CAMK yearly meeting
22.01.2025

KM3NeT: UHE neutrinos & more

Piotr Kalaczyński

Work supported by:

Nicolaus Copernicus Astronomical Center Polish Academy of Sciences

AstroCeNT Particle Astrophysics Science and Technology Centre International Research Agenda

AGH University of Krakow

CEAI Center of Excellence in Artificial Intelligence

European Funds Smart Growth

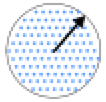
Republic of Poland

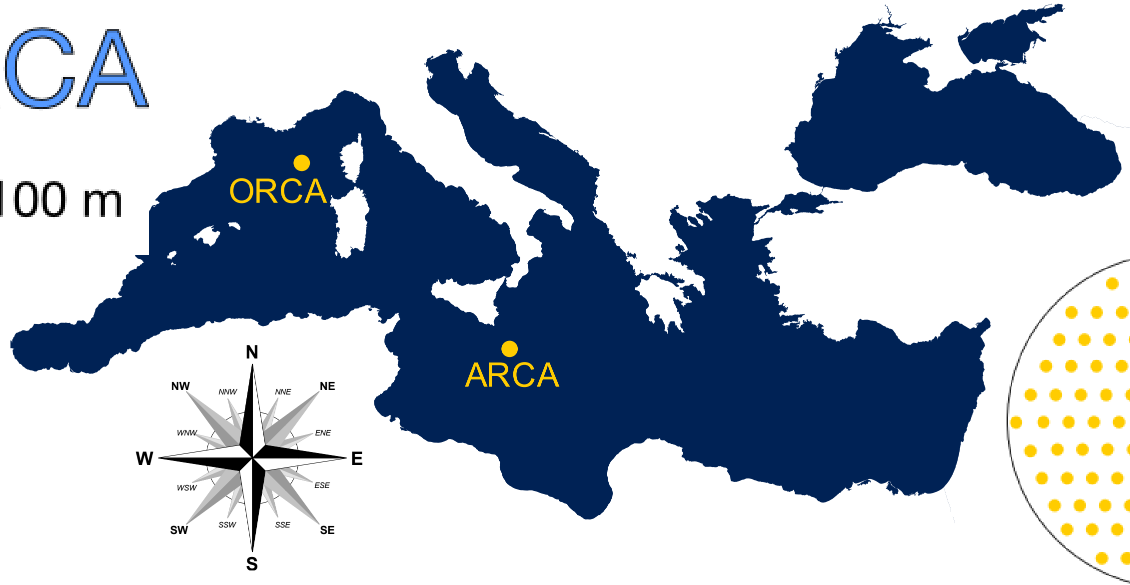
FNP Foundation for Polish Science

European Union European Regional Development Fund

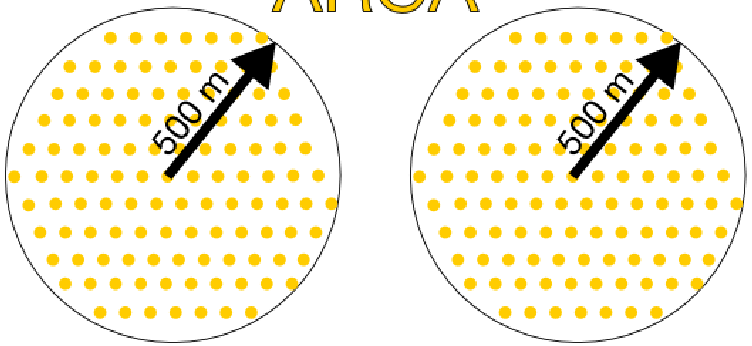
KM3NeT detectors: brief summary

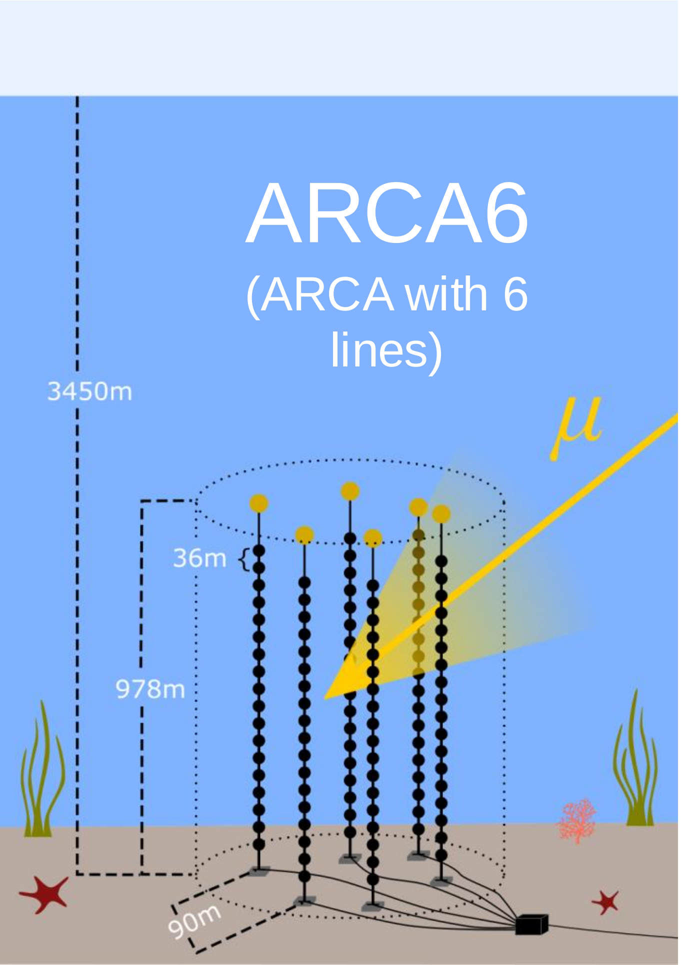
ORCA





ARCA





Detector	ARCA	ORCA
Depth	3.5 km	2.45 km
Volume	$1\ \mathrm{km}^3$ (1Gton)	$0.007\ \mathrm{km}^3$ (7Mton)
# lines	28 / 2x115	24 / 115
Topic	Astroparticle RCA*	Oscillation RCA*
Goal	ν_{astro}	m_ν hierarchy

*RCA : Research with Cosmics in the Abyss

Polish KM3NeT team: current status

Nicolaus Copernicus
Astronomical Center
Polish Academy of Sciences

AGH University of Krakow

AGH

ASTROCENT

Particle Astrophysics Science and Technology Centre
International Research Agenda

- me ☺
- Mariusz Suchenek

WFiIS AGH

WFiIS:
- Artur Ukleja
- Tomasz Szumlak
- Agnieszka Obłąkowska-Mucha
- Kalyani Mehta (PhD student)
- Amine Meskar (PhD student)
- Wiktoria Szewczyk (MSc student)

CEAI
Center of Excellence in Artificial Intelligence

- me ☺

Grants:

Under evaluation:	OPUS (NCN)
Next planned:	MNiSW grant

A little spoiler …

nature

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nature news article

NEWS | 21 June 2024

‘Fantastic’ particle could be most energetic neutrino ever detected

The ultra-high-energy neutrino was spotted by deep-sea detectors and could point to a massive cosmic event.

By Davide Castelvecchi

An observatory still under construction at the bottom of the Mediterranean Sea has spotted what could be the most energetic neutrino ever detected. Such ultra-high-energy neutrinos – tiny subatomic particles that travel at nearly the speed of light – have been known to exist for only a decade or so, and are thought to be messengers from some of the Universe’s most

Paper to be published in Nature on

12 February

stay tuned …

Our focus:

- ❖ Software development & maintenance:
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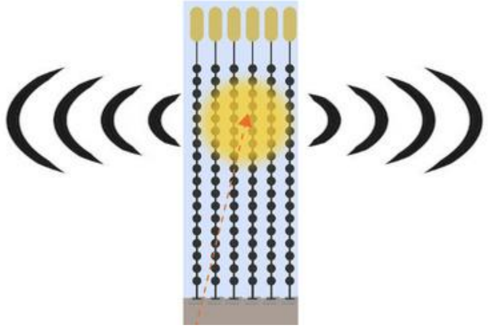

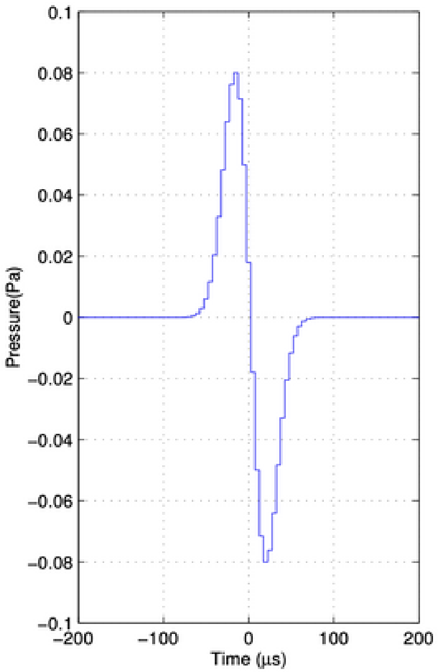

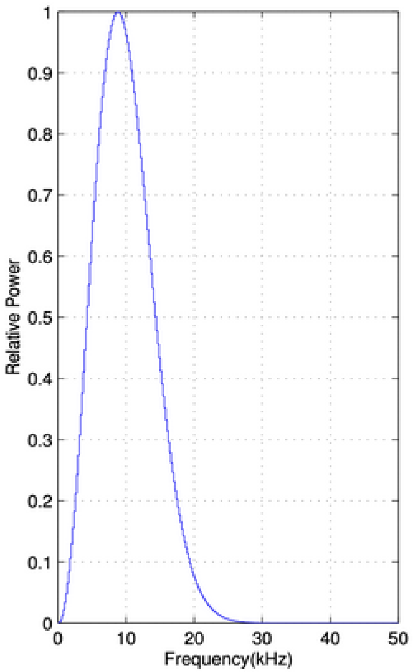

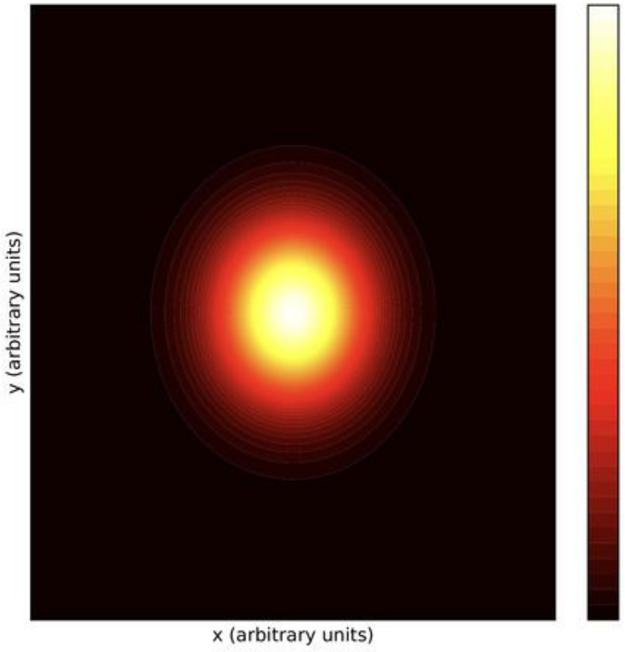

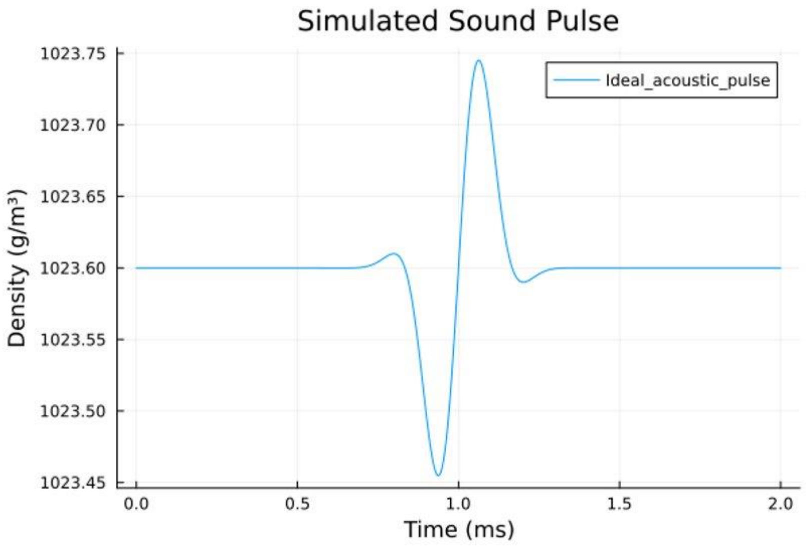

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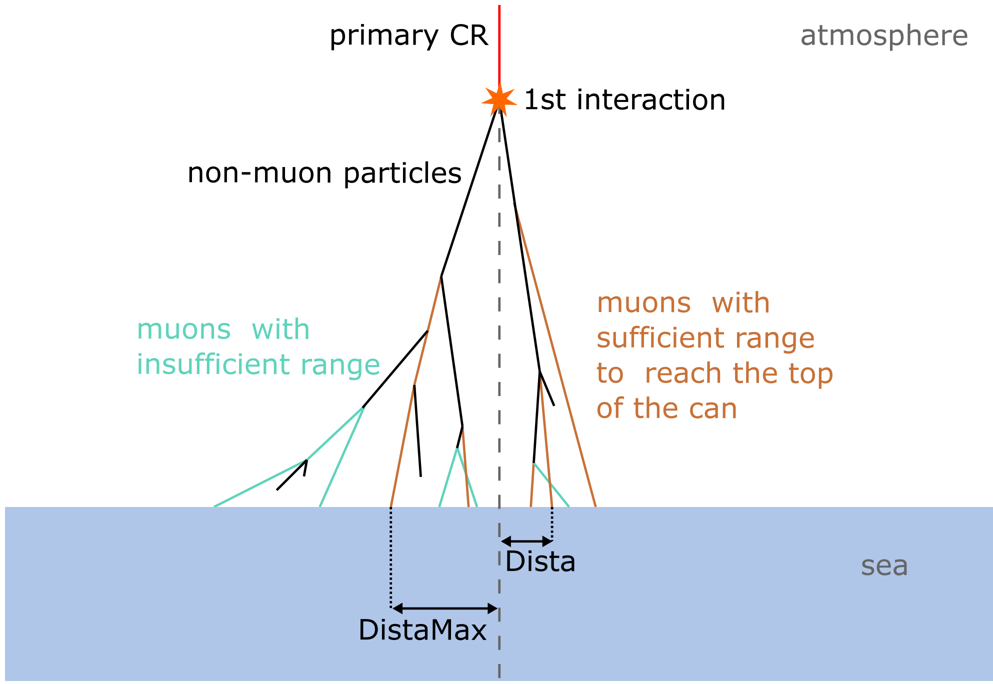
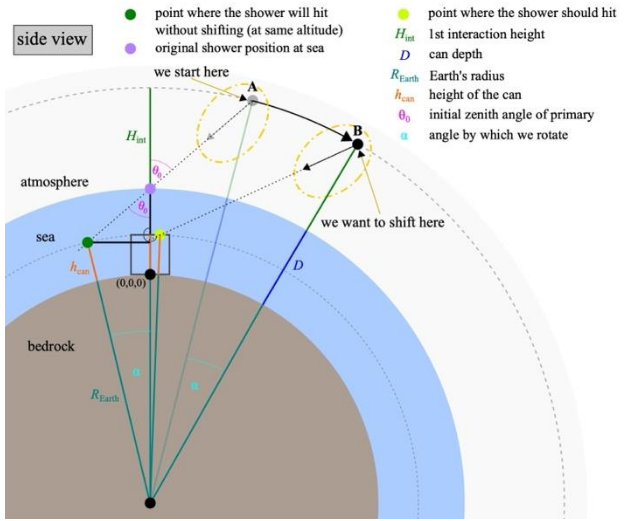
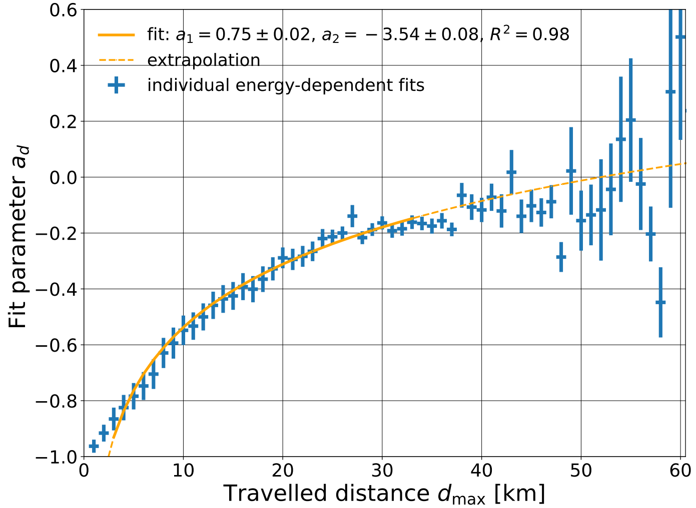
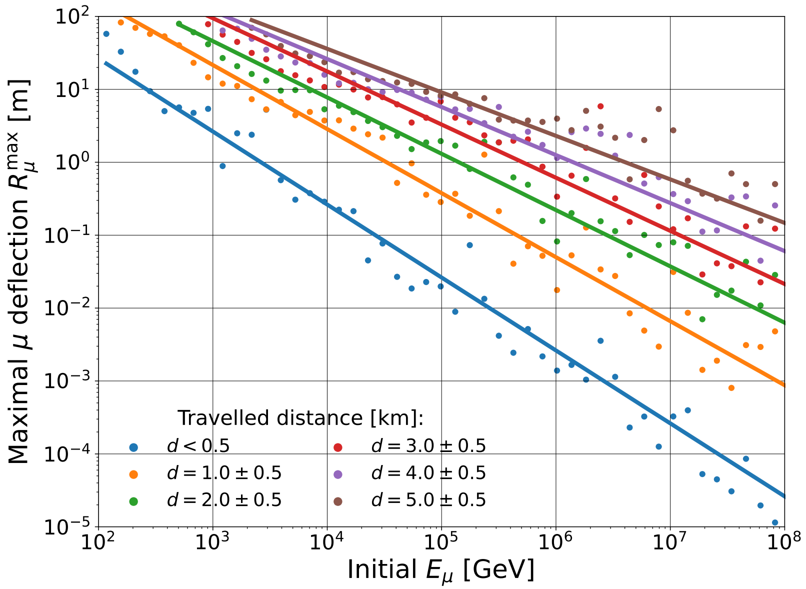
  - GENIE-based neutrino events generator
  - Processing of muons simulated with CORSIKA
    → Paper in CPC under review









Research plans in a nutshell

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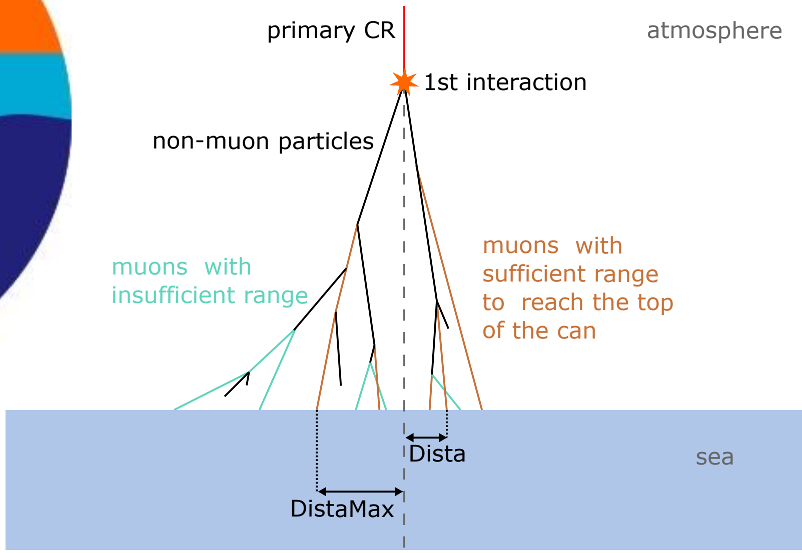
  - Using optical and/or acoustic data
  - Using ML & DL



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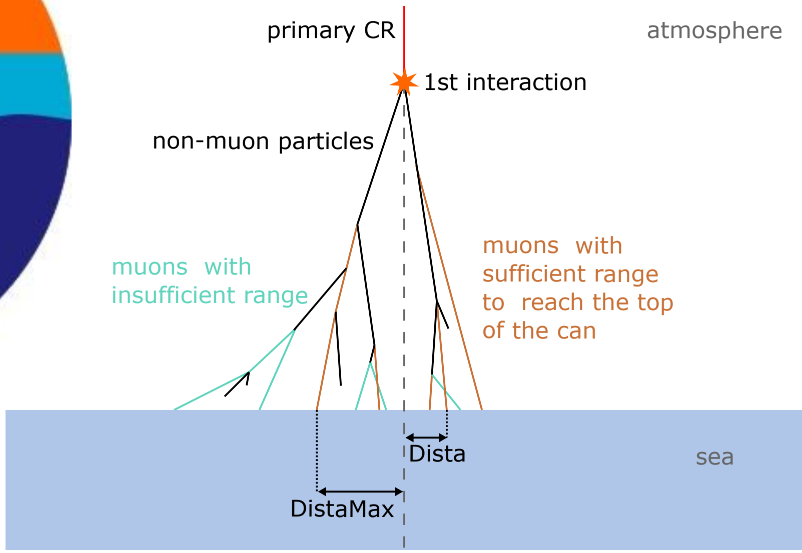

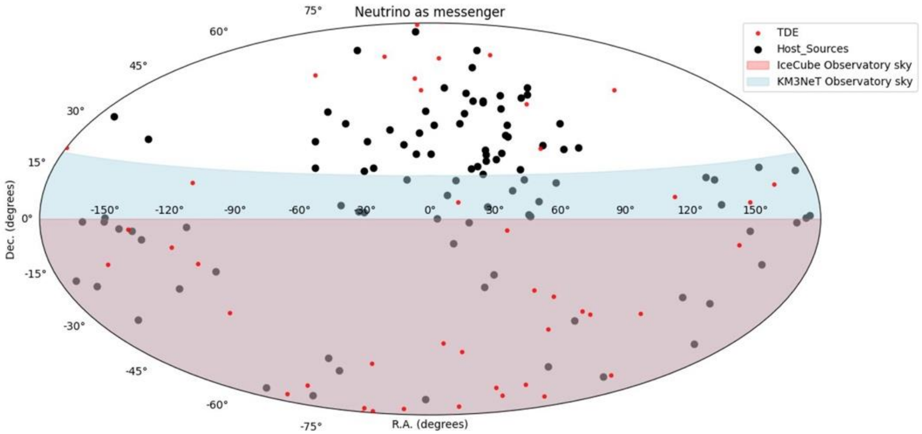

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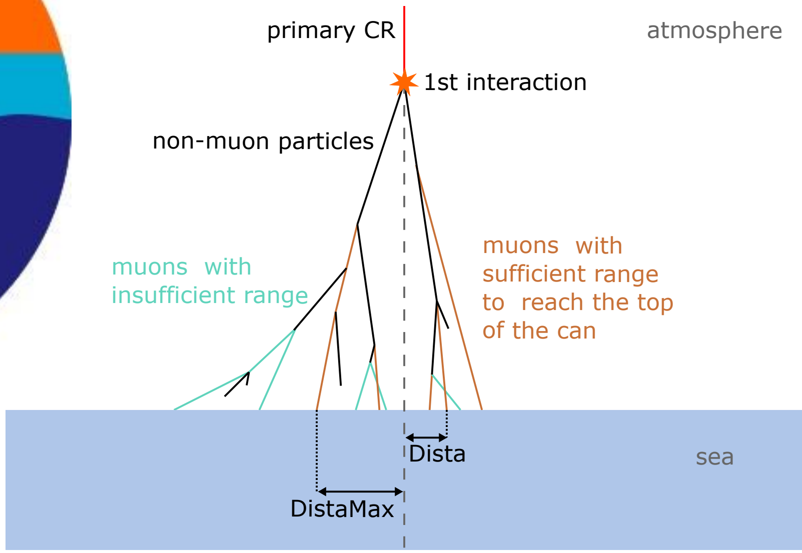
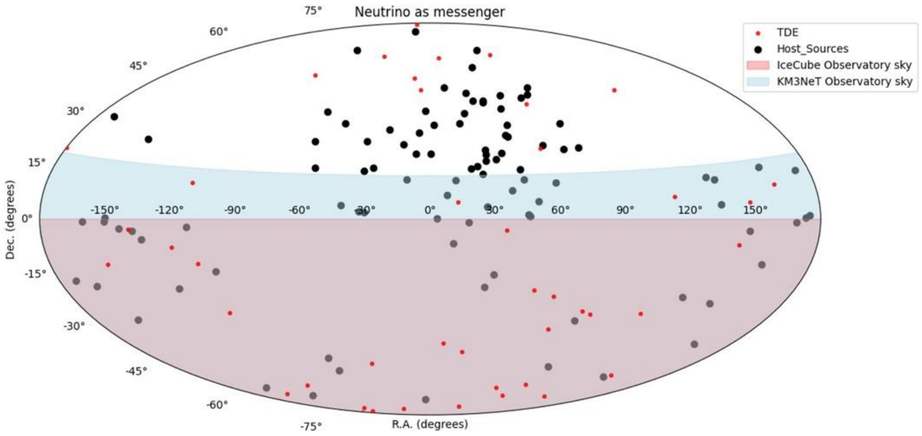
  - Using ML & DL
- ❖ Study of TDEs with neutrinos
- ❖ Muon bundle reconstruction
- ❖ Prompt muon sensitivity study
- ❖ …





TL&DR:

- KM3NeT grows & already collects valuable data
- Reliable simulations necessary
- Big potential for neutrino astronomy (and beyond)
- Stay tuned for more exciting results! ☺

Nature Paper – 12. Feb!

