Distinguishing atmospheric muon neutrinos from anti-neutrinos using large collider detectors

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Based on work done with Deep Ghosh, Biswarup Mukhopadhyay, arXiv:2409.THIS_WEEK

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Atmospheric Muon Neutrino vs Antineutrino Flux

Atmospheric neutrinos are produced in the interaction of primary cosmic rays (~90% protons, ~9% alpha particles, small amount of heavier nuclei) with the air molecules in the atmosphere, such as Nitrogen and Oxygen.

Depending on the energy of the primary proton, different mesons can be produced in these interactions:

$$p + Nitrogen \rightarrow \pi^{\pm}, \pi_0, K^{\pm}, K_L, K_S...$$

These mesons subsequently decay to generate a flux of atmospheric muons and neutrinos of different flavours.

At low energies, the most copiously produced mesons are charged and neutral pions, where the charged pions decay before reaching the sea-level (a 10 GeV pion travels ~ 0.5 km before decaying):

$$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$

$$\pi^{-} \rightarrow \mu^{-}\overline{\nu}_{\mu}$$

If the muon energy is less than ~ 2.5 GeV, it also decays within the ~15 km atmosphere:

$$\mu^{+} \rightarrow e^{+}\nu_{e}\overline{\nu}_{\mu}$$

$$\mu^{-} \rightarrow e^{-}\overline{\nu}_{e}\nu_{\mu}$$

Atmospheric Muon Neutrino vs Antineutrino Flux

Therefore for energies of order a GeV or so, we expect both charged pion decays to produce equal number of muon neutrino and muon anti-neutrinos, as long as the muons decay on their way to the sea-level:

$$R_{\nu\overline{\nu}} = \frac{N_{\nu_\mu}}{N_{\overline{\nu}_\mu}} \sim \mathcal{O}(1), \quad \text{upto a } \sim \text{GeV}$$

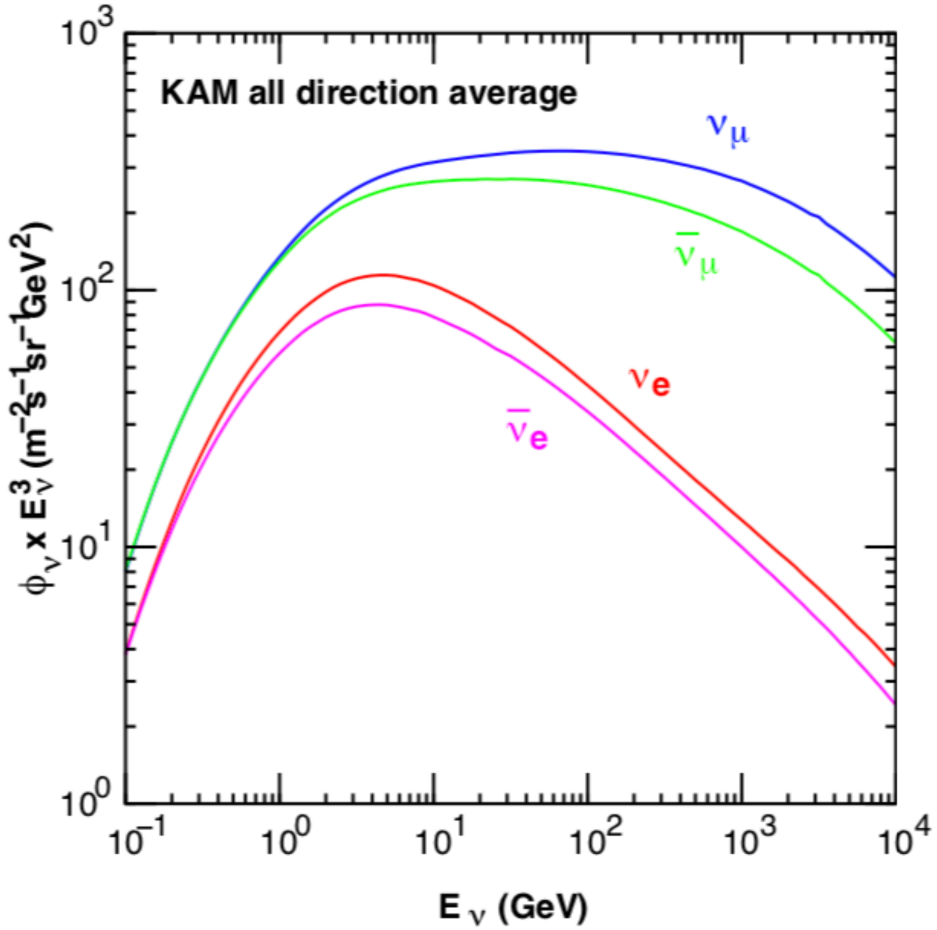
For higher energies, the muons do not decay before reaching sea-level, and the ratio starts to increase, as more $\pi^+(u\overline{d})$ are produced compared to $\pi^-(\overline{u}d)$ in proton interactions with air molecules, due to valence vs sea quark PDF differences.

At even higher energies, K-mesons are also produced in larger numbers, with more $K^+(u\overline{s})$ than $K^-(\overline{u}s)$ with the following dominant decay modes:

$$K^+ \to \mu^+\nu_\mu(64\%), \pi^0\mu^+\nu_\mu(3\%), \pi^+\pi^0(21\%), \pi^+\pi^+\pi^-(6\%), \pi^+\pi^0\pi^0(2\%)$$

Combining these inputs, we see that the ratio $R_{\nu\overline{\nu}}$ starts from 1 at low energies, and then grows at higher energies. Its value, averaged over all zenith angles is around 1.2 at 10 GeV neutrino energy, 1.4 at 100 GeV, 1.5 at 1 TeV, etc, using the flux model of Honda et al.

