Pizza-Seminar

do neutrinos travel faster than light?

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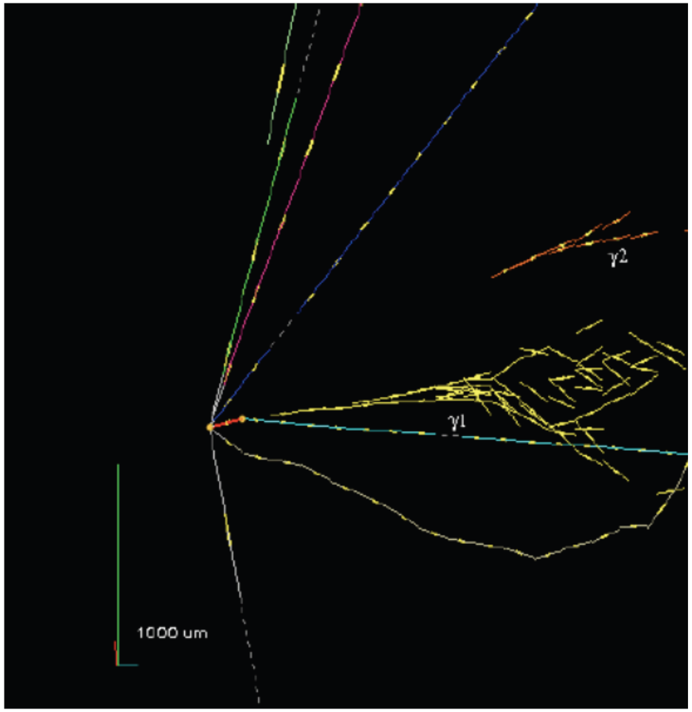
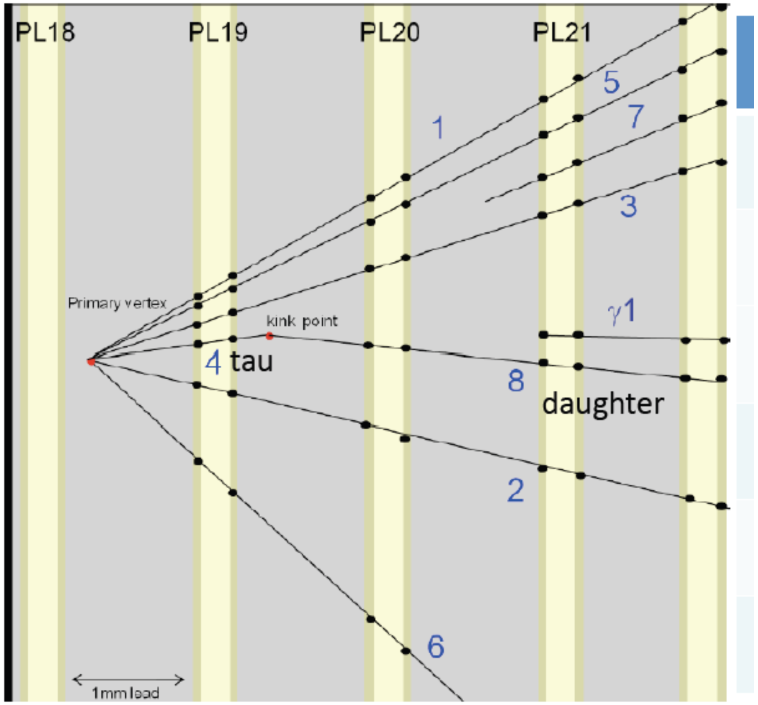
28.10.2011

Opera's ν_τ candidate





Likely decay mode: $\tau^- \rightarrow \rho\ (\rightarrow \pi^-\ \pi^0)\ \nu_\tau$

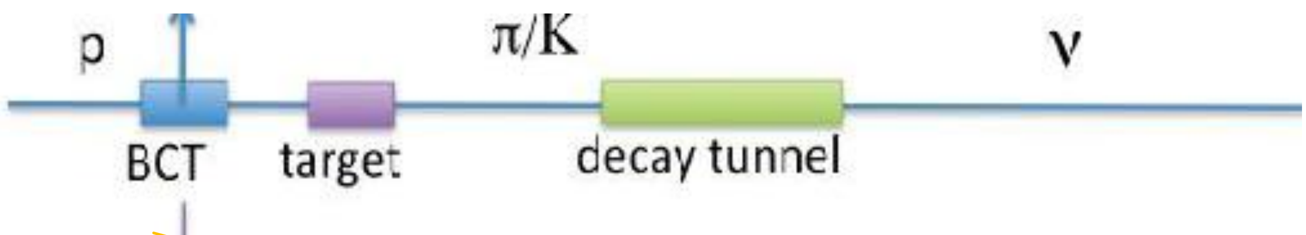
B.R. **$[\ \tau^- \rightarrow \rho\ (\pi^-\ \pi^0)\ \nu_\tau\ ]\ \approx 25\%$**

…Opera

measurement principle: $$v = \frac{\text{distance}}{\text{time of flight}}$$

… but no direct measurement of ν flight time and neutrino flight distance as ν can not be tagged at CERN … !!!

SPS accelerator

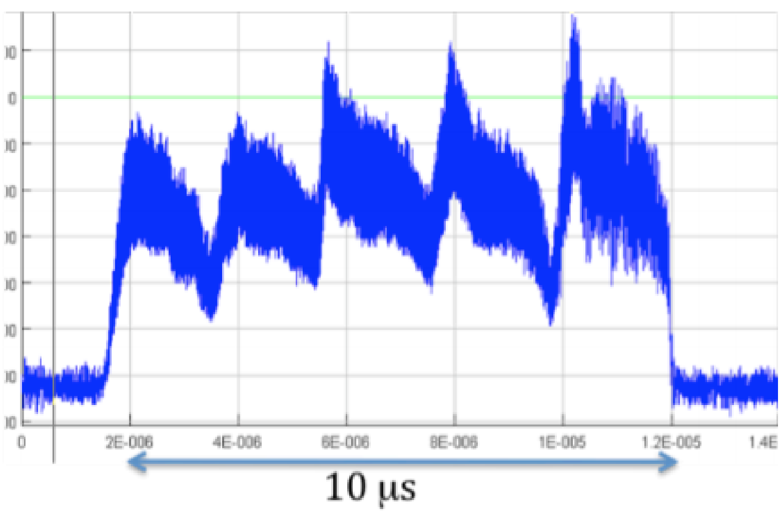


Spill: 2 x 10 μs, 50 μs apart, every 30 s there is beam with micro structure – some changes with time!
measure spill in statistical ensemble of all measured protons

