Over-constrain the PMNS Unitarity with HyperK

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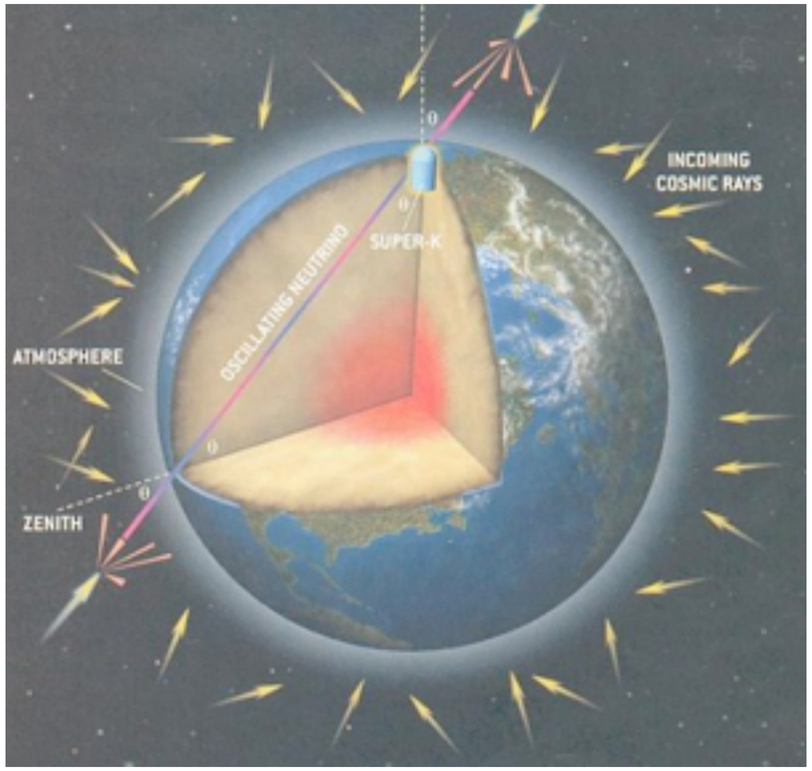
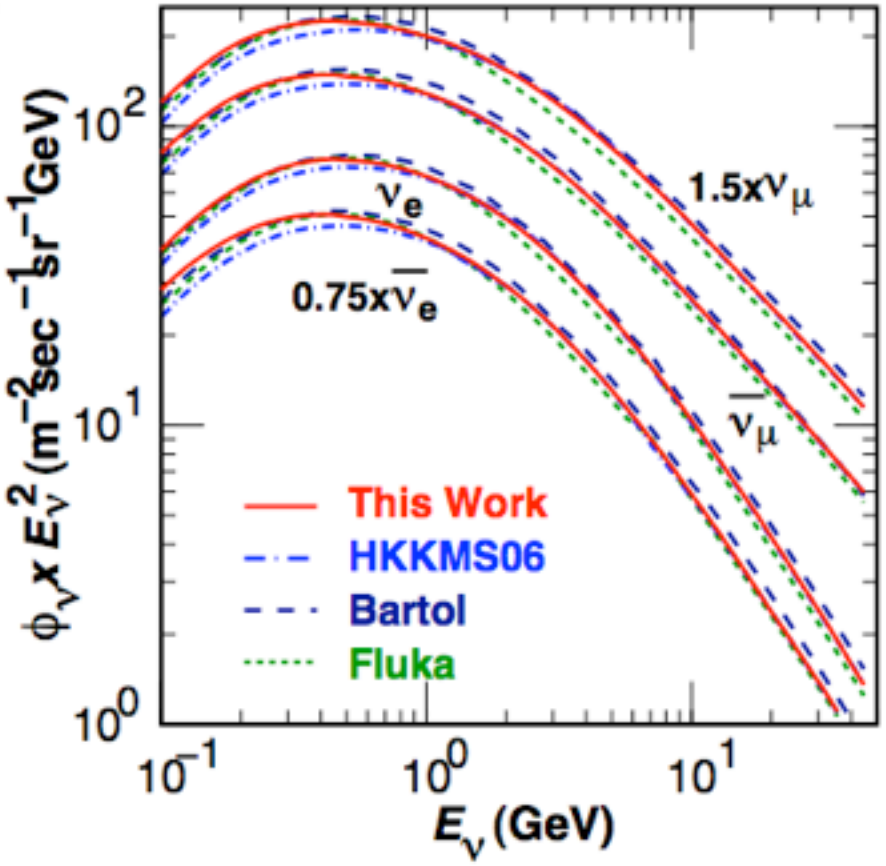
@HK-EU meeting, April 2015

Atmospheric neutrinos

- Atmospheric ν covers very wide range of oscillation parameter space:
  - Baseline length up to 13000km tagged by cos$\theta_{zenieth}$
  - Different types of neutrinos: ν_μ, ν_e and their anti-particles
  - Energy from subGeV to 10GeV up
- Significant statistics:
  - SK 250kton-years:
    SubGeV: 10k 1Re evts, 10k 1Rμ evts
    Multi-GeV: 2.5k 1Re evts, 2.5k 1Rμ evts
- Challenge: Systematics uncertainty
  - flux and cross section



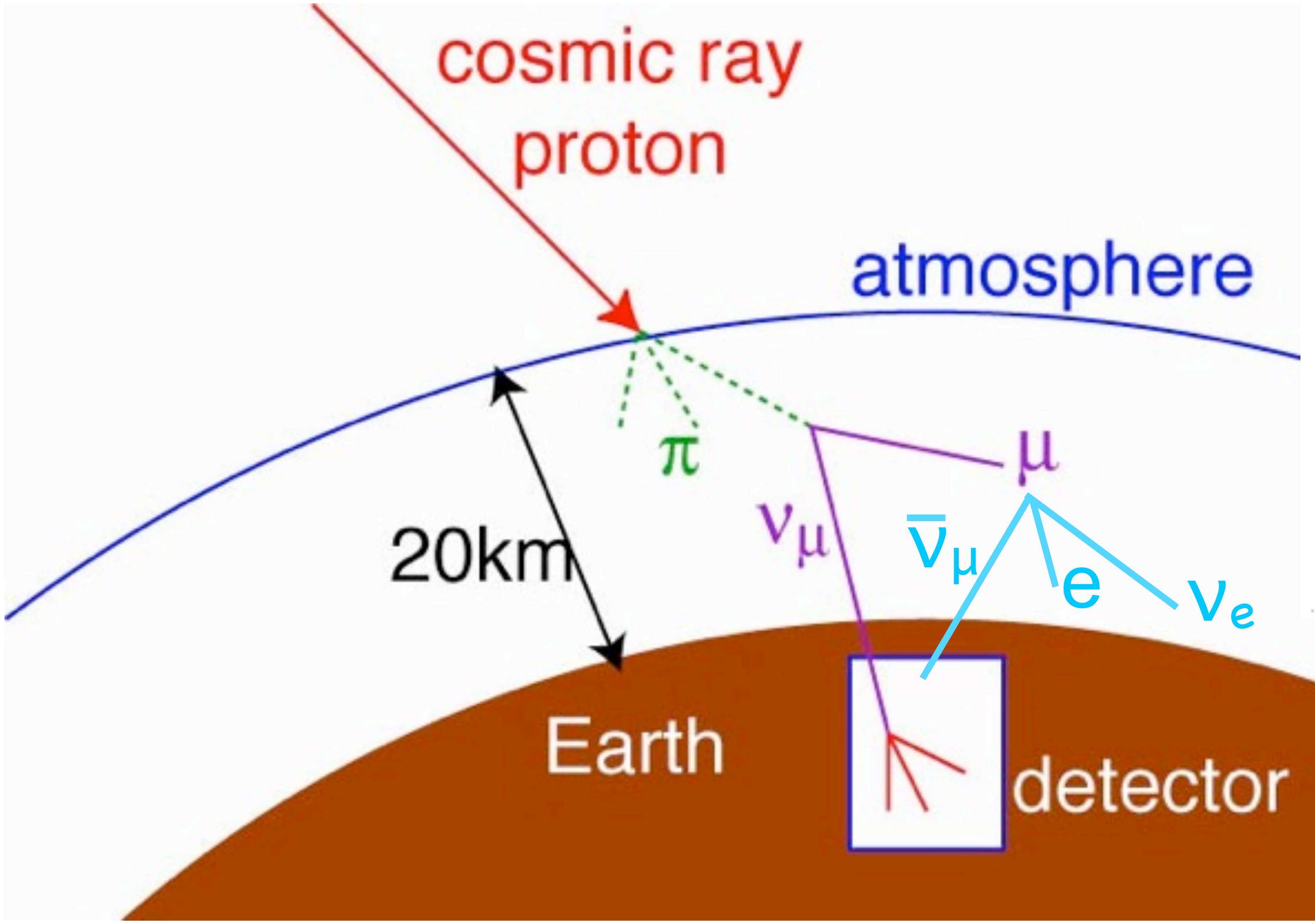


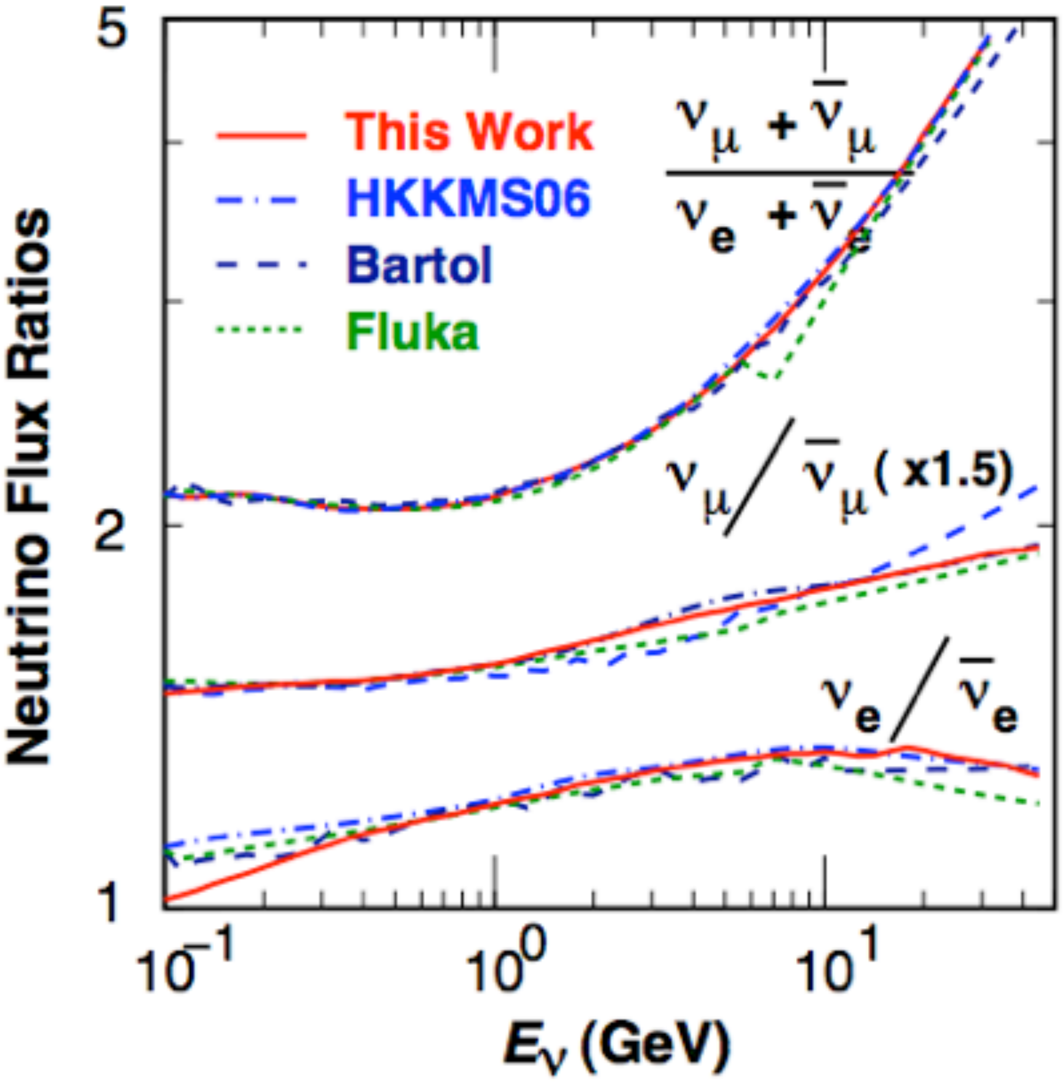
Atmospheric neutrinos

$r=\Phi(\nu_\mu)/\Phi(\nu_e) \sim 2$

for $E_\nu < 3$GeV

Produced by cosmic ray proton interacting in earth atmosphere:

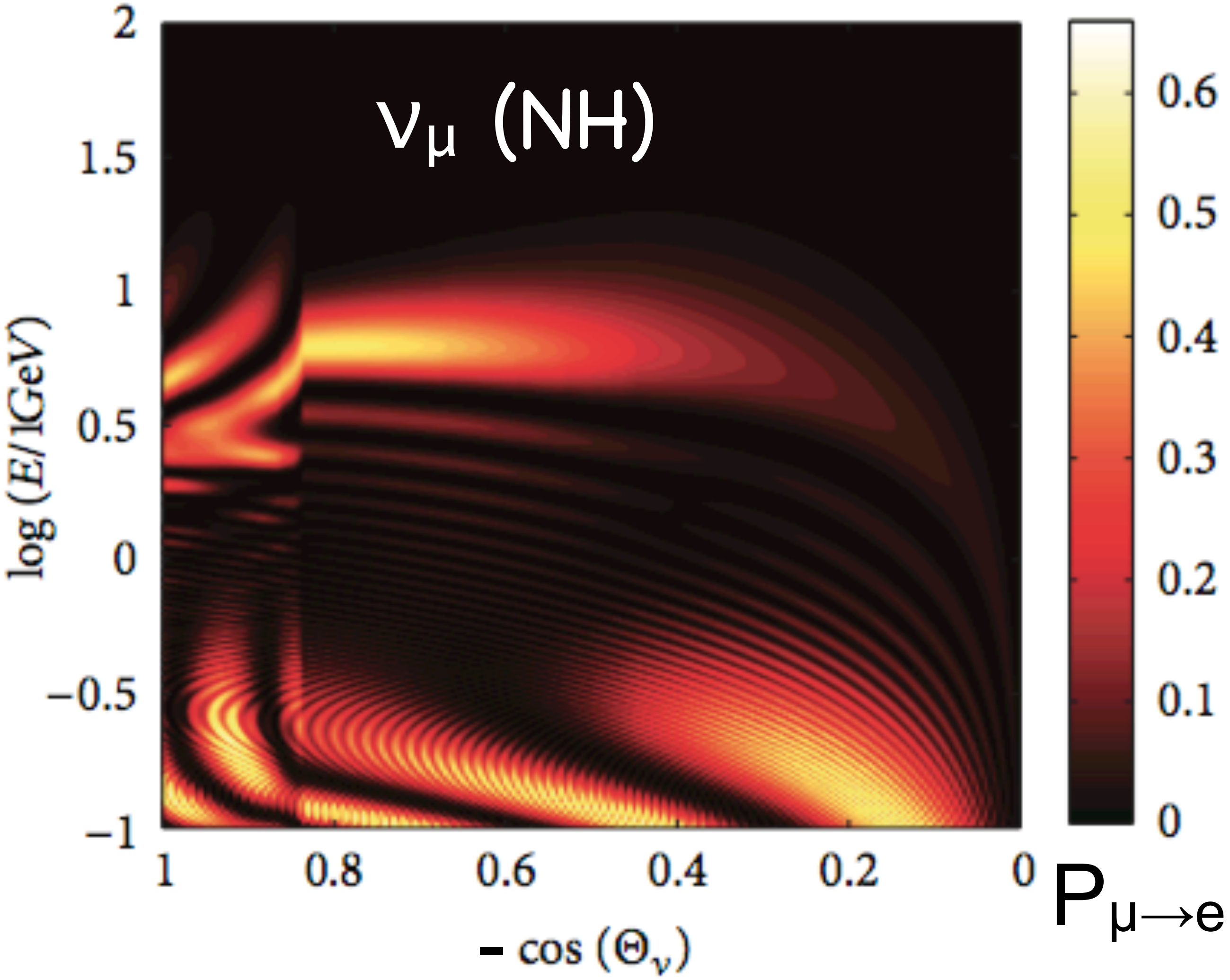


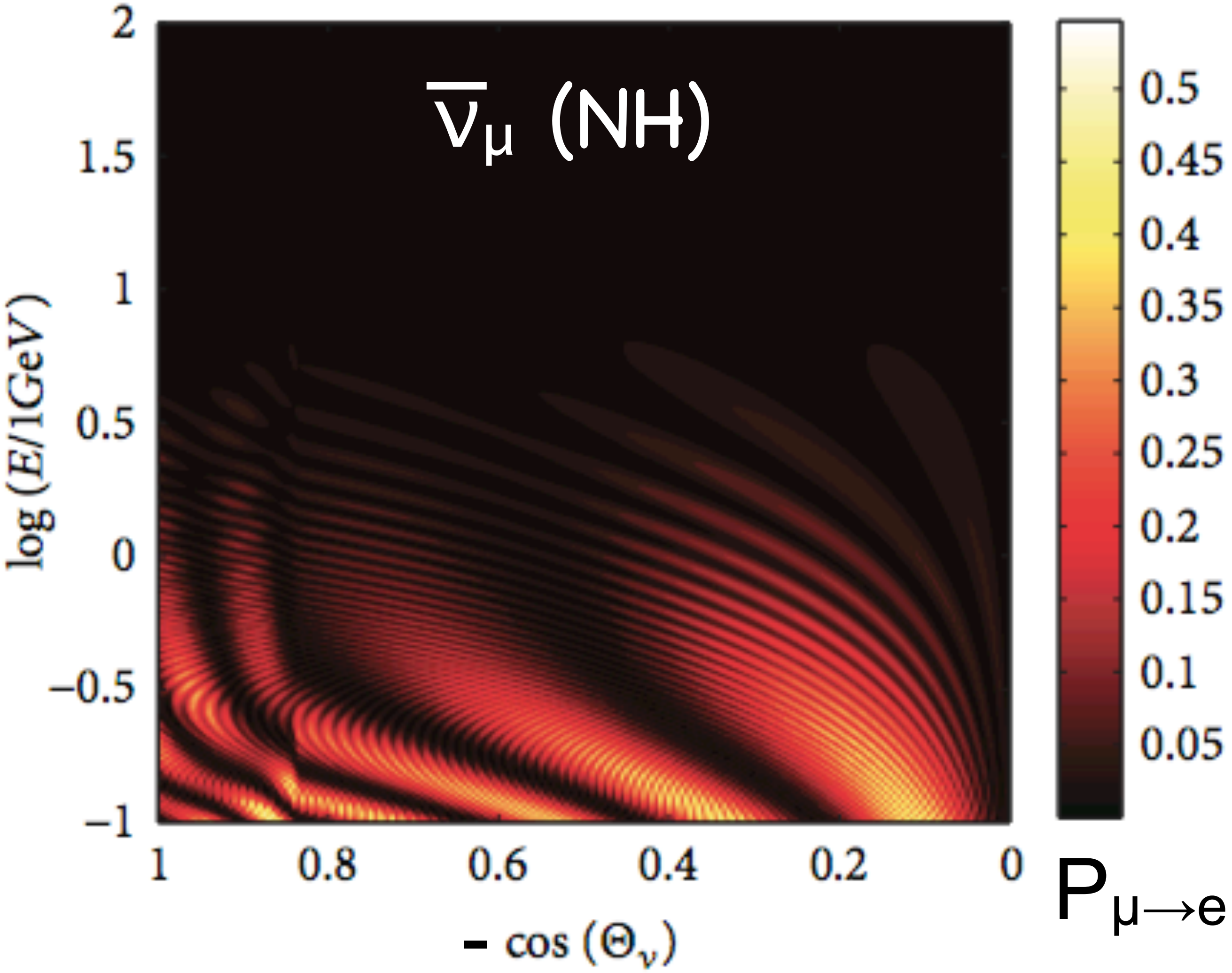


arXiv:1102.2688

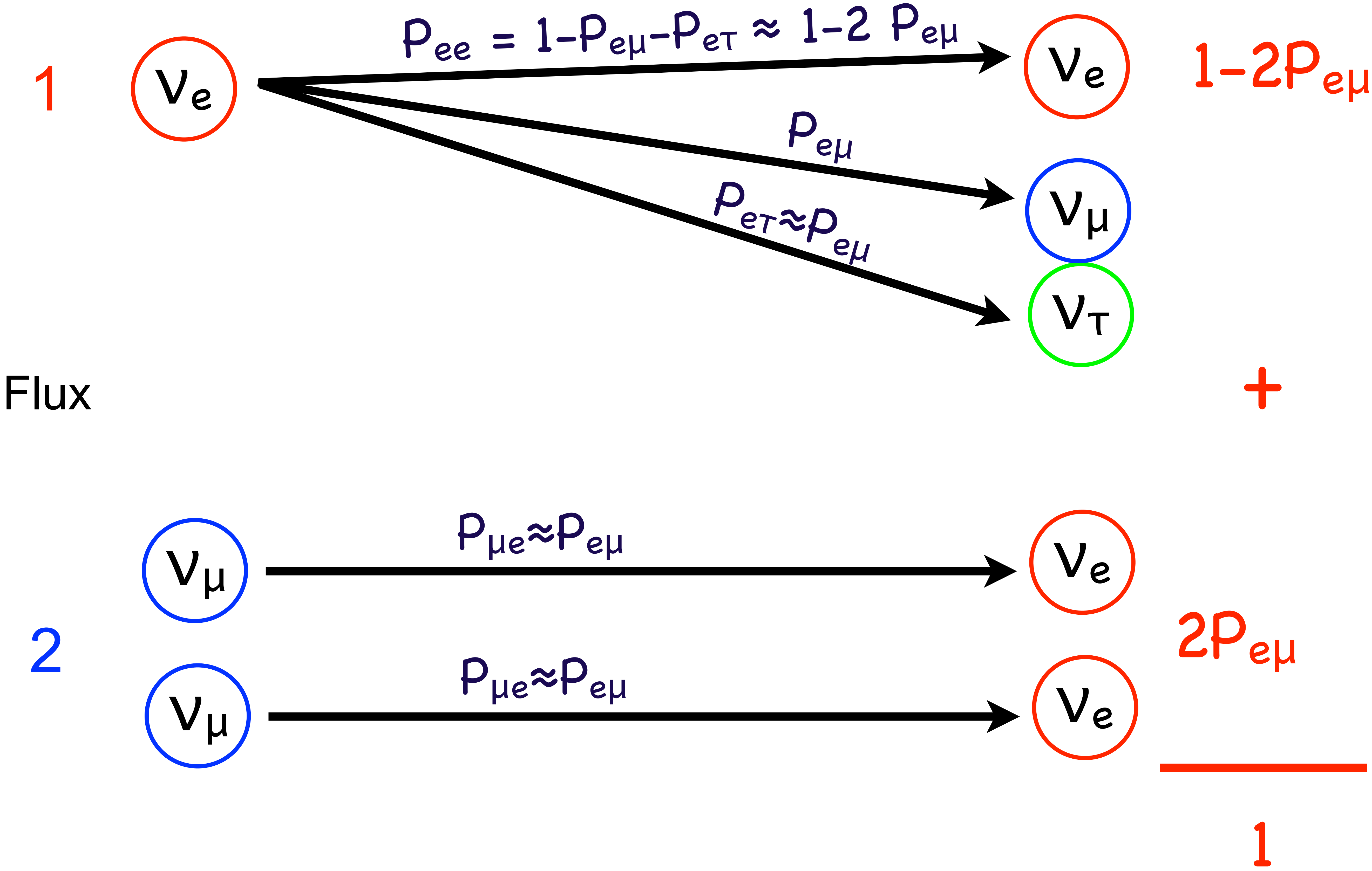
Atmospheric $\nu_\mu \rightarrow \nu_e$

- $\nu_\mu \rightarrow \nu_e$ at several GeV: matter oscillation resonance
  - Resonance in ν_μ for Normal hierarchy: hierarchy determination
- Δ_{12} oscillation in the sub-GeV region: large θ_{12} effect
  - Crossing the earth core at $\cos\theta_\nu \approx -0.85$
  - phase difference between ν and $\overline{\nu}$ due to matter effect





Cancellation of atm. ν_e appearance



1

ν_e

$P_{ee} = 1-P_{e\mu}-P_{e\tau} \approx 1-2\,P_{e\mu}$