Fluxes and Flux Ratios



Honda et al, 2015, absolute (anti-)neutrino fluxes

Significant uncertainties in the muon (anti-)neutrino flux ratio

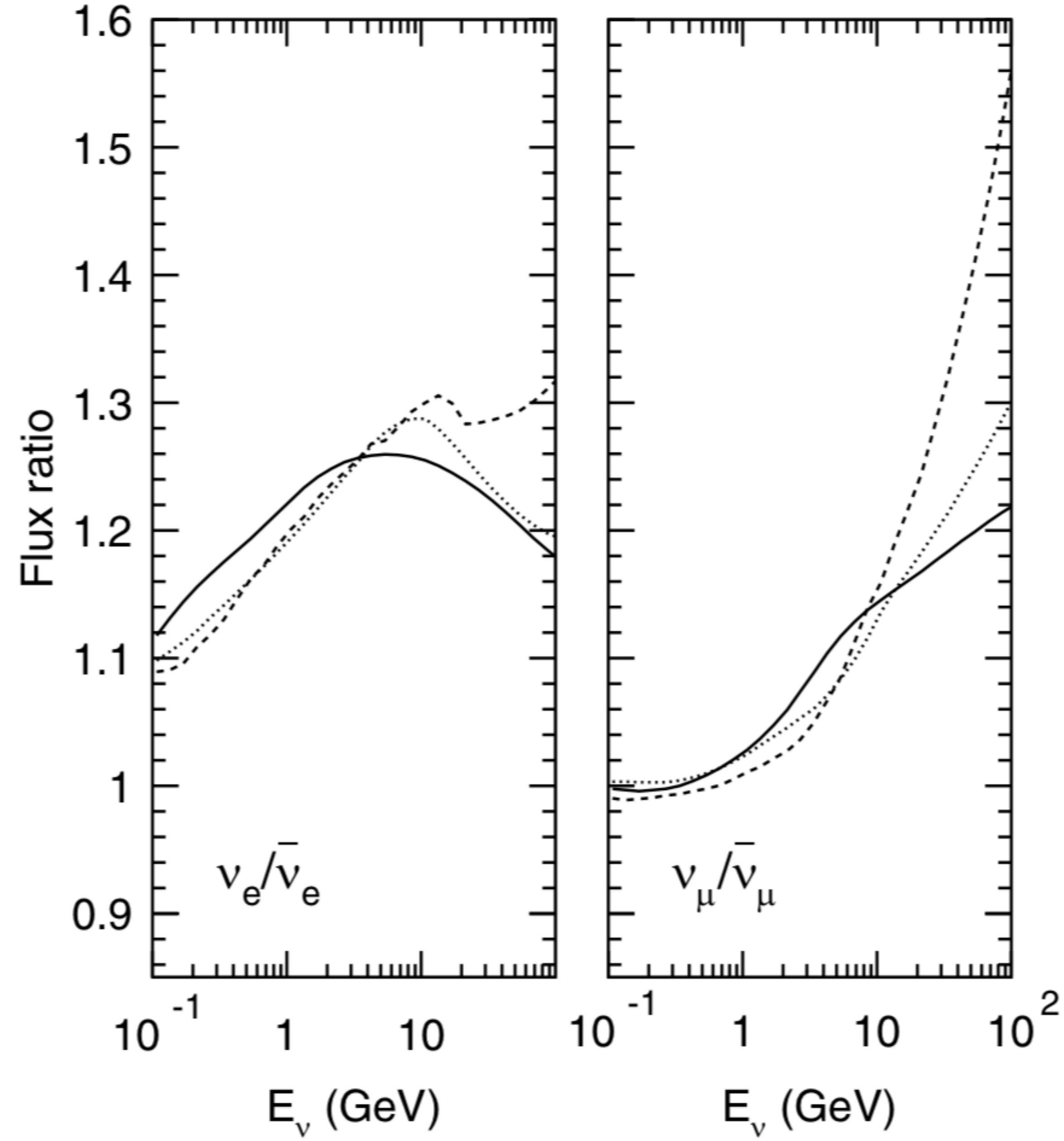
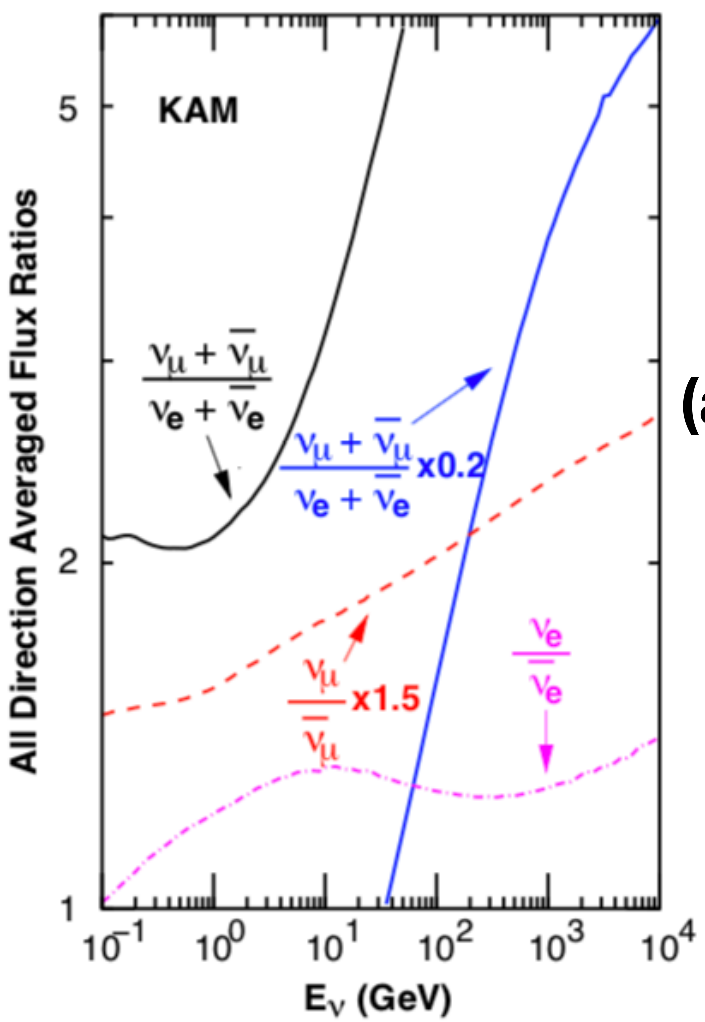


FIG. 4. The flux ratios of ν_μ to $\overline{\nu}_\mu$ and ν_e to $\overline{\nu}_e$ versus neutrino energy. Solid, dashed, and dotted lines show the prediction by [25,28,29], respectively, (same key as Fig. 3).

[25]: Battistoni et al, [28]: Honda et al, [29]:Barr et al



Honda et al, 2015, (anti-)neutrino flux ratios

Atmospheric Neutrino Detection

Although neutrinos are the most abundant cosmic rays at the sea level, their detection is hard due to small neutrino-nucleon scattering cross-sections.

The cross-section for producing a charged lepton (averaged over neutrino and anti-neutrino) in a broad energy range is approximately:

$$\sigma \simeq 0.5 \times 10^{-38}\mathrm{cm}^2 \times E_\nu\ (\mathrm{GeV})$$

The neutrino flux around 1 GeV energy, summed over all directions is around: $1\mathrm{cm}^{-2}\mathrm{s}^{-1}$

The interaction rate for 1 GeV atmospheric neutrinos is thus of order:

$$1\,\frac{\nu}{\mathrm{cm}^2\mathrm{s}} \times \frac{0.5 \times 10^{-38}\mathrm{cm}^2}{\mathrm{nucleon}} \times \frac{6 \times 10^{32}\mathrm{nucleons}}{\mathrm{kiloton}} \times \frac{3.15 \times 10^7\mathrm{s}}{\mathrm{year}} \sim 100\,\frac{\mathrm{neutrino\ interactions}}{\mathrm{kiloton\ year}}$$

Hence to study the charged current interactions of neutrinos, we need a detector of **at least few kilotons fiducial mass**, running for **few hundred live days**

In addition, to distinguish neutrinos from anti-neutrinos using charged current processes, we need a detector with an ability to **distinguish a charged lepton from an anti-lepton, possibly with a magnetic field**

Atmospheric Muon Neutrino vs Antineutrino: MINOS experiment

Although the MINOS experiment was operated primarily using a neutrino beam, it carried out a study of atmospheric neutrinos when the beam was OFF.

The MINOS far detector had a mass of 5.4 kton, but only around 4 kton fiducial mass was available for atmospheric neutrino studies.

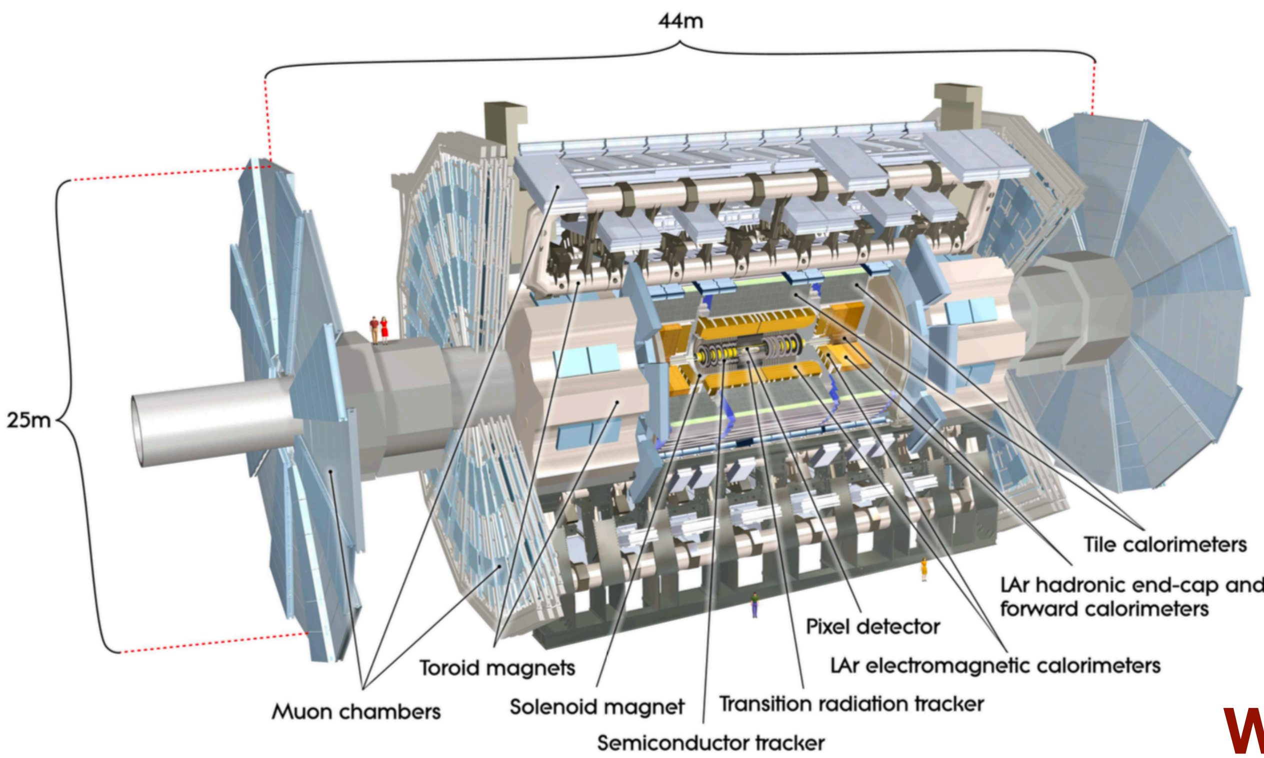
It had a magnetic field of 1.3 T in the far detector, making neutrino vs anti-neutrino studies feasible.

