Neutrino oscillations in matter and DUNE

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In matter $P_{\nu_\alpha \to \nu_\beta}$ $(\alpha, \beta = e, \mu, \tau)$ oscillation probabilities have the same forms as in the vacuum with replacement of vacuum oscillation parameters with matter ones. Namely mass eigenstates $m^2_\odot \to m^2_{21}$ $m^2_a \to m^2_{31}$ and replacements of angles $\theta_{12} \to \theta^m_{12}$ and $\theta_{13} \to \theta^m_{13}$. 23 angle and CP phase remain unchanged ($\theta^m_{23} = \theta_{23}$ $\delta^m = \delta$)
In good approximation [IP]

$$\sin 2\theta^m_{13} \simeq \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - \epsilon_a)^2 + \sin^2 2\theta_{13}}} \quad or \quad \cos 2\theta^m_{13} \simeq \frac{\cos 2\theta_{13} - \epsilon_a}{\sqrt{(\cos 2\theta_{13} - \epsilon_a)^2 + \sin^2 2\theta_{13}}} \tag{1}$$

$$\sin 2\theta^m_{12} \simeq \frac{\cos\theta'_{13} \sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - \epsilon_\odot)^2 + \cos^2\theta'_{13} \sin^2 2\theta_{12}}} \quad or \quad \cos 2\theta^m_{12} \simeq \frac{\cos 2\theta_{12} - \epsilon_\odot}{\sqrt{(\cos 2\theta_{12} - \epsilon_\odot)^2 + \cos^2\theta'_{13} \sin^2 2\theta_{12}}} \tag{2}$$

$$\frac{\Delta m^2_{21}}{2E} \simeq \frac{\Delta m^2_\odot}{2E} \sqrt{(\cos 2\theta_{12} - \epsilon_\odot)^2 + \cos^2\theta'_{13} \sin^2 2\theta_{12}}, \tag{3}$$

$$\frac{\Delta m^2_{31}}{2E} \simeq \frac{\Delta m^2_{ee}}{2E} + \frac{1}{2}\left(\frac{\Delta m^2_{21}}{2E} - \frac{\Delta m^2_\odot}{2E} \cos 2\theta_{12} - \cos^2\theta^m_{13} V\right) + \sin^2\theta^m_{13} V - \frac{3}{2} \sin^2\theta'_{13} \frac{\Delta m^2_{ee}}{2E} \tag{4}$$

$$\theta'_{13} = \theta^m_{13} - \theta_{13} \tag{5}$$

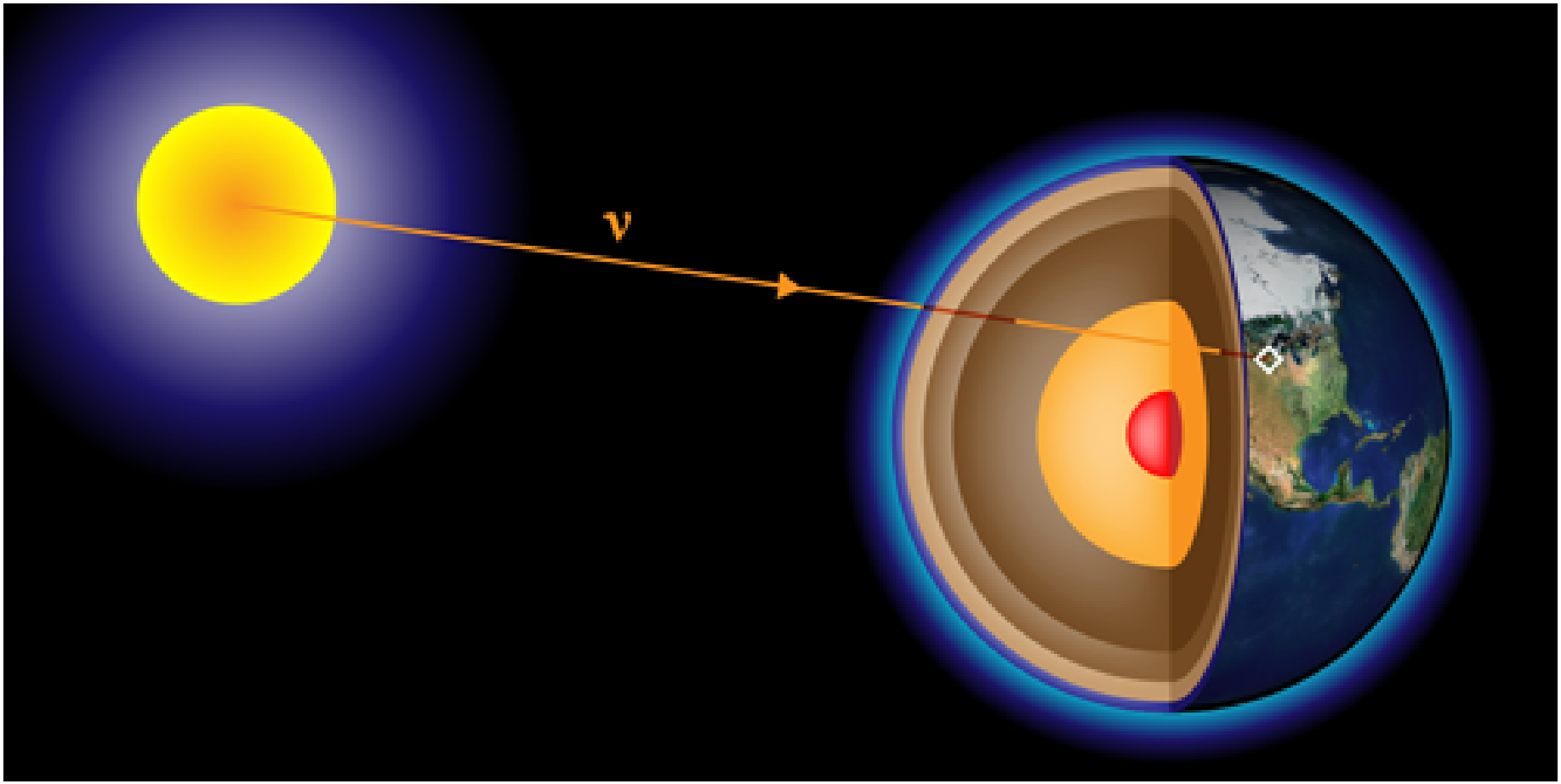
$$\epsilon_\odot = \frac{2EV}{\Delta m^2_\odot}\left(\cos^2\theta^m_{13} + \frac{\sin^2\theta'_{13}}{\epsilon_a}\right) \tag{6}$$

