The neutrino mass ordering and atmospheric neutrinos at DUNE

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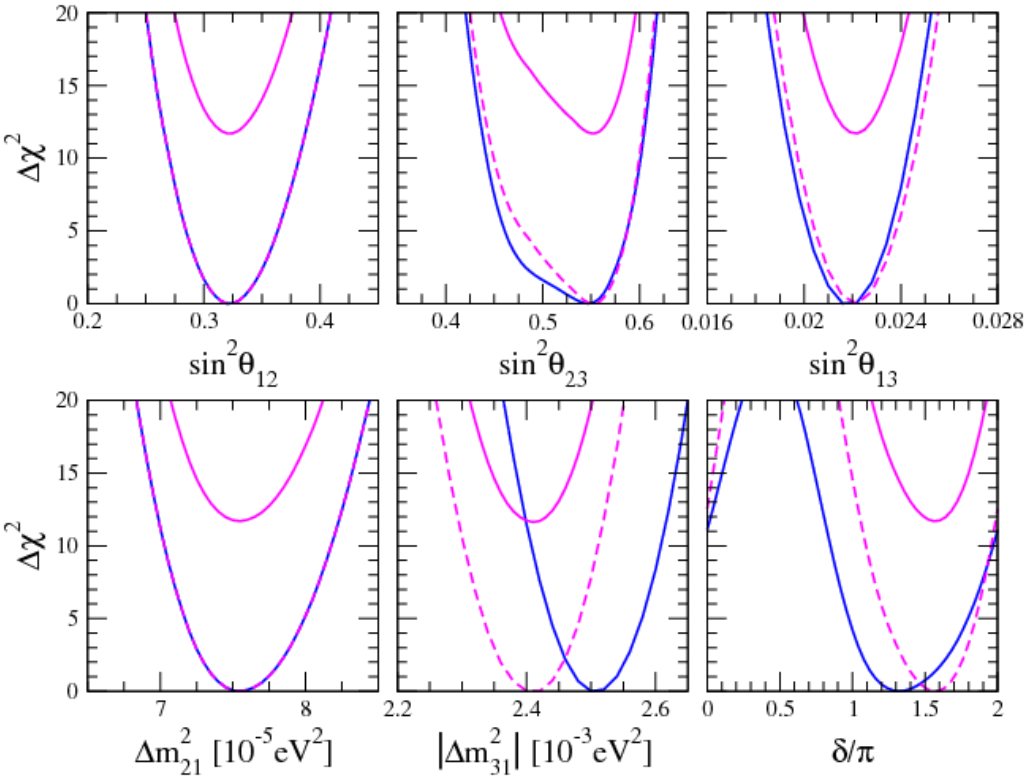
Three-neutrino oscillations

$$\nu_\alpha = \sum_k U^*_{\alpha k}\nu_k, P(\alpha \to \beta; E, L) = \sum_{k,j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}e^{i\frac{\Delta m^2_{kj}}{2E}L}$$

parameter	best fit $\pm 1\sigma$	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

