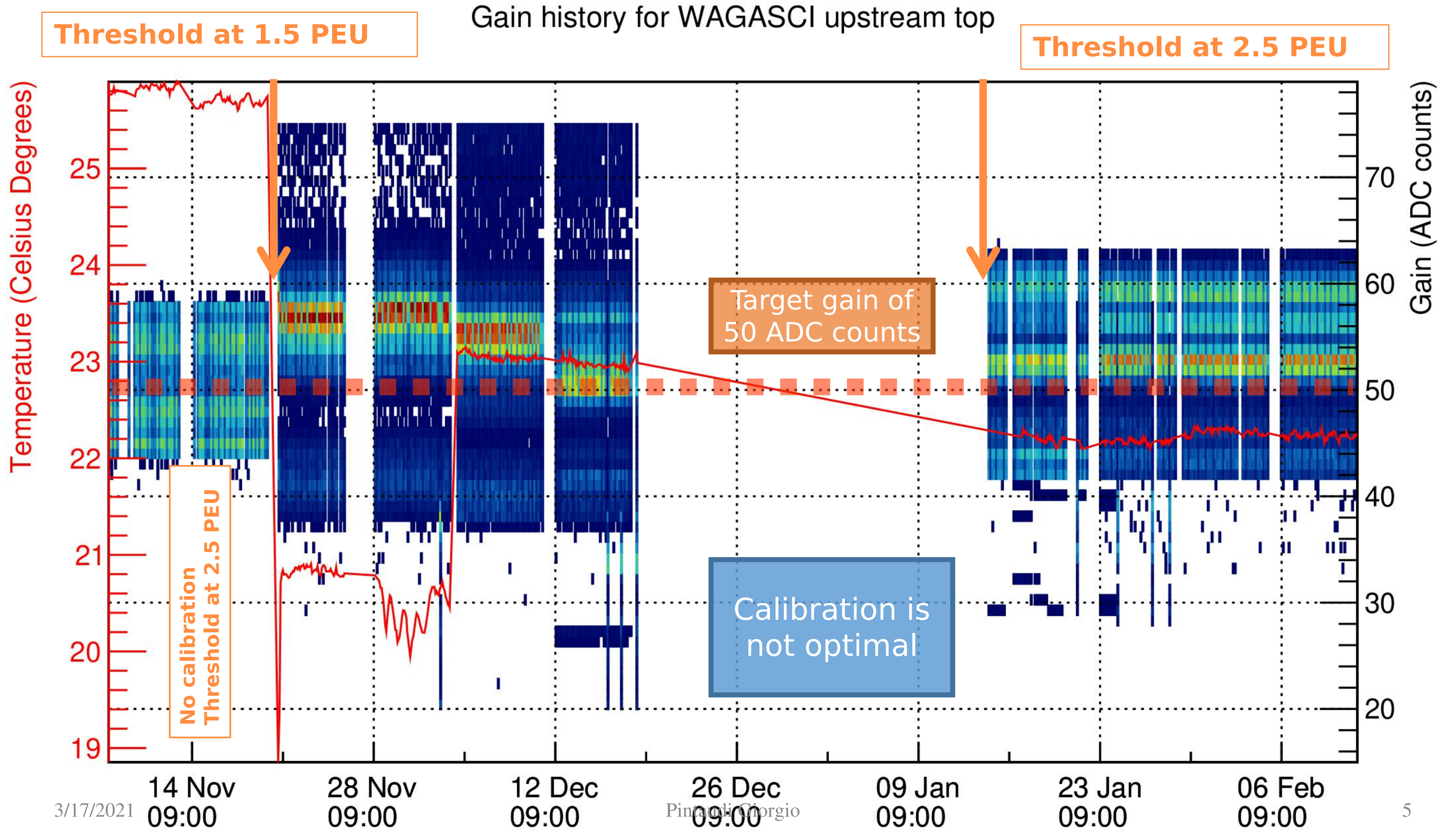
Because ND280 and WAGASCI are at a different off axis angle, they see two **different beam profiles** (with different peak energy).

It should be possible, by doing a WAGASCI-ND280 **joint analysis**, to gain access to a more restricted range of neutrino energies.

Agenda

- We are aiming at a measurement of **doubly-differential (angle and energy) cross-section of μ-neutrino on water and hydrocarbon and their ratio.**
- **The topology of interest is : CC 0π 0p (only a lepton in the visible final state)**
- The details of the cross section measurement are not yet finalized.
- The **detector performance evaluation** and track reconstruction is almost complete and is the main topic of this presentation.
- **Due to time constraint I am just focusing on the topics that I personally contributed to**. I am leaving out of the presentation the following studies:
    - Momentum and angle reconstruction in BabyMIND (Charlie Ruggles)
    - Detector performance of Proton Module and BabyMIND (Yasutome Kenji)
    - Detector performance of WallMRD (Takuya Kobata and Yasutome Kenji)

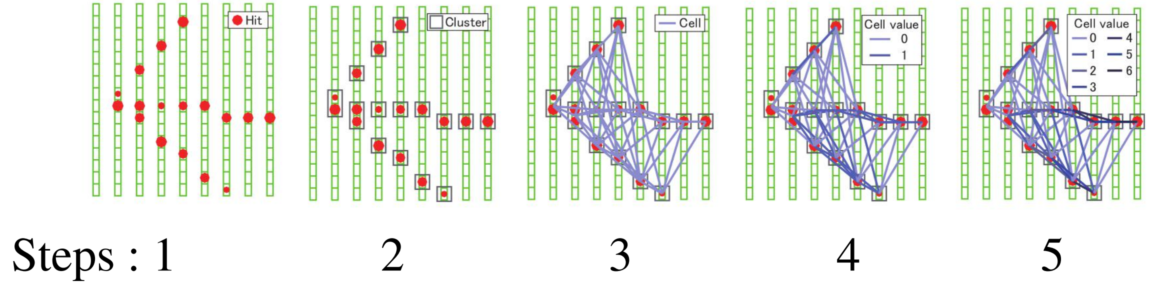
+100 points to anyone who can recognize this character


Gain history for WAGASCI upstream top
Threshold at 1.5 PEU
Threshold at 2.5 PEU
Temperature (Celsius Degrees)
Gain (ADC counts)
Target gain of 50 ADC counts
Calibration is not optimal
No calibration Threshold at 2.5 PEU
25
24
23
22
21
20
19
70
60
50
40
30
20
14 Nov 09:00
28 Nov 09:00
12 Dec 09:00
26 Dec 09:00
09 Jan 09:00
23 Jan 09:00
06 Feb 09:00

