Experimental Neutrino Physics in a Nutshell

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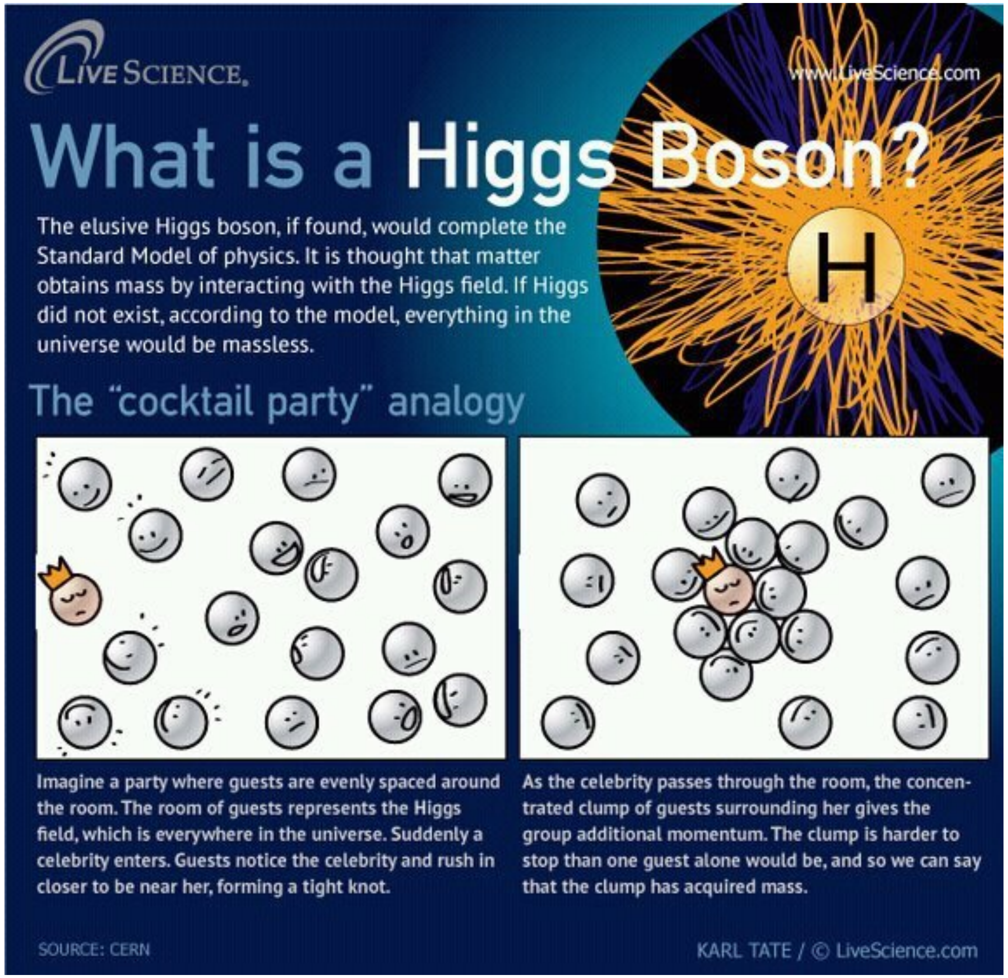
i.e A *practical* guide for
How to THINK/ADDRESS the things as a (*neutrino*) experimentalist

Some confessions

- I had a similar background to most Vietnamese theoretical students and encountered many difficulties during my first years of Ph.D. studies in US in experimental HEP .
- My goal is to introduce experimental neutrino physics with the most basic concepts.
- My experience with *accelerator-based neutrino oscillation* experiments may not be applicable to other fields.
- Many materials are borrowed from other talks, but citations are occasionally missed.
- Your feedback is valuable, and I will always be a student for listening to it.

Lecture style: A "*cocktail party*"



What is a Higgs Boson?

The elusive Higgs boson, if found, would complete the Standard Model of physics. It is thought that matter obtains mass by interacting with the Higgs field. If Higgs did not exist, according to the model, everything in the universe would be massless.

The "cocktail party" analogy

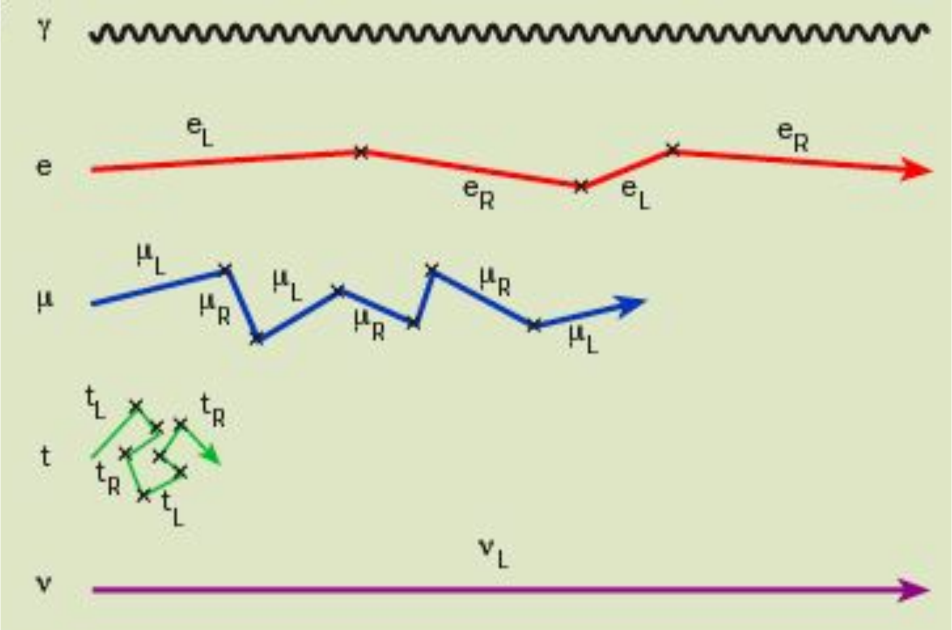
Imagine a party where guests are evenly spaced around the room. The room of guests represents the Higgs field, which is everywhere in the universe. Suddenly a celebrity enters. Guests notice the celebrity and rush in closer to be near her, forming a tight knot.

As the celebrity passes through the room, the concentrated clump of guests surrounding her gives the group additional momentum. The clump is harder to stop than one guest alone would be, and so we can say that the clump has acquired mass.

SOURCE: CERN

KARL TATE / © LiveScience.com

Simple version of "Neutrino in SM"



http://hitoshi.berkeley.edu/neutrino/neutrino4.html

Can you explain the left and the right by just looking at the title and illustration?

Lecture style: To *simplify* something such as...

It might be too difficult for young students with theoretical backgrounds to absorb in 10 days of the school.

Hypothesis testing /parameters determination

$$P(\nu_\mu \to \nu_e) = \boxed{4c_{13}^{\ 2}s_{13}^{\ 2}s_{23}^{\ 2}\sin^2\Delta_{31}}$$

Leading term — $\boxed{\theta_{13}}$

$$+8c_{13}^{\ 2}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CPC

$$\boxed{-8c_{13}^{\ 2}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}}$$

CPV

$$+4s_{12}^{\ 2}c_{13}^{\ 2}(c_{12}^{\ 2}c_{23}^{\ 2} + s_{12}^{\ 2}s_{23}^{\ 2}s_{13}^{\ 2} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

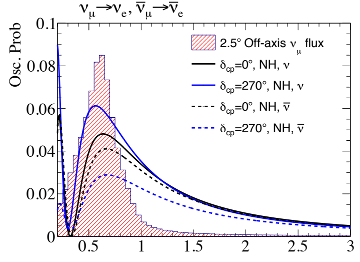
Solar

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

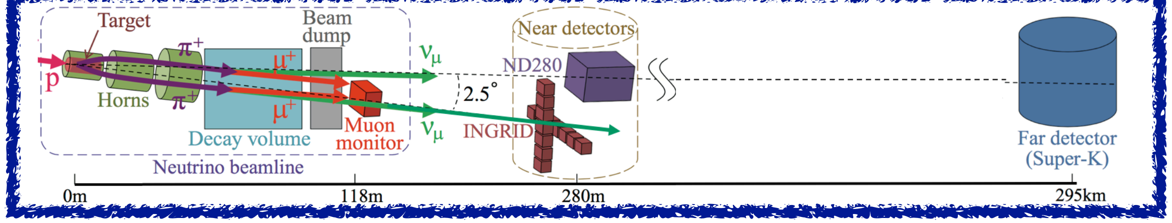
$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

replace δ by −δ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

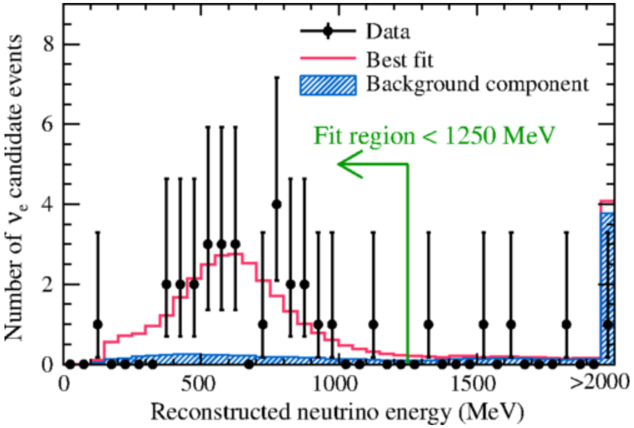
CP violating term introduced by interference among three-flavor mixing



Experiment setup



observed data

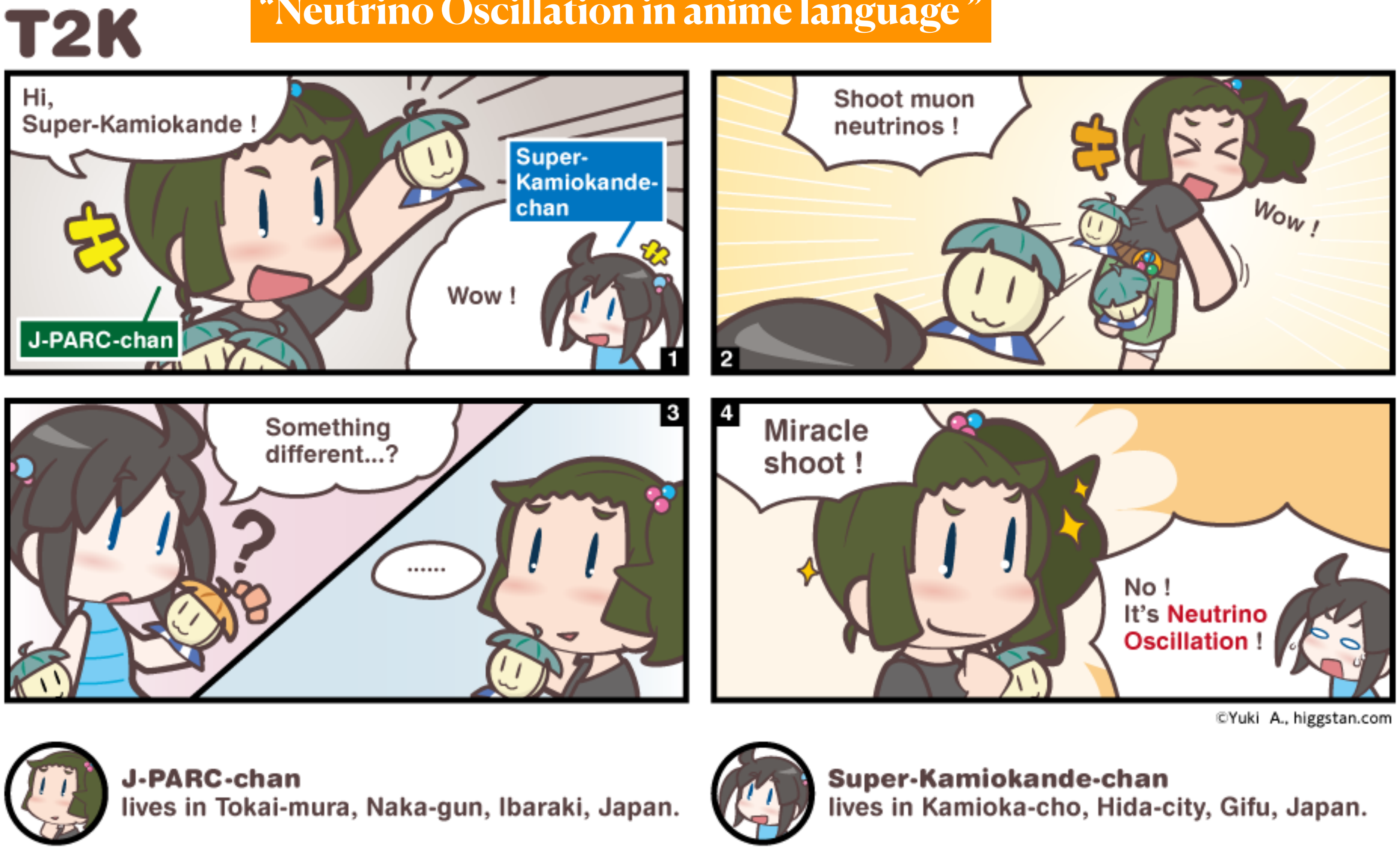


data-based statement

T2K has made the first observation of electron neutrino appearance in a muon neutrino beam...with a significance of 7.3 σ C.L. over the the hypothesis of $\sin^2 2\theta_{13} = 0$

…*with* something like

“Neutrino Oscillation in anime language”



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http://higgstan.com

Contents

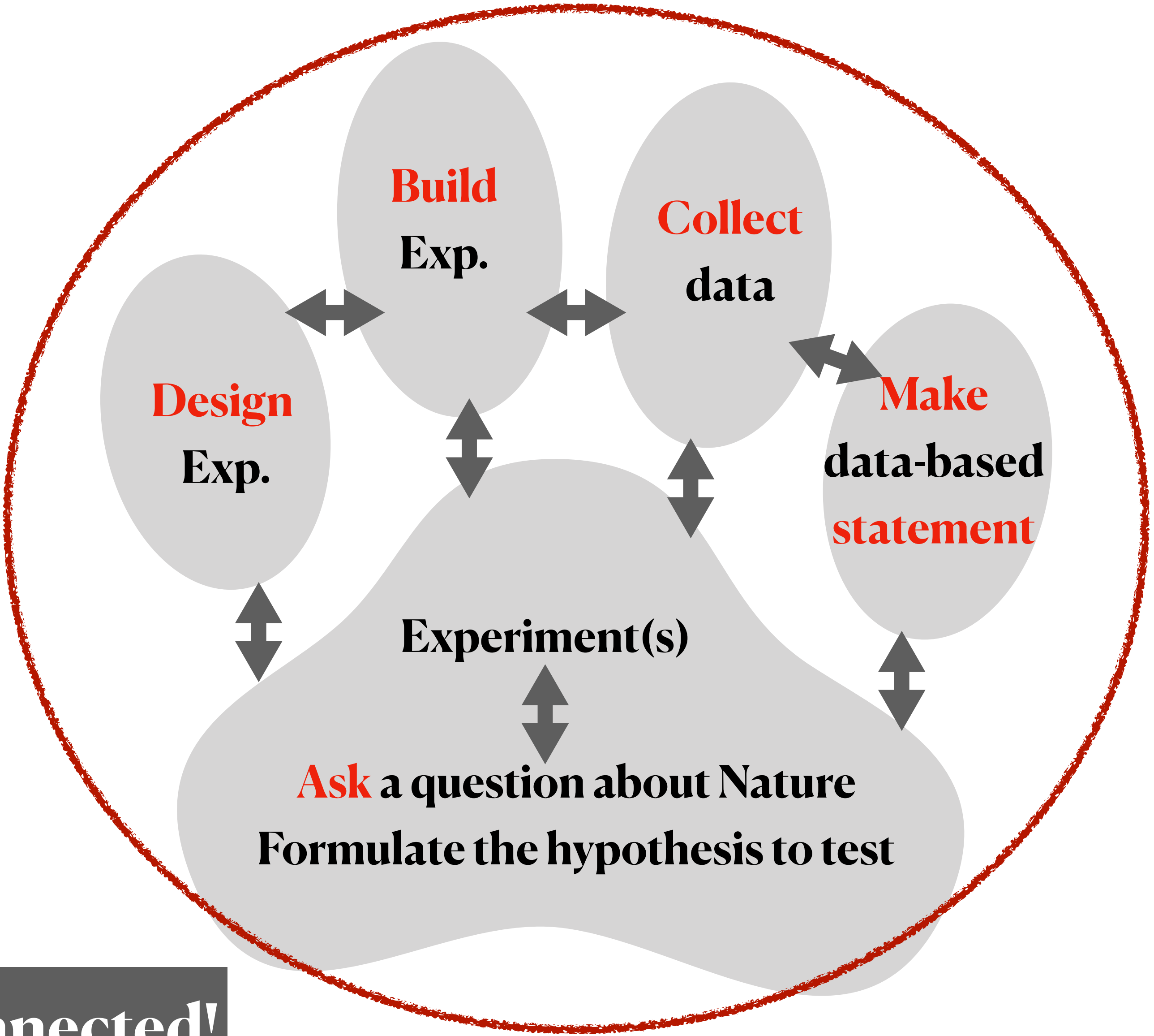
- **Basic steps as scientists**
  - **Ask** question(s), **Design** experiment, **Build** experiment, **Collect** data and **Make statement** based on data observation
  - *Examples with neutrino experiments*
- **Neutrino detection: A bird's eye view**
  - *A **complicated, interdisciplinary** field of Particle and Nuclear physics, Material science, Mechanics, Electronics, and Data mining*
- **Some selected topics (*personal choices*)**
  1) **Signal and background**
  2) **Hypothesis testing**
  3) **Sensitivity & Parameter estimation**
  4) **Systematics**
  5) **Monte Carlo usage**

Number of illustrations will be shown

code: https://github.com/cvson/nushortcourse

Feel free to download and play!

Basic steps as scientists



Design Exp.

Build Exp.

Collect data

Make data-based **statement**

Experiment(s)

Ask a question about Nature

Formulate the hypothesis to test

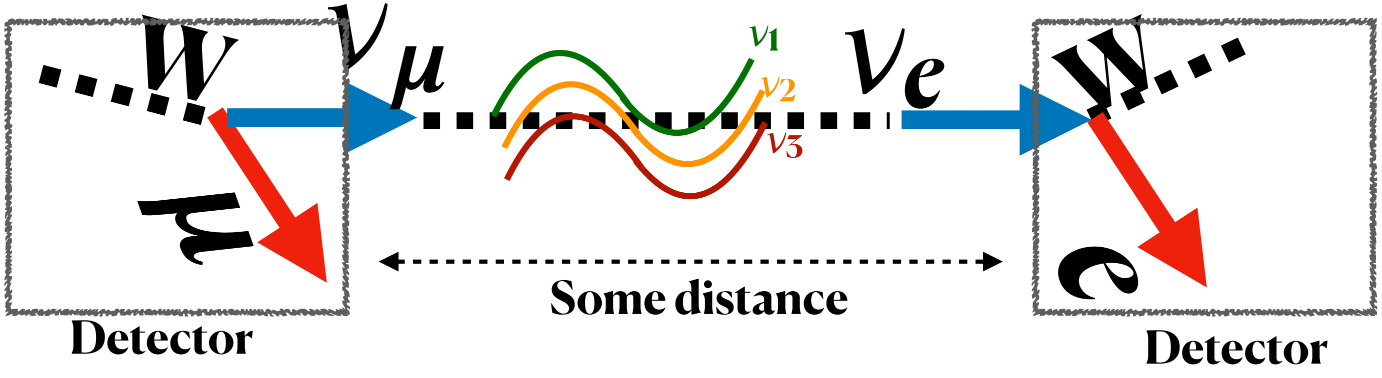
All connected!

Neutrino oscillations
in briefing

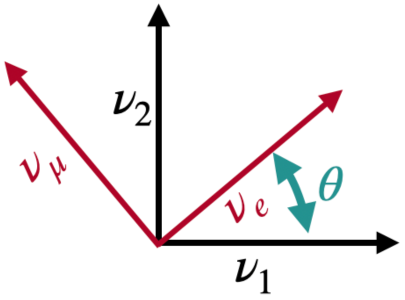
ref: Neutrino phenomenons and other lectures

Neutrino oscillations *in briefing*

Neutrino can change its flavor when give it time to propagate



- **Neutrino oscillations** require an existence of **neutrino mass spectrum**, i.e mass eigenstate ν_i with definite mass m_i (where *i* is 1, 2, 3* at least)
- It requires flavor eigenstate with definite flavor, ν_α (where α is e, μ, τ) must be **superpositions** of the mass eigenstates, *a fundamental quantum mechanic phenomenon*



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

flavor eigenstate

PMNS leptonic mixing matrix**

mass eigenstate

**It's still possible that there are more than 3 mass eigenstates*

***PMNS is shorted for Pontecorvo-Maki-Nakagawa- Sakata*

Simple exercise

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

flavor eigenstate

mass eigenstate

PMNS leptonic mixing matrix**

Show that U is unitarity if flavor eigenstates are orthogonal and mass eigenstates are orthogonal !

Relevant point: Why can we assume that the states (flavor/mass) are orthogonal?

PMNS leptonic mixing matrix

$$c_{ij} = \cos\theta_{ij}, \; s_{ij} = \sin\theta_{ij}$$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} \text{Diag}(e^{i\rho_1}, e^{i\rho_2}, 0)$$

- U_{PMNS} is 3x3 unitary matrix and parameterized with **3 mixing angles** $(\theta_{12}, \theta_{13}, \theta_{23})$ and **one irreducible Dirac CP-violation phase** δ_{CP}, *similar to CKM matrix of quark mixing*

- If neutrino is **Majorana particle,** there are **two additional CP-violation phases** (ρ_1, ρ_2), *which play no role in neutrino oscillations*

Neutrino oscillation experiments aim to measure the oscillation parameters and to test if PMNS matrix can describe well the data *or need some extension.*

Other exercise

Count the number of mixing angles and phases in the n x n unitary mixing matrix.

Answer on the white board

Ask a question: e.g. does $\nu_\mu \rightarrow \nu_e$ oscillation happen?

Why is addressing this question important?

- **Confirm** non-zero mixing angle, $\theta_{13} > 0$ or set higher limit for mixing angle θ_{13} (e.g. $\theta_{13} < \alpha$)
- If non-zero, can **measure** δ_{CP}, *which may be a source of matter-antimatter asymmetry in the Universe*

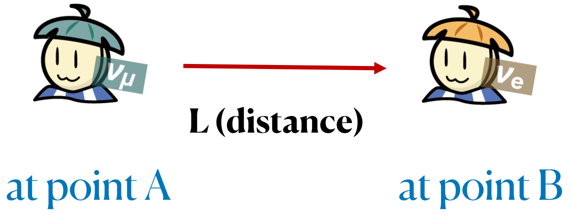
Supported knowledge

What have you already know at the time question posed?

- Neutrino oscillations confirmed
- Some upper limit on θ_{13} from reactor
- etc...

https://arxiv.org/abs/hep-ex/0106019

Do muon neutrinos transform into electron neutrinos at given distance of travel?



$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta m^2_{31} + \epsilon \sin \theta_{13} \sin \delta_{CP} \ldots$$

ref: Neutrino phenomenology lecture

Define goals of the exp. e.g. $\nu_\mu \rightarrow \nu_e$ search

Goal #1: Test theoretical hypothesis; basically yes/no question

may not be familiar with it yet(?)

- At some C.L., we observe the appearance of electron neutrino (i.e. $\theta_{13} \neq 0$)
- At some C.L., we reject the hypothesis that electron neutrino appeared (i.e. $\theta_{13} = 0$)

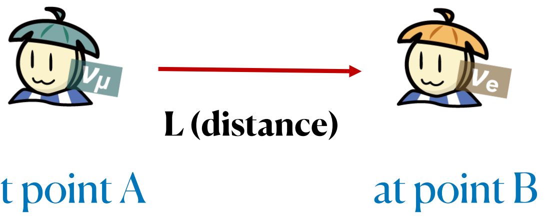
Goal #2: Estimate parameters of a **theoretical model** which used to describe the data

- Does the theoretical model (e.g. *neutrino oscillation*) give good description of the data?
- Allowed region for $\sin^2\theta_{13}$ at 68% C.L. (1σ) or 90% C.L., etc...

Driven by theoretical models

T2K, NOvA, etc

Do muon neutrinos transform into electron neutrinos at given distance of travel?



$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta m^2_{31} + \epsilon \sin \theta_{13} \sin \delta_{CP} \ldots$$

Hypothesis test and parameter estimation will be discussed later

How to conduct the $\nu_\mu \rightarrow \nu_e$ search?

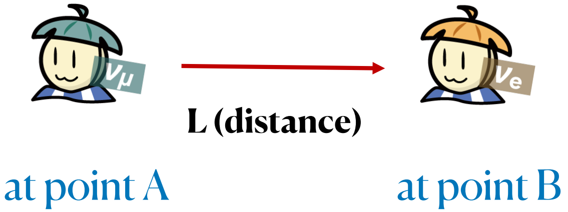
In principle, how can we conduct the search?

1. Need source of ν_μ
2. Put detector at some distance from ν_μ source
3. Look for ν_e appeared from ν_μ source in detector

Does it look simple ?

T2K, NOvA, etc

Do muon neutrinos transform into electron neutrinos at given distance of travel?



How to conduct the $\nu_\mu \to \nu_e$ search?

In principle, how can we conduct the search?

1. Need source of ν_μ (1)
2. Put detector (2) at some distance (3) from ν_μ source
3. Look for ν_e (4) appeared from ν_μ source (5) in detector

Things become more complicated when put into practice

(1) How can source be created? How well you understand the source? (composition, density, energy, timing, etc)

(2) What kind of detector you need? how big it is? Where do you put the detector?

(3) How can you choose distance? Typically your detector can't move from place to place.

(4) How can you identify ν_e?

(5) How do you know it coming from ν_μ source but not others?