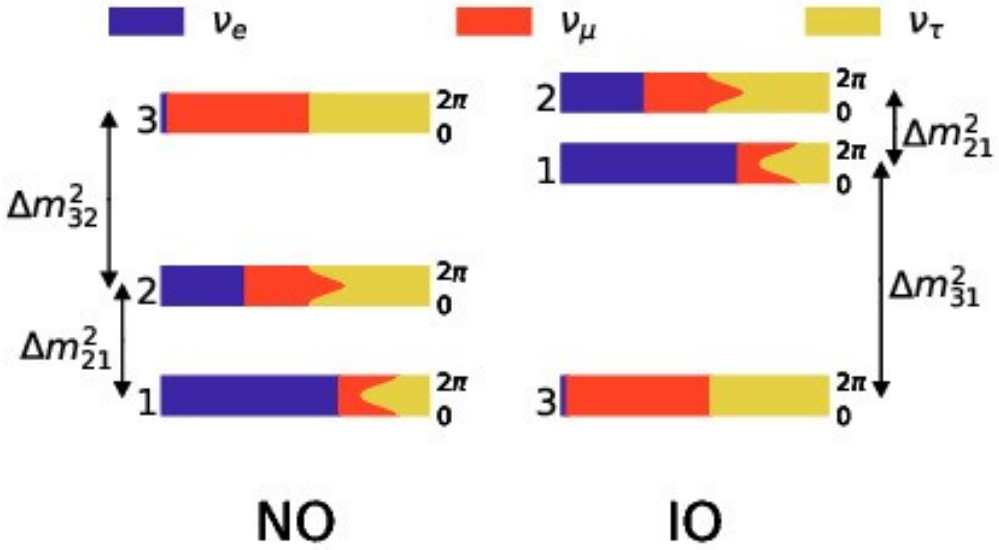


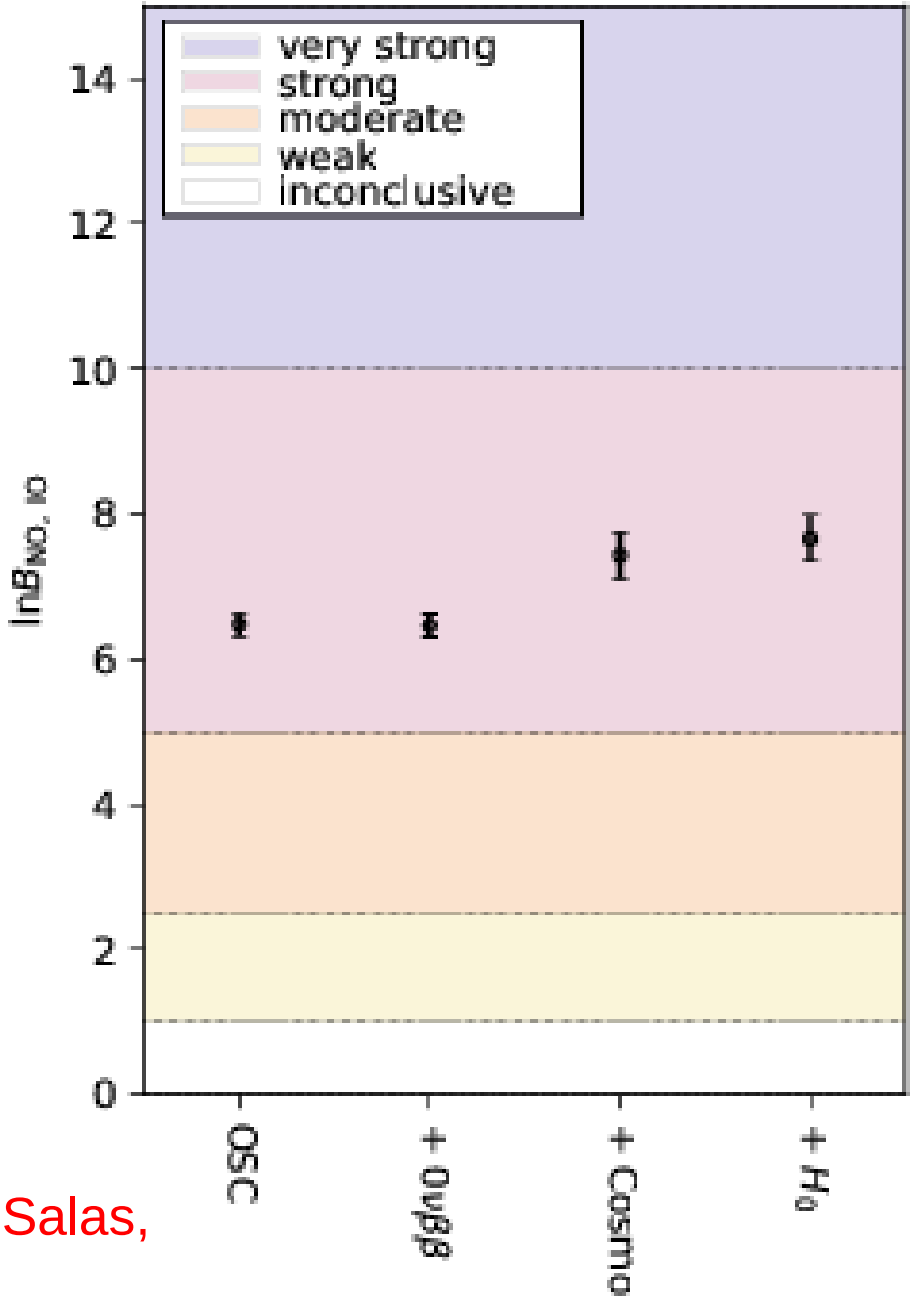
Phys.Lett. B782 (2018) 633-640, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle
https://globalfit.astroparticles.es/