$$\epsilon_a = \frac{2EV}{\Delta m^2_{ee}}, \qquad \Delta m^2_{ee} = c^2_{12}\Delta m^2_a + s^2_{12}(\Delta m^2_a - \Delta m^2_\odot) \tag{7}$$

$$V = \sqrt{2} G_F N_e \tag{8}$$

This semi-analytic approximate solution is valid for all energies.
For $P_{\bar\nu_\alpha \to \bar\nu_\beta}$ V$\to$ -V and $\delta \to -\delta$.
For normal mss hierarchy Δm^2_a is positive and for inverted mass hierarchy it is negative.

- continuation of the solar neutrino research at DUNE, day-night effect, possibility to see the core of the Earth, energy resolution ...
- CP violation observation via atmospheric neutrinos at DUNE



$$\Delta P_{ee} = -\frac{c_{13}^2}{2}(2P_{ee} - c_{13}^4 - 2s_{13}^4)\frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}}\sqrt{2}G_F \int_{x_0}^{x_f} dx\, N_e(x) \sin\frac{\Delta m_{21}^2}{2E}(x_f - x)$$

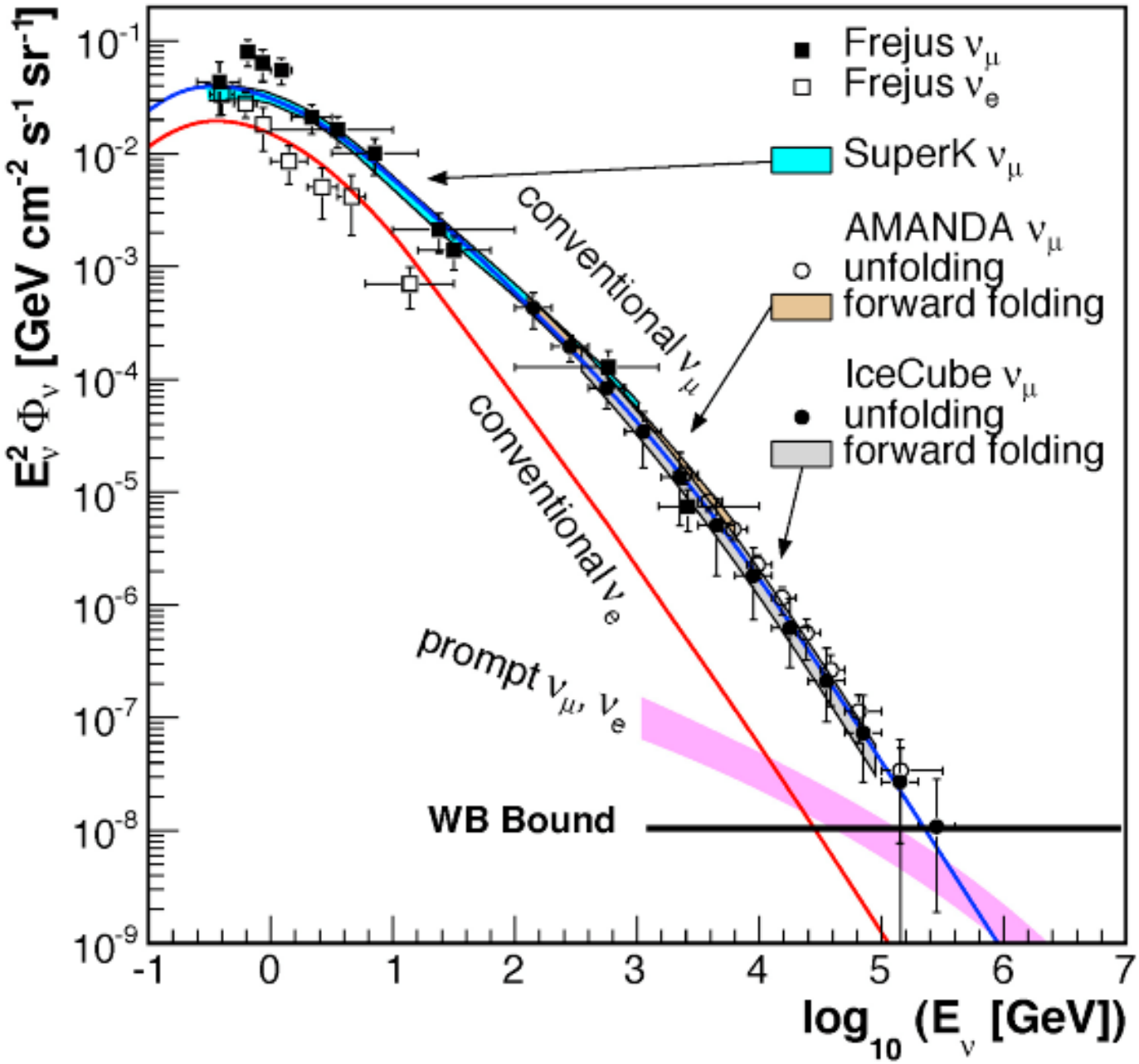
Preliminary Reference Earth Model (PREM) (Dziewonski & Anderson, 1981)									
Region	Radius (km)	α (m/s)	β (m/s)	ρ (kg/m3)	K_s (Gpa)	μ (Gpa)	γ	P (Gpa)	g (m/s2)
	0	11266.2	3667.8	13088.48	1425.3	176.1	0.4407	363.85	0
	200	11255.93	3663.42	13079.77	1423.1	175.5	0.4408	362.9	0.7311
	400	11237.12	3650.27	13053.64	1416.4	173.9	0.441	360.03	1.4604
	600	11205.76	3628.35	13010.09	1405.3	171.3	0.4414	355.28	2.1862
	800	11161.86	3597.67	12949.12	1389.8	167.6	0.442	348.67	2.9068
	1000	11105.42	3558.23	12870.73	1370.1	163	0.4428	340.24	3.6203
Inner	1200	11036.43	3510.02	12774.93	1346.2	157.4	0.4437	330.05	4.3251
Core	1221.5	11028.27	3504.32	12763.6	1343.4	156.7	0.4438	328.85	4.4002
	1221.5	10355.68	0	12166.34	1304.7	0	0.5	328.85	4.4002
	1400	10249.59	0	12069.24	1267.9	0	0.5	318.75	4.9413
	1600	10122.91	0	11946.82	1224.2	0	0.5	306.15	5.5548
	1800	9985.54	0	11809	1177.5	0	0.5	292.22	6.1669
	2000	9834.96	0	11654.78	1127.3	0	0.5	277.04	6.7715
	2200	9668.65	0	11483.11	1073.5	0	0.5	260.68	7.3645
	2400	9484.09	0	11292.98	1015.8	0	0.5	243.25	7.9425
	2600	9278.76	0	11083.35	954.2	0	0.5	224.85	8.5023
	2800	9050.15	0	10853.21	888.9	0	0.5	205.6	9.0414
	3000	8795.73	0	10601.52	820.2	0	0.5	185.64	9.557
	3200	8512.98	0	10327.26	748.4	0	0.5	165.12	10.0464
