Studying Neutrino Oscillations with KM3NeT

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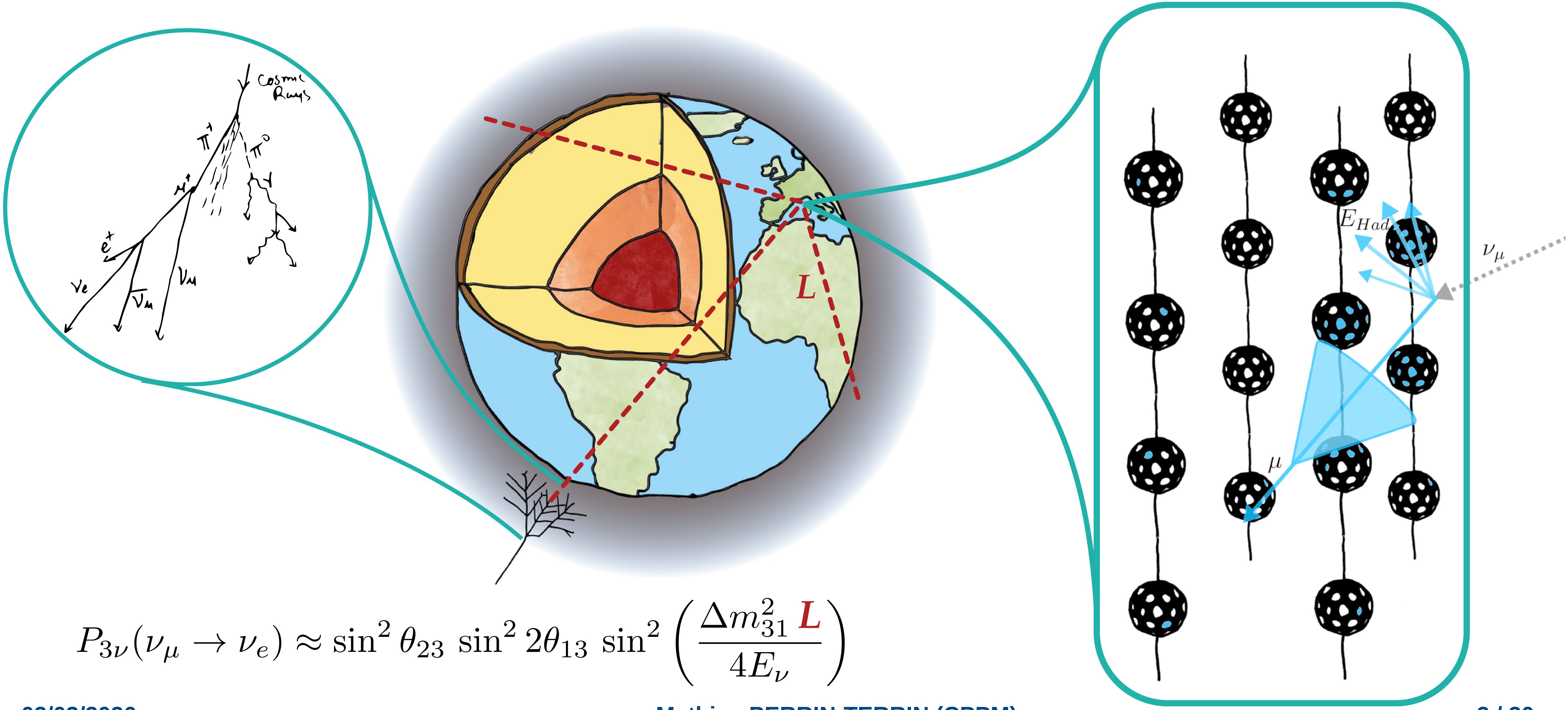
Experiment's Working Principle



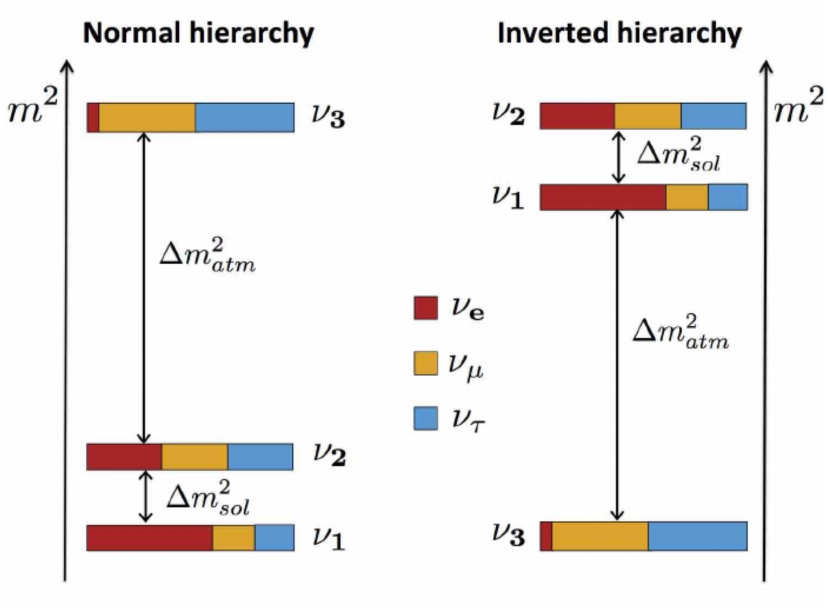
$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{31}\,L}{4E_\nu}\right)$$

Credits. S. Peña Martinez

Mass ordering with atmospheric neutrinos

- **NMO:** is ν_3 the heaviest of the lighest of the three neutrino mass eigenstates?
- **Matter** along the neutrino propagation makes the oscillation propability sensitive to NMO

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{31}\,L}{4E_\nu}\right)$$

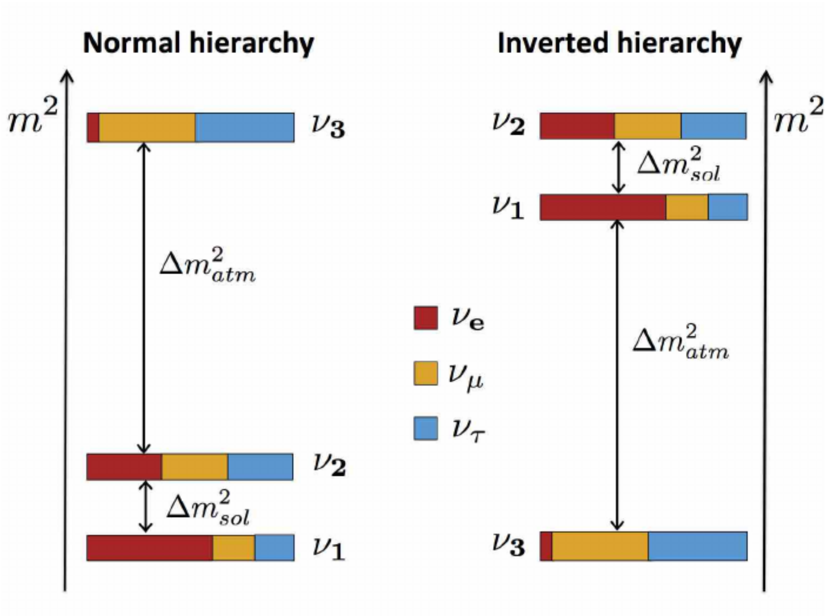


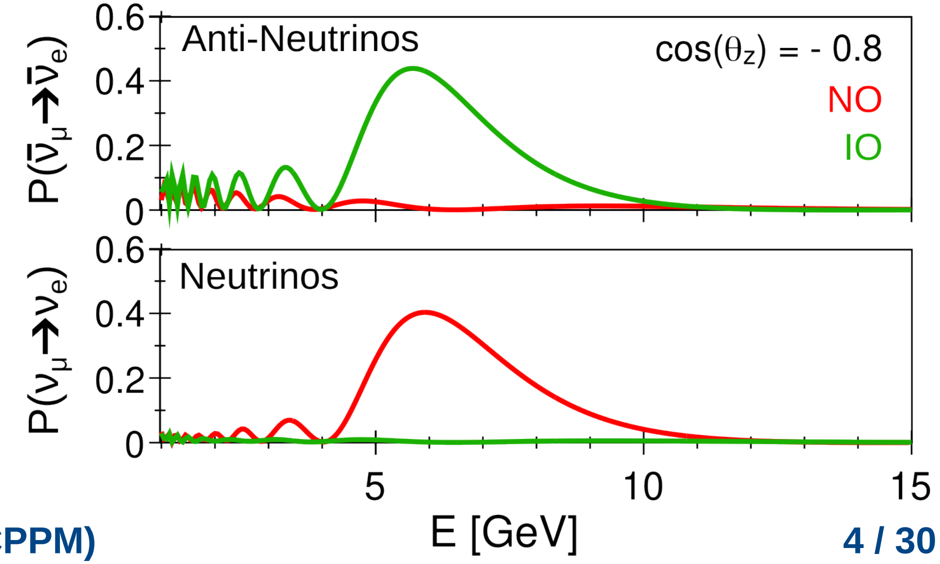
Mass ordering with atmospheric neutrinos

- **NMO:** is ν_3 the heaviest of the lighest of the three neutrino mass eigenstates?
- **Matter** along the neutrino propagation makes the oscillation propability sensitive to NMO

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} 2\sin^2\theta^m_{13} \sin^2\left(\frac{\Delta^m m^2 L}{4E_\nu}\right)$$

$$\sin^2(2\theta^m_{13}) \equiv \frac{(\Delta m^2_{31}\sin 2\theta_{13})^2}{(\Delta m^2_{31}\cos 2\theta_{13} \mp 2E_\nu V_{CC})^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2} \overset{\mathrm{RES}}{=} 1$$



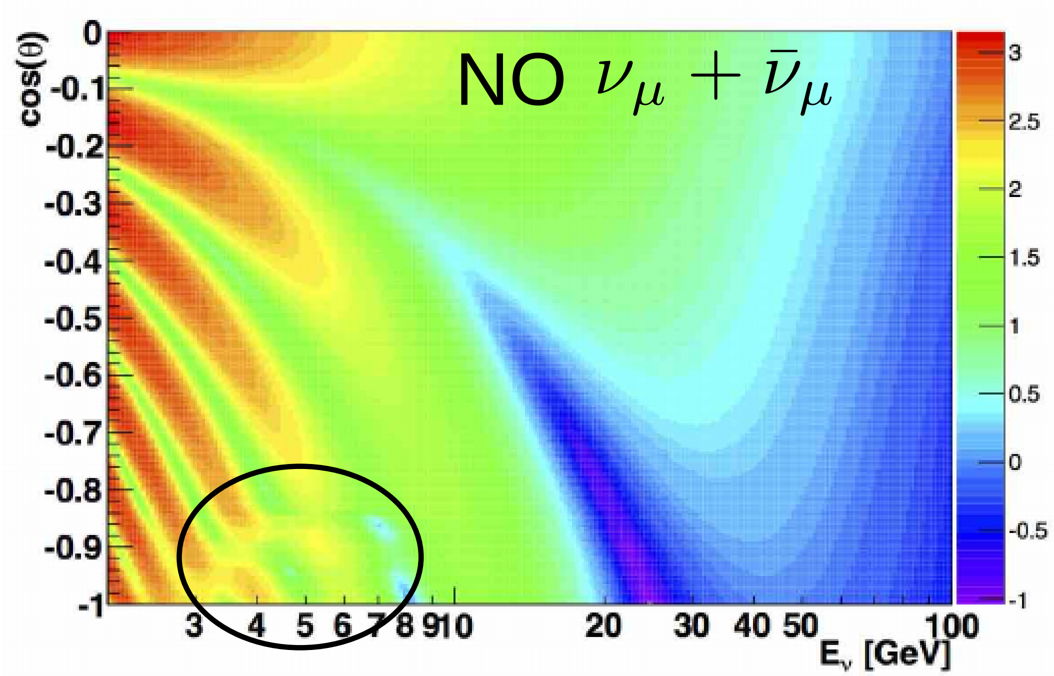


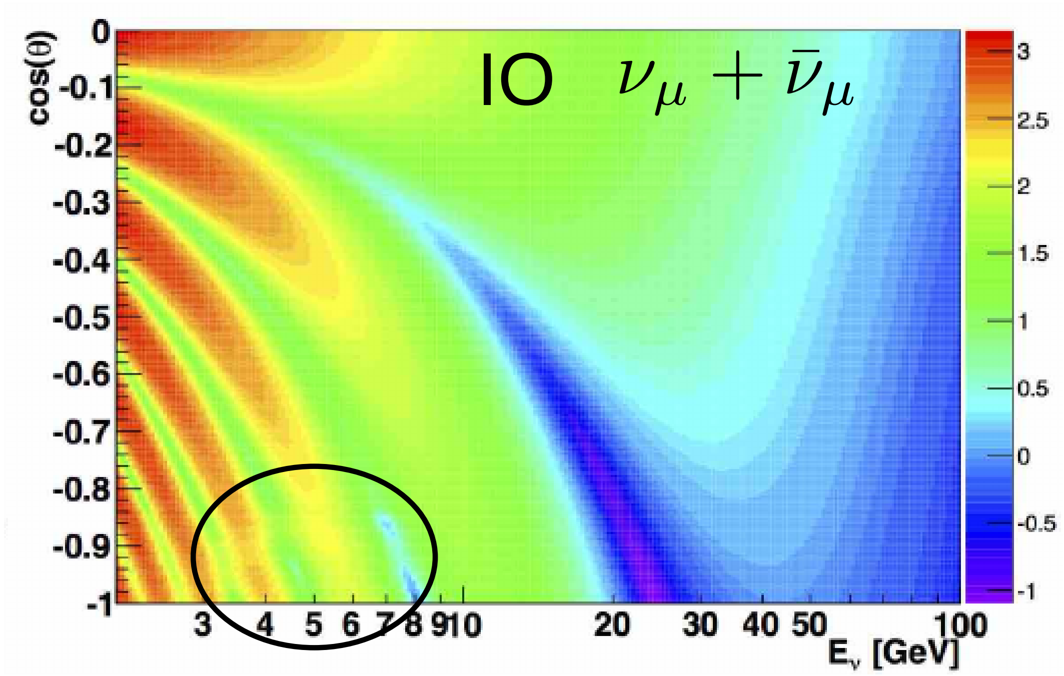
- **Resonnance** occurs at E = 7 GeV for
  - **neutrino** and **normal mass ordering**
  - **anti-neutrino** and **inverted mass ordering**

[J. Phys. , G43 , 084001 (2016)]

NMO Net Effect

- **Degeneracy between NMO and chirality** is broken by cross-section (and flux) difference between neutrinos and anti-neutrinos
- **Strong net effect** even without chirality measurement

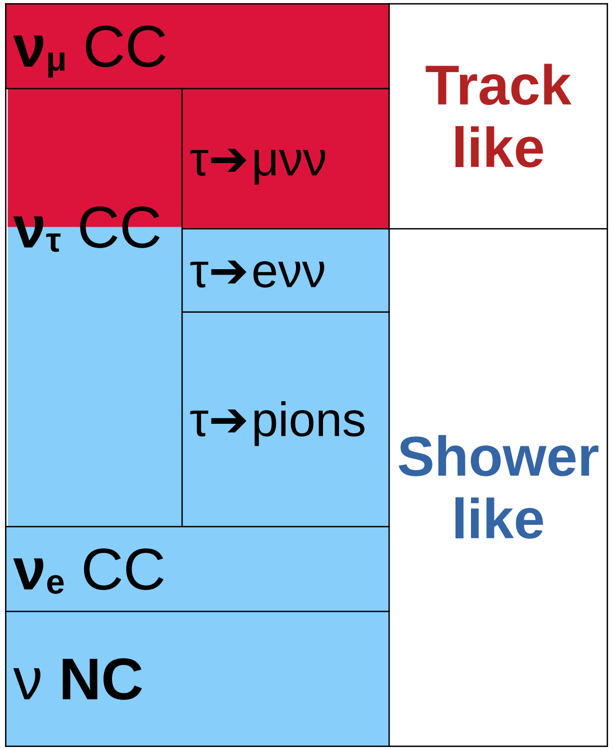


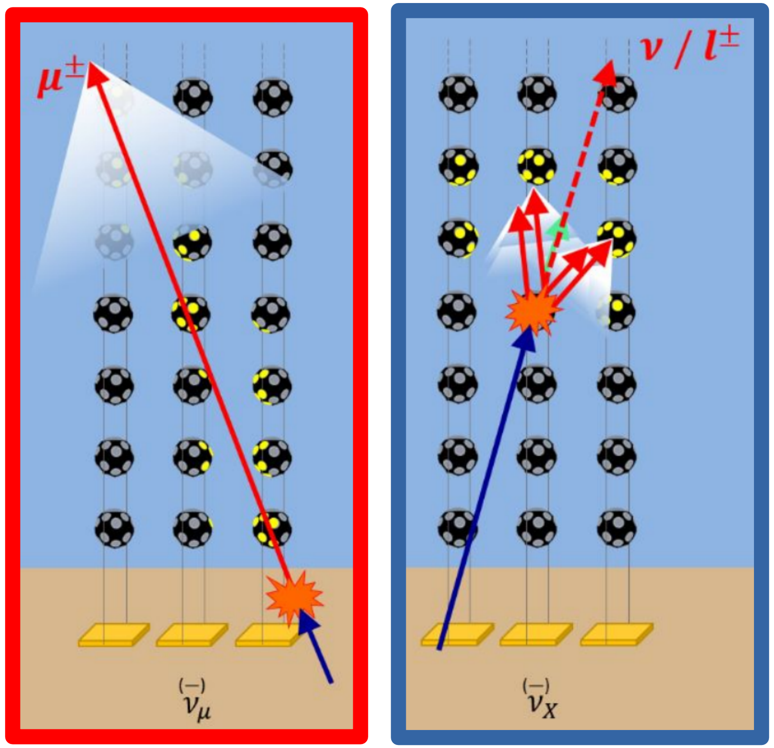


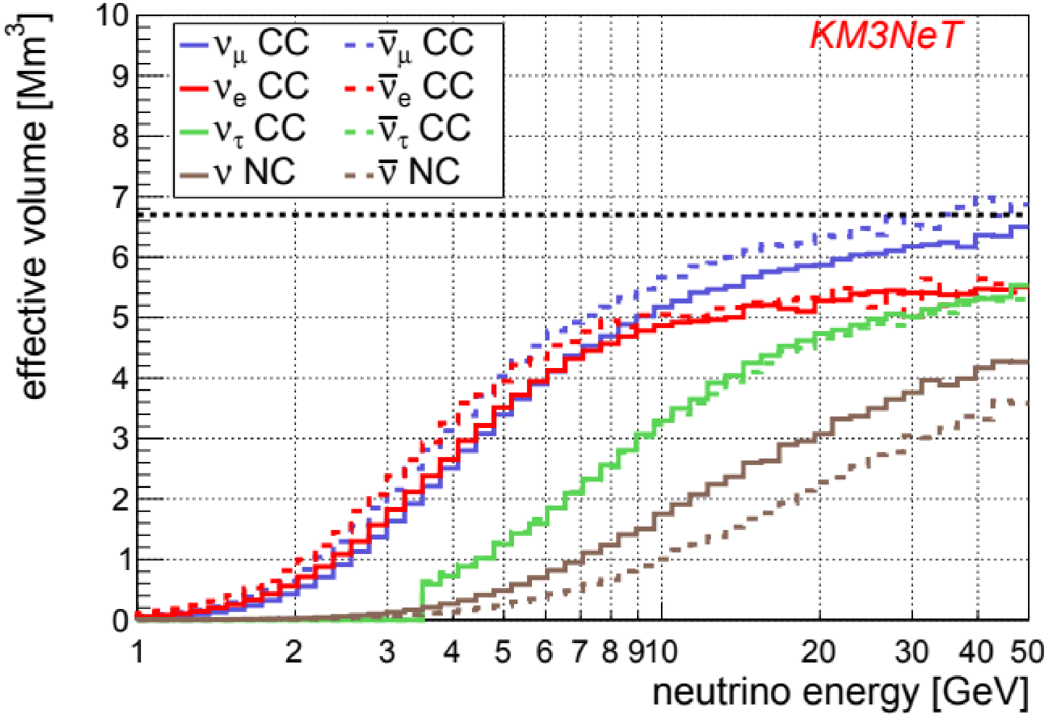
[Eur. Phys. J. C , 82 , 26 (2022)]

Mass ordering at KM3NeT/ORCA

- **ORCA** designed to collect **ν with energies of 1-100 GeV**
- Event topology (track/shower) allows to select **flavour enriched ν samples**