ν_e

$1-2P_{e\mu}$

$P_{e\mu}$

ν_μ

$P_{e\tau}\approx P_{e\mu}$

ν_τ

Flux

+

2

ν_μ

$P_{\mu e}\approx P_{e\mu}$

ν_e

ν_μ

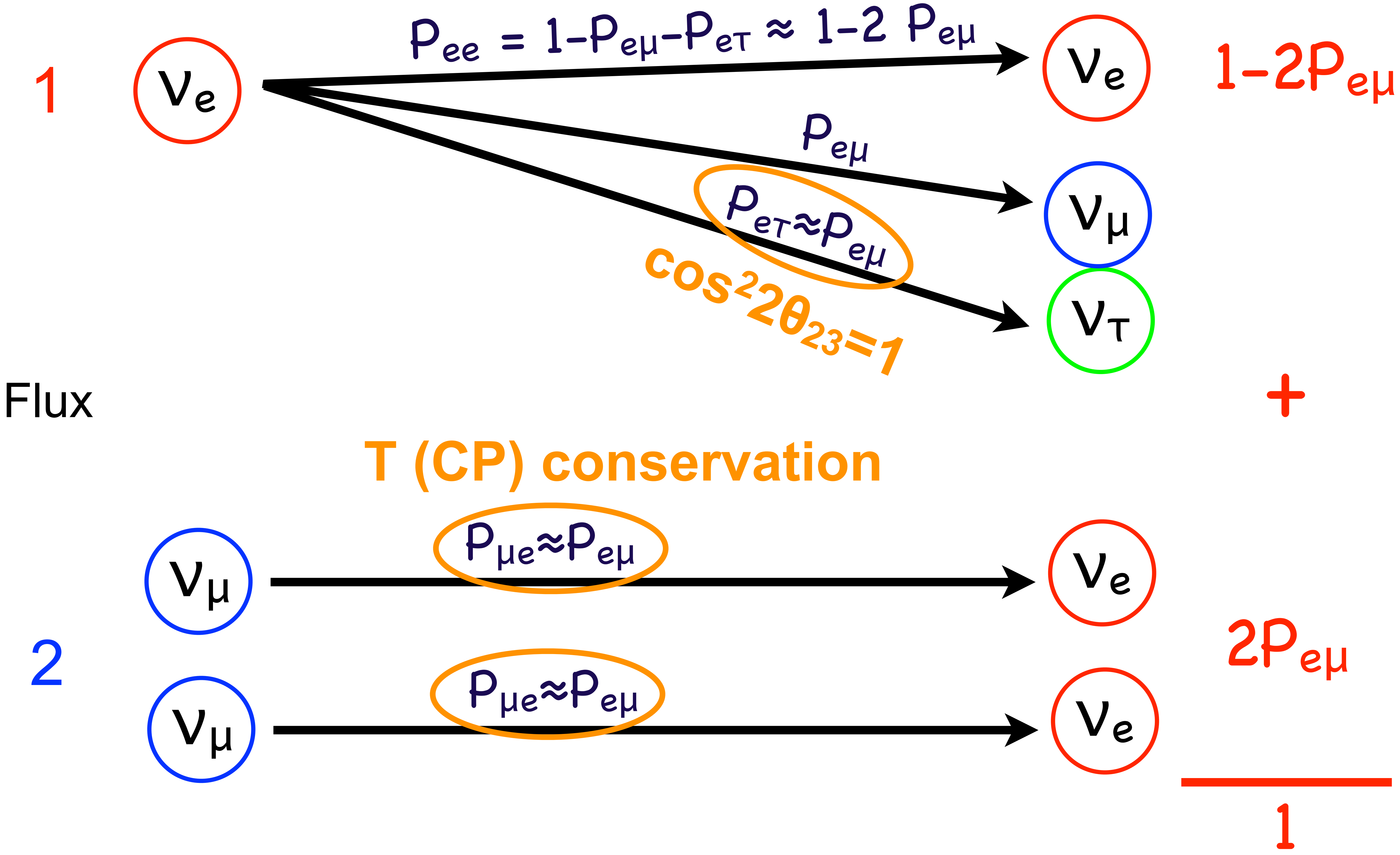
$P_{\mu e}\approx P_{e\mu}$

ν_e

$2P_{e\mu}$

1

atm. ν_e app. sensitive to T(CP) viol.



1

ν_e

$P_{ee} = 1 - P_{e\mu} - P_{e\tau} \approx 1 - 2\,P_{e\mu}$

$P_{e\mu}$

$P_{e\tau} \approx P_{e\mu}$

$\cos^2 2\theta_{23} = 1$

ν_e ν_μ ν_τ

$1 - 2P_{e\mu}$

Flux

+

T (CP) conservation

2

ν_μ ν_μ

$P_{\mu e} \approx P_{e\mu}$

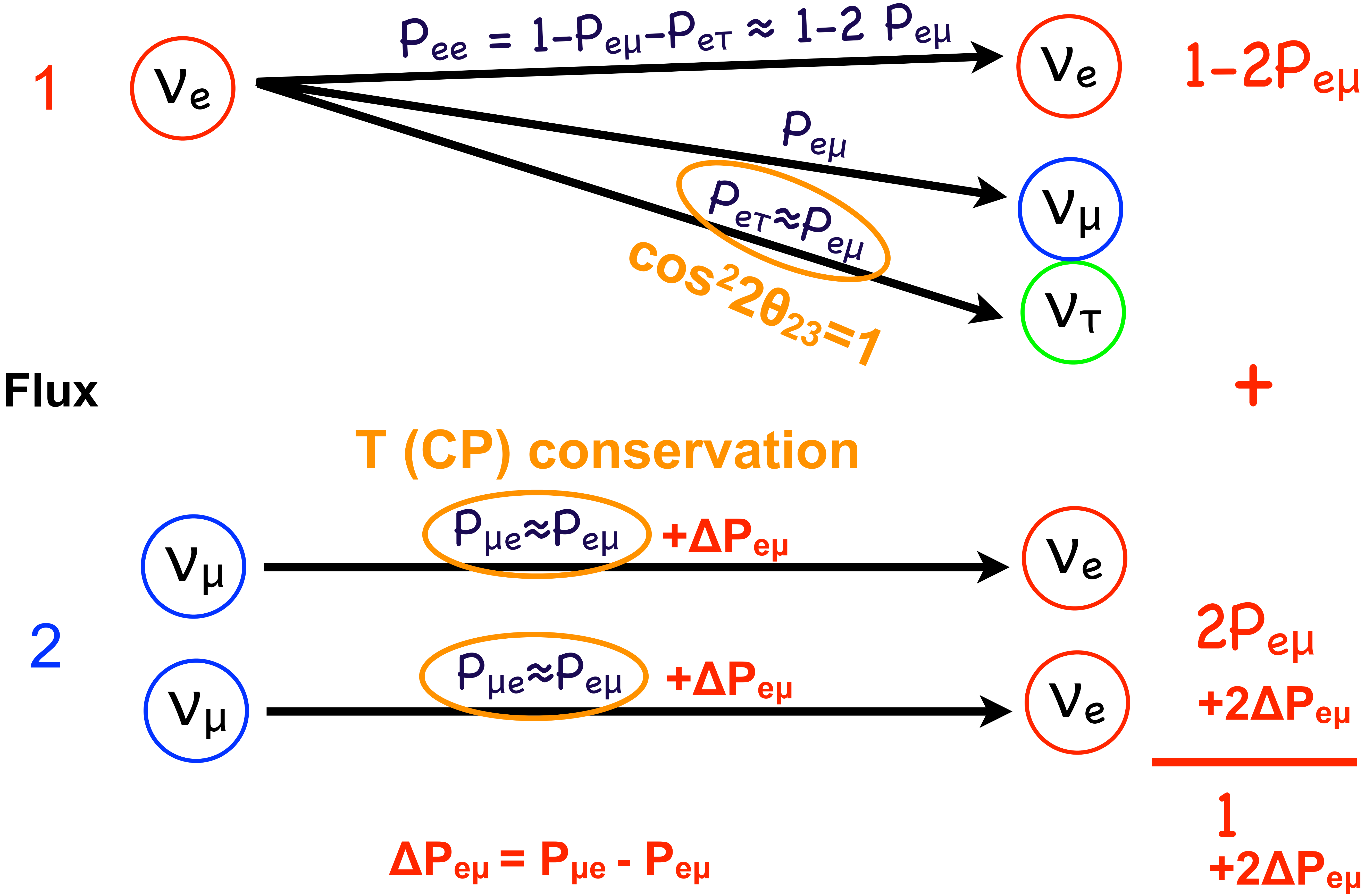
$P_{\mu e} \approx P_{e\mu}$

ν_e ν_e

$2P_{e\mu}$

1

atm. ν_e app. sensitive to T(CP) viol.



