Improving the Super-Kamiokande PMT modelling using the the photosensor test facility (PTF)

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SUPER SK

University of Victoria

TRIUMF

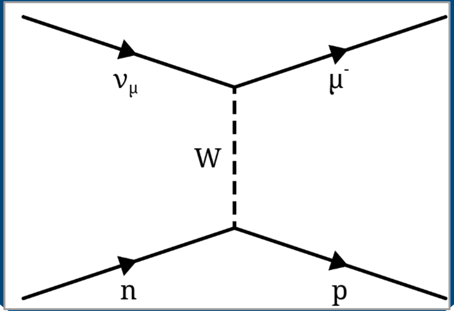
Outline

- Context
- Why ?
  - Motivations for measurements
- How ?
  - Overview of the set up
- What ?
  - Overview of the measurements
- Results
  - Integration of measurements into simulation

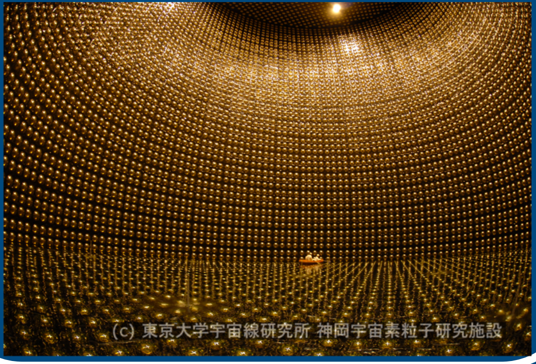
Super-Kamiokande experiment

- Goals: Detect neutrino mixing parameters, proton decay, search for dark matter

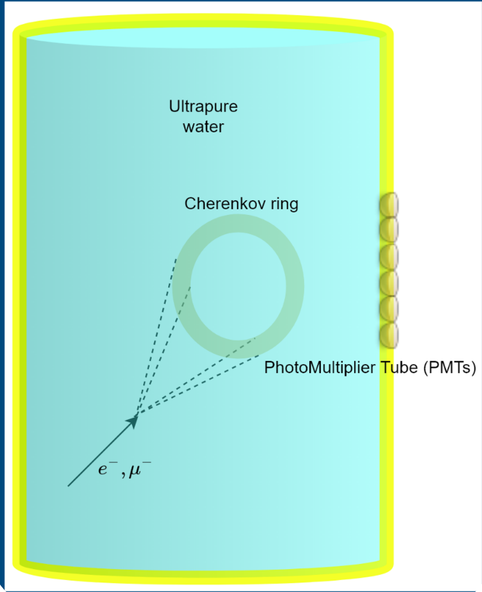
Neutrino interaction

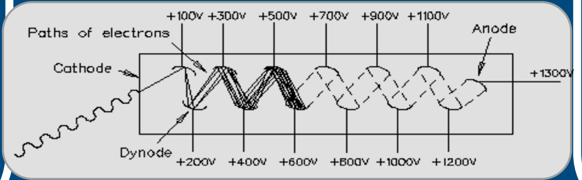


~11,000 photo-multiplier tube (PMT)

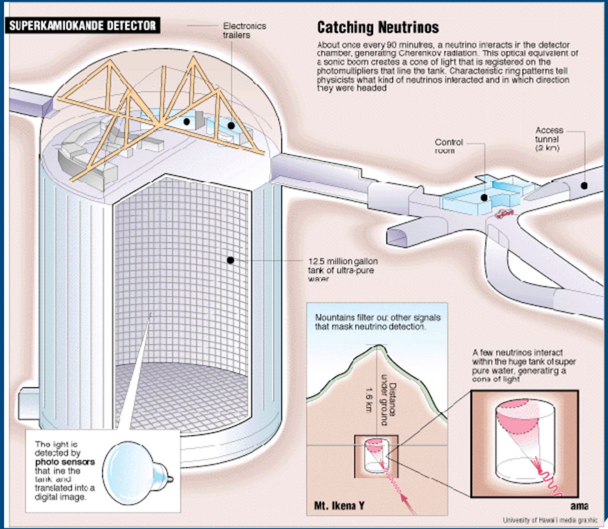


Neutrino events creating cherenkov radiation

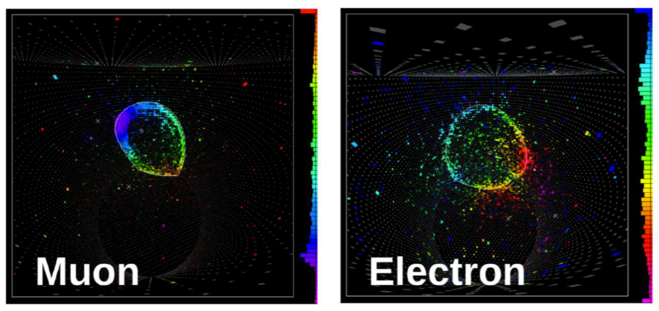




Super-Kamiokande



Neutrino events



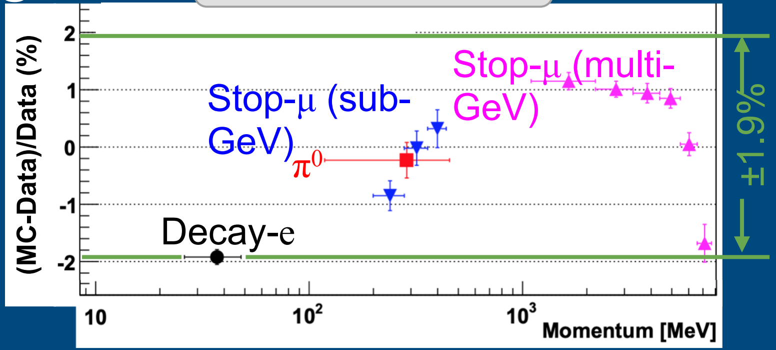
Motivations for PTF measurements

- Systematic error for
  Super-K high energy analysis (~2%)

- Can these be partially explained by PMT response mismodelling (eg. angular/magnetic field/polarization/wavelength effects)
    - Qualitative example

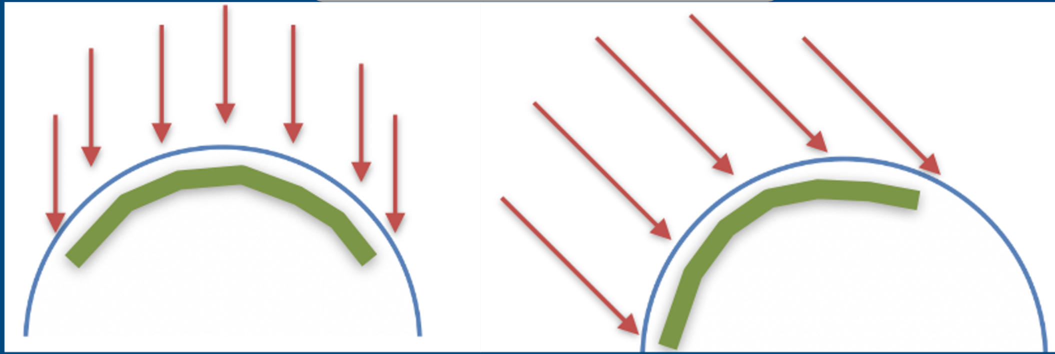
- Will become even more important for next generation neutrino experiment (no longer limited by statistical uncertainties)
    - 1% required for Hyper-k
        - See M.Hartz talk

Control samples



PTEP 2019,053F01

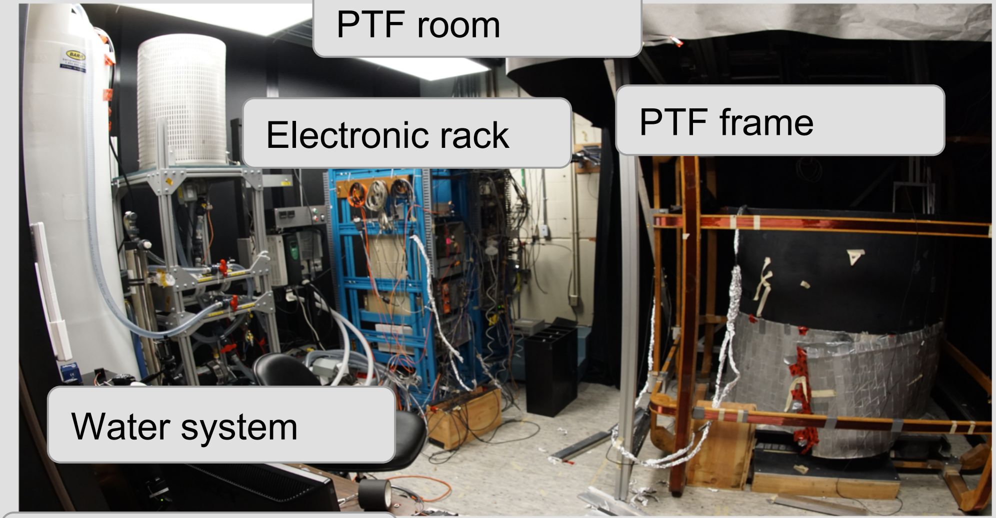
Photocathode hit region



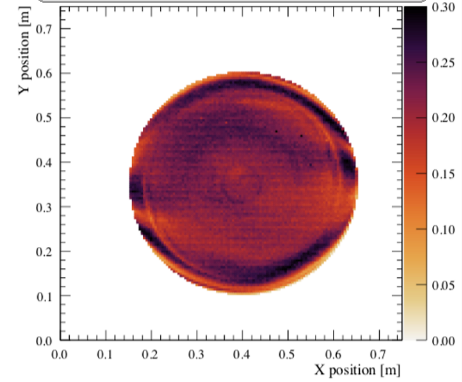
The Photosensor Test facility (PTF) at TRIUMF

- 3 pairs of Helmholtz coils (one in each direction)
  - Can control magnetic field
- 2 optical boxs (laser, sensors to measure tilt, rotation angle and magnetic field)
- DAQ to perform 2D scans of PMT
- Angular response and reflection measurements