T2K, NOvA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

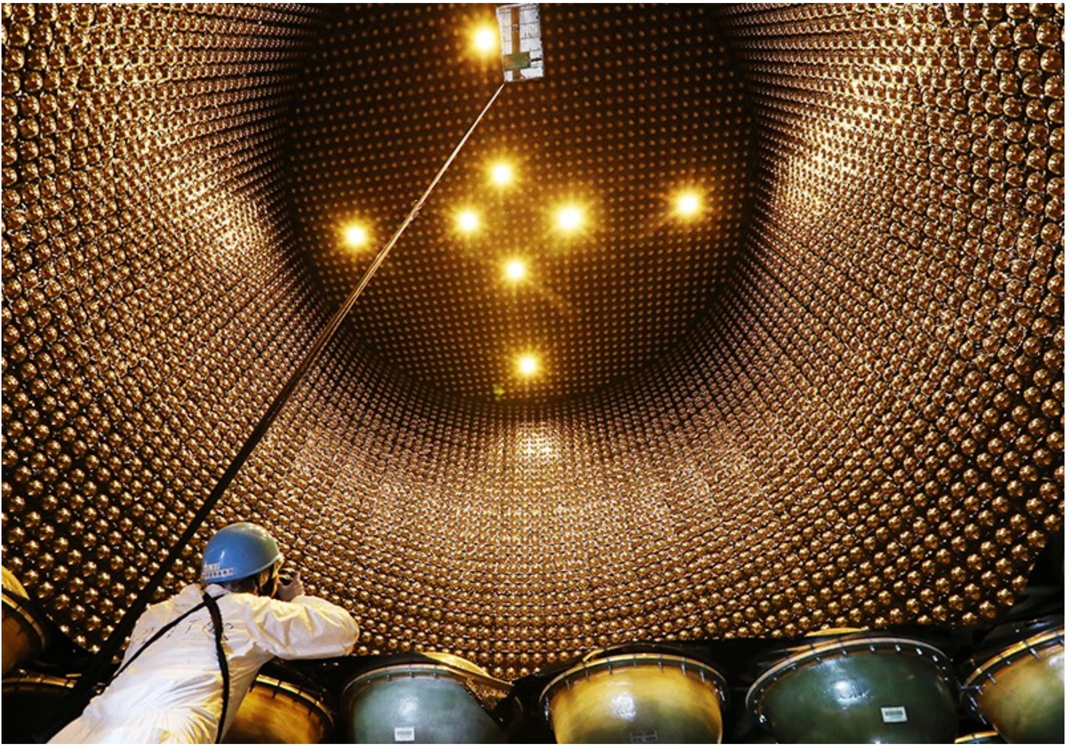
Design an experiment: Exhaustive investment of value, cost, and time

When designing an experiment, the following questions must be addressed. In reality, there are numerous additional questions to answered.

- **Think big, make cheap**. HEP experiment is typically very expensive.
  - What available facilities to use, e.g. *Birth of Kamiokande (ref. Prof. Oyama's lecture);T2K use Super-Kamiokande as far detector*
- How do you know you have the best among many possible experiment setups

  (can be conservative)
- **Most important**: guarantee success (*doesn´t mean you will get signal, but your experiment should achieve some measurement w/ unprecedented level of precision*)

Also, concern about the aesthetics

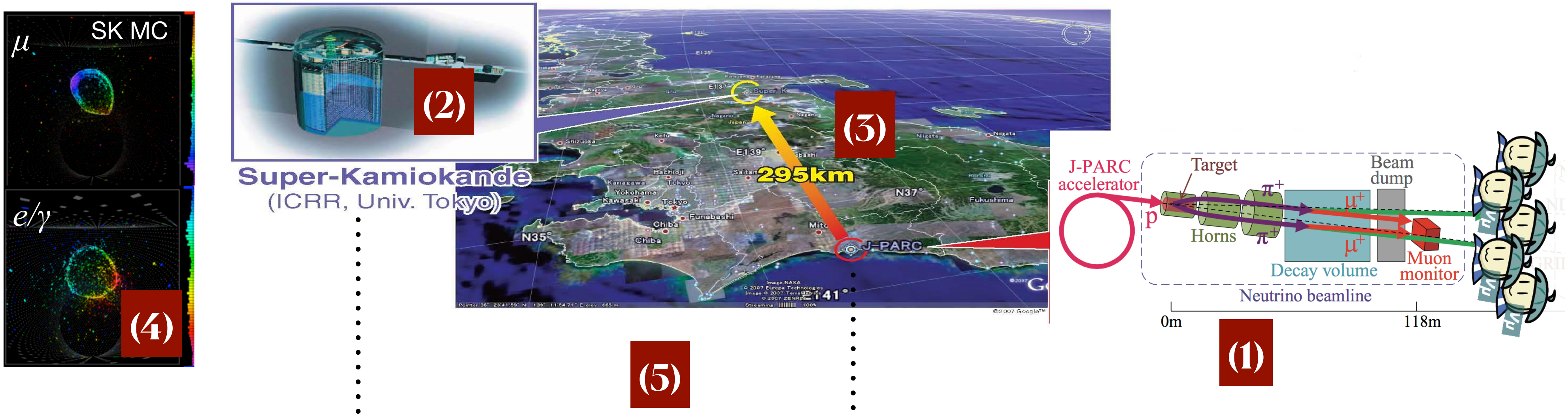


Design Exp.

T2K, NOvA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

Design an experiment e.g. T2K (placed in Japan)



GPS, timing synchronize

(1) How can source be created? How well you understand the source? (composition, density, energy, timing, etc)

(2) What kind of detector you need? how big it is? Where do you put the detector?

(3) How can you choose distance? Typically your detector can't move from place to place.

(4) How can you identify ν_e?

(5) How do you know it coming from ν_μ source but not others?

ref: T2K, Super-K, future experiments

Design Exp.

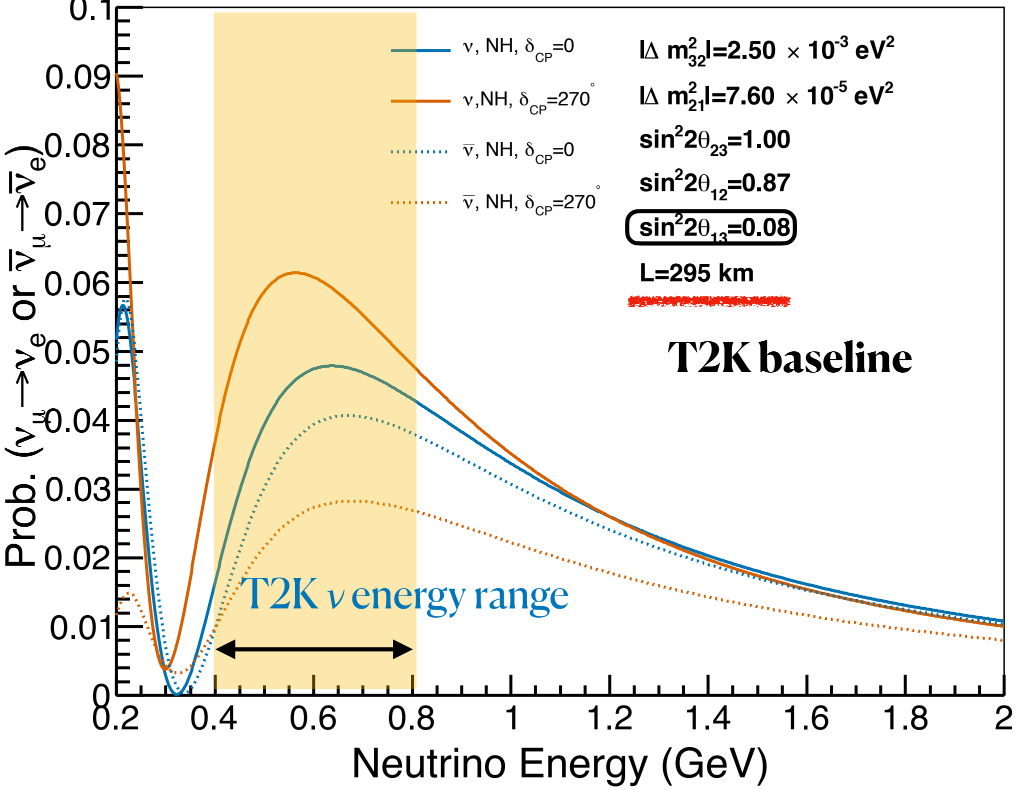
T2K, NOνA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

Design experiments: evaluate the sensitivity

Let's look at basic quality: $\nu_\mu \rightarrow \nu_e$ probability as function of energy. Basically this is **a counting experiment**

$$\boxed{N_{\nu_e} \sim \textbf{Prob.}(\nu_\mu \rightarrow \nu_e)}$$



https://github.com/cvson/nushortcourse/tree/master/OscCalculatorPMNS

At $\sin^2 2\theta_{13} = 0.08$,

Prob. is around 5%

(depend on δ_{CP} value;

smaller for anti-neutrino)

Since oscillation probability depends on neutrino energy, it's important to know energy of incoming neutrinos.

Design Exp.

T2K, NOvA, etc

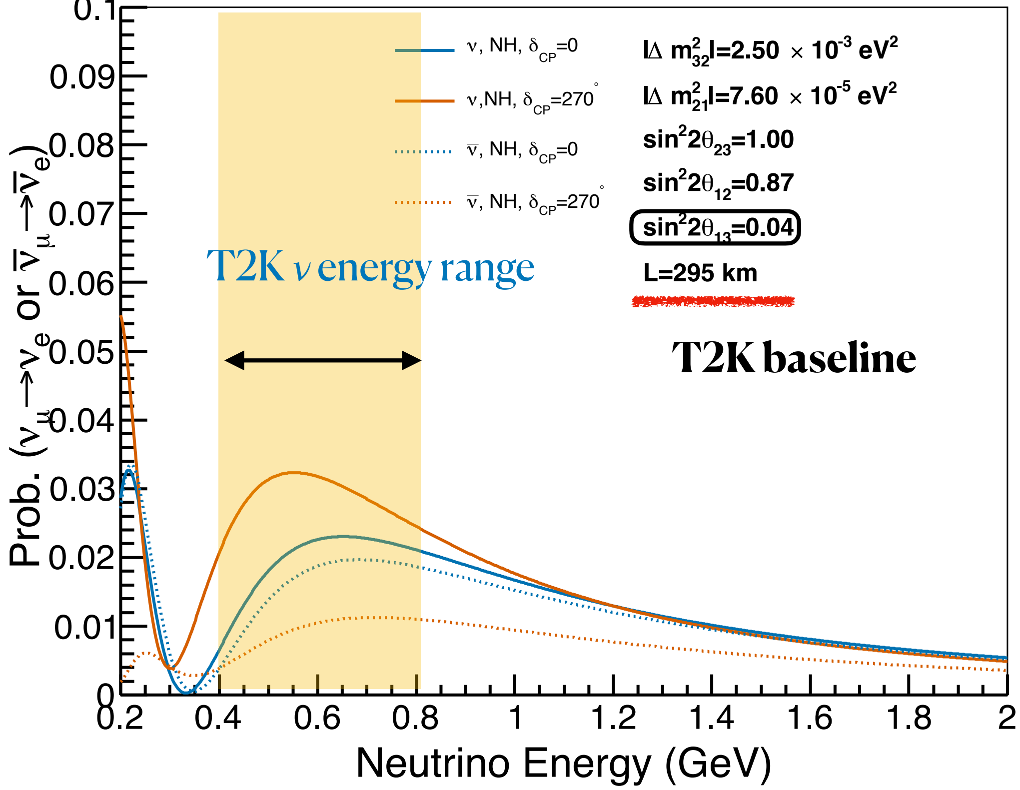
Do muon neutrino transform into electron neutrinos at given distance of travel?

ref: Neutrino phenomenology lecture

Design experiments: evaluate the sensitivity (cont'd)

Let's look at basic quality: $\nu_\mu \to \nu_e$ probability as function of energy. Basically this is **a counting experiment**

$\boxed{N_{\nu_e} \sim \textbf{Prob.}(\nu_\mu \to \nu_e)}$



T2K *ν* energy range

T2K baseline

https://github.com/cvson/nushortcourse/tree/master/OscCalculatorPMNS

At $\sin^2 2\theta_{13} = 0.04$

Prob. is around 2.5%

(depend on δ_{CP} value;

smaller for anti-neutrino)

Probability *depends* on values of $\sin^2 2\theta_{13}$(*also mass hierarchy, δ_{CP}*). Smaller probability means that with the same neutrino flux, number of observed events is smaller.

ref: Neutrino phenomenology lecture

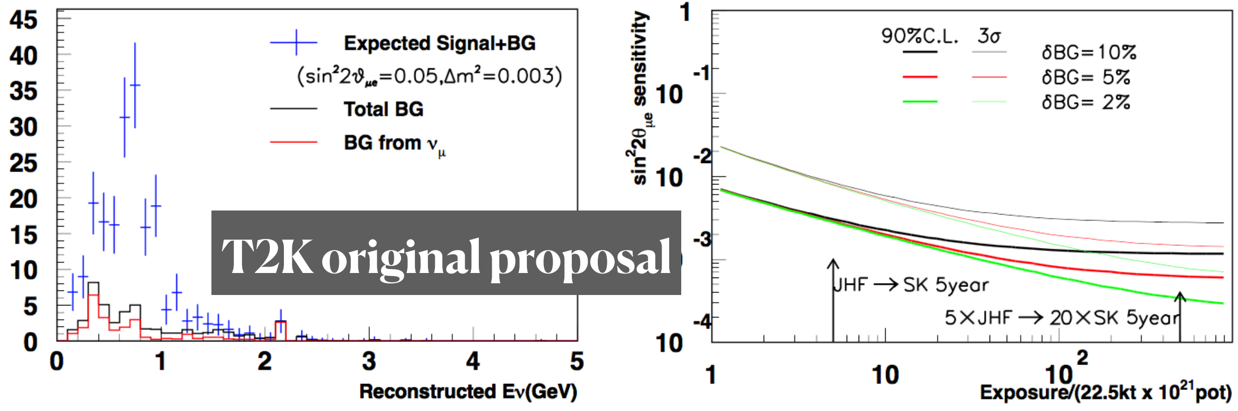
Design Exp.

T2K, NOvA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

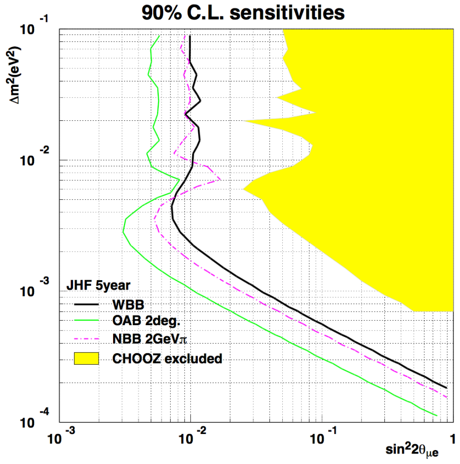
Design experiments: evaluate the sensitivity (cont'd)

hep-ex/0106019



T2K original proposal

Expected reconstructed neutrino energy distributions of expected signal+BG, total BG, and BG from ν_μ interactions for 5 years exposure of OA2°. Right: Expected (thick lines:) 90%CL sensitivity and (thin lines:) 3σ discovery contours as the functions of exposure time of OA2°. In left figure, expected oscillation signals are calculated with the oscillation parameters: $\Delta m^2 = 3 \times 10^{-3}$ eV^2,$\sin^2 2\theta_{\mu e}$ = 0.05. In right figures, Three different contours correspond to 10%, 5%, and 2% uncertainty in the background estimation.



$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23}$$

"NO" answer is also valuable. Both discovery and exclusion advance the human knowledge.

Normally, **physic potentials** (*how good/"sensitive"*) of designed detector much be computed for various scenario of underlying parameters:

- **Range of parameter(s)** in which detector can **explore**
- At what **values** of parameter(s), detector can make **observation/discovery**
- Evaluation at this stage may **simplify detector performance** (e.g. *systematic errors*)

Design Exp.

T2K, NOvA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

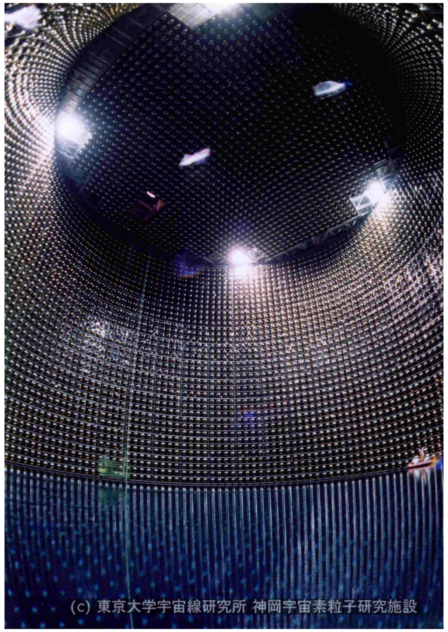
ref: Hyper-K/T2K lectures

Build experiment: huge efforts from many people

- Typically, neutrino detector is **big** (with few exception) and **take year(s) to build**
- Neutrino detector is often **located in deep underground** to cancel the noise from cosmic ray
  - big MONEY for this (e.g *NOvA is on surface although it is design to be underground*)
  - India controversy on INO building due to natural conservation
  - Hyper-K allocates lot of money to make cavern

Many additional considerations,

- How to access it?
- How to monitor it?
- How to maintain it?
- …



Build Exp.

Design Exp.

T2K, NOvA, etc

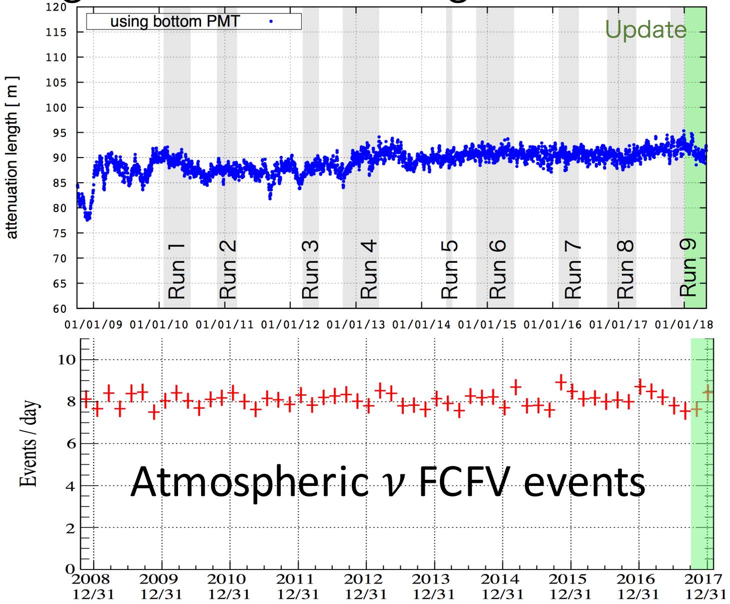
Do muon neutrino transform into electron neutrinos at given distance of travel?

ref: Hyper-K/future exp. lectures

Collect and record data (*and relevant conditions*)

- Data taking needs time: from year to decade (e.g., *Super-K 26 years, T2K 12 years*)
- Your detector may **NOT at same condition** during data-collecting period
    - Detector position can be unintentionally moved due to, e.g. *earthquake*
    - Some photosensors can be out-of-function
    - Light yield (*no. of photon per fixed amount of deposited energy*) can be changed *due to water quality, aging of scintillator, etc…* → affect conversion from observed signal to energy
    - etc…

Light attenuation length of water



Take high-quality data and keep experimental condition in **<u>control</u>** as much as possible → maximize the reliability & replication of the result!

Design Exp.

Build Exp.

Collect data

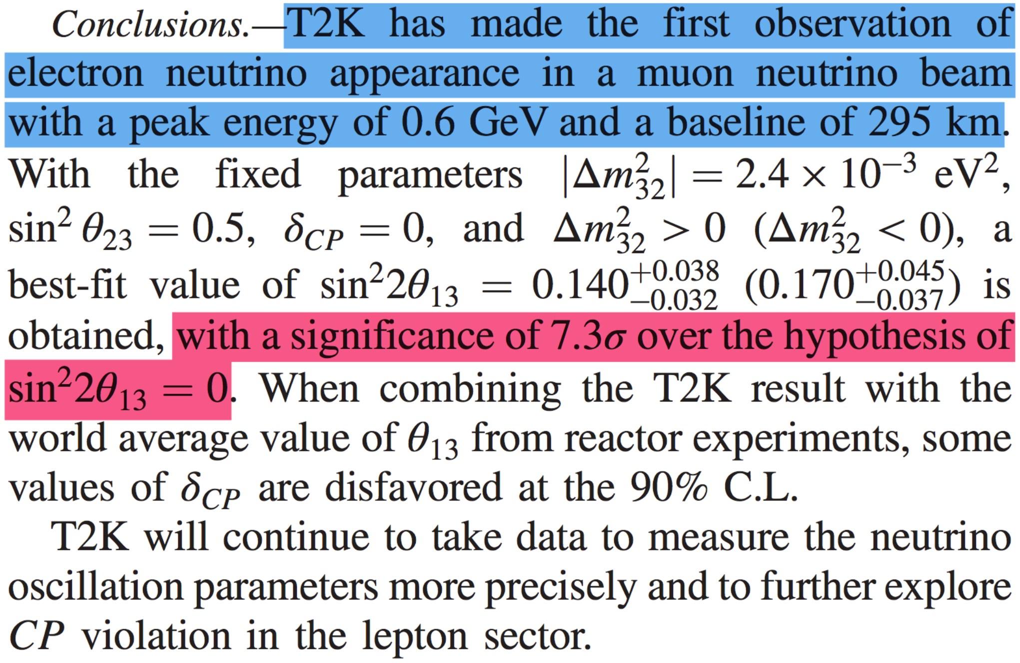
T2K, NOvA, etc

Do muon neutrino transform into electron neutrinos at given distance of travel?

ref: Super-K lecture/training

Make statement based on data (*compared to prediction*)

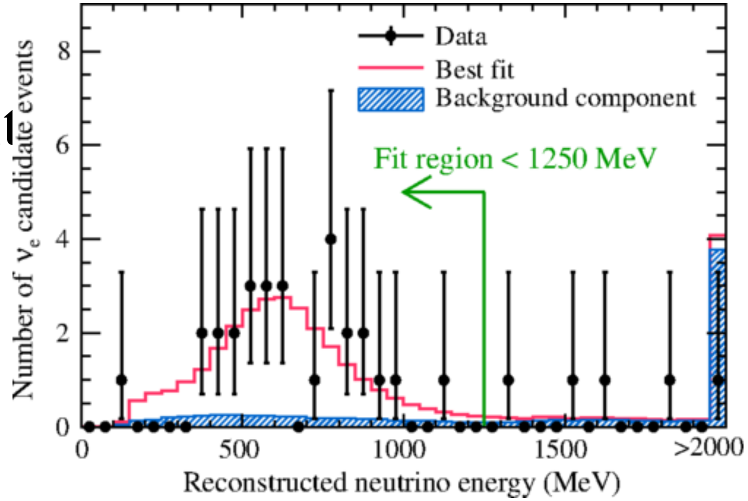
- The statement is never simple like "yes" or "no"
- It is always associated with level of uncertainty/ confidence (*or statistical significance*) as well as relevant assumptions
- If an observation is claimed, parameter's allowed range is estimated. If not, a parameter limit is set.
- E.g.:



Conclusions.—T2K has made the first observation of electron neutrino appearance in a muon neutrino beam with a peak energy of 0.6 GeV and a baseline of 295 km. With the fixed parameters $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\delta_{CP} = 0$, and $\Delta m^2_{32} > 0$ ($\Delta m^2_{32} < 0$), a best-fit value of $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$) is obtained, with a significance of 7.3σ over the hypothesis of $\sin^2 2\theta_{13} = 0$. When combining the T2K result with the world average value of θ_{13} from reactor experiments, some values of δ_{CP} are disfavored at the 90% C.L.

T2K will continue to take data to measure the neutrino oscillation parameters more precisely and to further explore *CP* violation in the lepton sector.

10.1103/PhysRevLett.112.061802



Build Exp.

Collect data

Design Exp.

make statement

T2K, NOvA, etc

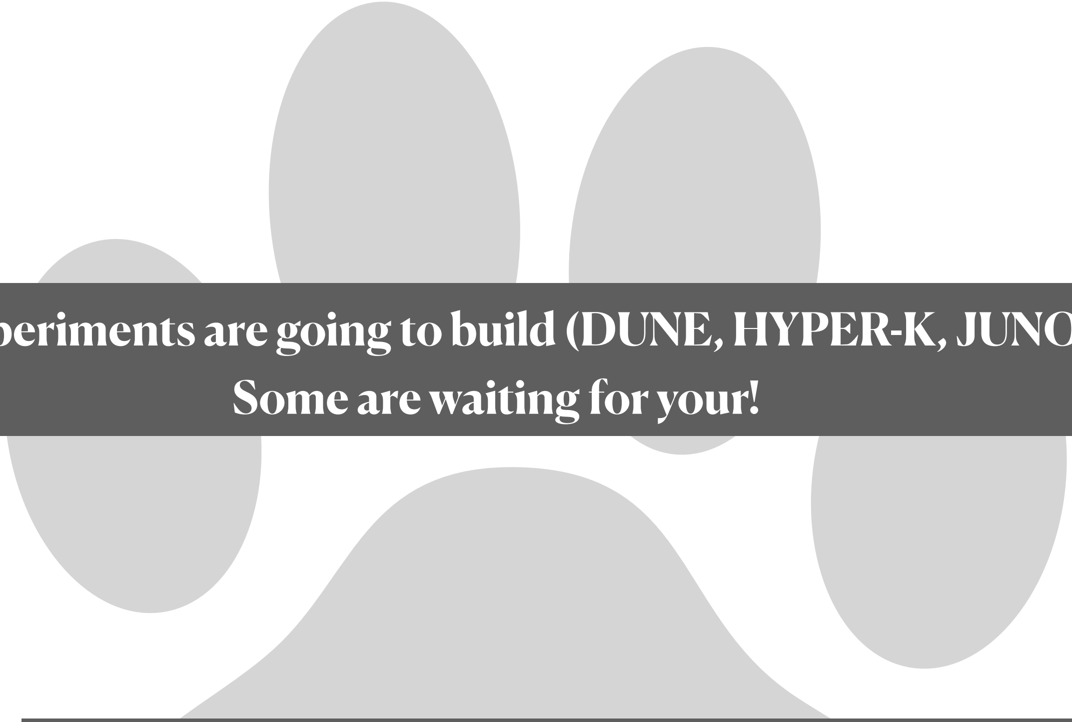
Do muon neutrino transform into electron neutrinos at given distance of travel?

Still many opening questions…Make your own path?

- Neutrinos are Majorana or Dirac particles?
- CP symmetry violated in neutrino oscillation?
- Neutrino mass ordering is inverted or normal?
- Is there 4th generation of neutrino?
- etc…

More questions from other lecturers

Still many opening questions…Make your own path?