Outer	3400	8199.39	0	10029.4	674.3	0	0.5	144.19	10.5065
Core	3480	8064.82	0	9903.49	644.1	0	0.5	135.75	10.6823
	3480	13716.6	7264.66	5566.45	655.6	293.8	0.3051	135.75	10.6823
	3600	13687.53	7265.75	5506.42	644	290.7	0.3038	128.71	10.5204
D"	3630	13680.41	7265.97	5491.45	641.2	289.9	0.3035	126.97	10.4844
	3630	13680.41	7265.97	5491.45	641.2	289.9	0.3035	126.97	10.4844
	3800	13447.42	7188.92	5406.81	609.5	279.4	0.3012	117.35	10.3095
	4000	13245.32	7099.74	5307.24	574.4	267.5	0.2984	106.39	10.158
	4200	13015.79	7010.53	5207.13	540.9	255.9	0.2957	95.76	10.0535
	4400	12783.89	6919.57	5105.9	508.5	244.5	0.2928	85.43	9.9859
	4600	12544.66	6825.12	5002.99	476.6	233.1	0.2898	75.36	9.9474
	4800	12293.16	6725.48	4897.83	444.8	221.5	0.2864	65.52	9.9314
	5000	12024.45	6618.91	4789.83	412.8	209.8	0.2826	55.9	9.9326
	5200	11733.57	6563.7	4678.44	380.3	197.9	0.2783	46.49	9.9467
	5400	11415.6	6378.13	4563.07	347.1	185.6	0.2731	37.29	9.9698
	5600	11065.57	6240.46	4443.17	313.3	173	0.2668	28.29	9.9985
Lower	5600	11065.57	6240.46	4443.17	313.3	173	0.2668	28.29	9.9985
mantle	5701	10751.31	5945.08	4380.71	299.9	154.8	0.2798	23.83	10.0143
	5701	10266.22	5570.2	3992.14	255.6	123.9	0.2914	23.83	10.0143
	5771	10157.82	5516.01	3975.84	248.9	121	0.2909	21.04	10.0038
	5871	9645.88	5224.28	3849.8	218.1	105.1	0.2924	17.13	9.9883
	5971	9133.97	4932.59	3723.78	189.9	90.6	0.2942	13.35	9.9686
	5971	8905.22	4769.89	3543.25	173.5	80.6	0.2988	13.35	9.9686
Transition	6061	8732.09	4706.9	3489.51	163	77.3	0.2952	10.2	9.9361
Zone	6151	8558.96	4643.91	3435.78	152.9	74.1	0.2914	7.11	9.9048
Low	6151	7989.7	4418.85	3359.5	127	65.6	0.2797	7.11	9.9048
Velocity	6221	8033.7	4443.61	3367.1	128.7	66.5	0.2796	4.78	9.8783
Zone	6291	8076.88	4469.53	3374.71	130.3	67.4	0.2793	2.45	9.8553
	6291	8076.88	4469.53	3374.71	130.3	67.4	0.2793	2.45	9.8553
Lid	6346.6	8110.61	4490.94	3380.76	131.5	68.2	0.2789	0.604	9.8394
	6346.6	6800	3900	2900	75.3	44.1	0.2549	0.604	9.8394
	6356	6800	3900	2900	75.3	44.1	0.2549	0.337	9.8332
	6356	5800	3200	2600	52	26.6	0.2812	0.337	9.8332
Crust	6368	5800	3200	2600	52	26.6	0.2812	0.3	9.8222
	6368	1450	0	1020	2.1	0	0.5	0.3	9.8222
Ocean	6371	1450	0	1020	2.1	0	0.5	0	9.8156

