Thesis title

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I hereby declare that I carried out this thesis independently, and only with the cited sources, literature and other professional sources.

I also declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Brighton, United Kingdom,
February 13, 2024

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Acknowledgements

School of Mathematical and Physical Sciences, University of Sussex

DOCTORAL THESIS

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by Róbert Králik

with supervision from Dr Lily Asquith and secondary supervision from

Prof Jeffrey Hartnell

ABSTRACT

Abstract

Keywords:

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1. Introduction

2. Theory of neutrino physics

Very brief history - Pauli, Fermi,... Fermi was the first to use them in his beta decay theory, after Pauli proposed them in his letter. First time detected by Reines and Cowan in 1956.

2.1 Neutrinos in the Standard Model

Neutrinos are fermions, their interactions are...

2.2 Neutrinos beyond the Standard Model

Neutrino oscillate and therefore have mass.

Theories of neutrino mass generation

I should discuss everything that is even briefly mentioned in the neutrino magnetic moment theory section.

- Dirac vs Majorana neutrinos
- Neutrino masses
- Neutrino interactions with electrons and nuclei
- Neutrino oscillations and their implications

3. NOvA experiment

What is NOvA and what is it trying to measure/detect? General overview and description of the following chapter.

Where is it located and general dispositions. It has three detectors and uses a neutrino beam from the NuMI at Fermilab.

Maybe timeline of NOvA or just a general overview

3.1 Source of neutrinos for NOvA

3.1.1 Simulation of neutrino beam

3.1.2 Package to Predict the FluX

Should I talk about this now or should I talk about the simulations (and their corrections) together?

3.1.3 Constraining the hadron production systematic uncertainty in NOvA

Again, should I discuss it here or somewhere else?

Systematic uncertainties related to the NOvA neutrino beam

Hadron production and focusing systematic uncertainties

Principal component analysis

Maybe briefly also mention the POT scaling normalization uncertainty.

3.2 NOvA detectors

General overview of the NOvA detector design and composition. List the percent-wise contribution of elements in the NOvA soup.

Segmentations and general proportions of the detectors, fibers.

The MIP energy loss for electrons (similarly to muons) can be found with a similar method as used in the AbsCal_technote_1stAna in TestBeam (page 2).

3.2.1 Data acquisition

APDs and how they work are pretty well described in the NOvA technical design report. For some reason the TDR I have downloaded doesn't have the full chapter 14. Full TDR can be found in docdb:2678 chapter by chapter.

APD signal first needs to be converted to a digital format with ADC (is there anything before that?). Maybe take a look at docdb:353.

This digital signal is then passed to the FPGA, which does the correlated sampling and time stamping [docdb:353].

TDR: Major components are the carrier board connector location at the left, which brings the APD signals to the NOvA ASIC, which performs integration, shaping, and multiplexing. The chip immediately to the right is the ADC to digitize the signals, and FPGA for control, signal processing, and communication. The front end electronics has the responsibility of amplifying and integrating the signals from the APD arrays, determining the amplitude of the signals and their arrival time and presenting that information to the data acquisition system (DAQ). Data from the ADC is sent to an FPGA where multiple correlated sampling is used to remove low frequency noise. This type of Digital Signal Processing (DSP) also reduces the noise level and increases the time resolution.

We are saving all the ADC and TDC (Time Digital Converter I believe) values to the RawDigit. Then they are fitting in the Calibrator to a functional form and converted to PE by fitting for the peak ADC.

"The chip will be used in its "Analog" mode in NOvA. In this mode, eight channels of integrator/shaper outputs are fed onto a multiplexer and driven by a differential amplifier onto the output pads. The multiplexer runs at 16 MHz, sending its signal output to the quad ADC. The ADC outputs, in turn, are sent in a continuous stream to an FPGA which processes the data and outputs it onto a data link. In these tests, the data link is standard USB 2.0" [docdb:1904]

DAQ Software (what happens to the signal after the FEBs) is described in docdb:1233. Not sure if this is the final design though.

3.2.2 Data processing

Basic description of the process from raw data to final predictions (or just cafs?)