See also: - Bari-group, Prog.Part.Nucl.Phys. 102 (2018) 48-72
- ν-fit, JHEP 1901 (2019) 106

Three-neutrino oscillations

- Neutrino mass ordering



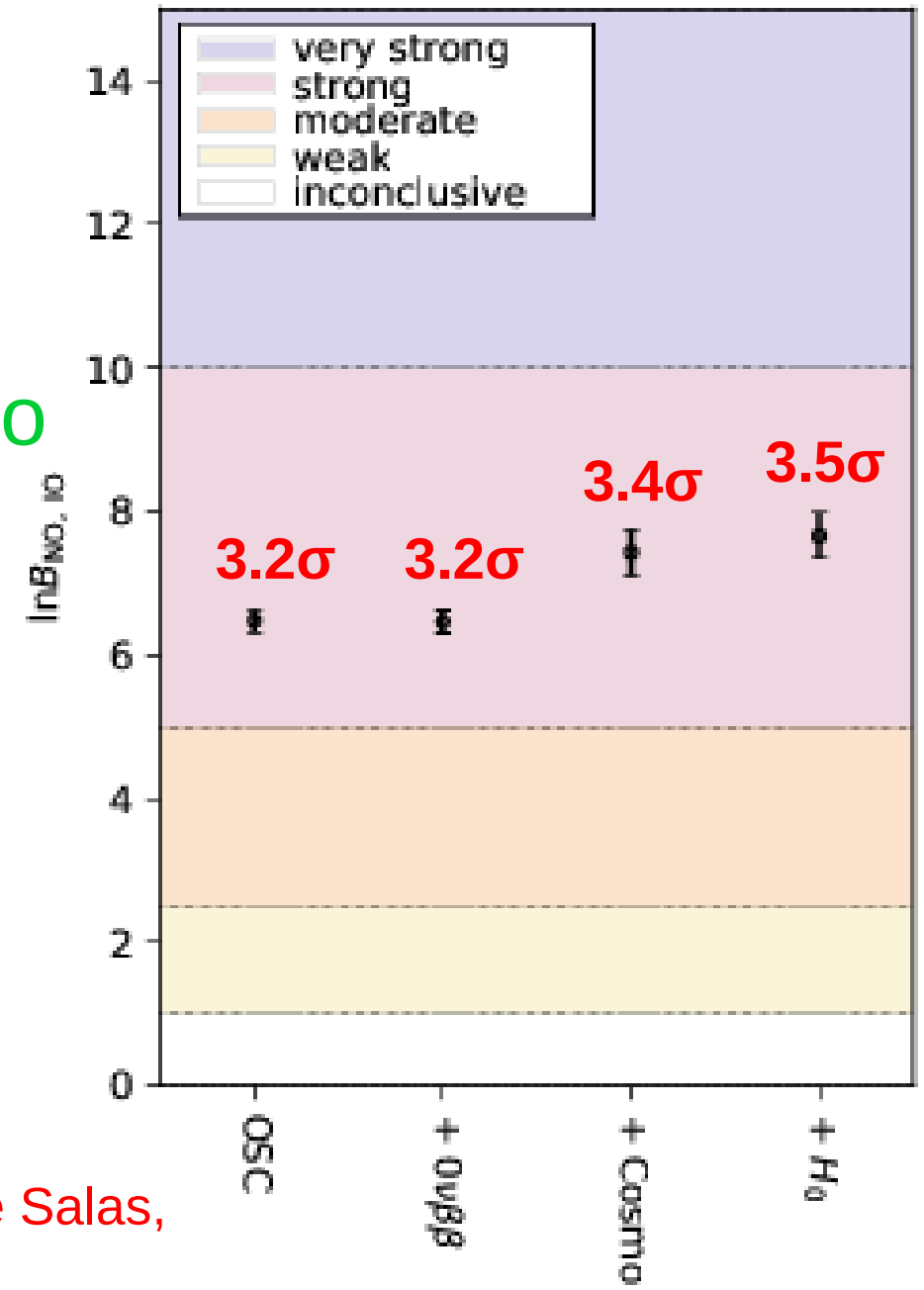


JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

Front. Astron. Space Sci. 5 (2018) 36, P.F. de Salas, S. Gariazzo, O. Mena, CAT, M. Tórtola

