Fishing the Sterile Neutrinos in Ice

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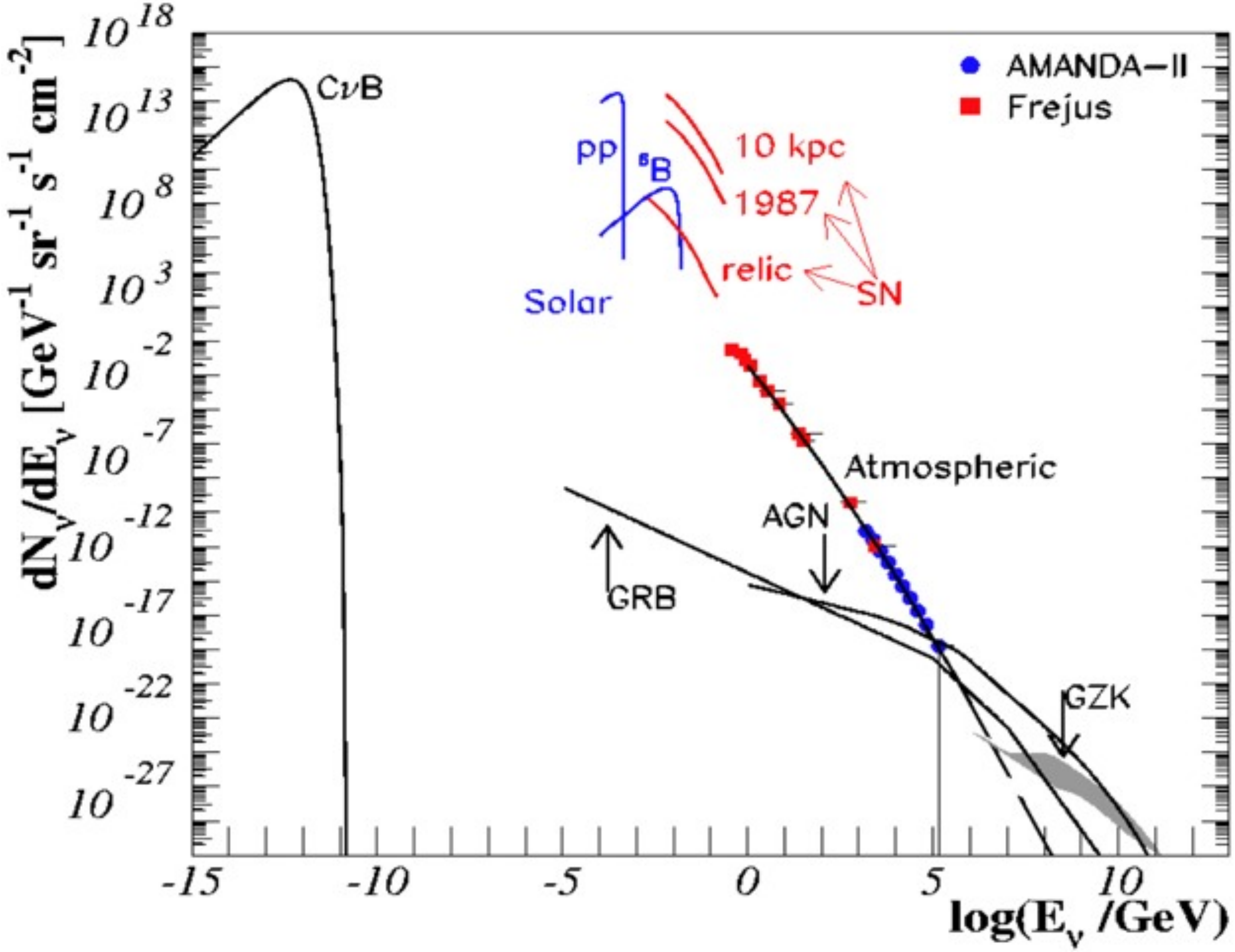
IPP11 – Sep 2011

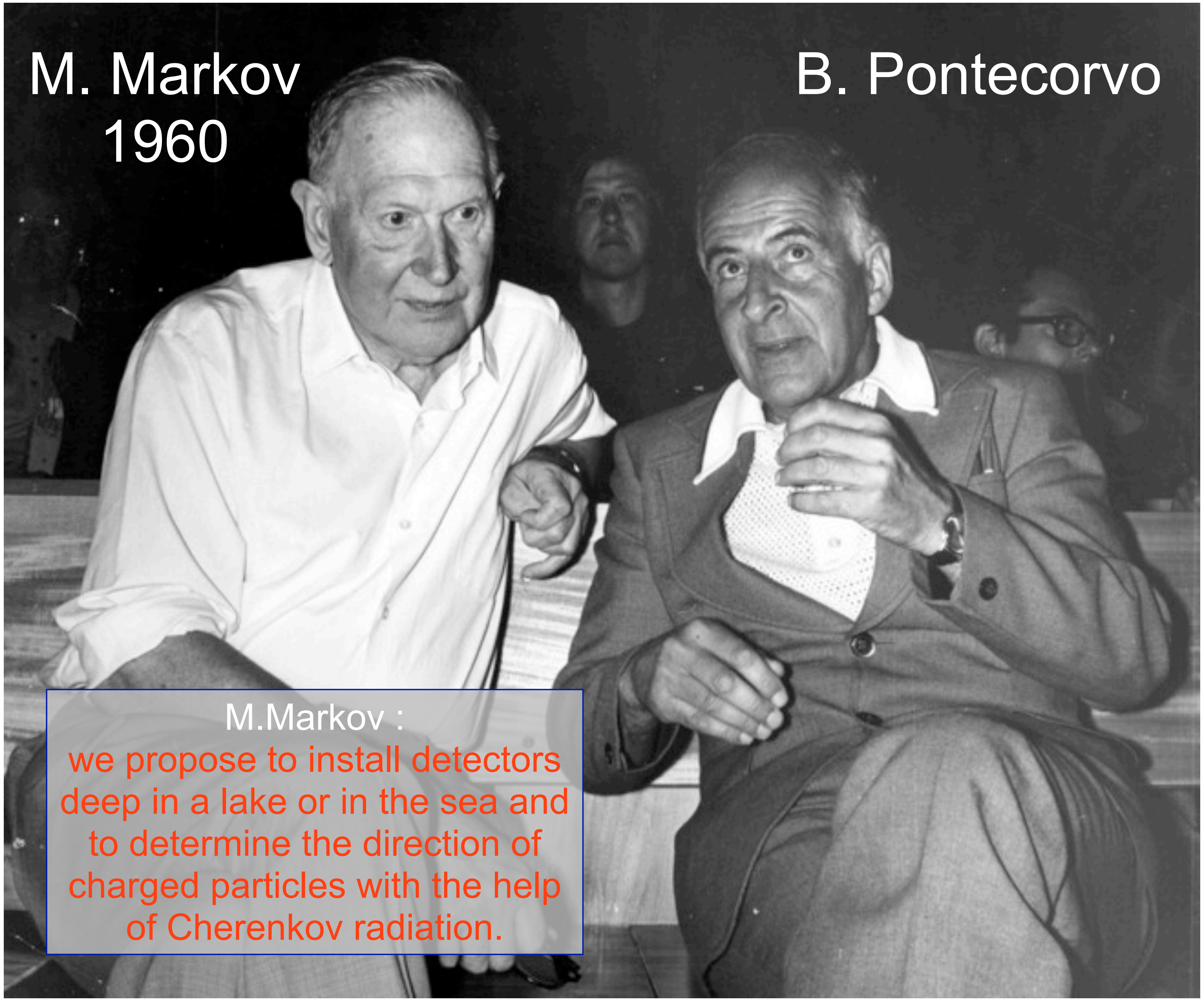
In collaboration with O. L. G. Peres and F. Halzen

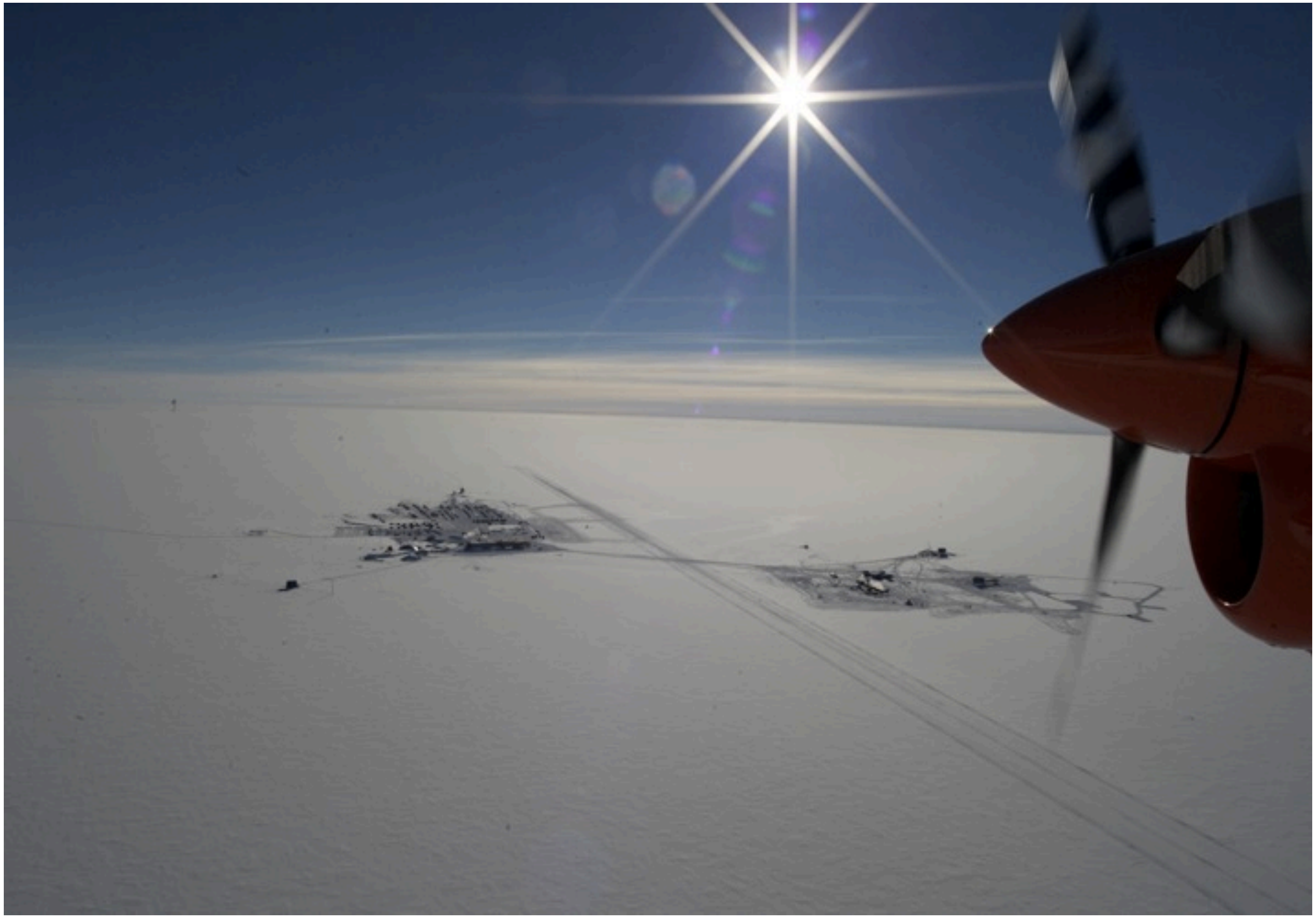
Outline:

- ✓ A brief introduction to IceCube
- ✓ Sterile neutrinos
- ✓ Effect of sterile neutrinos on ATM neutrinos
- ✓ Results

The Neutrino Sky

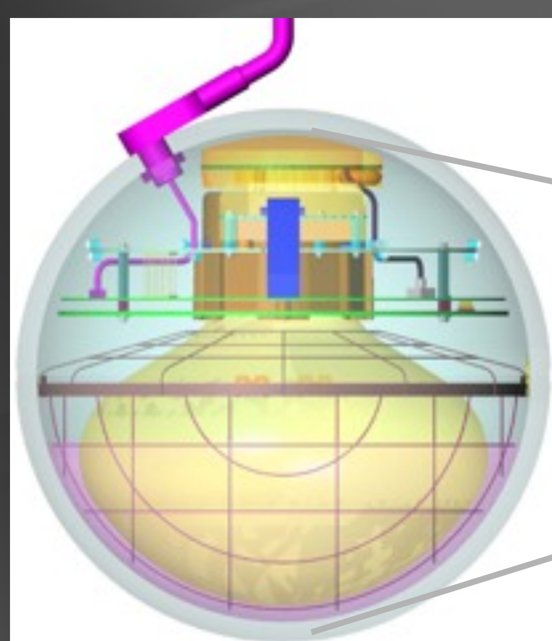



M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

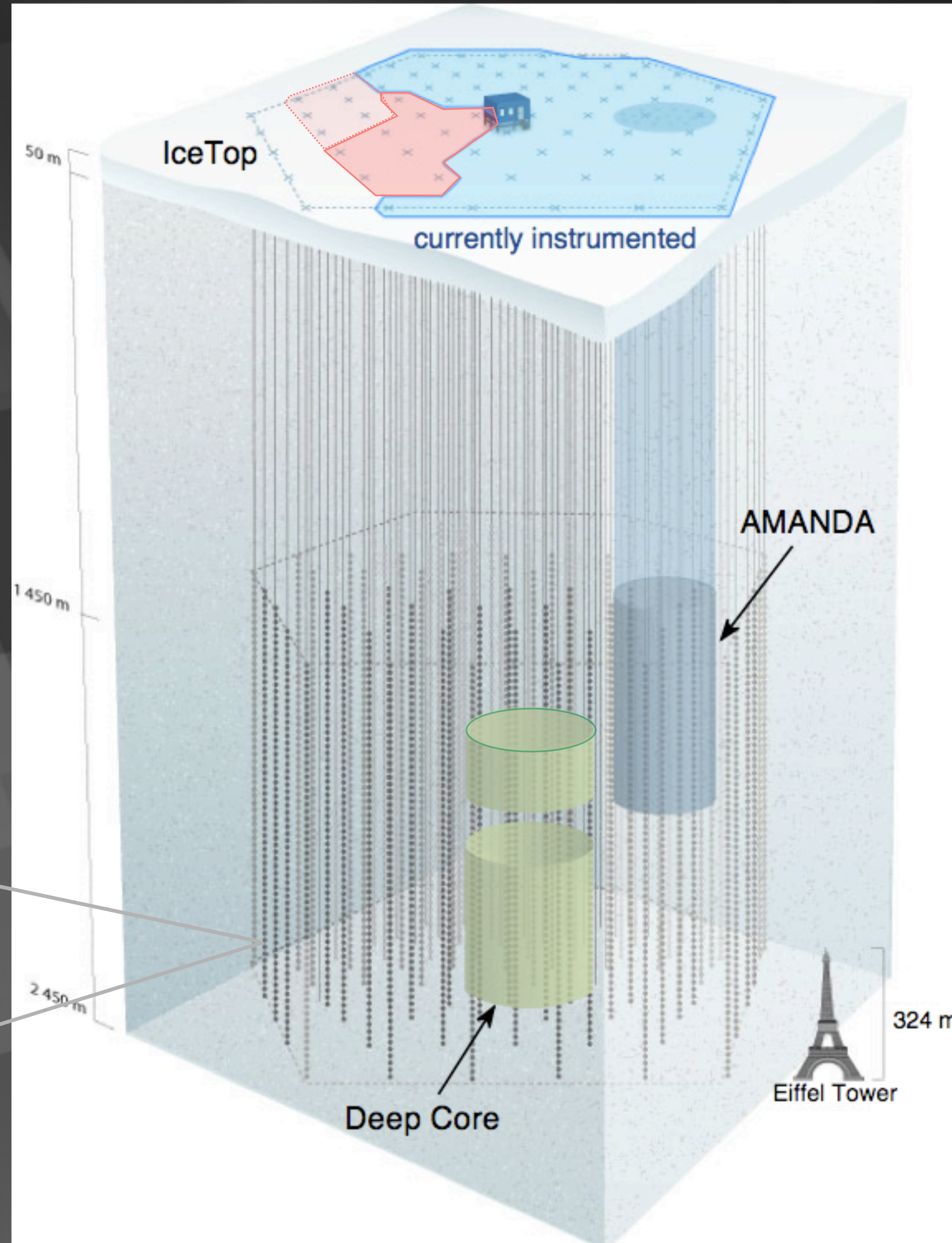


IceCube / Deep Core

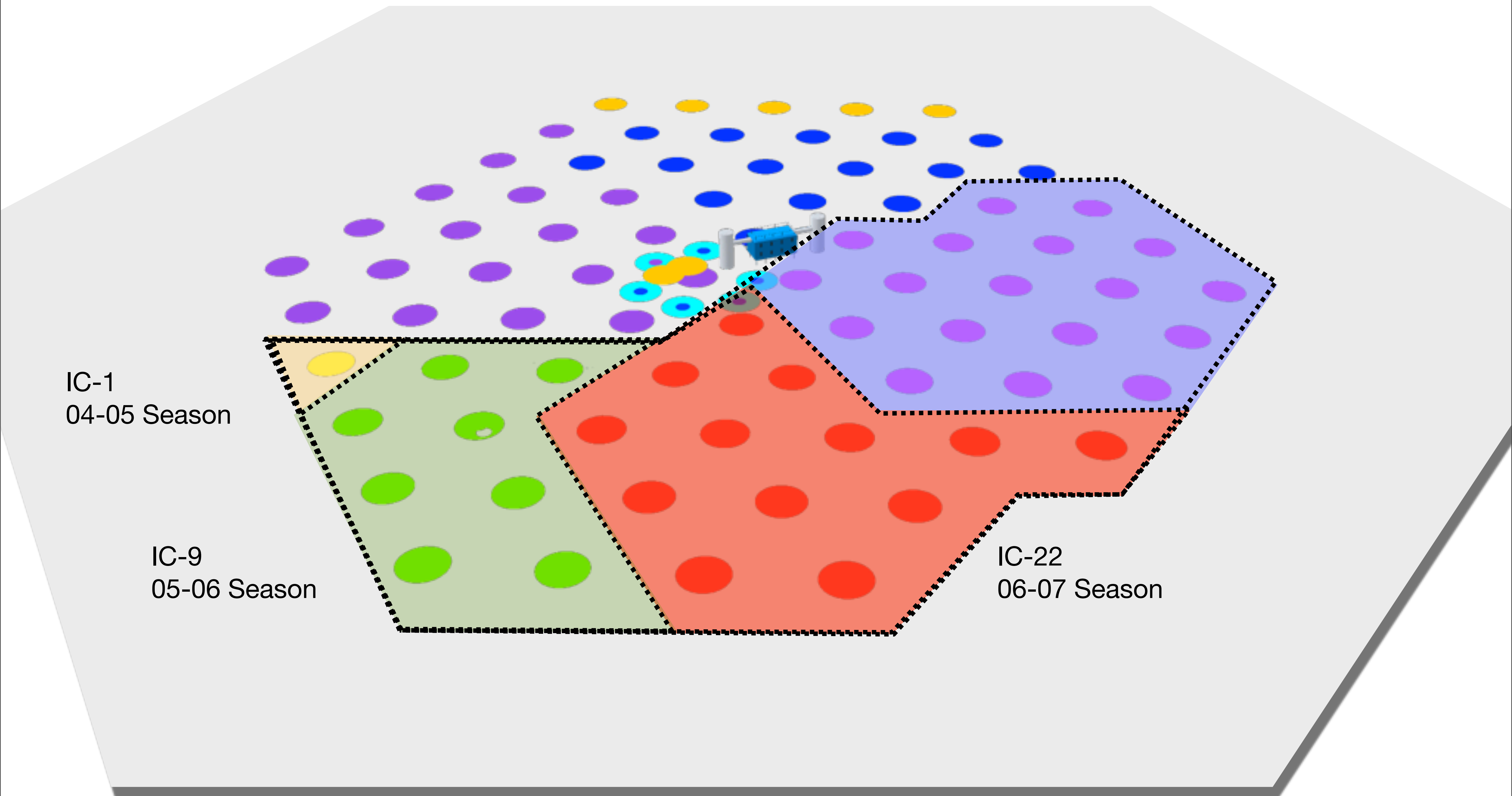
- 5320 optical modules on 86 strings (+ IceTop)
- detects ~220 neutrinos and 1.7x10^8 muons per day
- threshold 10 GeV
- angular resolution
  < 1 degree