Measurements of atmospheric neutrino and antineutrino interactions in the MINOS Far Detector were made, based on 2553 live-days of data. A total of 2072 candidate events are observed. These are separated into 905 contained-vertex muons and 466 neutrino-induced rock-muons, both produced by charged-current interactions.

For contained vertex events they reported a ratio of muon neutrino to anti-neutrino of about 2.2 (with a 10% statistical error) and for neutrino-induced rock muons a ratio of 1.6 (with a 15% statistical error). Energy dependence of this ratio was not reported.

MINOS Collaboration, arXiv:1208.2915

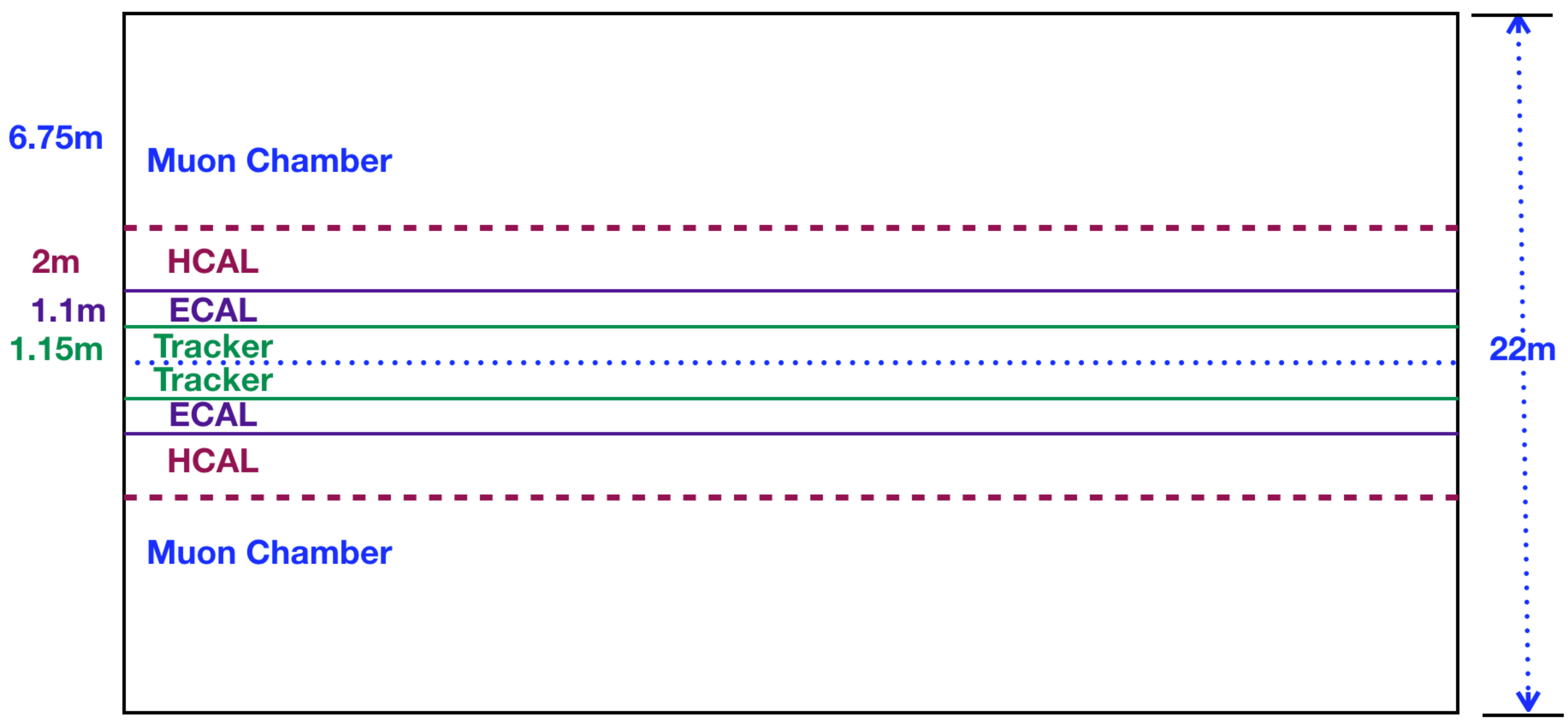
The ATLAS Detector @ LHC: Largest Collider Detector Ever Built



Overall weight of ATLAS: 7000 tons

Magnets: 2 T for the inner detector, 0.5 T (barrel), 1 T for muon end-caps

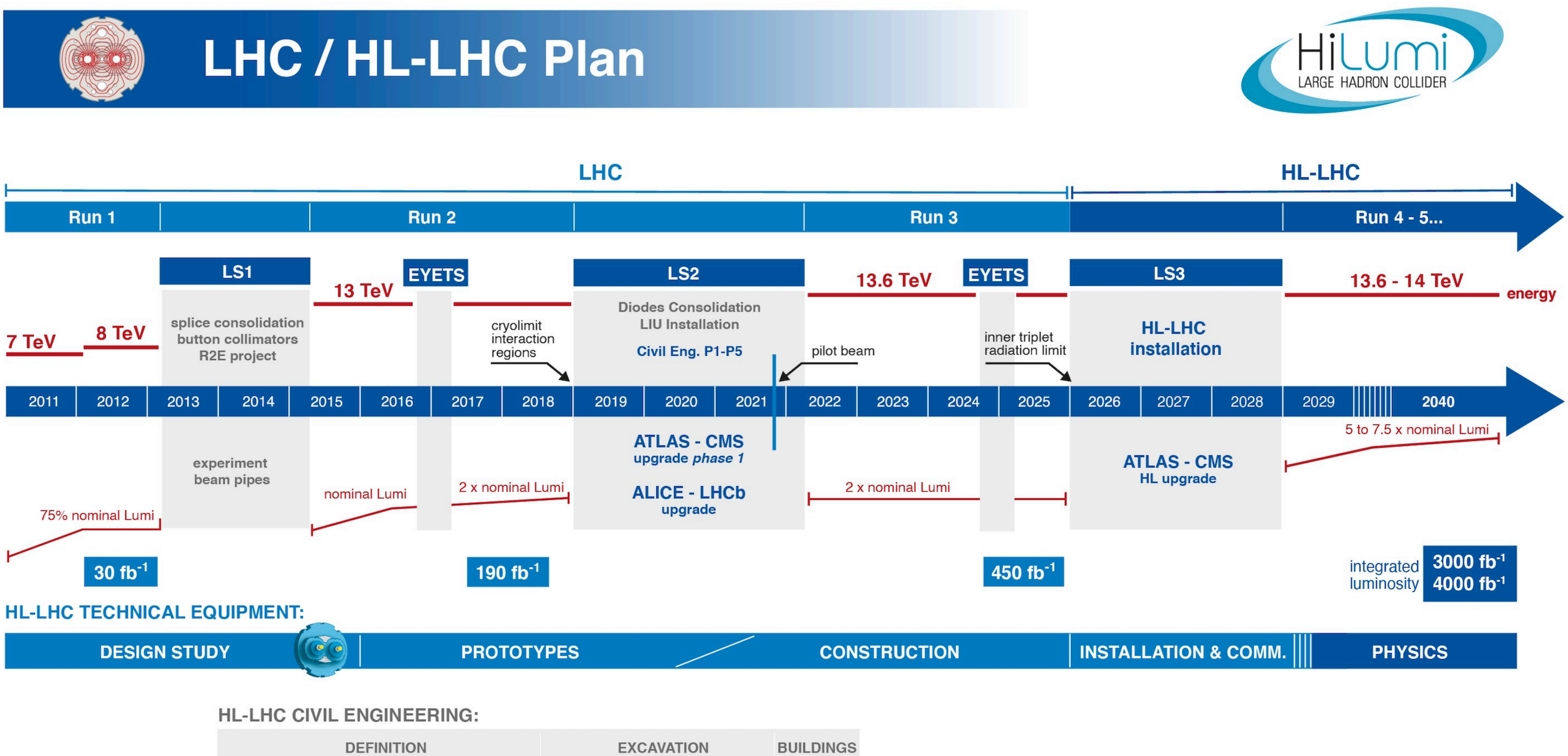
Weight of ATLAS HCAL (mostly iron): 4000 tons



How much time for neutrino studies using ATLAS?

The LHC beams are not in circulation during the winter months, while the detector and magnetic fields are ON during most of this period (for cosmic ray studies and detector alignment and other checks). If around 100 days per year are available with the detector/B-fields ON, but the LHC beams OFF, then in 10 years, 1000 live-days for neutrino physics should be feasible. If instead around 60 days/year are available, 15 years will be necessary for the same statistics.