Three-neutrino oscillations

- Neutrino mass ordering
- Combine with data from decay experiments and cosmological observation using conservative priors to obtain 3.5σ preference for normal ordering



JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

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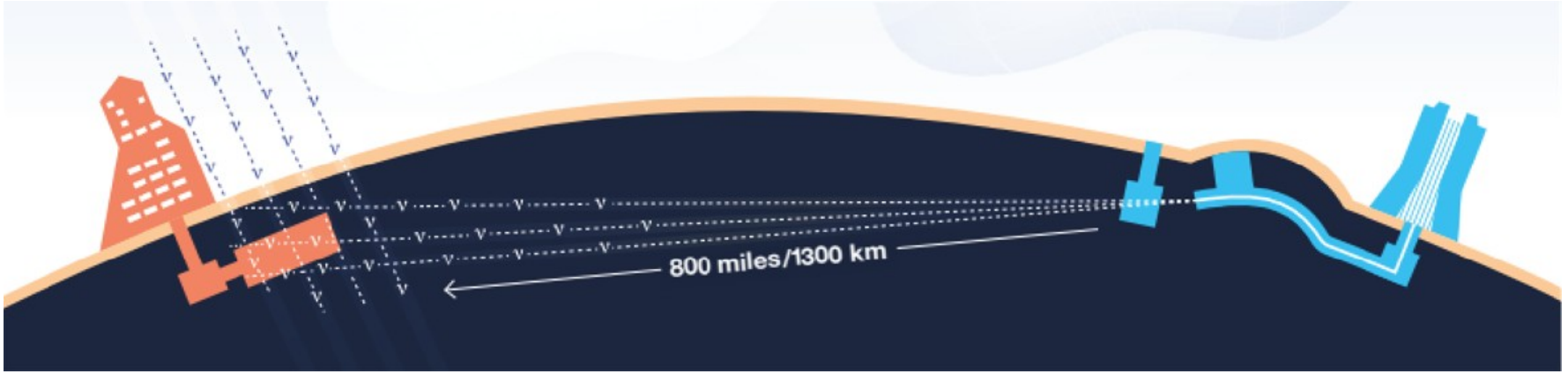
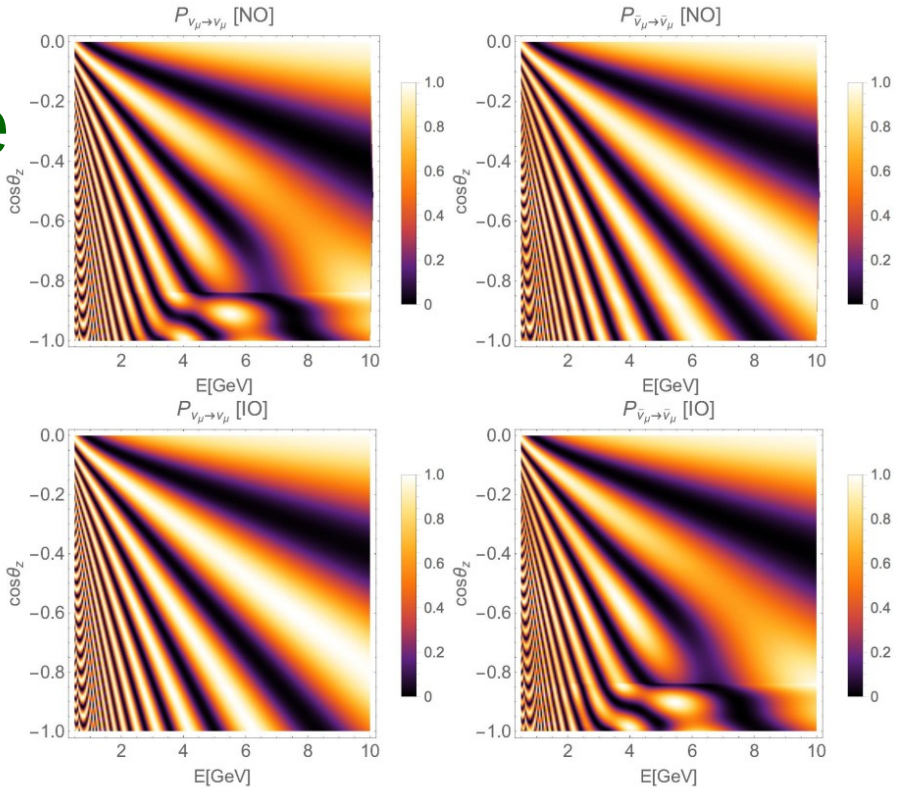
The DUNE experiment

