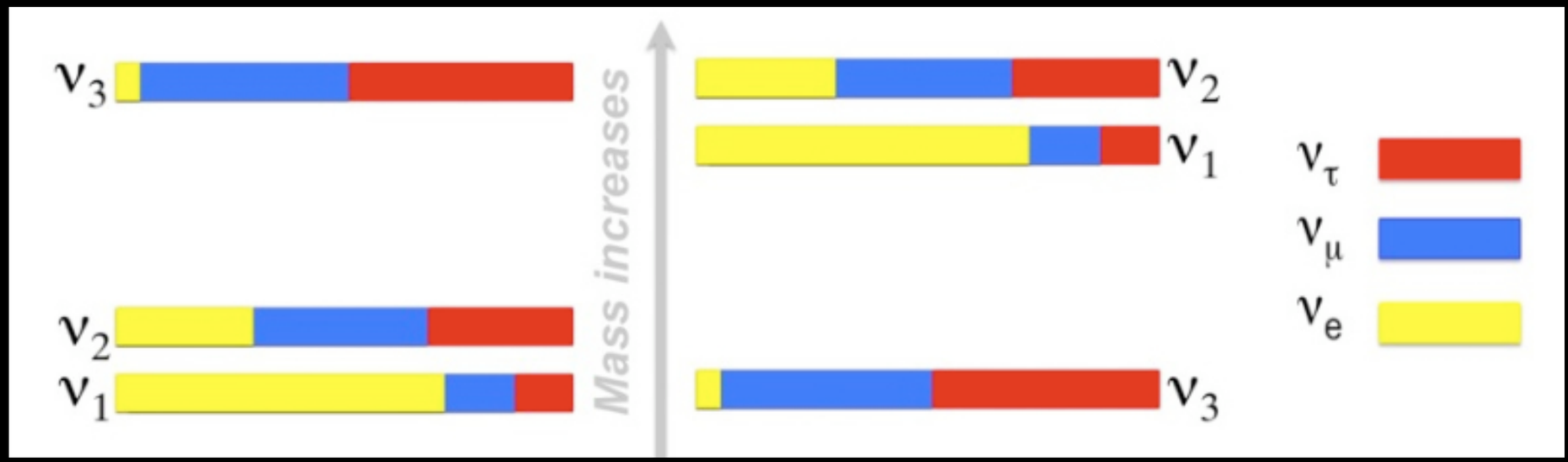
Mass Hierarchy, Muon Disappearance and Artificial Neutrino Beams



Francesco Vissani, INFN -- LNGS & GSSI
with Giulia Pagliaroli and Carolina Lujan-Peschard. Based on **arXiv:1301.4577**

Before the measurement of theta13...

- **Few theories with large theta13, e.g.:**
  - *those with random Yukawa entries --just a "setup"*
  - *supersymmetric SO(10) -- not a complete theory*
- **Few studies of hierarchy in this case:**
  - *Antares, IceCUBE*
  - *Monolith*
  - *Mton Argon Detector (Hyper-ICARUS)*

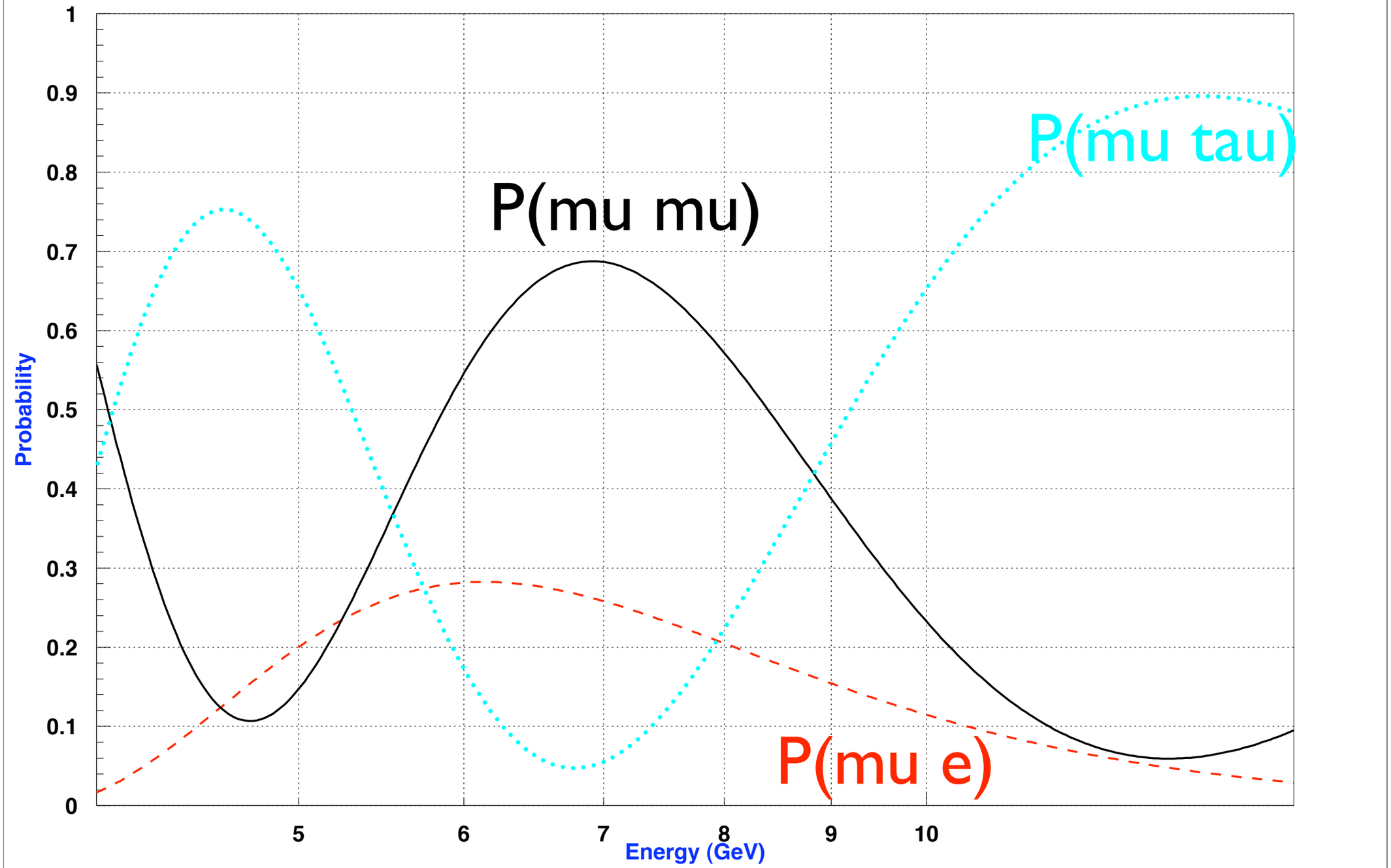
Present attempts to know the mass hierarchy...

- INO, 50kton of magnetized iron
- IceCUBE .... PINGU
- Antares/Nemo/Km3NET ..... ORCA

PINGU and ORCA in evolution, with the aim of optimizing the physics potential for the discrimination of mass hierarchy, especially using atmospheric neutrinos -- this workshop.