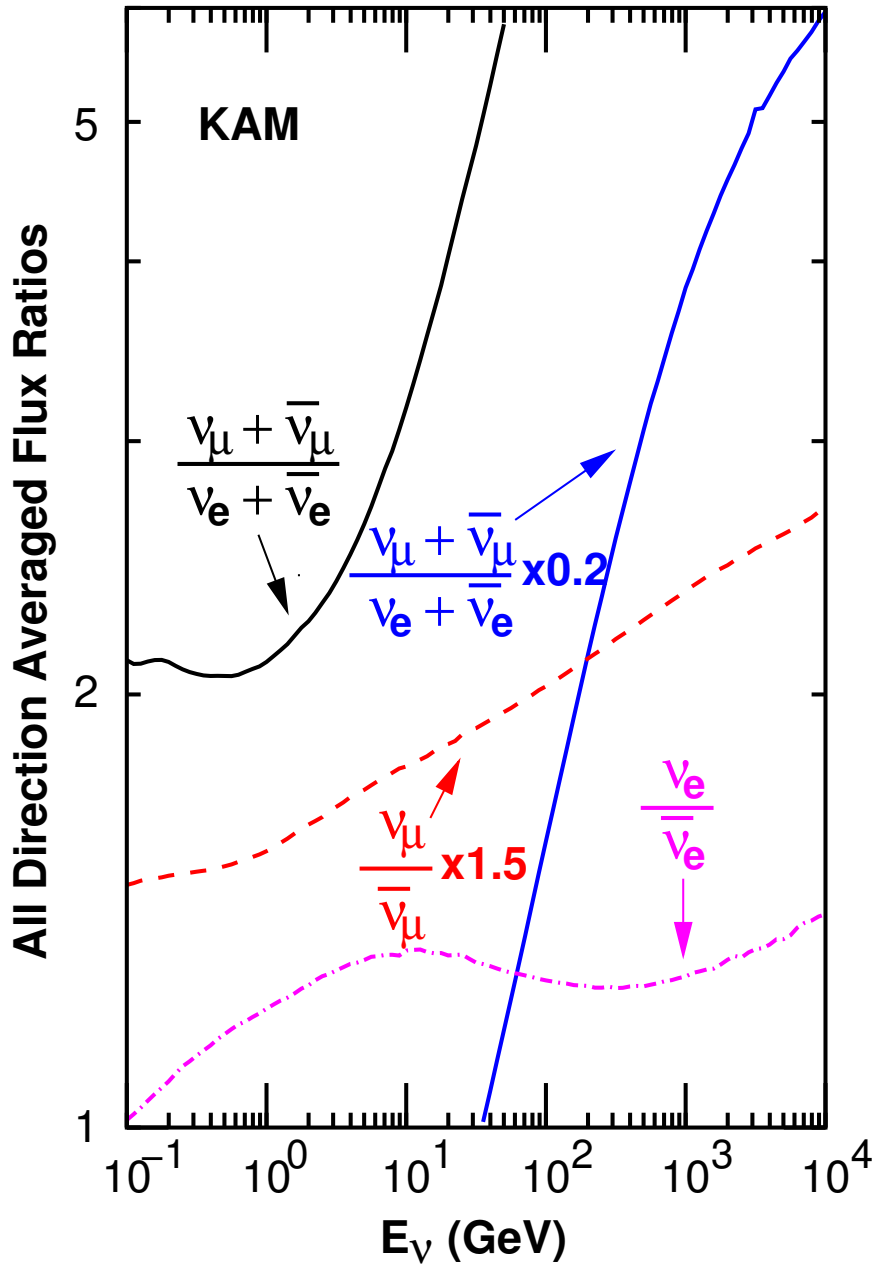
- solar neutrino detector
- Geophysics with high energy facility -DUNE
- chemical composition of the Earth (independent check)
- inform. about Earth's core
- ...

