SEARCH FOR
RIDENT EVENTS WITH
ICECUBE

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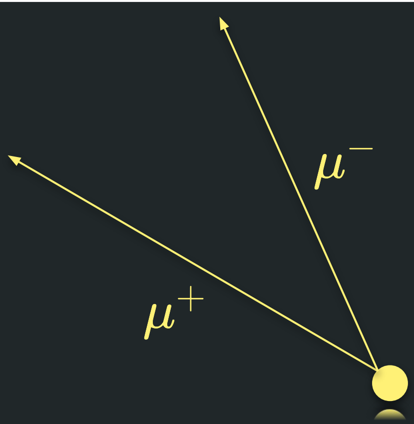
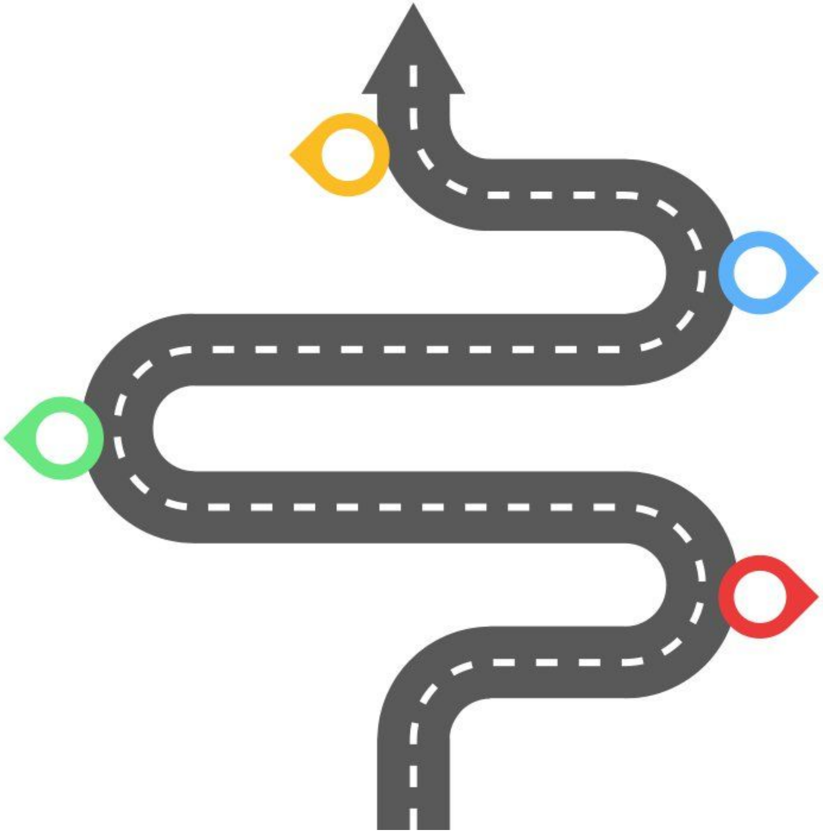
NOV 3, 2022



SUPERVISOR: JUAN PABLO YÁÑEZ GARZA

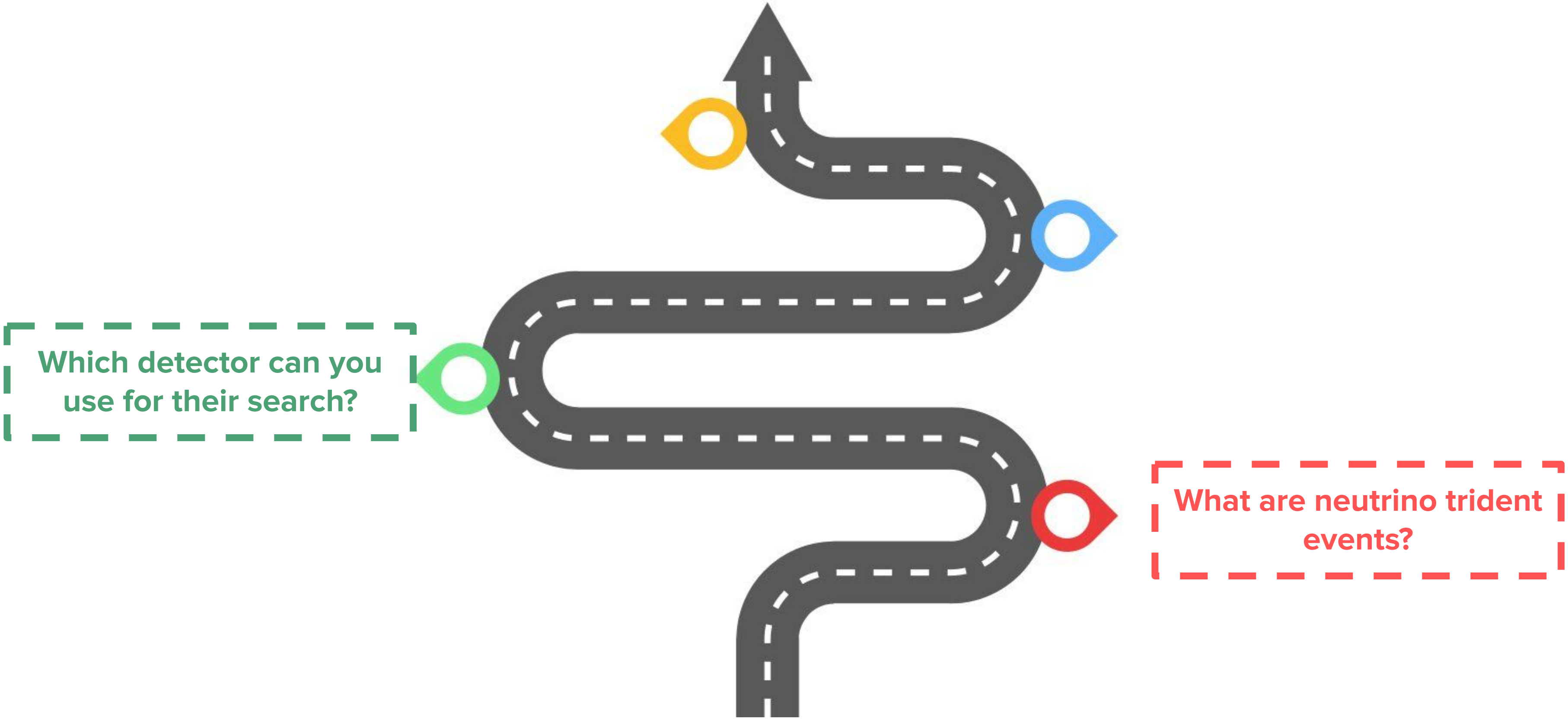
UNIVERSITY OF ALBERTA
ICECUBE NEUTRINO OBSERVATORY

ROADMAP [1/4]



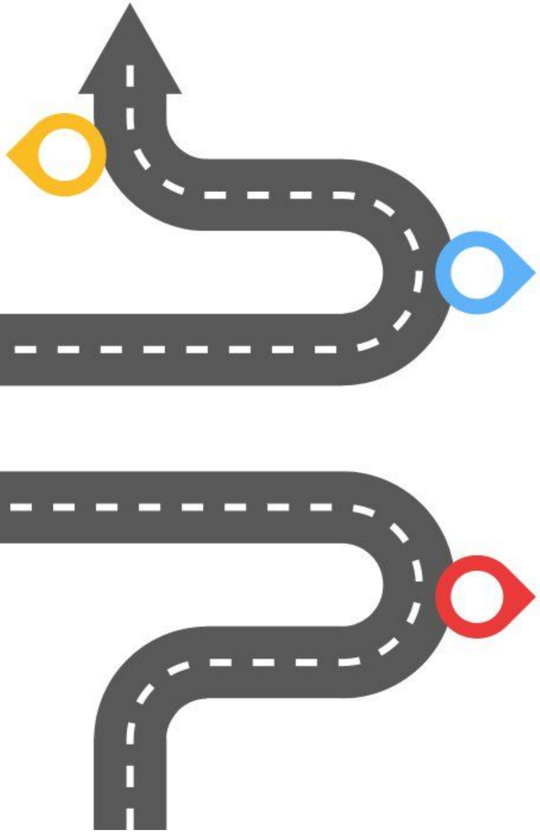
What are neutrino trident events?

ROADMAP [2/4]



Which detector can you use for their search?
What are neutrino trident events?

ROADMAP [3/4]



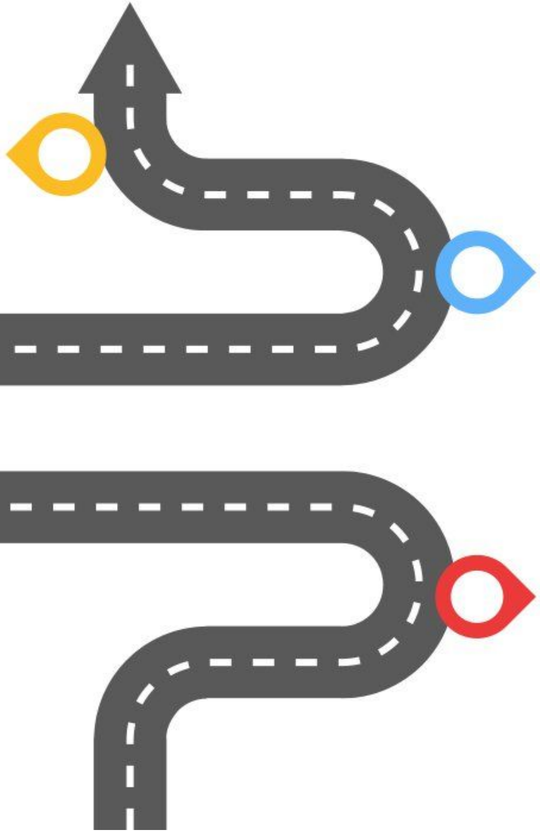
What features can you use for signal and background separation?

Which detector can you use for their search?

What are neutrino trident events?

ROADMAP [4/4]

Can you use a ML technique using the features extracted from the previous step?



What features can you use for signal and background separation?

Which detector can you use for their search?

What are neutrino trident events?

NEUTRINO TRIDENT PRODUCTION

DEEP INELASTIC SCATTERING (DIS): MUONIC CHANNEL

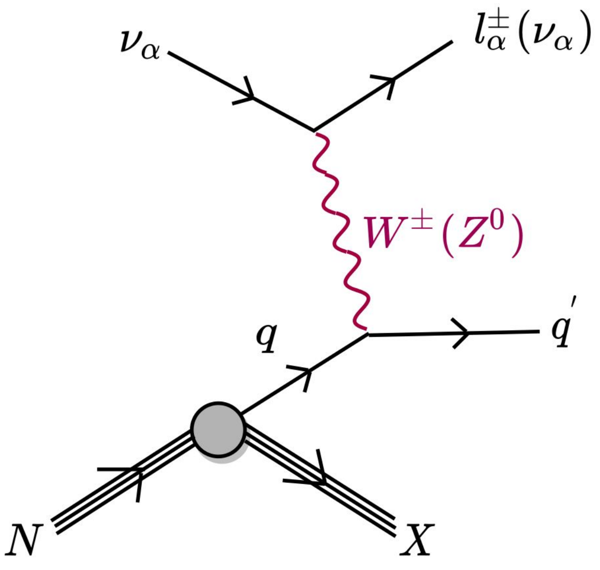
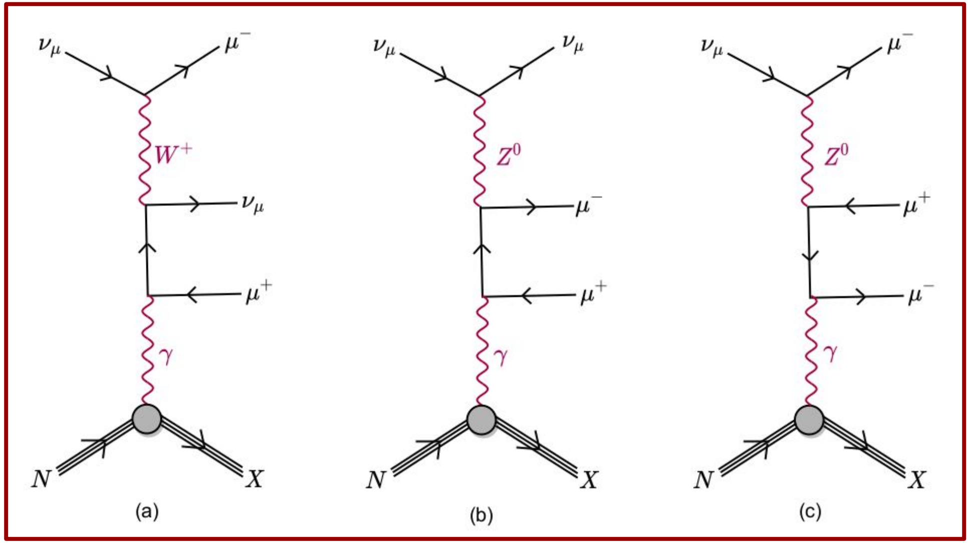
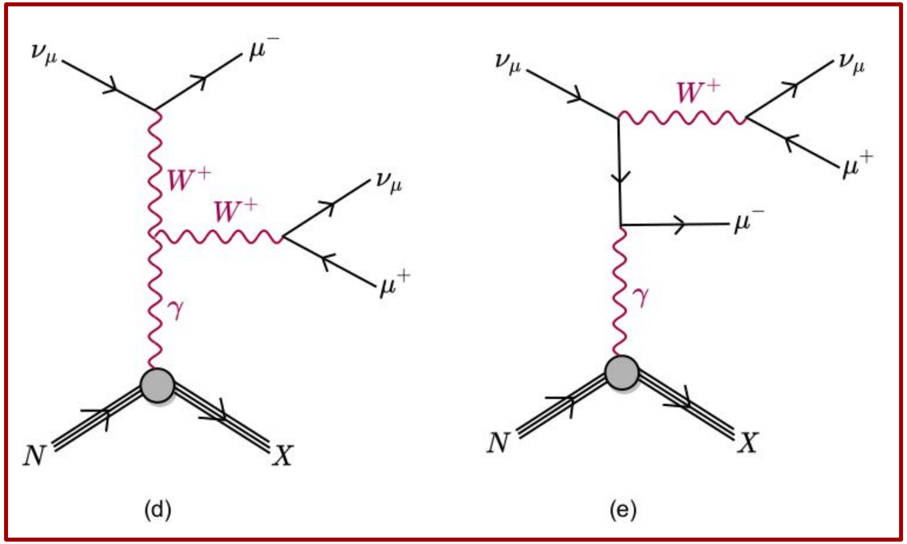


Fig: Feynman diagram for DIS: The dominant interaction involves one outgoing lepton.

- ❖ **Lepton-hadron scattering: An incoming neutrino interacts with a nucleus N and produces a charged lepton.**
- ❖ **If the energy of the neutrino is very high, nucleus is shattered and emits many new particles, a process called hadronization.**
- ❖ **Single Muon Channel: If the incoming neutrino is muon neutrino, then the outgoing lepton is a muon.**
- ❖ **Dominant Process.**

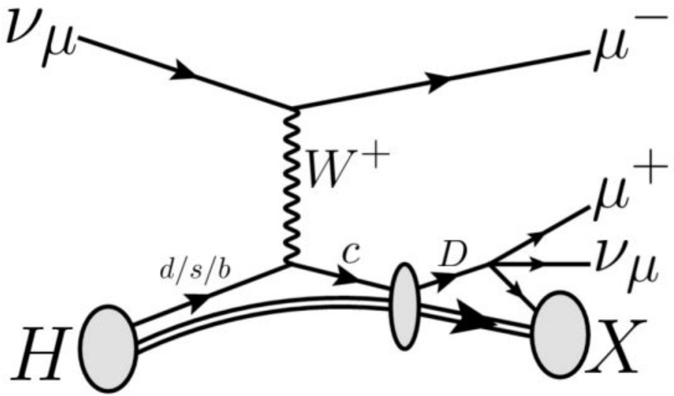
Charged Current DIS (CC-DIS): If the exchange is via a W boson.
Neutral Current DIS (NC-DIS): If the exchange is via a Z boson.





- **NTP: 3 leptons are produced (2 charged and 1 neutral). Hence, the name trident.**
- **If the incoming neutrino is a muon, and the outgoing leptons are 2 muons and a muon neutrino, then this channel is called muonic channel.**
- **Sub-dominant electroweak process due to addition of more vertices.**

CHARM MUONS



- Charm decays into a secondary muon. This is also a 2 muon signature.
- This cross-section is higher than the trident cross-section as this is a subset of CC-DIS interaction.

WHY SHOULD WE LOOK FOR DIMUONS?

- **The event rate of this process is a powerful probe to a well-motivated parameter space of new physics beyond the Standard Model.**
- **A deviation from the event rate predicted by the SM could be an indication of new interactions mediated by new gauge bosons**
- **<u>EXTRA CONTRIBUTIONS:</u> In particular, BSM (Beyond Standard Model) processes like supersymmetry can look for additional supersymmetric particles like Z' etc. in place of W/Z bosons.**
- **Thus, it serves as a powerful electroweak test for Standard Model and physics beyond Standard Model.**

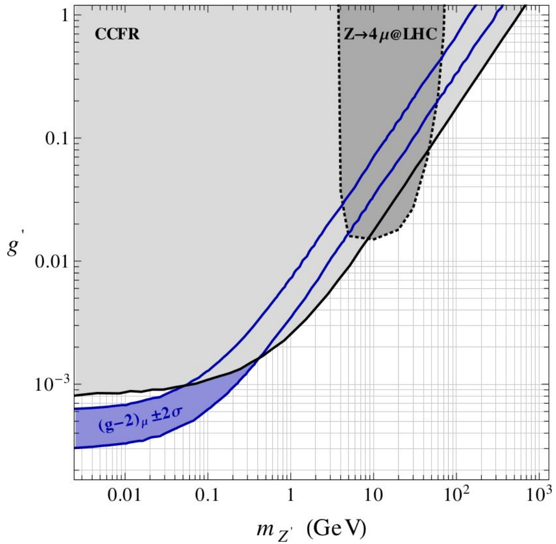
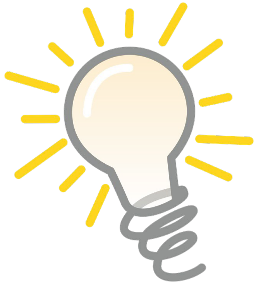


Fig: Z' boson parameter space. There are three regions here: grey contour with solid line is excluded by CCFR measurement of NTP model at 95% CL. The area between 4 {GeV} < mass of Z' < 60(GeV} is also excluded from the LHC measurement of Z boson decay to four leptons. The purple parameter space is the current favorable space for Z' boson search as highlighted by muon (g-2) discrepancy. This space is cutoff at 400 MeV mass. CCFR's measurement underscores the importance of looking for trident events in getting tighter constraints on the parameter space. Figure from *

* W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, "Neutrino trident production: A powerful probe of new physics with neutrino beams," Physical Review Letters, vol. 113, no. 9, p. 091 801, 2014.

WHERE TO LOOK FOR TRIDENTS?