KM3NeT

Thank you for your attention!

European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

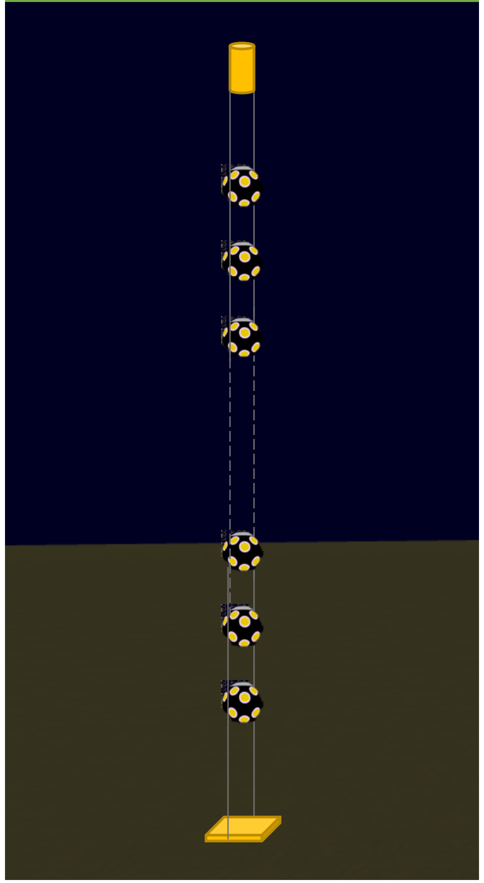
Backup

Detector design summary

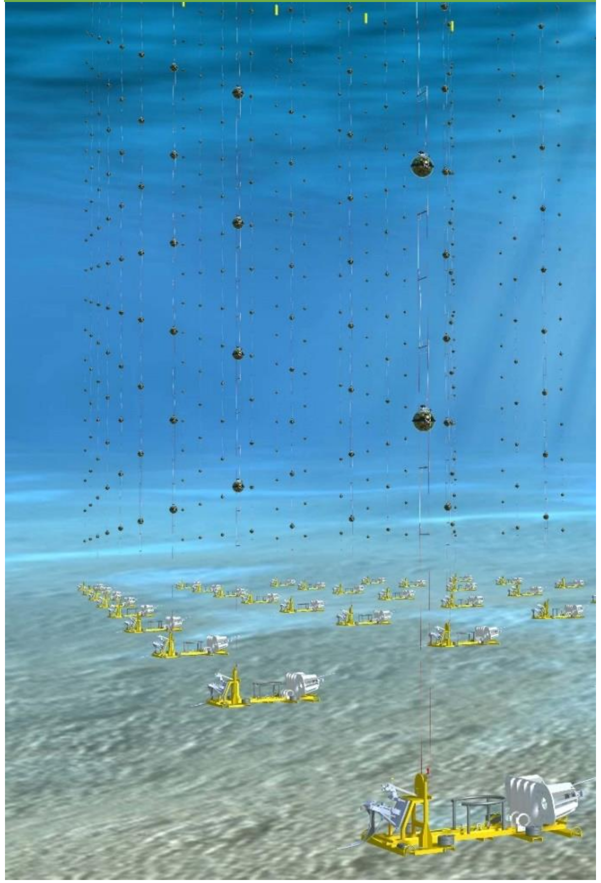
DOM:
71 unique components

1 DOM:
31 PMTs

1 string (DU):
18 DOMs



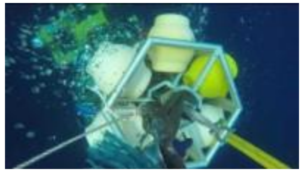
1 building block:
115 DUs



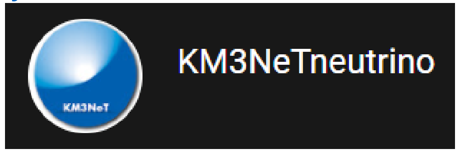
[DOM production:(@Nikhef)](#)

[Preparation for deployment:](#)

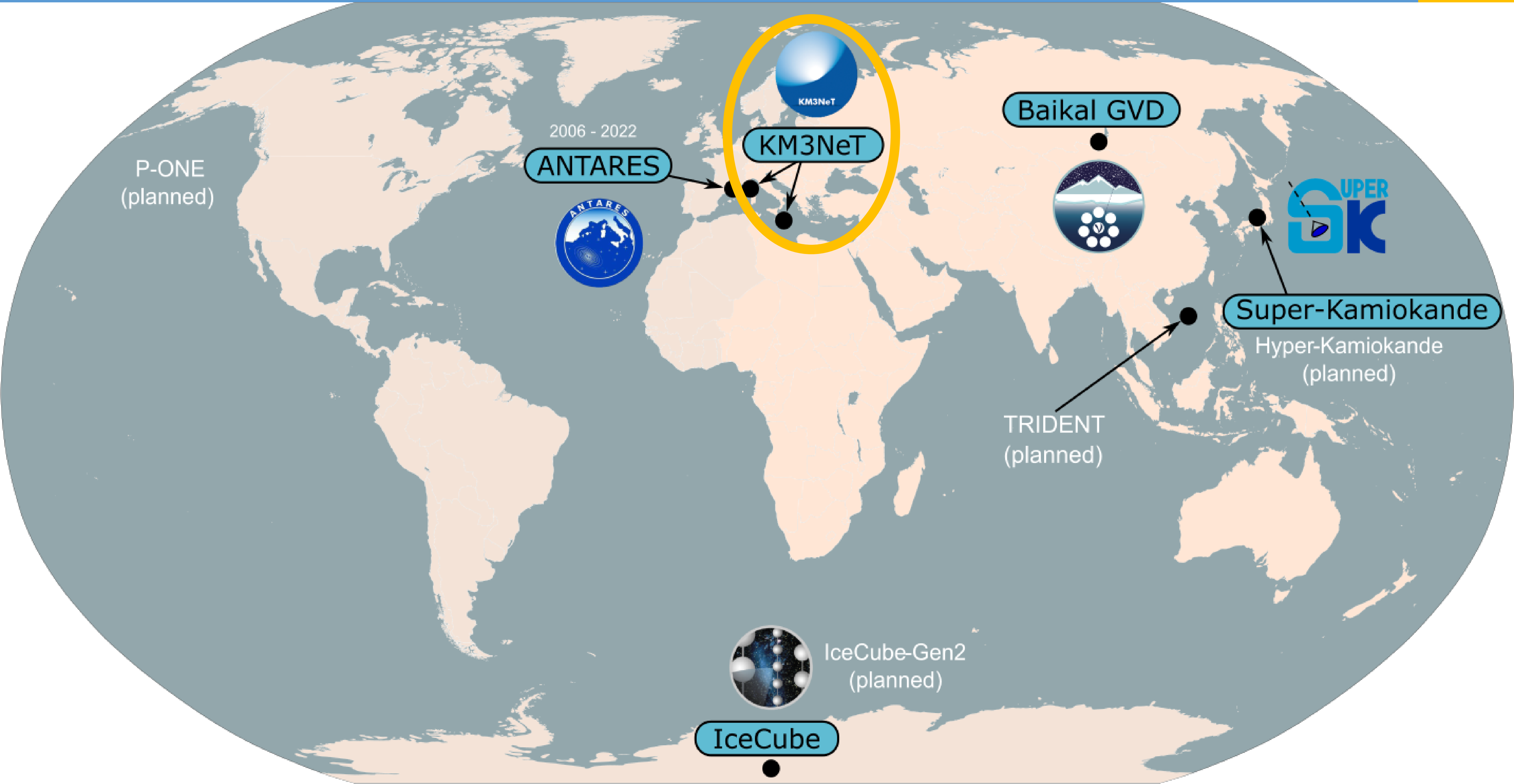
[String deployment:](#)



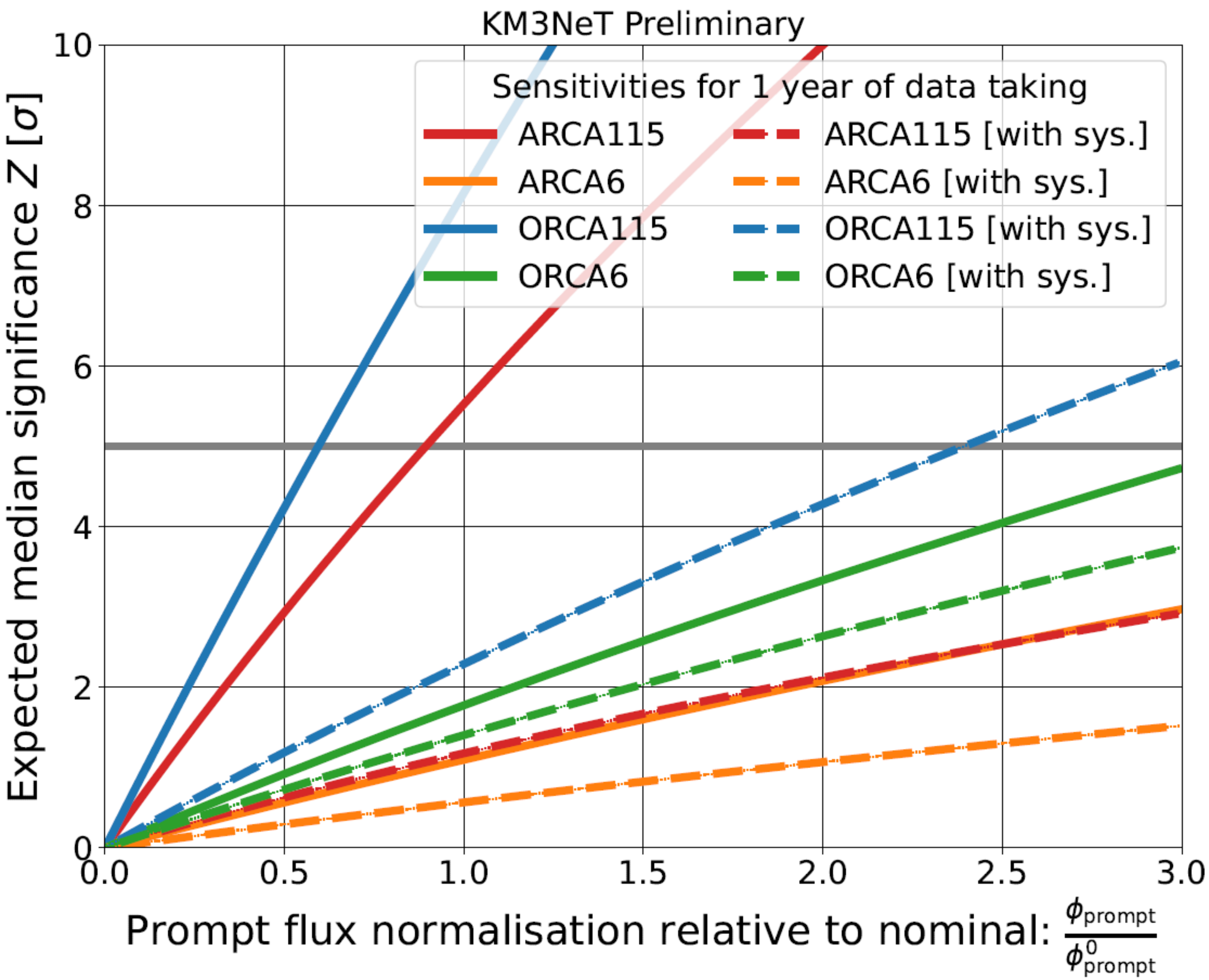
More at:
[youtube.com/KM3NeTneutrino](#)



Water Cherenkov ν telescopes



Sensitivities vs prompt norma



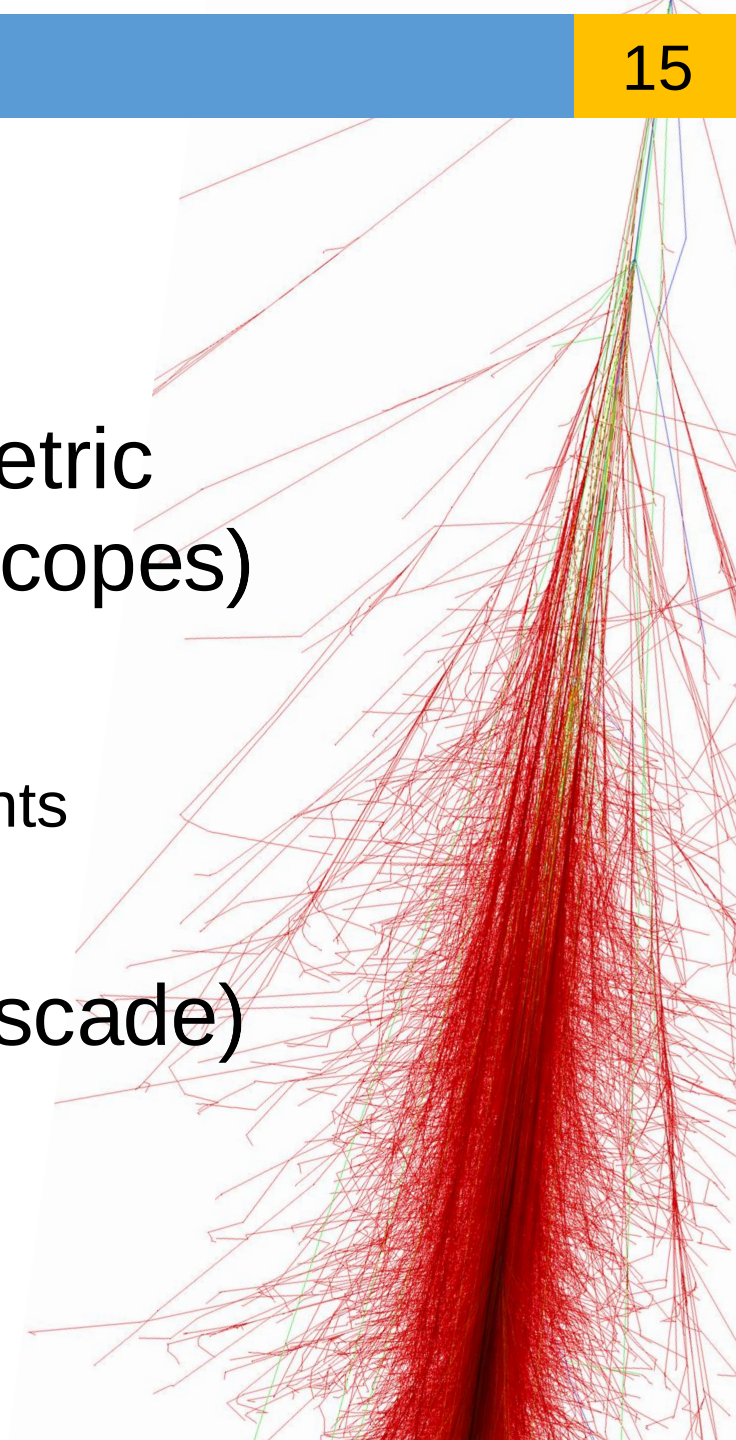
Comments:

- prompt flux normalisation has a linear effect on sensitivity
- still, systematics are the dominant issue

We have 2 options:

1. MUPAGE (atmospheric **MU**ons from **PA**rametric formulas: a fast **GE**nerator for neutrino telescopes)
   - developed for ANTARES
   - fast muon MC generator
   - based on parametric formulas and MACRO measurements
   - parameters can be freely tuned

2. CORSIKA (**CO**smic **R**ay **SI**mulations for **KA**scade)
   - developed for KASCADE
   - full simulation of air showers
   - customizable (models, primaries, etc.)



Digital Optical Module (DOM)

acrylic glass sphere with:

- 31 3” PMTs,
- readout electronics,
- pressure gauge,
- acoustic sensonrs,
- ...

2022 JINST 17 P0703

JATIS 7(1), 016001 (2021)

Photomultiplier Tube (PMT)

converts light into electric signal

JINST13 (2018) P05035

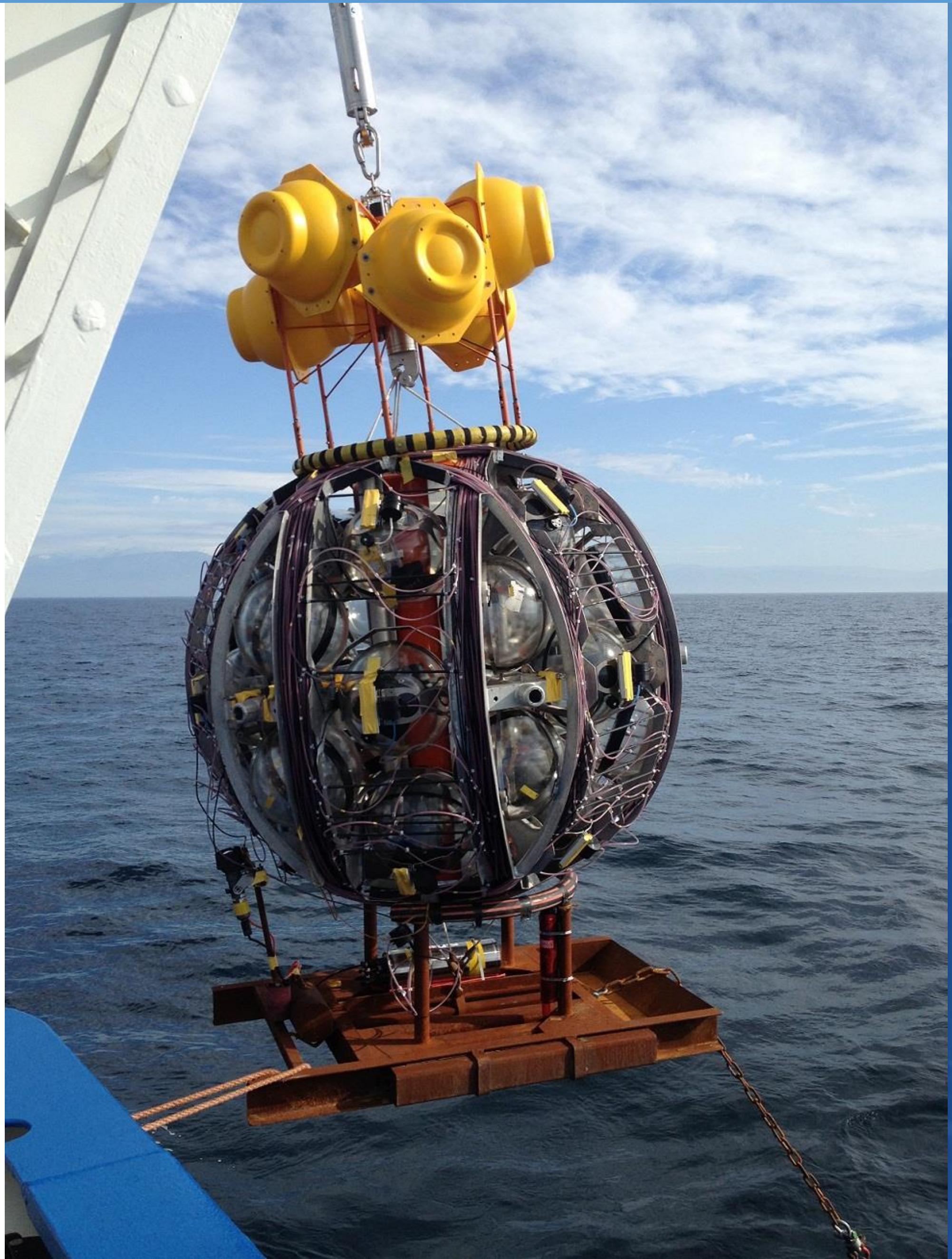
Detection Unit (DU):
vertical **string** with 18 DOMs

Eur. Phys. J. C 76 (2016) 76:54

Naming:

ORCA6 ↔ ORCA with 6 strings
ARCA2 ↔ ARCA with 2 strings
etc.

2020 JINST 15 P11027



DOM arrangement

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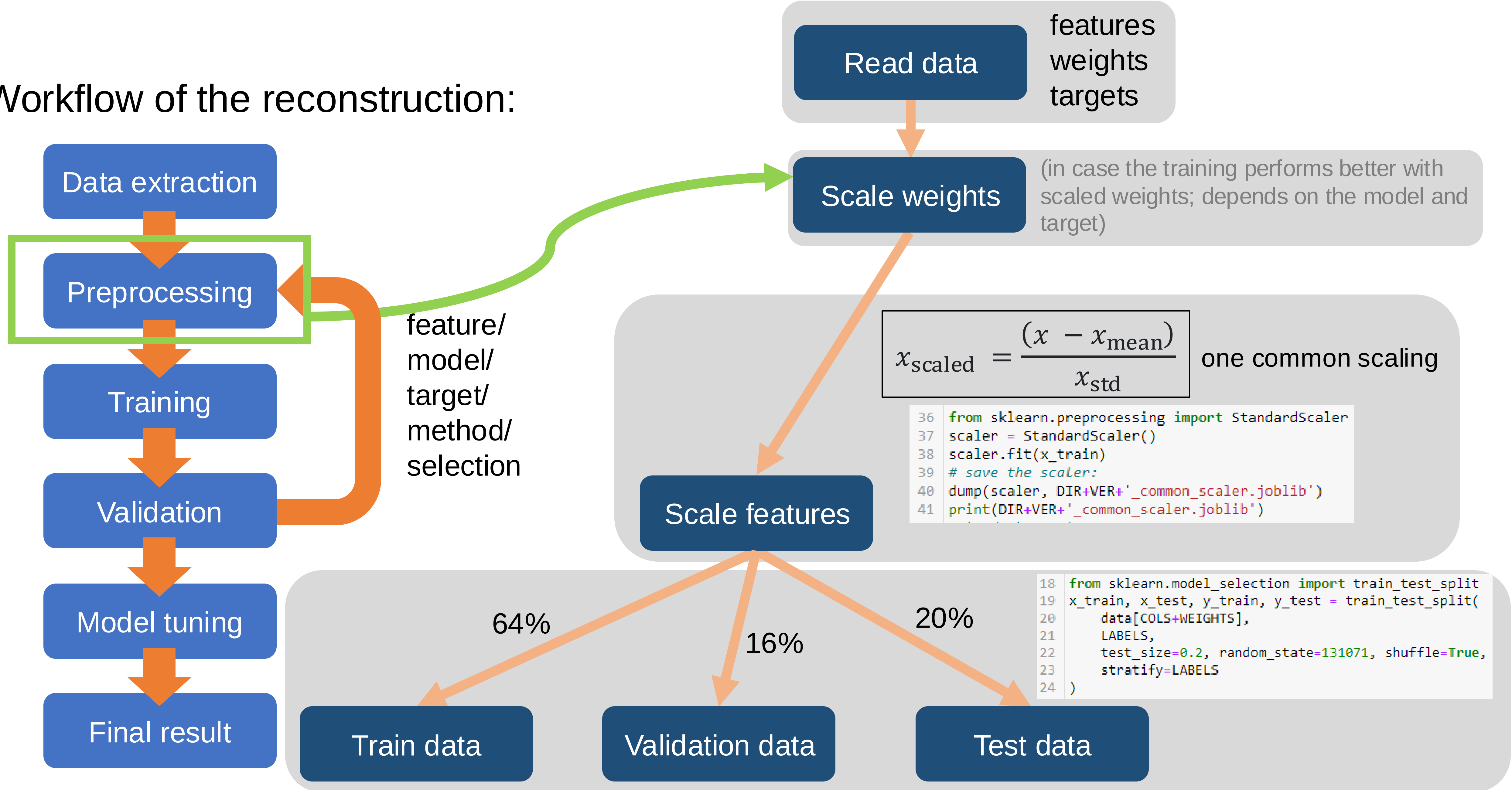
2020 JINST 15 P11027