Neutrinos@ATLAS: F. Vannucci, Petcov & Schwetz (2006), Kopp & Lindner (2007), Wen et al (2024)

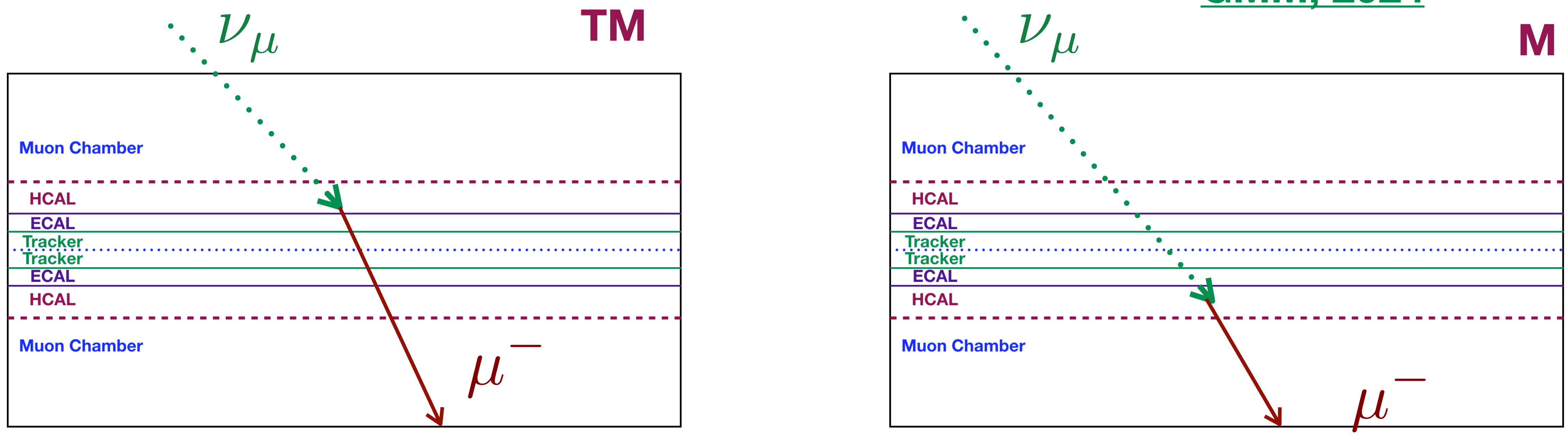


Atmospheric Neutrino induced Muons @ ATLAS detector

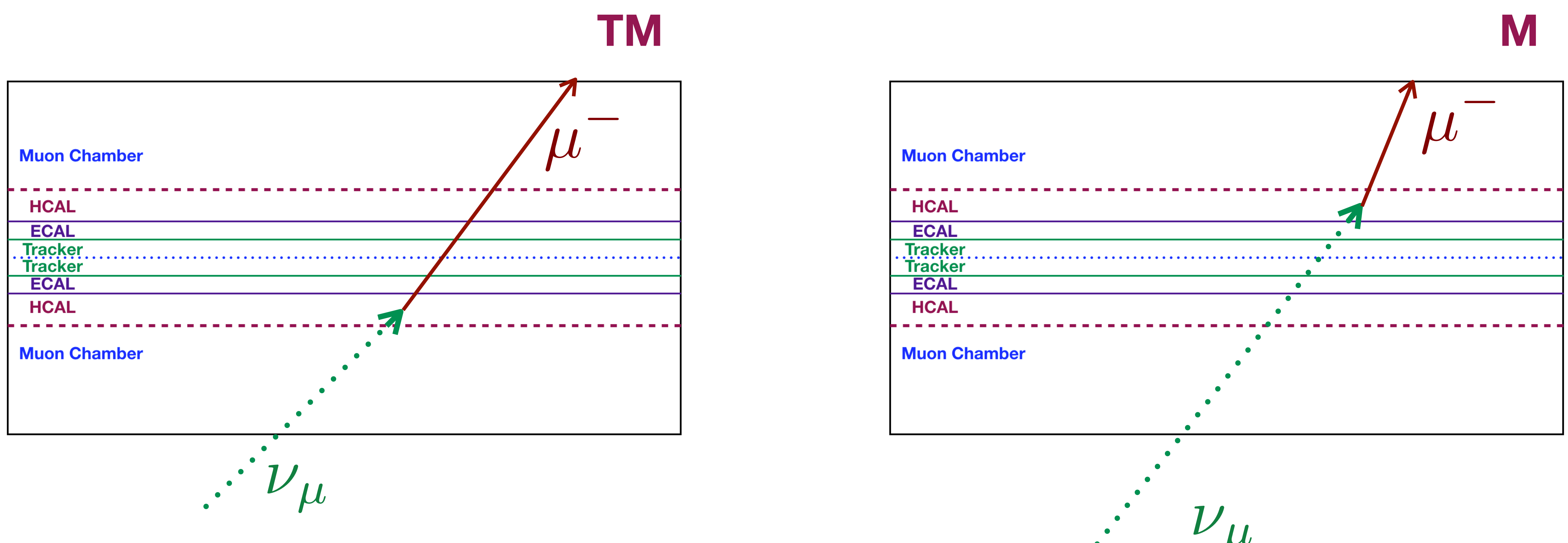
TM: Hits in Tracker and Muon Chamber: Necessary for low-energy muons

M: Hits only in Muon Chamber: Works for only high-energy muons

GMM, 2024



Downward going contained vertex events



Upward going contained vertex events

Eliminating Backgrounds: Cosmic Ray Muons in ATLAS

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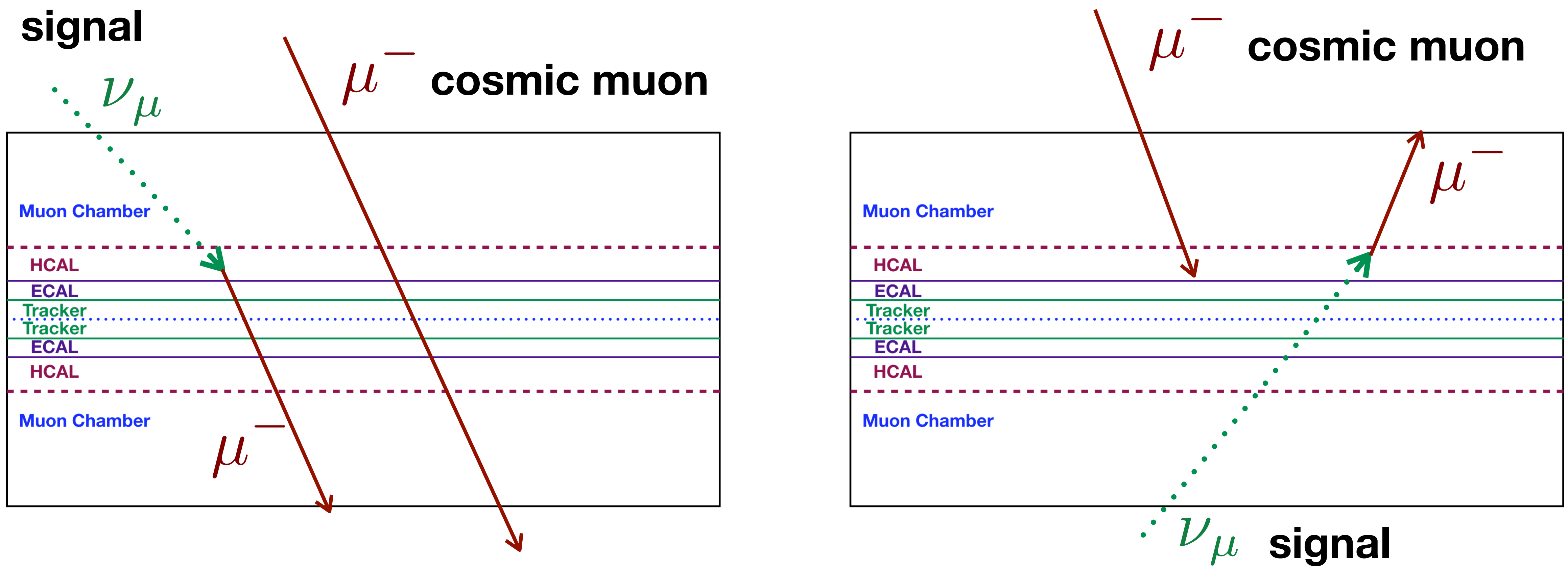


Down-going cosmic ray muons: cannot mimic down-going contained vertex atmospheric neutrino signal — cosmic muons first necessarily hit the upper muon chamber, while the signal muon is generated 7m deeper in the detector at the HCAL.