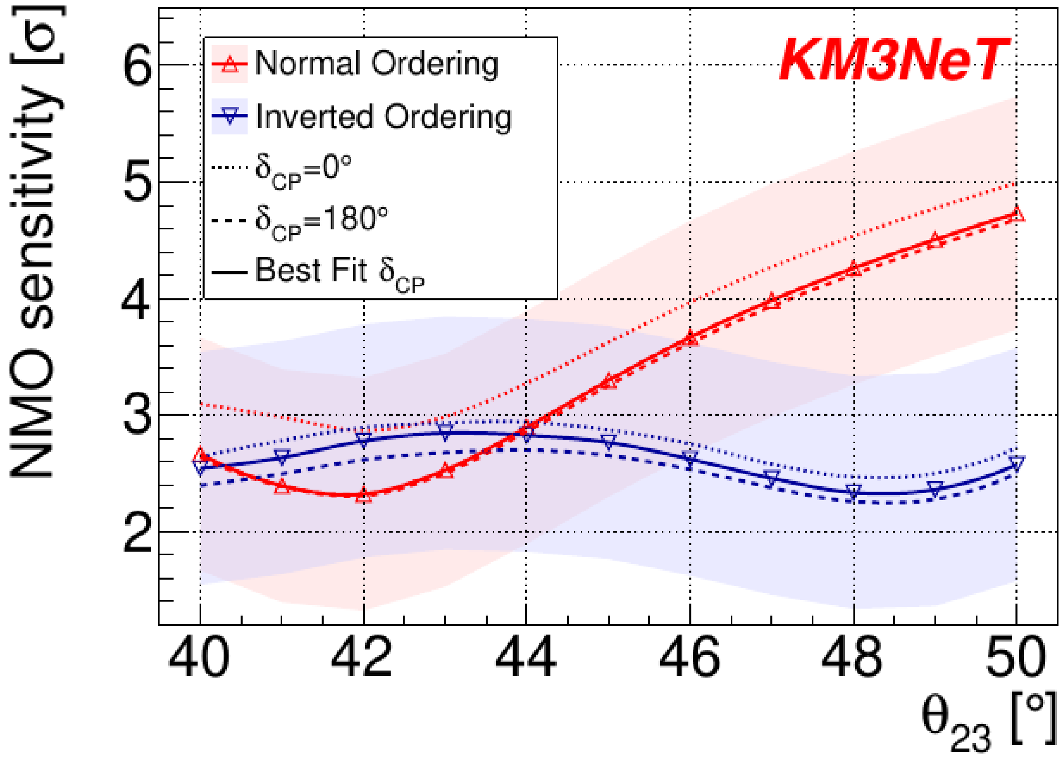


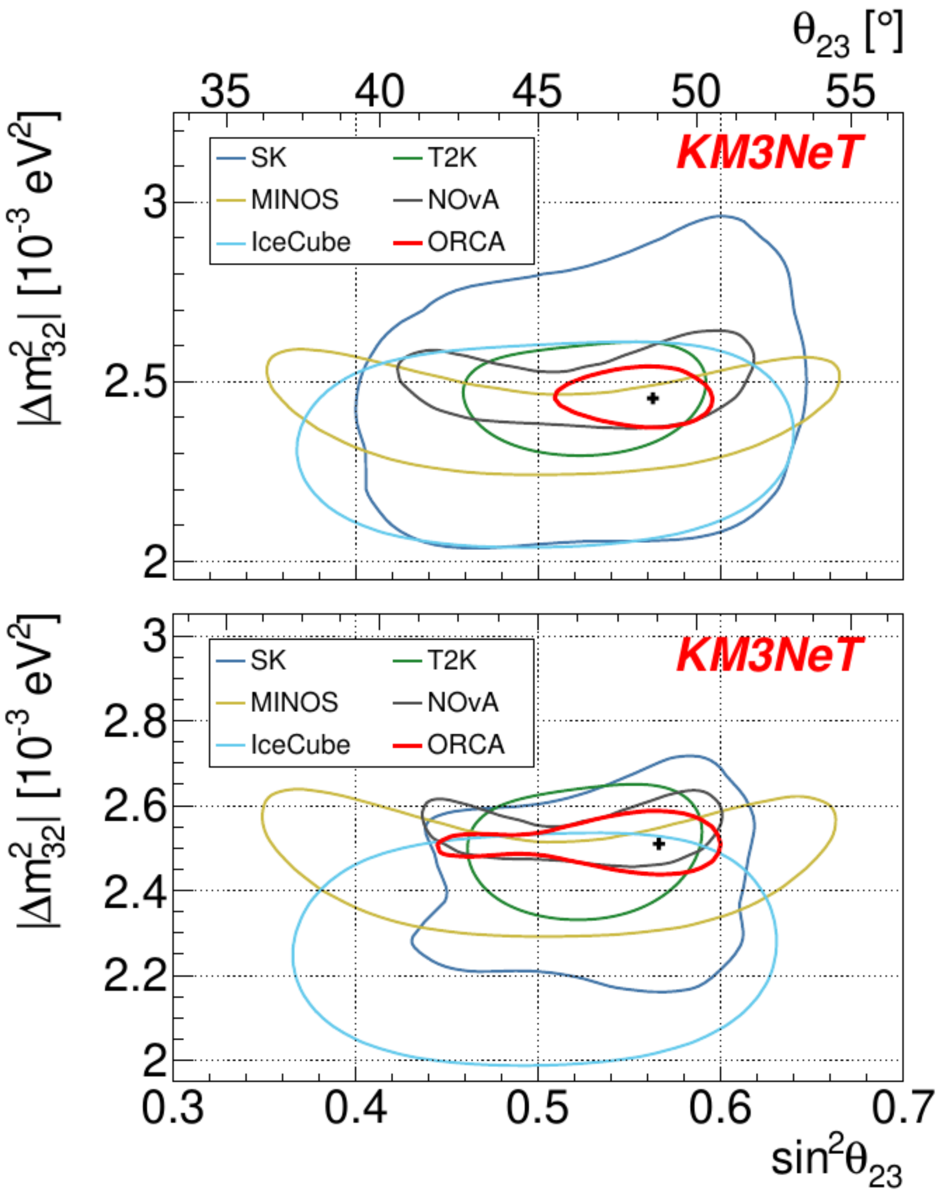


[Eur. Phys. J. C , 82 , 26 (2022)]

Sensitivity with full ORCA (3 years)

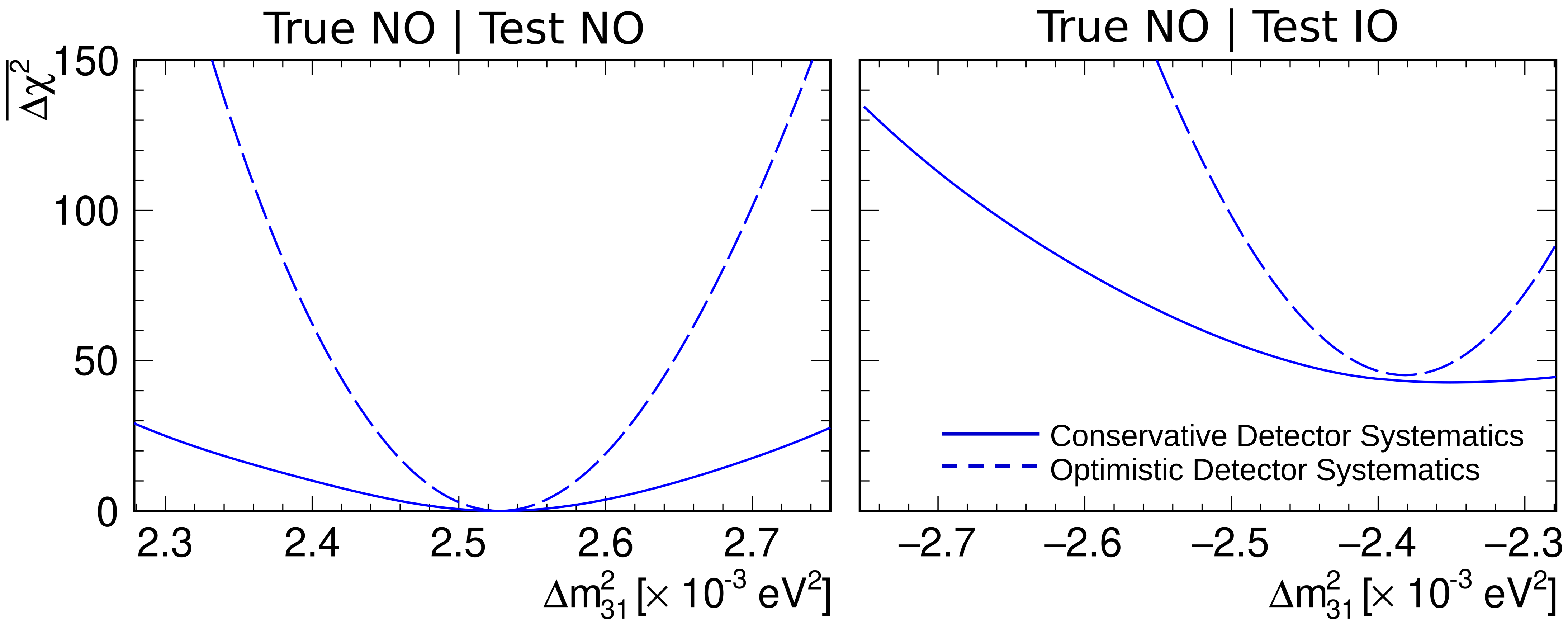
- Atmospheric oscillation parameters
- NMO sensitivity
  - strongly depends on θ_{23} for NO
  - band thickness corresponds to stat. fluct. (68% coverage)





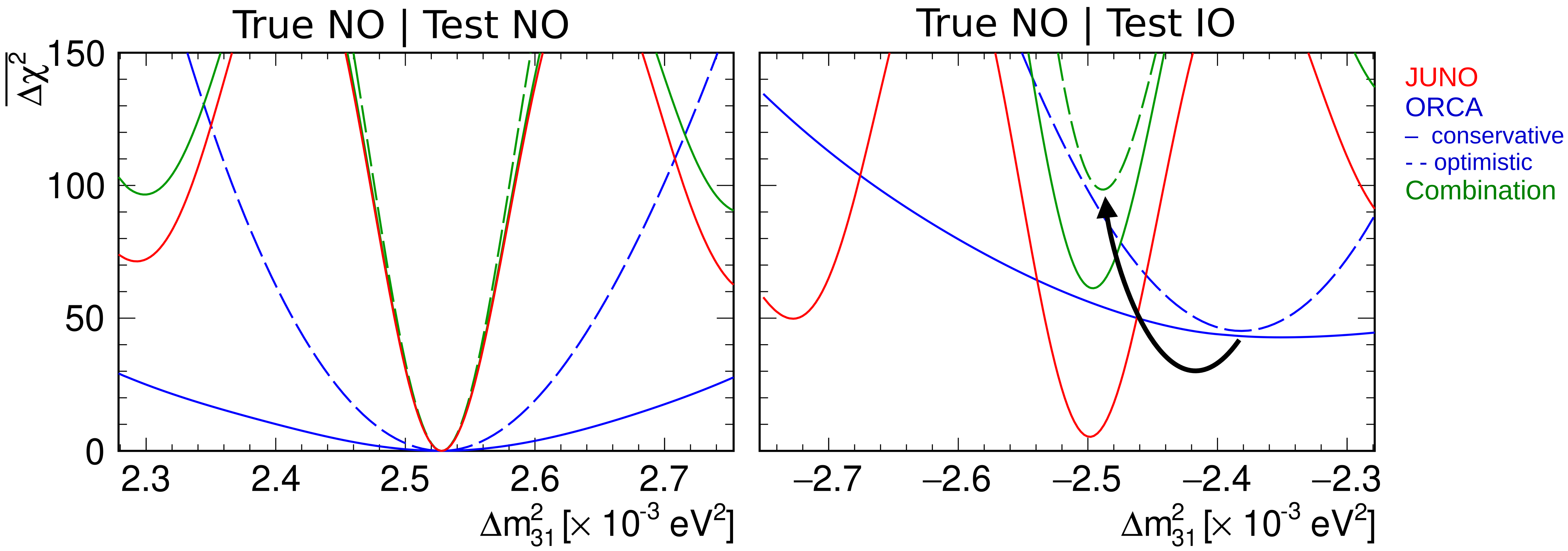
Mass ordering sensitivity with ORCA 115

- Degeneracy between NMO and Δm^2_{31}



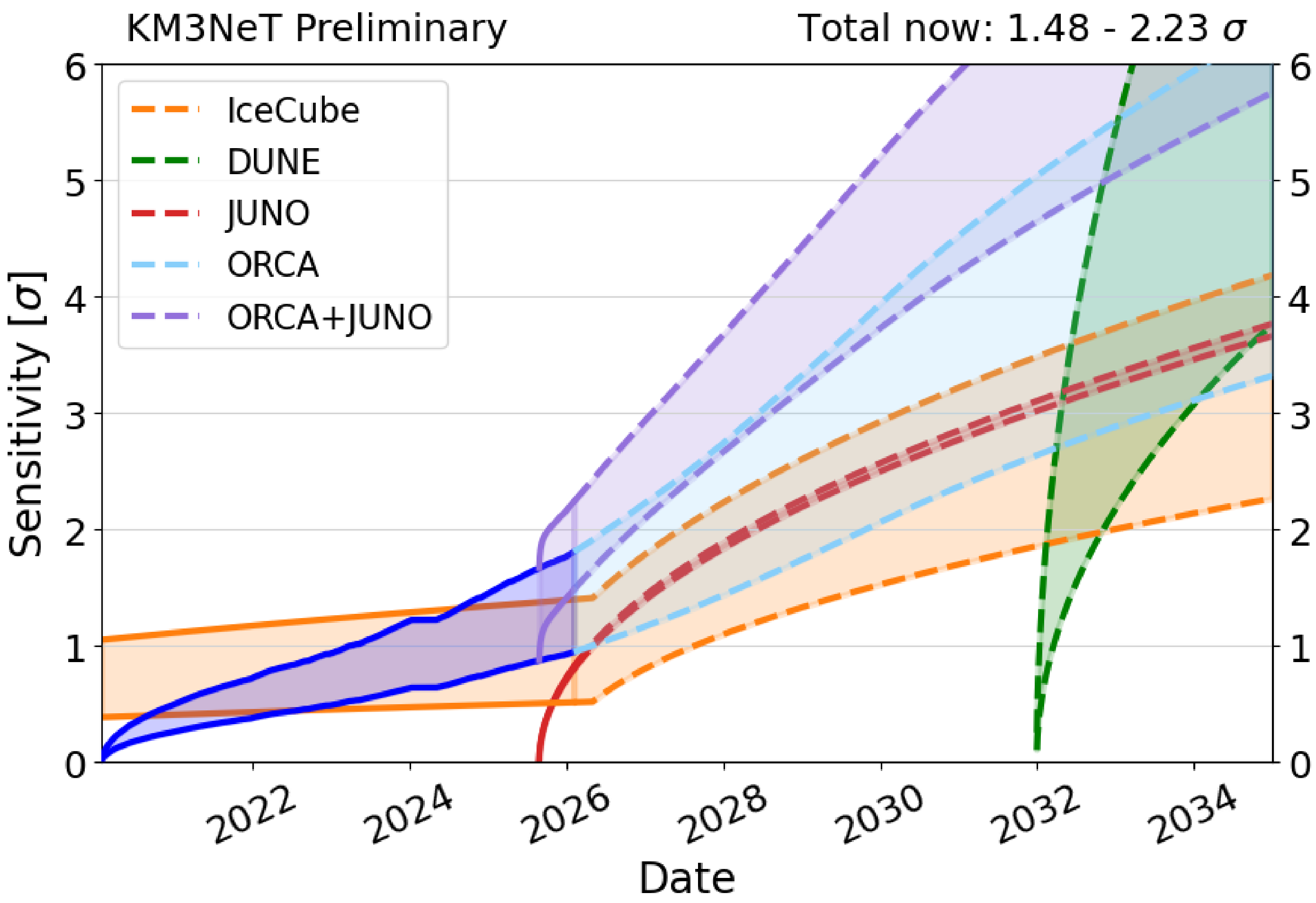
How to lift the degeneracy

- **JUNO** much **less affected** by NMO/Δm^2_{31} degeneracy
- JUNO's Δm^2_{31} measurement strongly **boosts ORCA sensitivity** (even without a full combination)



Projections for NMO Sensitivity

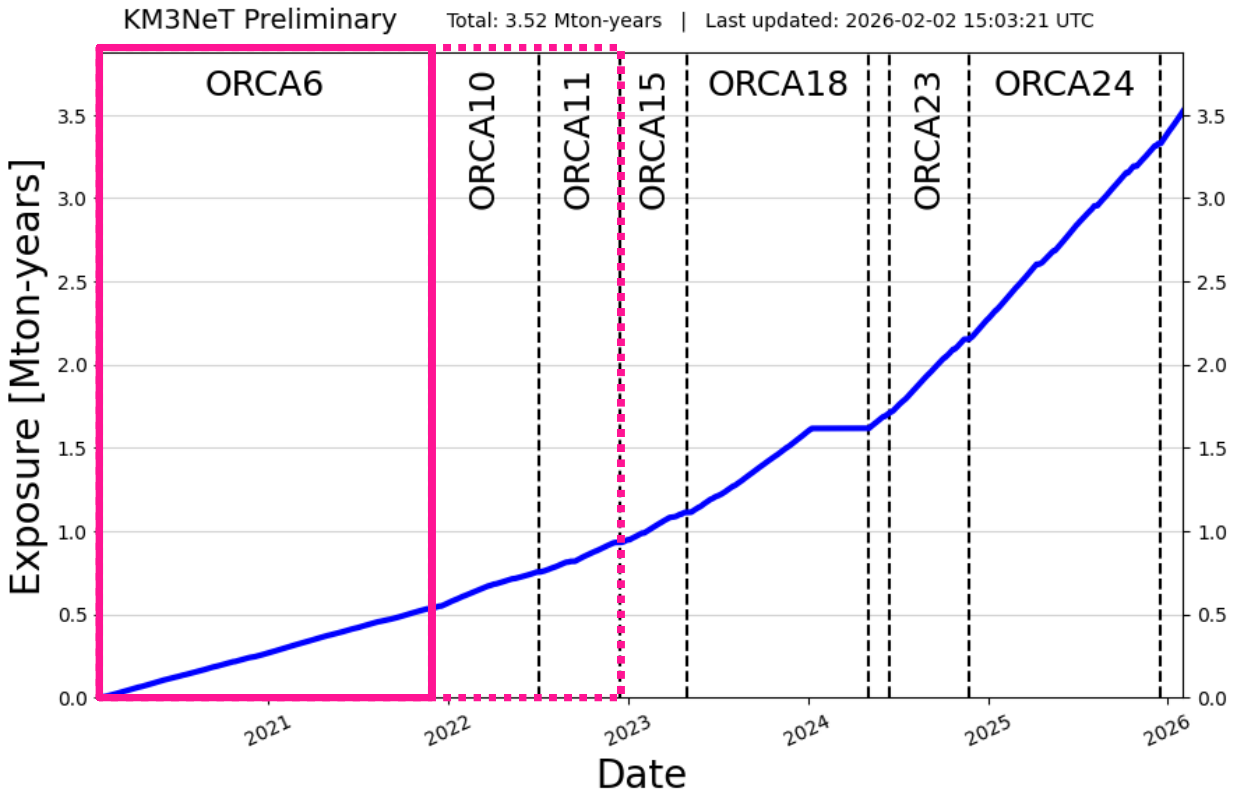
- **Projections** based on current construction schedule and conservative detector syst.
- **Band thickness** corresponds to favourable/disfavourable scenarii (NO/IO)
- **ORCA is the most sensitive experiment** (until DUNE starts)
- **JUNO/ORCA** synergy allows for **world's first determination (5σ) of the NMO**



Results on first data

- **Extensive set of analyses** performed on **ORCA6** (433kton.y) using methods similar to those used for full ORCA sensitivity

Standard Oscillations	JHEP10(2024)206
Sterile Neutrinos	JHEP02(2026)080
Lorentz Invariance Violation	In preparation
Quantum Decoherence	JCAP03(2025)039
Neutrino Decay	JHEP04(2025)105
Non Standard Interaction	JCAP02(2025)073
Tau appearance/NUNM	JHEP07(2025)213

