Online event reconstruction and classification in KM3NeT

Alessandro Veutro

on behalf of the KM3NeT collaboration

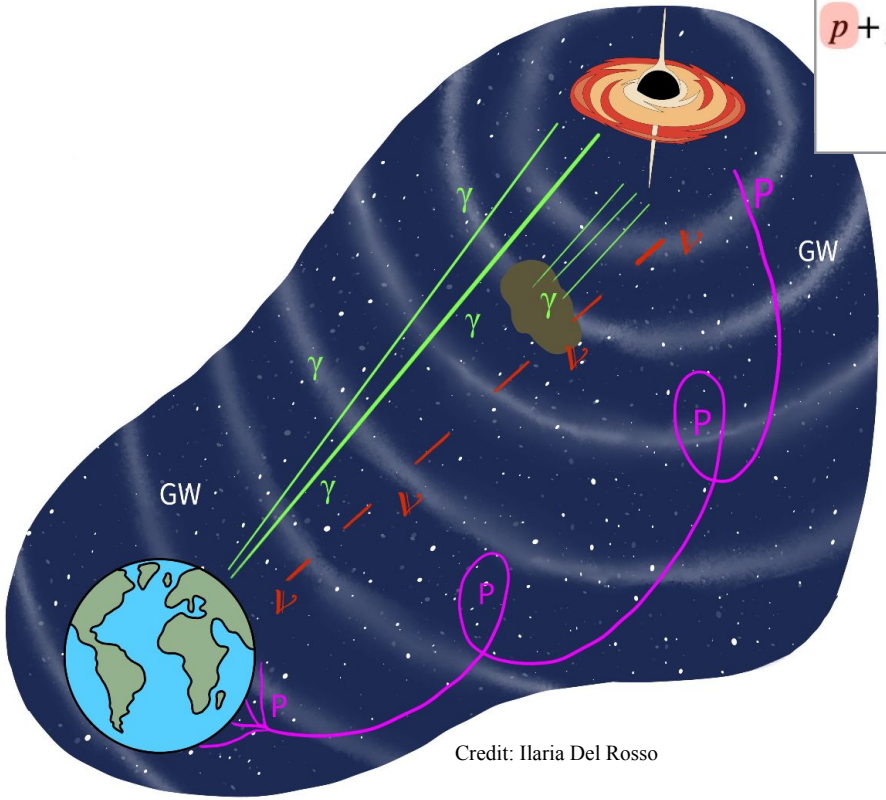
17th Marcel Grossmann Meeting, Pescara, 9th July 2024

SAPIENZA
UNIVERSITÀ DI ROMA

KM3NeT

INFN

How can we detect Extra-Galactic sources?



$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

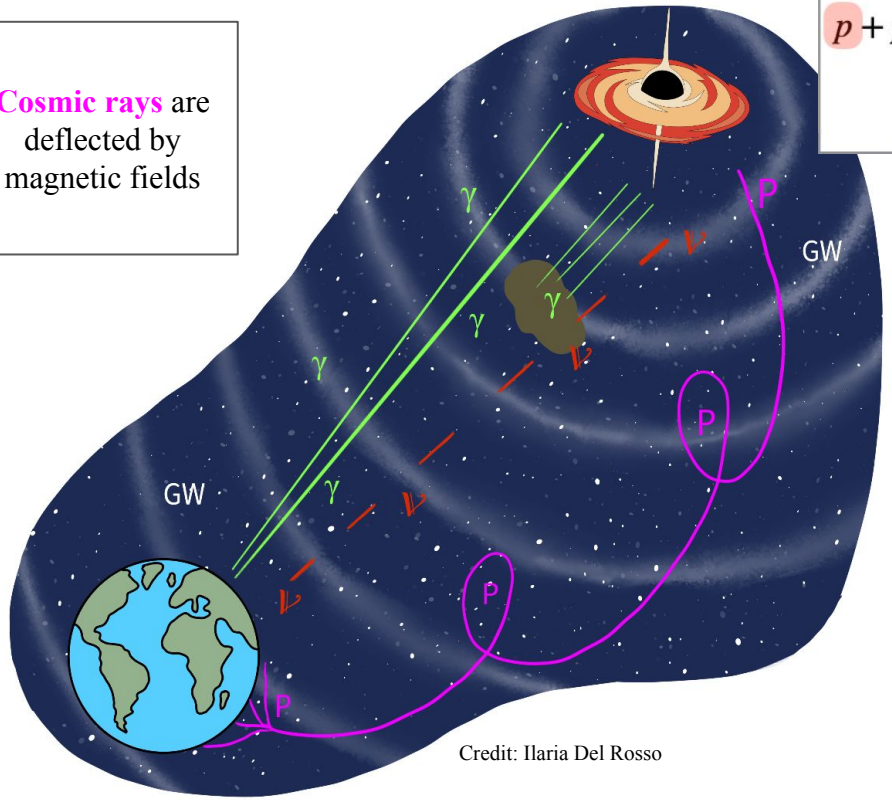
Credit: Ilaria Del Rosso

How can we detect Extra-Galactic sources?

Cosmic rays are deflected by magnetic fields

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

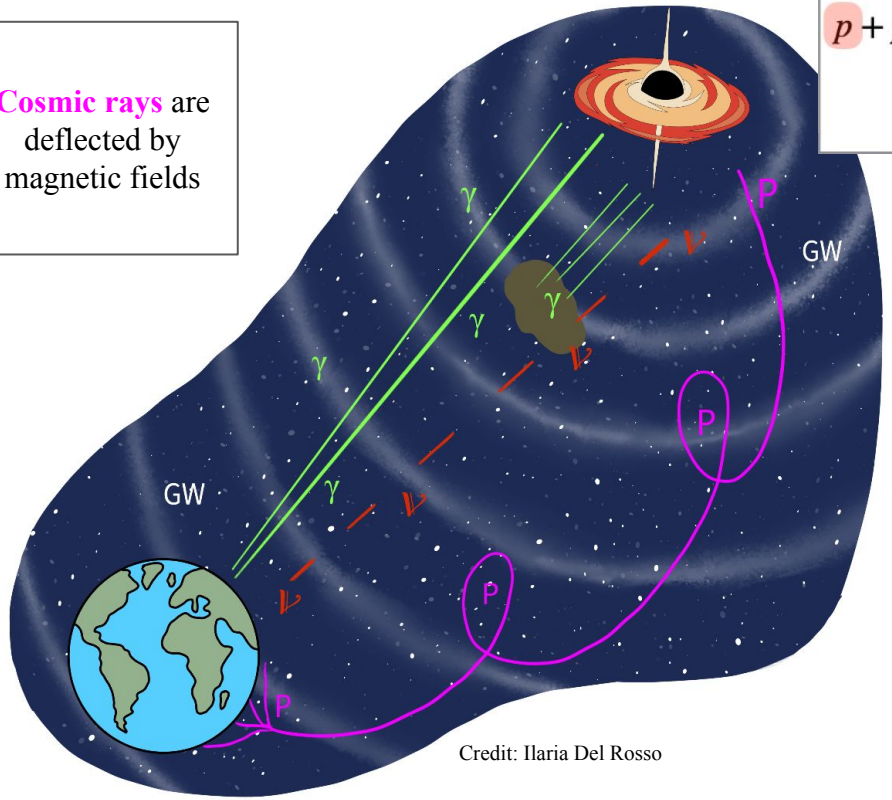
HADRON acceleration



Credit: Ilaria Del Rosso

How can we detect Extra-Galactic sources?

Cosmic rays are deflected by magnetic fields



Credit: Ilaria Del Rosso

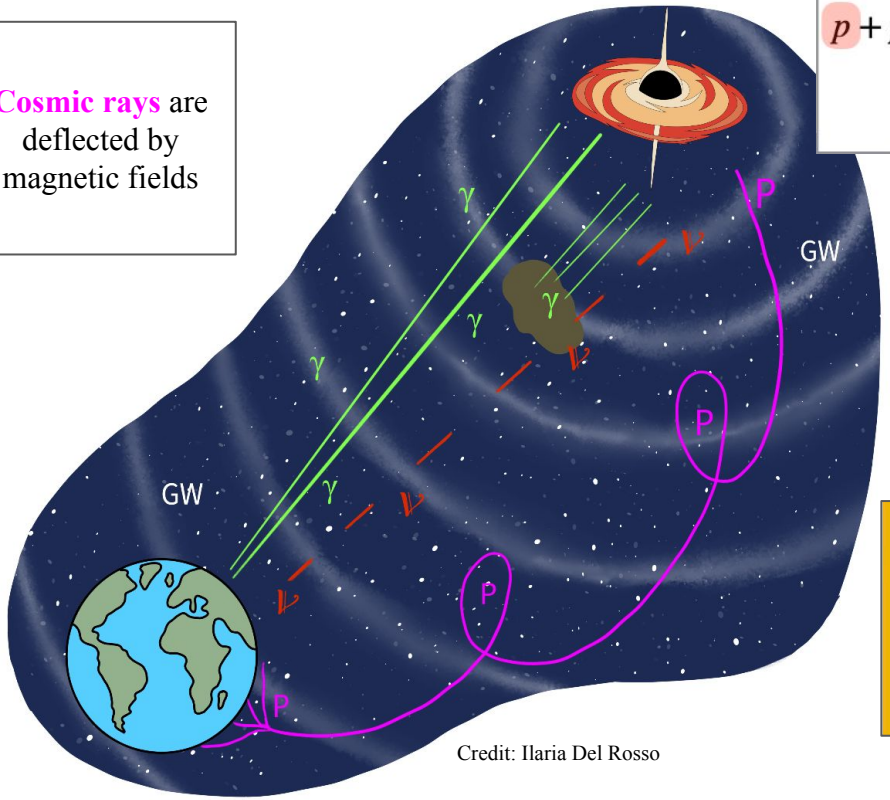
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

Gamma rays can be absorbed and are produced by multiple emission mechanisms

How can we detect Extra-Galactic sources?