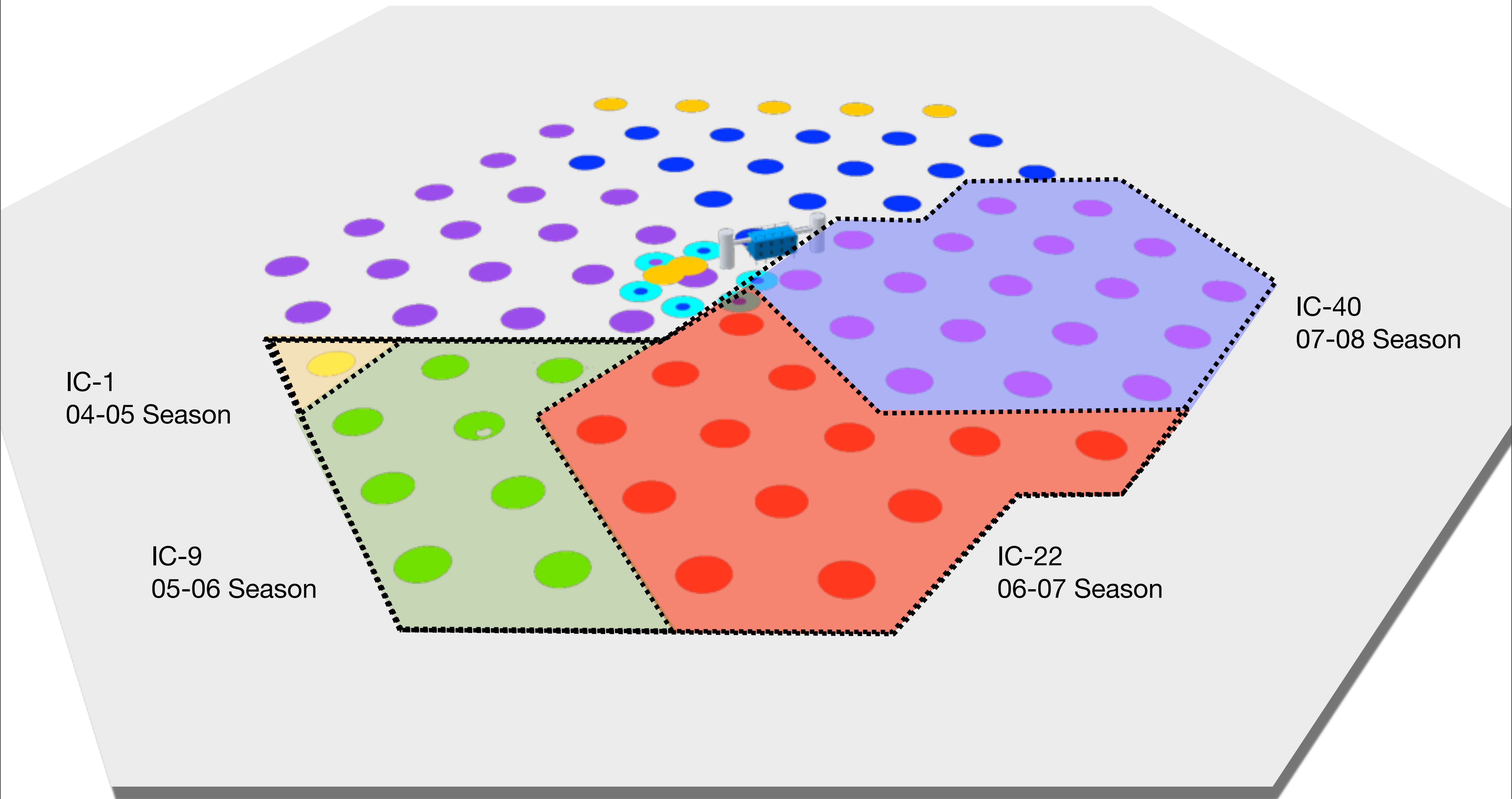
Digital Optical Module (DOM)



completed December 18, 2010



completed December 18, 2010



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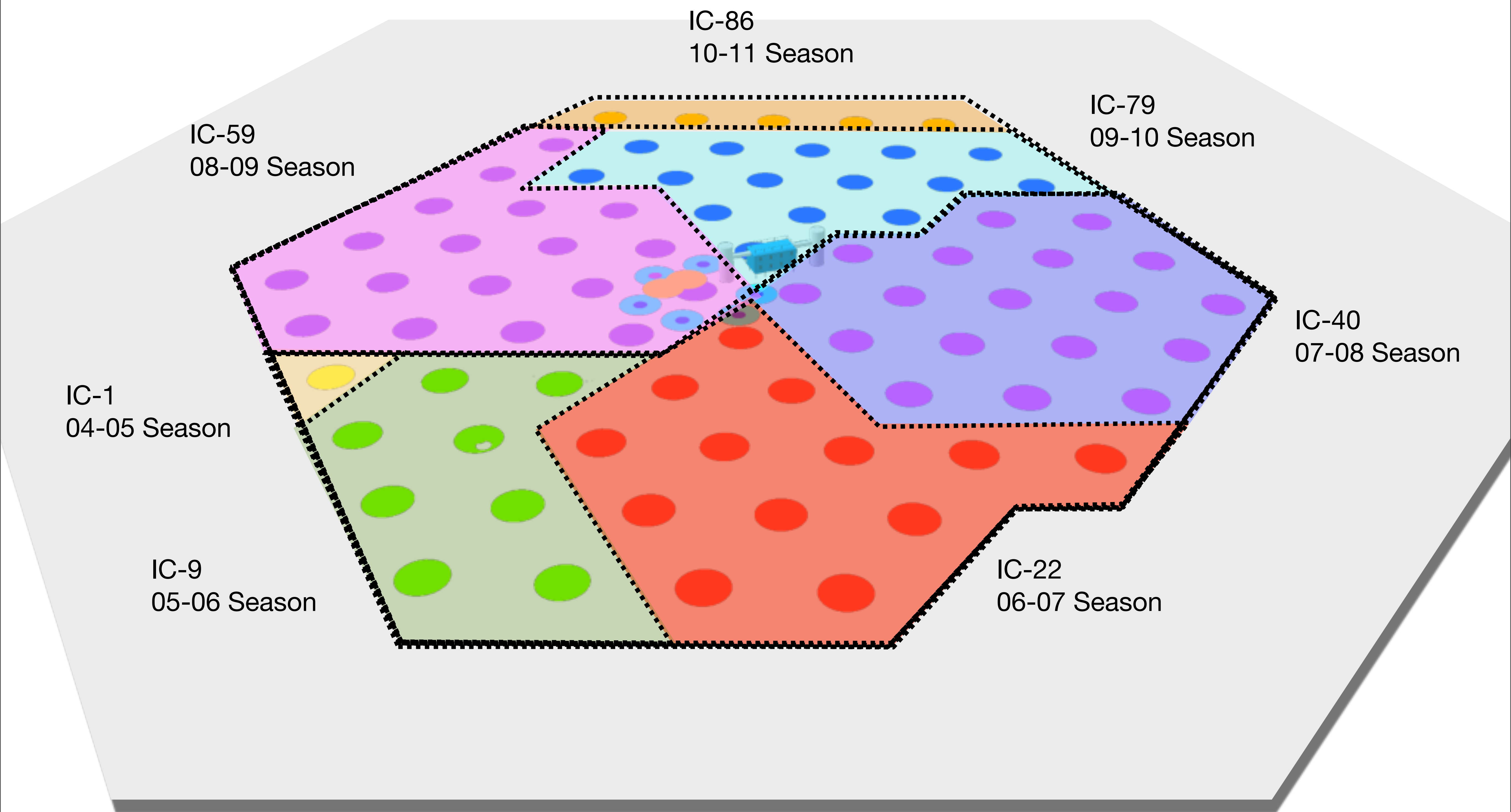
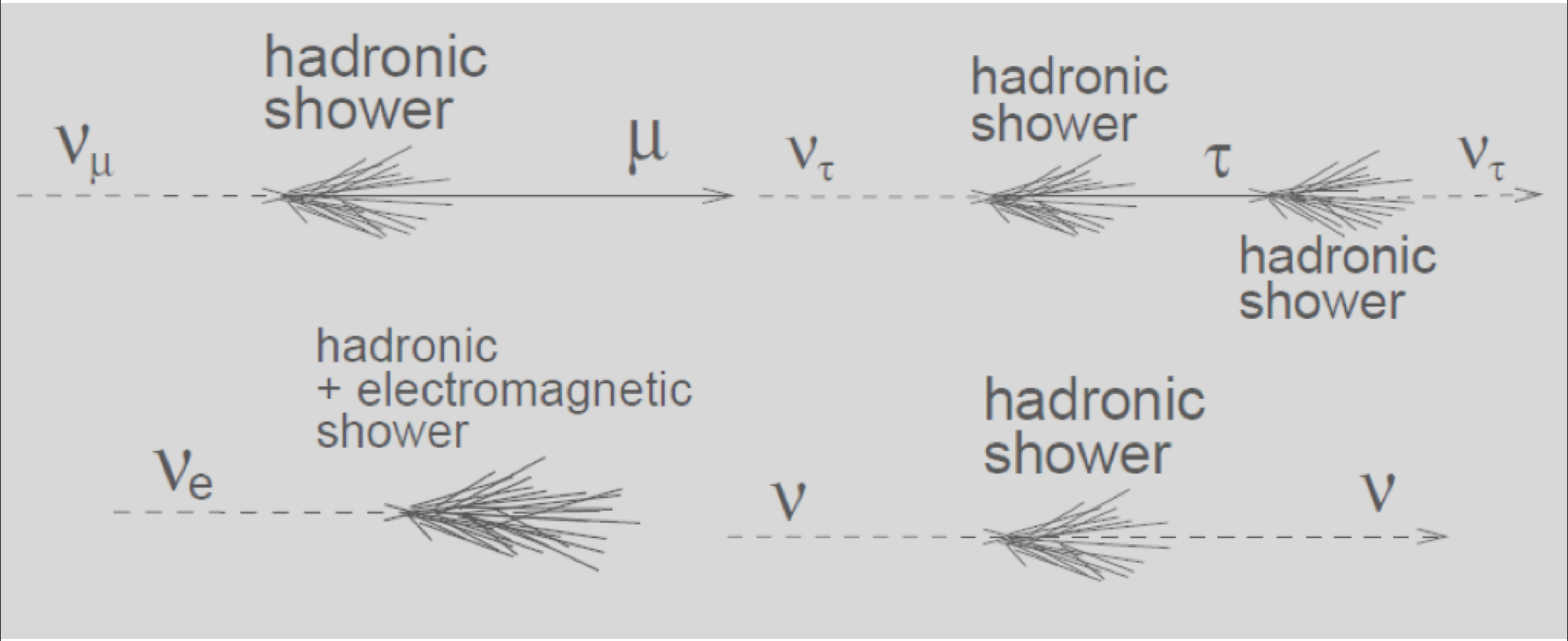
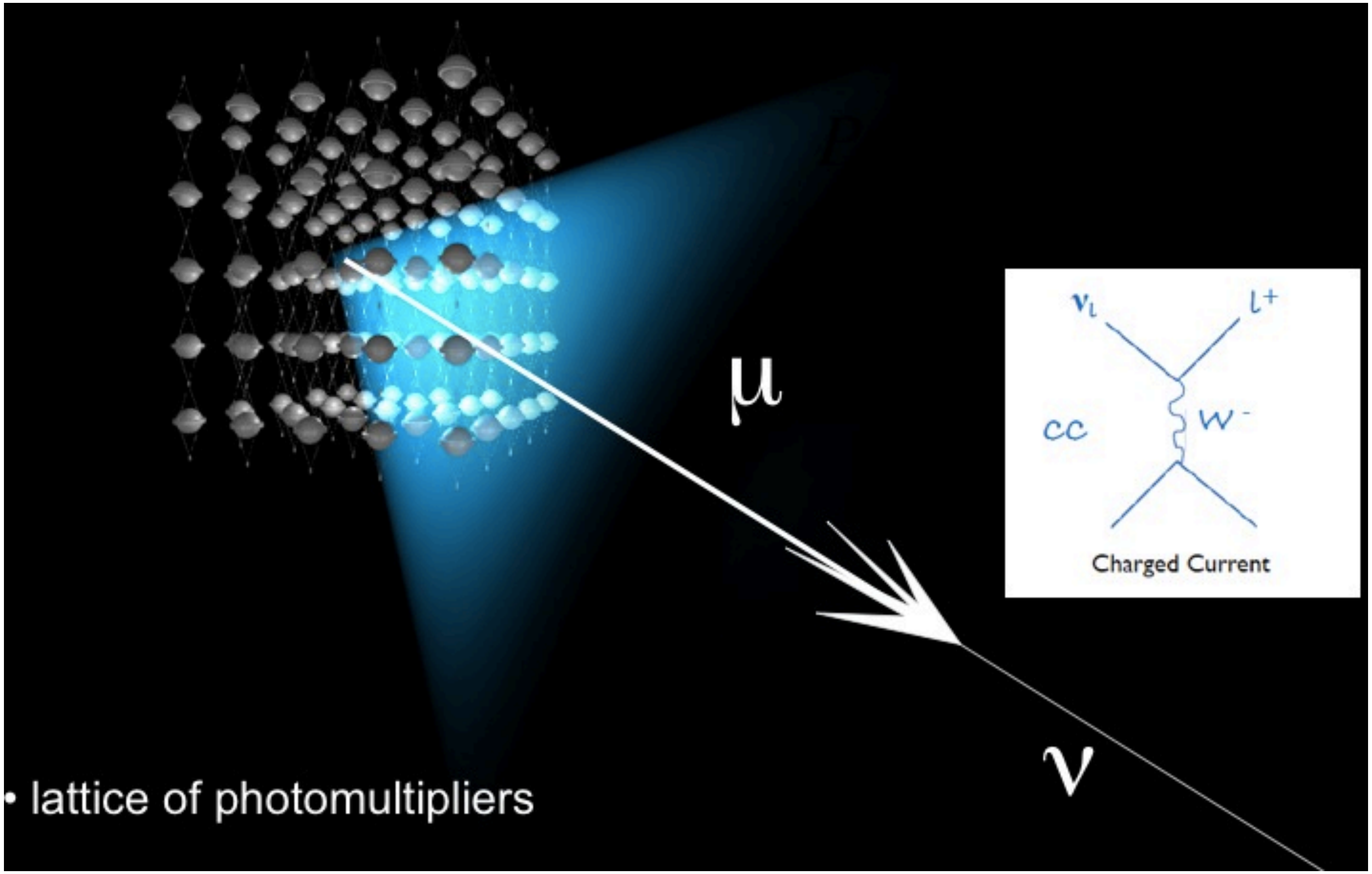
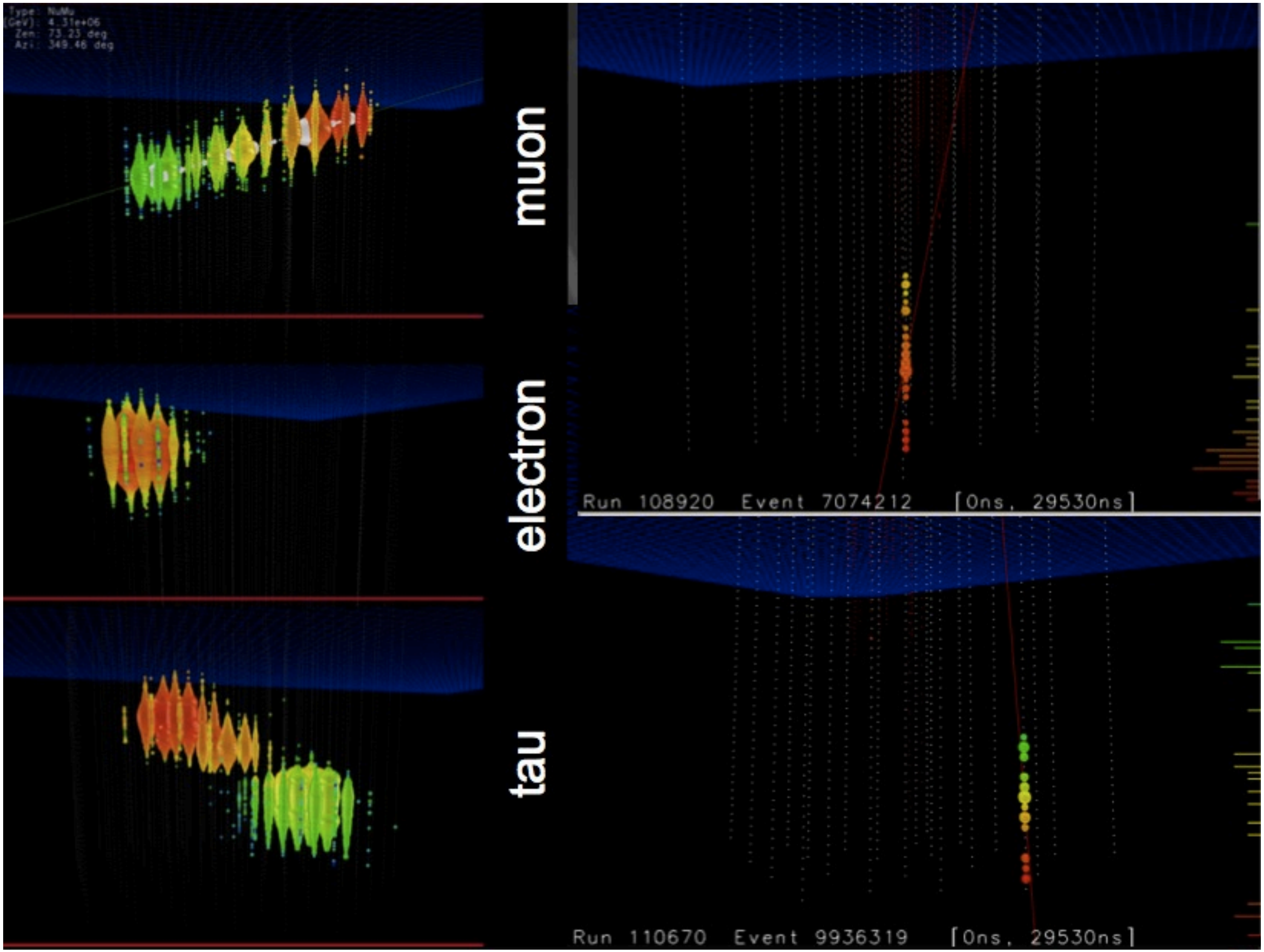
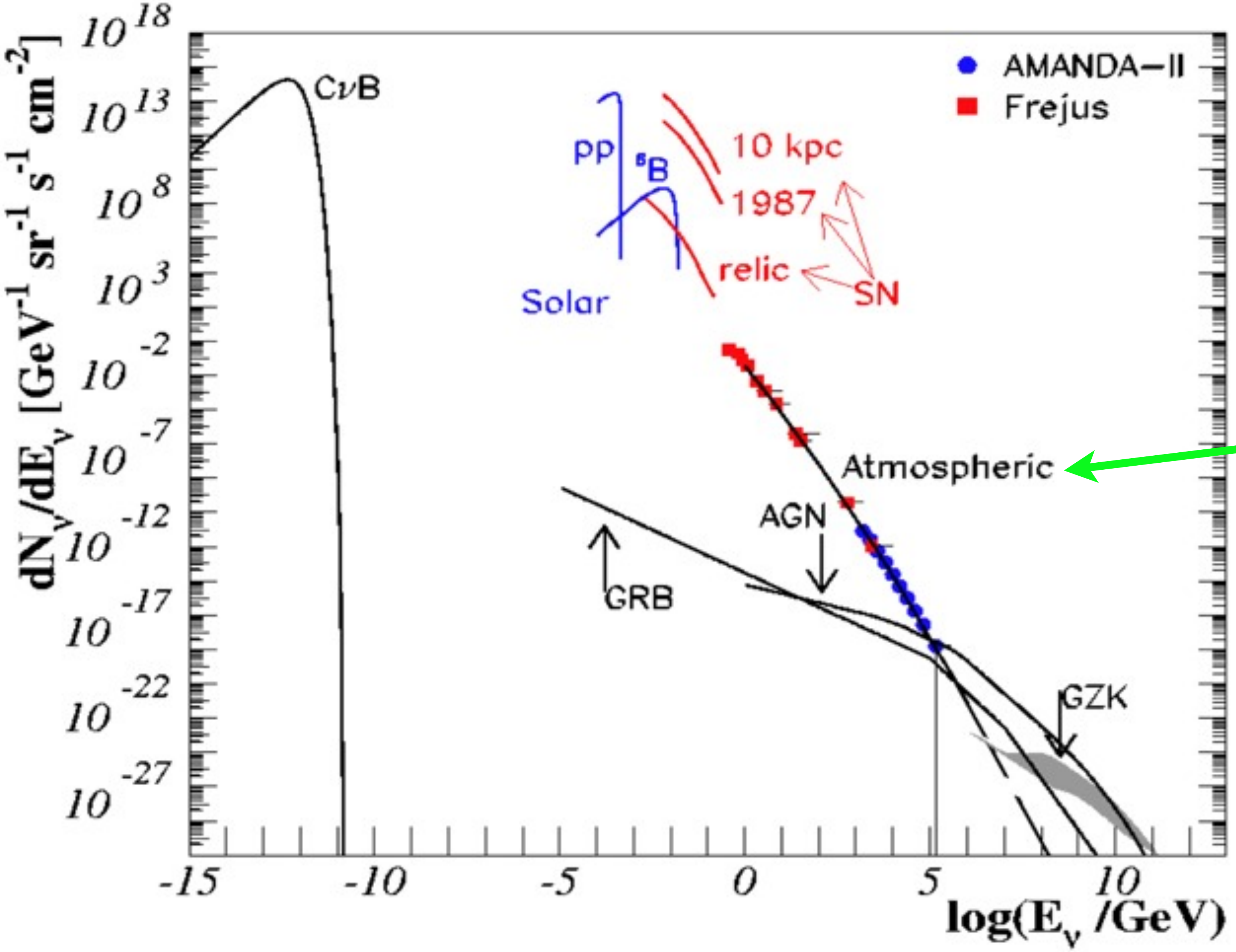


Flavors


hadronic
shower
ν_μ
μ
ν_τ
hadronic
shower
τ
ν_τ
hadronic
shower
hadronic
+ electromagnetic
shower
ν_e
hadronic
shower
ν
ν

