TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

Hyper-K potential to study the Leptonic Unitarity Triangle

@HK meeting, Jan.29, 2015

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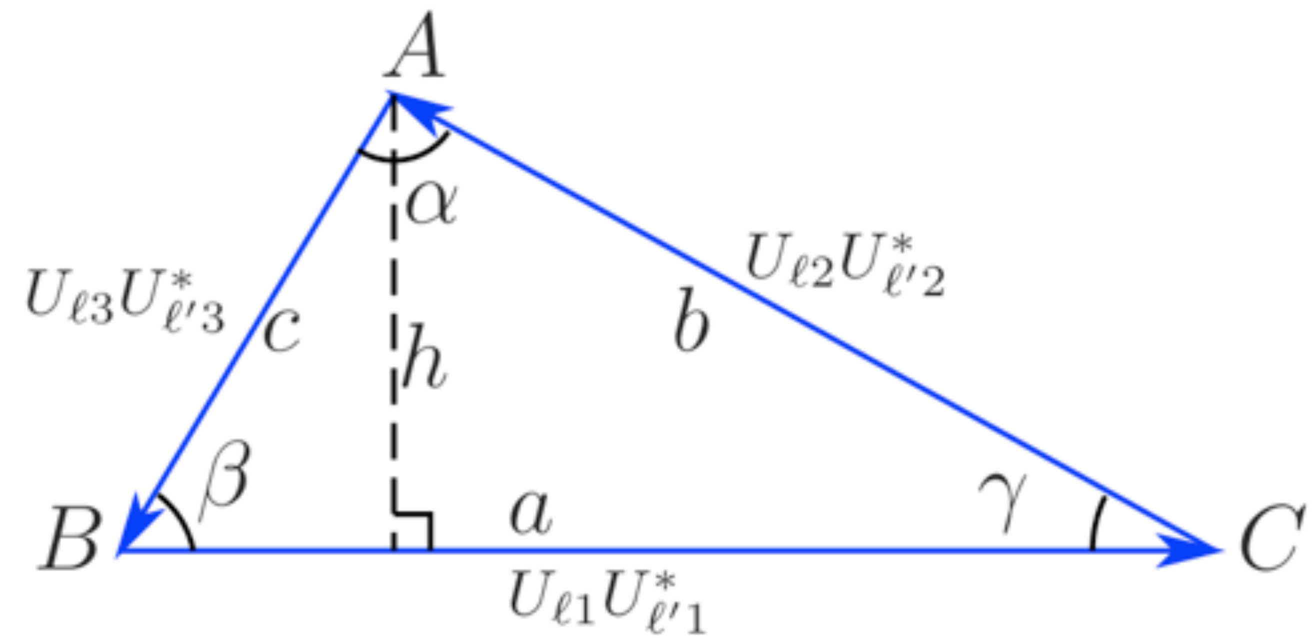
Unitarity of the PMNS matrix

- Unitarity condition: $U^\dagger U=1$
  - Normalization

$$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$$
$$|U_{\mu1}|^2+|U_{\mu2}|^2+|U_{\mu3}|^2 = 1$$
$$|U_{\tau1}|^2+|U_{\tau2}|^2+|U_{\tau3}|^2 = 1$$



  - Unitarity triangle

$$U_{e1}U^*_{\mu1}+U_{e2}U^*_{\mu2}+U_{e3}U^*_{\mu3} = 0$$
$$U_{\mu1}U^*_{\tau1}+U_{\mu2}U^*_{\tau2}+U_{\mu3}U^*_{\tau3} = 0$$
$$U_{\tau1}U^*_{e1}+U_{\tau2}U^*_{e2}+U_{\tau3}U^*_{e3} = 0$$

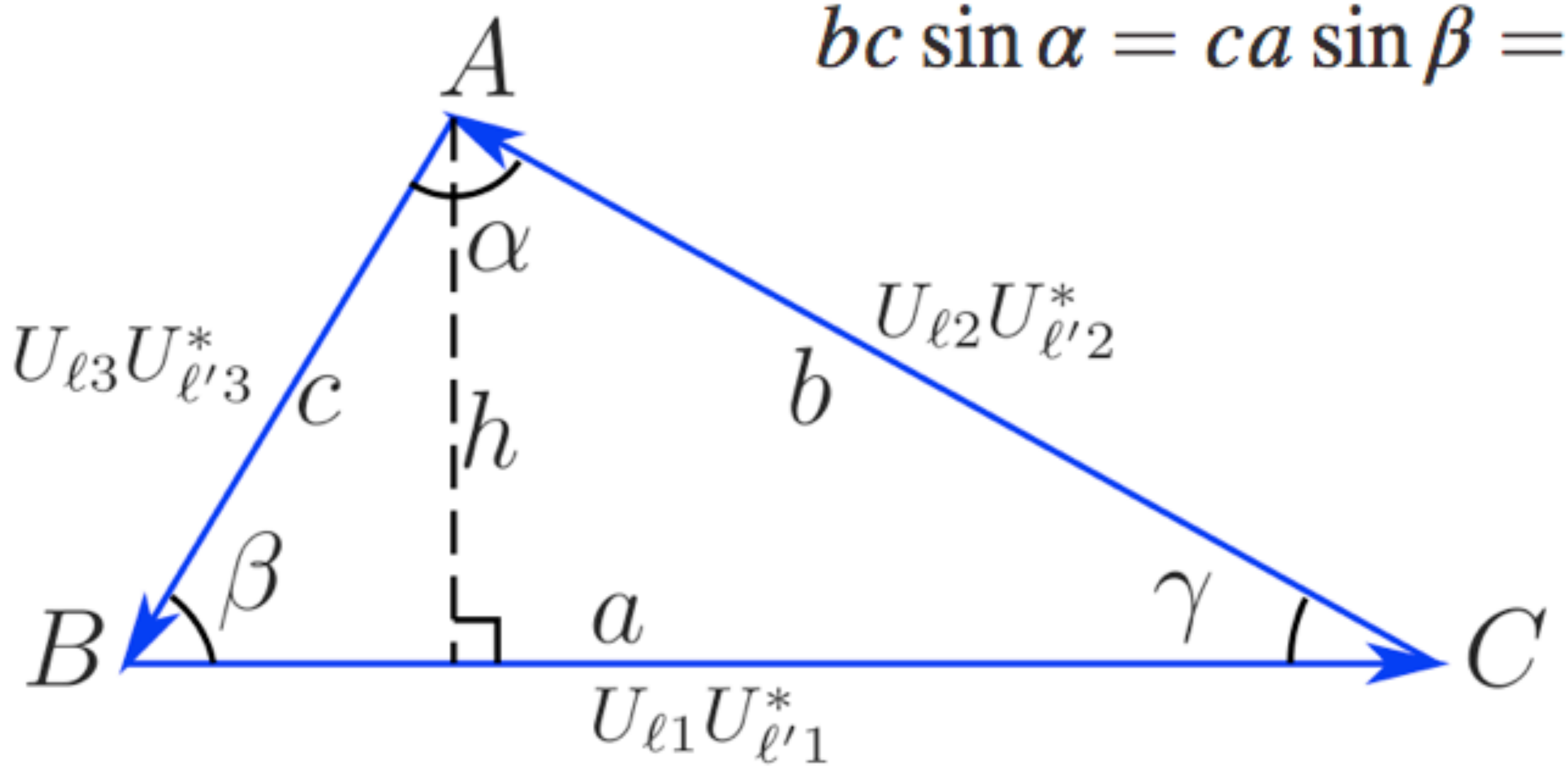
- Unitarity of PMNS is broken due to ν_R
  - 4th generation or new interactions, can also do it.

Lesson from CKM (quarks)

- **Normalization:** $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
  - $|V_{ud}|^2 < 1$ lead to the idea of Cabbibo angle: strange quark implication in nuclear β decay
- **Flavour Changing Neutral Current (FCNC)**
  - Unitarity prohibits FCNC
  - Already tested for charged leptons: e.g. $\mu \to e\gamma$
- **Unitarity triangle:**
  - Unitarity condition including CP phase is tested in B, K decays: works very well
  - Over-constrain the unitarity triangle to explore physics beyond Standard Model

Unitarity Triangle (PRD89(2014)073002)

$$bc\sin\alpha = ca\sin\beta = ab\sin\gamma = J.$$



$a=|U_{\ell 1}|\,|U_{\ell' 1}|$

$b=|U_{\ell 2}|\,|U_{\ell' 2}|$

$c=|U_{\ell 3}|\,|U_{\ell' 3}|$

Appearance

$$\boxed{\begin{aligned} P_{\ell\to\ell'} &= 4ab\sin(\Delta_{12}\pm\gamma)\sin\Delta_{12} \\ &+4bc\sin(\Delta_{23}\pm\alpha)\sin\Delta_{23} \\ &+4ac\sin(\Delta_{31}\pm\beta)\sin\Delta_{31} \end{aligned}}$$

or

$$\boxed{\begin{aligned} P_{\ell\to\ell'} &= a^2+b^2+c^2-2ab\cos(2\Delta_{12}\pm\gamma) \\ &-2bc\cos(2\Delta_{23}\pm\alpha)-2ca\cos(2\Delta_{31}\pm\beta) \end{aligned}}$$

$\Delta_{12}=\Delta m^2_{12}L/4E$

$\Delta_{23}=\Delta m^2_{23}L/4E$

$\Delta_{31}=\Delta m^2_{31}L/4E$

Disappearance

- Disappearance gives sides of the triangle:

$$\begin{aligned} P_{disapp} &= 1 - P_{\ell \to \ell} \\ &= 4|U_{\ell 1}|^2\,|U_{\ell 2}|^2 \sin^2\Delta_{12} \\ &\quad + 4|U_{\ell 2}|^2\,|U_{\ell 3}|^2 \sin^2\Delta_{23} \\ &\quad + 4|U_{\ell 3}|^2\,|U_{\ell 1}|^2 \sin^2\Delta_{31} \end{aligned}$$

At 1st oscil. max.

$$\Delta_{23} \sim \Delta_{13}$$
$$\sim 0.03\,\Delta_{12}$$

- Different L/E scale to untangle each contrib.
  - solar (Δ_{12}) and atmospheric (Δ_{23},Δ_{31}) scales
  - level crossing due to matter effect provides an additional handle

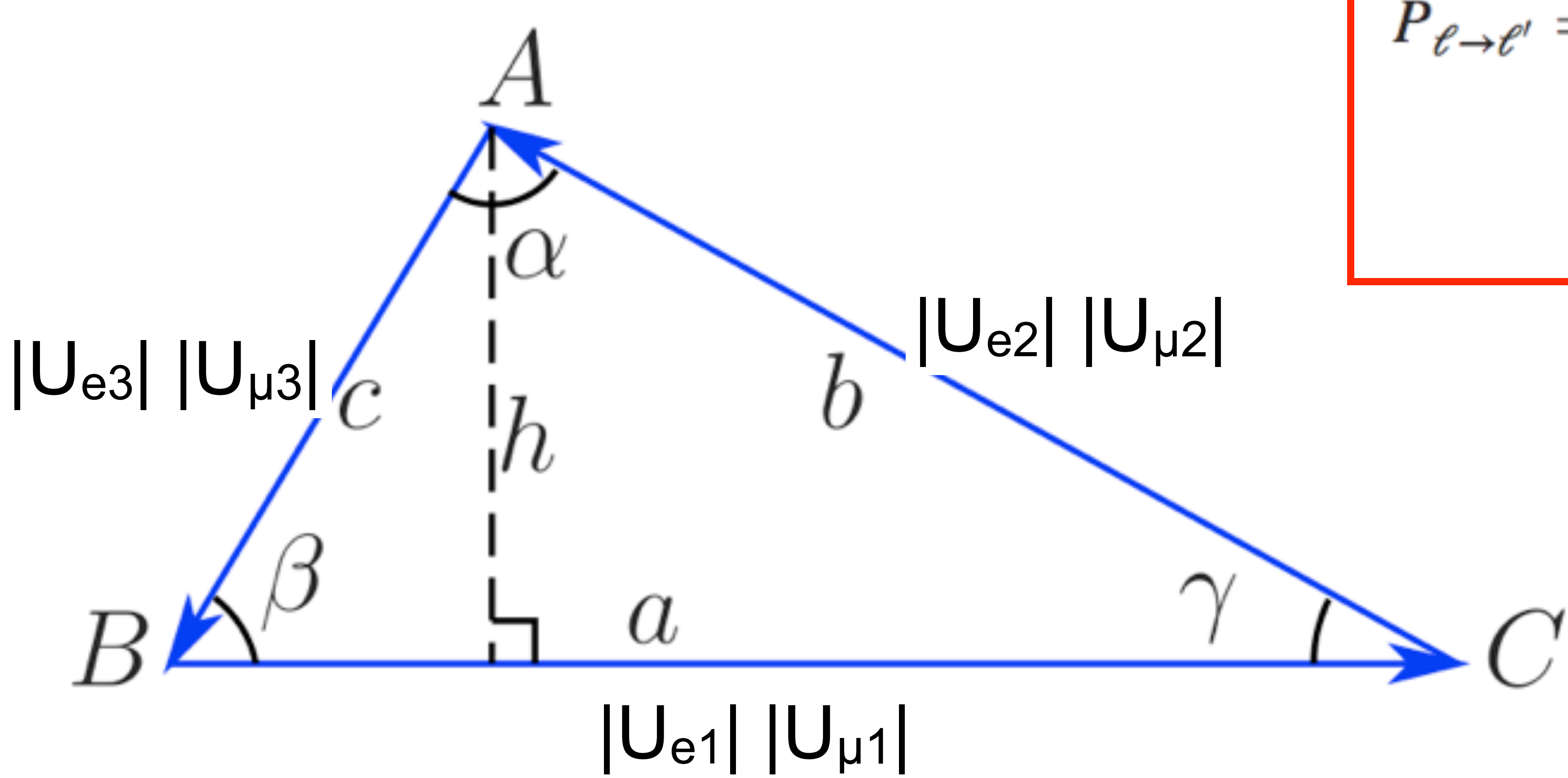
e-μ unitarity in PMNS

- e-μ part of unitarity can be studied best:

$$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$$
$$|U_{\mu 1}|^2+|U_{\mu 2}|^2+|U_{\mu 3}|^2 = 1$$

Normalization terms and sides of the triangle can be determined by disappearance

$$U_{e1}U^*_{\mu 1}+U_{e2}U^*_{\mu 2}+U_{e3}U^*_{\mu 3} = 0$$



$$\boxed{\begin{aligned} P_{\ell\to\ell'} &= 4ab\sin(\Delta_{12}\pm\gamma)\sin\Delta_{12} \\ &+ 4bc\sin(\Delta_{23}\pm\alpha)\sin\Delta_{23} \\ &+ 4ac\sin(\Delta_{31}\pm\beta)\sin\Delta_{31} \end{aligned}}$$