For the upward going contained-vertex signal with no hits at tracker first (i.e., produced at the upper HCAL), timing information is necessary from the RPC plates of the muon chamber. The cosmic muons hit the top-most layer earliest, and conversely for the signal muons. The timing resolution of RPC's is around 1.5 ns, and a muon travels the 7m muon chamber in about 23 ns, and the full ATLAS width of 22 m in about 73 ns.

Neutrino-Nucleon Scattering Rates: some more details

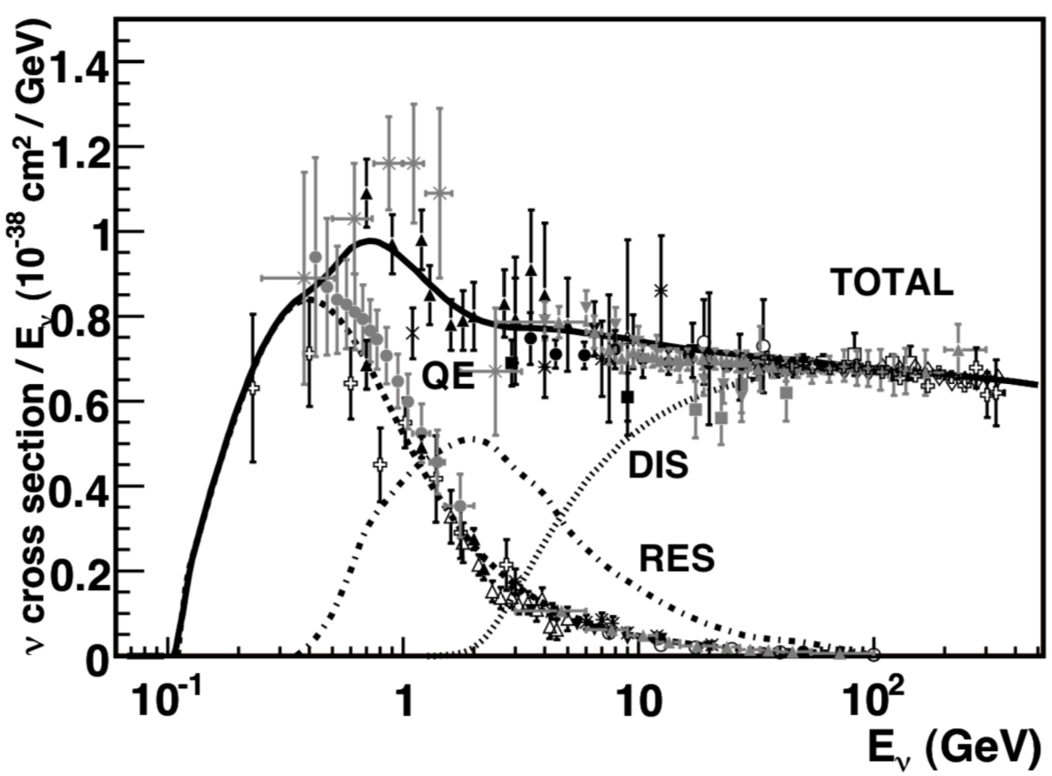
At low momentum transfer, there is a quasi-elastic process (nucleon changes type but does not break up): $\nu_\mu + n \rightarrow \mu^- + p$

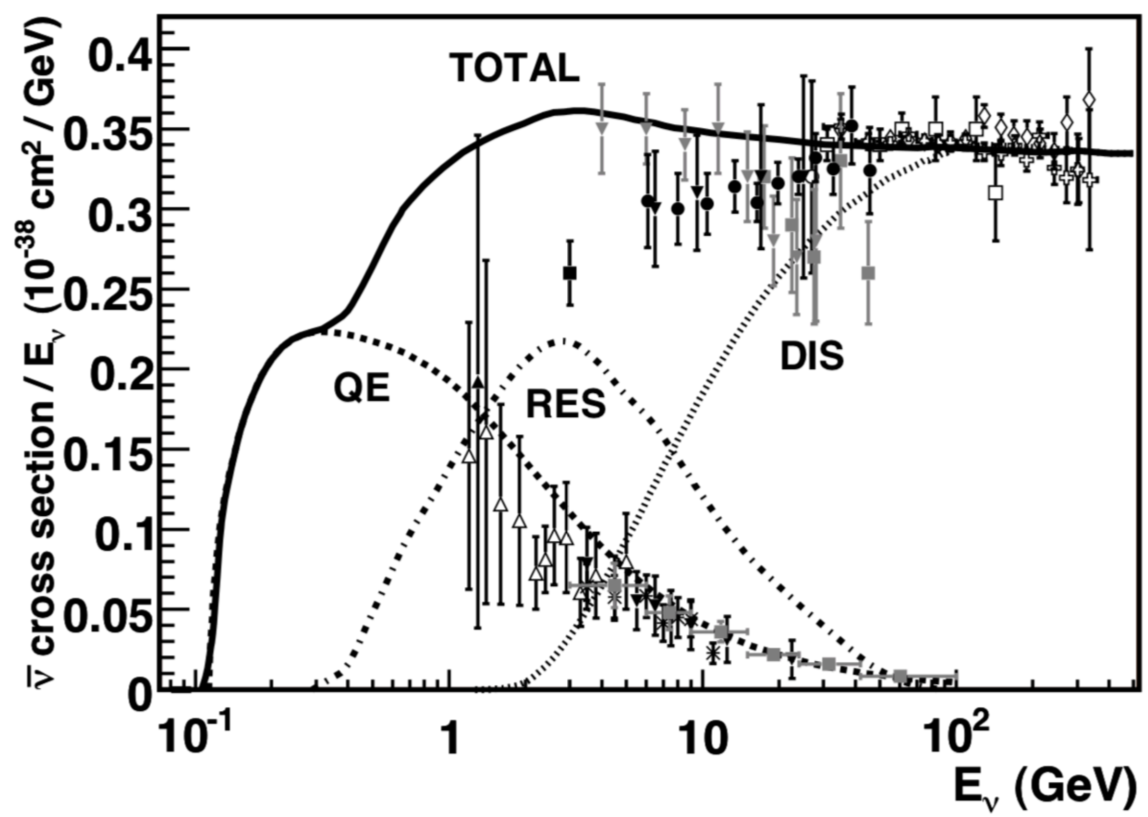
At slightly higher neutrino energies (a few GeV), resonant inelastic processes such as the following are observed: $\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + p + \pi^0$

At higher energies still, neutrino interactions are dominated by the neutrino deep inelastic scattering process:

$$\nu_\mu + N(n,p) \rightarrow \mu^- + X$$
$$\overline{\nu}_\mu + N(n,p) \rightarrow \mu^+ + X$$