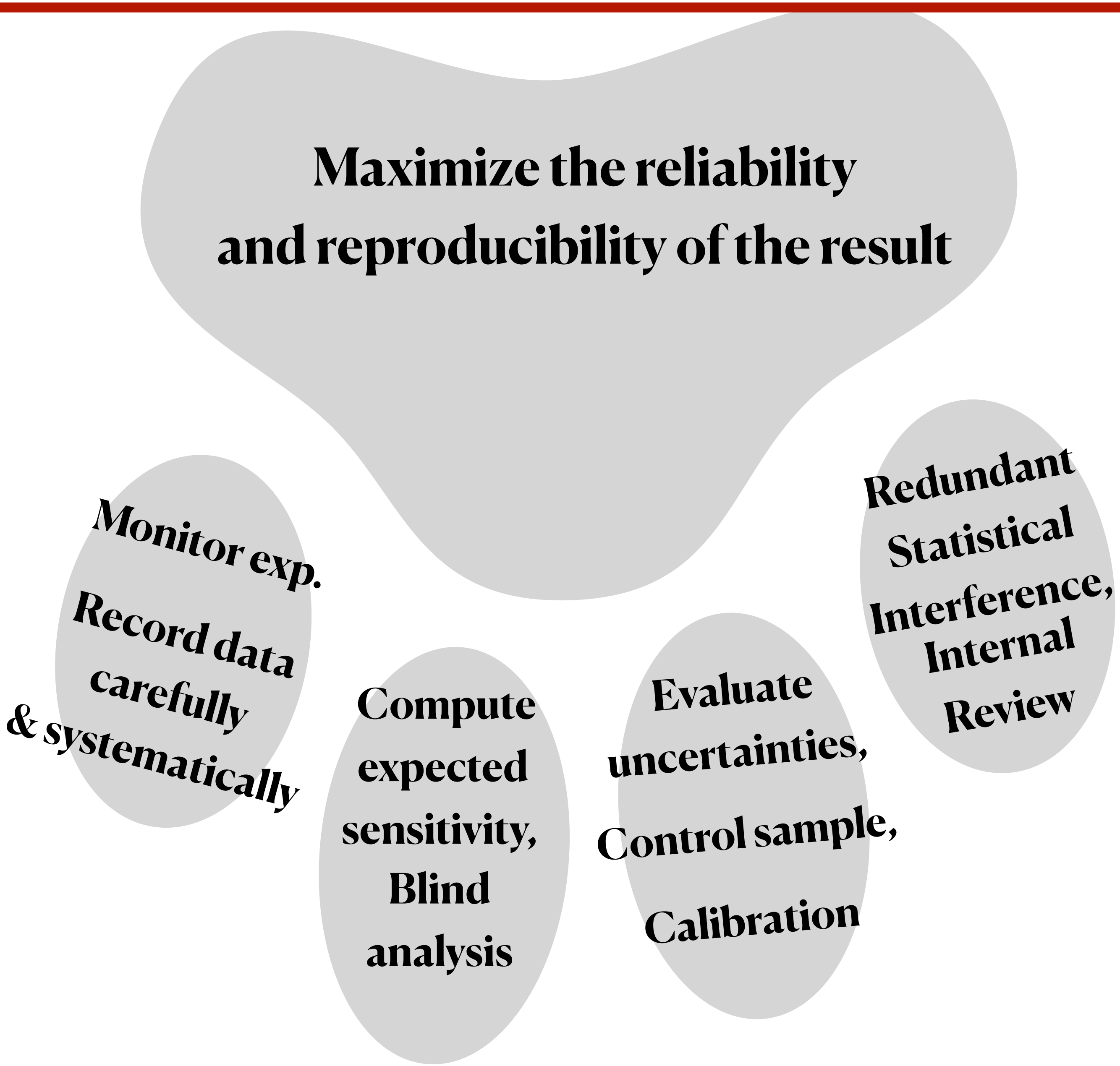
Some experiments are going to build (DUNE, HYPER-K, JUNO, etc)

Some are waiting for your!

- Neutrinos are Majorana or Dirac particles?
- CP symmetry violated in neutrino oscillation?
- Neutrino mass ordering is inverted or normal?
- Is there 4th generation of neutrino?
- Can right-handed neutrino exist? (In low-energy scale)
- Can the 3x3 mixing matrix be non-unitary?
- etc…

More questions from other lecturers

Keep in mind some good practices



Maximize the reliability and reproducibility of the result

Monitor exp.
Record data carefully & systematically

Compute expected sensitivity, Blind analysis

Evaluate uncertainties, Control sample, Calibration

Redundant Statistical Interference, Internal Review

Basics of Neutrino detection

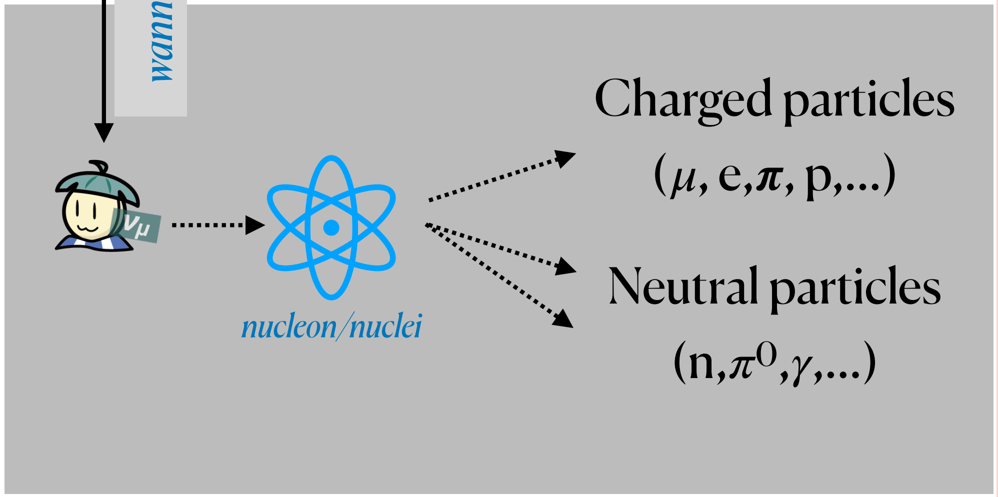
Bird's-eye view only.

Detailed in "particle and radiation detector" and others

Neutrino detection principle

Neutrinos can't be seen directly but can be traced when interacting with nucleon/nuclei with help of photon detectors/sensors

wanna know this



ν_μ

nucleon/nuclei

Charged particles

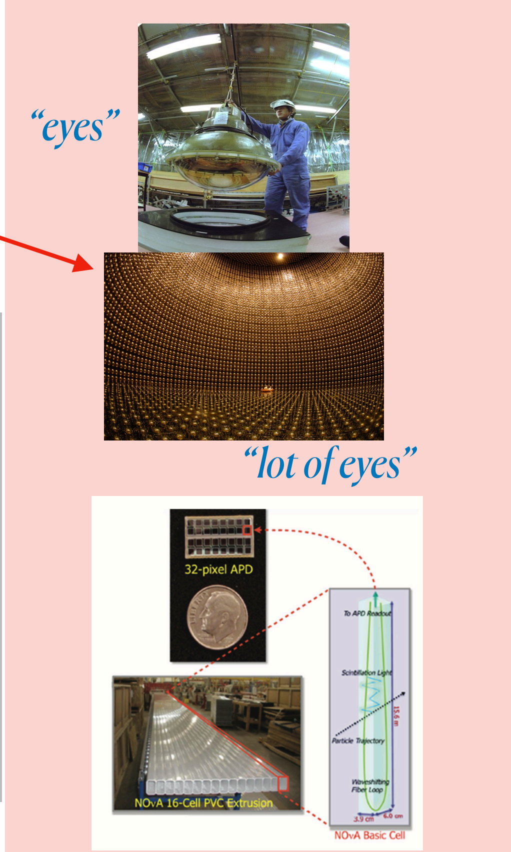
(μ, e,π, p,...)

Neutral particles

(n,π^0,γ,...)

Neutrino interactions

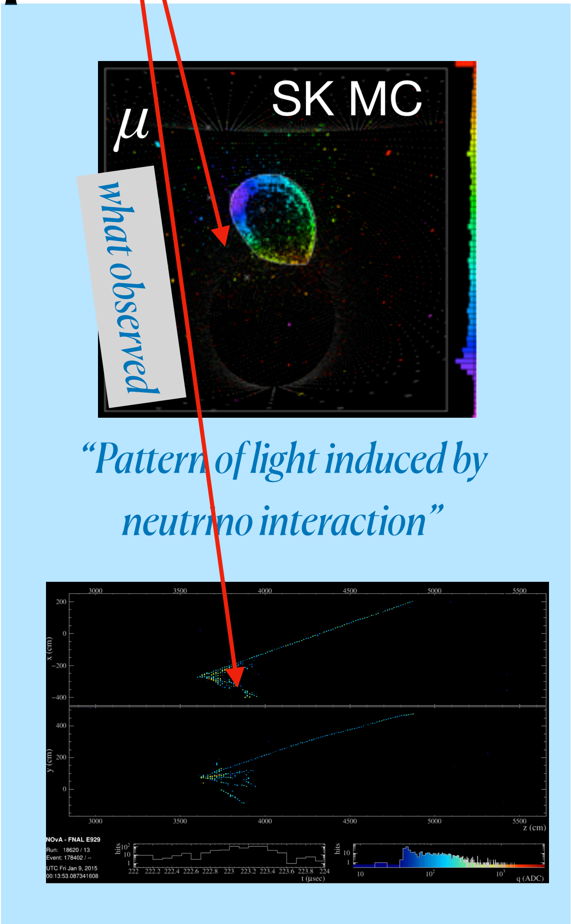
help to observe



"eyes"

"lot of eyes"

Photon detectors



what observed

"Pattern of light induced by neutrino interaction"

Event reconstruction

This is just a single illustration.

Many detection technique out there.

ref: Particle and Radiation detector lecture

What do we expect the detector to reveal?

- Is really neutrino (*interacting with matter in the detector*)?

- What's neutrino type/flavor? (e.g. ν_e, ν_μ, ν_τ)

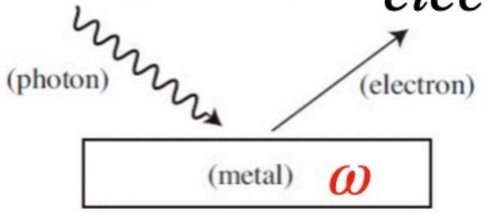
- What's neutrino energy? (*It's important for showing the neutrino oscillation pattern*)

-Where does neutrino come from? (e.g. *the Sun, atmospherics, reactor, accelerator, extragalactic objects…*)

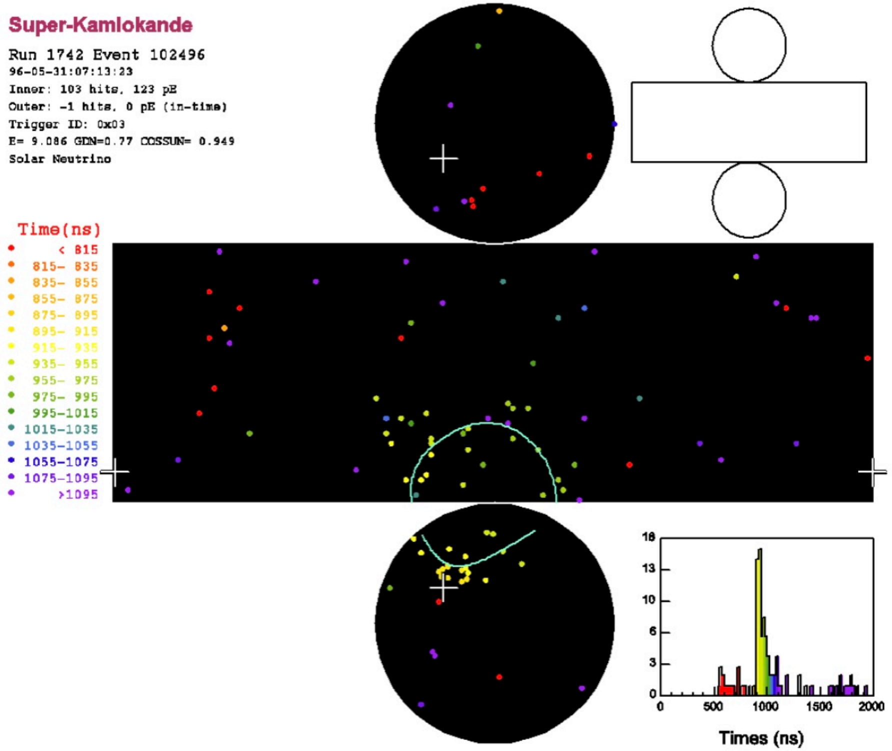
Basics of neutrino detection

- Neutrino **must interact** with matter (*water, scintillator, iron, argon…*) in the detector to be detected
  - Interactions results in **ionization or excitation of matter**; or **emission of the Cherenkov or transition radiation**
- Almost detectors base on the **charge detection**
  - At some points, *free electrons or current of charge* are produced
    - Photons can "*convert*" into photoelectron (p.e.) via the **photoelectric effect**

$$E_{photon} = hf \longrightarrow E_{electron} = hf - \omega$$



Trace of neutrinos: (typically) very faint flash of light

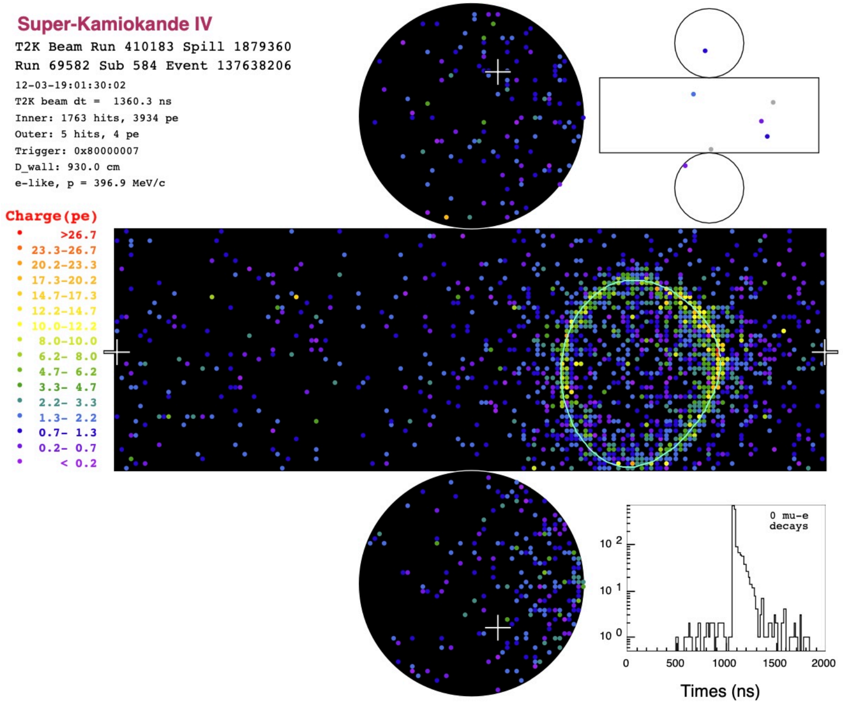


```
Super-Kamlokande
Run 1742 Event 102496
96-05-31:07:13:23
Inner: 103 hits, 123 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 0x03
E= 9.086 GDN=0.77 COSSUN= 0.949
Solar Neutrino
```

A ~ 9MeV solar neutrino candidate

123 p.e. counted in 103 PMT in few 100ns;

~ 1 p.e. per hit PMT



```
Super-Kamiokande IV
T2K Beam Run 410183 Spill 1879360
Run 69582 Sub 584 Event 137638206
12-03-19:01:30:02
T2K beam dt =  1360.3 ns
Inner: 1763 hits, 3934 pe
Outer: 5 hits, 4 pe
Trigger: 0x80000007
D_wall: 930.0 cm
e-like, p = 396.9 MeV/c
```

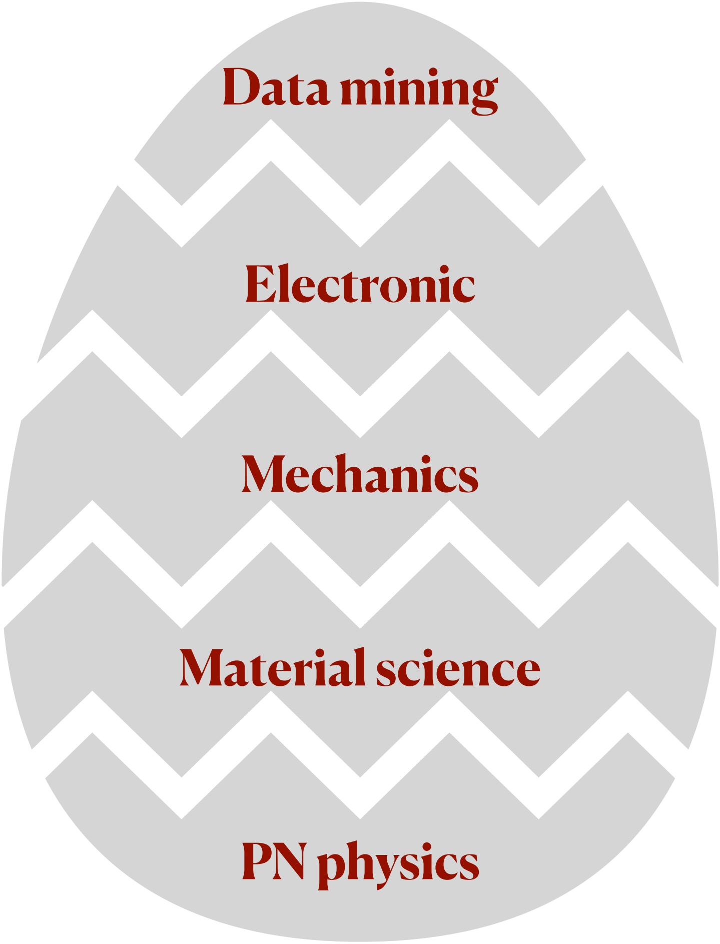
A ~400MeV ν_e candidate from T2K beam

3934 p.e. counted in 1763 hit PMT in few 100ns

~3-4 p.e. per hit PMT

In a blinking of LED

....~10^{15} photons are generated



Data mining

Electronic

Mechanics

Material science

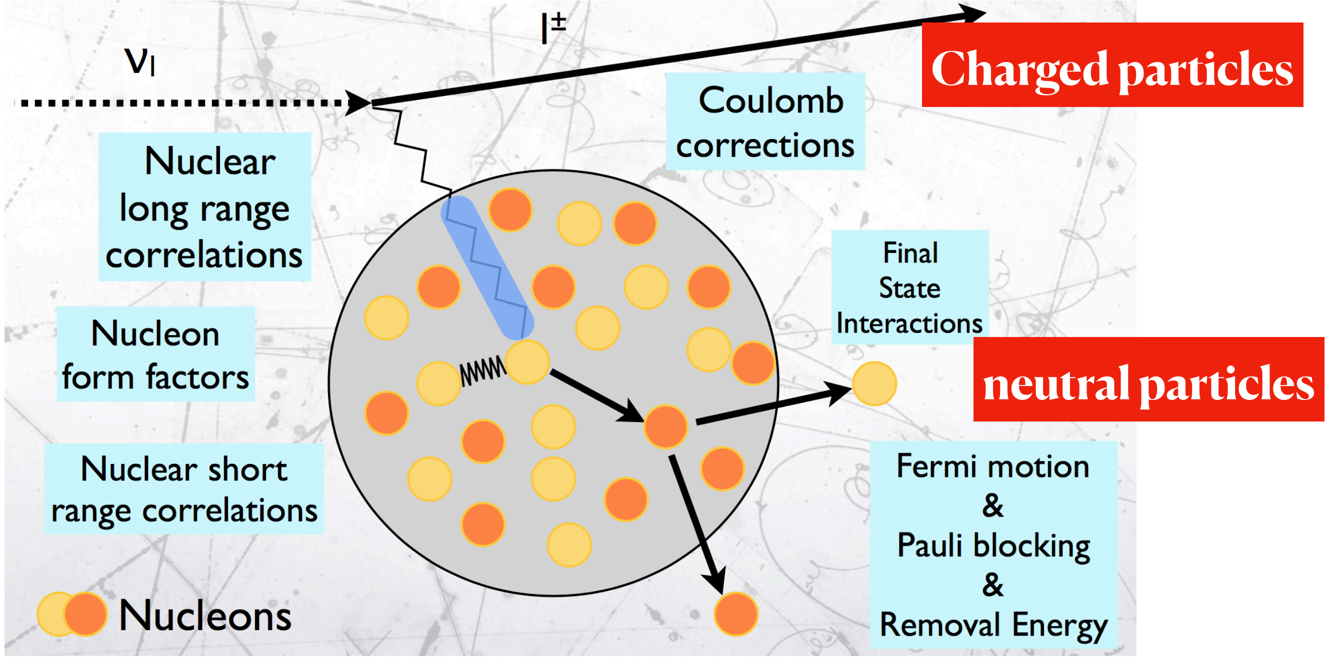
PN physics

Neutrino detection is a complicate, interdisciplinary field

Involved Particle and Nuclear physics

- Neutrino-nucleon/nuclei interaction is complicated
- For oscillation analysis, you need, essentially
  1. Particle identity
  2. Neutrino energy

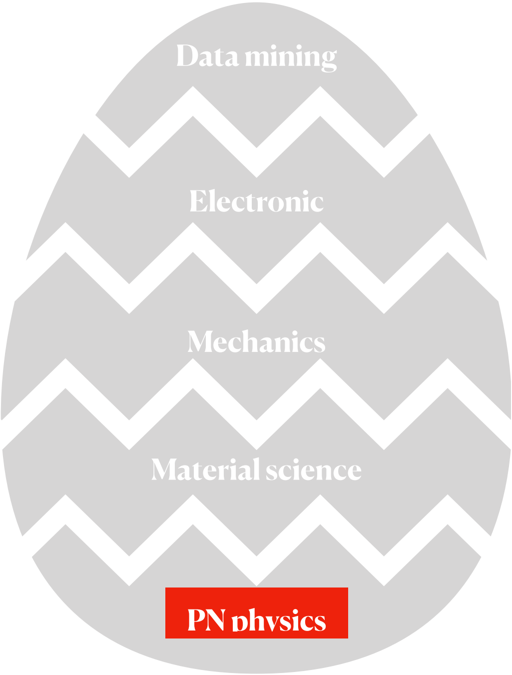
Based on induced charged particle in final state interaction



Charged particles

neutral particles

F. Sanchez, neutrino 2018

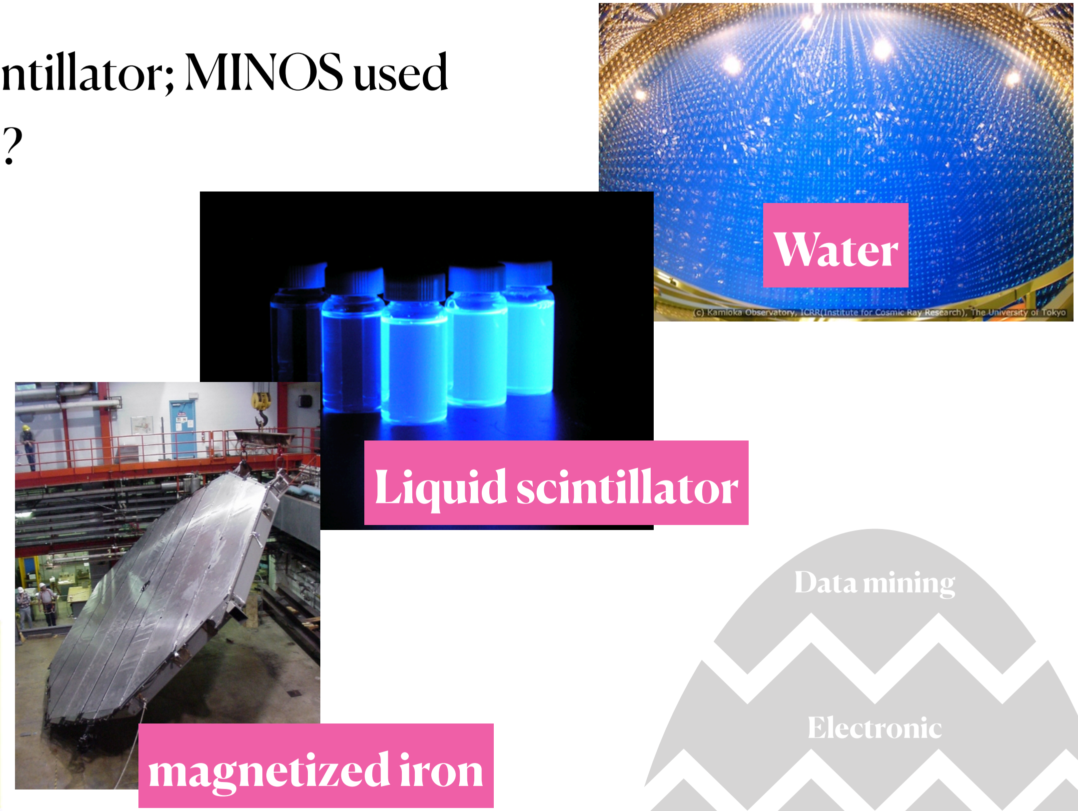


"Neutrino interaction" lecture

Material science in neutrino experiments

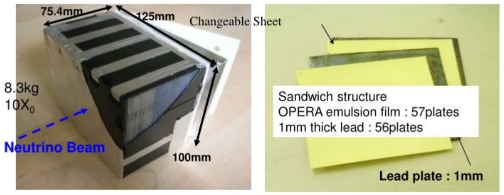
T2K far detector use water; NOvA use liquid scintillator; MINOS used magnetized steel, OPERA used Emulsion, etc…?

- T2K, NOvA needs to identify both ν_μ and ν_e
- MINOS focus on ν_μ and its antineutrino
- OPERA need to see ν_τ



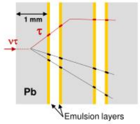
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

The OPERA ECC (Emulsion Cloud Chamber)



Sandwich structure
OPERA emulsion film : 57plates
1mm thick lead : 56plates

Emulsion



Life time(cτ) of τ is ~87μm

Material selection depends on particle you want to detect and its properties. Also detector size & our understanding of neutrino interaction on selected material are important factors.