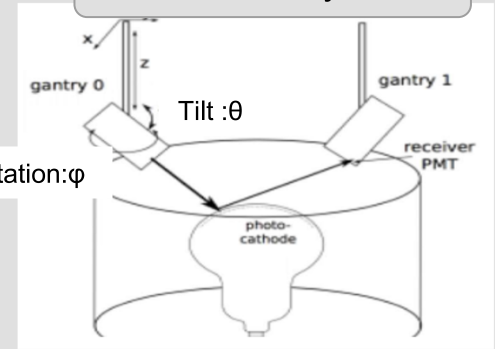
PTF room



PTF measurements

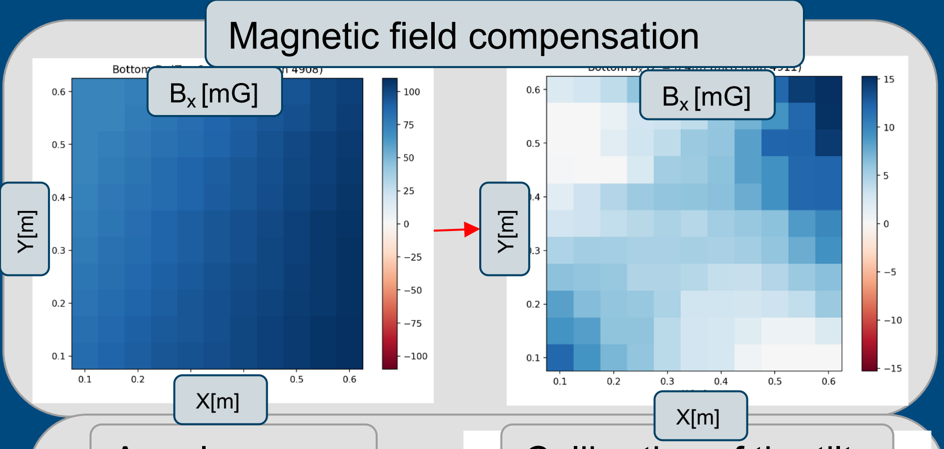


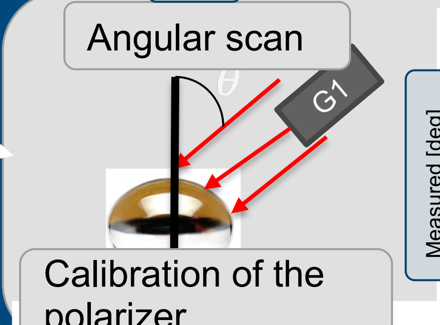
PTF Geometry

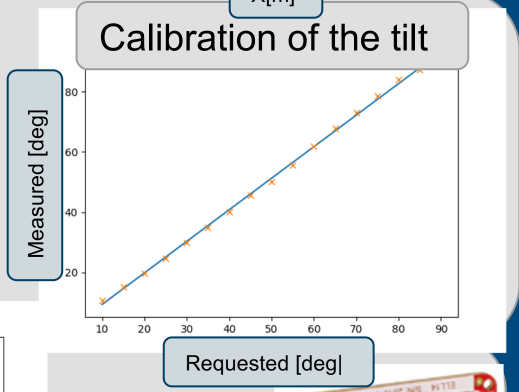


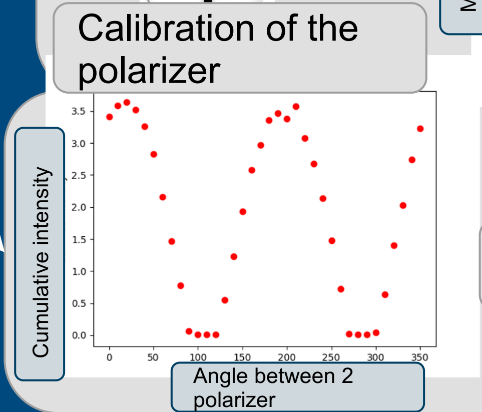
Potential measurements of PTF

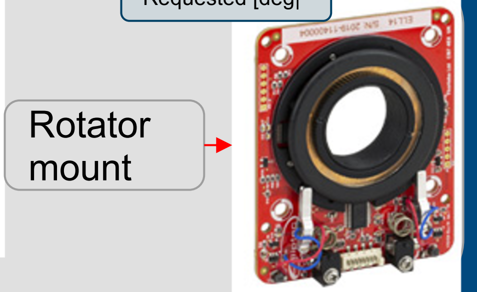
- PTF will be able to measure and separate external variables
  - Magnetic field
  - Angular dependance
  - Polarization dependance
  - Wavelenght dependance

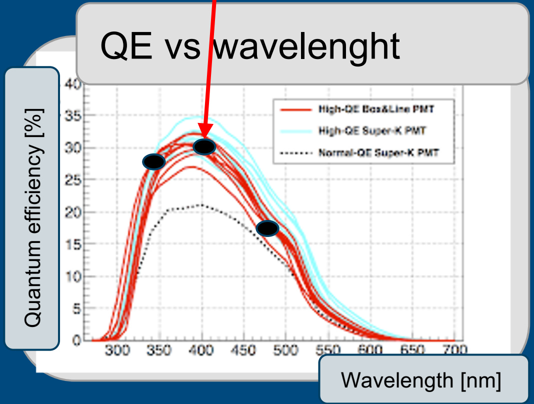








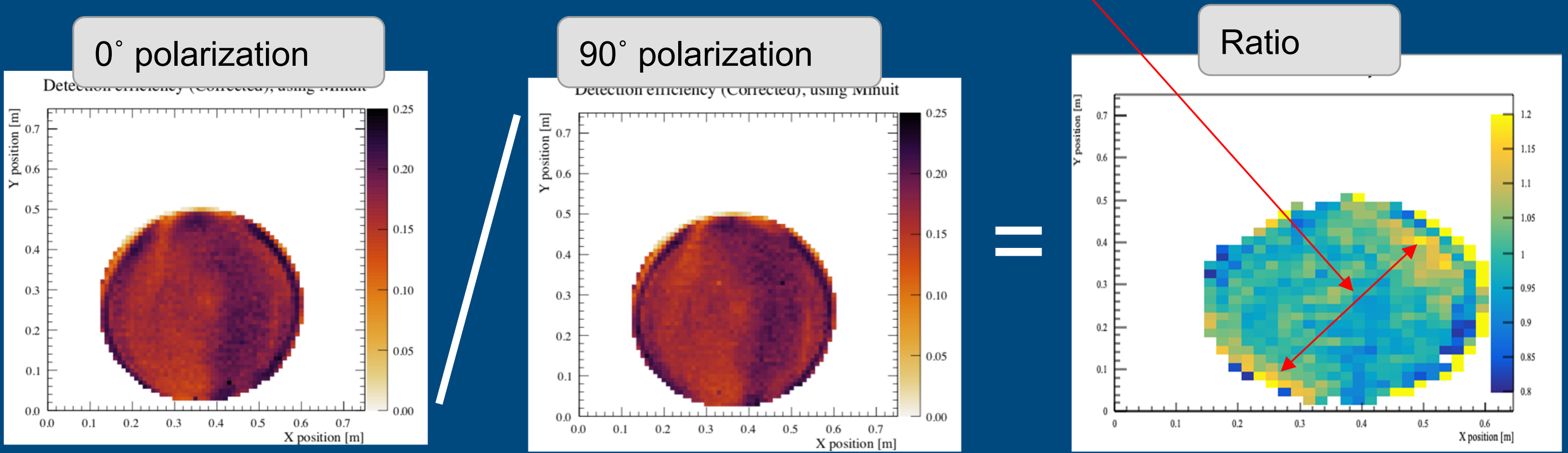




Polarization measurements

$$DE = \frac{\text{nb of photoelectron pulse}}{\text{nb of pulse}}$$

- Effect of polarization seems to be diagonal
    - Expectations: edges have more reflections so should be more affected
- Further investigation is required



Integration of measurements into simulations

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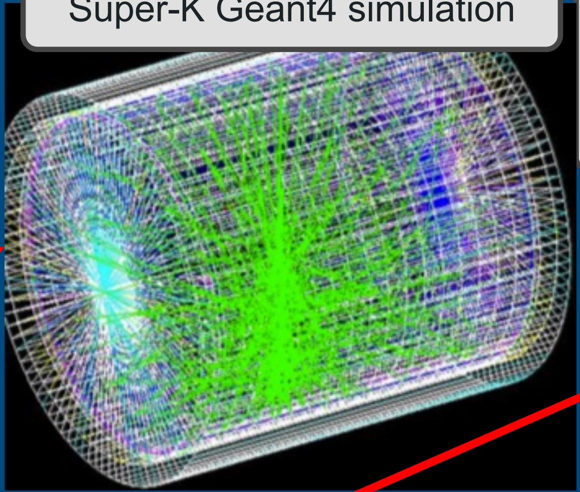
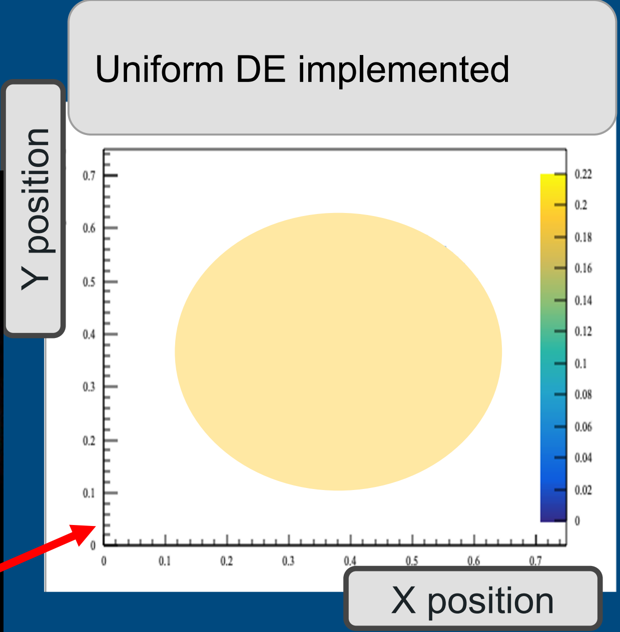
Simulation pipeline

- Simplest implementation :
  - Replace Uniform DE by position dependant DE





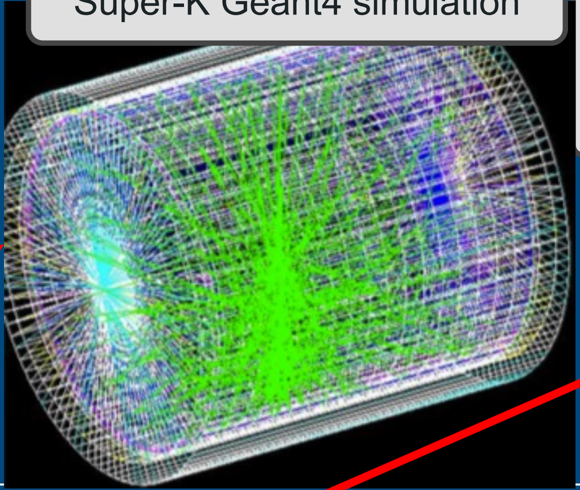
SKG4

True hits → Uniform DE → Digitize hits → Analysis (energy reconstruction, vertex position etc)