ML reco: general overview

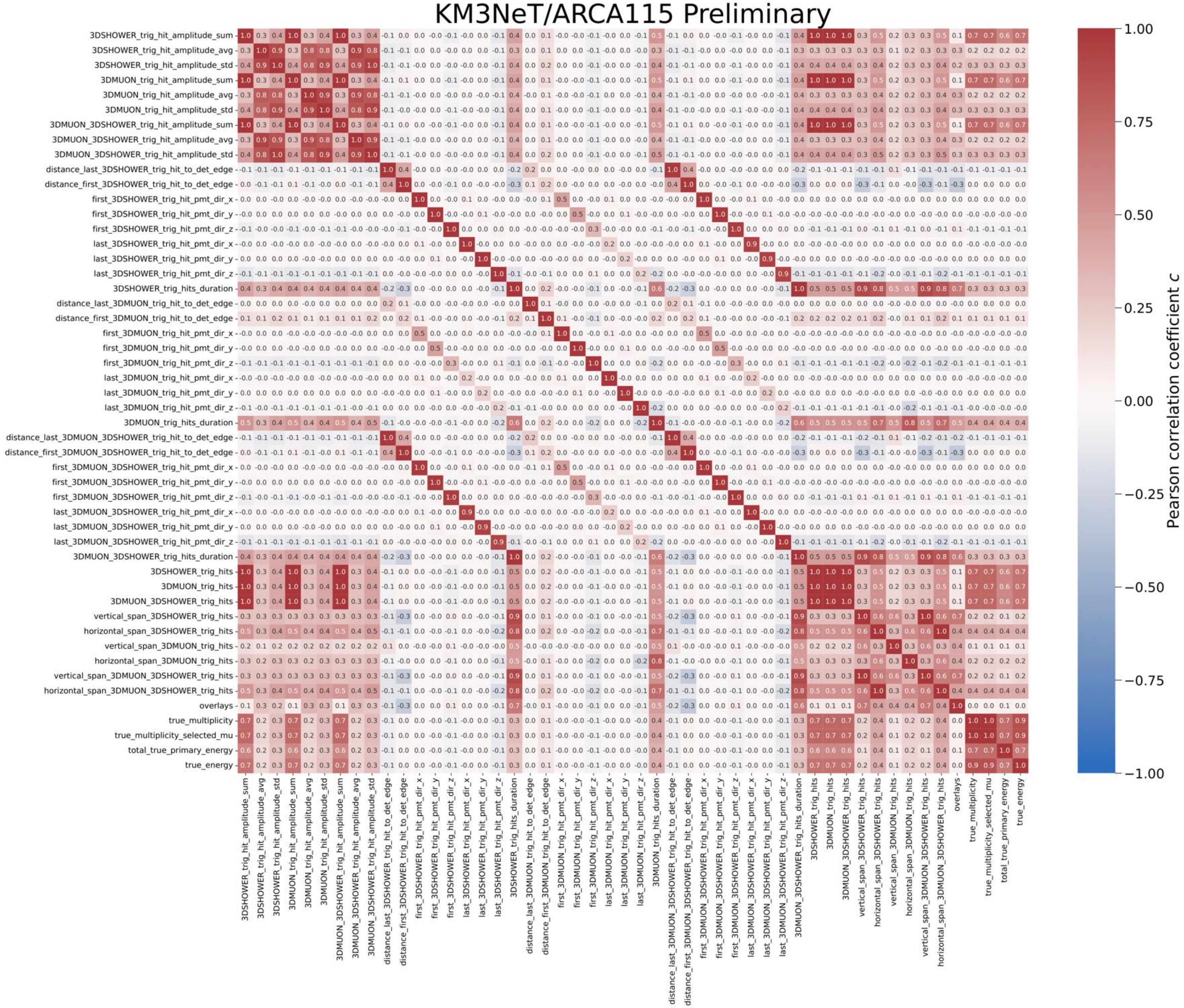
Workflow of the reconstruction:




```python
from sklearn.preprocessing import StandardScaler
scaler = StandardScaler()
scaler.fit(x_train)
# save the scaler:
dump(scaler, DIR+VER+'_common_scaler.joblib')
print(DIR+VER+'_common_scaler.joblib')
```

```python
from sklearn.model_selection import train_test_split
x_train, x_test, y_train, y_test = train_test_split(
    data[COLS+WEIGHTS],
    LABELS,
    test_size=0.2, random_state=131071, shuffle=True,
    stratify=LABELS
)
```

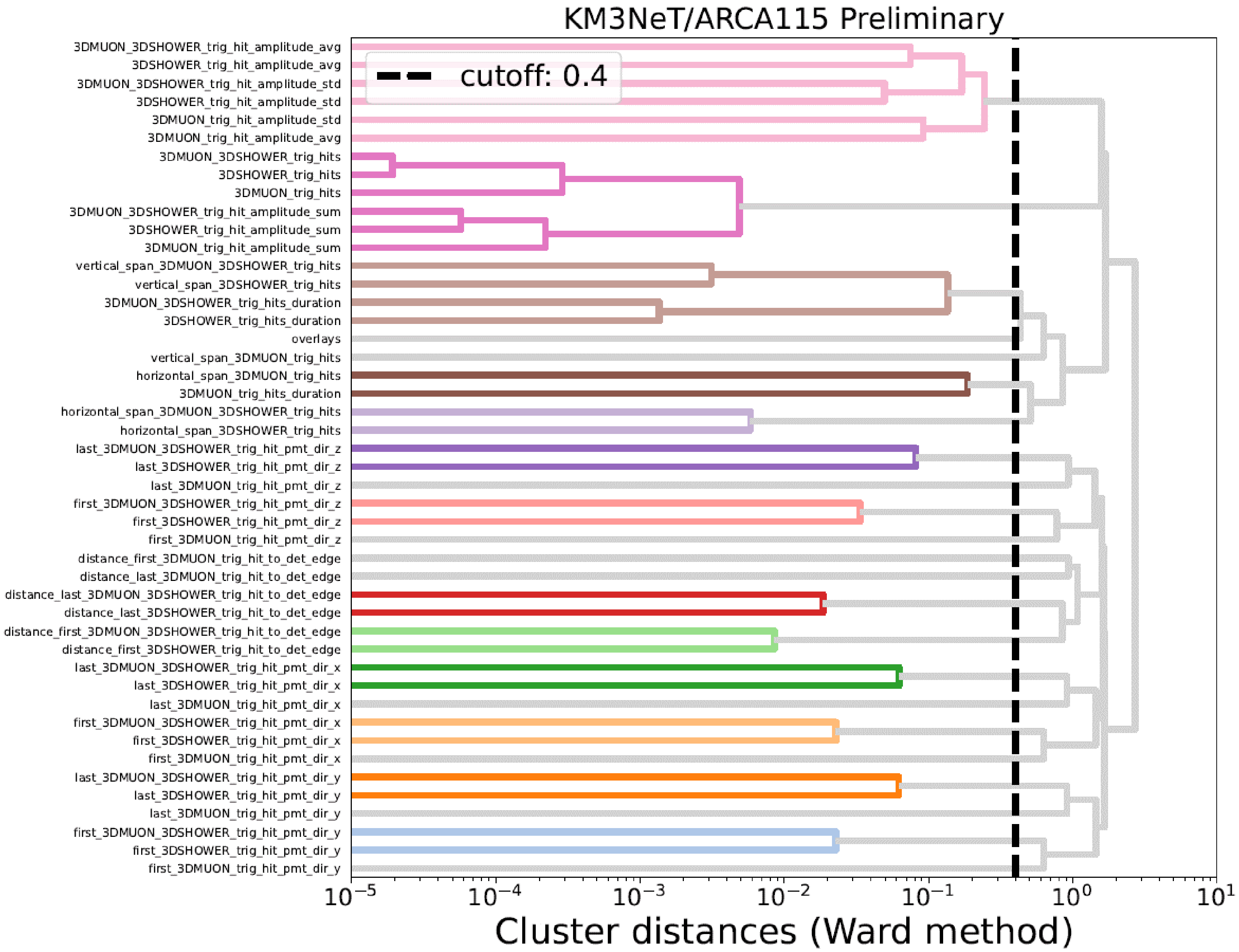
ML reco: features used for reconstruction



In total: 46 features (+4 targets)

Example for ARCA115
(the same was done for ARCA6, ORCA115 and ORCA6)

ML reco: feature clustering



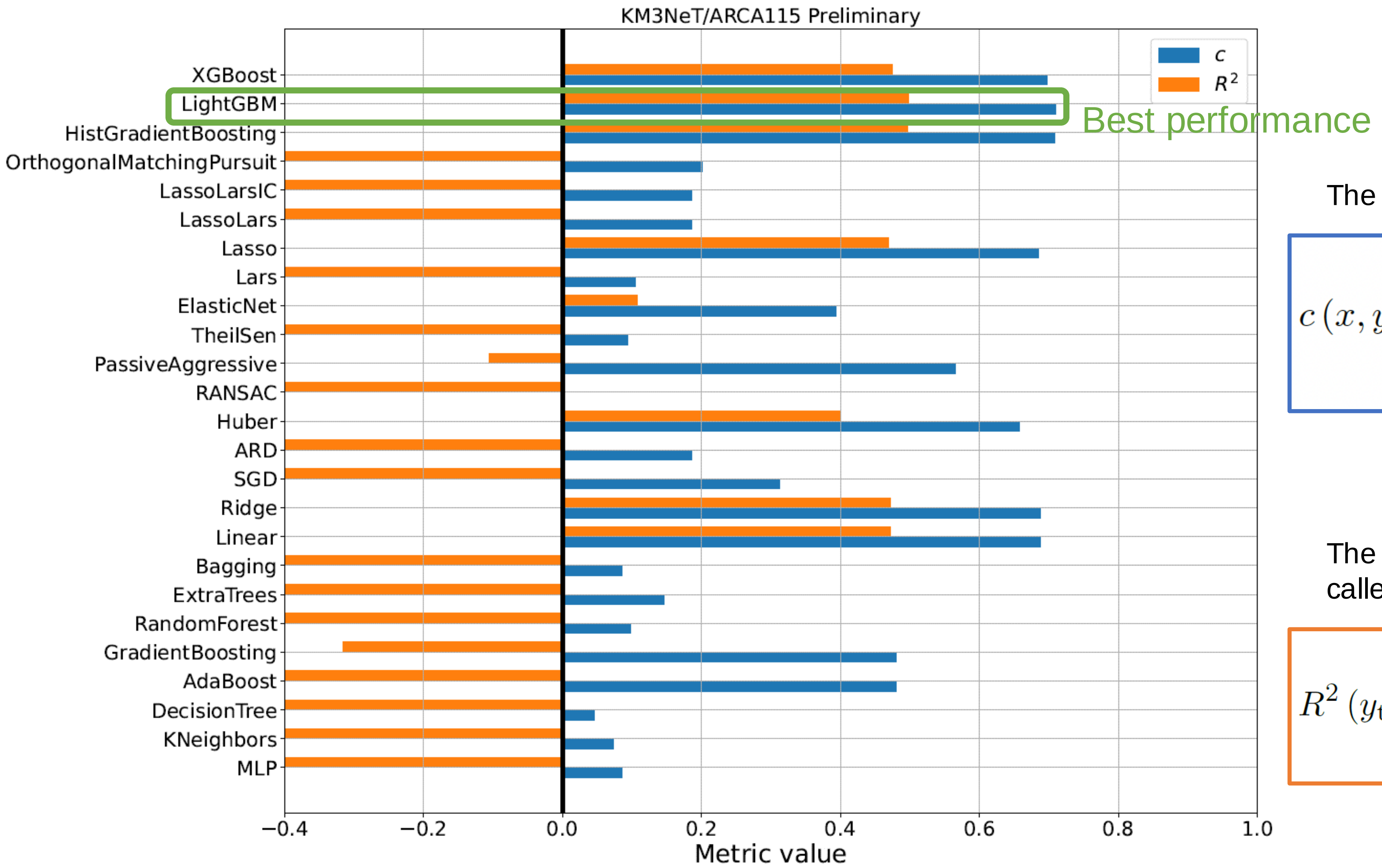
Cluster distance cutoff is arbitrary

Clusters are marked by different colors

Example for ARCA115
(the same was done for ARCA6, ORCA115 and ORCA6)

Bundle energy reco: best ML model selection

Performance comparison on a fraction (50k events) of the training dataset:



The (weighted) Pearson correlation coefficient:

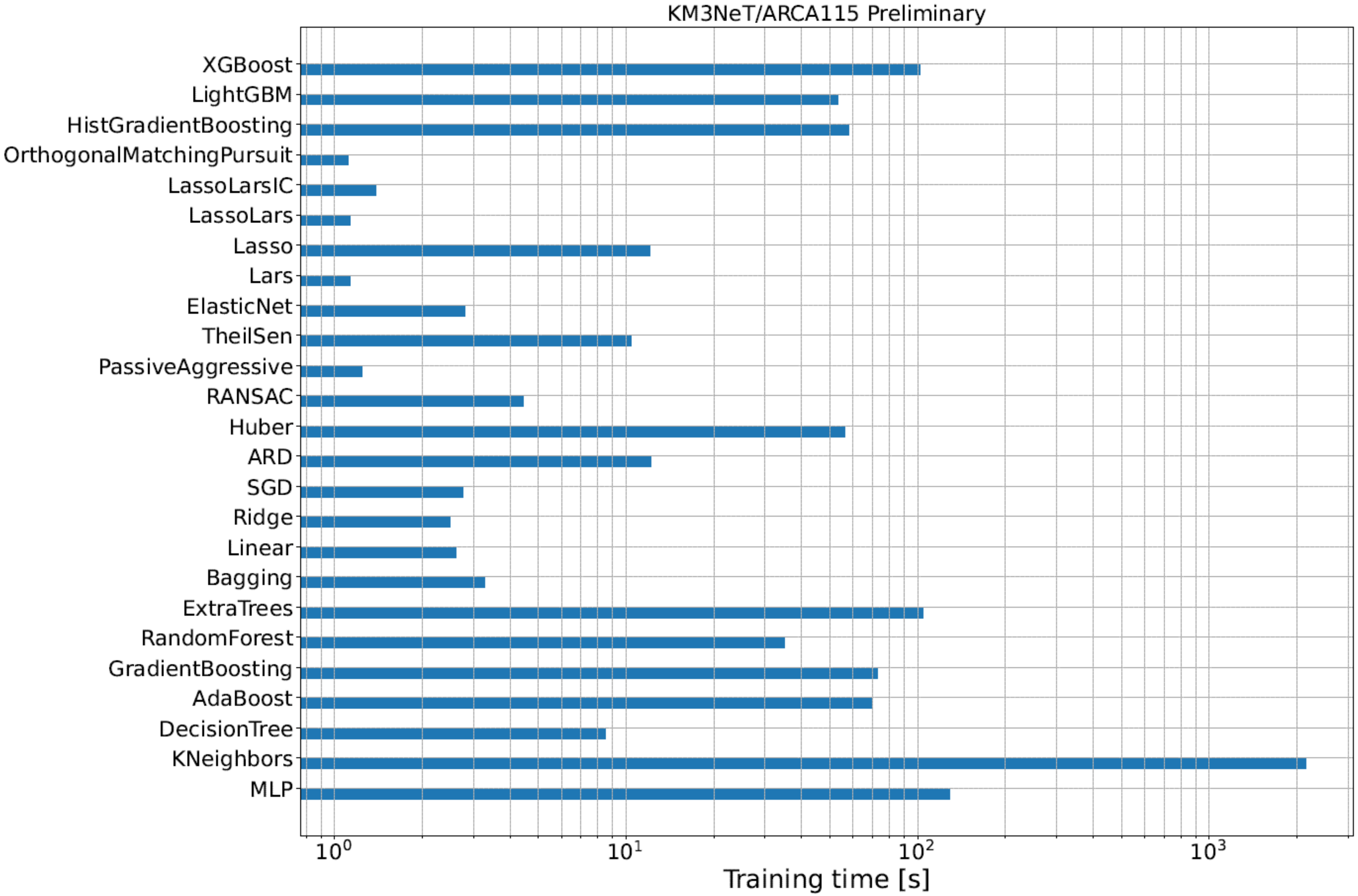
$$c\left(x,y\right)=\frac{\sum_i w_i\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)}{\sqrt{\sum_i w_i\left(x_i-\bar{x}\right)^2\sum_i w_i\left(y_i-\bar{y}\right)^2}}$$

The (weighted) R2-score,
called the coefficient of determination:

$$R^2\left(y_{\text{true}},y_{\text{pred}}\right)=1-\frac{\sum_i w_i\left(y_{\text{true}}-y_{\text{pred}}\right)^2}{\sum_i w_i\left(y_{\text{true}}-\bar{y}\right)^2}$$

Bundle energy reco: best ML model selection

Speed comparison on a fraction (50k events) of the training dataset:

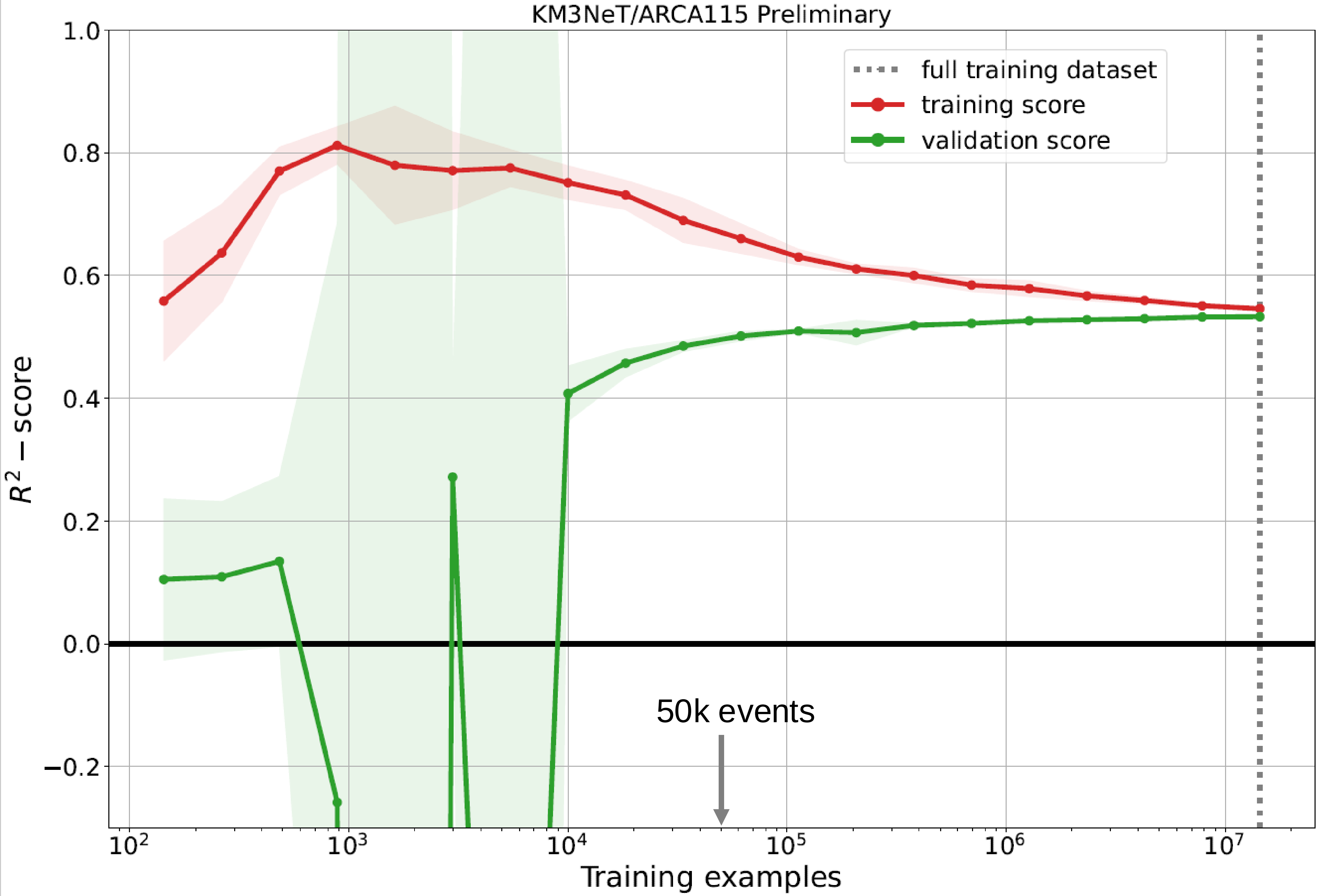


LightGBM:

- ❖ not the fastest, but still very decent
- ❖ + it turned out to scale up very well (entire dataset is orders of magnitude larger)

These times were obtained running with 20 CPU cores in parallel

Bundle energy reco: learning inspection

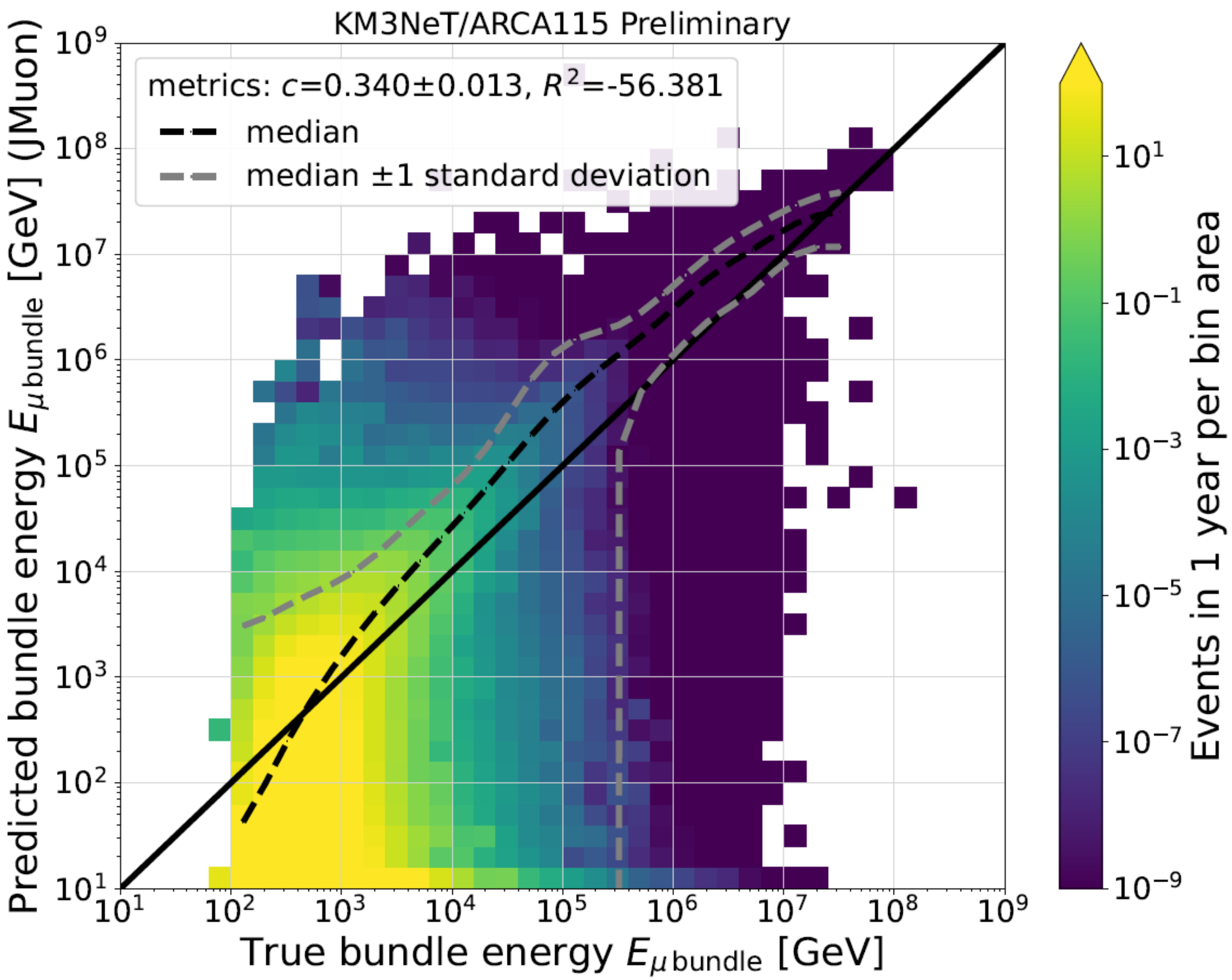


Here we see why 50k events were fine for testing (but e.g. 5k would not be)

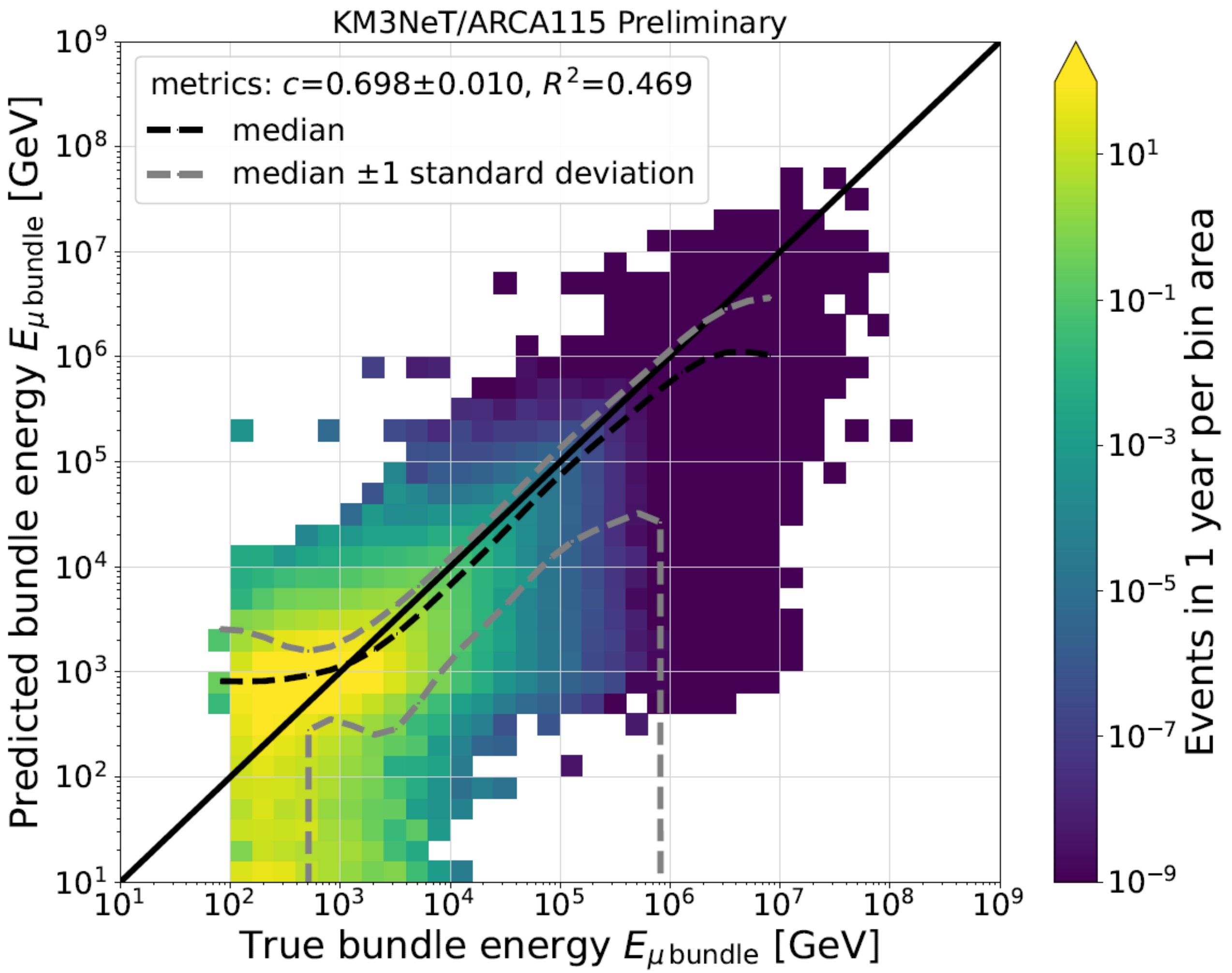
Bundle energy reco: basic comparison with JMuon