Cosmic rays are deflected by magnetic fields



Credit: Ilaria Del Rosso

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

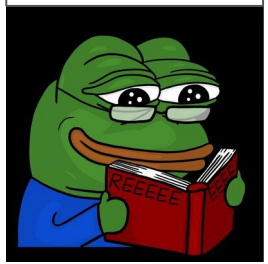
Gamma rays can be absorbed and are produced by multiple emission mechanisms

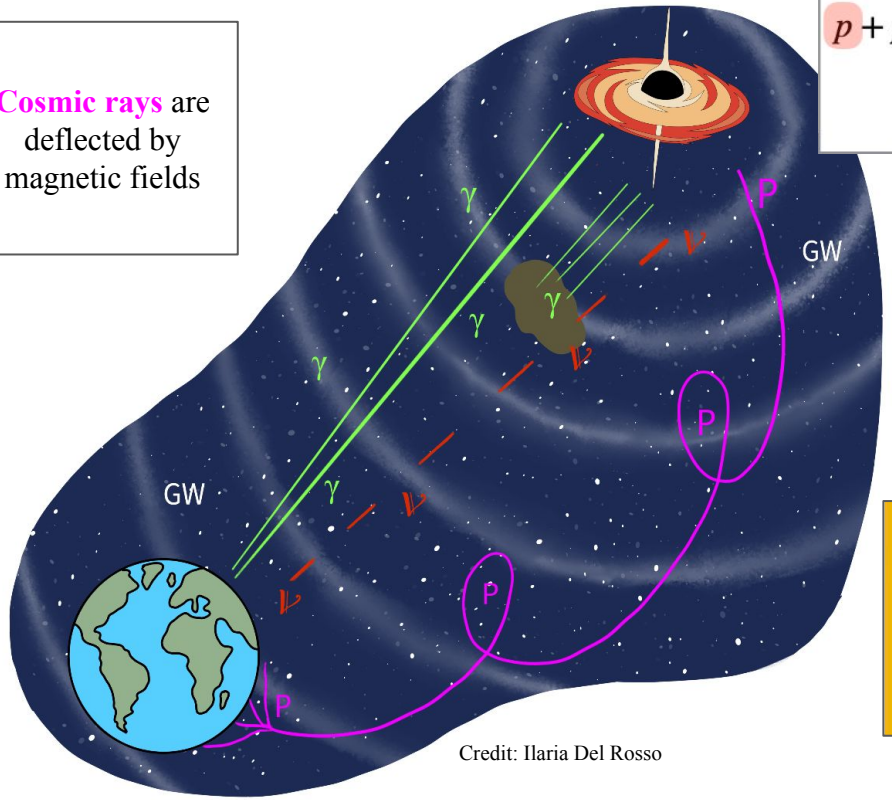
Neutrinos are ideal messenger in the search for distant astrophysical objects

How can we detect Extra-Galactic sources?

Cosmic rays are deflected by magnetic fields

Gravitational waves … that's another story





Credit: Ilaria Del Rosso

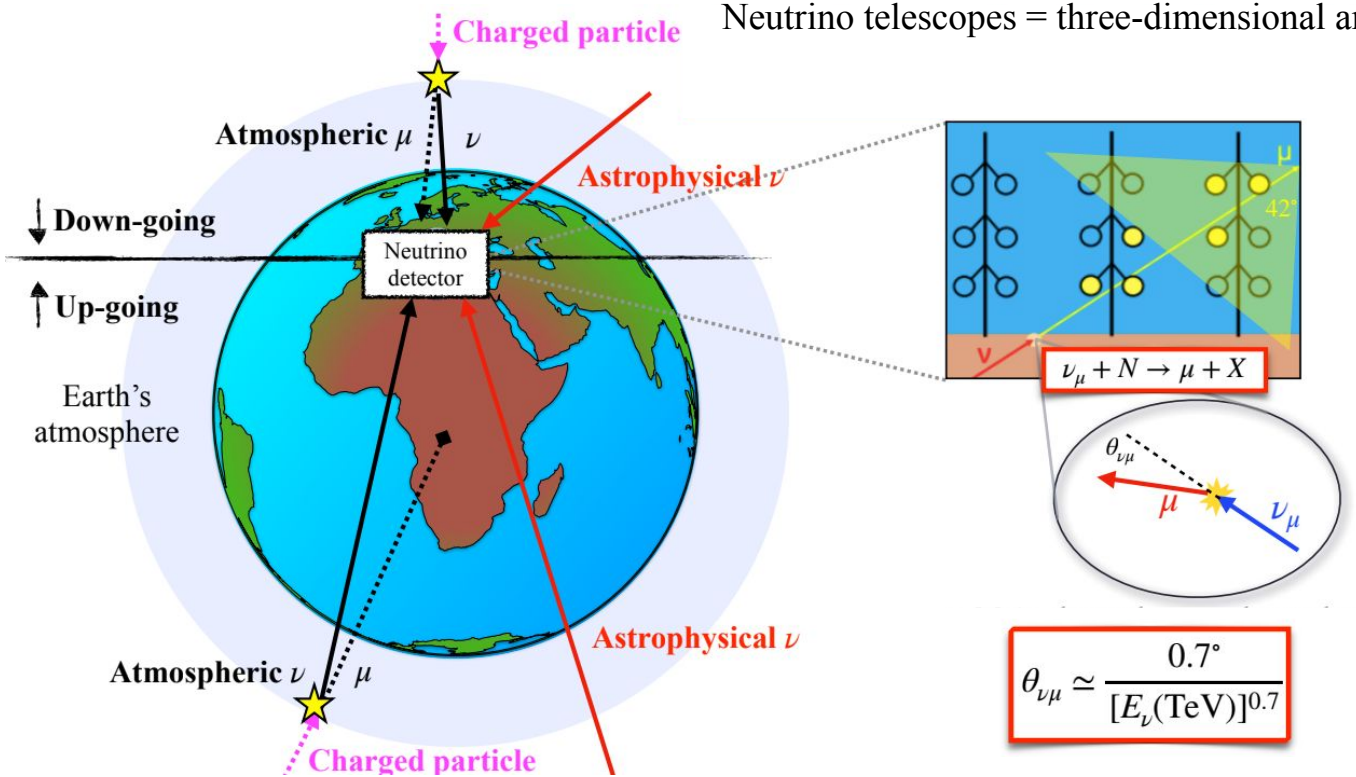
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

Gamma rays can be absorbed and are produced by multiple emission mechanisms

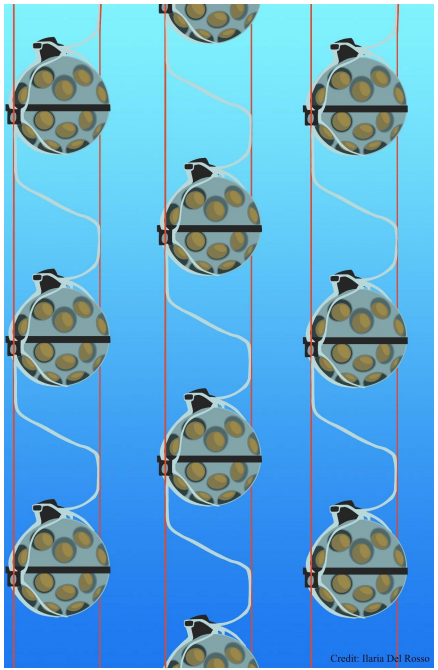
Neutrinos are ideal messenger in the search for distant astrophysical objects

Cherenkov neutrino telescope

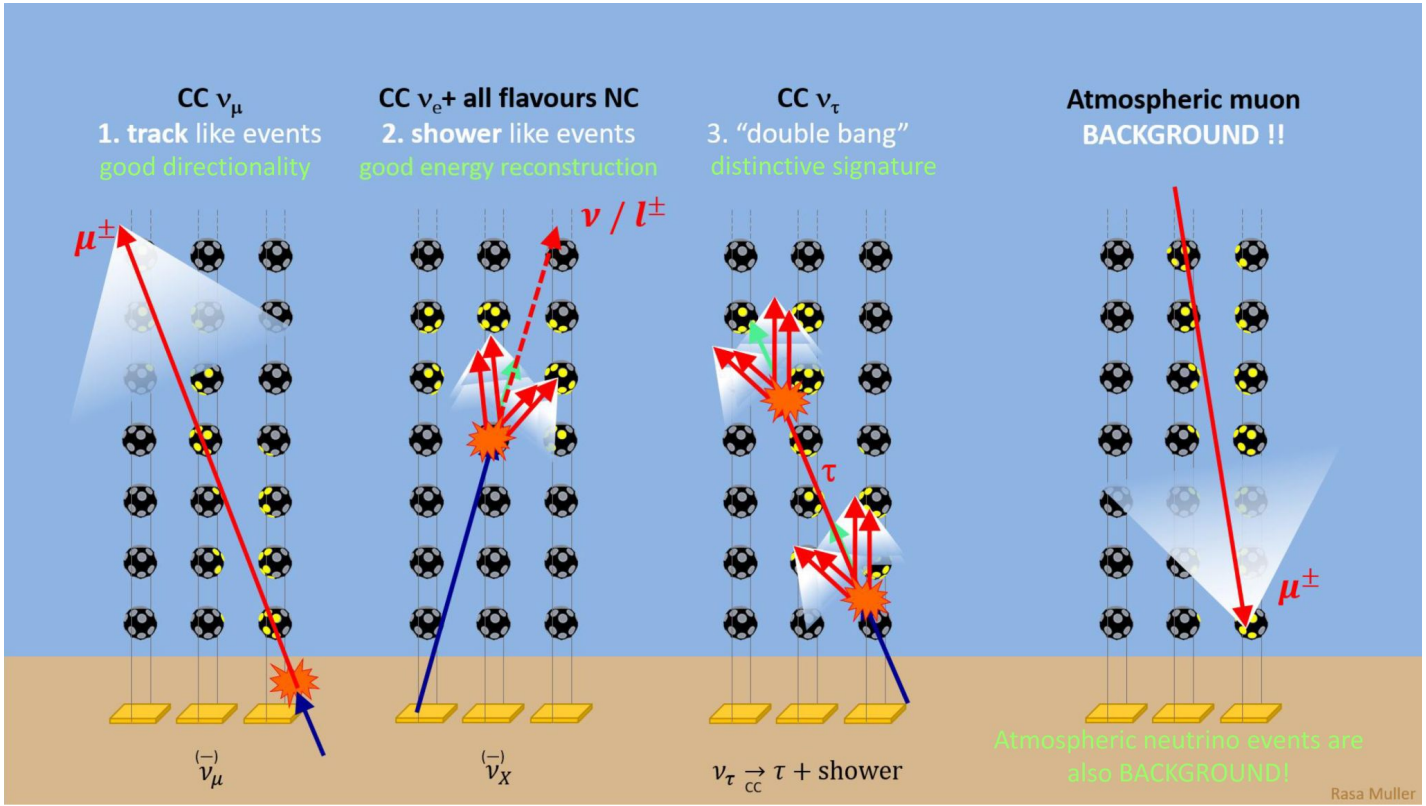


Neutrino telescopes = three-dimensional arrays of photomultiplier tubes (PMTs)