Δ_{13} : $\beta \sim \delta_{cp}$

Δ_{12} : $\gamma \sim \delta_{subGeV\text{-}atm}$

Δ_{23} : $\alpha \sim \delta_{nth\text{-}max}$

$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$

- Solar neutrino: $|U_{e2}|^2$
  - MSW conversion in the sun: $\nu_e \rightarrow \nu_2$ and detect ν_e
- KamLand: $|U_{e1}|^2|U_{e2}|^2$
  - Reactor ν_e disappearance at Δ_{12} scale of L/E
- Reactor θ_{13}: $|U_{e3}|^2\ (|U_{e1}|^2 + |U_{e2}|^2\ )$
  - Reactor ν_e disappearance at Δ_{12} scale of L/E
- All the parameters are measured. Better precision desired for KamLand measurement
  - JUNO experiment will achieve this in future

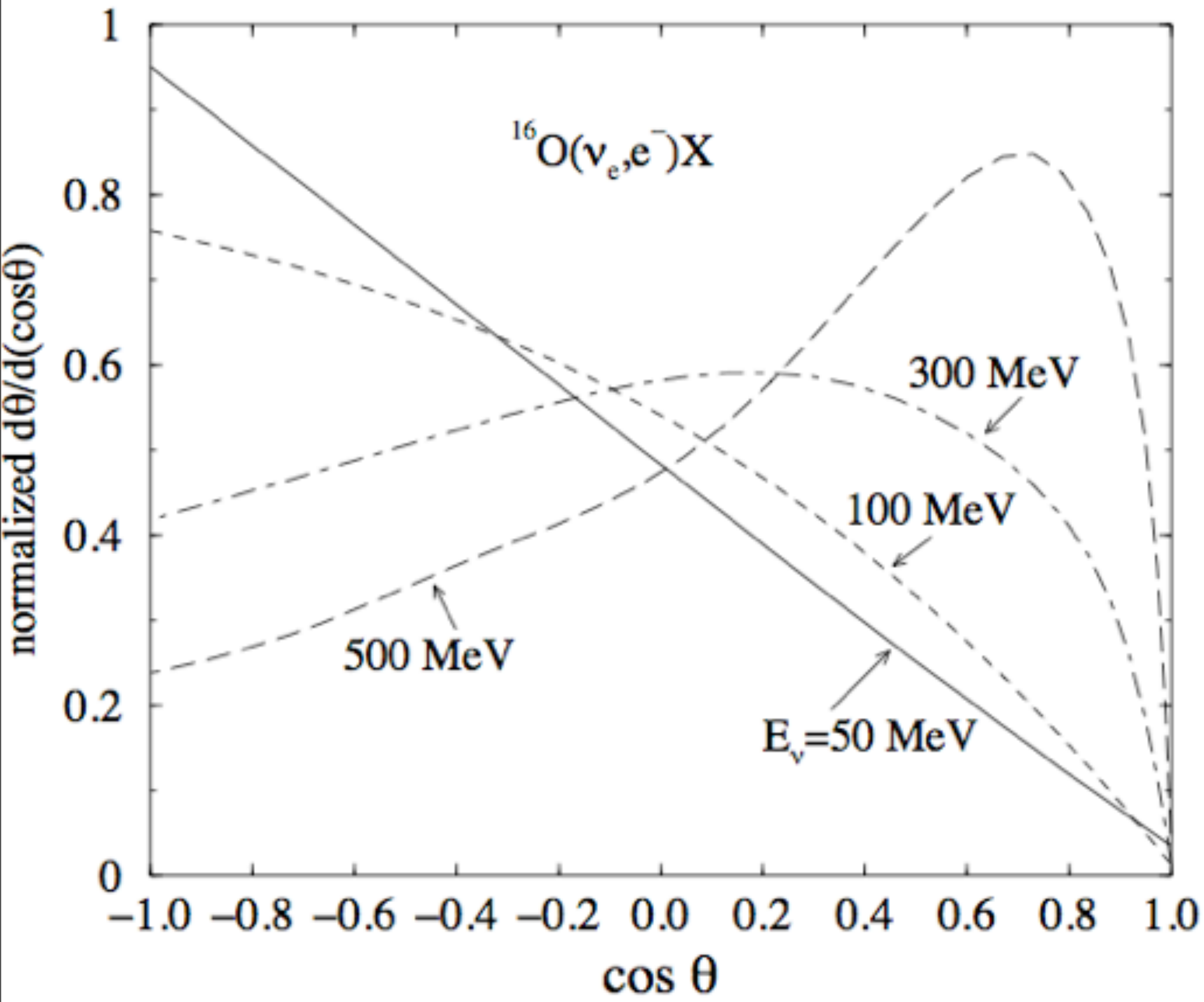
$|U_{\mu 1}|^2+|U_{\mu 2}|^2+|U_{\mu 3}|^2 = 1$

- LBL ν_μ disappearance: $|U_{\mu 3}|^2$ $(|U_{\mu 1}|^2 + |U_{\mu 2}|^2)$
  - This is what T2K/MINOS/NovA measure
- $\nu_\mu \rightarrow \nu_e$ atm. matter resonance: $(r|U_{\mu 3}|^2 - 1)$
  - Amplitude of the atmospheric mass hierarchy study [HK]
- Solar scale atm. ν_μ disapp. : $|U_{\mu 1}|^2|U_{\mu 2}|^2$
  - 0.4-0.8GeV up-going atm. ν_μ disapp. [HK]
  - zenith angle measurement: anti-ν_μ, proton energy cut
- 1-3GeV atm. ν_μ disapp. (4-6th max.) can untangle $|U_{\mu 1}|^2$ and $|U_{\mu 2}|^2$ terms in LBL disapp. [HK]
  - Δ_{13} and Δ_{23} show 30-20% difference
  - 2nd max. LBL detector could also do this.

Lepton angular distribution

Lepton from neutrino reaction goes backward at low energy

nucl-th/0311022



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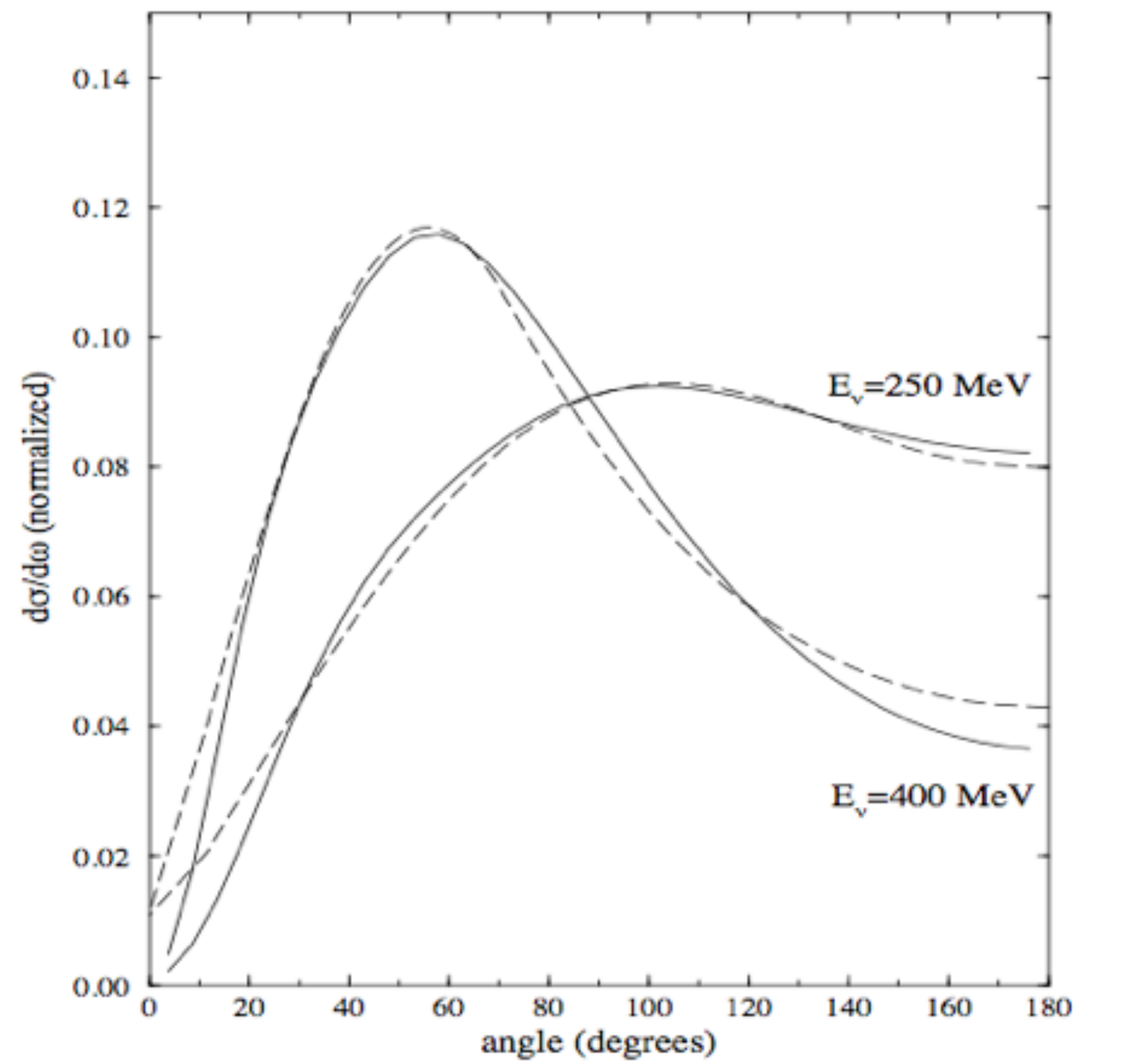


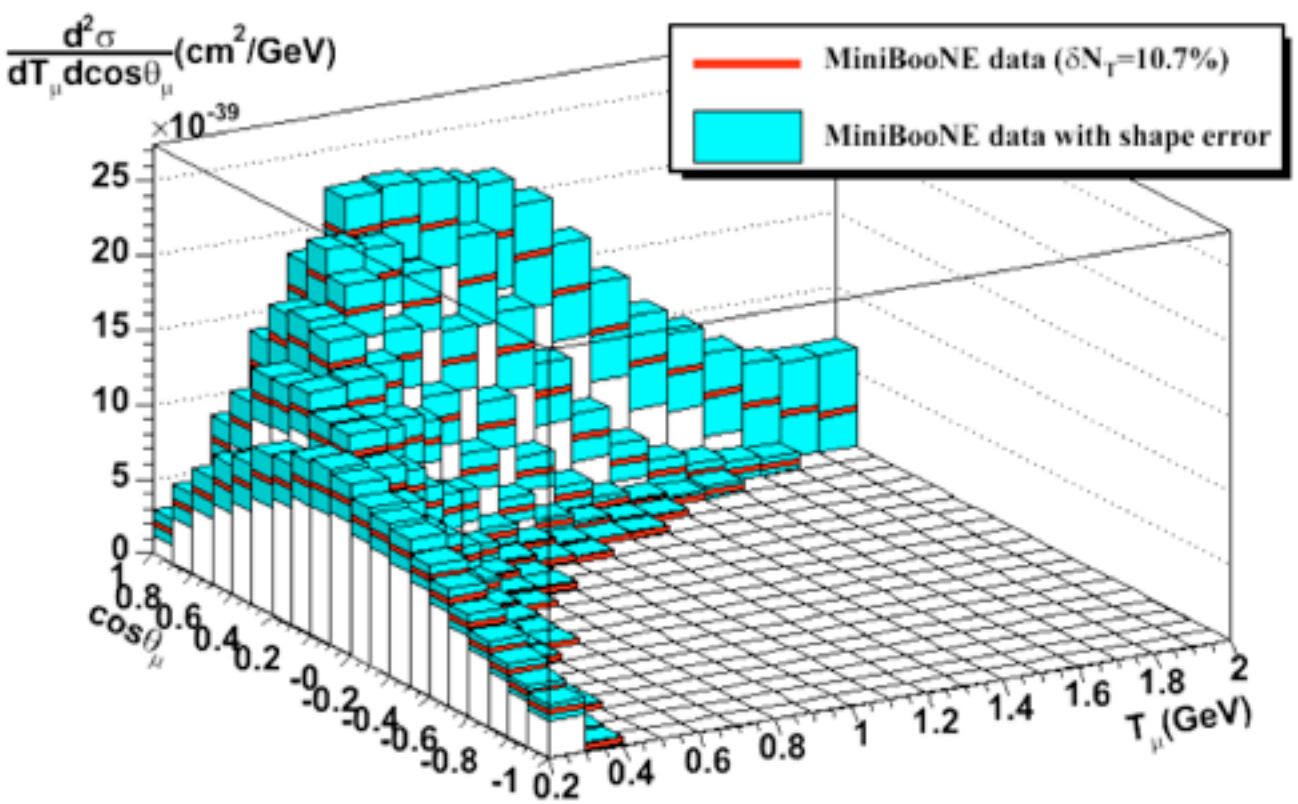
Neutrino direction measurement possible for E_ν > 400-500MeV

Cross section study by νPRISM is important.

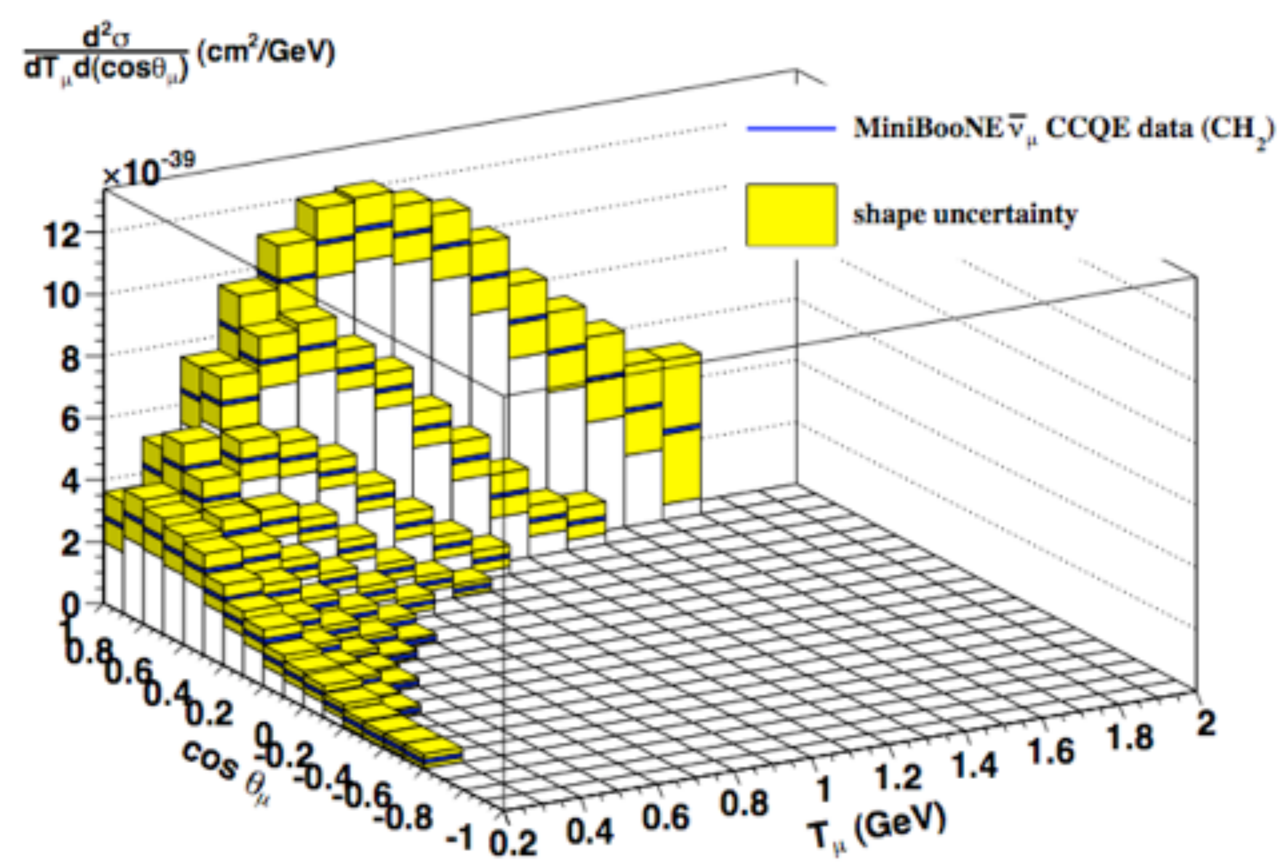
MiniBooNE differential x-sec

- Forward peak for anti-ν even for neutrino energy at 200MeV
  - $\bar{\nu}_e$ tagging by WbLs proton veto, Gd neutron tag?
  - $\bar{\nu}_e$ cross section is reasonably large at low E_ν