1

ν_e

$P_{ee} = 1 - P_{e\mu} - P_{e\tau} \approx 1-2\,P_{e\mu}$

ν_e

$1-2P_{e\mu}$

$P_{e\mu}$

ν_μ

$P_{e\tau} \approx P_{e\mu}$

$\cos^2 2\theta_{23} = 1$

ν_τ

Flux

+

T (CP) conservation

ν_μ $P_{\mu e} \approx P_{e\mu}$ **$+\Delta P_{e\mu}$** ν_e

2

ν_μ $P_{\mu e} \approx P_{e\mu}$ **$+\Delta P_{e\mu}$** ν_e

$2P_{e\mu}$

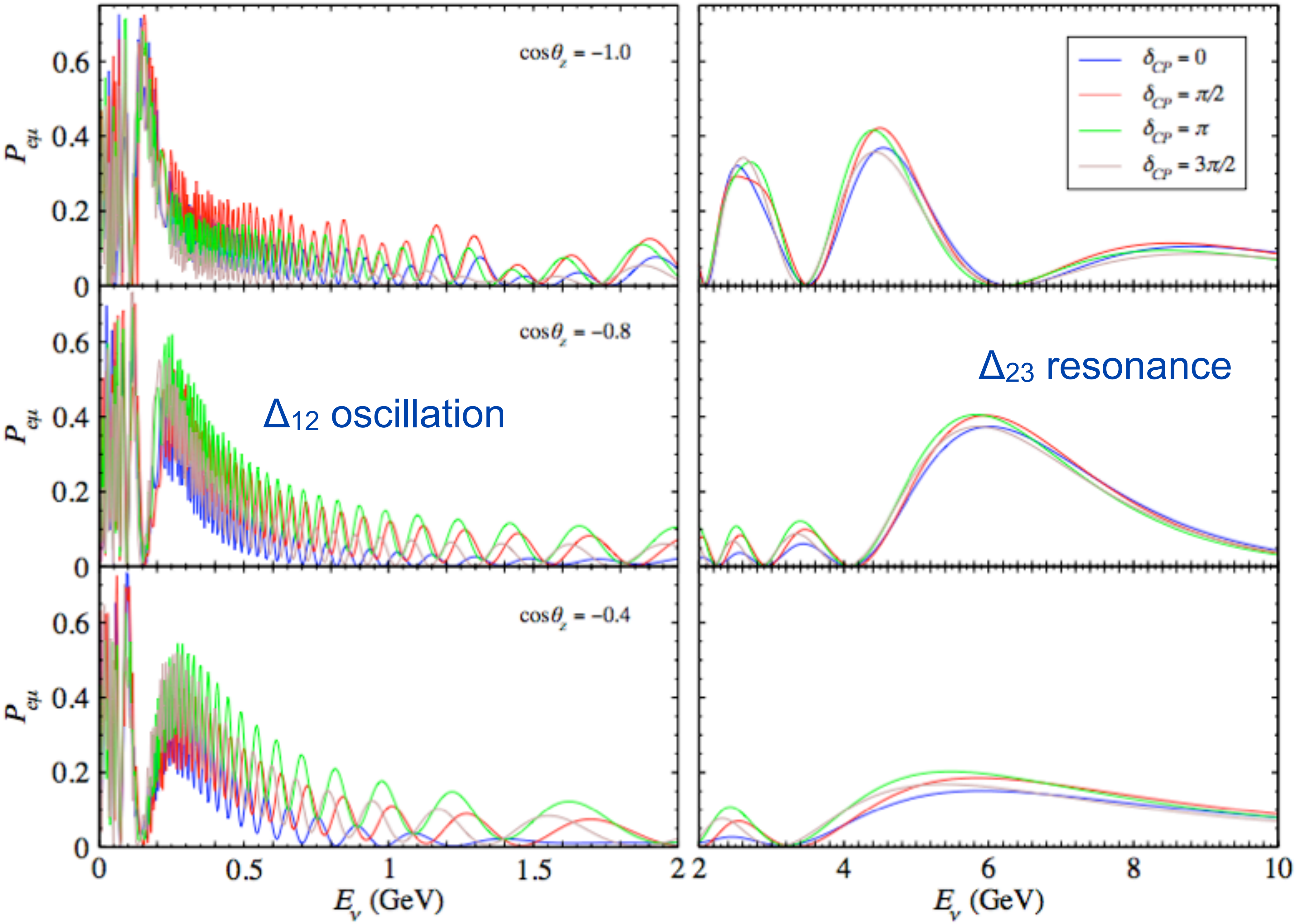
$+2\Delta P_{e\mu}$

1

$+2\Delta P_{e\mu}$

$\Delta P_{e\mu} = P_{\mu e} - P_{e\mu}$

arXiv:1406.1407 (Smirnov et.al.)



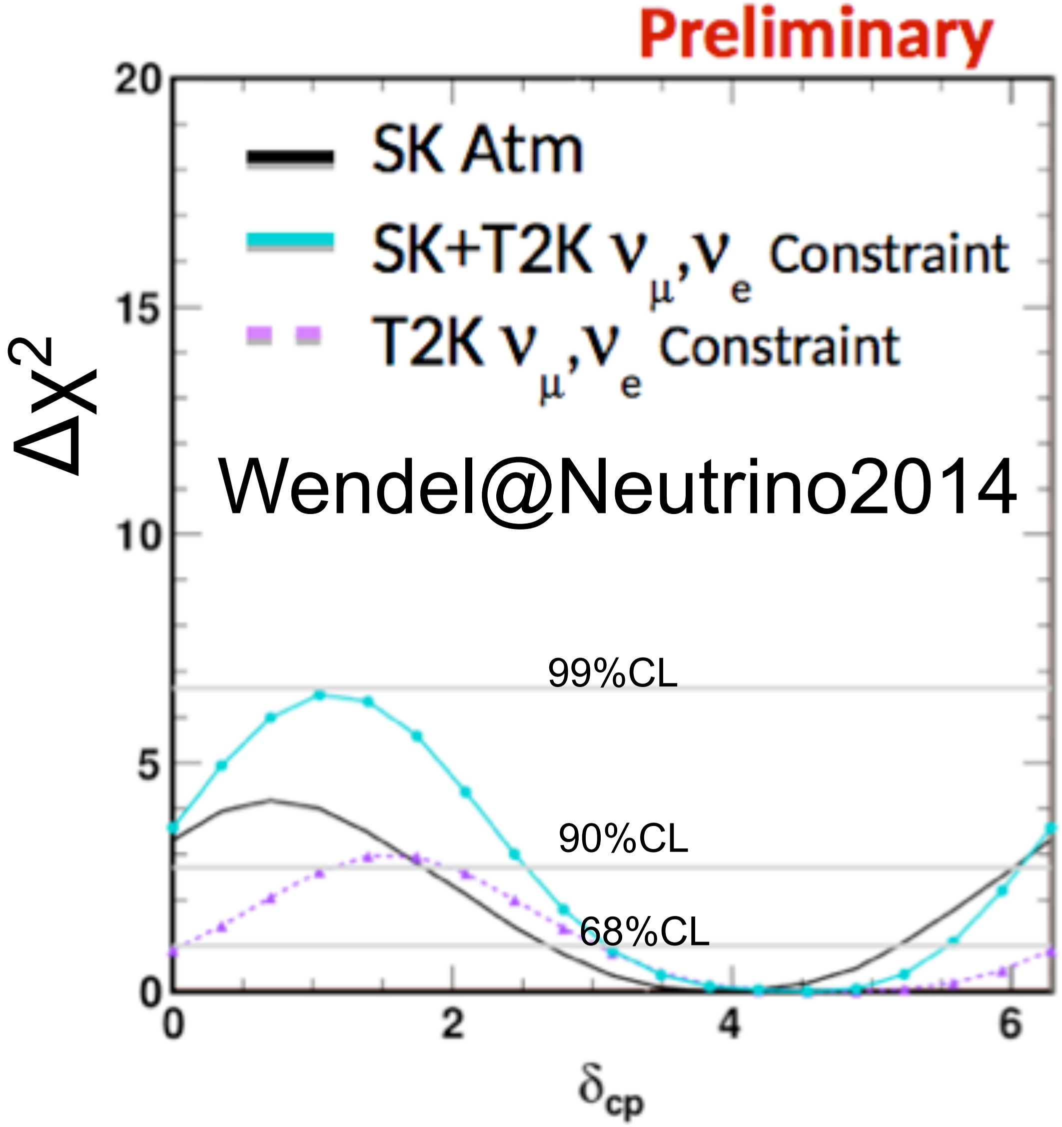
Δ_{23} resonance

Δ_{12} oscillation

CP violation effect is large! $P_{\mu e} \sim$ up to 20%

Atmospheric CP with SK

- Current SK CP sensitivity (~250kton-years):
  - CP signal size: up to several %
  - Stat. error = 1% [10k subGeV atm. ν_e events @SK]
  - $\Delta\chi^2=3.5$ at $\delta cp=0$ (rejects at 90%CL)
  - Large systematic uncertainties:
- Systematics to be improved:
  - Flux:
  - Cross section:
  - Detector response:



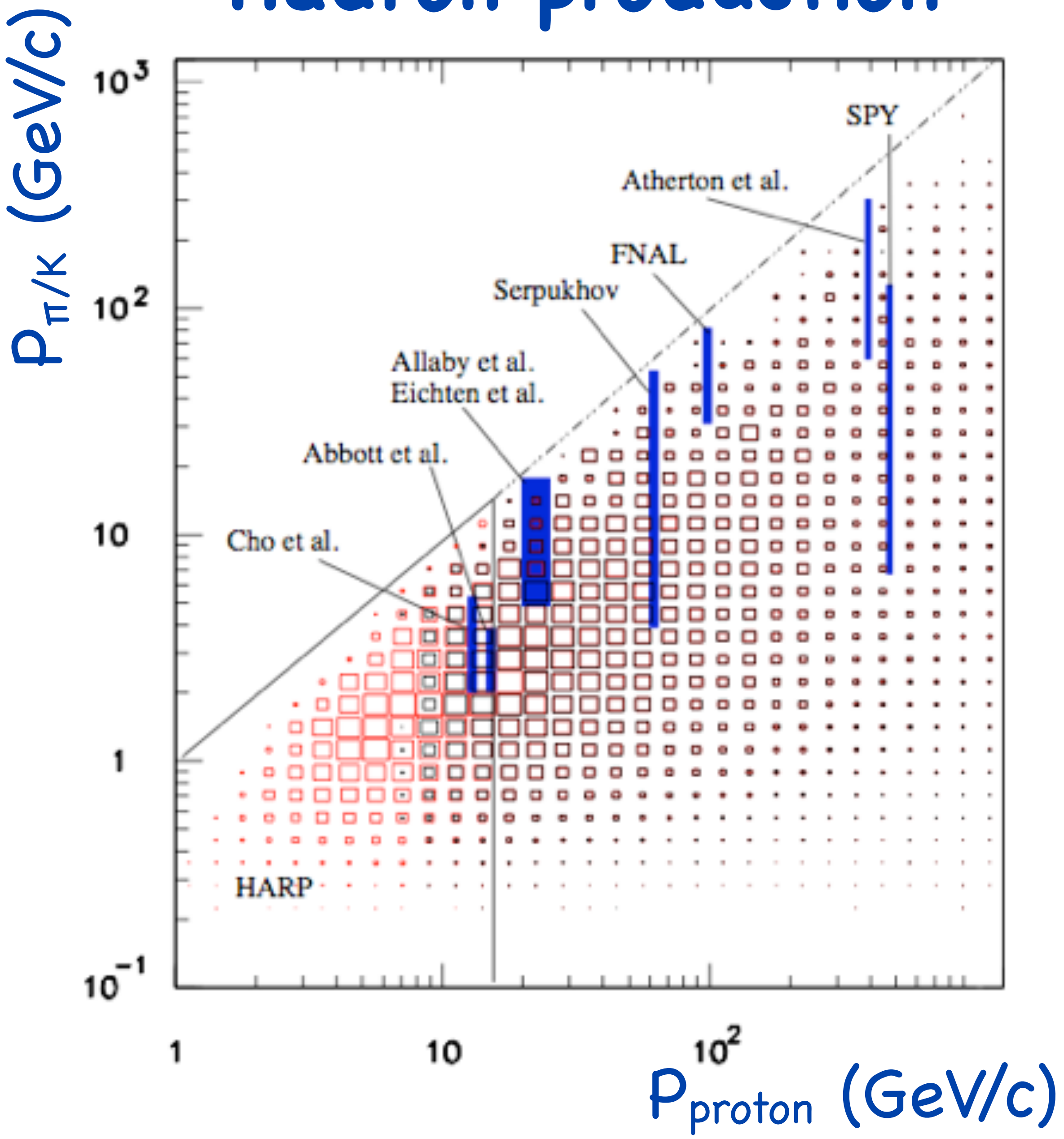
"Grain of Salt" ?