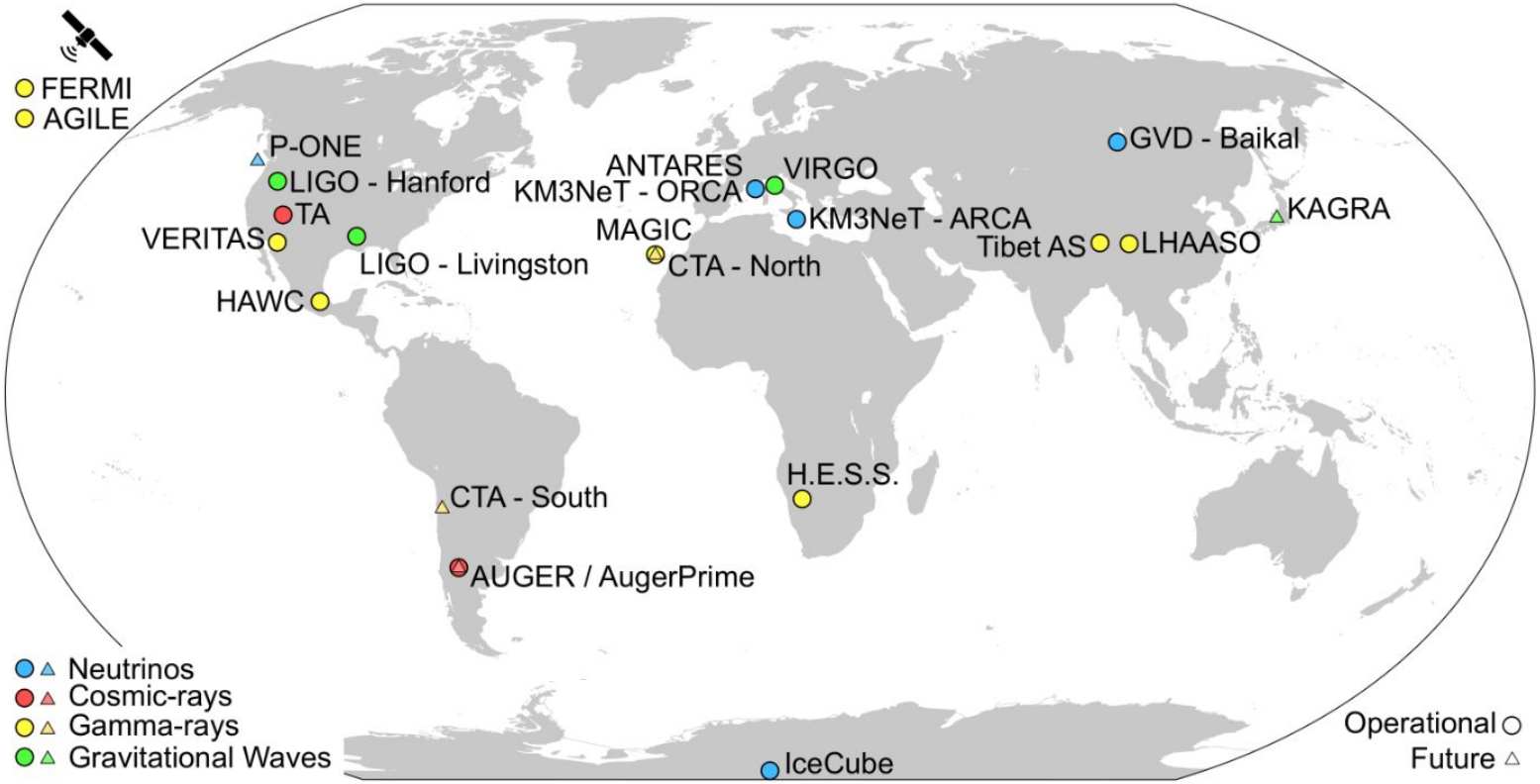
$$\theta_{\nu\mu} \simeq \frac{0.7^\circ}{[E_\nu(\mathrm{TeV})]^{0.7}}$$



Events topology in Cherenkov neutrino telescopes



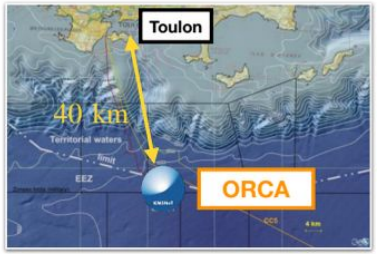
Multi-messenger community



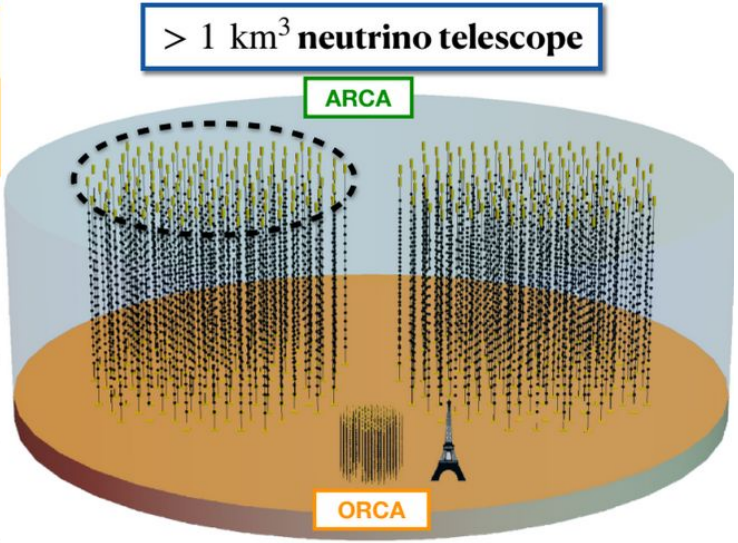
Multi-messenger community

KM3NeT

- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: **ORCA** (France) and **ARCA** (Italy) →**Same technology** but **different physics**
- Construction started in **2015**



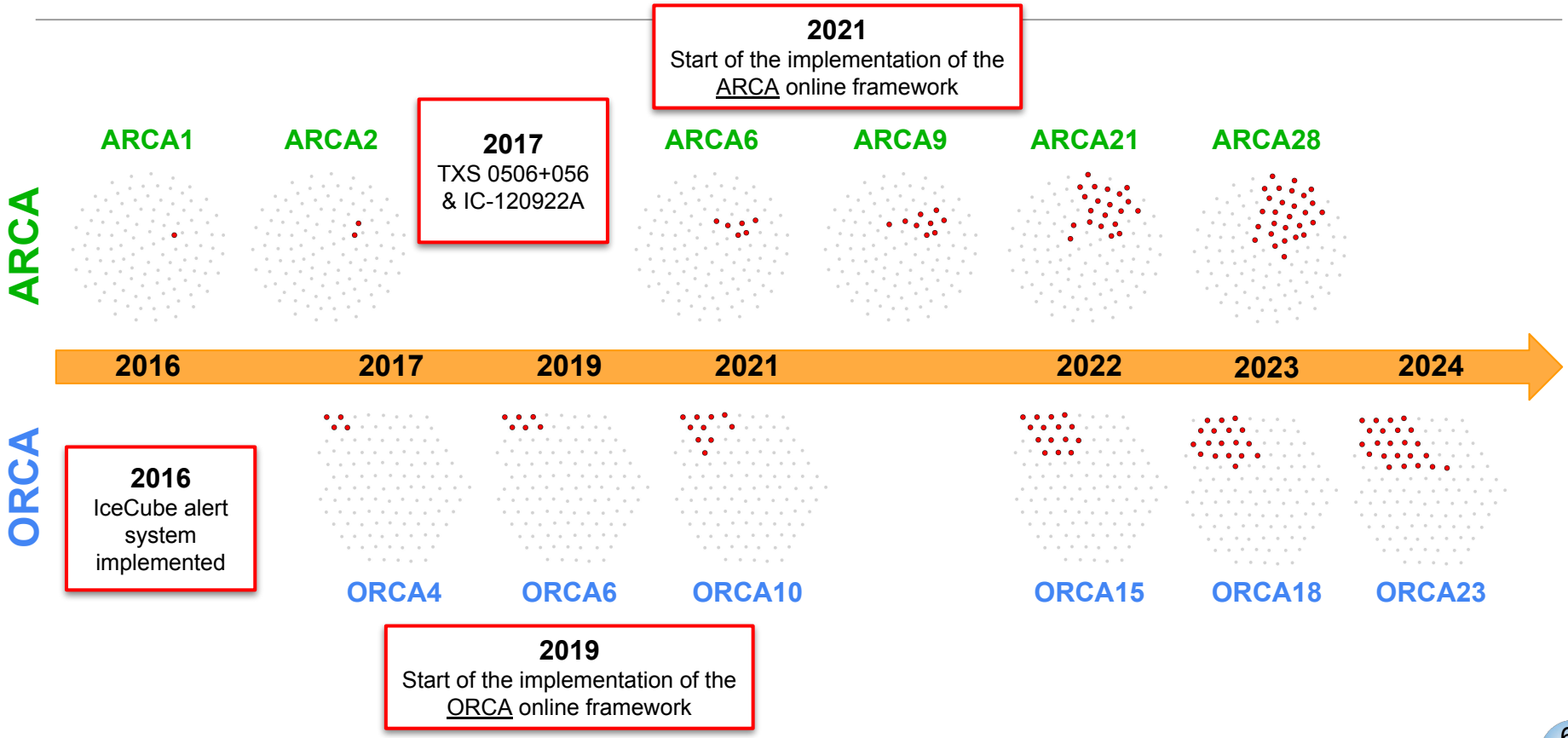
	Astroparticle **R**esearch with **C**osmics in the **A**byss	**O**scillation **R**esearch with **C**osmics in the **A**byss
Location	Italy (Sicilian coast)	France (coast of Toulon)
Depth	3450 m	2450 m
Number of DUs	**115 x 2 (2 BB)**	**115 (1 BB)**
Instrumented volume	~1 Gton	~7 Mton