neutrino CCQE



anti-neutrino CCQE

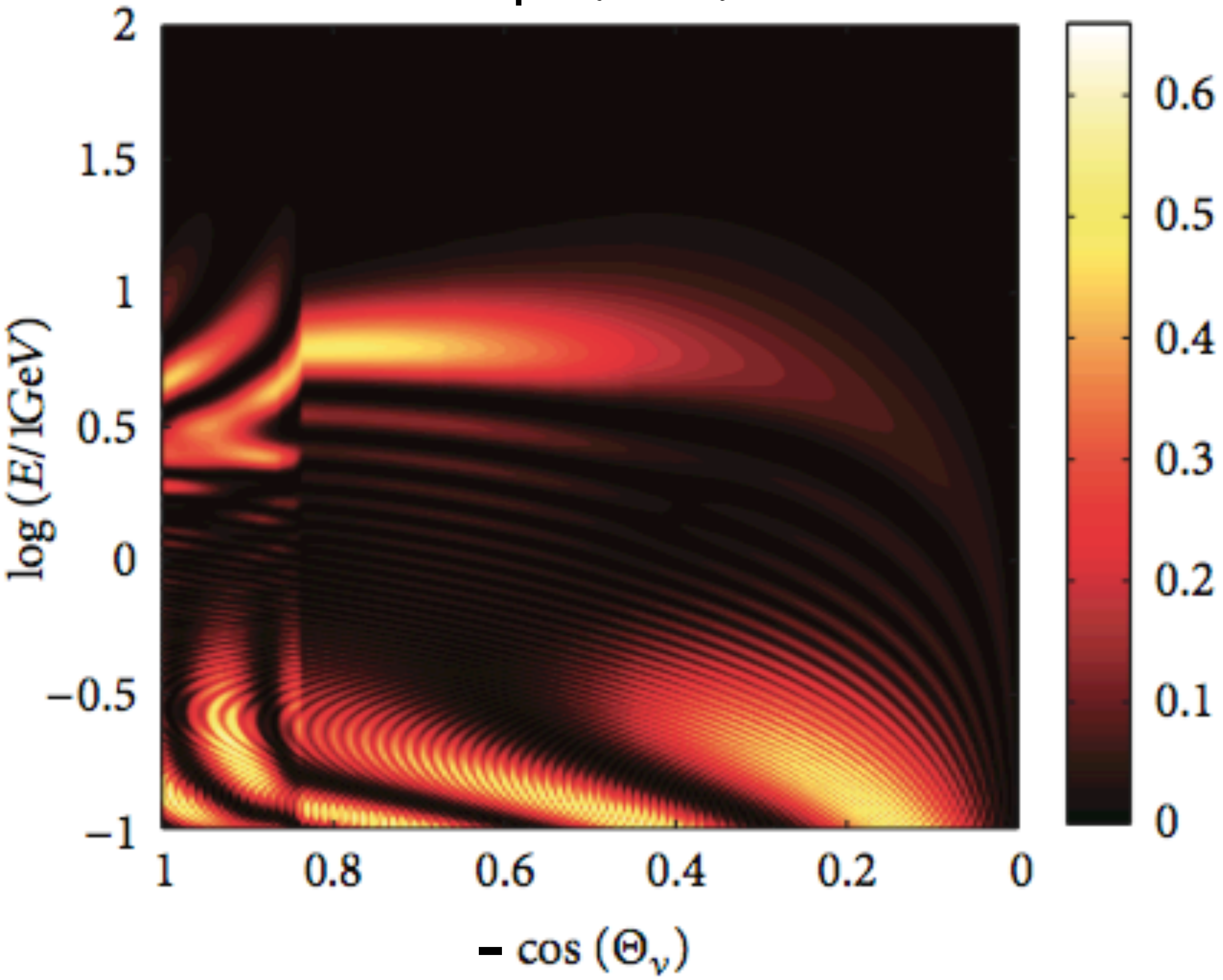


- CP study at Δ_{12} scale using sub-GeV atmospheric neutrios

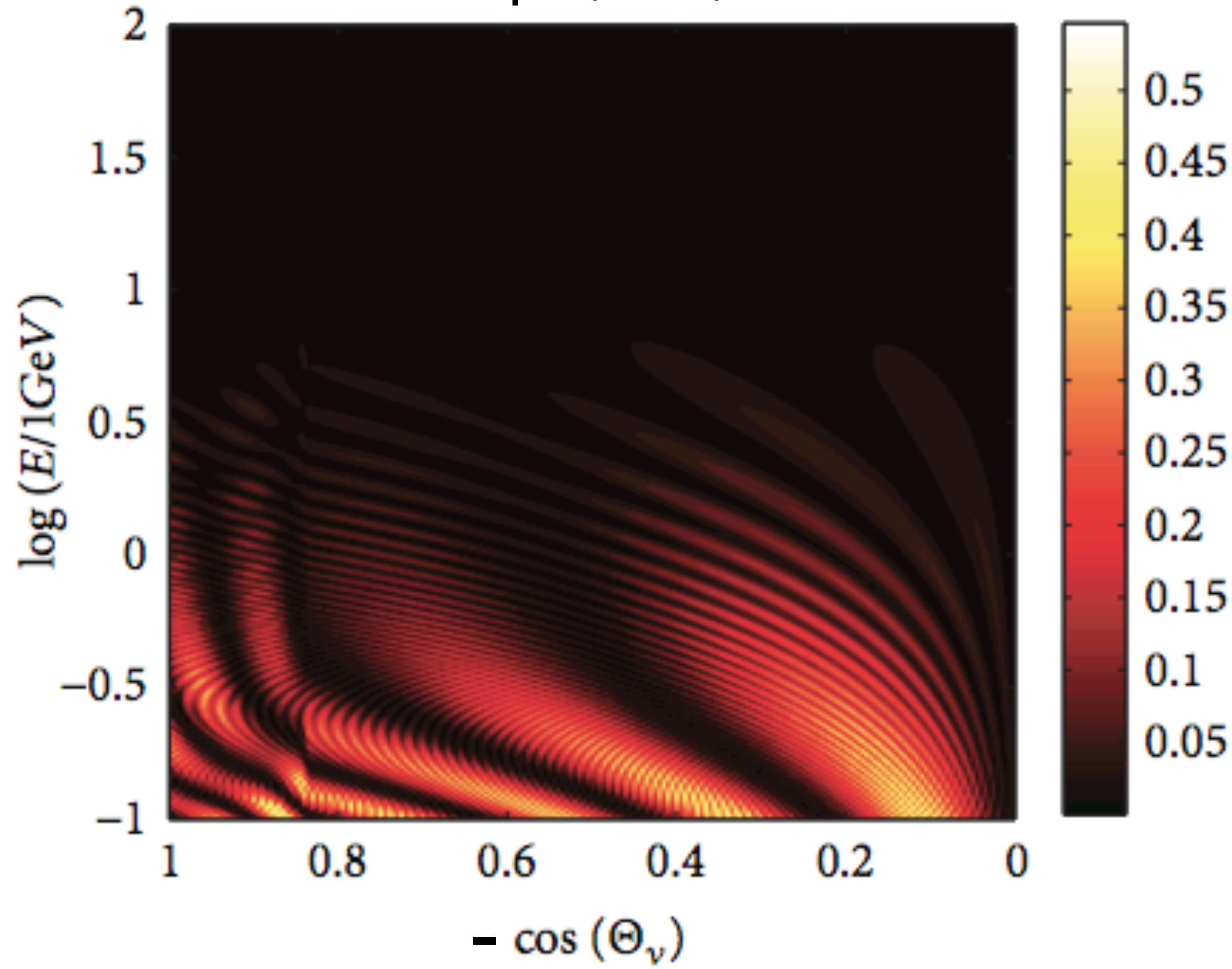
Atmospheric $\nu_\mu \to \nu_e$

- Δ_{12} oscillation below 1GeV: large θ_{12} oscillation effect
  - Above matter resonance (E_R=0.1GeV), $\nu_\mu \to \nu_e$ level crossing
  - phase difference between ν and $\bar{\nu}$ due to matter effect

ν_μ (NH)



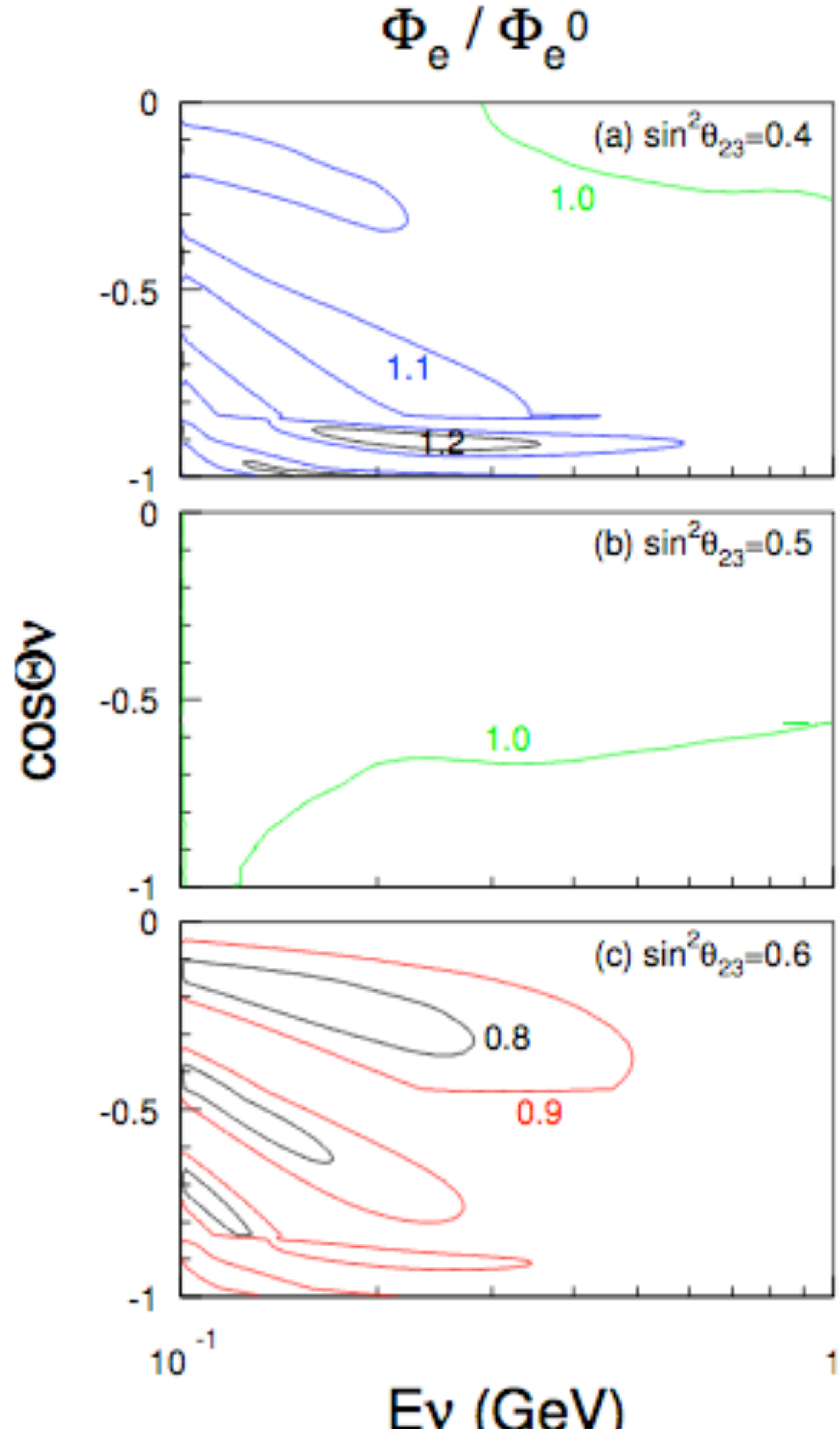
$\bar{\nu}_\mu$ (NH)



Can we measure this pattern?

Compensation due to r=2

- Observed ν_e is from
  - $\Phi(\nu_\mu) \times P_{\mu e} = \Phi(\nu_\mu) \times \sin^2\theta_{23} P_{ee}$
  - $\Phi(\nu_e) \times (1-P_{ee})$
- $r=\Phi(\nu_\mu)/\Phi(\nu_e)=2$, $\sin^2\theta_{23}=0.5$, they cancel: no effect!
  - r=2 for E < 3GeV
  - even cancels matter effect
- Some cases that avoid r=2
  - E_ν>3GeV (r>2) : mass hierarchy
  - $\sin\theta_{23}\neq 0.5$: constrained by T2K
  - CP violation!