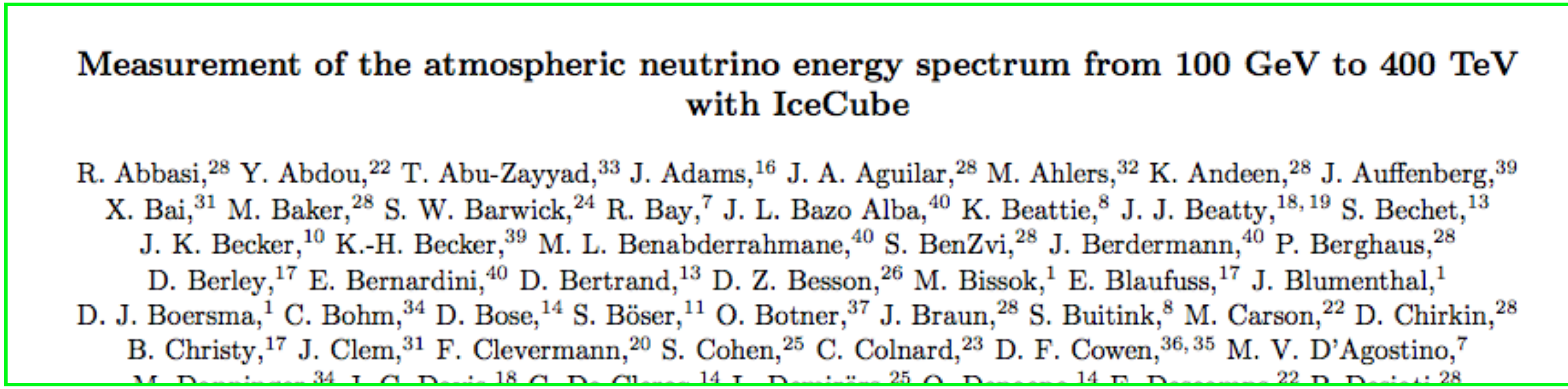

μ
ν
ν_l
l^+
cc
W^-
Charged Current
• lattice of photomultipliers


muon
electron
tau
Run 108920 Event 7074212 [0ns, 29530ns]
Run 110670 Event 9936319 [0ns, 29530ns]



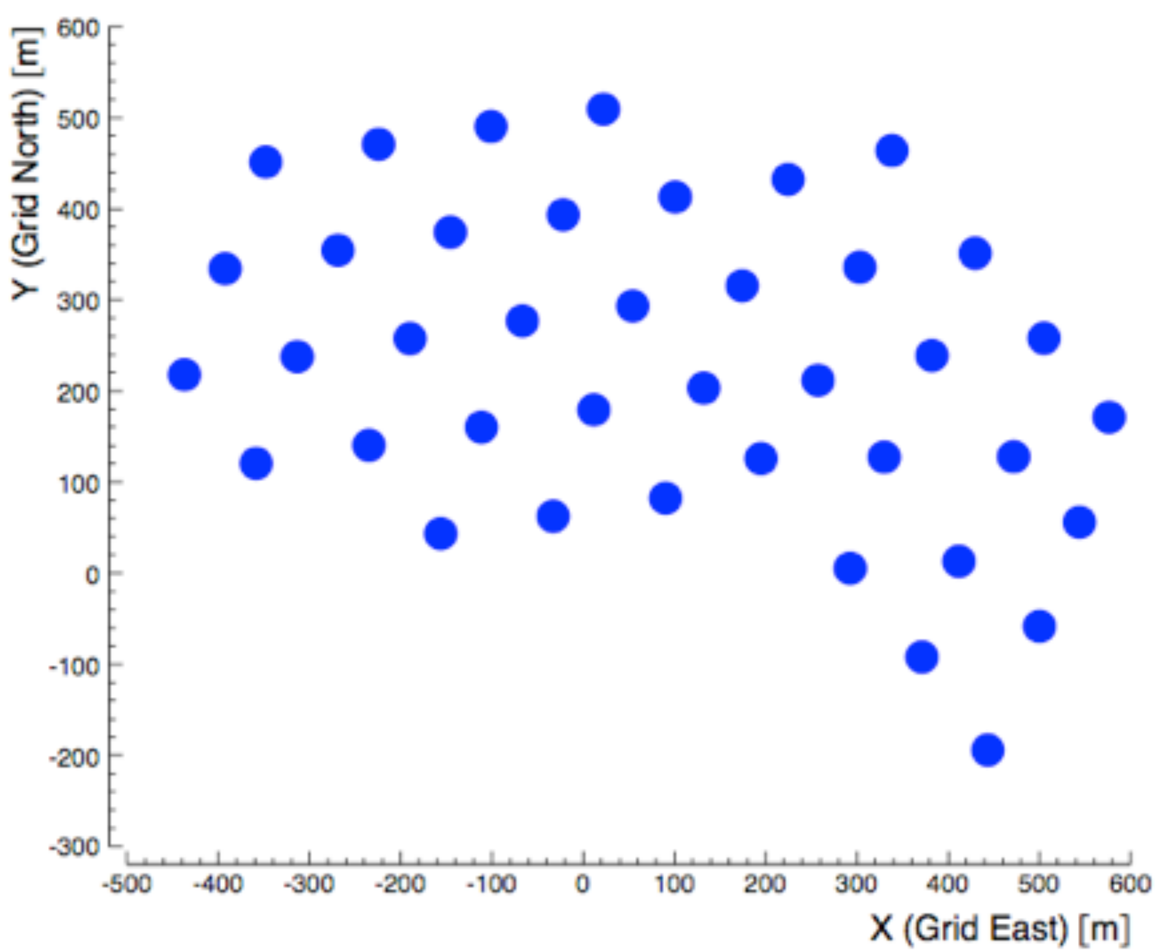
background for the astrophysical neutrino searches

astro-ph: 1010.3980



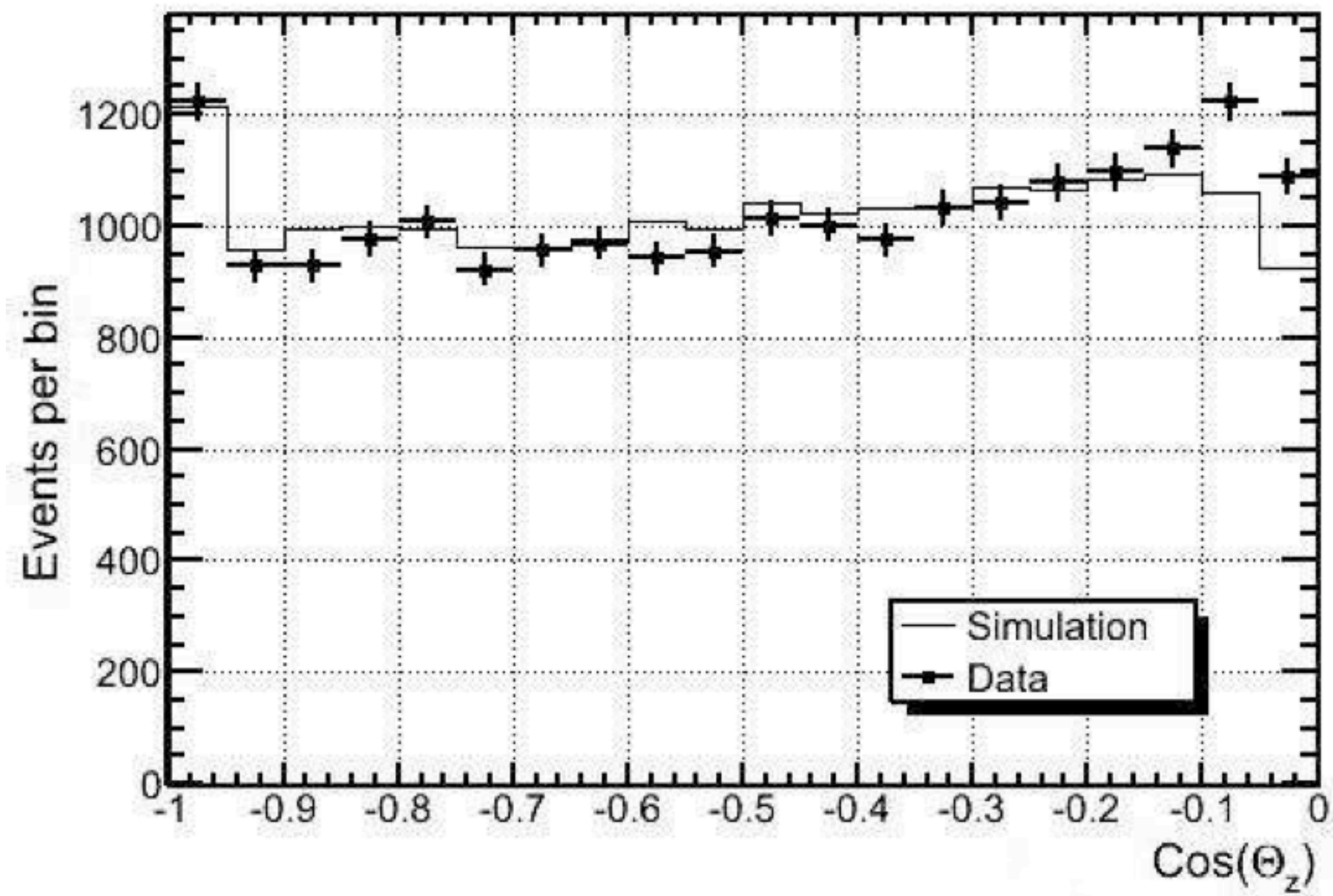
Measurement of the atmospheric neutrino energy spectrum from 100 GeV to 400 TeV with IceCube

R. Abbasi,[28] Y. Abdou,[22] T. Abu-Zayyad,[33] J. Adams,[16] J. A. Aguilar,[28] M. Ahlers,[32] K. Andeen,[28] J. Auffenberg,[39] X. Bai,[31] M. Baker,[28] S. W. Barwick,[24] R. Bay,[7] J. L. Bazo Alba,[40] K. Beattie,[8] J. J. Beatty,[18,19] S. Bechet,[13] J. K. Becker,[10] K.-H. Becker,[39] M. L. Benabderrahmane,[40] S. BenZvi,[28] J. Berdermann,[40] P. Berghaus,[28] D. Berley,[17] E. Bernardini,[40] D. Bertrand,[13] D. Z. Besson,[26] M. Bissok,[1] E. Blaufuss,[17] J. Blumenthal,[1] D. J. Boersma,[1] C. Bohm,[34] D. Bose,[14] S. Böser,[11] O. Botner,[37] J. Braun,[28] S. Buitink,[8] M. Carson,[22] D. Chirkin,[28] B. Christy,[17] J. Clem,[31] F. Clevermann,[20] S. Cohen,[25] C. Colnard,[23] D. F. Cowen,[36,35] M. V. D'Agostino,[7]



Overhead view of IceCube 40 string configuration

IceCube Col. (1010.3980)



$$N_{\rm events} = \int dt \int d\Omega \int dE \ . \ \Phi(E,\theta) \ . \ A^{\nu}_{\rm eff}(E,\theta)$$

The effective area is the area occupied by a hypothetical detector with the same collecting power as IceCube, but with 100% efficiency

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flux of atmospheric neutrinos with units of GeV^{-1} s^{-1} sr^{-1} cm^{-2}

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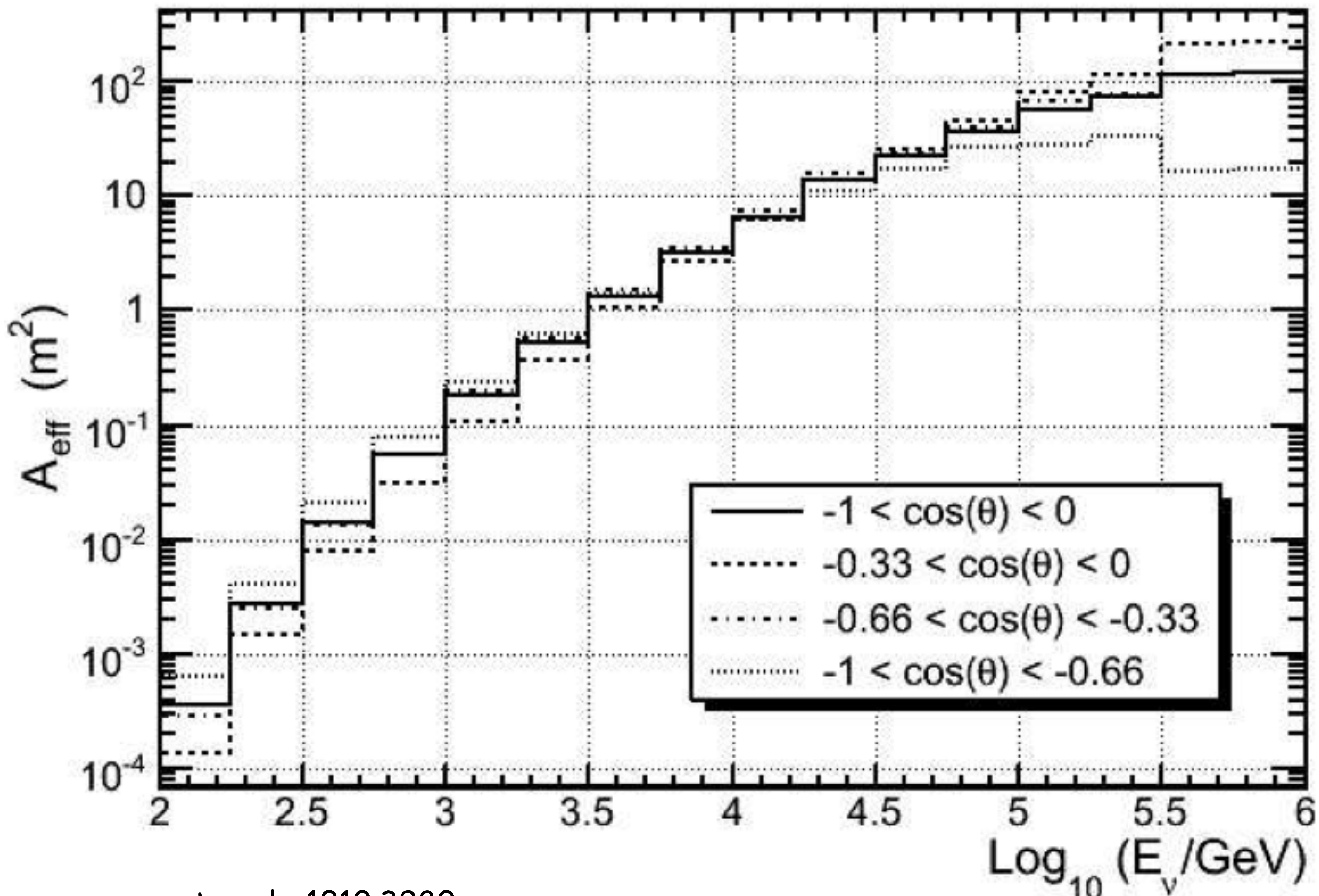
$$N_{\mathrm{events}} = \int dt \int d\Omega \int dE \;.\; \Phi(E,\theta) \;.\; A^{\nu}_{\mathrm{eff}}(E,\theta)$$

flux of atmospheric neutrinos with units of $\mathrm{GeV}^{-1}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{cm}^{-2}$

The neutrino effective area already contain the propagation and interaction of neutrinos in the Earth

IC40 neutrino effective area



astro-ph: 1010.3980

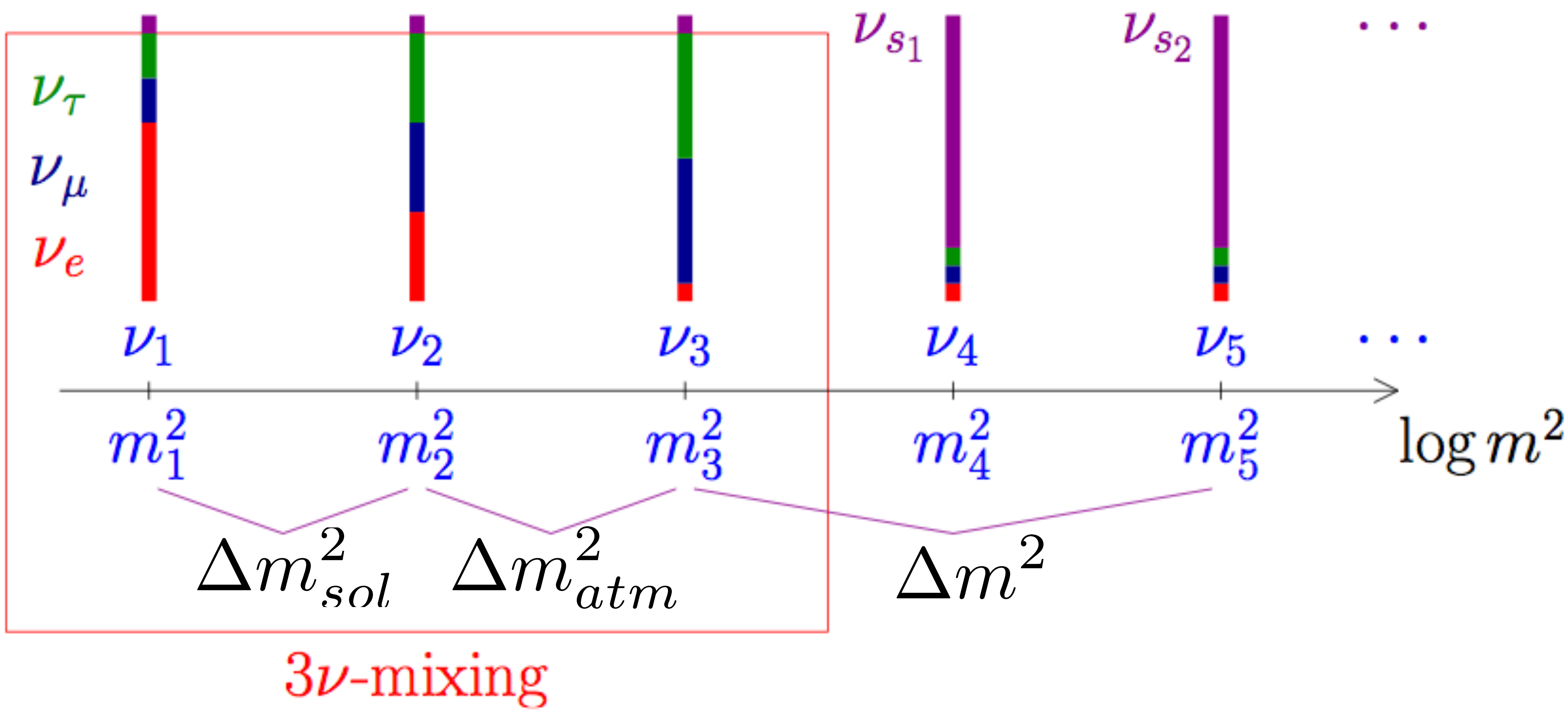
Sterile Neutrinos

Sterile means no standard model interactions

Oscillation Phenomenology in the presence of sterile neutrinos

✔ Active neutrinos (ν_e ,ν_μ ,ν_τ) can oscillate into sterile neutrinos (ν_s)

✔ Observables:
- Disappearance of active neutrinos
- Indirect evidence through combined fit of data

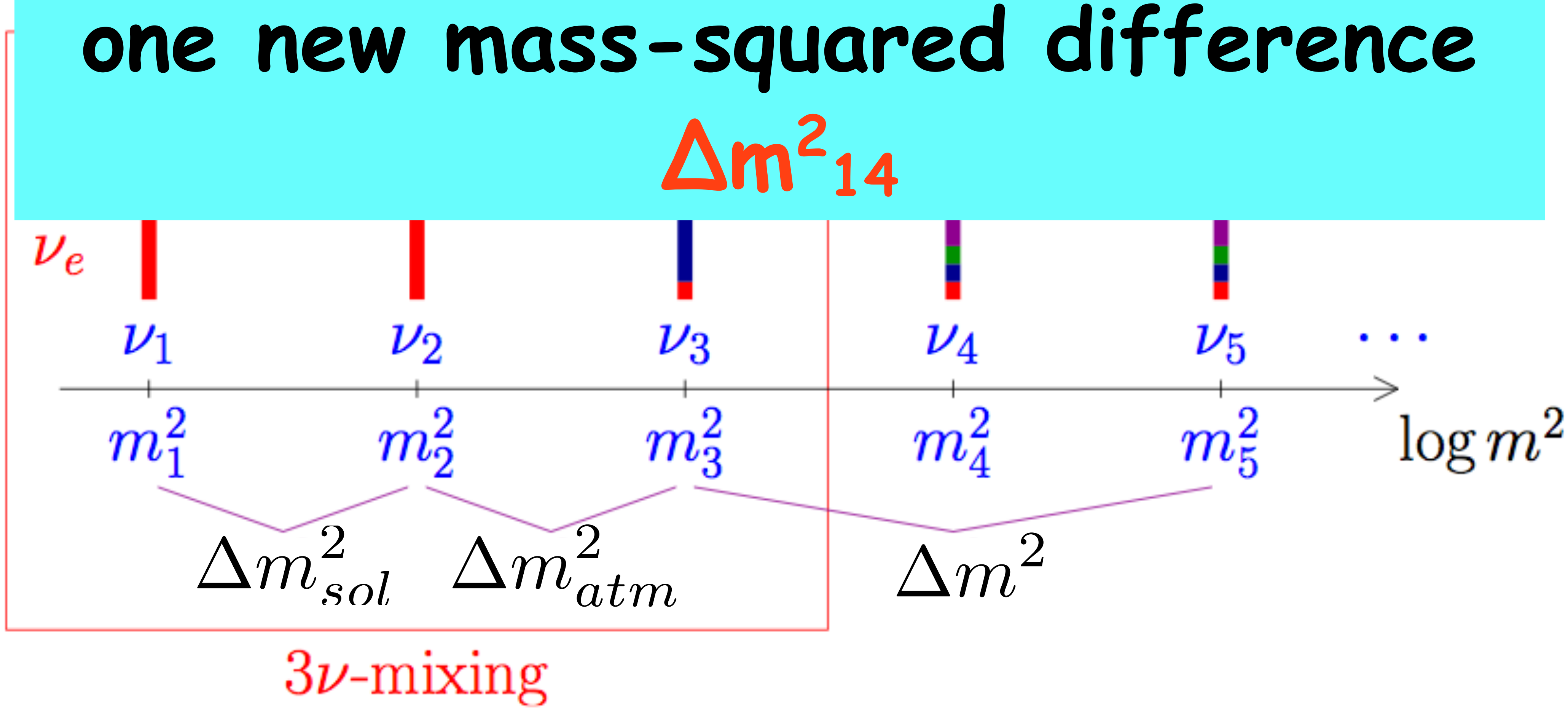


Oscillation Phenomenology in the presence of sterile neutrinos

✓ Active neutrinos (ν_e ,ν_μ ,ν_τ) can oscillate into sterile neutrinos (ν_s)