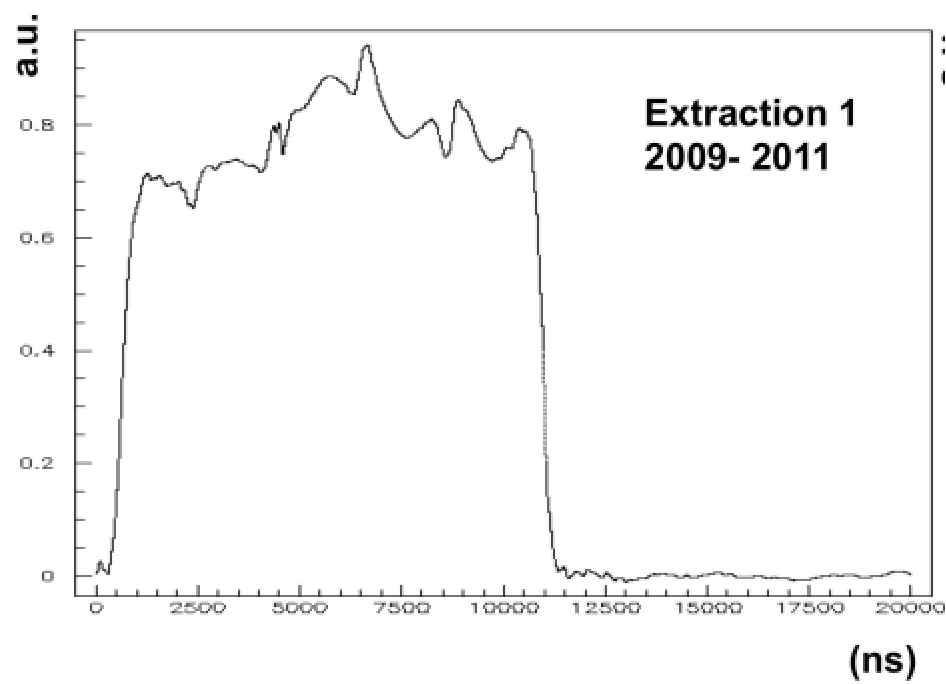
as all particles will travel with speed of light, no problem that proton is tagged and not pion / kaon …. not known, where neutrino is created in decay tunnel