Here I just compare LightGBM (no tuning whatsoever) and JMuon reco (non-ML reco)

JMuon

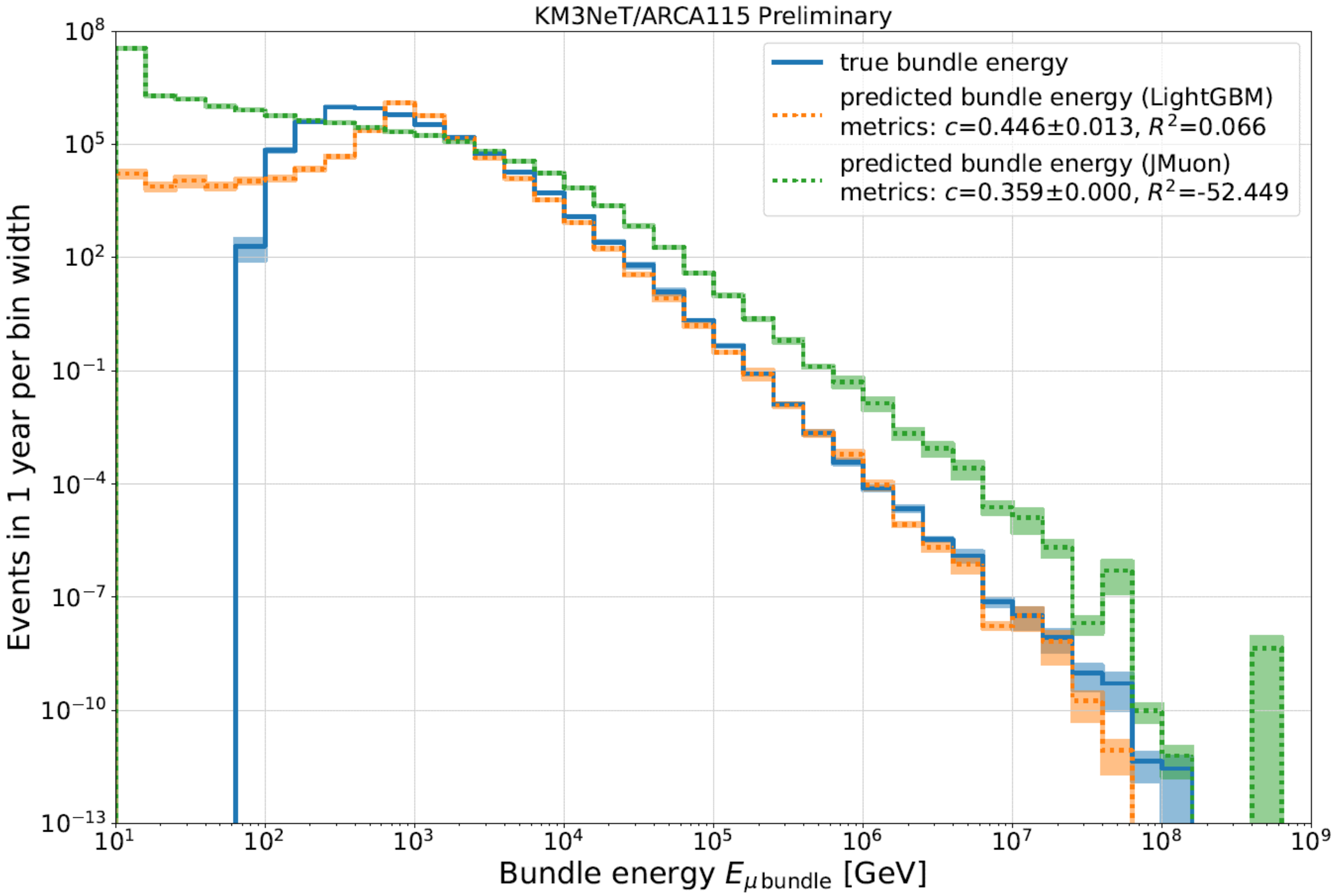


LightGBM



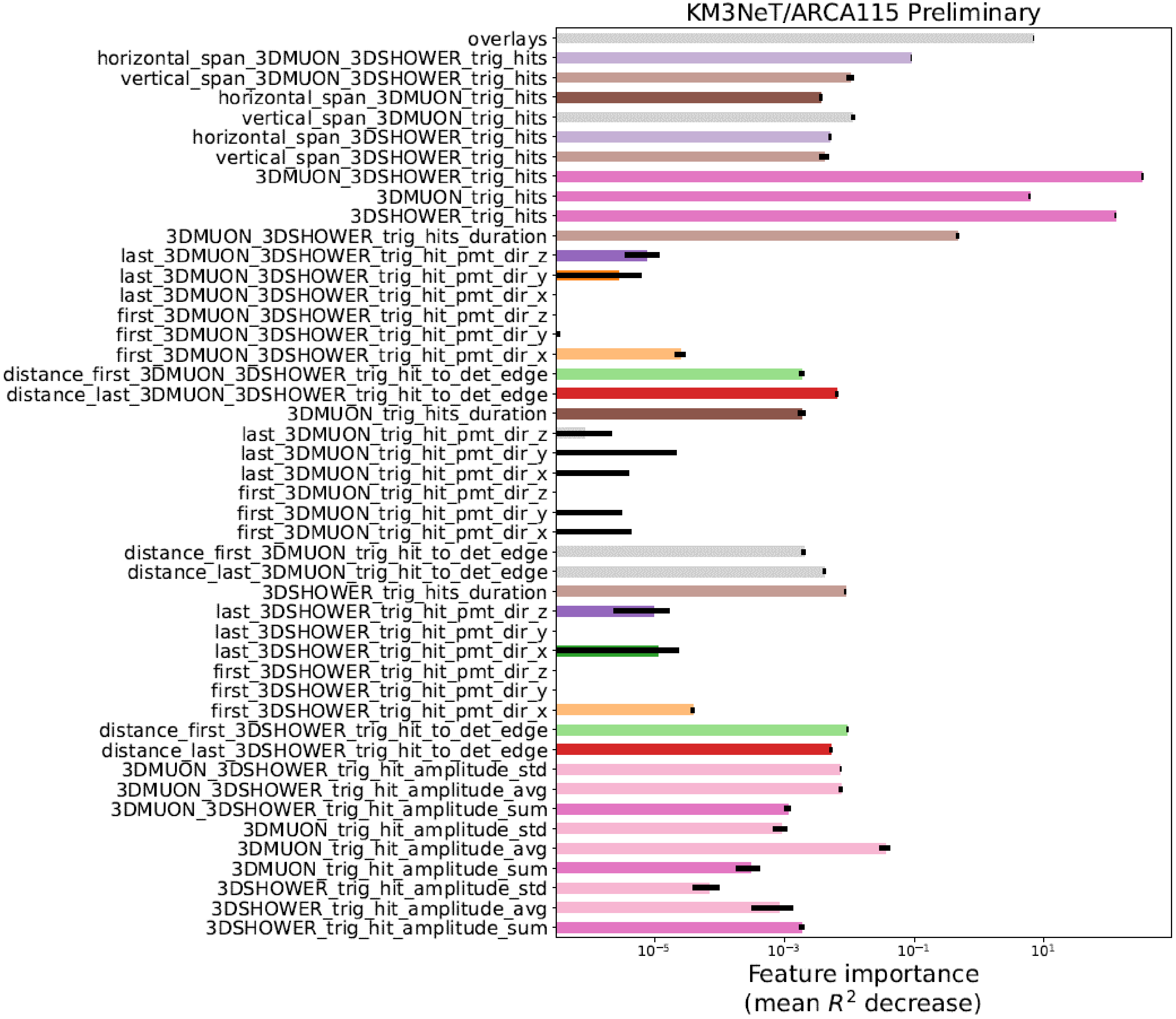
Bundle energy reco: basic result in 1D

Comparison in 1D:



Clearly even untuned ML approach reproduces the distribution much closer

Bundle energy reco: feature importance



Colors here are not random!

They match the feature clustering

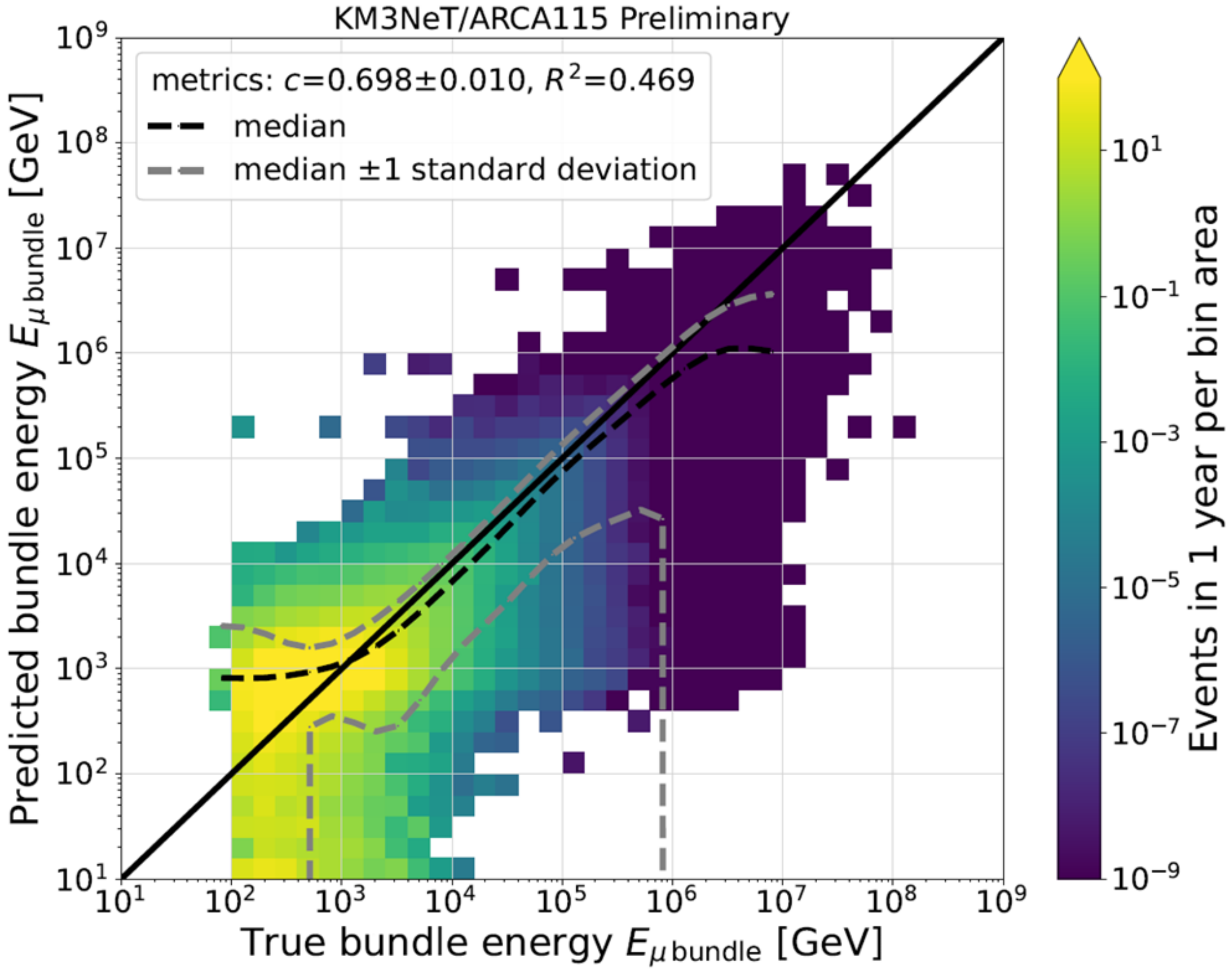
The idea:
Try to select only the most important feature in each cluster

Bundle energy reco: feature selection

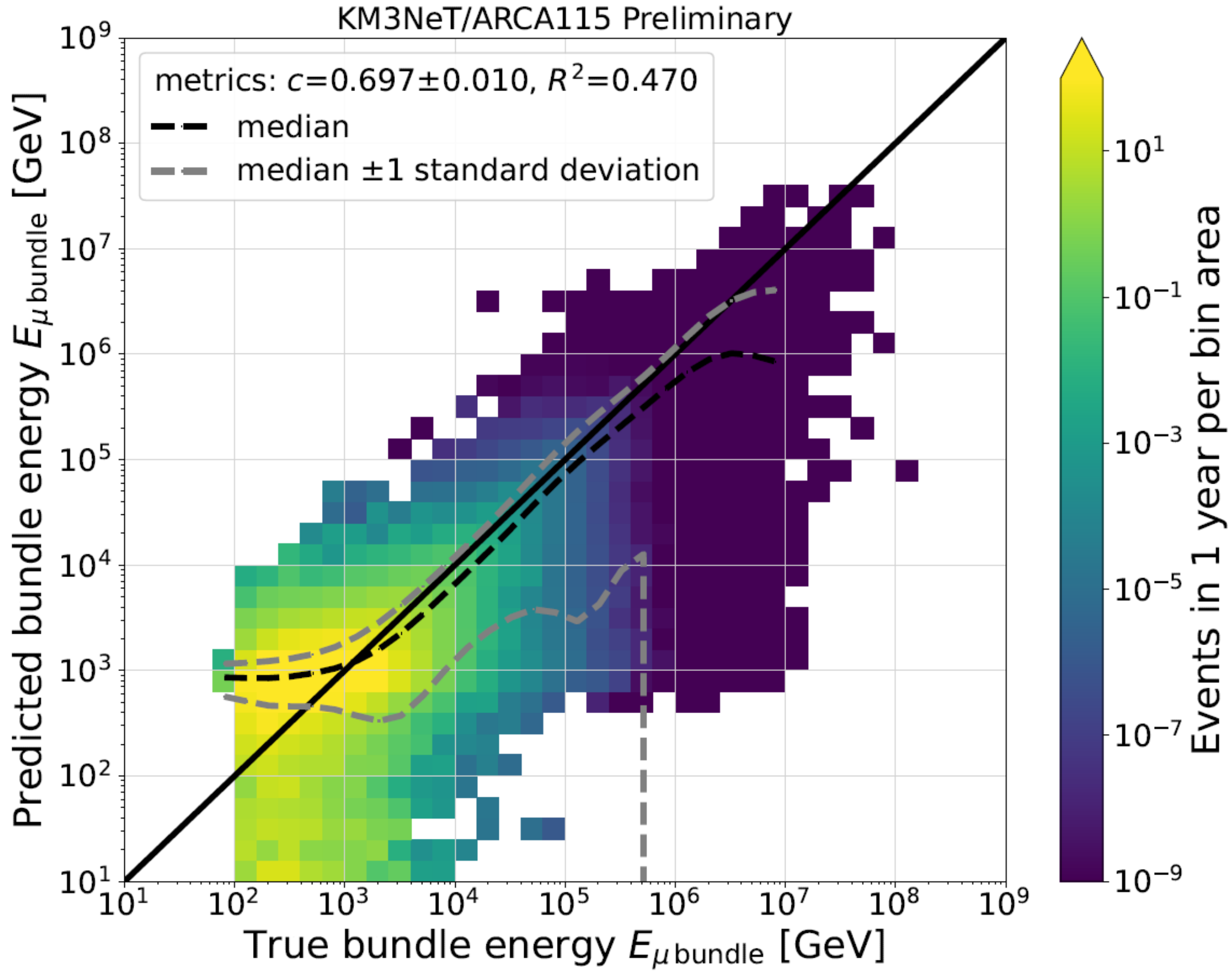
I considered 4 options:

1. All features
2. Features with importance>0 & only the most important one from each cluster
3. The most important feature only
4. Features with importance>0

1. All features



2. importance>0 & clustering



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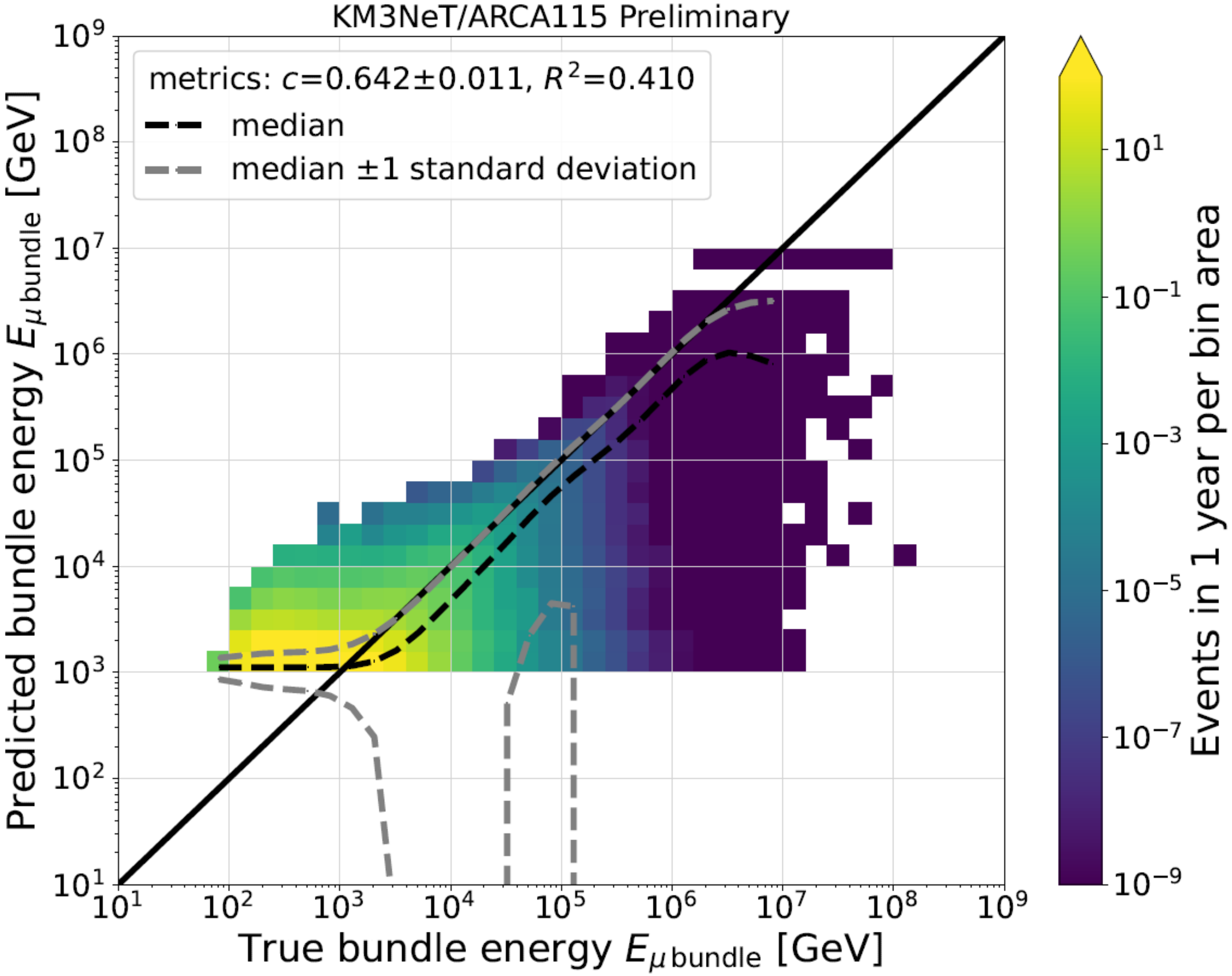
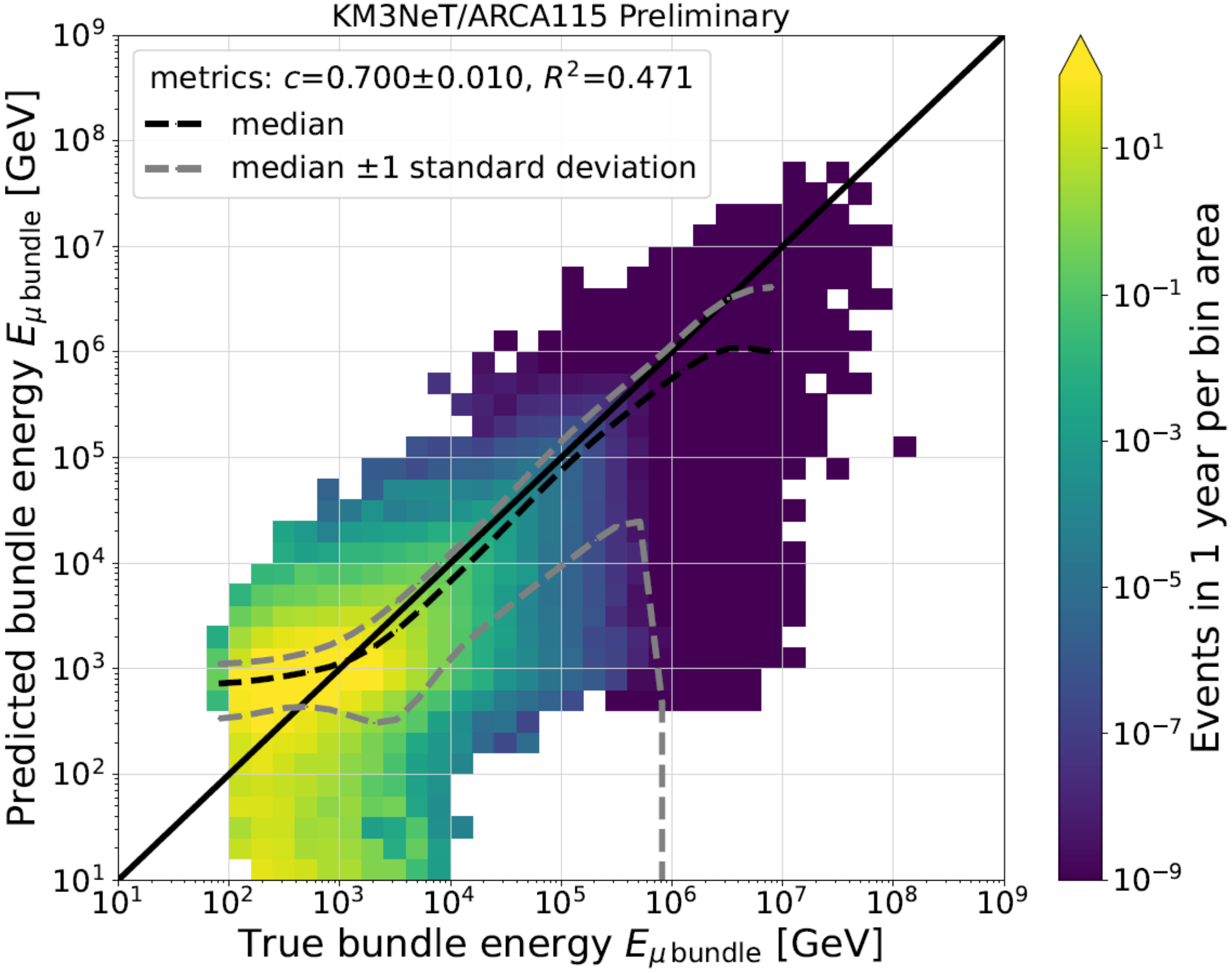
3. 3DMUON_3DSHOWER_trig_hits only