1 Building Block = 115 Detection Units
(1 BB = 115 DUs)

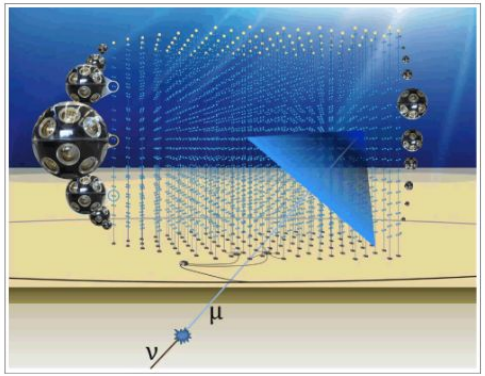
Credits: KM3NeT Collaboration

Status of the deployment



Multi-messenger program in KM3NeT

Data AcQuisition (DAQ) level



KM3NeT ORCA and ARCA

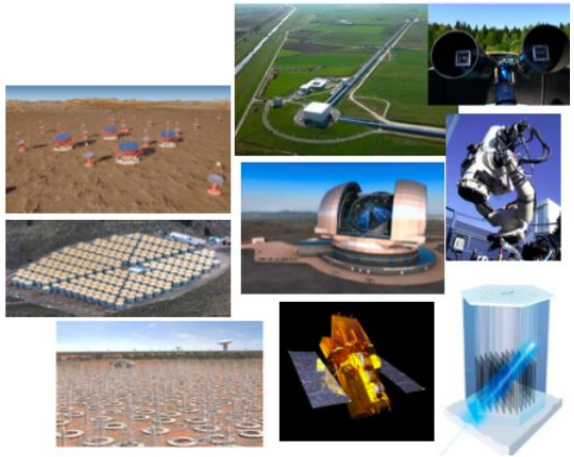
SENDING ALERTS

Send neutrino alerts to external communities for subsequent follow-ups

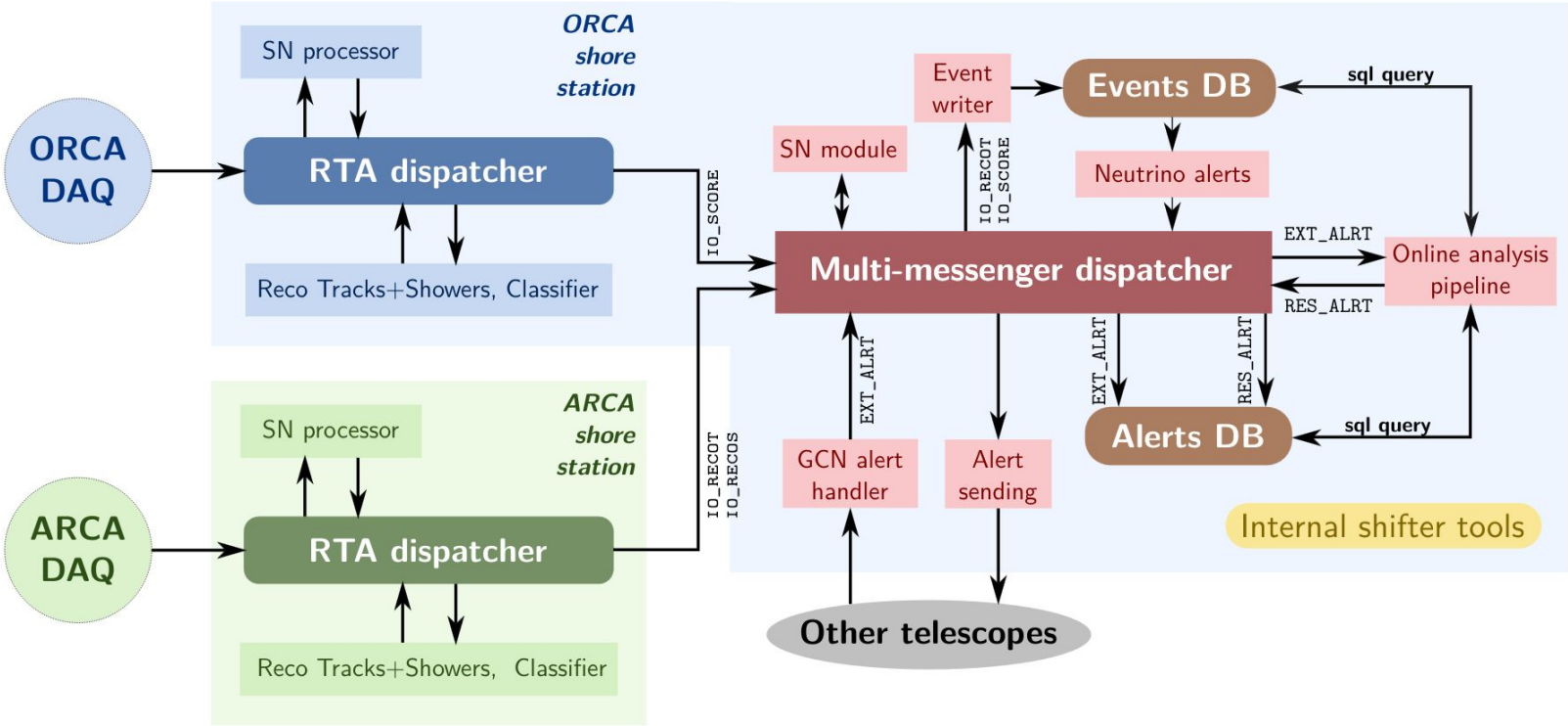
- Follow-up of EM/GW alerts
- Offline time/space correlation search with catalogues (GRB, AGN, SN, etc.)