Proton beam counter signal

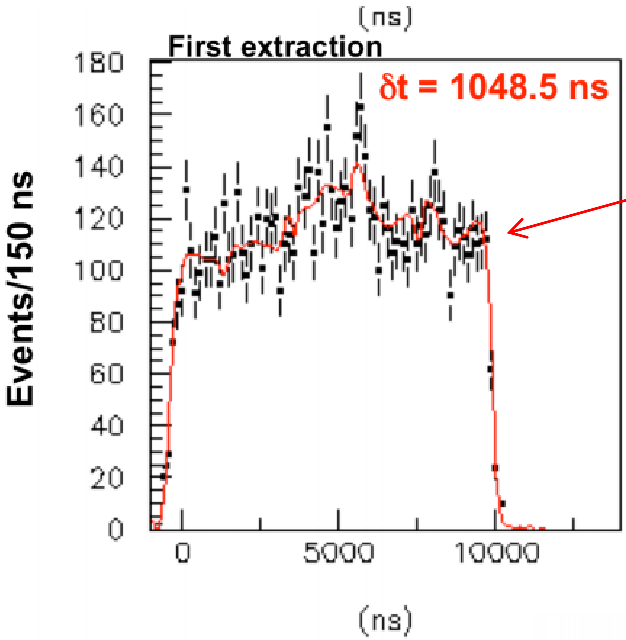
Typical signal of one spill



All spills summed over 2 years



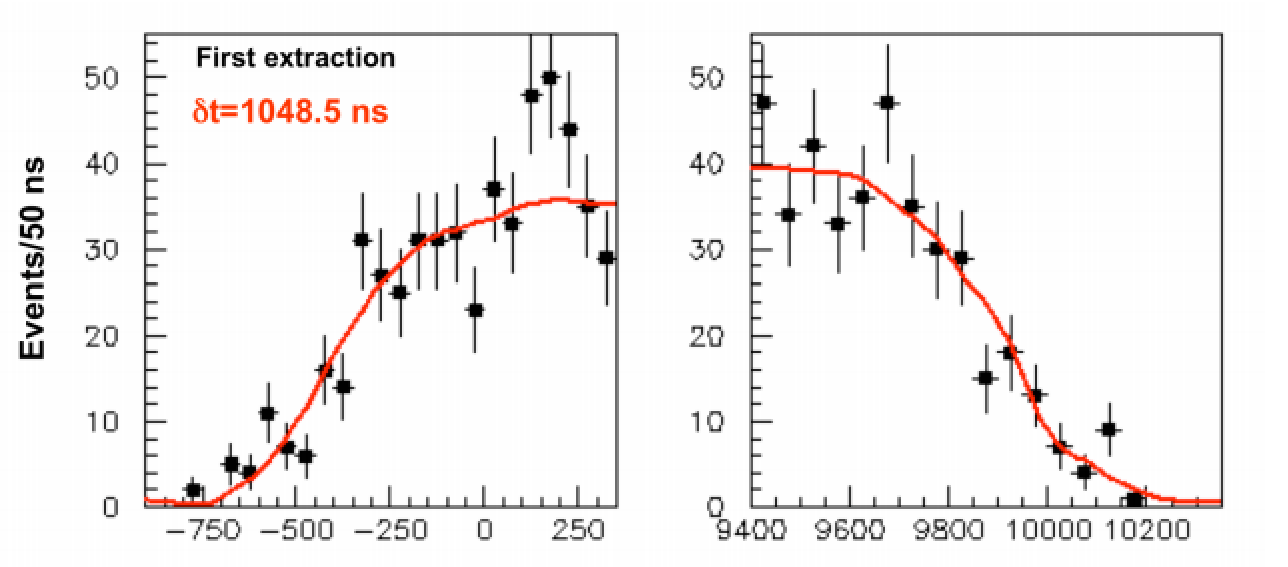
with fit to ν arrival time



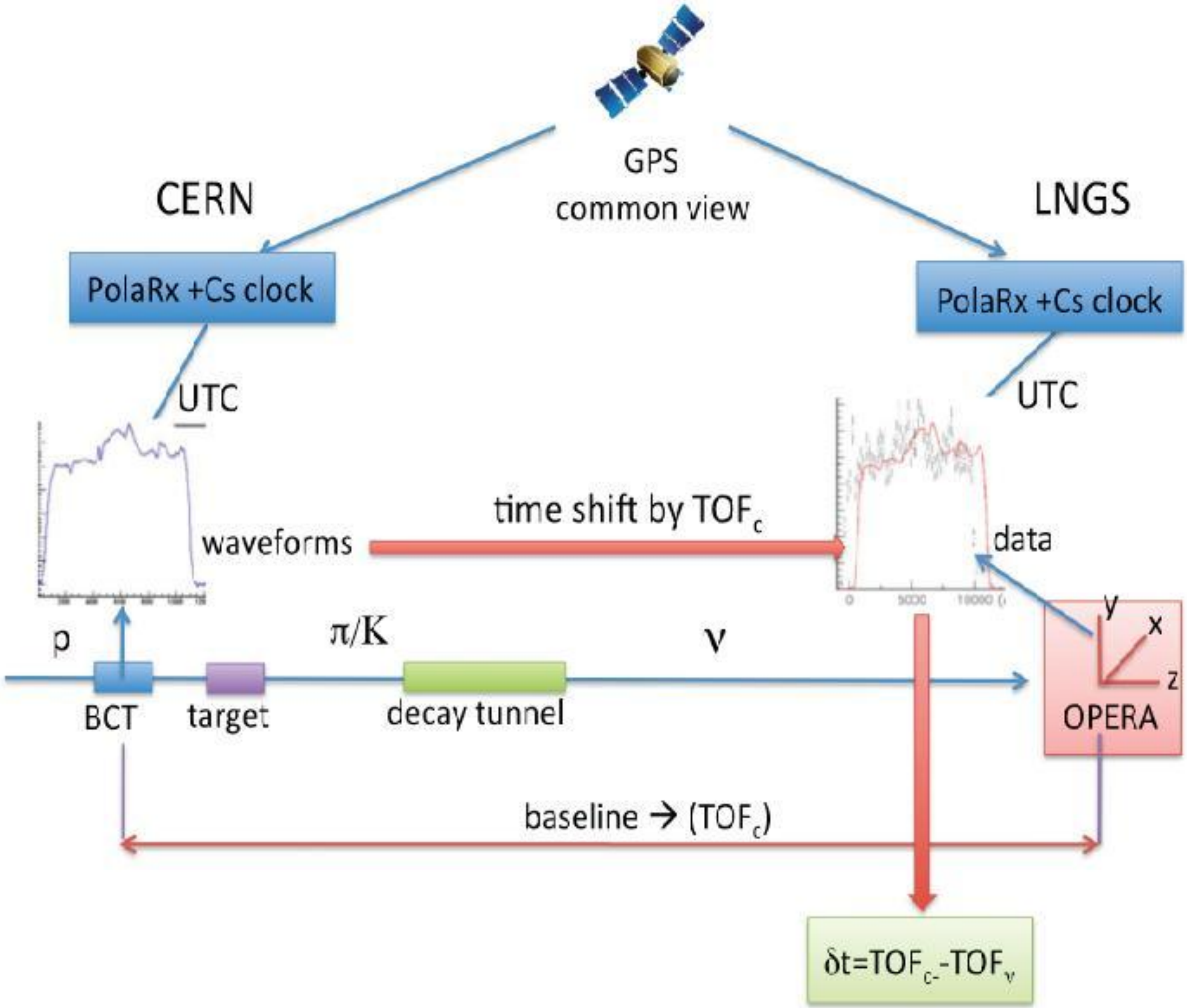
$\delta t = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns

$(v-c)/c = \delta t\,/(\text{TOF}'_c - \delta t) = (2.48 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$

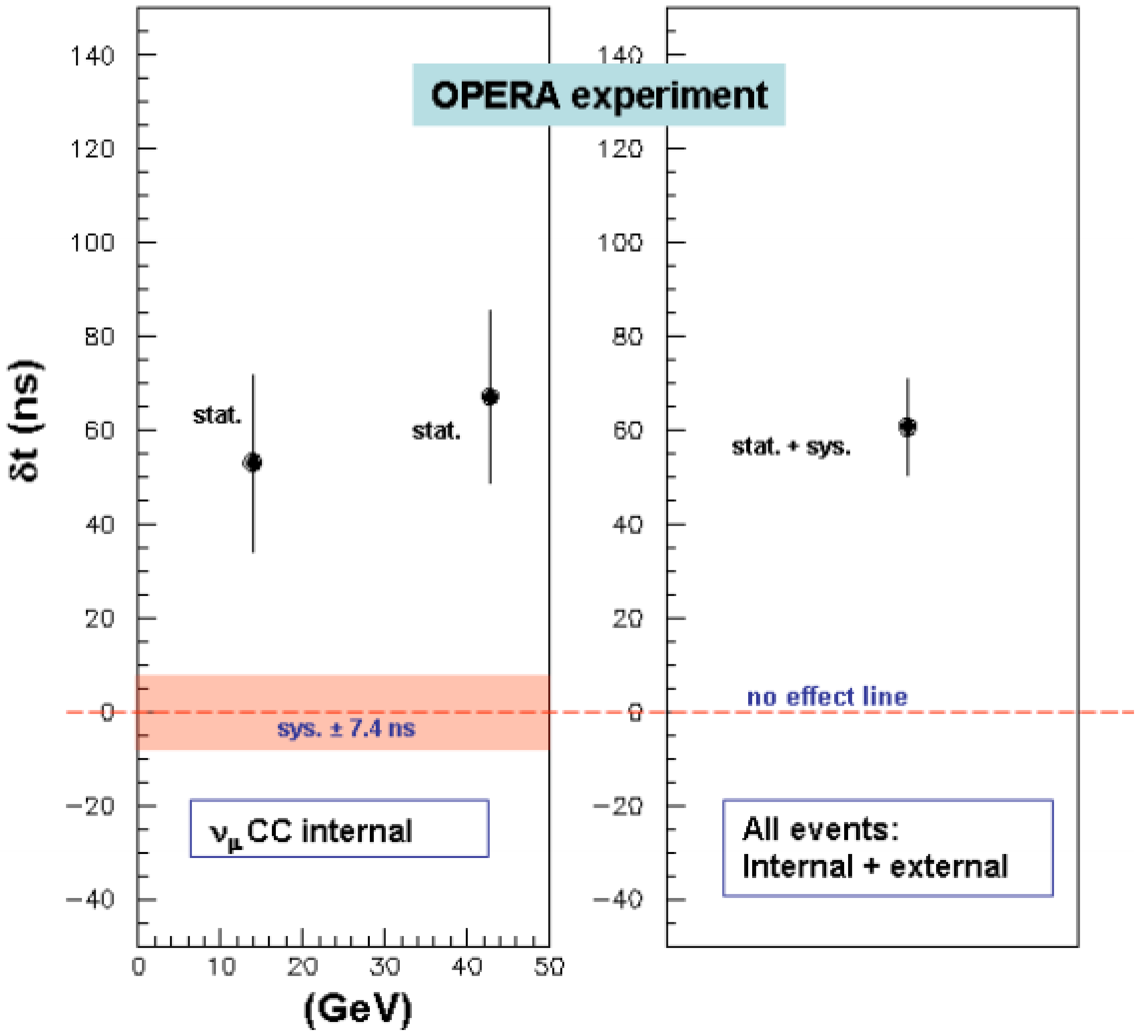
Note that 50 ns bins are used → effect is 60 ns
…just one bin shifted …