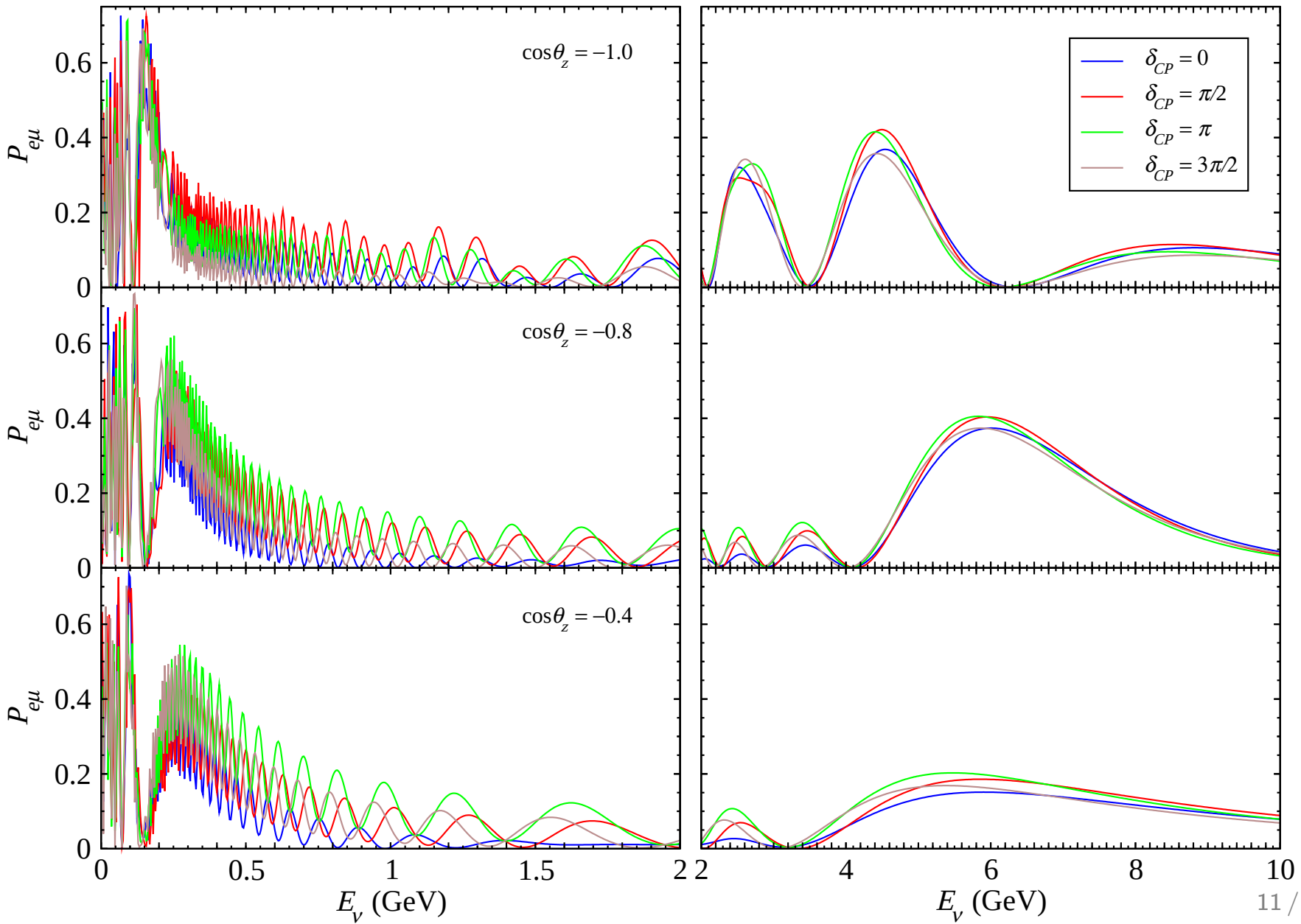
- triggering the event (simultaneous electron and 2-3 photons?)
- efficiency
- energy resolution
- background (above 10 MeV almost no rad. bakground)
- SP vs DP
- ...
- matter density profile under/around Homestake mine (PREM model is bad)