Data mining

Electronic

Mechanics

Material science

PN physics

Mechanics in neutrino experiments

One example

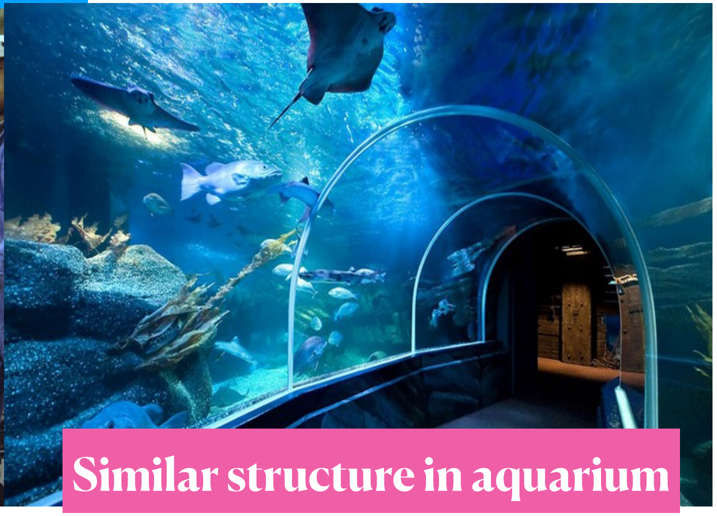
- In Nov 2001, Super-K suffered a serious blow, ~700 PMT tubes exploded (cost $3000 per each) (5000 PMT remain undamaged)

- Cause: one tubes (contain a vacuum) exploded, released energy, caused shock wave → chain reaction of explosion

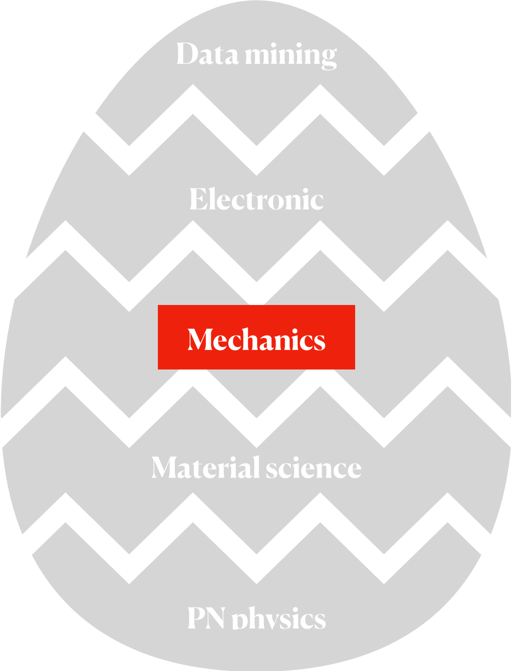
- To mitigate this possibility: Acrylic shield is developed and used

Bare PMT

PMT w/ acrylic shield



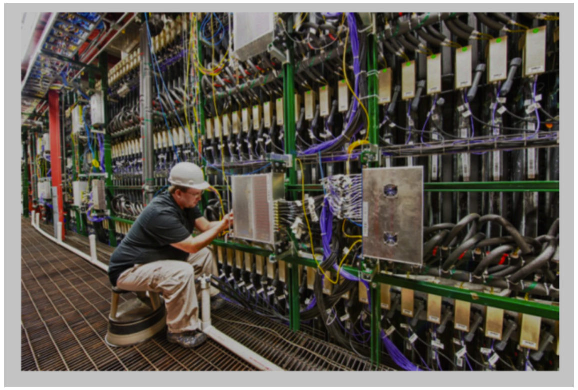
Similar structure in aquarium



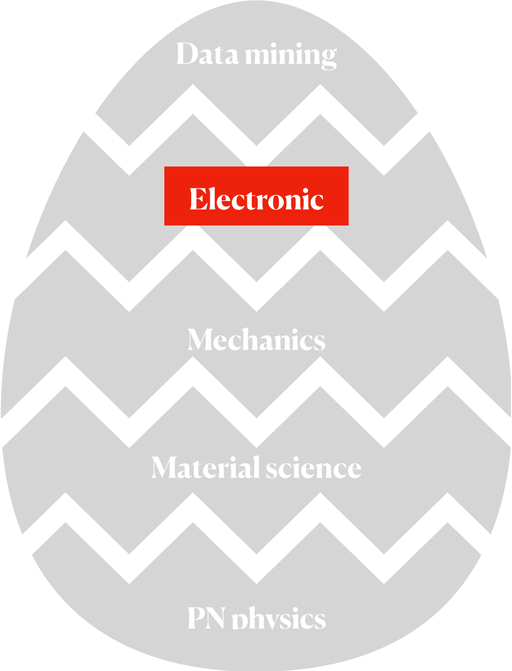
Electronics in neutrino experiments

- Number of photon sensor/ “eyes” per each detector is often very large: 13,000 channels in Super-K, 334,000 channels in NOvA far detector, ~60,000 in Super-FGD (T2K)
- With many “eyes”, a “nervous” system (*or Internet of things*) is needed to collect and manipulate data efficiently
  - “Eyes” don’t not always open; no need and not good for lifetime of electronics
  - “Eyes” actually operate when receiving “trigger” signal, and often within a predefined time window

Depend on how often your detector get data; how many events interact in your detector in a time window, etc…



Ex: NOvA electronics at Near Detector



Data mining

Electronic

Mechanics

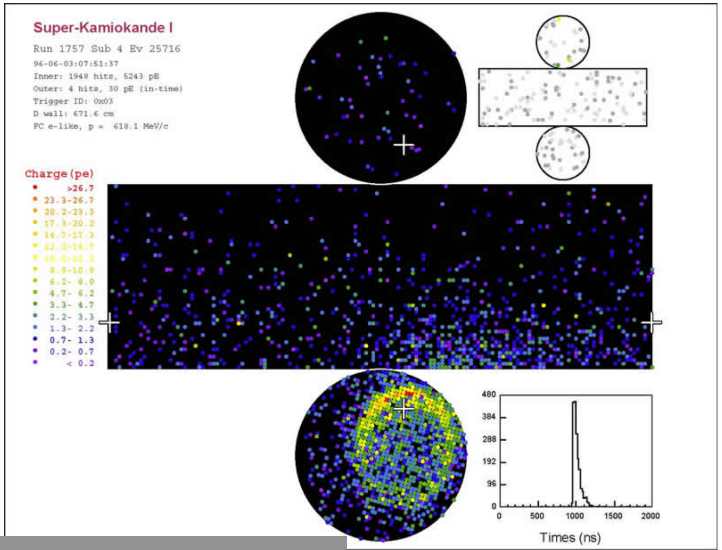
Material science

PN physics

Data mining in neutrino experiments

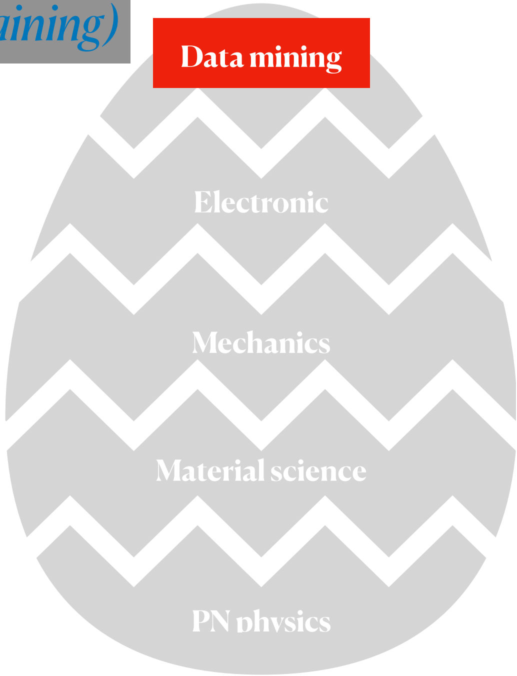
How do you know this is **likely** due to ν_e interaction?

- Basically, you need guidance from theory/simulation
- The method is something like this:
  1. Create a **detector simulation** to see what happens when particles enter your detector.
  2. Simulate various types of neutrino interactions (true info. *such as neutrino type, energy, direction, interaction point in detector,* is known)
  3. Obtain **pattern** for simulated neutrino events and store as an event library
  4. Compare your data pattern to library to determine how **likely** data match with types of simulated events



```
Run 1757 Sub 4 Ev 25716
96-06-03:07:51:37
Inner: 1948 hits, 5243 pE
Outer: 4 hits, 30 pE (in-time)
Trigger ID: 0x03
D wall: 671.6 cm
PC e-like, p =  618.1 MeV/c
```

(SK Software training)



Neutrino detection is complicate

Data mining

Electronic

Mechanics

Material science

PN physics

Neutrino detection is a complicate, interdisciplinary field.

You don’t need to know all of these. Expert in one field is probably enough.

Before going to some selected topics, let's have a quick digest on Histogram, *a conventional way to visualize data in HEP*

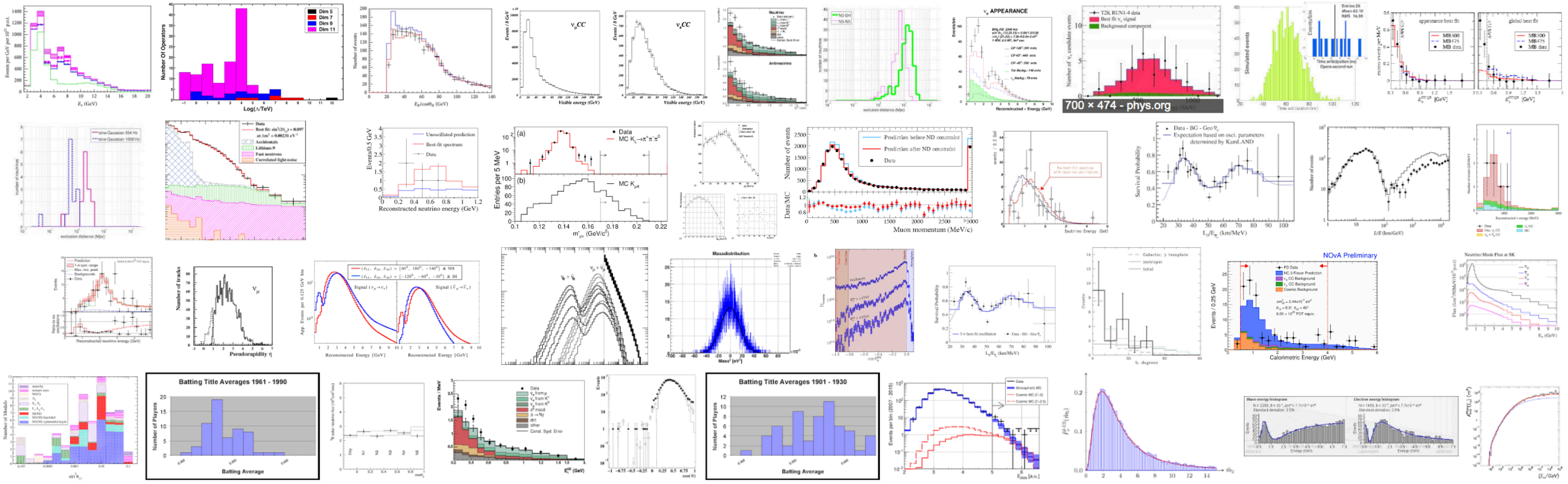
- Taking about experiment is to talk about data.
- To make number less boring, a "sexy" way to visualize it was invented, so-call Histogram

Histogram

https://en.wikipedia.org/wiki/Histogram

A **histogram** is an accurate representation of the distribution of numerical data. It is an estimate of the probability distribution of a continuous variable (quantitative variable) and was first introduced by Karl Pearson.

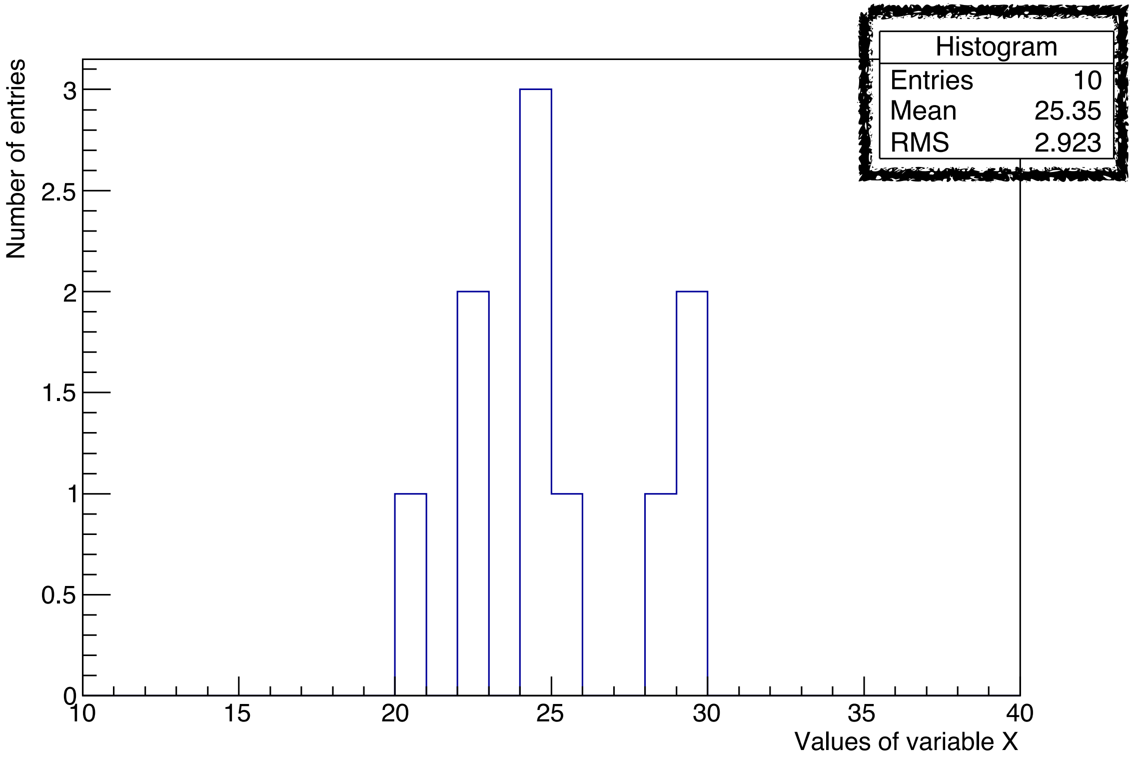
Go google image and type: histogram neutrino



Histogram

#entry	#value
0	29.9947
1	22.8262
2	28.909
3	24.8497
4	29.1213
5	24.7164
6	20.4956
7	24.6265
8	25.0396
9	22.9462

https://github.com/cvson/nushortcourse/tree/master/basic01



Histogram

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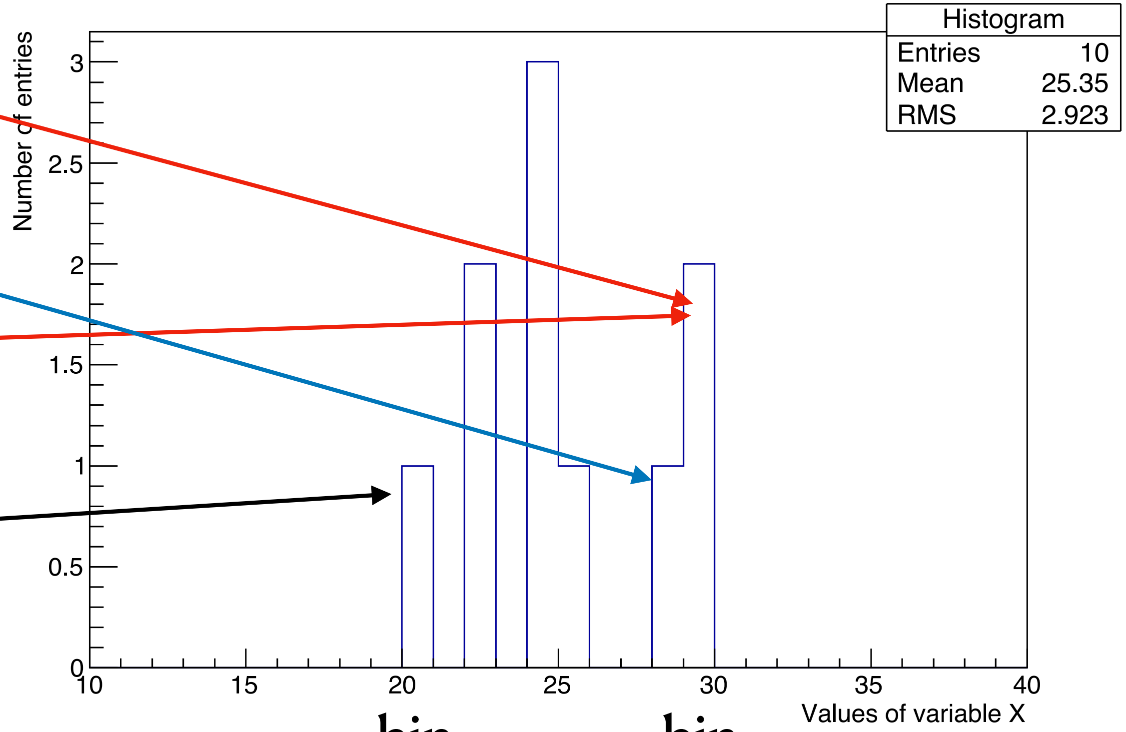


bin [20,21)

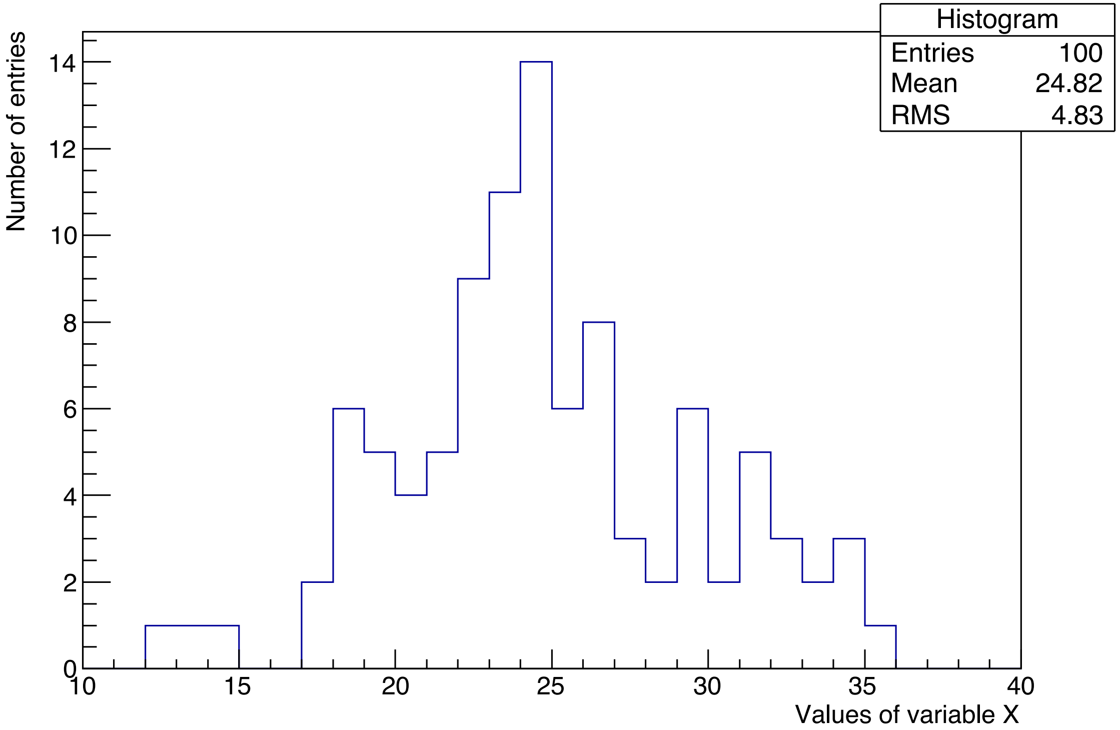
bin [29,30)

Histogram

100 entries in your sample

https://github.com/cvson/nushortcourse/tree/master/basic01

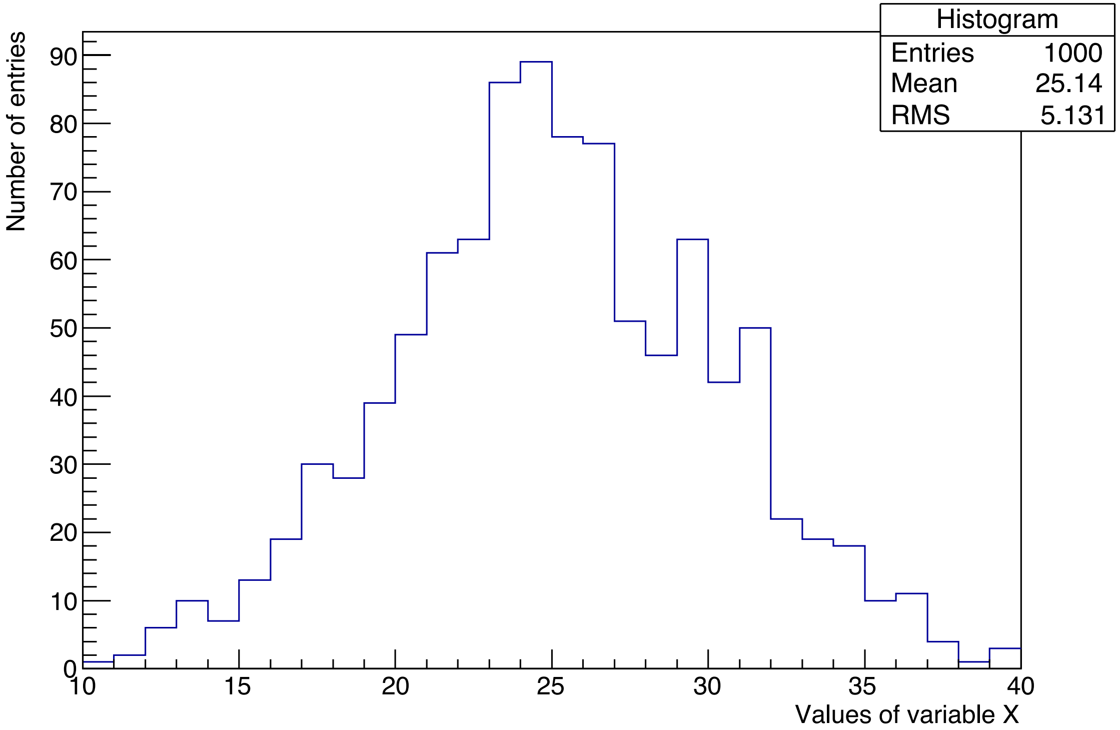
Can you guess data following which distribution?



Histogram

1000 entries in your sample (as data sample increased)

https://github.com/cvson/nushortcourse/tree/master/basic01



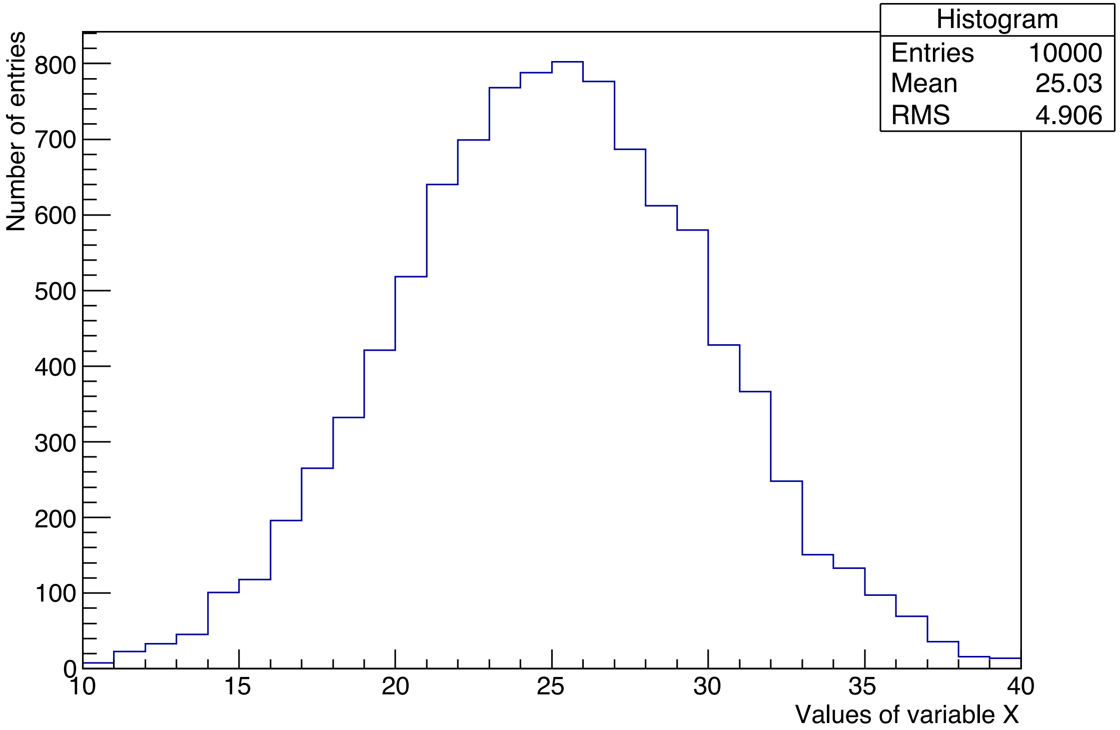
Can you guess data following which distribution?

Histogram

10000 entries in your sample (as data sample increased)

https://github.com/cvson/nushortcourse/tree/master/basic01

Can you guess data following which distribution?