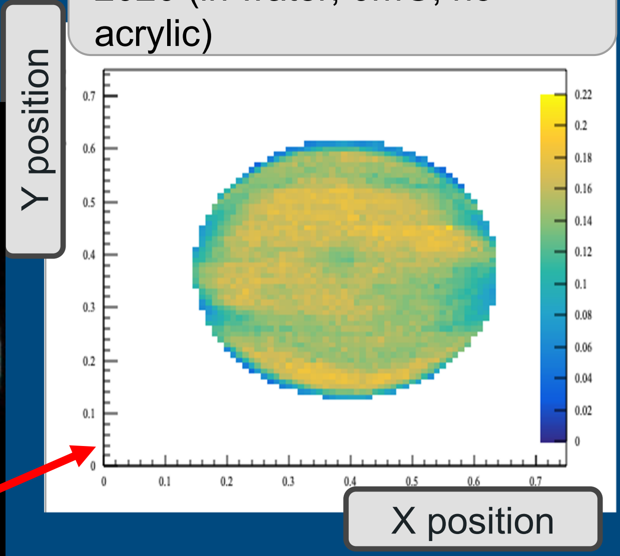
Simulation pipeline

- Simplest implementation :
  - Replace Uniform DE by position dependant DE

Super-K Geant4 simulation



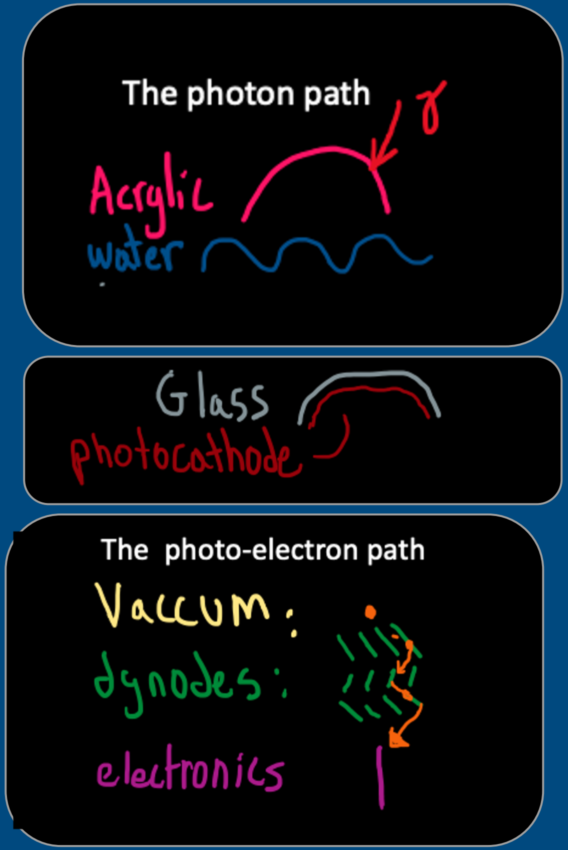
PMT measurements done in 2020 (in water, 0mG, no acrylic)



SKG4

True hits → PTF position dependant DE → Digitize hits → Analysis (energy reconstruction, vertex position etc)

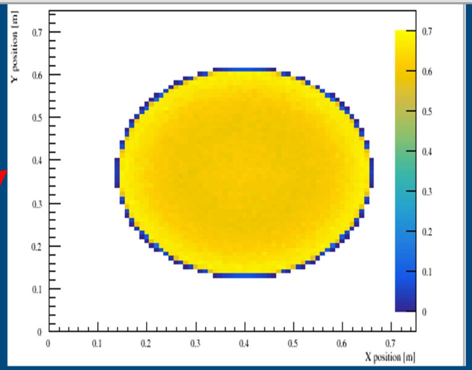
In detail: PMT Modelling



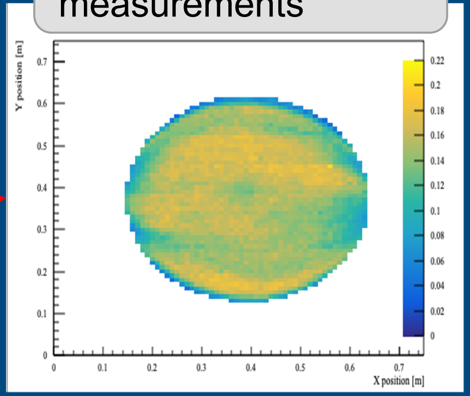
Simulation

PTF data

Step 1: Optical simulation assuming uniform DE in SKG4



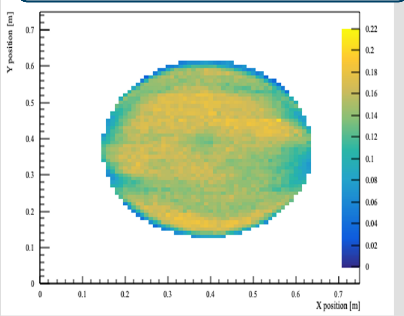
Step 2: Input PTF measurements



Modelling the experiment

Step 3: Build empirical model

DE measurements



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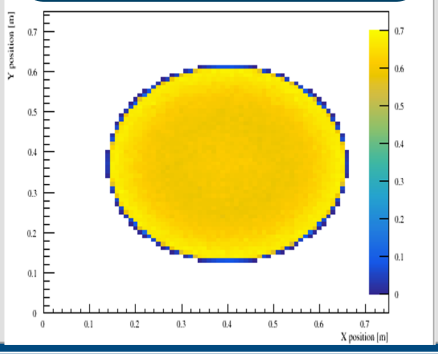
Simulation output, assuming uniform PMT response



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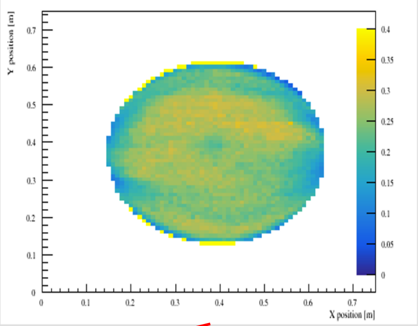
Empirical model of DE (corrected for known effects) for input to sim



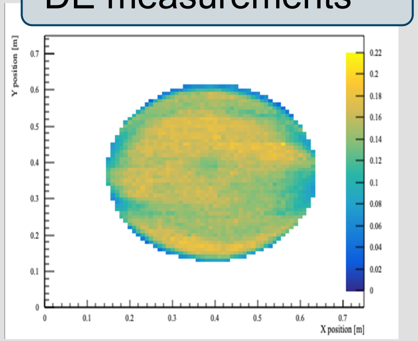
PTF implementation in (SKG4)

True hits → PTF position dependant DE → Digitize hits → Analysis (energy reconstruction, vertex position etc)

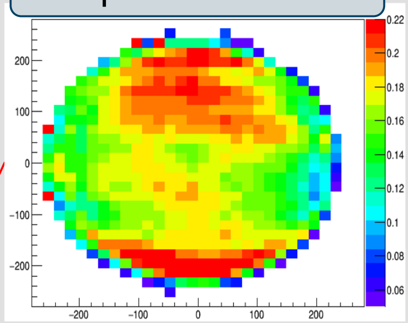
Integration of data into simulation

Step 4: Test empirical model (first cross check seems to be good)

DE measurements



Implemented DE

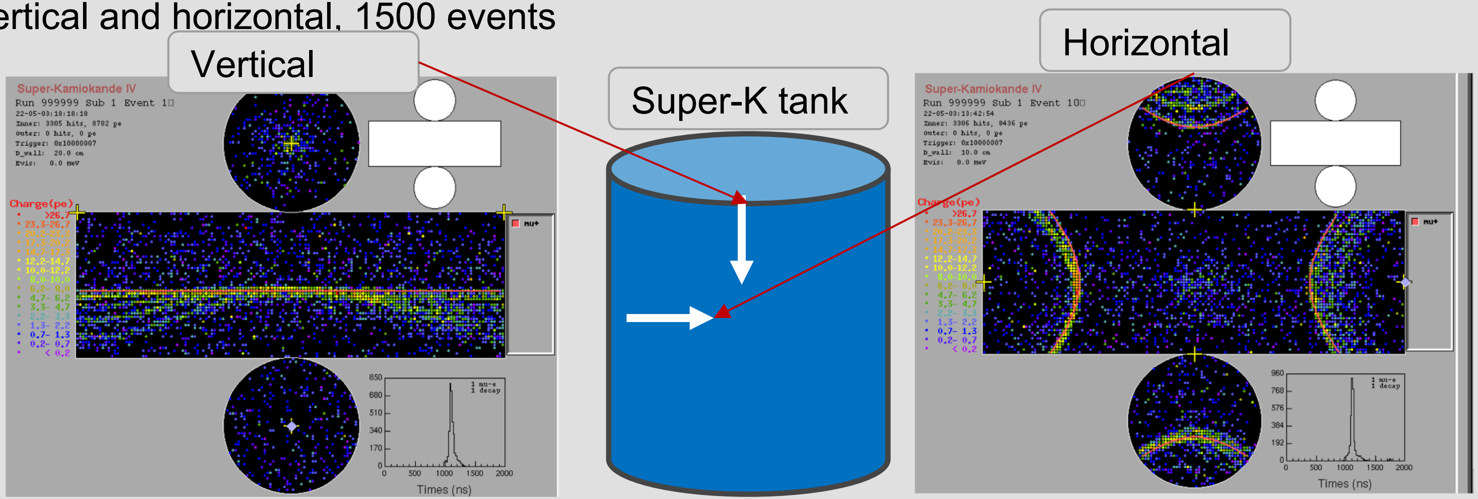


PTF implementation in (SKG4)

True hits → PTF position dependant DE → Digitize hits → Analysis (energy reconstruction, vertex position etc)

Integration of data into simulations (2)

Step 5: Apply empirical model on simple study : particle gun μ^+ ,E=1 GeV, dir= (0,0,-1;-1,0,0) vertical and horizontal, 1500 events