- One of the next generation neutrino experiments
- DUNE will consist of two detectors using liquid argon as interaction material
- Here we focus on DUNE as an experiment for atmospheric neutrinos



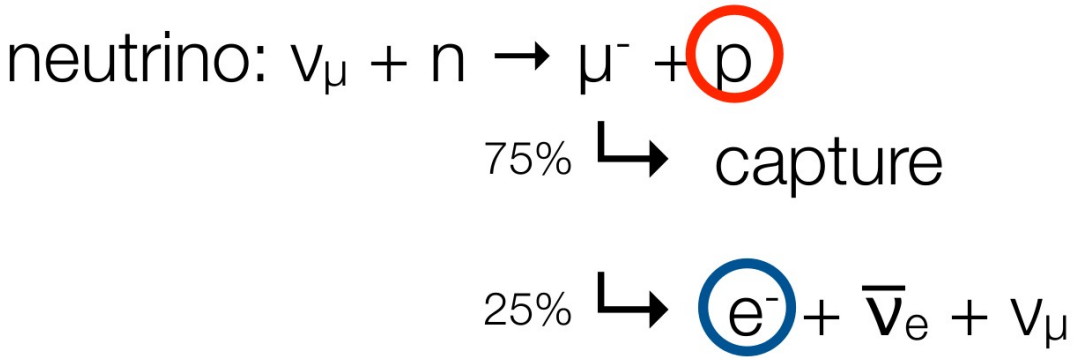
Atmospheric neutrino oscillations

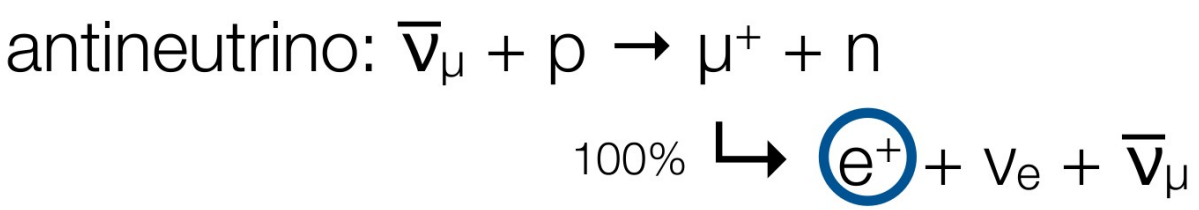
- DUNE will be able to measure the mass ordering using the muon-neutrino disappearance channel
- The disappearance probability $P_{\mu\mu}$ gets suppressed (enhanced) for normal (inverted) ordering due to matter effects
- Even though the appearance channel is more sensitive to matter effects, the disappearance channel is statistically more relevant