- Atm. ν offers wide range of L/E in oscillation studies
  - However, taken by the community with "grain of salt"
  - Good statistics, limited by "unknown" systematics
  - Accelerator ν may also hit such limit (e.g. nuclear effect)
- Exciting opportunity for precision atmospheric ν: Study of systematic errors on well controled data samples
  - Neutrino flux
    - AMS data provides precise primary cosmic ray flux
    - Limited by hadron production: **NA61** with E<15GeV capability?
  - Neutrino cross section
    - Model independent cross section study by **nuPRISM**
  - SK detector efficiency
    - **Calibration** to estimate errors based on PMT and water parameters

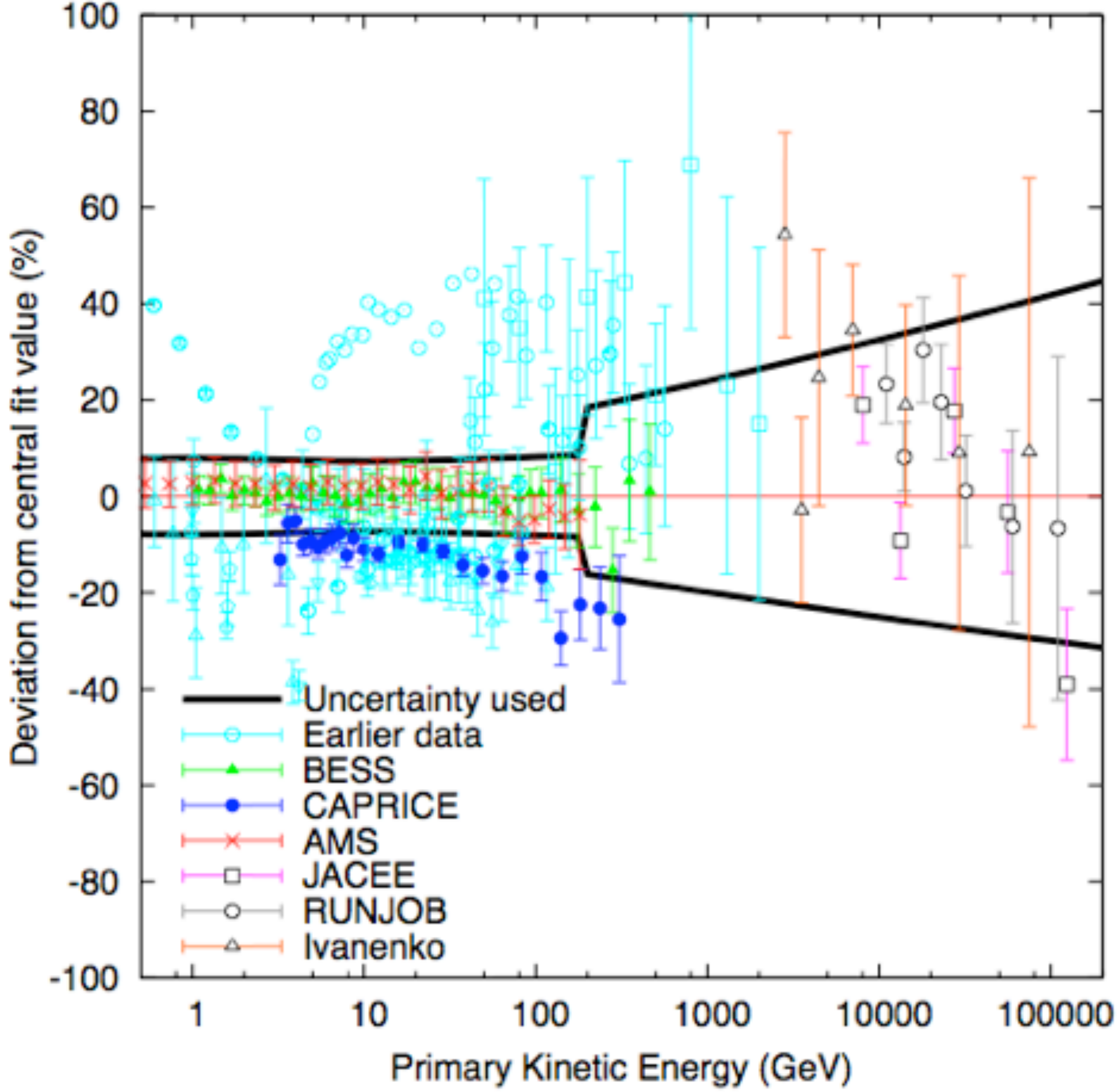
Sources of flux uncertainties

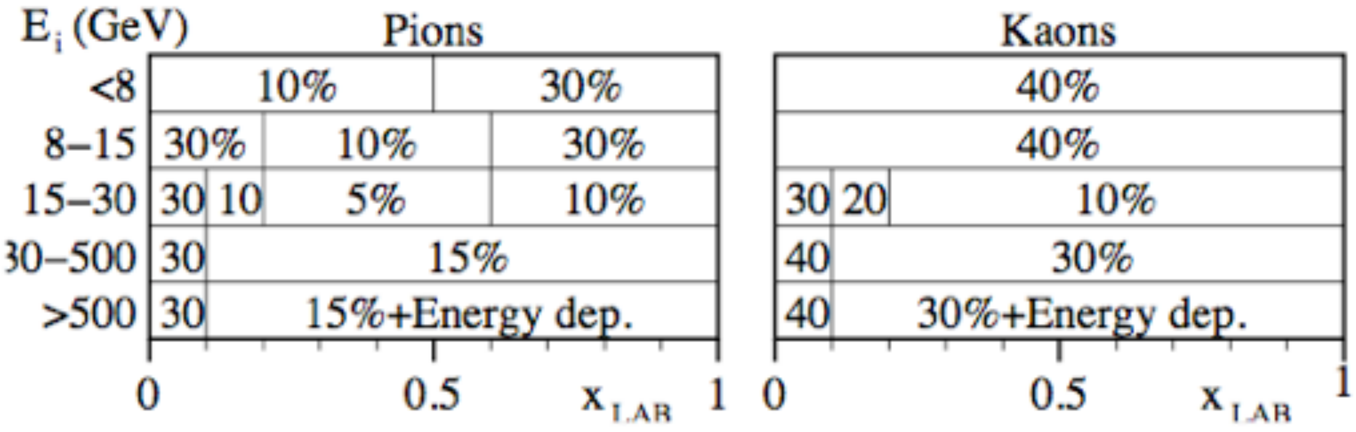
astro-ph/0611266

Hadron production



Primary cosmic ray flux



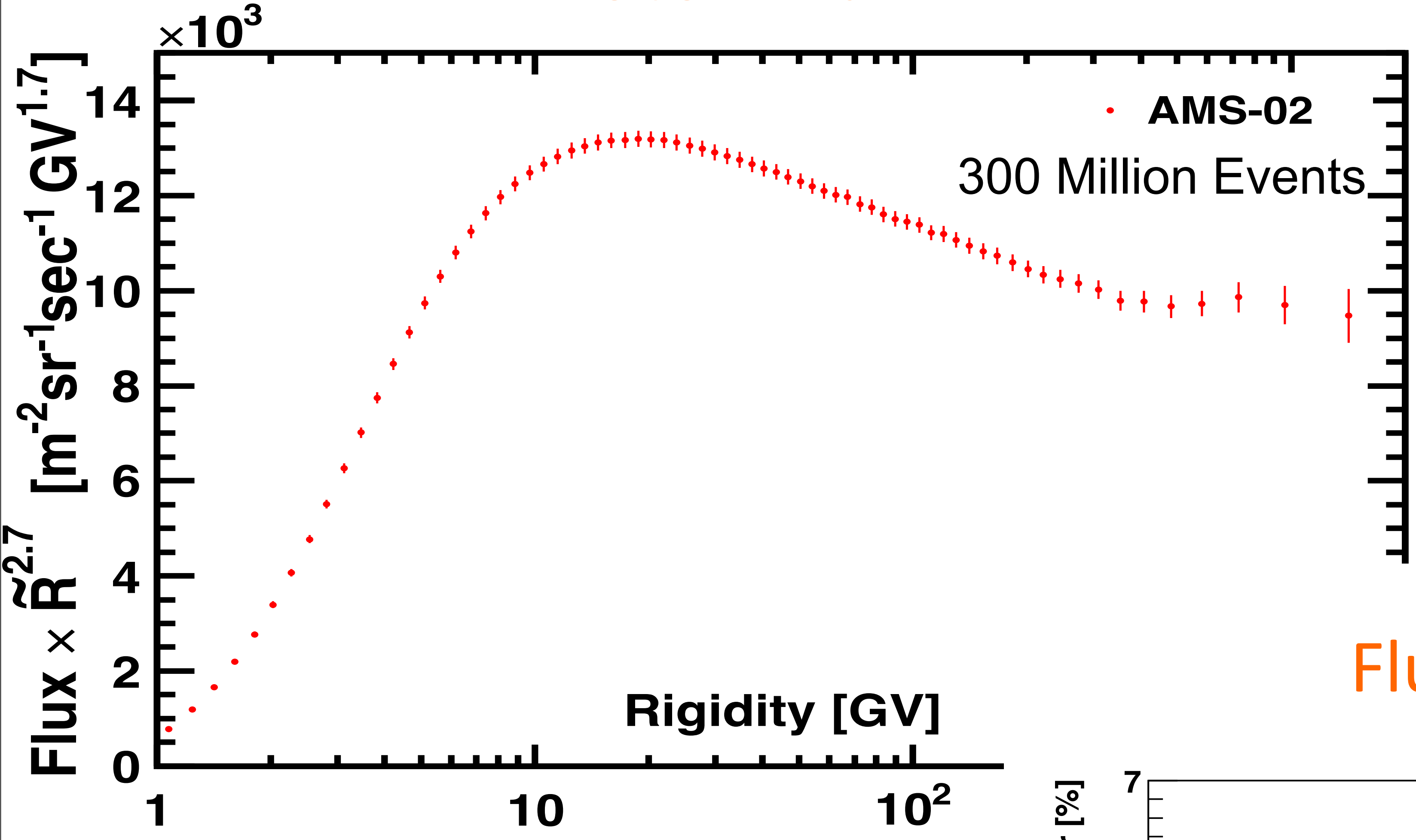


E_i (GeV)	Pions				Kaons		
<8	10%	30%			40%		
8–15	30%	10%	30%		40%		
15–30	30	10	5%	10%	30	20	10%
30–500	30	15%			40	30%	
>500	30	15%+Energy dep.			40	30%+Energy dep.	