4. importance>0



ML reco: general overview

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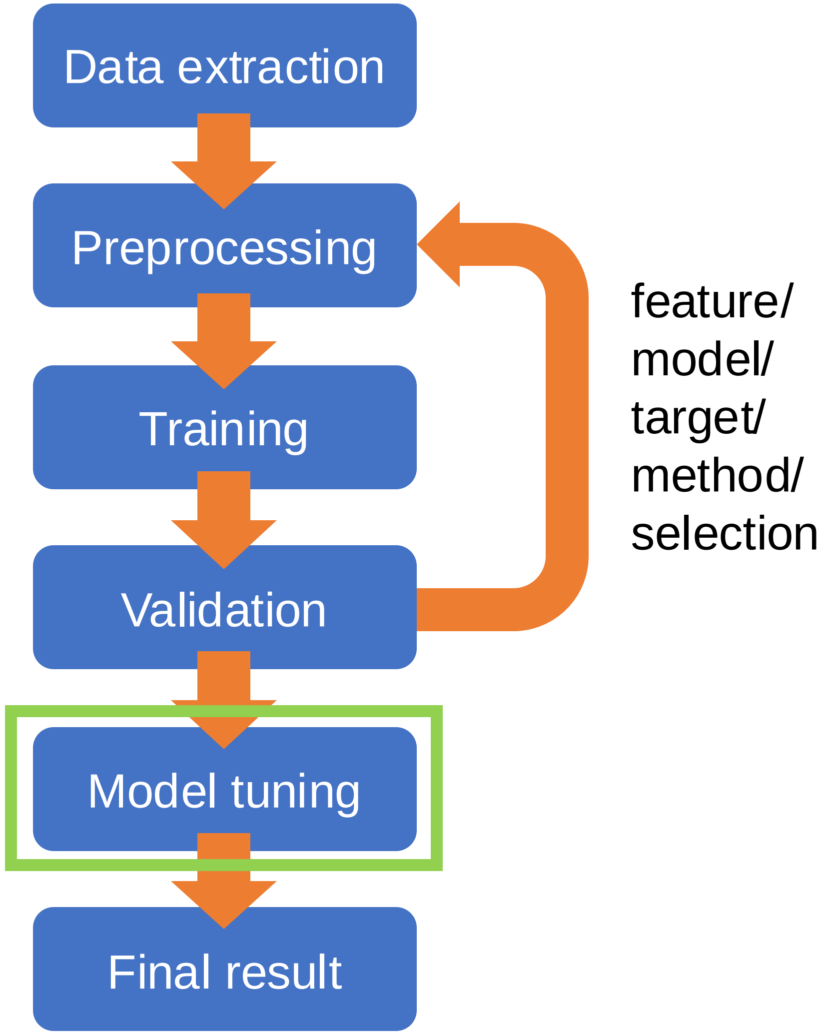
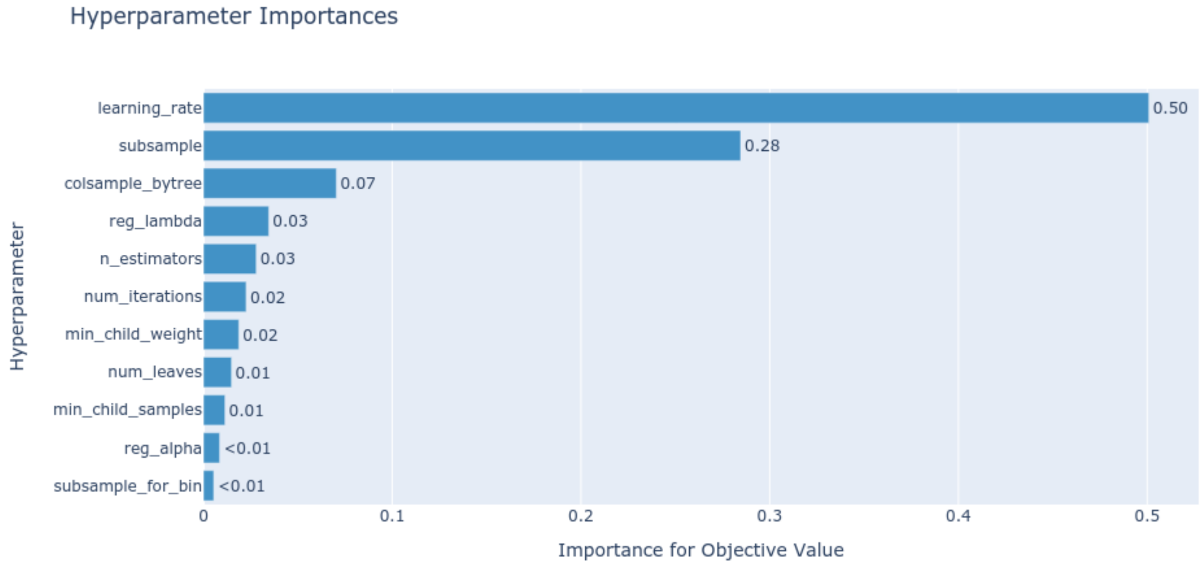
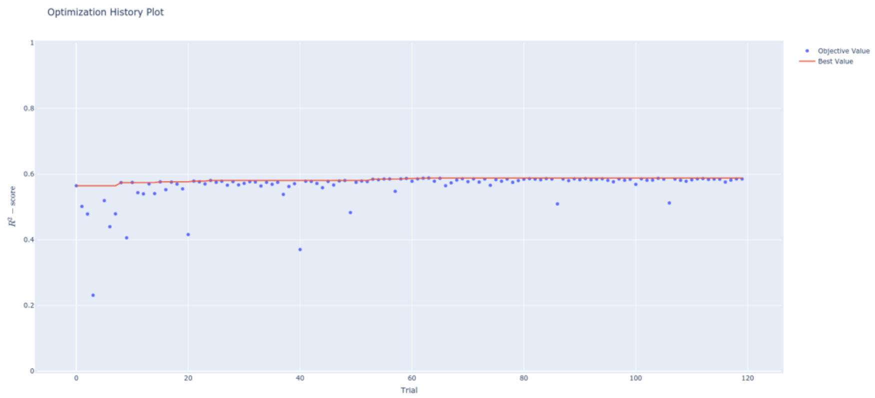
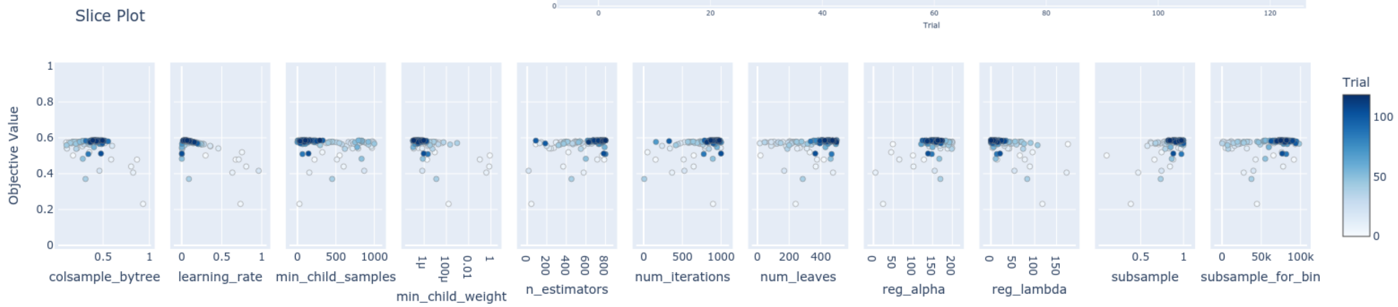
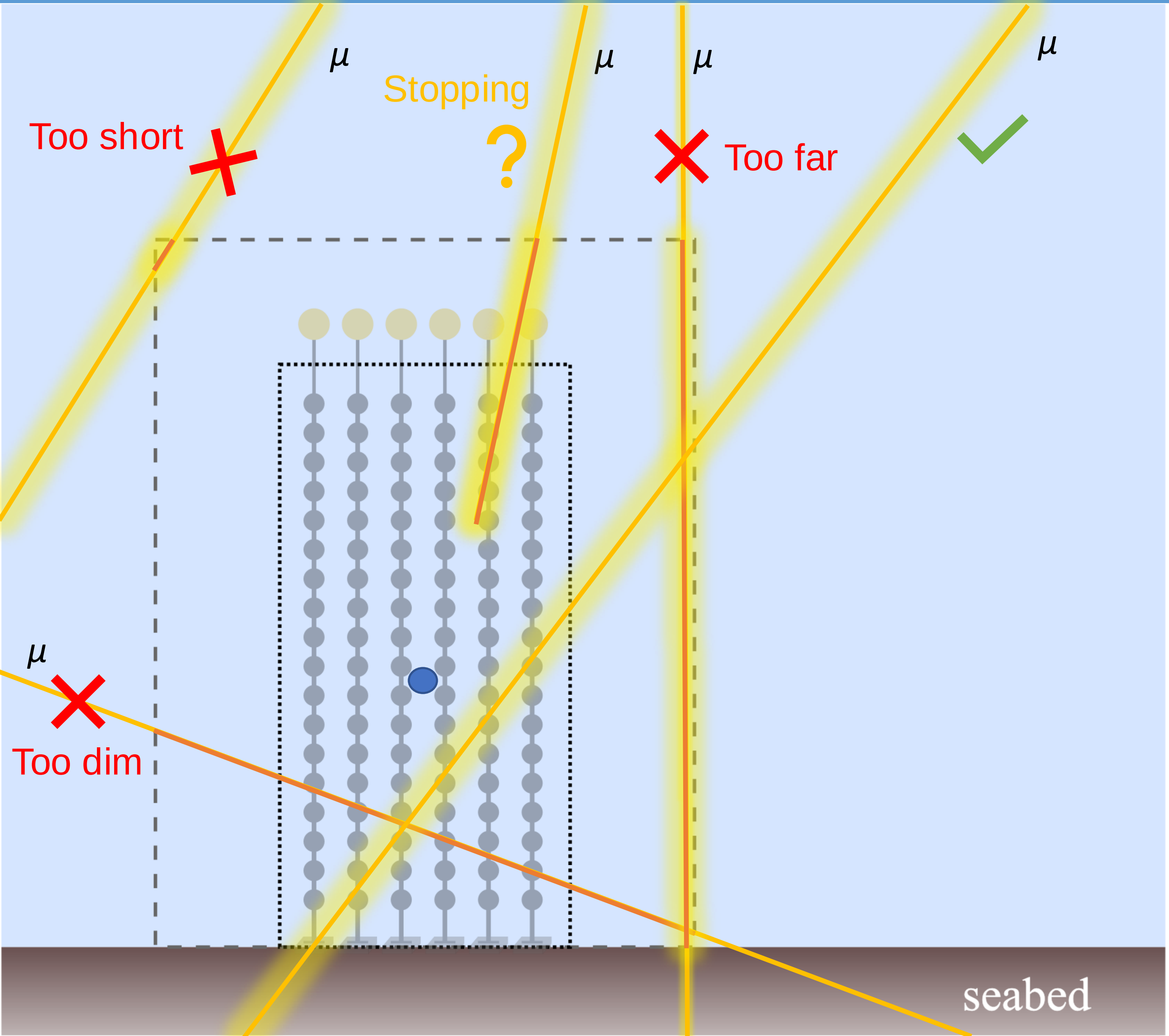








Multiplicity reco: muon selection



We want to exclude muons, which:

- Are too far from the detector
- Have too short pathlength inside the volume of interest
- Emit too faint light (have too low Energy)
- Basically are not visible or would be poorly reconstructed

How?

- Check the JMuon* likelihood $\mathcal{L}$ for single muon events against:
  - distance of muon from the DET center (●) for vertical muons → pick an optimal volume by shrinking the can by x as: $r_{\text{can}} - x,\ h_{\text{can}} - x$
  - muon pathlength L but for shrinked can
  - muon energy → E cut

*JMuon – standard muon track reco

Multiplicity reco: muon selection

Summary of the selction:

Detector	Minimal E_μ [GeV]	d_{max} [m]	minimal L_μ [m]
ARCA115	120	-	-
ARCA6	120	269.4	240
ORCA115	1	-	-
ORCA6	1	-	-

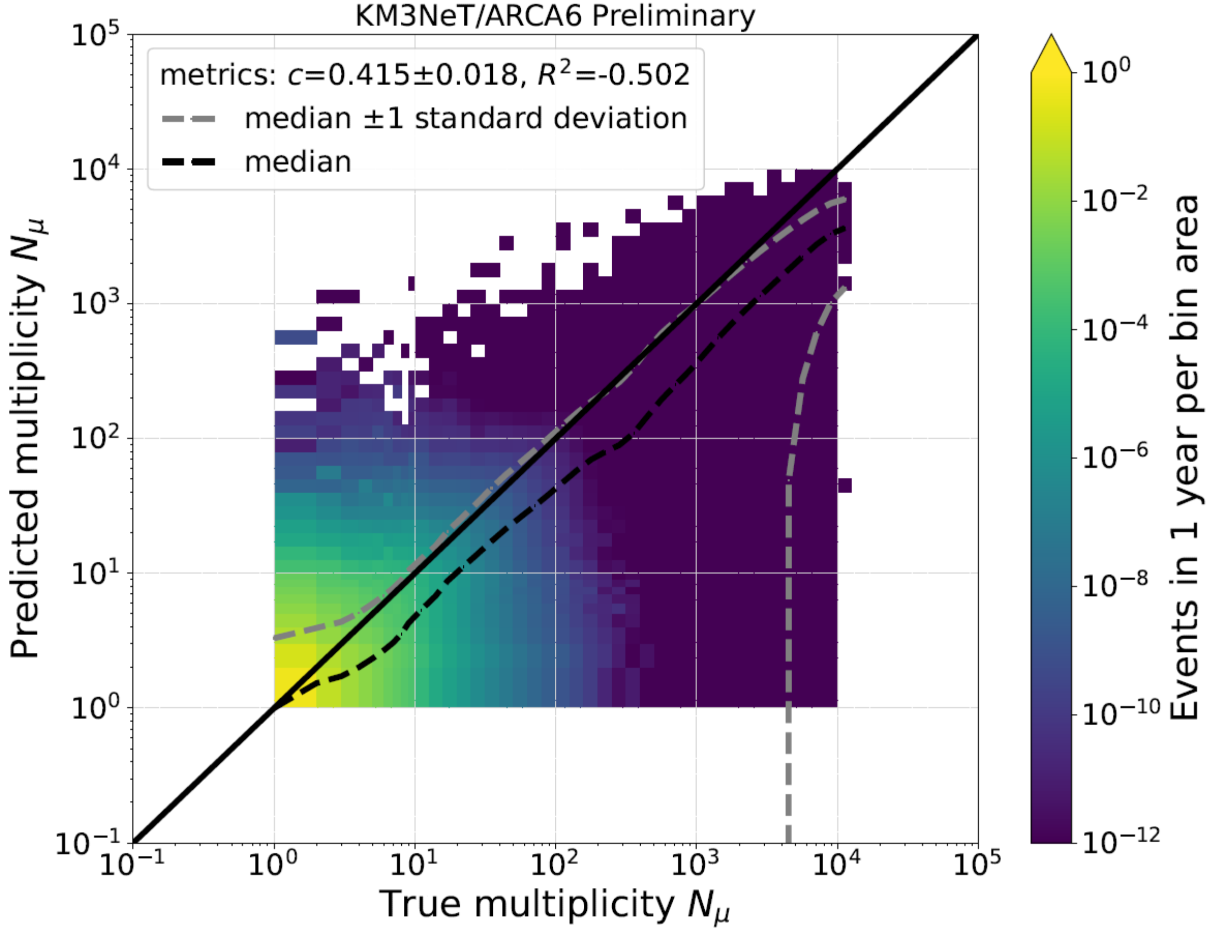
(plots in the backup)

This selection is used for further multiplicity results

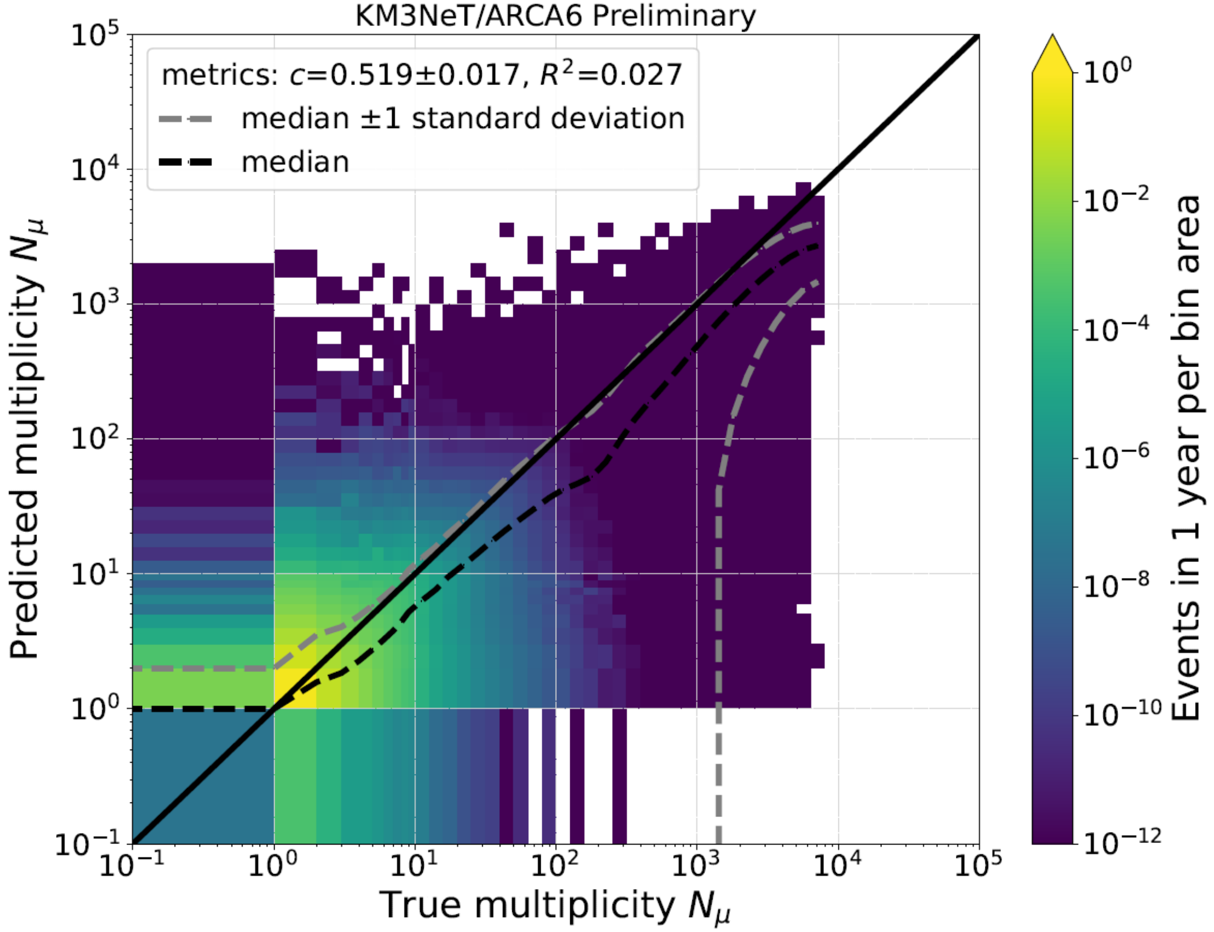
Multiplicity reco: muon selection check

Example of ARCA6, for which the effect is the most pronounced

All muons



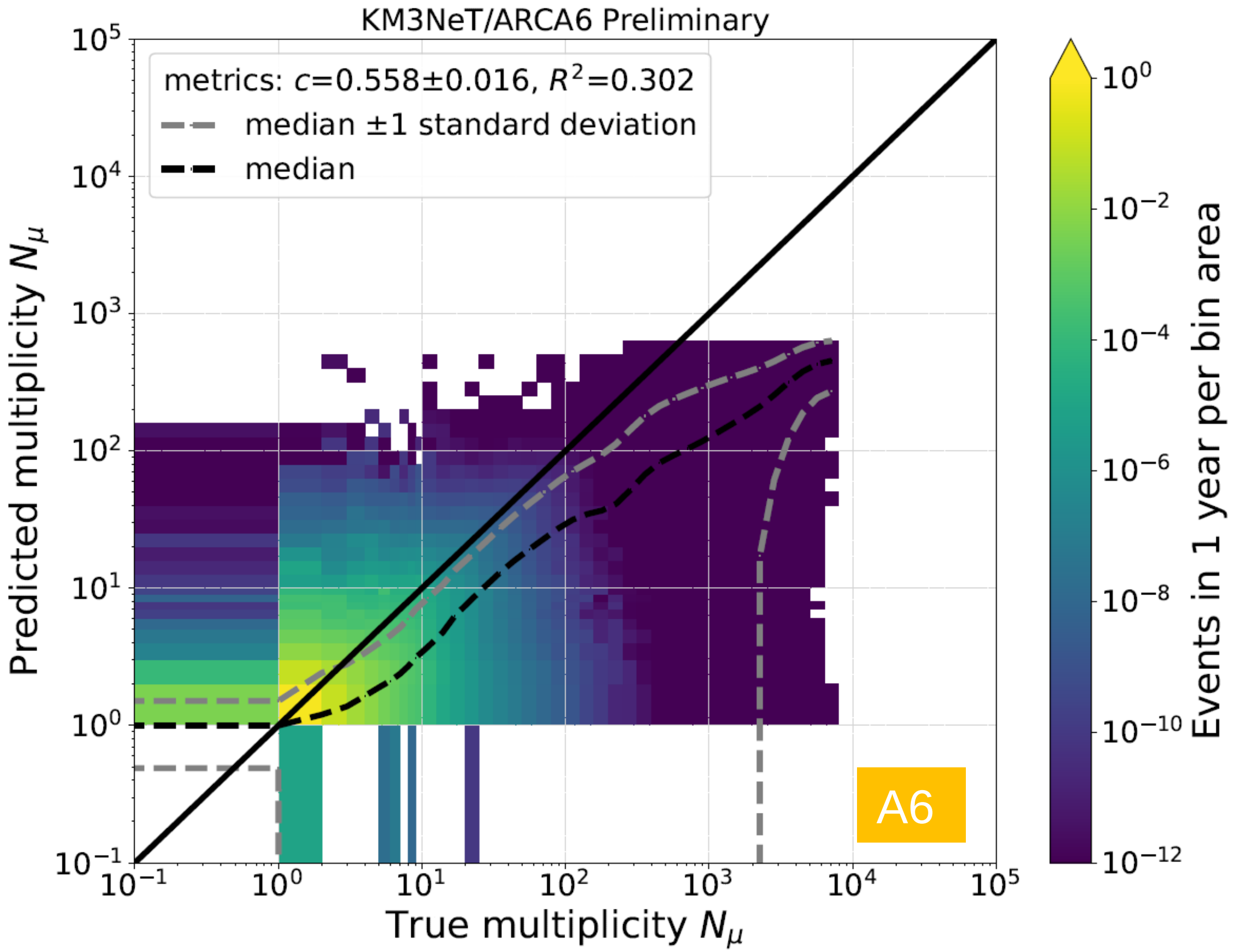
Selected muons



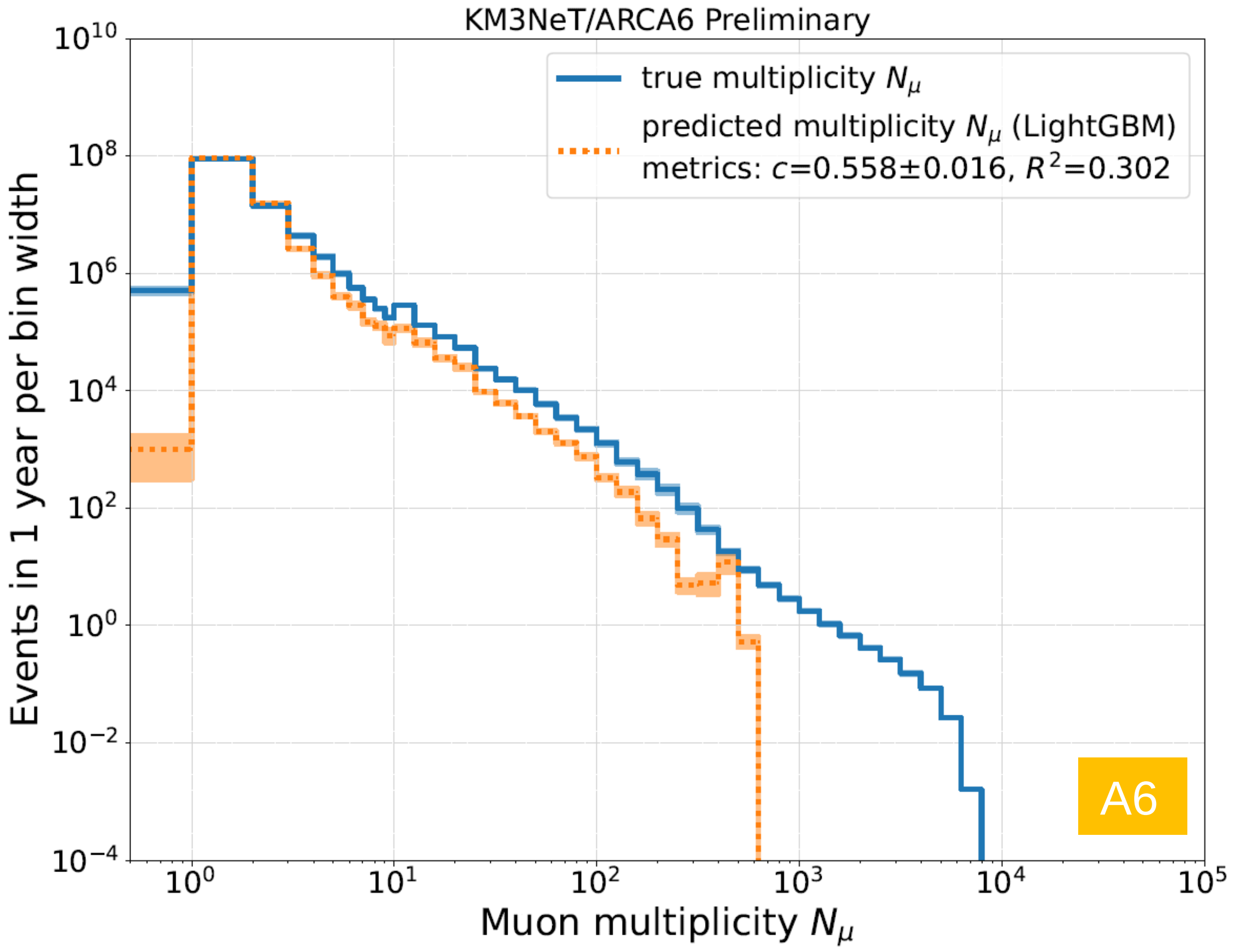
Analogical results obtained for ARCA115, ORCA115 and ORCA6

Example of the results for ARCA6:

2D: pred vs true



1D histograms



Poisson formula for BGD with non-negligible uncertainty: ref1 ref2 ref3

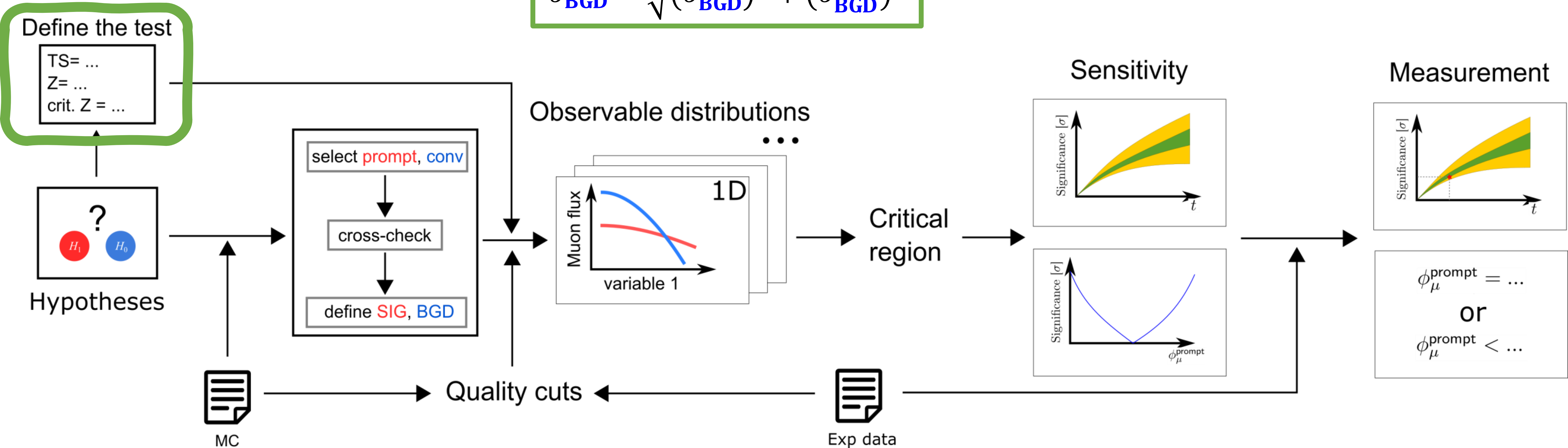
$$\text{TS: } q_0 = \begin{cases} 2 \cdot \left[N_{\mathbf{TOTAL}} \cdot \ln\left(\frac{N_{\mathbf{TOTAL}} \cdot (N_{\mathbf{BGD}} + \sigma^2_{\mathbf{BGD}})}{N^2_{\mathbf{BGD}} + N_{\mathbf{TOTAL}} \cdot \sigma^2_{\mathbf{BGD}}} \right) - \frac{N^2_{\mathbf{TOTAL}}}{\sigma^2_{\mathbf{BGD}}} \cdot \ln\left(1 + \frac{\sigma^2_{\mathbf{BGD}} \cdot (N_{\mathbf{TOTAL}} - N_{\mathbf{BGD}})}{N_{\mathbf{BGD}} \cdot (N_{\mathbf{BGD}} + \sigma^2_{\mathbf{BGD}})} \right) \right] & \text{for } N_{\mathbf{TOTAL}} \geq N_{\mathbf{BGD}} \\ 0 & \text{for } N_{\mathbf{TOTAL}} < N_{\mathbf{BGD}} \end{cases}$$

Significance: $Z = \sqrt{q_0}$

Critical Z: 5σ

systematic uncertainties are included:

$$\sigma_{\mathbf{BGD}} = \sqrt{\left(\sigma^{\text{stat}}_{\mathbf{BGD}}\right)^2 + \left(\sigma^{\text{syst}}_{\mathbf{BGD}}\right)^2}$$



Definition of signal and background

Definitions:

- prompt: μ „directly” from 1st interaction:
  - Possibly few parent particles
  - Parents with lifetime $\tau < \tau_{K_S^0}$
- conventional: all other μ

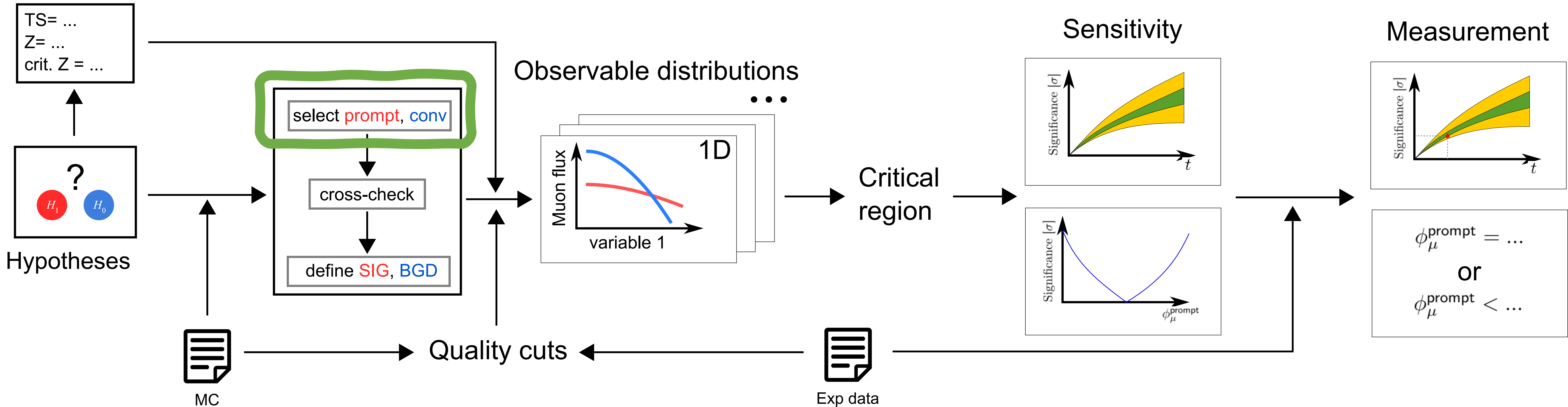
$\tau_{K_S^0} = 89.5\text{ps}$

MC → prompt μ:

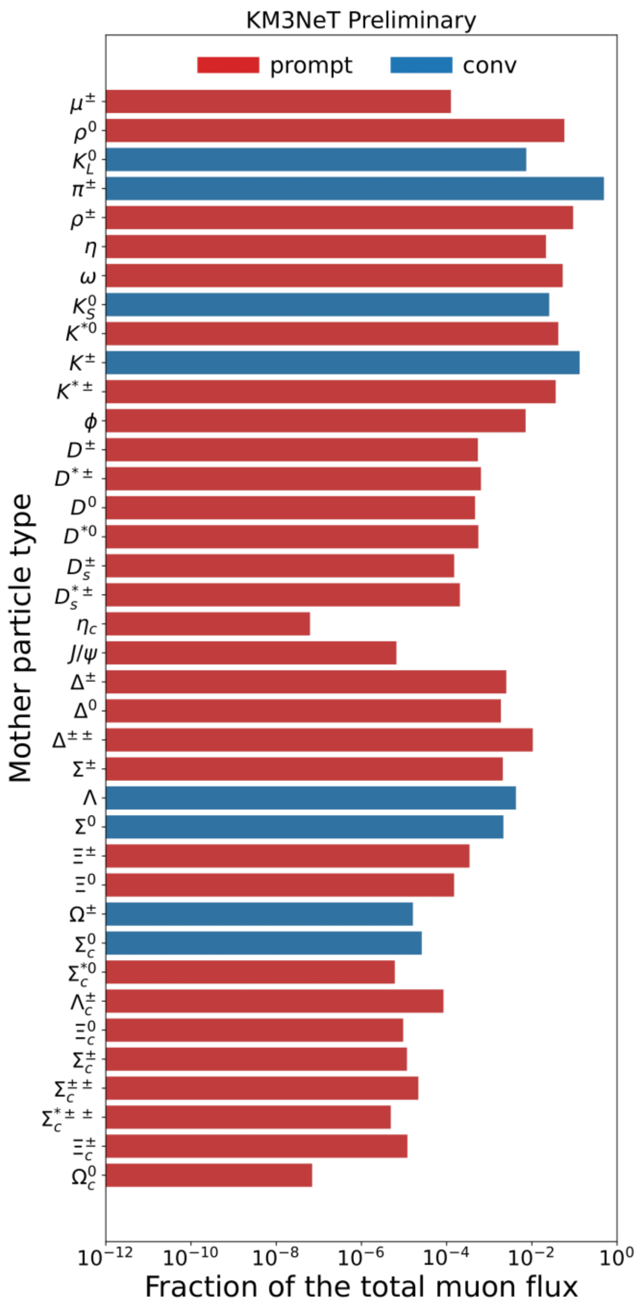
(hadronic counters)

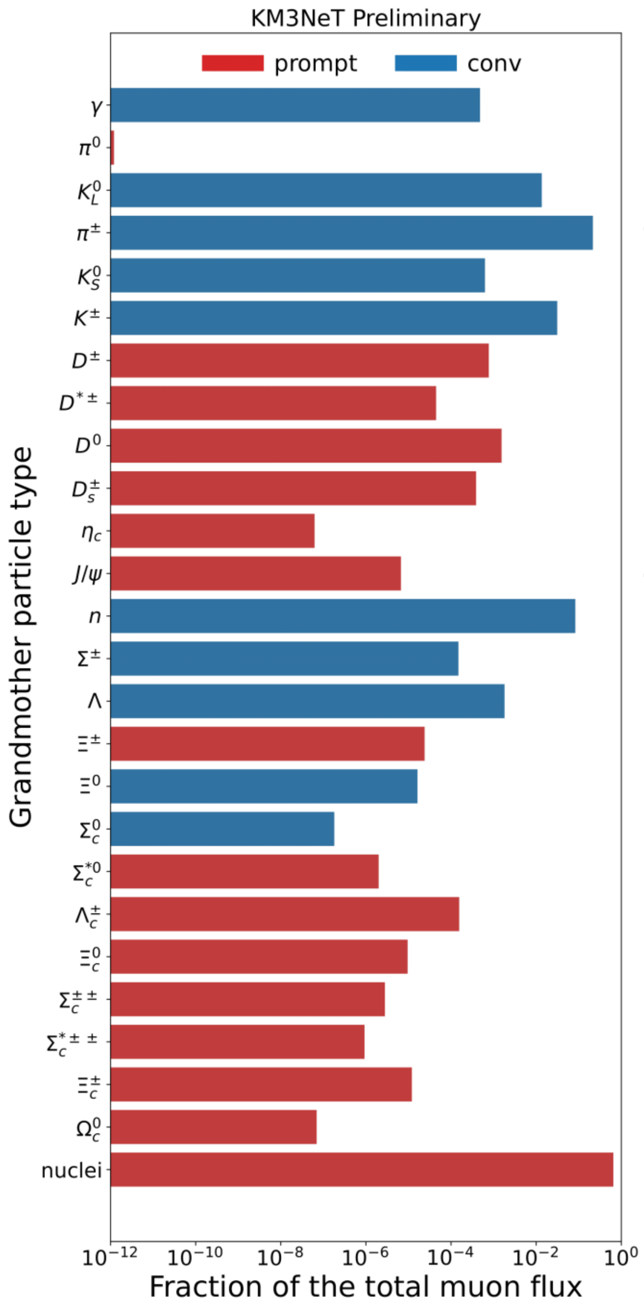
gmom	mom	h_{mom}	h_{μ}	EM counters
prim	muon	1	1	0
prompt	muon	any	any	0
prim	prompt	≤ 2	≤ 2	0
prompt	prompt	2	32	0
		3	33	0

Define the test



Prompt and conv parent particles





Note: 1 parent conventional → the muon is conventional.

The colours here only tell you if particles have short or long livetimes (if applicable).

Most muons originate from $\pi^{\pm}$ and $K^{\pm}$, as expected.

The most important prompt mother particles for muons are light vector mesons (η, ρ, ω), not D mesons (also expected).

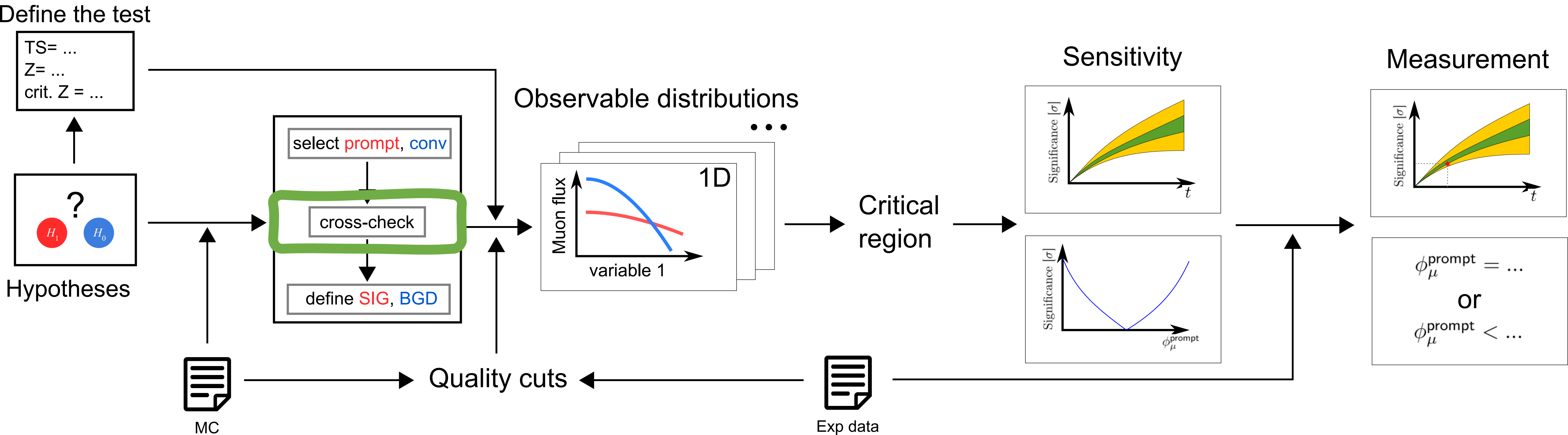
If mother is a muon or grandmother is the same nucleus as the primary, it means that there were just less interactions between shower start and muon creation.

NB: particles & antiparticles are counted together!
(and so are all nuclei, including hydrogen)

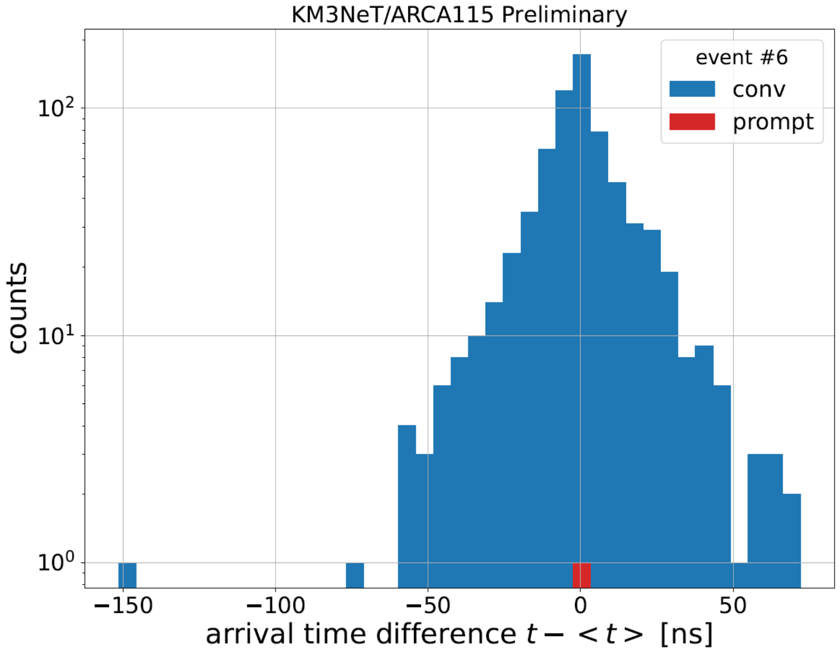
Check of prompt and conv definition

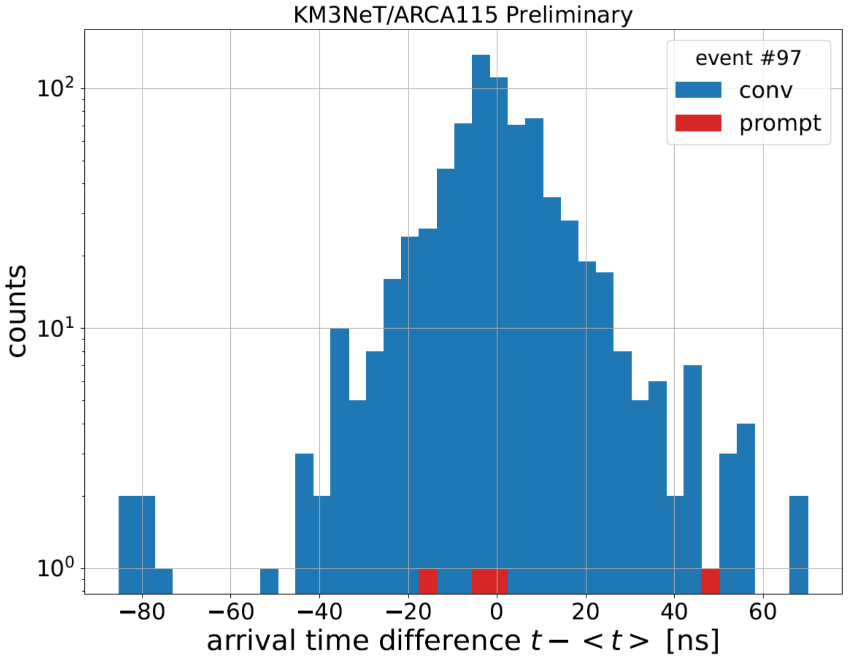
I look at 3 things:

1. Muon arrival time
2. Muon energy share
3. Muon production point

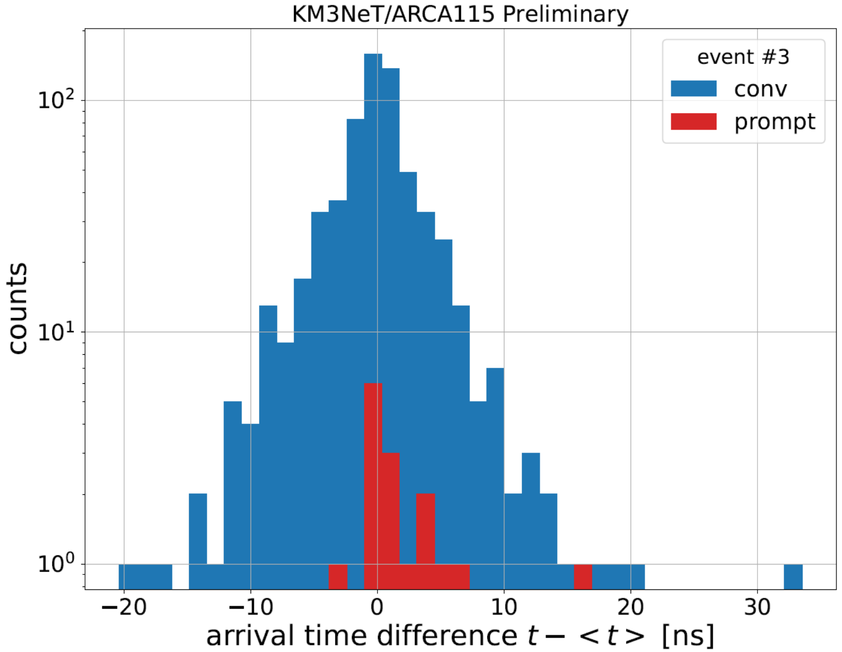


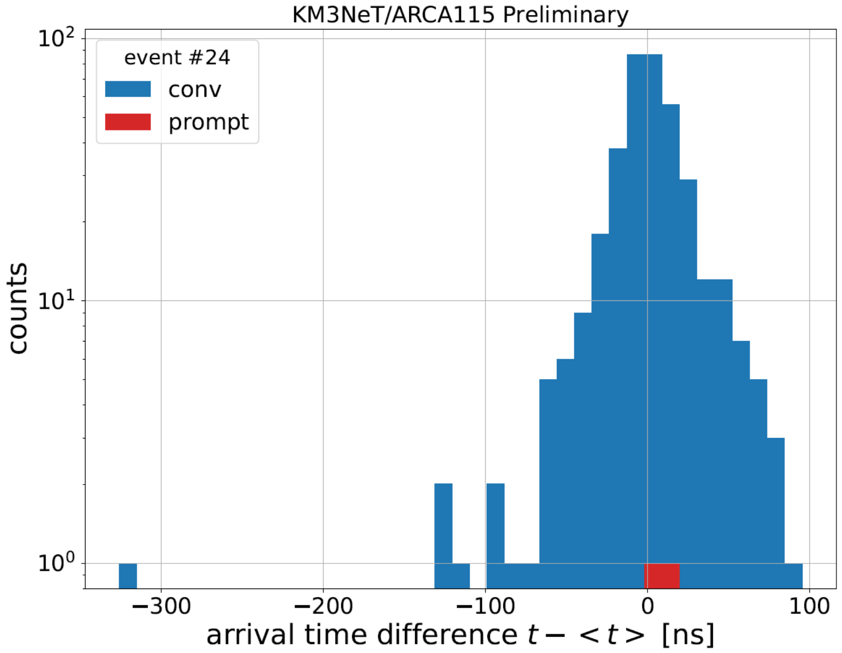
Muon arrival time





Proton events



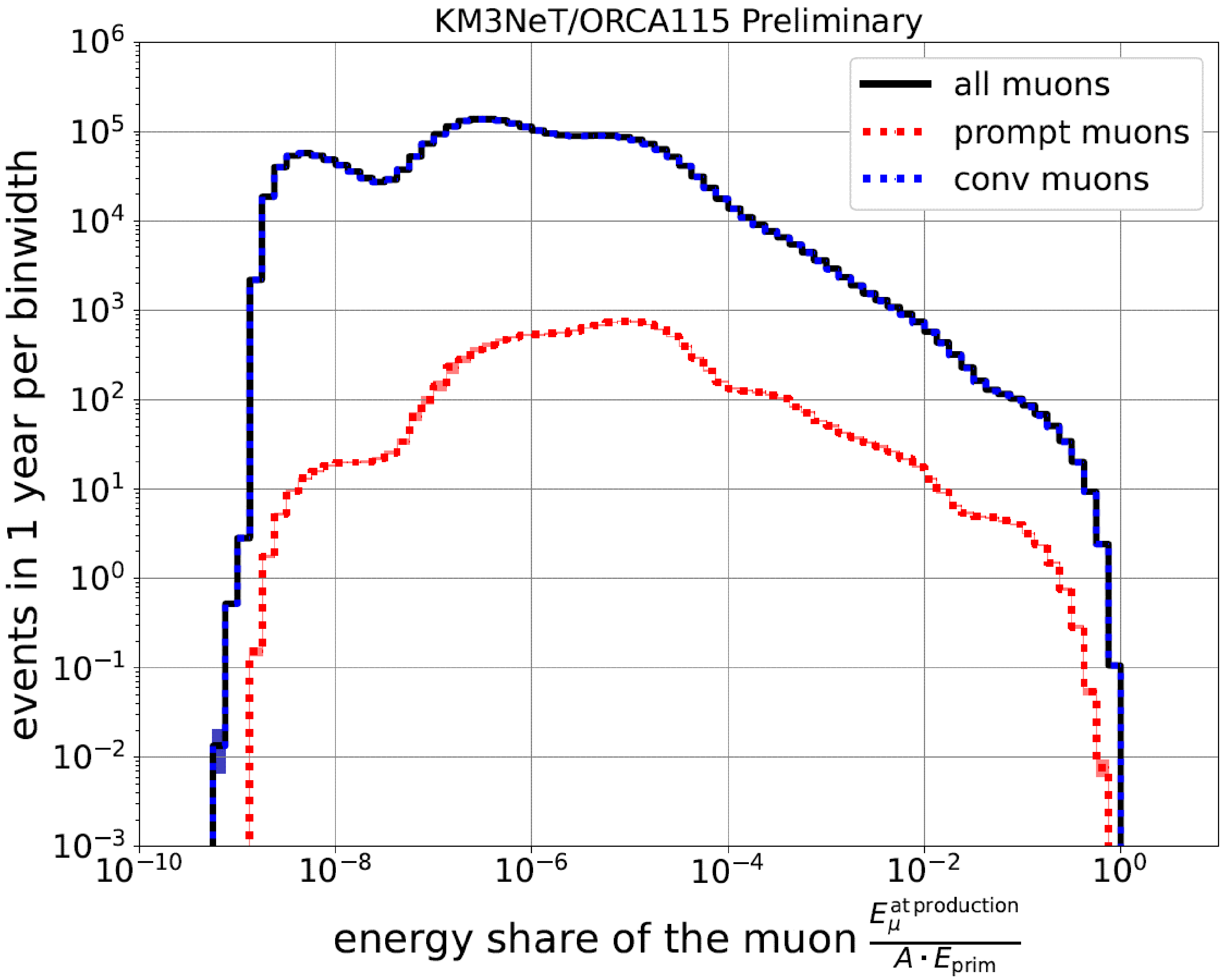


Iron events

arrival time: time between the first interaction of the primary and the muon crossing the can boundary

Conclusion here is that prompt is <u>not really evident from arrival times</u> on event-by-event basis
(which is a bummer, because this could have been measurable)