T (CP) violaiton

- Oscillogram formula (arXiv:0804.1466)

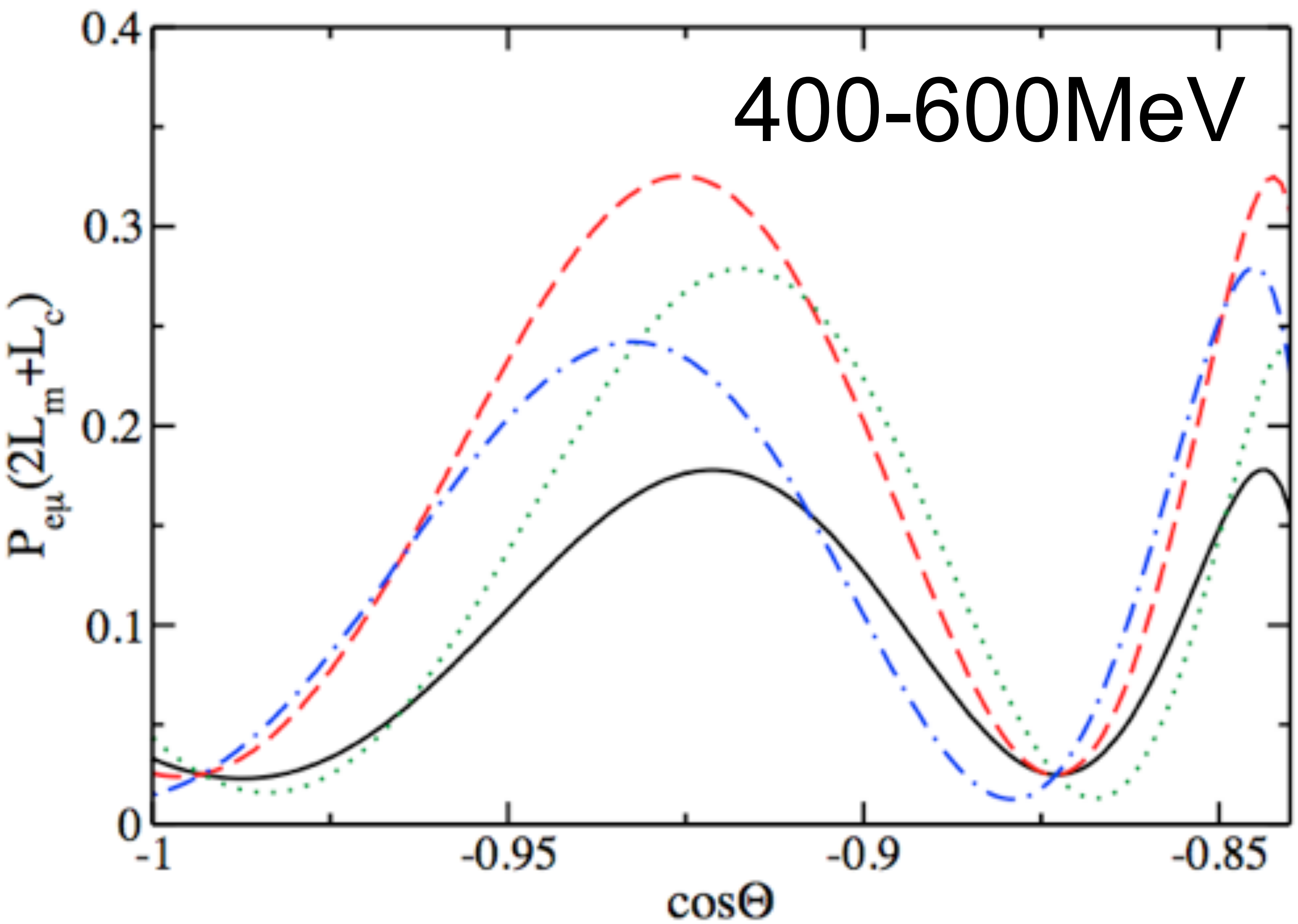
$$P_{\mu e} = c_{23}^2|A_{e\tilde{2}}|^2 + s_{23}^2|A_{e\tilde{3}}|^2 + 2\, s_{23}\, c_{23}\ \mathrm{Re}(e^{-i\delta} A^*_{e\tilde{2}} A_{e\tilde{3}})\,,$$
$$P_{\tau e} = s_{23}^2|A_{e\tilde{2}}|^2 + c_{23}^2|A_{e\tilde{3}}|^2 - 2\, s_{23}\, c_{23}\ \mathrm{Re}(e^{-i\delta} A^*_{e\tilde{2}} A_{e\tilde{3}})\,,$$

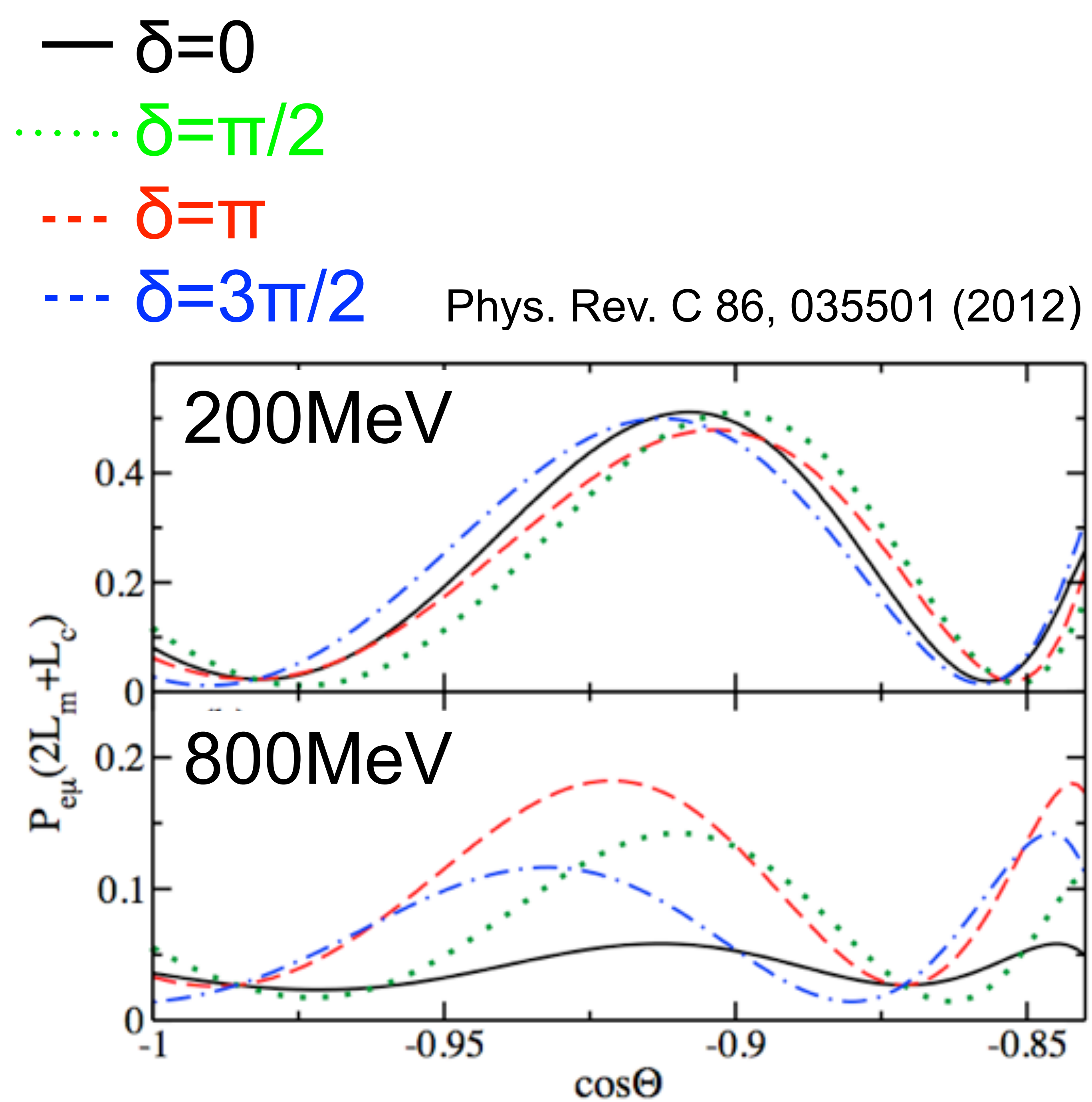
$1-P_{ee} = P_{\mu e}(-\delta) + P_{\tau e}(-\delta) = |A_{e2}|^2 + |A_{e3}|^2$
$2 \times P_{\mu e}(\delta) - (1-P_{ee}) \sim \mathrm{Re}(e^{i\delta} A^*_{e2} A_{e3})$

- $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ differs by T (CP) violation
  - All the oscillation due to Δ_{12} cancels including matter effects due to r=2, except for T violation
  - Opposit sign for $\bar{\nu}$, but luckily we mainly see ν_e: $\sigma(\nu_\mu \rightarrow \nu_e) \sim 5\ \sigma(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - **Very sensitive test of T-violation !**

arXiv:1207.5694

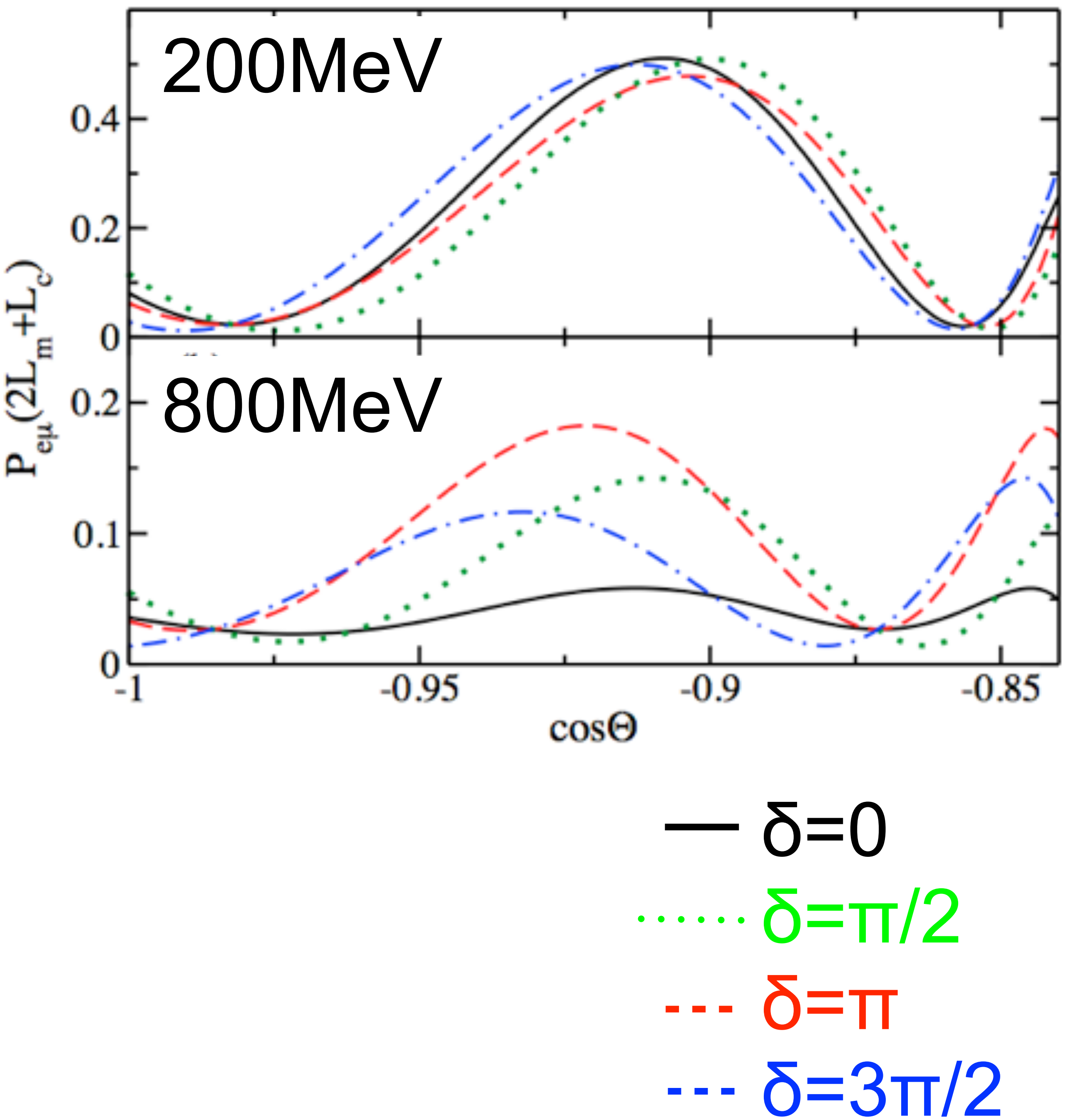
- $P_{\mu e}$=10-30% with significant CP violation, $P_{\mu e}$ (CP)~10-20%, for E_ν=400-800MeV (E_e=300-700MeV)