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)	$< 200\mathrm{GeV/n}$	2.74 ± 0.01	2.64 ± 0.02
	$> 200\mathrm{GeV/n}$	2.74 ± 0.03	2.64 ± 0.04

Primary Cosmic Ray Flux (AMS)

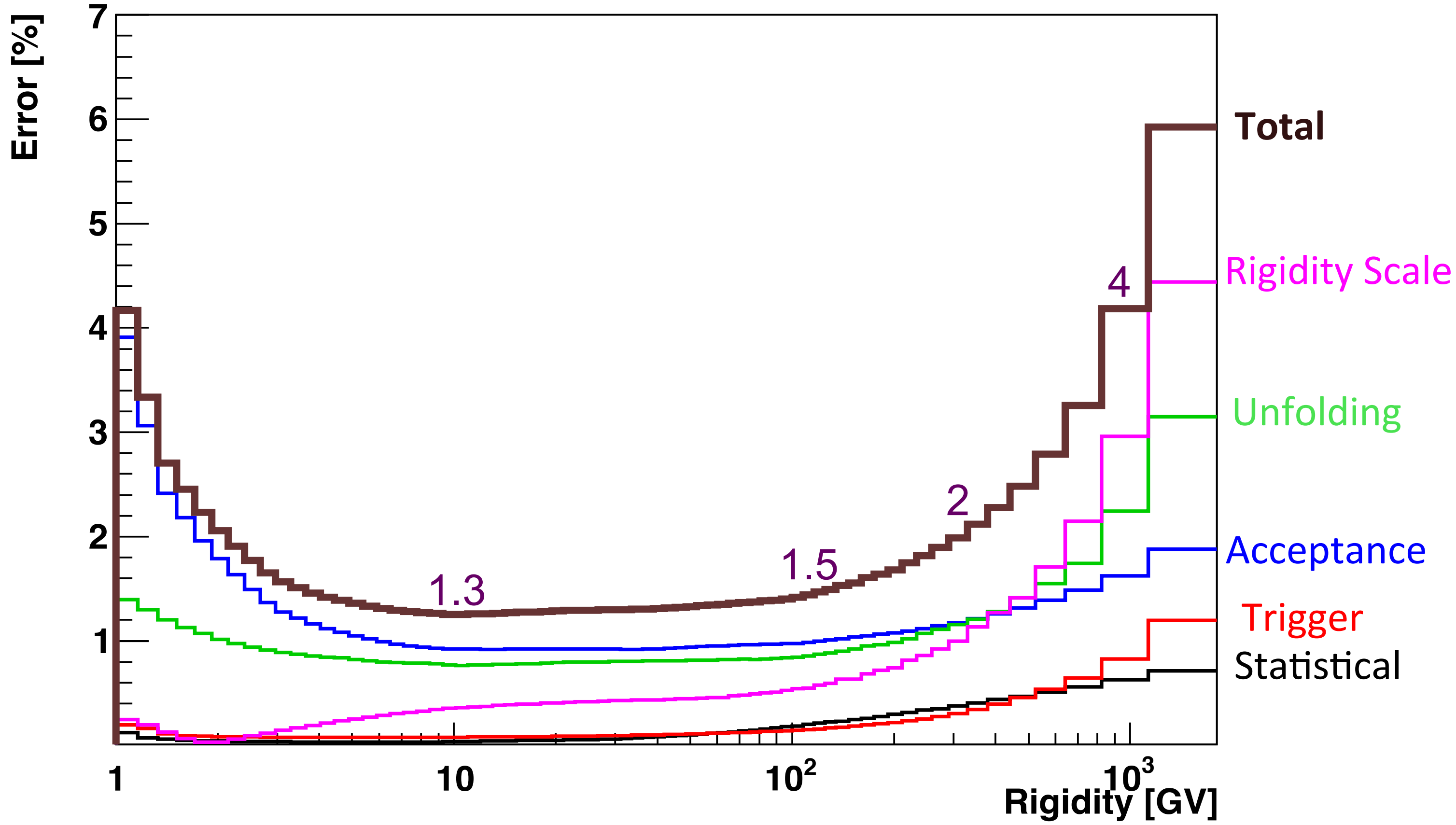
Proton Flux



AMS: April 2015

- Primary cosmic ray flux is now measured at 1-2% level.
- Open the door for very precise atm.ν studies

Flux Errors Breakdown



Neutrino physics in HyperK era

- T2K/NOvA (with reactor θ_{13}) are getting close to observing the leptonic CP violation
  - Could be discovered before HyperK or in the 1st year of HyperK, if δcp is at the current favored value.
  - Staged (quicker) version of HyperK?
- Multiple experiments are in preparation to determine the neutrino mass hierarchy
  - T2K/NOvA, JUNO, PINGU, INO, ...
- Can we go beyond at HyperK/DUNE (2025-)?
  - Testing the unitarity of PMNS matrix
    - Leptonic version of B-factory
    - Establish unitarity and CP violation from PMNS phase Or discover new physics (sterile ν, new interaction,...)

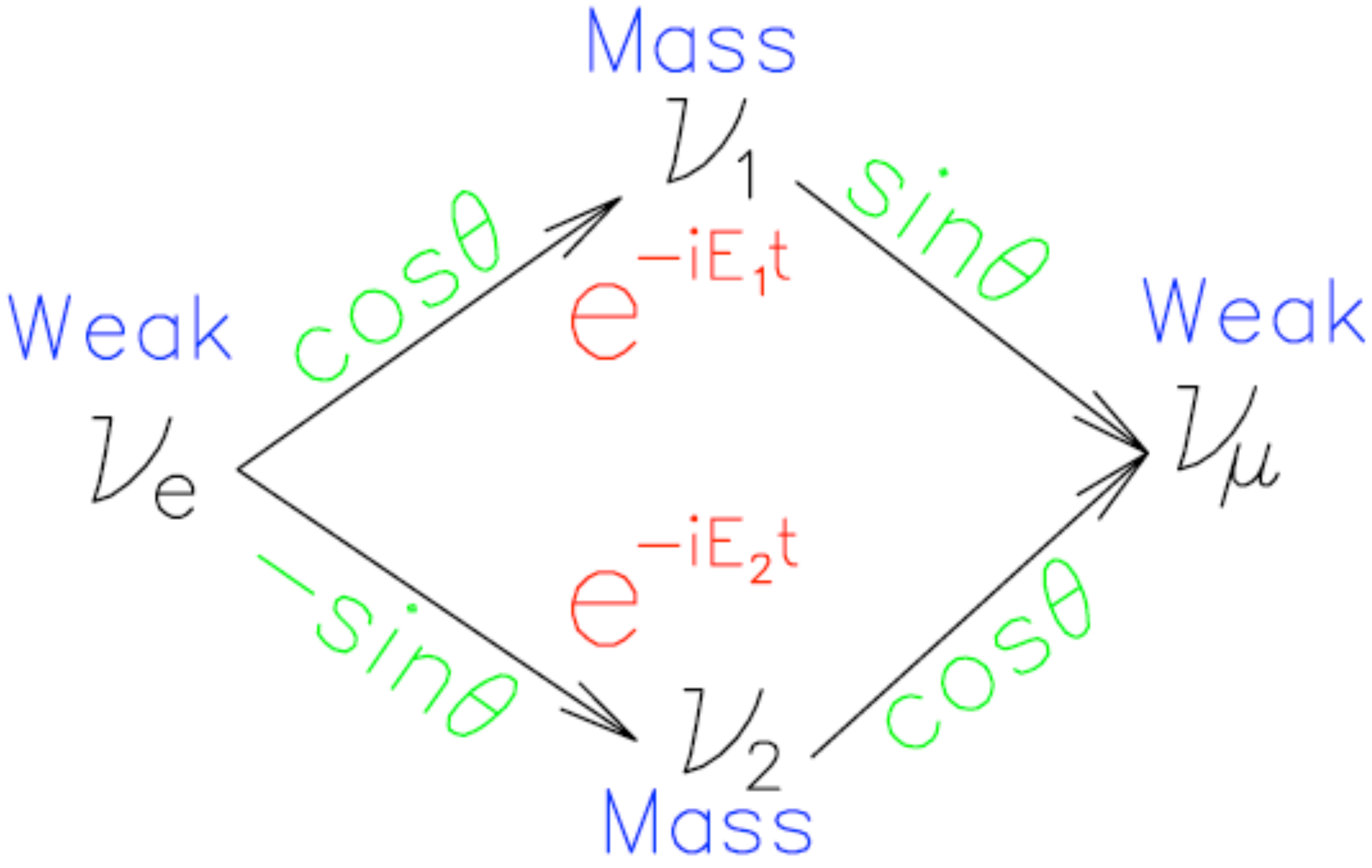
Neutrino Oscillation

$$
\begin{aligned}
&< \nu_l | \nu_i >= U_{li} : PMNS\ matrix \\
&\quad l = e, \mu, \tau : weak\ eigenstates \\
&\quad i = 1, 2, 3\ \ : mass\ eigen
\end{aligned}
$$

(Unitary matrix)

Neutrinos are produced and detected as weak eigenstates and travels as mass eigenstates:

Interferece

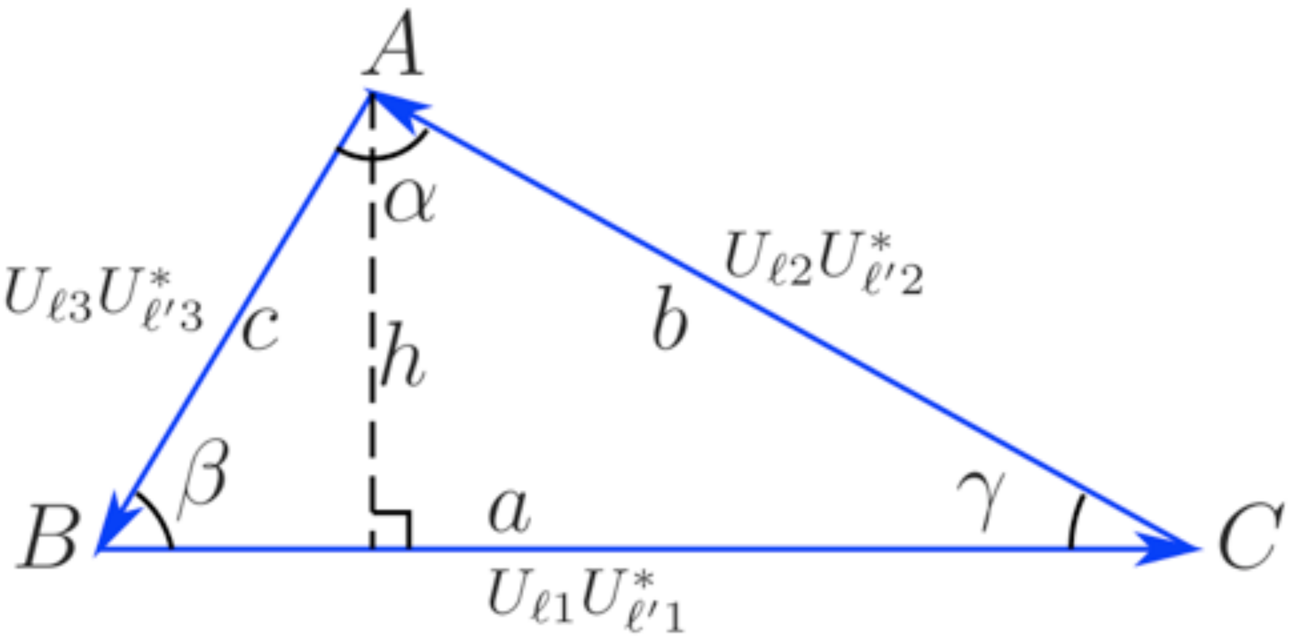


$$
\begin{aligned}
P_{l\to l'} &= |< \nu_{l'}(t) | \nu_l(t) > |^2 \\
&= |\sum_i < \nu_{l'} | \nu_i > e^{-iE_i t} < \nu_i | \nu_l > |^2 \\
&= |\sum_i U^*_{li} U_{l'i} e^{-im_i^2 L/2E}|^2 = \sum_{i,j} U^*_{li} U_{l'i} (U^*_{lj} U_{l'j})^* e^{-i(m_i^2 - m_j^2)L/2E}
\end{aligned}
$$