Reconstruction - describe the reconstruction tools used to get the final products, focusing on the electron reconstruction.

3.2.3 Detector calibration

How much should I describe the detector calibration here? Probably quite a lot. I should probably just use the entire NOvA calibration section from my Test Beam calibration technote.

3.2.4 NOvA Test Beam

Should this even be here? Maybe I should just mention TB in the beginning but leave the description of Test Beam to the special chapter.

3.2.5 Simulation of neutrino interaction

NOvA reweight of the neutrino interaction predictions

3.2.6 Simulation of detector response

Should I join this with the other simulation subsection?

3.2.7 Systematic uncertainties for NOvA detectors

Neutrino interaction systematic uncertainties

Energy scale systematic uncertainty

Cell edge calibration systematic uncertainty

Detector ageing systematic uncertainty

4. NOvA Test Beam detector calibration

What to include from the technotes?

4.1 NOvA Test Beam

Describe the test beam detector - copy from the technote

Describe the data and the selection - should this be a separate section?

4.2 Simulation of cosmic muons in the Test Beam detector

basically copy from the technote.

4.3 NOvA Test Beam detector calibration

Basically copy from the technote.

5. Contraining neutrino magnetic moment in the NOvA near detector

5.1 Theory of neutrino magnetic moment

5.2 Event selection

5.3 Fitting and hypothesis testing, parameter estimation

How do we find the value of or limit for the effective neutrino magnetic moment?

Large section on statistics in the PDG.

Maximum likelihood with binned data:

N bins with a vector of data $n = (n1, ..., n_N)$ with expectation values $\mu = E[n]$ and probabilities $f(n; \mu)$. Suppose the mean values μ can be determined as a function of a set of parameters θ (I assume for us there's either only one parameter - magnetic moment, or three parameters - mag. moment, scale of SM signal and scale of SM background). Then one may maximize the likelihood function based on the contents of the bins.

If the n_i is regarded as independent and Poisson distributed (which I'd say is the case for us), then the data are instead described by a product of Poisson probabilities,

$$f_p(n; \theta) = \prod_{i=1}^{N} \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i}, \tag{5.1}$$

where the mean values μ_i are given functions of θ. The total number of events n_{tot} thus follows a Poisson distribution with mean $\mu_{tot} = \sum_i \mu_i$.

When using maximum likelihood with binned data, one can find the maximum likelihood estimators and at the same time obtain a statistic usable for a test of goodness-of-fit. Maximizing the likelihood $L(\theta) = f_P(n; \theta)$ is equivalent to maximizing the likelihood ratio $\lambda(\theta) = f_P(n;\theta)/f(n;\hat{\mu})$, where in the denominator $f(n;\hat{\mu})$ is a model with an adjustable parameter for each bin, $\mu = (\mu_1, ..., \mu_N)$, and the corresponding estimators are $\hat{\mu} = (n_1, ..., n_N)$ (called the "saturated model").

Equivalently one often minimizes the quantity $-2\ln\lambda(\theta)$. For independent Poisson distributed n_i this is

$$-2\ln\lambda(\theta) = 2\sum_{i=1}^{N}\left[\mu_i(\theta) - n_i + n_i \ln\frac{n_i}{\mu_i(\theta)}\right], \tag{5.2}$$

where for bins with $n_i = 0$, the last term is zero. In our term $\mu_i(\theta)$ is the **expected number of events in bin i if magnetic moment is** θ and n_i is the observed (measured) number of events in that bin.

A smaller value of $-2\ln\lambda\left(\hat{\theta}\right)$ corresponds to better agreement between the data and the hypothesized form of $\mu(\theta)$. The value of $-2\ln\lambda\left(\hat{\theta}\right)$ can thus be translated into a **p-value as a measure of goodness-of-fit**. Assuming the model is correct, then according to **Wilk's theorem**, for **sufficiently large** μ_i and provided certain regularity conditions are met, **the minimum of** $-2\ln\lambda$ **follows a** χ^2 **distribution.** If there are N bins and M fitter parameters, then the number of degrees of freedom for the χ^2 distribution is $N - M$ if the data are threated as Poisson distributed - which they are for us.

