



ν_τ APPEARANCE MEASUREMENT IN KM3NeT/ORCA

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on behalf of the KM3NeT Collaboration

TAUP Conference, Vienne, 31/08/2023



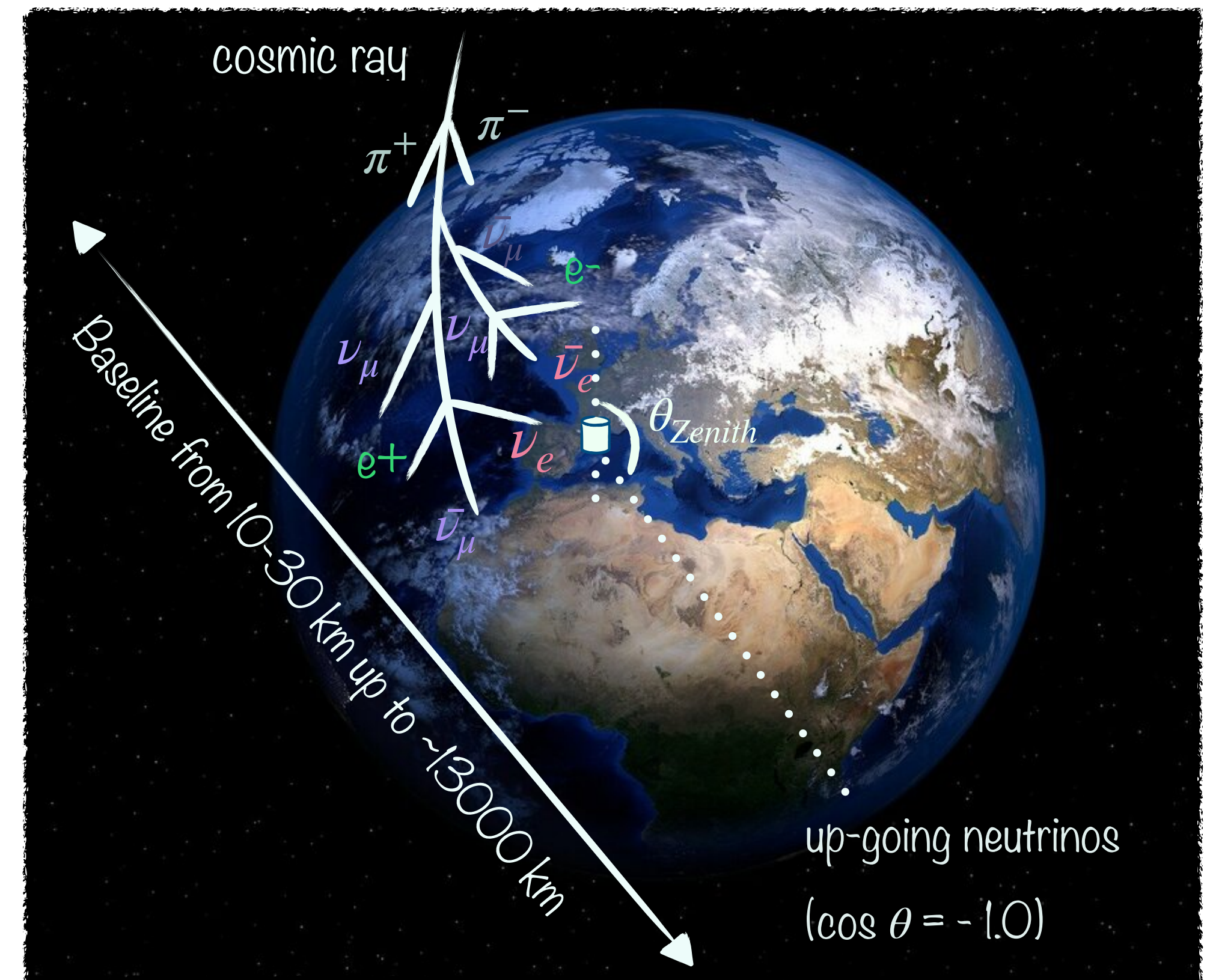


- The KM3NeT experiment
- Why search for ν_τ is important?
 - sensitivity to ν_τ -appearance in KM3NeT/ORCA
- First ν_τ -appearance analysis with KM3NeT/ORCA 6
 - Particle Identification (PID) techniques
 - ν_τ -normalization results
- Summary and outlook

Introduction

KM3NeT, Cubic Kilometre Neutrino Telescope: **Water Cherenkov neutrino telescope** under construction in the **deep Mediterranean Sea**

- atmospheric neutrinos: wide **energy range** and **baseline**
(\sim cosine zenith angle of the interacting neutrino)



Introduction

KM3NeT, Cubic Kilometre Neutrino Telescope: **Water Cherenkov neutrino telescope** under construction in the **deep Mediterranean Sea**

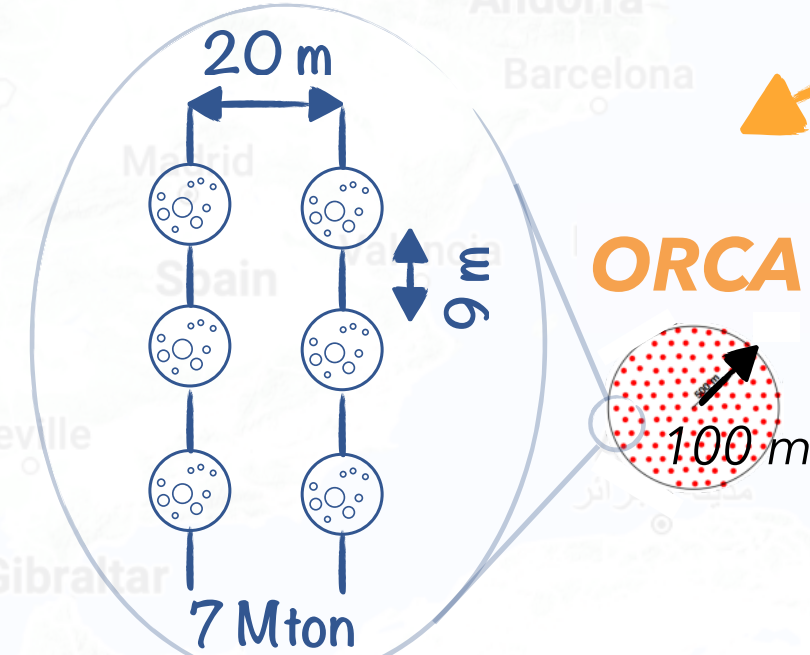
- atmospheric neutrinos: wide **energy range** and **baseline** (~cosine zenith angle of the interacting neutrino)

- two detection sites, **broad physics program**:

- **ARCA**, neutrino astronomy in $E \sim (\text{TeV}, \text{PeV})$
- **ORCA**, **neutrino oscillations** in $E \sim (3, 100) \text{ GeV}$

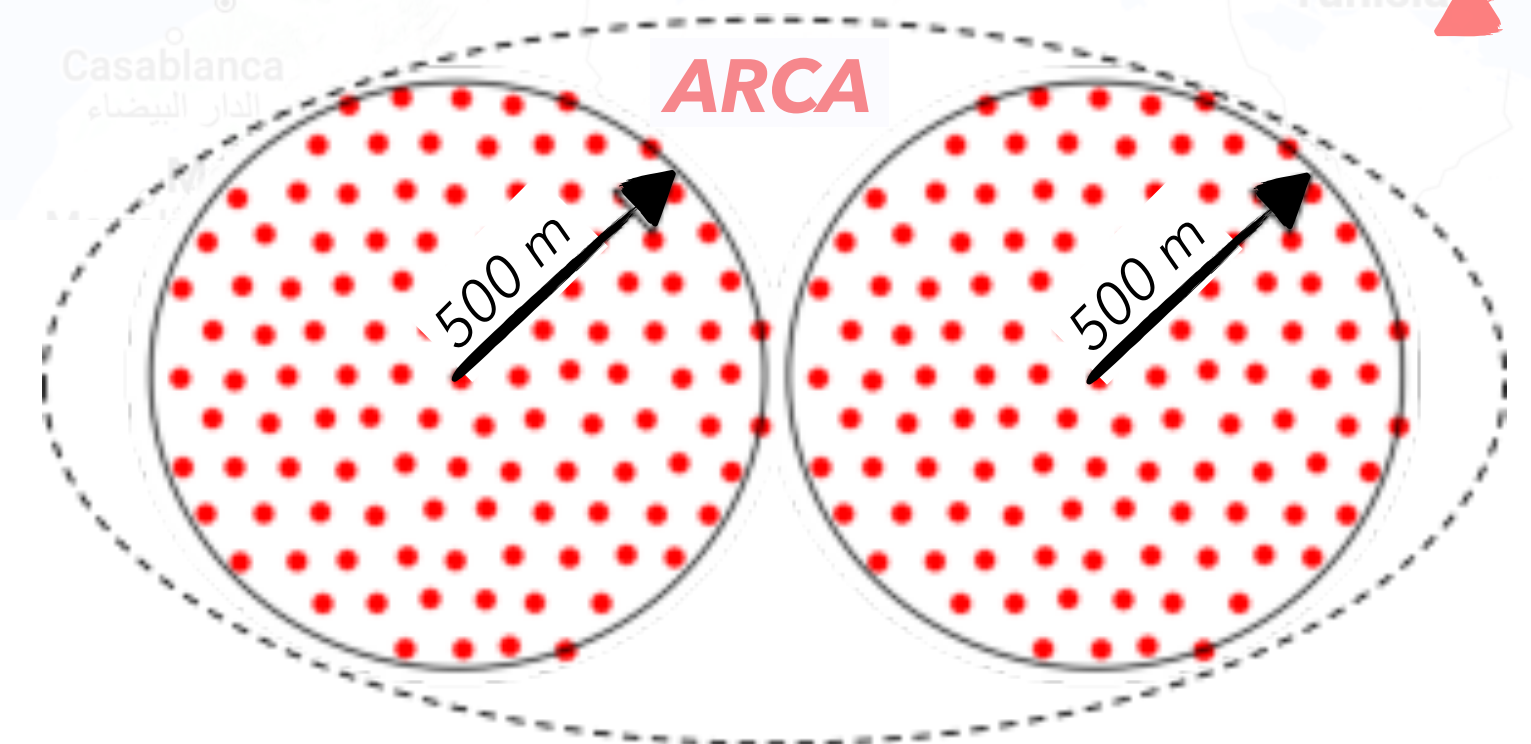
📍 offshore Toulon (France)

- depth: 2450 m
- Detection Units (DUs): 115
- instrumented vol. $\sim 18\%$



📍 offshore CapoPassero (Italy)

- depth: 3560 m
- DUs: 230
- instrumented vol. $\sim 9\%$

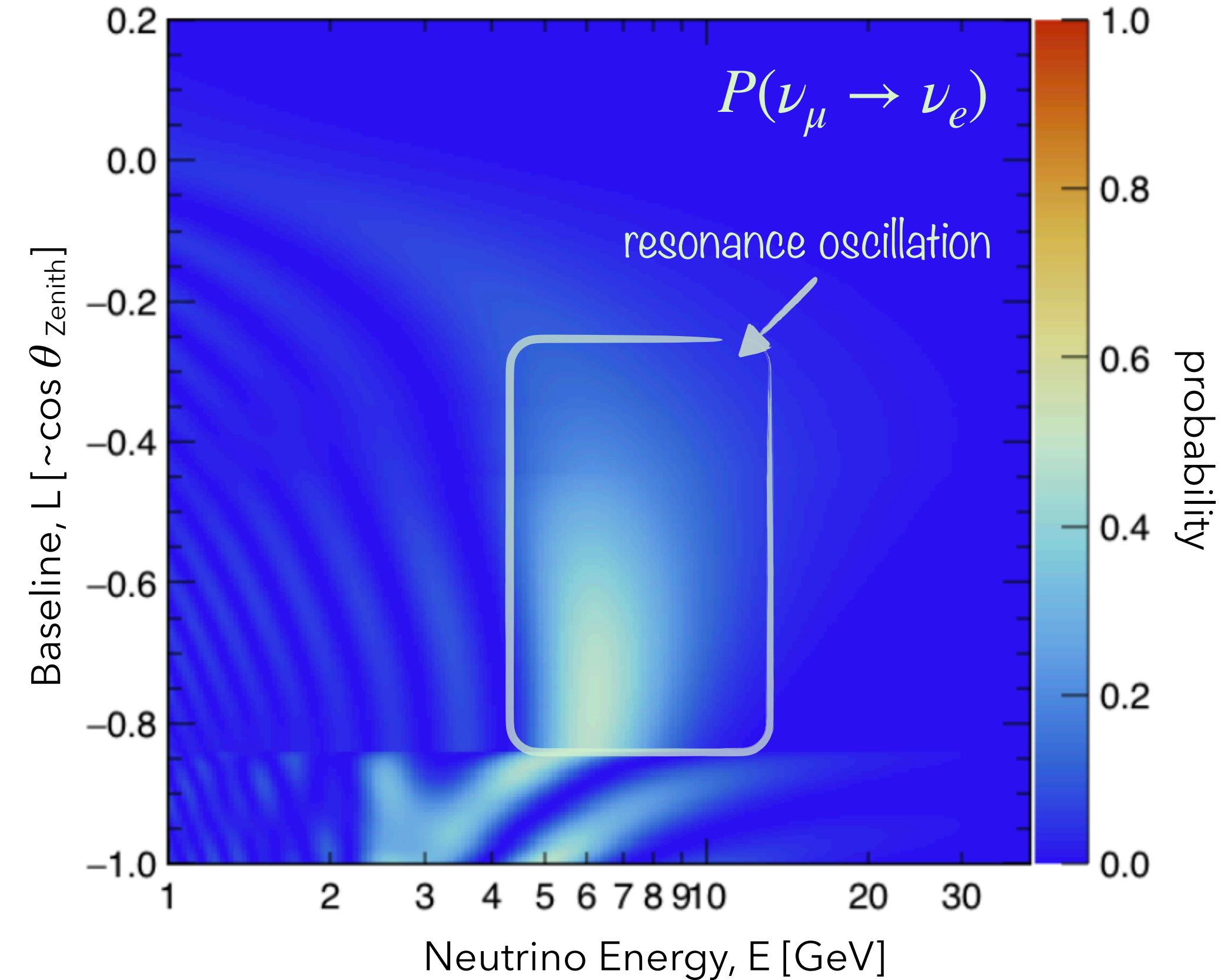


Introduction

KM3NeT, Cubic Kilometre Neutrino Telescope: **Water Cherenkov neutrino telescope** under construction in the **deep Mediterranean Sea**

- atmospheric neutrinos: wide **energy range** and **baseline** ($\sim \cos$ zenith angle of the interacting neutrino)
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 - **ARCA**, neutrino astronomy in $E \sim (\text{TeV}, \text{PeV})$
 - **ORCA**, **neutrino oscillations** in $E \sim (3, 100) \text{ GeV}$
 - ▷ precision in θ_{23} and Δm_{32}^2 **oscillation parameters**
 - ▷ measurement of **Neutrino Mass Ordering** thanks to sensitivity to matter effect resonance in the earth
 - ▷ other “low-energy” searches: **ν_τ appearance**, non-standard interactions, sterile searches, etc...