MC-MC comparison

-True hits → Uniform QE → -Total charge

-True hits → Get PTF position dependant DE → -Total charge

Total charge horizontal vs vertical case

- Muon
  - Nominal
    - Mean ratio : 0.98
  - PTF
    - Mean ratio: 0.96

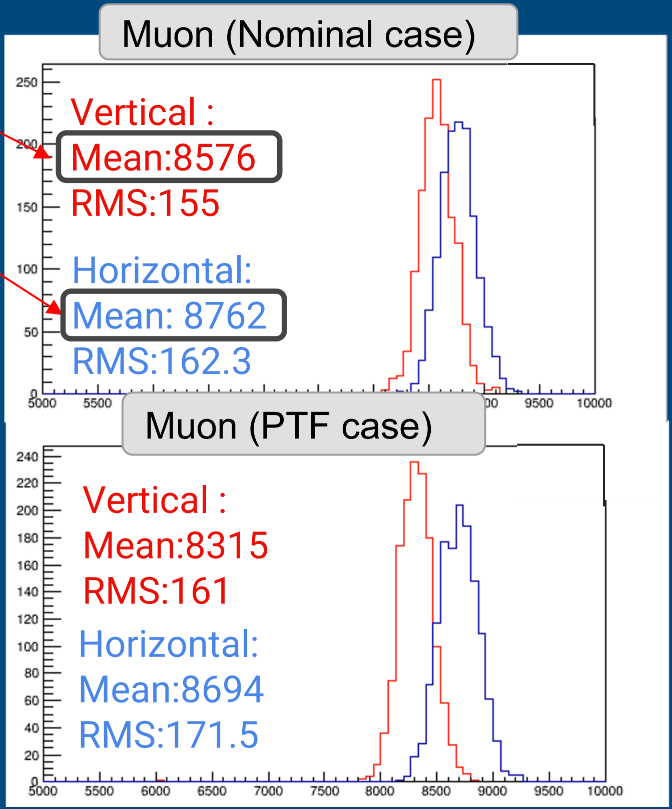
Mean ratio

$$\frac{\text{Mean Vertical}}{\text{Mean Horizontal}}$$

Second ratio $$\frac{\text{Ratio\_nominal}}{\text{Ratio\_PTF}}$$

↓

Difference: 2.34%

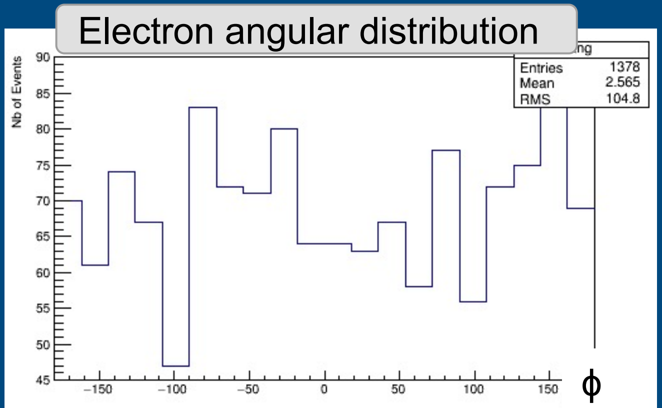


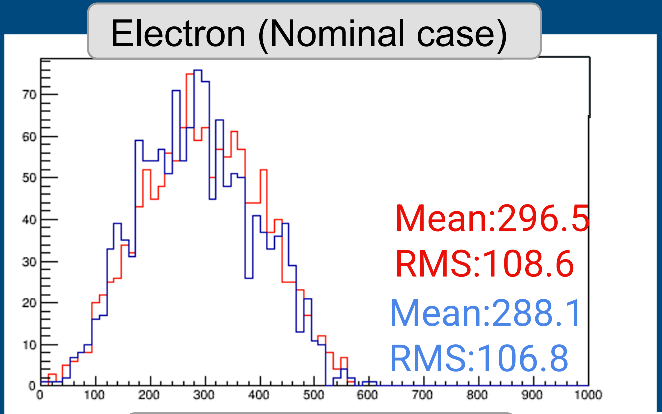
Total charge horizontal vs vertical case (2)

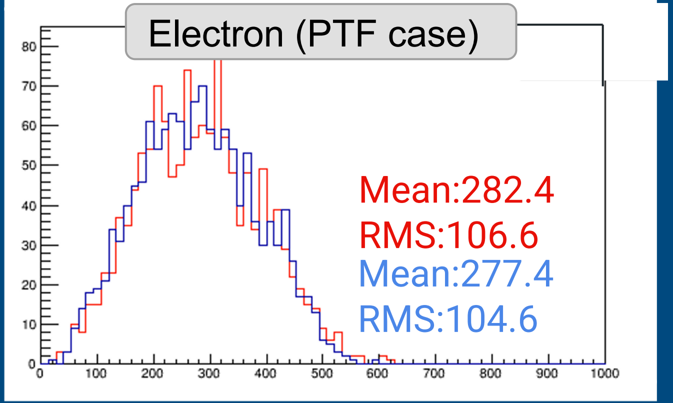
- Decay electron
  - Nominal
    - Mean ratio :1.03
  - PTF
    - Mean ratio: 1.02

Difference	1.09%

- Angular distribution







Conclusion

- The PTF facility was rebuild and improve to measure the PMT response
    - A better understanding of PMT response could decrease/characterize the systematic uncertainties associated to the detector
    - More measurements to come soon !
- Integration of measurements into simulation was started
    - Only MC-MC comparison and for simple case
    - An effect of ~2% was seen but more measurements are required

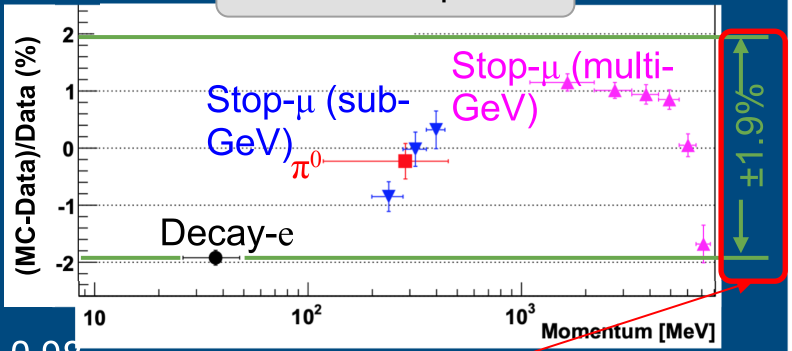
Thank you

Back up

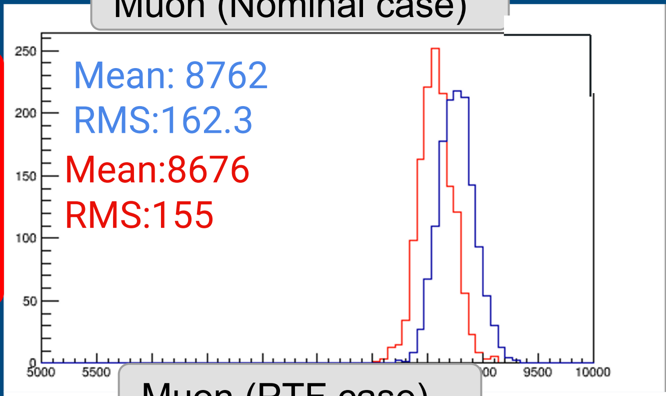
Total charge horizontal vs vertical case

- Muon
  - Nominal
    - Mean ratio : 0.98
  - PTF :
    - Mean ratio: 0.96
  - Difference 2.34%

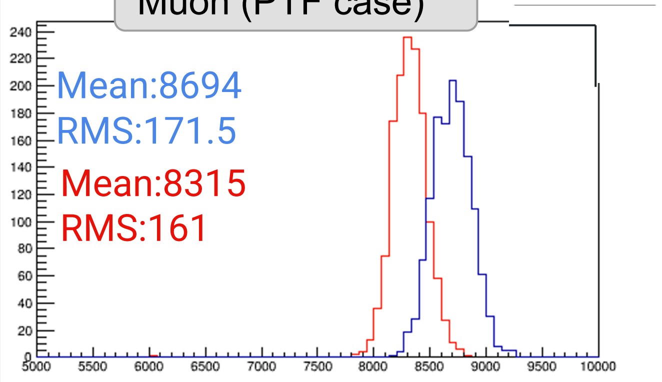
Control samples



Muon (Nominal case)



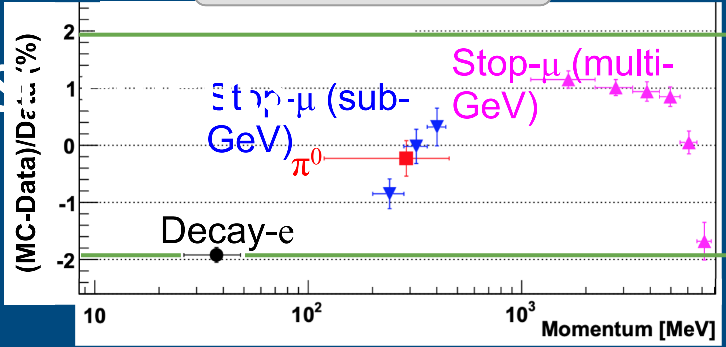
Muon (PTF case)



Motivations for PTF meas

- Significant systematic error for Super-K high energy analysis (~2%)
- Also for low energy solar neutrino (~0.5%)
- Can these be partially explained by PMT response mismodelling (eg. angular/magnetic field/polarization/wavelength effects)
  - Part of bottom-up calibration
  - Qualitative example
- Will become even more important for next generation neutrino experiment (no longer limited by statistical uncertainties)

Control samples



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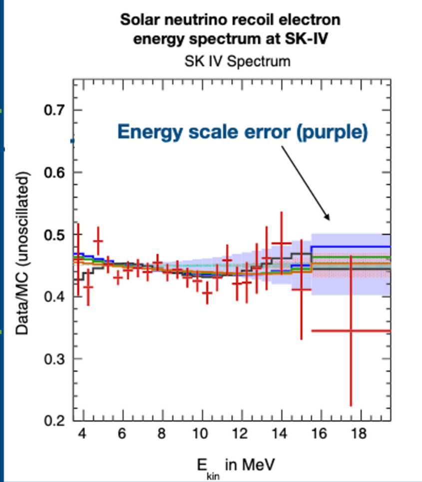
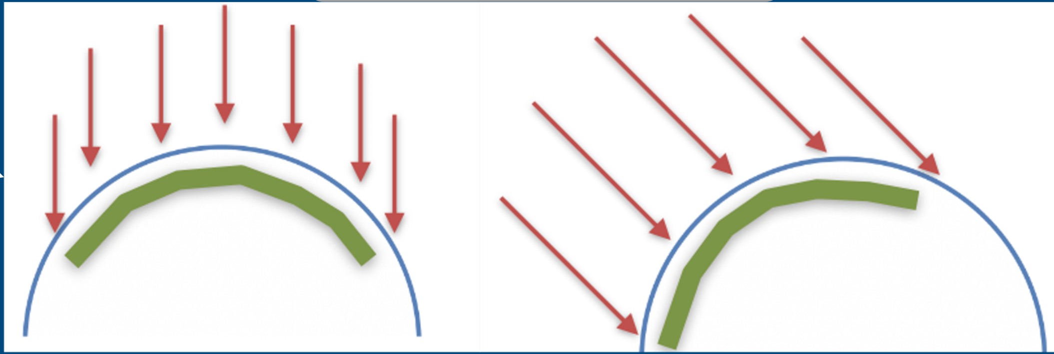