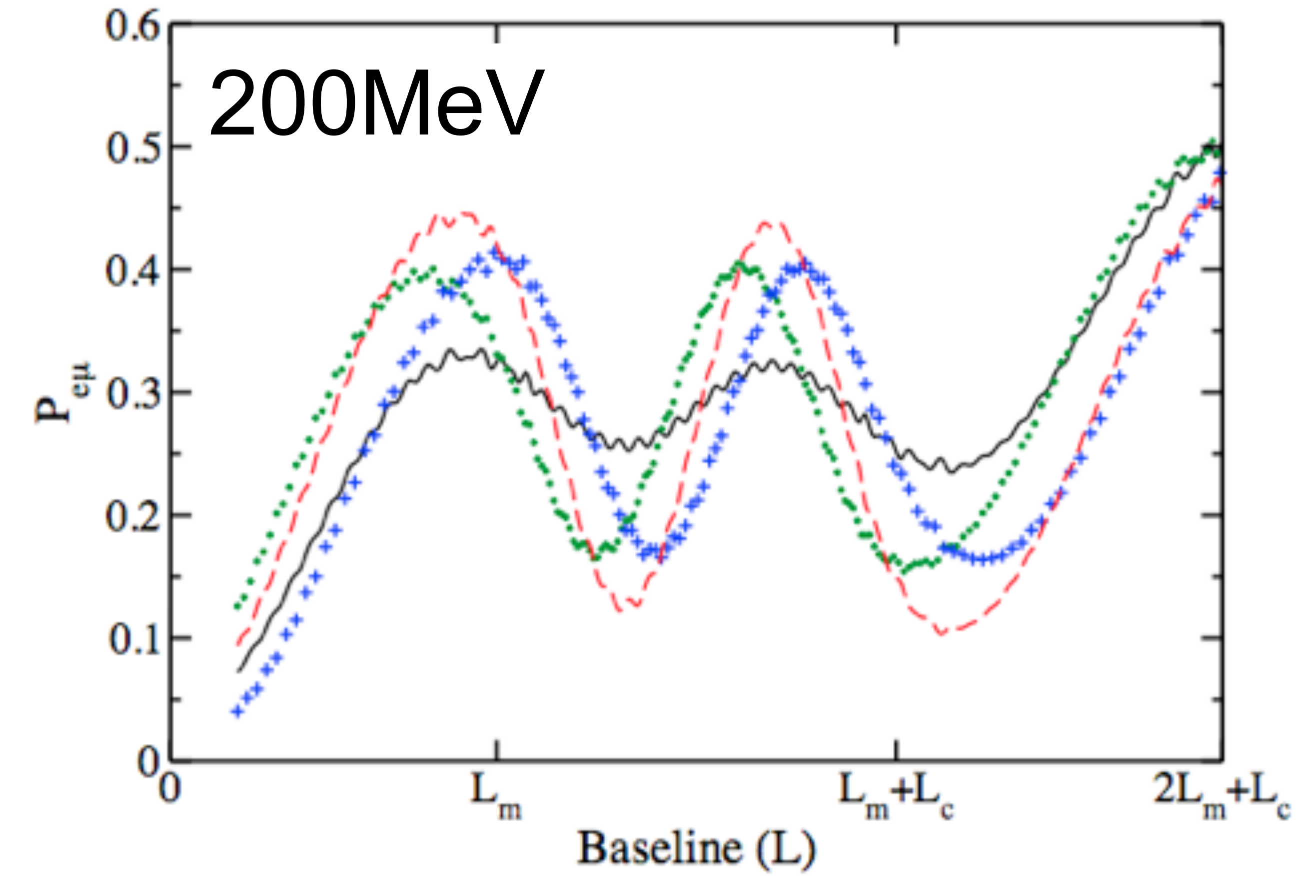


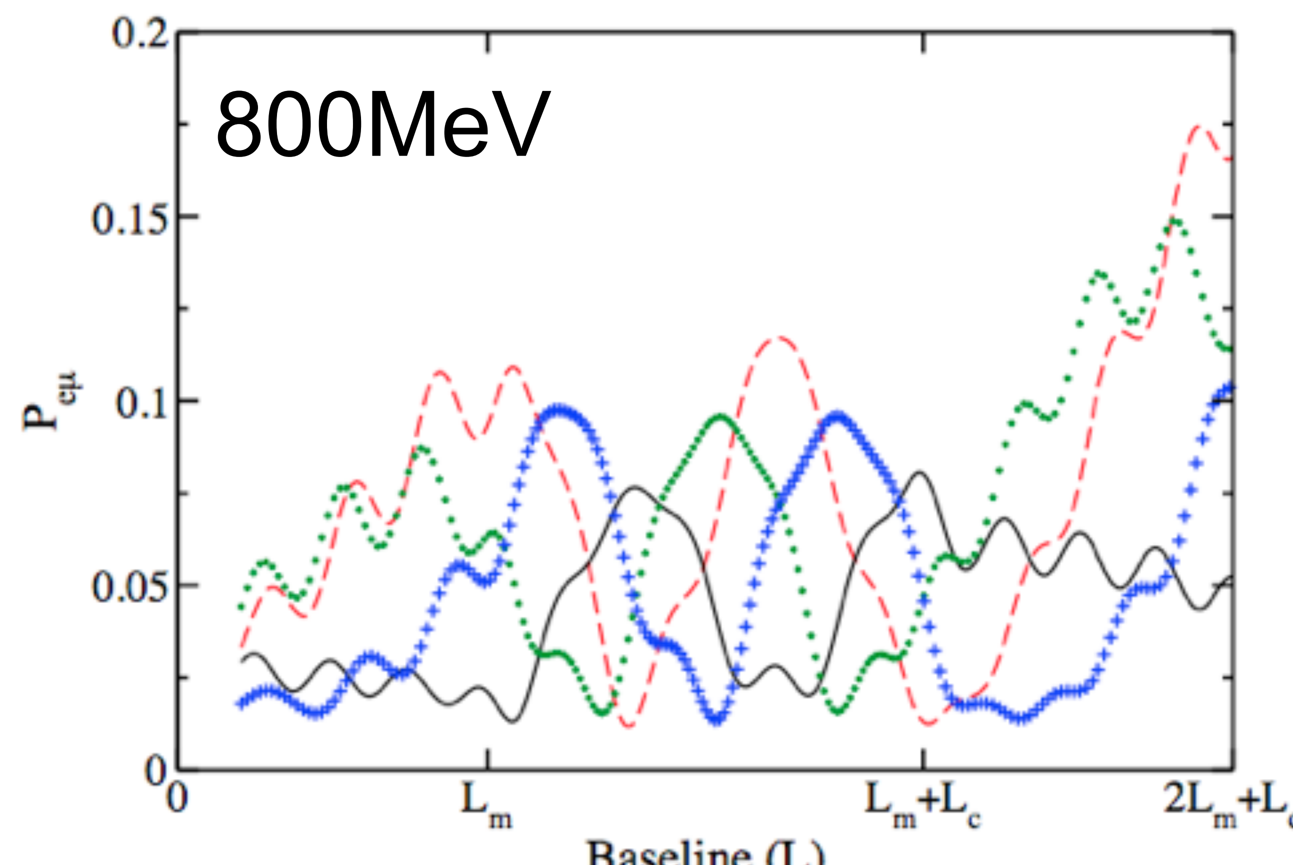


- $P_{\mu e}$(CP)=10% on average: 20% contribution in ν_e (up to 20% effect!)

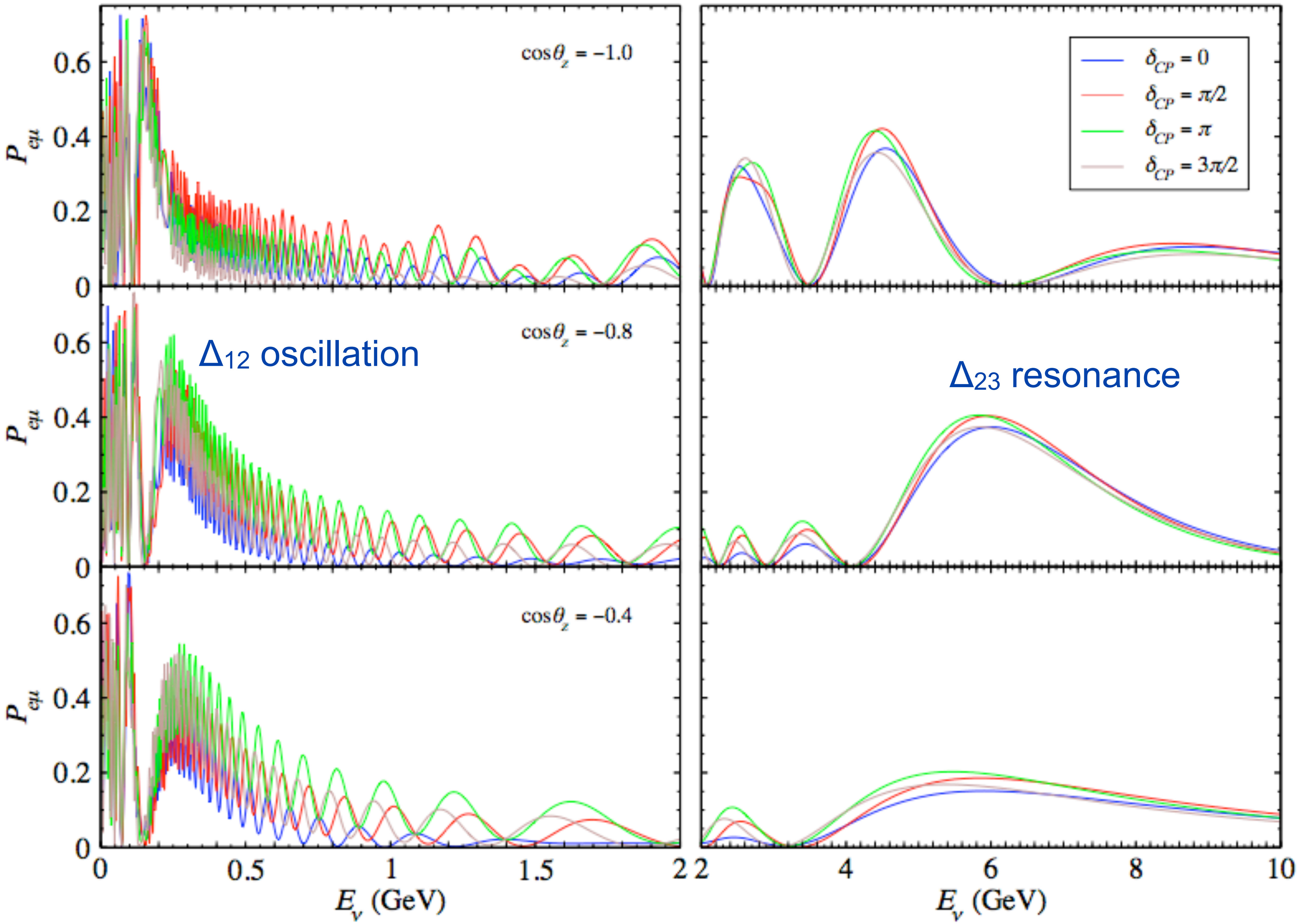
Oscillation through the earth







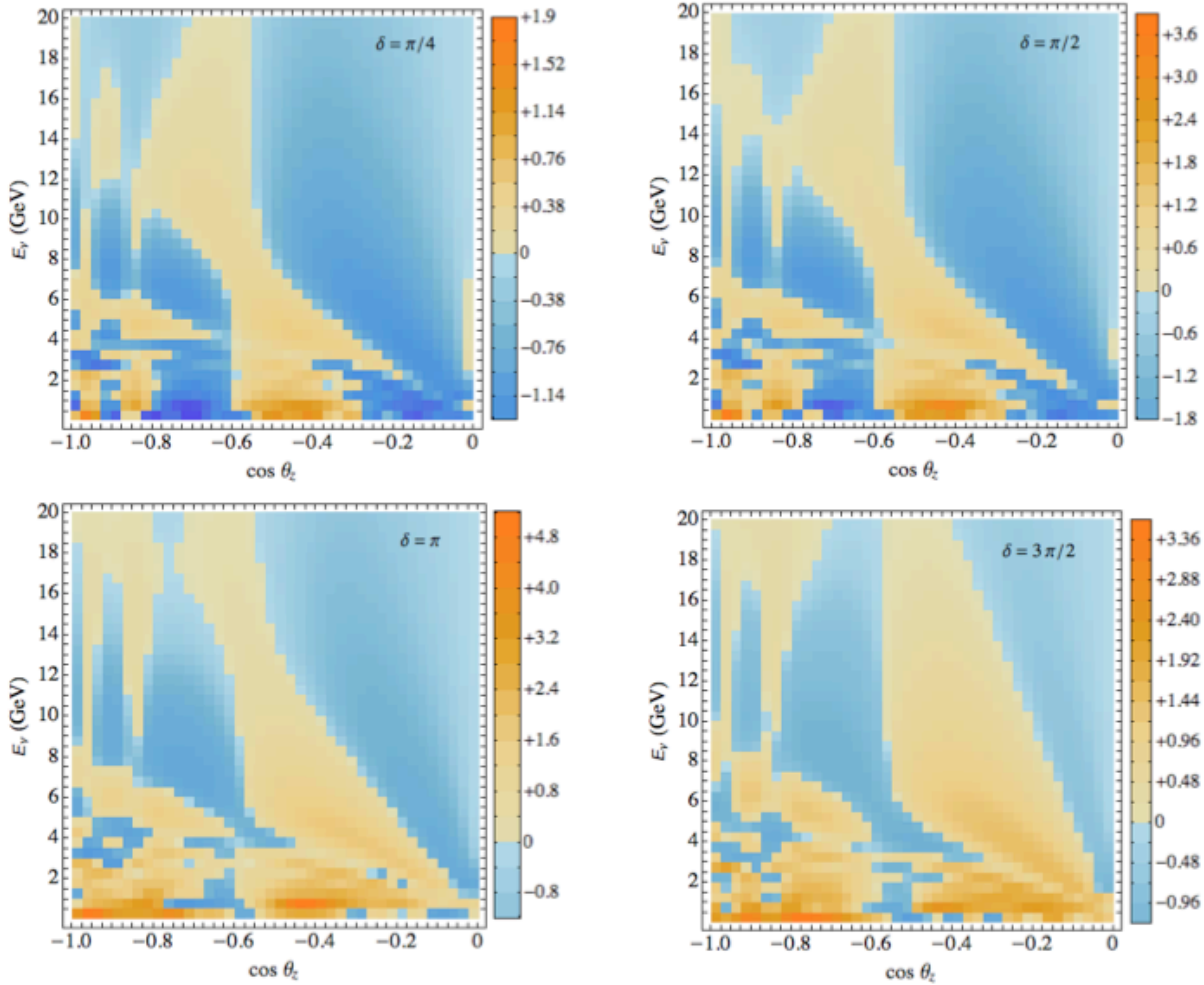
arXiv:1406.1407



1-3GeV region is also sensitive (4th-7th max of Δ_{13})

arXiv:1406.1407

- ν_e appearance (normal hierarchy)
- Super-PINGU
  - 2.2Mton-year
  - 4-year of HK
- $\Delta N/\sqrt{N}$
- Good sensitivity
  - E<1GeV
  - cosθ<-0.6

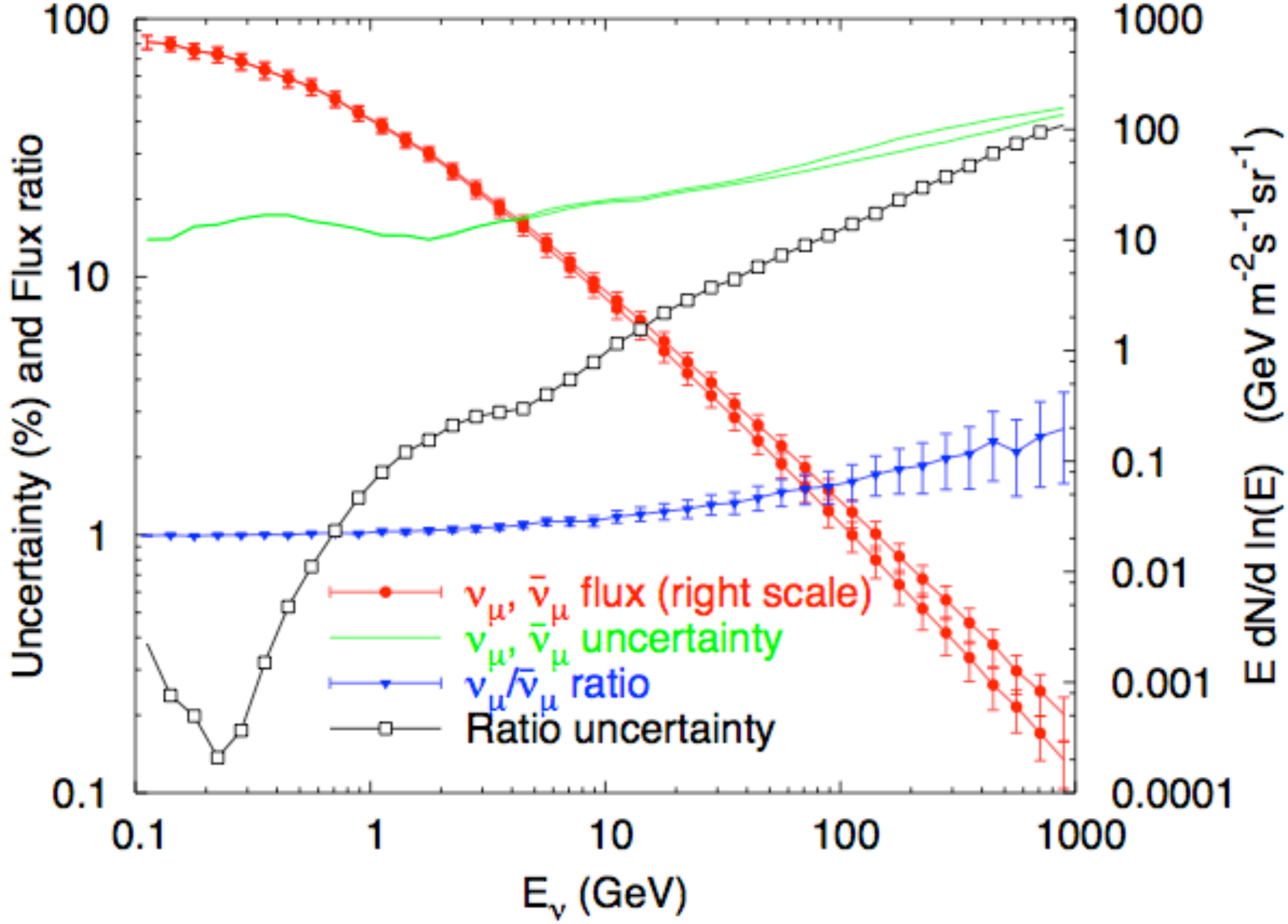


Slow dependence in energy and zenith angle:
modest subGeV angular and energy resolution is OK