✓ Obs

for 3+1 scheme: three new mixing angles θ_{14}, θ_{24}, θ_{34} and effectively one new mass-squared difference Δm^2_{14}



ATM Neutrinos

ν_μ - ν_s oscillations with $\Delta m^2 \sim 1$ eV^2 are enhanced in matter of the Earth in energy range 0.5 – few TeV

↓

This oscillation changes the energy spectrum and zenith angle distribution of the atmospheric neutrinos

↓

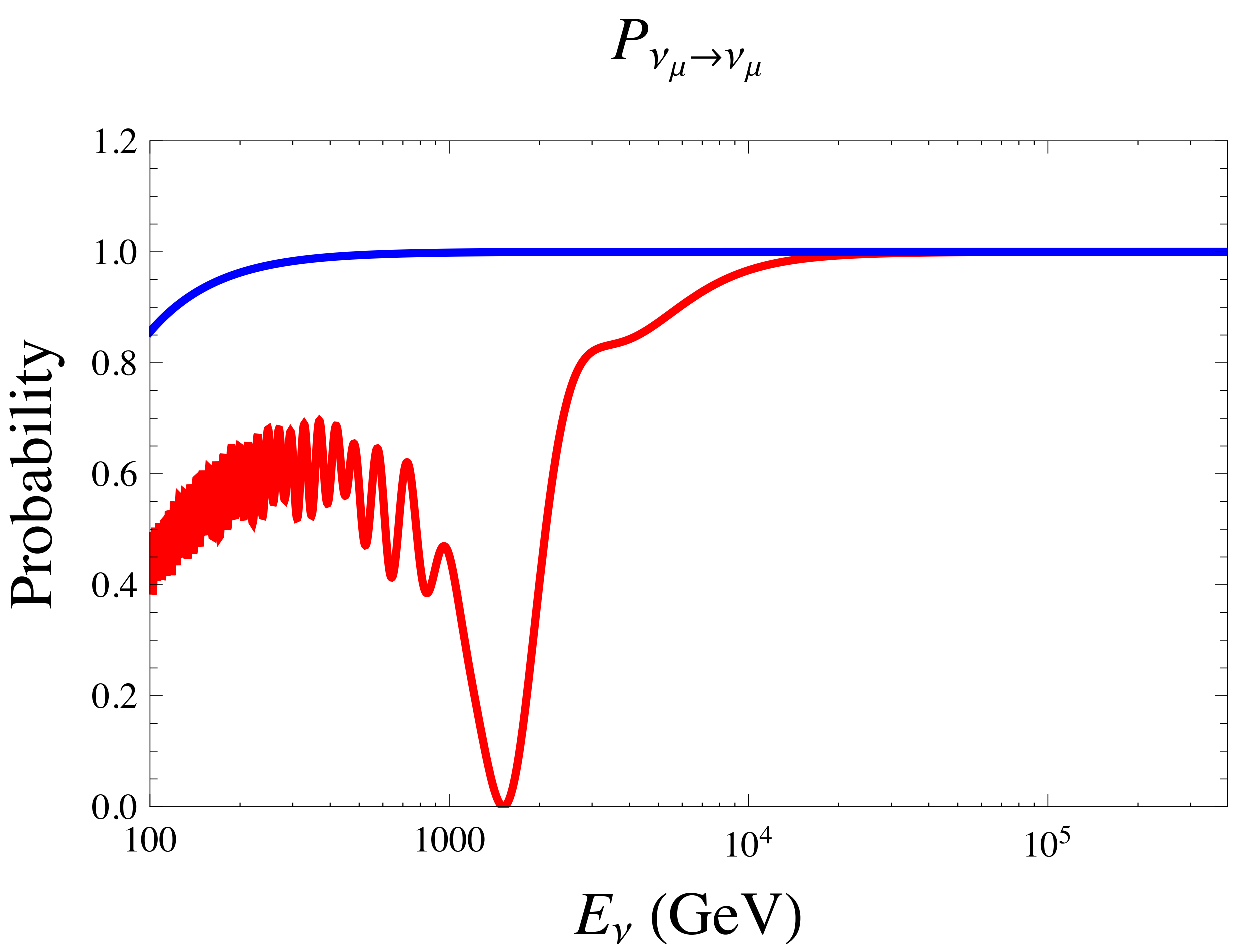
Thus, a distortion in the energy spectrum and zenith angle distribution of high energy atm neutrinos

H. Nunokawa, O. L. G. Peres, R. Zukanovich-Funchal
Phys. Lett B562 (2003) 279

S. Choubey
JHEP 0712 (2007) 014

S. Razzaque and A. Smirnov
1104.1390, [hep-ph]

Oscillation Probability

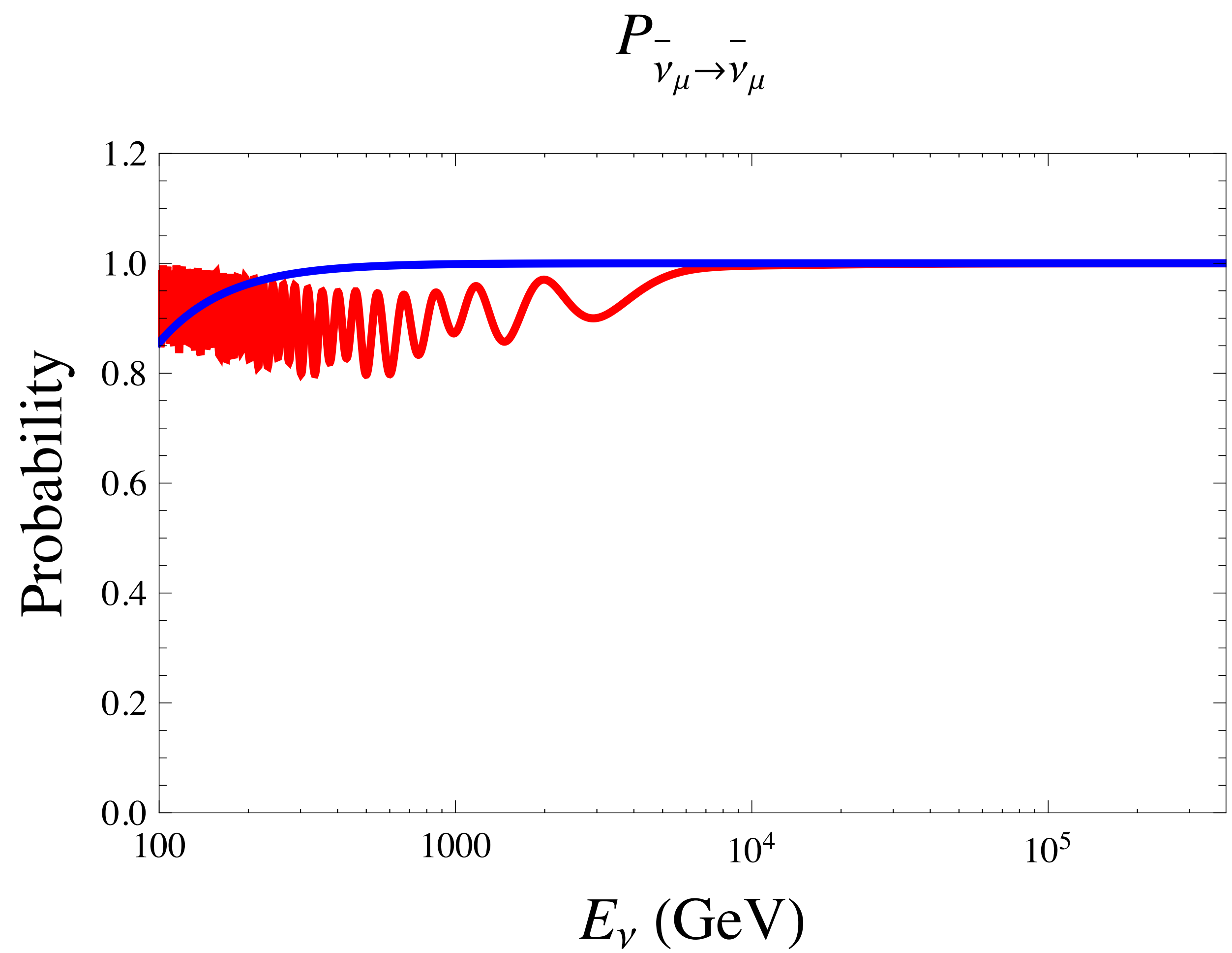


$$\Delta m^2_{41} = 0.6 \text{ eV}^2$$

$$\sin^2\theta_{14} = 0$$

$$\sin^2\theta_{24} = 0.04$$

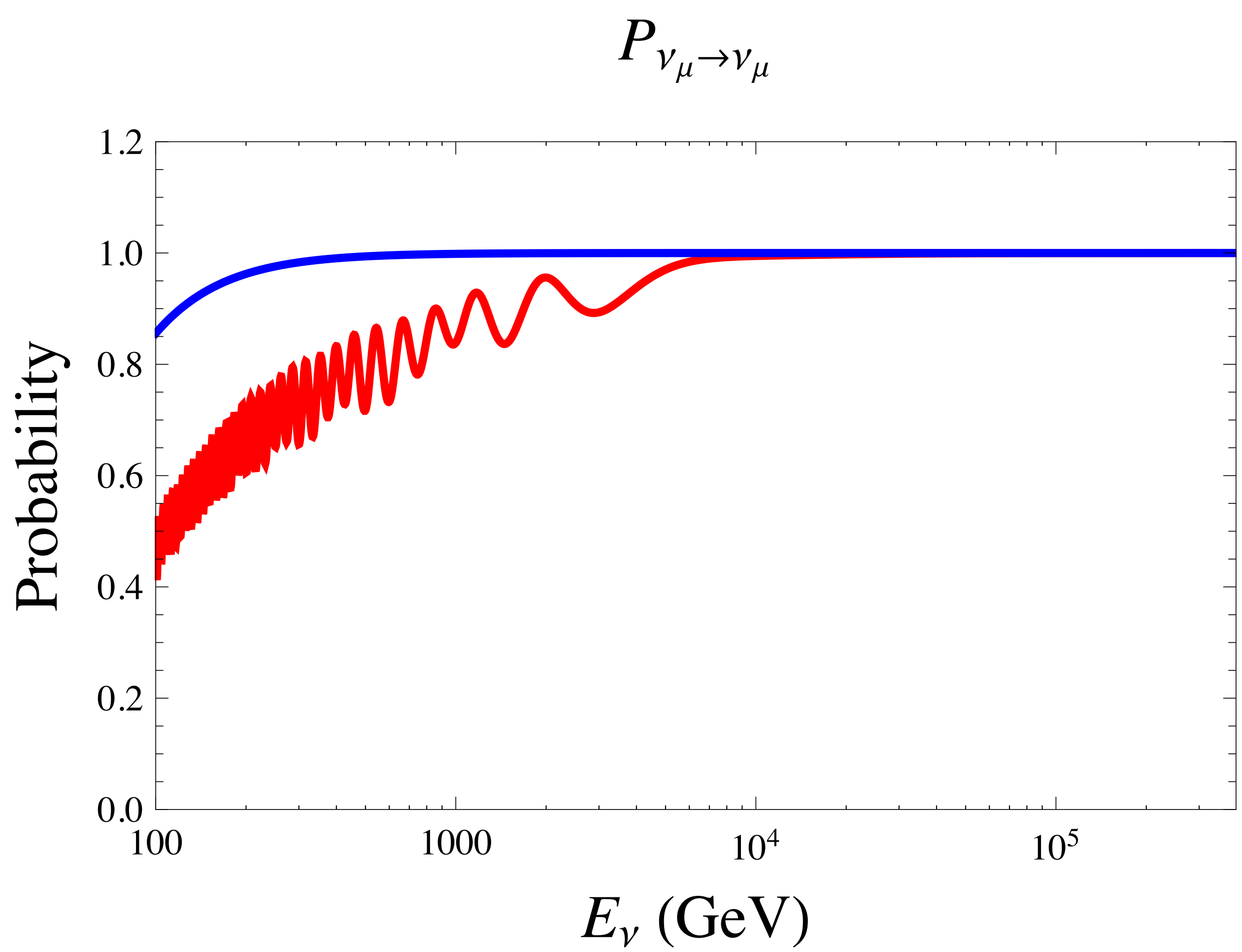
$$\sin^2\theta_{34} = 0.04$$



Inverted Hierarchy

θ_z=170 degrees

Oscillation Probability



$$\Delta m^2_{41} = 0.6\ \mathrm{eV}^2$$

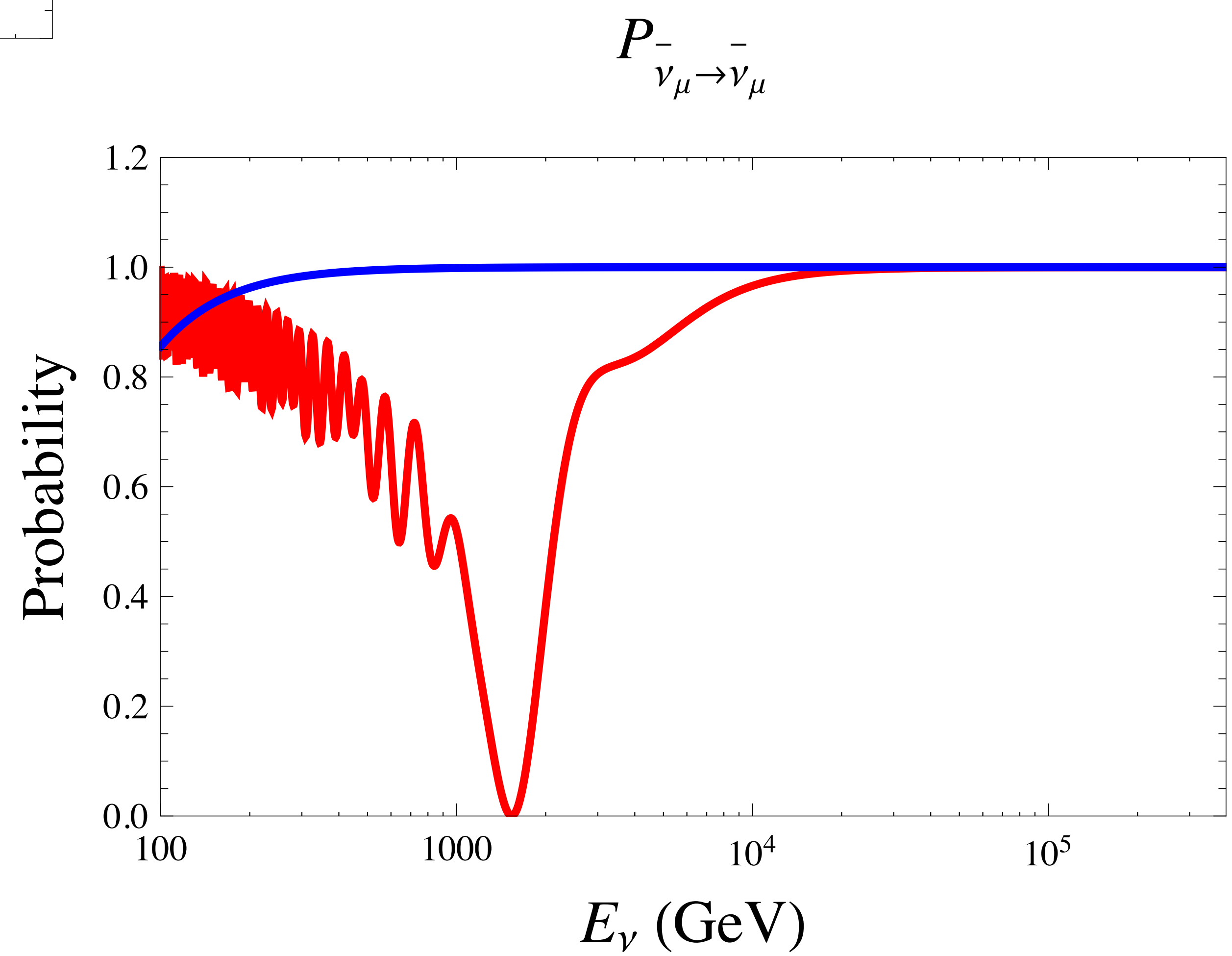
$$\sin^2\theta_{14} = 0$$

$$\sin^2\theta_{24} = 0.04$$

$$\sin^2\theta_{34} = 0.04$$

Normal Hierarchy

θ_z=170 degrees

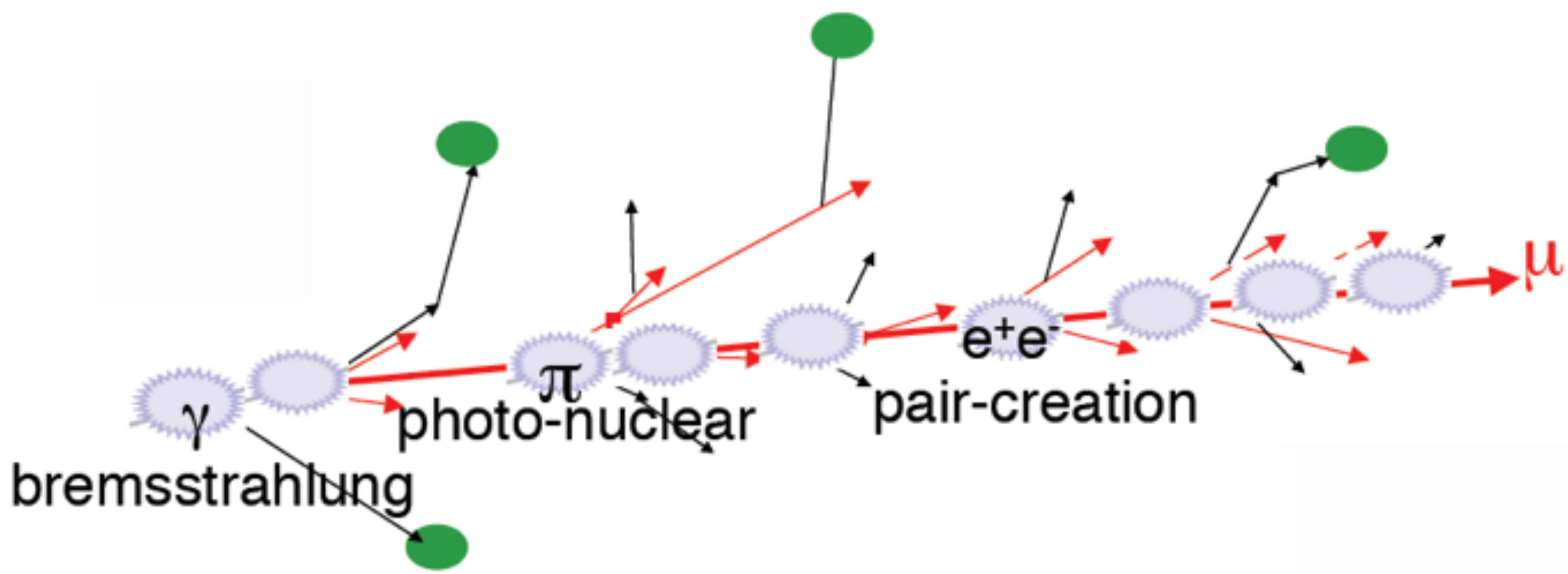


Muon Effective Area

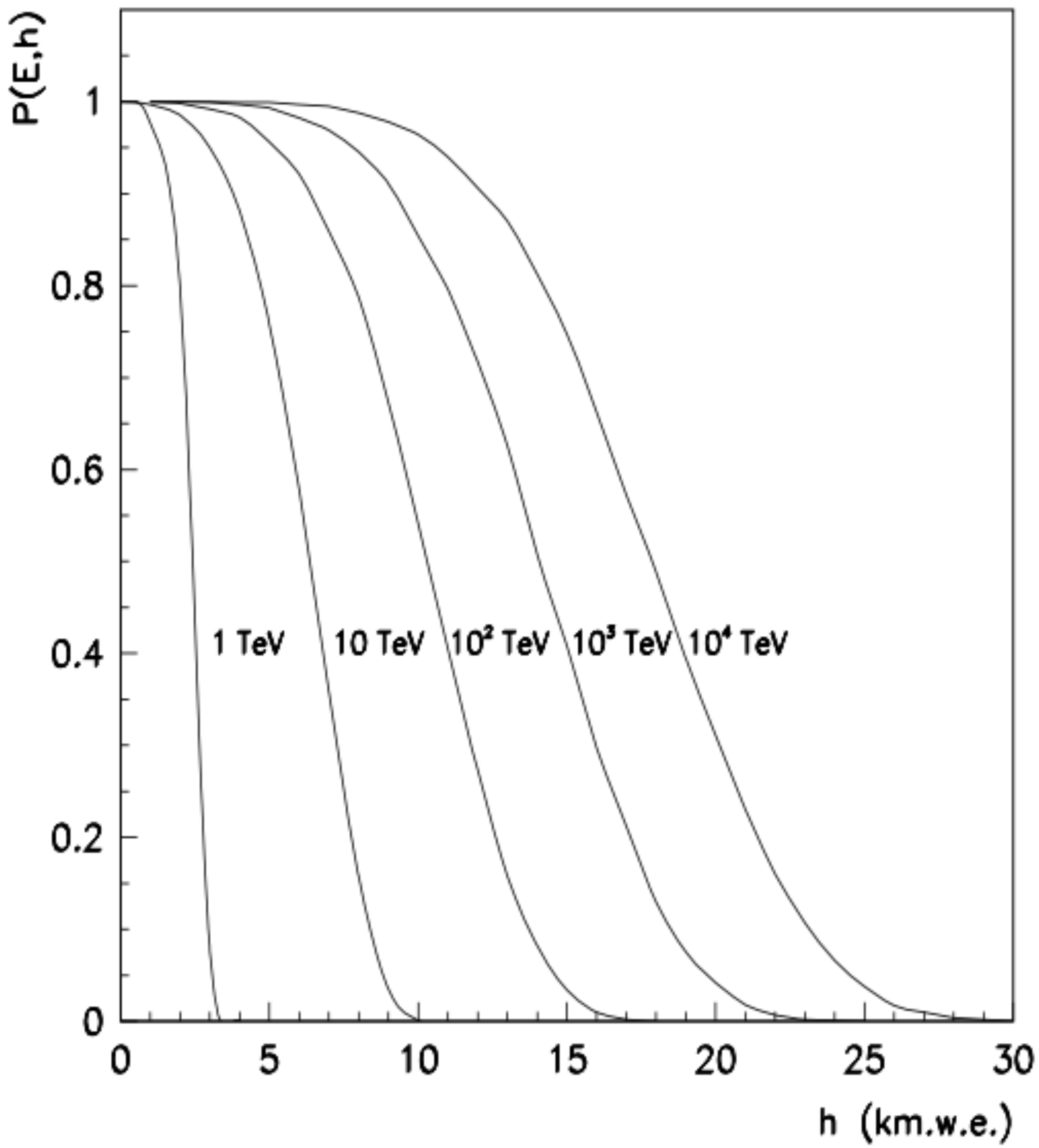
$$A^{\nu}_{\rm eff}(E_\nu,\theta_z) = \int dE^i_\mu dE^f_\mu \, {\rm damp}(E_\nu,\theta_z) \left[\rho \frac{d\sigma(E_\nu,E^i_\mu)}{dE^i_\mu}\right] RR(E^i_\mu,E^f_\mu) A^{\mu}_{\rm eff}(E^f_\mu,\theta_z)$$