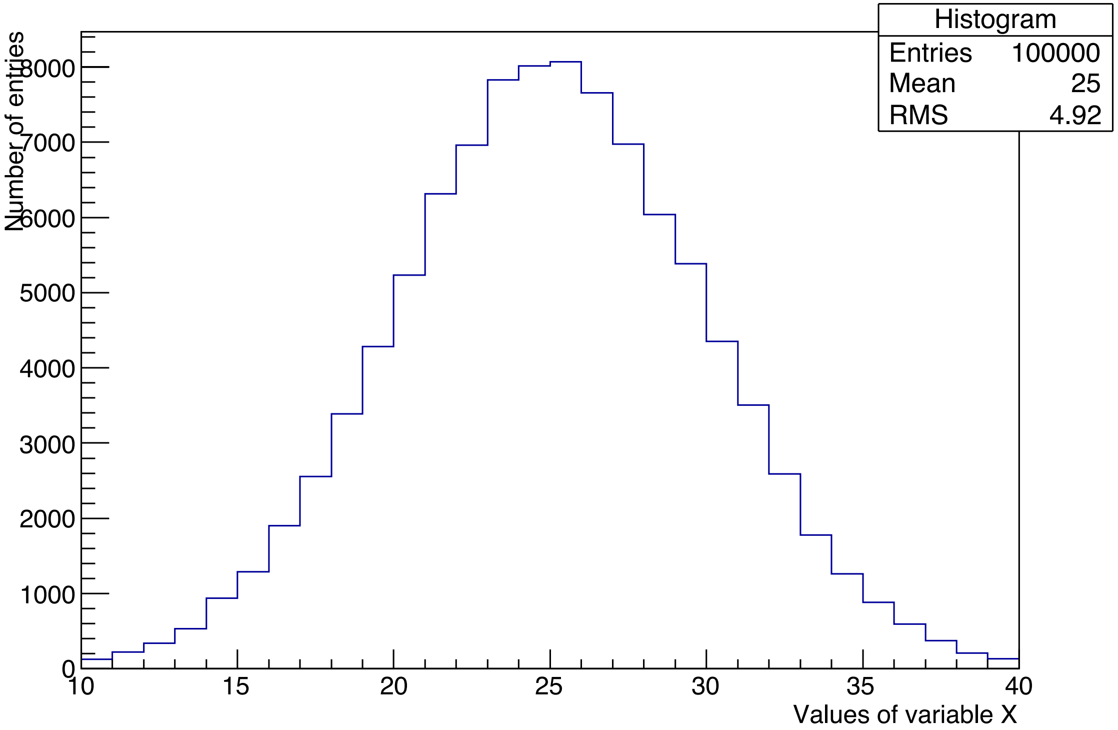


Histogram

100,000 entries in your sample

(as data sample increased)

https://github.com/cvson/nushortcourse/tree/master/basic01

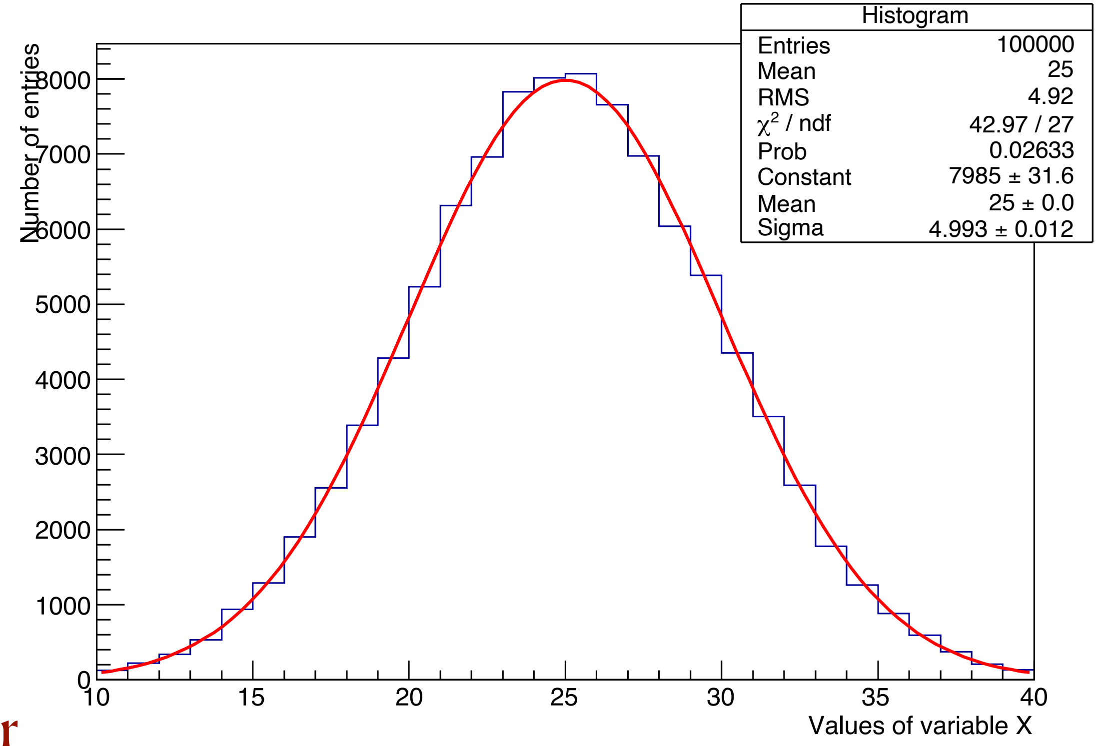


Can you guess data following which distribution?

Histogram

100,000 entries in your sample (as data sample increased)

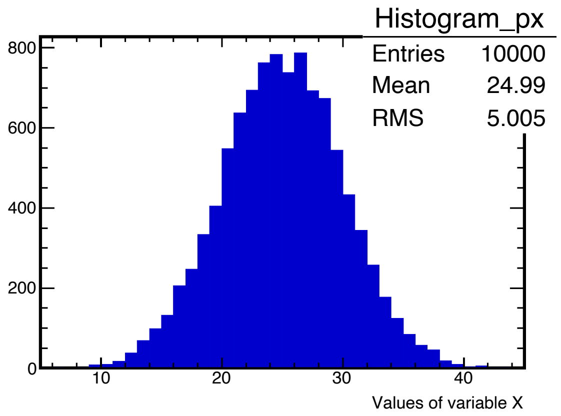
https://github.com/cvson/nushortcourse/tree/master/basic01



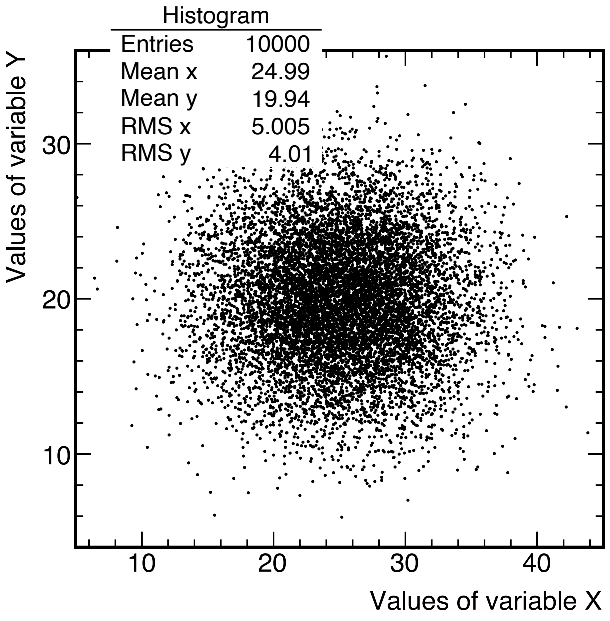
Indeed, it generated with Gaussian distribution with Mean = 25 and RMS =5

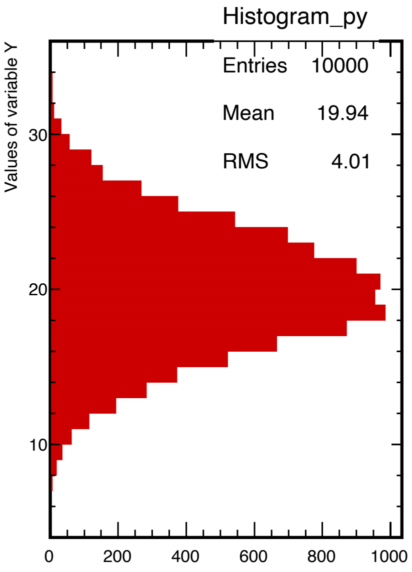
Your data might be underlying a particular distribution/pattern but it might not be easy to reveal if your data sample is not statistic enough.

Two-dimensional histogram



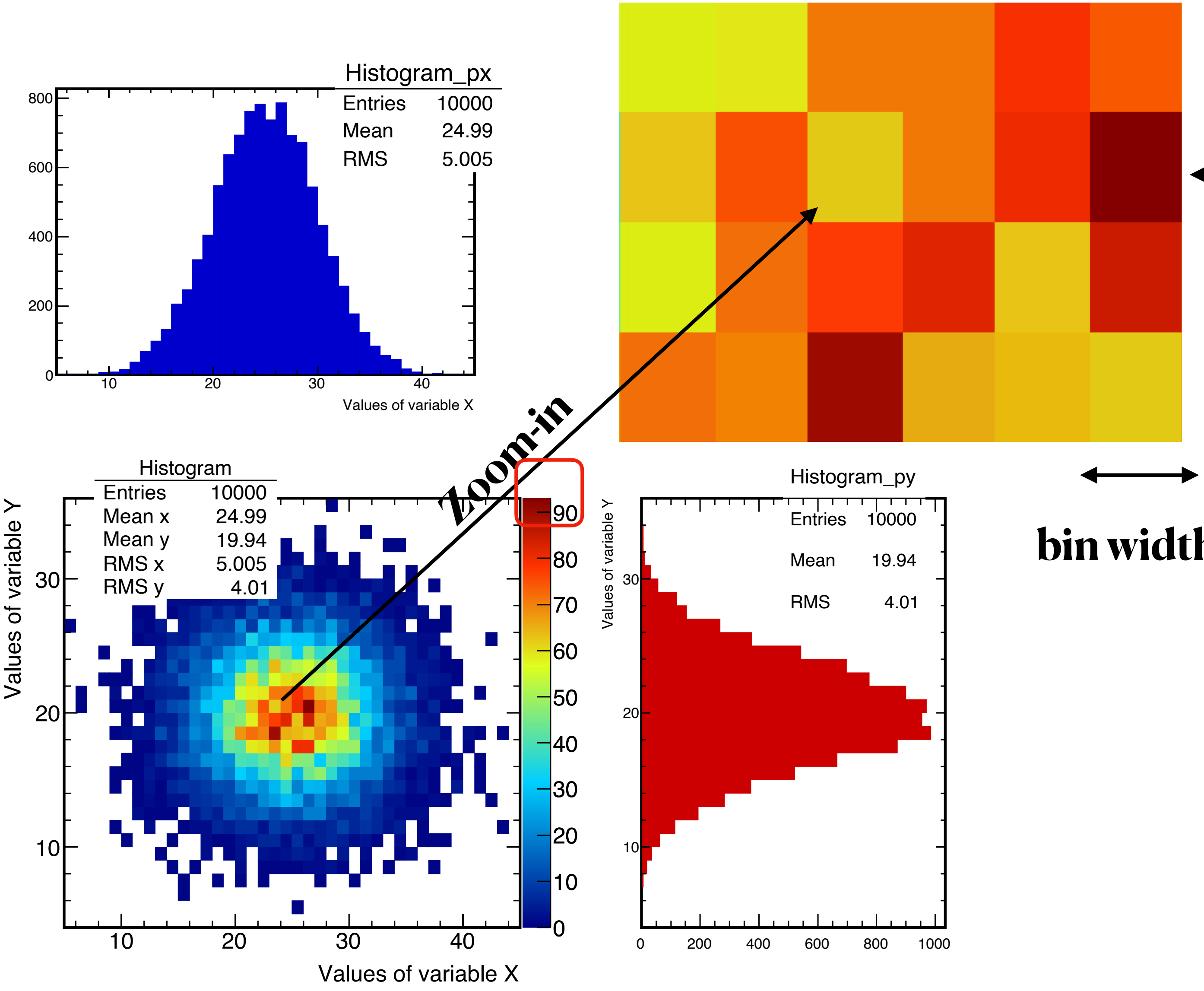
The histogram can be shown in more than one-dimension





https://github.com/cvson/nushortcourse/tree/master/basic01

Two-dimensional histogram



bin, ~90 entries

bin width in Y-view

bin width in X-view

https://github.com/cvson/nushortcourse/tree/master/basic01

Bin width may vary and is not fixed

Some selected topics

1) Signal and background
2) Hypothesis test
3) Sensitivity & Parameter estimation
4) Systematics
5) Monte Carlo usage 101

Signal and Background

Signal: For what you consider as object to study, e.g. ν_e **from** ν_μ **beam**

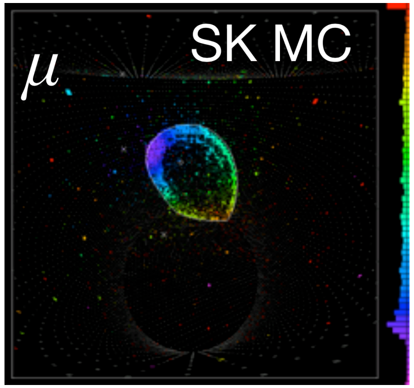
Background: Anything else

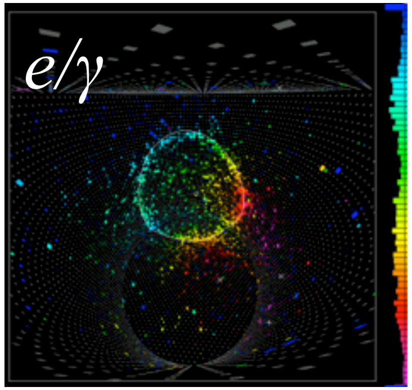
Measurement is performed on a **selected** sample which contains both **signal** and **background**. *Background is always present since your sample selection is not perfect.*

- **It's important to define clearly what's signal**. Sometime it's not straightforward, e.g.
    - **For oscillation analysis**, ν_e from ν_μ beam observed at far-site detector is signal but **intrinsic** ν_e **is background**
    - **For understanding neutrino source composition**, ν_e cross-section is measured at near-site detector, **intrinsic** ν_e **is signal**
- In selected data sample, **ratio of signal-to-background does matter**, not only absolute number of signal.

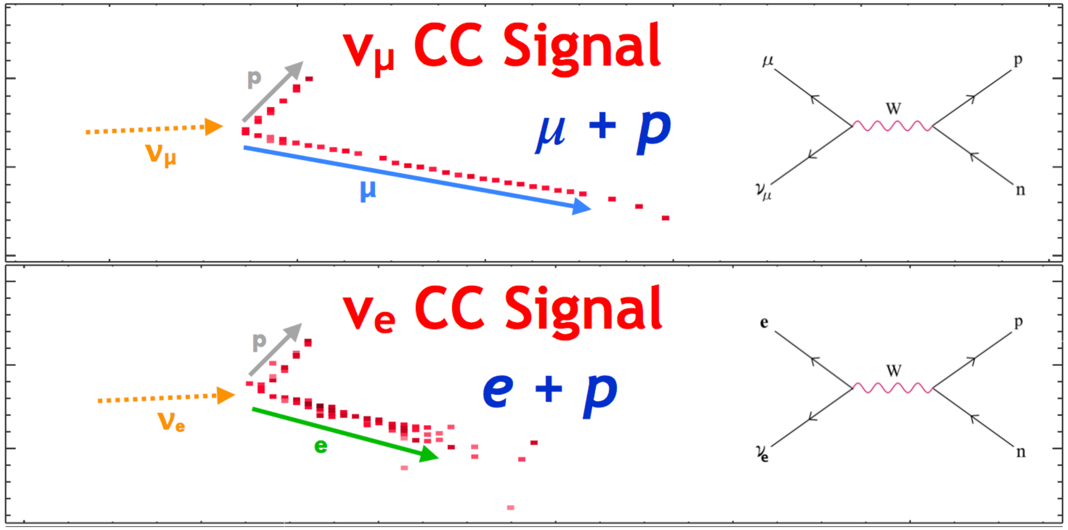
Signal vs. Background: Classification problem

Super-Kamiokande,
Water-cherenkov technique





NOvA, scintillator technique



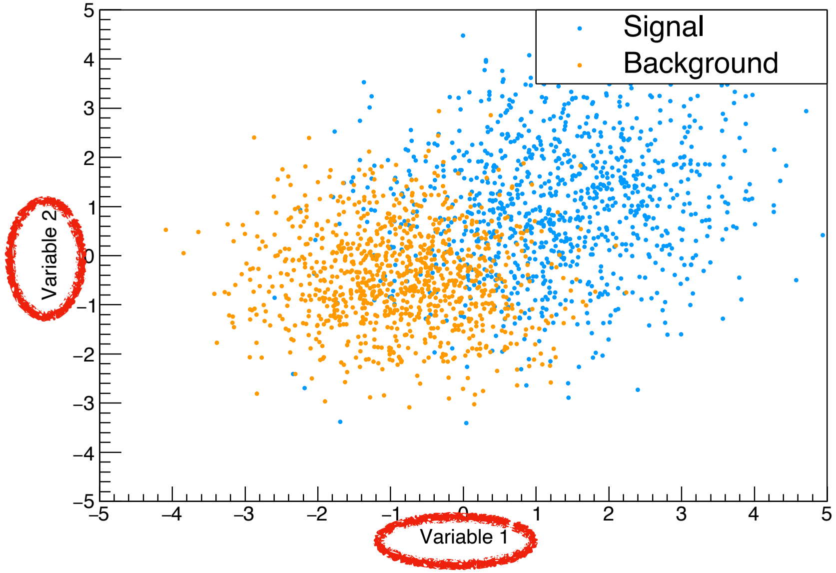
Electron with EM activity, look more fuzzy than muon.

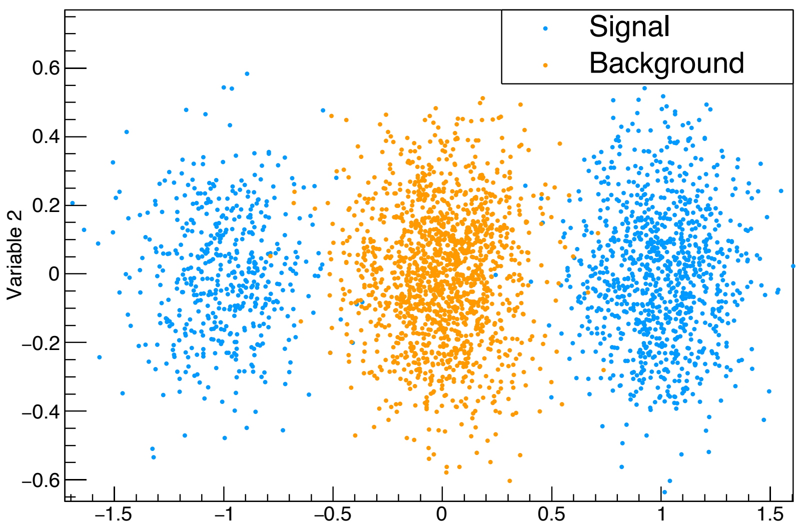
This guides your eyes but we need quantitative things

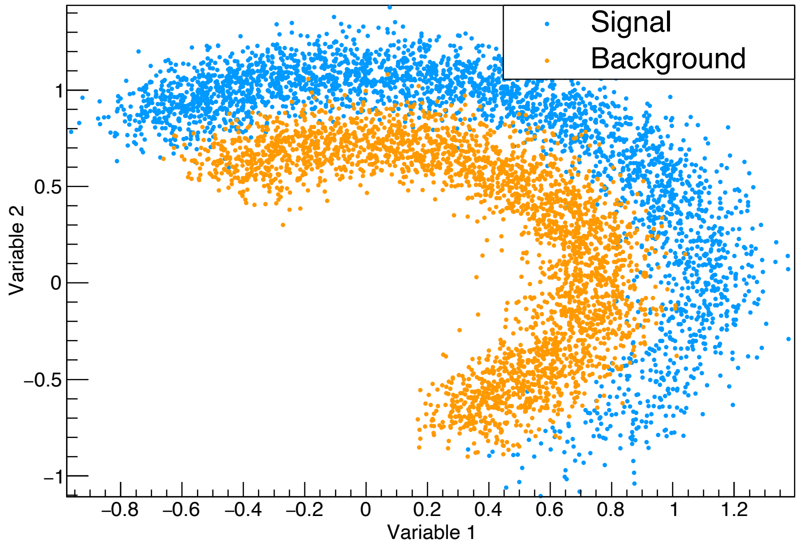
You need **machinery/tool to separate signal from background.** The "fuzzy" thing is quantized into one or multiple variables which is used to build *likelihood* of data to be signal or to be background. (*Some (deep) machine learning can skip the middle steps.*)

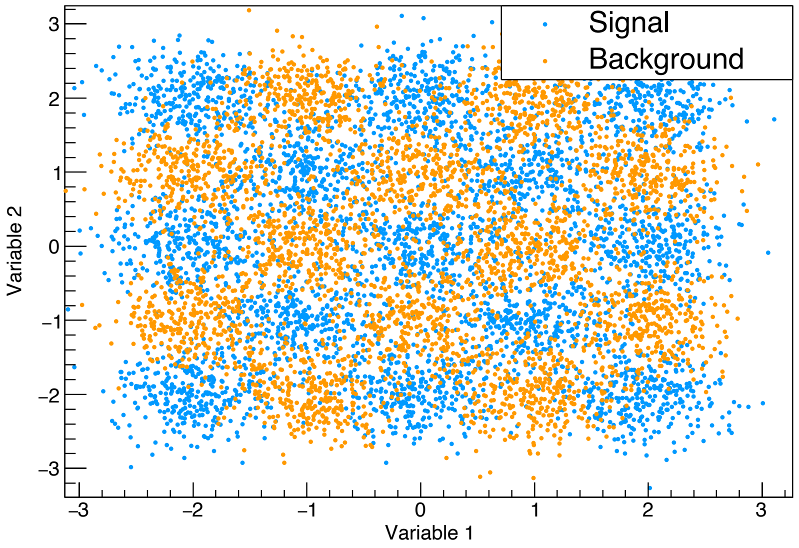
Signal vs. Background: Example of data classification

https://github.com/cvson/nushortcourse/tree/master/datamining



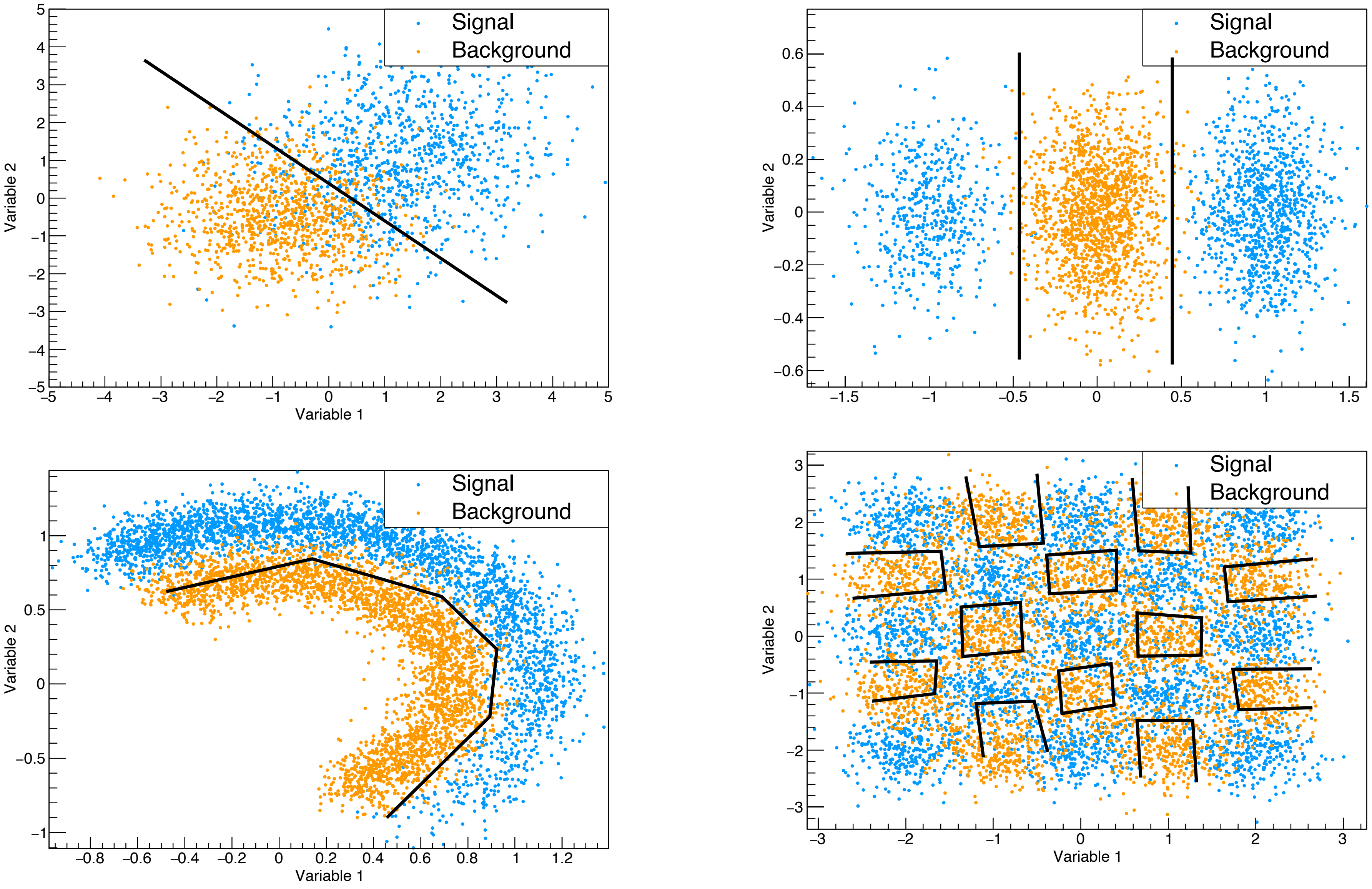






Signal vs. Background: by eyes

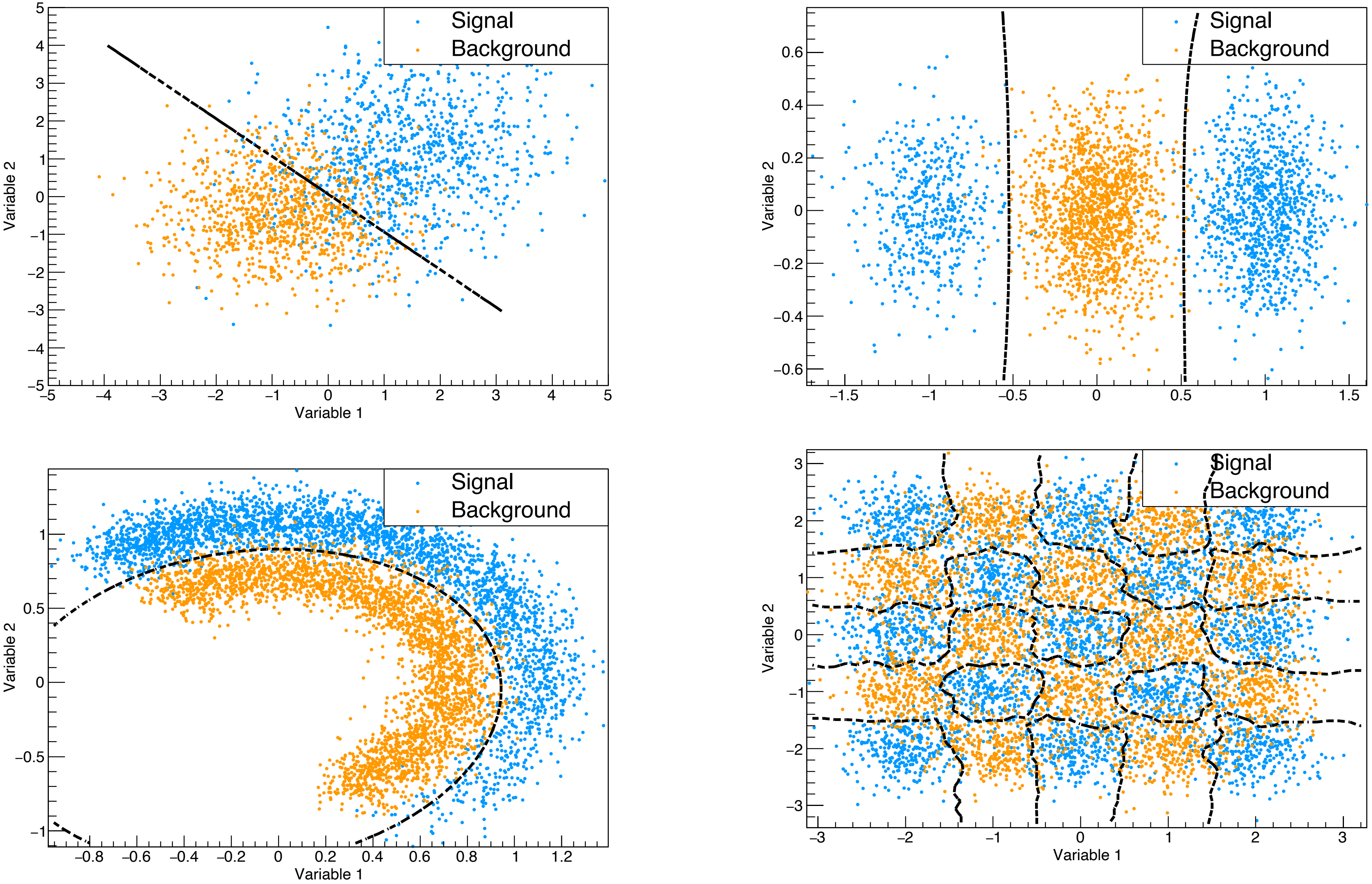
https://github.com/cvson/nushortcourse/tree/master/datamining