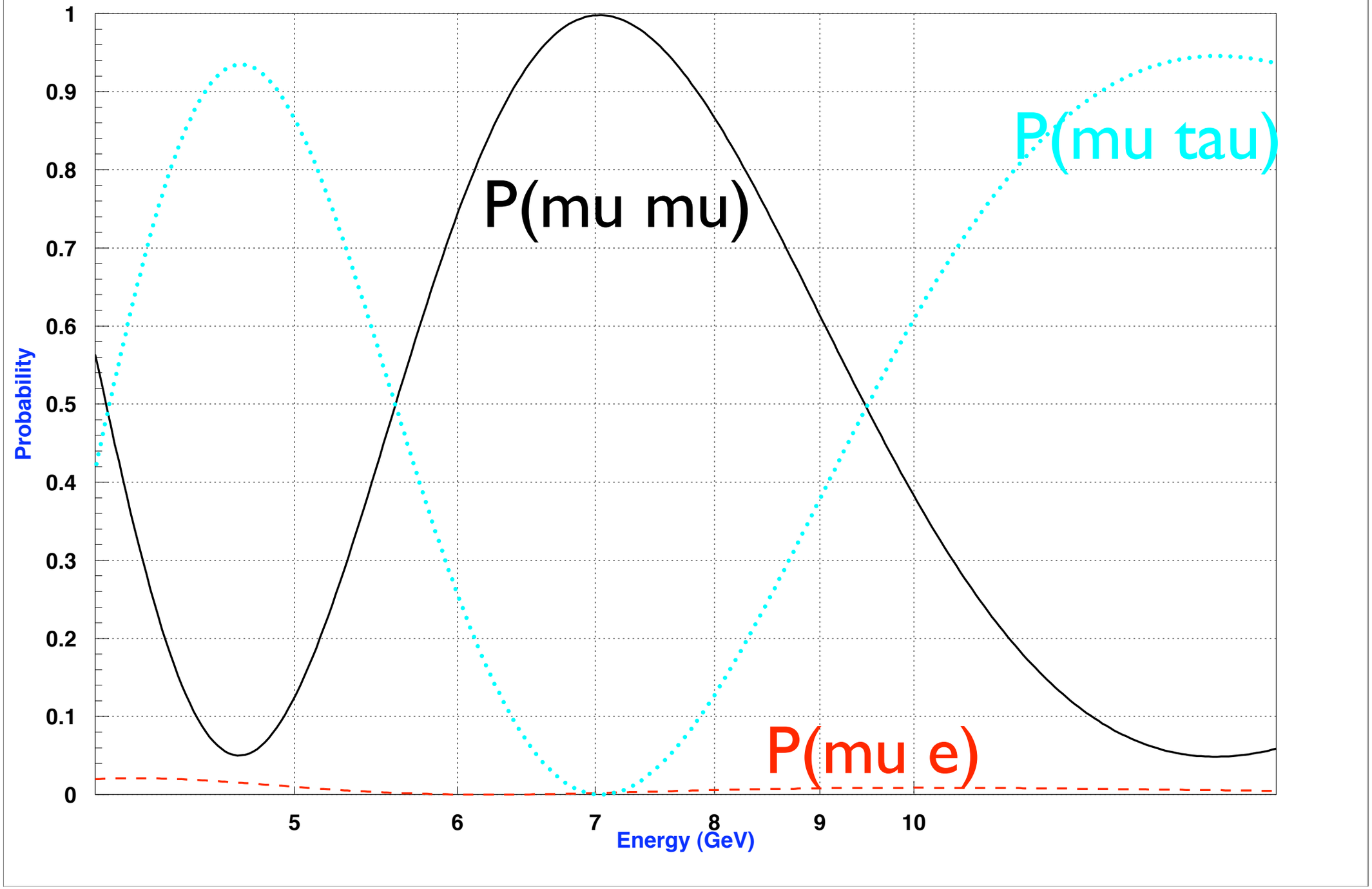
WHY NOT ARTIFICIAL NEUTRINOS?

- Now that theta13 is know, planning an ideal experiment for mass hierarchy is possible.
- The matter effect indicates 6-8 GeV as optimal energy.
- A large enough oscillation phase dictates distances of 6000-8000 km as optimal.
- Let us have a close look to the oscillation probabilities!



NORMAL HIERARCHY, 7000 km

http://pcbat1.mi.infn.it/~battist/cgi-bin/oscil/index.r



INVERSE HIERARCHY, 7000 km

http://pcbat1.mi.infn.it/~battist/cgi-bin/oscil/index.r

First: Formulate the Idea

- *The matter effect implies also large muon disappearance.*
- *A Distance of 6000-8000 km amplifies this effect.*
- *Present experiments have Distance~700-800 km & Mass~few kton. The events scale as Mass/Distance^2: thus, we need more mass.*
- *1 Mton=(100m)^3 is enough: we want a `small' muon telescope.*
- *Moreover, we want to identify muons of a few GeV. Thus, the telescope must be sufficiently `fine grained'.*

Practical Questions Follow...

Consider a muon detector of 1 Mton able to see 10-40 meters tracks --- 1 GeV is about 4 meters.

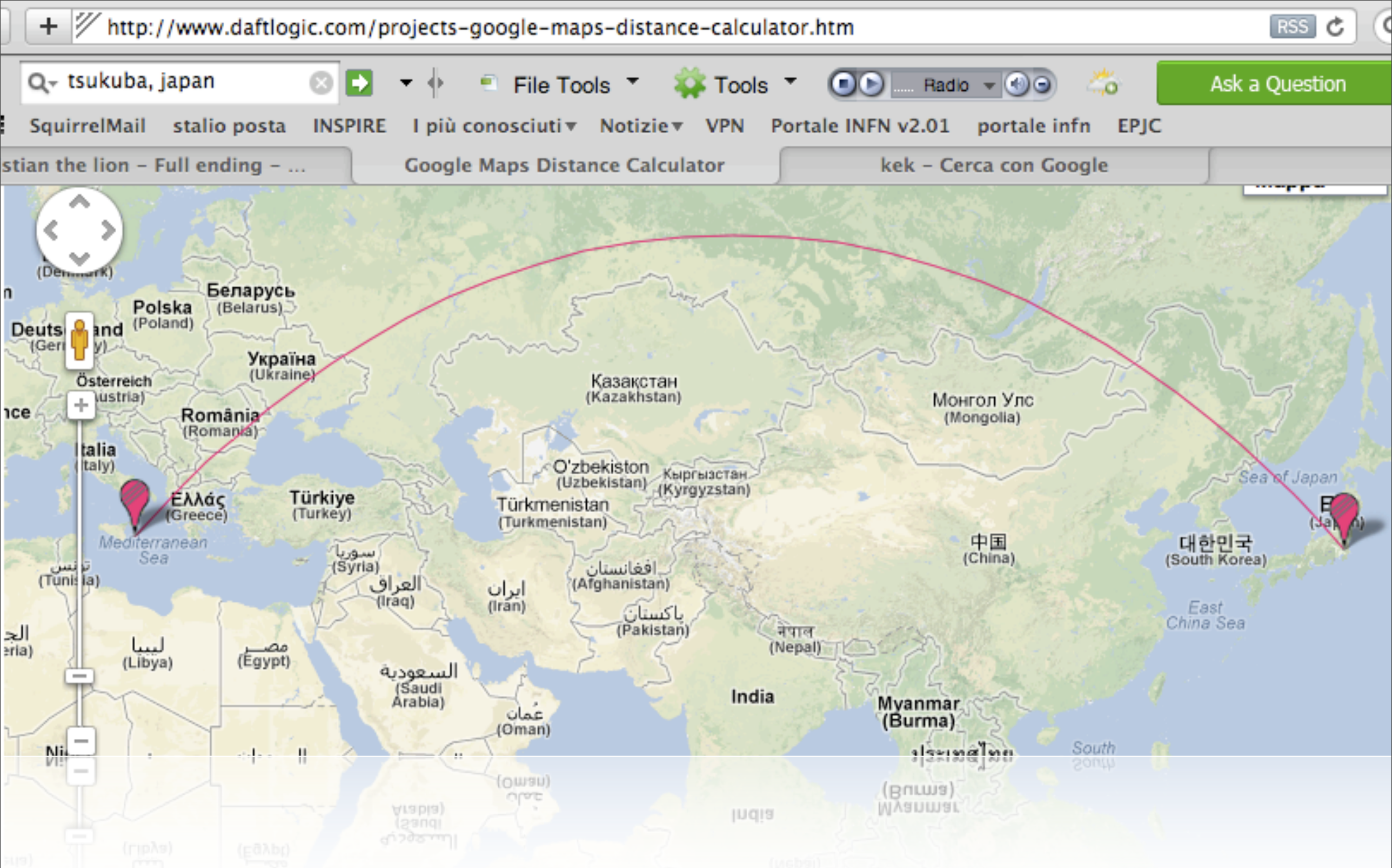
Check whether some existing neutrino source and neutrino detector could fit the desired distance.

