Neutrino Oscillations Overview

- **Standard Model**: neutrinos are massless.
- **Solar neutrino problem**.
- **Solar neutrino solution**: Neutrinos oscillate.
- Neutrinos have mass.

\[
\nu_e \quad \nu_\mu \quad \nu_\tau
\]
\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta) \sin^2\left( \frac{1.27 \Delta m^2 L}{E} \right) \]

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} e^{i\delta} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Flavor (Eigenstate) = (Mixing Matrix) Mass (Eigenstate)

\[
U = \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\times \begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-\sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\times \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\]

3-mixing angles

Solar: \( \theta_{12} \sim 33^\circ \)

\( \sin^2 2\theta_{13} < 0.2 \) at 90\% CL
(or \( \theta_{13} < 13^\circ \) and \( \delta = ?? \))

Atmospheric: \( \theta_{23} \sim 45^\circ \)
Inverse Beta Decay (IBD)

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

- Prompt signal
- Delayed signal
- Total \( E_\gamma \sim 8\,\text{MeV} \)

\( \tau \sim 30\,\mu\text{s} \)
Chooz Detector

Calibration Glove-Box:

Outer Veto:
Scintillator panels

Target $\nu$:
$\text{LS; } 80\% \text{ C}_{12}\text{H}_{26} + 20\% \text{ PXE} + 0.1\% \text{ Gd}$
$+ \text{ PPO } + \text{ Bis-MSB}$

$\gamma$ Catcher:
$\text{LS; } 80\% \text{ C}_{12}\text{H}_{26} + 20\% \text{ PXE} + \text{ PPO } + \text{ Bis-MSB}$

Non scintillating Buffer:
mineral oil

Buffer vessel & 390 10” PMTs:
Stainless steel 3 mm

Inner Muon Veto:
mineral oil $+$ 70 8” PMTs

Steel Shielding:
17 cm steel, All around

$10.3 \text{ m}^3$

$22.6 \text{ m}^3$

$114 \text{ m}^3$

$90 \text{ m}^3$
Why are Veto Systems Necessary?

- High energy muons can enter the detector, capture on nuclei, producing fast neutrons.
- Spallation from cosmic ray muons can create $^9$Li, which can beta-decay to produce neutrons capturing on Gd.
- Neutrons created in the rock can propagate to target and scatter off a proton, whose recoil mimics positron signal.
- Tag near miss muon backgrounds.
- Outer + inner? Redundancy is good!
In the OV:
- Many modules
- Each module has 64 fibers (channels) that feed into one PMT

Geometrically overlapping hits indicate possible muon
From Light to Electric Signal...

The fiber holder which connects on to the PMT face

Each module in OV has 64 WLS fibers connected to 64 channels on one PMT
What is OV Calibration?

- Almost 3000 PMT channels used in the OV.
- Each channel is slightly different (PMT channel, scintillator response, fiber response).
- Must apply a gain to each such that the same light input yields the same electronic output.
- Importance: accurate background rejection depends on a calibrated system.

To equalize the PMT response to light, we need some constant intensity light source that takes all variables into account.

\[ \mu + \text{scintillator} = \mu \]
DCOV Calibration Strategy

- Read in ~4 hours of OV data.
- Isolate muon signals from background radiation signals.
- Calculate the necessary gain constants for each pixel.
- Apply the new gain constants on a hardware level.
- Take more data.
- Repeat.
Double Chooz Offline Group Software
Outer Veto Data Structure

- Data stored in terms of EnDeps

---

MyEnDep->InitOVHitInfoIter(); // initialises the iterator

while( const OVHitInfo* myOVHitI = dynamic_cast<const OVHitInfo*>( MyEnDep->NextOVHitInfo() ) ) // loops over ONE HIT
{

    // DOGS channel = 64*module + channel, so dividing (since it's INT) truncates channel
channel = myOVHitI->GetChNum();
charge = myOVHitI->GetCharge();
module = channel/64;
channel -= module*64; // channel numbering starts from 0 to 63
My Program (Offline): Isolating Muons (PseudoCode)

- Once for every EnDep:
  - GeometricOverlap function
    - Within each module, find the hits in geometrically overlapping strips.
      - Loose cuts on minimum ADC.
    - Returns a list of overlapping strip ("muon") hits, and a list of all "left-over" non-overlapping strip hits (which will be useful later).
  - ModuleOverlap function
    - Check if active modules are overlapping. None? Return;
What about the “left over” hits?

- Non geometrically overlapping hits checked for crosstalk.
- Crosstalk:
  - Light spillage (~6%)
  - Generates a single-PE peak
  - Used to calculate ADC2PE conversion factor (noise reduction)
Crosstalk Channel Checker

- CrosstalkChecker function.
- Map applied to check that which “left over” hits are crosstalk hits (are adjacent to muon channels on PMT face).