- **Dimuon events in the high energy regime (100 GeV ~ 10 PeV) [2] where increase in the cross-section can lead to the observation of trident events in neutrino telescope detectors like IceCube, Antares etc.**
- **The detections of TeV–PeV neutrinos by IceCube have already been a breakthrough.**
- **High instrumented volume of IceCube (1km^3)**
- **IceCube has 10 years of data.**

ICECUBE DETECTOR

ICECUBE DETECTOR

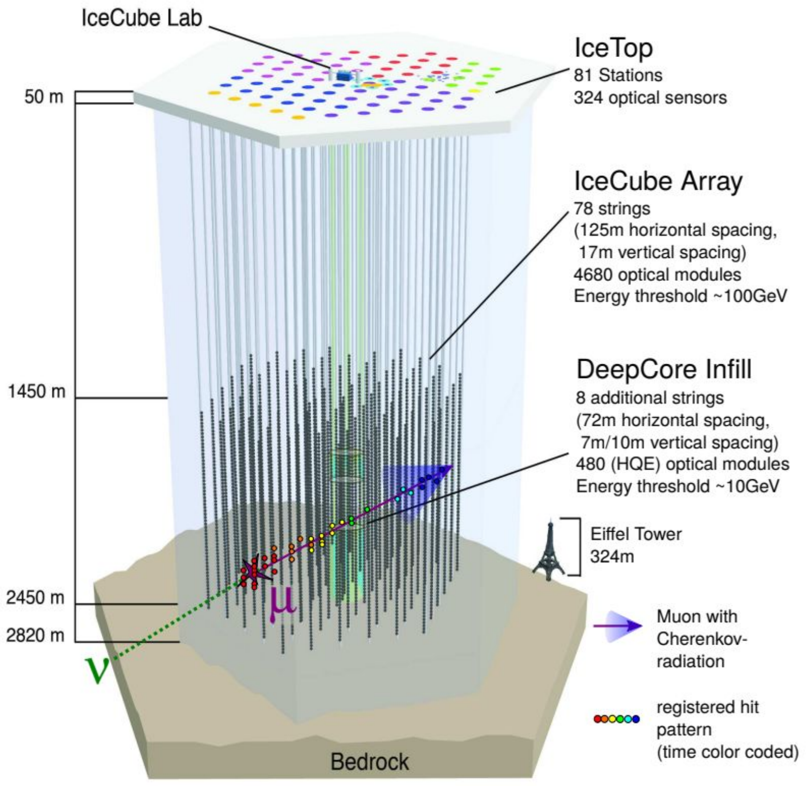
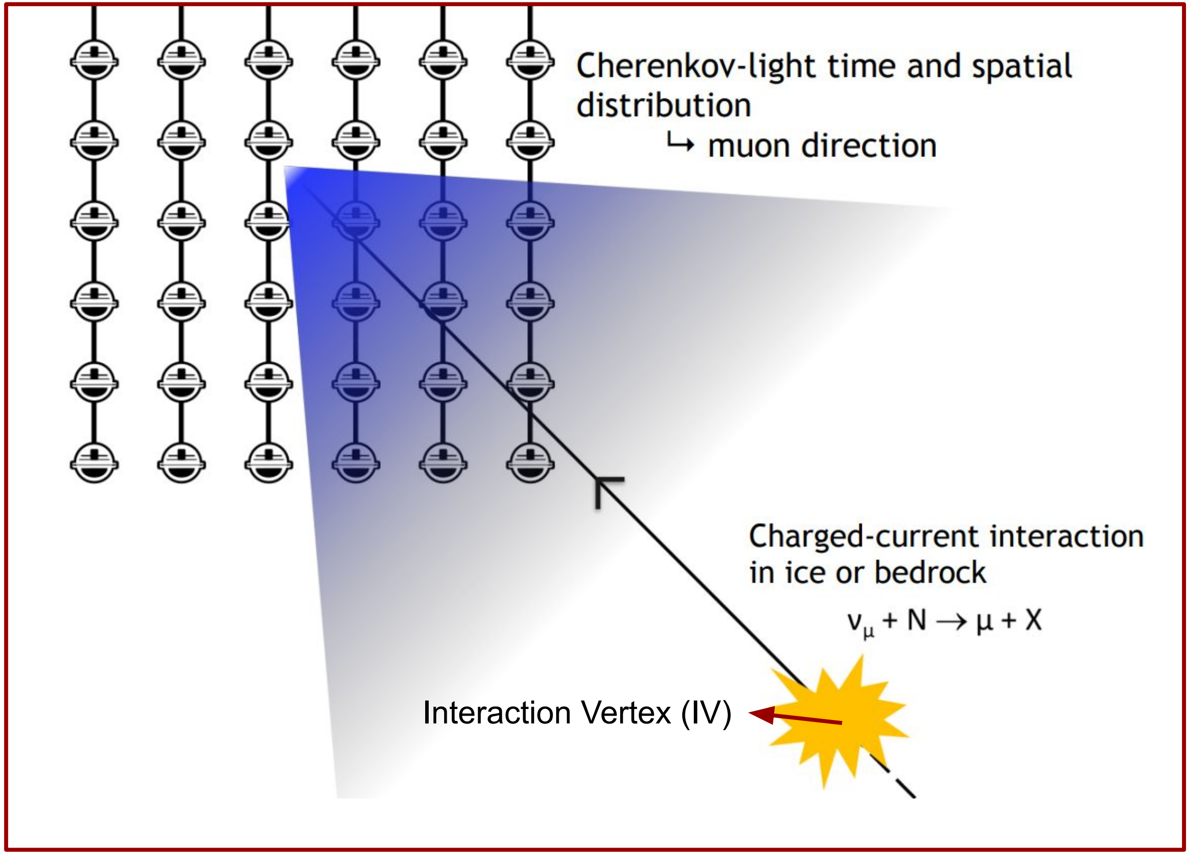


Figure from:
https://user-web.icecube.wisc.edu/~mda65/talks/thesis.pdf

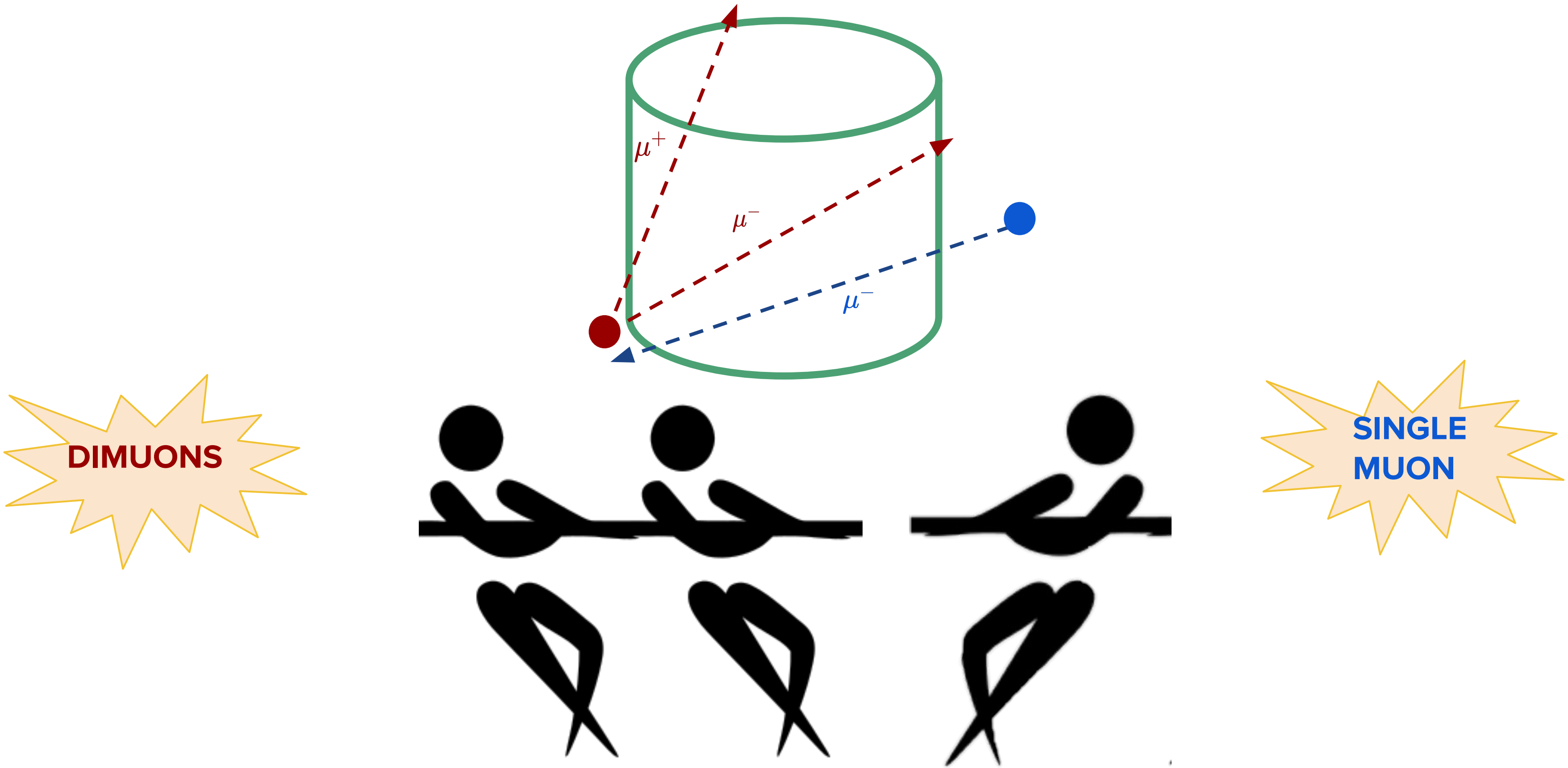
- **Neutrino Telescope at the geographical South Pole**
- **Optical sensors (Digital Optical Modules: DOMs) deployed in a 3-D hexagonal lattice along cables (‘strings’), starting from 1.5 km below Earth’s surface to minimize atmospheric background from cosmic rays.**

CHERENKOV CONE: OPTICAL EQUIVALENT TO A SONIC BOOM



- **A charged particle in ice can travel faster than speed of light and emit Cherenkov radiation.**
- **It is this light that is measured by DOMs and quantized into discrete hits. Hence the prefix: digital**

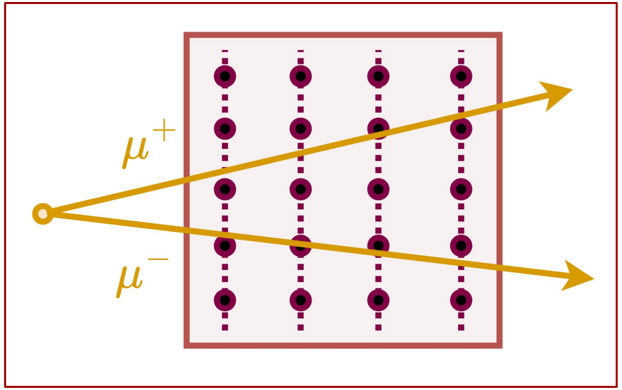
CLASSIFICATION



SEARCH FOR TRIDENT EVENTS

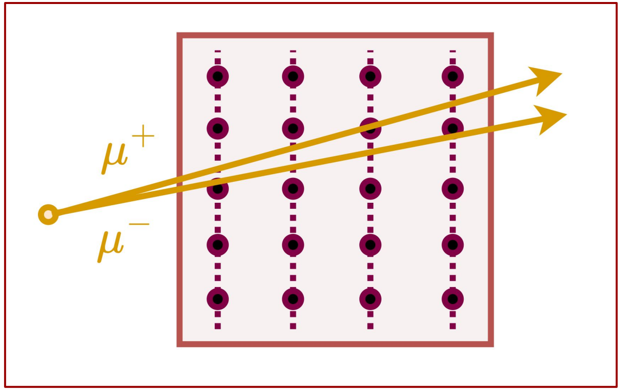
DIMUON CLASSES

CLASS-A



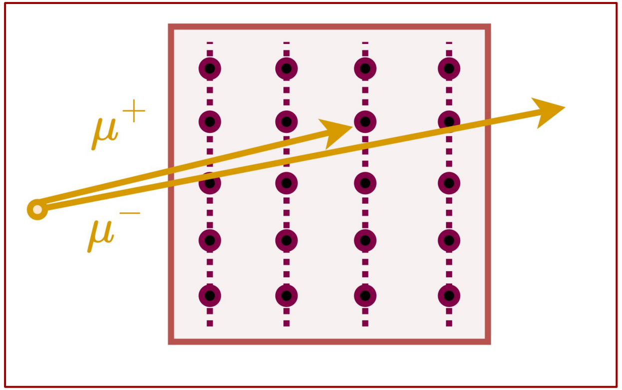
- Track_length: Both >=200m
- Separation: >=25m

CLASS-B



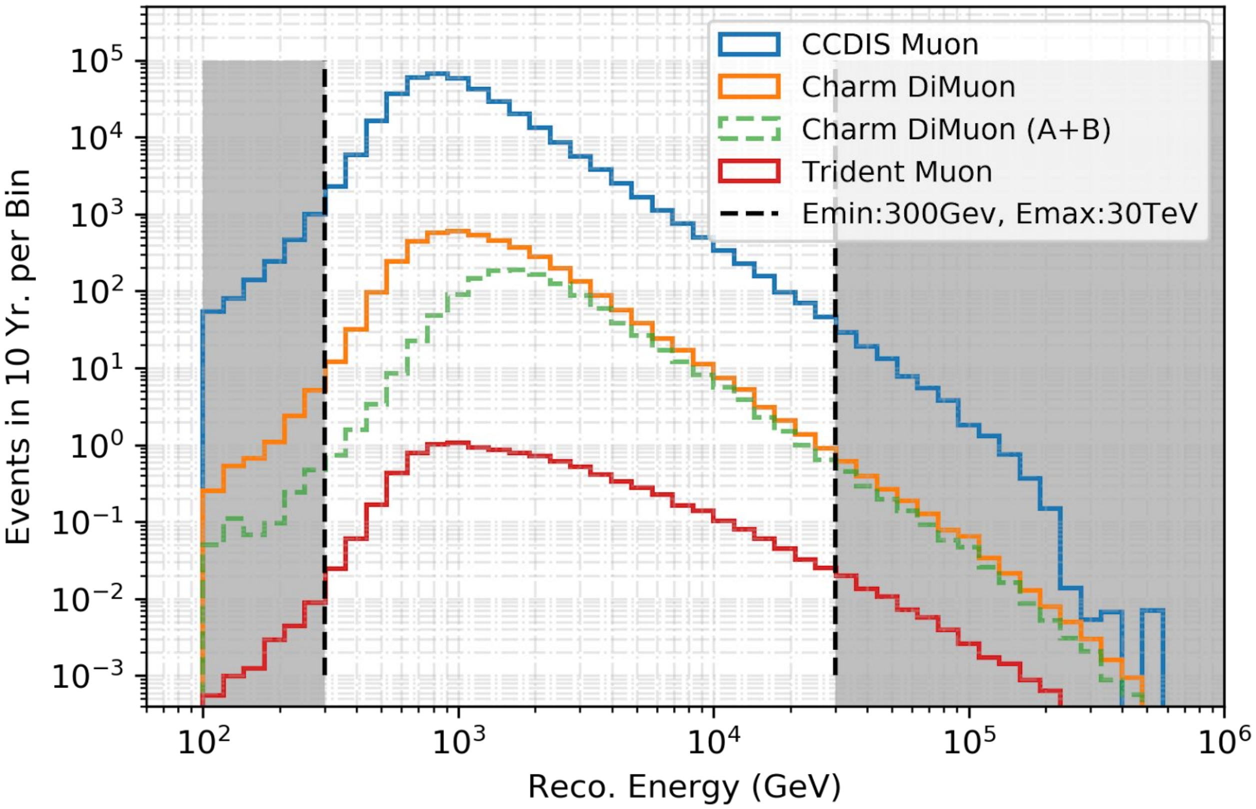
- Track_length: Both >=200m

CLASS-C



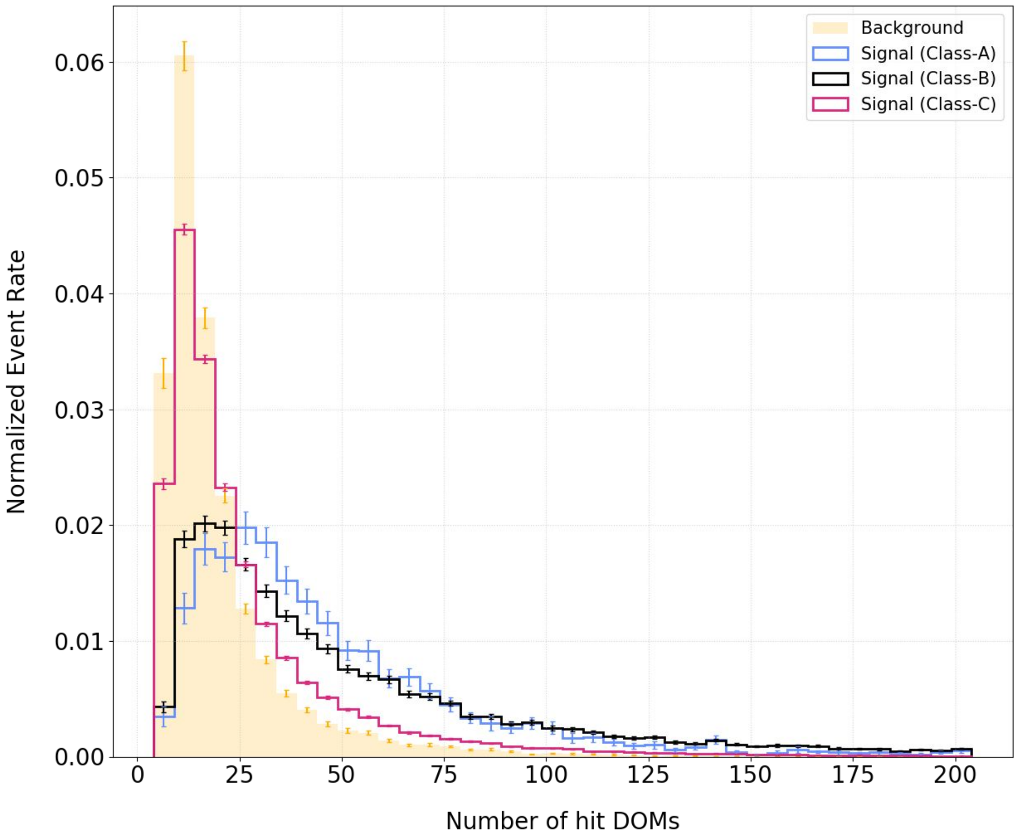
- Track_length: Atleast one <200m

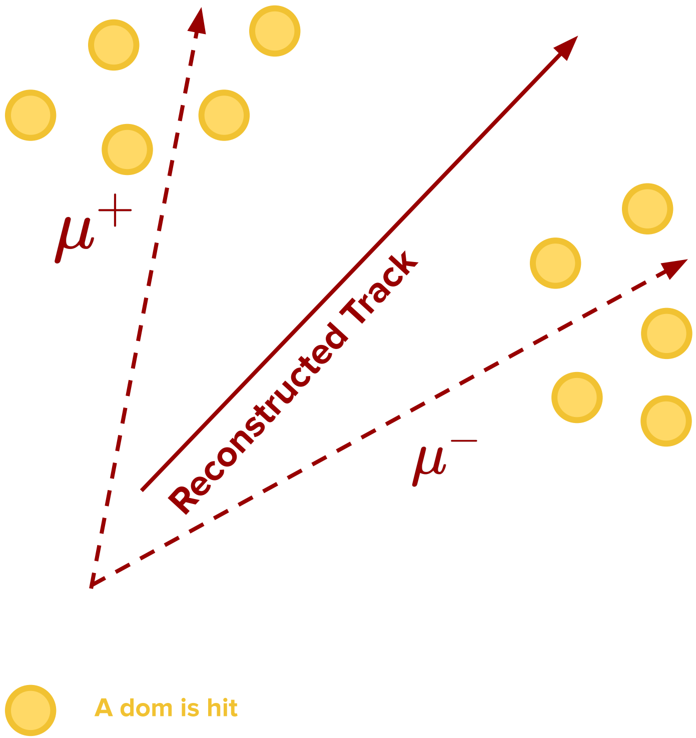
EVENT RATE



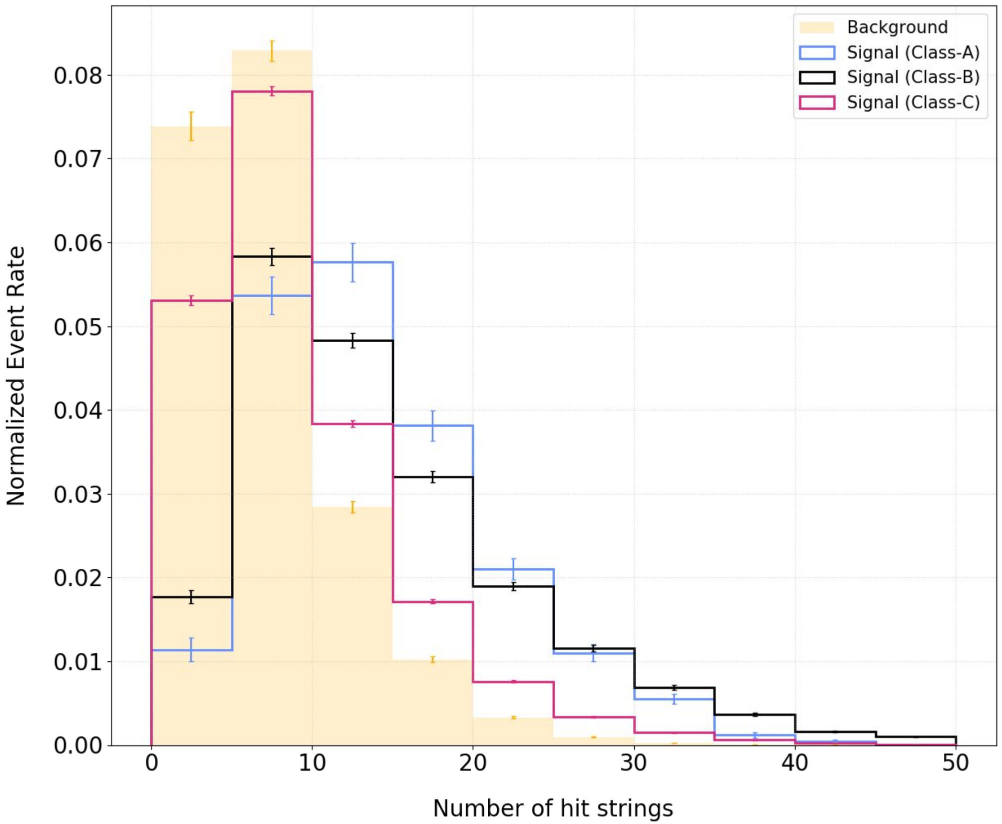
CCDIS Muon
Charm DiMuon
Charm DiMuon (A+B)
Trident Muon
Emin:300Gev, Emax:30TeV
Events in 10 Yr. per Bin
Reco. Energy (GeV)