Common view: make sure that the same satellite is looked at …



Any energy dependence?



Nothing obvious …

With $E^{2.5}$ dependence expect factor 16 !

… Opera

result of measurement over 730 km: (731278.0 ± 0.2) m

absolute time between CERN and Gran Sasso known to **~ 2 ns**
~ 730 km distance known to **~ 0.2 m**

…based on 5489 ν_μ *with 1 7 GeV average energy:*

neutrinos arrive 60 ns ± 6.9 ns (statistical) ± 7.4 ns early

*detector positions would have to be wrong by 0.3 m/ns * 60 ns ~ 18 m*

nota bene: position measurement with GPS „easy"; problem is „extrapolation" into tunnel
precision absolute time measurement more complicated:
GPS absolute accuracy O(40 ns); significant uncertainties e.g. due to changing „index of refraction" in atmosphere – *under control e.g. in radio interferometry*
checked and corrected with 2 cesium clocks by Swiss Metrology Institute and by PTB in Braunschweig

… other experiments

MINOS (Fermilab → Soudan) 734 km, average neutrino energy ~ xx GeV

2007 publication: ~ 15 km/s faster than speed of light
but only 1.8 standard deviation significance significance
poor time resolution of 64 ns, 9 times worse than at CERN
small sample of 473 events

nota bene: absolute timing not well measured
GPS signal travels by light fiber to detector for 5500 ns with 46 ns uncertainty
… at CERN 8300 m fiber delay known to 1 ns !

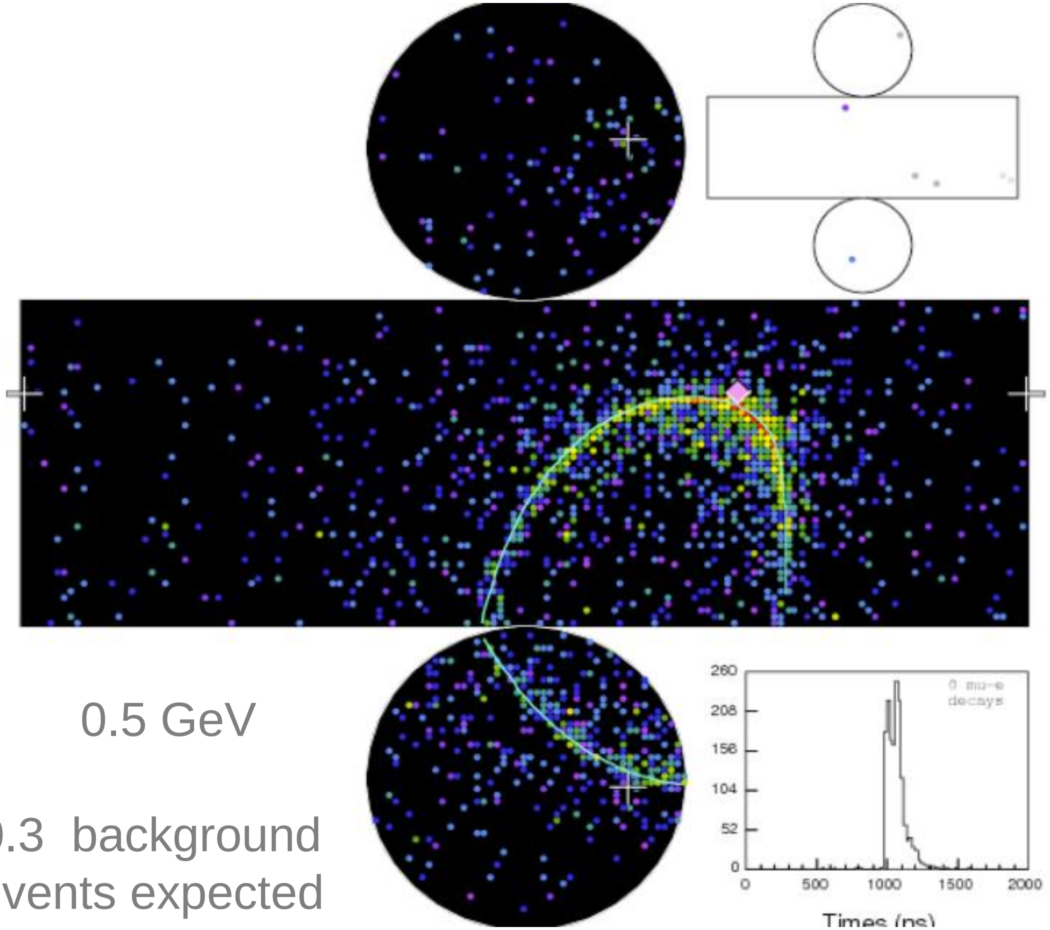
Minos will remeasure delay time to decrease absolute time accuracy from 64 to 35 ns
include 4 more years of data → results will be out in about 6 months

Minos+: include precision clocks → needs new data → results in 2014

T2K

T2K 300 km base line experiment J-PARC→ Super-K; first interactions 2010!