Take a conventional muon neutrino beam, from pion decay --- E(nu) is about E(p)/20.

Calculate the number of muon events, assuming to know only E(mu), or also E(had) -- i.e., E(nu).

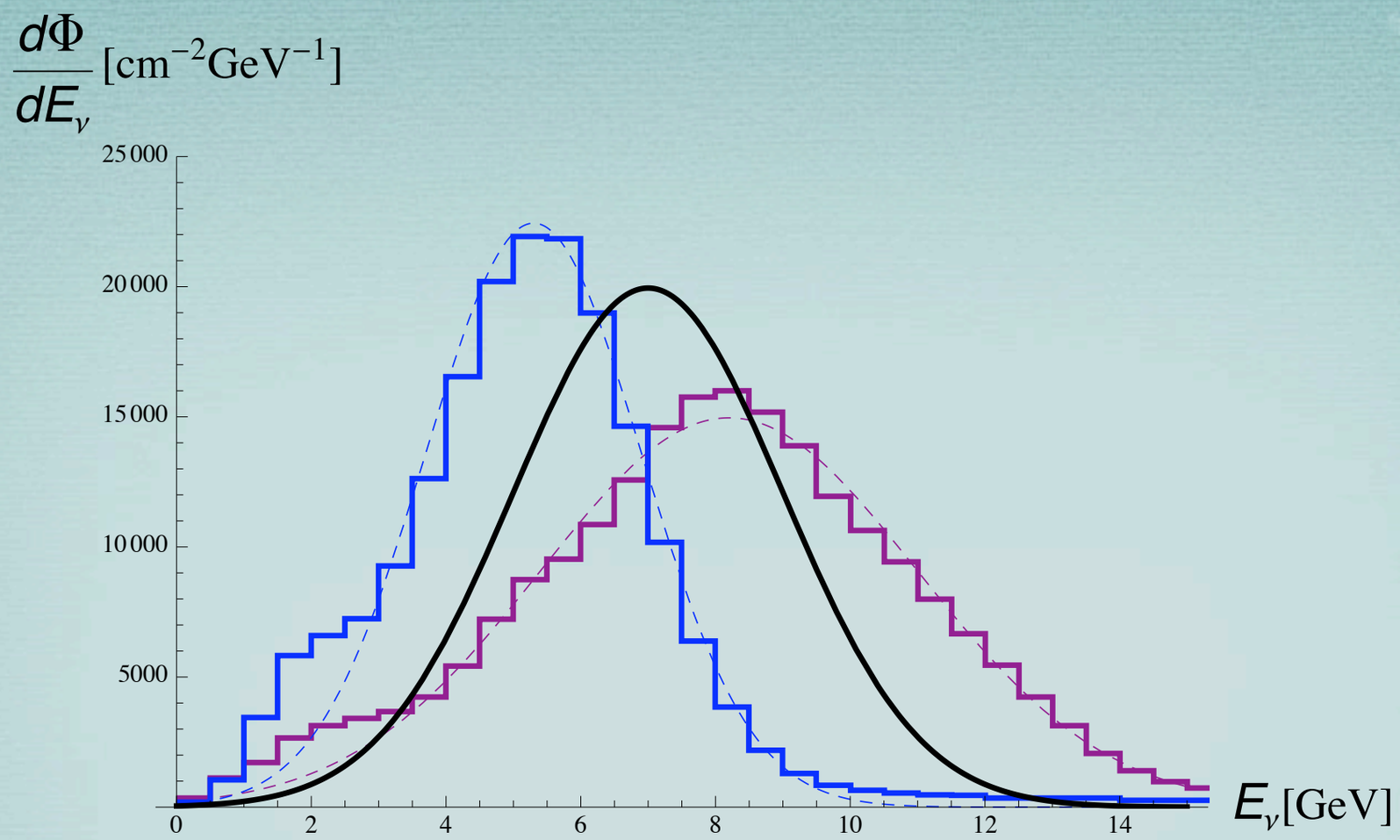
Source-detector distances

	Fermilab	CERN	J-Parc
South-Pole	11600 km	11800 km	11400 km
Sicily	7800 km	1200 km	9100 km
Baikal Lake	8700 km	6300 km	3300 km



E.g.: Tsukuba-Sicily is too large, 9100 km; moreover, the energy of the beam is low.