Track seeding : evaluation of two algorithms is ongoing

Cellular Automaton

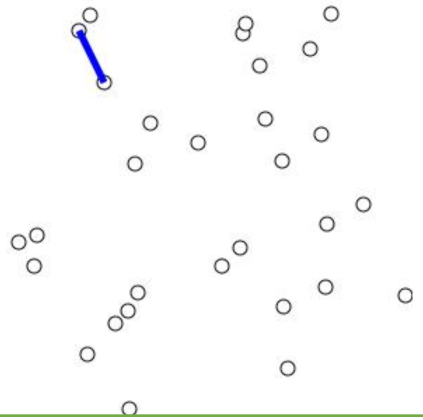
- Easy to implement and tune
- Based on algorithm used for INGRID
- **Need to make assumptions on geometry, by using a huge set of if/else statements**
- Do not make use the charge information
- Simple noise suppression by threshold cut
- **Current default** (parameter tuning is complete)



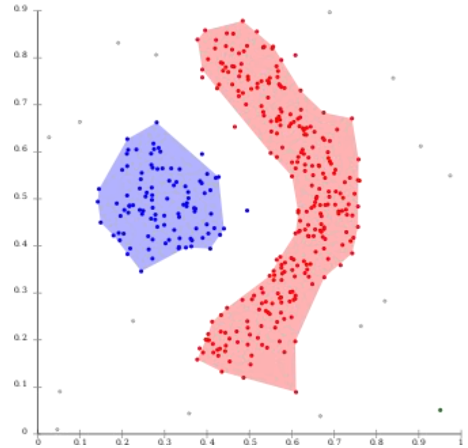
example of CAT algorithm connecting hits inside the INGRID detector (the plane structure and the upstream-downstream direction is an assumption of the algorithm)

Minimum Spanning Tree

- Implemented using the ND280 SFGD library (Jarnik-Prim-Dijkstra algorithm)
- Advanced noise suppression using DBSCAN algorithm
- **No assumption made on geometry (only hit position is used)**
- Use the charge information for seeding
- **Experimental** (parameter tuning is ongoing)



example of MST connecting the vertices of a graph.



Example of DBSCAN algorithm separating hit clusters (blue and red) from noise (grey)

What is a Minimum Spanning Tree?

- **In layman’s terms, it is a way of connecting vertices of a graph together so that the sum of the distance between the vertices is minimal.**
- In graph theory, the connections between vertices are usually called edges.
- The distance function can be arbitrarily defined and is usually called weight.

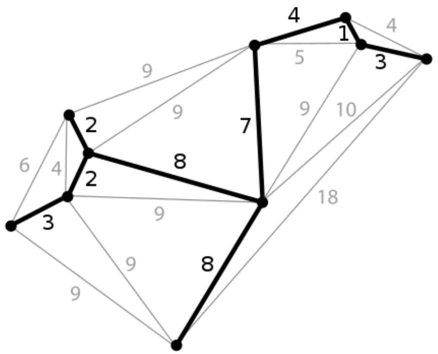
Graph theory slang

Particle Physics slang translation

- vertices → hits
- edges → connections
- weight → euclidean distance (can be weighted by the energy deposit)
- MST → set of clusters candidates

Example of minimum spanning tree:

- The vertices are the circles
- The edges are the lines
- The weights are the numbers
- **The MST is the set of the bold lines**



Travelling salesman problem
(Visit all cities covering the least distance)

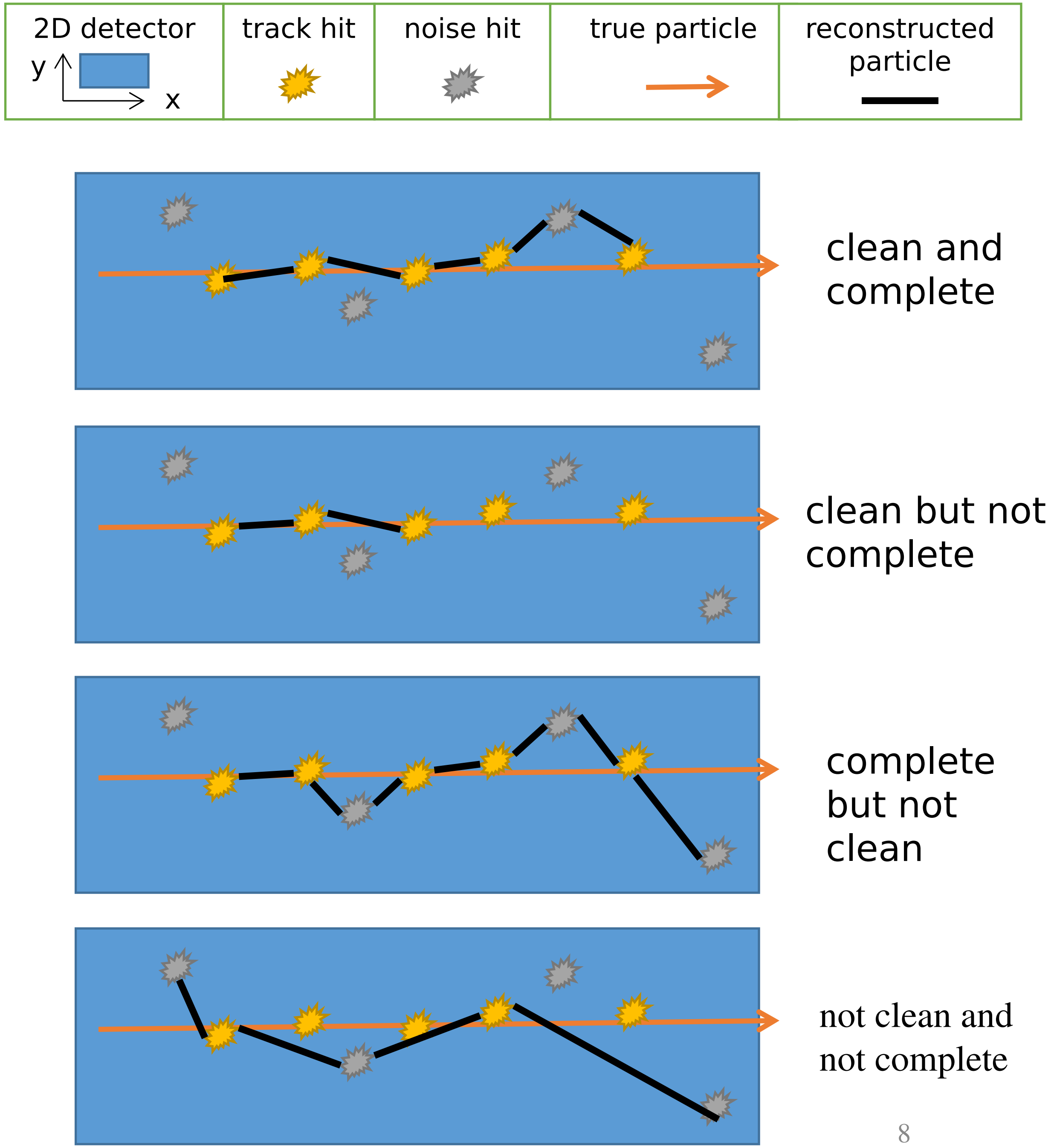
Reconstruction efficiency and parameter tuning