Decision rule/boundary

Signal vs. Background: by machine learning

https://github.com/cvson/nushortcourse/tree/master/datamining

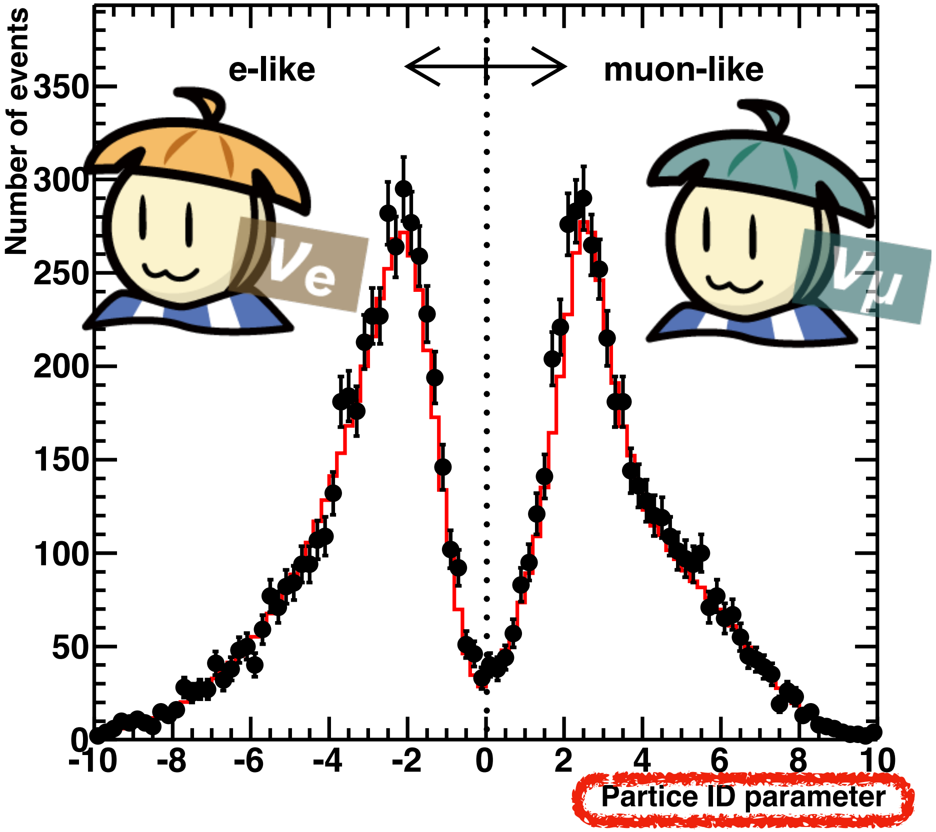


Decision rule/boundary

Signal vs. Background: ID parameter

- To make selection (or decision rule/boundary), typically a **likelihood** of data to be signal/background is built. *Sometimes called particle identification* (ID)
- **Background is unavoidable**
- **Enhance signal and suppress background** is important in HEP analysis, especially in neutrino experiment where statistics is limited.
    - can be from hardware side or software side
- **It's (big) money** can be saved when you can improve your selection since it is effectively equivalent to collecting more data or enlarge your detector

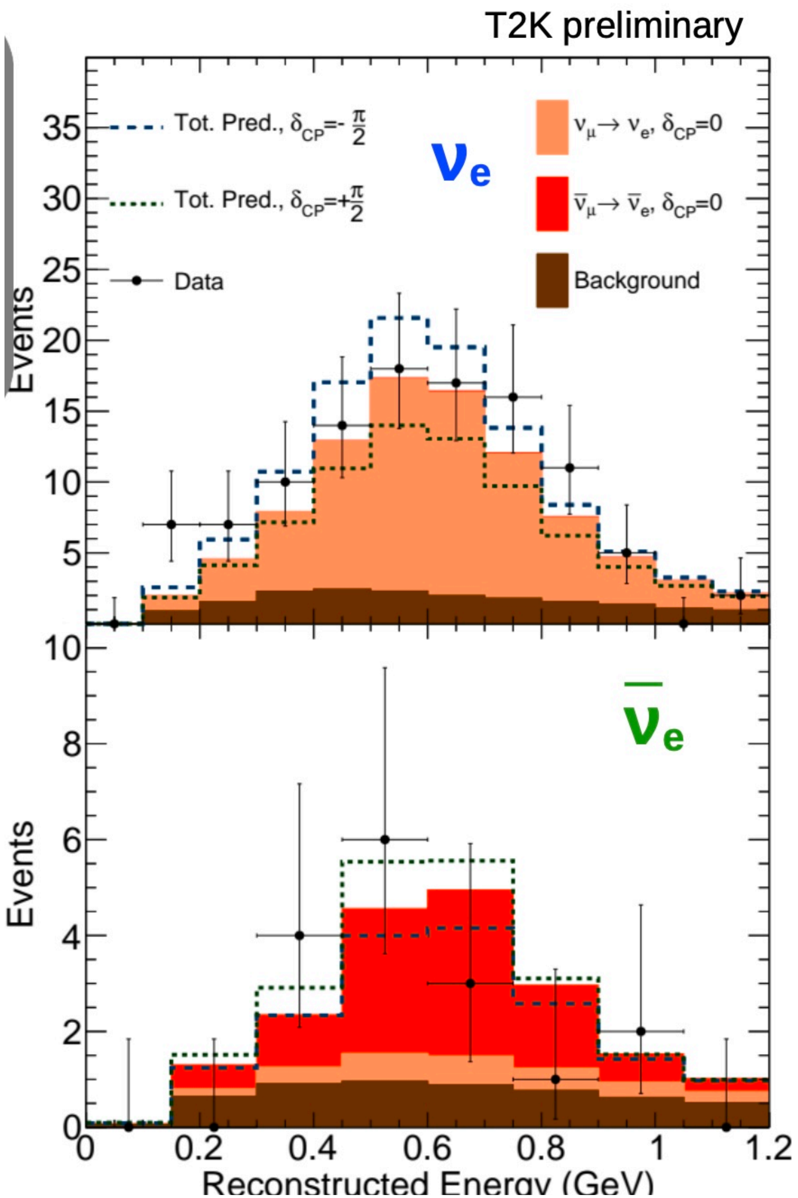
Ex: atmospheric neutrinos observed in Super-Kamiokande



Red curve is what machine learned

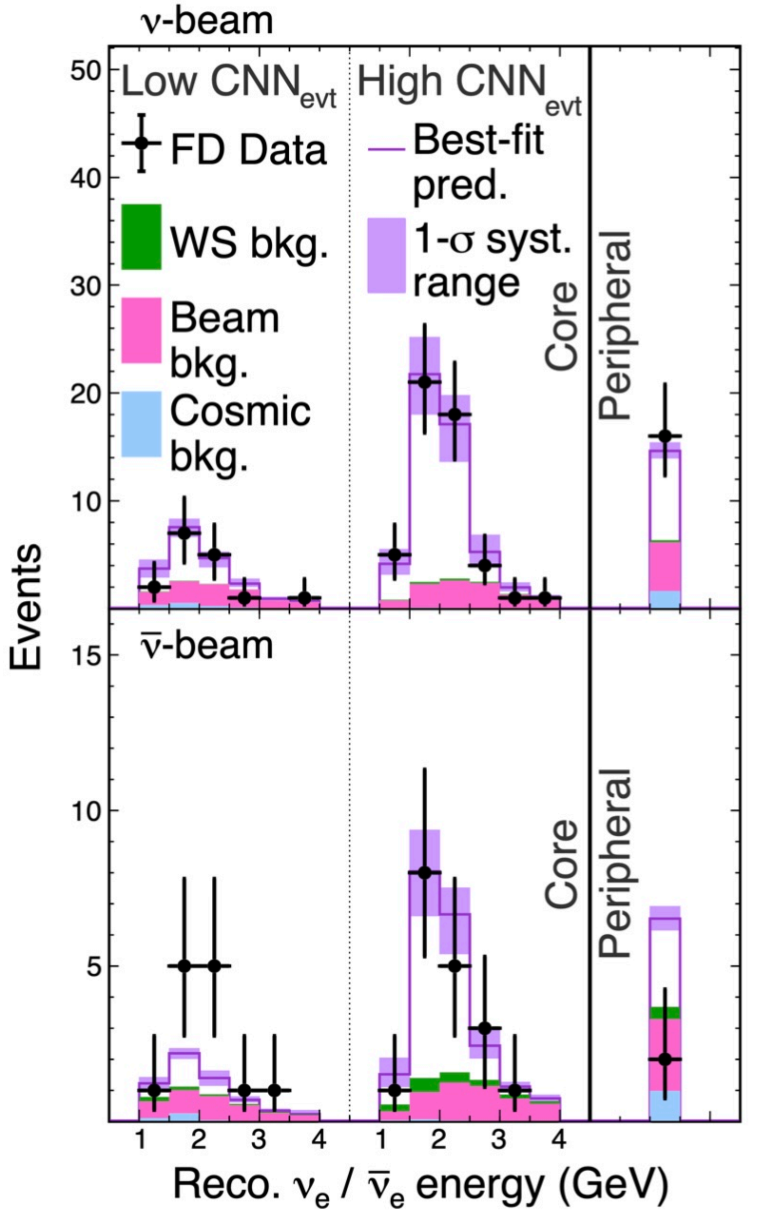
Black dots are your data

Signal and Background: Example from real data



T2K, Neutrino 2022

2020 data set: https://arxiv.org/abs/2108.08219



NOvA, Neutrino 2022

Some selected topics

1) Signal and background
2) Hypothesis testing
3) Sensitivity & Parameter estimation
4) Systematics
5) Monte Carlo usage

Hypothesis testing

Attempt to see if data being consistent with a theoretical model

- **H_0: Null hypothesis** — typically what we want to "reject" (e.g. *Standard Model*)
- **H_1: Alternative/Test hypothesis** — what we want to examine (e.g. *New Physics*)

E.g.:

H_0: CP is conserved in the leptonic mixing; H_1: CP is violated in the leptonic mixing

Or

H_0: Neutrino mass ordering is normal; H_1: Neutrino mass ordering is inverted

Four possible outcomes

Data are consistent with H_0 but not H_1
New physics (model) is disfavored

Data are consistent with H_1 but not H_0,
Evidence/observation of the new physics (model)

Data are consistent with both H_0 and H_1,
data is not sensitive enough to tell difference

Data are consistent with neither H_0 or H_1,
other physics (model) is required

Hypothesis testing (cont'd)

Hypothesis H_0: $\theta_{13} = 0$

Hypothesis H_1: $\theta_{13} \neq 0$

In testing a hypothesis H_0, there are two kinds of errors:

- **Type-I error**: erroneously reject H_0 although H_0 is true
  - i.e. "falsely discover" $\theta_{13} \neq 0$ although the true is $\theta_{13} = 0$
- **Type-II error**: erroneously accept H_0 (*or reject H_1*) although H_0 is false (*or H_1 is true*)
  - i.e. "fail to observe" $\theta_{13} \neq 0$ although the true is $\theta_{13} \neq 0$

H_0: you are not pregnant


Type I Error


Type II Error

Hypothesis testing (cont'd)

Hypothesis H_0: $\theta_{13} = 0$

Hypothesis H_1: $\theta_{13} \neq 0$

In testing a hypothesis H_0, there are two kinds of errors:

- **Type-I error**: erroneously reject H_0 although H_0 is true
  - i.e. "falsely discover" $\theta_{13} \neq 0$ although the true is $\theta_{13} = 0$

Prob. is α

- **Type-II error**: erroneously accept H_0 (*or reject H_1*) although H_0 is false (*or H_1 is true*)
  - i.e. "fail to observe" $\theta_{13} \neq 0$ although the true is $\theta_{13} \neq 0$

Prob. is β

When you make statement, it should include two errors (α, β).

- **(1-α) (%) is normally mentioned as Confidence Level (C.L.), set at beginning of the test as toleration level, e.g 0.05 or 95% C.L.**
- **(1-β) (%) is probability that you make "observation" at (1-α) (%) C.L. We care this error especially when e.g. *due to statistic fluctuation*, you are very lucky to make observation or very unlucky to make no observation**

The less error you have, the higher confidence level you are

“…Hypotheses can be ruled out, never be proved to be true.”

–Karl Popper

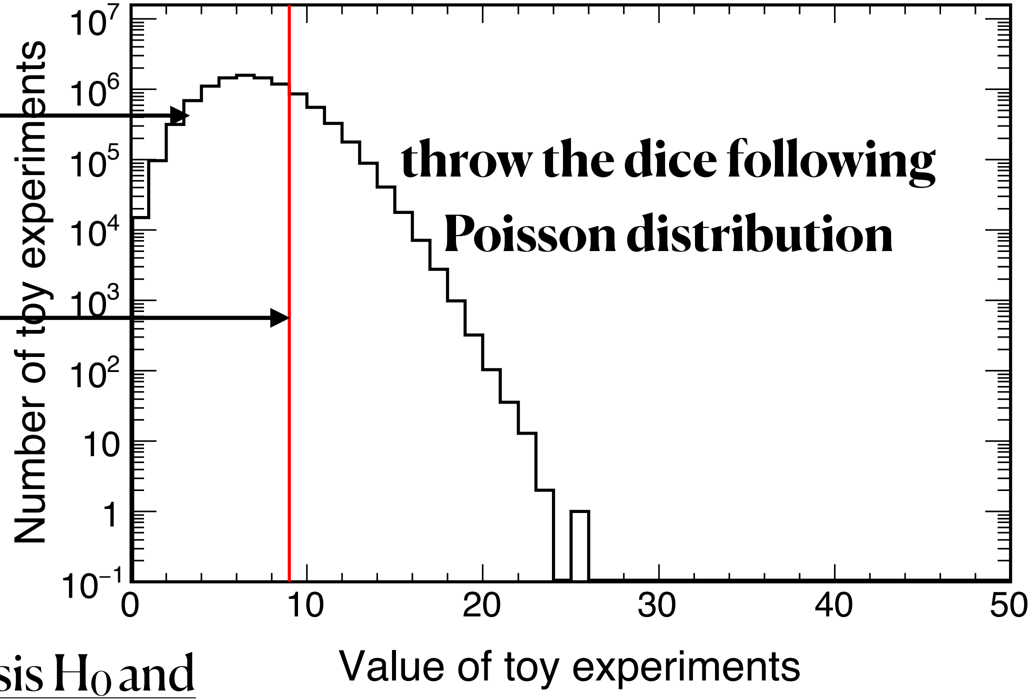
Hypothesis testing: Example w/ T2K exp.

Hypothesis H_0: data agree with background (no $\overline{\nu}_e$ signal)

T2K: “appearance” of $\overline{\nu}_e$

- Background: 6.5 events
- Data: 9 events

https://github.com/cvson/nushortcourse/tree/master/basic01



throw the dice following Poisson distribution

$$\text{p-value} = \frac{\text{No. of toy exp., value > 9}}{\text{All of toy exp.}} = 0.208$$

p-value> 0.05: data **failed to reject** hypothesis H_0 and the result is **statistically nonsignificant**.

if you are familiar with ROOT, can try
p-value = 1-ROOT::Math::poisson_cdf(8,6.5);

Read p-value, eg.
https://en.wikipedia.org/wiki/P-value

Hypothesis testing: Example from NOvA

Hypothesis H$_0$: data agree with background (no $\overline{\nu}_e$ signal)

NOvA: appearance of $\overline{\nu}_e$

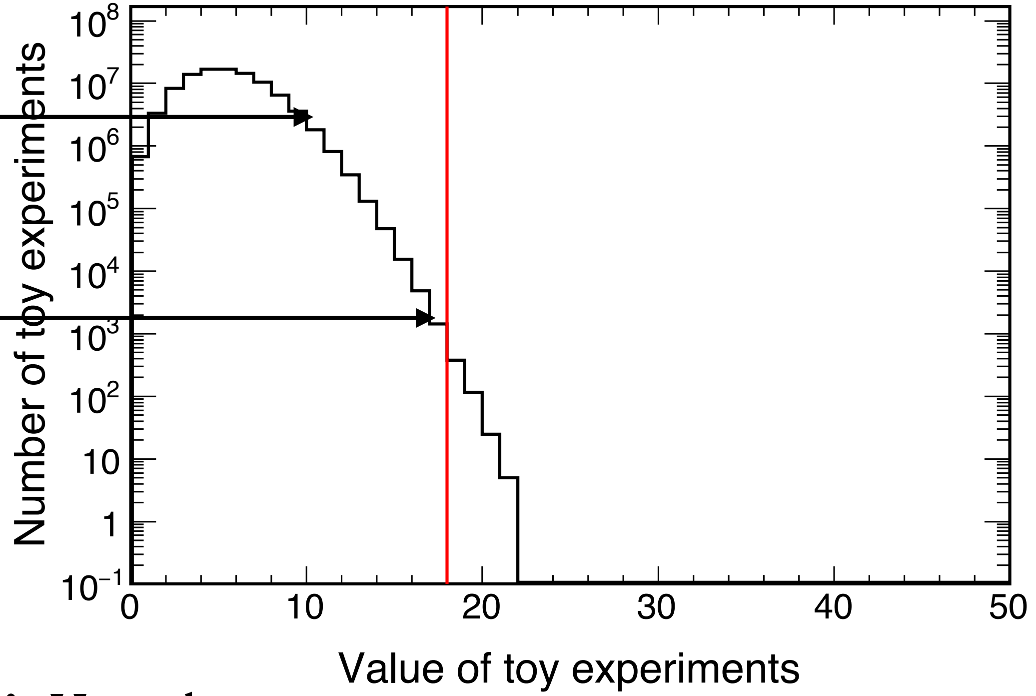
- Background: 5.3 events

- Data: 18 events

$$\text{p-value} = \frac{\text{No. of toy exp., events > 18}}{\text{All of toy exp.}}$$

$$= 5.27e-6$$

https://github.com/cvson/nushortcourse/tree/master/basic01



p-value< **0.05:** data **reject hypothesis H$_0$** and the result is **statistically significant**, (*but not observation yet!*)

```
p-value = 1-ROOT::Math::poisson_cdf(17,5.3);        5.41634e-06
sigma = TMath::NormQuantile(1 - p-value);          4.39985
```

< 5σ (level of discovery)

Some selected topics

1) Signal and background
2) Hypothesis test
3) Sensitivity & Parameter estimation
4) Systematics
5) Monte Carlo usage

Sensitivity

You might hear, e.g.

without mentioning to data

- **T2K has good "sensitivity" on CP violation**
- **NOvA has good "sensitivity" on both CP violation and mass hierarchy**

"Good" sensitivity means you can reject some hypothesis, i.e make observation of something, with high confidence level (1-α)(%) with high probability (1-β)(%)

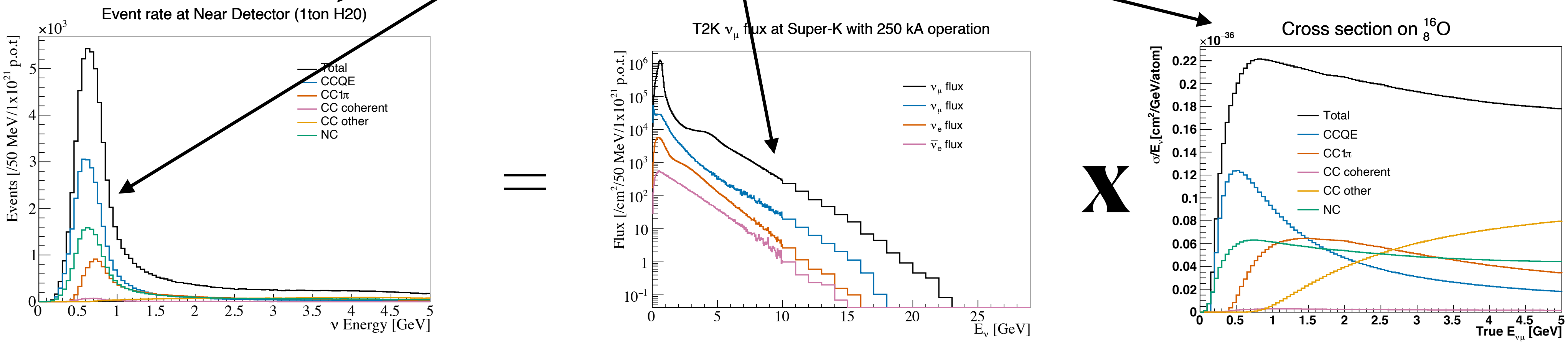
For sensitivity, normally only quote C.L. while keep (1-β)(%) = 50%

Prediction of rate of events occurred in detector

To give some sense on sensitivity and parameter estimation, we will follow one specific example

$$N_i = \Phi_{flux} \times \boxed{\sigma} \times M_{det} \times \epsilon$$

Detection efficiency assume a constant (<1)



Assumes no oscillation happens yet e.g. observation at Near Detector

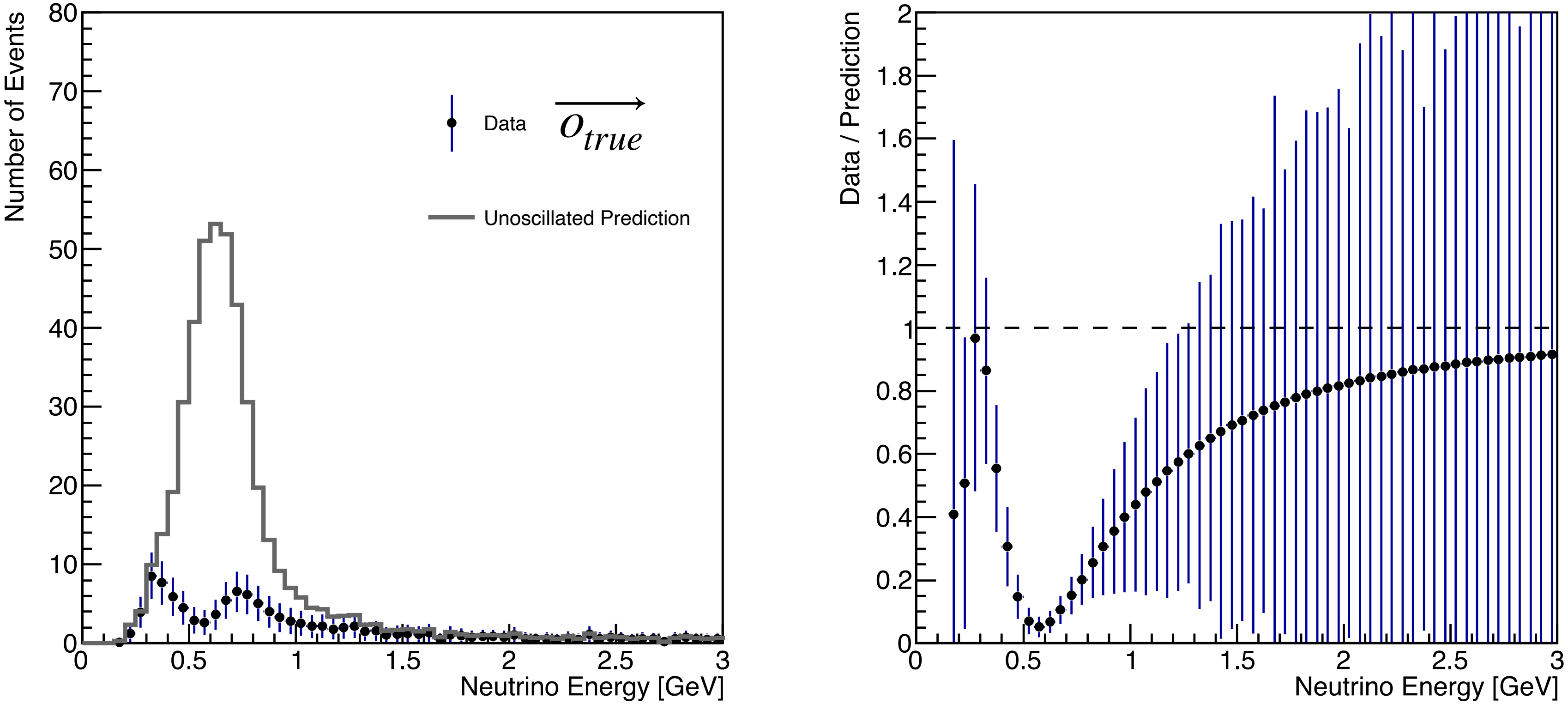
https://github.com/cvson/nushortcourse/tree/master/eventpred

Prediction with oscillation

$$N_i(\overrightarrow{o}) = \Phi_{flux} \times \sigma \times M_{\mathrm{det.}} \times \epsilon \times P(\overrightarrow{o})$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu}$$

where $\overrightarrow{o} = (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$