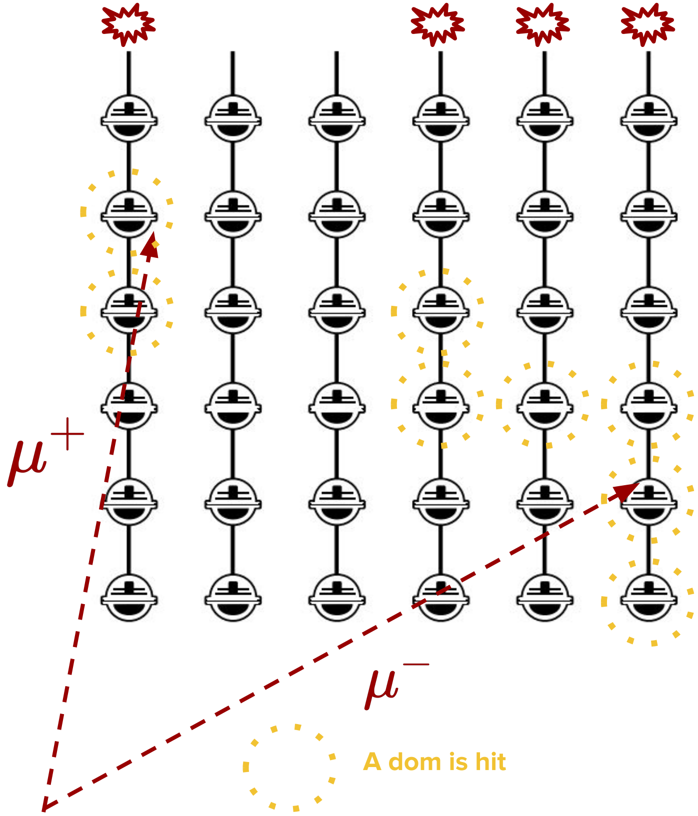
FEATURES: NUMBER OF HIT DOMs



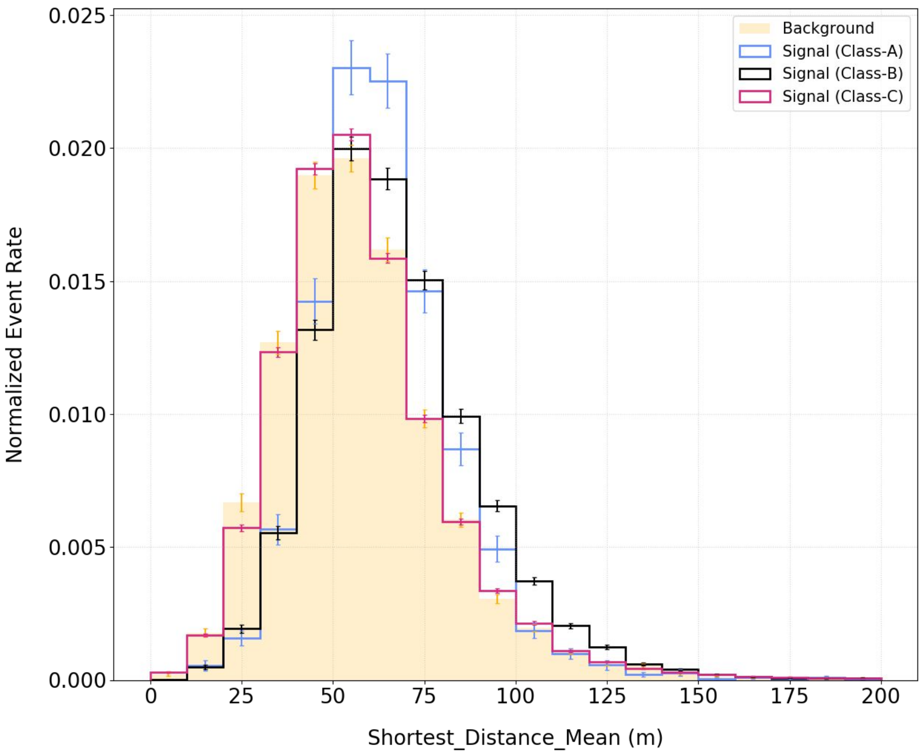


FEATURES: NUMBER OF HIT STRINGs

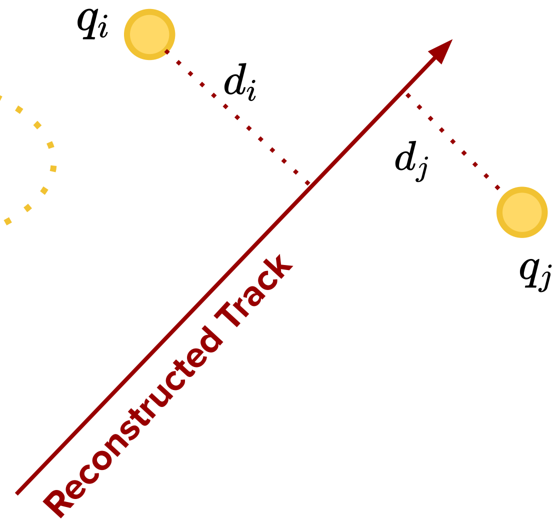




FEATURES: SHORTEST DISTANCE MEAN



$$\bar{d} = \frac{1}{Q}\sum_{i=1}^{N} q_i d_i$$



N : Number of hit DOMS

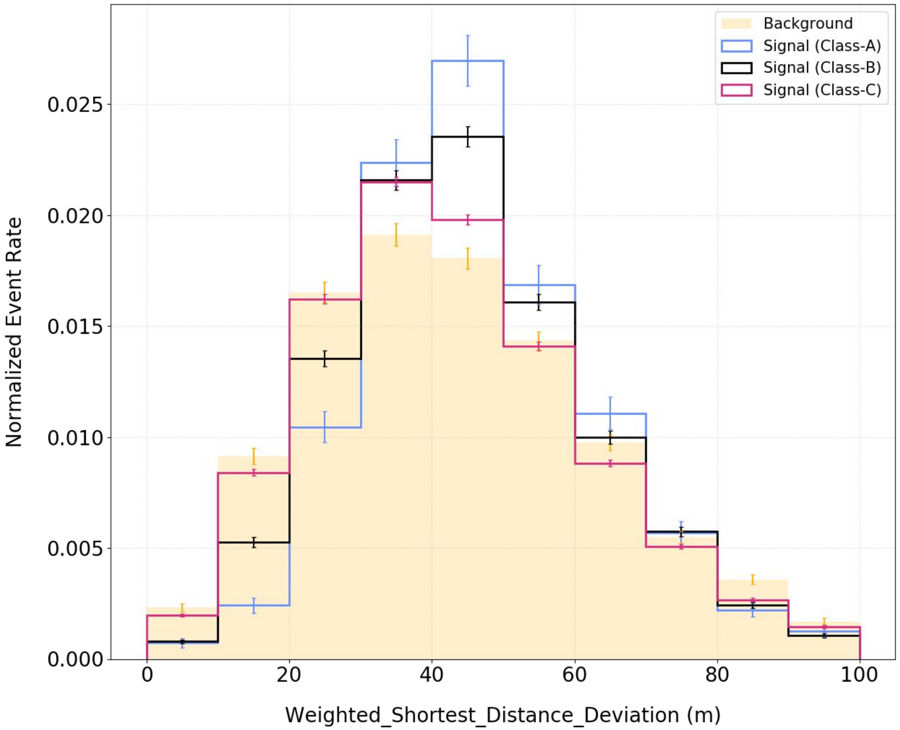
Q : Total charge (light) of all hit DOMs

d_i : Distance of closest approach of the ith hit DOM from the track.

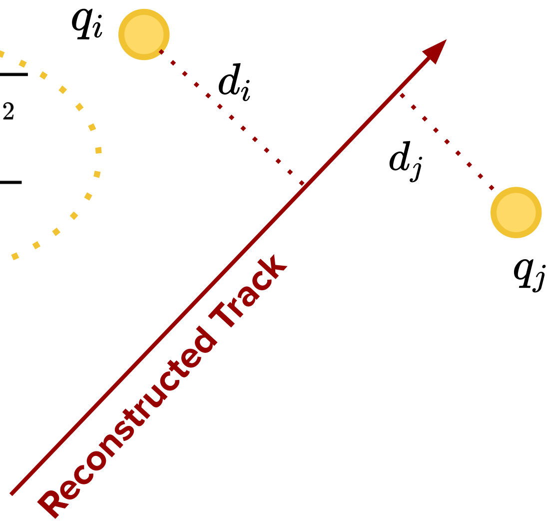
q_i : Total light seen by ith hit DOM.

$\bar{d}$: Average separation of hit DOMs from the track.

FEATURES: WEIGHTED SHORTEST DISTANCE DEVIATION



$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} q_i (d_i - \bar{d})^2}{\frac{M-1}{M} Q}}$$



M : Number of non-zero charge values

σ : Weighted standard deviation of the distance of closest approach.

FEATURES: CLUSTERING [1/2]

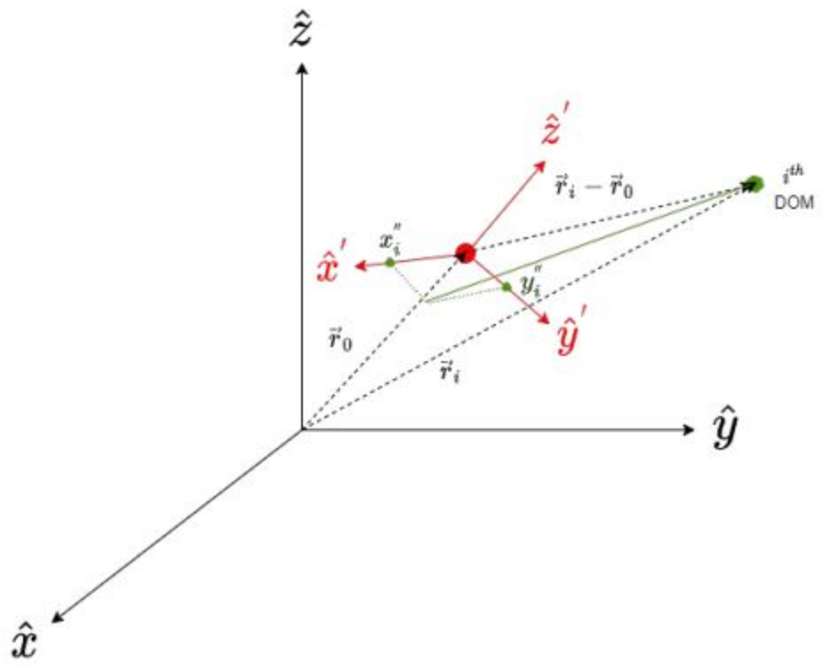
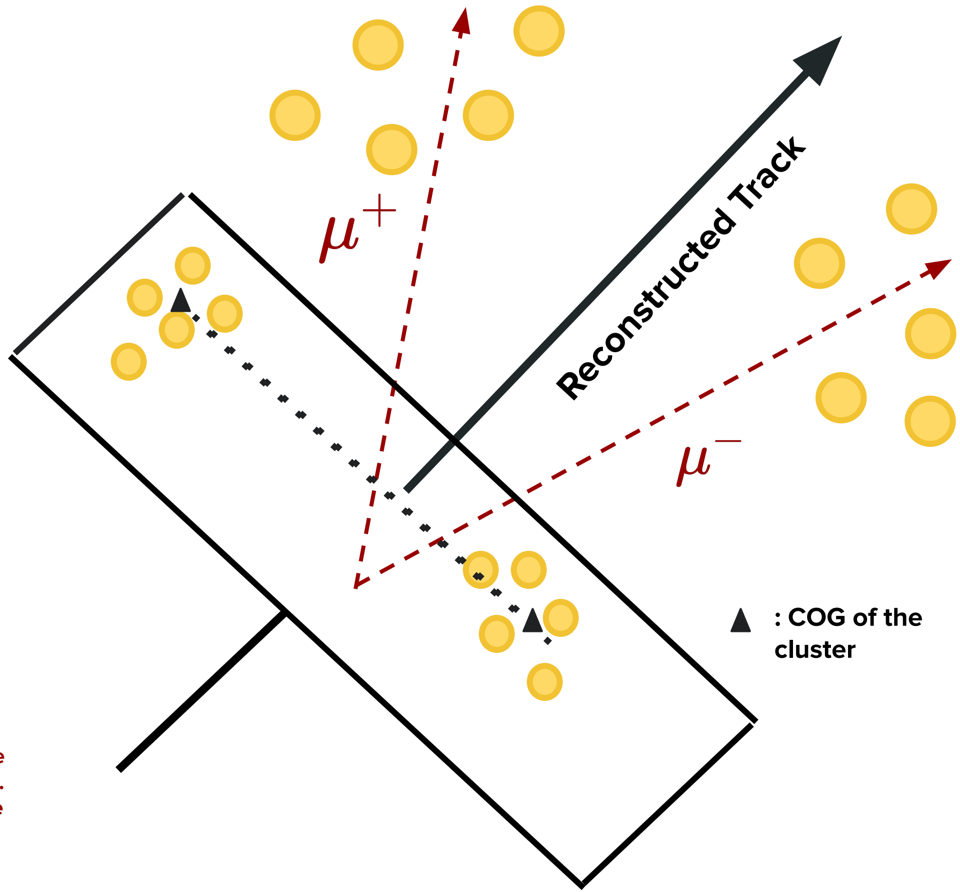
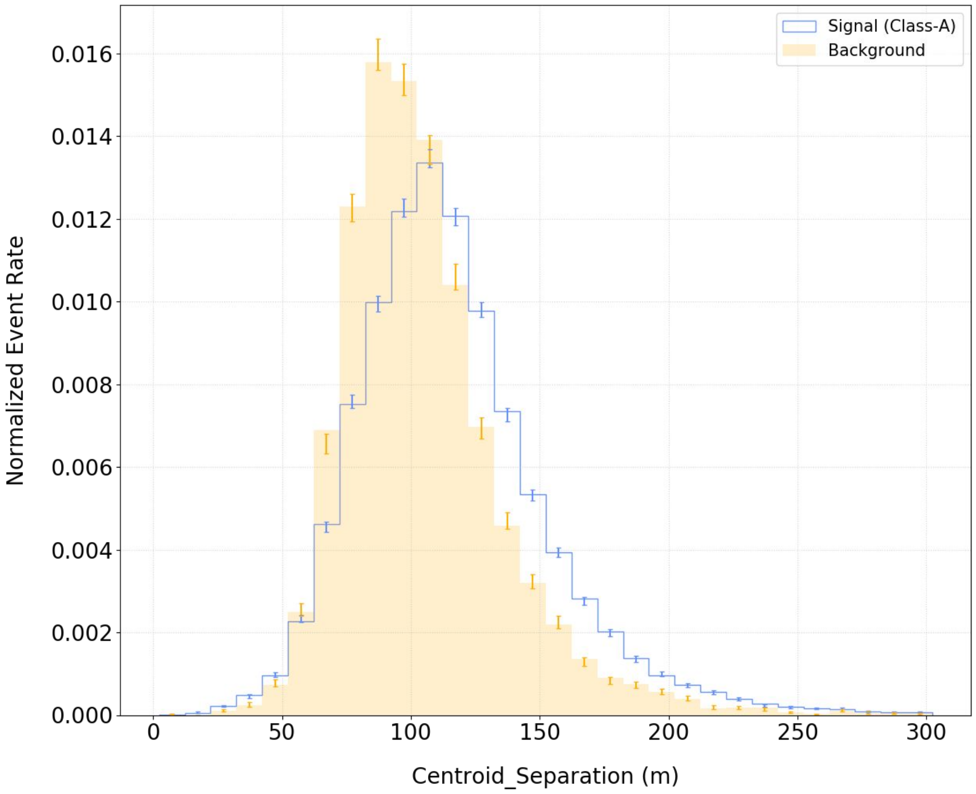


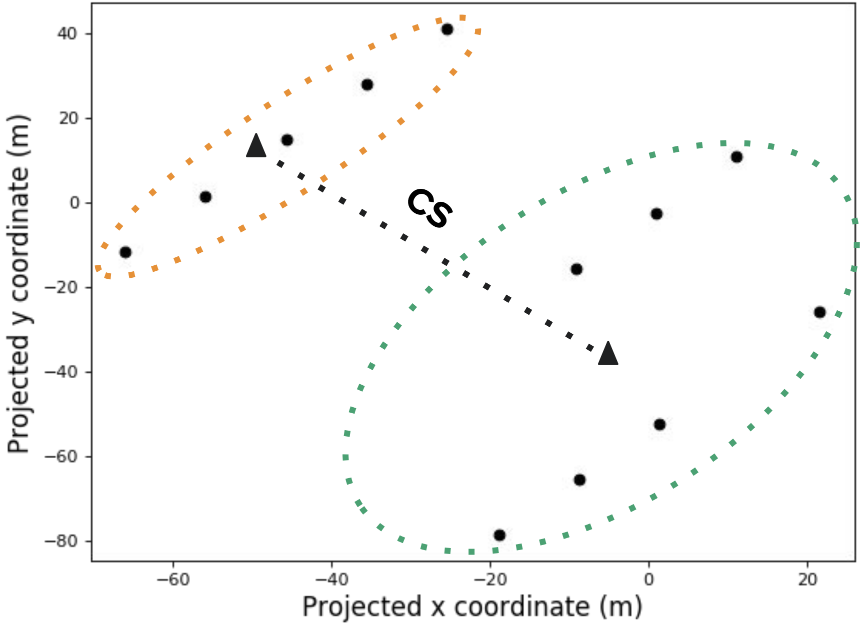
Fig: This figure depicts two coordinate systems. The unprimed coordinate system is the detector coordinate system. The primed coordinate system is the track's coordinate system. The primed x-y plane contains the track's starting point. The track's direction forms the primed z axis. All the hit DOMs are projected into the primed x-y plane.