Phys.Rev.D94,052010

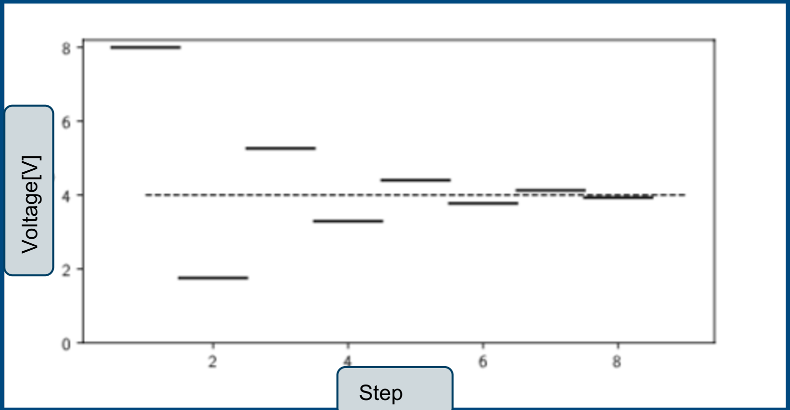
Photocathode hit region



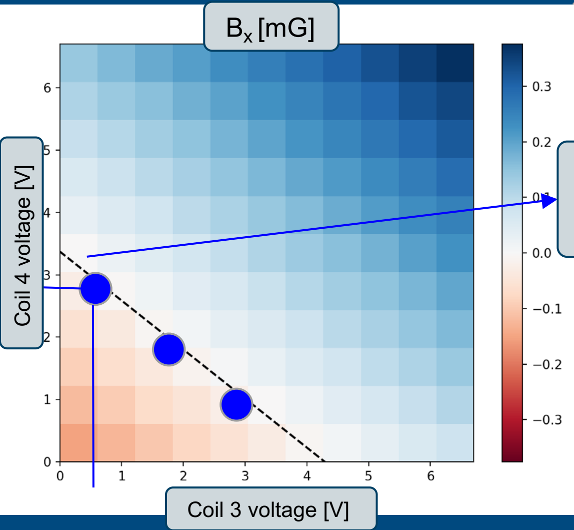
Compensating the magnetic field

- Try to make the magnetic field as uniform as possible
  - Using G-IRON passive shielding
- Degauss procedure is needed
  - Metals structure surrounding PTF creates their own magnetic field
  - Needs to be simultaneously for all directions

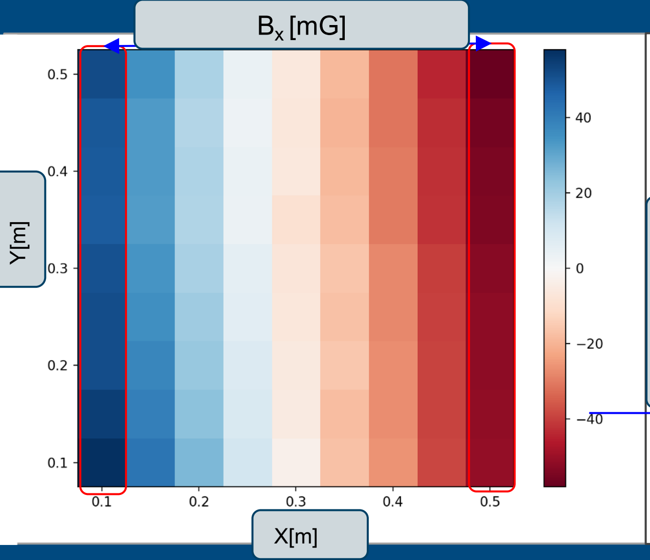
Example of a degauss procedure



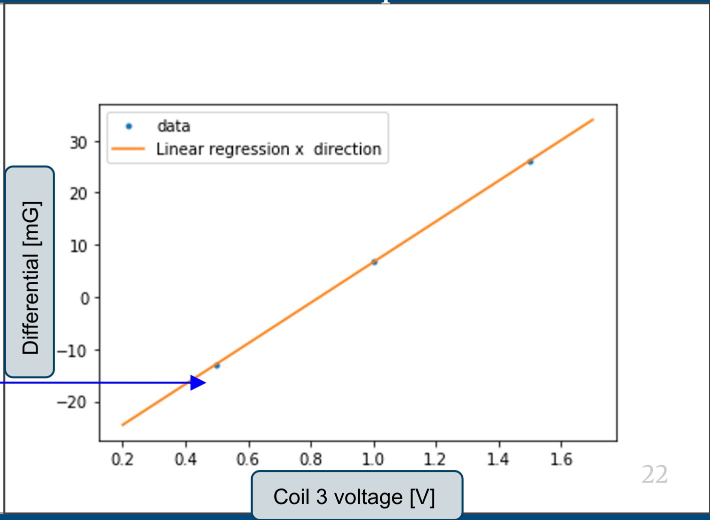
1-Voltage scan



2-Spatial scan :



3-Differential plot



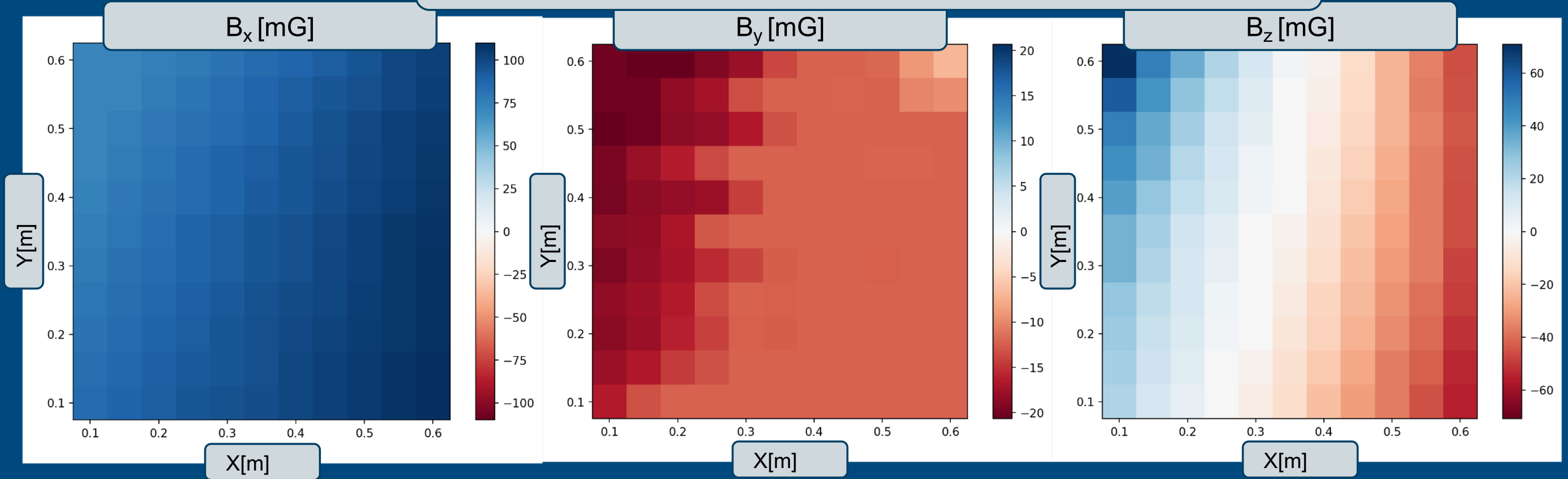
Compensation of the magnetic field

- Compensated to 0 but also different offset
  - Input from Super-K magnetic field measurements
  - Seems to work within 20mG or so
    - Z direction has a larger gradient

Compensation table

Compensation (V)	Coil 1	Coil 2	Coil 3	Coil 4	Coil5	Coil6
0mG(all direction)	3.0	4.1	0.1	0.558	0.1	0.55
+100mG(x direction)	3.0	4.1	-1.0	-1.35	0.1	0.6
+50mG(x direction)	3.0	4.1	-0.5	-0.7	0.1	0.6
-100mG (x direction)	3.0	4.0	2.0	1.5	0.1	0.45
-50mG (x direction)	3.0	3.95	1.0	1.06	0.1	0.6
+100mG (y direction)	3.0	3.65	0.1	0.91	2.0	1.32
+50mG (y direction)	3.0	3.8	0.1	0.7	0.5	1.32
-100mG (y direction)	3.0	3.86	0.1	0.2	-1	-1.3
-50mG (y direction)	3.0	4.05	0.1	0.35	-0.5	-0.7
+100mG (z direction)	4.0	4.8	0.1	1.228	0.1	0.42
-100mG (z direction)	3.0	2.27	0.1	0.268	0.1	0.46