A reconstructed cluster A is said to be a match for a true cluster B if the following two conditions are satisfied:

1. **Completeness condition** : the 80% of hits of the cluster B belongs to the cluster A
2. **Cleanliness condition** : 80% of the hits of cluster A belongs to the cluster B

The reconstruction efficiency is defined as:

$$\epsilon = \frac{\#\ reconstructed\ clusters}{\#\ true\ clusters}$$



Reconstruction efficiency and parameter tuning

A reconstructed cluster A is said to be a match for a true cluster B if the following two conditions are satisfied:

1. **Completeness condition** : the 80% of hits of the cluster B belongs to the cluster A
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The reconstruction efficiency is defined as:

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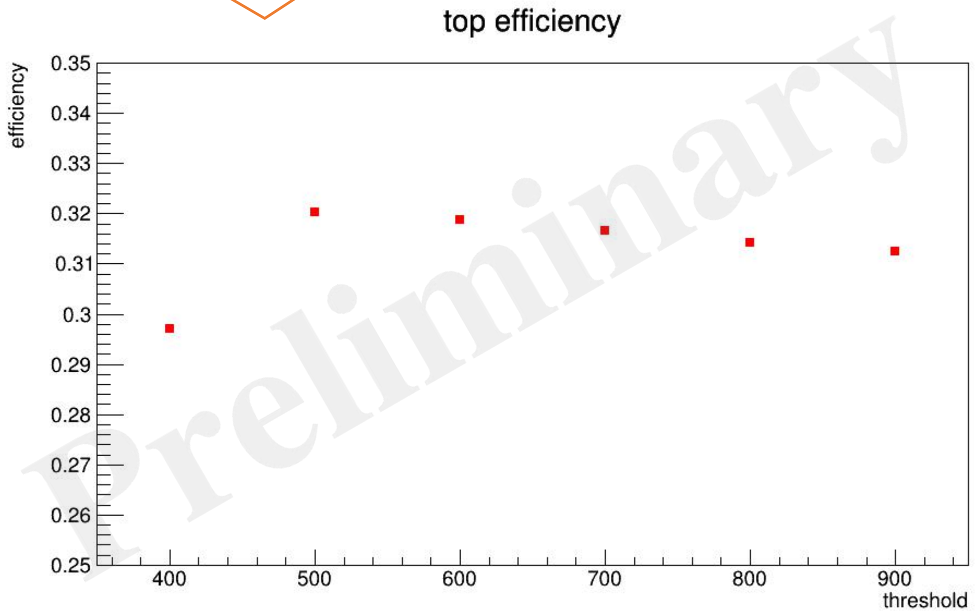
Each parameter of the track seeding algorithm is tuned by selecting the maximum of the reconstruction efficiency. The absolute efficiency depends on the sample and the efficiency definition and is not very significant per se.



example of arbitrary parameter of CAT algorithm tuned using the definition on the left. Plot by Takayasu-san.

Monte Carlo simulation of the detector response

Scintillator response

$$dL = S \frac{dE}{1 + k_B \frac{dE}{dx}}$$

- S : scintillation efficiency (included in M)
- k_B : Birk's constant (0.0208 ± 0.0023 cm/MeV)
- dE : infinitesimal energy deposit
- dL : infinitesimal light yield
- dE/dx : energy loss

Assumptions :

- The scintillator bars are so thin that the energy loss inside them is almost constant
- The scintillator efficiency factor is not directly measured and is included in the M factor (see the MPPC response)

Light collection response

Modeled as **simple exponential loss** : because the distance between the fiber and the hit point is at max a few centimeters we assume a simple exponential loss for the collected photons.

$$L_* = L_0 \, e^{-\frac{x}{\gamma}}$$

- L_0: light yield at hit point
- L_x: light yield at MPPC
- x: distance between hit point and fiber
- γ: empirical attenuation factor (4 ± 0.5 cm)

This correction factor is due to the not perfect collection of all the photons produced by the particle in the scintillator by the wavelength shifting fiber, due to geometrical acceptance, fiber

Fiber response

Modeled as **simple exponential loss** : because the length of the fiber is about 1m and is relatively smaller than the attenuation length, the assumption of monochromatic source of about 500 nm (green) should hold.

$$L_x = L_* \, e^{-\frac{x}{\lambda}}$$

- L_0: light yield at hit point
- L_x: light yield at MPPC
- x: distance between hit point and MPPC
- λ: attenuation length (241.7 cm)

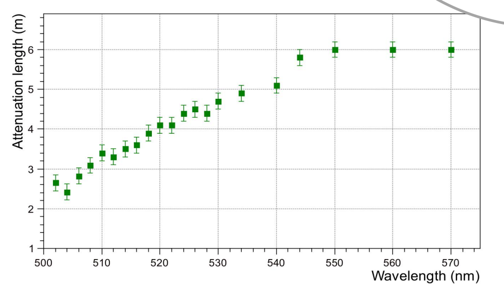


FIG. 5: The attenuation length of Y11 fiber vs wavelength.

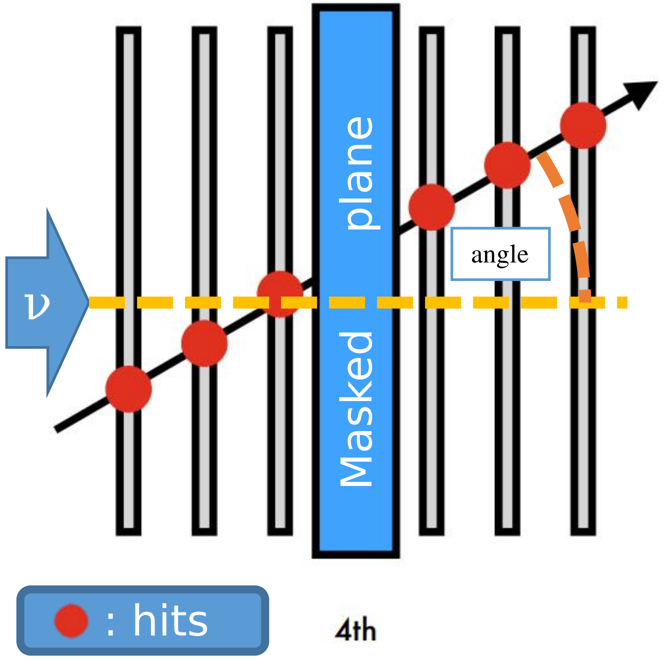
https://arxiv.org/pdf/1110.2651.pdf

MPPC response

Many corrections are applied to the light yield in sequence :