http://www.daftlogic.com/projects-google-maps-distance-calculator.htm



Published NUMI Beams - ME & HE

rescaled to a distance of 7800 km

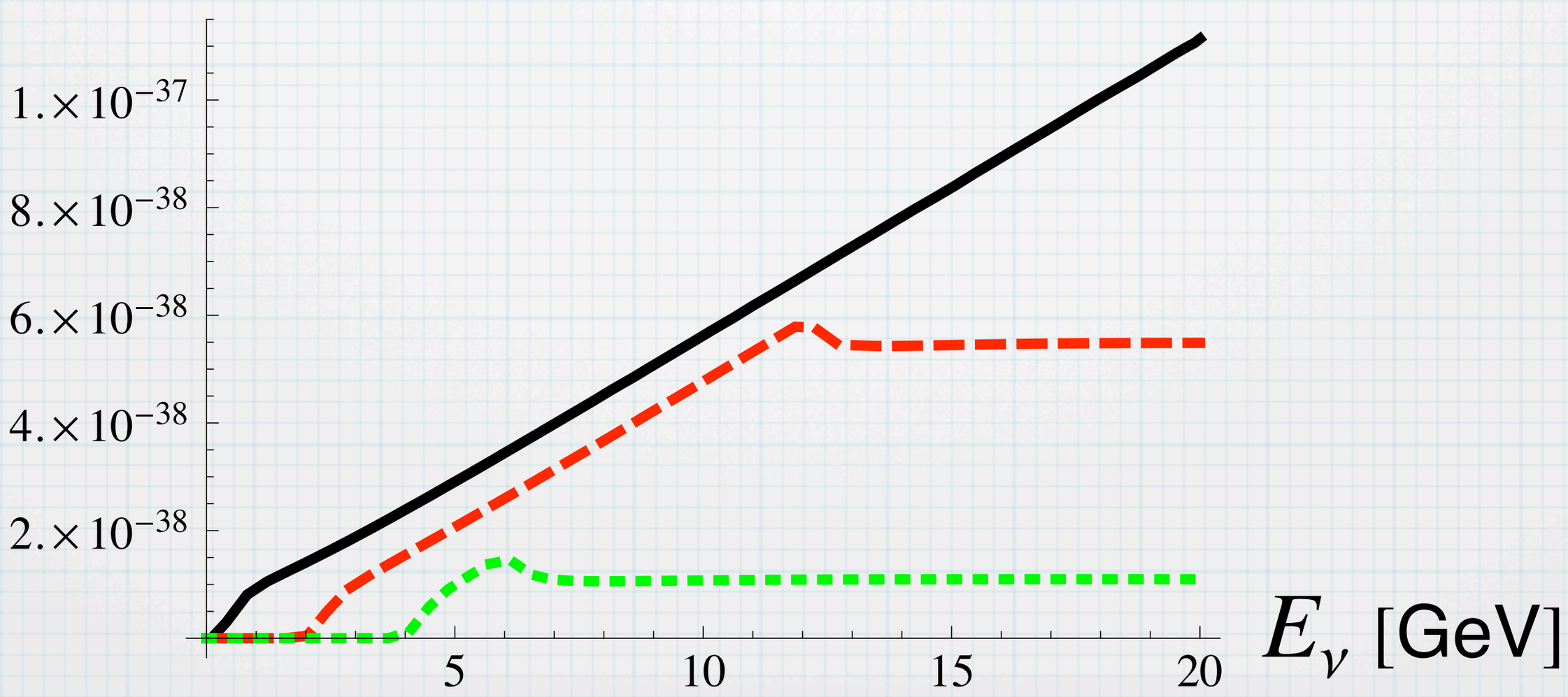
Cross Section for Muon Production: QEL+Delta+DIS