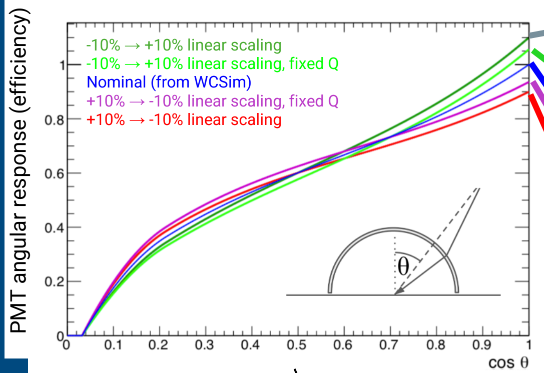
Example setting X=100mG, y=0mG, Z=0mG



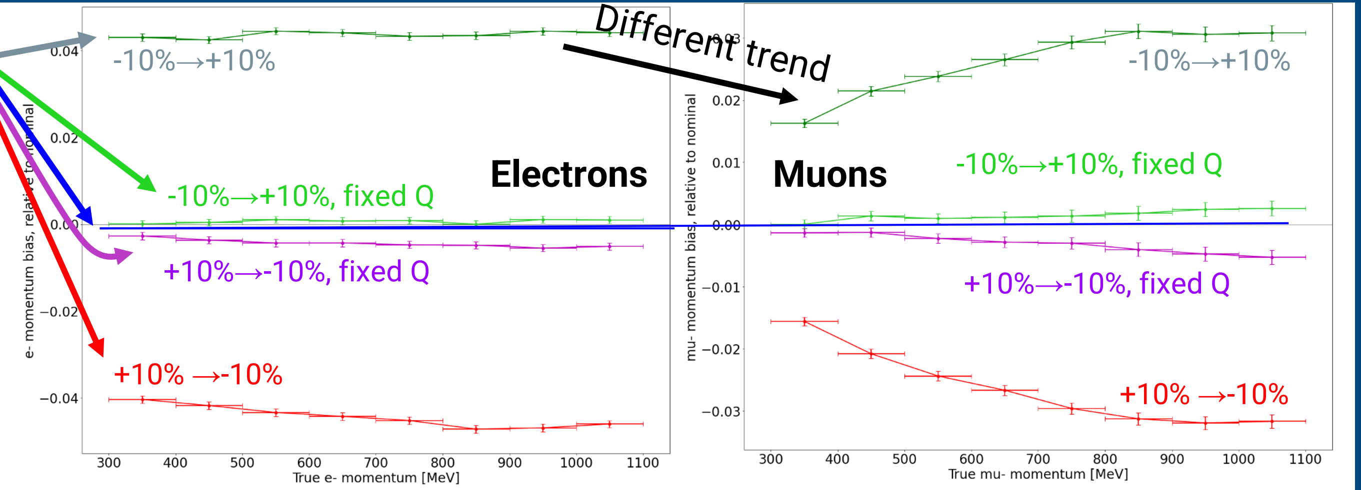
Effect of PMT Angular Response on Reconstruction

Variations at MC level

Reconstructed Momentum Bias in HK (N. Prouse, HK calibration)

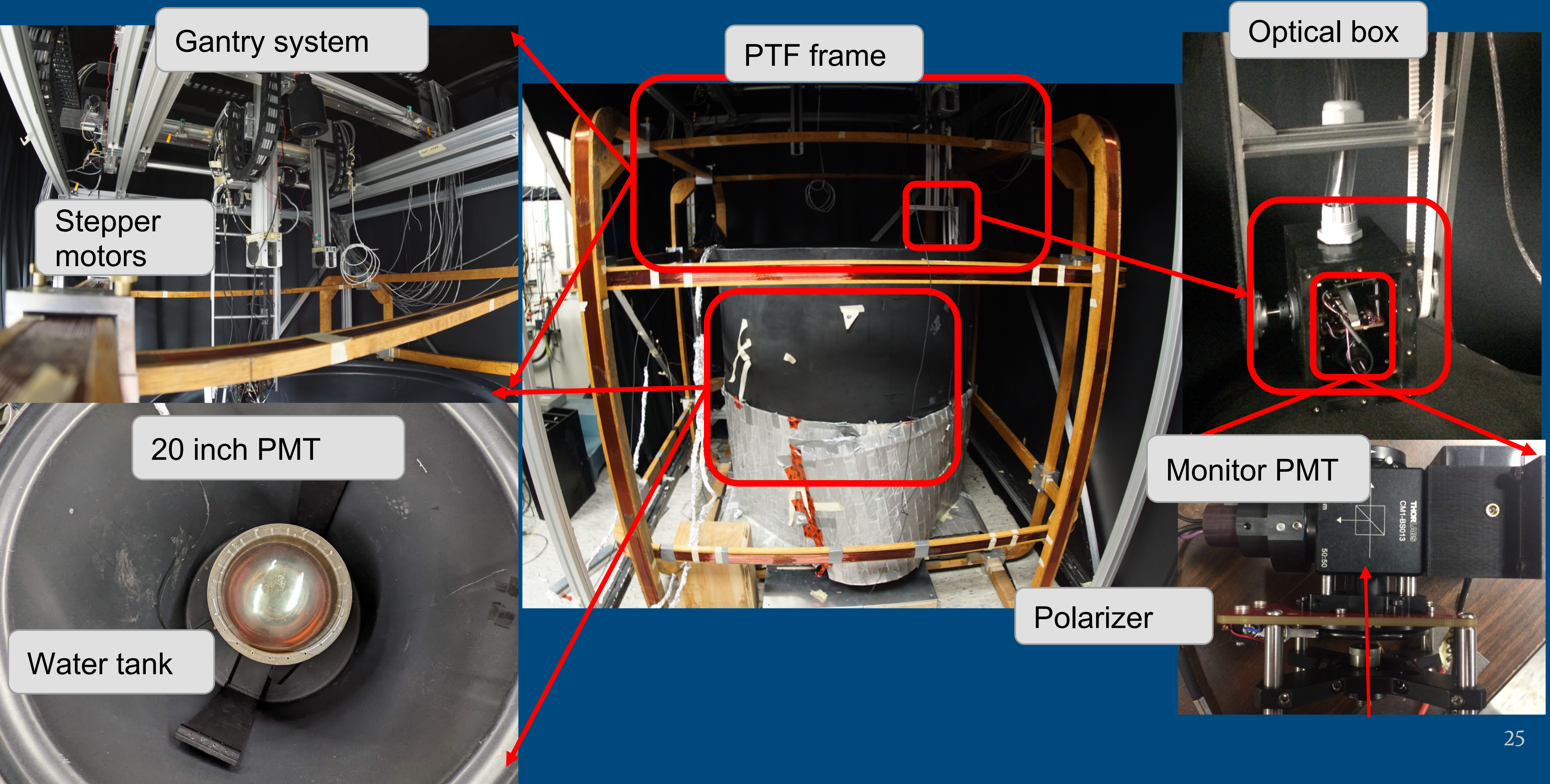


Input to fitqun



- Varying angular response can change the total charge
- “**fixed Q**”: scaled overall efficiency averaged over all events to study case of no change in total charge
  - Assumes degeneracies with other detector (e.g. water) parameters are fully constrained
  - Can still have ~0.5% bias in reconstructed momentum
- Different trends indicate not fully correlated between e/μ

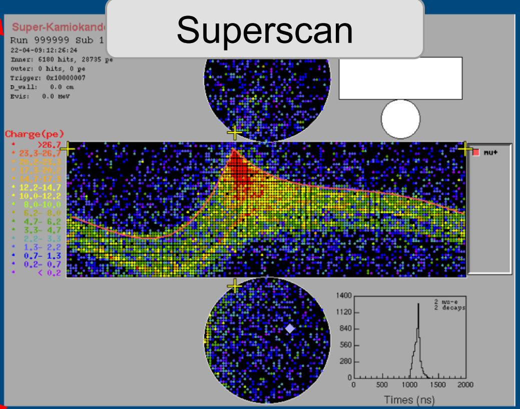
PTF in pictures

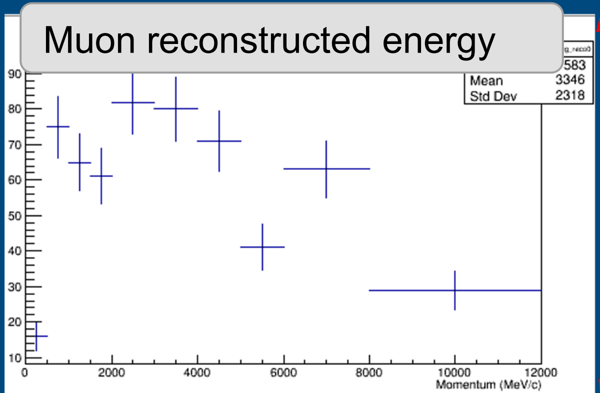


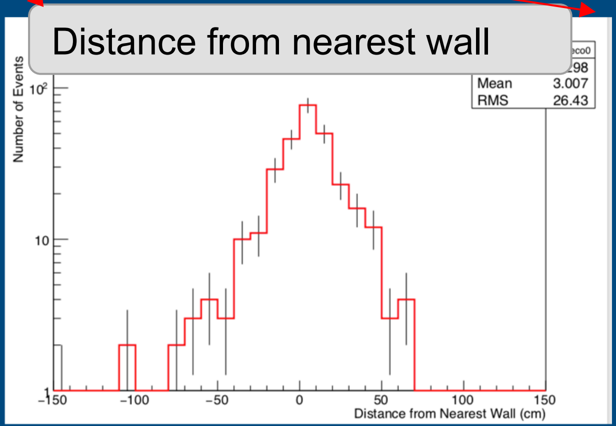
Pipeline is ready !

- Some text file are empty, partially finished
    - Takes ~50hours for 9 text files on local cluster
- Move to something quicker for first comparaison with PTF measurements

Cosmic muon text file → SKG4 (SK4 geometry) → root2zbs → fiTQun (SKDETSIM tuning) → zbs2root → Cosmic muon analysis → MC-MC comparaison

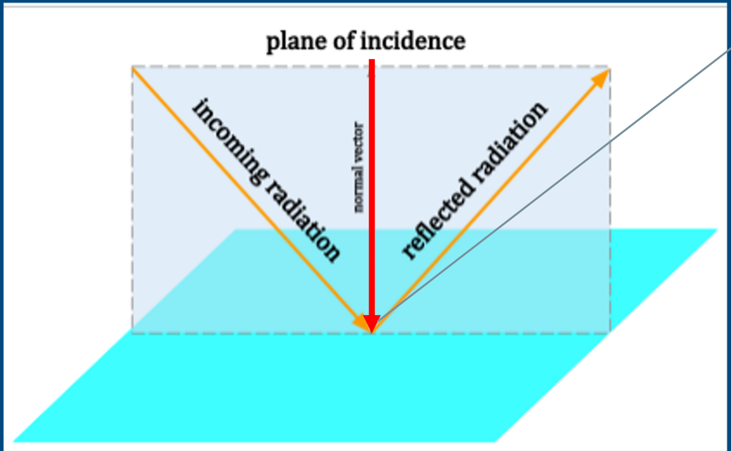






SKG4 local coordinates system

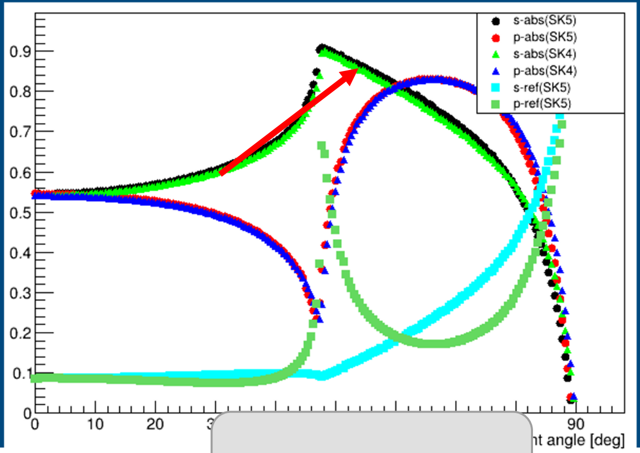
- S and P designation are in terms of the plane of incidence of the photon (parallel vs perpendicular)
- Done for incoming photons
- Calculate incidence plane angle and randomize s or p polarization
- At the center no s or p polarization