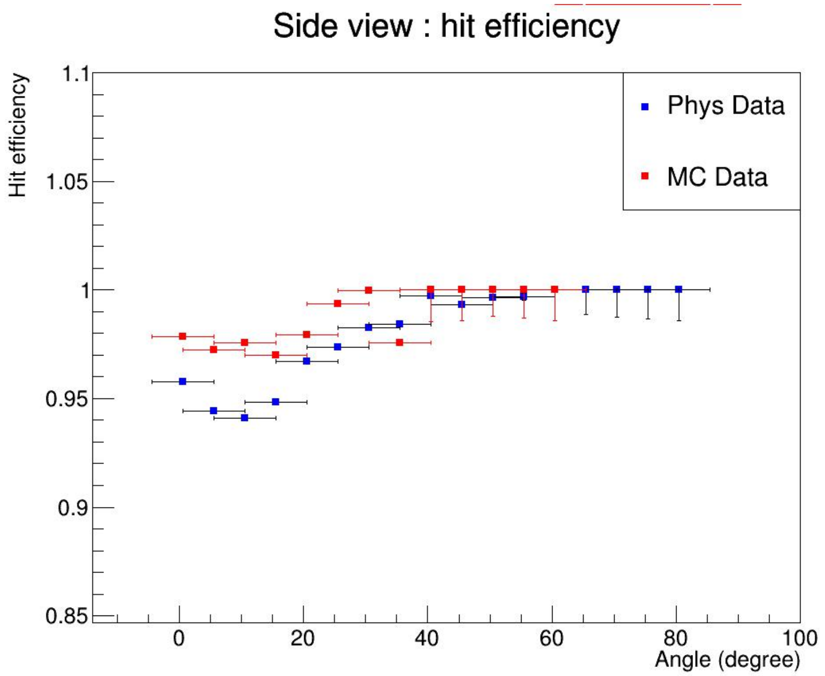
1. **Light yield (MeV) to PE (Photo-electrons) convertion** (tuned with MC)
   $PE_0 = M \cdot L_0$, where M : MeV to PE convertion factor (#PE / MeV)
2. **Finite pixel number effect and Poisson fluctuations**: because the number of pixels of each MPPC is finite and if multiple photons hit the same pixel the response is the same. The values were taken from MPPC data sheet.
   $PE_1 = n(1 - e^{-\varepsilon \cdot PE_0/n})$, where n = 716 : number of pixel, ε = 35% : PDE
3. **Cross-talk and after-pulse**
   $PE_2 = \frac{PE_1}{1-\rho}$, where ρ = 0.052 : empirical constant
4. **Fluctuation of gain** from pixel to pixel : random gaussian spread of light yield
   $PE_3 = gauss(\mu = PE_2, \sigma = 0.031)$

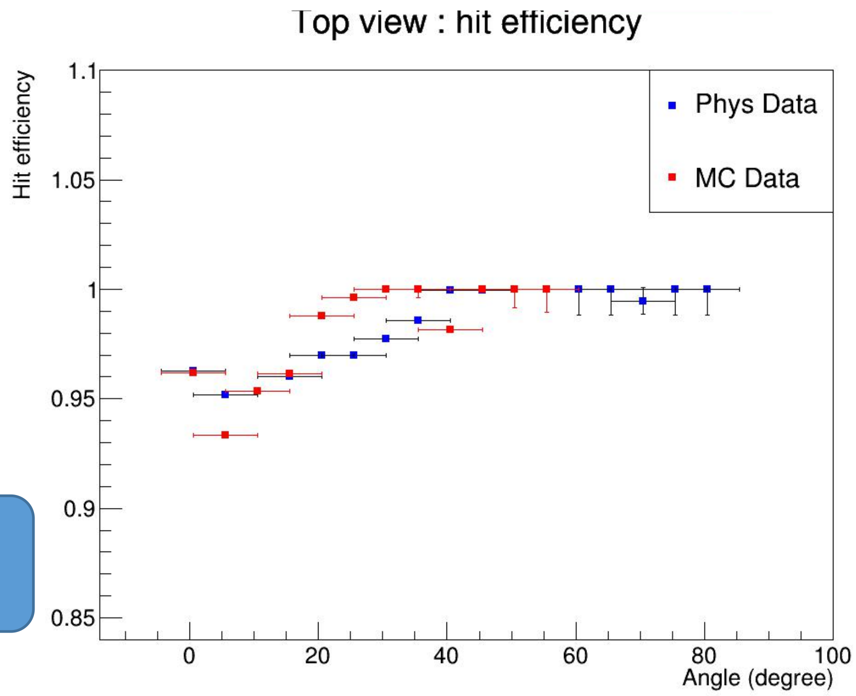
Hit efficiency of WAGASCI detector using the MST track seeding algorithm



1. Reconstruction : select only sand-muons-like tracks
2. Mask the target plane (for example 4th plane)
3. Only select tracks having hits in neighbouring planes ($\mathbf{n_0}$)
4. Check if the masked plane has an hit or not ($\mathbf{n_1}$)