RECEIVING ALERTS

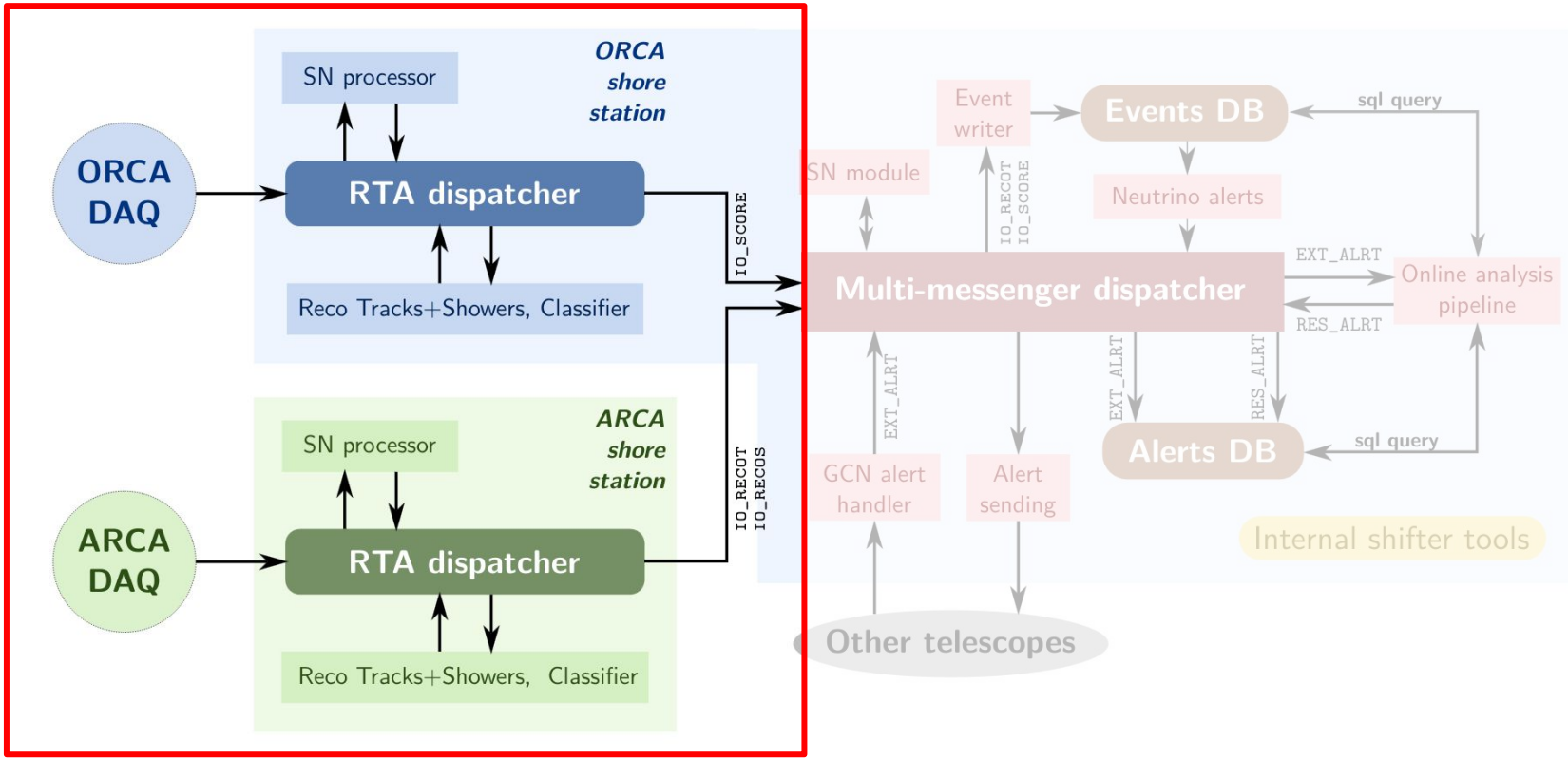
EM/MM external communities



Real-Time Analysis framework



Real-Time Analysis framework



Driving factors in multi-messenger detections

ANGULAR RESOLUTION

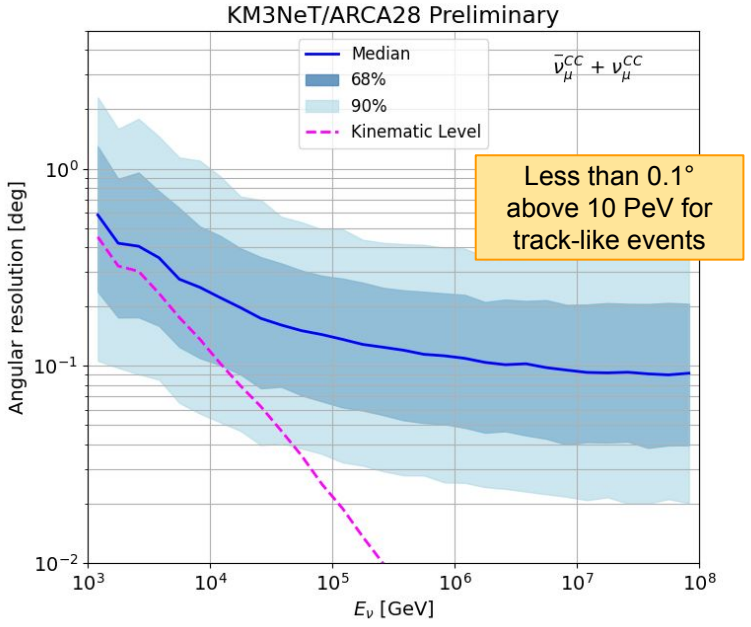
BACKGROUND REJECTION

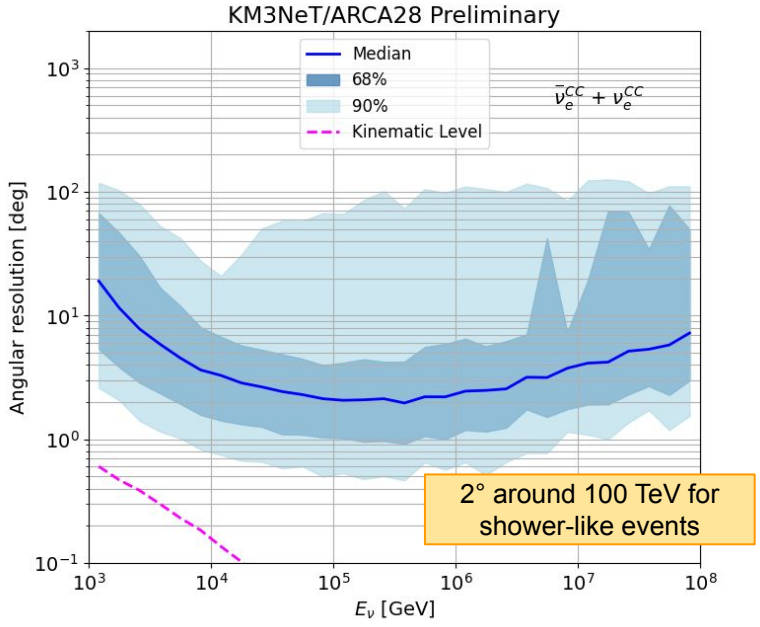
RESPONSE TIME

WELL-DEFINED FOLLOW-UP STRATEGY

Driving factors in multi-messenger detections

ANGULAR RESOLUTION



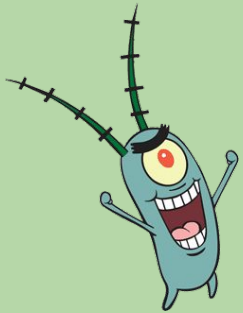


Driving factors in multi-messenger detections

ANGULAR RESOLUTION

Less than 0.1° for track-like events
Around 2° for shower-like events

BACKGROUND REJECTION



bioluminescence

^{40}K

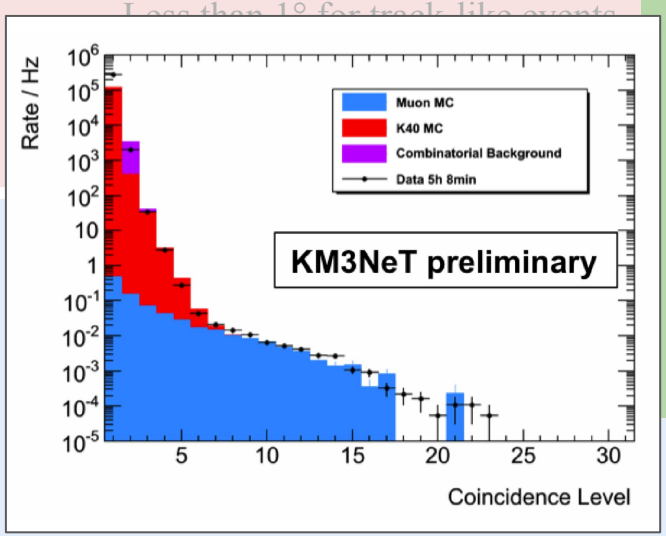
atmospheric muons

RESPONSE TIME

Driving factors in multi-messenger detections

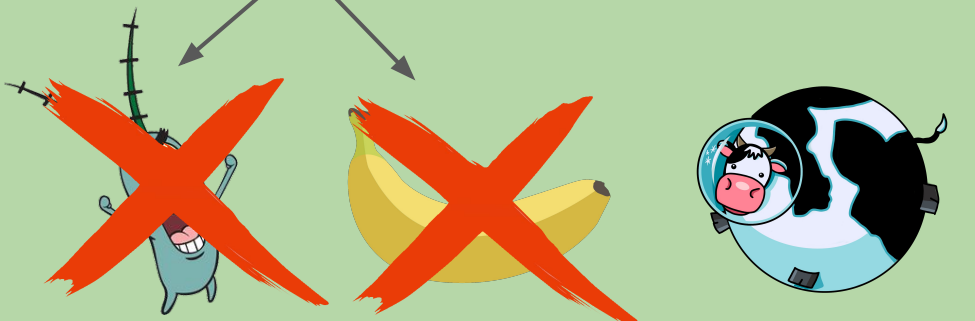
ANGULAR RESOLUTION

Less than 1° for track-like events



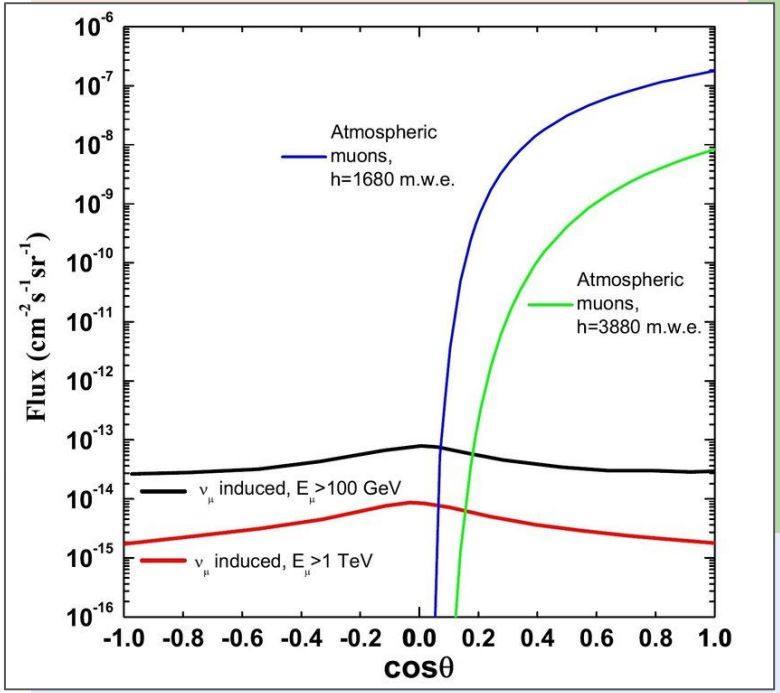
BACKGROUND REJECTION

Time coincidence of hits



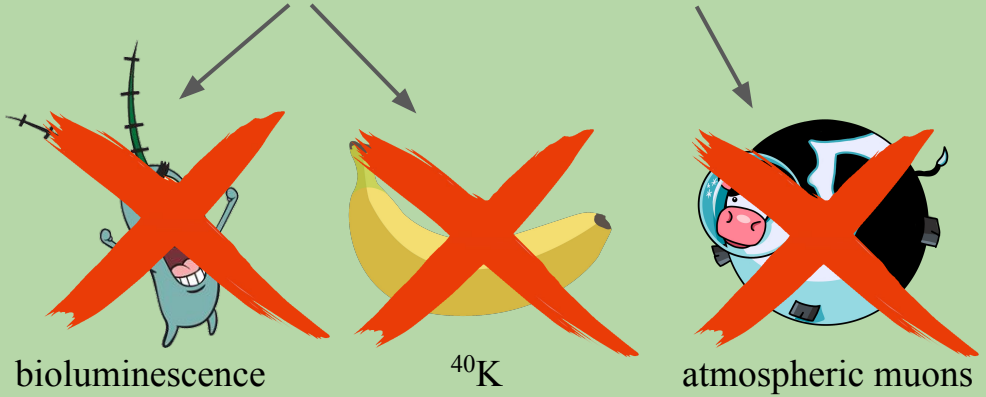
bioluminescence | ^{40}K | atmospheric muons

Driving factors in multi-messenger detections



BACKGROUND REJECTION

Time coincidence of hits and up-going events selection



bioluminescence ^{40}K atmospheric muons

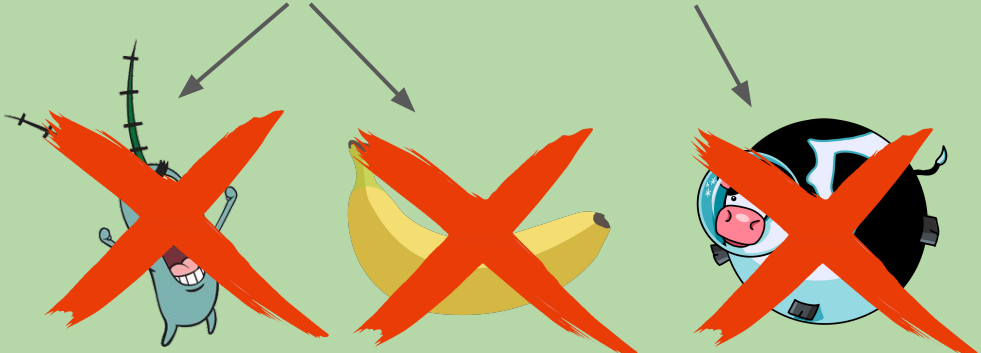
Driving factors in multi-messenger detections

ANGULAR RESOLUTION

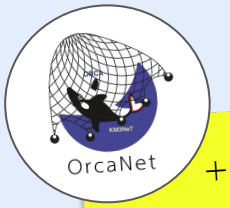
Less than 0.1° for track-like events
Around 2° for shower-like events