Rebecca's talk!

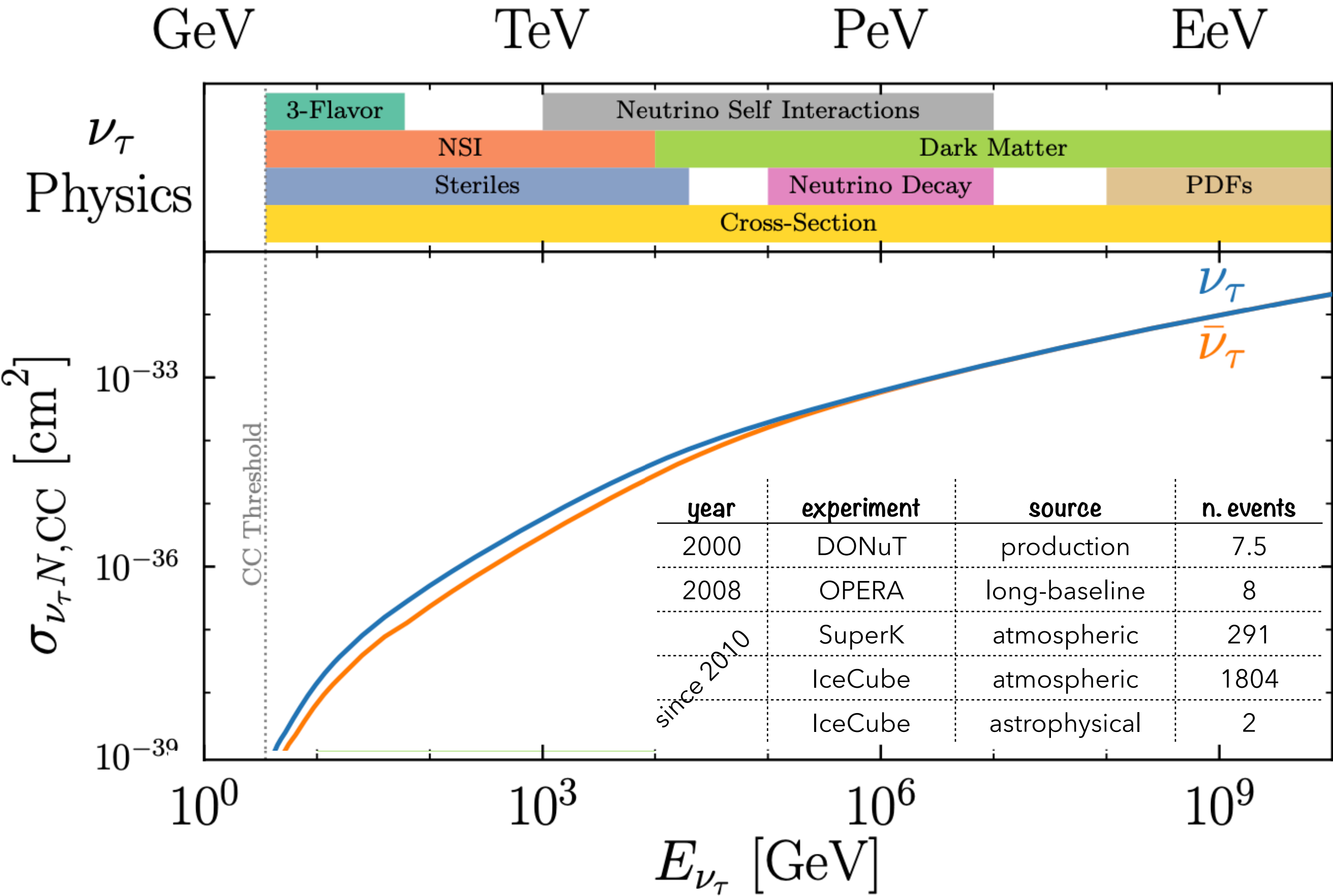


Alfonso's talk!

Why search for ν_τ appearance?

- ν_τ is still one of the less studied SM particles (only ~2100 detected so far)
 - low cross-section
 - relatively high detection/production energy
- unitarity of the PMNS matrix as a **test of the three flavors paradigm**
 - from next-generation neutrino experiments, constraints on PMNS elements $\leq 10\%$ ($< 1\%$ in e-row, but $\sim 10\%$ in τ -row)

$$\begin{pmatrix}
 U_{e1} & U_{e2} & U_{e3} & ? \\
 U_{\mu1} & U_{\mu2} & U_{\mu3} & ? \\
 U_{\tau1} & U_{\tau2} & U_{\tau3} & ? \\
 ? & ? & ? & ?
 \end{pmatrix}
 \sim
 \begin{matrix}
 & \nu_1 & \nu_2 & \nu_3 \\
 \nu_e & \boxed{} & \boxed{} & \boxed{} \\
 \nu_\mu & \boxed{} & \boxed{} & \boxed{} \\
 \nu_\tau & \boxed{} & \boxed{} & \boxed{}
 \end{matrix}$$



Why search for ν_τ appearance?

- ν_τ is still one of the less studied SM particles (only ~ 2100 detected so far)

- low cross-section
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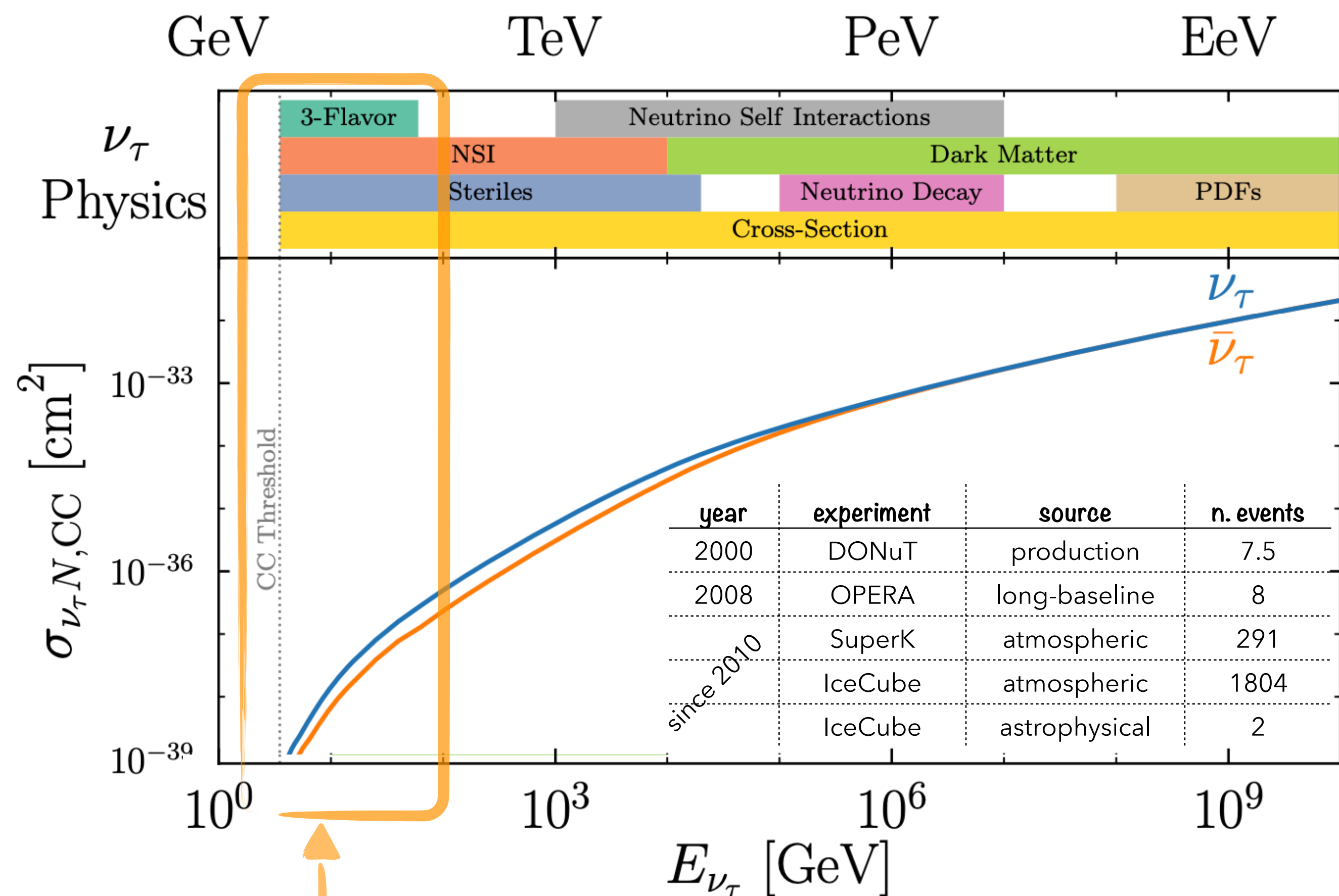
- unitarity of the PMNS matrix as a **test of the three flavors paradigm**

- from next-generation neutrino experiments, constraints on PMNS elements $\leq 10\%$ ($< 1\%$ in e-row, but $\sim 10\%$ in τ -row)

- constraint of ν_τ **cross-section**

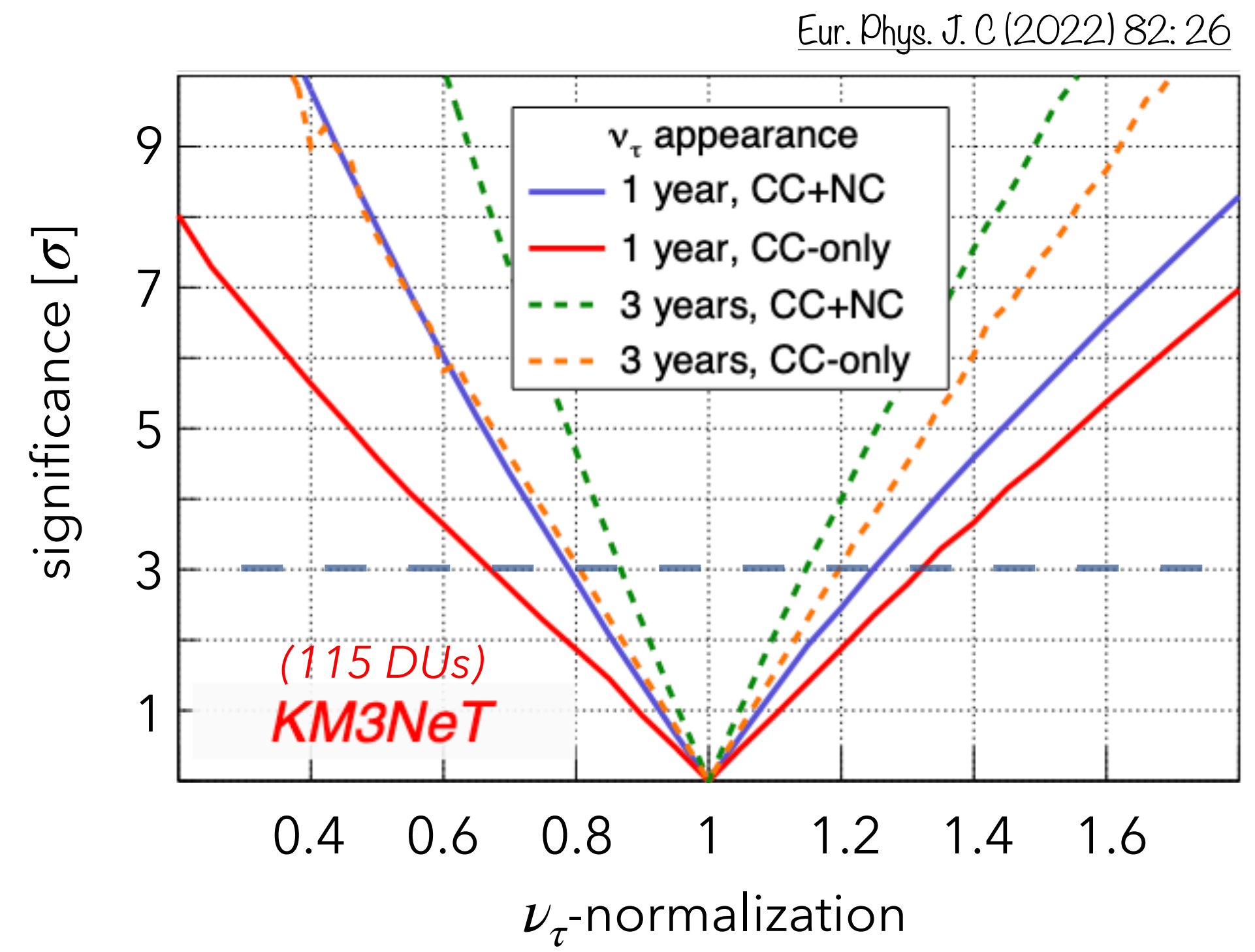
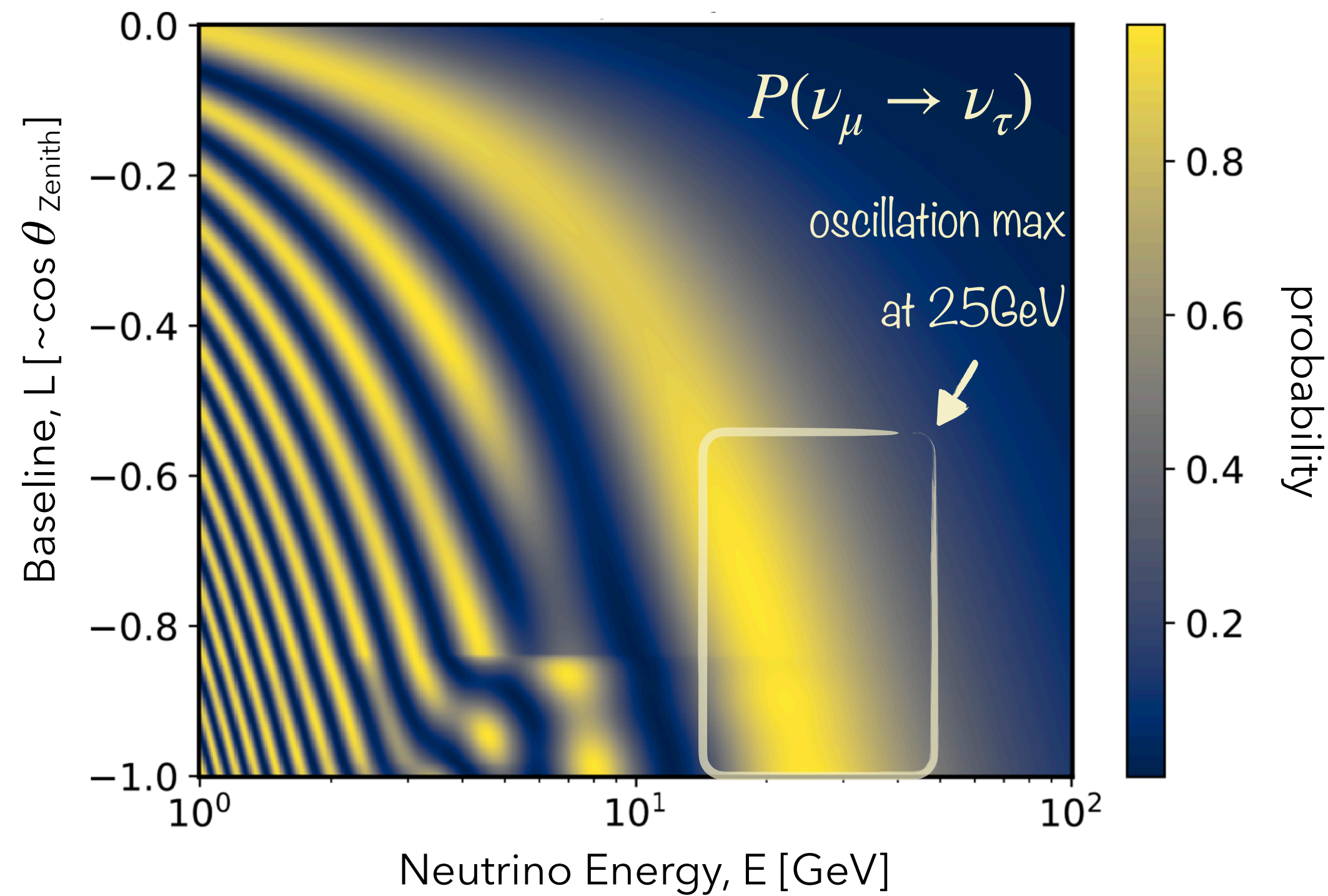
- **sterile neutrino coupling with ν_τ**