Systematics

- Neutrino flux (astro-ph/0611266)
  - Primary cosmic ray flux (AMS, BESS, etc.)
  - Hadron production (HARP, etc.): dominant flux error
    - Follow-up of the HARP experiment is needed!
  - Geomagnetic field effect (east-west effect)
- Ratio mesurements reduce systematics to 2-3%
  - ν_e/ν_μ
  - up/down, up/horizontal
- Neutrino cross section
  - nuPRISM solves this E_ν=400-800MeV range

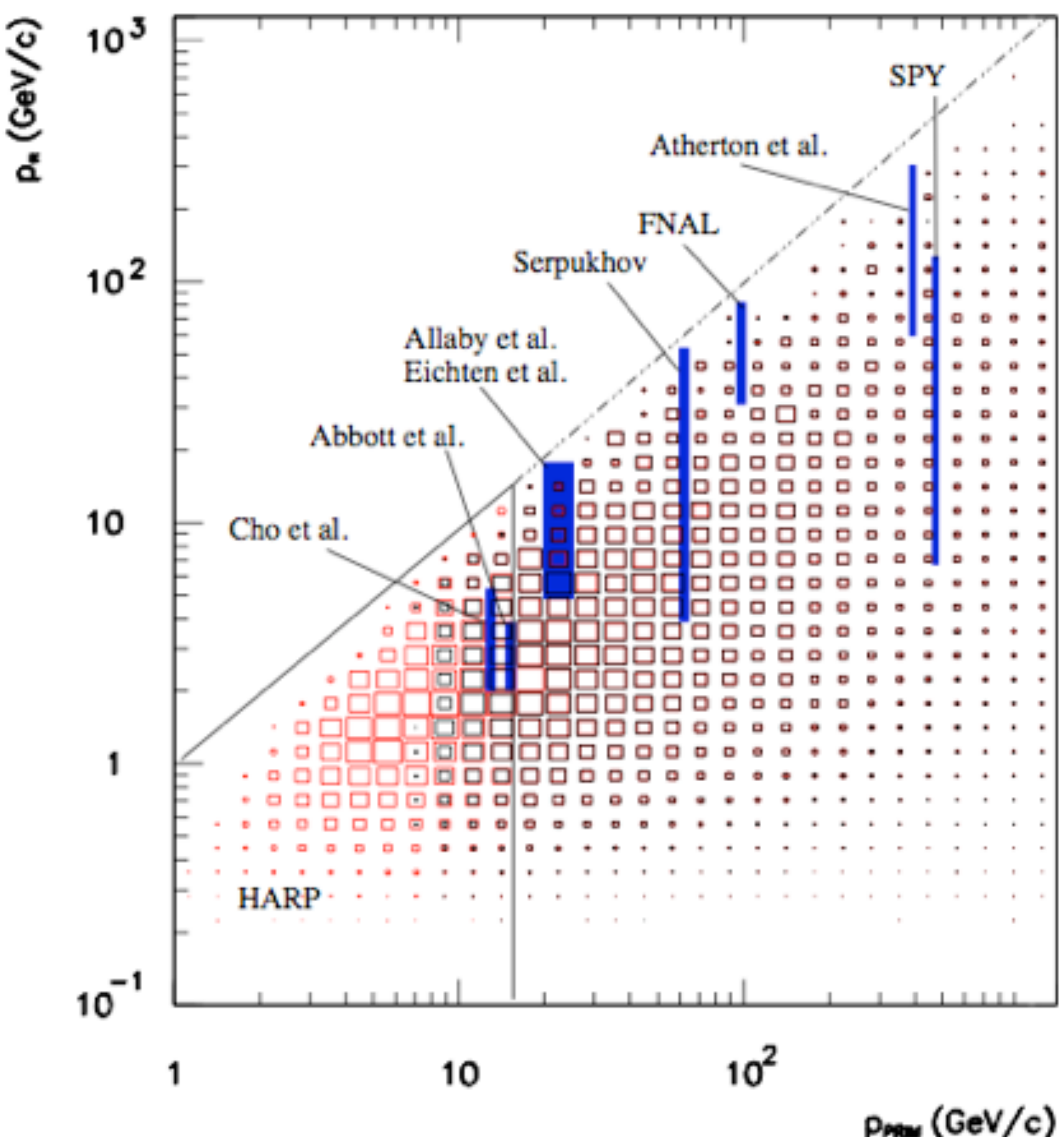
astro-ph/0611266



- Normalization error is ~12%

Sources of flux uncertainties

Hadron production



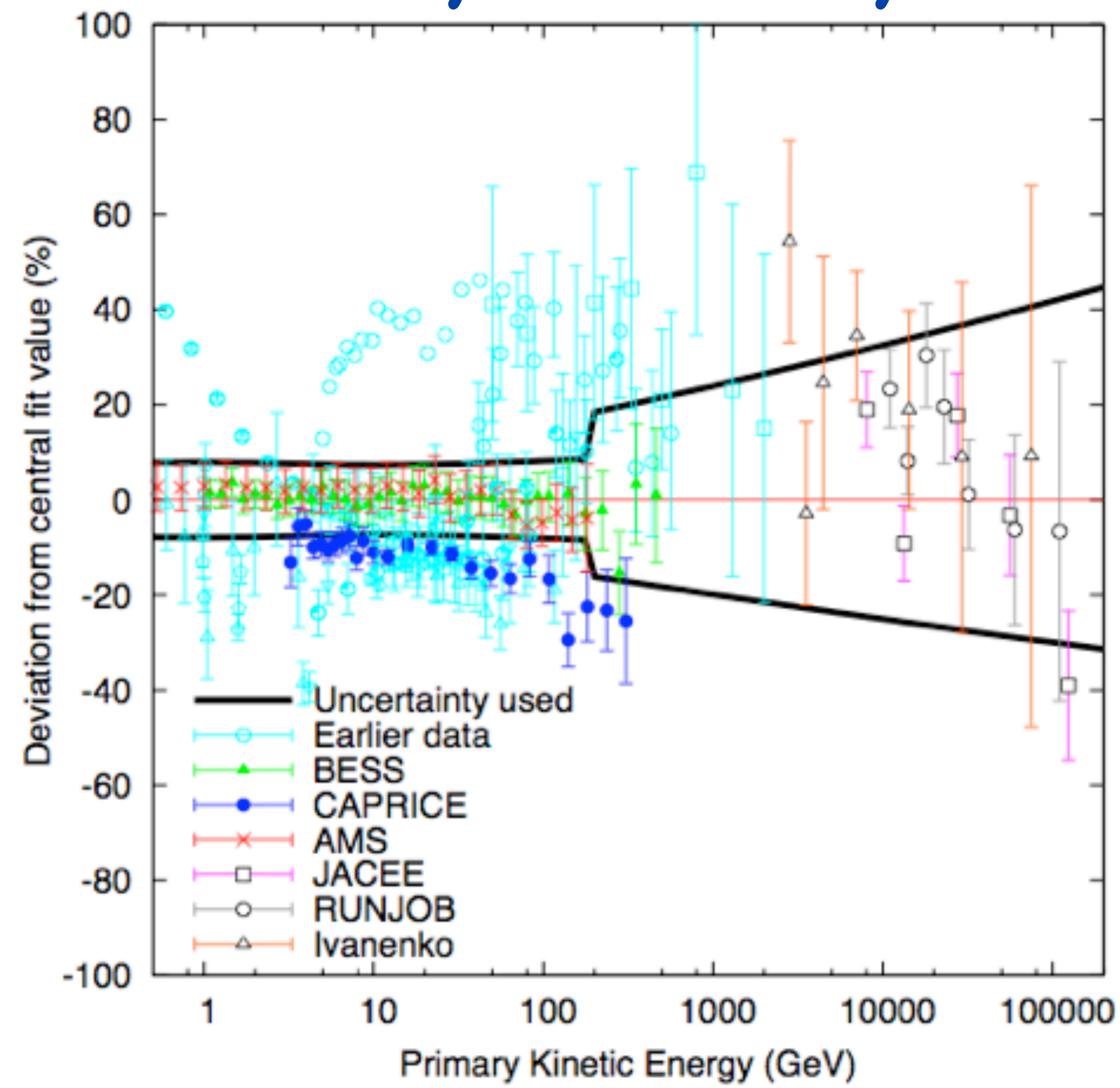
E_i (GeV)	Pions				
<8	10%	30%			
8–15	30%	10%	30%		
15–30	30	10	5%	10%	
30–500	30	15%			
>500	30	15%+Energy dep.			

x_{LAB}: 0, 0.5, 1

E_i (GeV)	Kaons		
<8	40%		
8–15	40%		
15–30	30	20	10%
30–500	40	30%	
>500	40	30%+Energy dep.	

x_{LAB}: 0, 0.5, 1

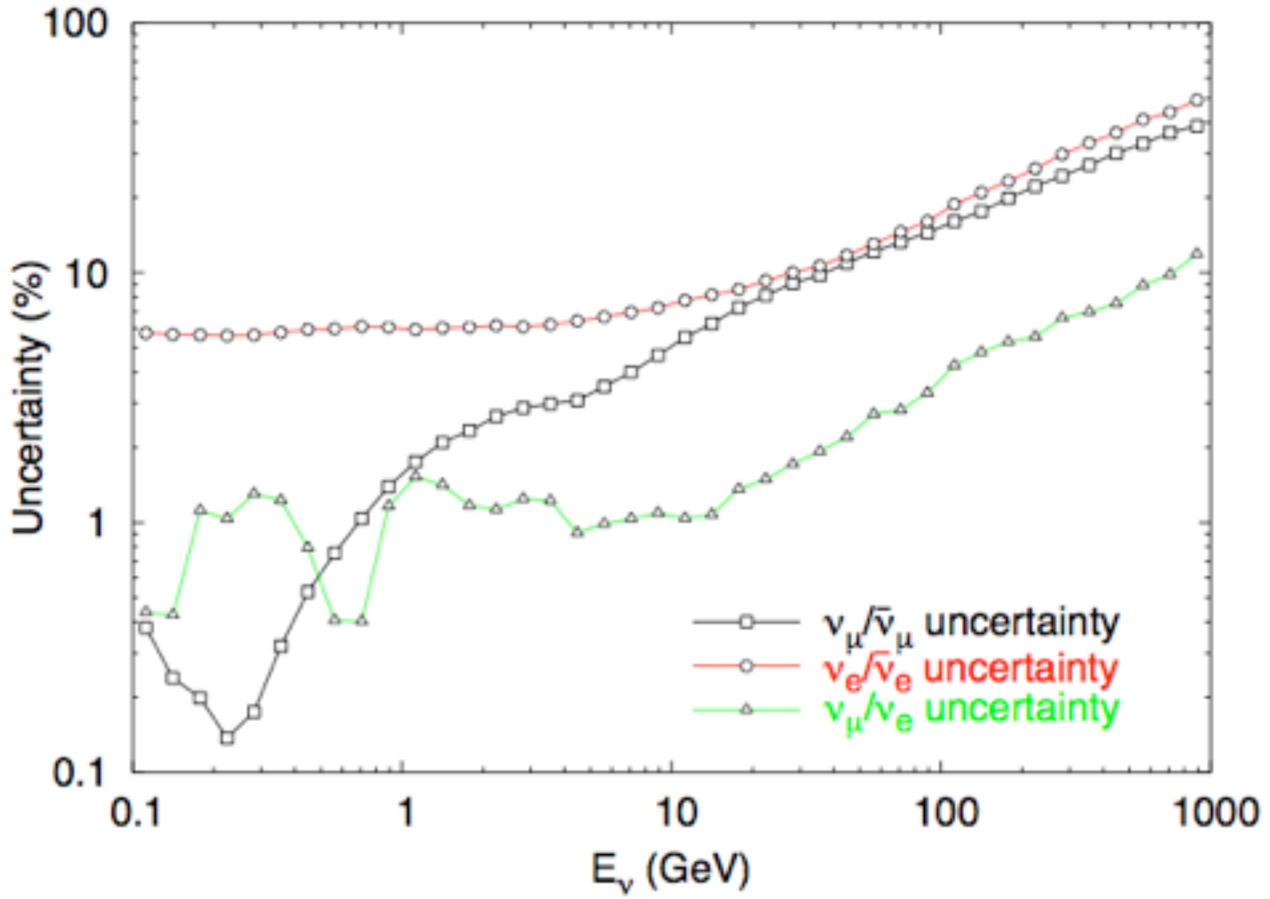
Primary cosmic ray flux

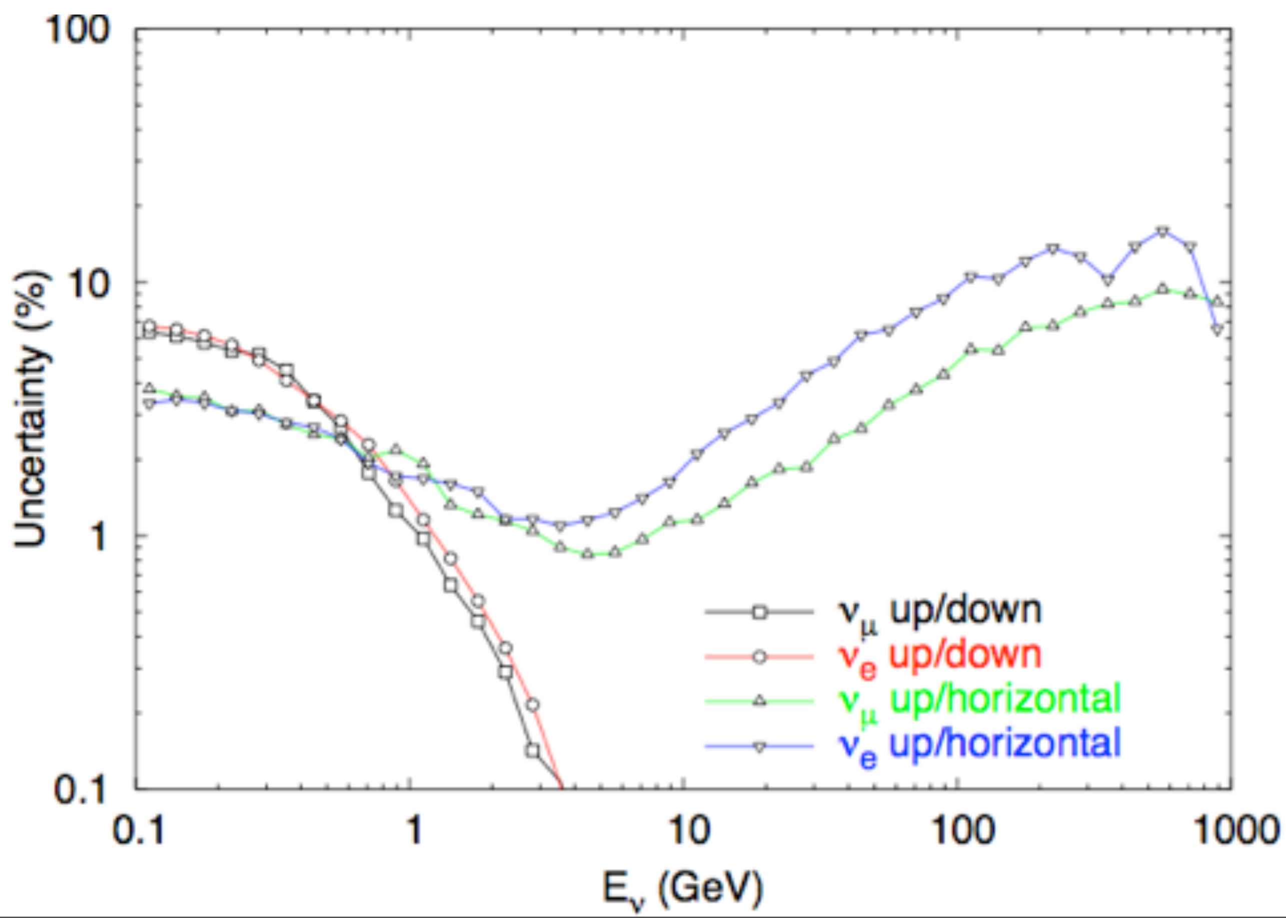


Parameter	Proton fluxes	Nuclear fluxes
a (normalization)	1.49 ± 0.10	0.060 ± 0.004
b	2.15 ± 0.025	1.25 ± 0.03
c	-2.21 ± 0.02	-0.14 ± 0.02
d (index) < 200GeV/n	2.74 ± 0.01	2.64 ± 0.02
> 200GeV/n	2.74 ± 0.03	2.64 ± 0.04