BACKGROUND REJECTION

Time coincidence of hits and up-going events selection

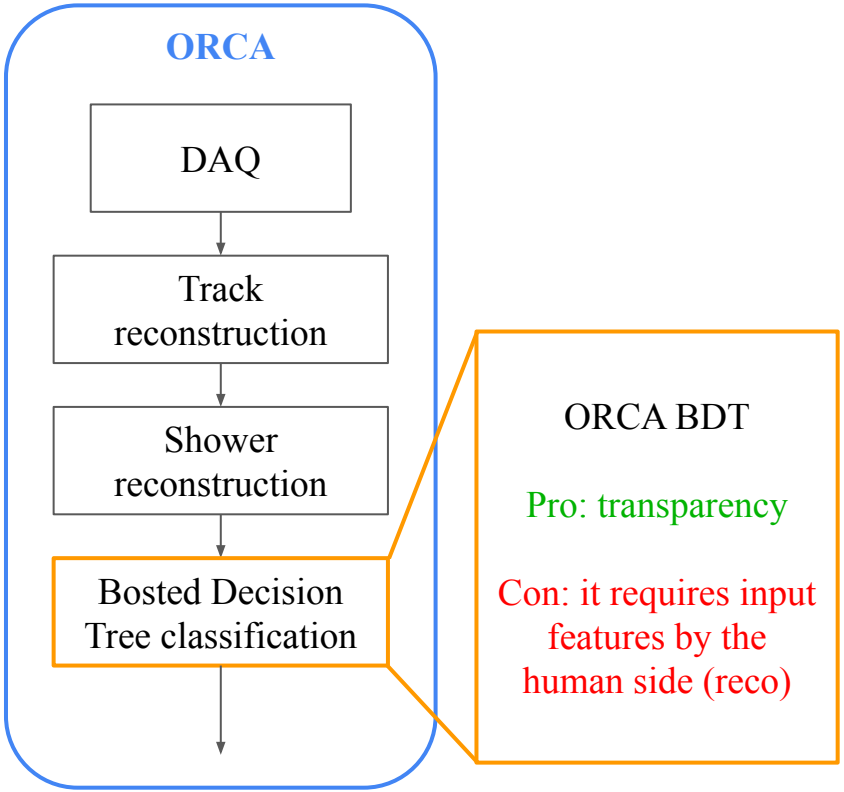


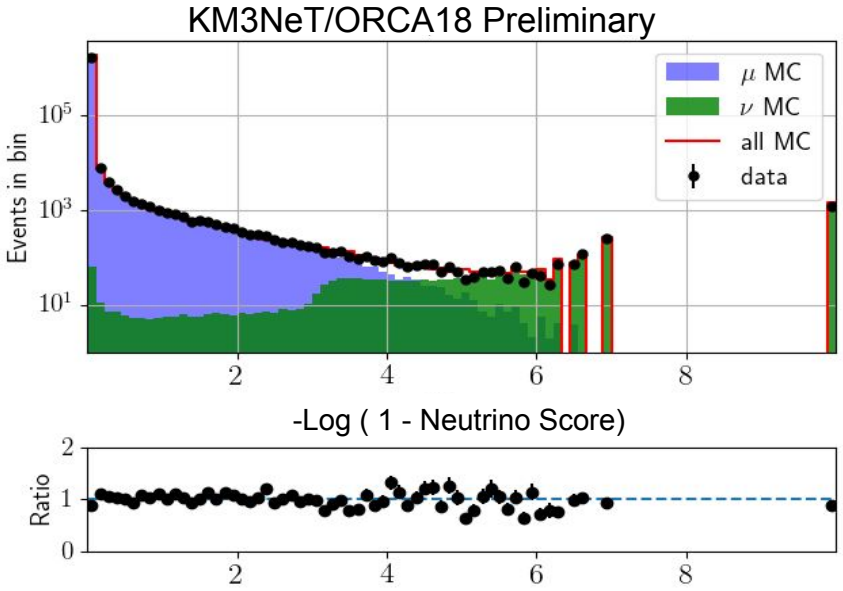
bioluminescence ^{40}K atmospheric muons



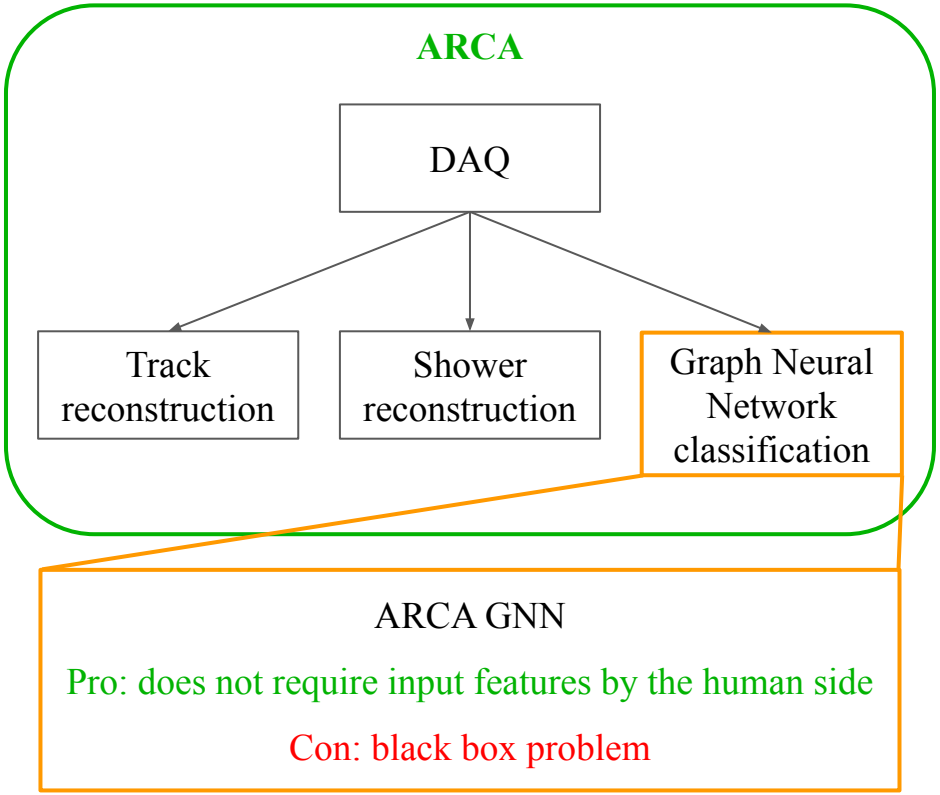
+ Machine learning techniques

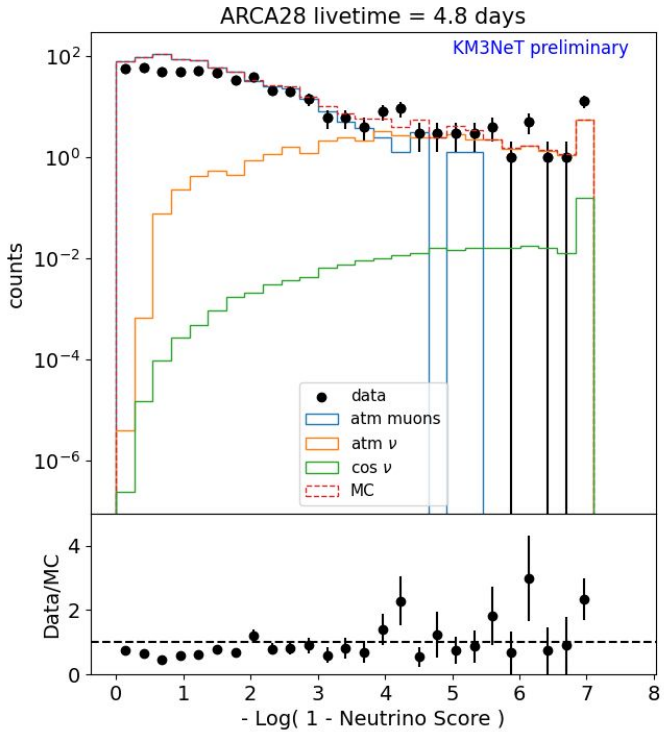
Machine Learning in KM3NeT/ORCA





Machine Learning in KM3NeT/ARCA

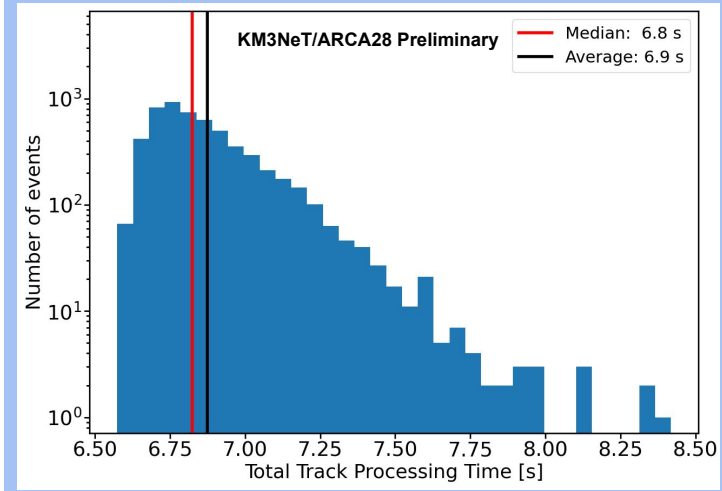


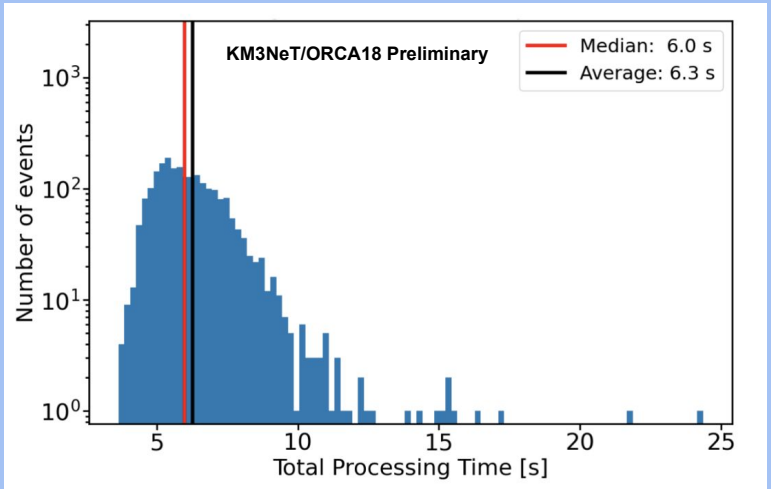


Driving factors in multi-messenger detections

RESPONSE TIME

Triggered events are processed in real-time **in less than 7 s** for ARCA and ORCA





Driving factors in multi-messenger detections

ANGULAR RESOLUTION

Less than 1° for track-like events
Around 2° for shower-like events

BACKGROUND REJECTION

RESPONSE TIME

Total event processing time below 7 s for bot
and ORCA

WELL-DEFINED ALERT FOLLOW-UP STRATEGY

See Massimo Mastrodicasa's talk on
"*Neutrino real-time follow-ups with KM3NeT* "!