energy region accessible in KM3NeT/ORCA via oscillation



Sensitivity to ν_τ appearance in KM3NeT/ORCA

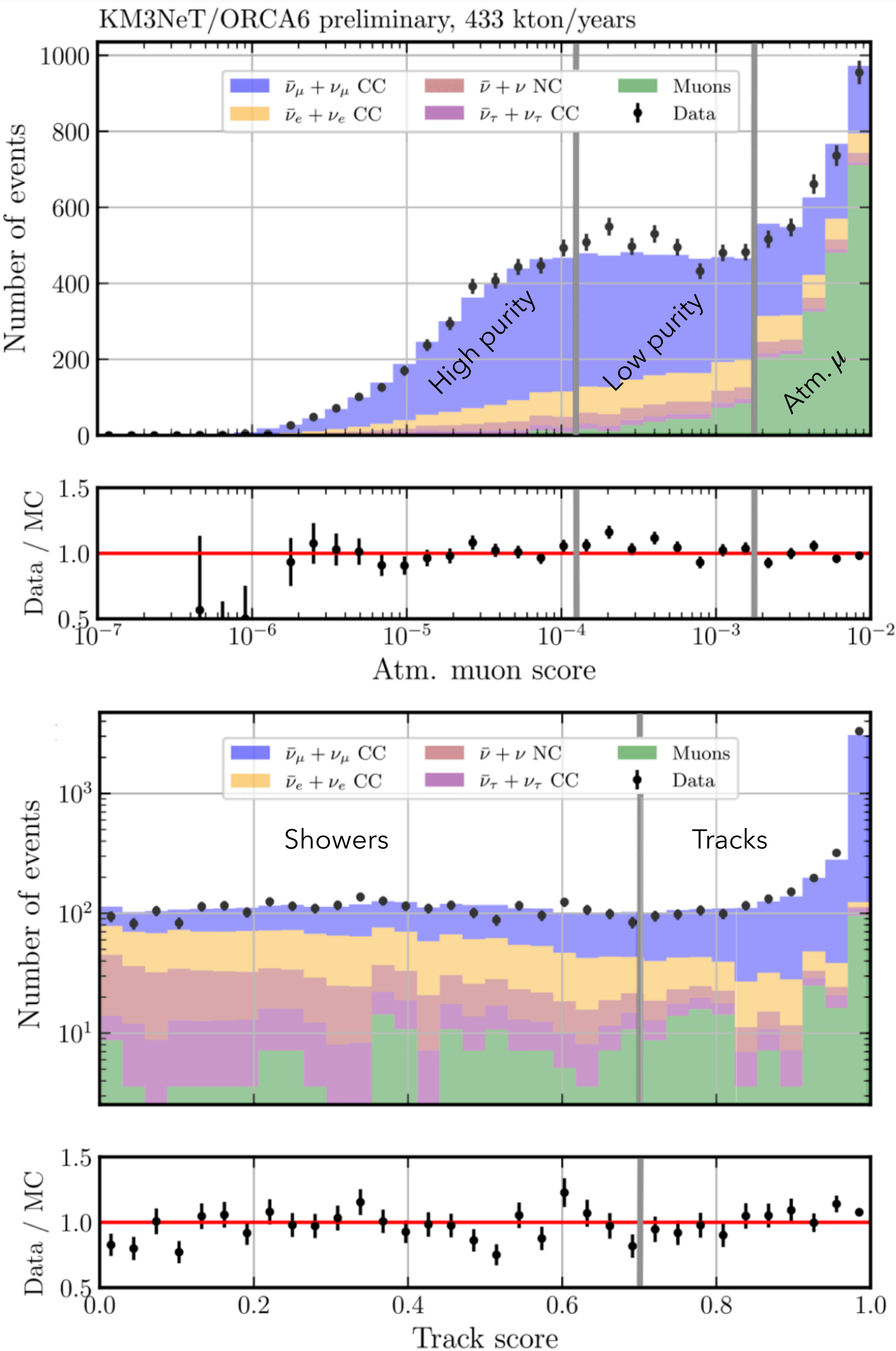
- **unprecedented ν_τ statistics:** 3000 ν_τ events/year in full geometry
 - using unitarity (hypothesis of ν_τ norm = 1)
 - analysis performed on a statistical basis: **excess in shower sample** (*good shower reconstruction is critical!!*)



Current detector geometry: KM3NeT/ORCA 6

- **KM3NeT/ORCA 6** longest data-taking in stable conditions
 - 433 kton-years (510 days, Mar '20 - Nov '21)
 - track and shower reconstruction for each event
- **background rejection**
 - atmospheric muons (reconstructed down-going)
 - optical noise (^{40}K decay, PMT dark counts, bioluminescence)
- **neutrino selection and classification**
 - **Boosted Decision Tree (BDT)** algorithm
 - three classes: high/low purity track, and showers

Selection	All events	Atm. muons	$\nu_{\mu}/\bar{\nu}_{\mu}$ CC	$\nu_{\tau}/\bar{\nu}_{\tau}$ CC
High Purity Tracks	1870	7	1779	20
Low Purity Tracks	2001	83	1792	18
Showers	1959	21	908	130
433 kton-years	5830	111	4480	169

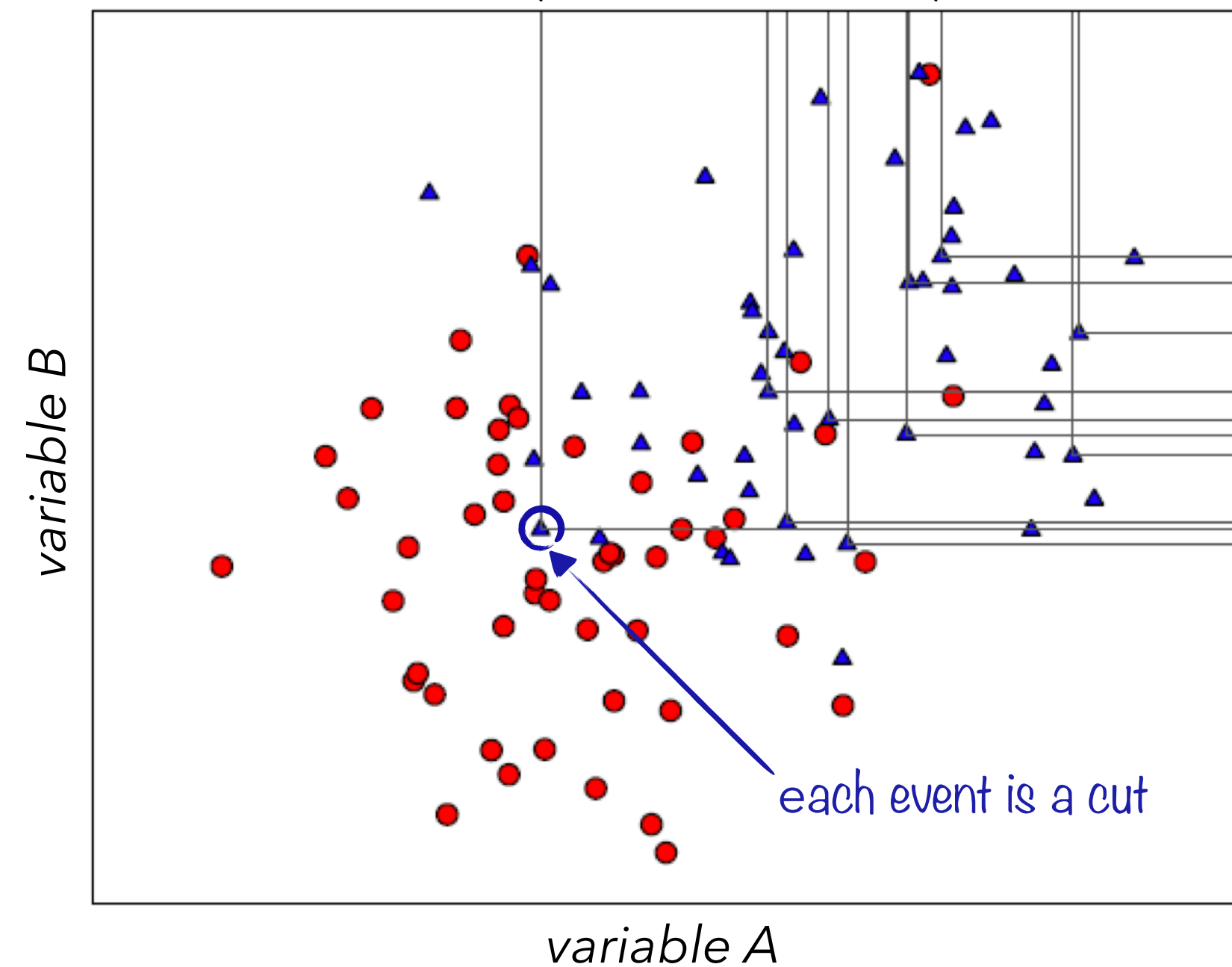


RGS: alternative selection to separate between tracks and showers

- Random Grid Search (RGS)