$$efficiency = \frac{n_0}{n_1}$$

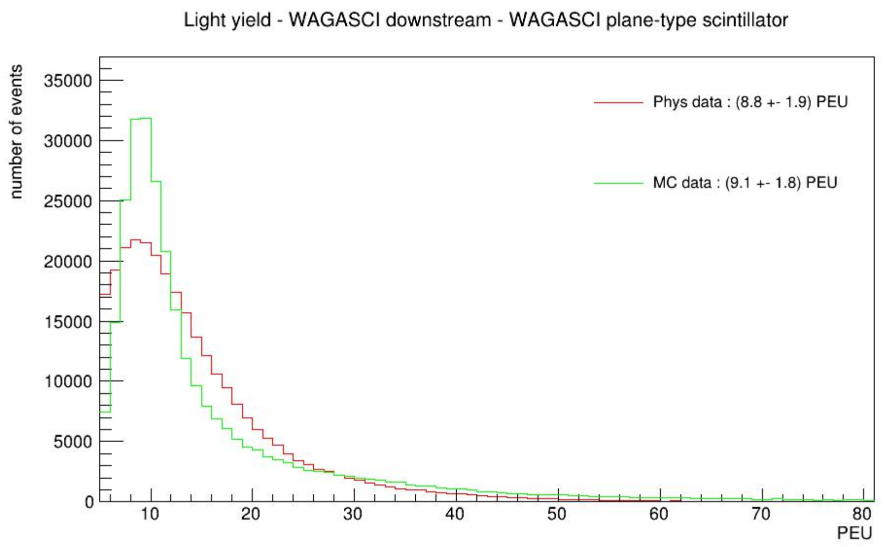


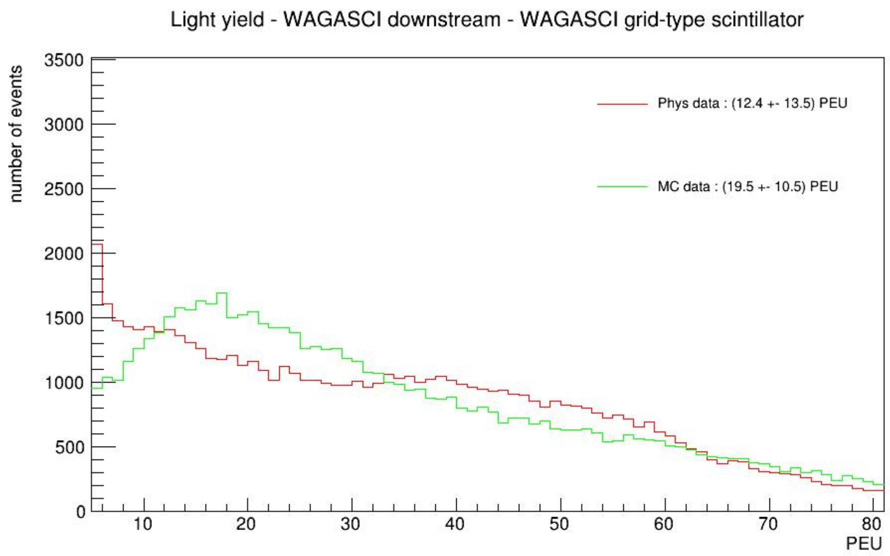


The agreement of MC and real data is around 3%. I think that by tuning the MC and improving the track seeding algorithm we can reach a better agreement.

Light yield in WAGASCI detector

- Light yield is evaluated using sand-muon tracks
- The electronics response has not been implemented yet because we need to perform a test bench of the electronics. *A characterization of the SPIROC2D chip was already done * by the developers but we need to do it again using the same configuration used for the Physics data taking.*
- The calibration of WAGASCI is far from perfect, that could also explain the discrepancy in the light yield of MC and real data.





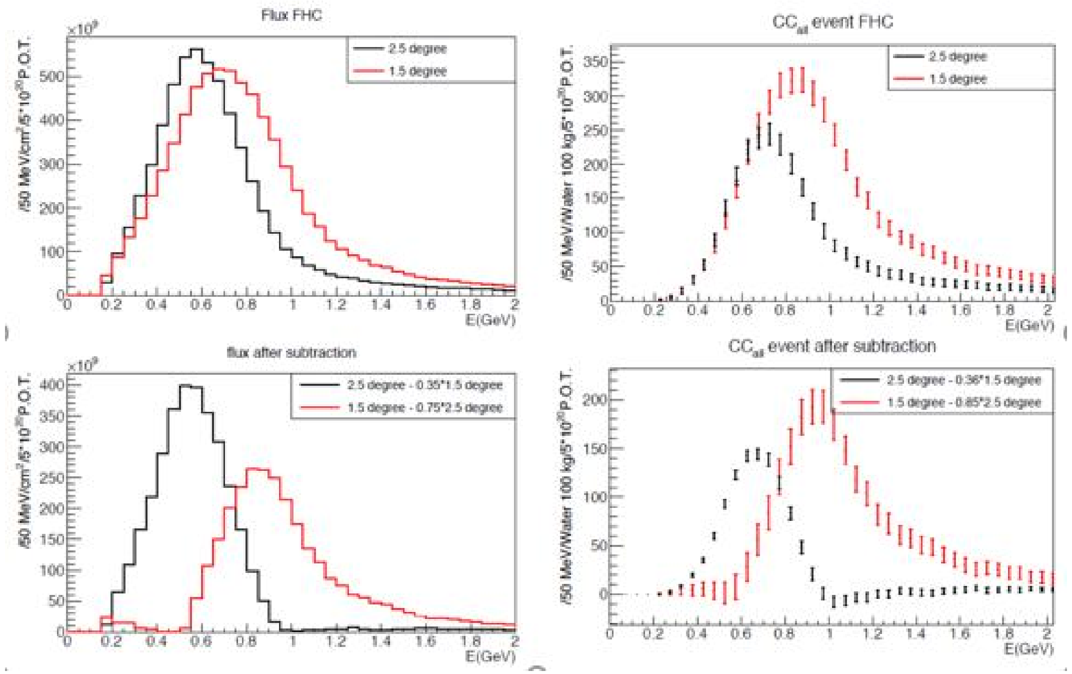
Conclusion and plans for the near future

- **Track reconstruction** :
  - need to improve the tuning of the algorithm parameters of the MST algorithm
  - need to evaluate which is the best algorithm for each subdetector
- **MC simulation of detector response** :
  - need to implement the electronics response
  - need to further tune the detector response parameters for the WAGASCI detector
- **Detector evaluation** :
  - need to evaluate the track matching efficiency between WAGASCI and WallMRD / BabyMIND
  - need to evaluate the reconstructed vertex position for WAGASCI
  - need to evaluate momentum and angle reconstruction efficieciency of tracks originating from the WAGASCI detector
- **Before the cross-section measurement :**
  - need to finalize what is the topology of the signal
  - need to define the phase-space for the xsec measurement
  - need to define event selection criteria