Probability density

$$RR(E^i_\mu,E^f_\mu) = \int_0^\infty \mathcal{P}(E^i_\mu,E^f_\mu,X)\, dX$$

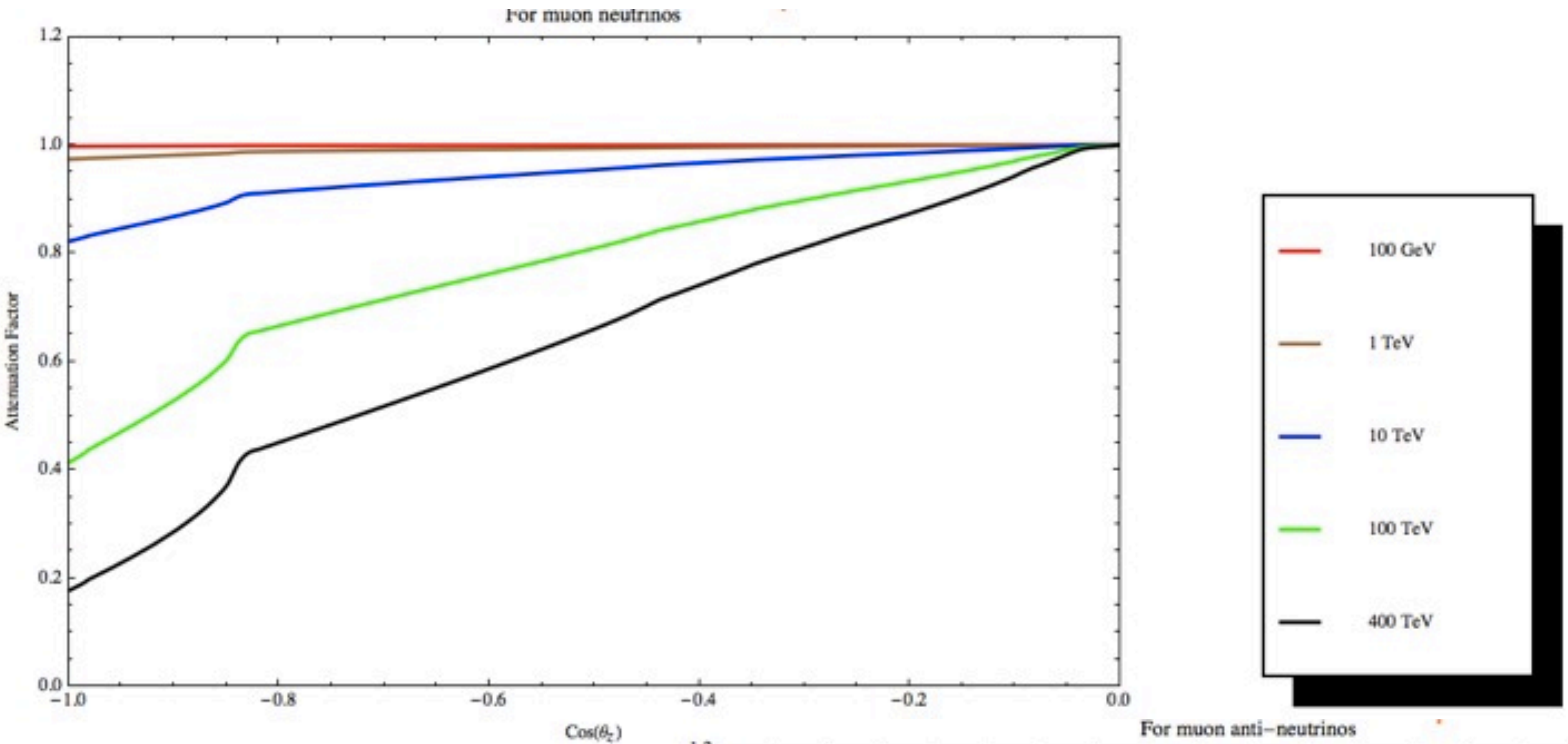


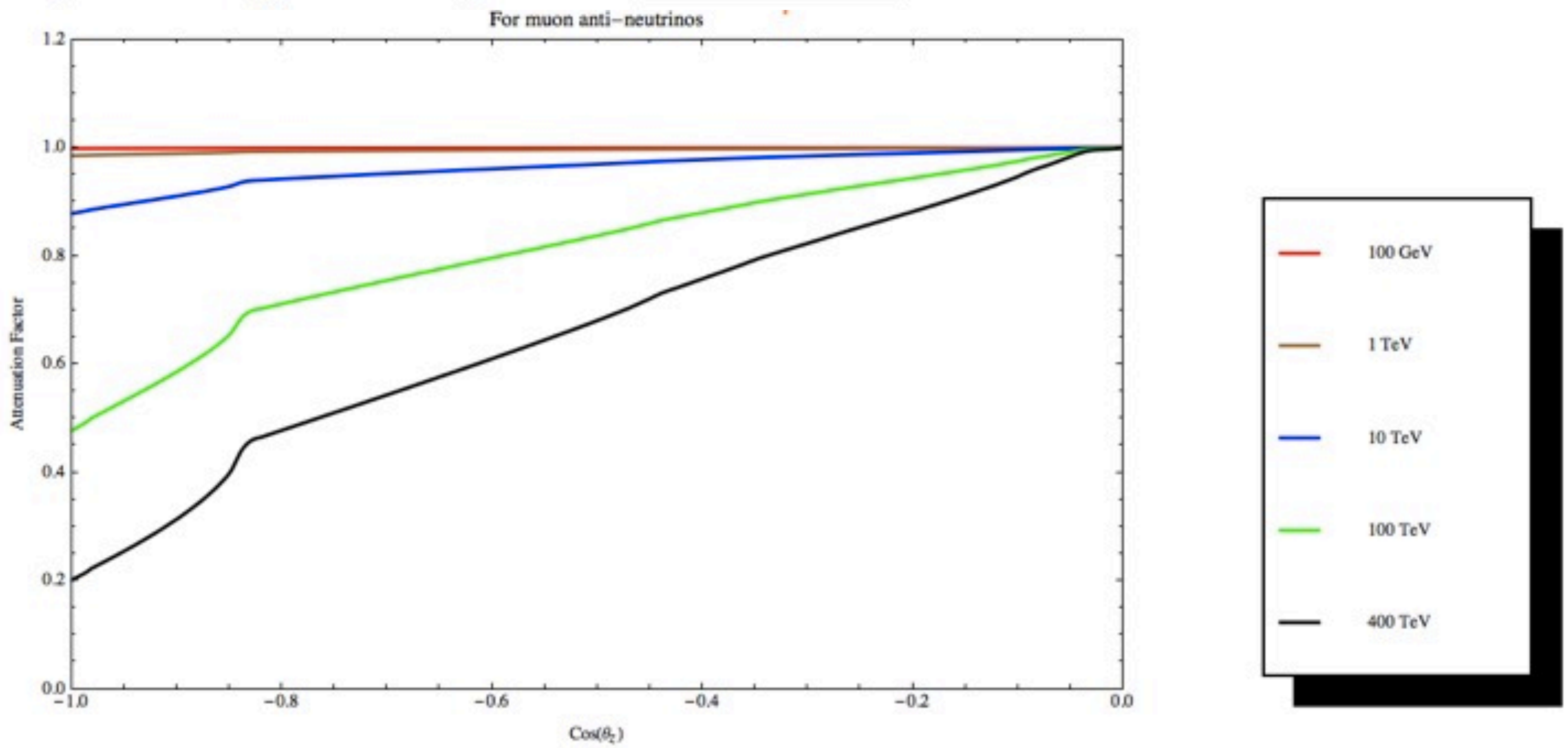
Survival Probabilities



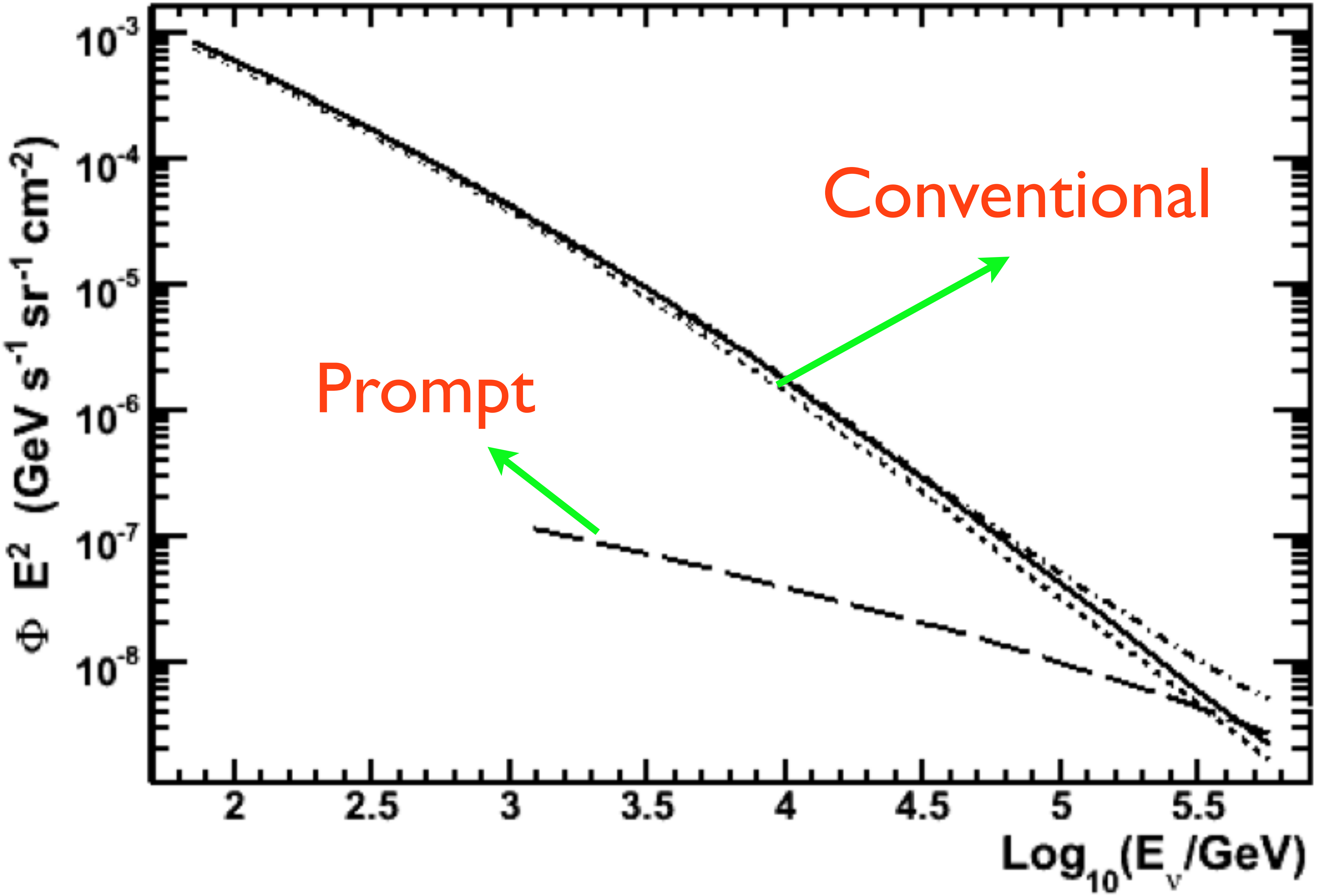
Damping Factors

IPP11, Tehran



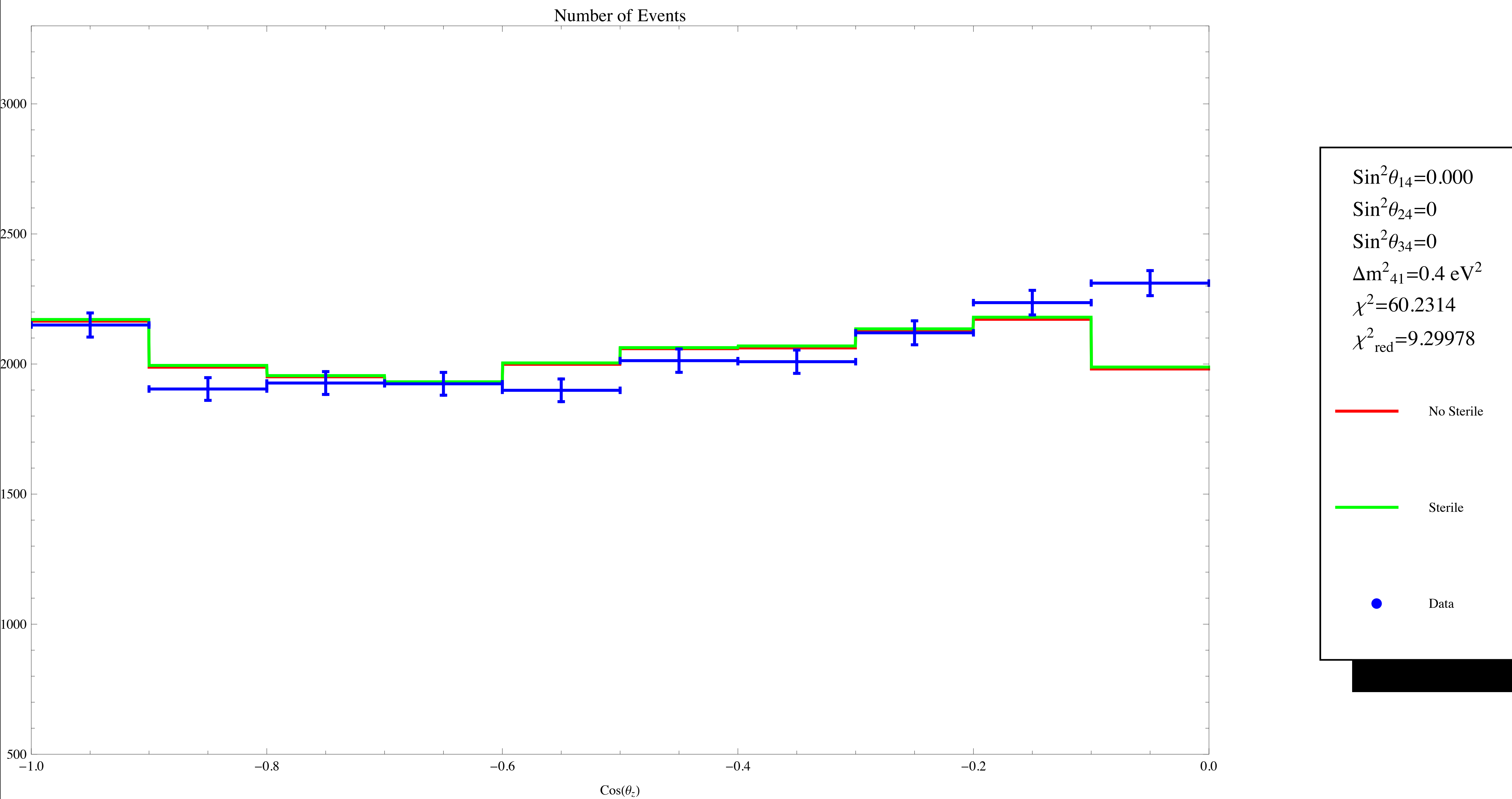


ATM Flux (Honda+Volkova)