astro-ph/0611266

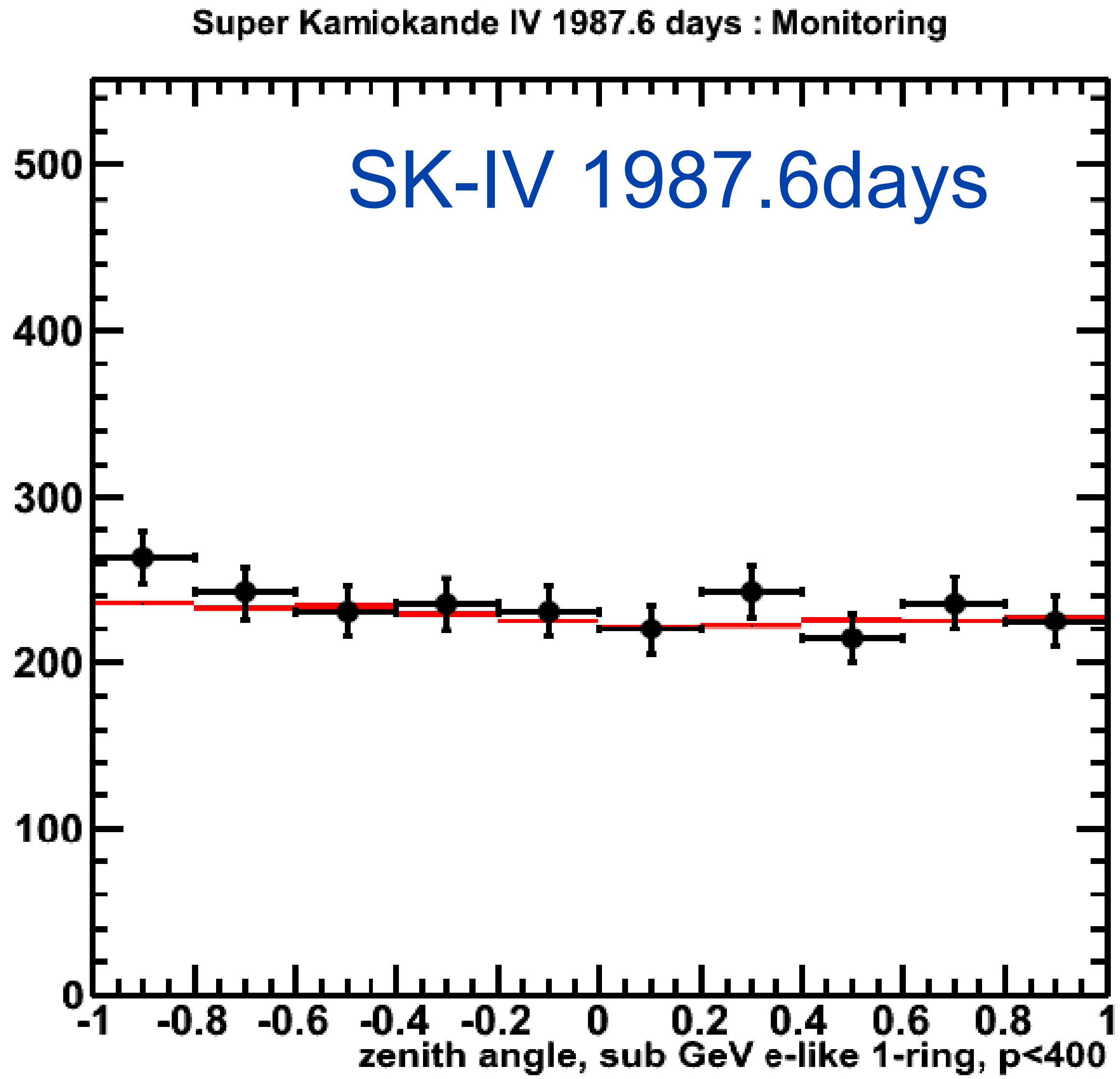
- Systematics cancels for the ratios:
  - ν_e/ν_μ (~1%)
    - charge asymmetry in $\nu_e/\bar{\nu}_e$ need improvement
    - hadron production study like HARP helps
  - up/down (~2-5%) up/horizontal (~2-3%)
    - up/horizontal~2-3%
    - East-west effect to test geomagnetic field

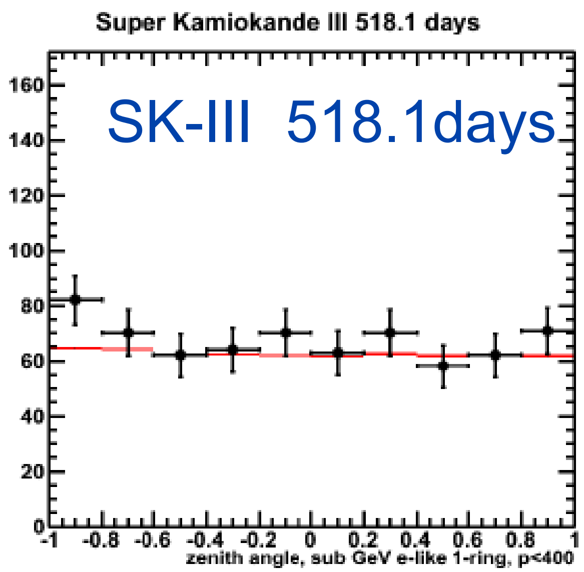


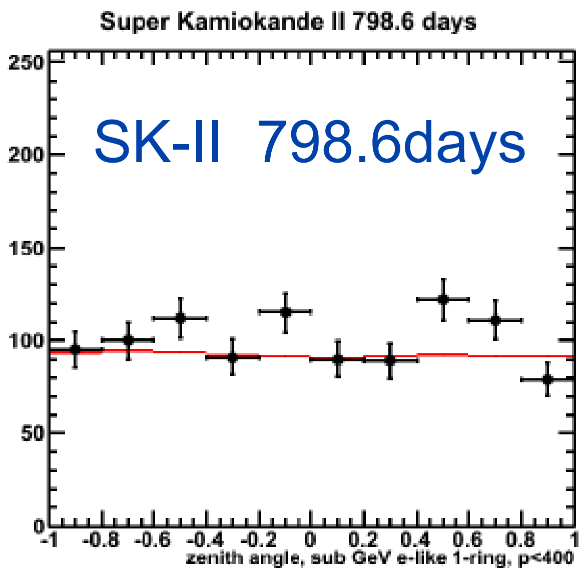


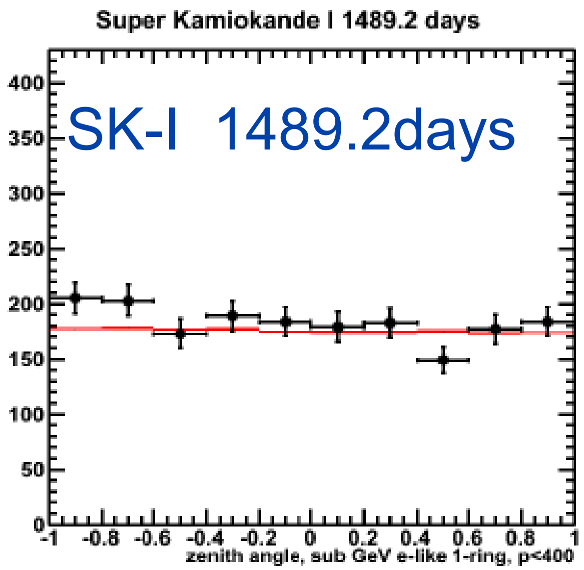
subGeV 1R e-like (p<400MeV/c)

(Expected to be flat without signal)



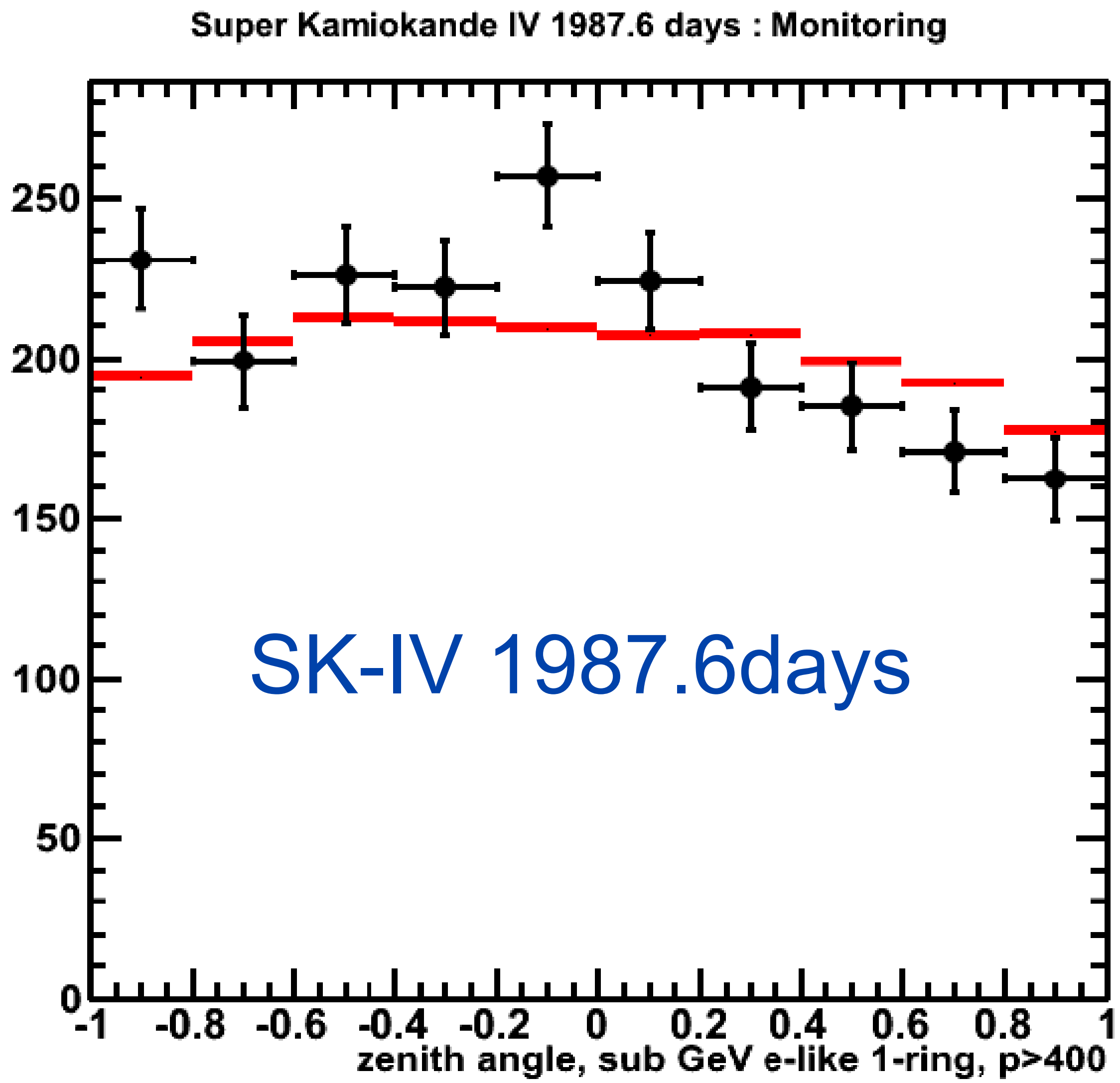


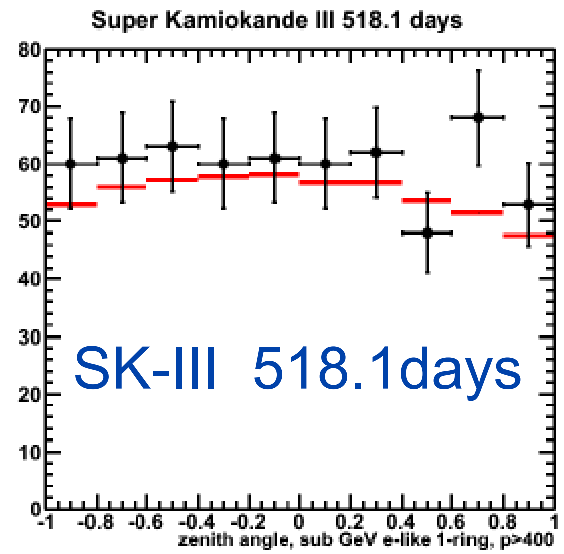


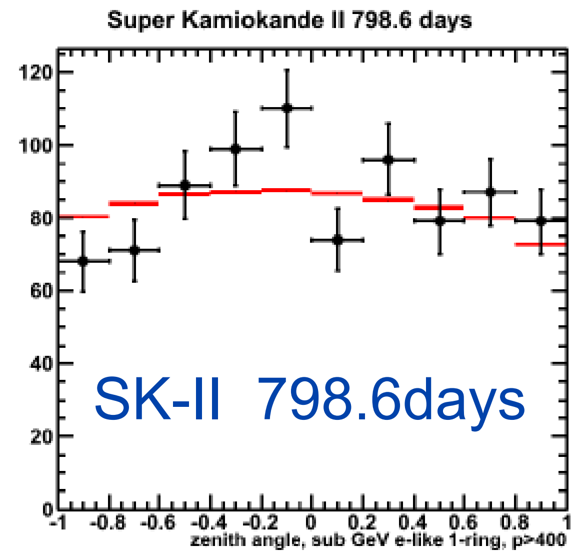


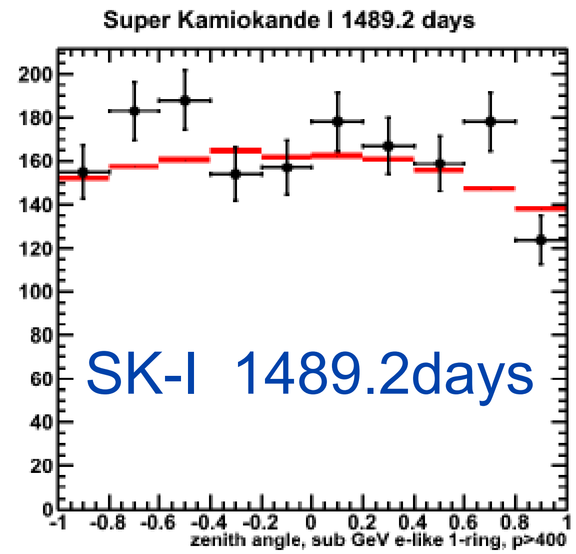
Hint of of enhancement
@ $\cos\theta < -0.4$

subGeV 1R e-like (p>400MeV/c)