Driving factors in multi-messenger detections

ANGULAR RESOLUTION

Less than 0.1° for track-like events
Around 2° for shower-like events

BACKGROUND REJECTION

Time coincidence of hits and up-going events selection + Machine Learning techniques

RESPONSE TIME

Total event processing time below 7 s for both ARCA and ORCA

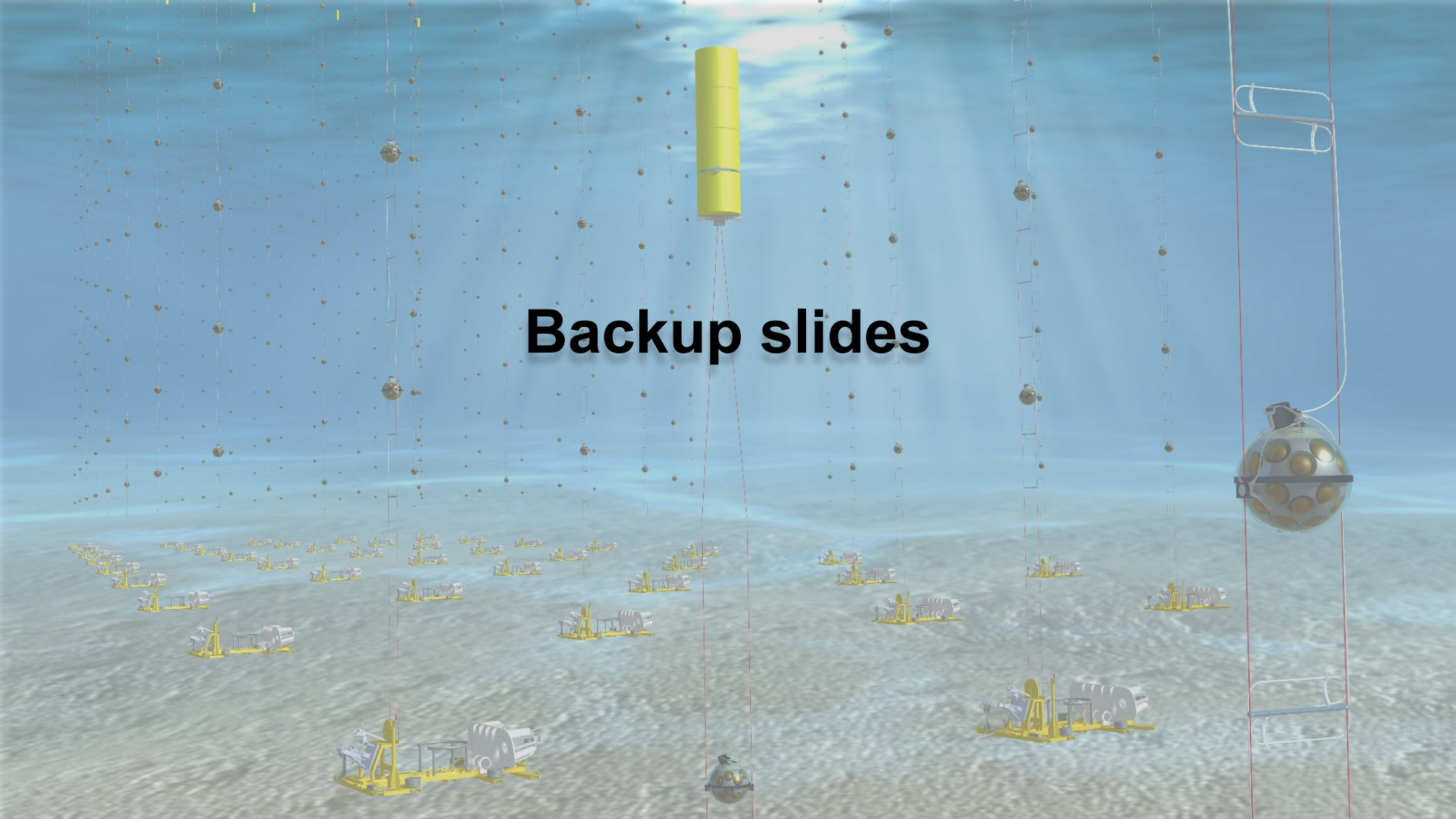
WELL-DEFINED ALERT FOLLOW-UP STRATEGY

See Massimo Mastrodicasa's talk on "*Neutrino real-time follow-ups with KM3NeT*"!

Take-home message!

KM3NeT has started to play its role in the field of the real-time multimessenger astronomy!

Thank you for your attention!

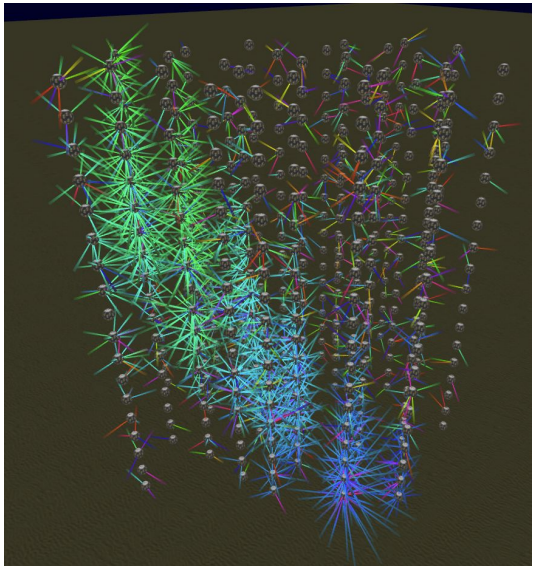


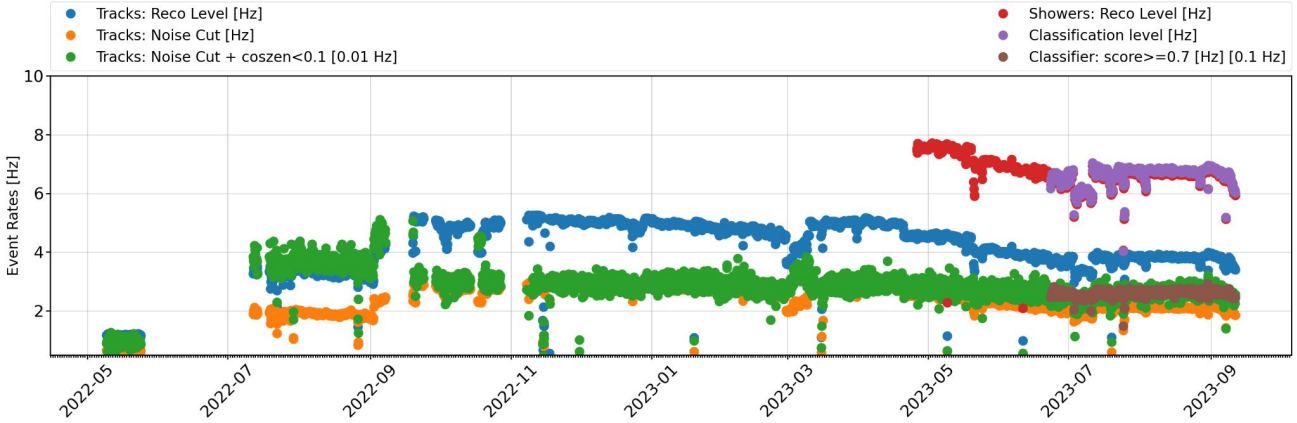
Backup slides

GNN classifier

GNN takes as input graphs, which are unordered sets of nodes and links.
This makes GNN very flexible and suitable for a moving detector such as KM3NeT.

In the following, we will focus on the ***atmospheric muon vs neutrino*** classifier, which has been running in the online pipeline since June 2023 (see below).
The output of the muon vs neutrino classifier is the ***neutrino score***, a number between 0 and 1, that can be interpreted as the probability of a given event to be a neutrino.