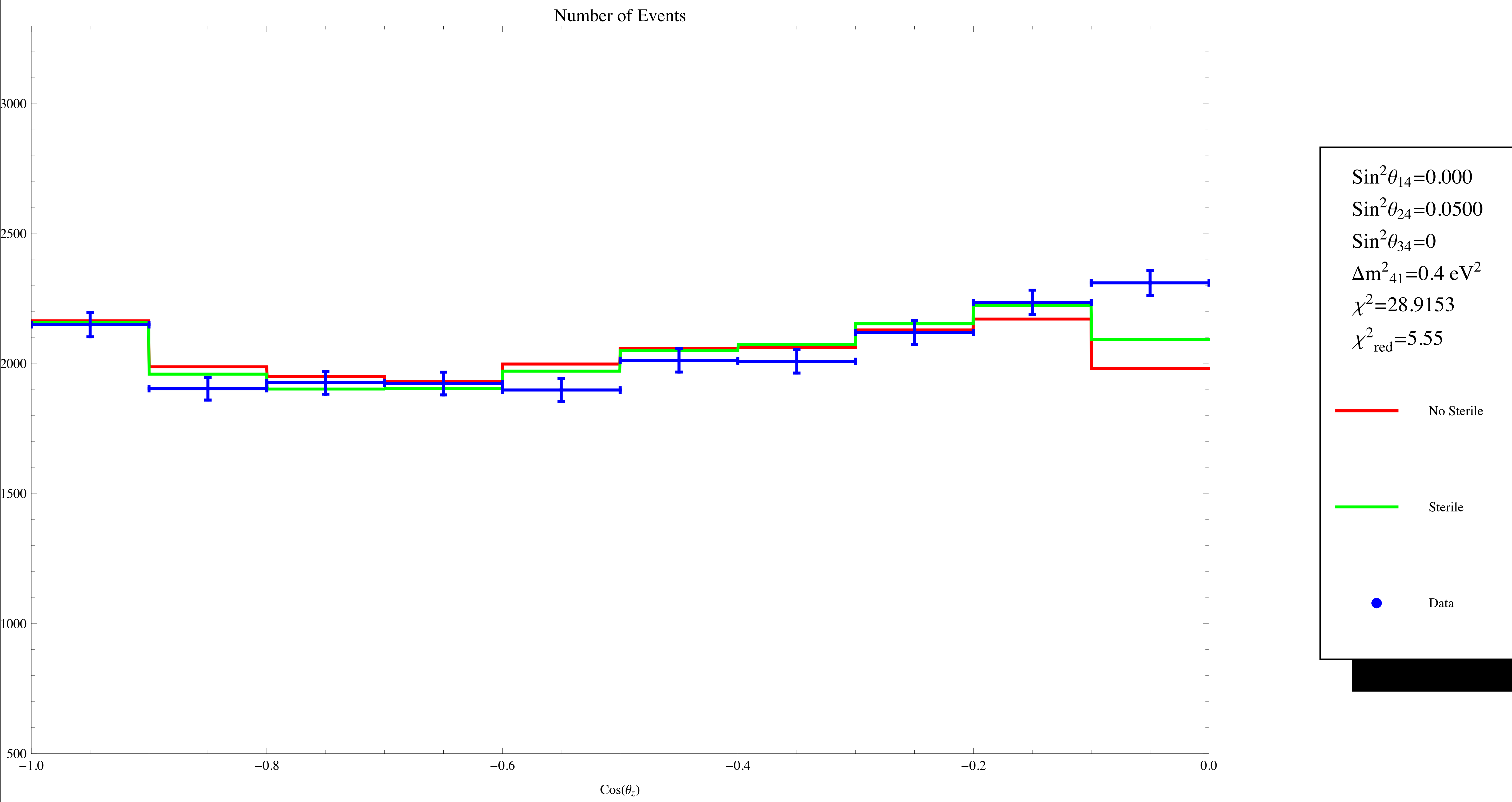


Number of Events in IC40

IPP11, Tehran

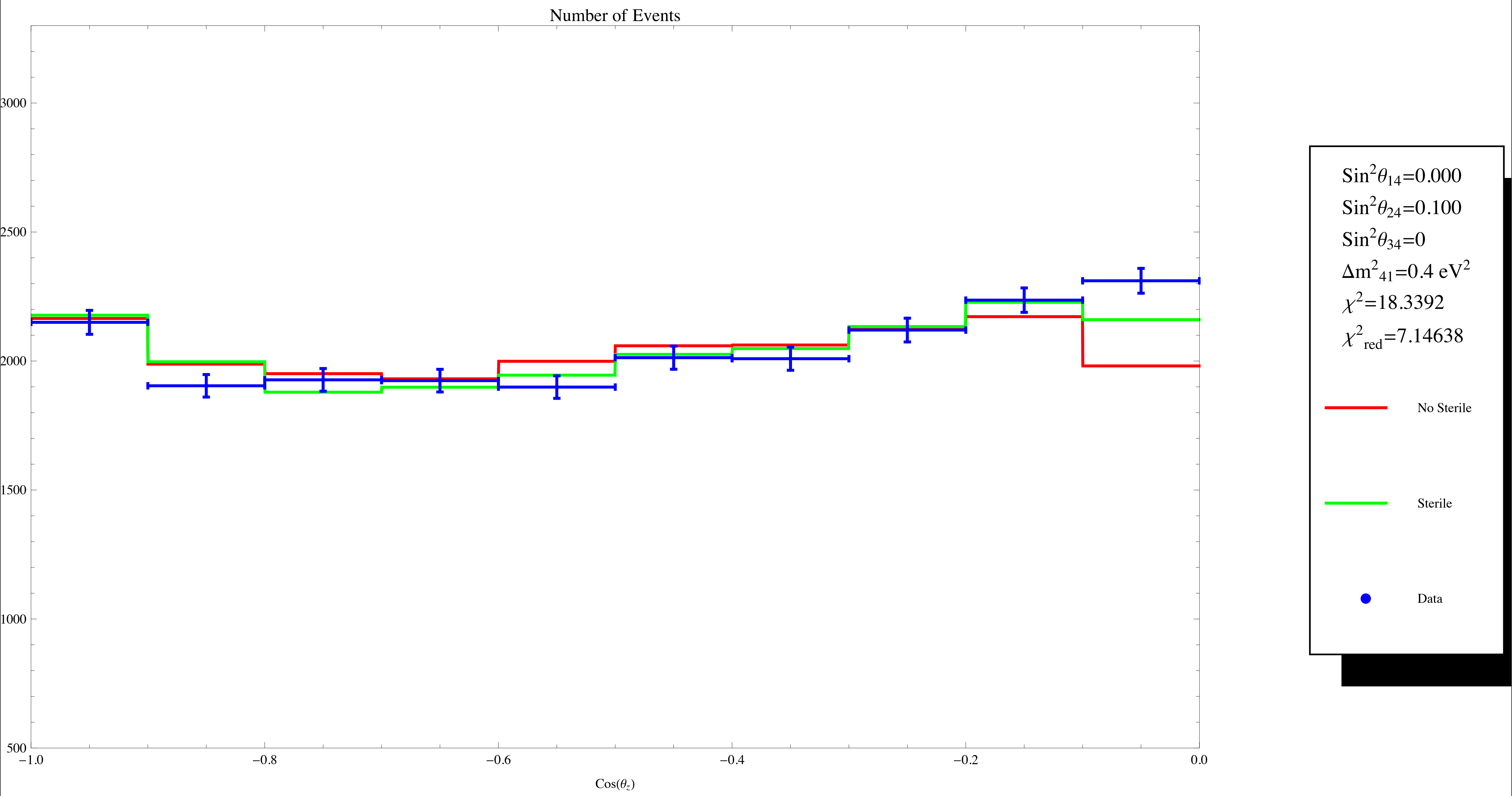


Number of Events in IC40



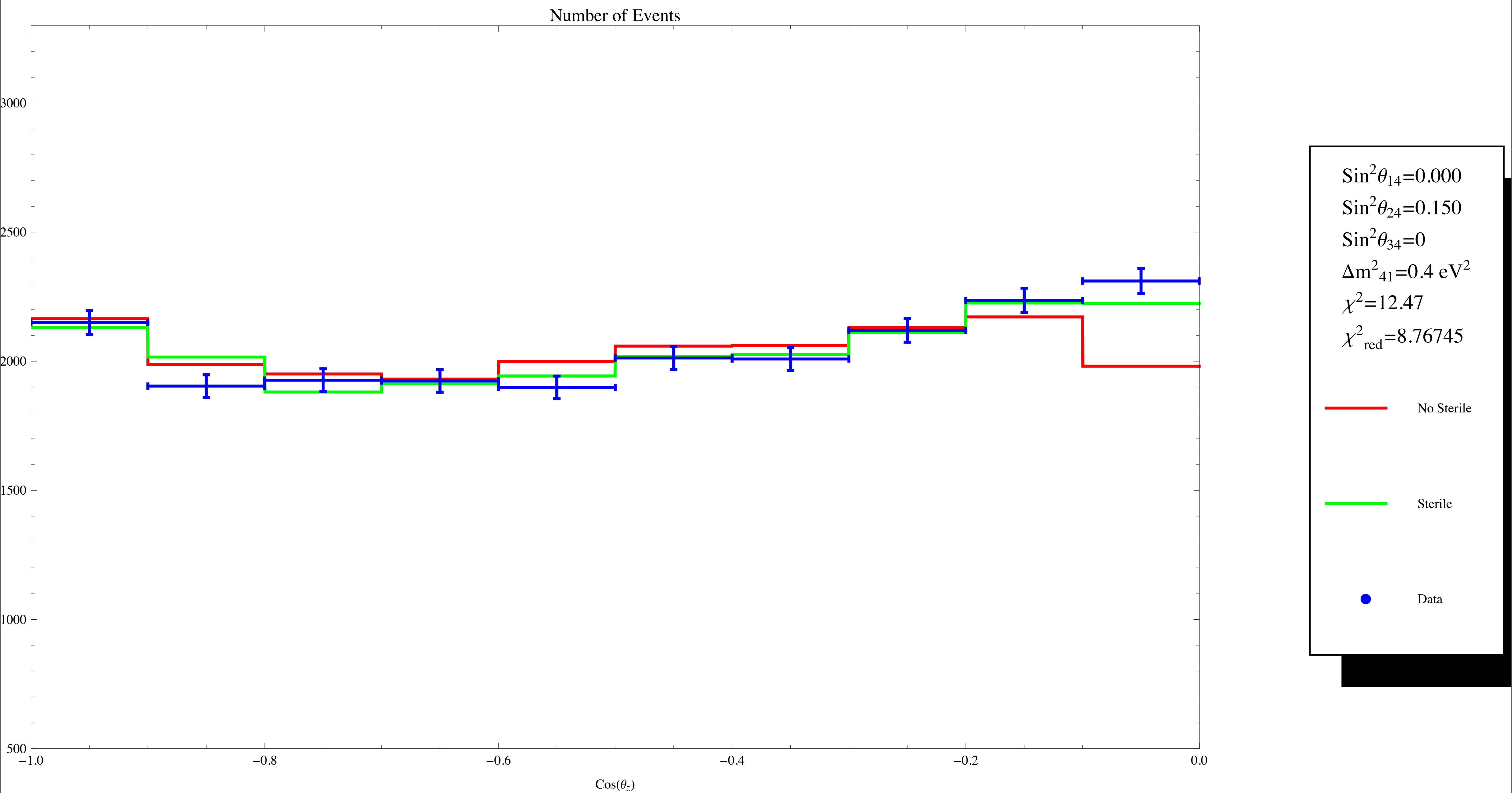
IPP11, Tehran

Number of Events in IC40



Number of Events in IC40

IPP11, Tehran



Number of Events in IC40

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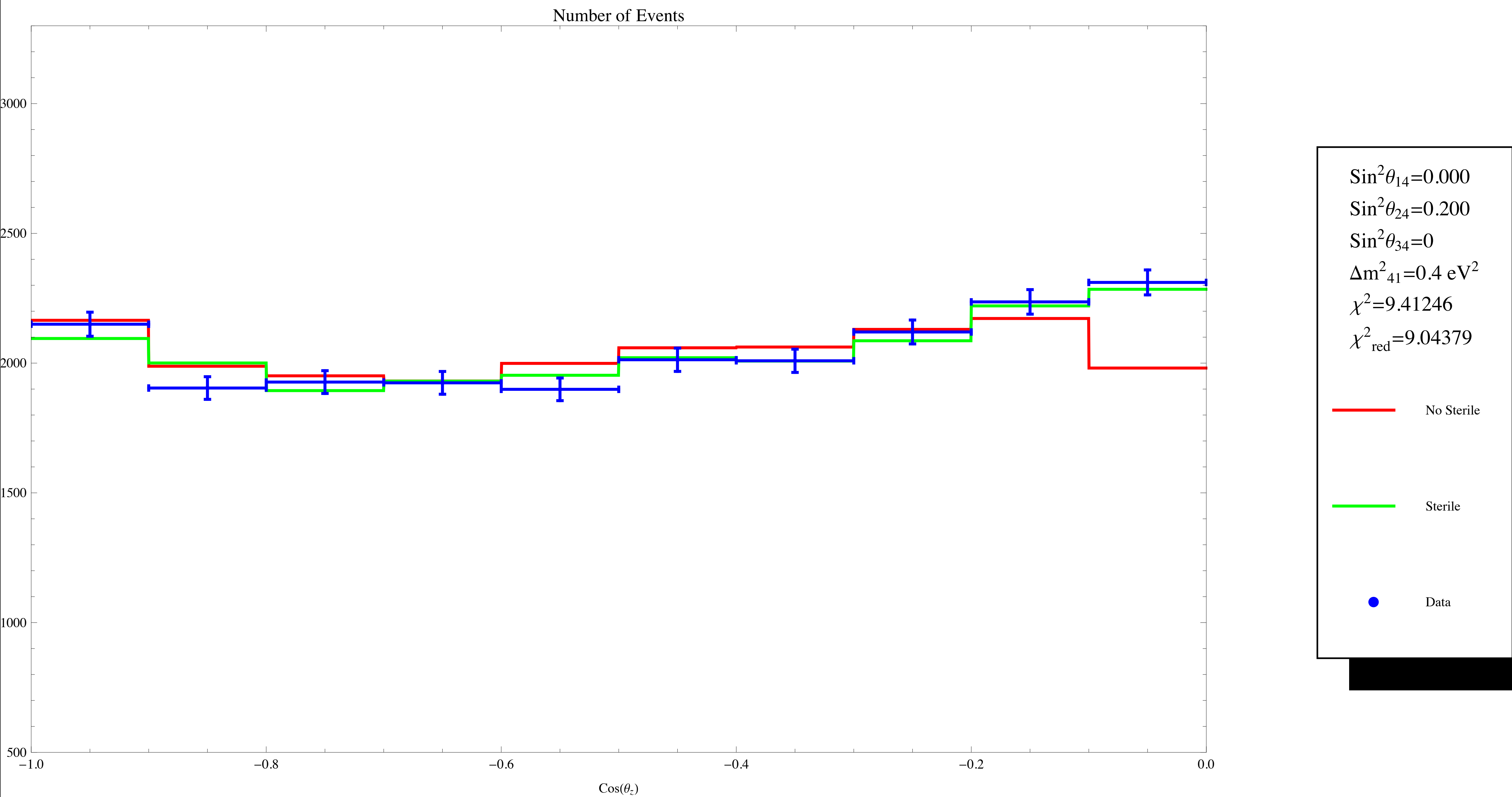

Number of Events in IC40

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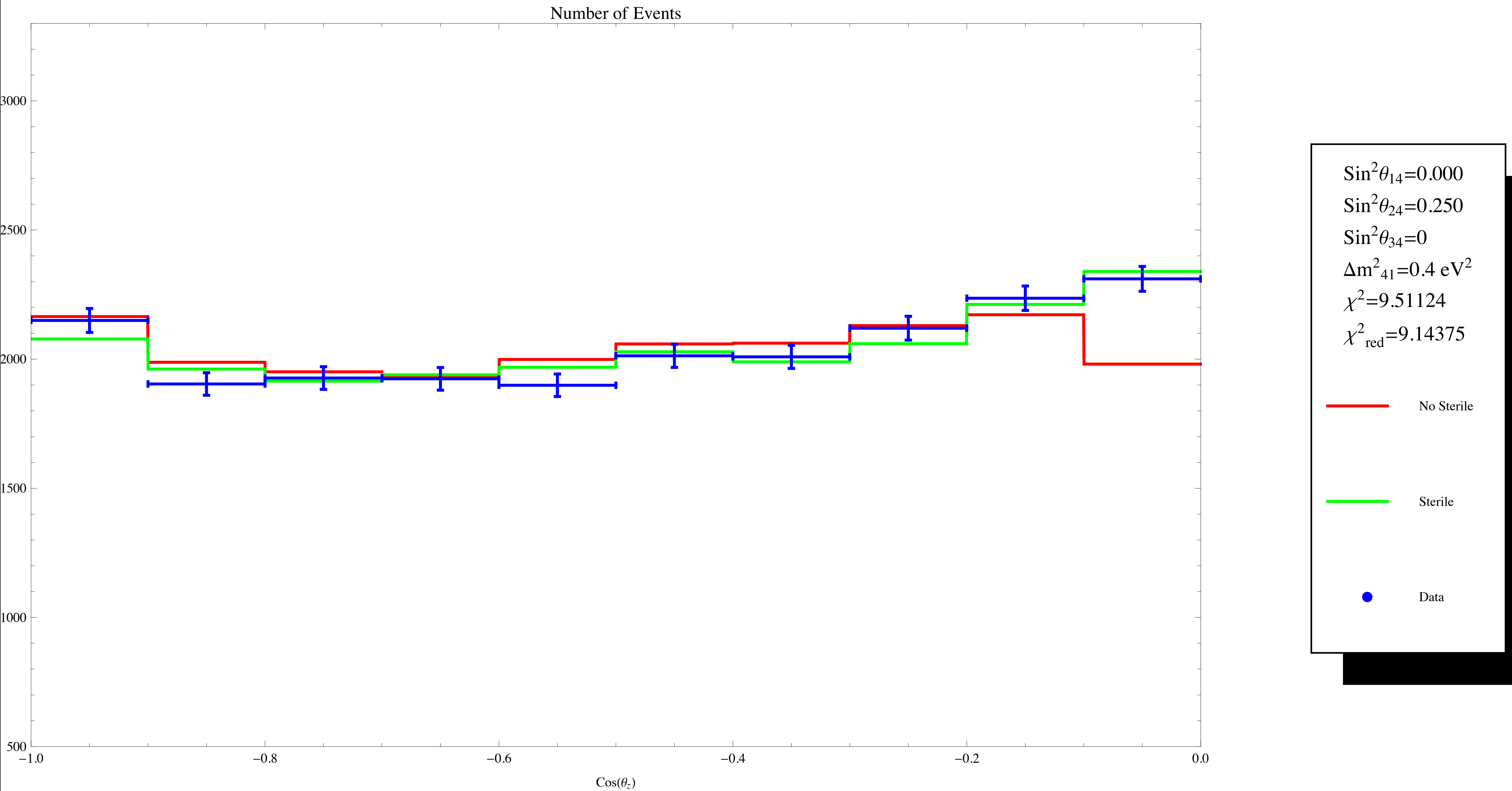
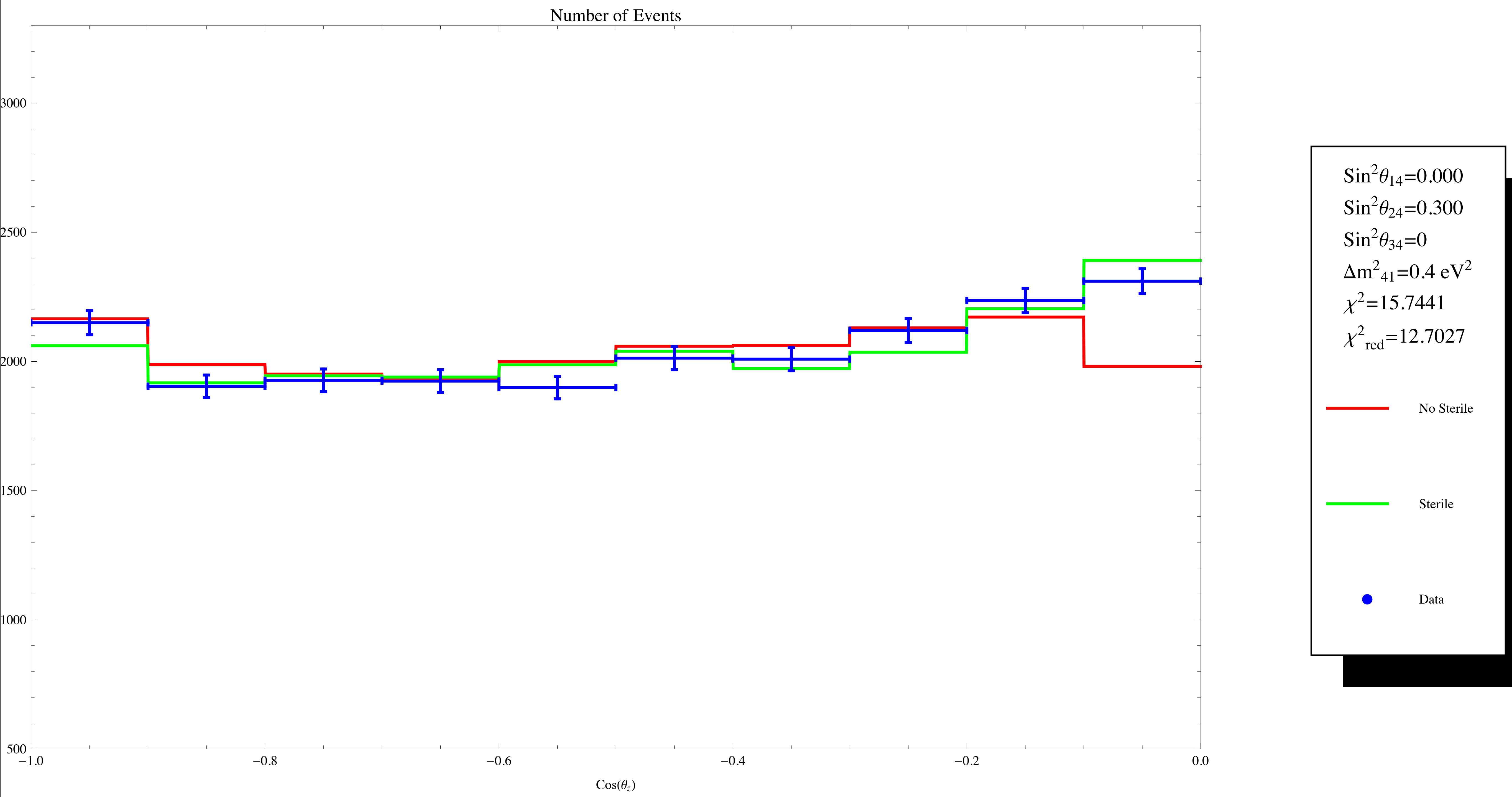