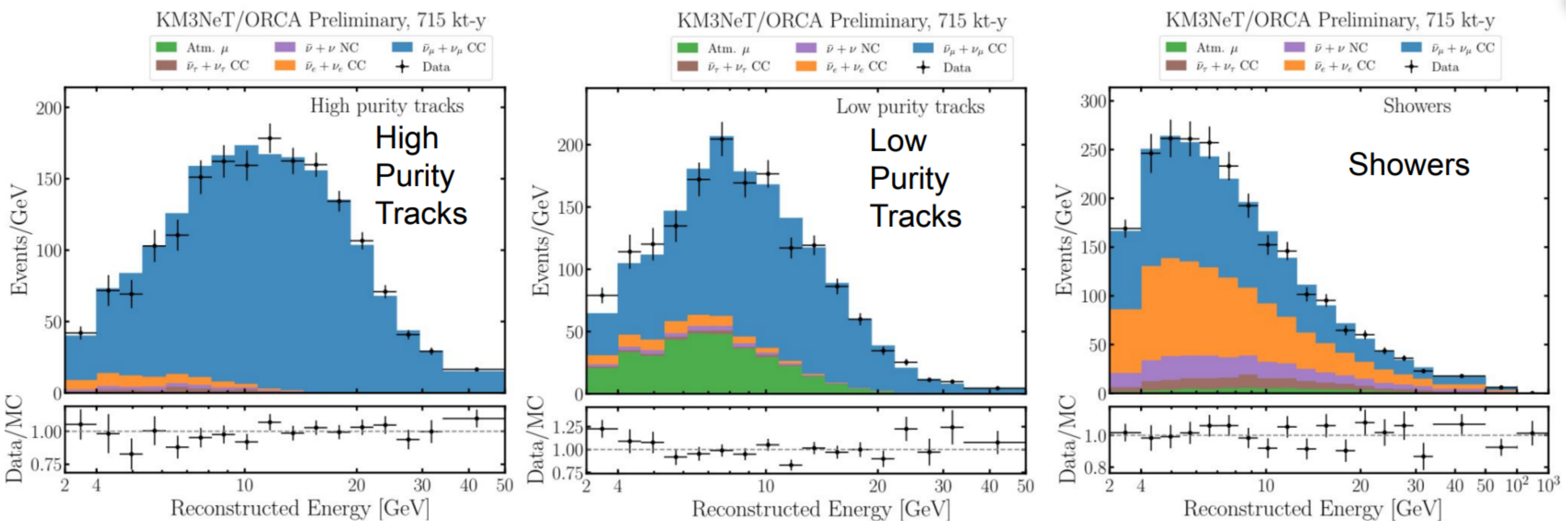


- ORCA6 **public data** set released: https://zenodo.org/records/15715220
- Update for standard oscillations shown in conference (2023) with **715 kton.y (ORCA6-11)**

https://doi.org/10.5281/zenodo.13234815

The data

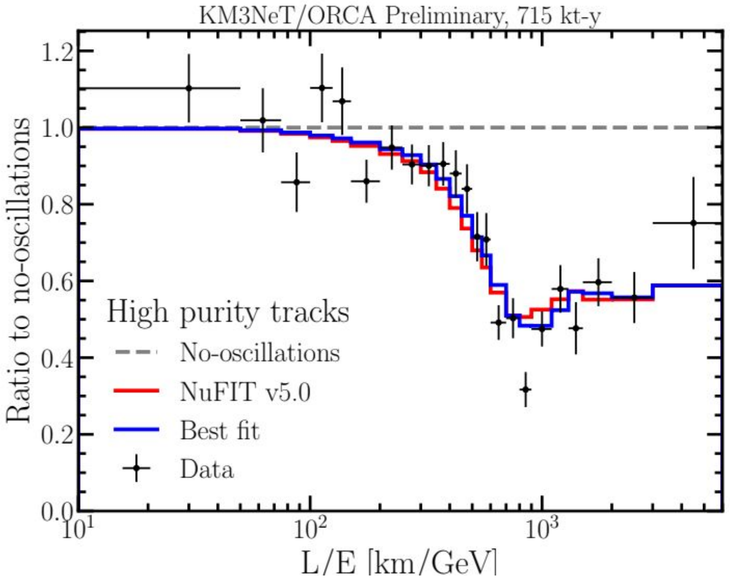
- After selection: **9751 neutrino candidates** (715 kton.y)
- Separated in **three classes**:
  - high purity-tracks (i.e. with minimal muon contamintion)
  - low purity tracks
  - showers
- **Good data/MC agreement**

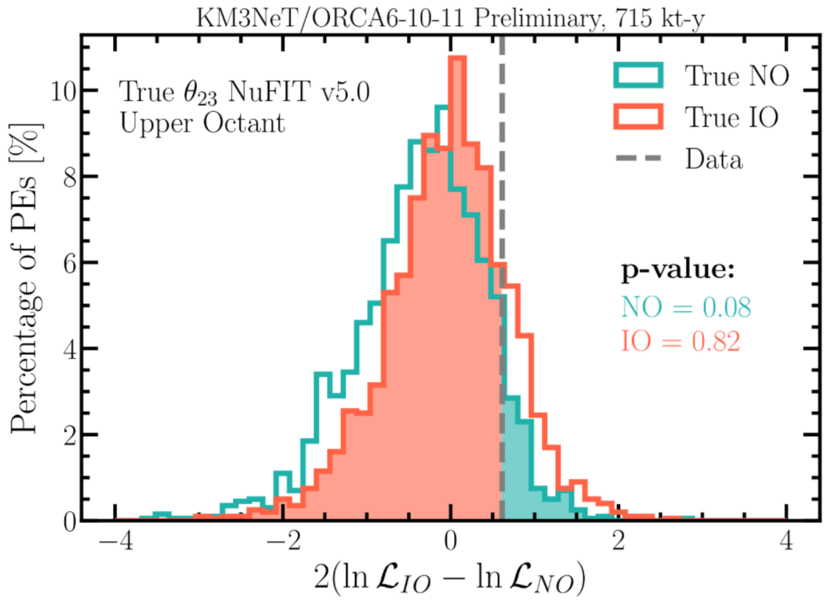


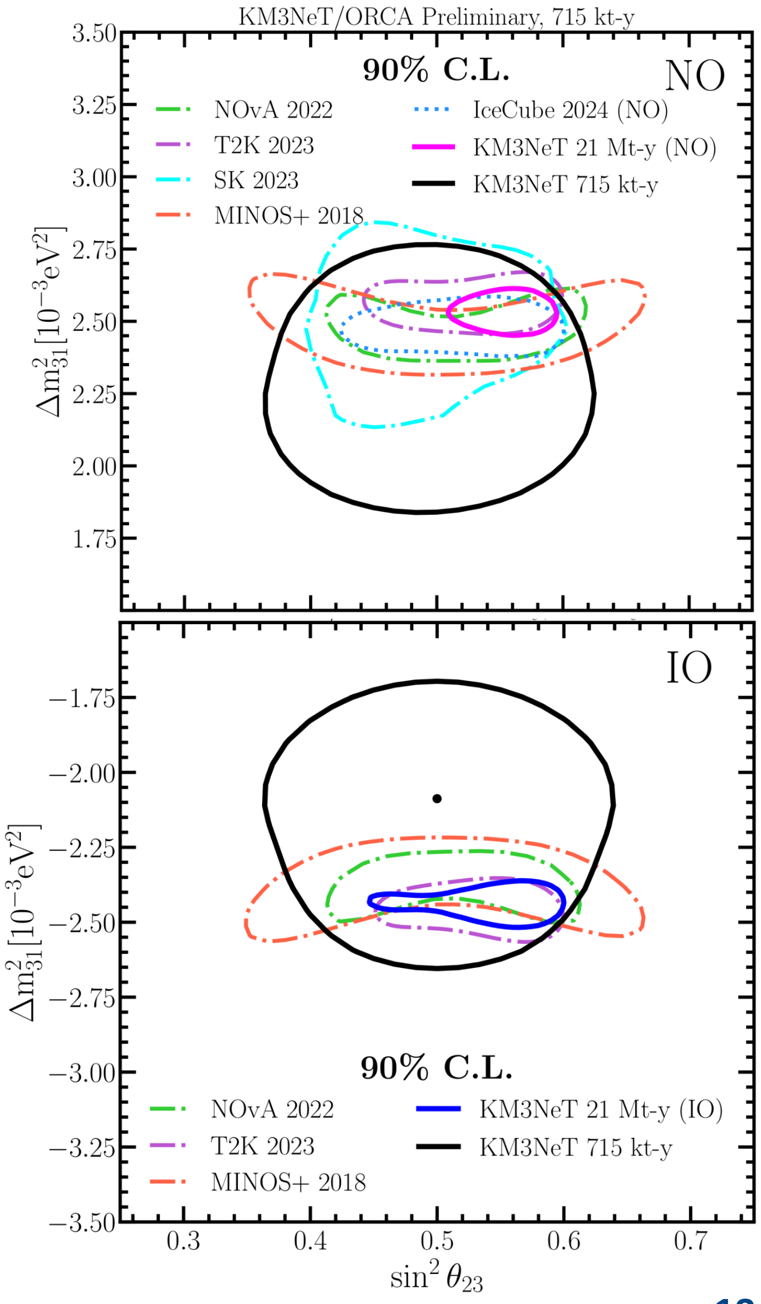
https://doi.org/10.5281/zenodo.13234815

Standard Oscillations

- **Oscillations pattern** clearly visible in L/E



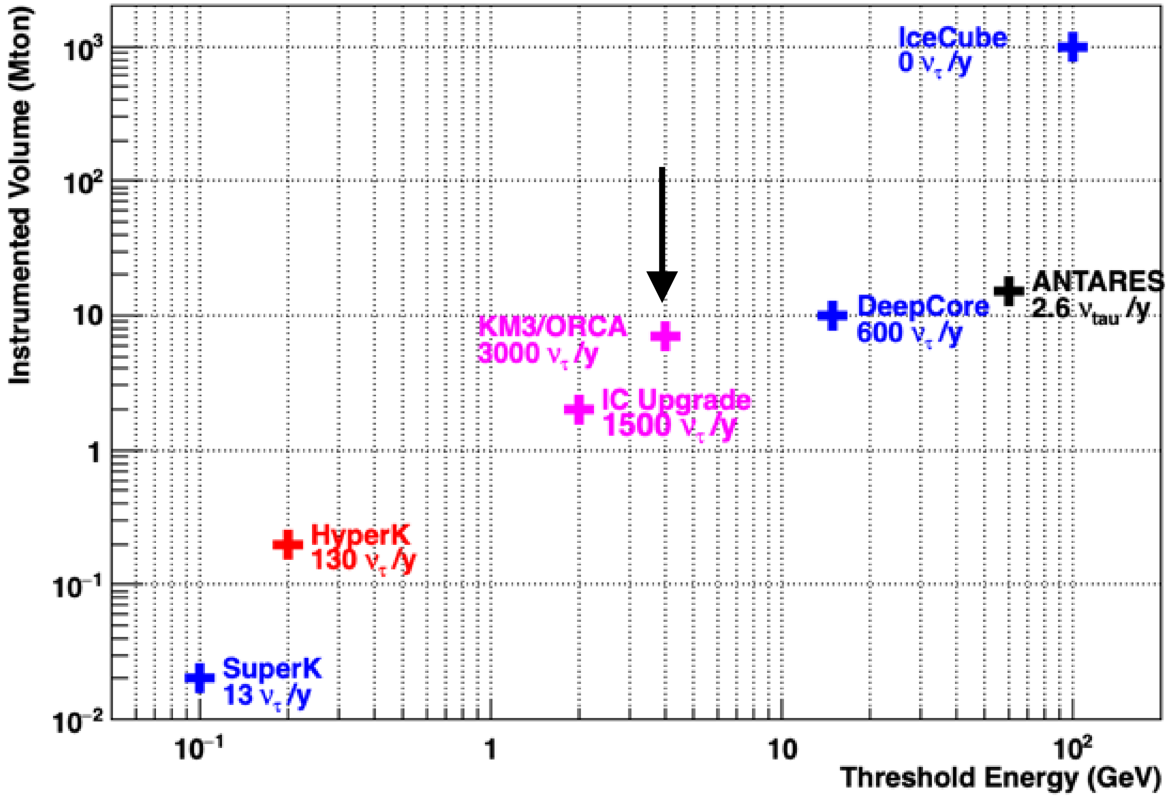


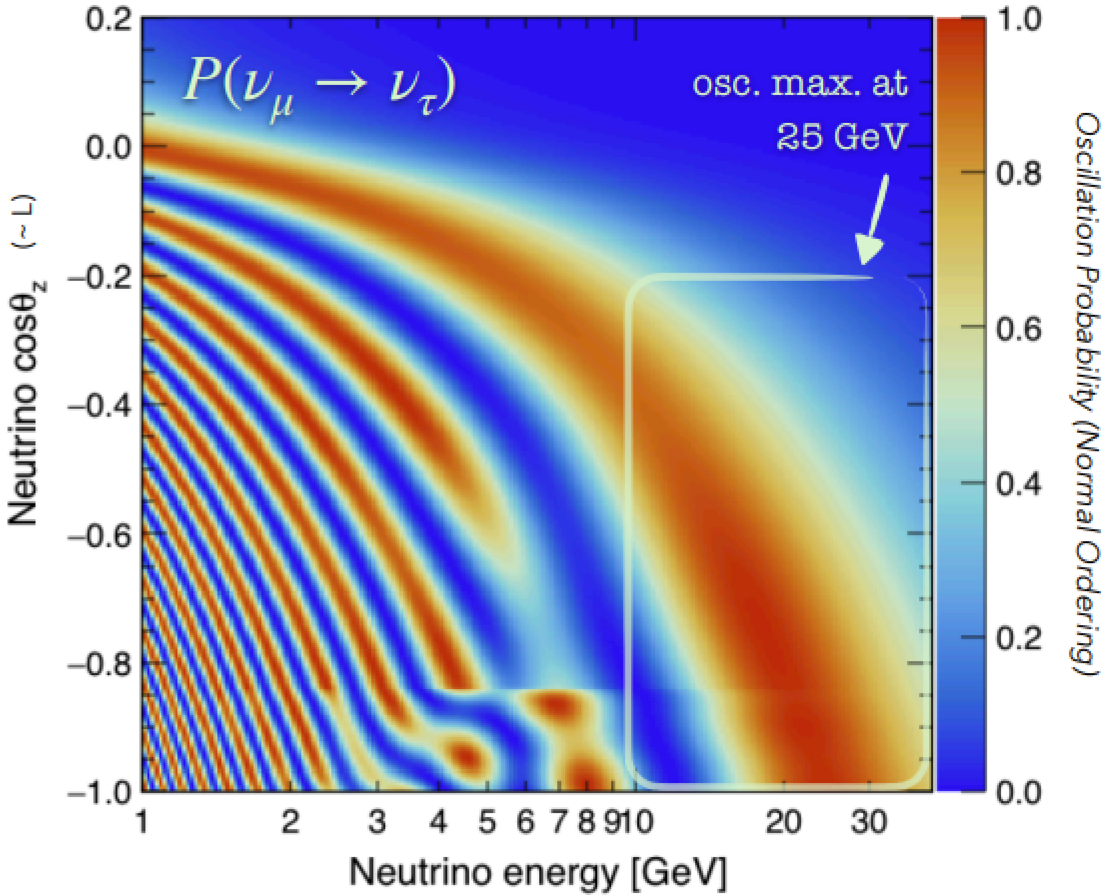


- **Contour** on $\sin^2\theta_{23} \times \Delta m^2_{31}$ getting competitive
  On going efforts to improve syst. affecting Δm^2_{31} precision
- Sensitivity to **NMO** remains limited

Tau Neutrinos

- ORCA accesses **one of the world's largest ν_τ sample**



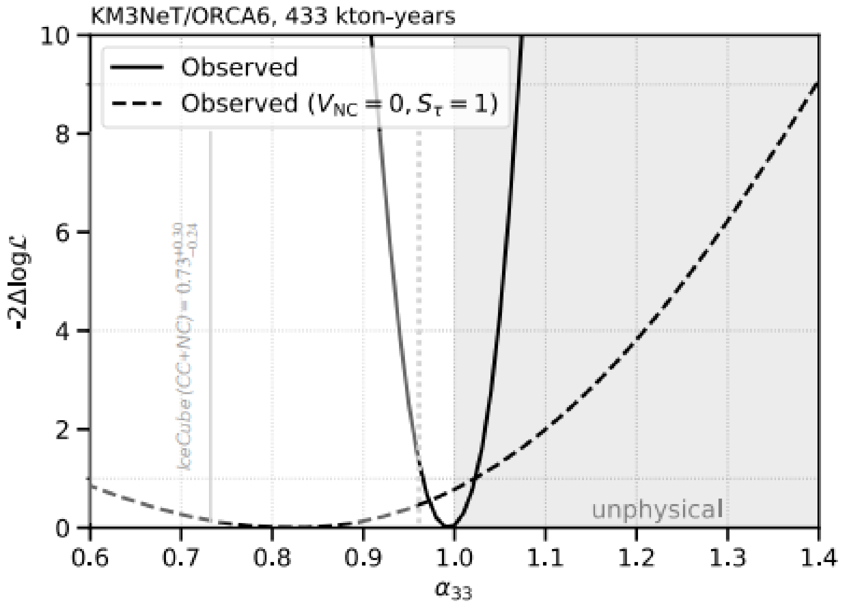


Based on:
[1] arXiv:1711.09436. [2] arXiv:1901.05366. [3] arXiv:2502.01443. [4] arXiv:1805.04163. [5] arXiv:2307.15295. [6] arXiv:2103.09885.

JHEP07(2025)213

Tau Neutrinos

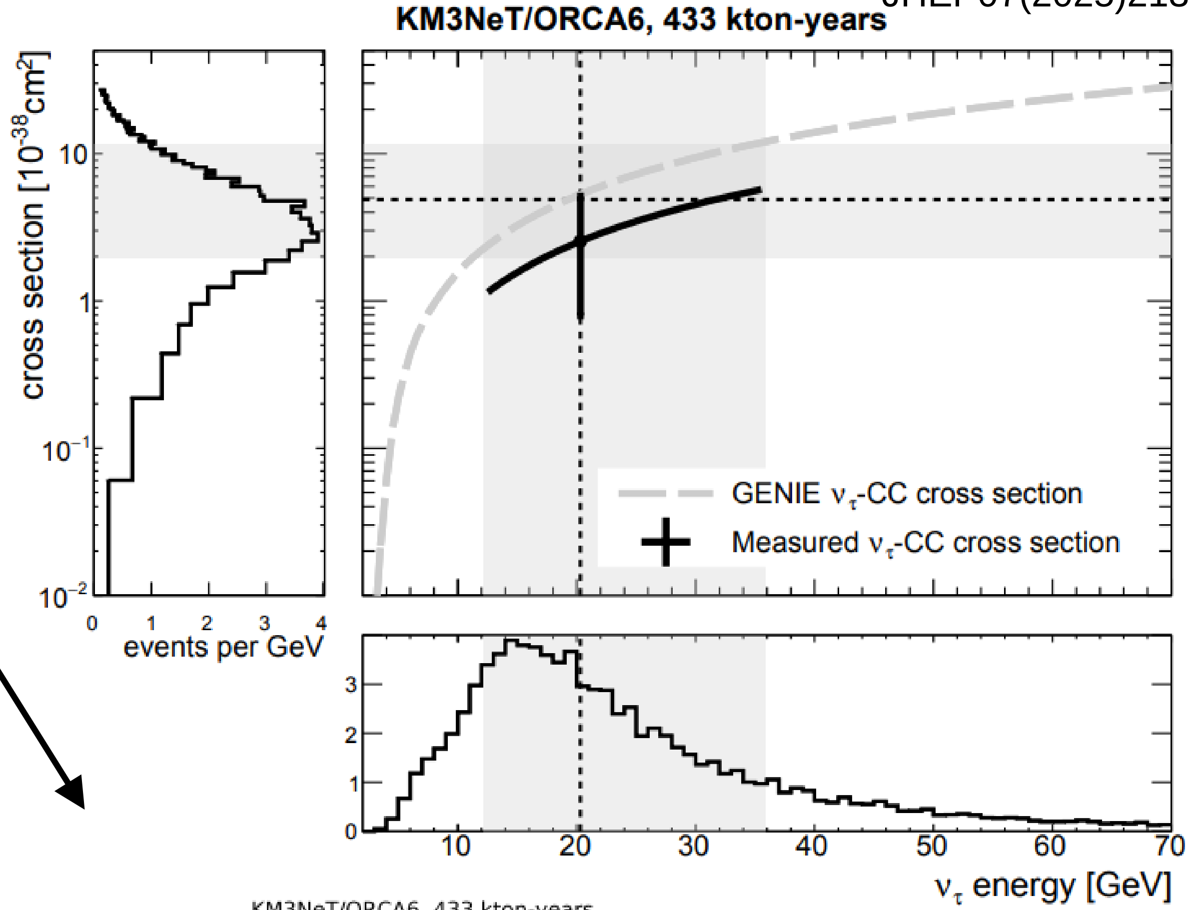
- **ORCA6 ν_τ sample** exploited to
  - measure ν_τ **cross section**
  - constrain ν_τ **normalisation**
  - constrain **non-unitarity mixing**