Original goal: test θ_{13} dependent on CP-phase δ and reach $\theta_{13} \sim 4^0$ by mid 2011



0.5 GeV

0.3 background events expected

candidates for $\nu_\tau \to \nu_e$ appearance ...

if true, θ_{13} large,

… but needs confirmation

… T2K

Earthquake damage

restart spring 2012

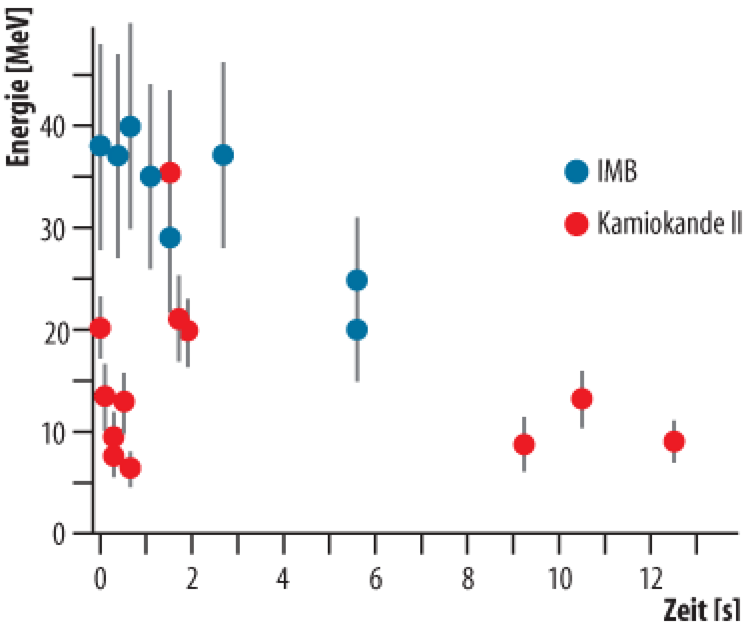
Will have much improved absolute timing

Nota bene: T2K spill structure much better suited than CERN‘s
(ns wide spills …)
but baseline 295 km, average energy ~ 3 GeV

What is known

SN 1987A neutrinos (168 000 LJ distance) :

~ 24 neutrinos seen ~ 3 h before light could escape dense medium



average
positron energy
~ 25 MeV

predominant reaction:

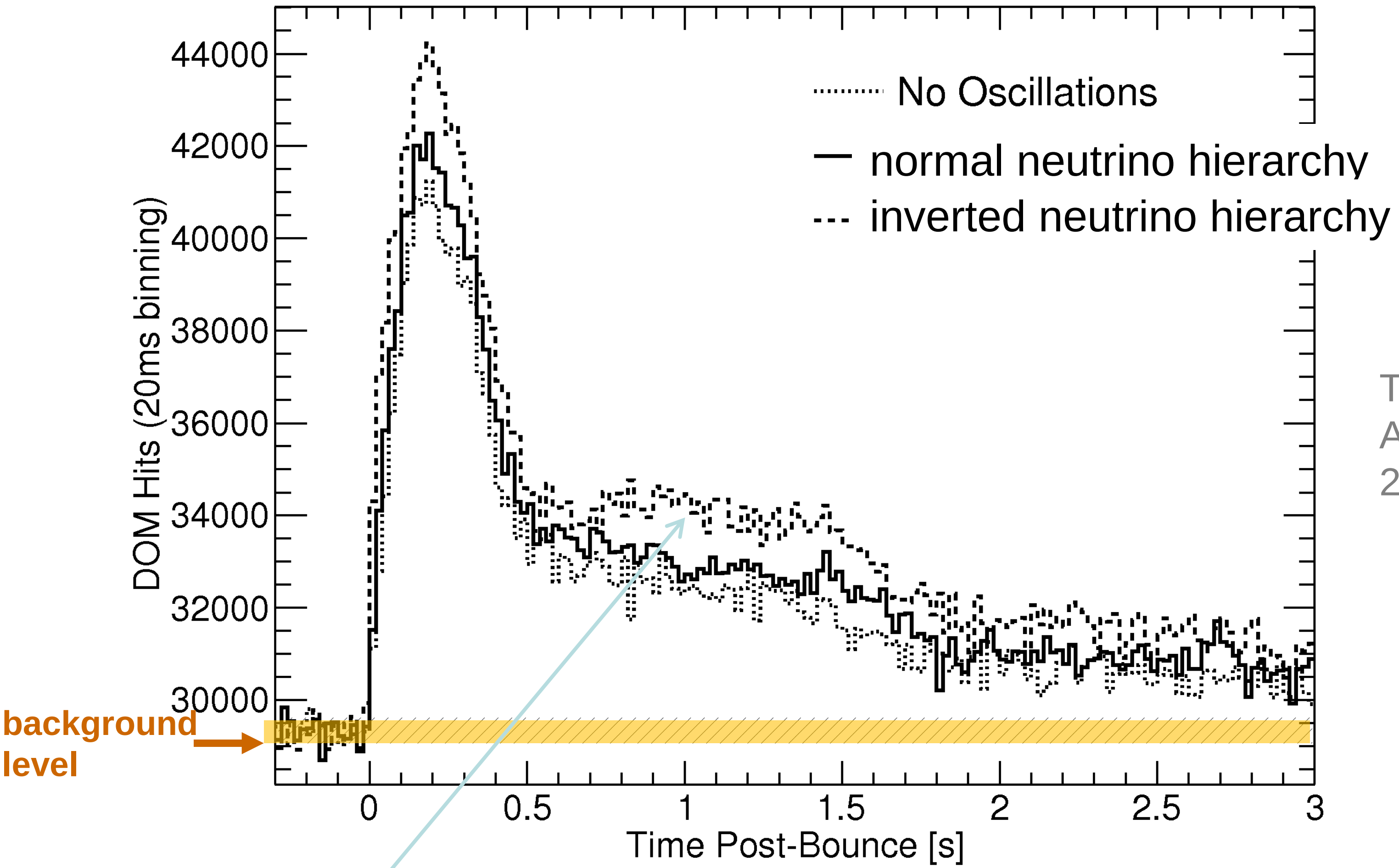
$$\bar{\nu}_e p \rightarrow n e^+$$

ν_e , and neutral current ν_μ, ν_τ
only a few percent contribution

if

Expected rate distribution (IceCube)

submitted to A&A astro-ph 1108.0171



Totani et al. Astrop. Phys. 496, 216 (1998)

clear differences in model shapes for normal and inverted hierarchy!