Formaggio, Zeller, 2013



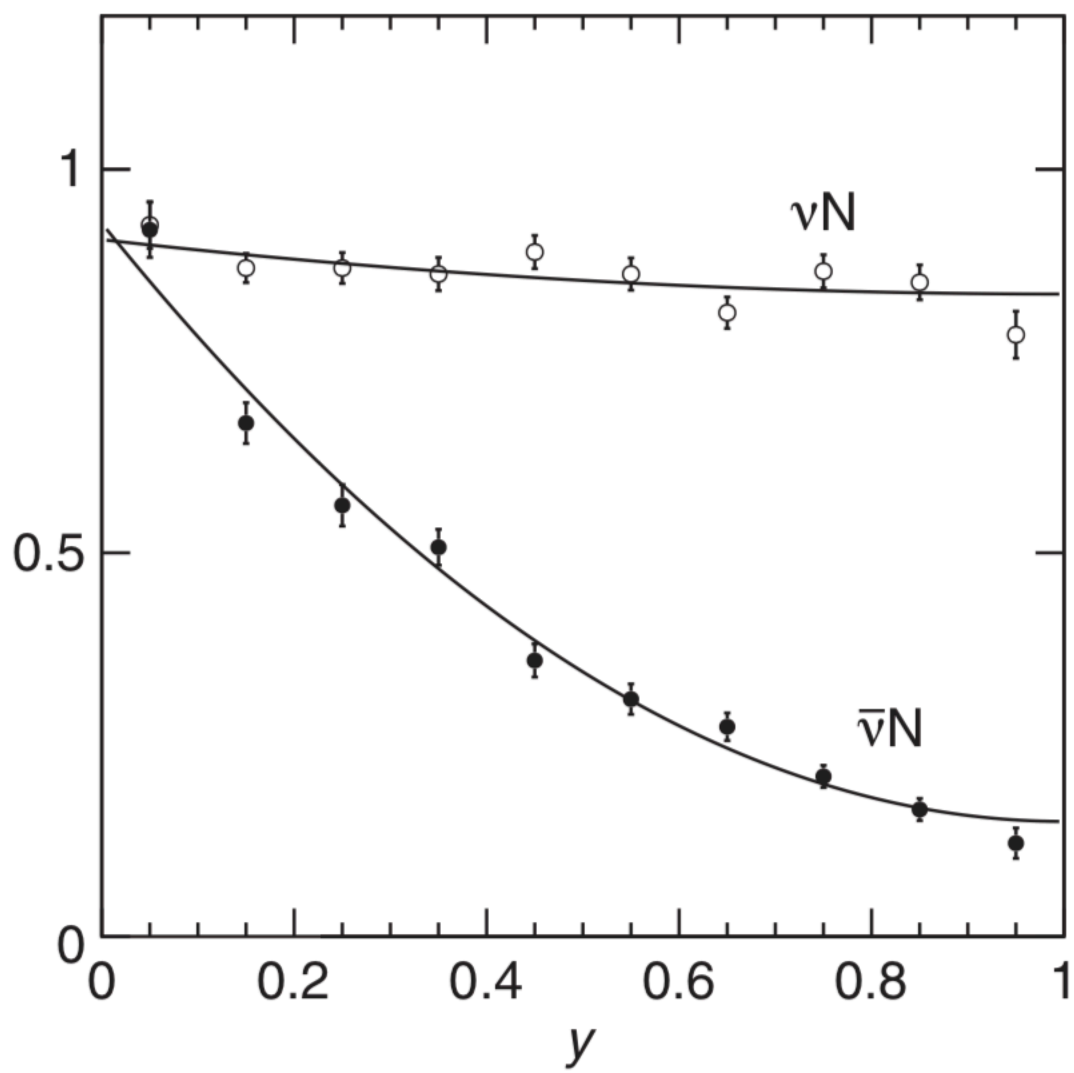


Neutrino cross-sections are larger than anti-neutrino cross-sections

Neutrino-Nucleon Deep Inelastic Scattering Rates

$$\frac{d\sigma_{\nu N \to \mu^- X}}{dE_\mu} \simeq \frac{G_F^2 m_N}{\pi}\left[0.4 + 0.1\frac{E_\mu^2}{E_\nu^2}\right]$$

$$\frac{d\sigma_{\overline{\nu} N \to \mu^+ X}}{dE_\mu} \simeq \frac{G_F^2 m_N}{\pi}\left[0.4\frac{E_\mu^2}{E_\nu^2} + 0.1\right]$$



$$y = 1 - \frac{E_\mu}{E_\nu}$$

Contained Vertex Events at ATLAS

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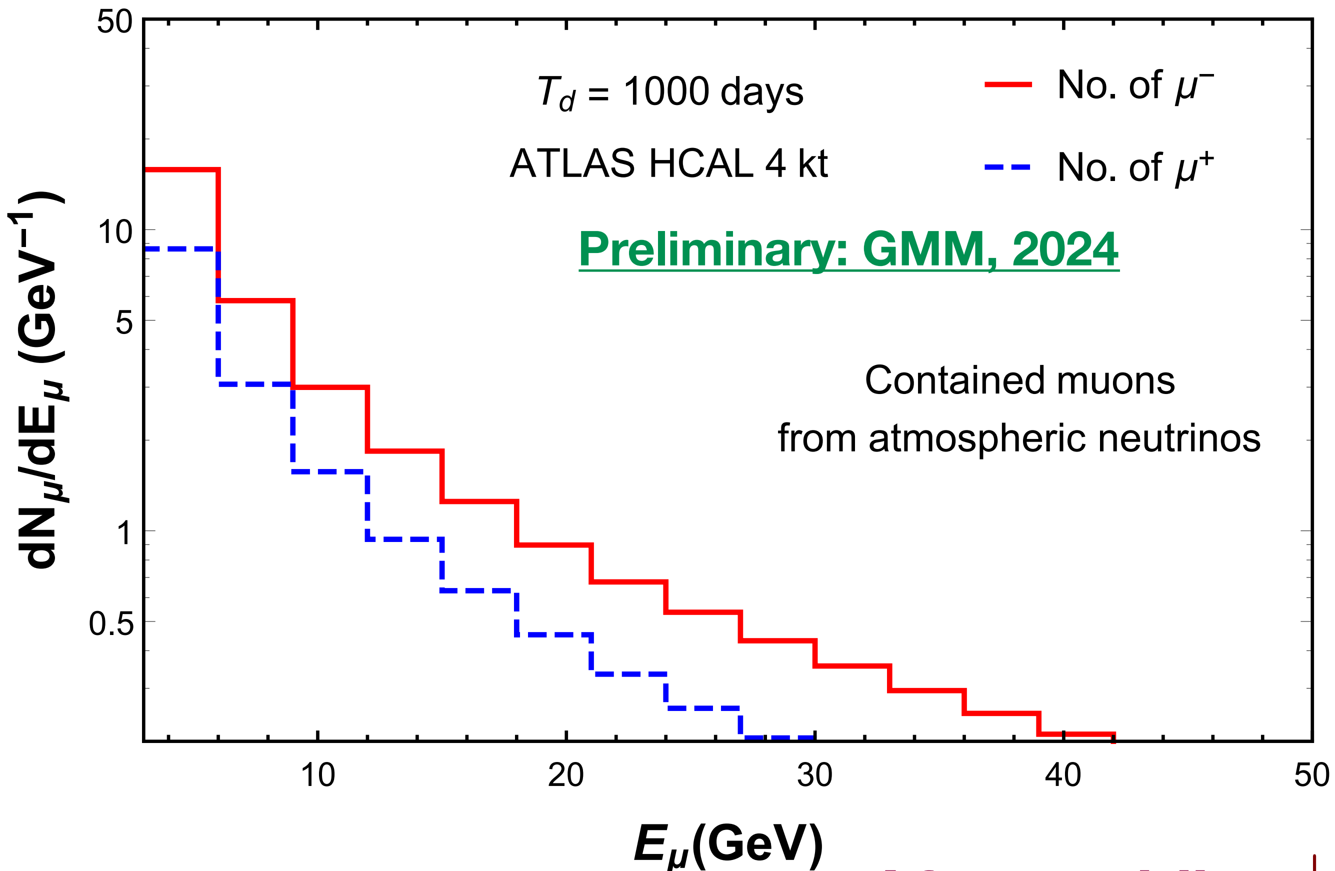
11 kton-year exposure (1000-live days)



Before rapidity and event selection cuts

E_μ	N_{μ^-}	N_{μ^+}	N_{μ^-}/N_{μ^+}
> 3 GeV	102	54	1.89
> 5 GeV	64	33	1.94
> 10 GeV	33	17	1.94
> 20 GeV	17	8	2.13

TM: Tracker + Muon Chamber Hits

M: Only Muon Chamber Hits

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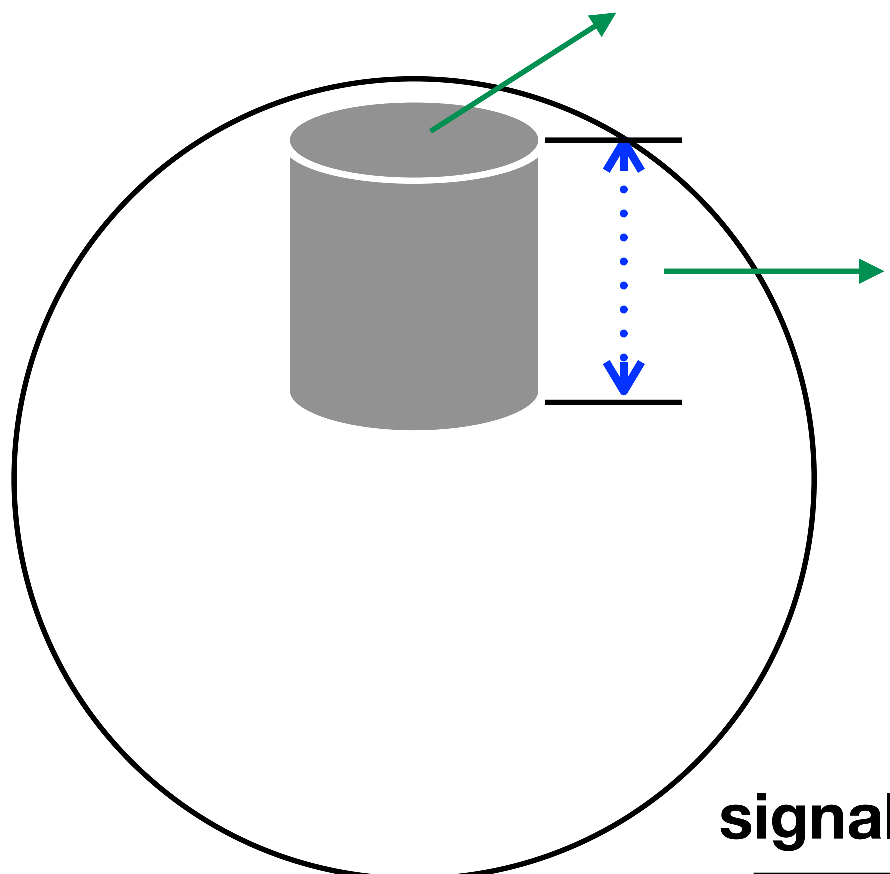
After rapidity $|\eta| < 2.5$ and event selection cuts