- optimized cut-based approach, more effective in the signal region

C. Bath et al., Comp. Phys. Comm. vol. 228, p 245-257 (2018)

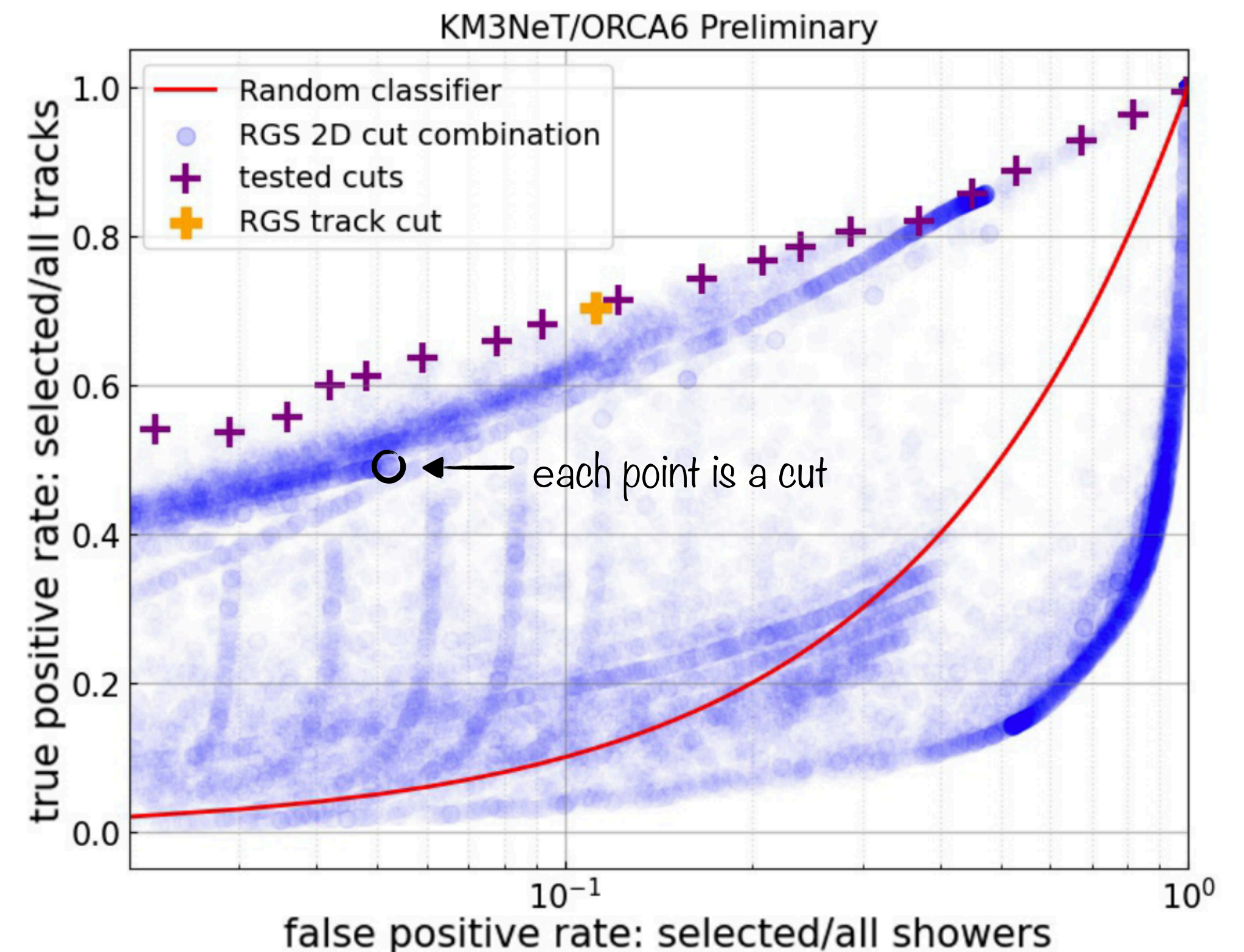
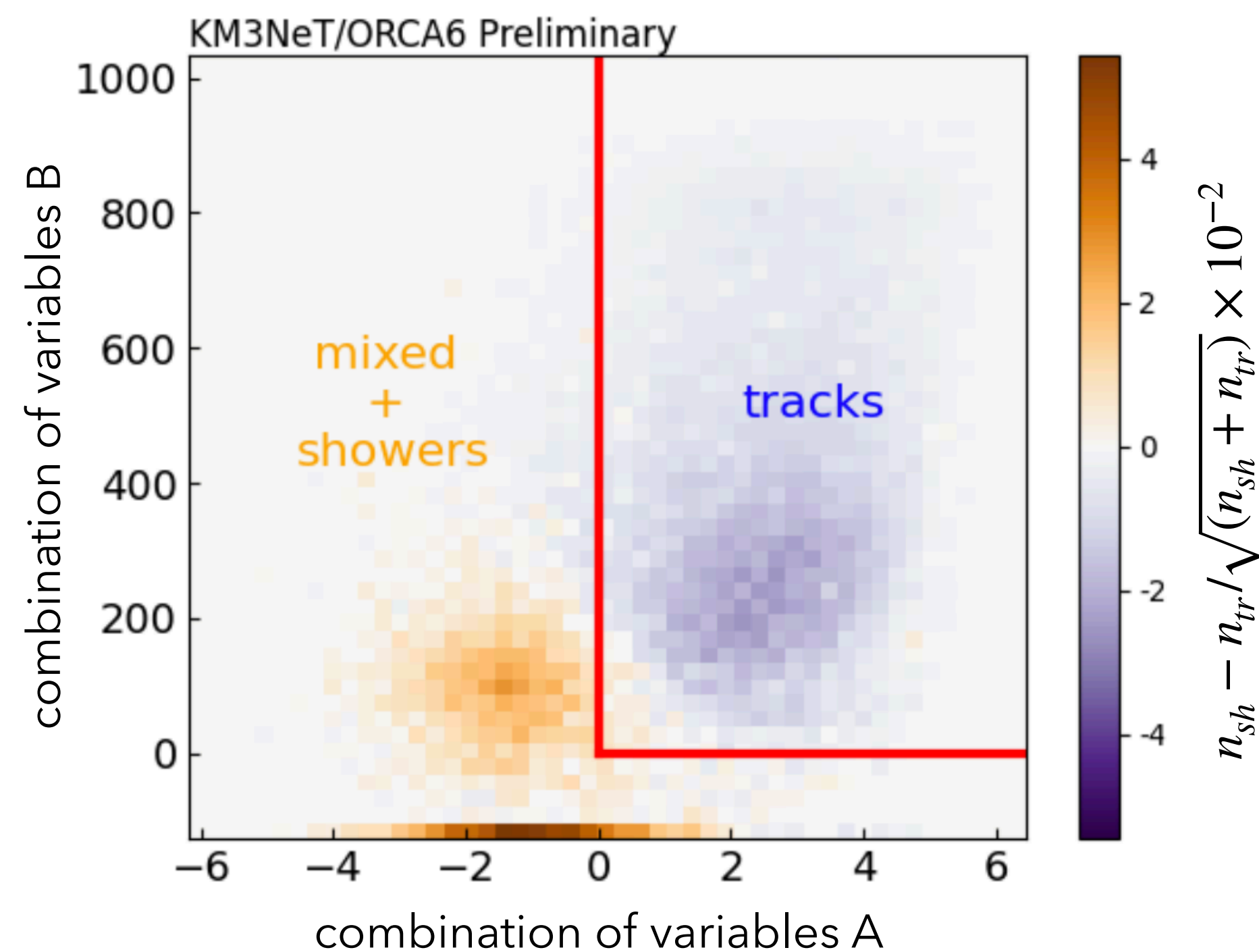


RGS: alternative selection to separate between tracks and showers

PoS ICRC2023 (2023) 1191

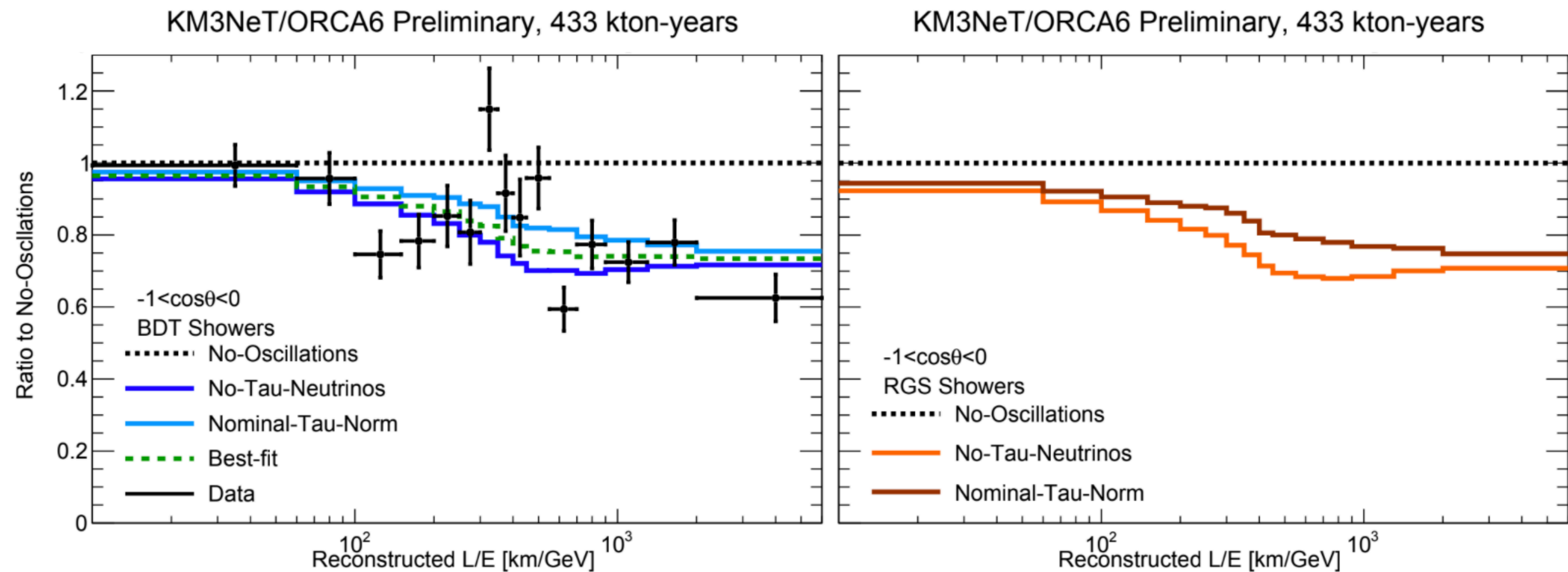
- Random Grid Search (RGS)

- optimized cut-based approach, more effective in the signal region (showers)
- no training needed, **smaller number of variables** compared to BDT, **and competitive performance**
- robust and adaptable to study new features for better shower-identification



RGS: alternative selection to separate between tracks and showers

- At the analysis level, consistent results are obtained by comparing the two selections

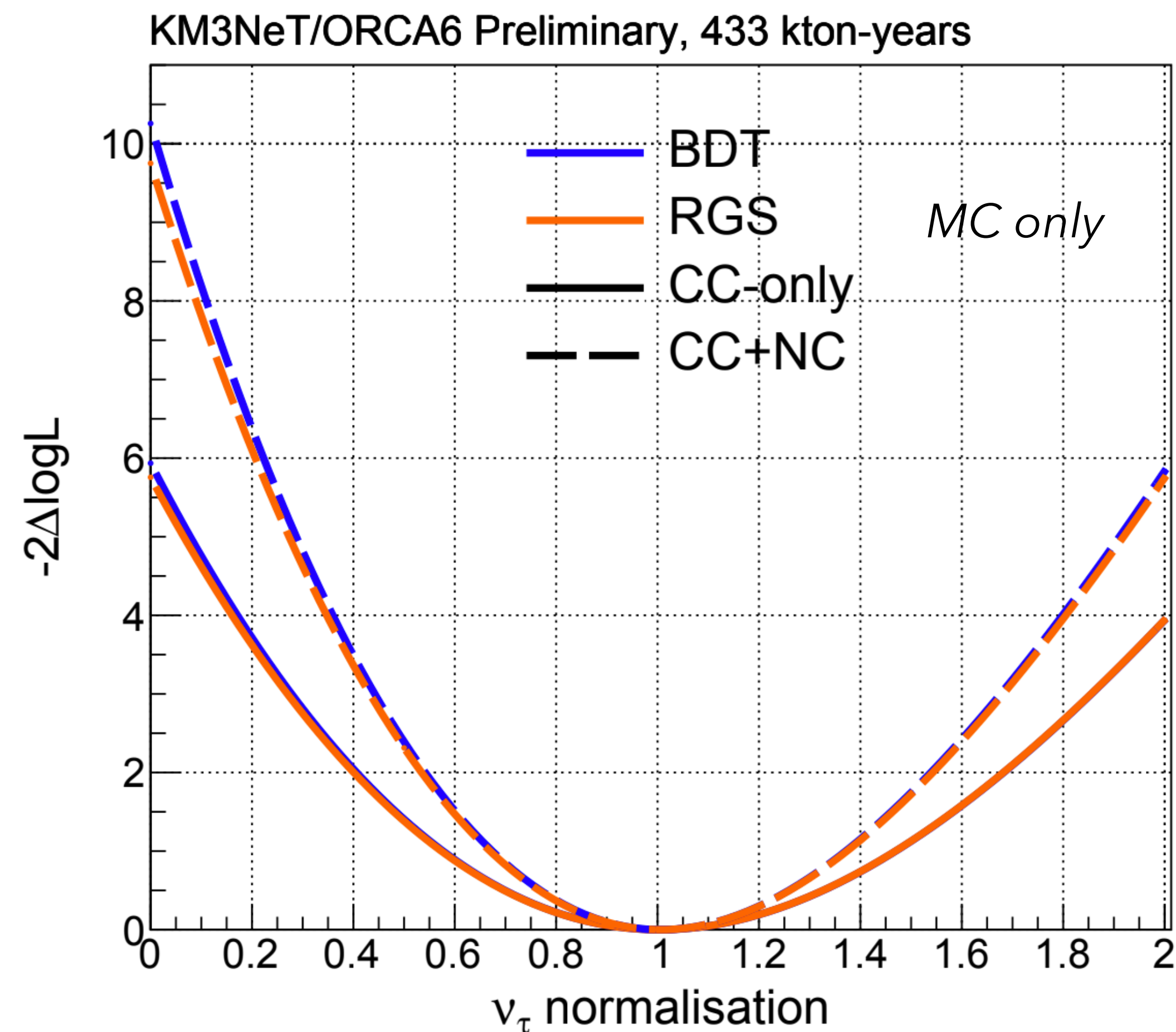


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ν_τ normalisation fit in KM3NeT/ORCA 6

- 2D binned log-likelihood fit of reconstructed energy and cosine zenith distributions, for the three classes
- ν_τ -normalization, scanned between 0 and 2
 - among all systematics, strongest impact of light simulation at high-energy (>50 GeV) and shower normalization

Systematics	Priors
Spectral Index	± 0.3
$\nu_{\text{hor}}/\nu_{\text{ver}}$	$\pm 2\%$
$\nu_\mu/\bar{\nu}_\mu$	$\pm 5\%$
$\nu_e/\bar{\nu}_e$	$\pm 7\%$
ν_μ/ν_e	$\pm 2\%$
NC Normalisation	$\pm 20\%$
Energy scale	$\pm 9\%$
High-energy Light Simulation	$\pm 50\%$
Overall Normalisation	free
Track Normalisation	free
Shower Normalisation	free
Muon Normalisation	free