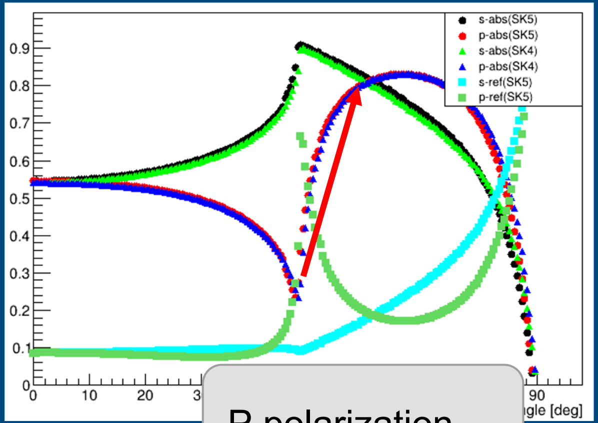

```
+       p_type = -1; // other
        if(cosAngle==0||cosAngle==1||1./(cosAngle*cosAngle)-1<=0)
  Polarization_Type = "other";
      else{
        if(Dir*Pol>0.0001) Polarization_Type = "other";
        else{
            G4ThreeVector pWaveDir = (Dir+Normal/cosAngle)/sqrt(1.
  /(cosAngle*cosAngle)-1.);
            pWaveDir = pWaveDir.unit();

            G4double Cp = pow((Pol*pWaveDir),2);
+             if(G4UniformRand()<Cp){ Polarization_Type = "p"; p_type = 1;
  }
+             else{ Polarization_Type = "s"; p_type = 2; }
            //if(G4UniformRand()<Cp) Polarization_Type = "s";//before DETSIM
  BUGFIX
            //else Polarization_Type = "p";//before DETSIM BUGFIX
        }
```

Absorption coefficient

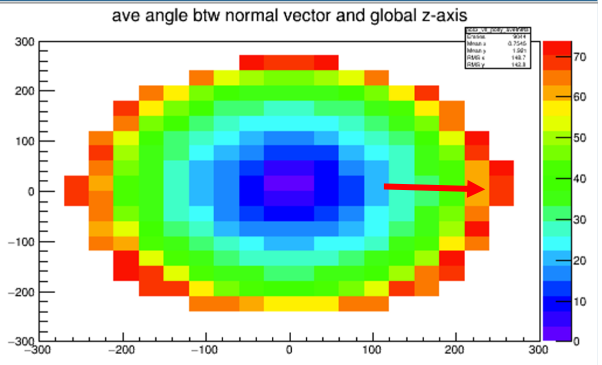
- Initial conditions
  - X polarization
- See effect of p vs s polarization
- See the maximum predicted

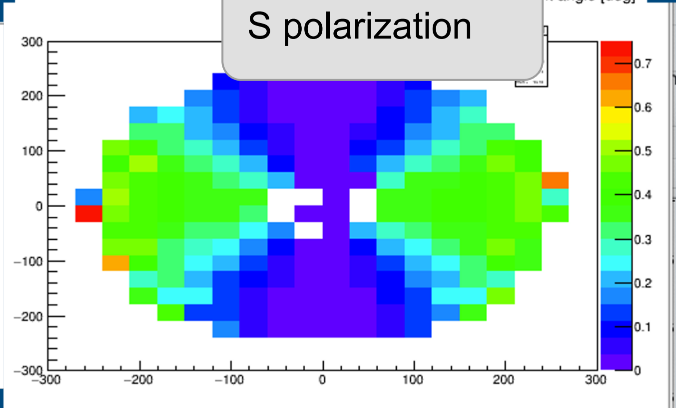


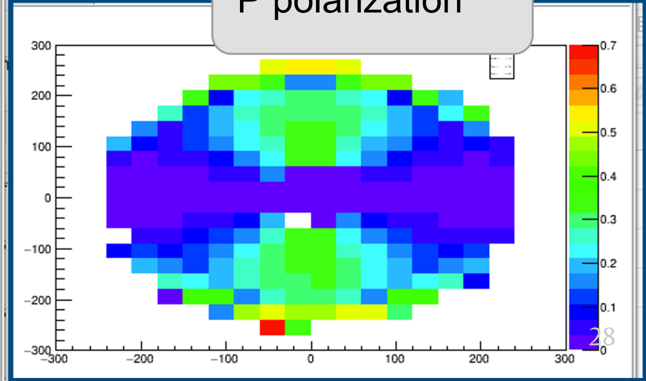
S polarization



P polarization

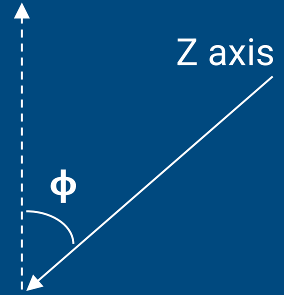


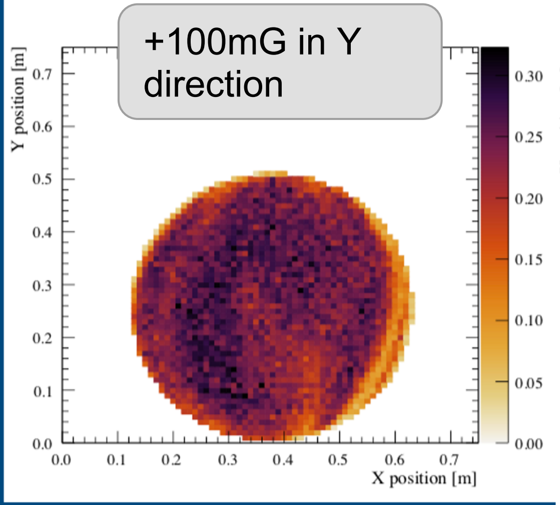


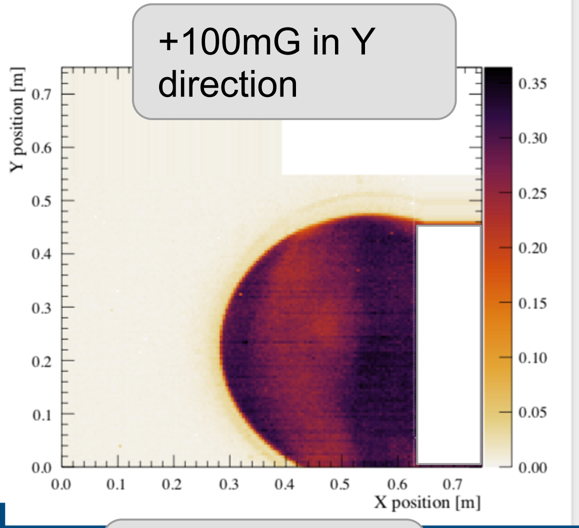


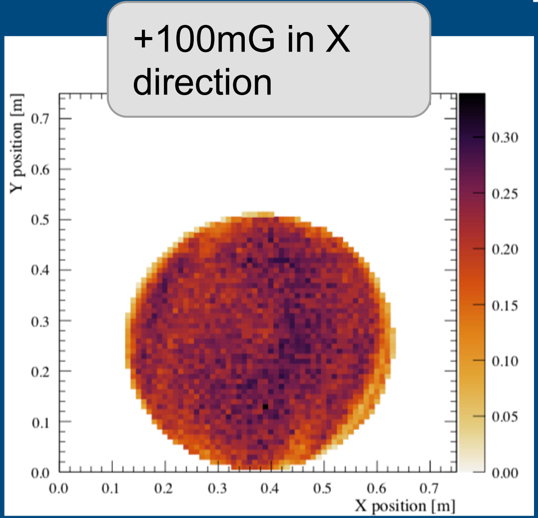
Potential study

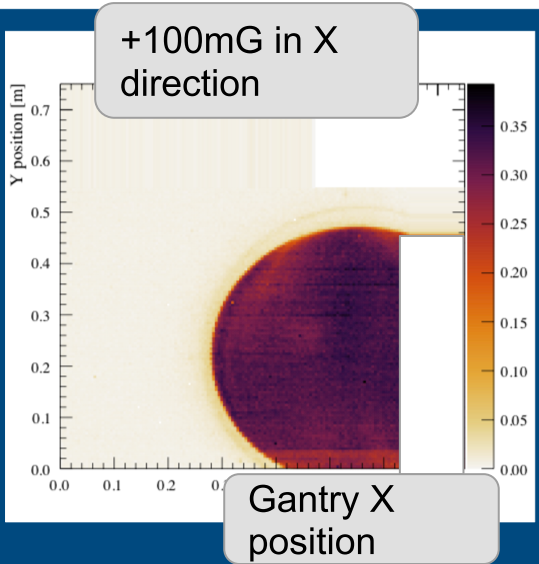
- Angular scan (60°) + magnetic field
- Angular response move region of high efficiency
  - Same position but deformed ?
- Highest possible resolution (0.5cm)
  - Clearly see the effect of the temperature variations
- In terms of gantry position
  - Off center scan