Are all neutrinos equally fast?

clearly, rest mass makes some difference,
but could there be additional reason, why neutrino species travel at different speeds?

3 mechanisms proposed:

weak equivalence principle broken by different couplings of neutrino species to gravitational field
Gasperini, Phys. Rev. D 39:3606,1989
Halprin & Leung Phys. Rev. Lett, 67:14 1991
Lorentz invariance broken by different maximal achievable velocities of neutrino species (*)
Coleman & Glashow, Phys. Lett. B 405:249, 1997 and others…
„Quantum decoherence“

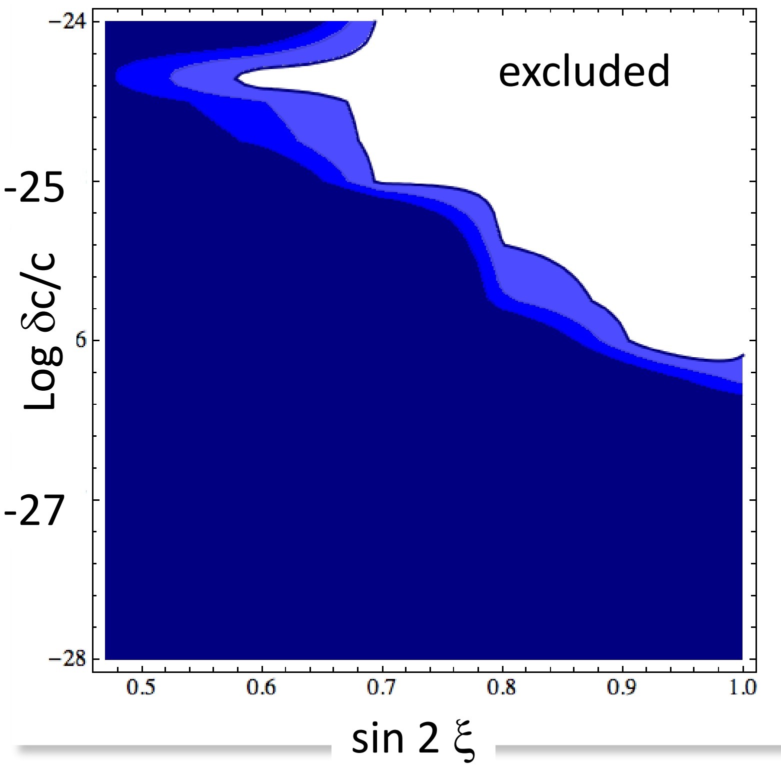
(*) flavor eigenstates ν_α and velocity eigenstates ν_j — if different, oscillations analogous to mass induced oscillations

but oscillation length ~ $1/(\Delta\beta E)$ not ~ $E/\Delta m^2$

Exotic Oscillations (IceCube)

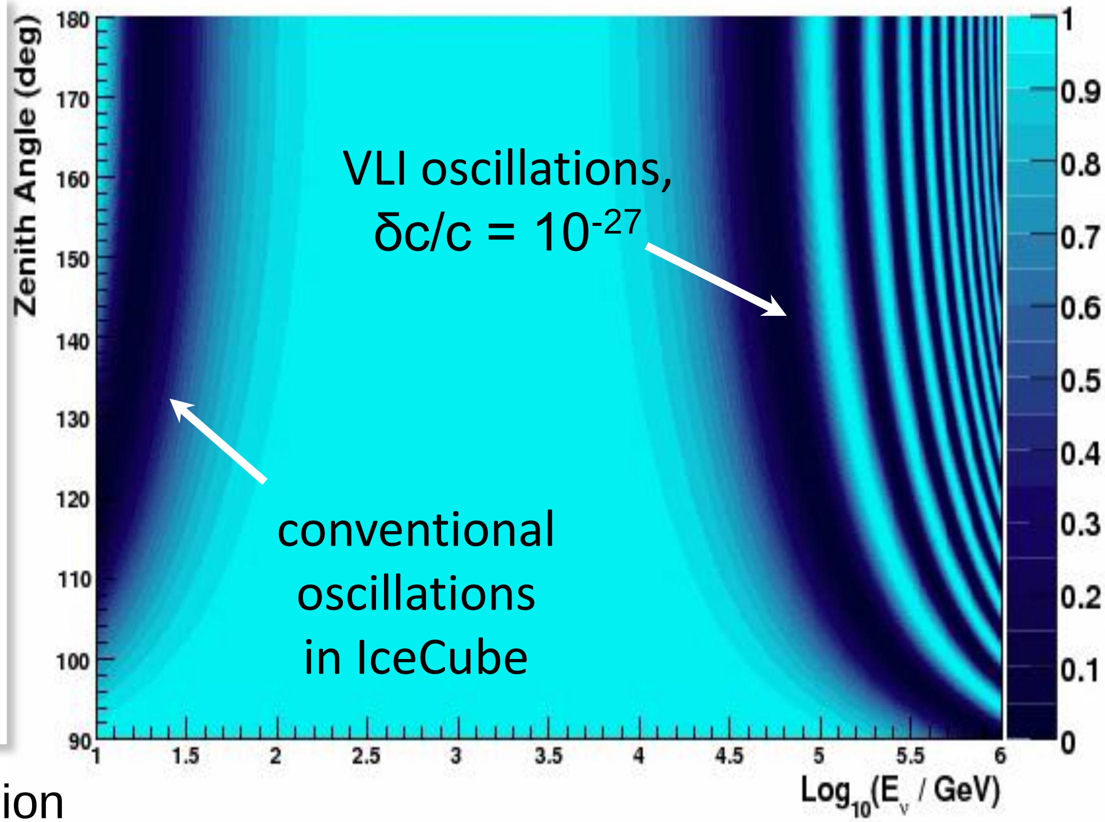
standard oscillations $\propto 1/E$
quantum gravity oscillations $\propto E$ (or E^2) $\rightarrow$ look at high energies!!!