Unitarity of the PMNS matrix

- Unitarity condition: $U^\dagger U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
  - Normalization

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

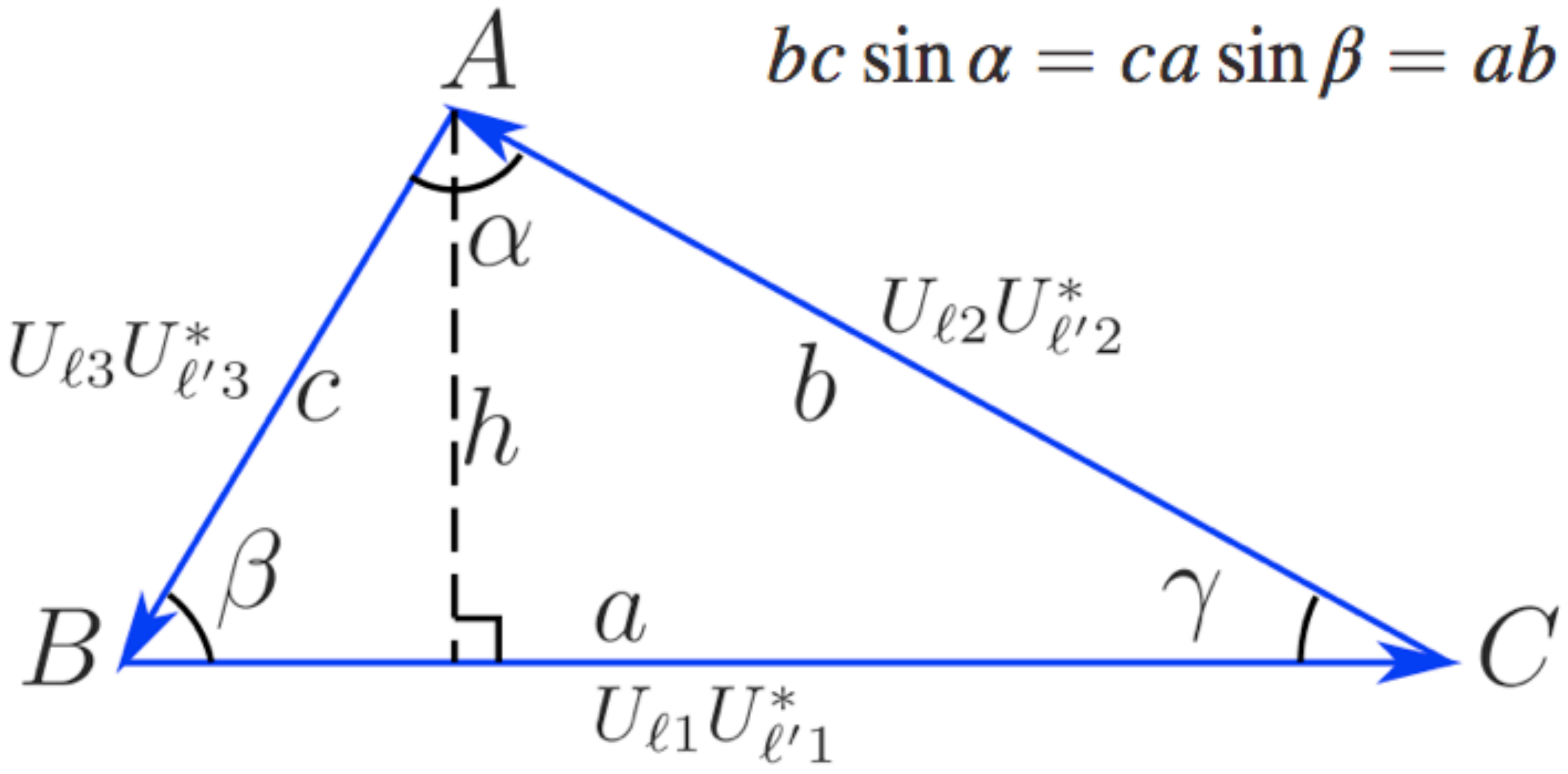


  - Unitarity triangle

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

- New physics can break the Unitarity of PMNS
  - sterile neutrino or new interactions

Unitarity Triangle (PRD89(2014)073002)



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

$a=|U_{\ell 1}|\ |U_{\ell' 1}|$
$b=|U_{\ell 2}|\ |U_{\ell' 2}|$
$c=|U_{\ell 3}|\ |U_{\ell' 3}|$

$\Delta_{12}=\Delta m^2_{12}L/4E$
$\Delta_{23}=\Delta m^2_{23}L/4E$
$\Delta_{31}=\Delta m^2_{31}L/4E$

Appearance

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

Each of the CP angles (α,β,γ) correspond to each L/E oscillation length; Δ_{23}, Δ_{31}, Δ_{12}

Disappearance

- Disappearance tests normalization part of unitarity and the sides of the unitarity triangle:

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

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

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

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

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

- Different L/E scale to untangle each contributions
  - solar (Δ_{12}) and atmospheric (Δ_{23},Δ_{31}) scales
  - At 1st oscillation max. $\Delta_{23} \sim \Delta_{13} \sim 0.03\,\Delta_{12}$:
    - Higher osc. max and matter effect provide additional handles

e-μ unitarity in PMNS

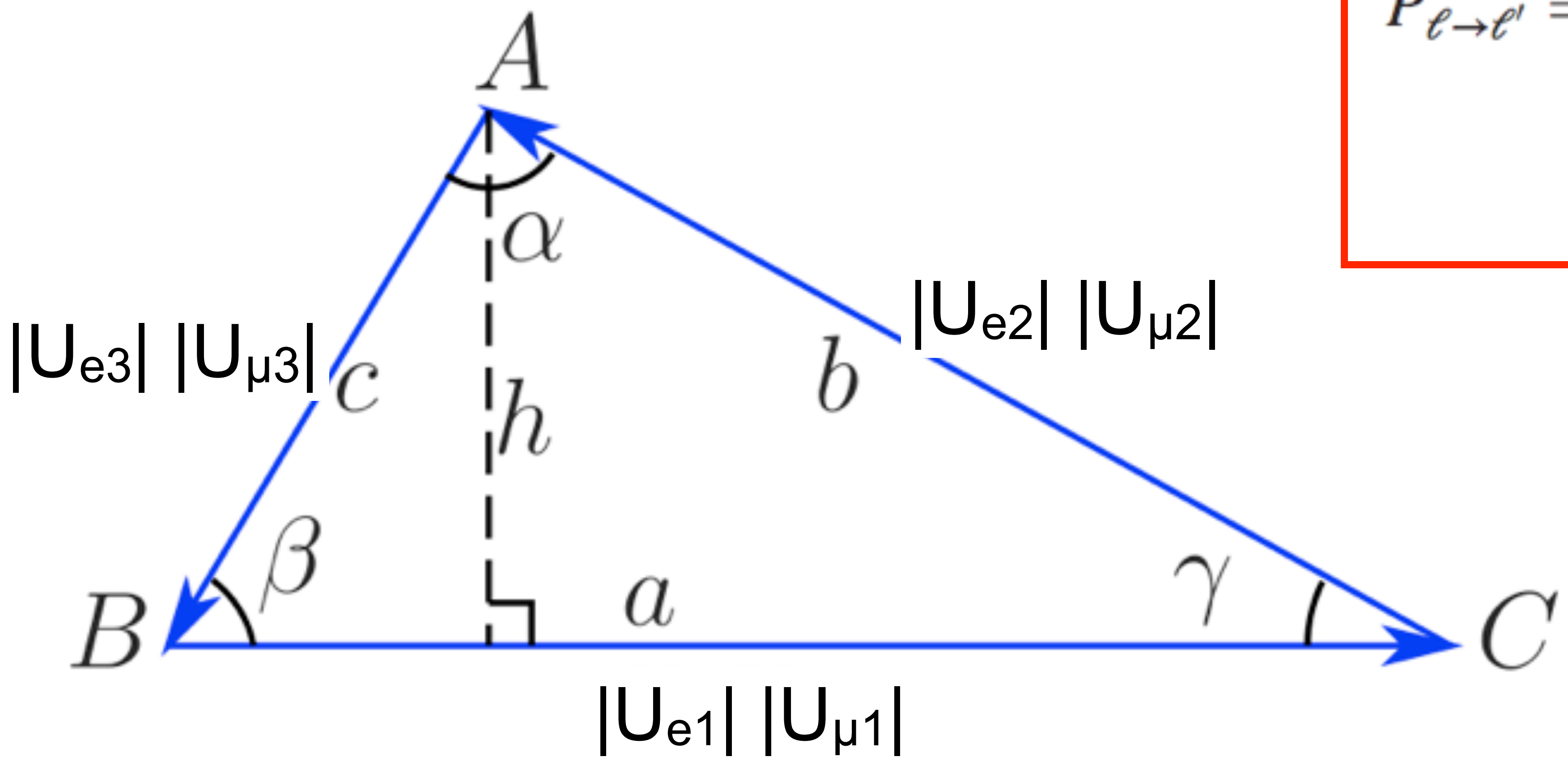
- e-μ part of unitarity can be studied best:

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

$$|U_{\mu1}|^2+|U_{\mu2}|^2+|U_{\mu3}|^2 = 1$$

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

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



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

Δ_{13} : $\beta \sim \delta_{cp}$

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

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

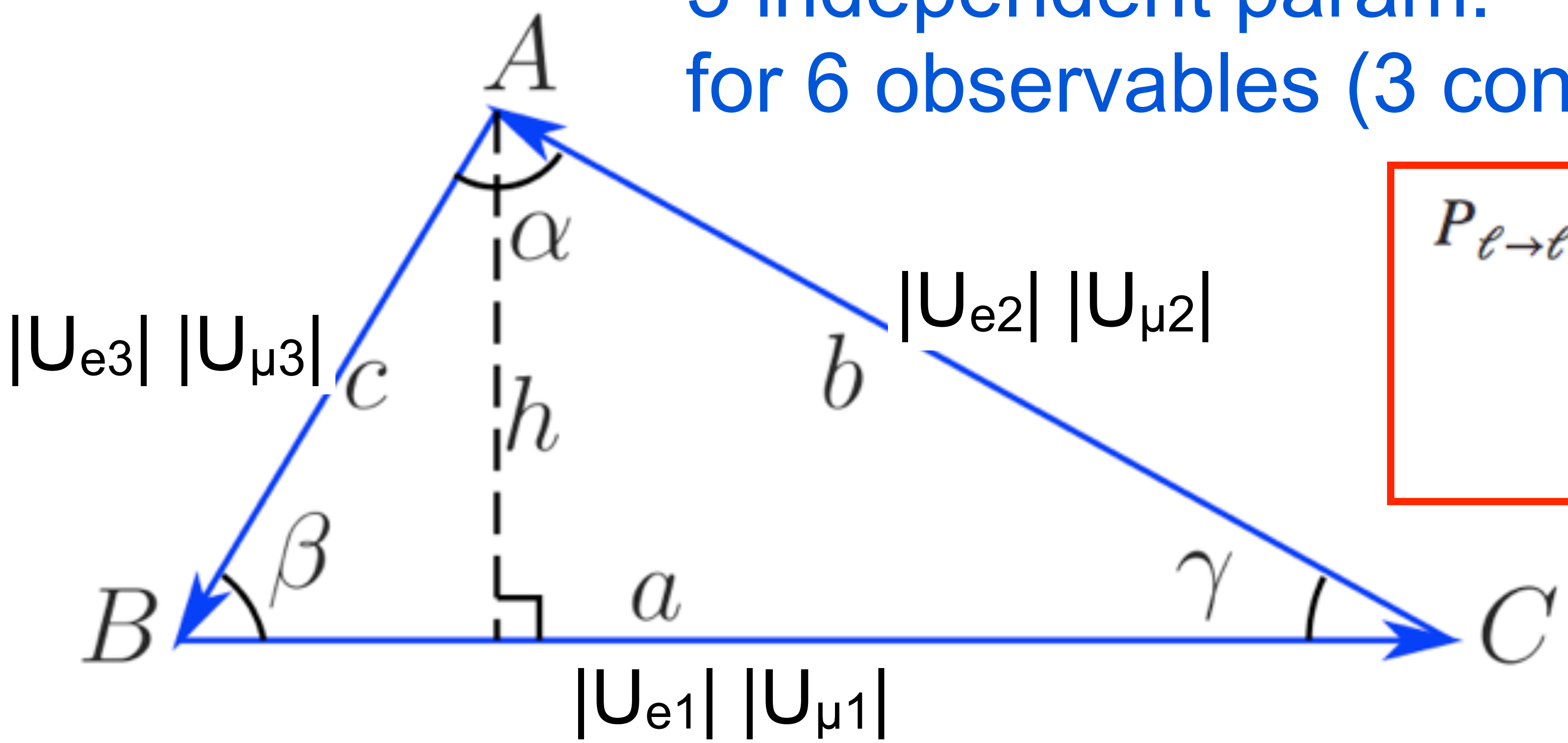
$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$

- 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_{13} scale of L/E
- All the parameters are measured:
  - Better precision for $|U_{e1}|^2$ and $|U_{e2}|^2$ expected by JUNO, untangling Δ_{23} and Δ_{31} contributions

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

- LBL ν_μ disappearance: $|U_{\mu 3}|^2$ ($|U_{\mu 1}|^2$ + $|U_{\mu 2}|^2$)
  - T2K/MINOS/NOvA measure this.
- $\nu_\mu \rightarrow \nu_e$ atm. matter resonance (3-8GeV): ($r|U_{\mu 3}|^2$ -1)
  - Amplitude of the atm. ν 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]
  - Precise zenith angle needed: $\bar{\nu}_\mu$ (with neutron tag)
- 1-3GeV atm. ν_μ disapp.: $|U_{\mu 1}|^2$ / $|U_{\mu 2}|^2$
  - 4-6th oscl. max: 20-30% phase shift btw Δ_{13}&Δ_{23} [HK]
- Good potential to untangle all three parameters: HyperK will play a major role

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

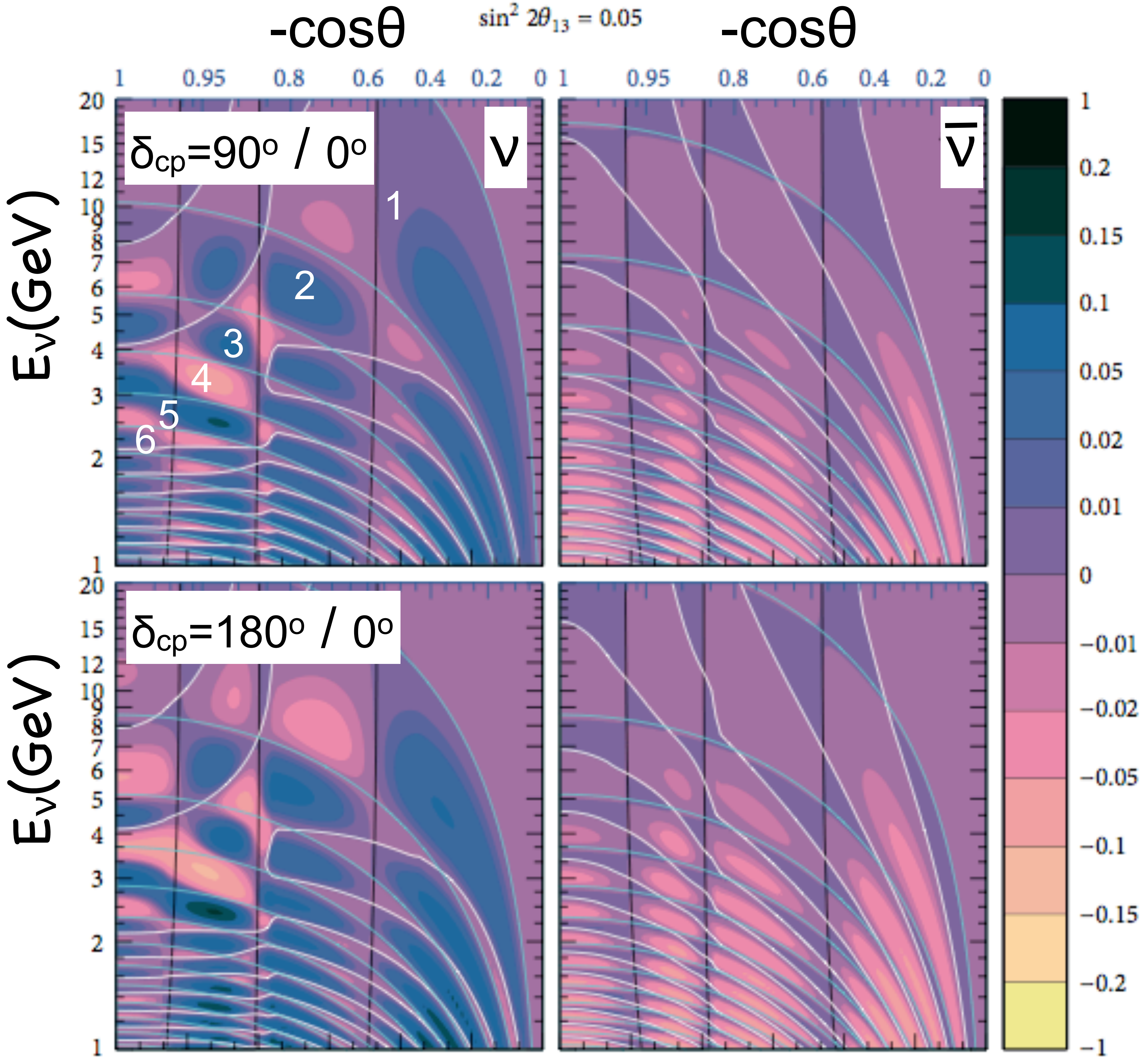


3 independent param.
for 6 observables (3 constraints)

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

- a,b,c can be determined by the disappearance
  - 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. $\nu_\mu \to \nu_e$
  - T2K/T2HK/DUNE will determine combination of α and β [HK]
  - γ can be determined by the 0.5-0.8GeV atm. $\nu_\mu \to \nu_e$ [HK]
  - Atm. $\nu_\mu \to \nu_e$ (2nd to 10th max.) untangles $\beta(\Delta_{31})$ and $\alpha(\Delta_{23})$ [HK]

ΔP_{CP} oscillogram



CP effect:
E~2-5GeV
cosθ~0.9
(1st-10th
Δ_{23} max)

Summary

- Atm. ν covers wide range of oscillation parameters
  - Realistic scenario emerges to control systematic uncertainties:
    - Precise AMS cosmic ray measurement
    - Precision hadron production study established by NA61: need to be extended also below 15GeV by beamline modification
    - nuPRISM proposal for model independent ν cross section study
- Precision test of e-μ PMNS Unitarity
  - 9 parameters with 5 constraints to be tested
    - $|U_{e1}|^2, |U_{e2}|^2, |U_{e3}|^2$, $|U_{\mu1}|^2, |U_{\mu2}|^2, |U_{\mu3}|^2$, α, β, γ
    - Unitarity triangle (3 constraints), normalization (2)
  - All 9 parameters can be measured:
    - Typical expected accuracy would be 10-20%
    - HyperK will lead the new measurements: $|U_{\mu i}|^2$, α, β, γ (JUNO will improve $|U_{ei}|^2$)
  - HyperK will play leading role in establishing PMNS paradigm, similar to B-factory in CKM

Backup slides

Unitarity triangle

Calculation is simpler without Unitarity

$$
\begin{aligned}
P_{l\to l'} &= |<\nu_{l'}(t)|\nu_l(t)>|^2 \\
&= |\sum_i <\nu_{l'}|\nu_i> e^{-iE_it} <\nu_i|\nu_l>|^2 \\
&= |\sum_i U^*_{li}U_{l'i}e^{-im_i^2L/2E}|^2 = \sum_{i,j} U^*_{li}U_{l'i}(U^*_{lj}U_{l'j})^*e^{-i(m_i^2-m_j^2)L/2E}
\end{aligned}
$$

$$
\begin{aligned}
&= |U^*_{l1}U_{l'1}|^2 + |U^*_{l2}U_{l'2}|^2 + |U^*_{l3}U_{l'3}|^2 \\
&+ 2Re[U^*_{l1}U_{l'1}[U^*_{l2}U_{l'2}]^*e^{-i(m_1^2-m_2^2)L/2E} \\
&+ 2Re[U^*_{l2}U_{l'2}[U^*_{l3}U_{l'3}]^*e^{-i(m_2^2-m_3^2)L/2E} \\
&+ 2Re[U^*_{l3}U_{l'3}[U^*_{l1}U_{l'1}]^*e^{-i(m_3^2-m_1^2)L/2E} \\
&= a^2 + b^2 + c^2 \\
&\quad -2ab\cos(2\Delta_{12}+\gamma) \\
&\quad -2bc\cos(2\Delta_{12}+\alpha) \\
&\quad -2ca\cos(2\Delta_{12}+\beta) \\
&= 4ab\sin(\Delta_{12}+\gamma)\sin\Delta_{12} \\
&+ 4ab\sin(\Delta_{23}+\alpha)\sin\Delta_{23} \\
&+ 4ab\sin(\Delta_{31}+\beta)\sin\Delta_{31}
\end{aligned}
$$

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

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

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