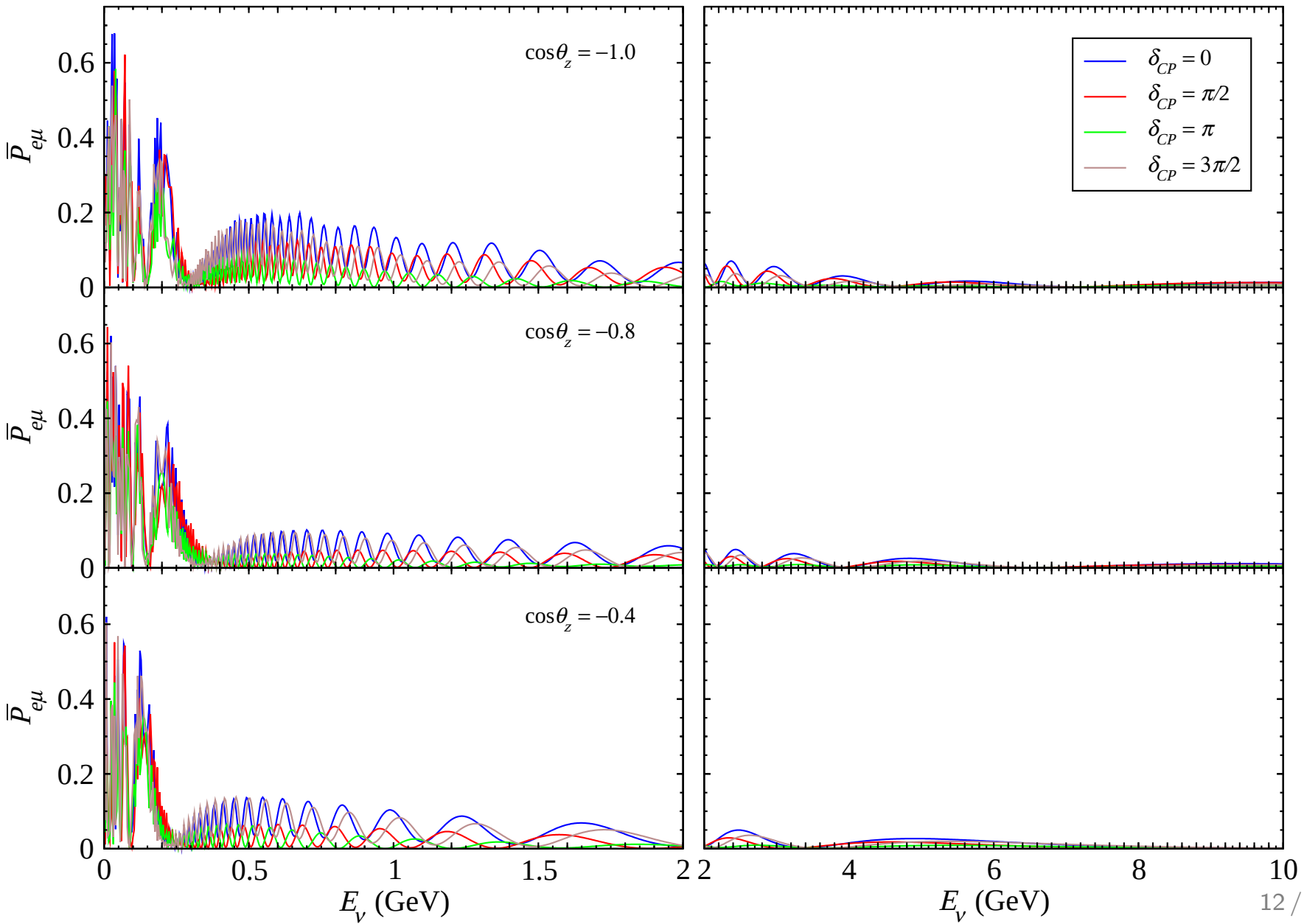
CP violation- atmospheric neutrinos

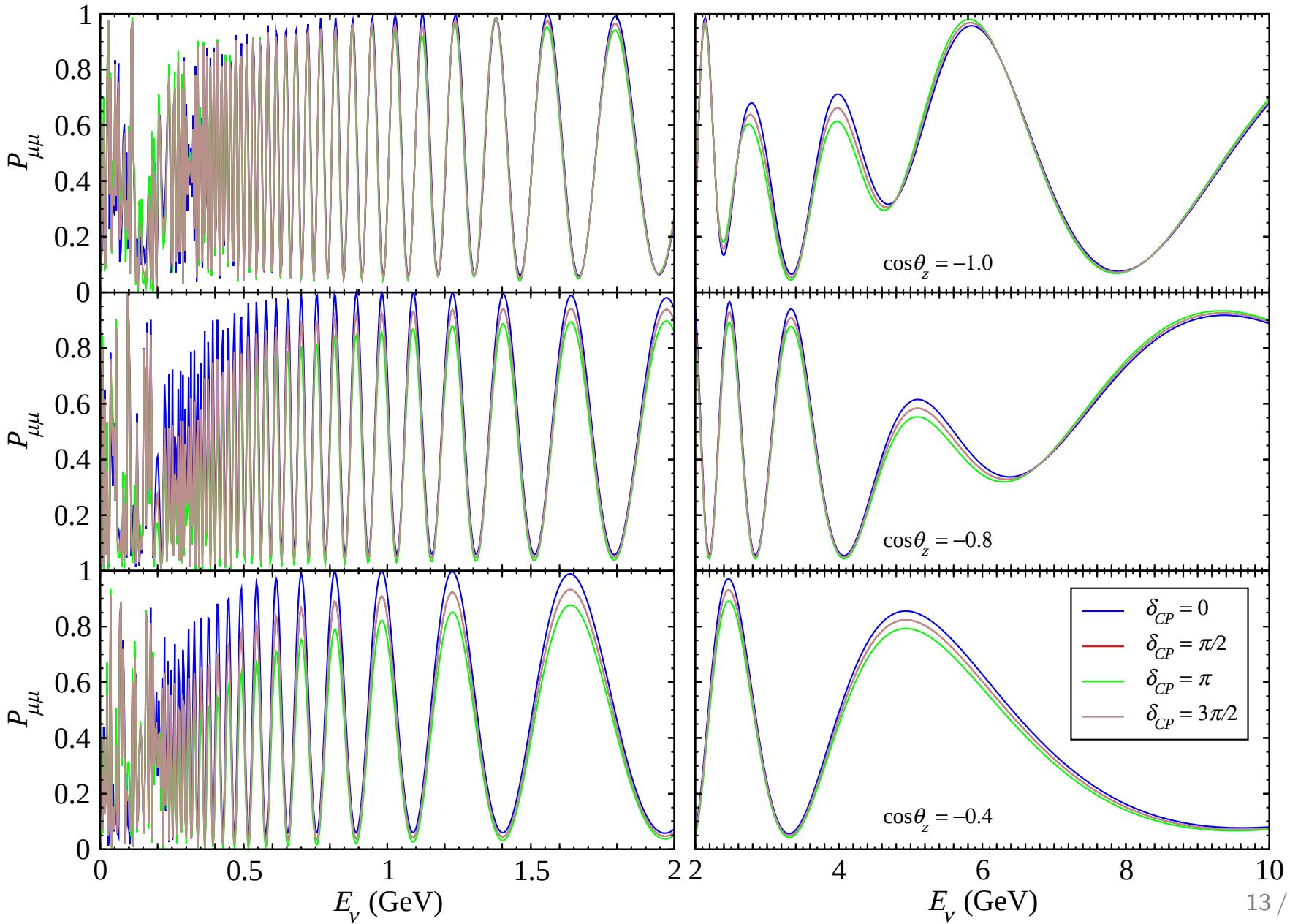
- Super-PINGU for measurement of the leptonic CP-phase with atmospheric neutrinos
  Smirnov and Razzaque
- few Mt WC detector with energy threshold (0.2-1) GeV
-
- LiAr 40kt is equivalent Mt WC
- WC does not distinguish between ν and $\bar{\nu}$ $(\nu + \bar{\nu})$
- in LiAr cross section (CC quasi elastic) for neutrinos is much larger than for antineutrinos
- no cancelation between ν and $\bar{\nu}$ (CP)
- much better energy resolution
- at DUNE one can expect to have same size CP violation as at Super-PINGU