Total, 0<Emu<Enu

Partial, 2 GeV< Emu<12 GeV

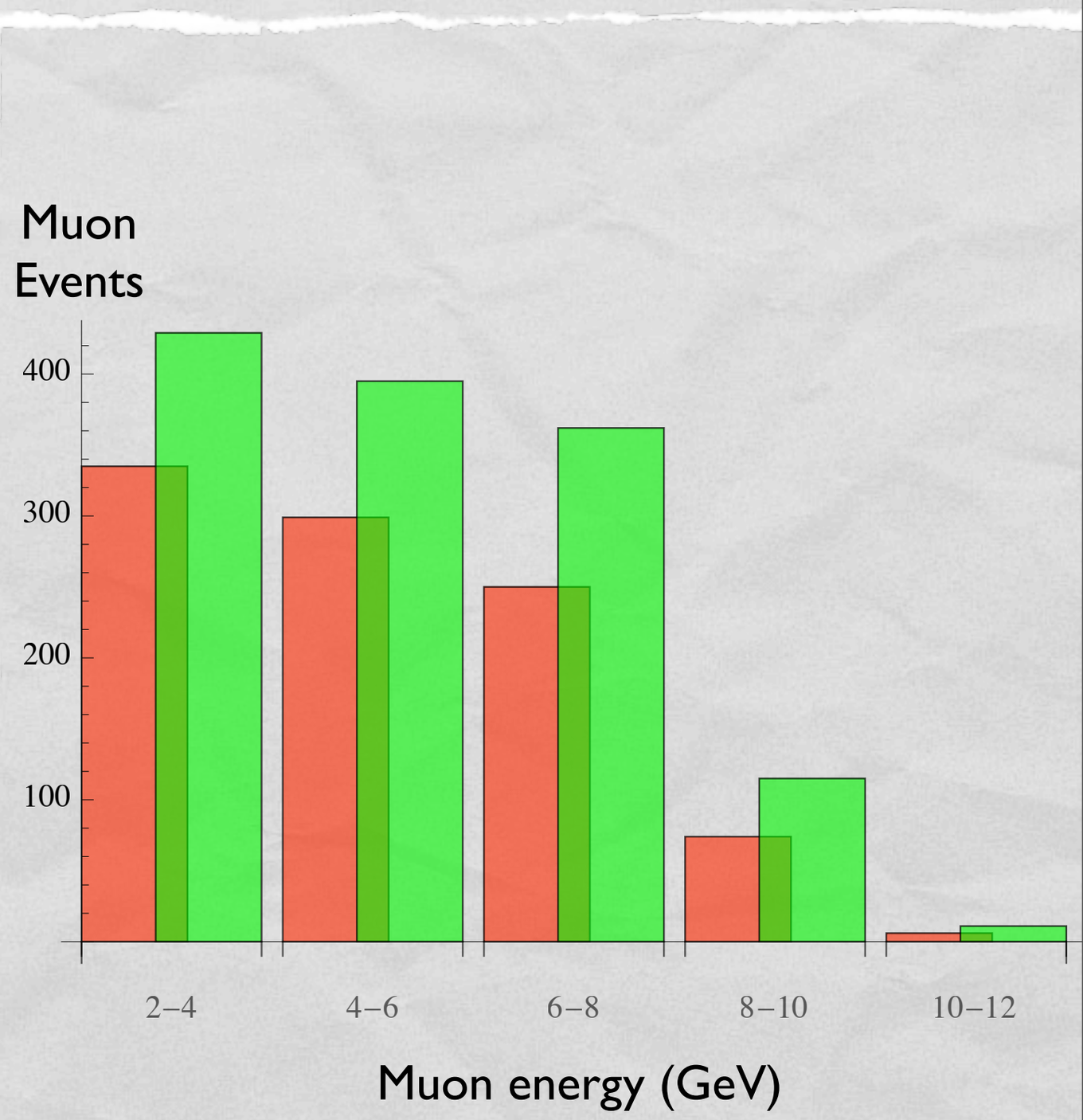
Partial, 4 GeV<Emu<6 GeV

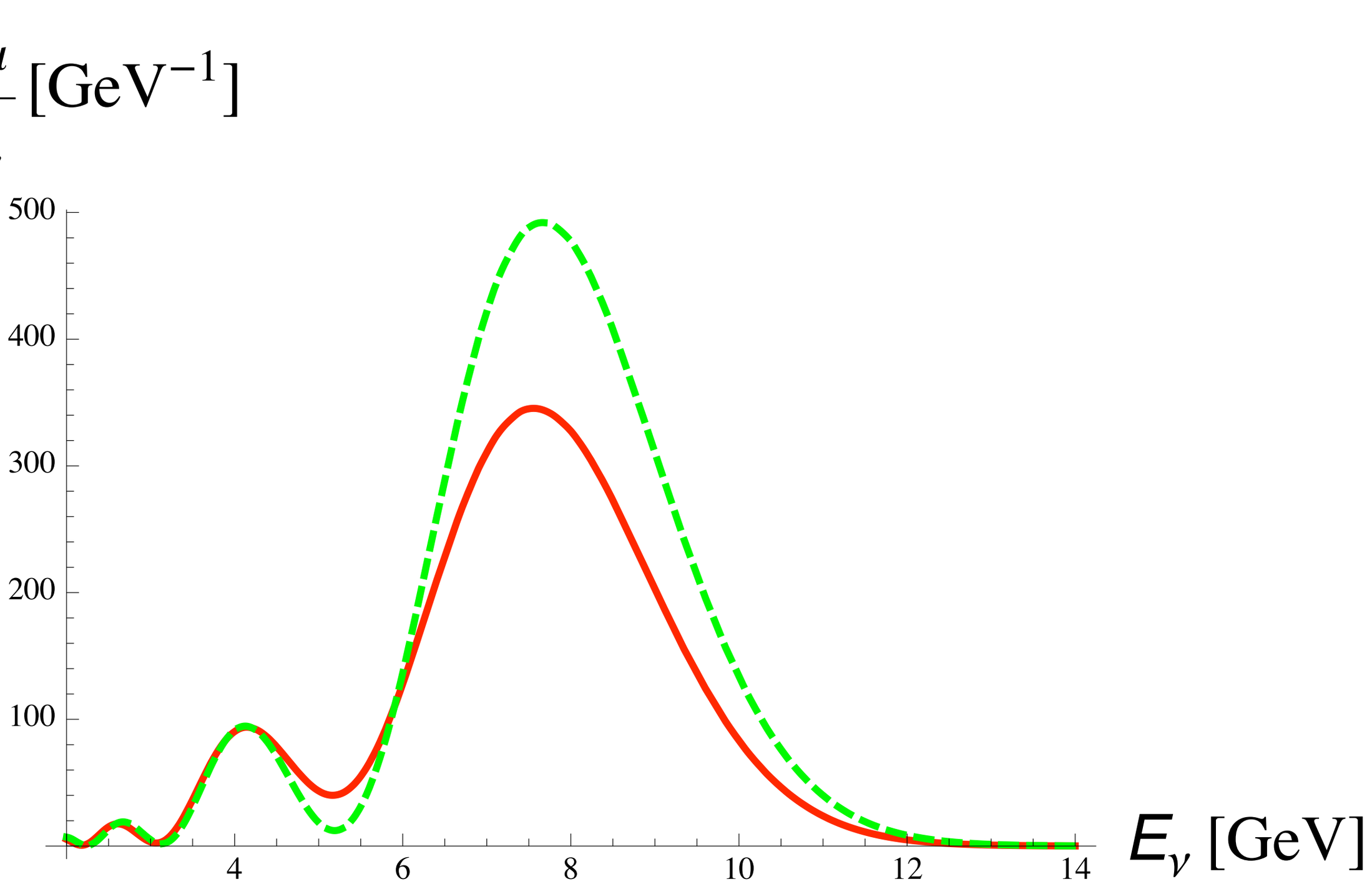
σ_ν [cm^2]



ANSWER / RESULTS

- ... 950 events for normal hierarchy...
- ... and 1300 events for inverted hierarchy.
- 30% difference, as expected: bunched in time, directional, with a "hard" spectrum.





The neutrino spectrum

(assume that hadrons are measured)

Summary and Prospect

- Present experiments not optimized for mass hierarchy. But now, we have enough information to safely plan the next steps.
- 10^{20} p.o.t. give 1000 events in one Mton detector; 30% less muon events for normal hierarchy -- a big difference.
- Events are well characterized; no need to see also the hadrons. Various possible options for the locations.
- Inverting the polarity, the matter effect works the other way round.

If you like the idea, feel free to use it; there is no copyright, for us it was enough to have fun by exploring it.

News from Gran Sasso

New PhD School on Astro-particle Physics at L'Aquila:

http://www.gssi.infn.it/

New APPEC Center for theoretical Particle Physics: Gran Sasso+ APC + DESY

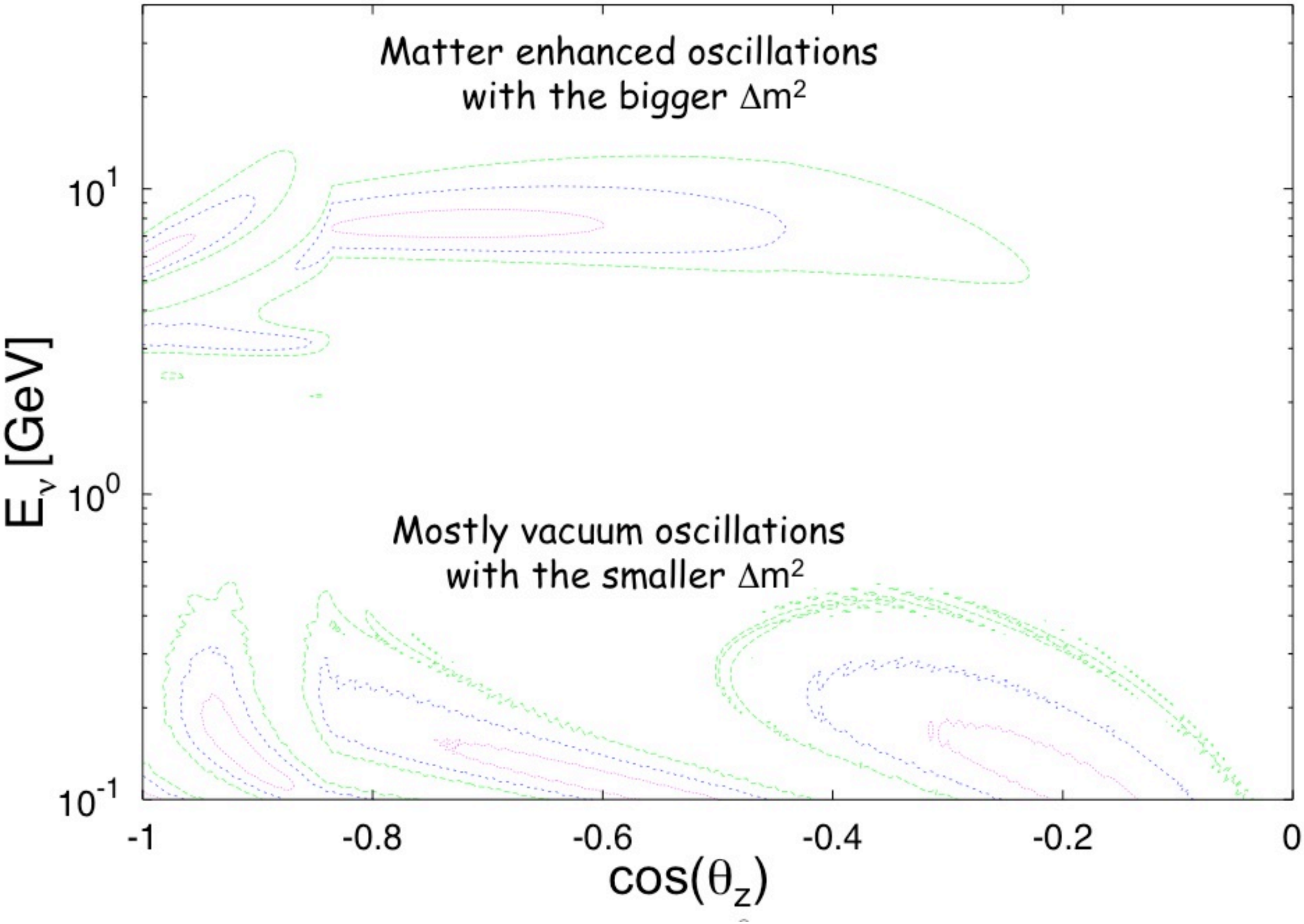
DISCUSSION

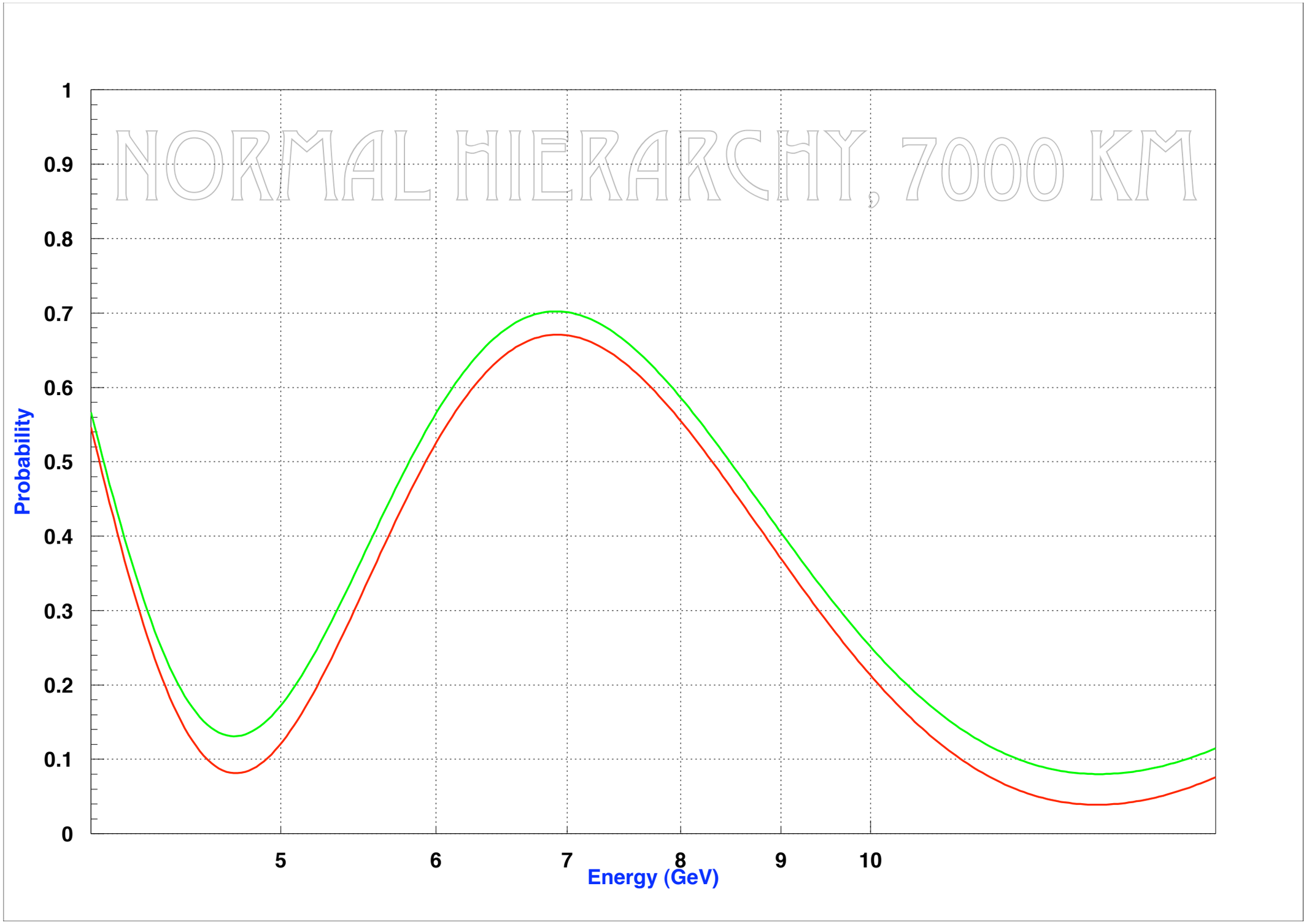
AFTER THE WORKSHOP

I thank various colleagues (Brunner, De Jong, Palomares-Ruiz and many more) for the stimulating discussions, and in the hope to make my answers more precise, I added some slides in the following pages:

- Slide 19: Oscillogram of P(e e) from my presentation at La Thuile 2003.
- Slides 20-24: Variation of P(mu mu) within the ranges of Lisi et al 2012.
- Slide 25: Plot of the cross section over energy.
- Slide 26: Opinion of Gran Sasso Engineers on a tunnel inclined at 30^0.

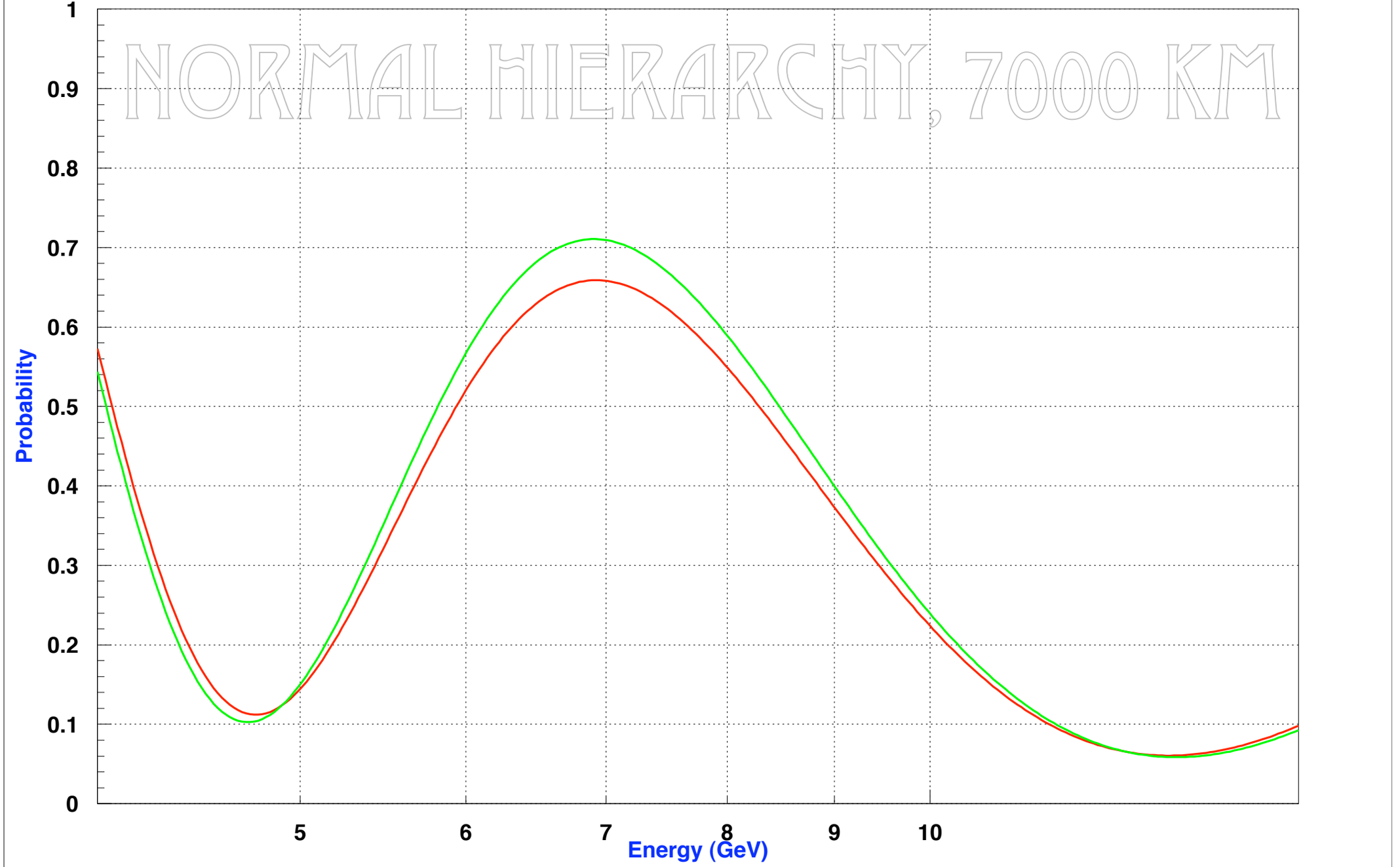
P_{ee} in the Earth = 0.3, 0.5, 0.7 (La Thuile 2003)