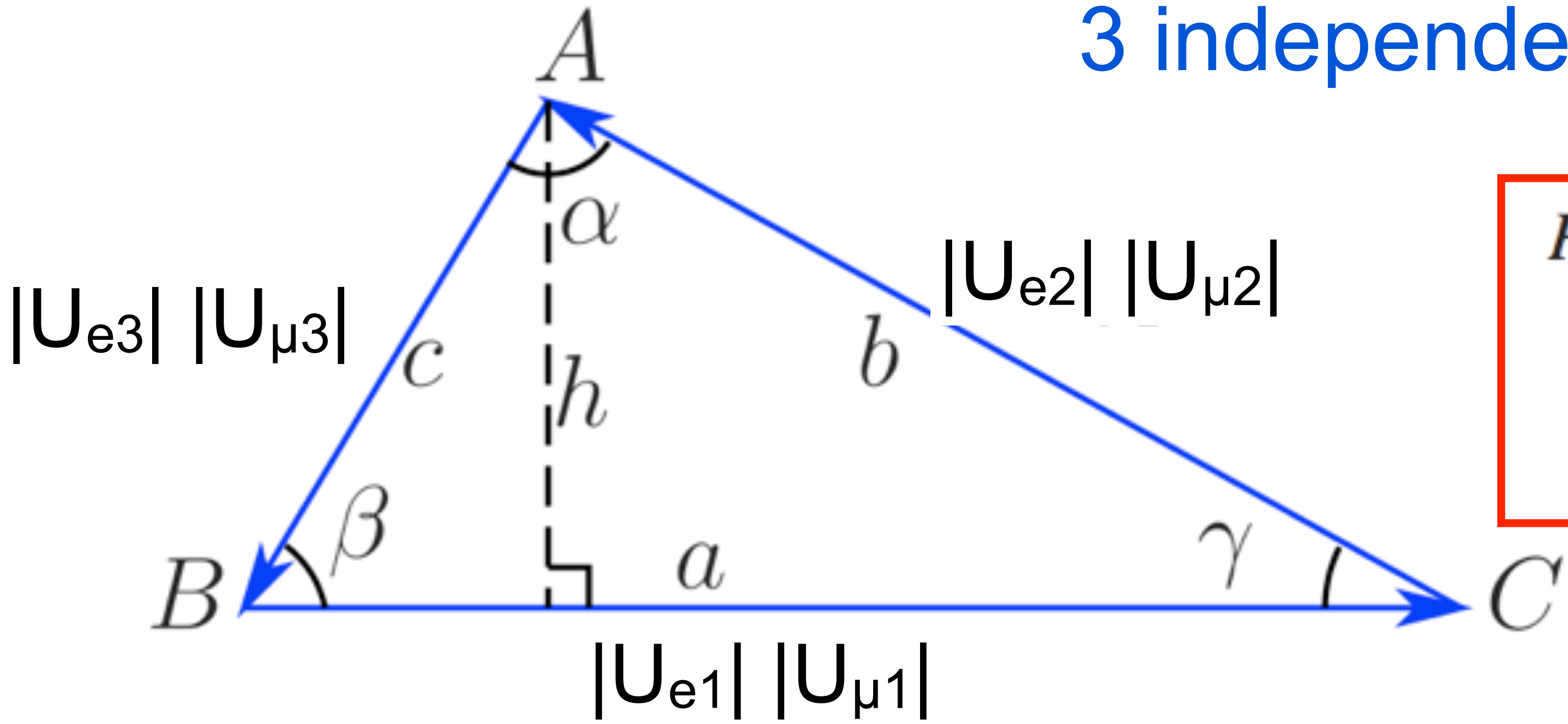








$U_{e1}U^*_{\mu 1}+U_{e2}U^*_{\mu 2}+U_{e3}U^*_{\mu 3} = 0$

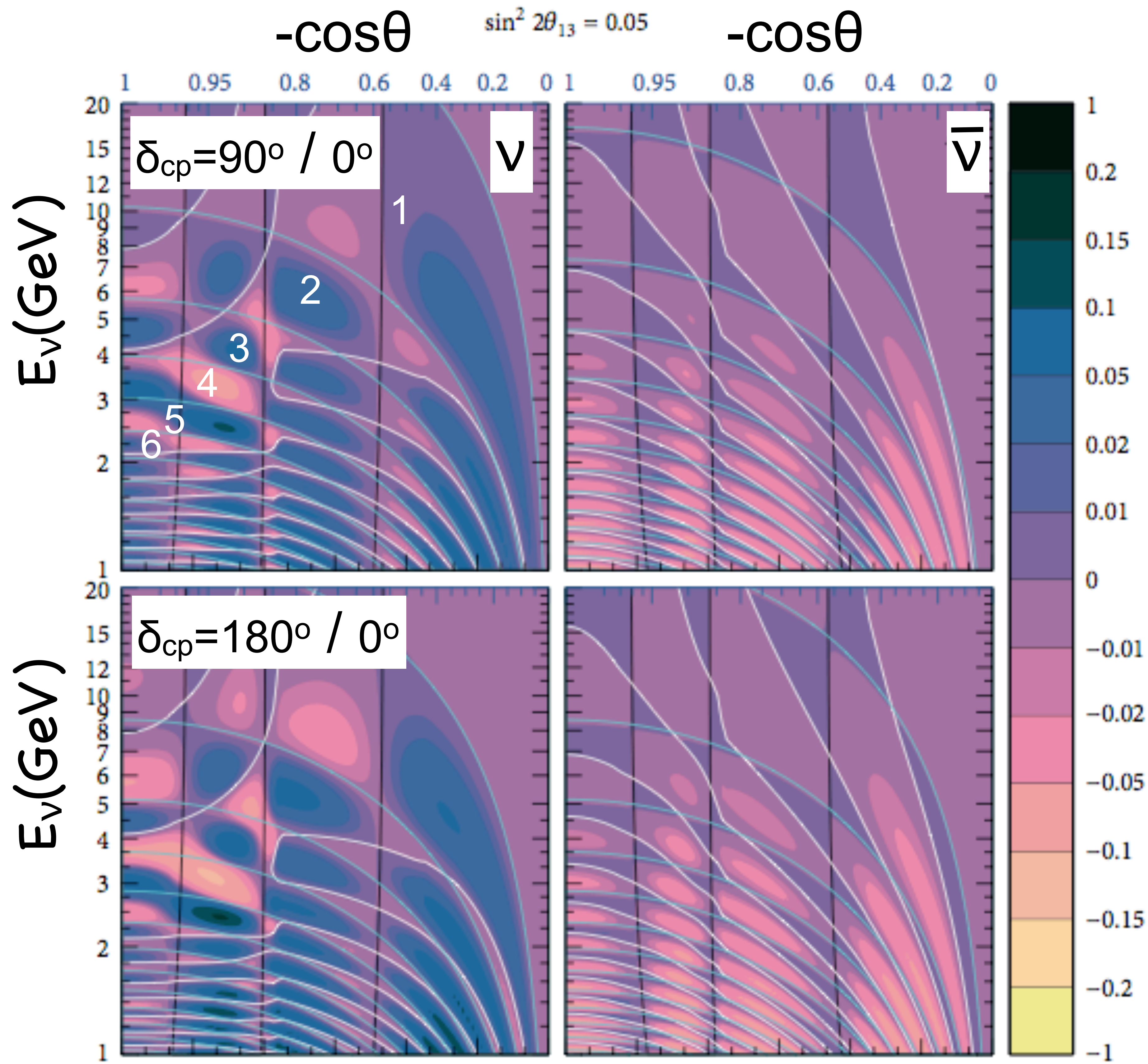


3 independent parameters

$$P_{\ell\to\ell'} = 4ab\sin(\Delta_{12}\pm\gamma)\sin\Delta_{12} + 4bc\sin(\Delta_{23}\pm\alpha)\sin\Delta_{23} + 4ac\sin(\Delta_{31}\pm\beta)\sin\Delta_{31}$$

- a,b,c can be determined by disappearance measurements
  - amplitude of $\nu_\mu\to\nu_e$ appearance also constrains a+b
- α,β from LBL $\nu_\mu\to\nu_e$ appearance, γ from atm. $\nu_\mu\to\nu_e$
  - comparison between ν and anti-ν: phase changes signs
  - T2K/T2HK determines β
  - γ is determined by the 0.5-0.8GeV atm. $\nu_\mu\to\nu_e$
  - 1-3GeV atm. $\nu_\mu\to\nu_e$ helps separating $\beta(\Delta_{31})$ and $\alpha(\Delta_{23})$ terms

ΔP_{CP} oscillogram



CP effect:
E~2-5GeV
cosθ~0.9
(4-6th
Δ_{32} max)

Summary

- Sub-GeV neutrino for CP study may be possible
  - Peak of atmospheric ν event rate
  - Directional information available @ E> 0.4-0.5GeV
  - $r=\Phi(\nu_\mu)/\Phi(\nu_e)=2$ cancels all the oscillation signal except for CP violation.
  - Large CP violation $\nu_\mu \rightarrow \nu_e$ (10-20%) possible at 400-800MeV
  - **If Oscillation pattern is seen, it is likely CP violation!**
  - ν_μ disappearance ($|U_{\mu 1}|$ $|U_{\mu 2}|$) is also possible
- Systematic errors can be handled by
  - taking ratios: up/horizontal, up/down, ν_μ/ν_e
  - hadron production studies (more precise HARP exp.)
  - Sub-GeV neutrino cross section study is essential (nuPRISM)

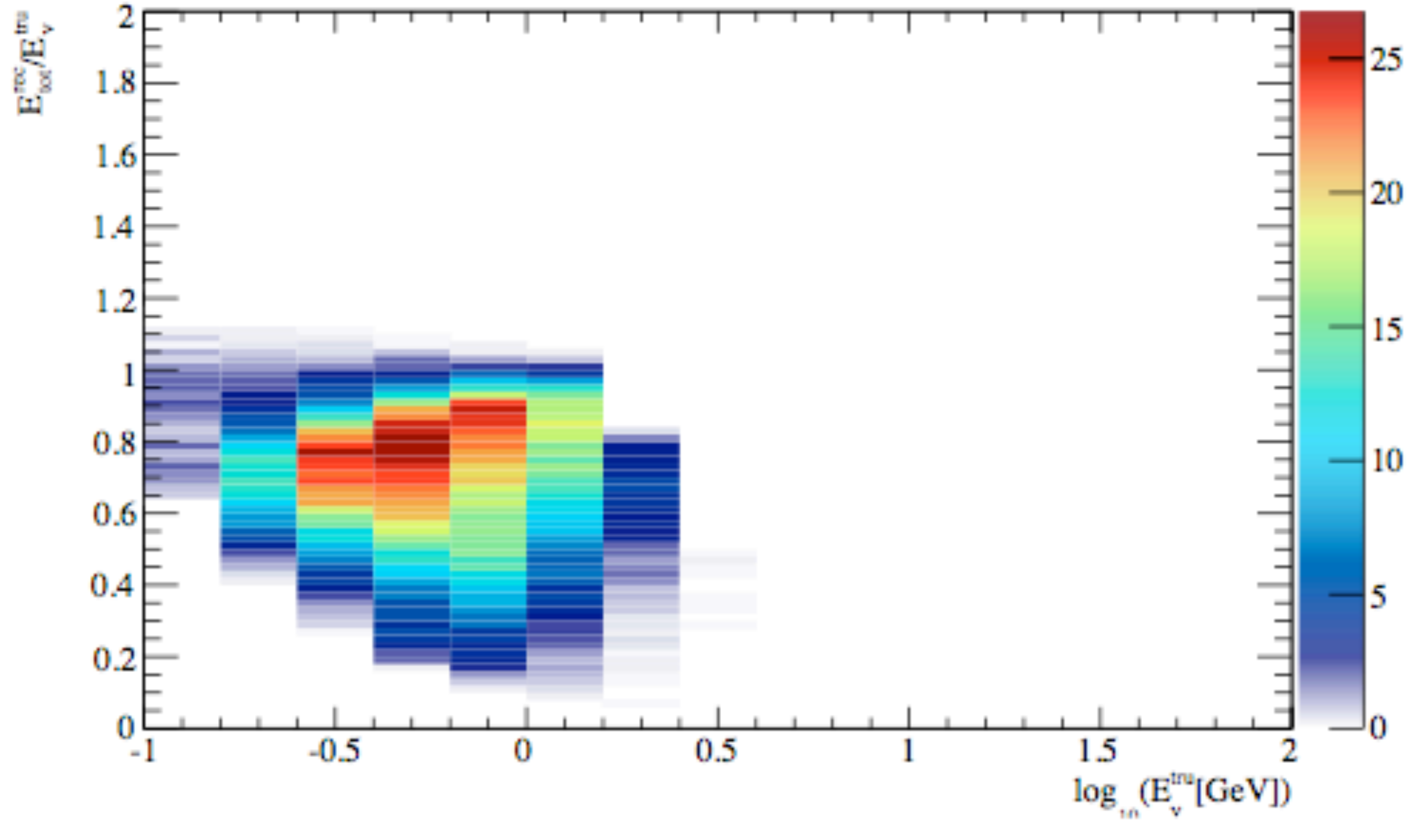
More provocative note

- We could access all the sides and angles of the lepton unitarity triangle: HyperK leads this!
- The current SK data may already be sensitive to these parameters:
  - $\cos\theta_\nu < -0.4$ for sub-GeV ν_e (hint already there?)
  - Further improvements:
    - improved fiTQun reconstruction
    - zoom in to sensitive energy region: E_e=0.3-0.7GeV
    - anti-neutrino study: opposite CP, good angular resolution
    - update oscillation simulation Prob3++
- νPRISM sub-GeV cross section study and precise hadron production study like HARP would be essential for this precision measurement.

Energy and angular resolution

Sub-GeV e 0dcy

Energy



Direction