FEATURES: CLUSTERING [2/2]



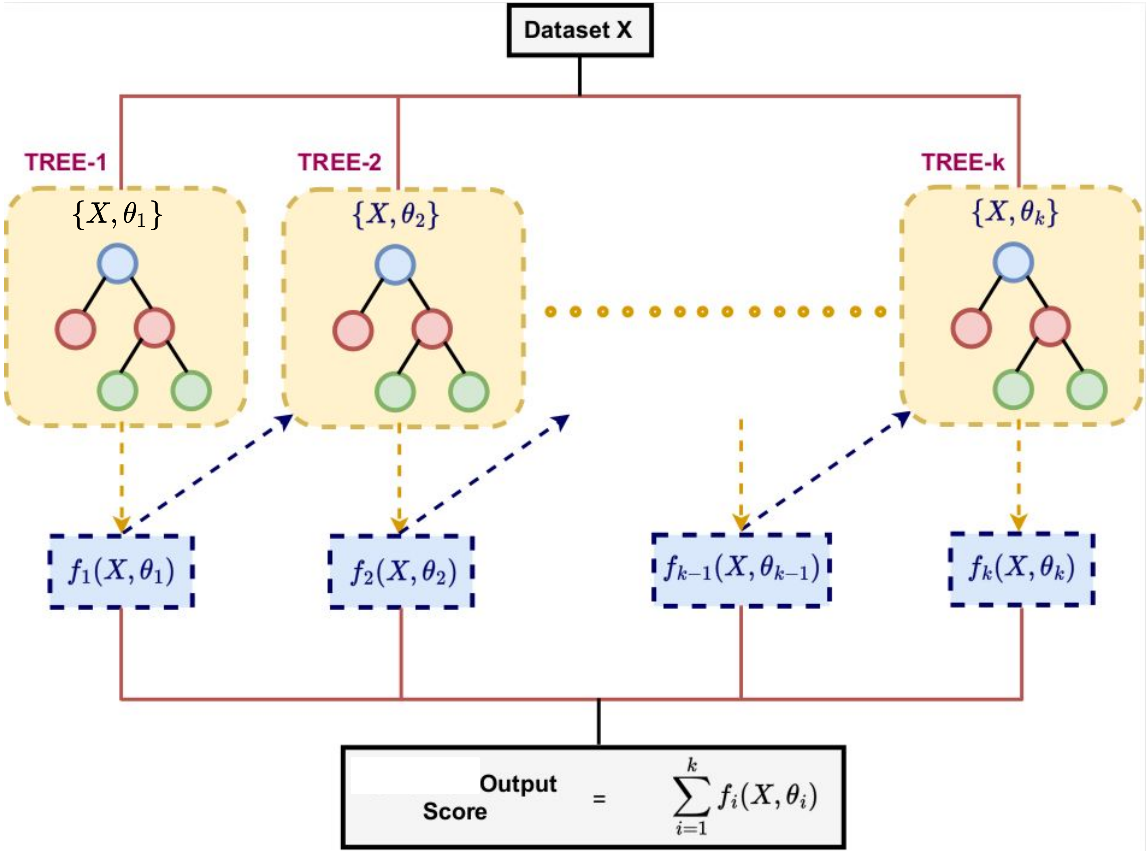
KMEANS Clustering Example



CS : Centroid Separation

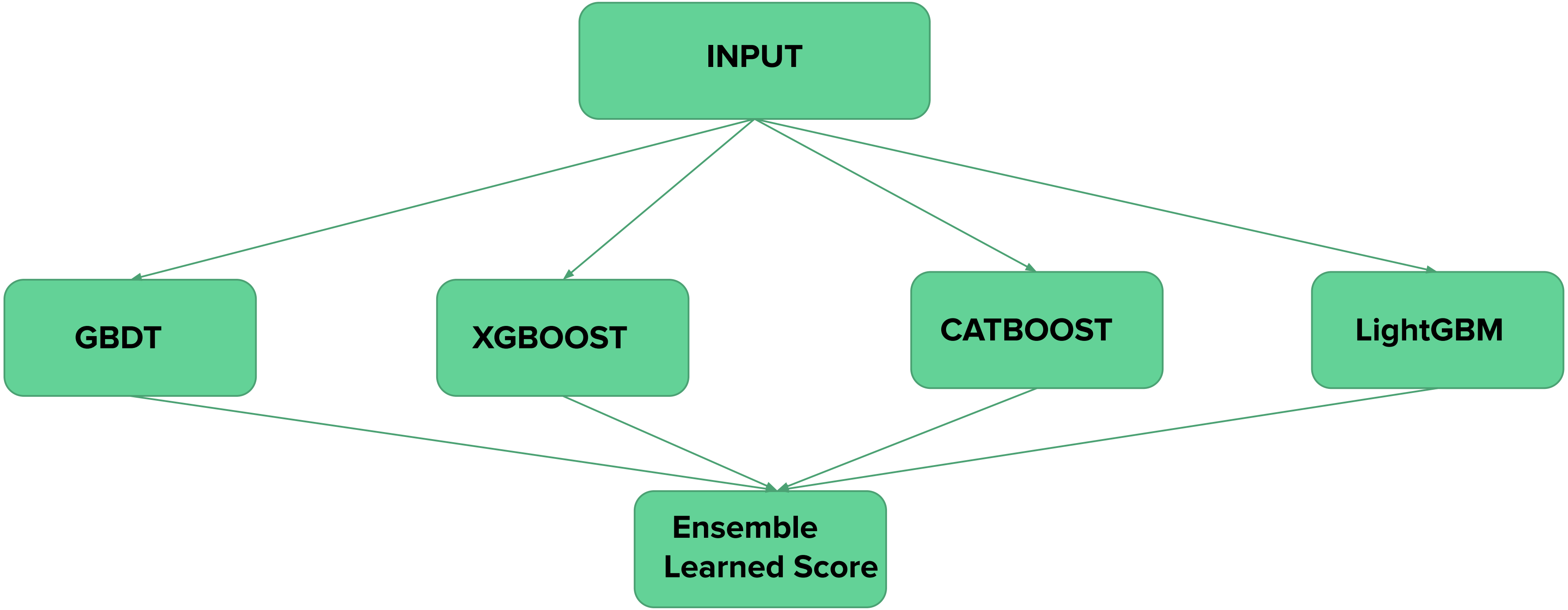
MACHINE-LEARNING ANALYSIS

BOOSTed decision tree



- Together we learn from the mistakes of our past.
- Start with a decision tree and get its output
- Compare this output with the actual output.
- If they are not the same, those events are assigned incorrectly.
- Correct for these mistakes in the next tree.
- Repeat until the stopping condition.

Ensemble Learning



RESULTS: TRAINING AND VALIDATION [1/3]

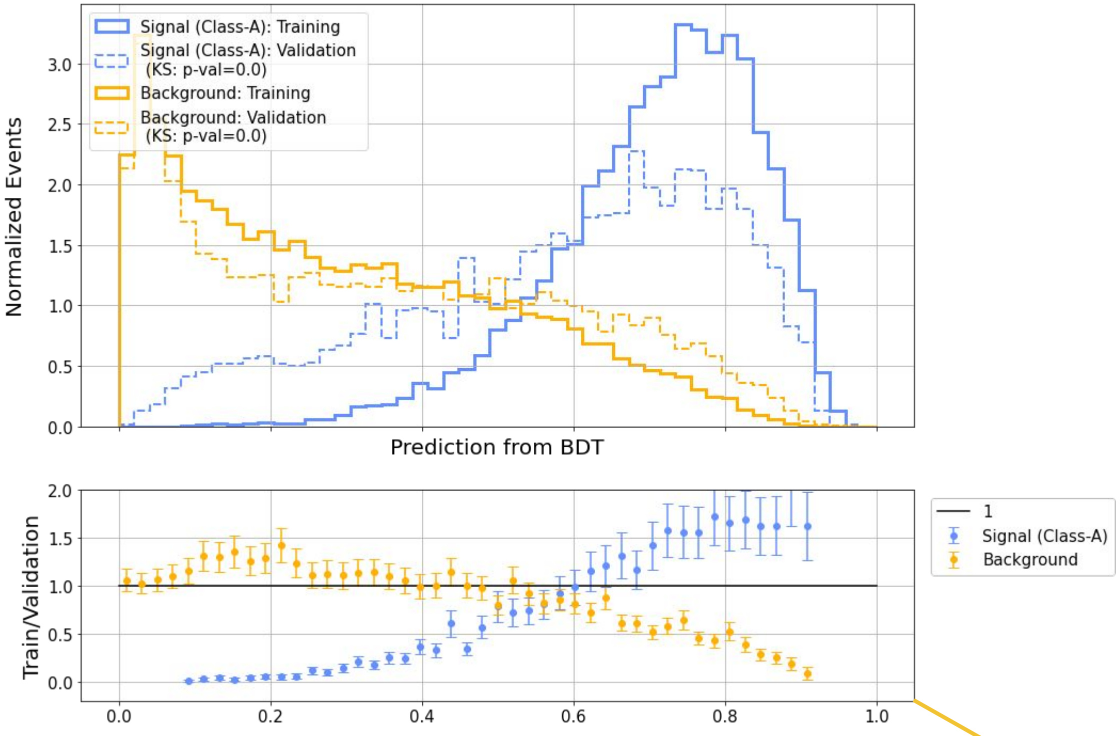


Fig: Training and Validation results using BDT. The optimized values for number of trees and tree depth are 663 and 12 respectively.

- **BDT Score: 1 means signal and 0 is background.**
- **Train on only Class-A events.**
- **Split the training sample into training and validation (80-20).**

68%

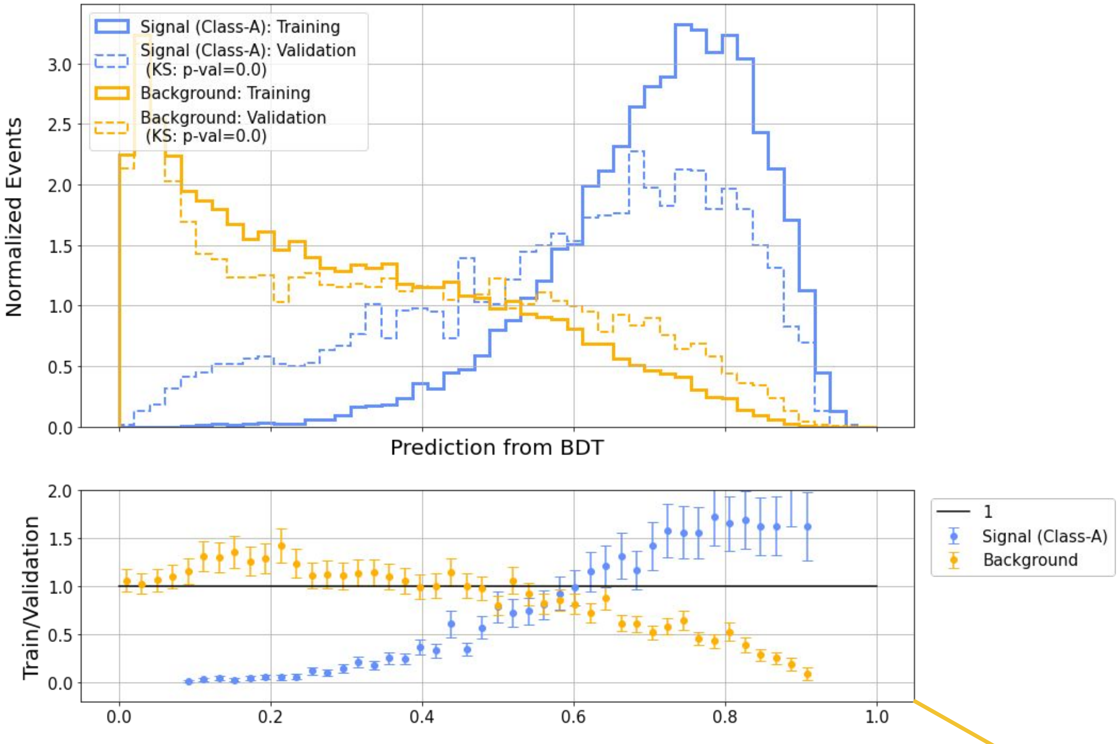


Fig: Training and Validation results using BDT. The optimized values for number of trees and tree depth are 663 and 12 respectively.

68%

- **Train on only Class-A events.**
- **Split the training sample into training and validation (80-20).**
- **Optimize the hyperparameter values like tree depth, number of trees etc.**
- **Test the validation.**
- **Use Kolomogorov-Smirnov Test (KS) to check if the two-distributions are identical.**
- **If not, there is overtraining.**
- **By decreasing the tree depth and the number of trees, reduce overtraining.**

RESULTS: TRAINING AND VALIDATION [3/3]

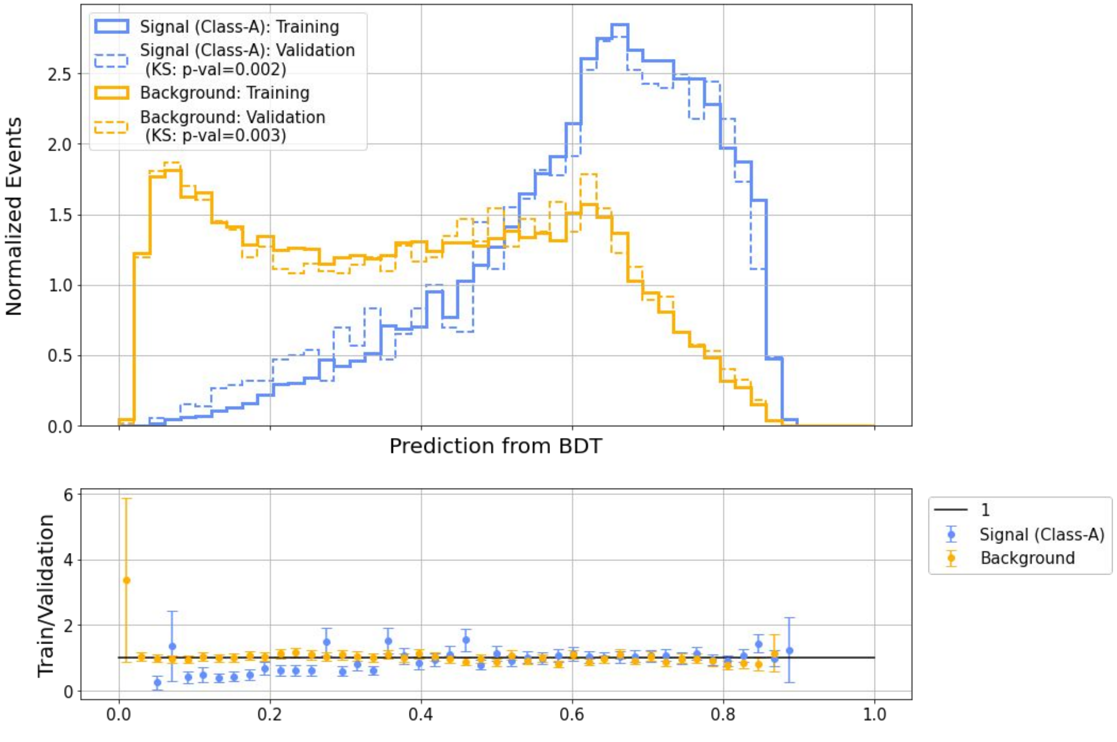


Fig: Training and Validation results using BDT. The optimized values for number of trees and tree depth are 200 and 5 respectively.

- **This is the final selection. The KS-values for both signal background are more than 0.001 (decided cut).**
- **Cannot get rid of overtraining completely.**
- **Accept some.**

RESULTS: TESTING

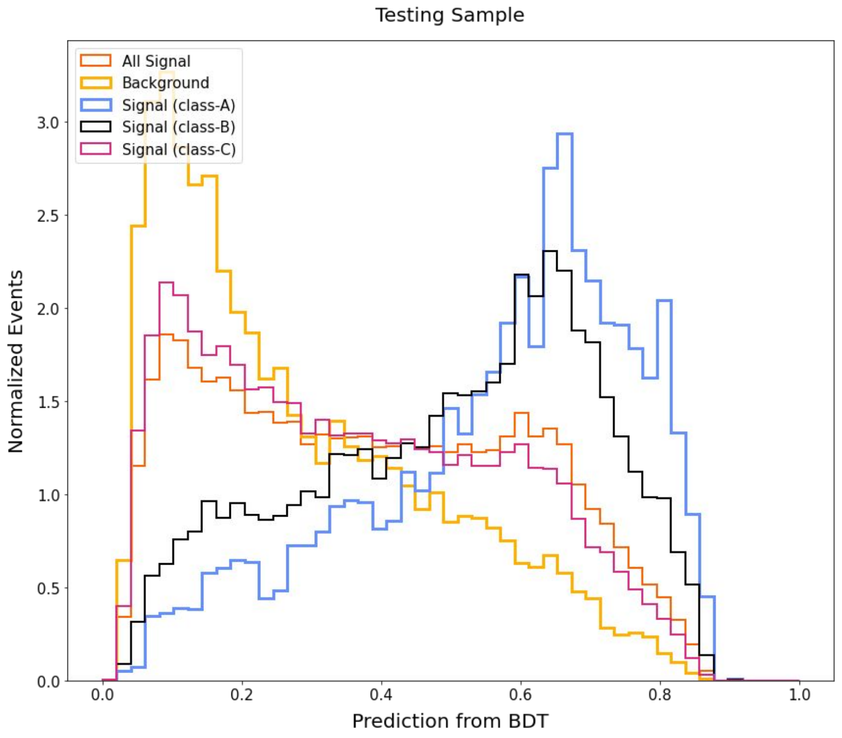


Fig: Testing Results. There is significant improvement over singal to background separation using XGBOOST.

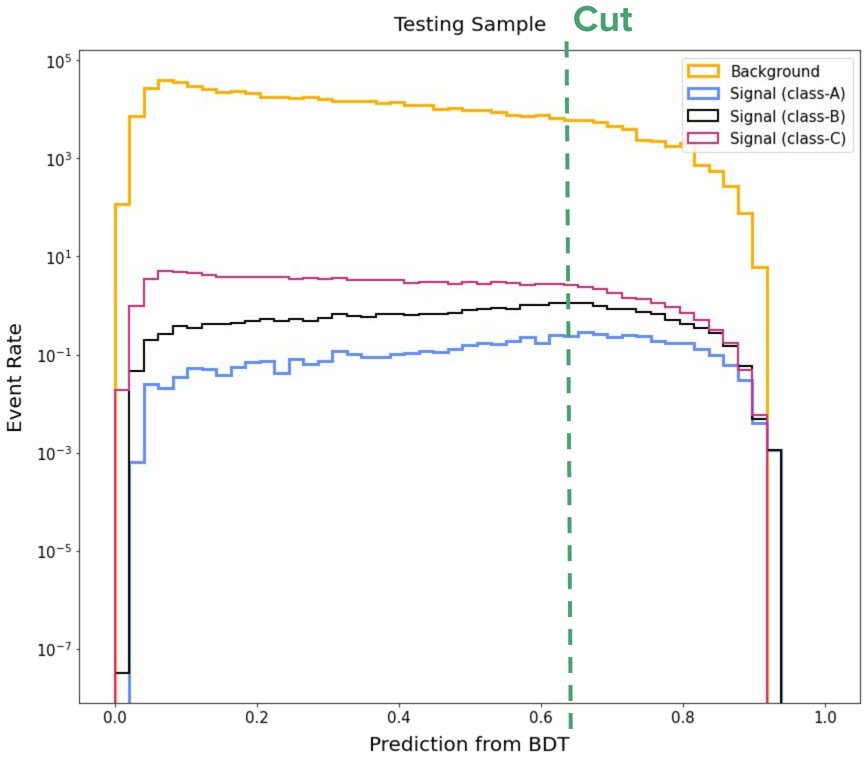


Fig: Testing Results. Non-normalized actual Event Rate in log scale.

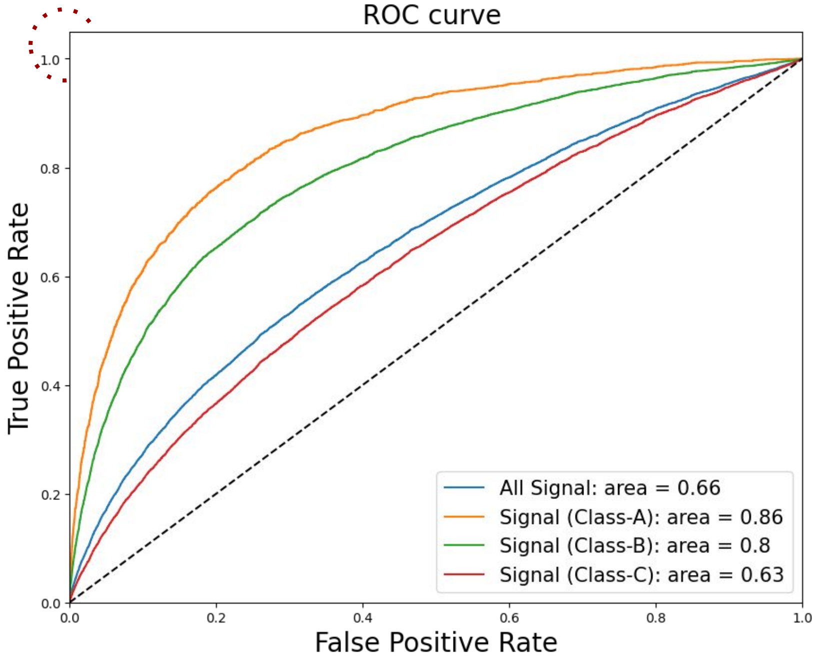


Fig: ROC-AUC Curve. Class-A with background has the maximum area in this curve (Around 0.86).