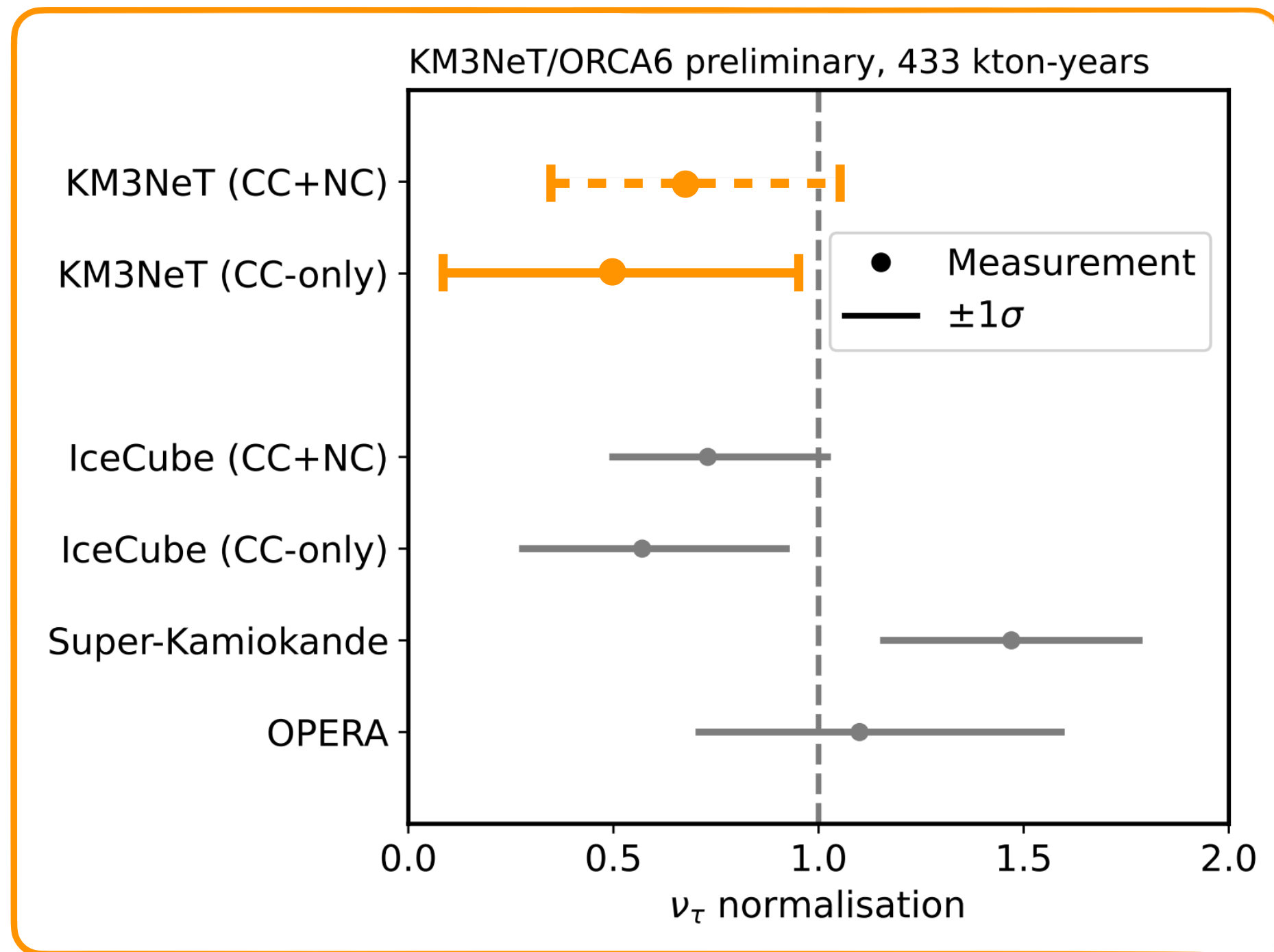
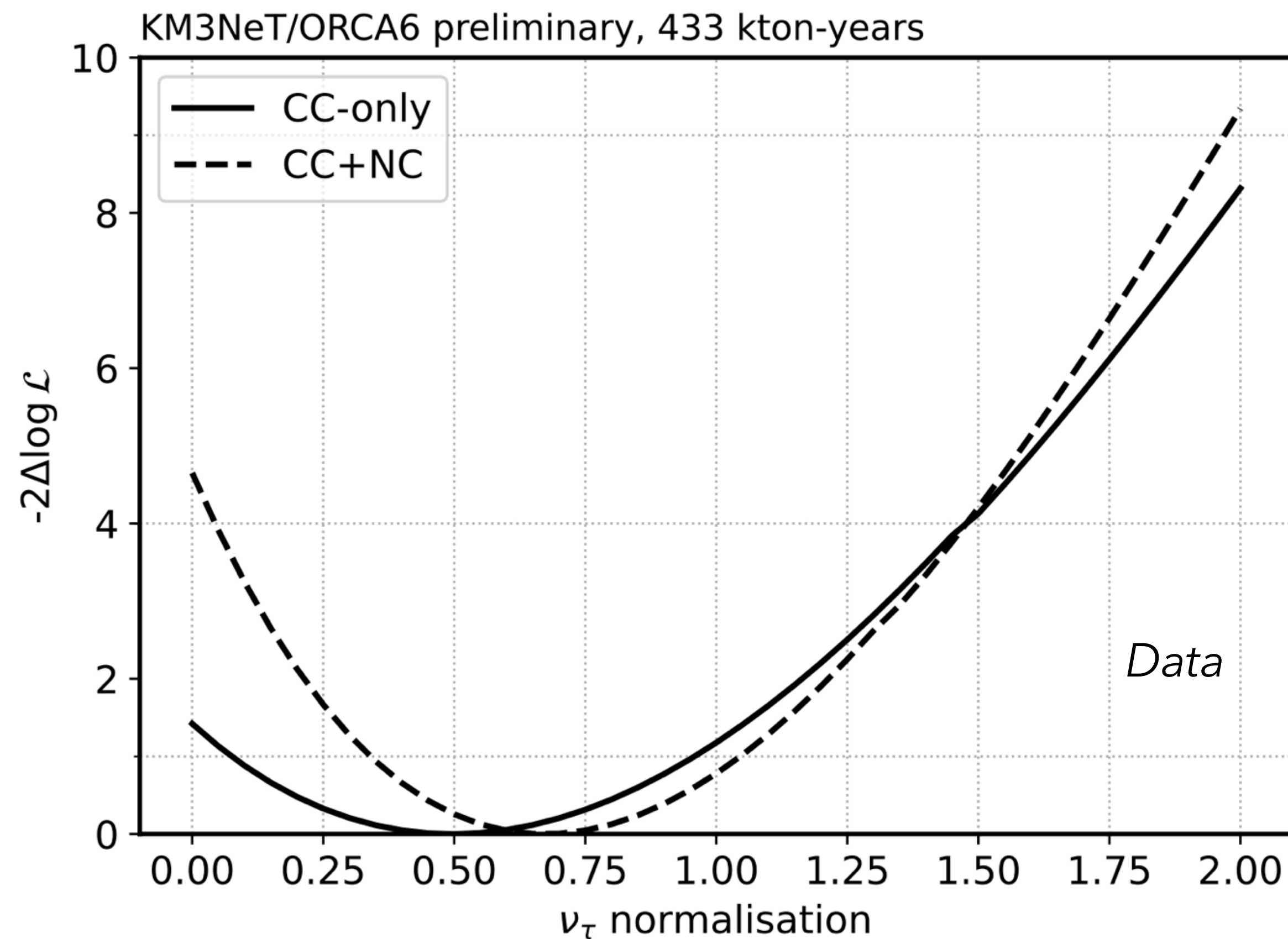


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ν_τ normalisation fit in KM3NeT/ORCA 6

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- With only 5% of final fiducial volume, competitive results with other experiments
- From fitting the data, **no clear evidence excluding $n_{\nu_\tau} = 1$**



- **CC-only:** ν_τ -norm = $0.50 \pm_{0.42}^{0.46}$
 $n_{\nu_\tau} = 0$, favored within 1.2σ

- **CC+NC:** ν_τ -norm = $0.67 \pm_{0.33}^{0.37}$
 $n_{\nu_\tau} = 0$, disfavoured with 2.2σ

Summary and outlook

- Precise measurement of ν_τ **appearance** is a key study to test the **three neutrino-flavor paradigm**
- Thanks to its active volume, KM3NeT/ORCA will exploit an unprecedented statistics
- A first measurement of the n_{ν_τ} has been performed in the KM3NeT/ORCA 6 geometry
 - two alternative selections have been used: **RGS** gives compatible results with BDT classification
 - analysis performed on a statistical basis: ν_τ **tagged as an excess in the shower sample (169 candidates)**
 - **no clear evidence excluding $n_{\nu_\tau} = 1$**
- Better precision, larger statistics, and a direct search for ν_τ in the shower sample are expected from the analysis of the larger geometries in the coming months ...**stay tuned!**

..thanks for your attention!



Extra Slides



KM3NeT: technology

- 3" Hamamatsu PMTs assembled into a **spherical structure for a 4π coverage**:

- high time precision (\sim ns)

- good spatial resolution (\sim 10 cm)

Eur. Phys. J. C 80, 99 (2020)

J. Phys. G: Nucl. Part. Phys. 43 084001 (2016)



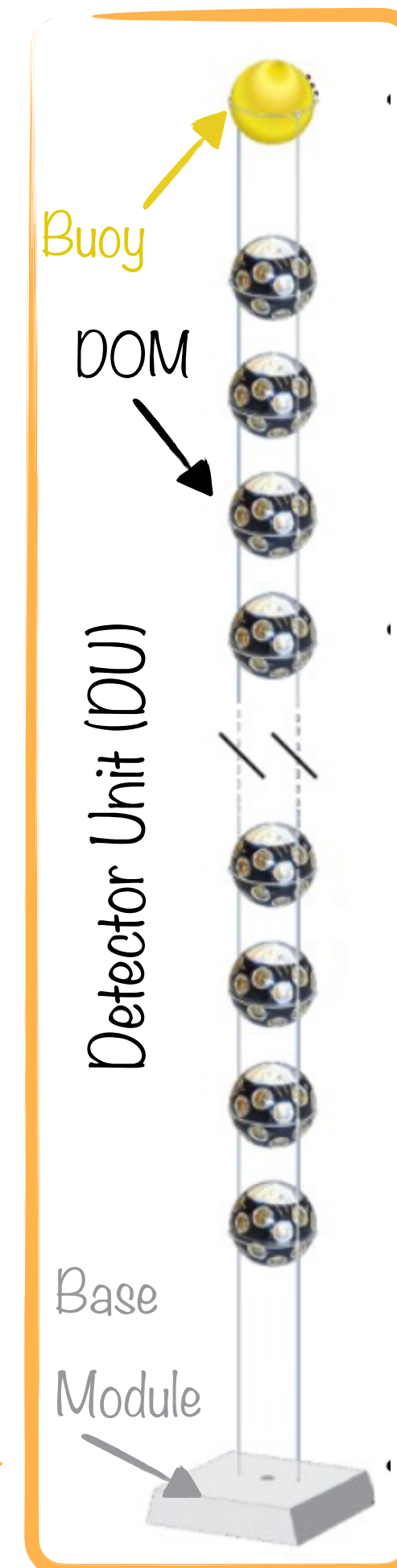
3" PMTs

x 31

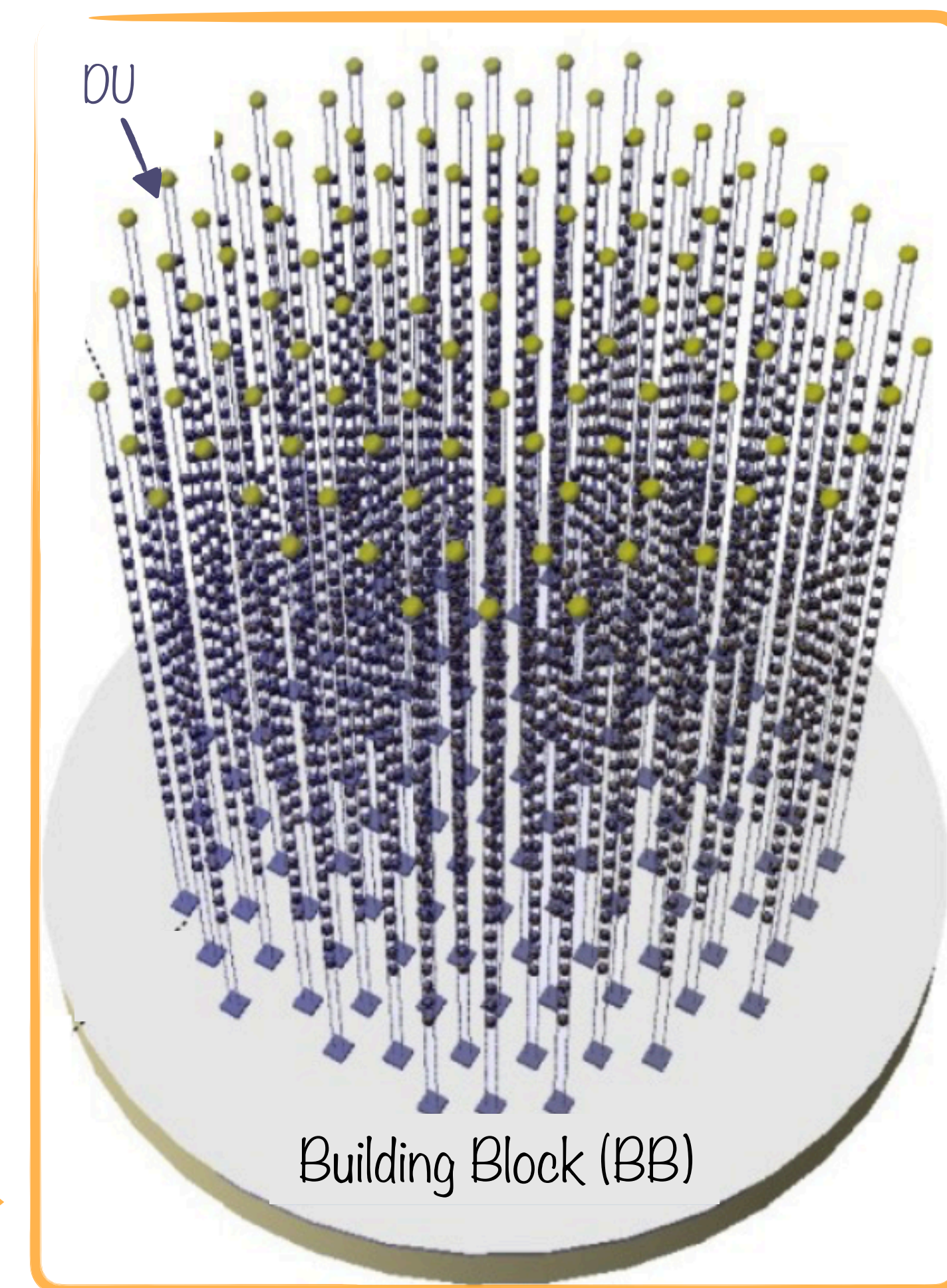


Digital Optical Module (DOM)