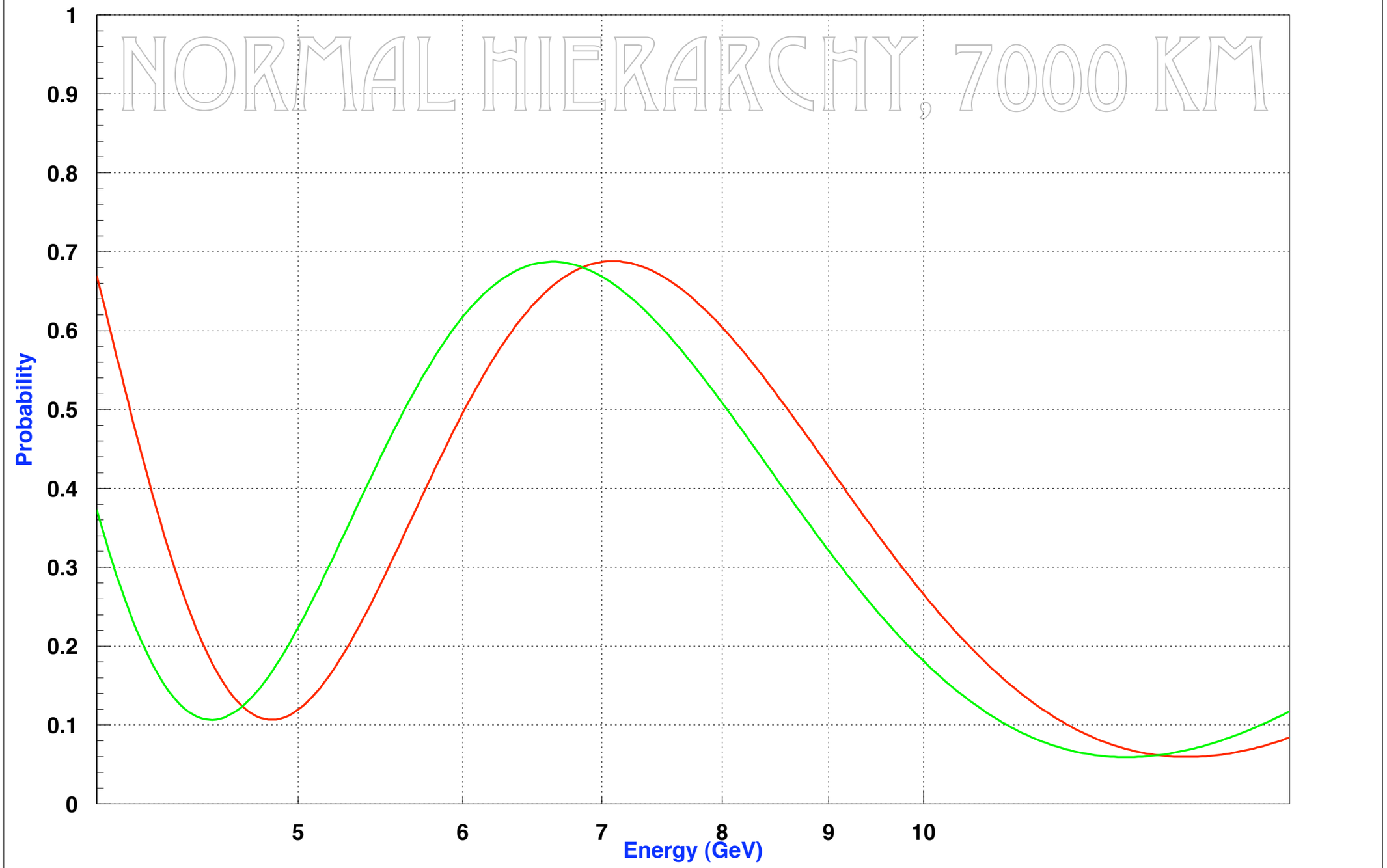
P(mu mu) if theta(23)=37.2^0-39.8^0

(1 sigma range of hep-ph/1205,5254, Lisi et al)