Muon energy share

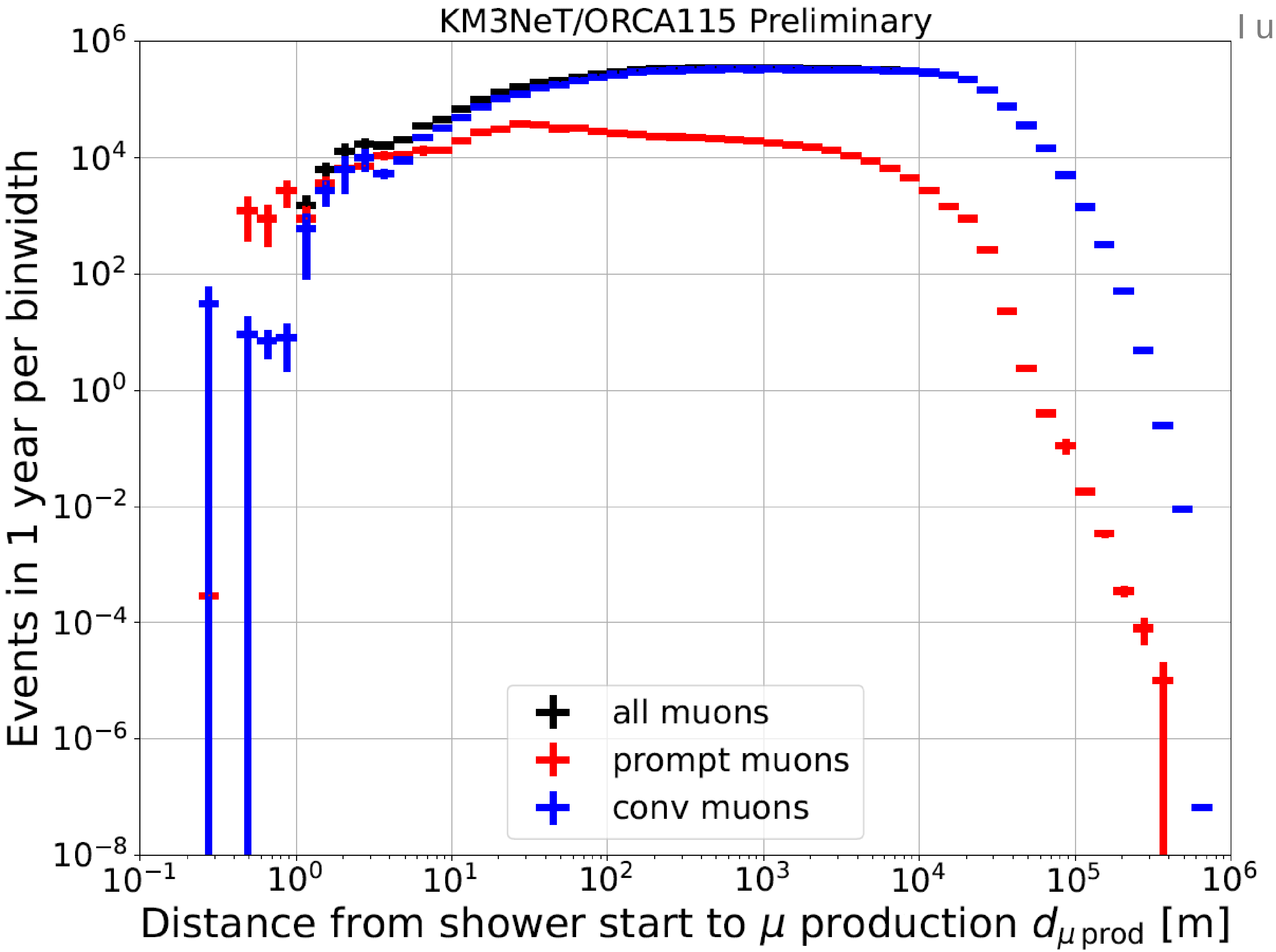


I use ORCA115 to boost the statistics

Prompt muons indeed tend to carry a larger portion of the total primary energy

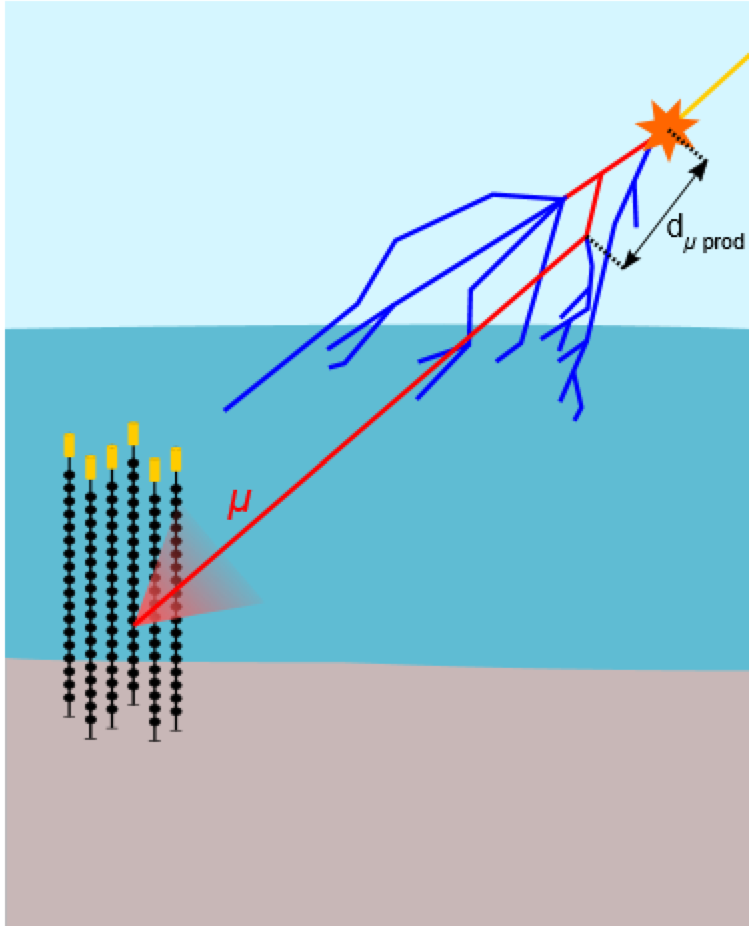
The wiggles are coming from the contributions of different primaries

Muon production point



I use ORCA115 to boost the statistics

Prompt muons indeed are more often produced close to the 1st interaction



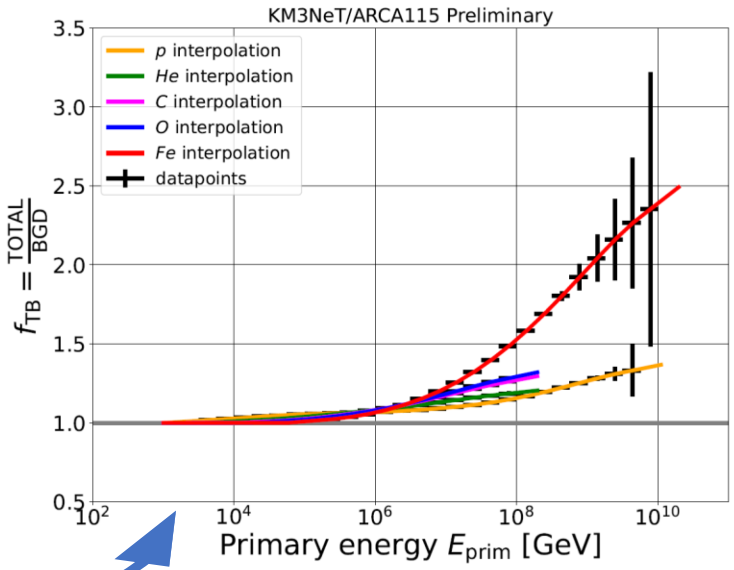
Definition of signal and background

Definitions:

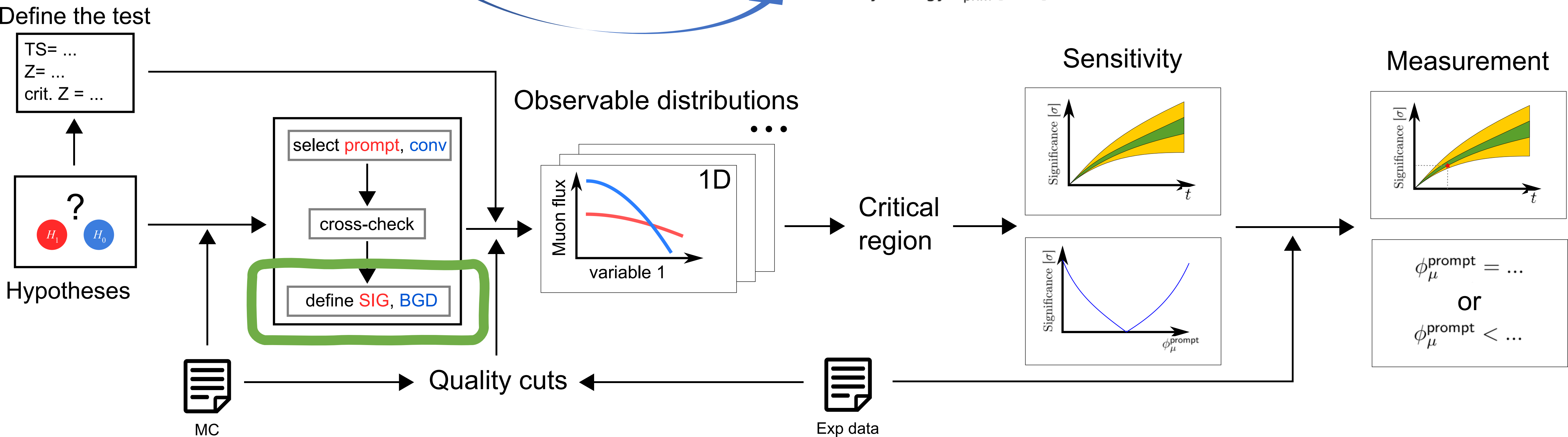
- SIG: ≥ 1 prompt μ in bundle
- BGD: 0 prompt μ in bundle

BGD has to be reweighted:

$$w_{\mathrm{BGD}} = w_{\mathrm{event}}(\mathrm{prim}, E_{\mathrm{prim}}) \cdot f_{\mathrm{TB}}\,(\mathrm{prim}, E_{\mathrm{prim}})$$

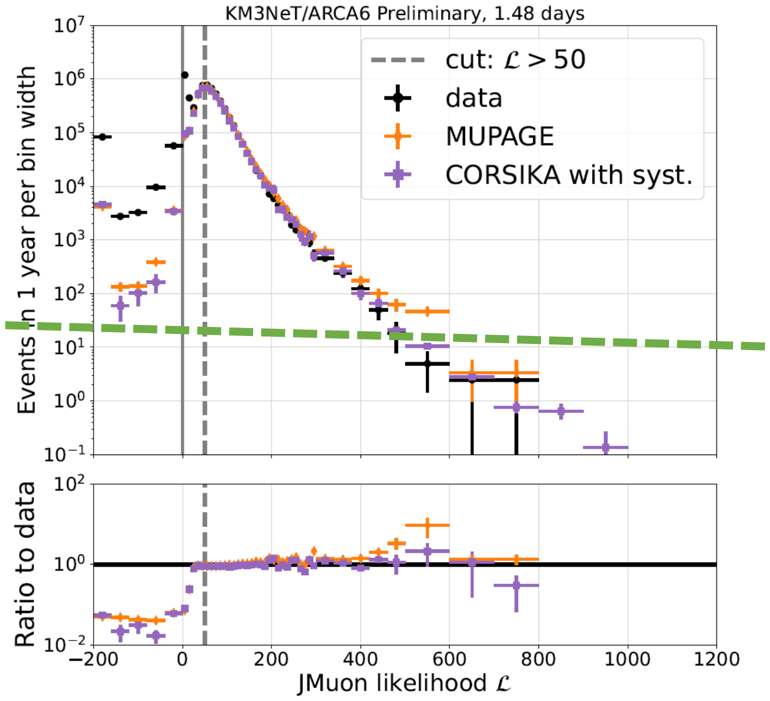


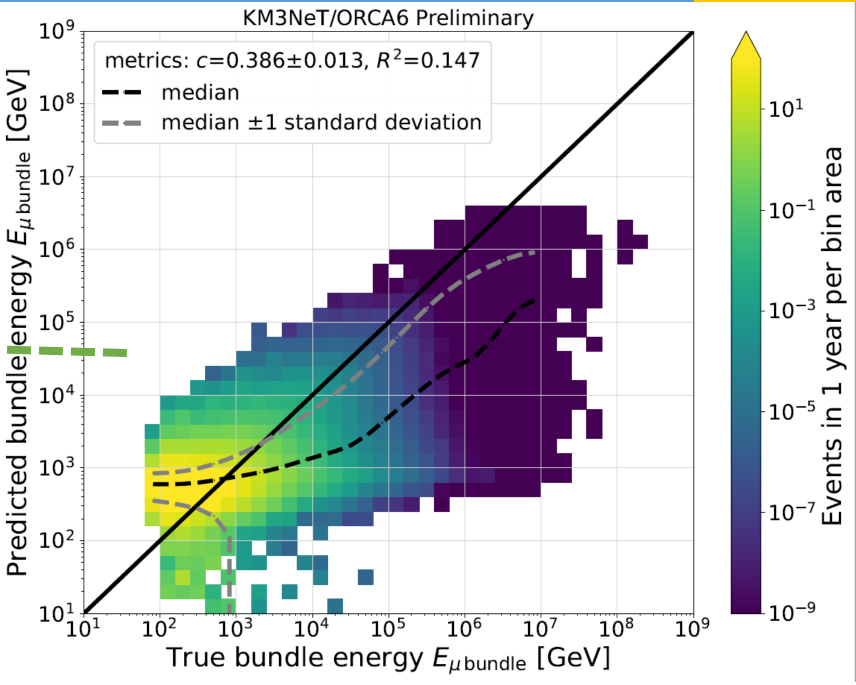
Note:
Ideally, f_{TB} should be evaluated at generation, but that's not possible
(or we could use 2 separate MC's, but it's not possible yet)

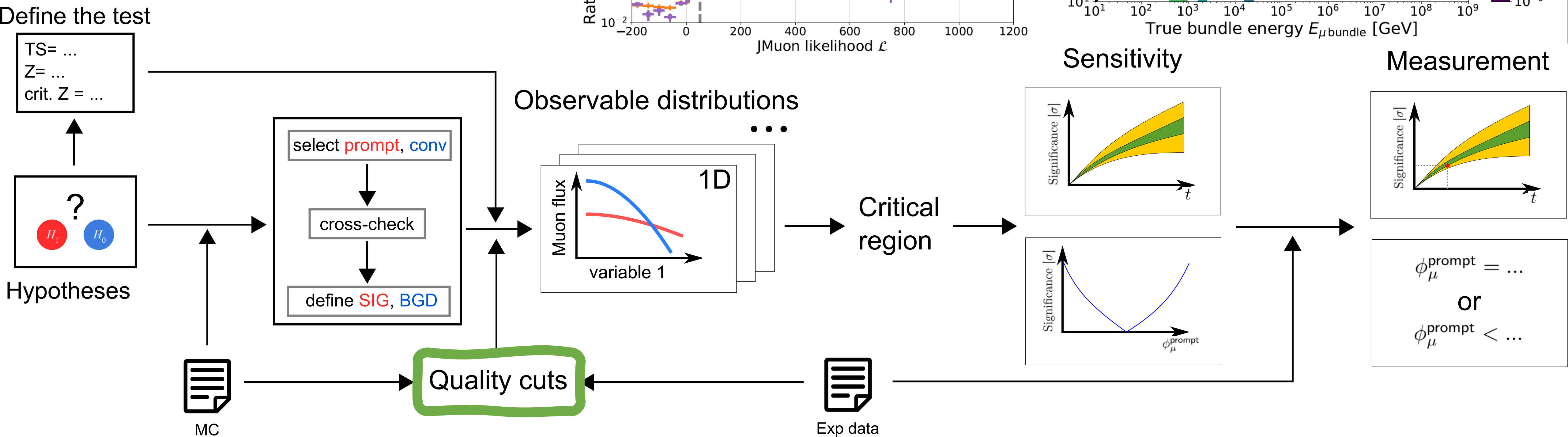


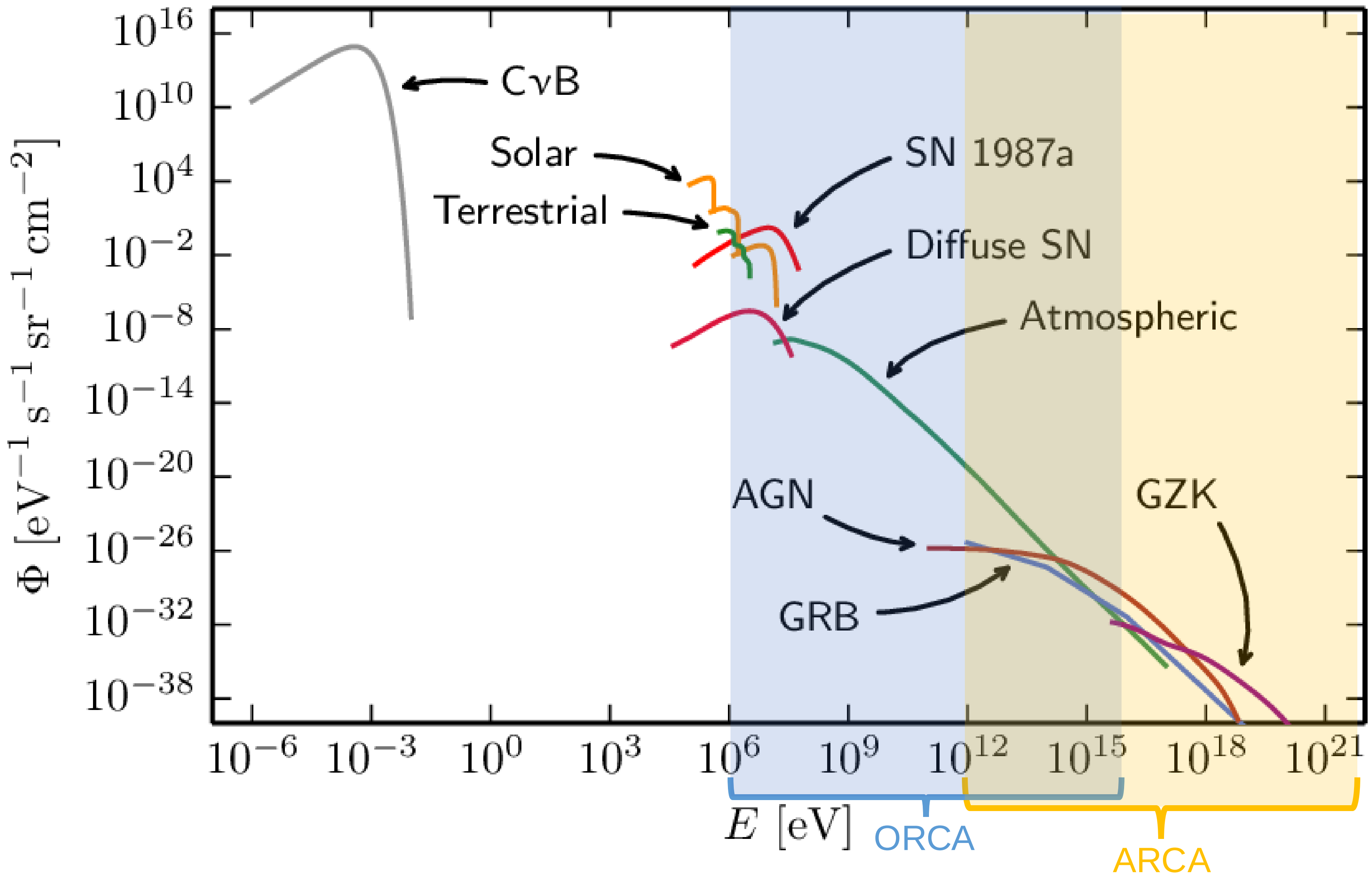
The quality cuts:

- Likelihood cut:
  - ARCA: $\mathcal{L} > 50$
  - ORCA: $\mathcal{L} > 280$
- ML reco reliability cut:
  - ARCA115: $E_{\mathrm{bundle}} > 3\mathrm{TeV}$, $N_\mu > 0$
  - ARCA6: $E_{\mathrm{bundle}} > 3\mathrm{TeV}$, $N_\mu > 0$
  - ORCA115: $E_{\mathrm{bundle}} > 300\mathrm{GeV}$, $N_\mu > 0$
  - ORCA6: $E_{\mathrm{bundle}} > 800\mathrm{GeV}$, $N_\mu > 0$







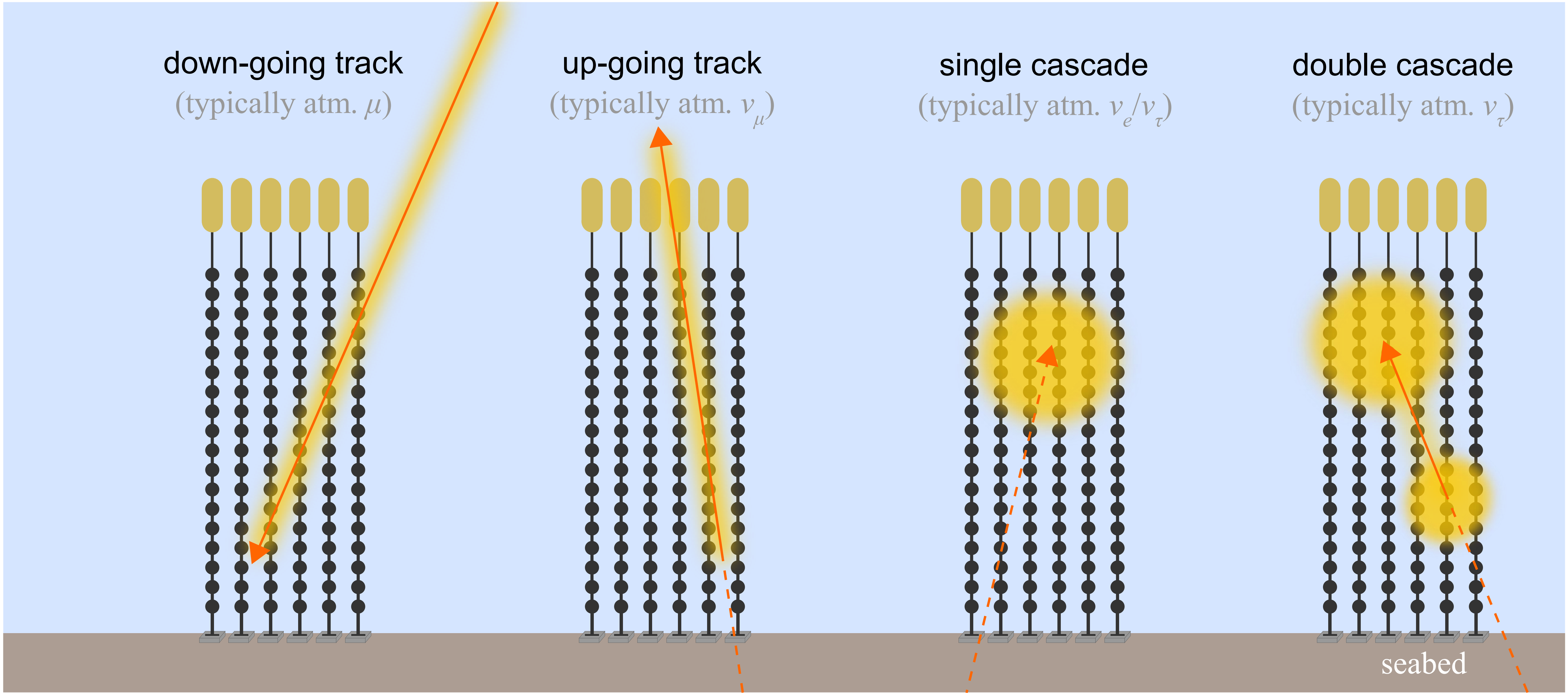


L. Mohrmann, Characterizing cosmic neutrino sources – a measurement of the energy spectrum and flavor composition of the cosmic neutrino flux observed with the IceCube Neutrino Observatory, Humboldt U., Berlin (2015)