	Actual Positive	Actual Negative
Predicted Positive	True Positive (TP)	False Positive (FP)
Predicted Negative	False Negative (FN)	True Negative (TN)

$$\text{True Positive Rate} = \frac{\text{TP}}{\text{TP+FN}}$$

$$\text{False Positive Rate} = \frac{\text{FP}}{\text{FP+TN}}$$

RESULTS: Approximate Median Significance (AMS)

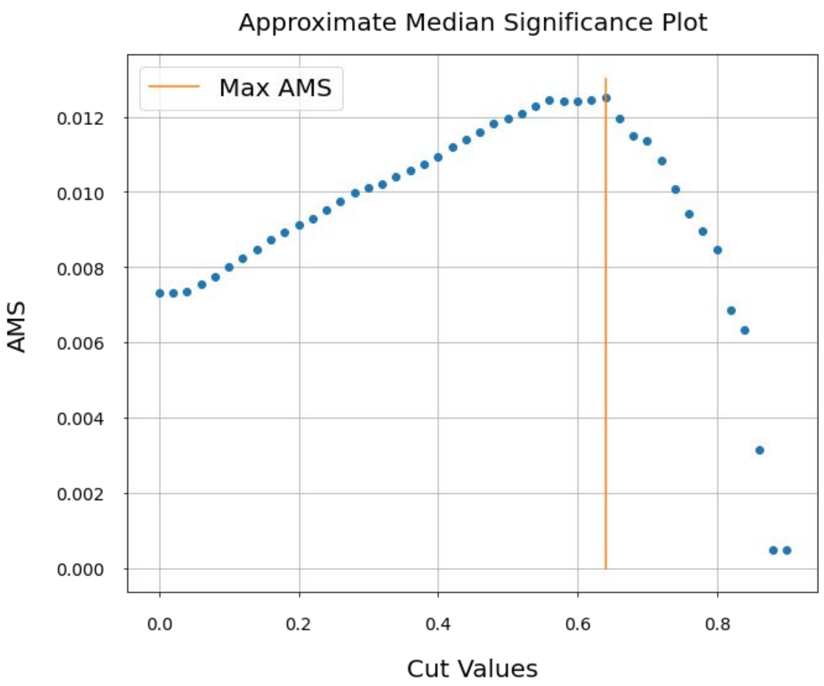


Fig: AMS Plot. The max value of AMS happens at the cut threshold of 0.64.

$$\text{AMS} = \sqrt{2(N_s + N_b)\log(1 + \frac{N_s}{N_b}) - N_s}$$

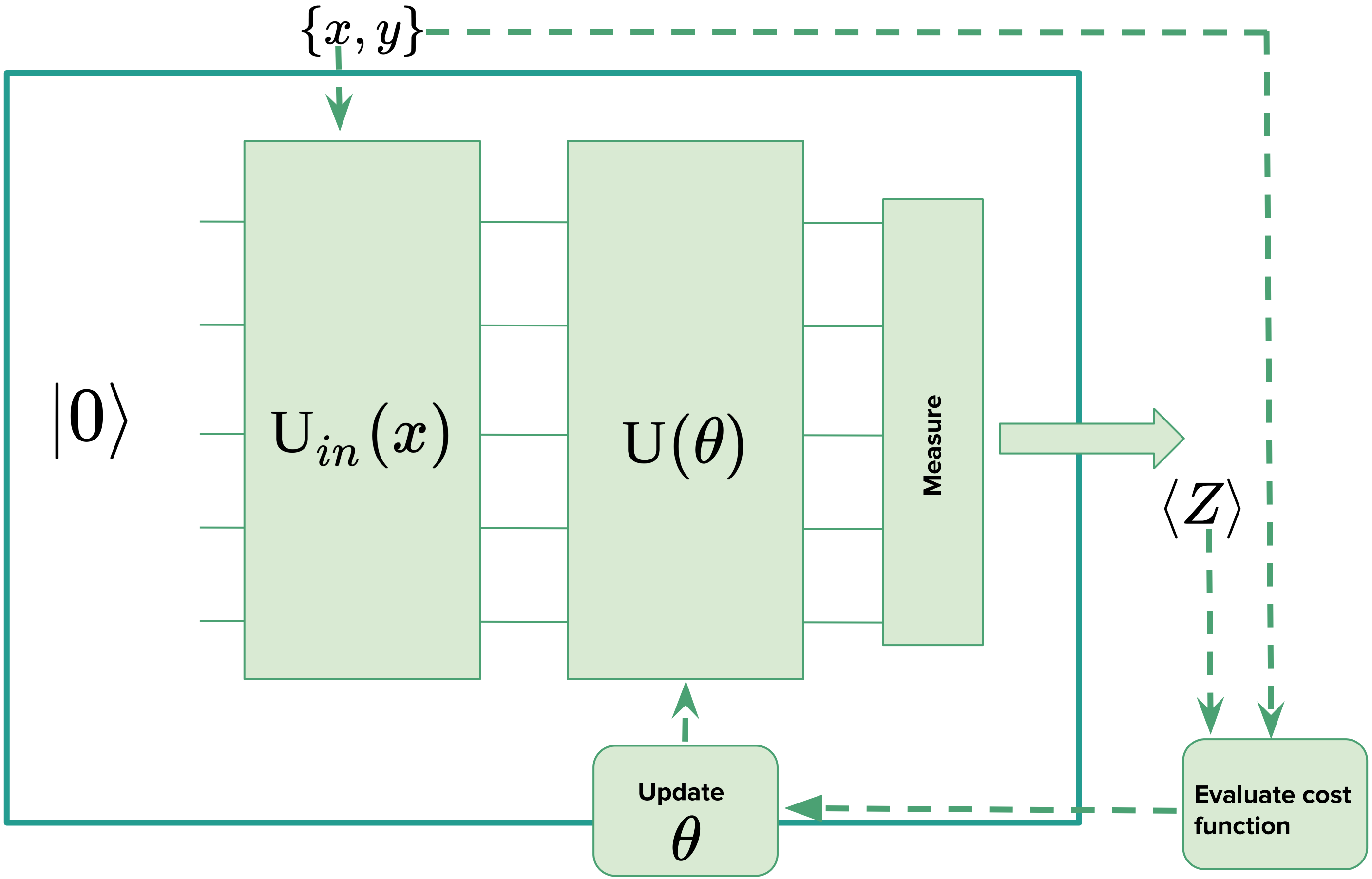
N_s : Number of signal events

N_b : Number of background events

- **In case of high background, AMS is asymptotically equal to**

$$\frac{N_s}{\sqrt{N_b}}$$

QUANTUM MACHINE LEARNING ARCHITECTURES



RESULTS: ROC-AUC

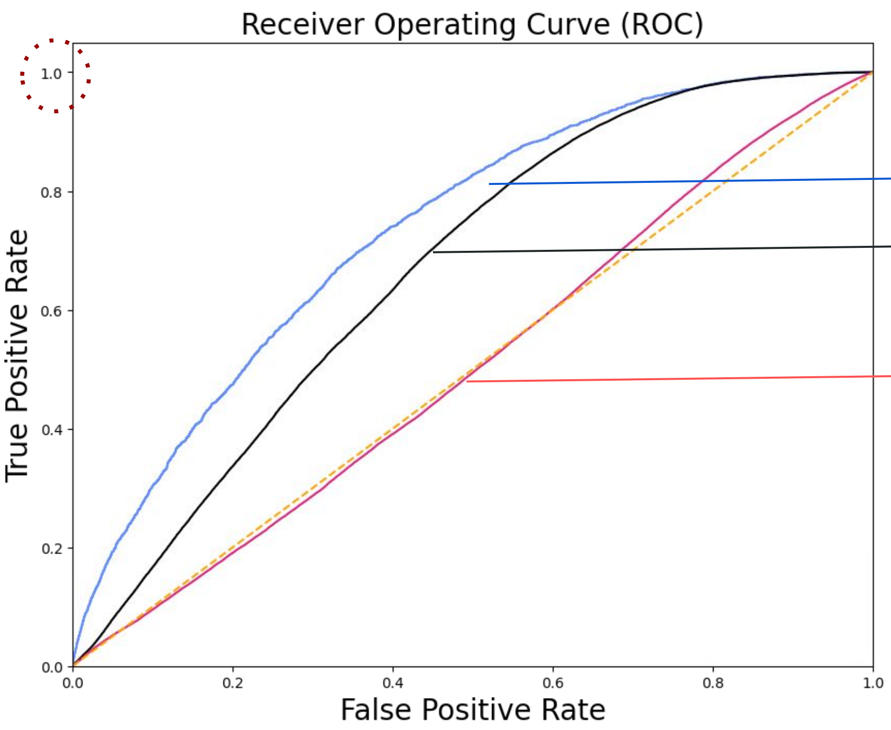


Fig: The blue curve represents the ensemble learning and the black curve represents the roc-auc for the quantum algorithm using IBMQ

Classical Ensemble-Decision Trees (Class-A) (0.75)

Quantum Variational Algorithm (Class-A) (0.7)

Classical Ensemble-Decision Trees (Class-C) (0.51)

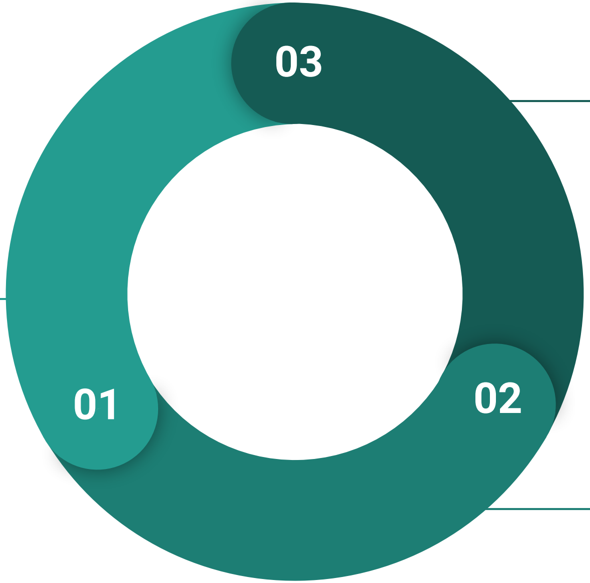
CONCLUSIONS

CONCLUSIONS

NEUTRINO TRIDENT EVENTS

Production of three outgoing leptons

Powerful probe into search for BSM bosons.



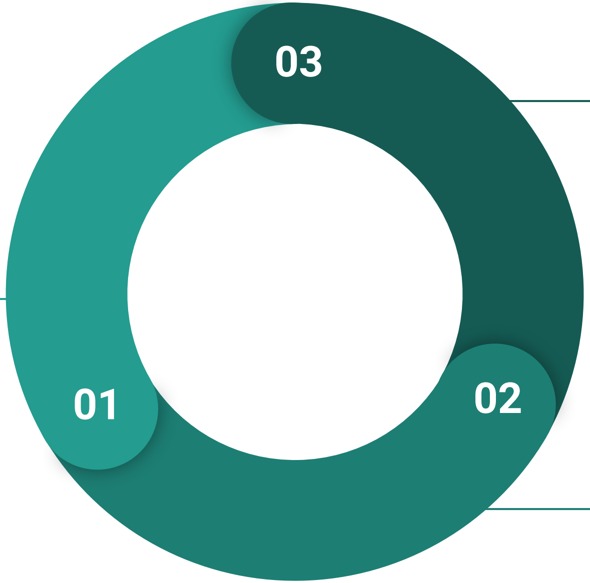
ML-Decision Trees

They amplified the difference between signal and background by looking into the higher-dimensional sub-spaces of the features.

IceCube detector

Features based on detector resolution and geometry properties, Cherenkov light distribution: Used for signal/background separation.

NEXT STEPS



GET PLOTS FOR CHARM DIMUONS

See how the BDT distribution looks like for charm dimuons

Decide Cuts

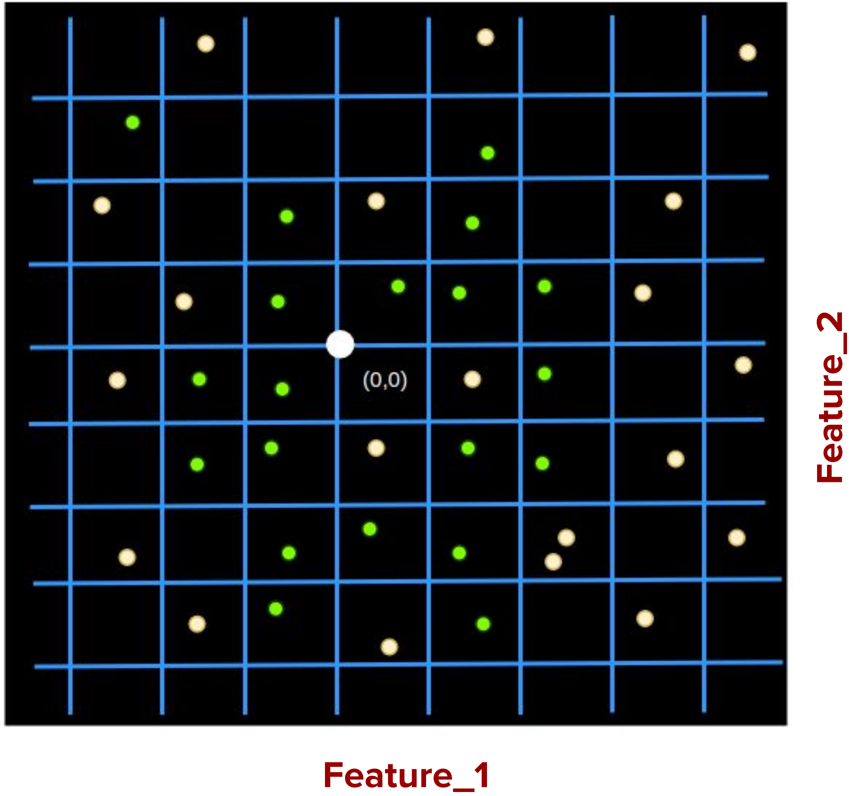
What cut can be used beyond which one can say that there is signal?

IceCube Data

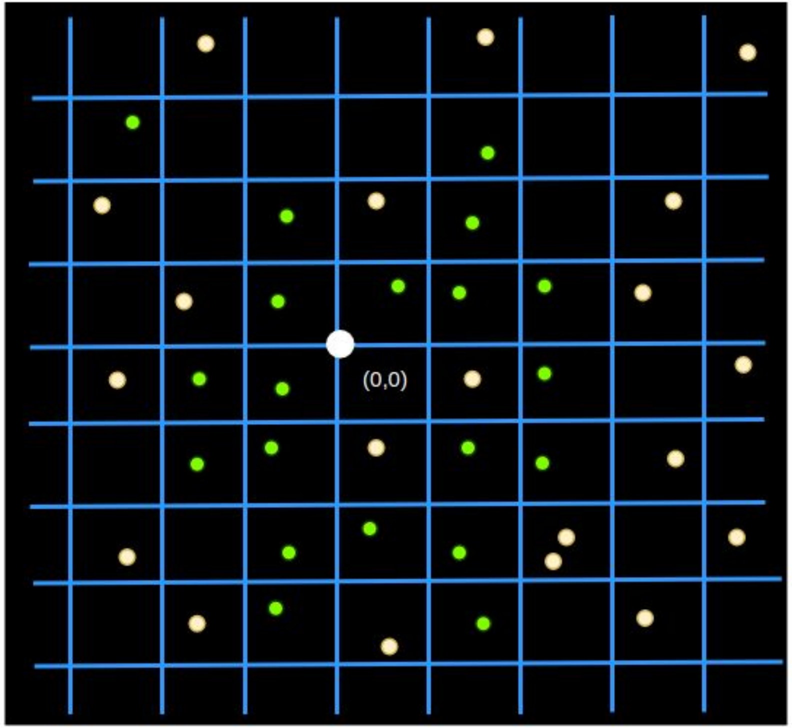
Check how is the real data performing on XGBOOST.

THANK-YOU

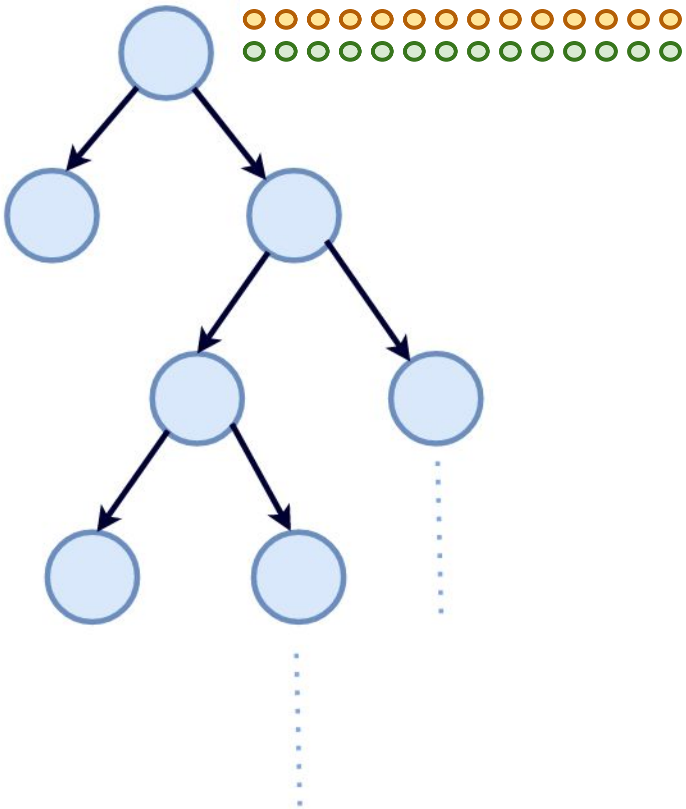
BACKUP-SLIDES



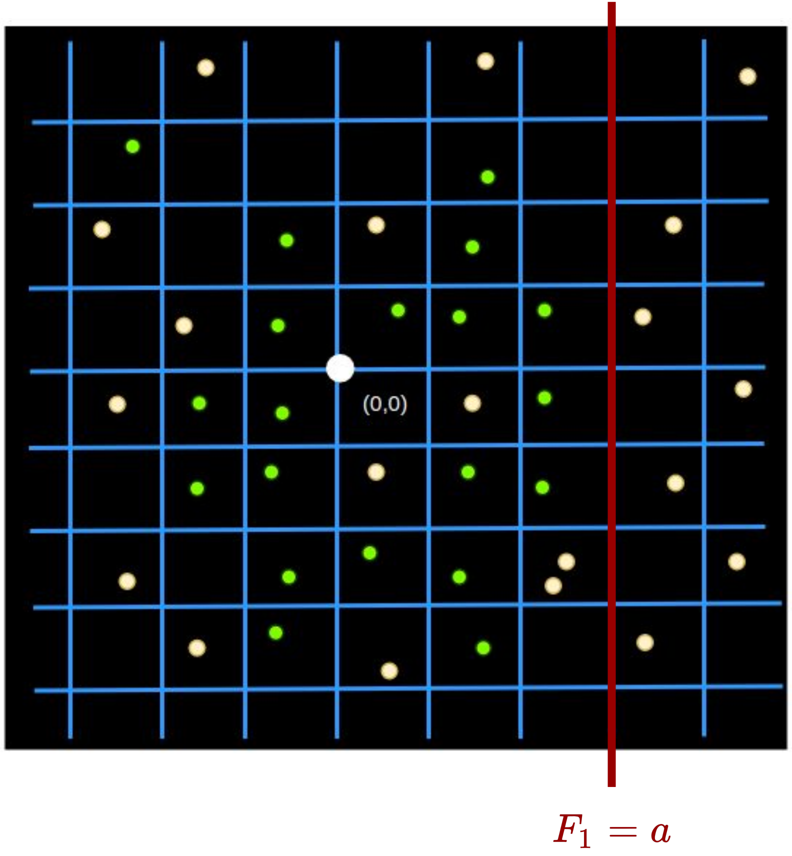
Can you use a line to separate one class events from the other?