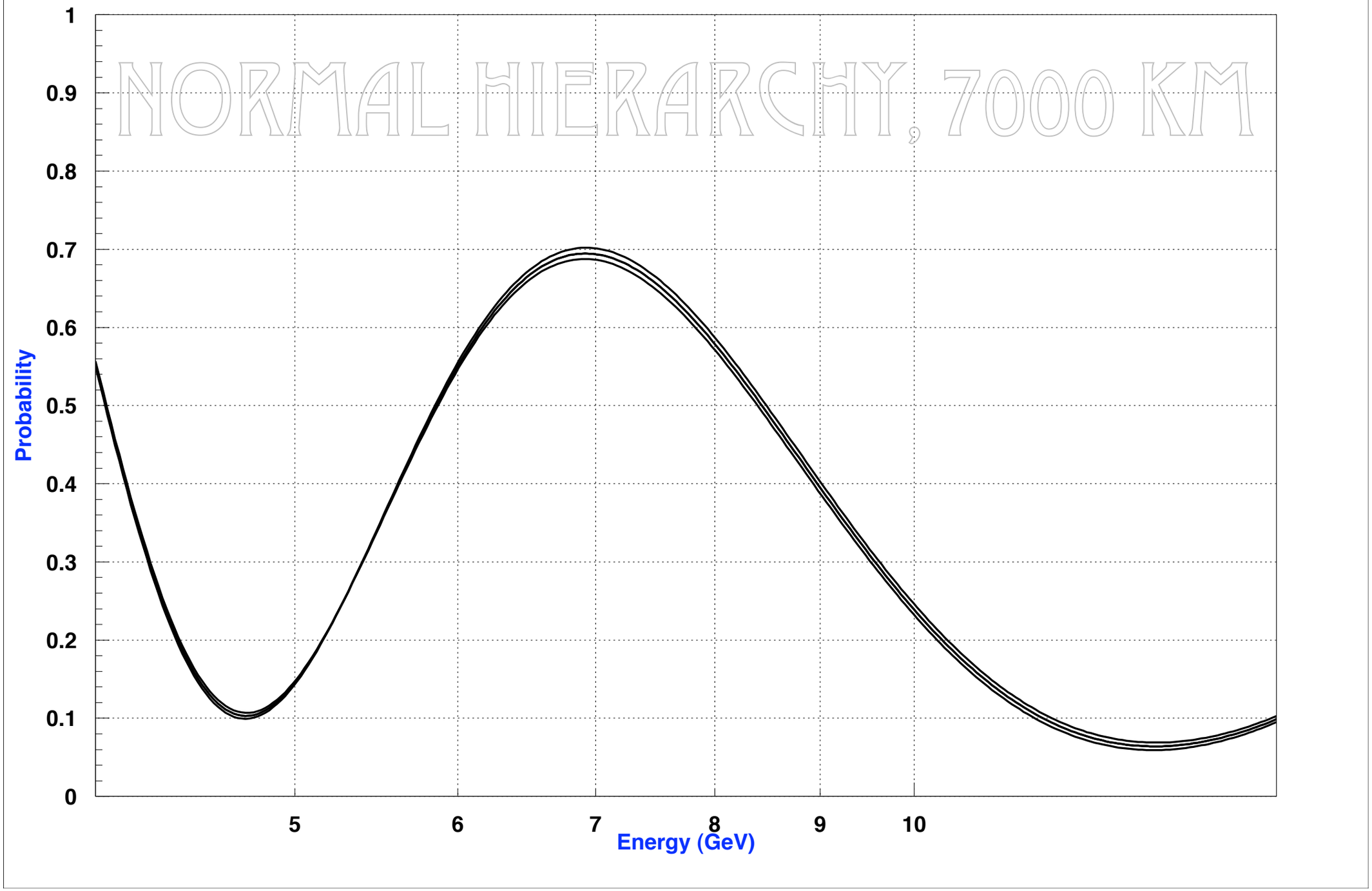
P(mu mu) if theta(13)=8.5^0-9.4^0

(1 sigma range of hep-ph/1205,5254, Lisi et al)



P(mu mu) if Dm^2_{23}=(2.29-2.45)*10^{-3} eV^2

(1 sigma range of hep-ph/1205,5254, Lisi et al)



P(mu mu) varying CP phase=0^0,90^0,180^0,270^0

Stability of the Expected Number of Muons

- 3% variation with theta(23) and theta(13) (NH), less with Delta m^2(23), using the present 1 sigma ranges.
- If 90% of the electrons are rejected, contamination for NH is 40 events, i.e., 4%.
- The number of taus decaying leptonically into mu is 26 events for NH, 24 for IH: No significant impact.

Cross Section for Muon Production

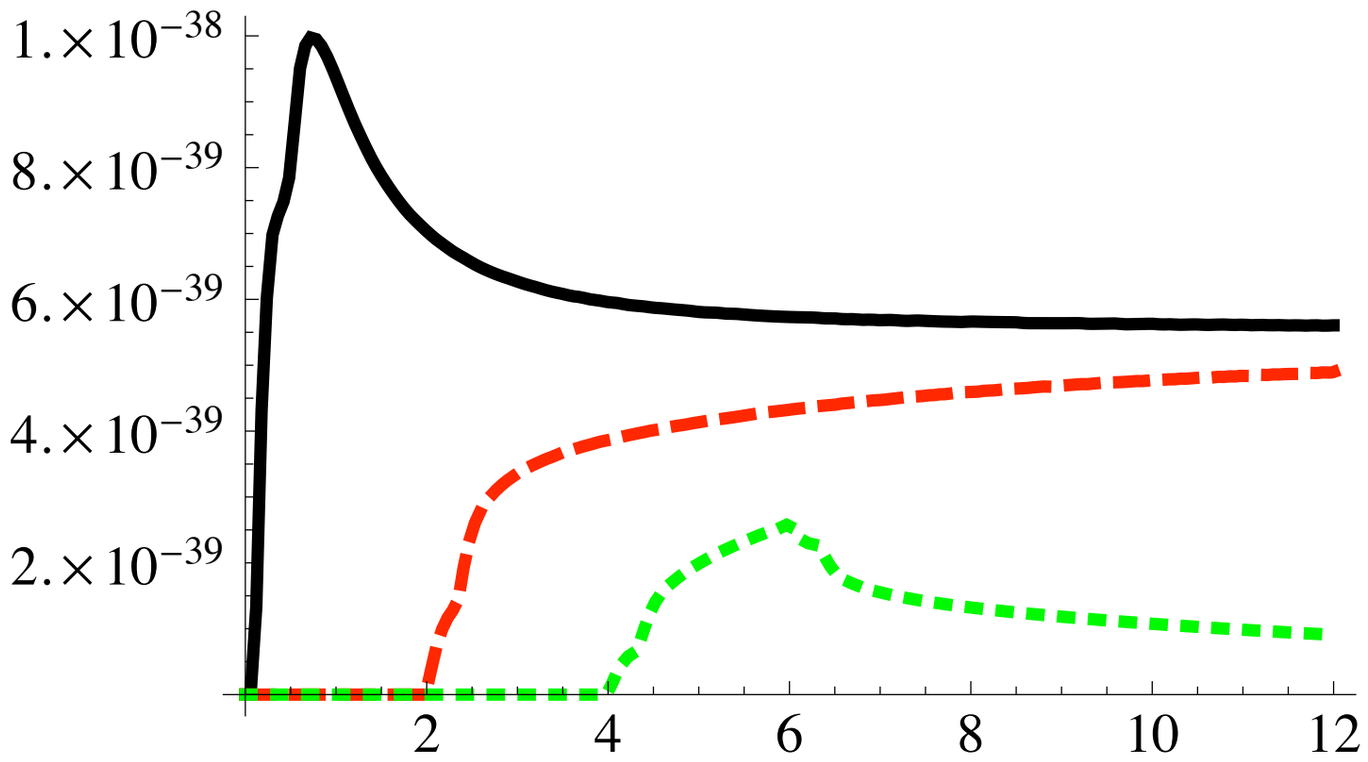
QEL+
Delta+
DIS

Total, 0<Emu<Enu

Partial, 2 GeV< Emu<12 GeV

Partial, 4 GeV<Emu<6 GeV

σ_ν / E_ν [cm²/GeV]



E_ν [GeV]

AN ENGINEERGING ISSUE

- The ~20 GeV neutrino beam of CERN has a tunnel of about 1 km; its approximate diameter is 3 m, its cost is10 Meuro/km.

- We need to launch a neutrino beam with 30^0 inclination and with an energy 3 times smaller.

- I asked Gran Sasso engineers whether a 0.5 km tunnel with such inclination (reaching 250 m depth from beginning) is conceivable.

- Answer: TBM (Mechanical Moles) with tracks can do this at speed of about 1m/hour; one can consider stairs in the tunnel.