VLI: speed of light = f(neutrino flavor) parameters: $\delta c/c$, $\sin 2\xi$, phase η



other experiments exclude low ξ region

Muon neutrino survival probability



Summary experimental limits

Opera: $\delta = \frac{(v_\nu^2 - v_c^2)}{v_c^2} = 5\times10^{-5}$ muon neutrino time delay

SN1987A: $\delta = \frac{(v_\nu^2 - v_c^2)}{v_c^2} < 4\times10^{-9}$ anti-electron neutrino time delay
(3 hour ν/γ time delay due to opacity)

Icarus: $\delta = \frac{(v_\nu^2 - v_c^2)}{v_c^2} < 4\times10^{-8}$ Cohen/Glashow Cherenkov radiation at superlumial speeds due to weak currents
$\nu_\mu \rightarrow \nu_\mu + \gamma$ $\nu_\mu \rightarrow \nu_\mu + e^+e^-$
(no signal seen)

Super-K: $\delta = \frac{(v_\nu^2 - v_c^2)}{v_c^2} < 1.4\times10^{-8}$ muon and anti-muon neutrinos
(no depletion in cosmic rays)

note that the latter limits are valid only for „true tachyons“

Summary

if effect is real:

effect must be dependent on energy (at least $E^{2.5}$) to be consistent with SN 1987 A → contradicts OPERA energy dependent results?

or anti-neutrinos behave differently from neutrinos

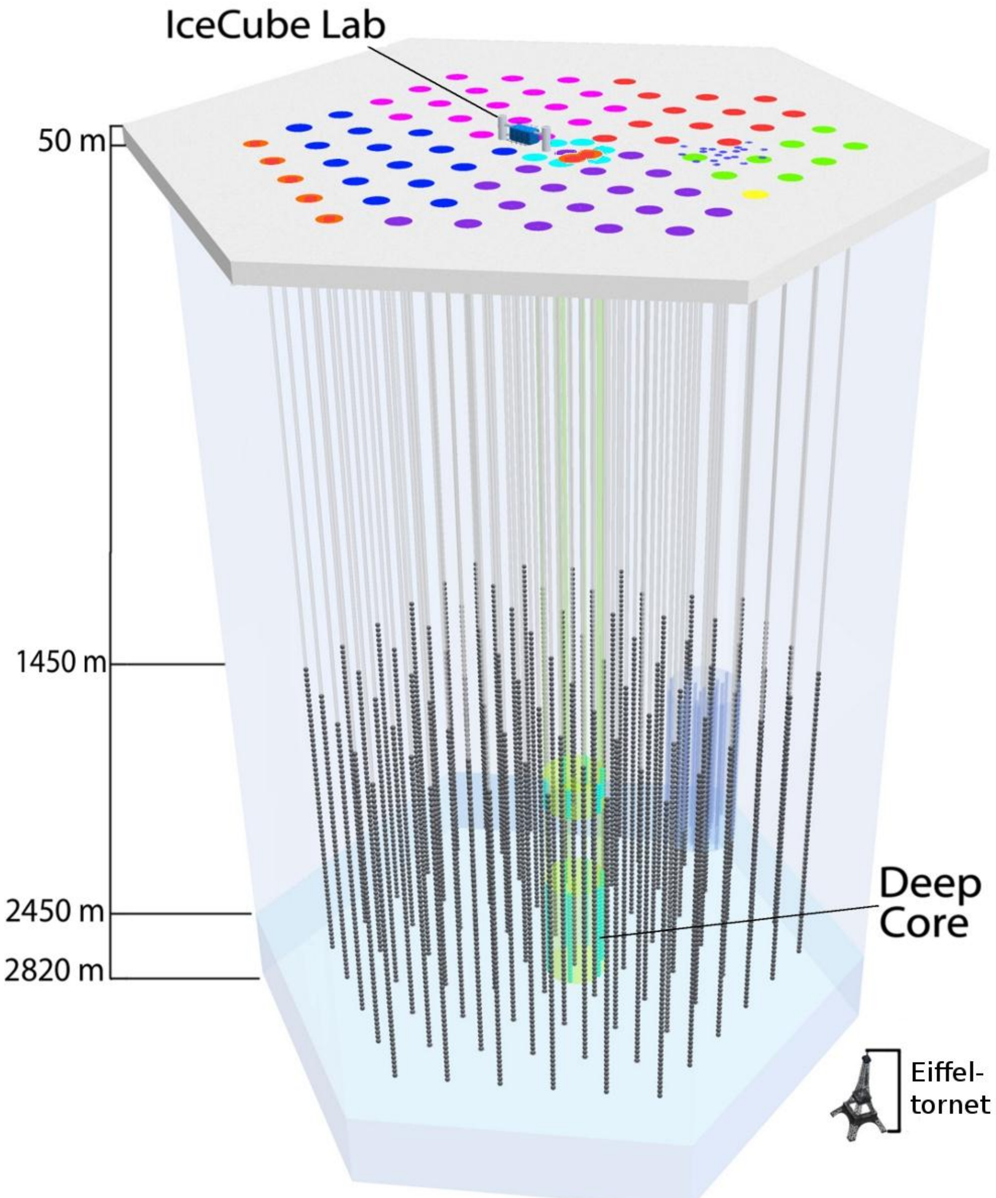
or effect is flavor dependent (only if IceCube limits not relevant)