Backup slides

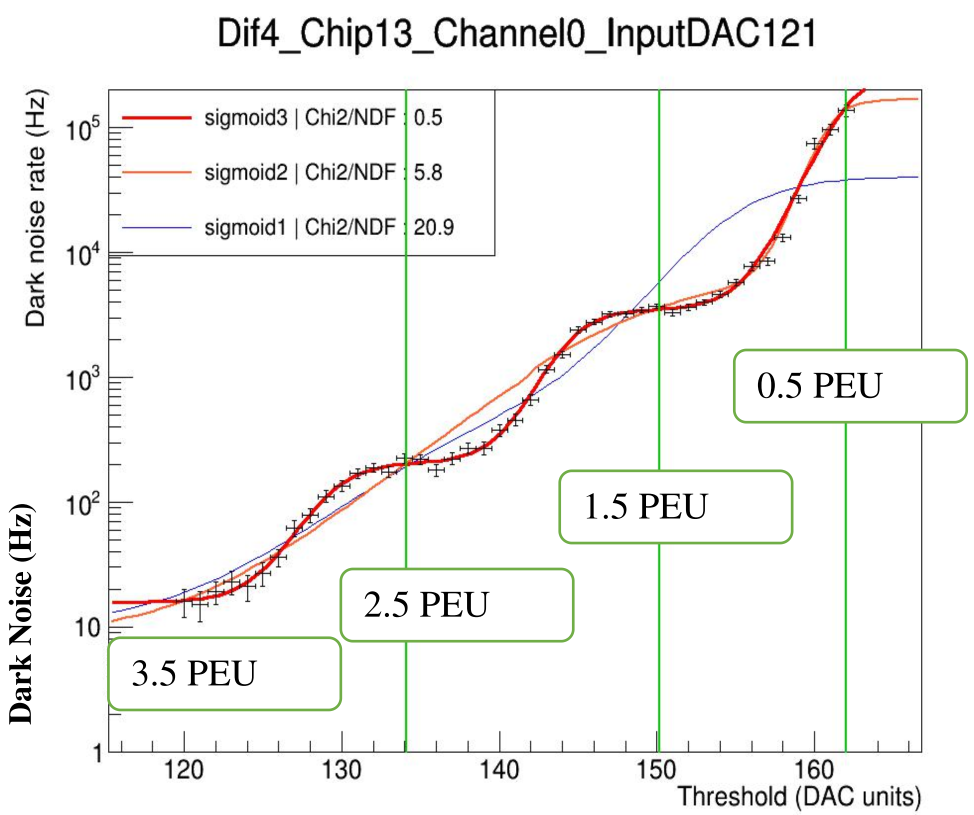
WAGASCI / Baby MIND experiment

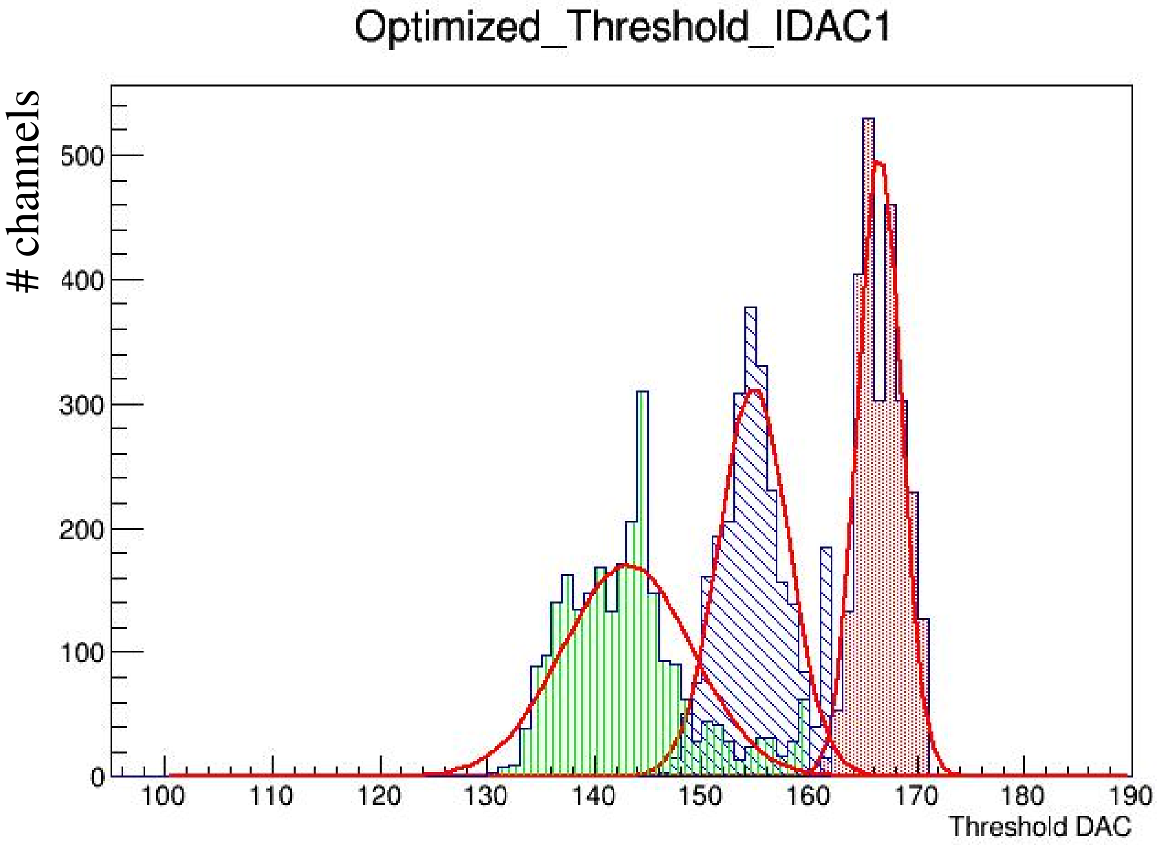
	Current ND280	WAGASCI
volume ratio	The ND280 FGD2 target is half carbon, half water while the SK target is pure water (Water:CH ~ 50:50)	The WAGASCI target is **prevalently water (Water:CH ~ 80:20)**
Angular acceptance	ND280 has limited sensitivity to side and backwards escaping muons	WAGASCI has good sensitivity to **side-going muons** thanks to the two SideMRDs
Individual contribution	It is a big detector so the individual contribution is very specialized and can be “lost/not recognizable”	It is a relatively small detector so the **individial contribution is huge** and immediately recognizable



Because ND280 and WAGASCI are at a different off axis angle, they see two different beam profiles (with different peak energy). It is possible, by doing a joint analysis, gain access to a more restricted range of neutrino energies.

Scurve calibration of WAGASCI and WallMRD detectors





The threshold DAC is the threshold adjustment DAC. Because of a design flaw in the ASIC the threshold is applied on the undershoot of the signal. That is why the X axis of the plots is reversed.

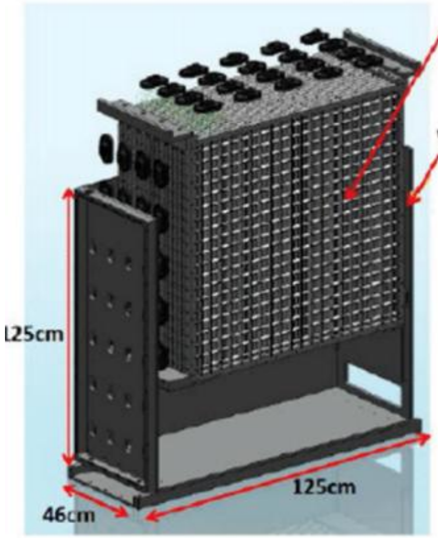
Red: 0.5 PEU Optimized threshold
Blue: 1.5 PEU Optimized threshold
Green: 2.5 PEU Optimized threshold

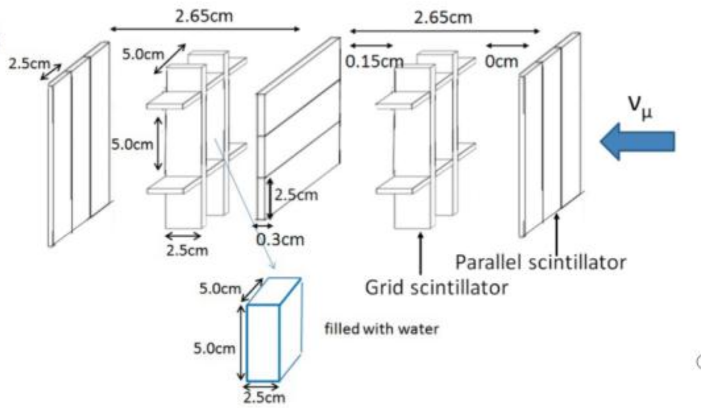
Target detectors

Focus of today's presentation

WAGASCI

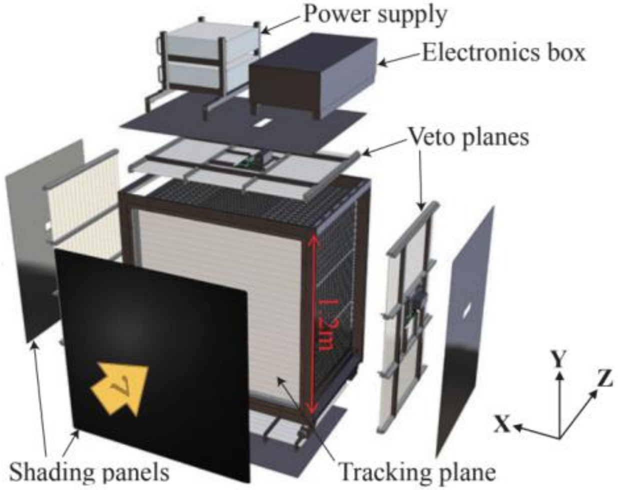
- 4π full angular acceptance
- Main target is 500kg of water (passive target)
- Readout system: scintillator, WLS fiber, MPPC
- Grid-like structure