The method of least squares coincides with the method of maximum likelihood in a special case where the independent variables are Gaussian distributed - so I suppose this means that if I have enough events in each single bin, then I could equate the method of log likelihood and the method of least squares...

5.3.1 Nuisance parameters

In general the model is not perfect, which is to say it cannot provide an accurate description of the data even at the most optimal point of its parameter space. As a result, the estimated parameters can have a systematic bias. One can improve the model by including in it additional parameters. That is, $P(x|\theta)$ is replaced by a more general model $P(x|\theta,\nu)$, which depends on parameters of interest θ and *nuisance parameters* ν. The additional parameters are not of intrinsic interest but must be included for the model to be sufficiently accurate for some point in the enlarged parameter space.

Although including additional parameters may eliminate or at least reduce the effect of systematic uncertainties, their presence will result in increased statistical uncertainties for the parameters of interest. This occurs because the estimators for the nuisance parameters and those of interest will in general be correlated, which results in an enlargement of the contour.

To reduce the impact of the nuisance parameters one often tries to constrain their values by means of control or calibration measurements, say, having data **y** (I assume for us this would represent a control sample - like they use in the ND group). For example, some components of y could represent estimates of the nuisance parameters, often from separate experiments. Suppose the measurements y are statistically independent from x and are described by a model $P\left(y|\nu\right)$. The joint model for both x and y is in this case therefore the product of the probabilities for x and y, and thus the likelihood function for the full set of parameters is

$$L\left(\theta,\nu\right) = P\left(x|\theta,\nu\right) P\left(y|\nu\right). \tag{5.3}$$

Note that in this case if one wants to simulate the experiment by means of Monte Carlo, both the primary and control measurements, x and y, must be generated for each repetition under assumption of fixed values for the parameters θ and ν.

Using all of the parameters (θ,ν) to find the statistical errors in the parameters of interest θ is equivalent to using the *profile likelihood*, which depends only on θ. It is defined as

$$L_p\left(\theta\right) = L\left(\theta,\hat{\nu}\left(\theta\right)\right), \tag{5.4}$$

This equation is supposed to have double hat for the neutrino on RHS but that throws an error when compiling... where the double-hat notation indicates the profiled values of the parameters ν, defined as values that maximize L for the specified θ.

5.3.2 Unbinned parameter estimation

If the total number of data values is small, the unbinned maximum likelihood method is preferred, since binning can only result in a loss of information, and hence the larger statistical errors for the parameter estimates. Does't this mean that if the number of events for the neutrino magnetic moment analysis is small, it would be better to do a completely unbinned maximum likelihood method, instead of a single bin method?

5.3.3 Subsection

Subsubsection

6. Conclusion

Glossary

PMNS	Pontecorvo-Maki-Nakagawa-Sakata (matrix)
SNU	Solar Neutrino Unit
CC	Charged Current (interaction)
NC	Neutral Current
MSW	Mikheyev-Smirnov-Wolfenstein (effect)
SK	Super-Kamiokande (experiment)
NO	Normal Ordering (of masses)
IO	Inverted Ordering (of masses)
SBL	Short Baseline
LBL	Long Baseline
LSND	Liquid Scintillator Neutrino Detector
MiniBooNE	Mini Booster Neutrino Experiment
SBN	Short Baseline Neutrino (program)
NOvA	NuMI Off-axis ν_e Appearance (experiment)
NuMI	Neutrinos from the Main Injector
ND	Near Detector
FD	Far Detector
FHC	Forward Horn Current (neutrino mode)
RHC	Reverse Horn Current (antineutrino mode)
HC	Horn Current
LE	Low Energy (mode of NuMI)
ME	Medium Energy (mode of NuMI)
APD	Avalanche Photodiode
CVN	Convolutional Neural Network
MC	Monte Carlo
PPFX	Package to Predict the Flux
CMS	Center of Mass (frame)
BENDecomp	Beam Electron Neutrino Decomposition

Bibliography