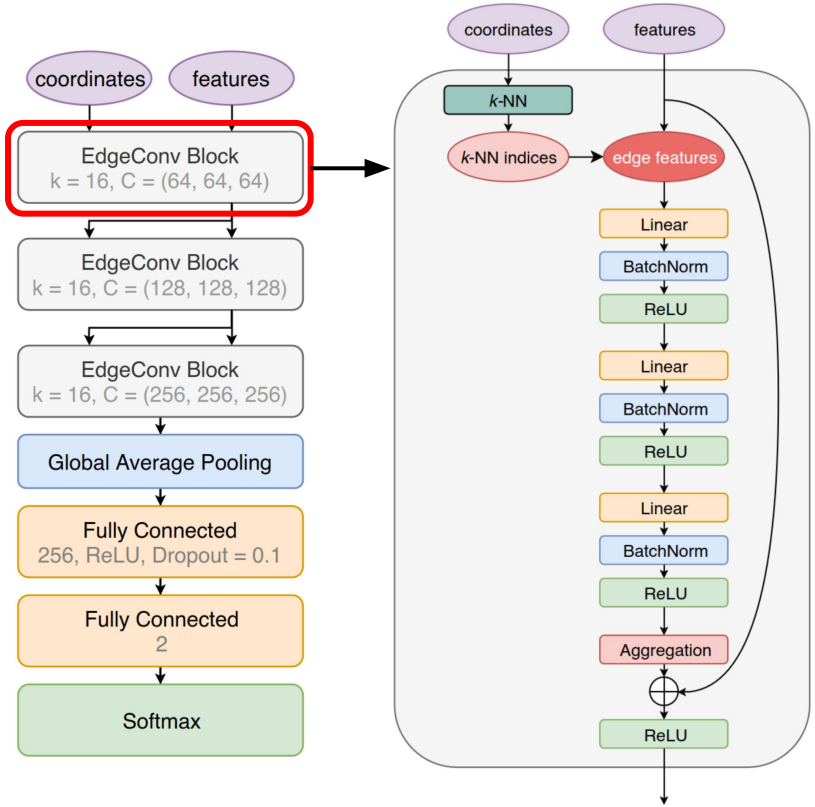




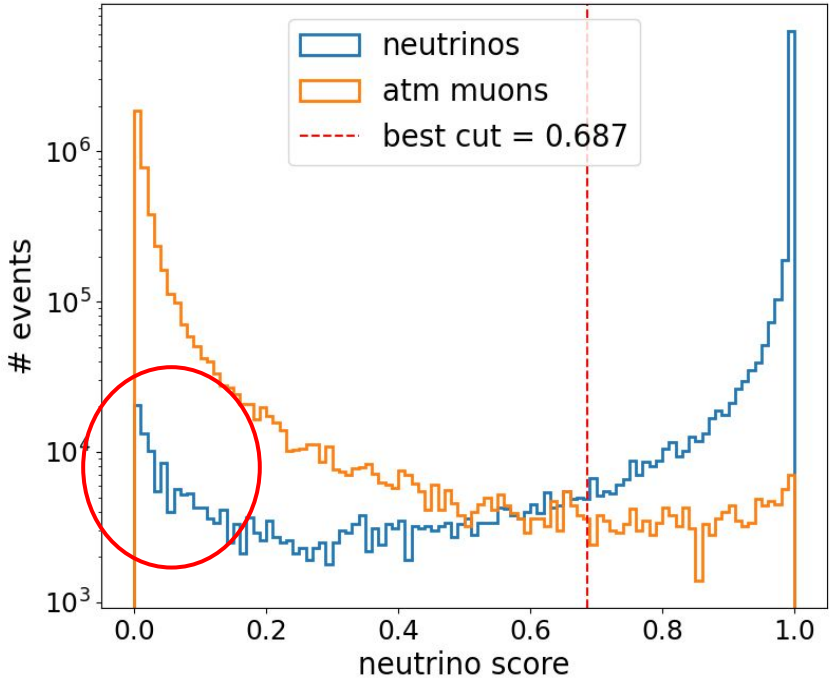
GNN model

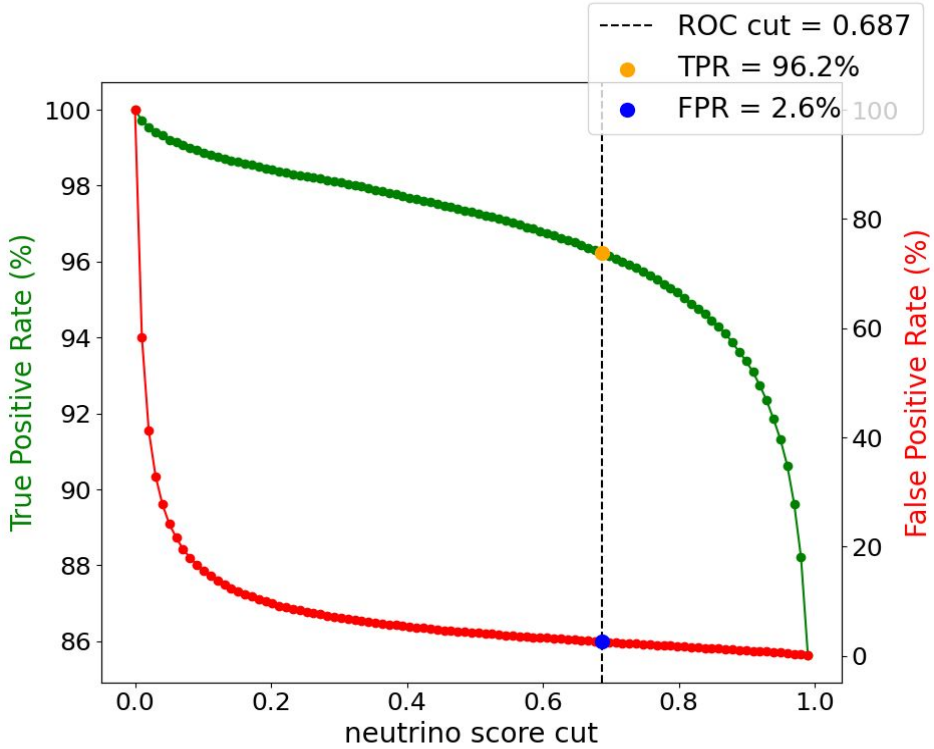
The GNN model implemented in KM3NeT is based on the **ParticleNet** architecture (see here for reference), which makes extensive use of **EdgeConv** (edge convolution) operations and also adopts the dynamic graph update approach.

The EdgeConv block starts with finding the k nearest neighboring particles for each particle, using the "coordinates" input of the EdgeConv block to compute the distances.

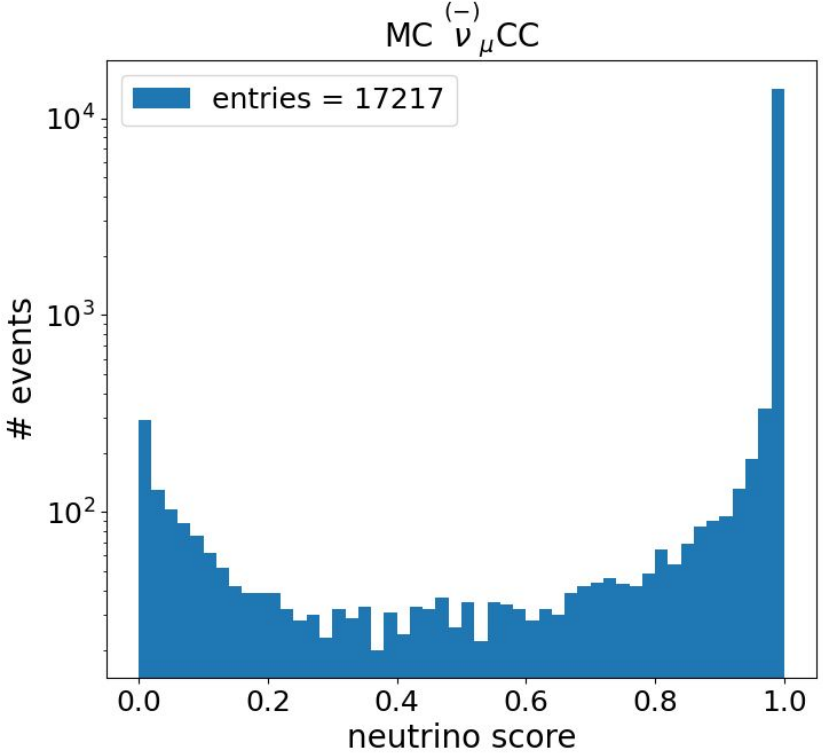


GNN performance



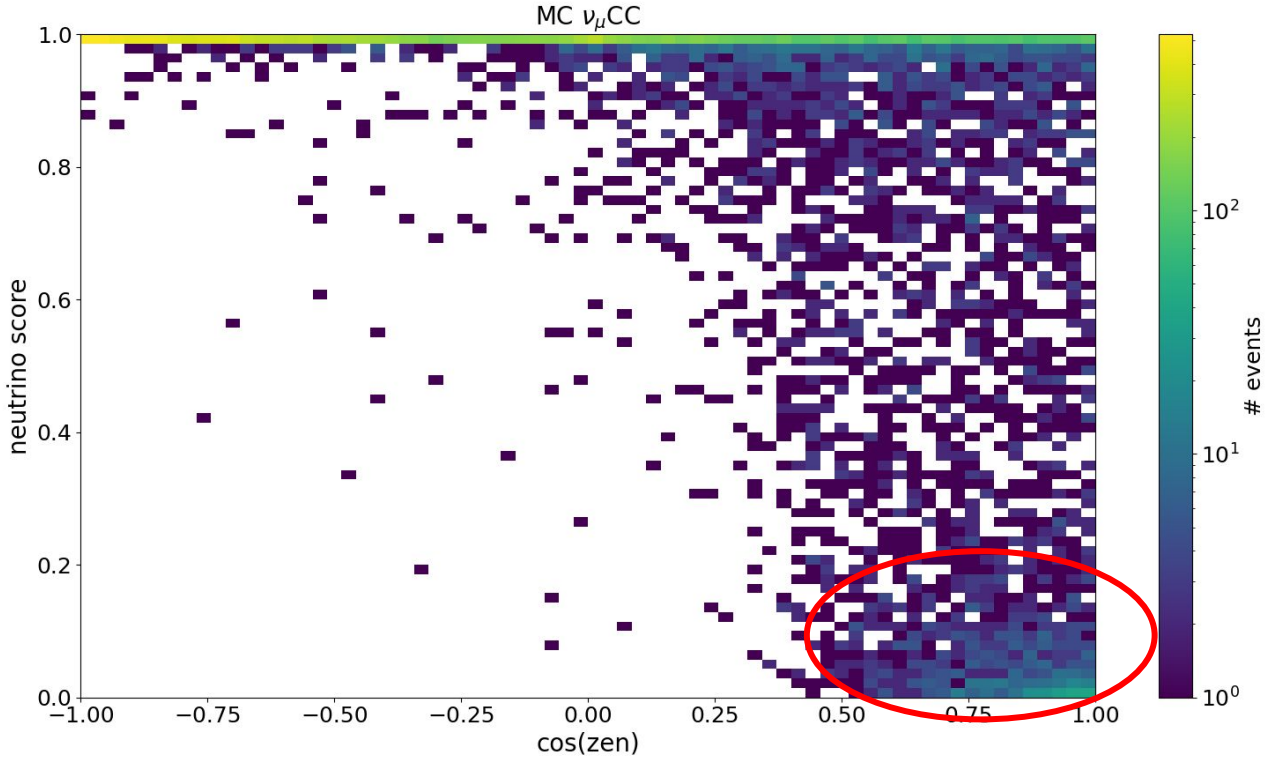


GNN performance on track-like events

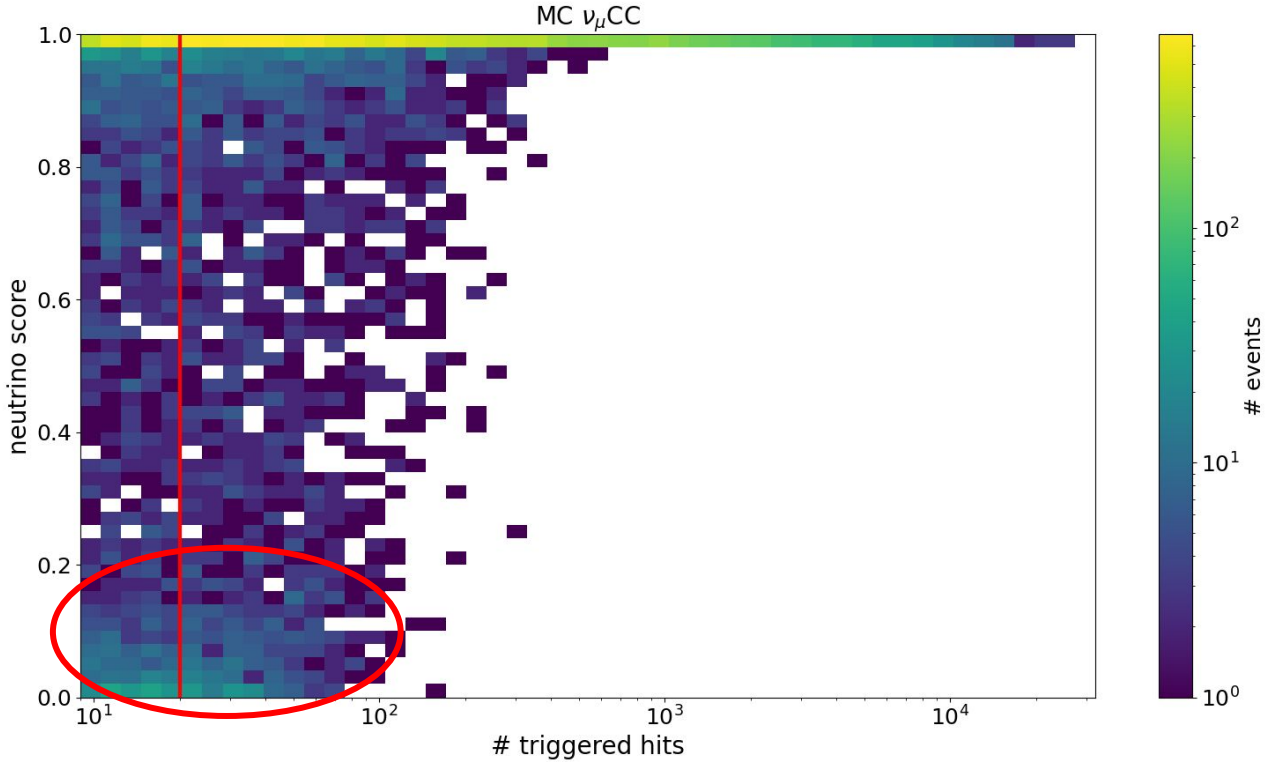


Indistinguishable from an atmospheric muon except for energy and direction

GNN performance on track-like events



GNN performance on track-like events



Low energy down-going ν_μCC are indistinguishable from atmospheric muon