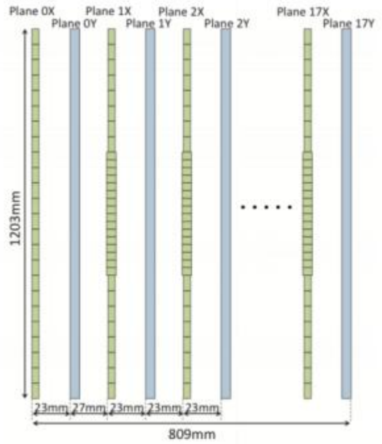




Proton Module

- forward acceptance
- fully active scintillator target (556 kg CH)
- Readout system: scintillator, WLS fiber, MPPC





Muon range detectors

WallMRD

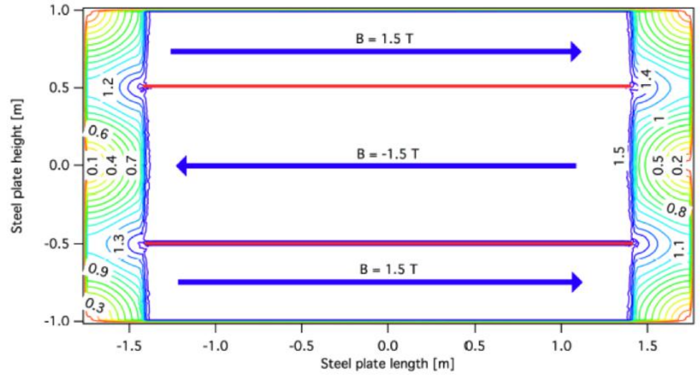
Wall MRD

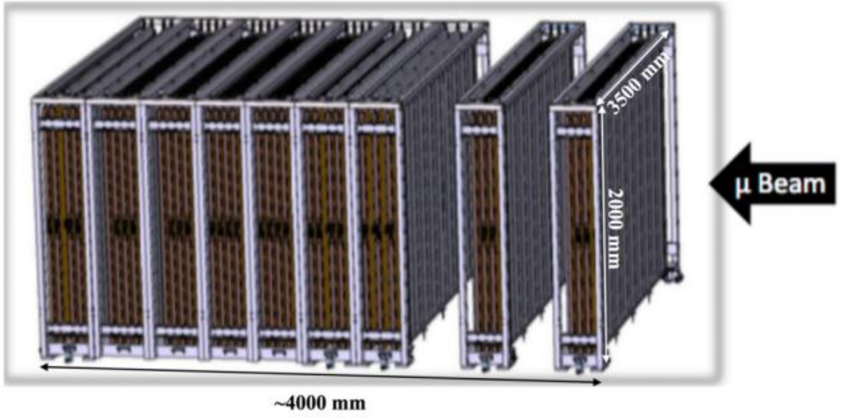
- Sandwich-structure of iron planes and scintillator tracking planes
- Readout system: scintillator, WLS fiber, MPPC
- **Detect side going muons**
- Measure momentum by range

Baby MIND

- Iron-core magnet modules and scintillator tracking planes
- Readout system: scintillator, WLS fiber, MPPC
- Detect forward going muons
- **Measure momentum by range and curvature**
- **Non uniform magnetic field to keep particles inside tracking region**