Energy	N_{μ^-}	N_{μ^+}	N_{μ^-}/N_{μ^+}	Category
$3 \leq E_\mu \leq 10$ GeV	31	17	1.82	Only TM
$5 \leq E_\mu \leq 10$ GeV	14	7	2.00	Only TM
$E_\mu > 10$ GeV	30	15	2.00	TM & M
$E_\mu > 20$ GeV	15	7	2.14	TM & M
Total: $E_\mu \geq 3$ GeV	63	32	1.97	

External Upward-going Events at ATLAS

ATLAS Effective Area A ~ 22m x 40m ~ 880 m²



Rock column of effective muon range r

Number of nucleons =

$$\rho_{\text{rock}} \times A \times r \times N_A$$

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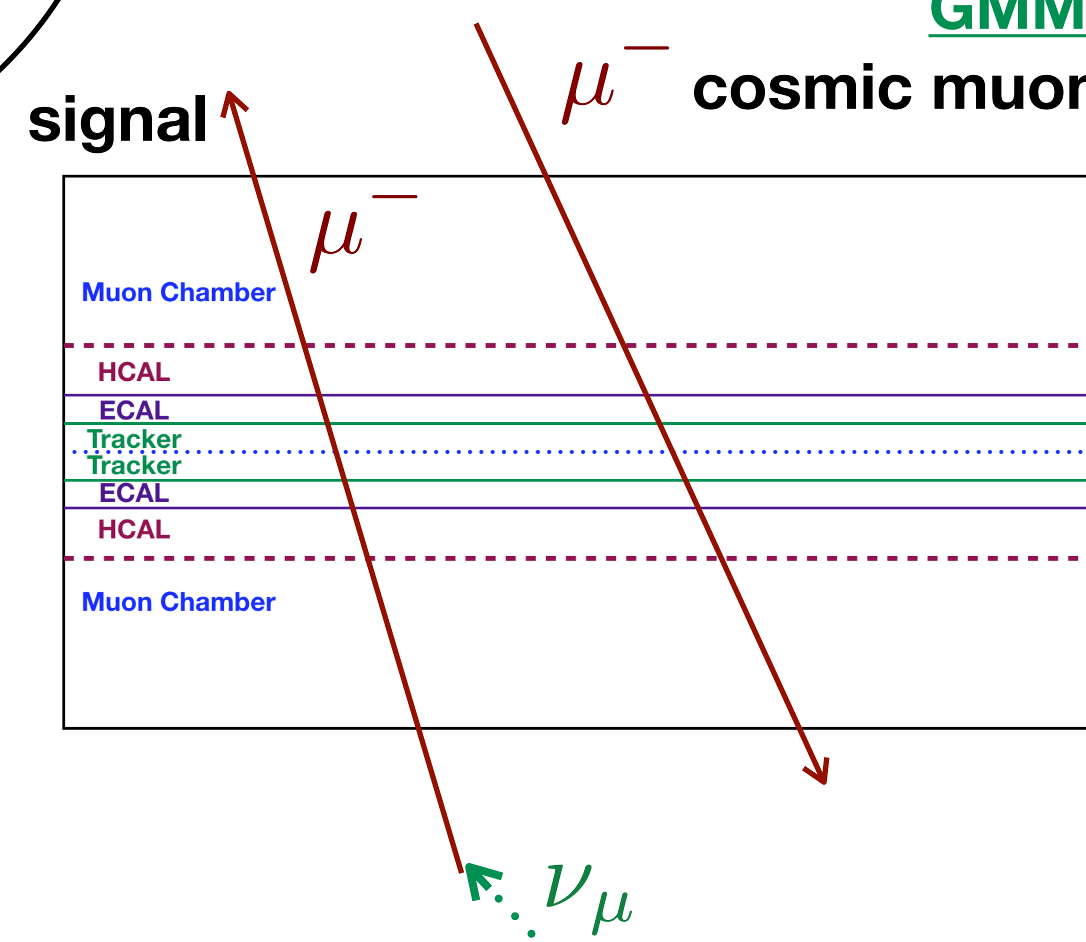

Timing information is the key in distinguishing these events from cosmic ray muons

Event rate much larger due to the large effective mass for the rock column, higher the muon energy, higher the range

External Upward-going Events at ATLAS

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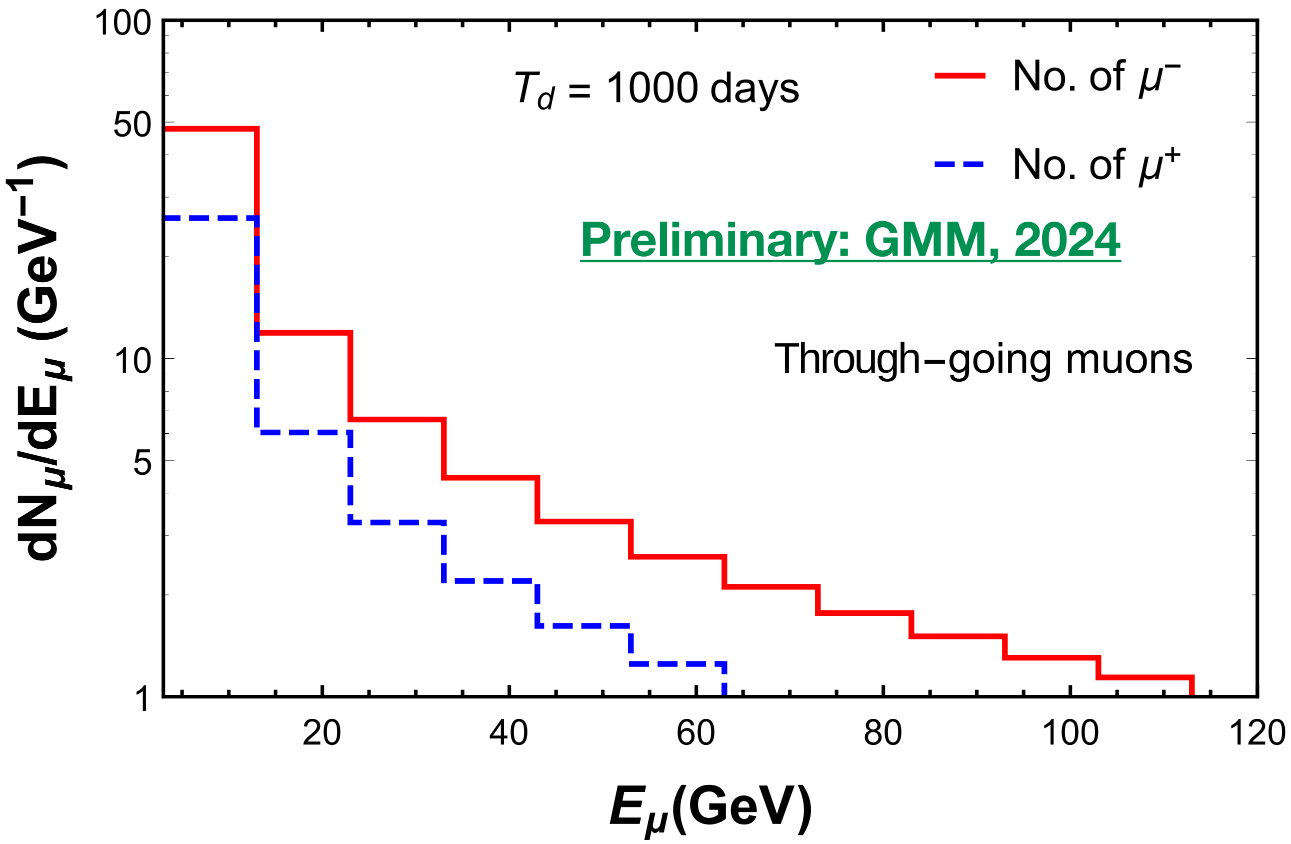

Before event selection cuts

E_μ	N_{μ^-}	N_{μ^+}	N_{μ^-}/N_{μ^+}
> 3 GeV	700	341	2.05
> 5 GeV	624	300	2.08
> 10 GeV	517	244	2.12
> 20 GeV	409	189	2.16