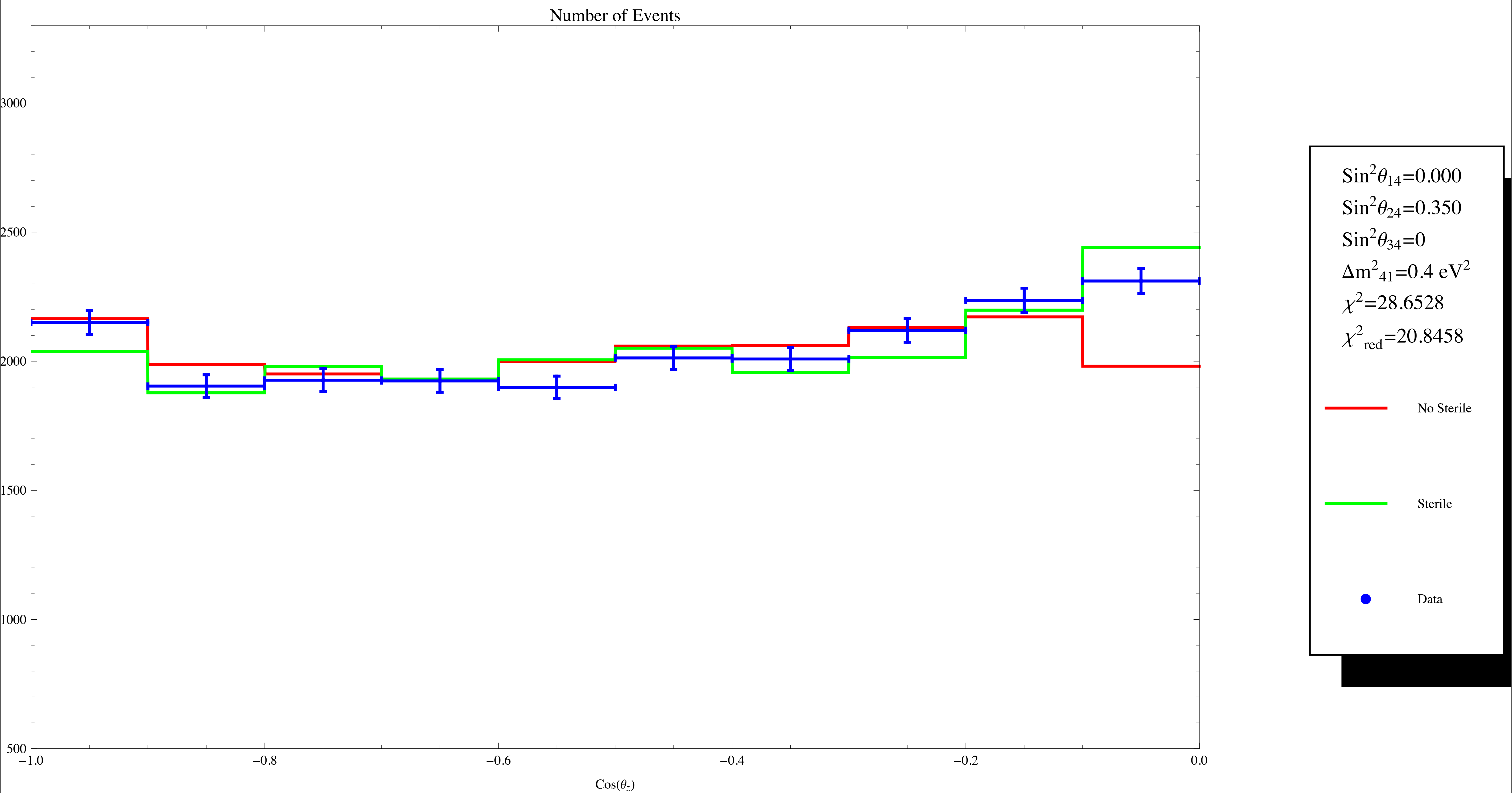
Number of Events in IC40

IPP11, Tehran



Number of Events in IC40

IPP11, Tehran



Number of Events in IC40

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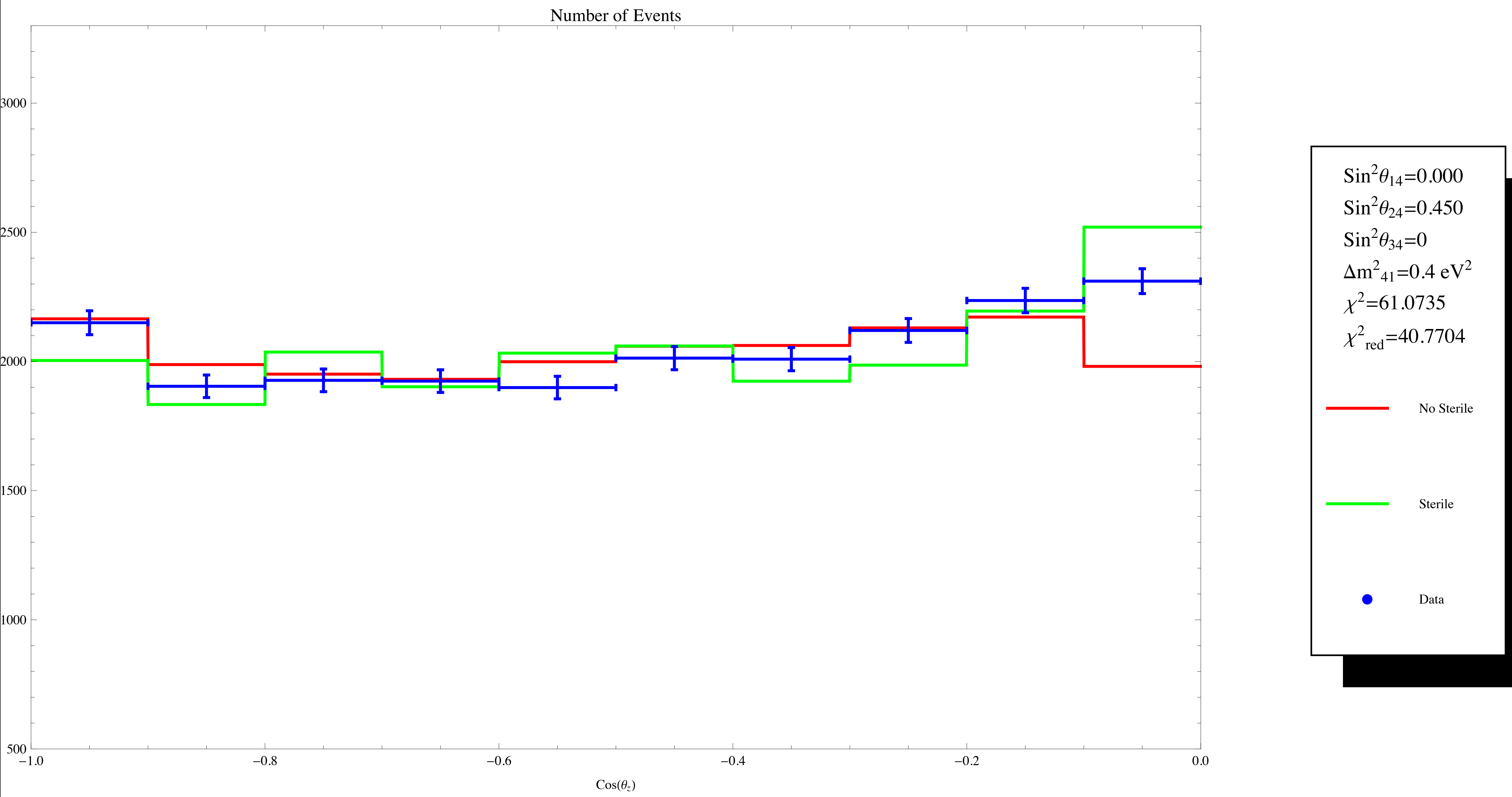
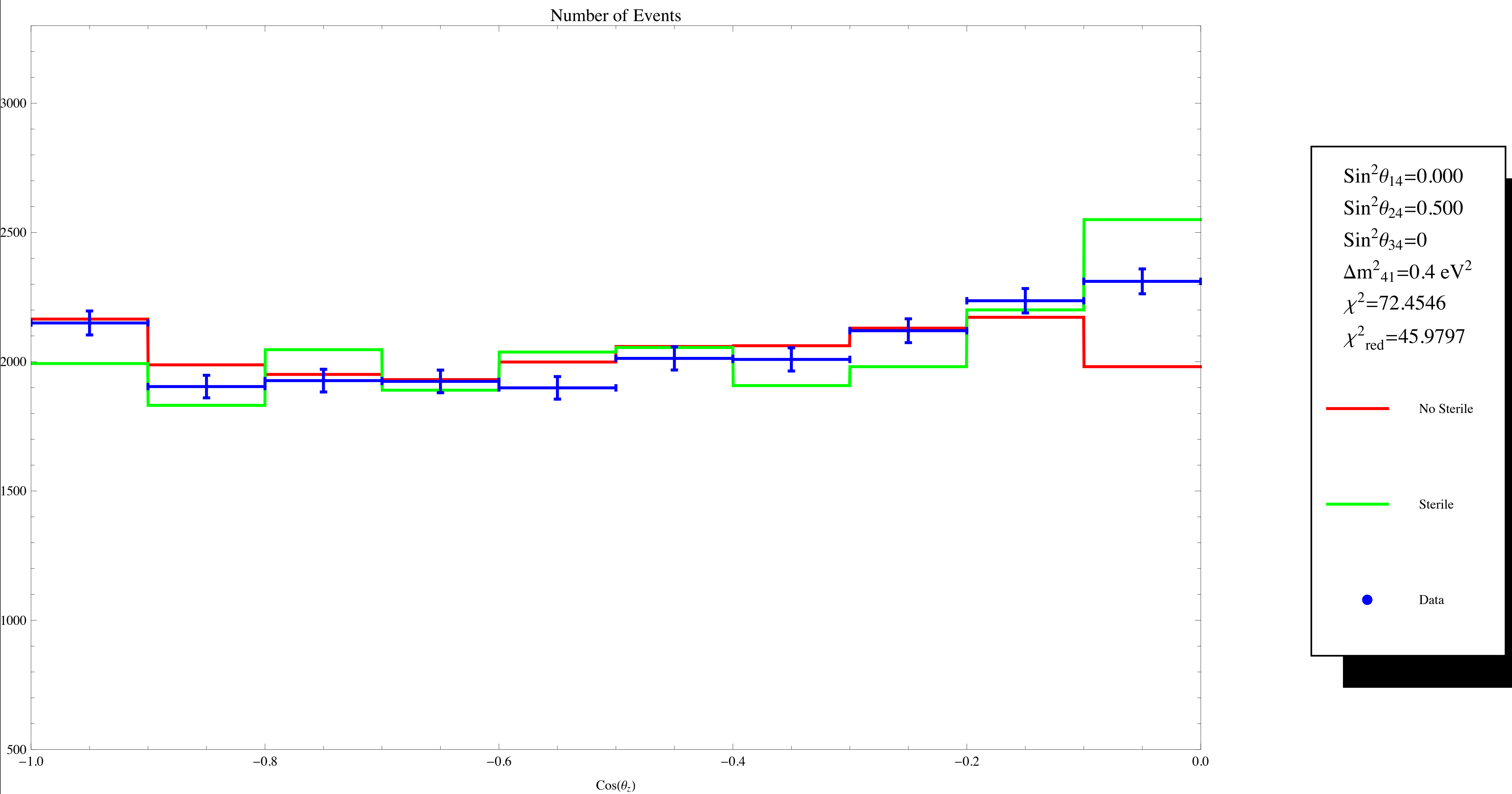


Number of Events in IC40

IPP11, Tehran



But

- ✓ Systematics
- ✓ Pion to Kaon ratio
- ✓ Zenith acceptance of PMTs
- ✓ Ice properties
- ✓ CR flux, composition (IceTop)

What To Do?

Doing the same analysis for AMANDA 8 years data and waiting for IC59 data

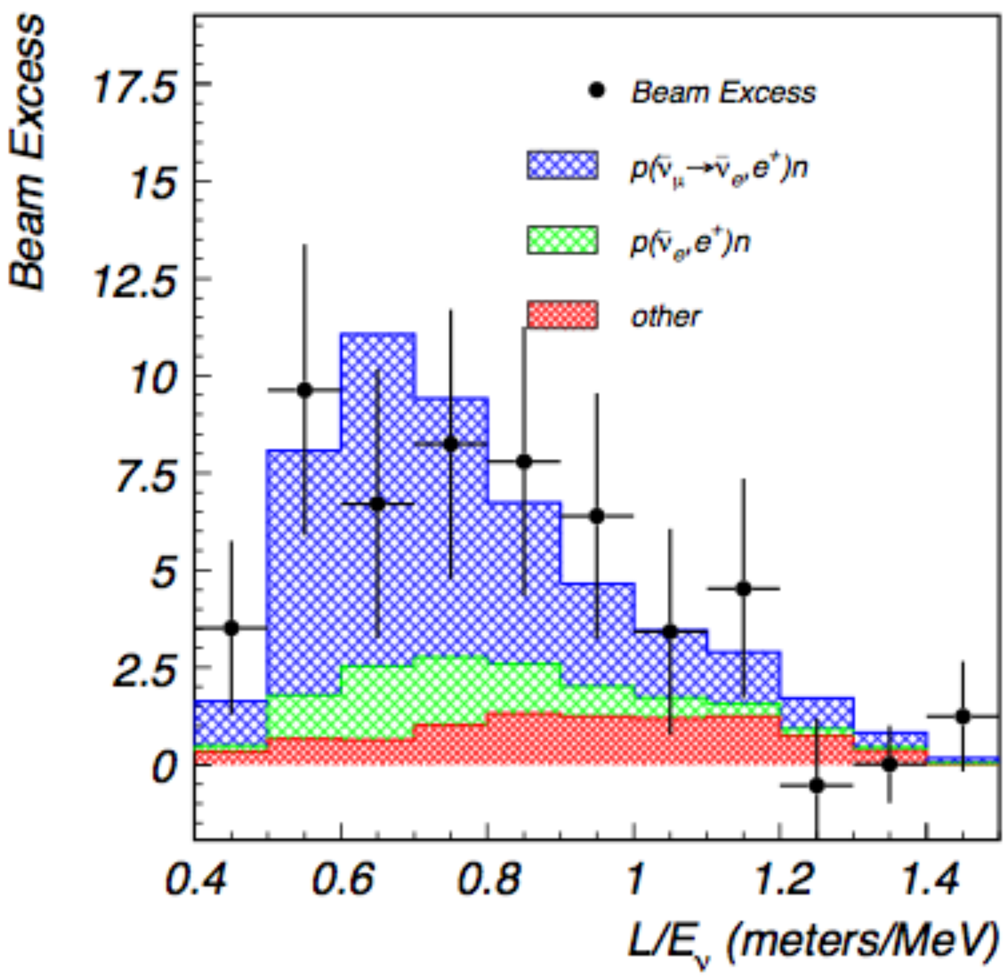
Work in progress ......

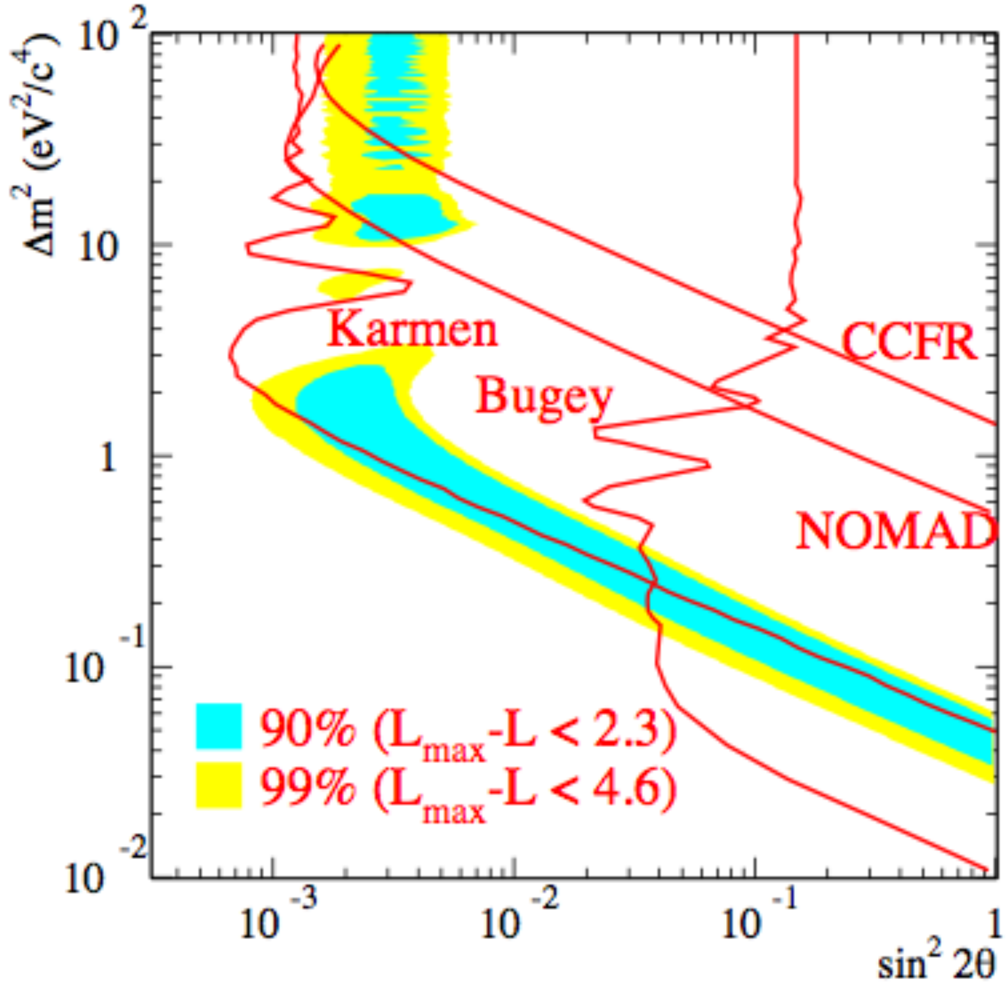
Thank you!

LSND

[LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\mathrm{m}$ $\quad 20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$



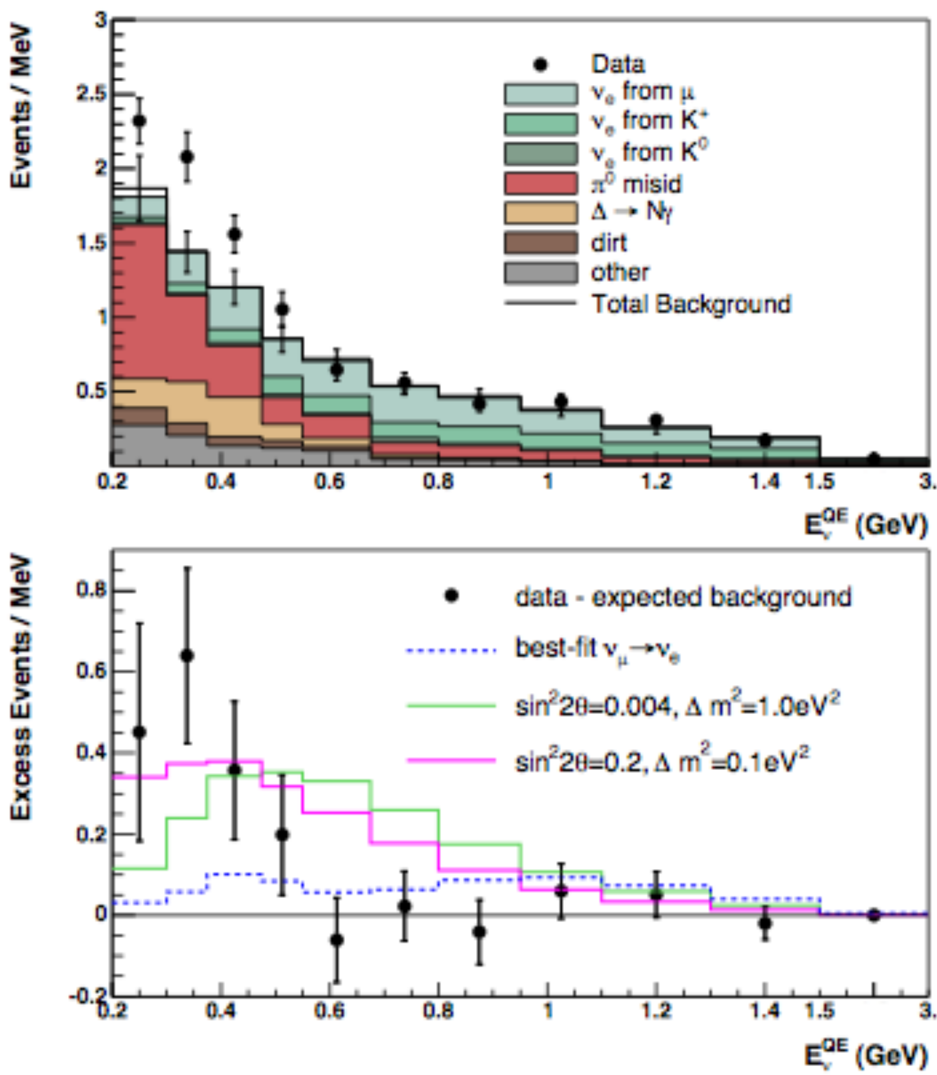


$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$

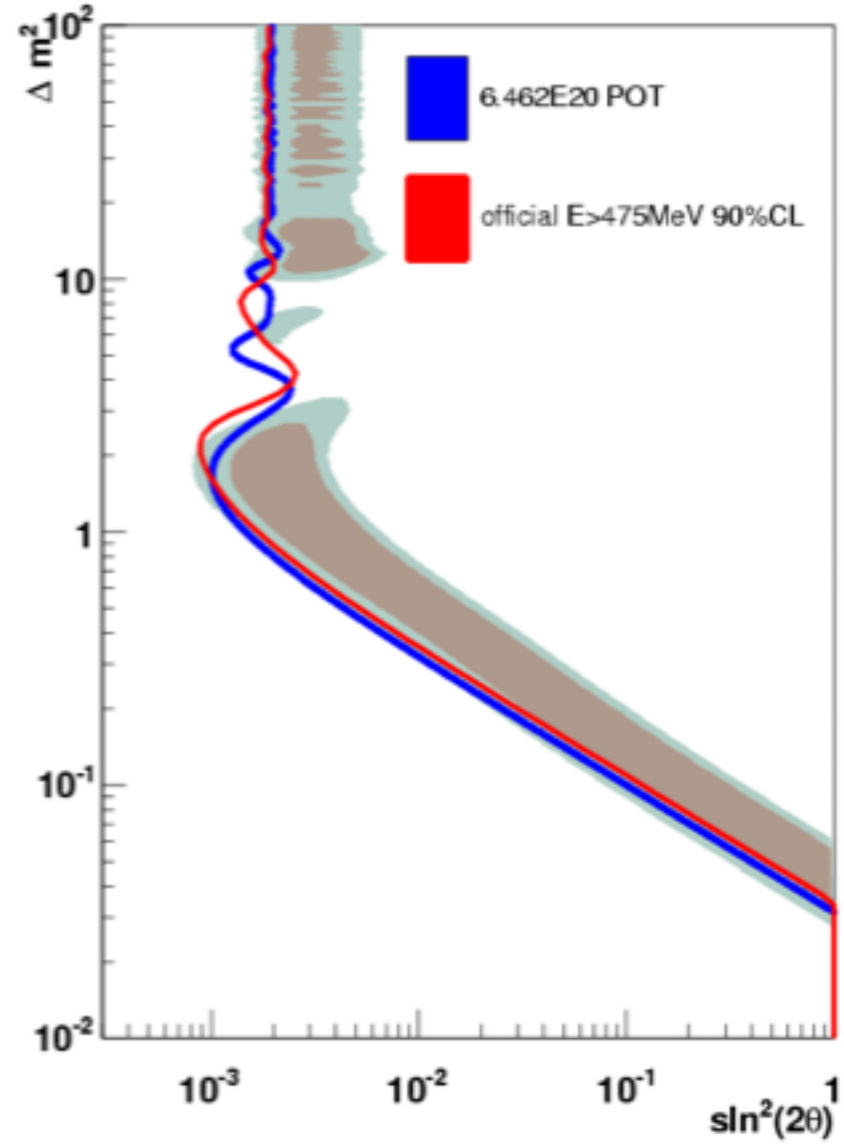
MiniBooNE Neutrinos

[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

$\nu_\mu \to \nu_e$ $\quad L \simeq 541$ m $\quad 475$ MeV $\leq E \lesssim 3$ GeV