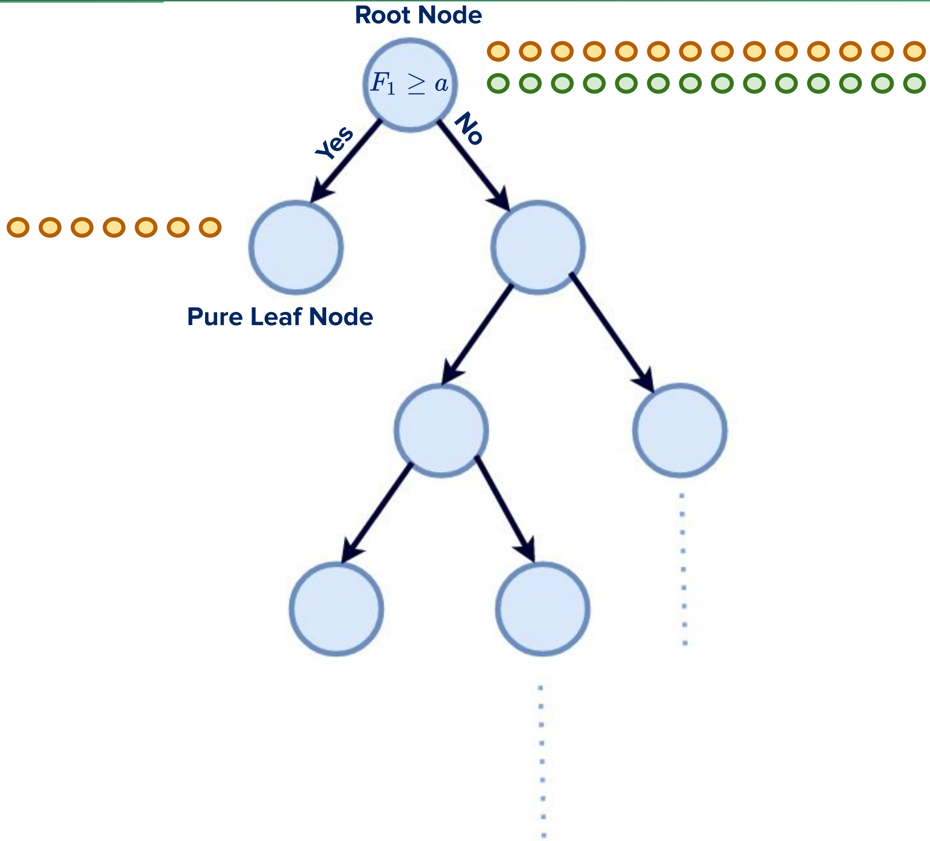


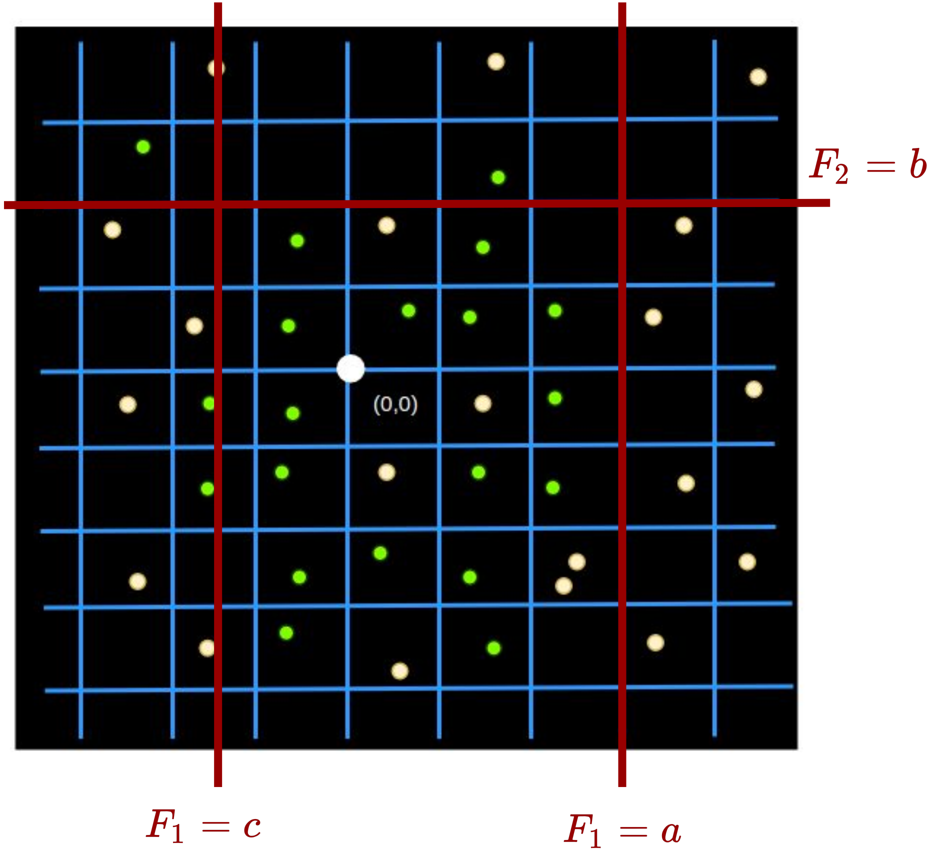
(0,0)

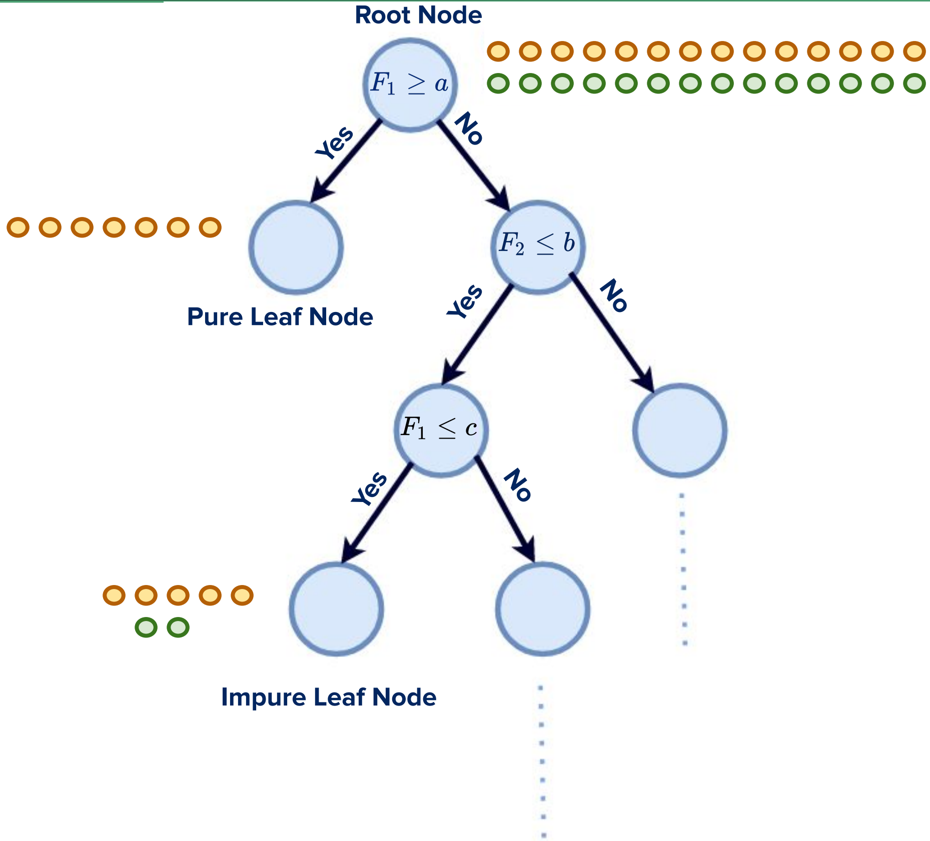


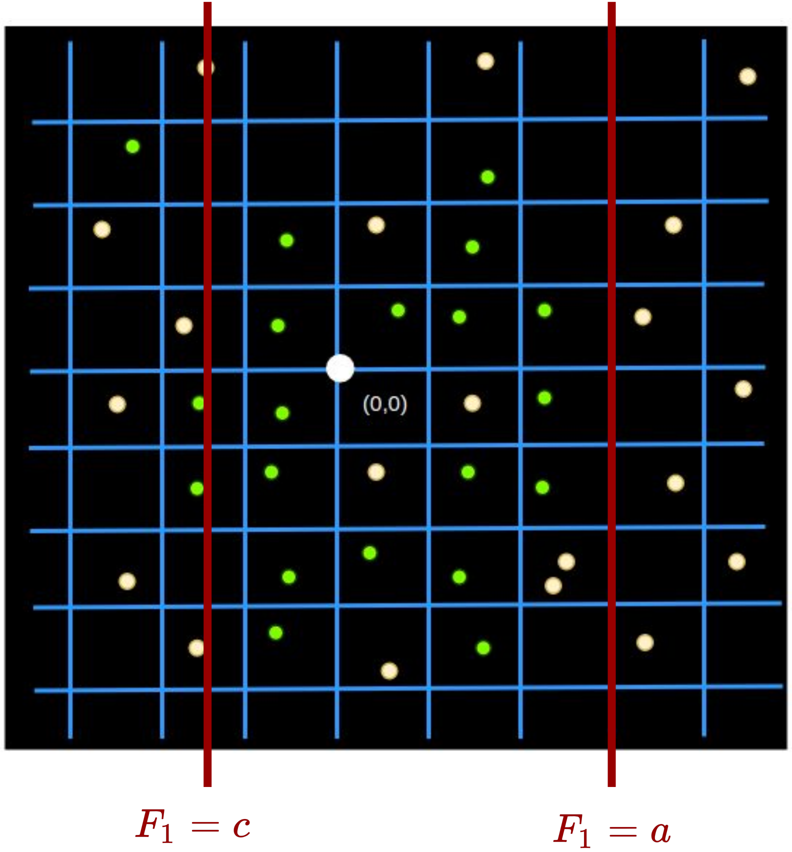
Root Node

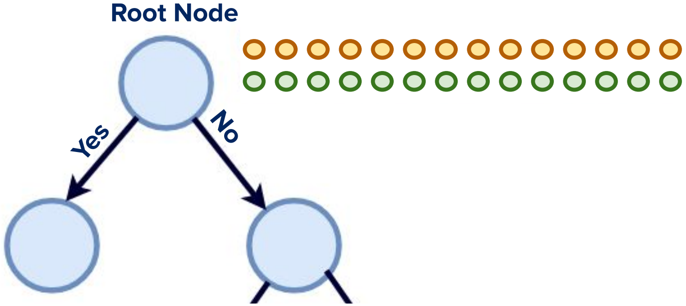

(0,0)
$F_1 = a$

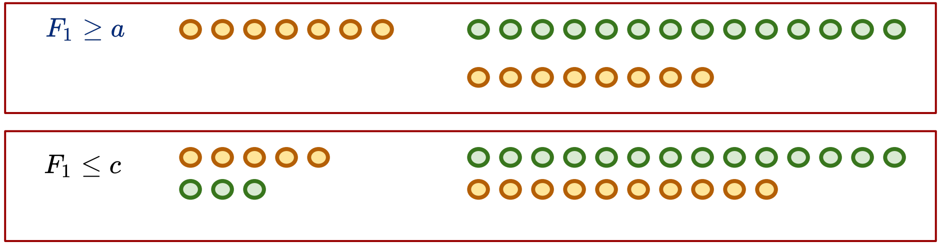

Root Node
$F_1 \geq a$
Yes
No
Pure Leaf Node


(0,0)
$F_2 = b$
$F_1 = c$
$F_1 = a$

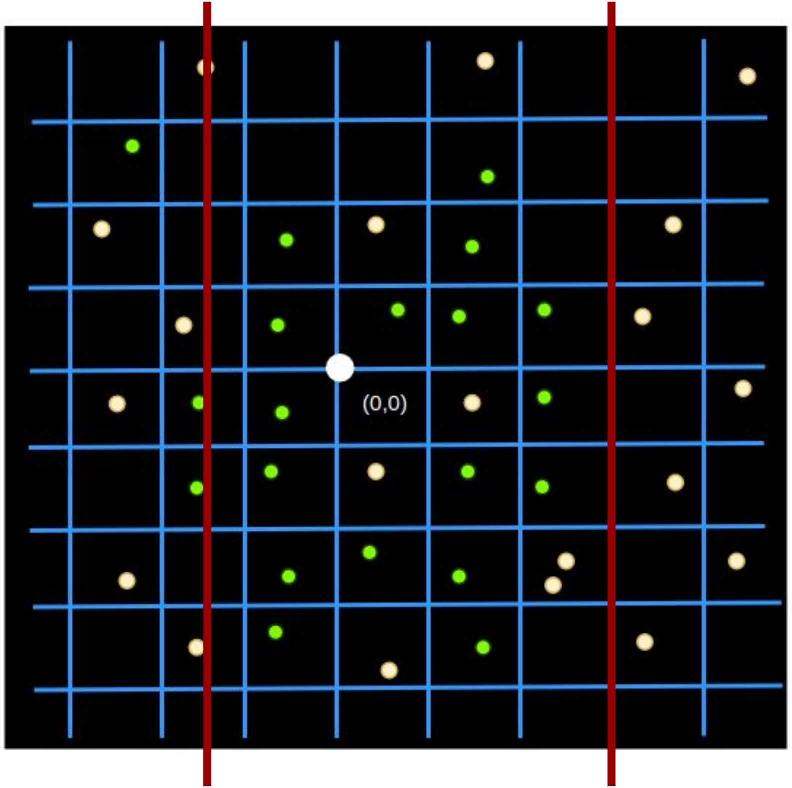

Root Node
$F_1 \geq a$
Yes
No
Pure Leaf Node
$F_2 \leq b$
Yes
No
$F_1 \leq c$
Yes
No
Impure Leaf Node


(0,0)
$F_1 = c$
$F_1 = a$

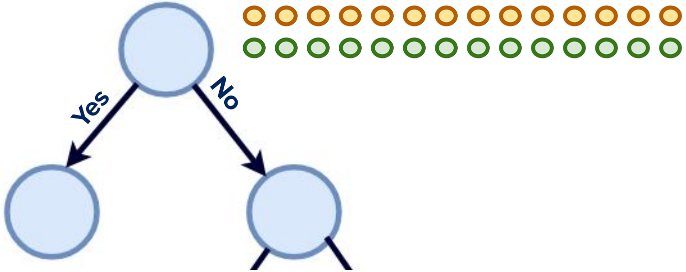

Root Node
Yes
No

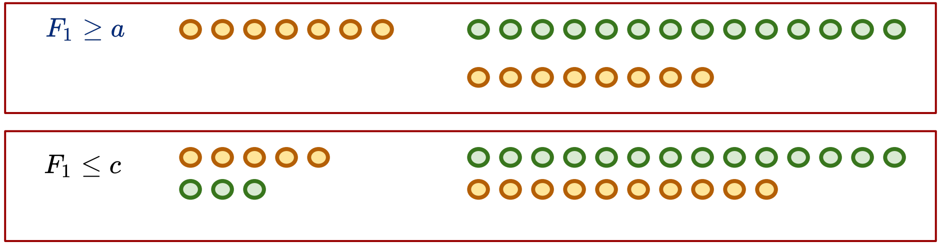

$F_1 \geq a$
$F_1 \leq c$

DECISION TREES: CLASSIFY FOR US [6/9]



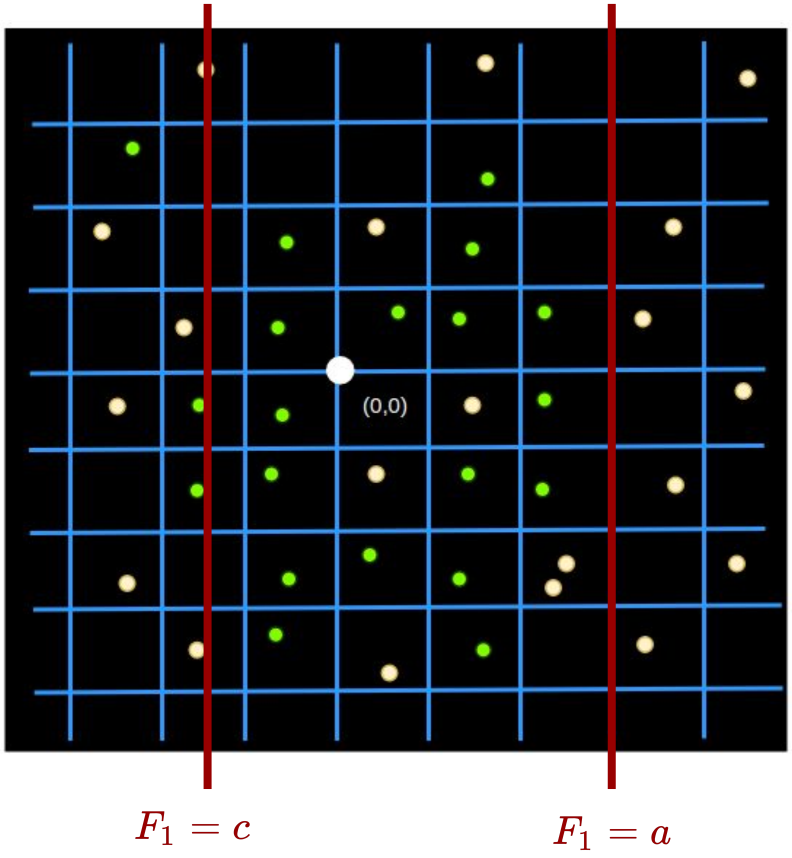
$F_1 = c$ $F_1 = a$

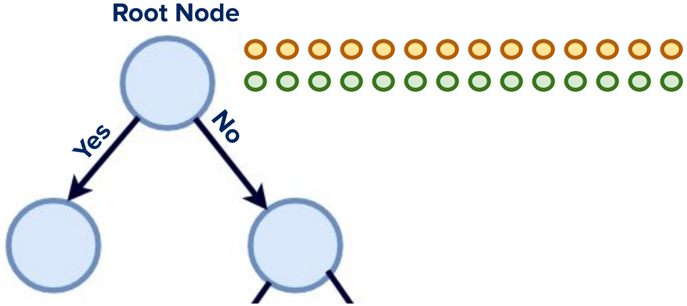


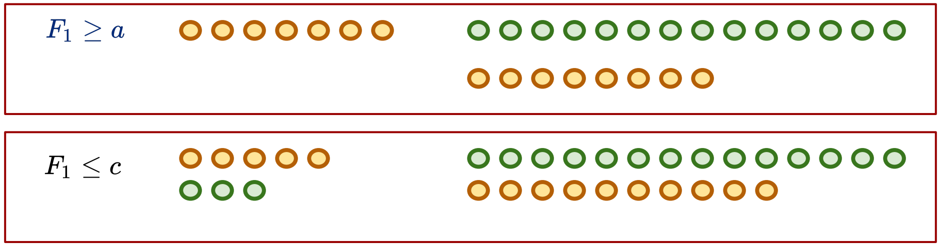


$$\text{Entropy}_{\text{node}} = -\sum_{i=1}^{2} p_i \log_2 p_i$$

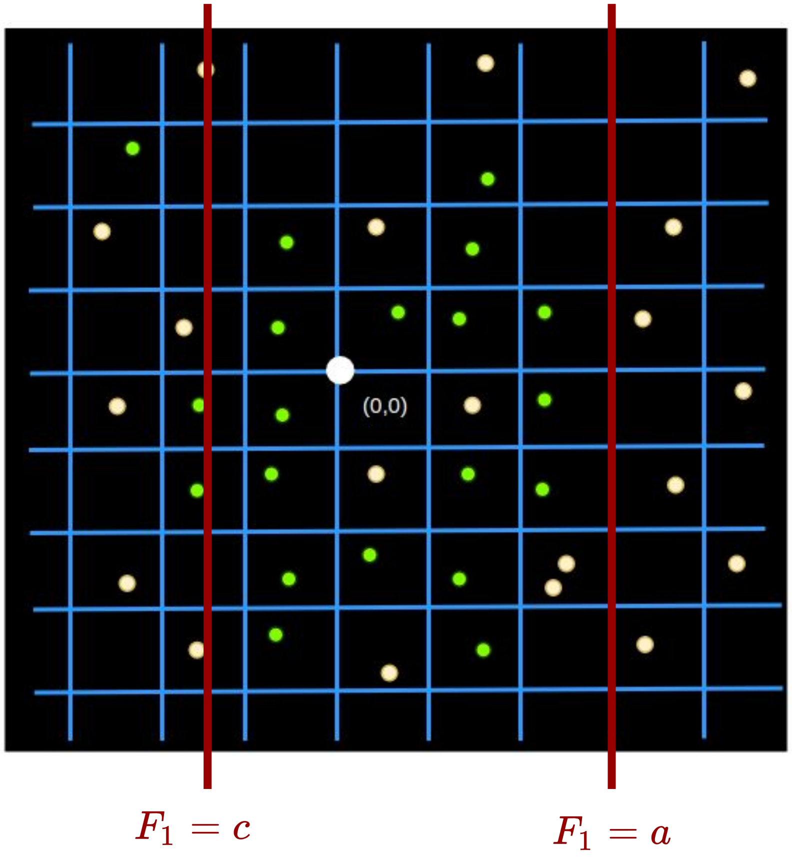
p_i **: probability of each class (signal and bkg.)**