Event topologies at DUNE

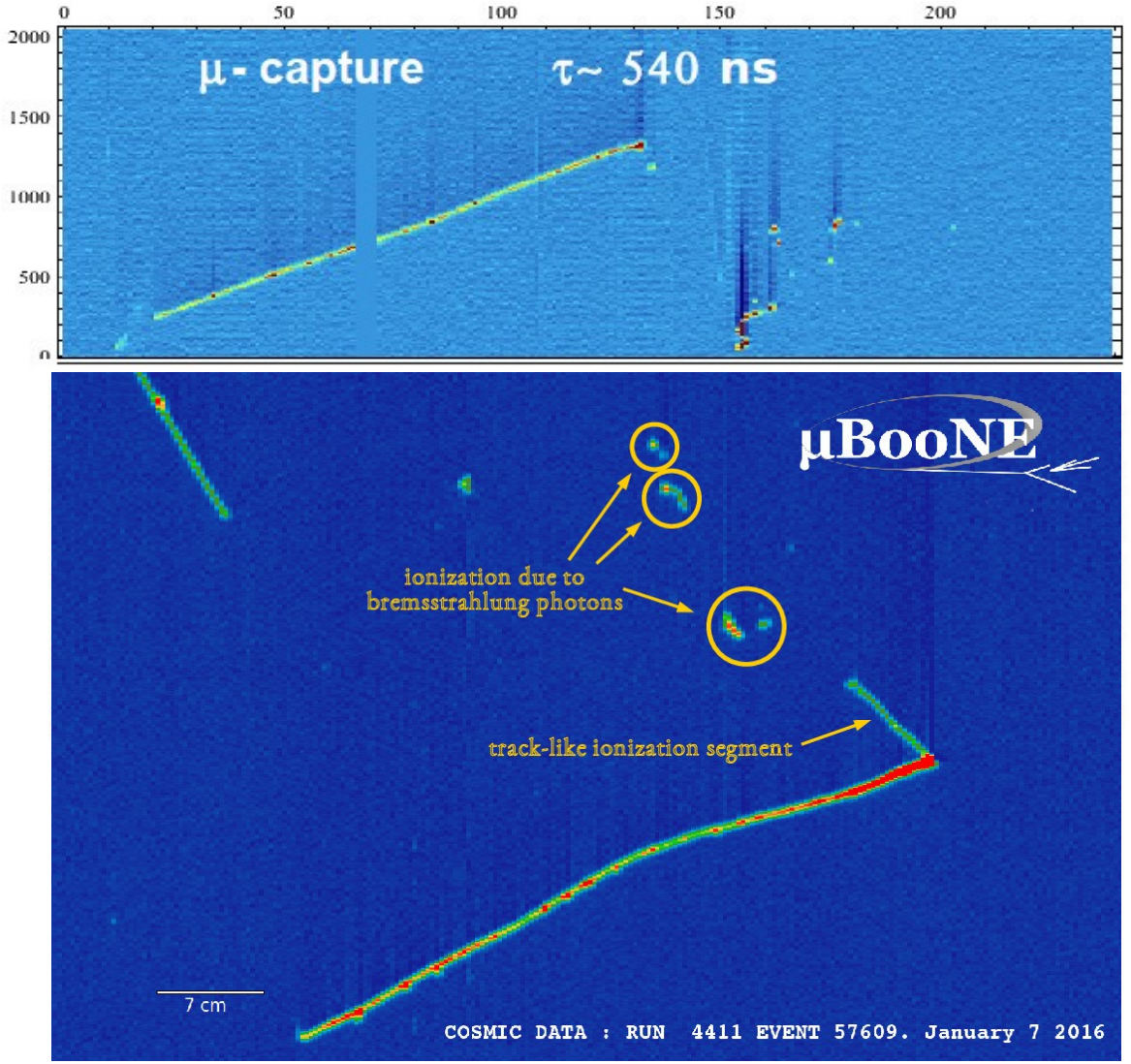
- Roughly 75% percent of the muons are going to be captured by protons in Argon
- Anti-muons can not get captured and decay





Event topologies at DUNE

- This results in distinguishable topologies



- Capture event in ArgoNeuT

  LArIAT Collaboration, arXiv:1406.5560

- Decay event in MicroBooNE

  MicroBooNE Collaboration, JINST 12 (2017) no.09

- Events have to be CONTAINED to allow charge tagging

Analysis

- We simulate the signal from atmospheric neutrinos at DUNE taking into account fluxes (Barr et al), interactions (GENIE) and detector geometry (DUNE)
- Next we try to reproduce this signal with the “wrong” mass ordering
- In the simulation we have to account for systematic uncertainties of the experiment. We also marginalize over the relevant oscillation parameters

Barr, Gaisser, Lipari, Robbins, Phys. Rev. D70 (2004) 023006
GENIE team, Nucl. Instrum. Meth. A614 (2010) 87–104