[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]



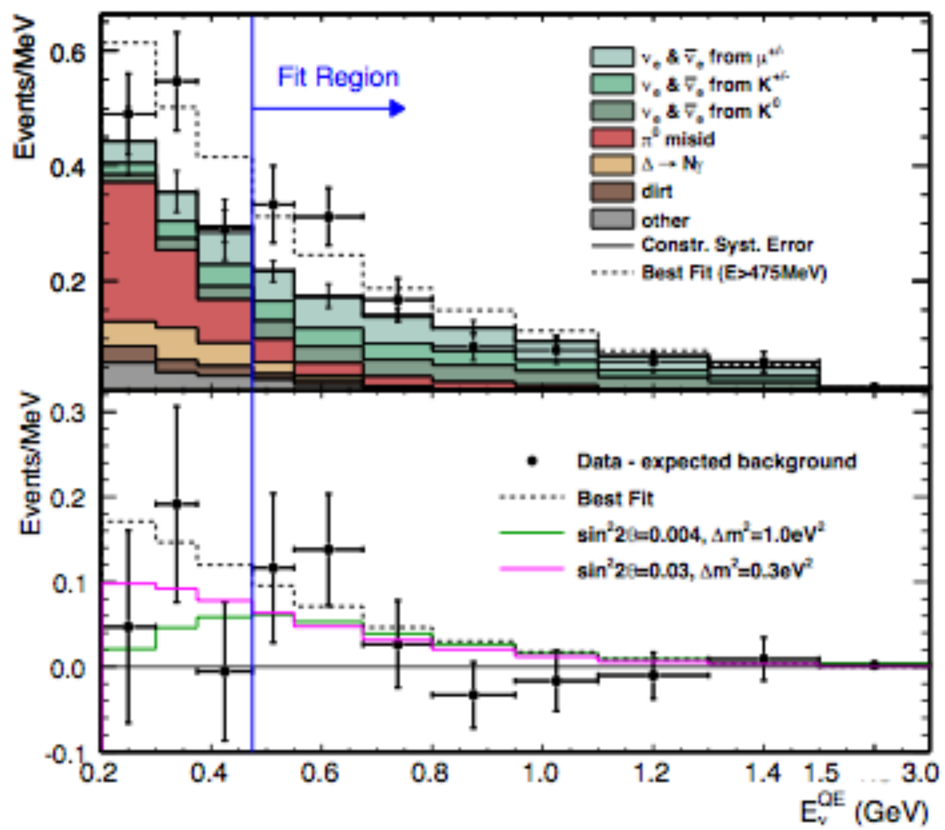
[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

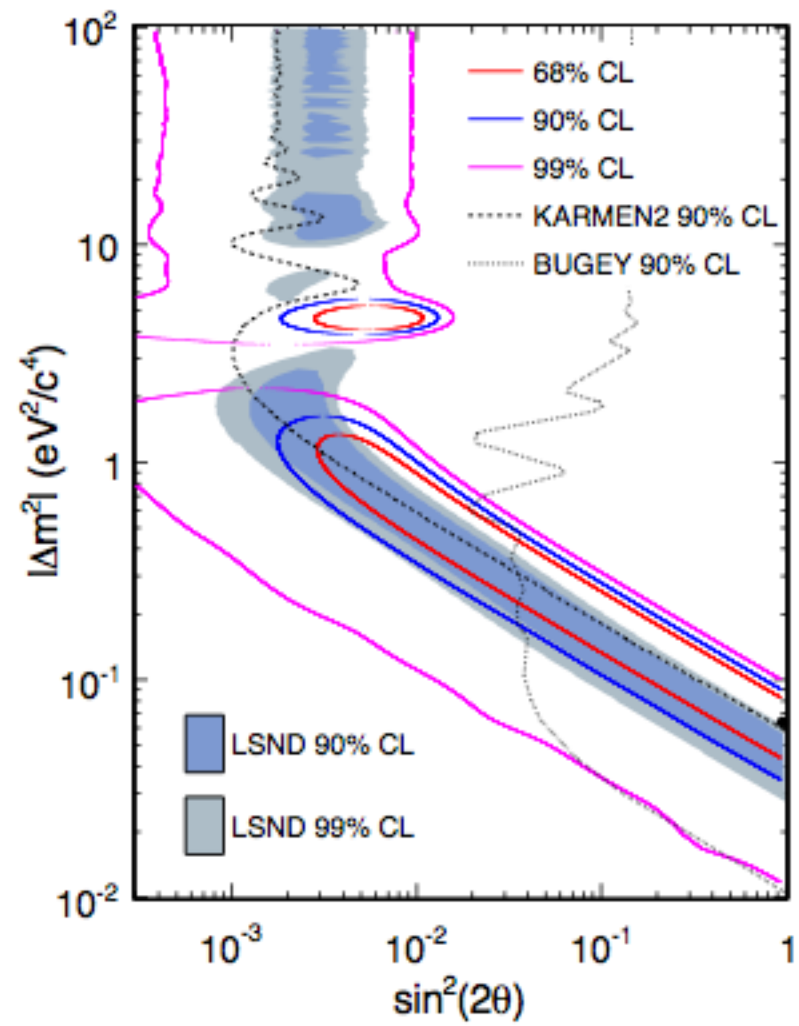
MiniBooNE Antineutrinos

[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 541\,\text{m}$ $\quad 475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

Similar L/E but different L and E $\Longrightarrow$ Oscillations!

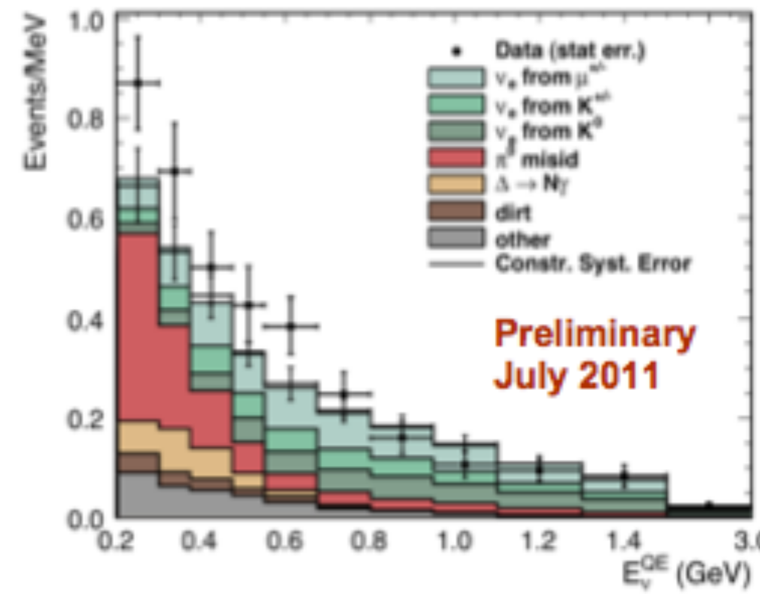
Updated MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ Result

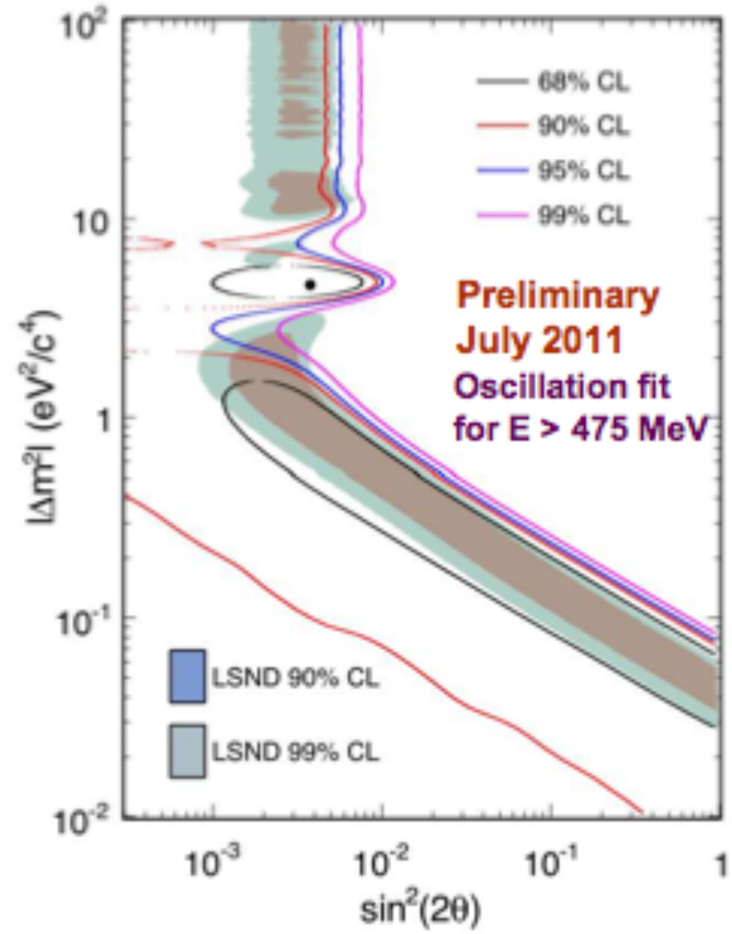
- Updated result from previous publication
  - 5.66E20 ⇒ 8.58E20 protons-on-target (x1.5)
  - Reduced systematic uncertainties especially backgrounds from beam K^+ decays

- For E > 475 MeV (>200 MeV), oscillations favored over background only (null) hypothesis at the 91.1% CL (97.6% CL)
  - Consistent with LSND but less strong than previous result (99.4%)
  - Best fit: χ^2 prob. = 35.5% (51%)
    Null: χ^2prob. = 14.9% (10%)

- Low energy excess now more prominent for antineutrino running than previous result
  - For E< 475 MeV, excess = 38.6 ± 18.5 (For all energies, excess = 57.7 ± 28.5)
  - Neutrino and antineutrino results are now more similar.

- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (~x2 from this update)
  - Full data set will probe LSND signal at the 2-3 sigma level



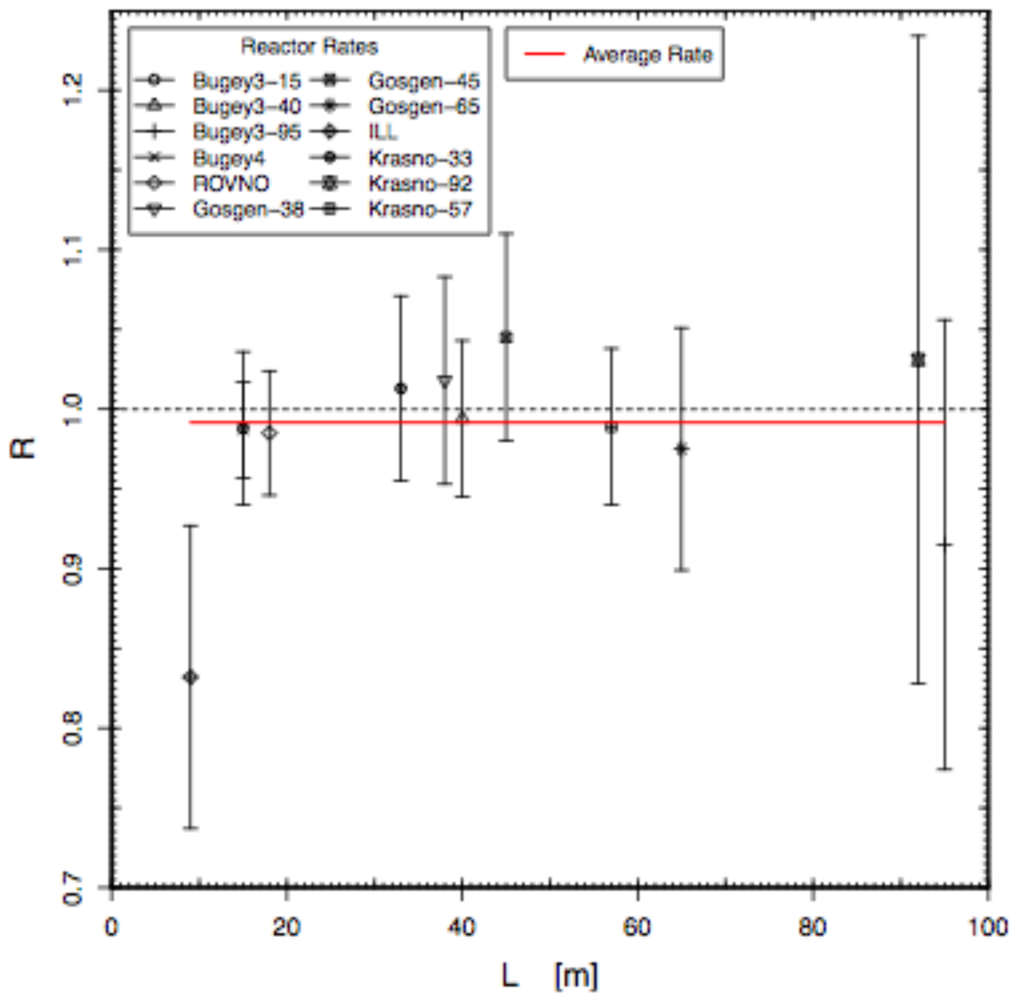


from M. Shaevitz, PANIC11, 26 July 2011

Reactor Antineutrino Anomaly

[Mention et al, arXiv:1101.2755]

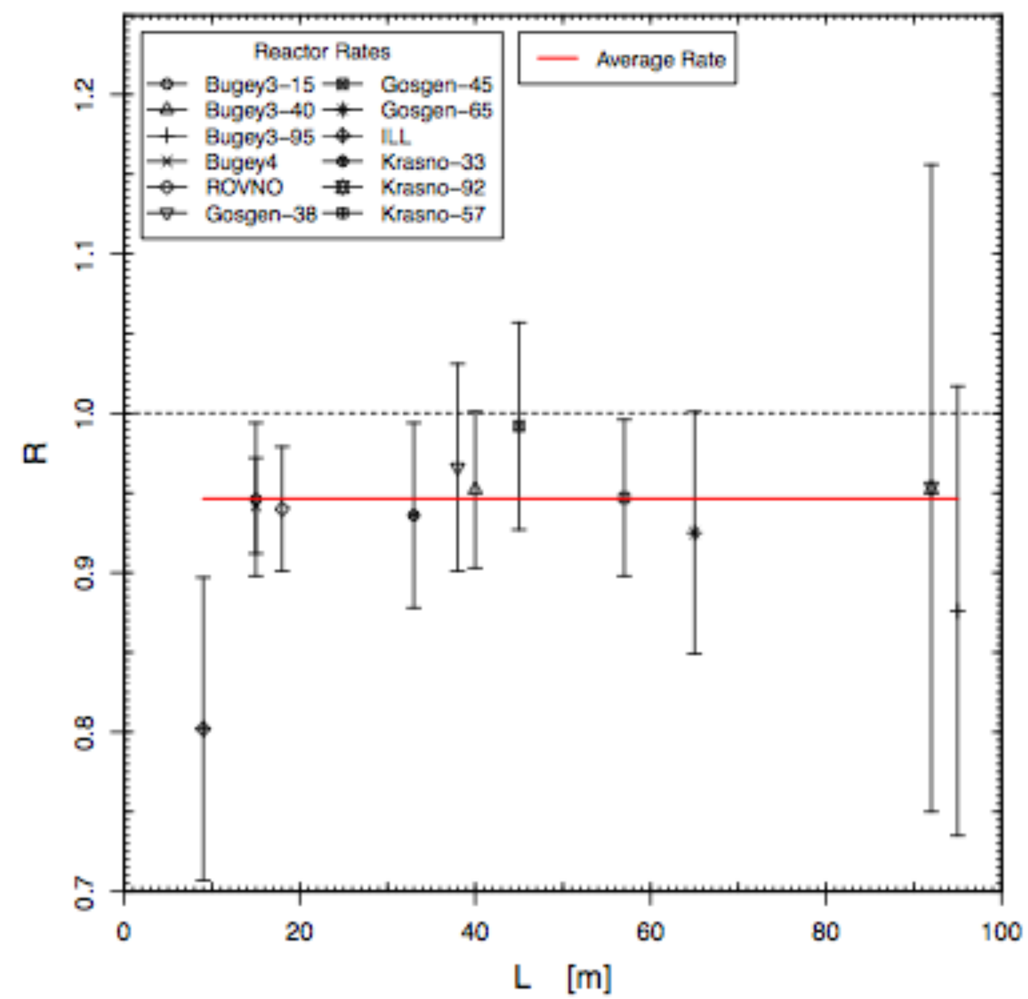
Old Reactor $\bar{\nu}_e$ Fluxes



$$\overline{R} = 0.992 \pm 0.024$$

New Reactor $\bar{\nu}_e$ Fluxes

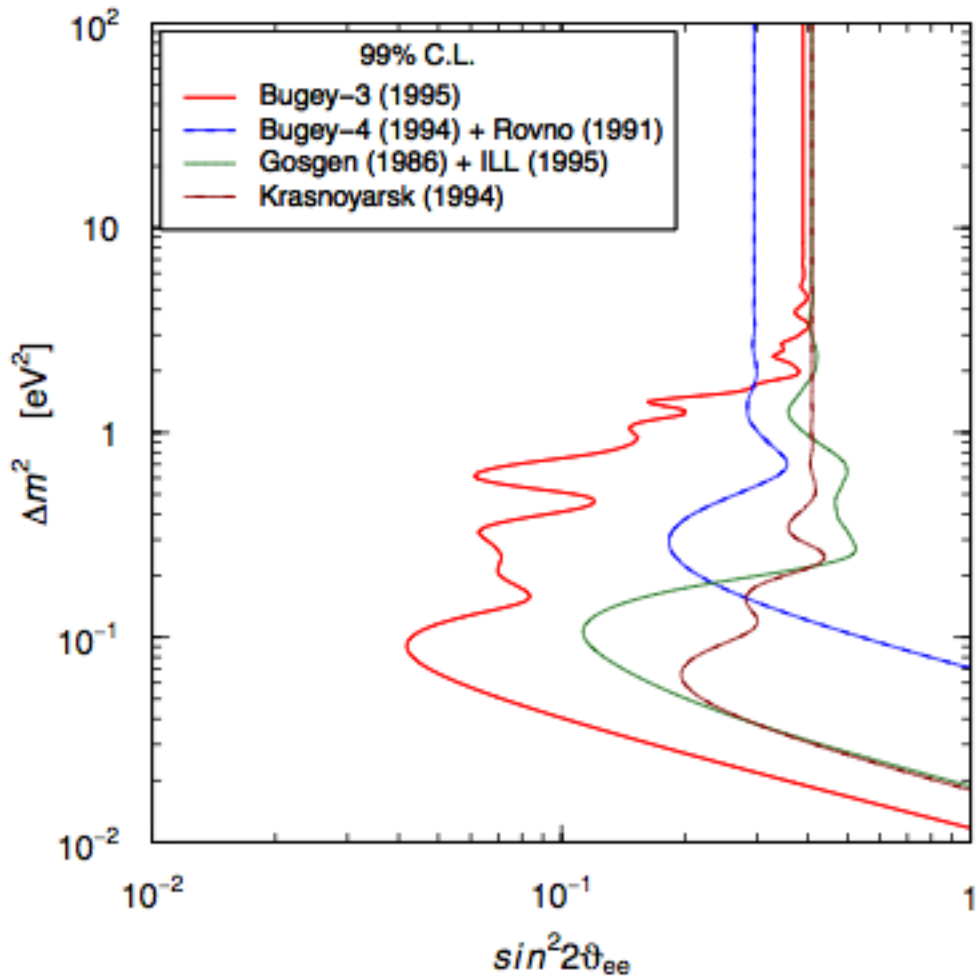
[Mueller et al, arXiv:1101.2663]



$$\overline{R} = 0.946 \pm 0.024$$

Reactor Antineutrino Anomaly

$\bar{\nu}_e$ Disappearance



New Reactor $\bar{\nu}_e$ Fluxes

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