x 18

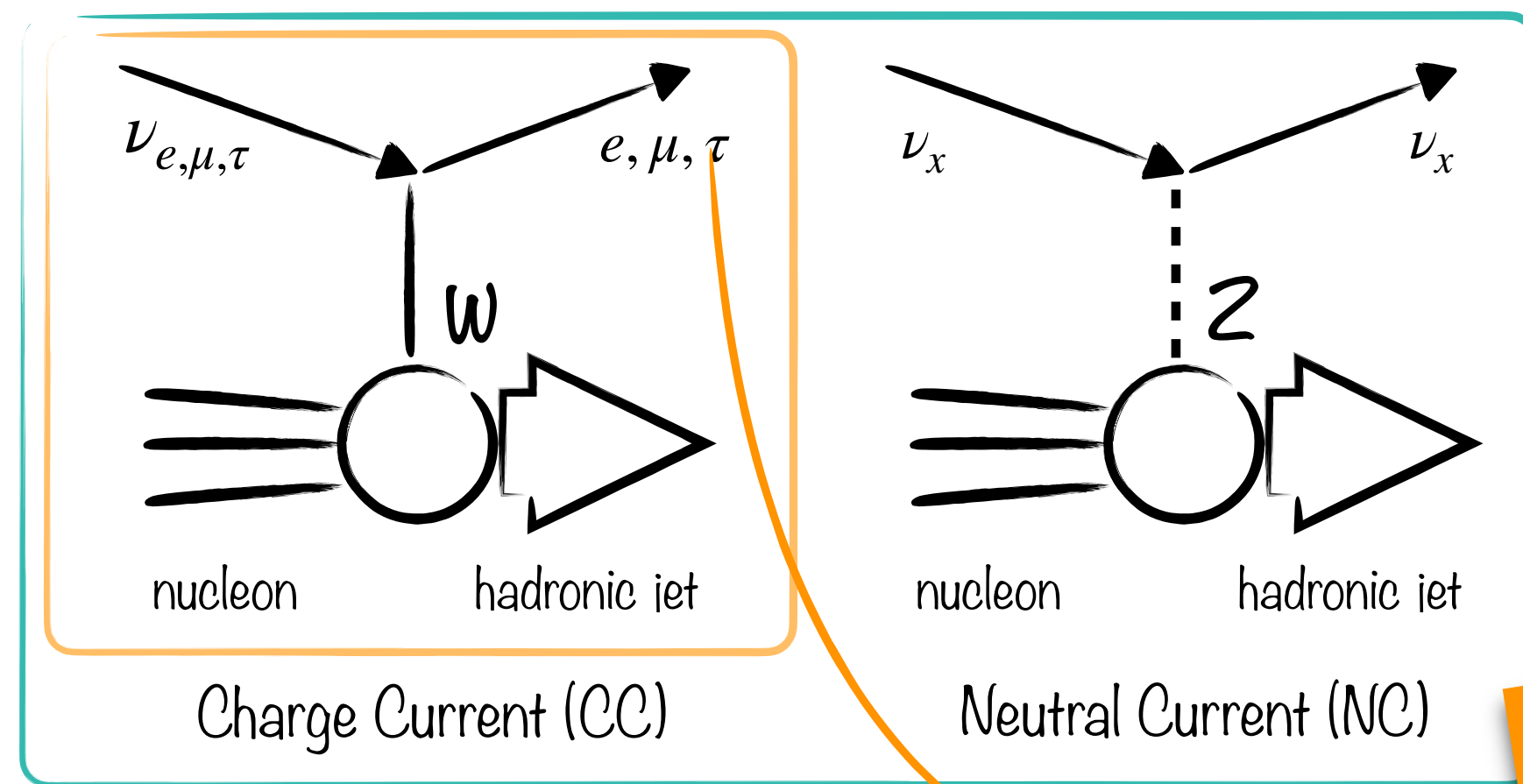


x 115



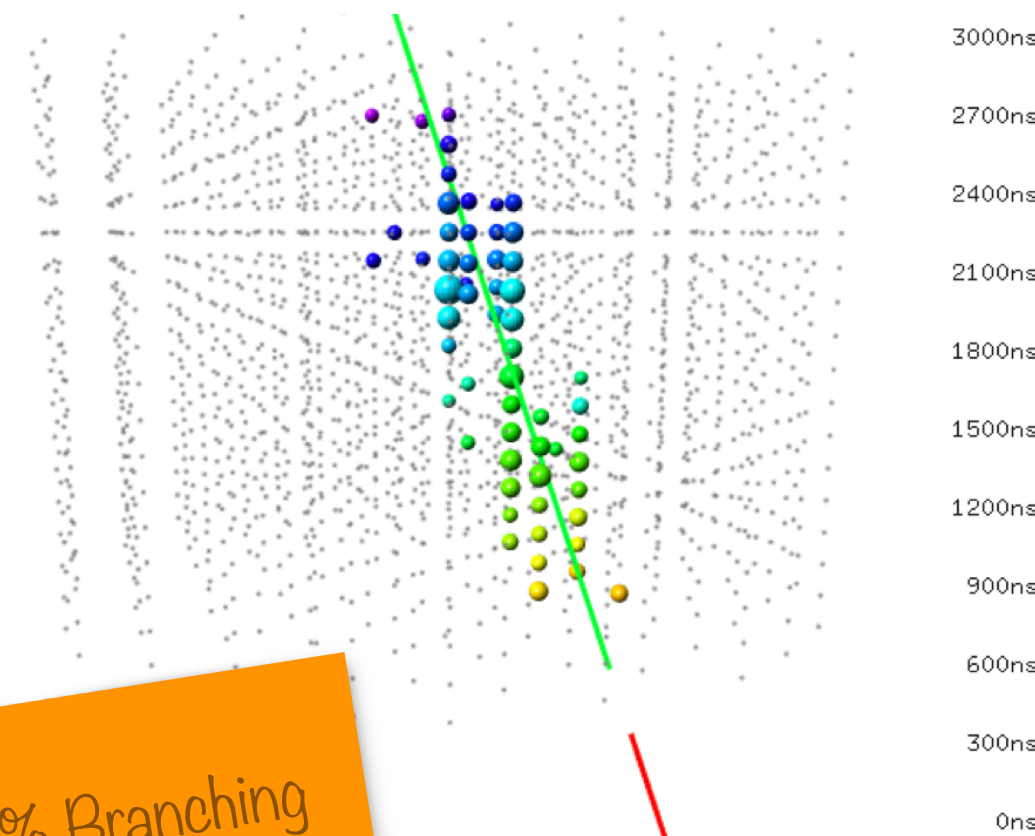
KM3NeT/ORCA: neutrino topologies

- Depending on the neutrino flavor and interaction, two event topologies can be reconstructed:
 - **track-like** events, very elongated and easier to be reconstructed
 - **shower-like** events, more spherical

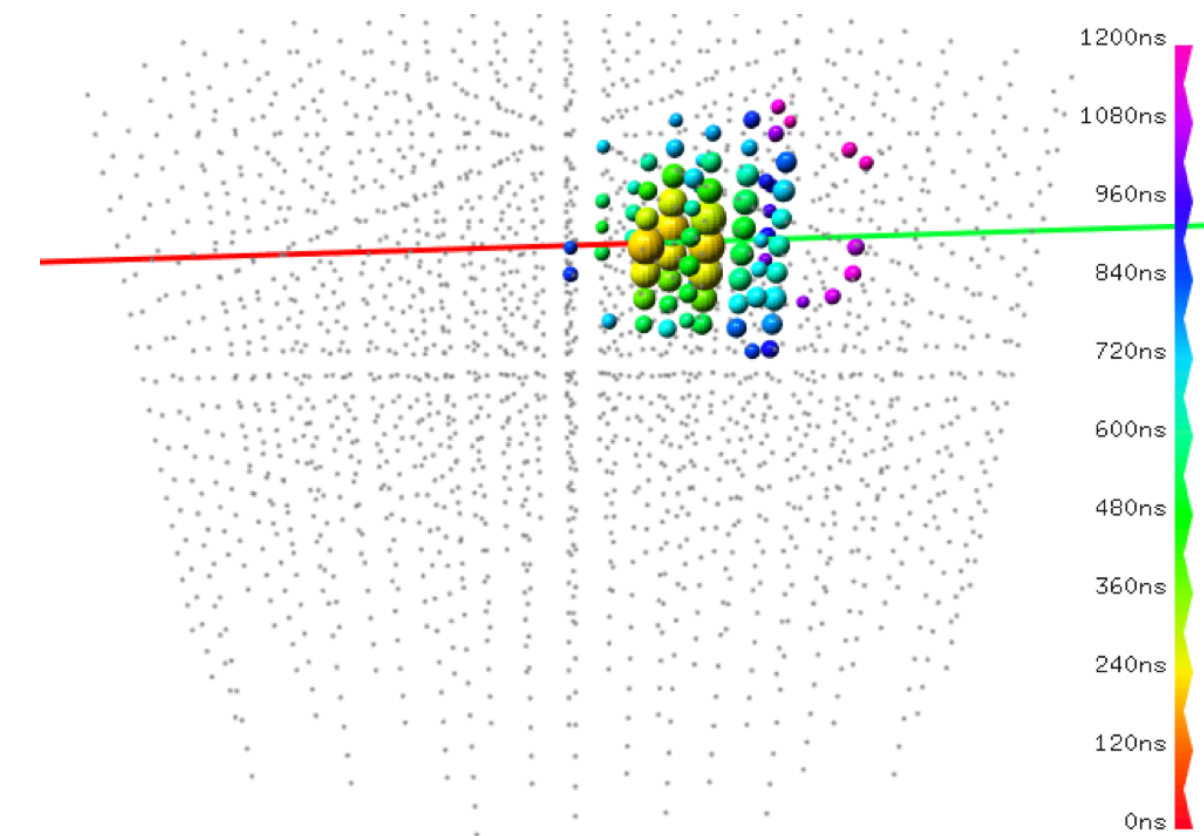


track-like events

there is a 17% Branching Ratio of ν_τ that can create track-like events



shower-like events



KM3NeT/ORCA: neutrino topologies

- Depending on the neutrino flavor and interaction, two event topologies can be reconstructed

- maximum likelihood algorithms optimized for the two topologies:

- ▷ based on **track and shower hypotheses** per event

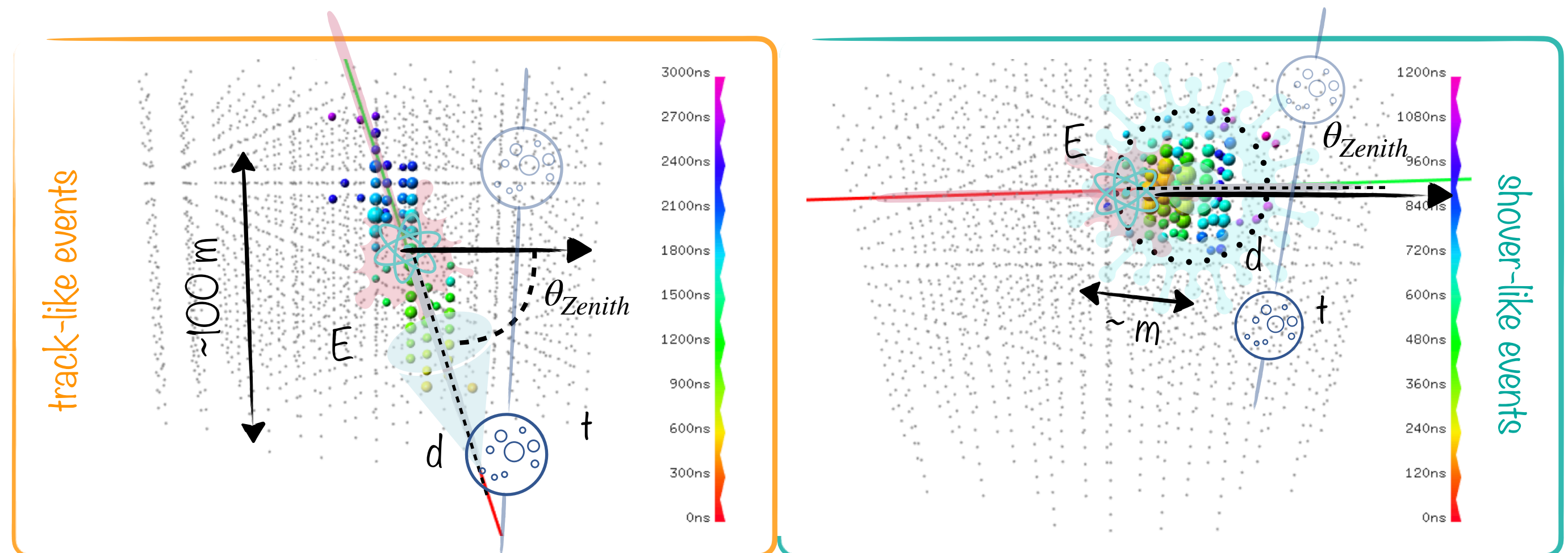
- ▷ **causality** for hit selection

- ▷ **time** in each PMT

- ▷ **vertex** and **direction** determination matching the topology hypothesis

- ▷ **energy estimation**

- compared to full ORCA, **new reconstruction algorithm for showers** uses **single-PMT information** (instead of single-DOM)