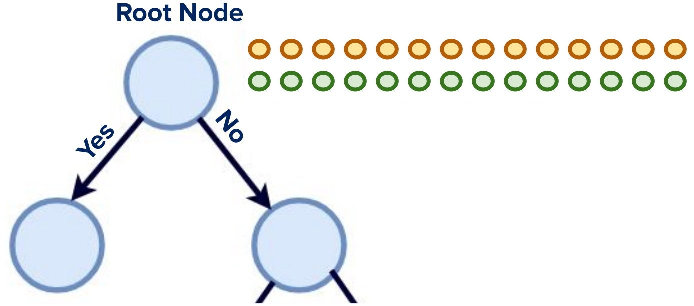






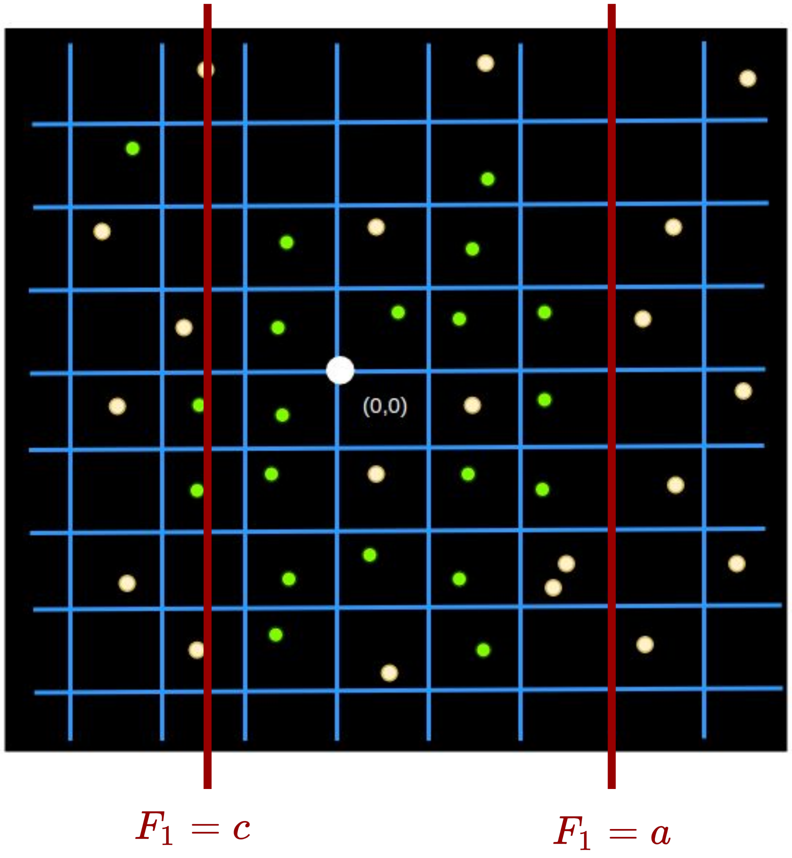
- **Clearly entropy of root node is 1 (max. value).**

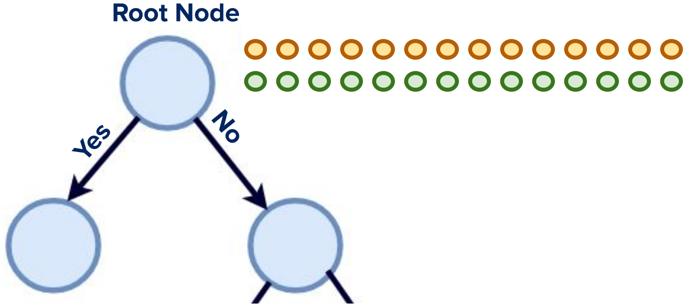


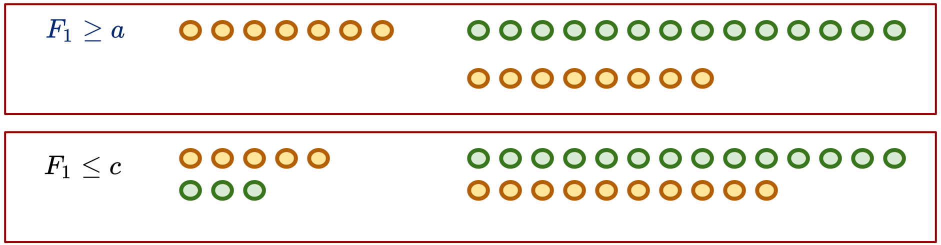


$F_1 \geq a$	○○○○○○○	○○○○○○○○○○○○○○ ○○○○○○○○
$F_1 \leq c$	○○○○○ ○○○	○○○○○○○○○○○○○○ ○○○○○○○○○○

- Clearly entropy of root node is 1 (max. value).
- Entropy for ☐ is 0 (Pure leaf node).





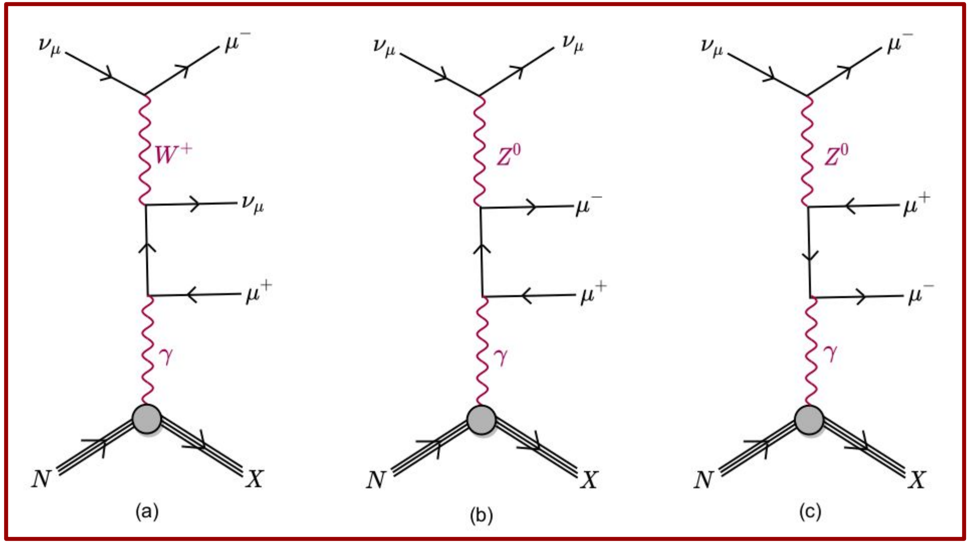


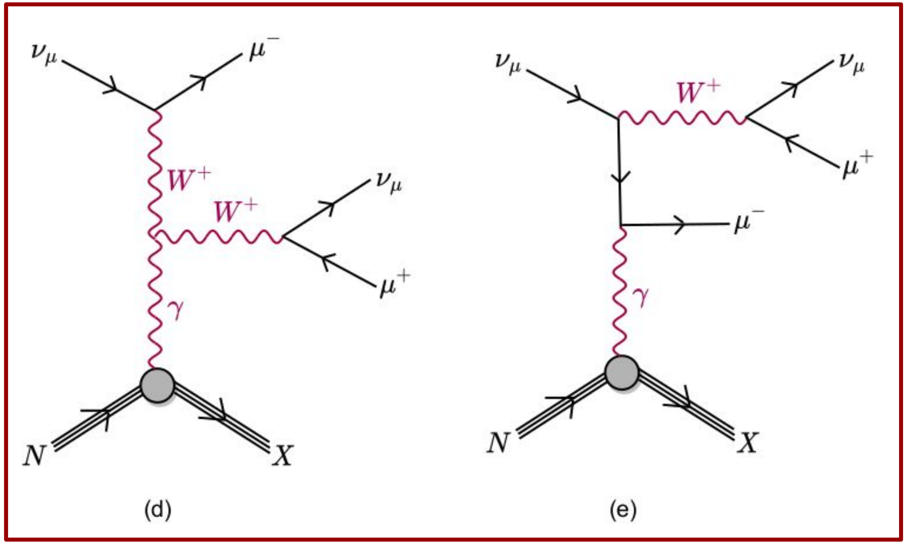
$$\text{Information Gain} = \text{Entropy}_{parent} - \sum_j \alpha_j \text{Entropy}_{daughter_j}$$

1

$$\alpha_j : \frac{\text{Total points in } j^{th} \text{ daughter node}}{\text{Total points in parent node}}$$

NEUTRINO TRIDENT EVENTS: MUONIC CHANNEL





❖ **Diagrams d and e: W-Bosons are ON-SHELL. High energy neutrinos (above ~ 3TeV) [1] can produce on-shell W boson via these diagrams and enhance the eventrate at the detectors.**

1. https://indico.fnal.gov/event/44492/contributions/214325/attachments/143935/182431/WIN_2021_Poster

CROSS-SECTION

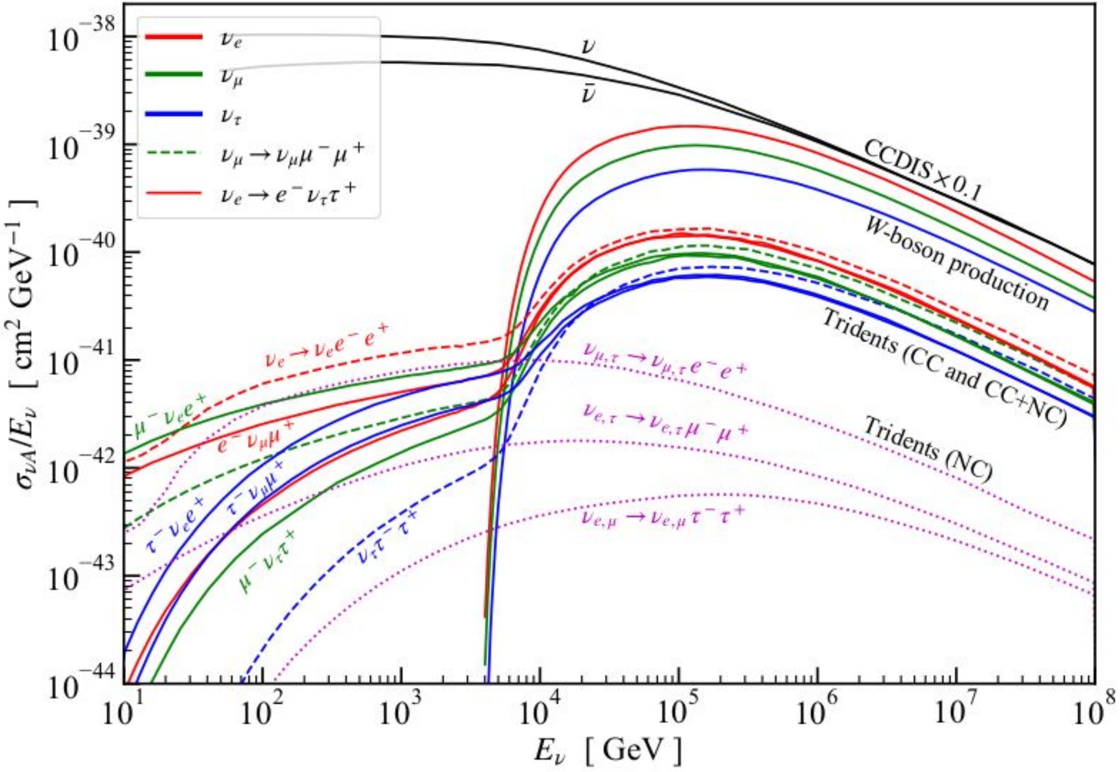
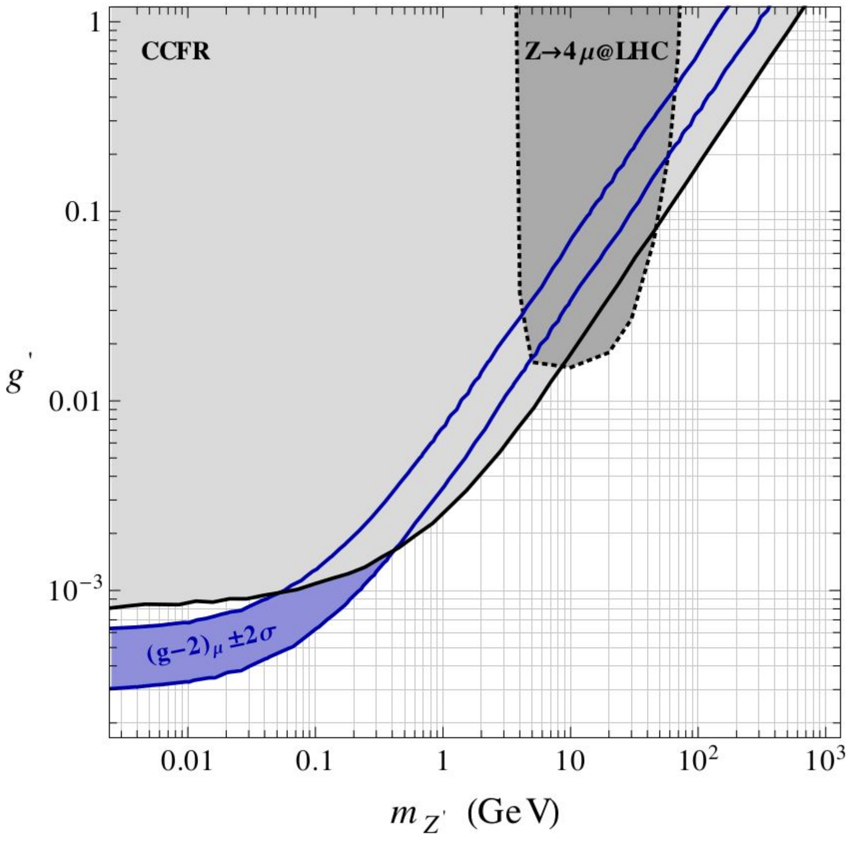


Fig: Total cross-section for simuons and dimuons against incoming neutrino energy. Figure from [1]

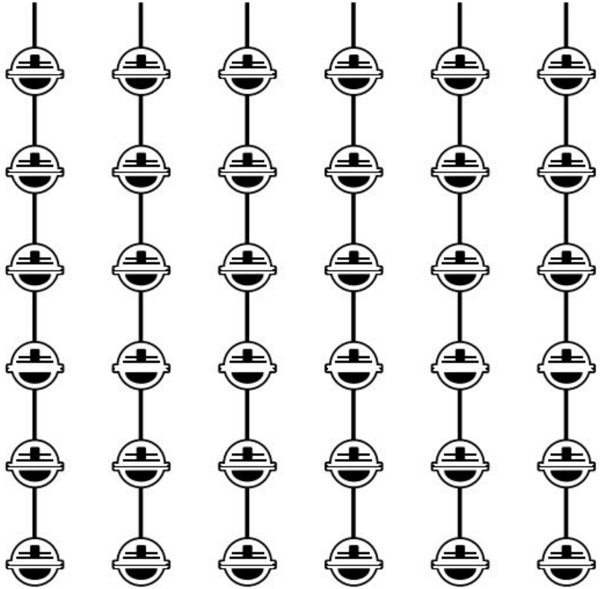
- ❖ **In the energy range [10 GeV - 3 TeV], the ordinary CC-DIS cross-section is roughly 10000 orders of magnitude higher than the trident cross section.**
- ❖ **At roughly 3 TeV range, trident cross-section jumps due to the resonance effect from the on-shell W-boson channels.**
- ❖ **Beyond 100 TeV, the trident cross-section starts to decrease.**

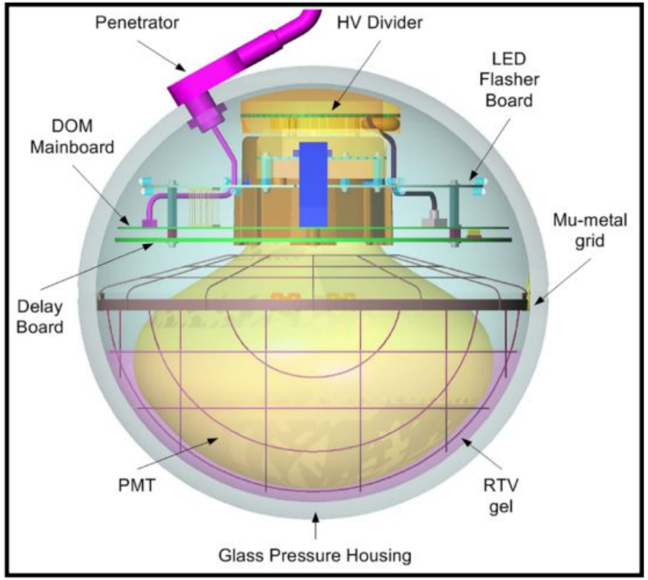
1. https://arxiv.org/abs/1910.08090

BSM



DIGITAL OPTICAL MODULE (DOM): DATA ACQUISITION MODULES

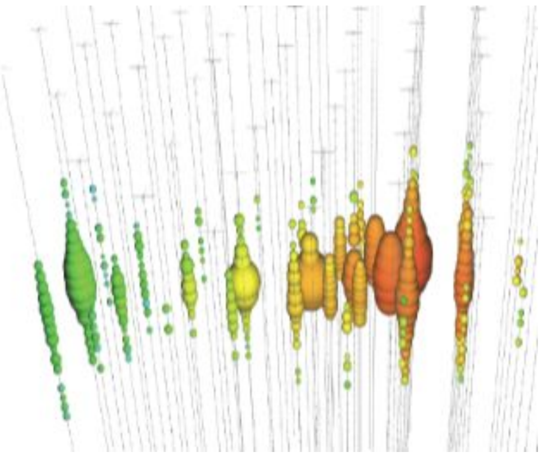




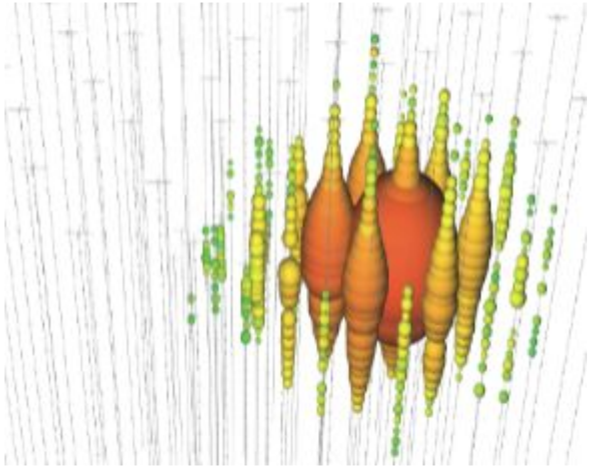
- ❖ **13 mm thick glass sphere containing a Photo-Multiplier Tube (PMT) to measure light.**