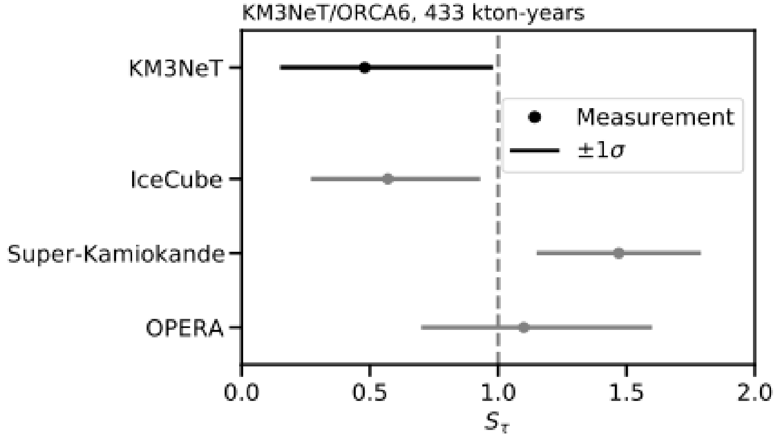


$$N = \alpha\, U_{\mathrm{PMNS}}$$

$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

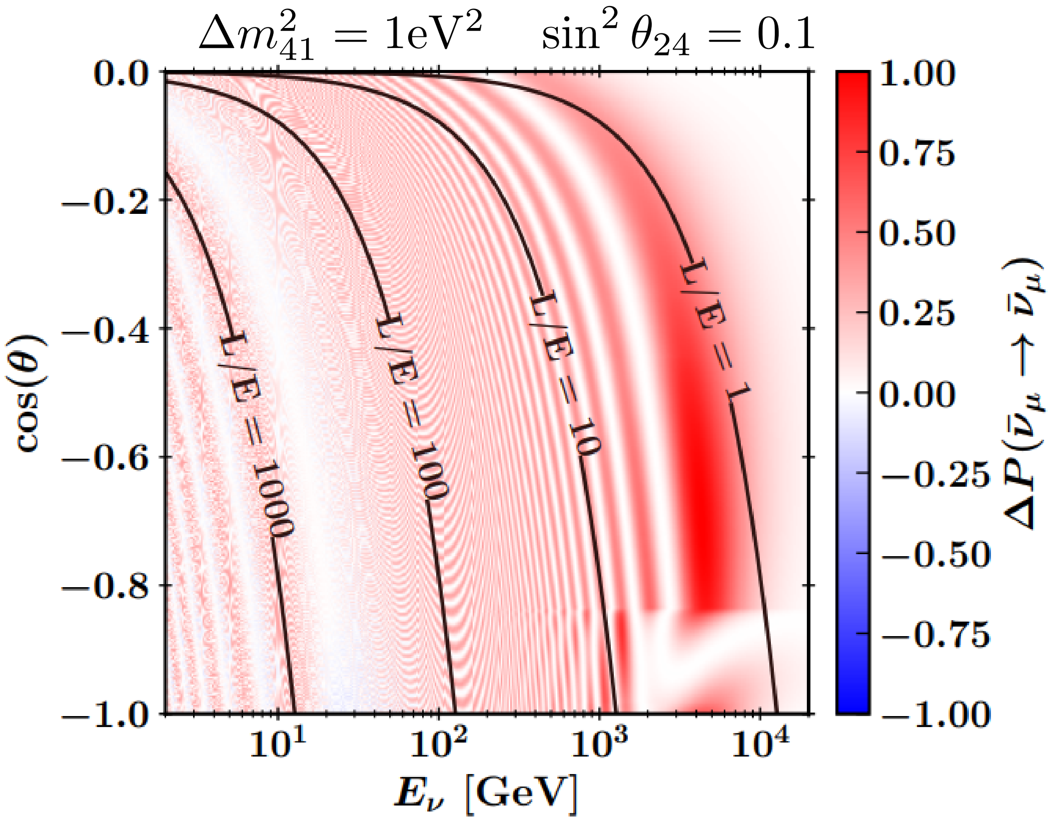
Best limit on α_{33}: [0.95, 1.04] at 95% CL

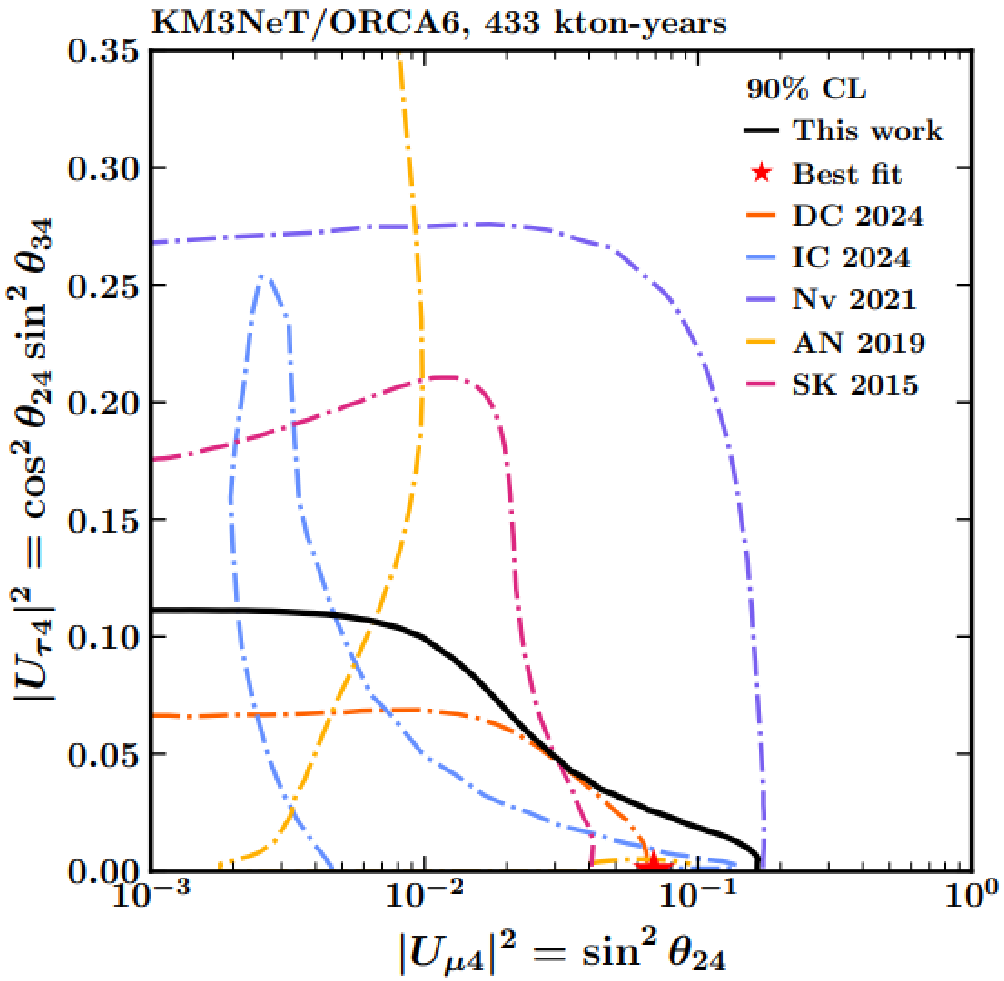




Search for sterile neutrinos

- ORCA6 search for **sterile neutrino above 1eV²** already gives **competitive results**
- **Complementarity ORCA/ARCA** to cover wider energy regime





https://doi.org/10.22323/1.501.1058

Lorentz Invariance Violation

- **Lorentz invariance*** can be violated in models trying to unify QFT&GR

- Model independent search using **EFT** (SME)

PMNS

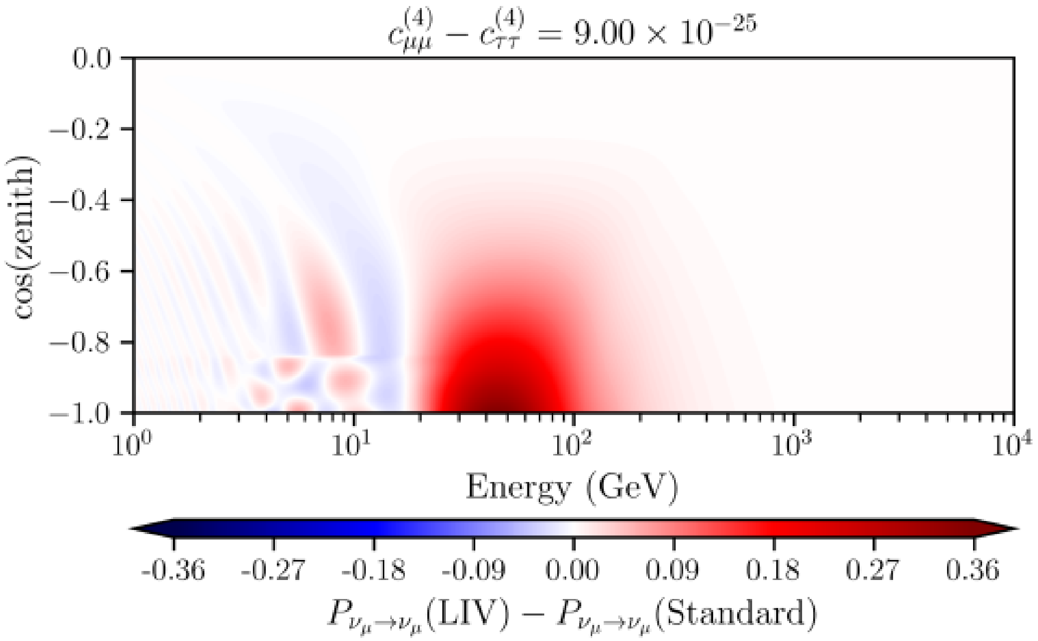
Std Osc. Hamiltonian

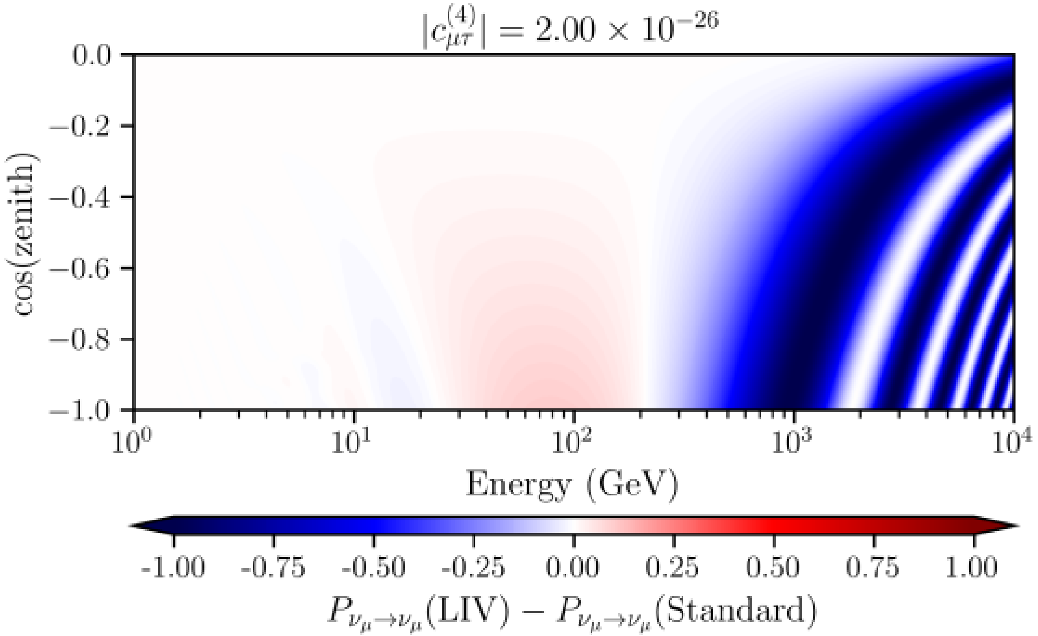
$$H = U H_0 U^\dagger + H_I + \boxed{H_{LIV}}$$

Matter Effect Hamiltonian

$$\boxed{H_{LIV}} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2 \mathring{a}^{(5)} - E^3 \mathring{c}^{(6)} + \ldots$$

- **Complementarity ORCA/ARCA** to test the H_{LIV} terms in different energy regimes



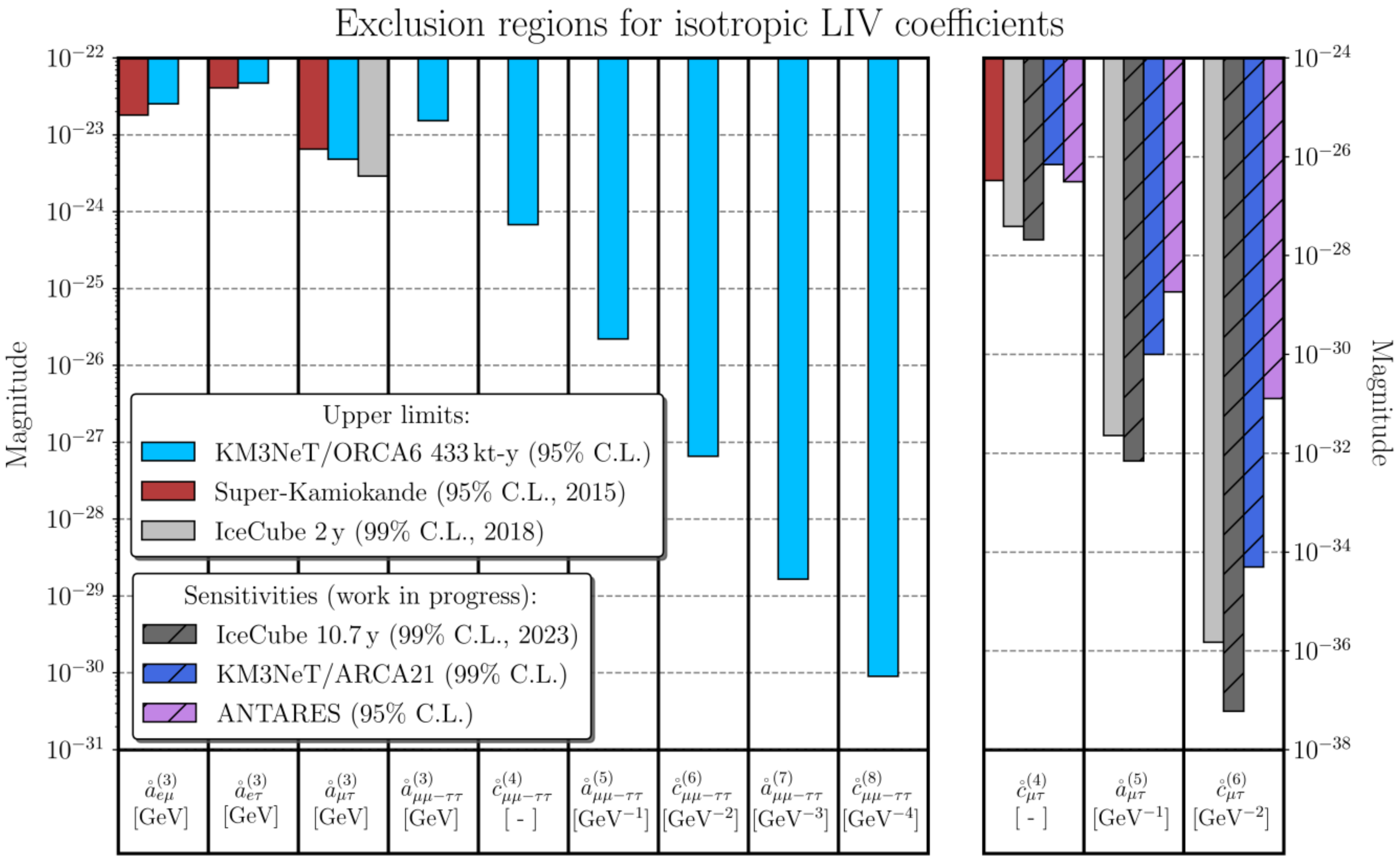


*Lorentz Invariance: physics is identical for all interial obervers

https://doi.org/10.22323/1.501.1058

Lorentz Invariance Violation

- **ORCA6 and ARCA21** data set already put **very competitive constraints**



Non Standard Neutrino Interactions

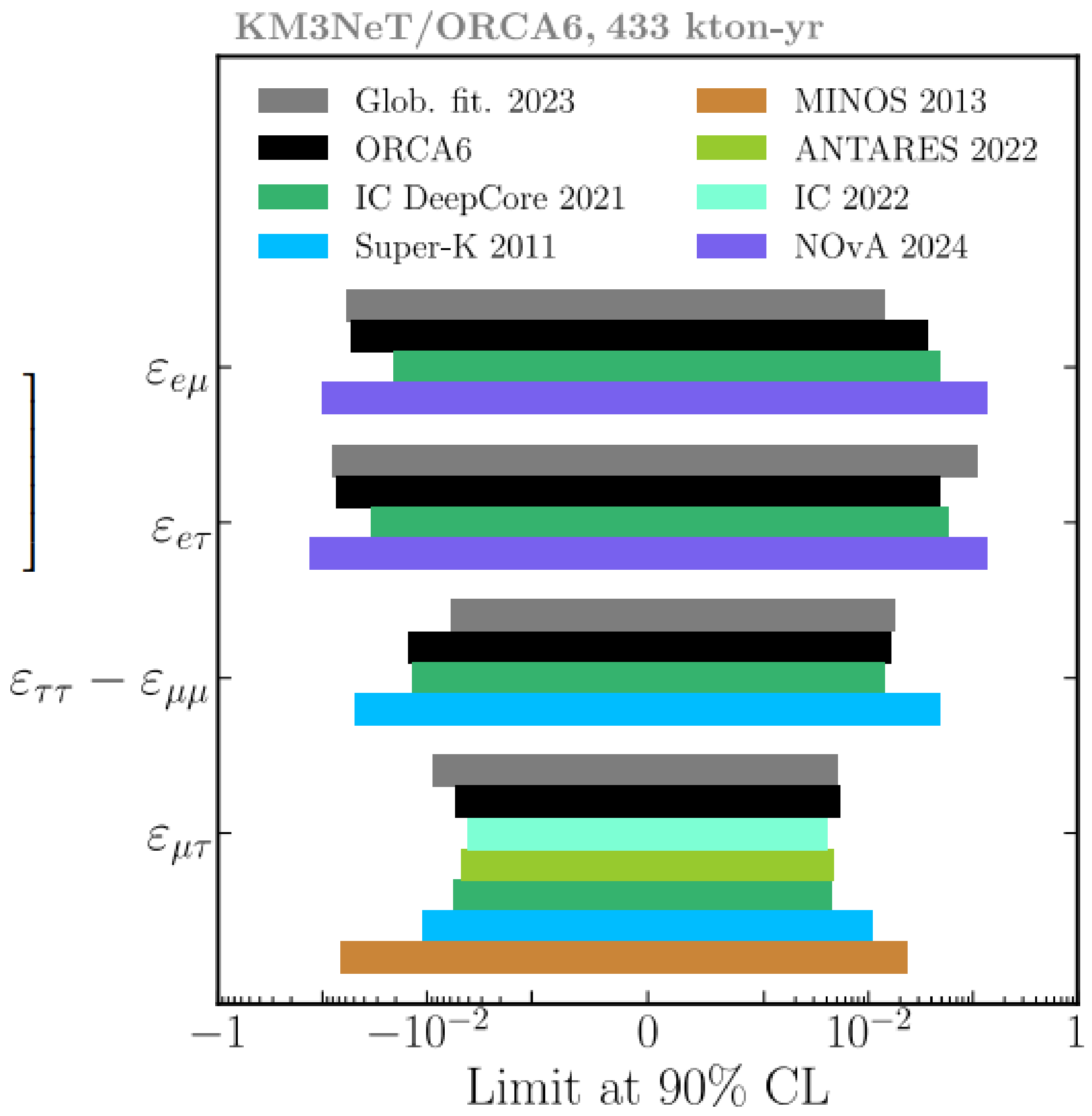
- **NSI** typically arise in models providing mechanisms to explain the **origin of ν masses**

- Model independent search with **EFT**:

$$\mathcal{H}_{\text{eff}} = \frac{1}{2E}\mathcal{U}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{bmatrix}\mathcal{U}^{+} + A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^{*} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^{*} & \varepsilon_{\mu\tau}^{*} & \varepsilon_{\tau\tau} \end{bmatrix}$$

- **NC-NSI** affect ν oscillations in matter by modifying coherent forward scattering

- ORCA6 data provide **competitive results**



Quantum Decoherence

- Oscillations affected by **decoherence**, described by a damping term

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} \tilde{U}_{\alpha i}\tilde{U}^*_{\beta i}\tilde{U}^*_{\alpha j}\tilde{U}_{\beta j} \boxed{e^{-i\Delta\tilde{E}_{ij}t-\gamma_{ij}t}}$$

$$\gamma_{ij} = \gamma^0_{ij}\left(\frac{E}{\text{GeV}}\right)^n$$

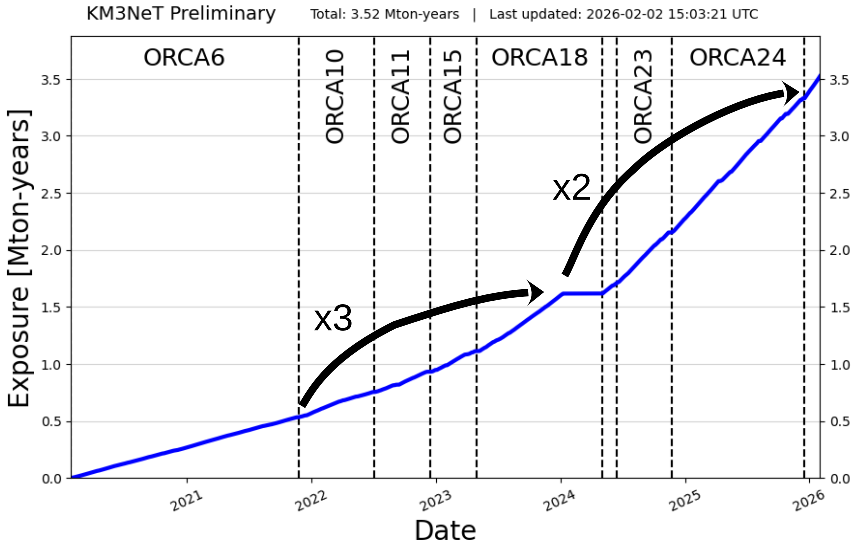
- **ORCA** well suited to study **n = -2, -1**

  ARCA well suited to study **n = 0, 1, 2, 3**

- **ORCA6** data allows to set limits comparable to **DeepCore** but other exp. at **lower energy** (RENO, KamLAND, T2K) put stronger bounds for n<0.