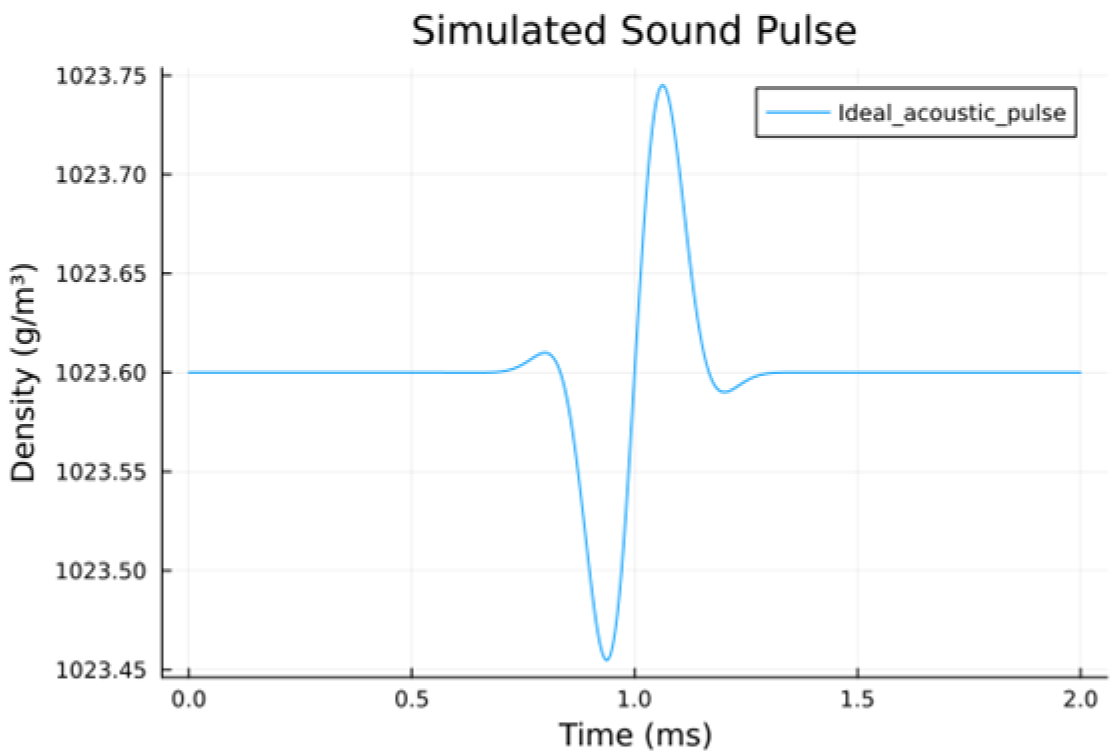
Event topologies

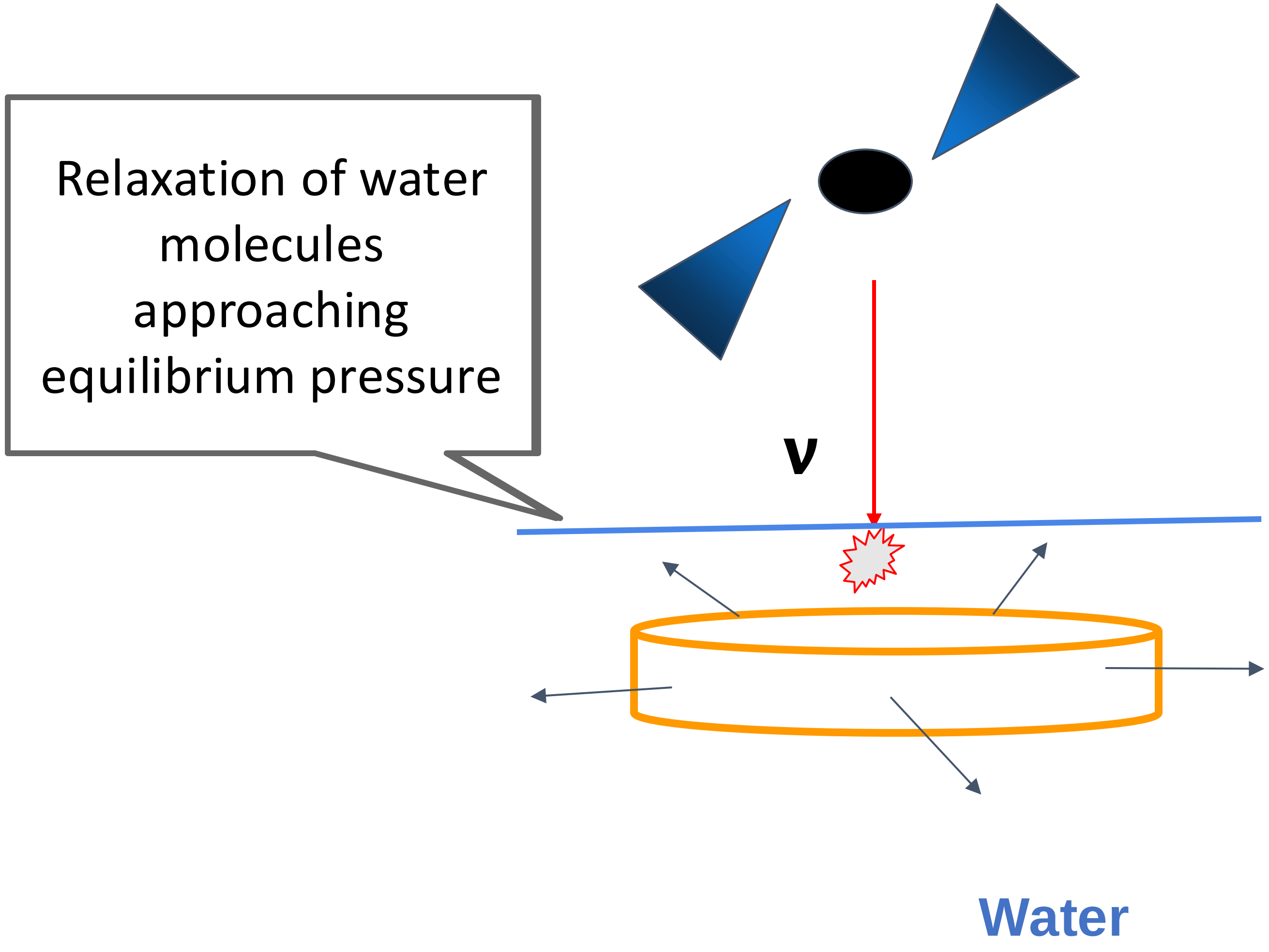
Examples of basic event topologies:

Classes based on combinations of:
- ❖ Direction
- ❖ Shape



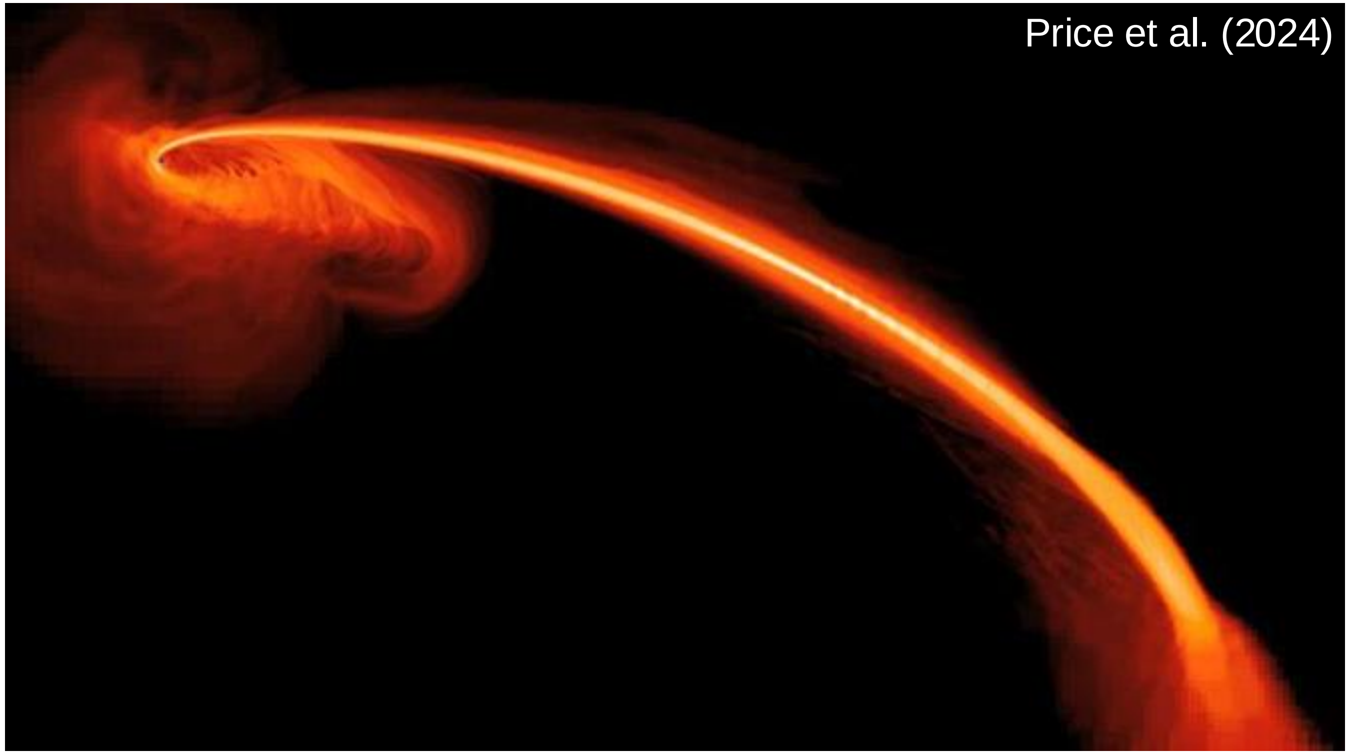
- UHE neutrinos may also interact with water and produce acoustic pulse





- High-energy neutrino emission is correlated with temporal and spatial emissions across all the multi-messenger

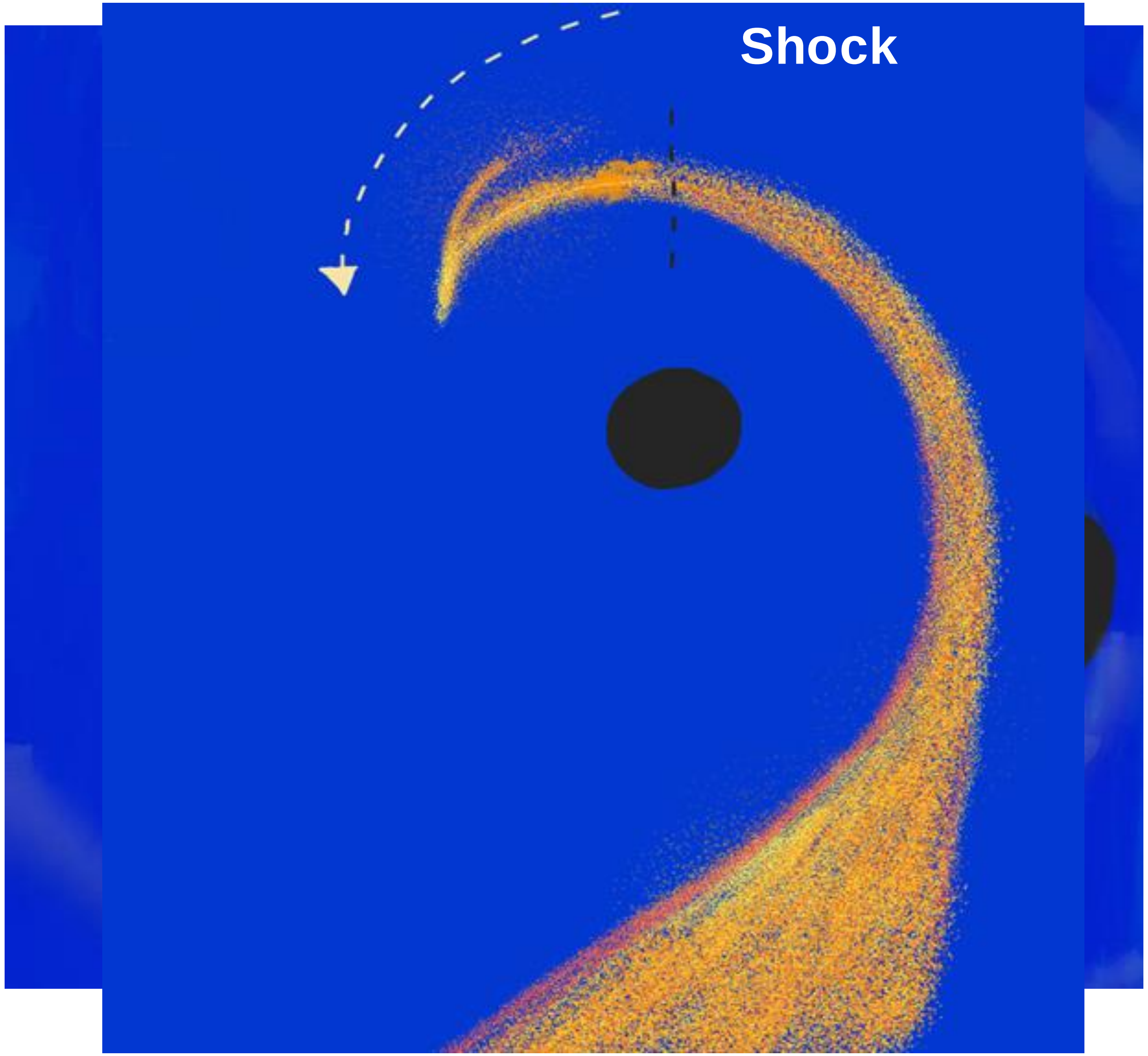
- Tidally disrupted events are one of the potential candidates of high energy neutrinos


Price et al. (2024)

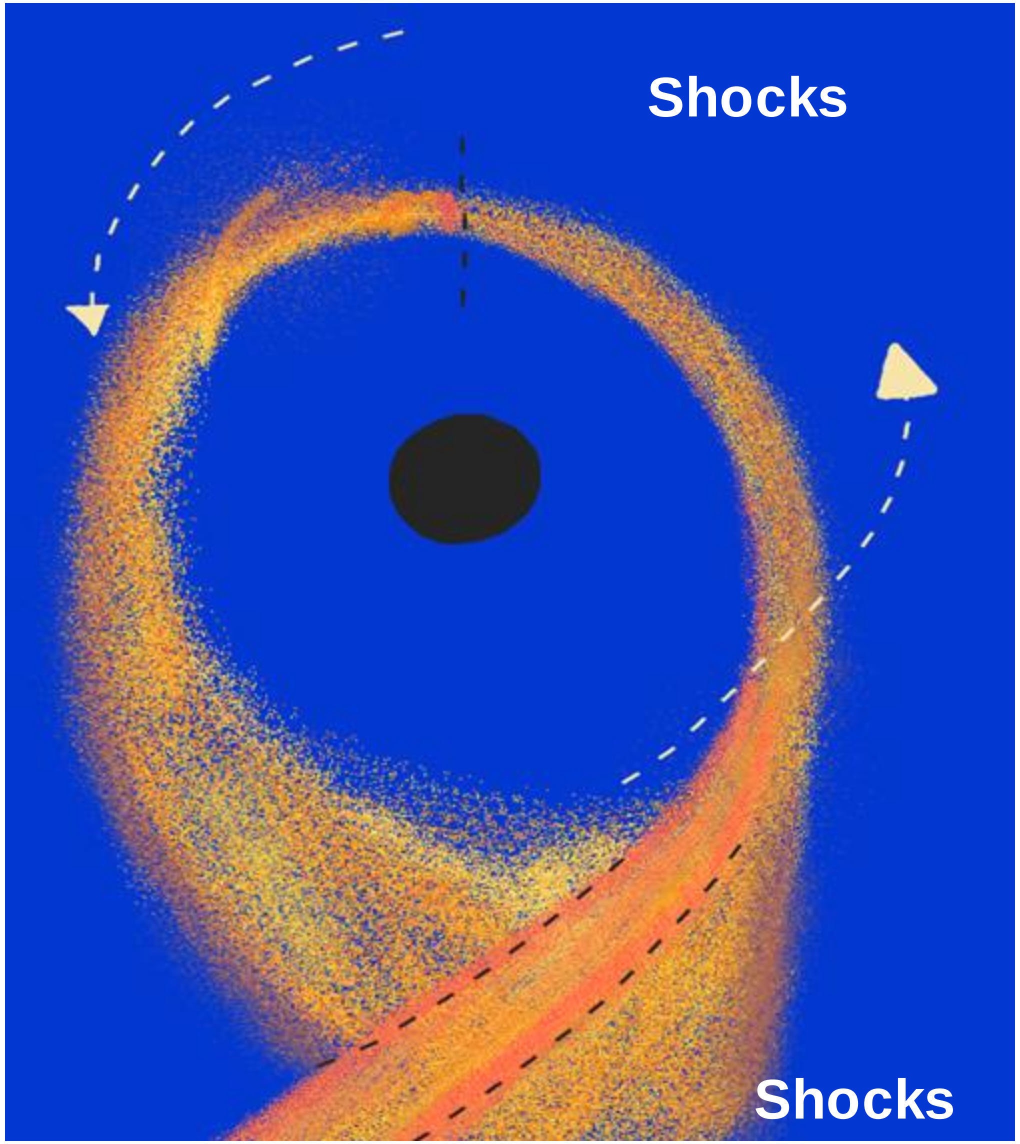
- Tidally disrupted events (TDE): Theoretical concept of massive black holes and star system reaching Roche limit

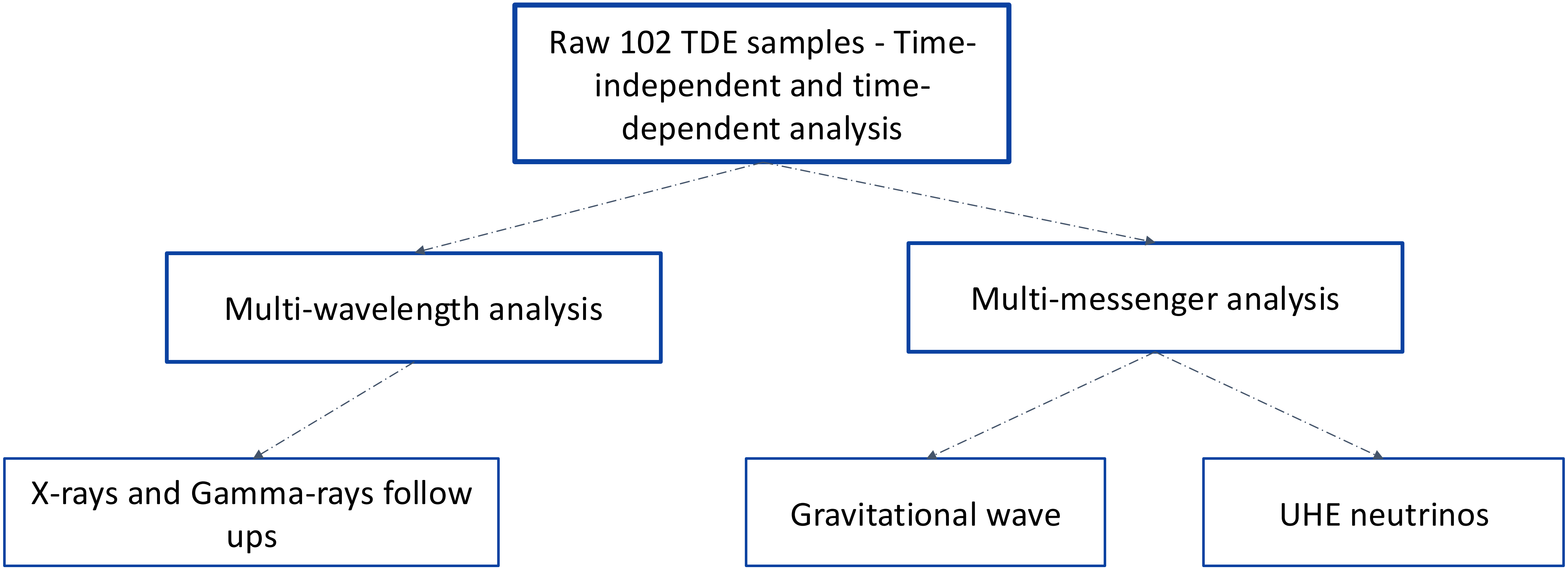
- Main sequence stars of mass 1 - 10 $M_\odot$ and black hole mass 10^6 - $10^{12} M_\odot$

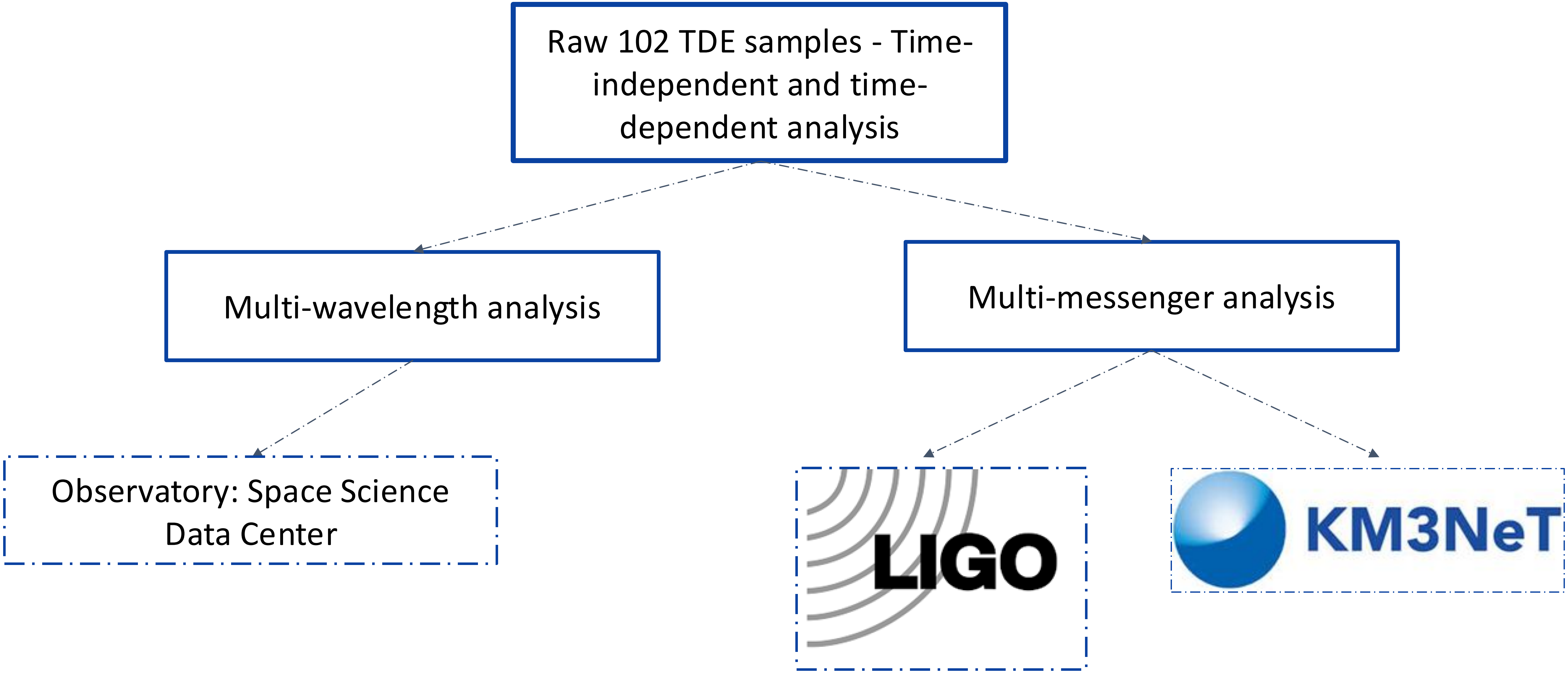
- TDE comprises of jet and fallback accretion system

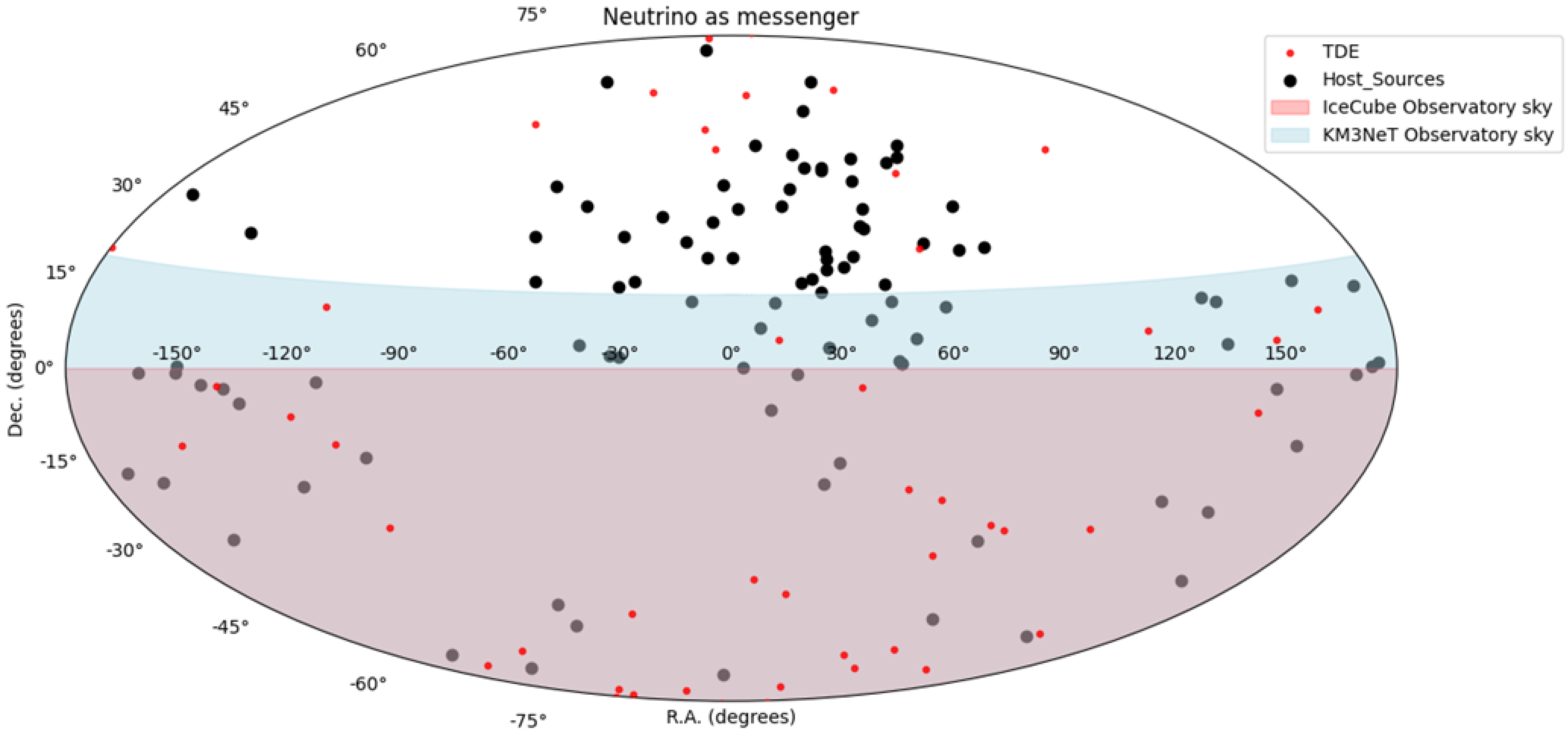


- Multi-messenger properties:
    - Spectral classification by UV - optical color diagram into TDE-H, TDE-H+He, and TDE-He
    - At X-ray and radio energies non-thermal emissions
    - Very high-energy neutrinos of TeV and PeV
    - Gravitational waves candidate up to 10 Hz




Raw 102 TDE samples - Time-independent and time-dependent analysis
Multi-wavelength analysis
Multi-messenger analysis
X-rays and Gamma-rays follow ups
Gravitational wave
UHE neutrinos


Raw 102 TDE samples - Time-independent and time-dependent analysis
Multi-wavelength analysis
Multi-messenger analysis
Observatory: Space Science Data Center
LIGO
KM3NeT


Neutrino as messenger
TDE
Host_Sources
IceCube Observatory sky
KM3NeT Observatory sky
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
Dec. (degrees)
R.A. (degrees)