Figure from:
https://iucss.sitehost.iu.edu/sme2021/lectures

PARTICLE SIGNATURES IN ICECUBE

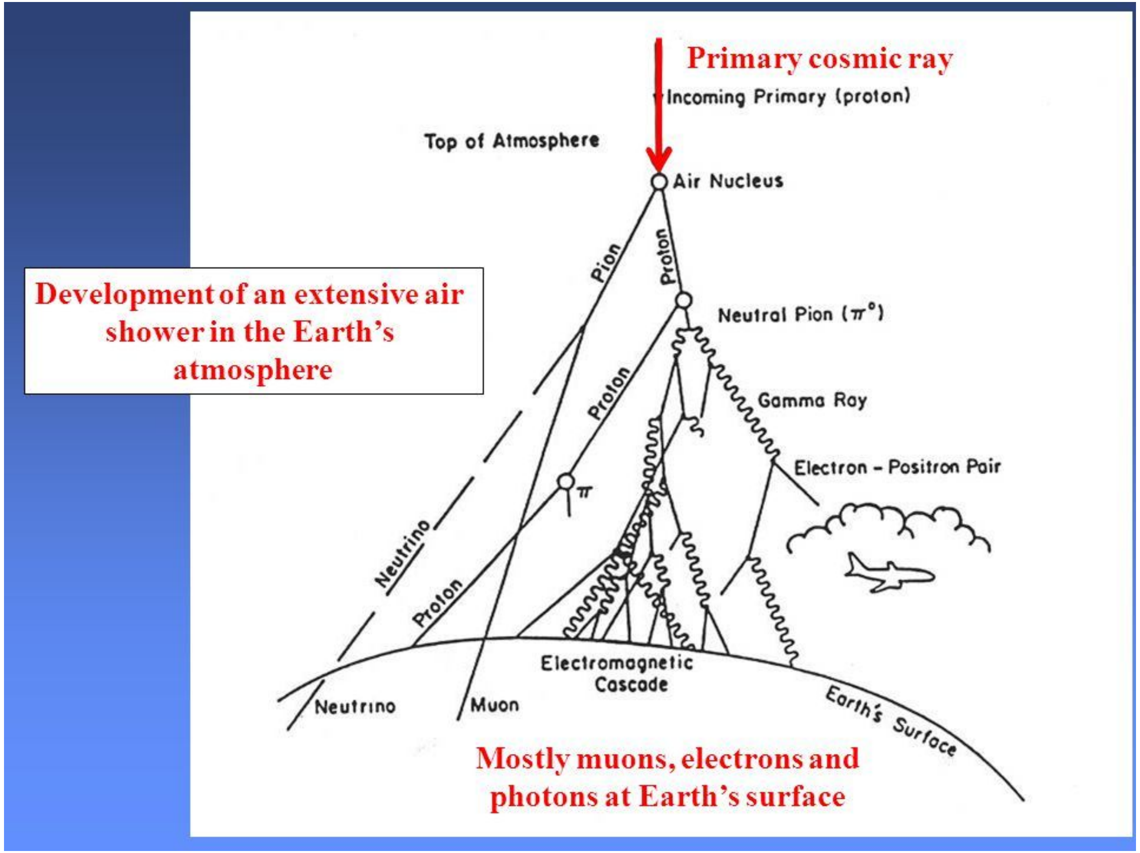


MUON
(TRACK)

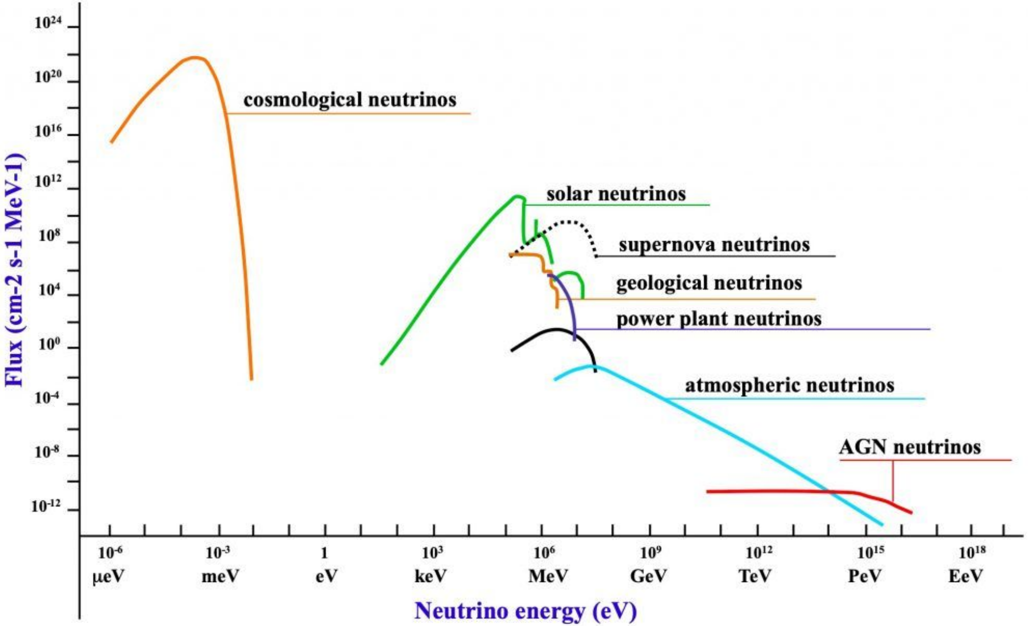


ELECTRON
(CASCADE)

EXTENSIVE AIR SHOWERS



FLUX SOURCES

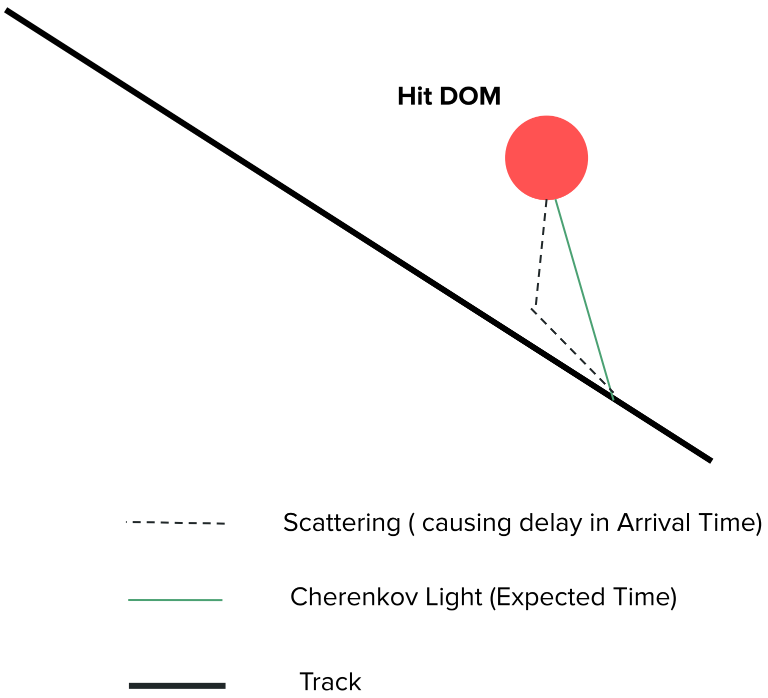


TRACK RECONSTRUCTION

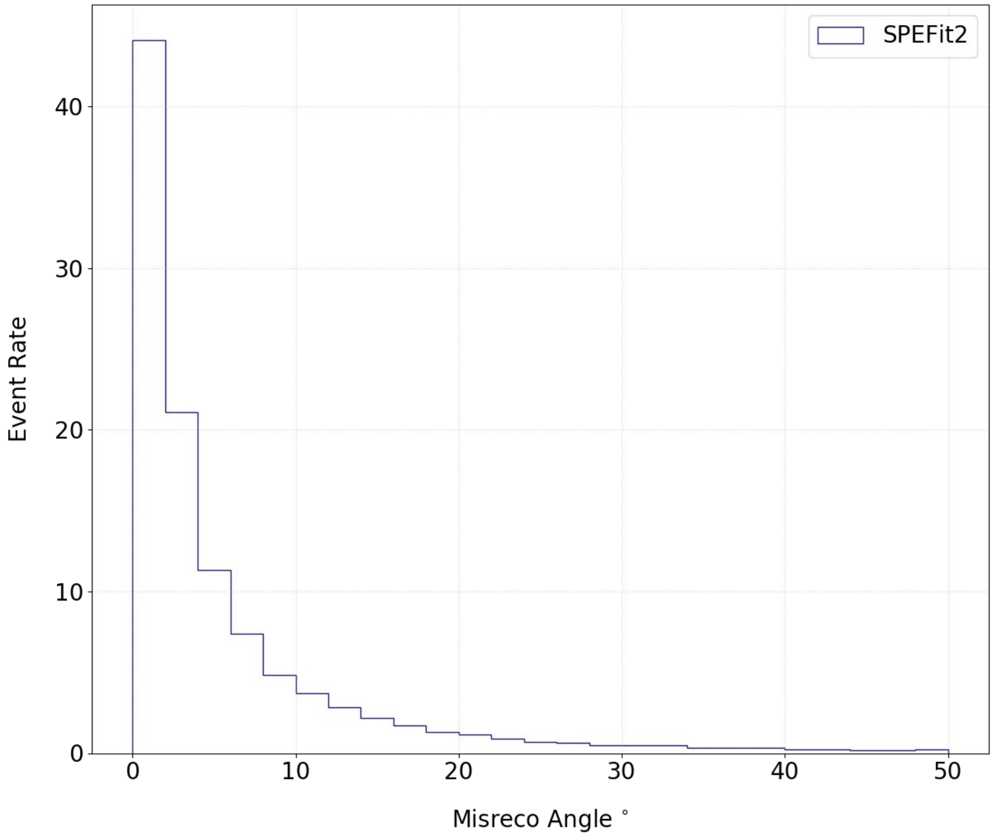
- Track reconstruction problem: Given a set of observations, the goal is to recover the track of a muon

- Challenges: Light propagating through the ice is affected by scattering and absorption. As a result, the Cherenkov light radiated by a muon can arrive early or late than the expected time on a DOM due to ice scattering. Therefore, we measure the quantity called time residual= geometric time-arrival time.

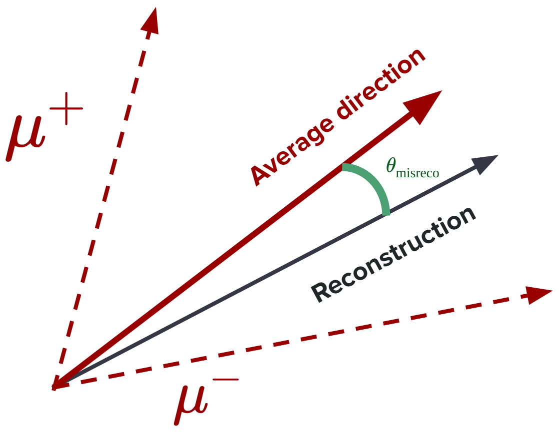
- Hypothesis: Single Muon



TRACK RECONSTRUCTION



- **SPEFIT2: minimization of time residuals gives a reconstructed track almost in the middle of the double muon tracks.**

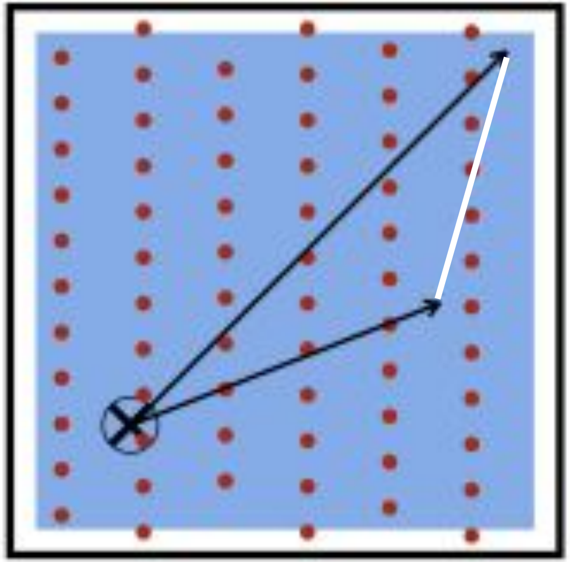


EVENT-RATE ESTIMATION FOR TRIDENT EVENTS AT ICECUBE

Selection Criteria:

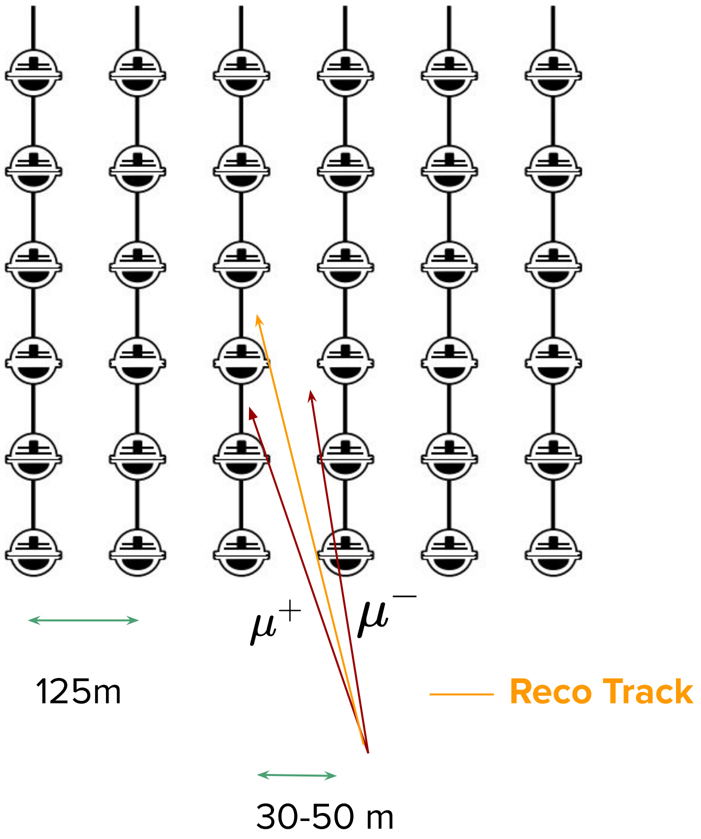
1. Neutrino sources: Atmospheric showers and astrophysical neutrino flux.
2. Highest track separation (white line) of the dimuons inside the IceCube detector is greater than 20m.

<u>**Event Rate Prediction:**</u> A total of 41 events is predicted to satisfy the selection criterion as double-track trident events in 10 years of IceCube data.



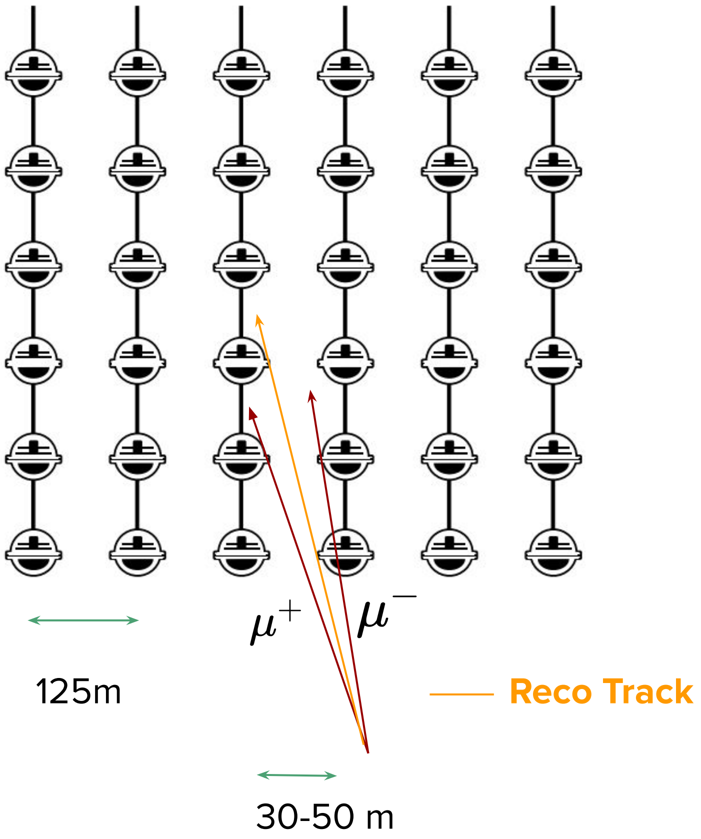
[3] D. E. Groom, N. V. Mokhov and S. I. Striganov, Atom. Data Nucl. Data Tabl. 78, 183-356 (2001) doi:10.1006/adnd.2001.0861

SEARCH CHALLENGES WITH ICECUBE [1/2]



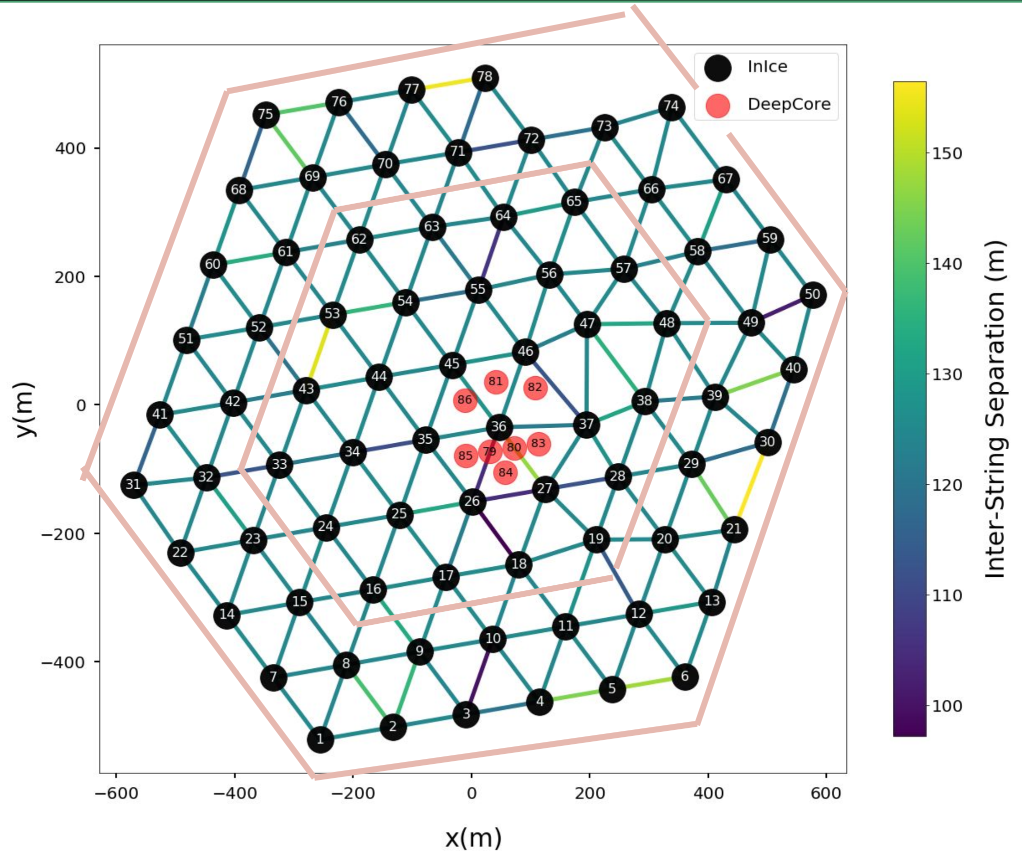
- Typical separation between the muons ~ O(30-50 m).
- Inter-string distance is 125 m.
- The two muons pass between two strings.

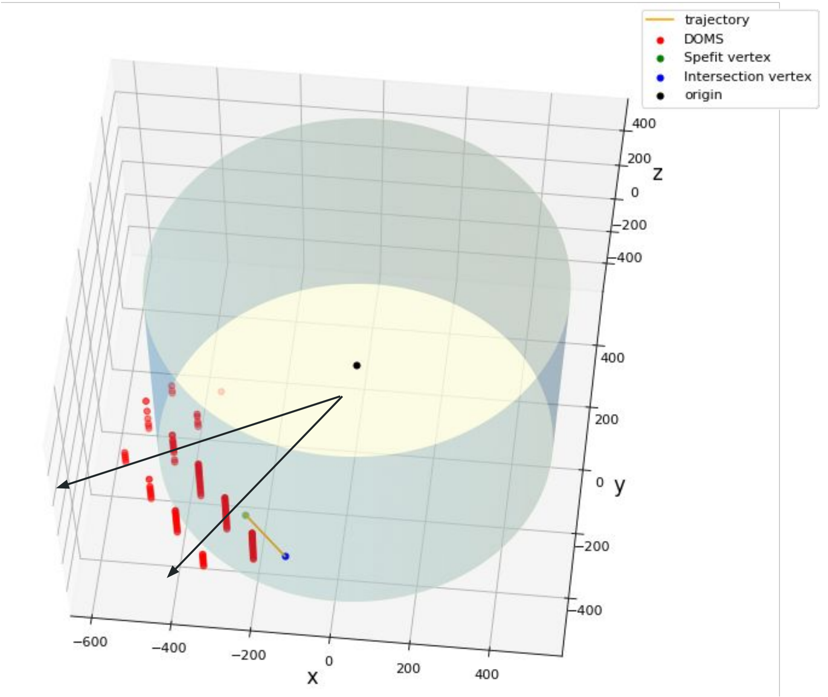
SEARCH CHALLENGES WITH ICECUBE [2/2]



- Typical separation between the muons ~ O(30-50 m).
- Inter-string distance is 125 m.
- The two muons pass between two strings.
- They almost mimic the behavior of a single muon.
- Since IceCube's medium is ice, there is light scattering.

DETECTOR TOP VIEW: GEOMETRY OPTIMIZATION





Outer two layers of the detector