	Upper Limits on γ31 [GeV] n=-2	n=-1
ORCA6 NO, **90%CL**	$8.4\cdot10^{-21}$	$2.7\cdot10^{-22}$
arXiv:2306.14699 γ31=γ32 NO/IO, 90%CL	$6.9\cdot10^{-25}$ **RENO**	$2.1\cdot10^{-23}$ **T2K**
ORCA6 NO, **95%CL**	$11.7\cdot10^{-21}$	$4.2\cdot10^{-22}$
DeepCore γ31=γ32 NO, 95%CL	$4.3\cdot10^{-20}$	$2.0\cdot10^{-21}$

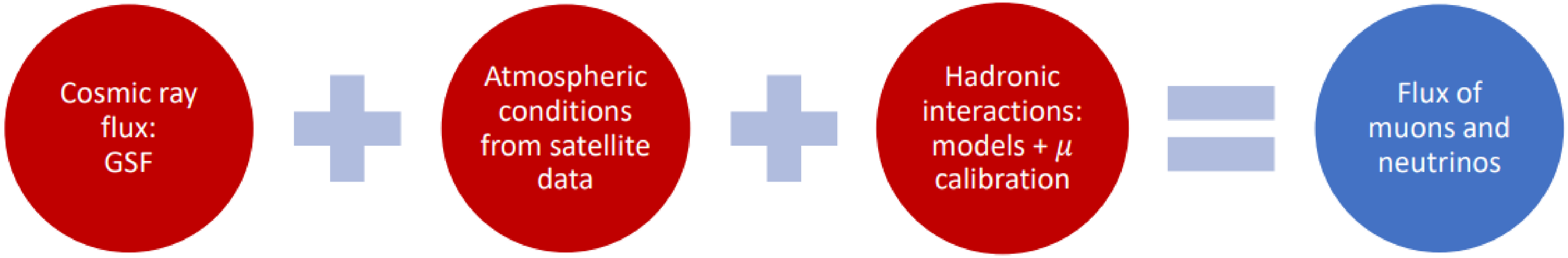
Analysis Plans



Next round of analyses on-going with **ORCA18 by summer** and **ORCA24 by end of the year**

Major **improvement** of the treatment of **systematics**

- **Neutrino flux**
  - replace Honda flux by **Daemonflux** (data driven model, physics driven uncertainties, coherent ν and μ fluxes description)



Dembinski, Fedynitch, Gaisser, ICRC 2017 & H. Dembinski 2019

A. Fedynitch, M. Huber PRD 106 (2022)

JPY, A. Fedynitch, PRD 107, 123037 (2023)

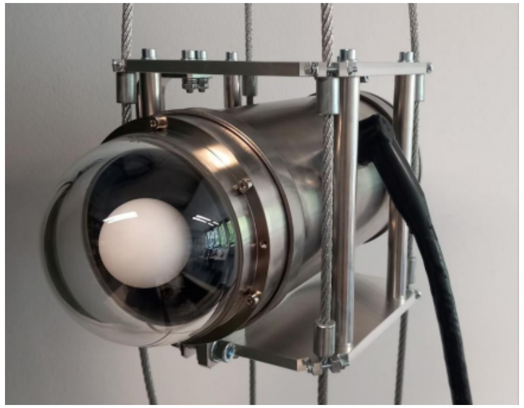
  - migration **coordinated with IceCube** to homogenise analysis tools in view of combined analyses

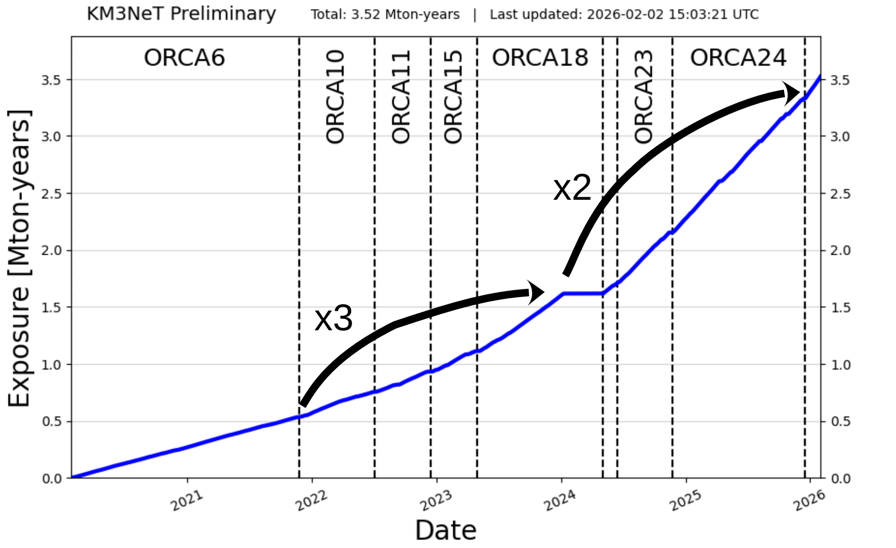
Analysis Plans

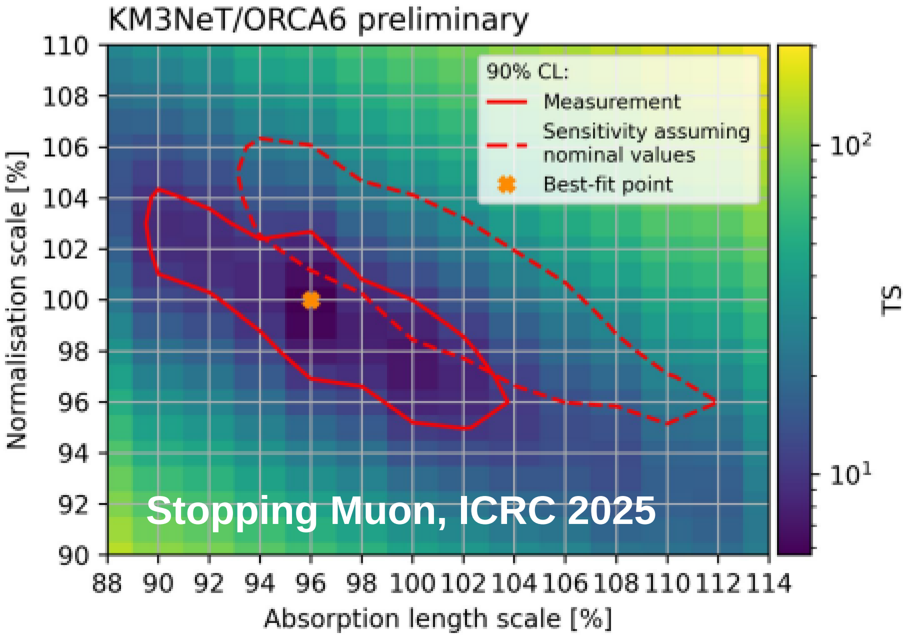
Next round of analyses on-going with **ORCA18**

Major improvement of the treatment of **systematics**

- **Neutrino flux**
- **Detector response**
  - replace naive **energy-scale** by **physics driven effects**
  - **simulate** detector reponse for different **DOM efficiencies & water absorption length**
  - **measure** abs. length and DOM efficiency with stopping μ (time dependent meas.) and/or other sources (^{40}K, POCAM, T-REX)





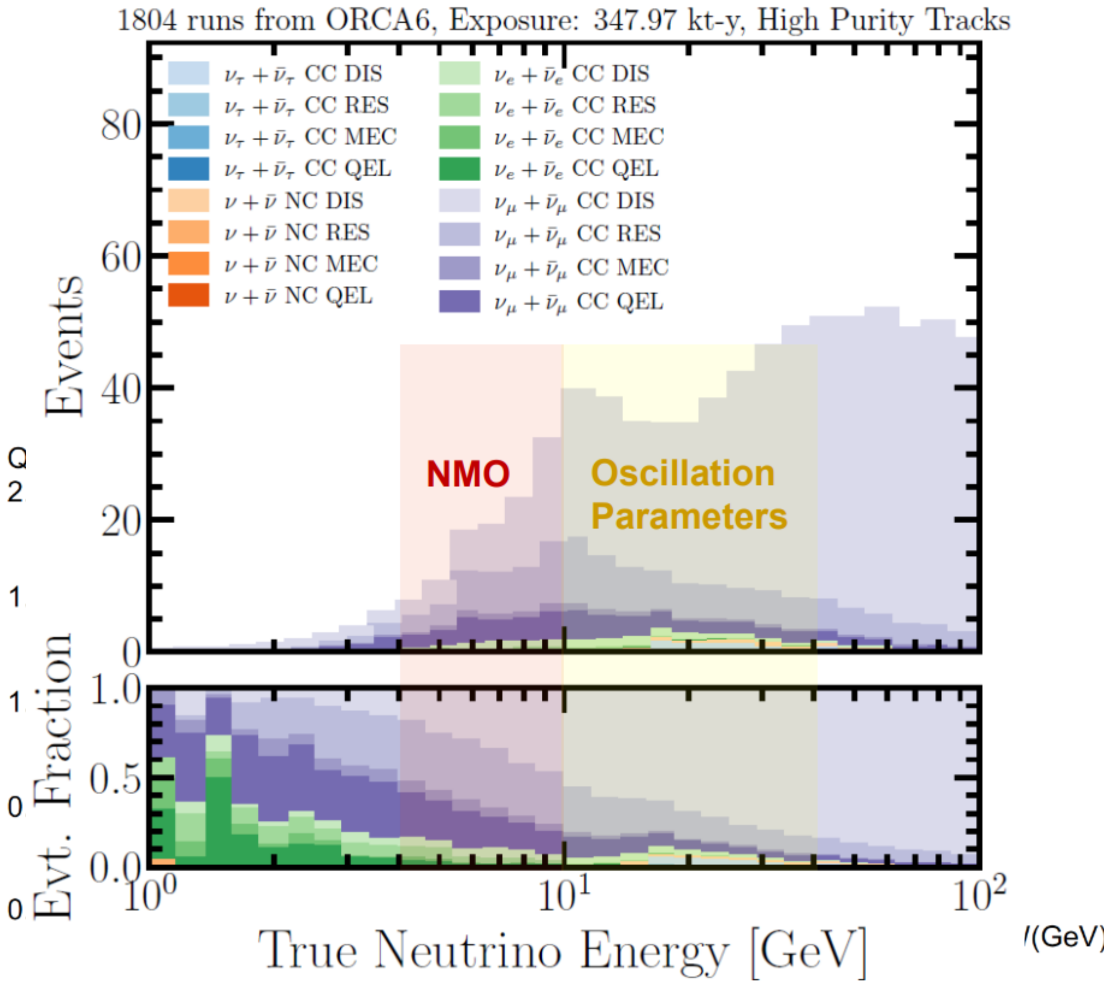


Analysis Plans

Next round of analyses on-going with **ORCA18**

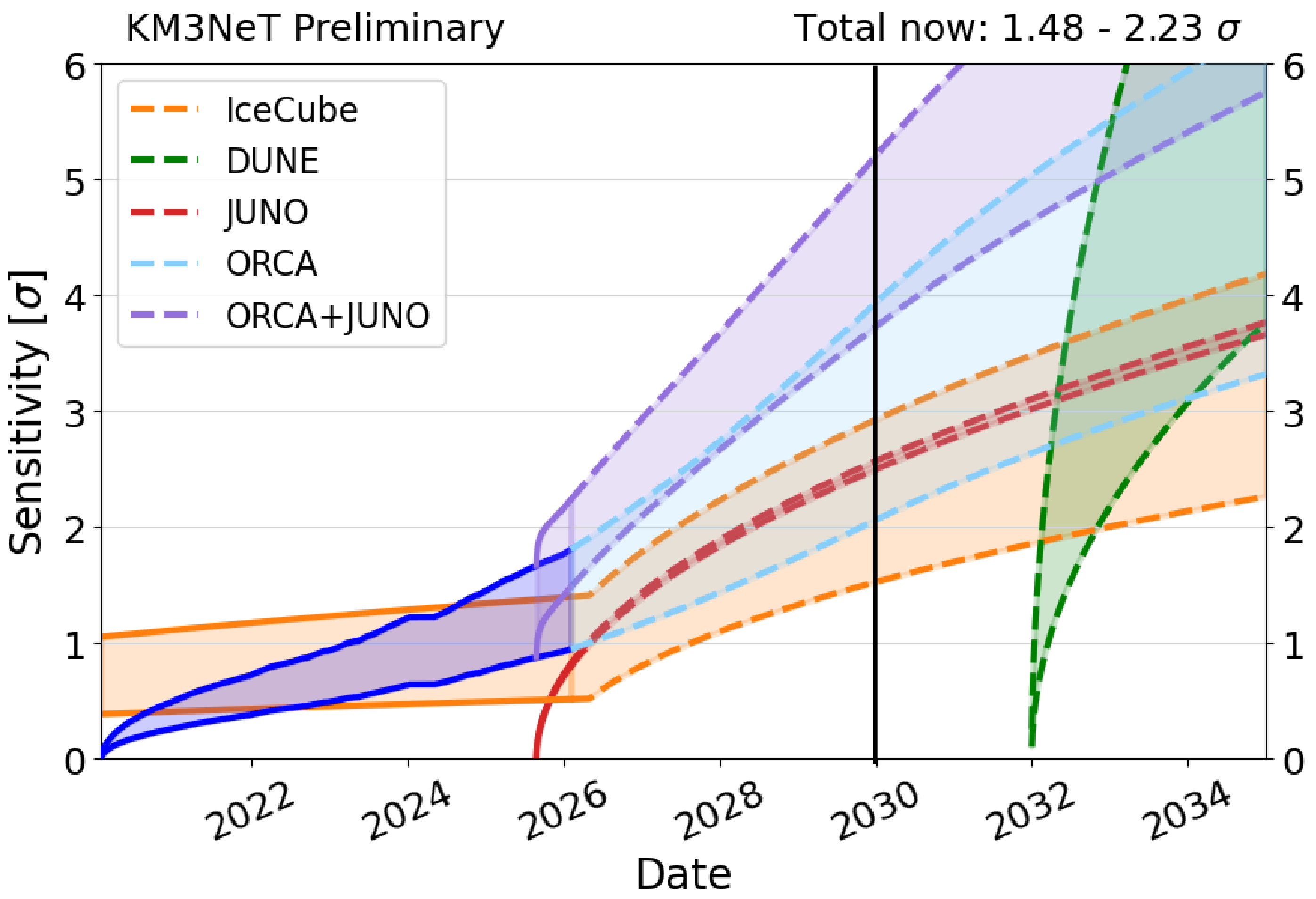
Major improvement of the treatment of **systematics**

- **Neutrino flux**
- **Detector response**
- **Neutrino-cross section**
  - **short term:**
    scaling of different x-section processes (RES, DIS, QE, ν_τ, NC)
  - **long term:**
    replace simple scaling factors with event reweighting using GENIE with modified parameters and possibily other generators (Nuisance framework)



Prospects by 2030

- **NMO:**
  - 2 – 4σ ORCA alone
  - 3.5 – 5σ ORCA/JUNO
- **θ_{23}**
  - 4-7% relative precision
- **ν_τ x-section**
  - 5% relative precision
- **BSM**
  - improvement x4 wrt ORCA6



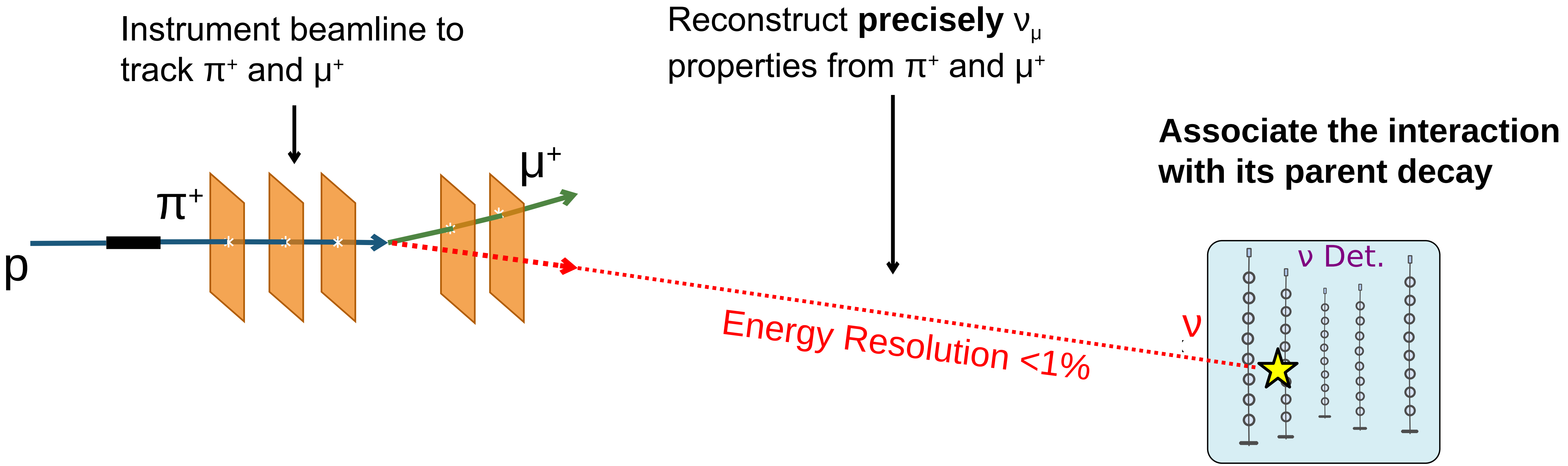
[Eur. Phys. J. C , 82 , 465 (2022)]

Long term plans

- Emergence of
  - **megaton scale neutrino detectors** (i.e. ORCA)
  - **very high intensity trackers** (HL-LHC)

  opens the possibility of **accelerator based <u>tagged</u> long baseline experiments**

- **Neutrino Tagging:**



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Long term plans

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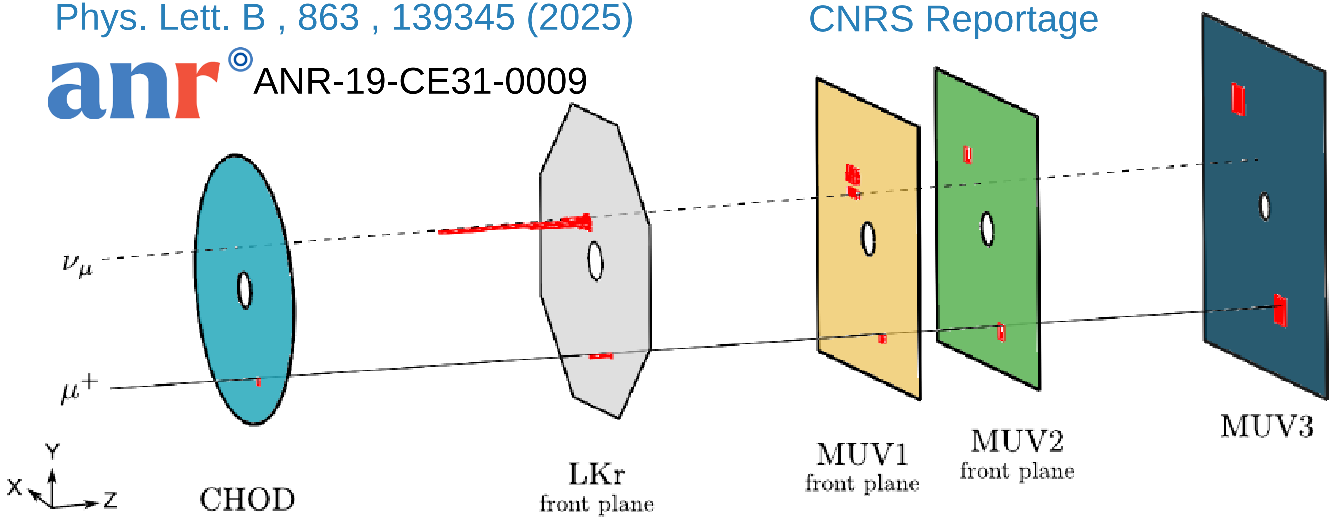
  - **megaton scale neutrino detectors** (i.e. ORCA)
  - **very high intensity trackers** (HL-LHC)

  opens the possibility of **accelerator based <u>tagged</u> long baseline experiments**
- **First <u>tagged</u> neutrino candidate with NA62**

Phys. Lett. B , 863 , 139345 (2025)

CNRS Reportage

anr ANR-19-CE31-0009



https://nuscope.web.cern.ch/

nuSCOPE
neutrino SPS COmplex for Precision Experiments

ESPPU Contribution

- Project of a **short baseline <u>tagged</u> neutrino experiment at CERN (nuSCOPE)**

[Eur. Phys. J. C , 82 , 465 (2022)]

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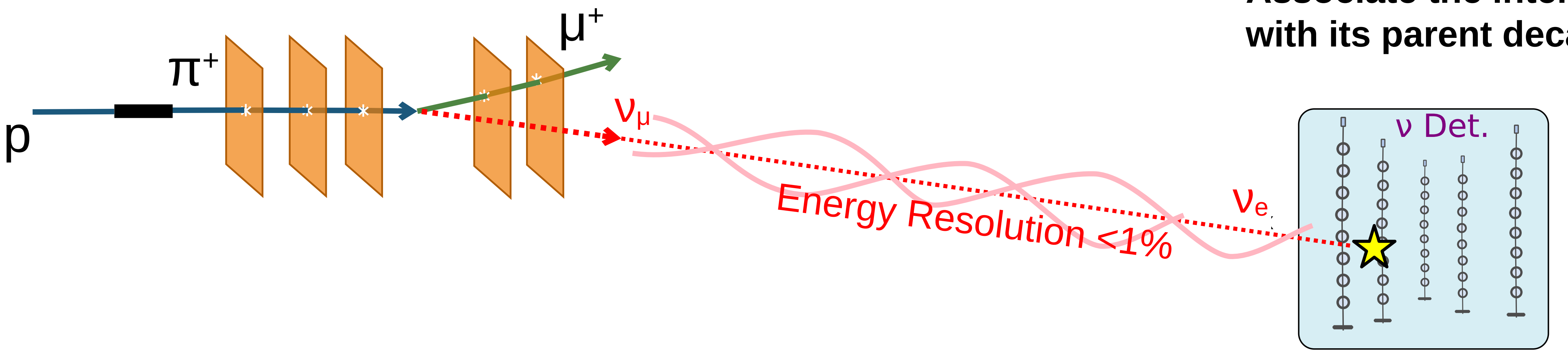
- Emergence of
  - **megaton scale neutrino detectors** (i.e. ORCA)
  - **very high intensity trackers** (HL-LHC)

  opens the possibility of **accelerator based <u>tagged</u> long baseline experiments**
- **Neutrino Tagging for oscillations**

Determine on an **per-event-basis** which ν changed flavour!