Analysis

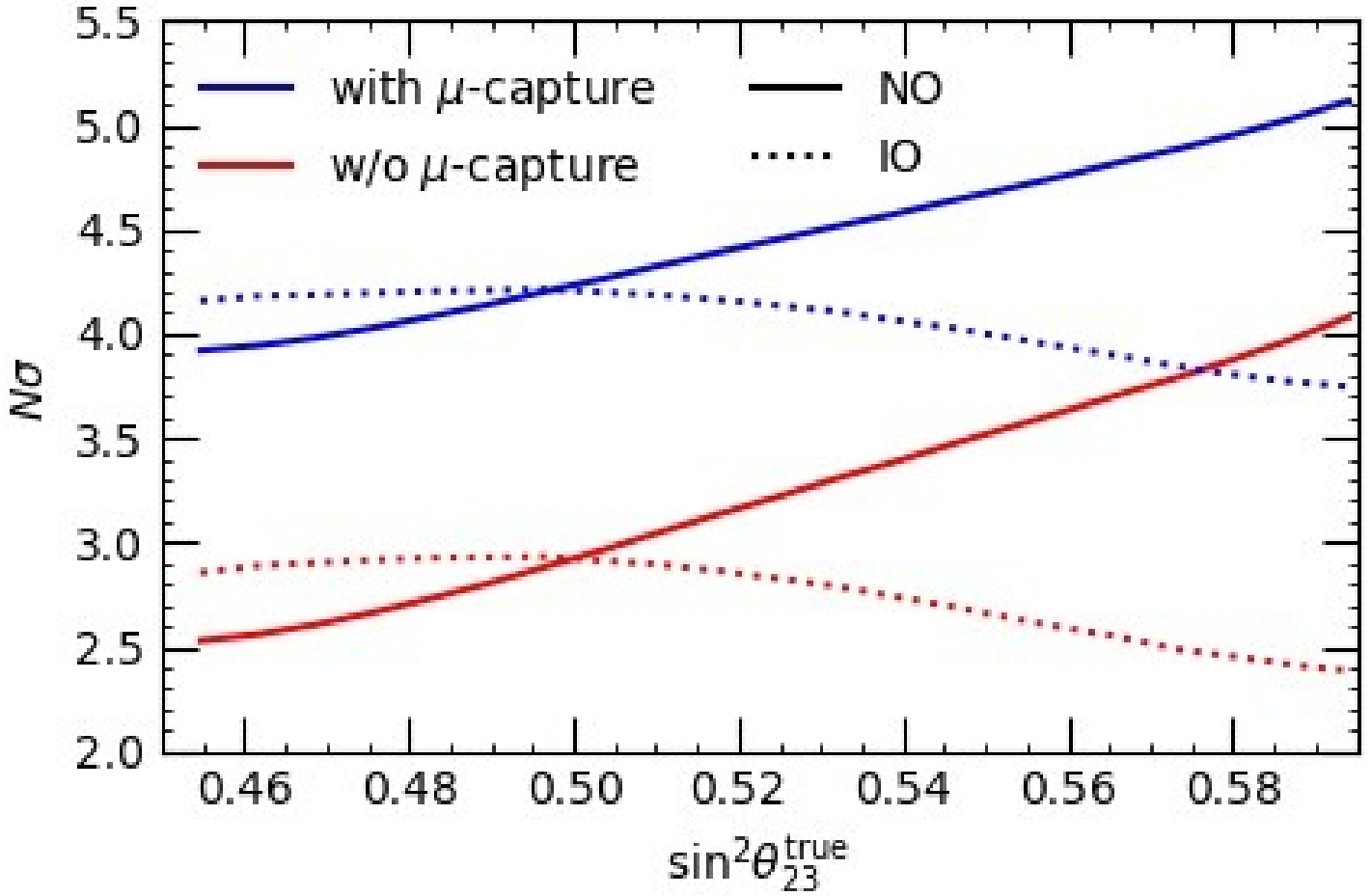
- We perform two different analyses, one without and one with charge tagging via muon capture

$$\chi^2_A(\sin^2\theta_{23}^{\text{true}}) = \min_{\text{sys},\Delta m^2_{31},\theta_{13},\theta_{23}} \left\{ \chi^2_{\mu^-+\mu^+} + \chi^2_{e^-+e^+} \right\}$$

$$\chi^2_B(\sin^2\theta_{23}^{\text{true}}) = \min_{\text{sys},\Delta m^2_{31},\theta_{13},\theta_{23}} \left\{ \chi^{2,\text{cap}}_{\mu} + \chi^{2,\text{rest}}_{\mu} + \chi^2_{e^-+e^+} \right\}$$

Result

- The sensitivity to the mass ordering increases a lot!
- For true normal ordering 4-5σ for all values of the atmospheric angle



CAT, S. Gariazzo, R. Hajjar, O. Mena, M. Sorel, M. Tórtola, arXiv:1905.03589

Conclusions

- DUNE can be used as an experiment for atmospheric neutrinos
- Using charge tagging via muon capture increases the sensitivity to the mass ordering considerably and makes (ATM-) DUNE compatible with experiments like ORCA, PINGU and INO
- The same technique could be used to reduce backgrounds in the beam analysis

Gràcies!