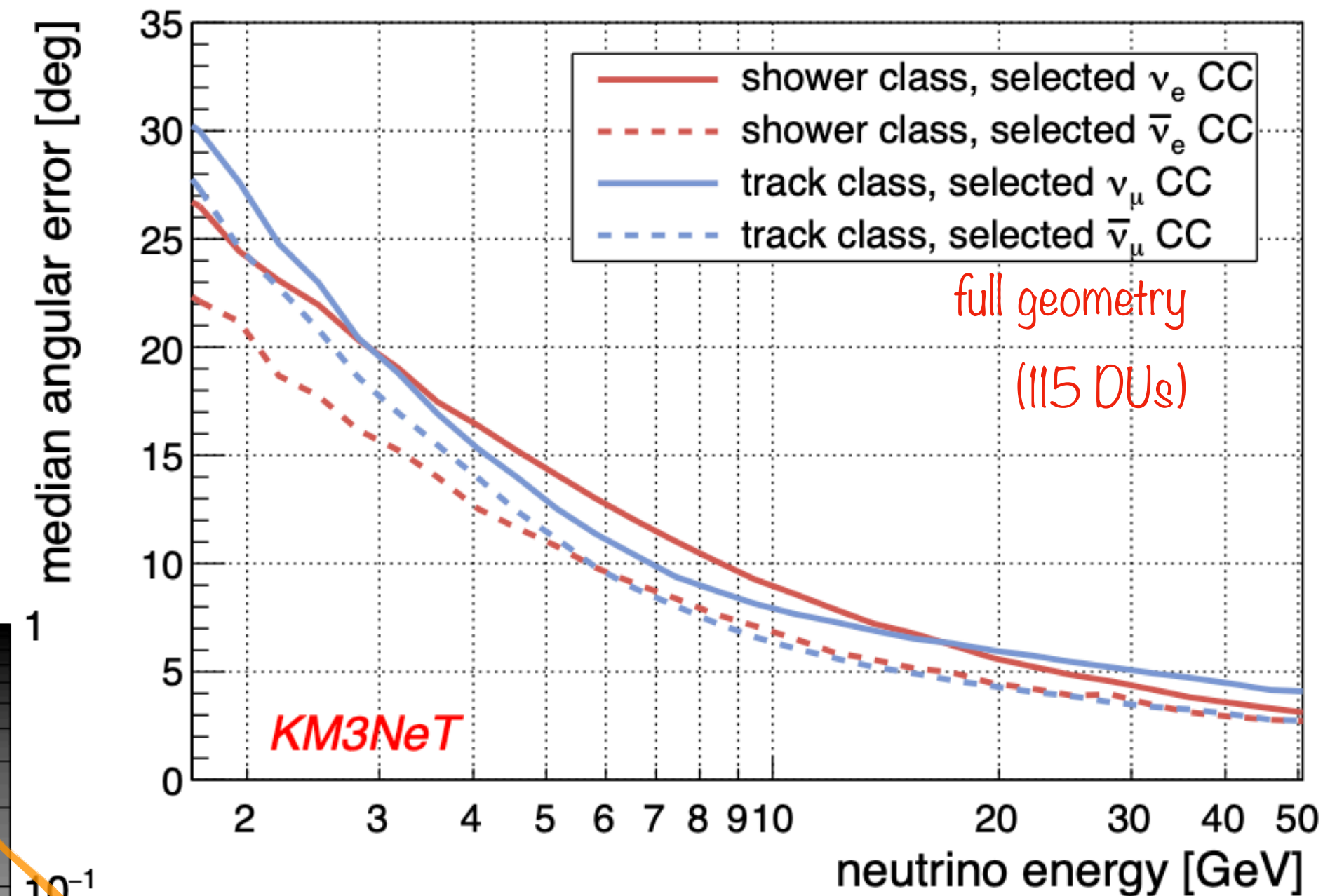
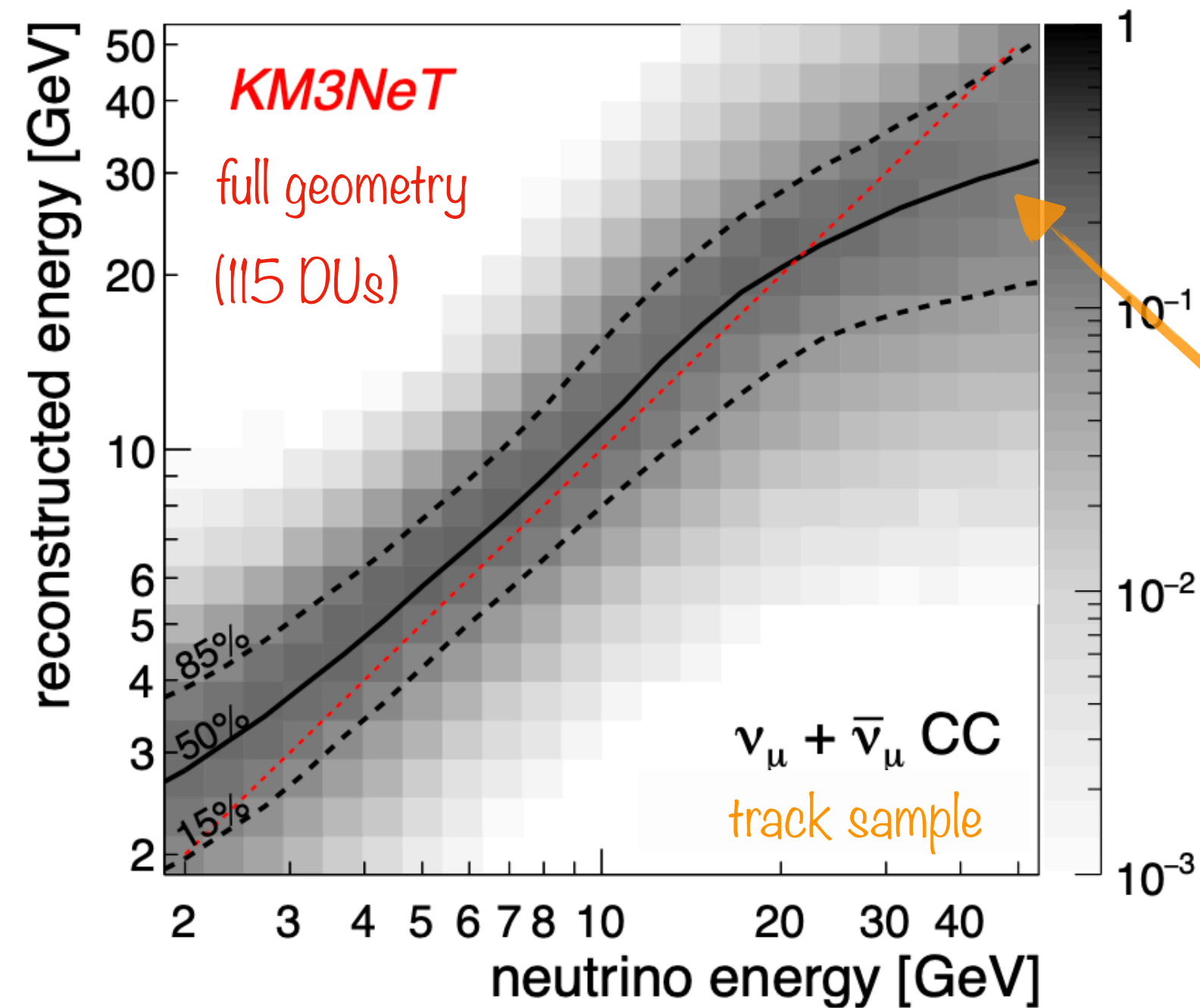
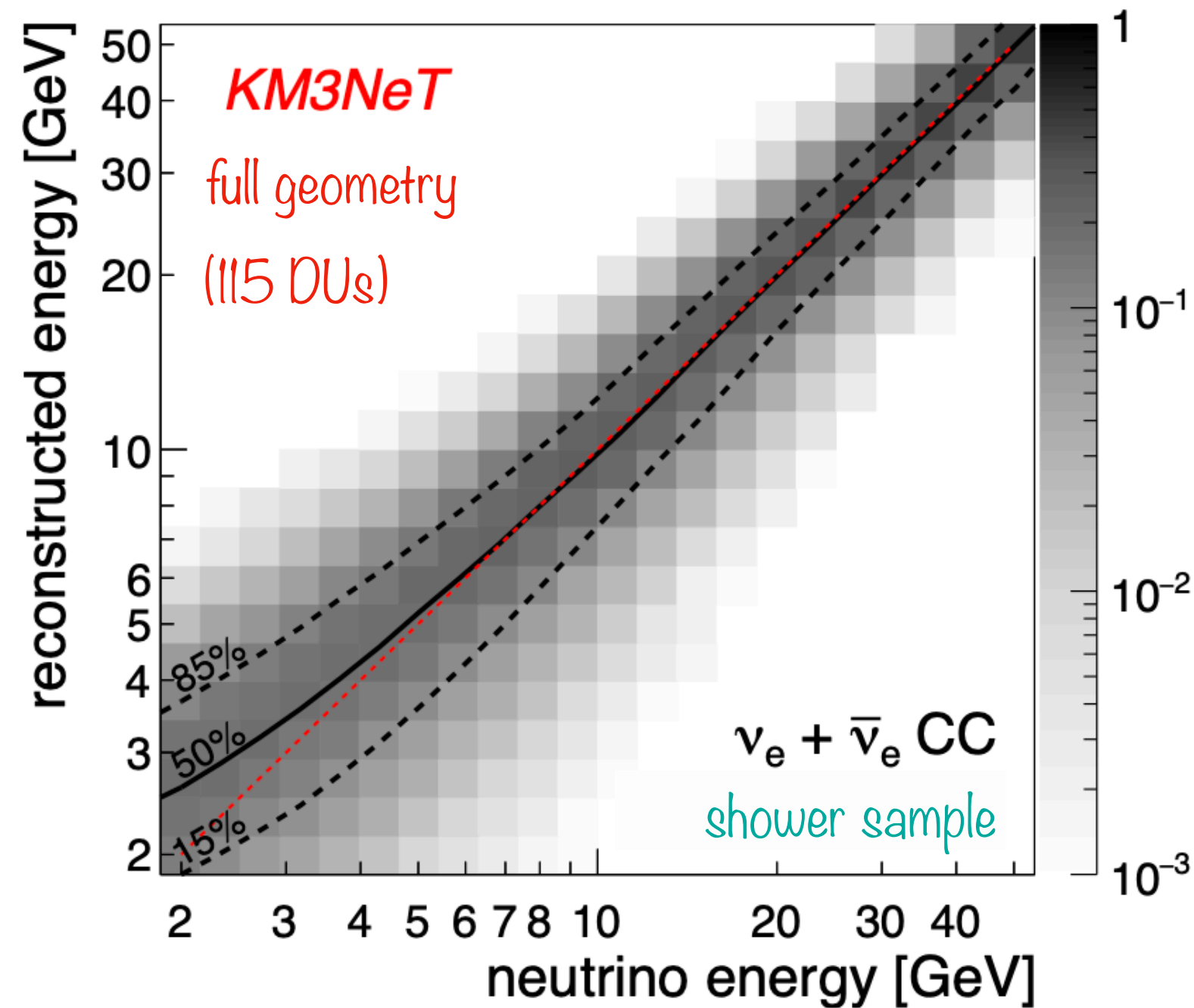
KM3NeT/ORCA: events reconstruction

- Sensitivity to event **reconstruction performance** in **full ORCA**

- up to **5° resolution** for both topologies

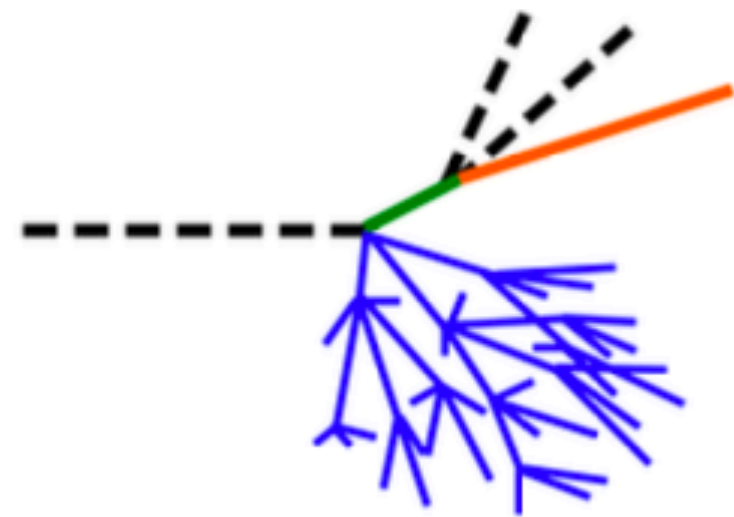
- **linear energy estimation** in the full energy range

Eur. Phys. J. C (2022) 82: 26

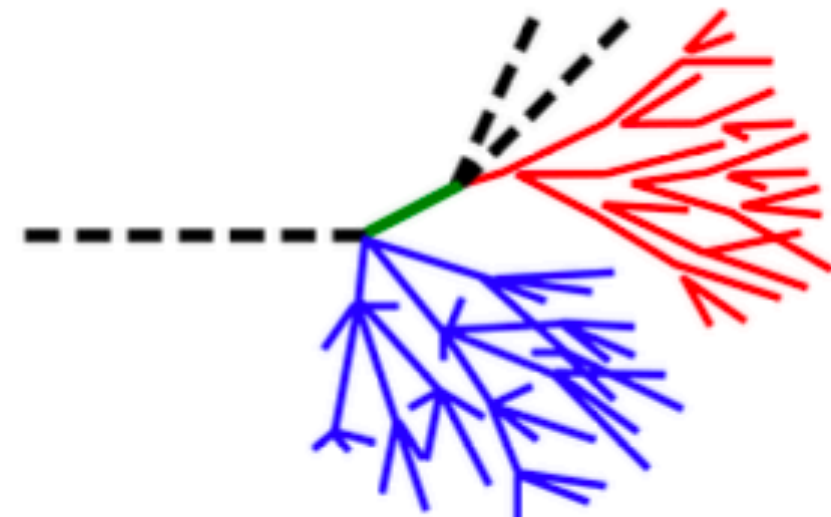


very elongated events (real int. vertex,
outside the instrum. vol.)

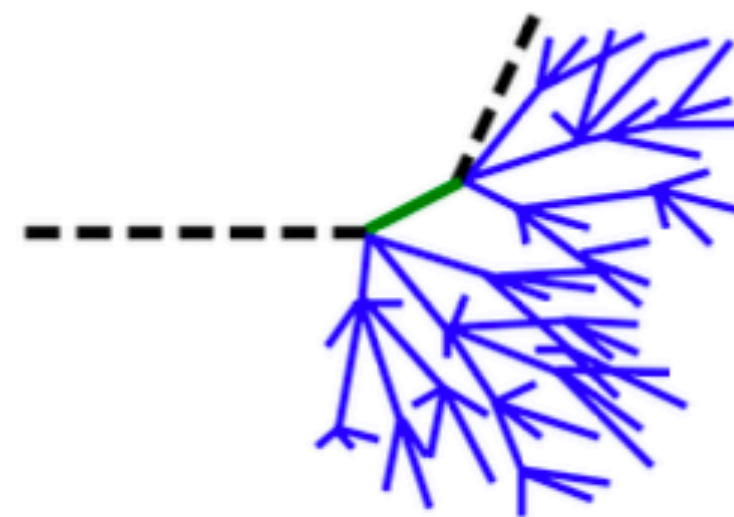
$\bar{\nu}_\tau$ CC



hadronic shower and μ track
($\tau^\pm \rightarrow \mu^\pm \bar{\nu}_\mu \bar{\nu}_\tau$, $\sim 17\%$ BR)



hadronic shower and EM shower
($\tau^\pm \rightarrow e^\pm \bar{\nu}_e \bar{\nu}_\tau$, $\sim 18\%$ BR)



hadronic shower
($\tau^\pm \rightarrow \text{hadrons}$, $\sim 65\%$ BR)

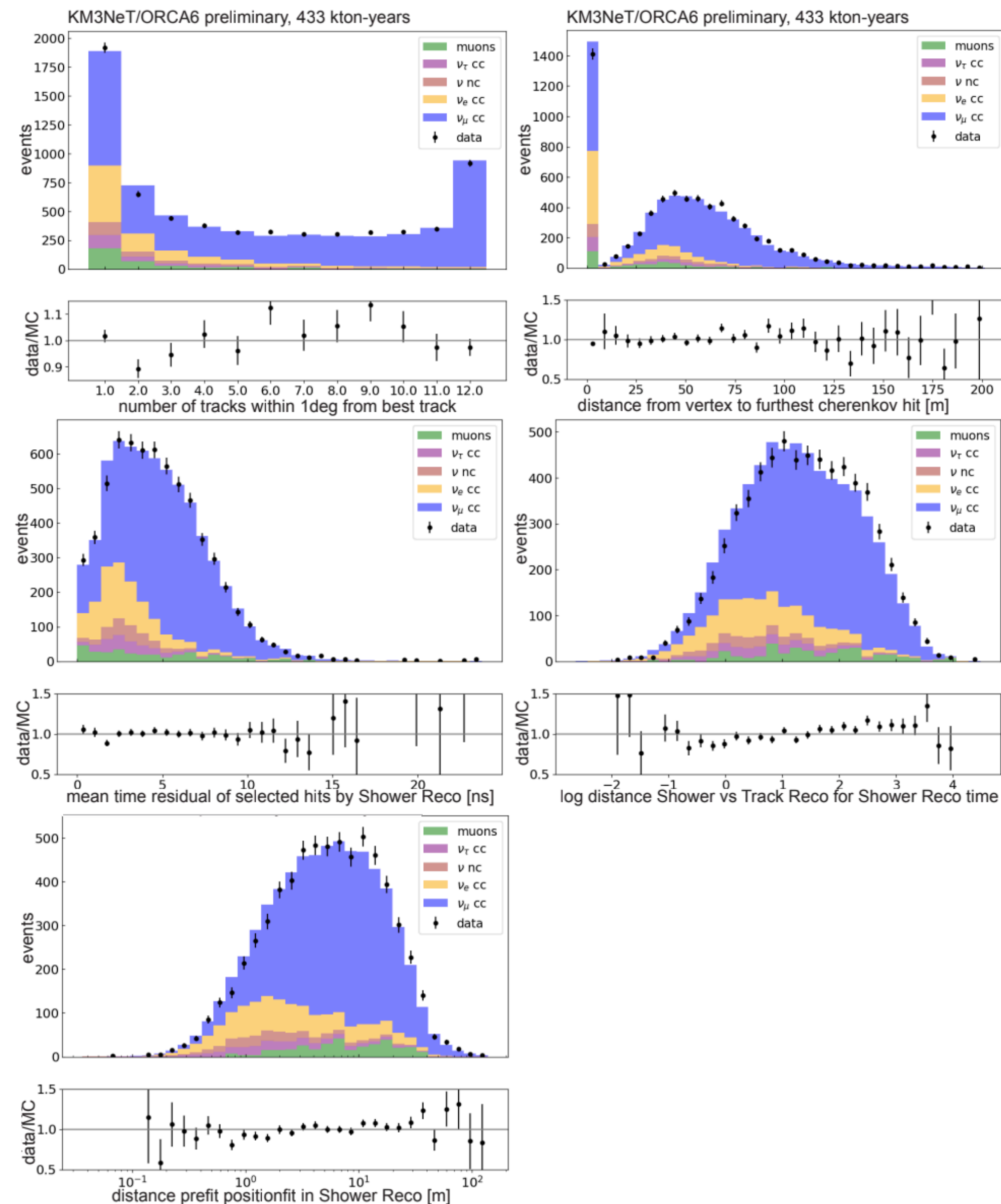
track-like events

shower-like events

ν_τ normalisation fit in KM3NeT/ORCA 6

- data/MC comparison for the top five best RGS variables used in the ν_τ normalization fit (right plots)
- in slide 11, combinations A and B are shown on the left plot
- list of RGS variables used to distinguish between track and shower-like events (bottom-table)