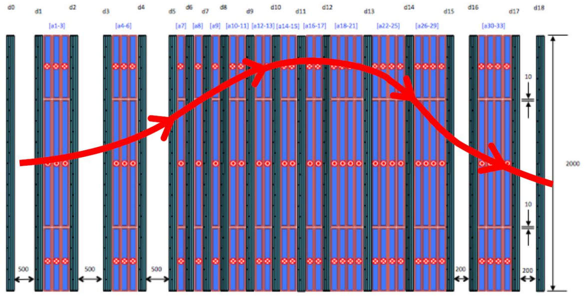
Baby MIND magnetic field front view





Baby MIND

Baby MIND magnetic field side view

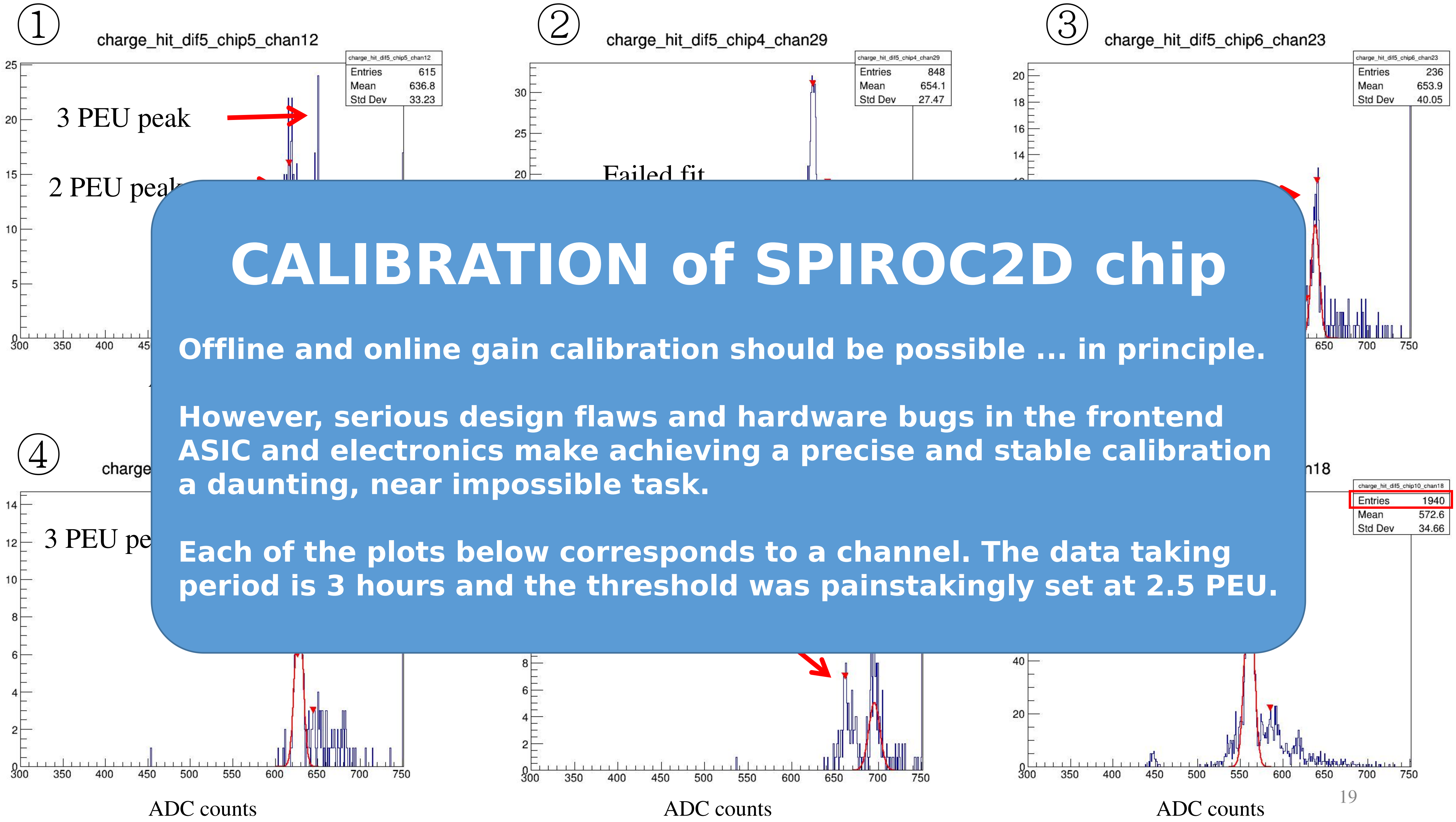


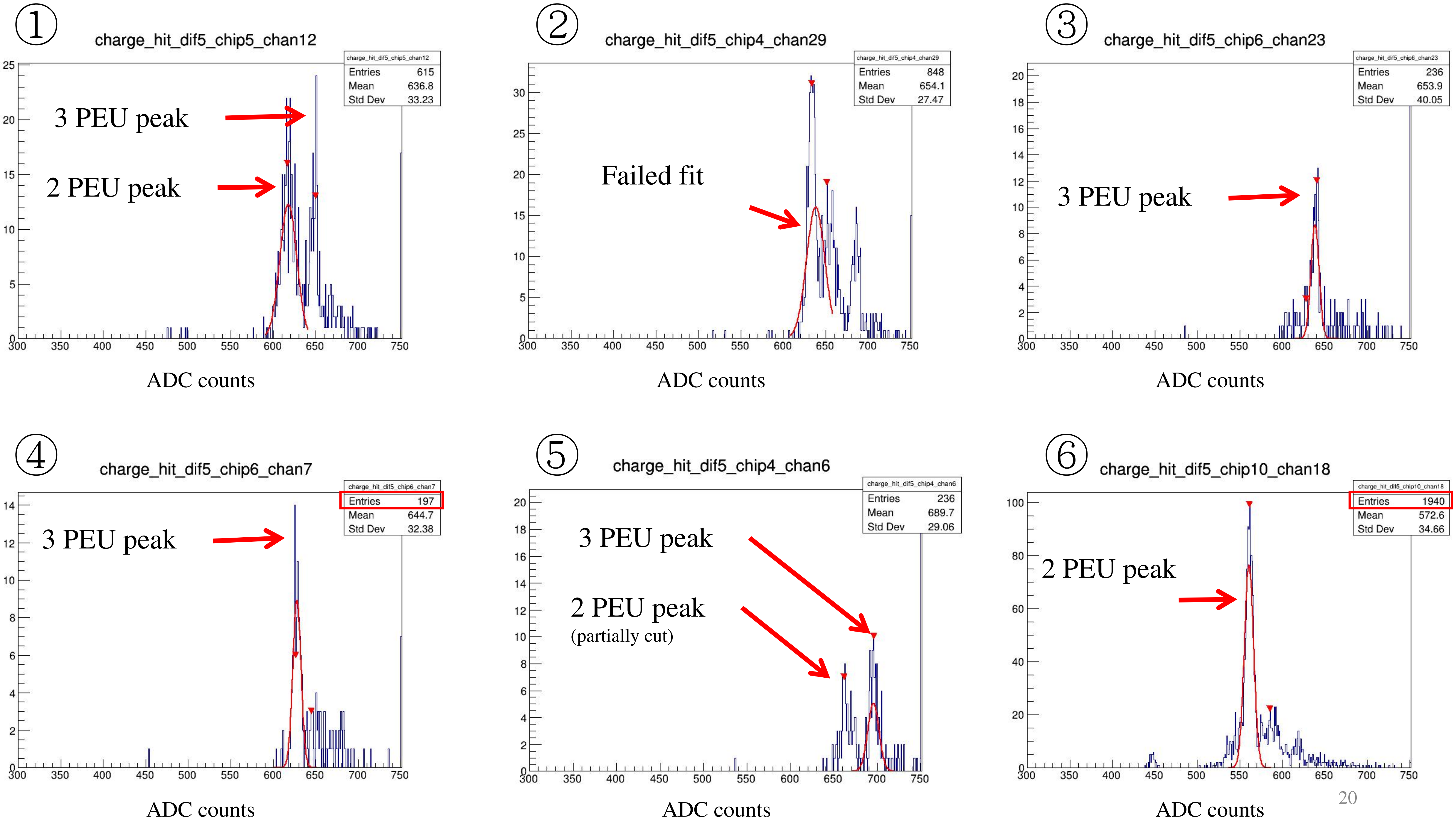
CALIBRATION of SPIROC2D chip

Offline and online gain calibration should be possible … in principle.

However, serious design flaws and hardware bugs in the frontend ASIC and electronics make achieving a precise and stable calibration a daunting, near impossible task.

Each of the plots below corresponds to a channel. The data taking period is 3 hours and the threshold was painstakingly set at 2.5 PEU.




①
charge_hit_dif5_chip5_chan12
Entries 615
Mean 636.8
Std Dev 33.23
3 PEU peak
2 PEU peak
ADC counts
②
charge_hit_dif5_chip4_chan29
Entries 848
Mean 654.1
Std Dev 27.47
Failed fit
ADC counts
③
charge_hit_dif5_chip6_chan23
Entries 236
Mean 653.9
Std Dev 40.05
3 PEU peak
ADC counts
④
charge_hit_dif5_chip6_chan7
Entries 197
Mean 644.7
Std Dev 32.38
3 PEU peak
ADC counts
⑤
charge_hit_dif5_chip4_chan6
Entries 236
Mean 689.7
Std Dev 29.06
3 PEU peak
2 PEU peak
(partially cut)
ADC counts
⑥
charge_hit_dif5_chip10_chan18
Entries 1940
Mean 572.6
Std Dev 34.66
2 PEU peak
ADC counts