Here, oscillation is applied to make "fake" data. Sensitivity study is typically conducted with "fake" data (*which you know the truth behind*)

https://github.com/cvson/nushortcourse/tree/master/sensitivity

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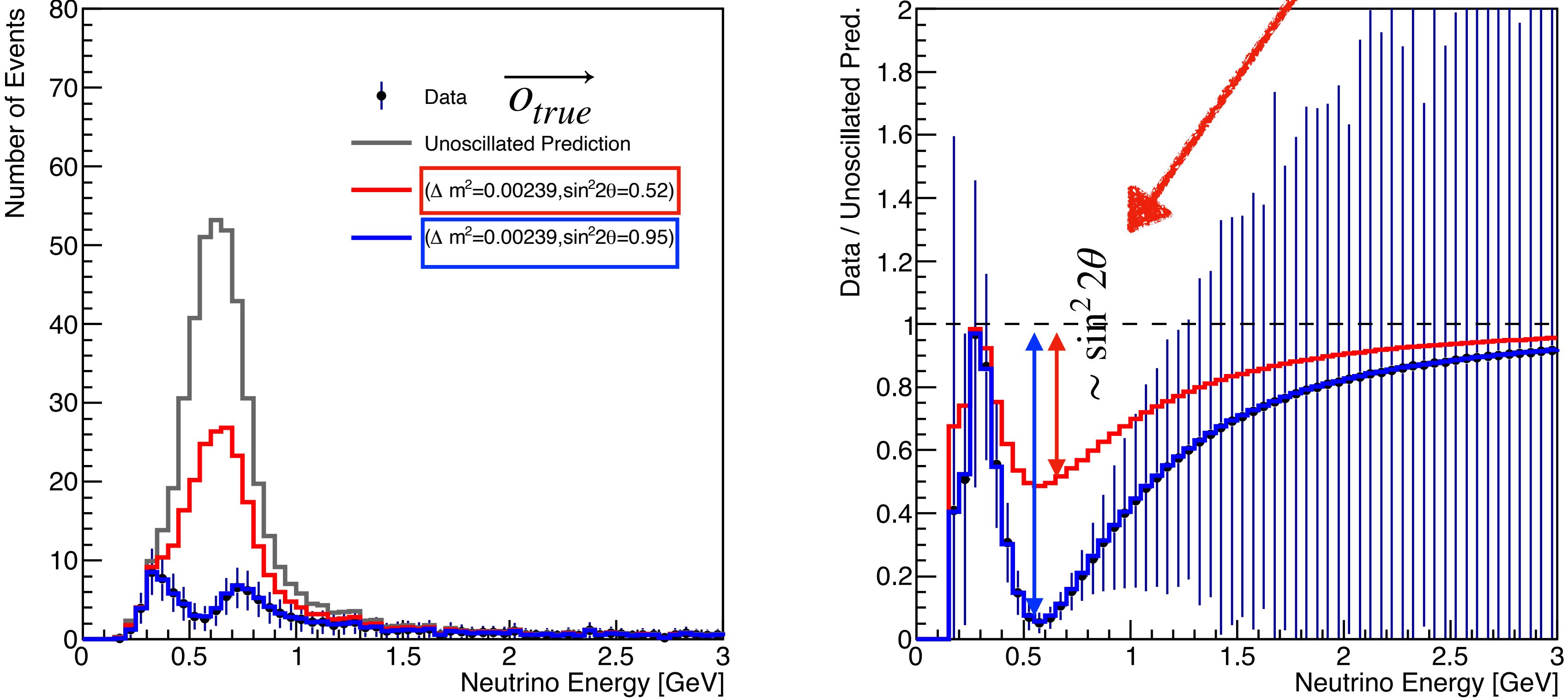

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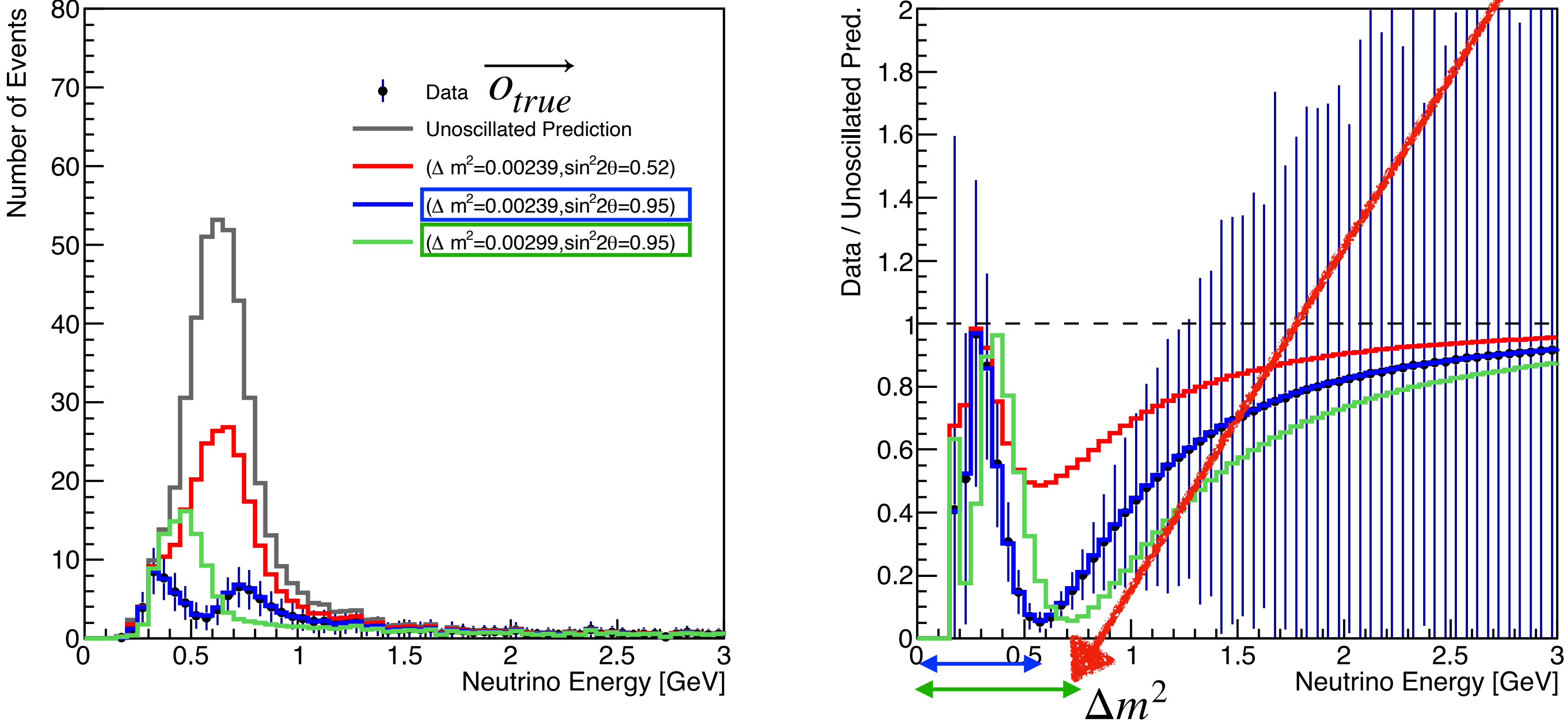

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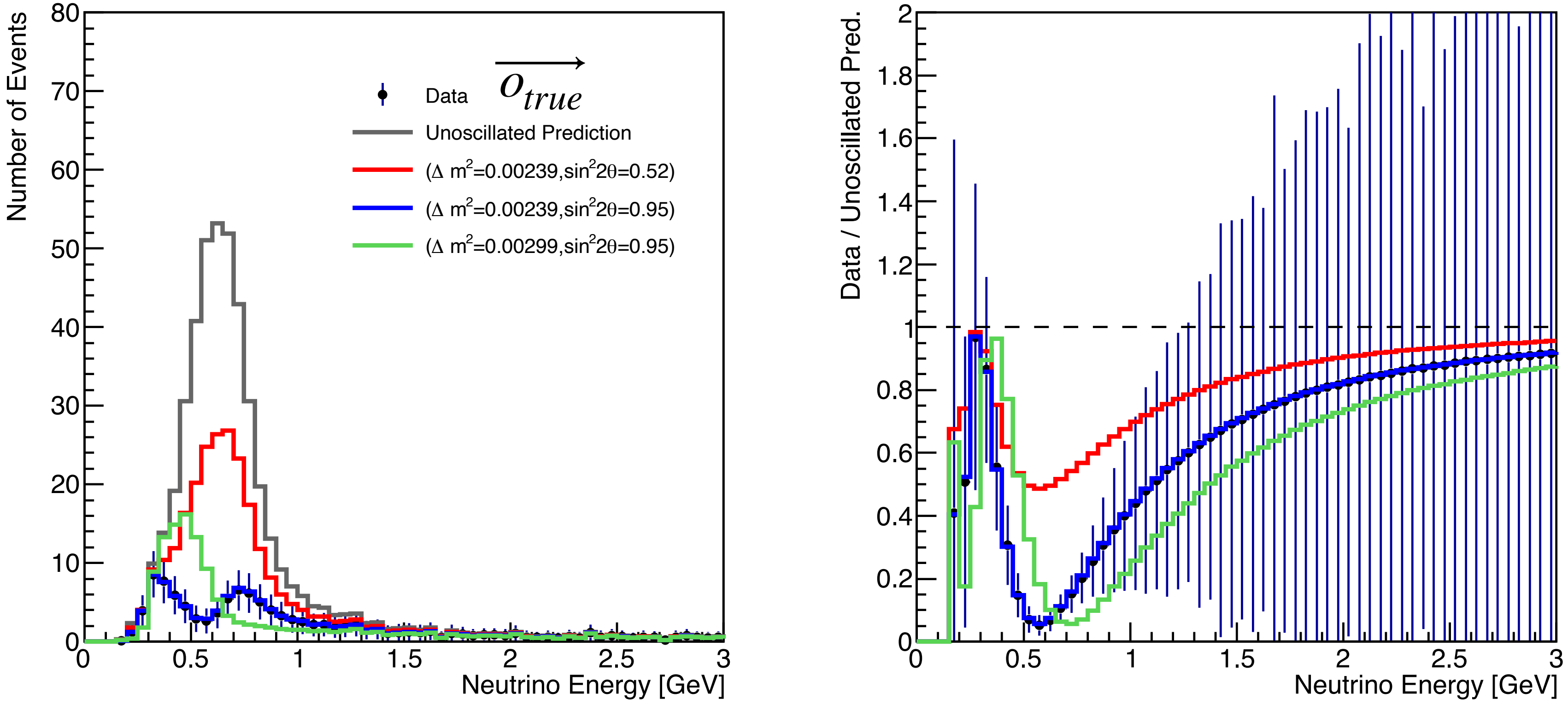
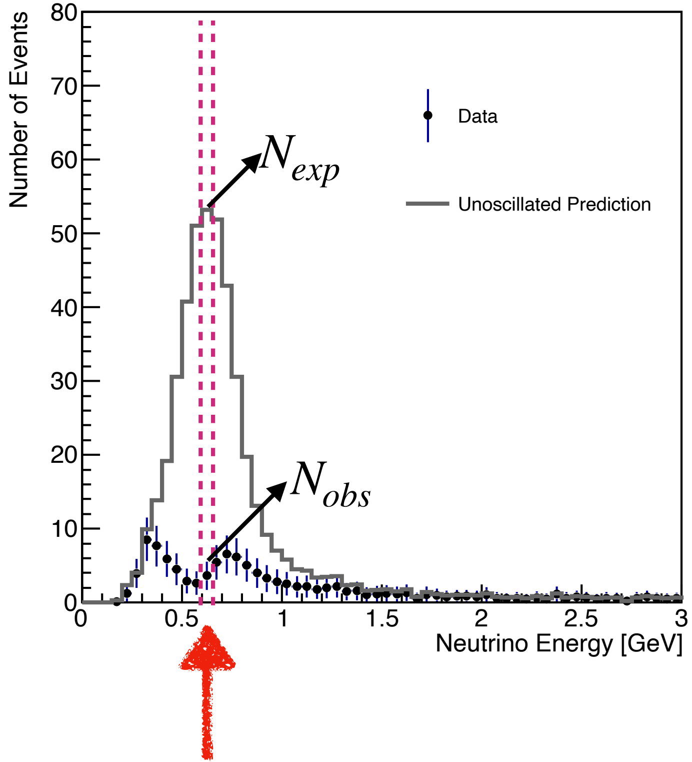
$$\overrightarrow{o} = (\Delta m_{21}^2, \Delta m_{31}^2, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$$



Data is well described by the blue line rather than the red and the green. But is it the “best” parameter to describe the data yet?

Parameter estimation



Energy bin i

- When we talk about parameter(s), we need predefine a model

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu}$$

- Given data and model, how do we estimate parameter(s)?
  - One need **quantify the difference between data and prediction** at various parameter values
  - Method to quantify is not unique, e.g. Maximum likelihood

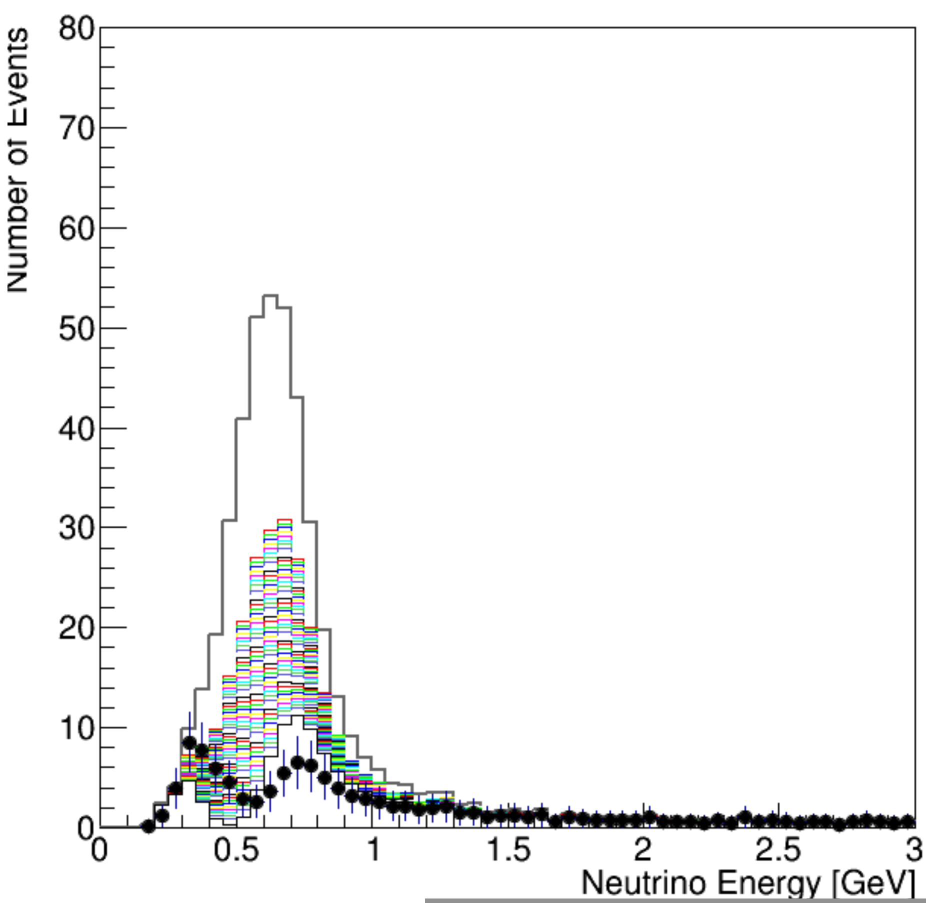
$$\chi^2(\overrightarrow{o_k}, \overrightarrow{o_{true}}) = \sum_i \chi^2 \left(N_i(\overrightarrow{o_k}), N_i(\overrightarrow{o_{true}})\right)$$

$$\log \chi^2 = \sum_i 2(N_{exp.} - N_{obs.}) - 2N_{obs.} \,.\, log(N_{exp.}/N_{obs.})$$

What's the best parameters to describe your data?

https://github.com/cvson/nushortcourse/tree/master/sensitivity

.gif file https://imgur.com/a/zkMN2R3



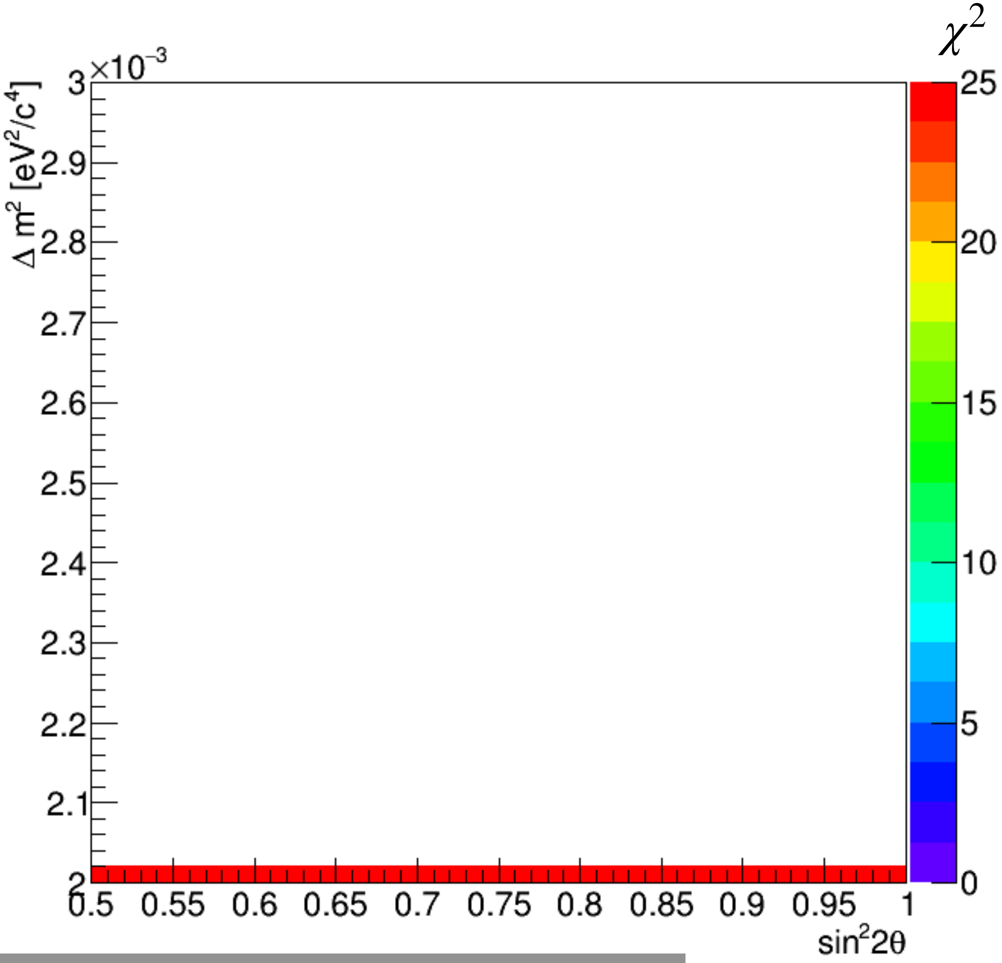
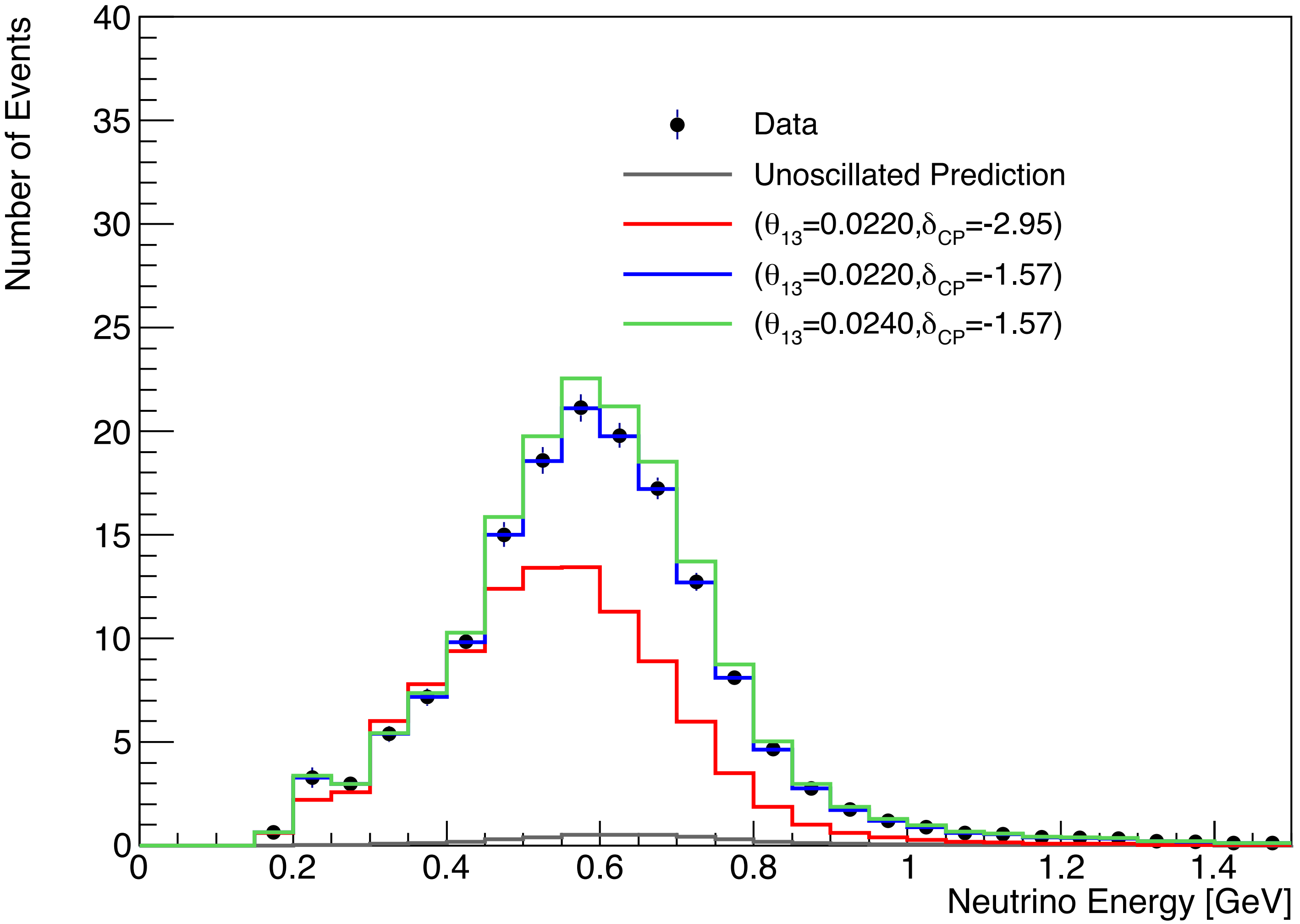


Illustration for comparing data with various prediction on the left with χ^2 calculated corresponding on the right. From this, confidence intervals are extracted (not going to detail now)

Other example with Electron neutrino appearance search

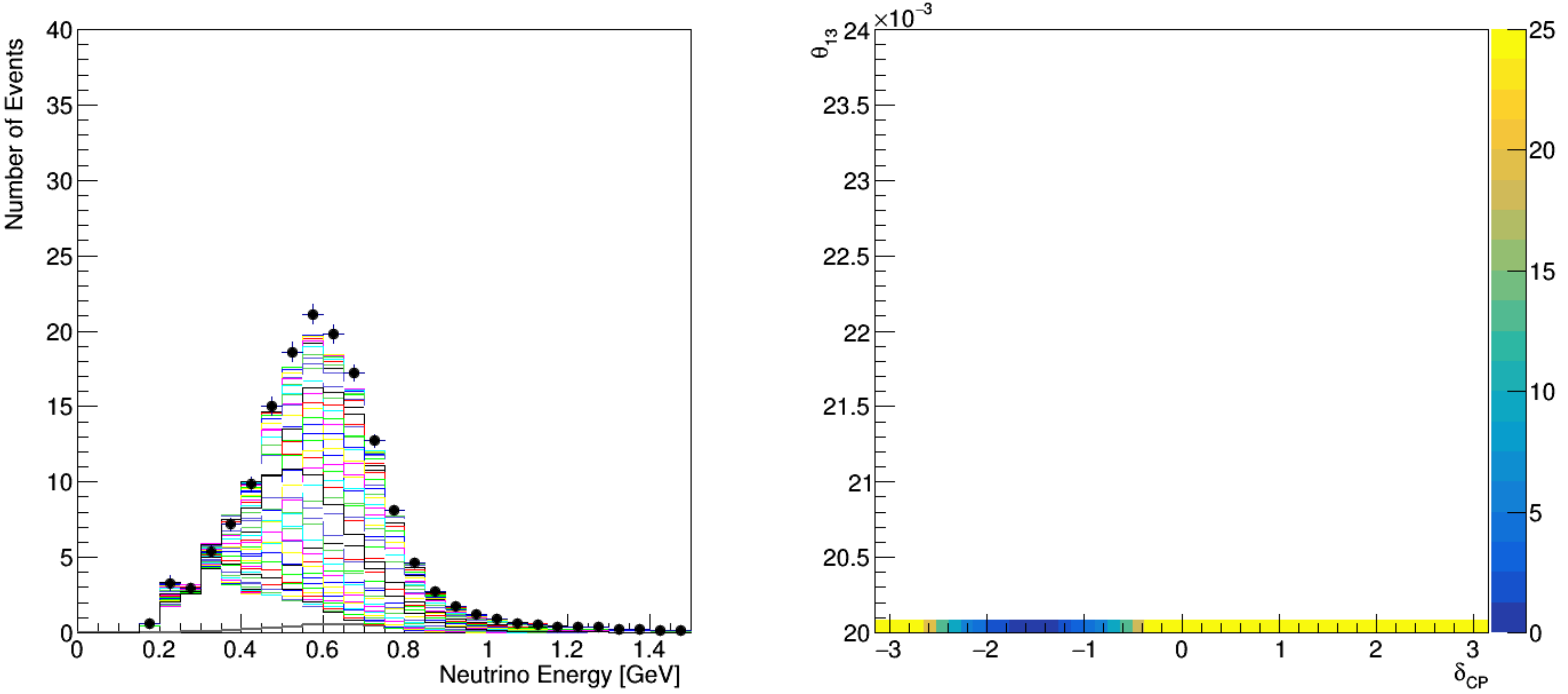
https://github.com/cvson/nushortcourse/tree/master/sensitivity