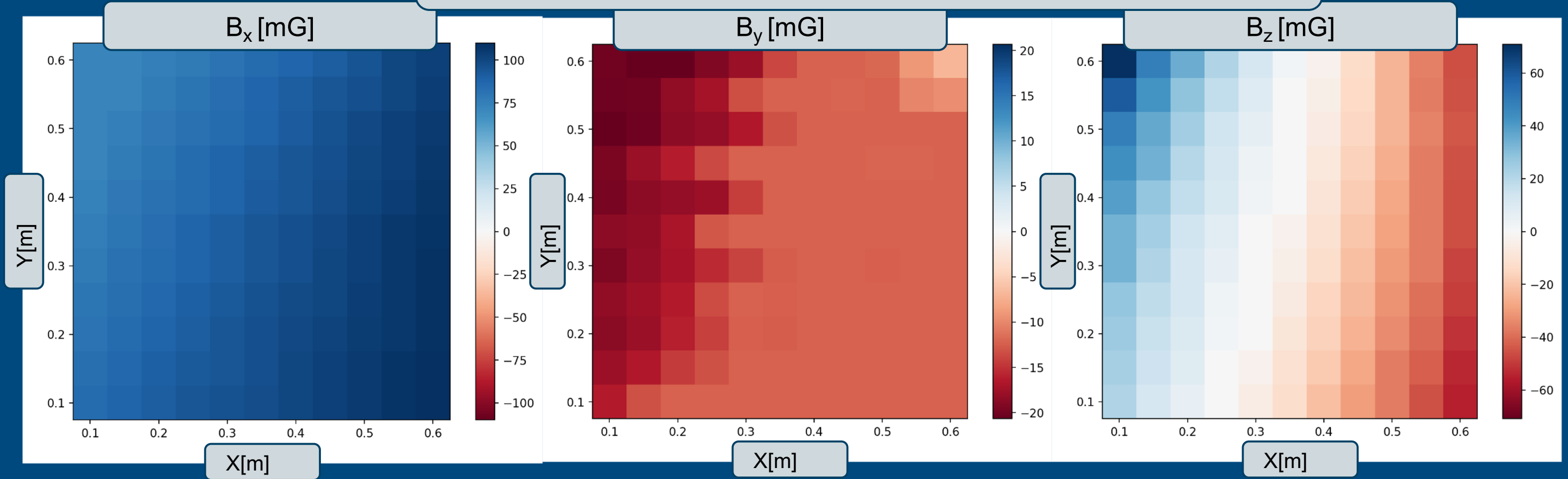
Compensation of the magnetic field

- Compensated to 0 but also different offset
  - Input from Super-K magnetic field measurements
  - Seems to work within 20mG or so
    - Z direction has a larger gradient

Compensation table

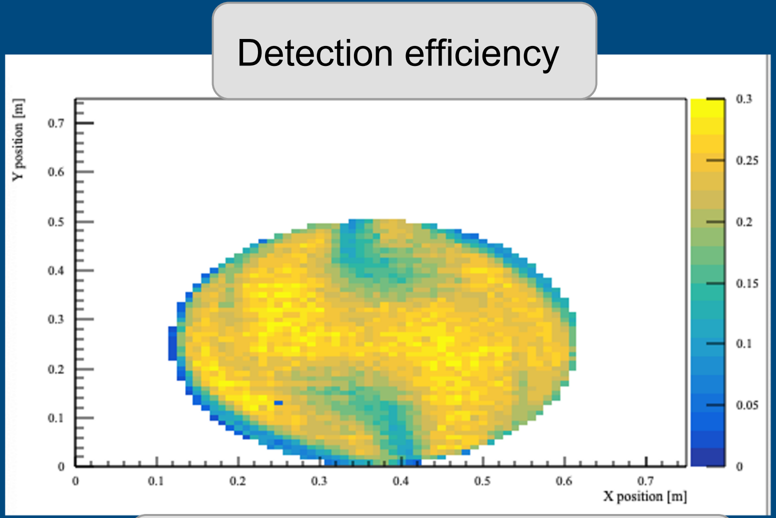
Compensation (V)	Coil 1	Coil 2	Coil 3	Coil 4	Coil5	Coil6
0mG(all direction)	3.0	4.1	0.1	0.558	0.1	0.55
+100mG(x direction)	3.0	4.1	-1.0	-1.35	0.1	0.6
+50mG(x direction)	3.0	4.1	-0.5	-0.7	0.1	0.6
-100mG (x direction)	3.0	4.0	2.0	1.5	0.1	0.45
-50mG (x direction)	3.0	3.95	1.0	1.06	0.1	0.6
+100mG (y direction)	3.0	3.65	0.1	0.91	2.0	1.32
+50mG (y direction)	3.0	3.8	0.1	0.7	0.5	1.32
-100mG (y direction)	3.0	3.86	0.1	0.2	-1	-1.3
-50mG (y direction)	3.0	4.05	0.1	0.35	-0.5	-0.7
+100mG (z direction)	4.0	4.8	0.1	1.228	0.1	0.42
-100mG (z direction)	3.0	2.27	0.1	0.268	0.1	0.46

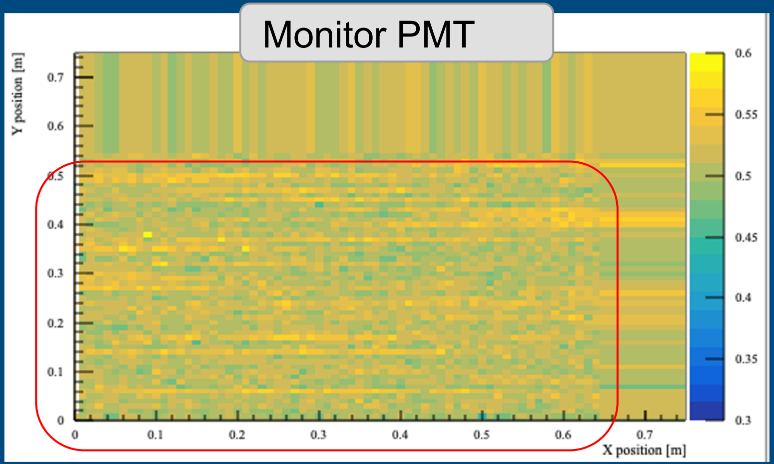
Example setting X=100mG, y=0mG, Z=0mG

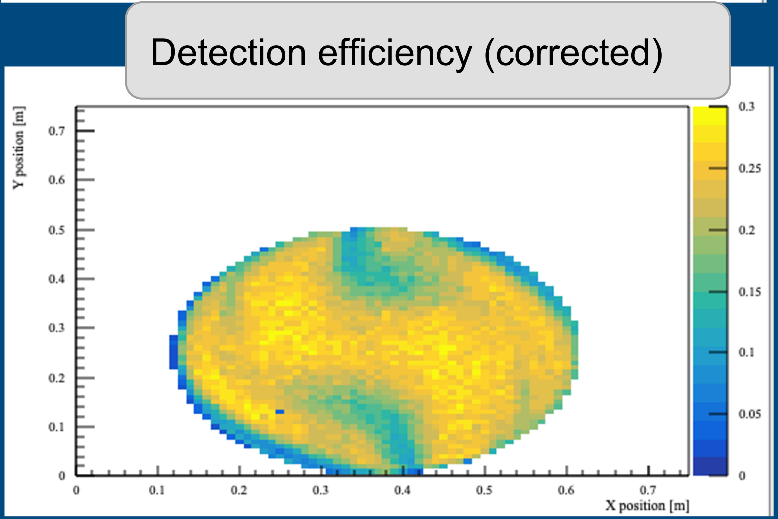


No compensation effect

- Uncompensated magnetic field
- DE plot were generated
  - Results looks good
  - Analysis pipeline is replicating previous results
  - All PMT are working as expected







The magnetic field in Kamioka

- Earth field is compensated in Super-K
- Older measurements (2013)
  - Showed ± 80 mG in Z, ± 100 mG in Y and ± 80 mG in X
- Newer measurements
  - Showed ± 100 mG in 3 directions

Does it as an impact ?
YES!

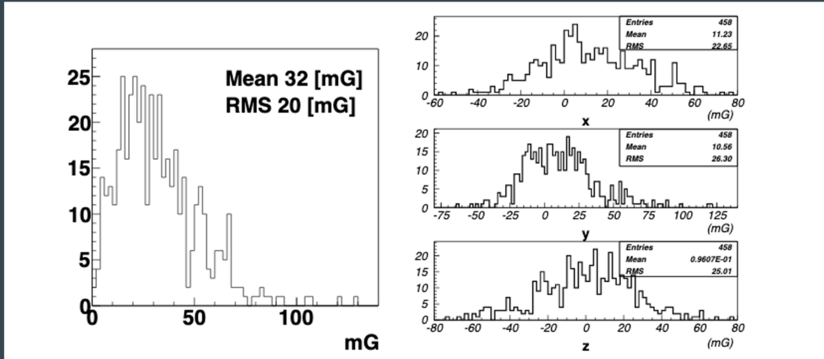


Figure 1: Distribution of magnitude of the residual magnetic field at different locations in the detector. The left figure shows the magnitude; the right figures show the value along the usual SK coordinate system axes.

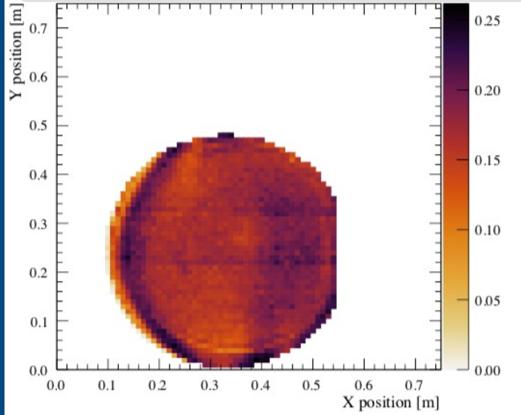
Data taking plan

- Relocation happened in 2020
  - Delays due to COVID and unexpected problems
- Finally ready for data taking
  - First water scan was done !
  - Running angular scan !

DE

Count of photoelectron pulse
The number of pulse

First water measurements!



List of parameters to caracterize : x/y/θ/φ/B/λ/ε/T			
			Time (hours)
Usual scan			18
Magnetic field scan			
(-100mG,-50mG,0mG,50mG,100m		4	
Total scan		4	72
Angular scans 1 (θ)			
(0°- 40°) step of 10°		4	
(40°- 80°) step of 5°		8	
90°		1	
Total scan		13	234
Angular scan 2 (ϕ), θ fix			
(0°- 90°) step of 10°		9	
Total scan		9	162
Polarization of the light (affects the reflection)			
(0°, 45°,90°)		3	
Total		3	54
Wavelenght dependance			
(375nm, 405nm, 510nm)		3	
Total		3	54

- Decay electron
    - Nominal
    - Mean ratio :1.03
- PTF
    - Mean ratio: 1.02
- Difference: ~1.09%
- Angular distribution

Decay electron
Nominal
Mean ratio :1.03
PTF
Mean ratio: 1.02
Difference: ~1.09%
Angular distribution