Neutrinos can not be tachyonic if Cohen /Glashow right …

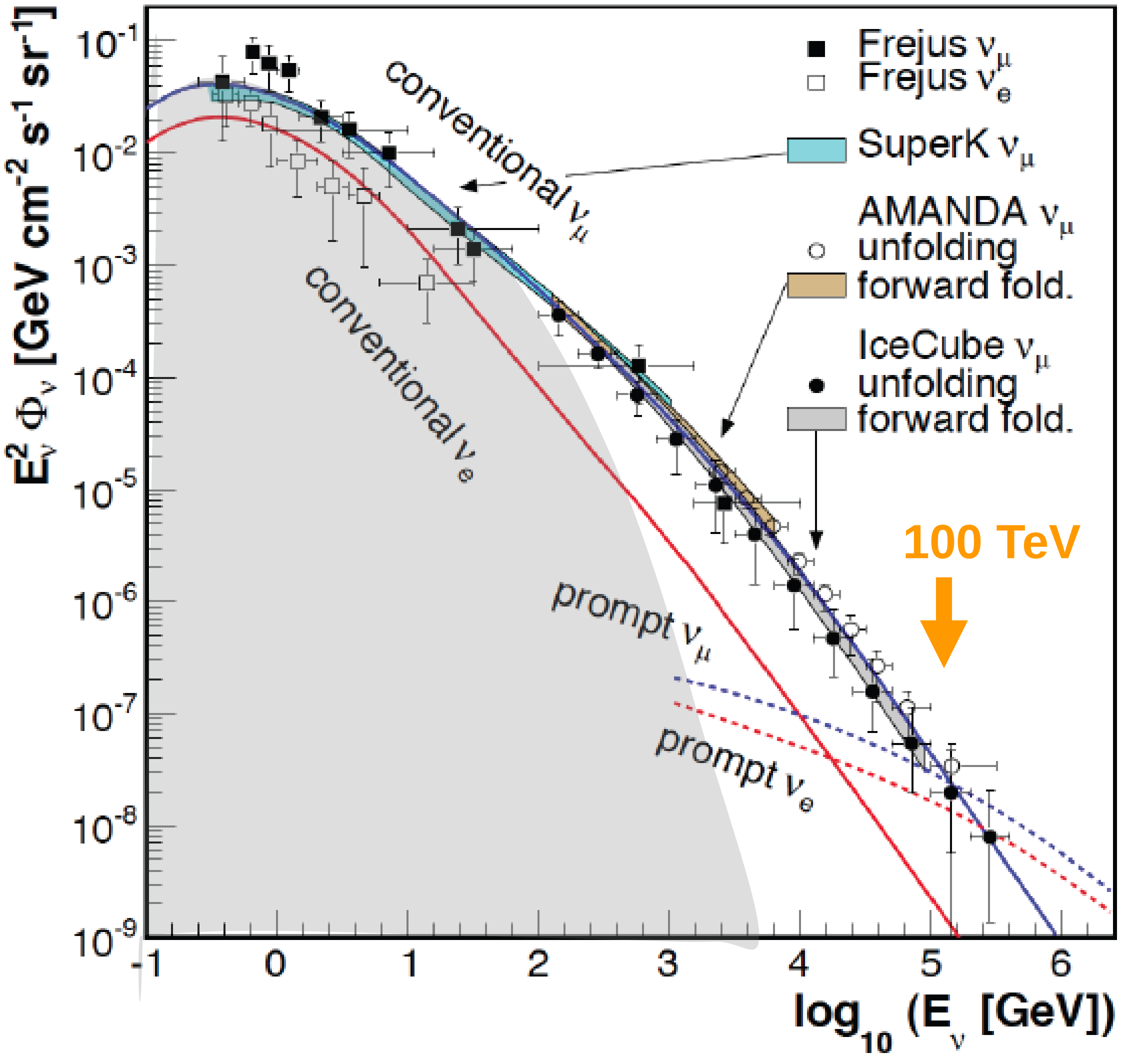
Technical issues being debated:
systematic effects in using „proton template“
absolute time determination (GPS, Sagnac effect…)

Best: wait till confirmed or excluded by MINOS or T2K or other measurements

IceCube



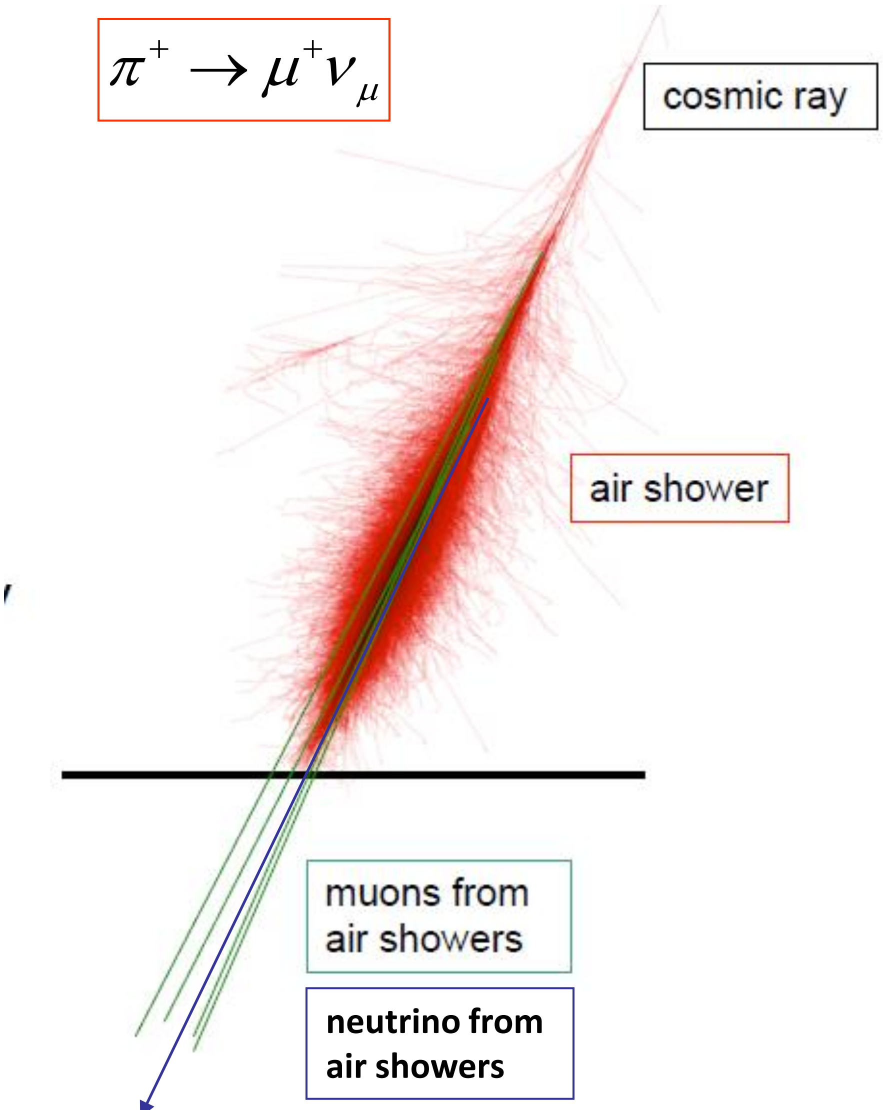
IceCube atmospheric neutrino spectrum



Grey:
(would expect depletion by tachyonic radiation (Glashow, Cohen)

Size of effect needs to be investigated

…can one do test with IceCube?



idea: muons and neutrinos coproduced in atmosphere at ~ 20 km height

look for variables that are sensitive to difference in neutrino / muon arrival times

difficult measurement in IceCube
but comparison IceTop / IceCube

several papers:

e.g. . Cohen, Glashow **arXiv:1109.6562**