For CP violation

https://github.com/cvson/nushortcourse/tree/master/sensitivity

.gif file https://imgur.com/a/jikEQSL



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For CP violation

.gif file https://imgur.com/a/cQfNjT0

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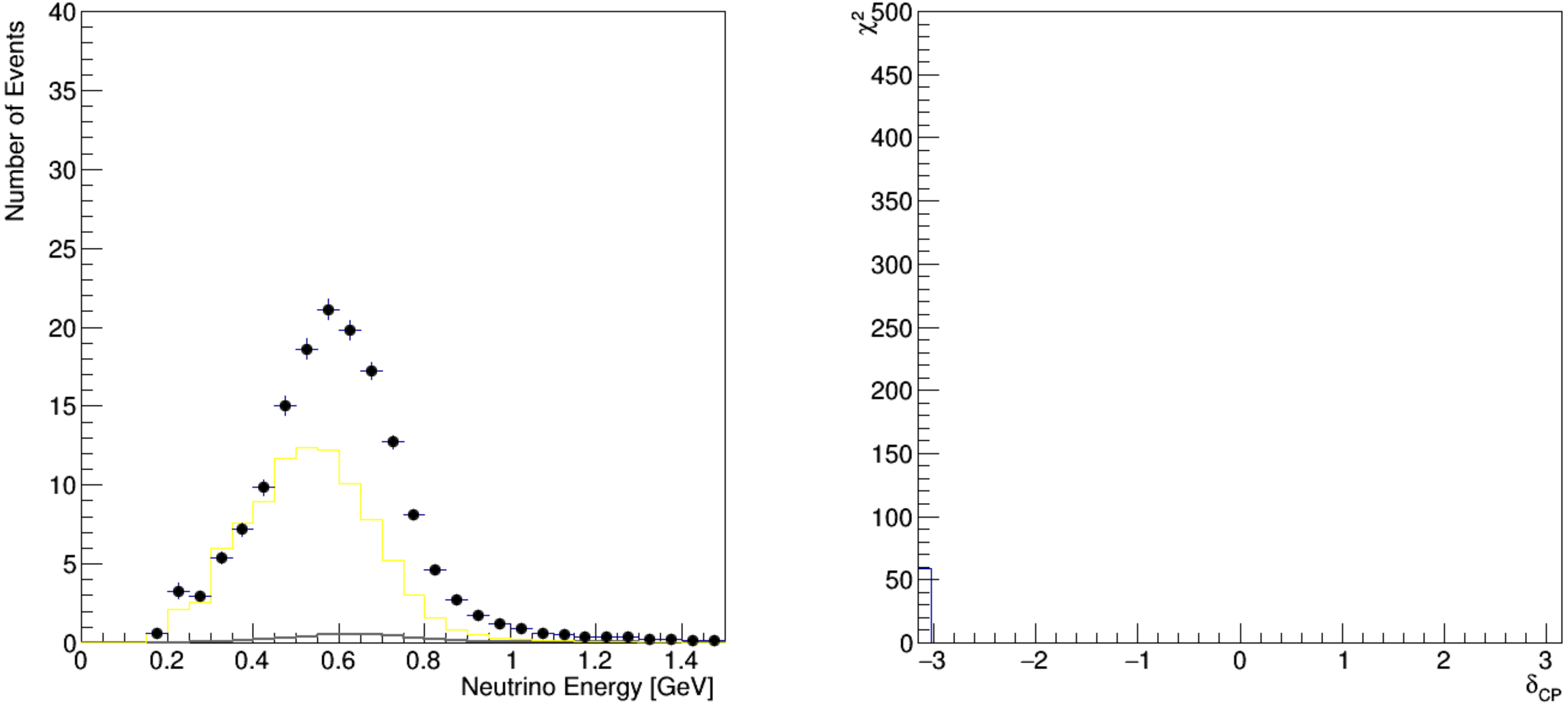


Illustration for comparing data with various prediction on the left with χ^2 calculated corresponding on the right. From this, confidence intervals are extracted (not going to detail now)

Some selected topics

1) Signal and background
2) Hypothesis test
3) Sensitivity & Parameter estimation
4) Systematics
5) Monte Carlo usage

Systematic sources

without quoting error, your result is meaningless

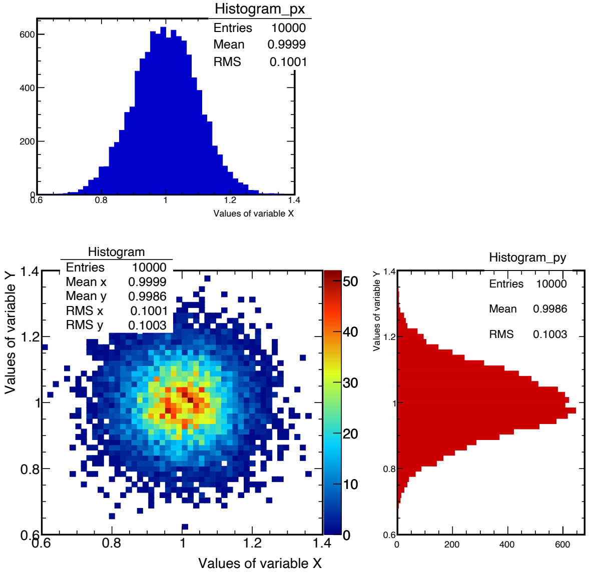
For neutrino exp., there are basically three sources of errors

- **Neutrino source**
  - Proton beam condition (use monitors but still error)
  - Pion/Kaon production when proton hits on target: this is the most dominant error, external data from other experiments are used
  - Current uncertainty level of 10%, but can improved
- **Neutrino interaction model**
  - Statistic is challenging
  - Nuclear effect
  - Final state interaction
- **Detector systematics**
  - Secondary interaction
  - Detector response

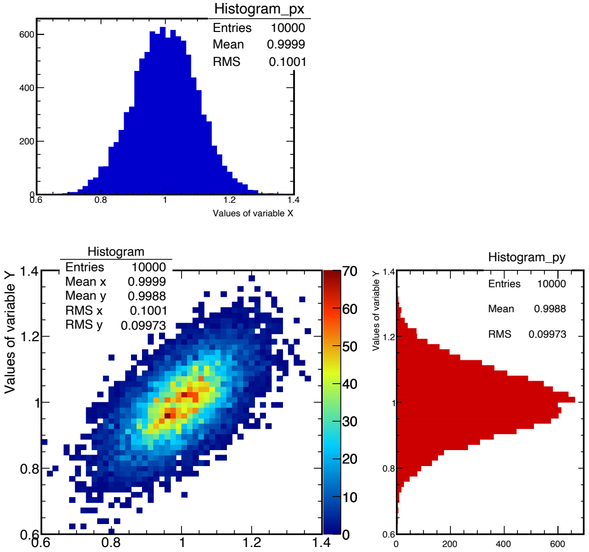
Another source is the uncertainty on the "other" oscillation parameters One experiment are typically sensitive to a subset of parameters

Systematic sources

Not just systematic value matter
but covariance btw systematics is also important

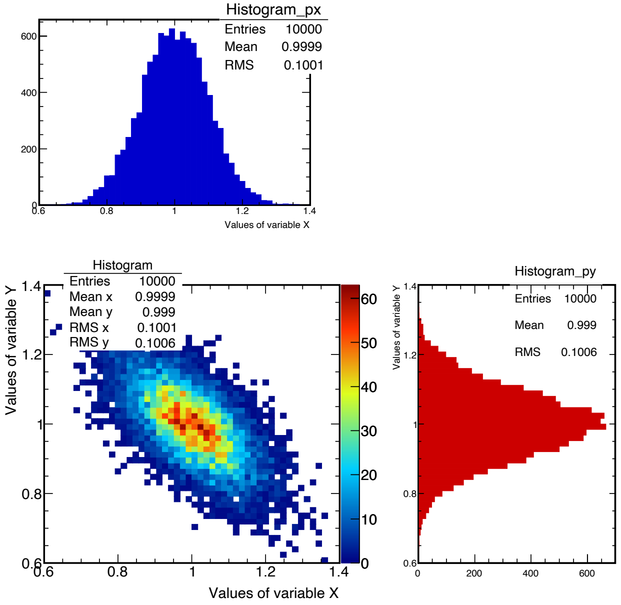


No covariance btw. 2 para.



Positive covariance btw. 2 para.

Assume two variables
follow gaussian with mean = 1.0 and σ =0.1



Negative covariance btw 2 para.

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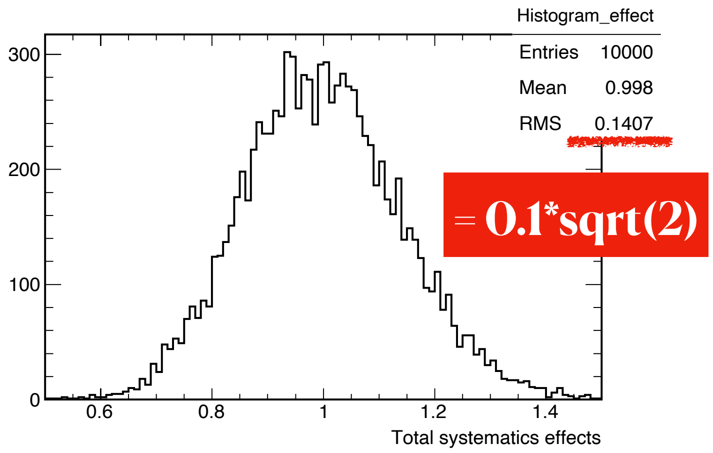
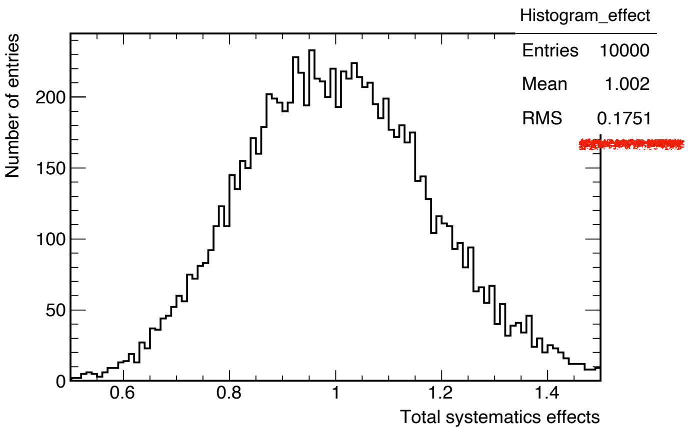


= 0.1*sqrt(2)

No covariance btw. 2 para.



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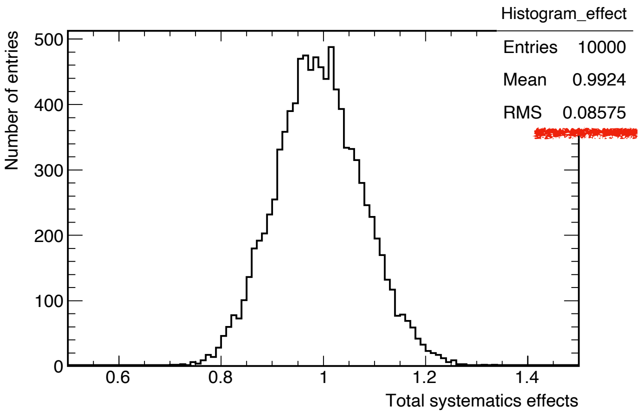

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Assume two variables
follow gaussian with mean = 1.0 and σ =0.1

Because of this, global data combination is non-trivial

Some selected topics

1) Signal and background
2) Hypothesis test
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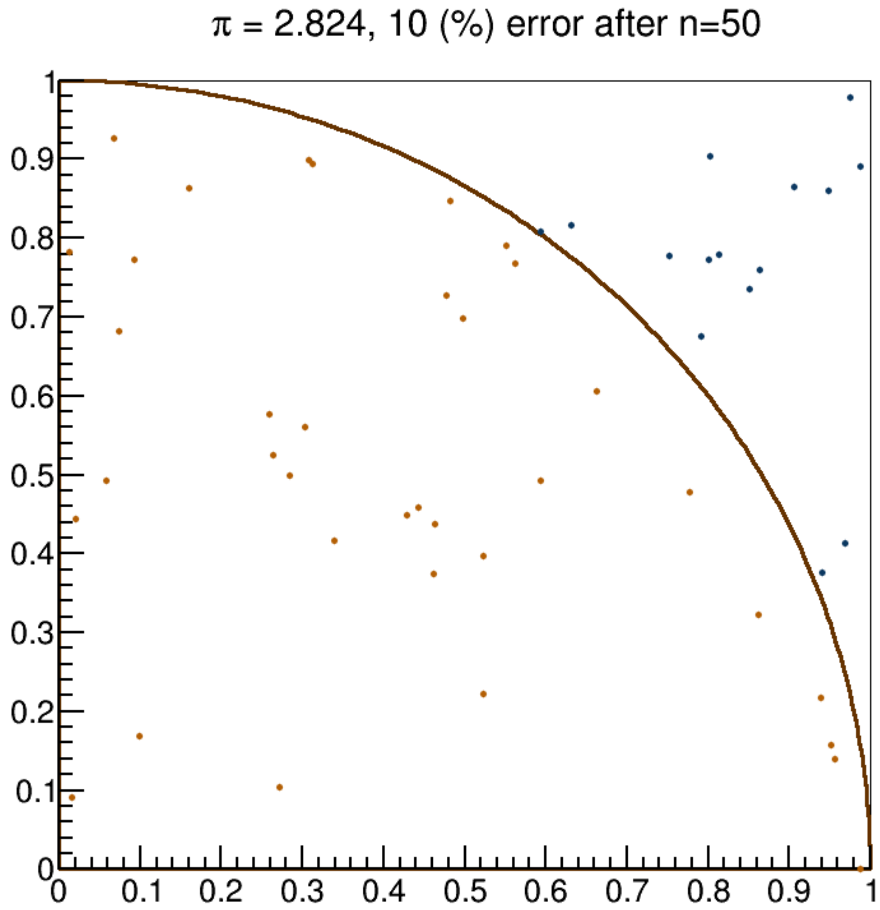
5) Monte Carlo usage

Monte Carlo usage

Pi calculation method

- Random throw points (dots)
    - If inside the circle, you count
- Ratio of counts inside the circle to all throw points is proportional to area ratio of 1/4 circle and corresponding square

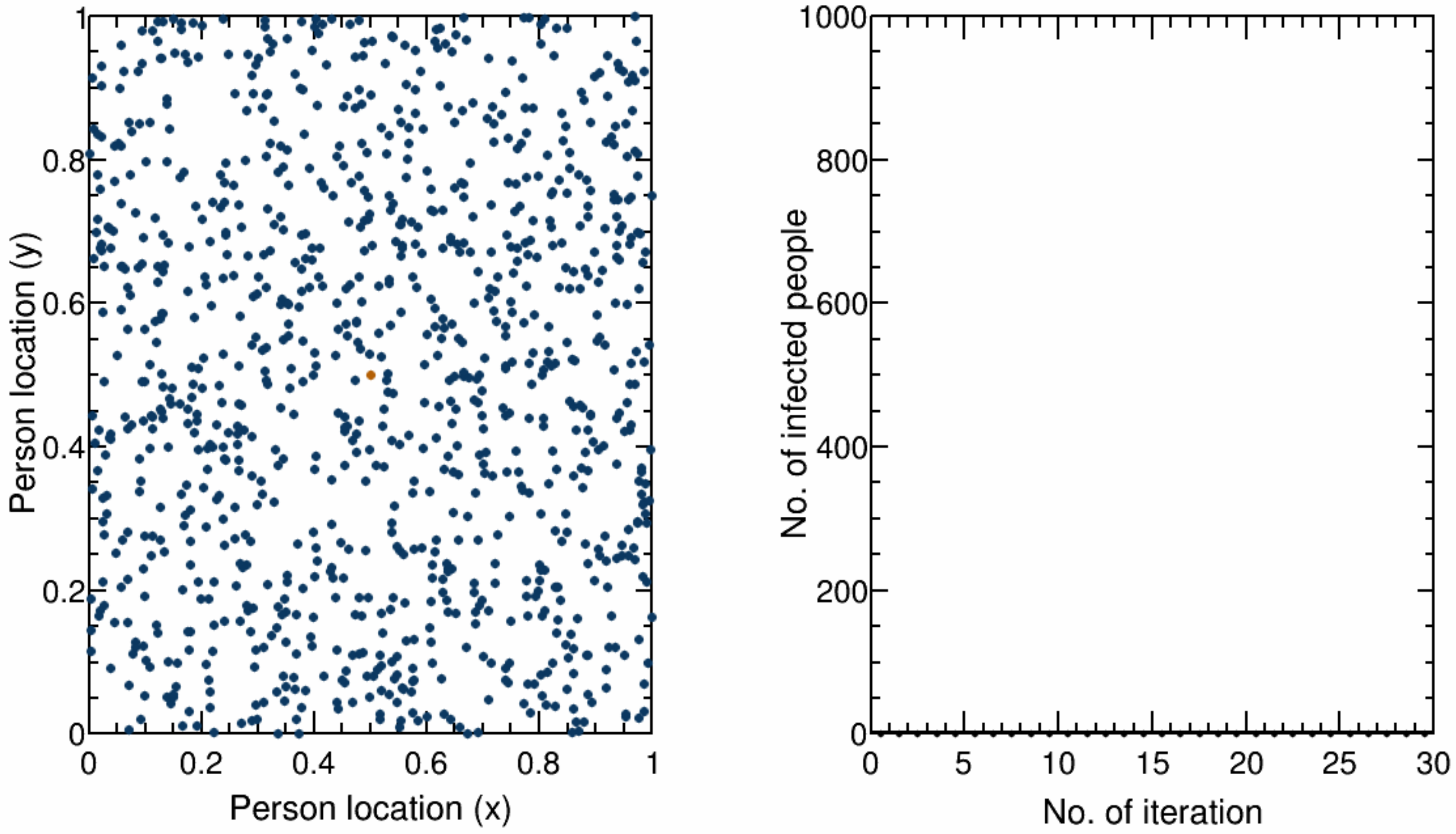


https://github.com/cvson/nushortcourse/tree/master/mctoy

see gif at https://imgur.com/a/hBJXmcK

Toy model of virus transmission

A static model: People don't move / (effectively social distance)



● **infected**

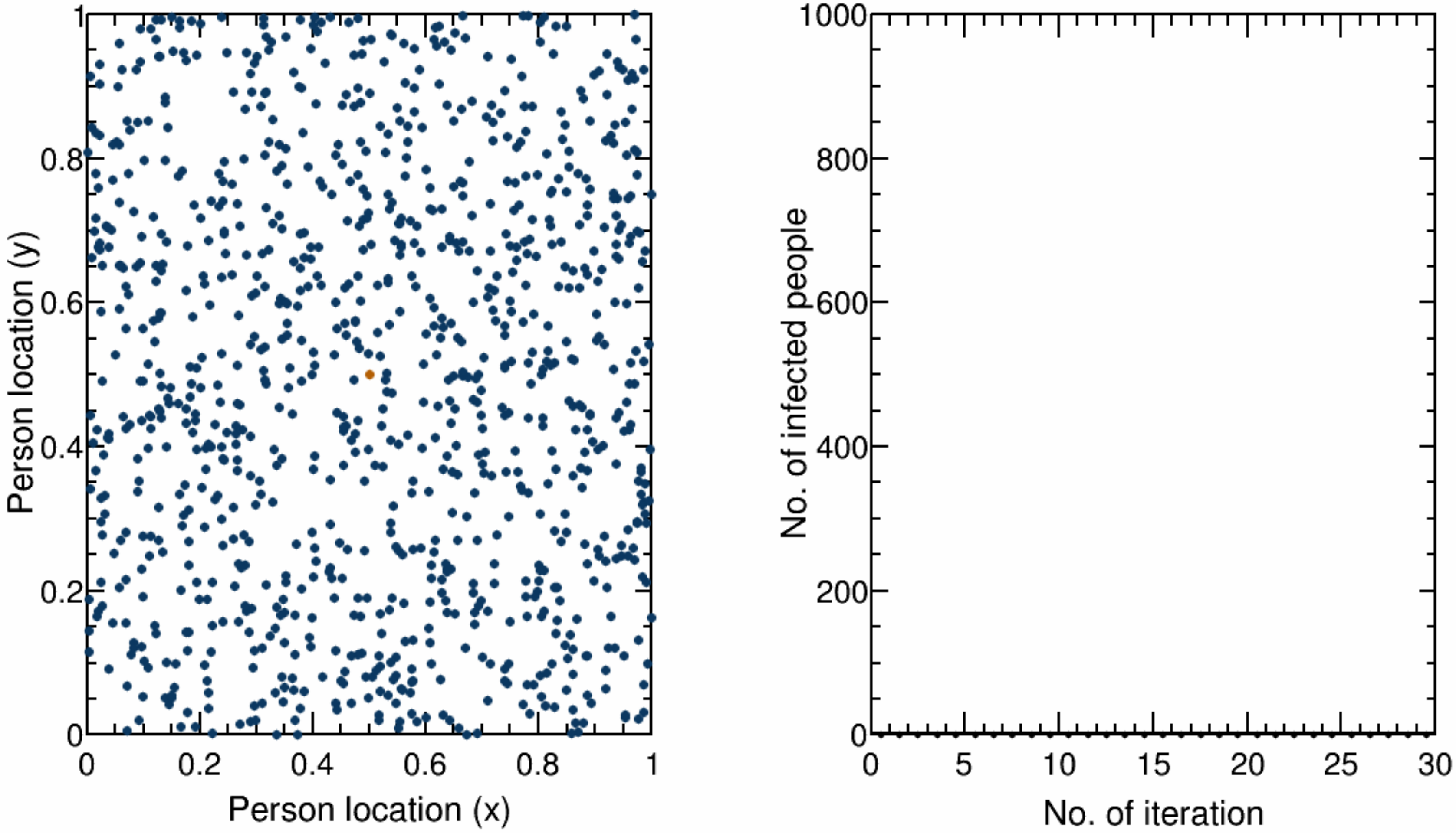
● **Non-infected**

https://github.com/cvson/nushortcourse/tree/master/mctoy

See gif at https://imgur.com/a/gzV92ZC

Toy model of virus transmission

A dynamic model: People move as their wish (or no social distance)



● **infected**

● **Non-infected**

https://github.com/cvson/nushortcourse/tree/master/mctoy

Monte Carlo usage

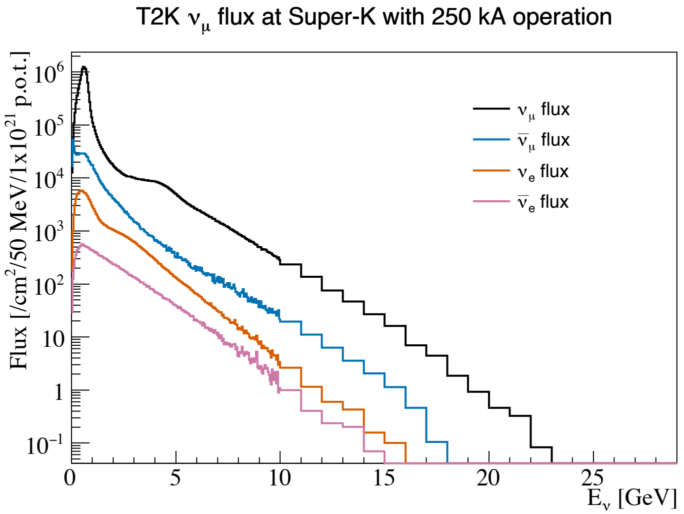
Thumb rule: randomly go through all possibilities under predefined rule

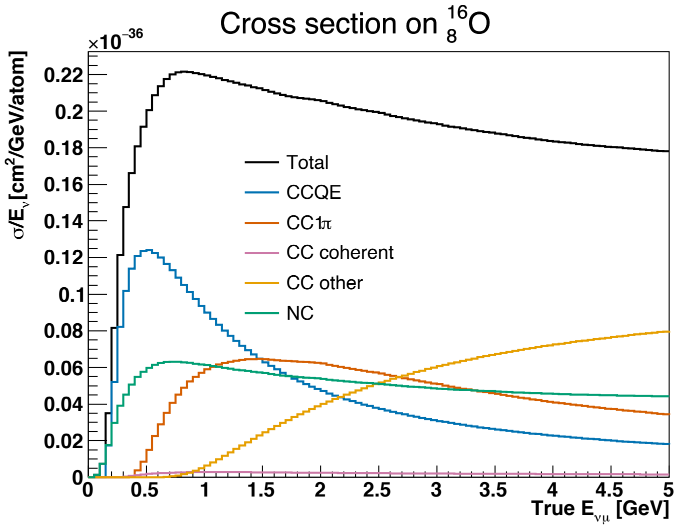
Neutrino Event generator is one example

- Neutrino energy follows some distribution → Generate a lot of neutrinos with energy follow that distribution

- There are many possible interactions for a definitive energy with different cross section → There a lot of neutrinos generated, each of them can go different interactions

- Four-momentum of out-going particles are not fixed (can be random as long as the conservations (*energy, momentum, etc…*) are satisfied)





To conclude

Four golden lessons

Steven Weinberg

Scientist

Advice to students at the start of their scientific careers.

1. **No one knows everything, and you don't have to**

2. **Go for the messes — that's where the action is**

   (Neutrino physics is still a mess more or less)

3. **Forgive yourself for wasting time** (You will never be sure which are right problems to work on)

4. **Learn something about the history of science** (As a scientist, you're probably not going to get rich… But you can get great satisfaction by recognizing that your work in science is a part of history.)

https://www.nature.com/articles/426389a.pdf

Mistake is always out there

“Neutrino mistakes: wrong tracks and hints, hopes and failures”

—- By Maury Goodman at History of the Neutrino, 2018

- SIN report of $\mu \rightarrow e\,\gamma$
- High y anomaly
- NuTeV Helium bag events
- Klapdor’s $0\nu\beta\beta$ signal
- LSND/eV “sterile” νs
- IMB limit on ν oscillations
- Alternating neutral currents
- Reines-Sobel ν oscillations
- Vanucci PS191 oscillations
- BNL 776 & 816 oscillations
- BEBC oscillations
- HPW “super” trimuons
- Oscillations in Bugey
- Majoron emission in $0\nu 2\beta$ PNL/USC
- SPT vs. V-A

- Superluminal νs
- 17 keV ν
- NuTeV anomaly
- Tritium endpoint $(-)m^2$
- Kolar events
- Early atmospheric ν lack of polarization
- MINOS anti-ν θ_{23}
- God’s mistake
- ν grammar
- Labels for $\Delta m^2{}_{ab}$
- PDG m(ν) encoding
- Which ν is a particle?
- Karmen time anomaly
- Time variations in Troitsk $m_\nu{}^2$
- ITEP $m(\nu_e)$ = 30 eV in 1980

**I was in MINOS exp.
& work for both
wrong tracks**

Mistake is always out there

Auxiliary Detector

Soudan mine, Feb. 2012
716m from surface

ints, hopes and failures”

f the Neutrino, 2018

- Superluminal νs
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e?

ly

roitsk m_ν^2

in 1980

Surface of Soudan mine
Feb. 2012

I was in MINOS exp.
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wrong tracks

...but gain a lot of experience

Thank you for listening and good luck!