2D combination $Z = y - (ax + b)$					
RGS track class definition: $A \& B$					
pars.	feature x	feature y	coeff a	coeff b	cut dir.
comb. A	n. tracks within 1°	log pre/pos fit dist. Shower Reco	-0.2356	+ 1.9124	$Z > 0$
comb. B	furthest Cherenkov hit	mean time residual of sel. hits	-5.0702	+125.6146	$Z > 0$
RGS shower class definition: $(\bar{A} \text{ or } \bar{B}) \& (C \& D \& F)$					
comb. C	log pre/pos fit dist. Shower Reco	furthest Cherenkov hit	-0.0101	+71.1553	$Z < 0$
comb. D	log pre/pos fit dist. Shower Reco	mean time residual of sel. hits	-3.0422	+7.4538	$Z < 0$
comb. E	mean time residual of sel. hits	log dist. Shower vs Track reco	-0.3291	+2.503	$Z < 0$

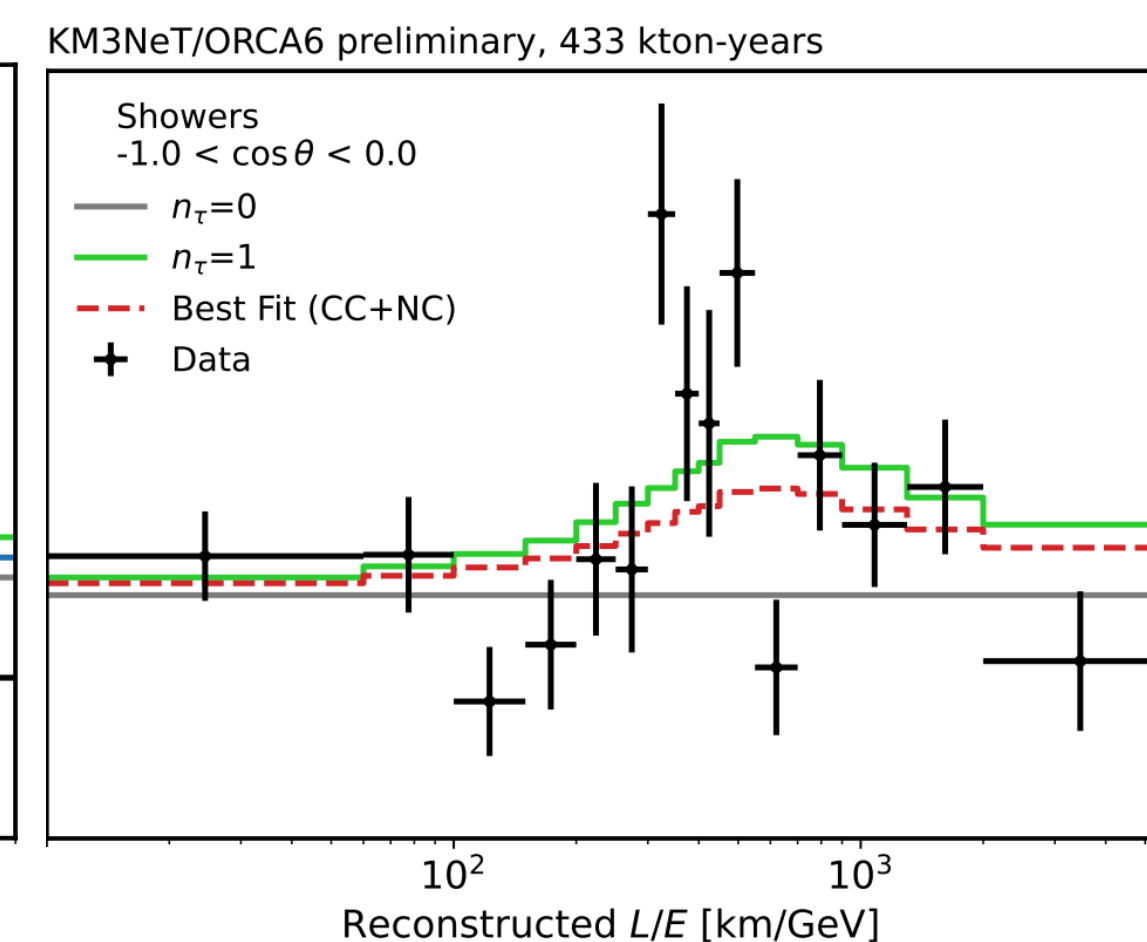
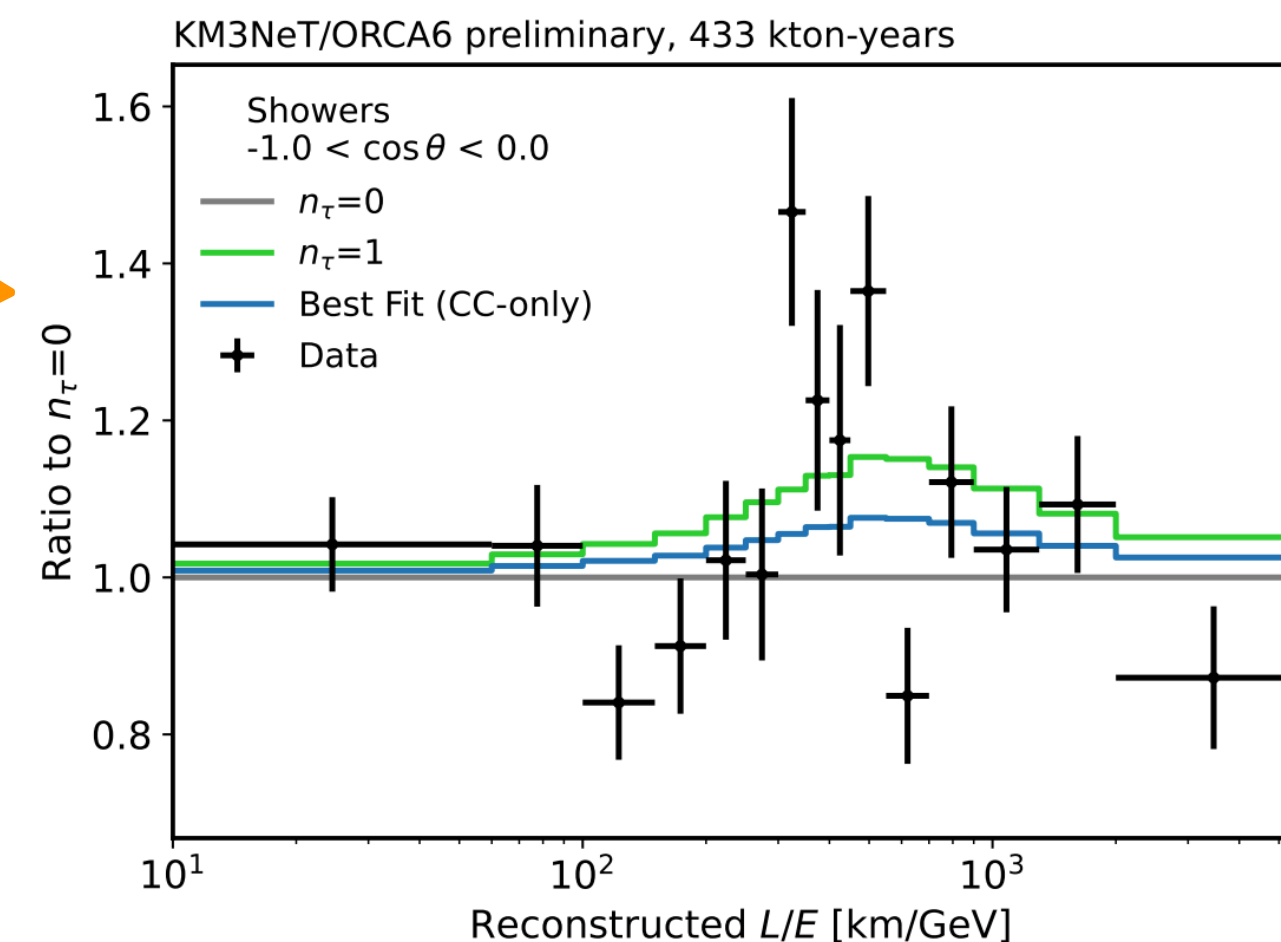
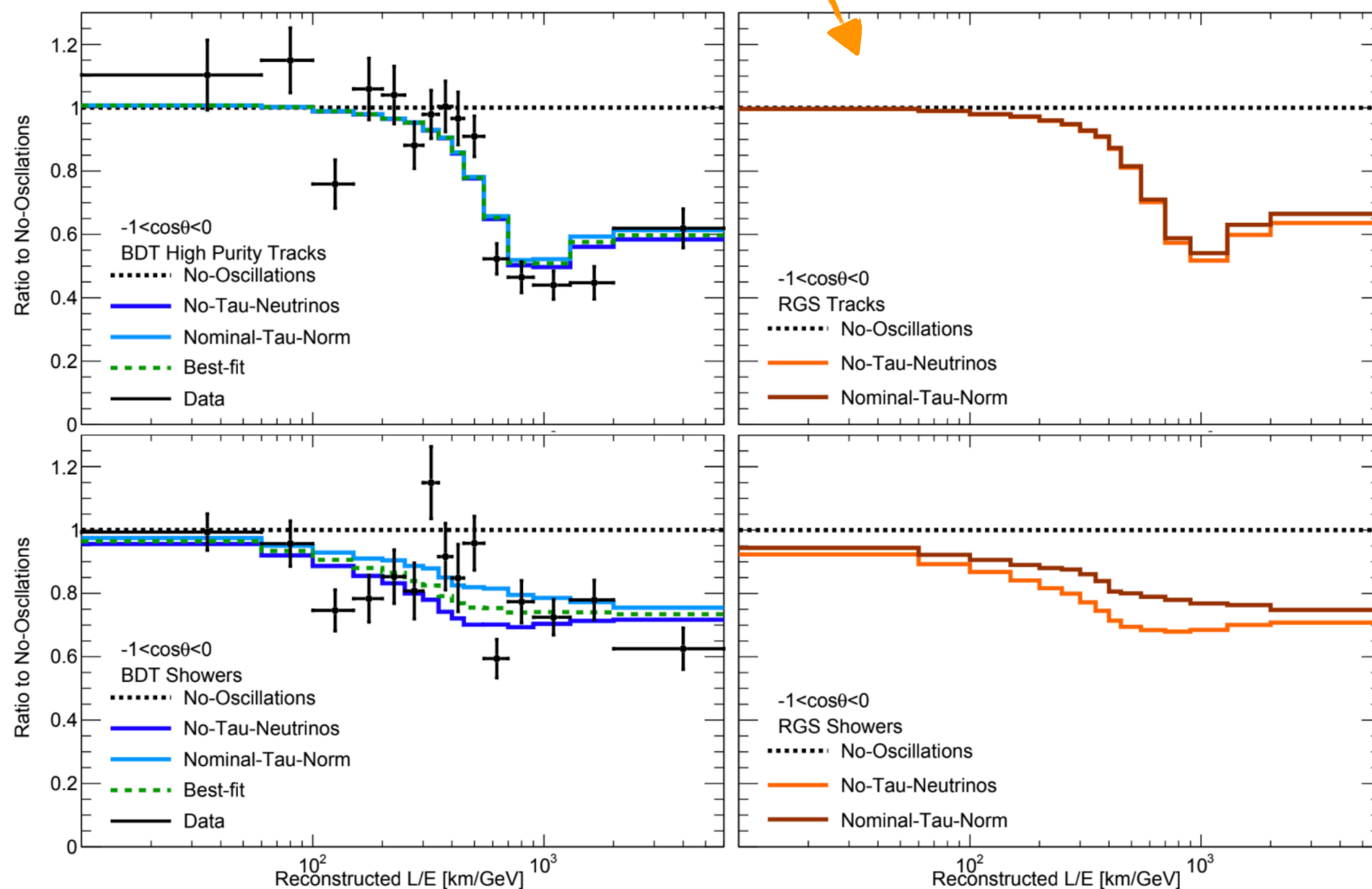


ν_τ normalisation fit in KM3NeT/ORCA 6

- dependence on L/E for the track and shower classes

○ based on BDT selection

○ based on RGS selection



Selection	HP Tracks	LP Tracks	Showers	Total
ν_μ CC	1167	1189	672	3028
$\bar{\nu}_\mu$ CC	612	604	236	1452
$\nu_\mu + \bar{\nu}_\mu$ CC	1779	1792	908	4480
ν_e CC	37	62	434	533
$\bar{\nu}_e$ CC	14	23	172	207
$\nu_e + \bar{\nu}_e$ CC	51	85	606	742
ν_τ CC	14	13	94	121
$\bar{\nu}_\tau$ CC	6	6	37	49
$\nu_\tau + \bar{\nu}_\tau$ CC	20	18	130	169
ν NC	10	17	226	253
$\bar{\nu}$ NC	3	5	67	75
$\nu + \bar{\nu}$ NC	13	22	294	329
Atm. Muons	7	83	21	111
Total MC	1870	2001	1959	5830
Total Data	1868	2002	1958	5828

ν_τ normalisation fit in KM3NeT/ORCA 6

- among all systematics for the ν_τ -normalization fit, the strongest impact is due to light simulation at high-energy (>50 GeV) and shower normalization

Systematics	Priors
Spectral Index	± 0.3
$\nu_{\text{hor}}/\nu_{\text{ver}}$	$\pm 2\%$
$\nu_\mu/\bar{\nu}_\mu$	$\pm 5\%$
$\nu_e/\bar{\nu}_e$	$\pm 7\%$
ν_μ/ν_e	$\pm 2\%$
NC Normalisation	$\pm 20\%$
Energy scale	$\pm 9\%$
High-energy Light Simulation	$\pm 50\%$
Overall Normalisation	free
Track Normalisation	free
Shower Normalisation	free
Muon Normalisation	free