Associate the interaction with its parent decay



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Long term plans

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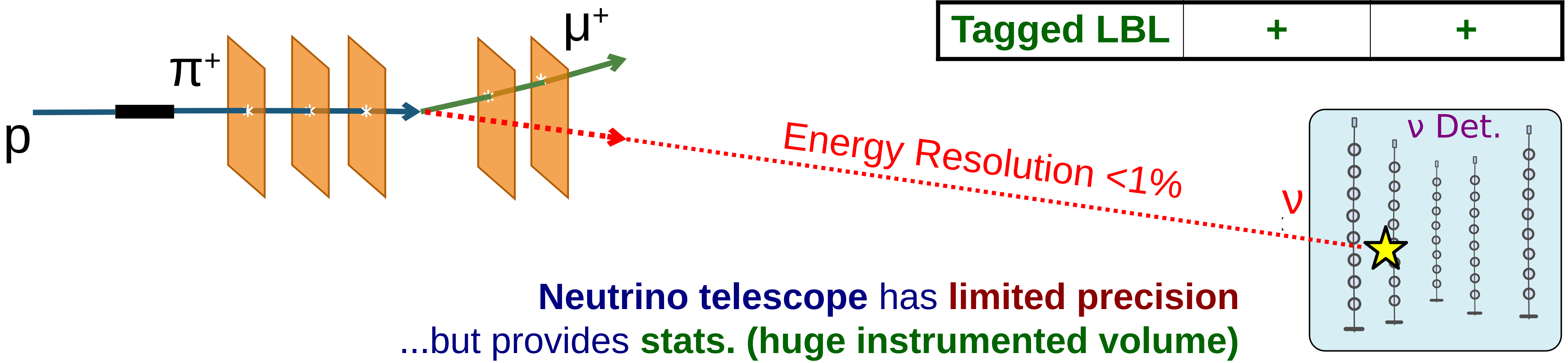
  - **megaton scale neutrino detectors** (i.e. ORCA)
  - **very high intensity trackers** (HL-LHC)

  opens the possibility of **accelerator based <u>tagged</u> long baseline experiments**

- **A win-win combination**

	Statistics	Precision
Trackers	–	+
ν telescope	+	–
Tagged LBL	+	+

Trackers limit the beam intensity
...but provide **ultimate precision**

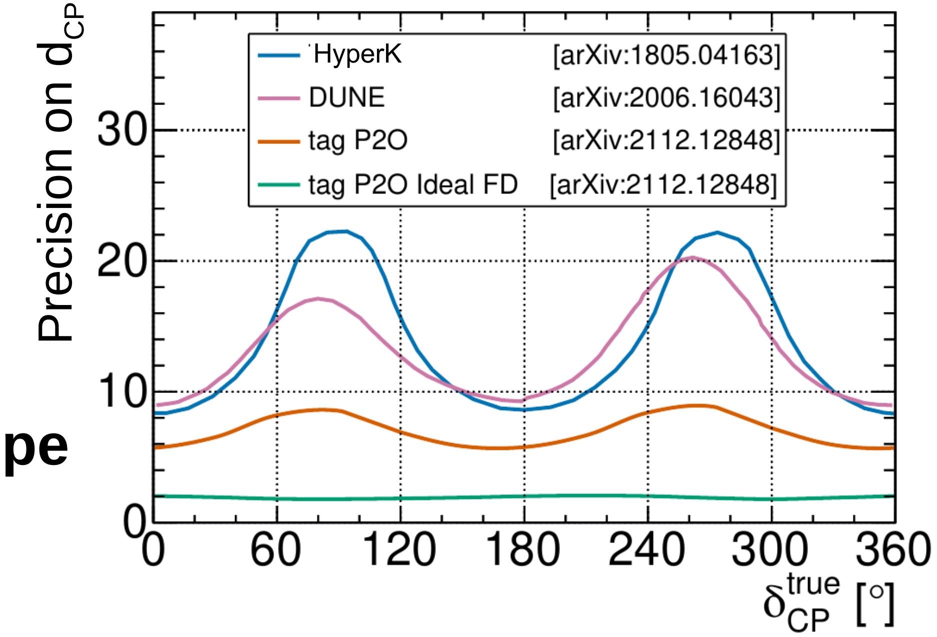


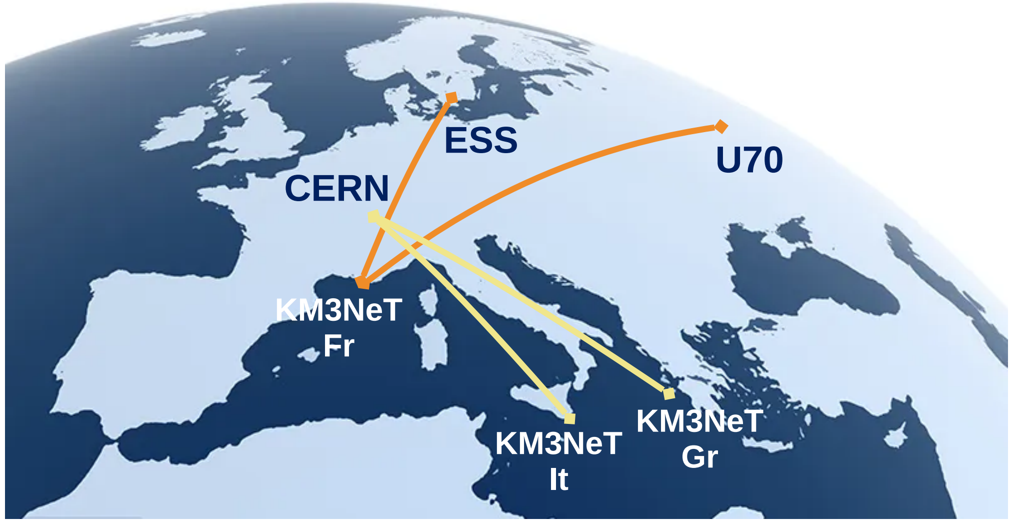
Neutrino telescope has **limited precision**
...but provides **stats. (huge instrumented volume)**

Long term plans

- **<u>Preliminary</u> studies** are encouraging
  - beamline design [within CERN PBC] (EPJC 2024 84:1024)
  - sensitivity studies (EPJC 2022 83:465)
- Several options with **existing infrastructures in Europe**

[Eur. Phys. J. C (2022) 83:465]





		Baseline km	Energy GeV	
U70	KM3NeT-Fr	2600	5.0	See P2O
ESS	KM3NeT-Fr	1500	2.9	
CERN	KM3NeT-It	1300	2.5	
CERN	KM3NeT-Gr	1700	3.3	See NESTOR, C2GT

Conclusions

- KM3NeT has a **unique potential to determine the NMO**
- Neutrino **physics program extends well beyond NMO**, exploiting **ORCA/ARCA complementarity**
- **First results** with 5% of the total detectors (ORCA6) are already **competitive**
- ORCA opens **long term perspectives** from next-generation of accelerator based neutrino experiments

Thank you for your attention

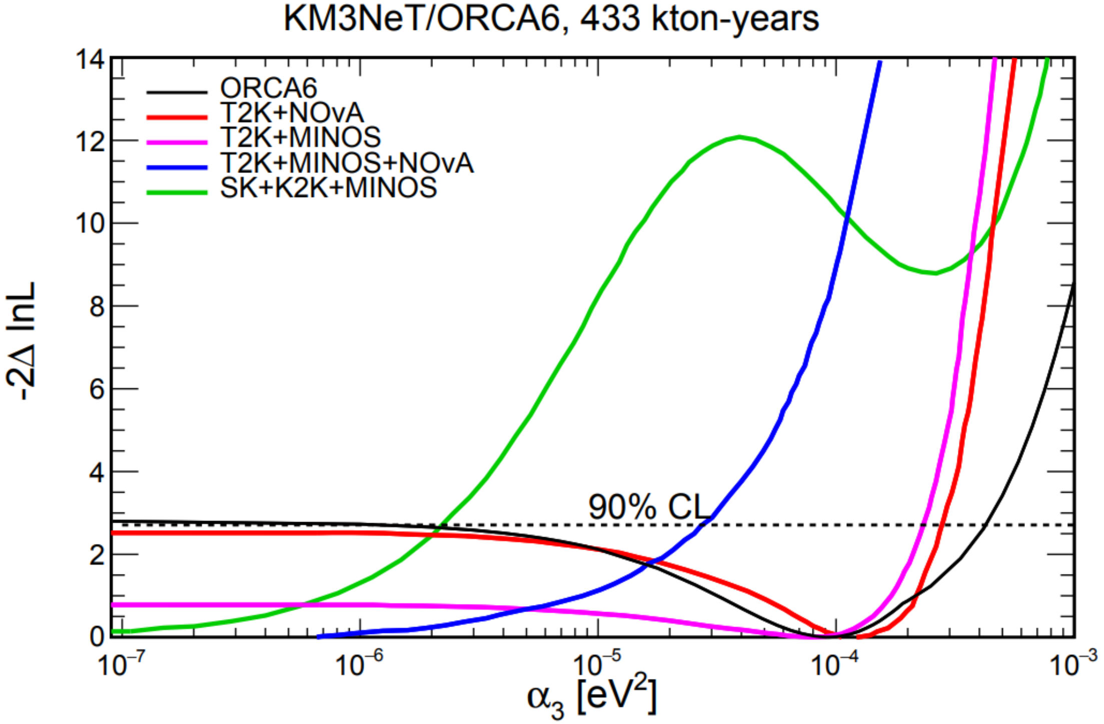
Neutrino Decay

- Hypothesis: neutrino decay to invisible products
- Analysis focusses on ν_3 decay (others constrained by solar and Super Novae)
- Model independent search with EFT

$$H_{\text{Total}} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + U\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -i\alpha_3\end{pmatrix}U^\dagger\right] + \begin{pmatrix}V & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

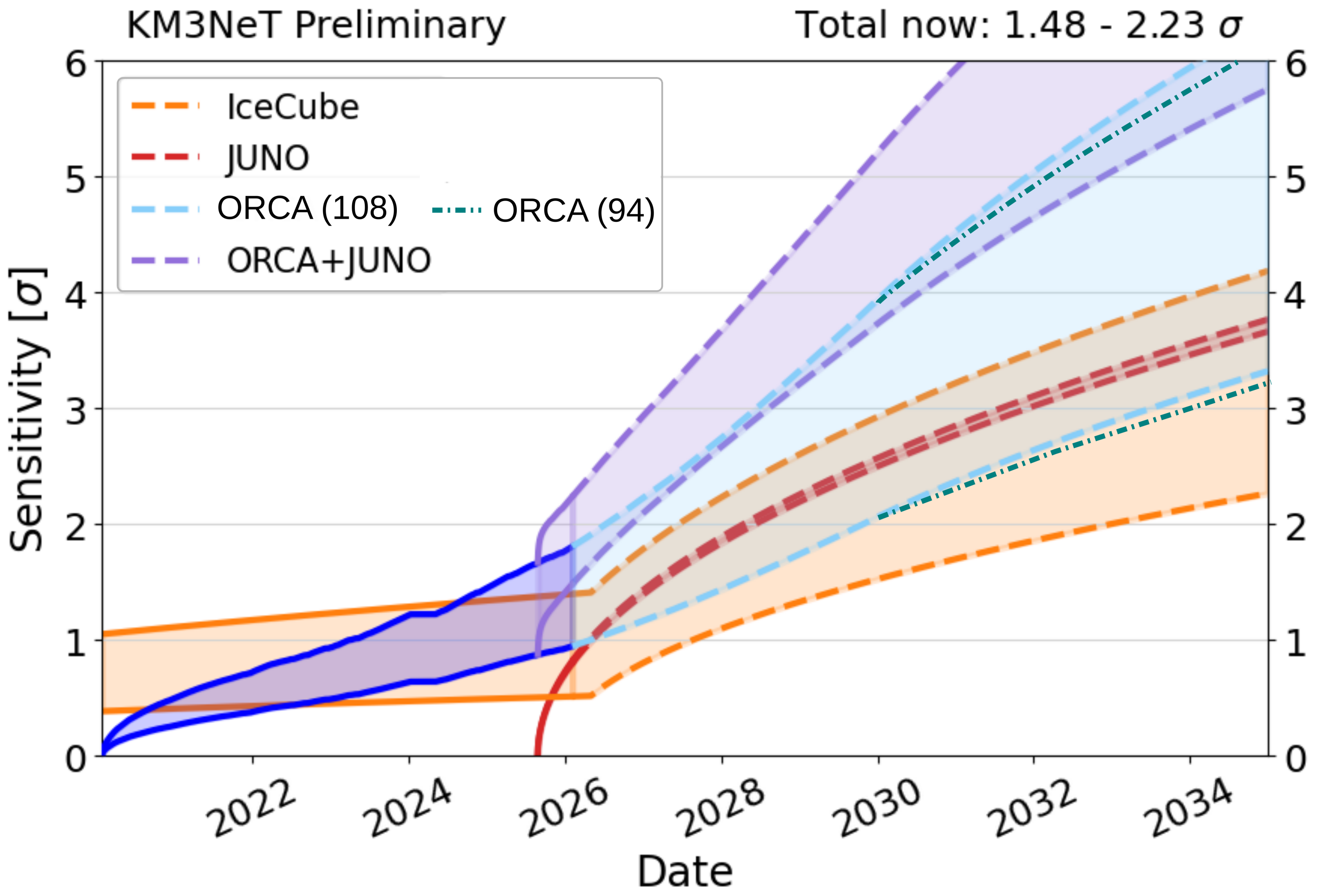
- ORCA6 measured $\alpha_3 = 0.92^{+1.08}_{-0.57} \times 10^{-4}\ \text{eV}^2$ compatible with 0 (SM) at 2.1σ

Experiment	UL (90% CL) [10^{-6}eV^2]
ORCA6 (433 kton-year)	[10, 380]
ORCA (70 Mton-year)	3.7
T2K, NOνA	290
T2K, MINOS	240
T2K, NOνA, MINOS	27
K2K, MINOS, SK I+II	2.3
DUNE (5ν+$5\bar{\nu}$) yr	13
MOMENT (10 yr)	24
ESSnuSB (5ν+$5\bar{\nu}$) yr	16 – 13
JUNO (5 yr)	7
INO-ICAL (10 yr)	4.4



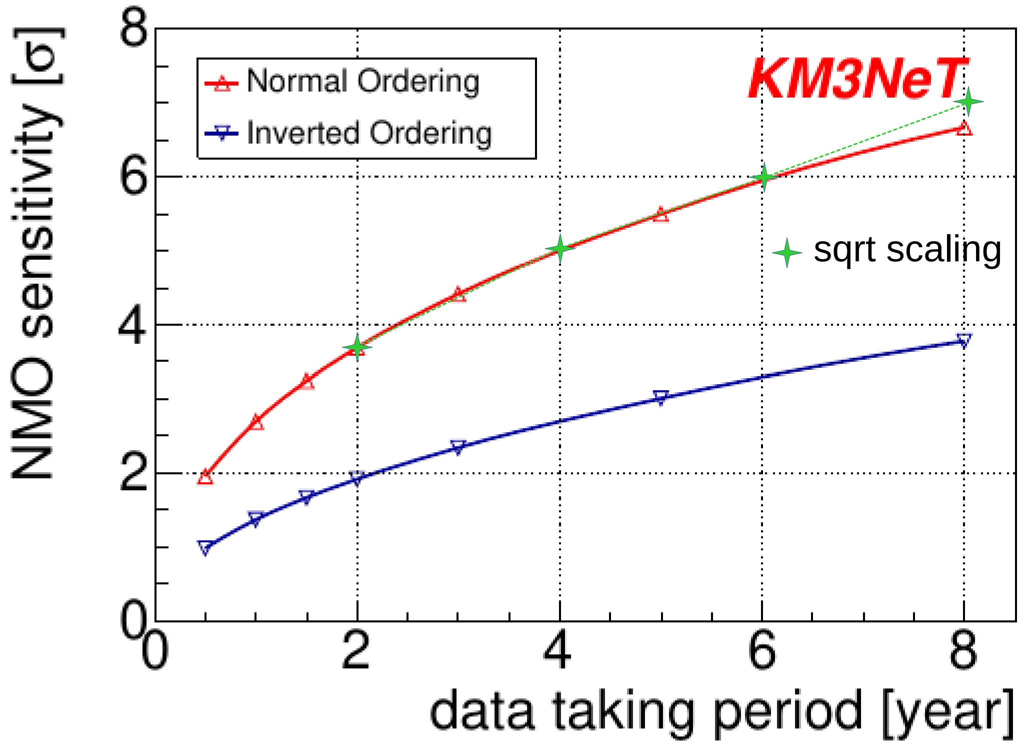
Influence of the DU number

- Limited impact on NMO by reducing DU number from 108 to 94
- Budgeting for 94 DUs increases the risks for the scientific impact of ORCA