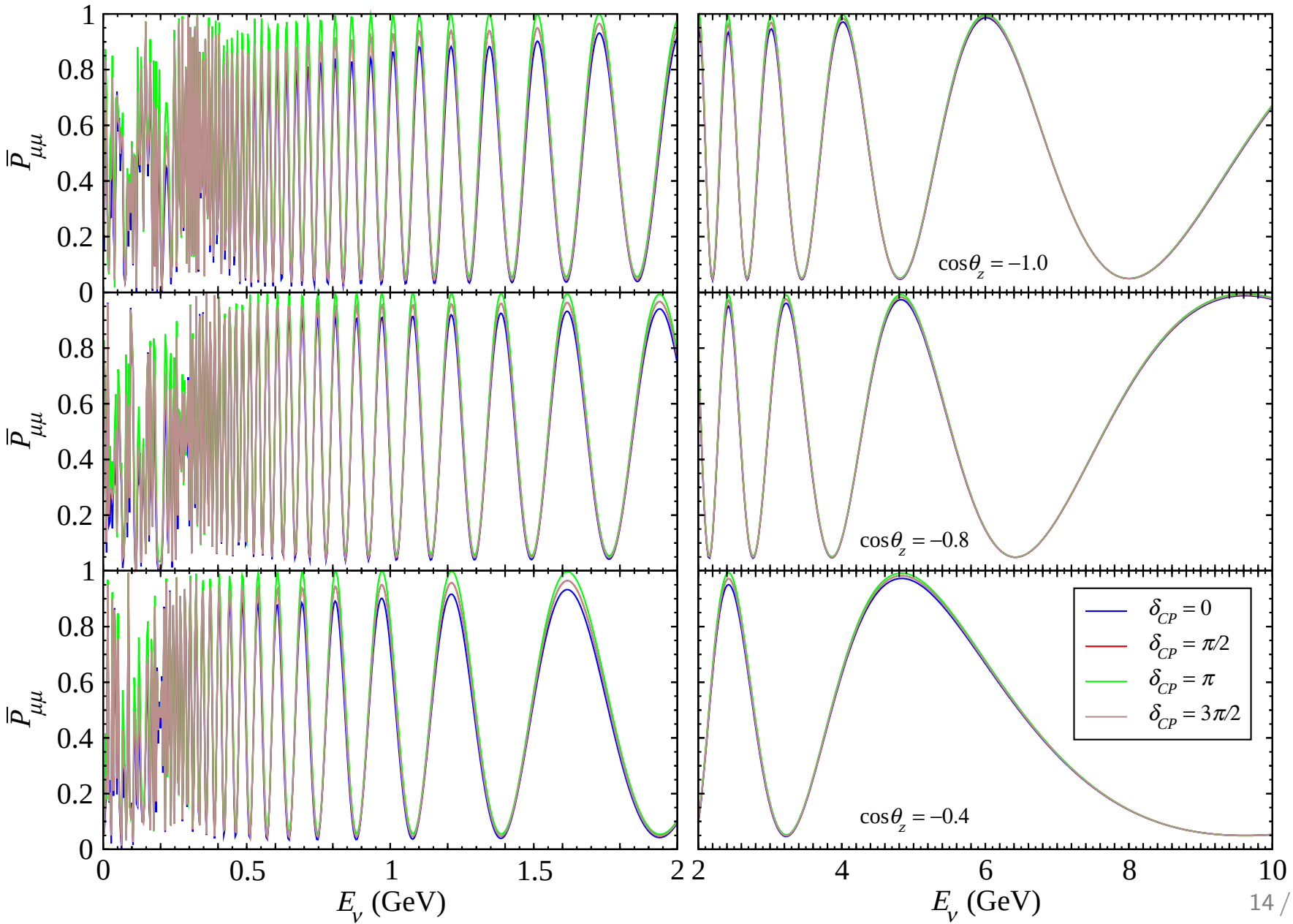

$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-1
0
1
2
3
4
5
6
7
$\log_{10}(E_\nu$ [GeV])
Frejus ν_μ
Frejus ν_e
SuperK ν_μ
AMANDA ν_μ
unfolding
forward folding
IceCube ν_μ
unfolding
forward folding
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
WB Bound


KAM
All Direction Averaged Flux Ratios
$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$
$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$ x0.2
$\frac{\nu_\mu}{\bar{\nu}_\mu}$ x1.5
$\frac{\nu_e}{\bar{\nu}_e}$
5
2
1
10^{-1}
10^0
10^1
10^2
10^3
10^4
E_ν (GeV)


$\cos\theta_z = -1.0$
$\cos\theta_z = -0.8$
$\cos\theta_z = -0.4$
$P_{e\mu}$
E_ν (GeV)
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = \pi$
$\delta_{CP} = 3\pi/2$


$\cos\theta_z = -1.0$
$\cos\theta_z = -0.8$
$\cos\theta_z = -0.4$
$\bar{P}_{e\mu}$
0
0.2
0.4
0.6
0
0.5
1
1.5
2
2
4
6
8
10
E_ν (GeV)
E_ν (GeV)
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = \pi$
$\delta_{CP} = 3\pi/2$


$P_{\mu\mu}$
E_ν (GeV)
$\cos\theta_z = -1.0$
$\cos\theta_z = -0.8$
$\cos\theta_z = -0.4$
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = \pi$
$\delta_{CP} = 3\pi/2$


$\bar{P}_{\mu\mu}$
E_ν (GeV)
$\cos\theta_z = -1.0$
$\cos\theta_z = -0.8$
$\cos\theta_z = -0.4$
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = \pi$
$\delta_{CP} = 3\pi/2$

- angular resolution
- energy resolution
- efficiency
- $e - \mu$ distinction (from under the first resonance energy (300 MeV) till several GeV)
- ...

THANK YOU