![PMT Face Diagram]

- Muon Hit Channels
- Possible Crosstalk Channels
- Possible Double Crosstalk Counts
BEFORE Applying Cross-Talk Map to Ensure Crosstalk in “leftover” Hits from Geometrically Overlapping EnDep

~30 min of data taken at Chicago
**AFTER** Applying Cross-Talk Map to Ensure Crosstalk in “leftover” Hits from Geometrically Overlapping EnDep

~30 min of data taken at Chicago
More Cuts: Likelihoods

- Likelihood = the probability that a given ADC corresponds to a muon hit, or a radiation hit.

- Calculated by normalizing the area of muon distribution and radiation distribution for each (64*44) channel to one, dividing muon/radiation bin-by-bin, and taking the log.
  - Log likelihoods > 0 correspond to higher probability of muon, < 0 correspond to higher probability of radiation.

- Initialized to some value for the first run, and calculated at the end of the program (to be applied on the next round of data).

- What’s really cool about likelihoods?

Likelihoods for different hits are independent.
Likelihoods Cont.

- Since likelihoods for different hits are independent (orthogonal), we can multiply (sum) them together!

\[ P_{\text{sum}} = \log(\prod_i \text{likelihood}_i) = \sum_i \log(\text{likelihood}_i) \]

- Make a hard cut on the log likelihood sum
  - Summation allows for more variation in individual hits while still corresponding to a muonic EnDep.
Summed Log Likelihood

Summed Log Probability for 4 Fold Coincidence

- Counts
- LOG LIKELIHOOD

Radiation

Muons

Entries: 7228
Mean: -1.027 ± 0.04741
RMS: 4.03 ± 0.03352
Underflow: 14
Overflow: 26

mulikecutoversum
Optimization of “mulikecutoversum”

- Higher cut decreases efficiency but increases purity.
- Attempt to maximize efficiency * purity.
- MegaMini Module:
  - Run over same data with various cut values, output #4fold in top, #4fold in bottom, #8 folds.
  - Can calculate efficiency and purity knowing individual module efficiencies.
Example Final Muon Peak

(4-fold) Geometric Overlap hits in Module 19, Channel 58

Counts

Entries: 659
Mean: 307.8 ± 7.565
RMS: 194.2 ± 5.349
Underflow: 0
Overflow: 45

ADC

0 100 200 300 400 500 600
My Program (Offline): Calculating ADC2PE via Crosstalk

- **Values of interest:**
  - Using Crosstalk hits, can calculate ADC2PE conversion factor
    - Used to make cuts above noise threshold ((1/3) PE) in the Muon distribution.
  - Using Muon distribution, can calculate 64*44 (64*68) gain constants
  - And the spread over all modules/channels

\[
\text{new}_i^j = \frac{ADC_{\text{avg}}^j}{ADC_i^j} \times \text{old}_i^j
\]

\[
\text{spread} = \frac{\text{RMS}_{\text{avg}}}{\text{mean}_{\text{avg}}}
\]
My Program (Offline)
Calculating Gain Constants, Spread

- Gain constants uploaded to MySQL, retrieved by DC OV Calib (run control) to be applied to next round of data taking.

- Likelihoods uploaded to MySQL to be applied to next round of data analysis (to purify muon sample).

- Spread gives estimation of difference between every channel in the system, used to indicate equalization of PMT response for Muons for each pixel.
Well, does it work?

- Using MegaMini \((x, y, x, y)\) and Chicago \((x, x)\), simulate multiple iterations with only one data sample.
  - Run over data, calculate gains, run over data again
  - This time, divide hits by “old” gain and multiply by “new” gain.
    - Simulates applying “new” gain on a hardware level.

(a) MegaMini Spread Minimization Test Results

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Avg muon ADC</th>
<th>RMS(_{all,channels})</th>
<th>Spread (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>202.47</td>
<td>27.00</td>
<td>13.33</td>
</tr>
<tr>
<td>final</td>
<td>278.72</td>
<td>8.77</td>
<td>3.15</td>
</tr>
</tbody>
</table>

(b) Chicago Module Spread Minimization Test Results

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Avg muon ADC</th>
<th>RMS(_{all,channels})</th>
<th>Spread (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>179.09</td>
<td>39.42</td>
<td>22.01</td>
</tr>
<tr>
<td>first</td>
<td>261.59</td>
<td>21.64</td>
<td>8.27</td>
</tr>
</tbody>
</table>

Difference due to lack of attenuation length corrections
Acknowledgements

- Camillo Mariani
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BACKUP SLIDES

------ BACKUP SLIDES ------
Outer Veto System at Double Chooz Far Detector

OV design for near detector consists of upper and lower tracking planes

Each plane is fully active and consists of modules oriented in both X and Y directions

OV modules consist of 2 layers of 64 scintillator strips with WLS fibers connected to a multi-anode PMT
Take Data using new/initial gain constants

MySQL Upload:
- Gain Consts
- Spread
- Likelihoods

Output:
- ADC2PE (64x44)
- Muon ADC (64x44)
- Gain Consts (64x44)
- Spread
- Likelihoods (64x44)
The Double Chooz Detector