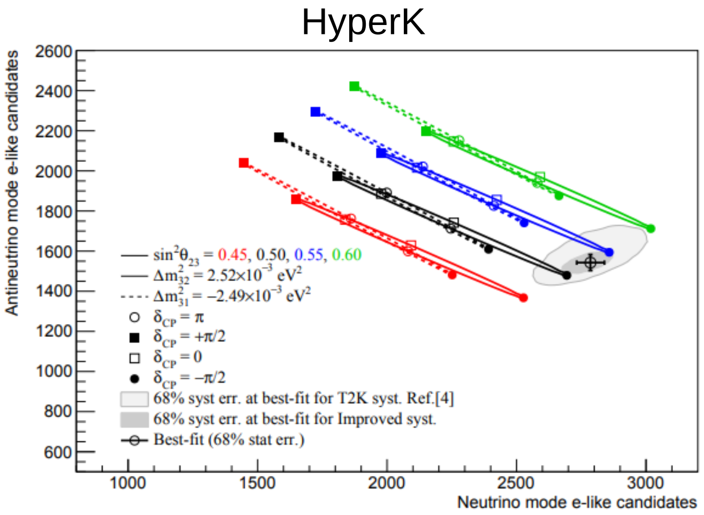


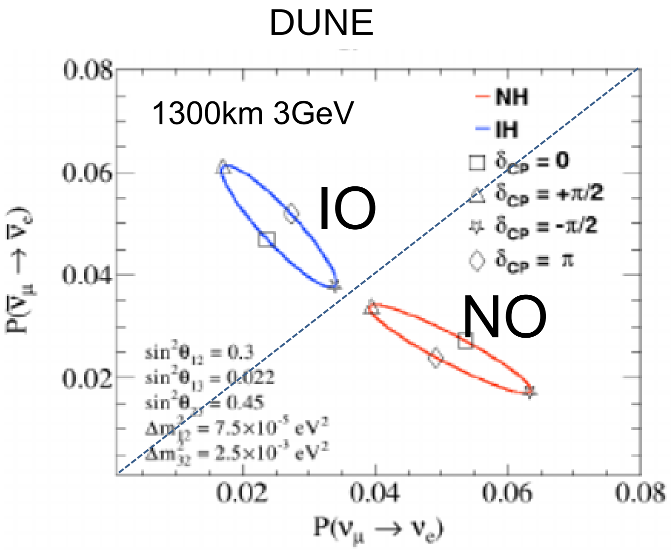
Stats vs Syst

- ORCA is dominated for a long time by statistical uncertainties

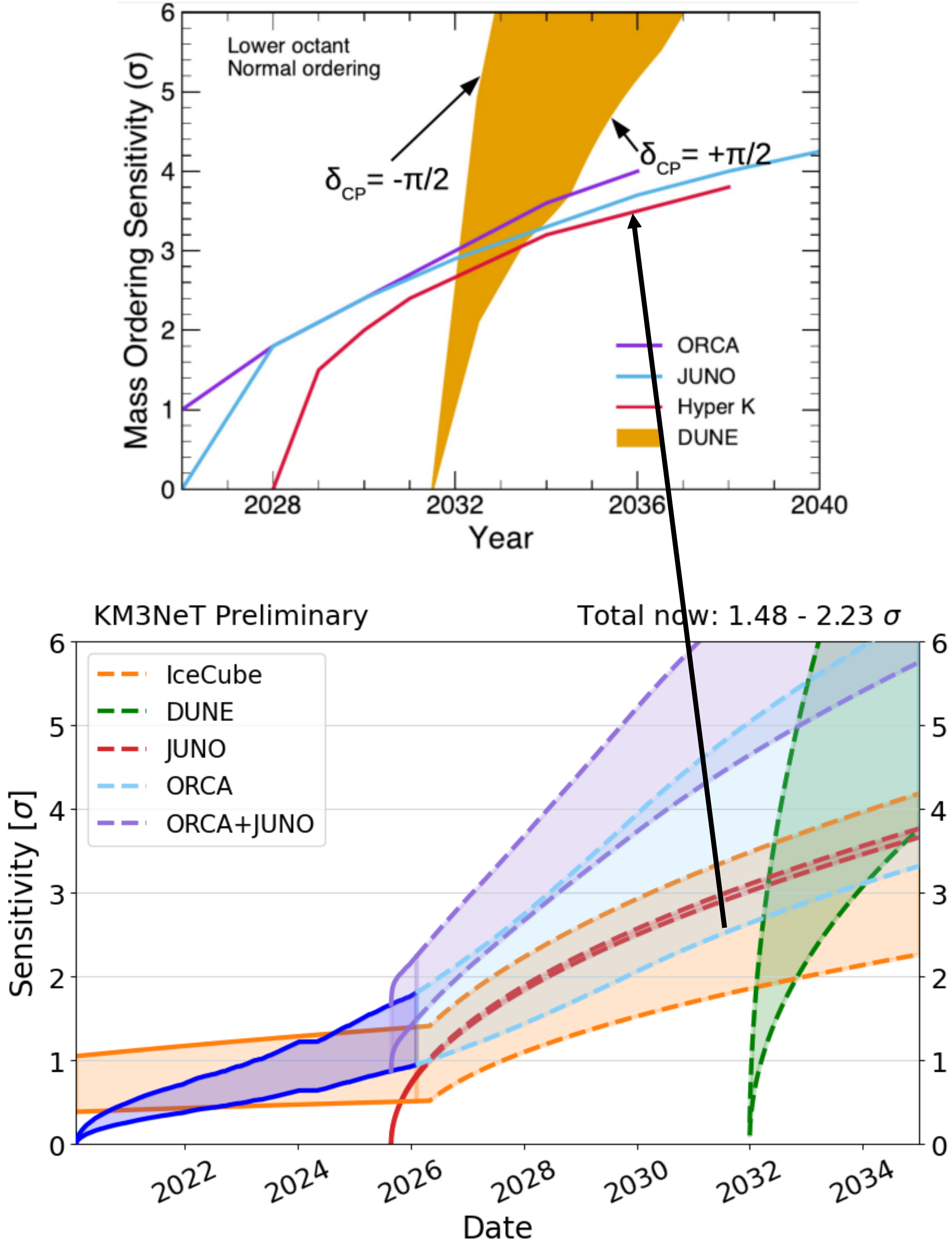


ORCA / HyperK / DUNE



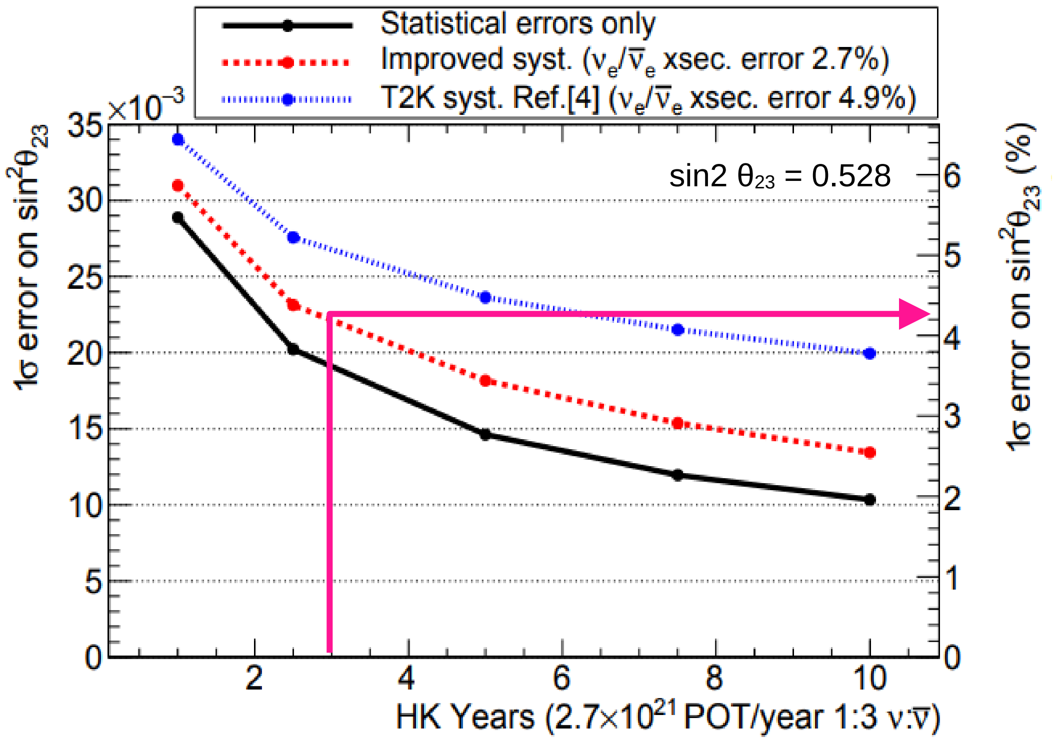


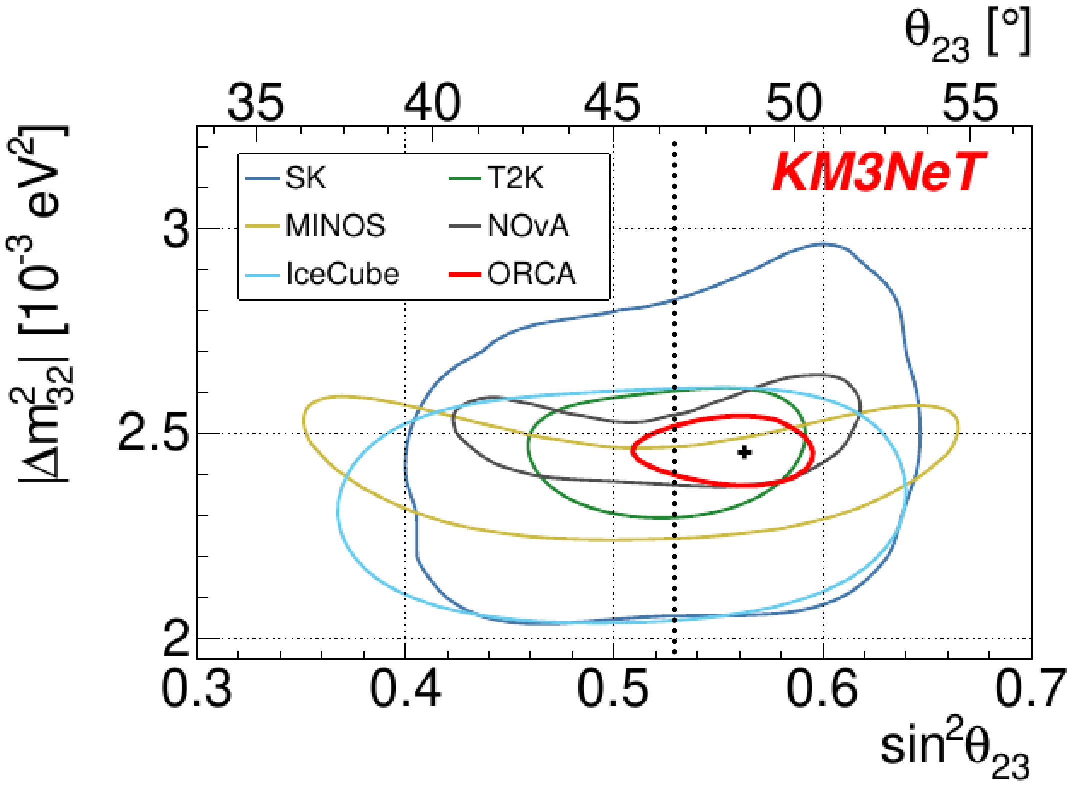
inverted ordering). In Hyper-Kamiokande, the mass ordering will be measured with atmospheric neutrinos: the combination of atmospheric and beam neutrinos [12] reaches between 3.5 and 4.5σ MO determination in 6 years of data taking, depending on the value of $\sin^2\theta_{23}$ in the 1σ interval from presently available oscillation measurements. In-



Comparision with HyperK for θ_{23}

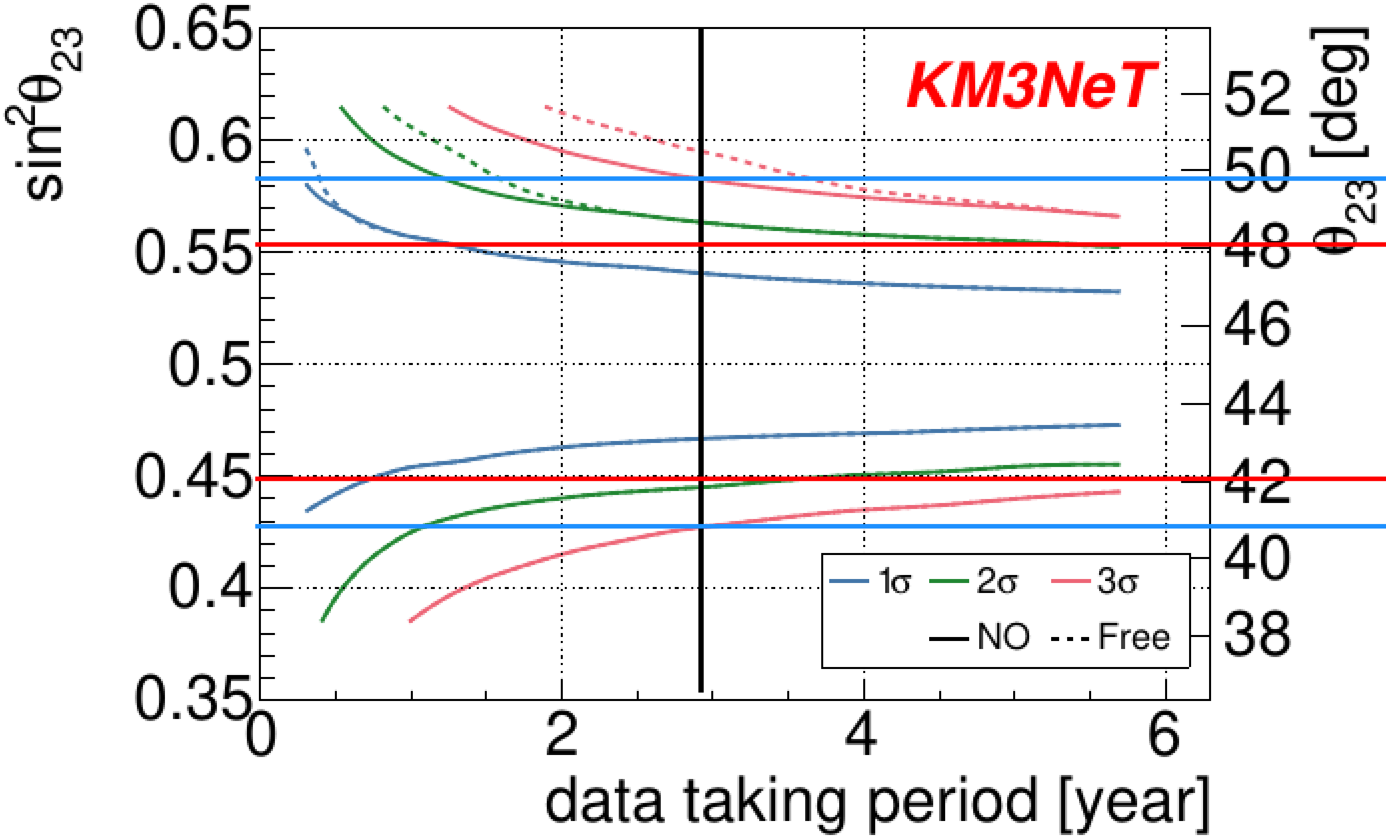
- After 3 years **ORCA's** precison on θ_{23} (NO, 48deg) is **4-6%**
- **HyperK** is sligthly better (**4%** but at $\sin^2\theta_{23} = 0.528$)

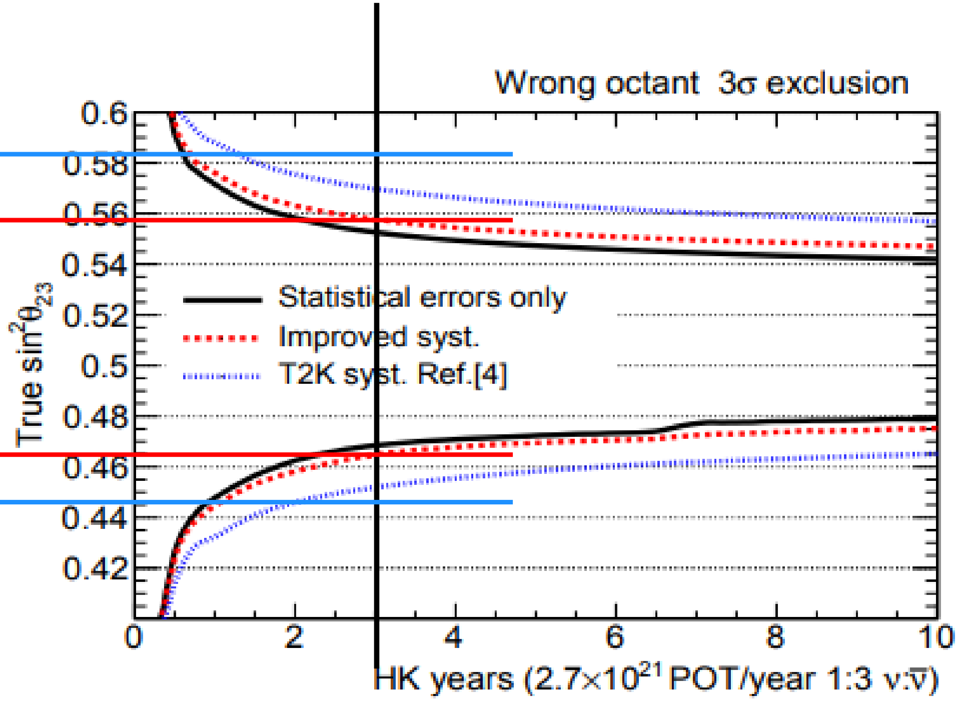




Comparision with HyperK for θ_{23} octant

- **HyperK has a better capability of determining θ_{23} octant**
- This information could boost ORCA's NMO sensitivity

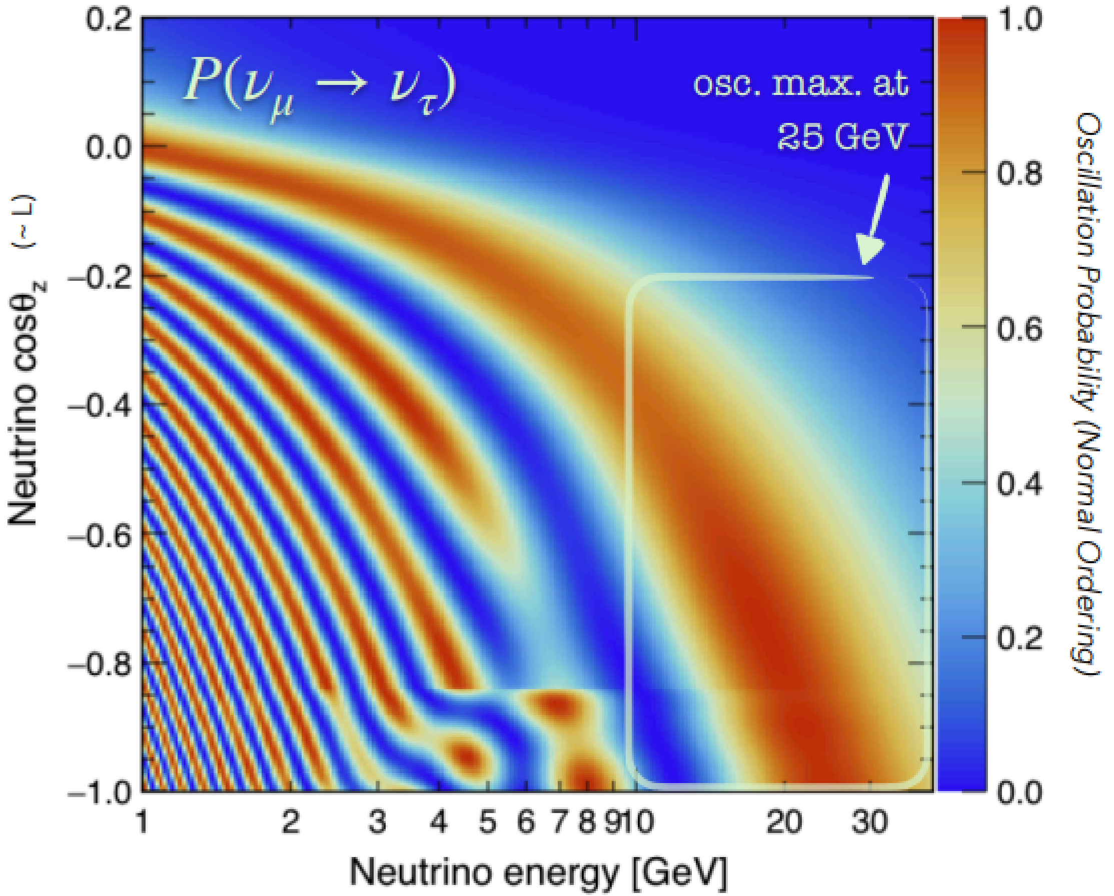




Tau Neutrinos

- ORCA accesses one of the world's largest ν_τ sample

Experiment		Nb ντ	Effective Energy Threshold [GeV]
SK(14.6y)	[1]	185	6.4
Deep Core(3y)	[2]	1800	37
ORCA6 (1.4y)	**[3]**	**185**	**13**
HK (from 2028)	[4]	140	7.3
IC Upgrade (from 2026)	[5]	1460/y	7.8
Full ORCA	**[6]**	**3000/y**	**13**



[1] arXiv:1711.09436. [2] arXiv:1901.05366. [3] arXiv:2502.01443. [4] arXiv:1805.04163. [5] arXiv:2307.15295. [6] arXiv:2103.09885.