After event selection cuts with $|\eta| < 2.5$

Energy	N_{μ^-}	N_{μ^+}	N_{μ^-}/N_{μ^+}
$3 \leq E_\mu \leq 10$ GeV	164	87	1.82
$5 \leq E_\mu \leq 10$ GeV	96	50	1.89
$E_\mu > 10$ GeV	464	219	1.92
$E_\mu > 20$ GeV	368	171	2.12
Total: $E_\mu \geq 3$ GeV	630	307	2.05

Energy dependence of the charged muon ratio

After selection cuts

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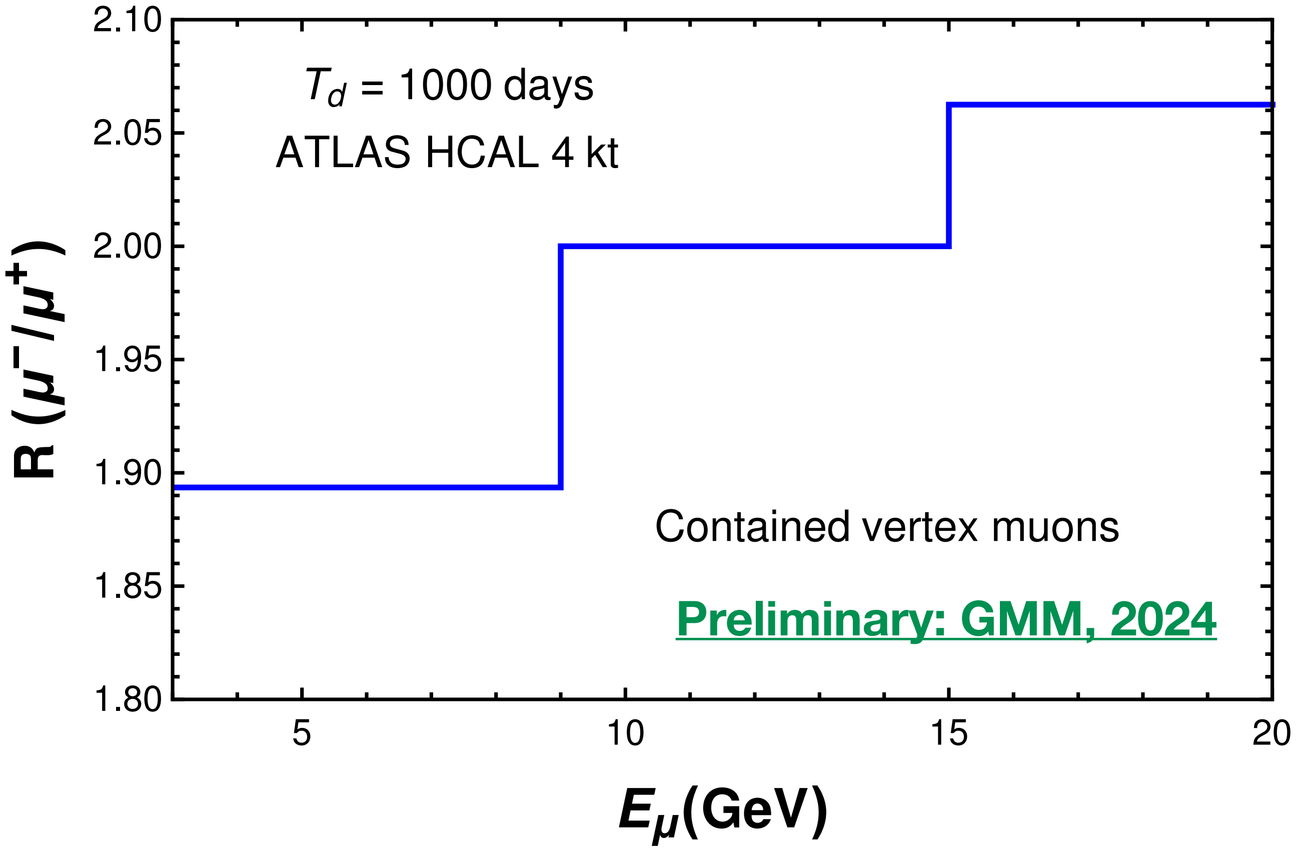

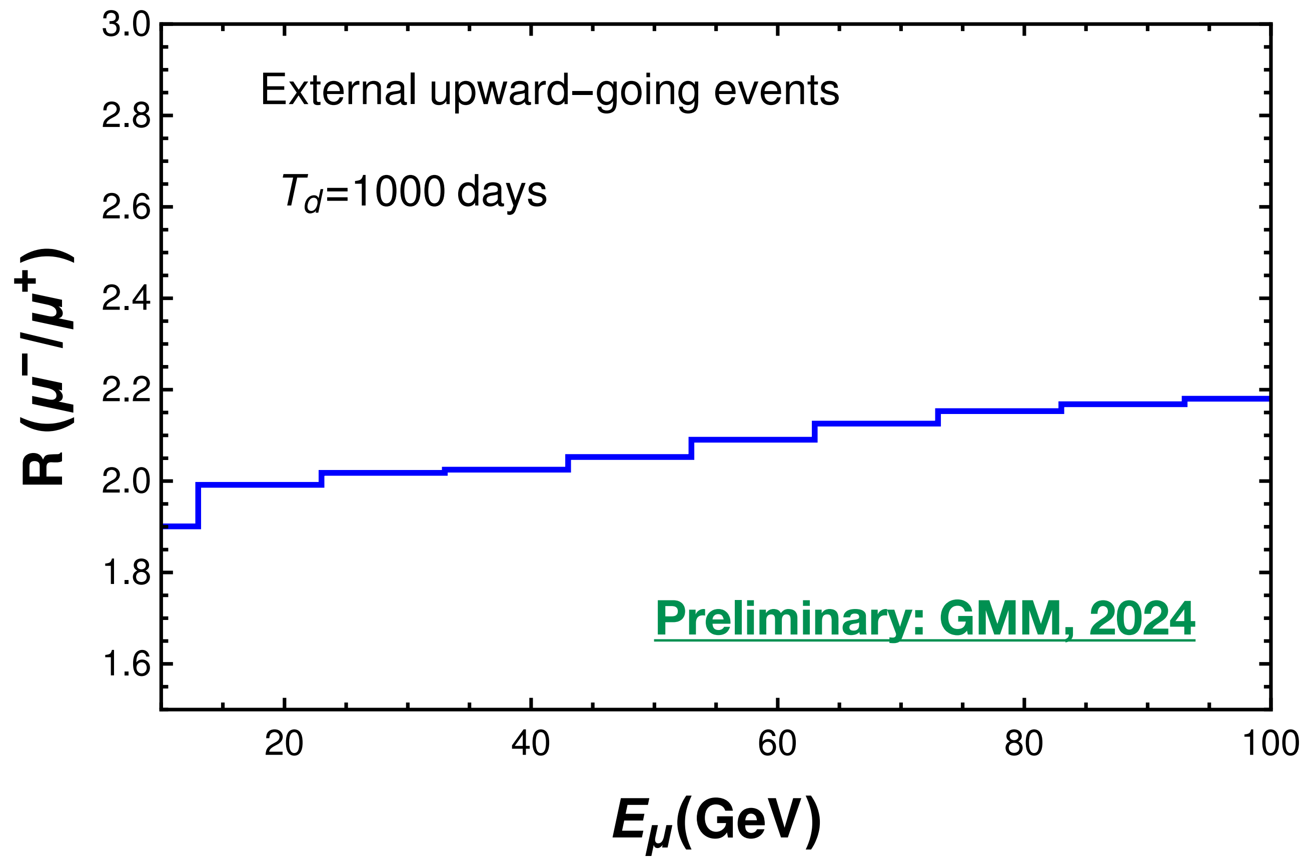

Summary

The ratio of atmospheric muon neutrinos and anti-neutrinos is an important quantity, for which there is still a large uncertainty in the prediction of the flux models.

Therefore, it is important to be able to directly measure this quantity in neutrino physics experiments, as a function of neutrino energy.

However, most neutrino detectors do not distinguish between muon neutrinos and anti-neutrinos.

Magnetized detectors can discriminate on an event-by-event basis between (anti-)neutrino induced events by measuring the electric charge of the (anti-)muon: MINOS experiment had such a detector.

The large collider detector ATLAS at CERN LHC can be used for this purpose during the periods when the LHC beams are OFF — it is sufficiently heavy for neutrino physics (the hadron calorimeter weighs 4 kilotons), and finely instrumented to reject cosmic ray muon backgrounds.

While contained-vertex events are the most striking, upward going outside events have a larger rate due to the much larger fiducial mass available from the rock-column in the earth below the detector.