Quantum Decoherence

- Oscillations affected by **decoherence**, described by a damping term

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} \tilde{U}_{\alpha i}\tilde{U}^*_{\beta i}\tilde{U}^*_{\alpha j}\tilde{U}_{\beta j} e^{-i\Delta\tilde{E}_{ij}t - \gamma_{ij}t}$$

$$\gamma_{ij} = \gamma^0_{ij}\left(\frac{E}{\text{GeV}}\right)^n$$

	Upper limits [GeV]			
	$n=-2$		$n=-1$	
ORCA6, 90 %CL	NO	IO	NO	IO
Γ_{21}	$2.8\cdot10^{-21}$	$\mathbf{4.6\cdot10^{-21}}$	$1.1\cdot10^{-22}$	$\mathbf{1.9\cdot10^{-22}}$
Γ_{31}	$\mathbf{8.4\cdot10^{-21}}$	$2.2\cdot10^{-21}$	$\mathbf{2.7\cdot10^{-22}}$	$0.8\cdot10^{-22}$
$\Gamma_{21}=\Gamma_{31}$	$\mathbf{4.1\cdot10^{-21}}$	$2.9\cdot10^{-21}$	$\mathbf{1.8\cdot10^{-22}}$	$1.1\cdot10^{-22}$
ORCA6, 95 %CL	NO	IO	NO	IO
Γ_{21}	$3.7\cdot10^{-21}$	$\mathbf{6.9\cdot10^{-21}}$	$1.6\cdot10^{-22}$	$\mathbf{3.0\cdot10^{-22}}$
Γ_{31}	$\mathbf{11.7\cdot10^{-21}}$	$3.2\cdot10^{-21}$	$\mathbf{4.2\cdot10^{-22}}$	$1.3\cdot10^{-22}$
$\Gamma_{21}=\Gamma_{31}$	$\mathbf{5.2\cdot10^{-21}}$	$3.6\cdot10^{-21}$	$\mathbf{2.3\cdot10^{-22}}$	$1.4\cdot10^{-22}$

- **ORCA** well suited to study **n = -2, -1**

  ARCA well suited to study **n = 0, 1, 2, 3**

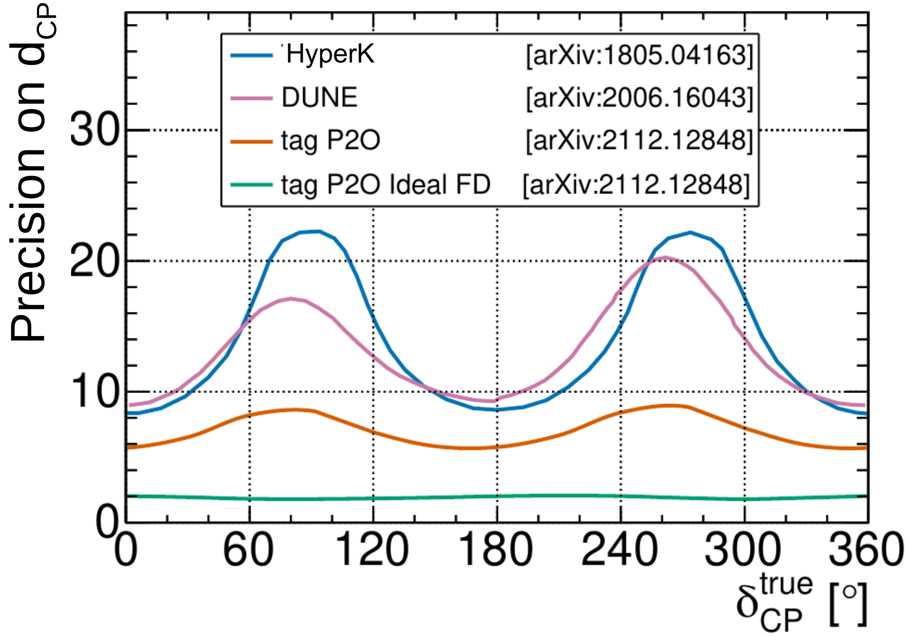
	Upper limits [GeV]			
	$n=-2$		$n=-1$	
Reported in [14], 90 % CL				
$\Gamma_{21}=\Gamma_{32}$	$7.9\cdot10^{-27}$ (KL)		$1.8\cdot10^{-24}$ (KL)	
$\Gamma_{31}=\Gamma_{32}$	$6.9\cdot10^{-25}$ (R)		$2.1\cdot10^{-23}$ (T2K)	
$\Gamma_{21}=\Gamma_{31}$	$7.9\cdot10^{-27}$ (KL)		$1.8\cdot10^{-24}$ (KL)	
Reported in [18], 95 %CL	NO	IO	NO	IO
$\Gamma_{21}=\Gamma_{32}$	$7.5\cdot10^{-21}$	$\mathbf{5.0\cdot10^{-20}}$	$3.5\cdot10^{-22}$	$\mathbf{2.3\cdot10^{-21}}$
$\Gamma_{31}=\Gamma_{32}$	$\mathbf{4.3\cdot10^{-20}}$	$1.4\cdot10^{-20}$	$\mathbf{2.0\cdot10^{-21}}$	$5.8\cdot10^{-22}$
$\Gamma_{21}=\Gamma_{31}$	$\mathbf{1.2\cdot10^{-20}}$	$8.3\cdot10^{-21}$	$\mathbf{5.4\cdot10^{-22}}$	$3.6\cdot10^{-22}$

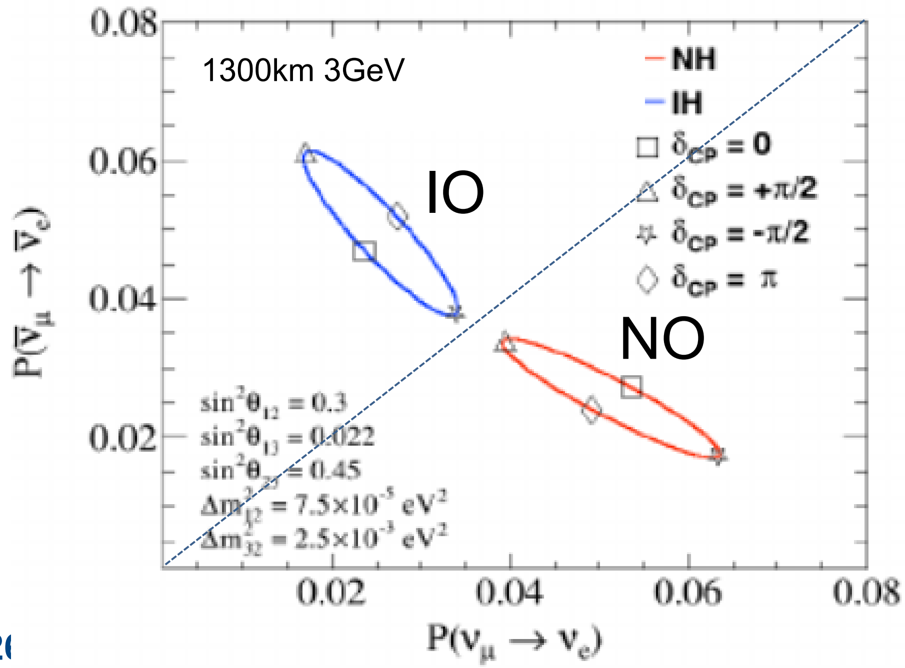
- **ORCA6** data allows to set limits comparable to **DeepCore** but other exp. at **lower energy** (RENO, KamLAND, T2K) put stronger bounds for $n<0$

What about tagged LBL

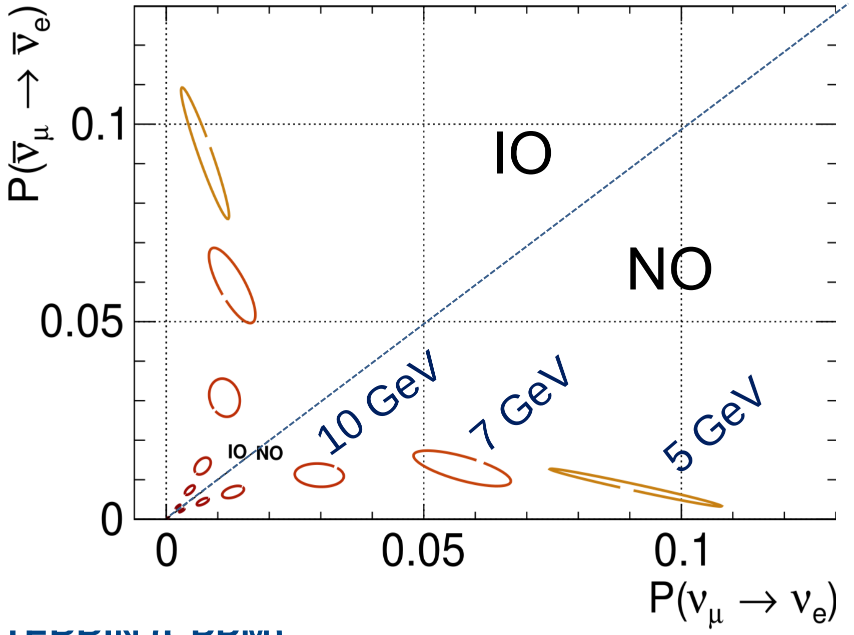
- **<u>Preliminary</u> studies** are encouraging
  - beamline design [within PBC] (EPJC 2024 84:1024)
  - sensitivity studies (EPJC 2022 83:465)
- Tagging give access to **multiple ellipses** on bi-probability plot
  - some are more circular
  - apsides not always reached at 90 or 270°
  - only with a wide band beam (challenging without horn)

[Eur. Phys. J. C (2022) 83:465]

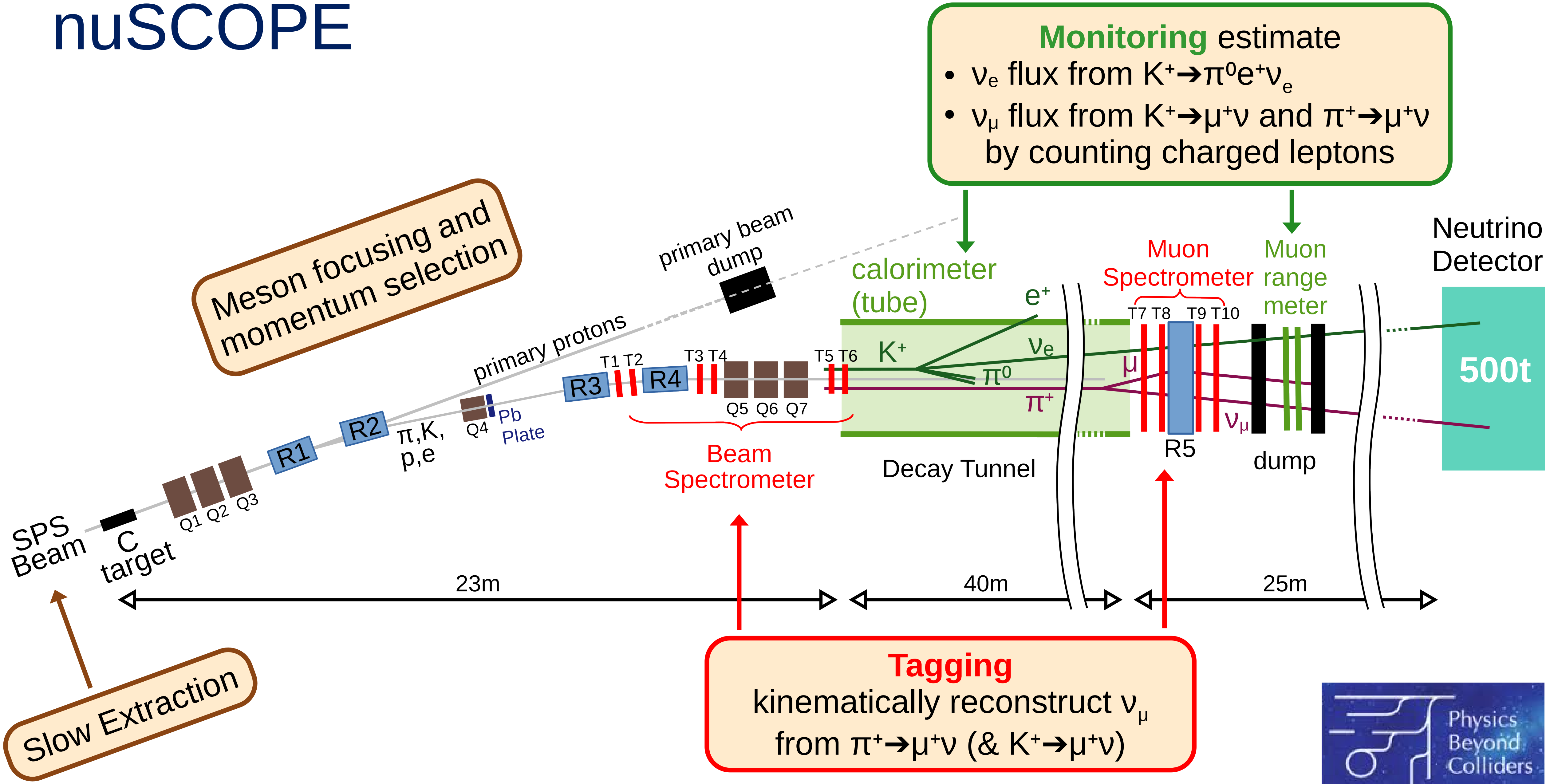




tagging



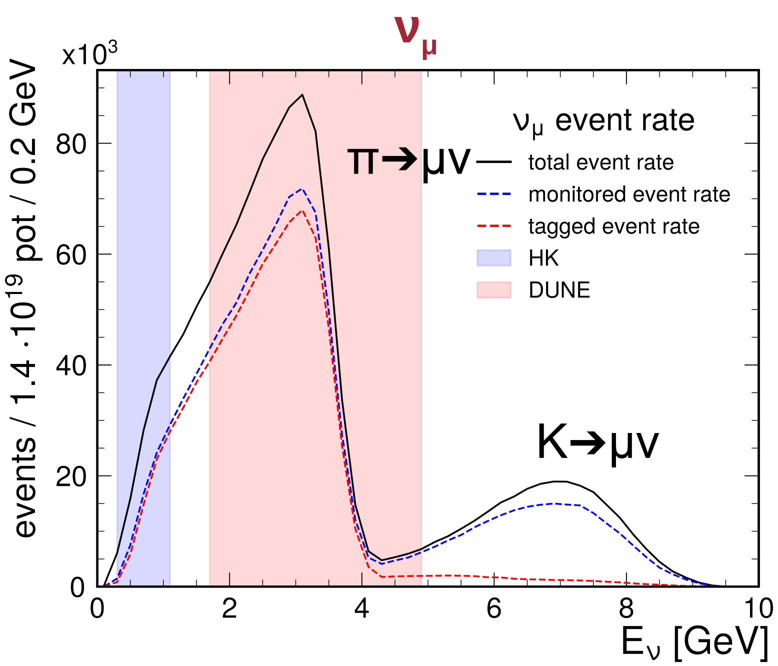
nuSCOPE

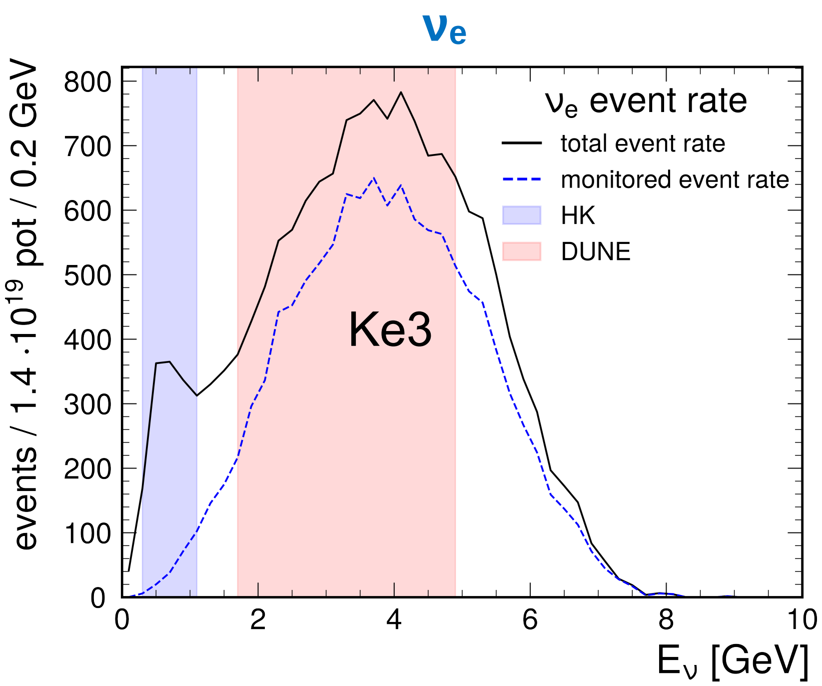


Monitoring estimate
• ν_e flux from $K^+ \rightarrow \pi^0 e^+ \nu_e$
• ν_μ flux from $K^+ \rightarrow \mu^+ \nu$ and $\pi^+ \rightarrow \mu^+ \nu$ by counting charged leptons
Meson focusing and momentum selection
primary beam dump
primary protons
calorimeter (tube)
Muon Spectrometer
Muon range meter
Neutrino Detector
500t
e^+
K^+
ν_e
π^0
π^+
μ
ν_μ
T1 T2
T3 T4
T5 T6
T7 T8
T9 T10
R1
R2
R3
R4
R5
Q1 Q2 Q3
Q4
Q5 Q6 Q7
Pb Plate
π,K, p,e
SPS Beam
C target
Beam Spectrometer
Decay Tunnel
dump
23m
40m
25m
Slow Extraction
Tagging
kinematically reconstruct ν_μ from $\pi^+ \rightarrow \mu^+ \nu$ (& $K^+ \rightarrow \mu^+ \nu$)

Neutrino detector and interaction rates

- **Reference detector:**
  500t of liquid argon (4x4x22.3m³) similar to protoDUNEs at 25m from decay tunnel end
  Improved time resolution (300ps) assuming more photon coverage (R&D for 3rd/4th DUNE detector)
- On-going studies using a **100t water Cerenkov or WBLS detector**
- **Large fraction of neutrino are monitored and tagged**





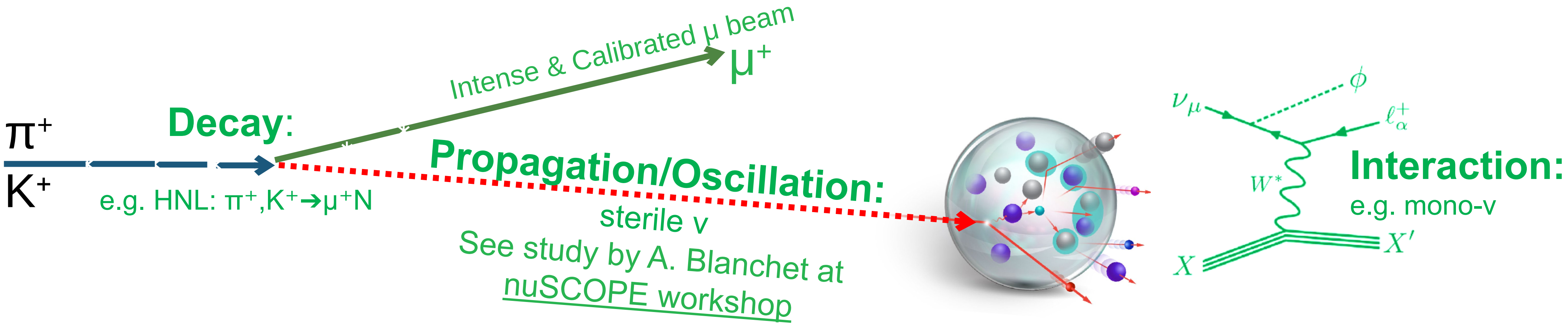
	Event per 1.4×10^{19} POT	
	500t LAr	100t Water
ν_μ	1.3×10^6	
Monitored ν_μ	1.0×10^6	
Tagged ν_μ	**0.76×10^6**	**0.14×10^6**
ν_e	1.7×10^4	
Monitored ν_e	1.2×10^4	

Rich physics program

Neutrino Interactions

large ν interaction samples.
flux knowledge, energy resolution

Beyond Standard Model



Kaon Physics

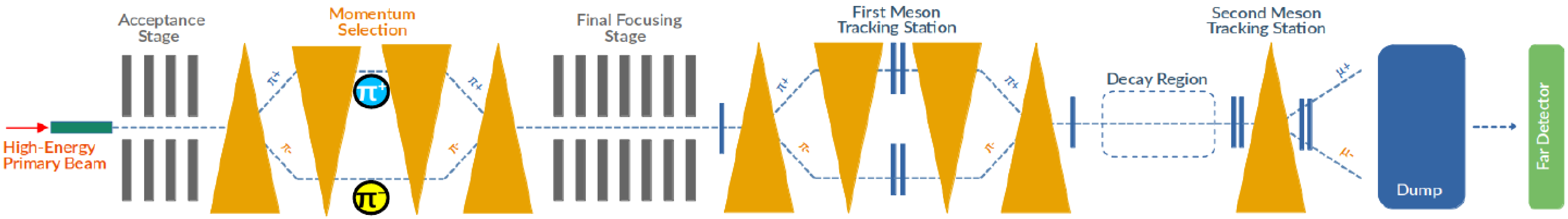
ultra rare decay exploiting large stats

Nuclear Physics/QCD

repeat electron scattering exp. but with ν as probe
access axial structure...

Tagged LBL Beamline

- Beam line designed to exploit the fact that the tagger determines the neutrino chirality (ν / $\bar{\nu}$): both π^+ and π^- are transported



- Flux is sufficently intense but too narrow to fully take advantge of the tagging energy resolution

  => more studies are needed