CONSTRAINING LORENTZ VIOLATION USING ICECUBE HIGH ENERGY NEUTRINO FLAVOR RATIO MEASUREMENT

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in preparation

OUTLINE

- Introduction
- Previous constraints on Lorentz violation parameters
- New constraints on Lorentz violation parameters from IceCube flavor ratio analysis
- Summary

INTRODUCTION

- Flavor discrimination

Probe the flavor transition,
ex: ν oscillation, ν decay,
Lorentz Violation(LV)

$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0$ ⟷ $\Phi_e : \Phi_\mu : \Phi_\tau$

Generate the source

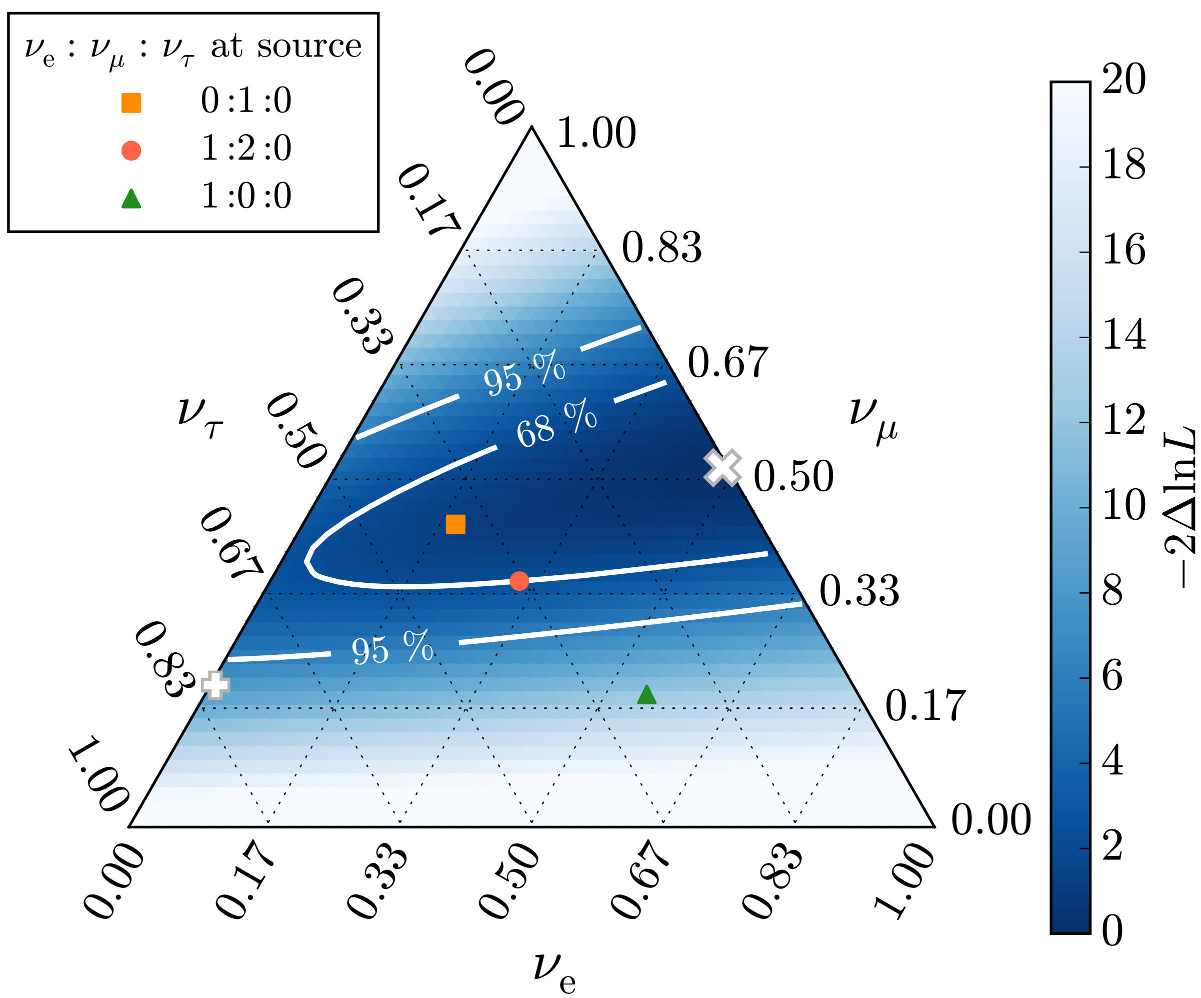
detected at the Earth

$$(\Phi_e:\Phi_\mu:\Phi_\tau)=P_{\alpha\beta}(\Phi_e^0:\Phi_\mu^0:\Phi_\tau^0)$$

INTRODUCTION

M. G. Aartsen *et al.* (IceCube Collaboration), Astrophys.J. 809 (2015) no.1, 98

- IceCube flavor ratio analysis
- Event selection: E_ν=25TeV - 2.8PeV



INTRODUCTION

- Lorentz Violation based on the Standard model extension(SME)
  - $H_{tot} = H_{standard} + \delta H_{LV}$
- General effective hamiltonian
  - $\delta H_{LV} = \frac{1}{|\vec{p}|}\begin{pmatrix} [(a_L)^{\mu}p_{\mu} - (c_L)^{\mu\nu}p_{\mu}p_{\nu}]_{ab} & -i\sqrt{2}p_{\mu}(\epsilon_+)_{\nu}[(g^{\mu\nu\sigma}p_{\sigma} - H^{\mu\nu})C]_{ab} \\ i\sqrt{2}p_{\mu}(\epsilon_+)^*_{\nu}[(g^{\mu\nu\sigma}p_{\sigma} + H^{\mu\nu})C]^*_{ab} & [-(a_L)^{\mu}p_{\mu} - (c_L)^{\mu\nu}p_{\mu}p_{\nu}]^*_{ab} \end{pmatrix}$
- Isotropic case
  - $\delta H_{LV(\nu)} = +\begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & 0 & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & 0 \end{pmatrix} - \frac{4E}{3}\begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & 0 & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & 0 \end{pmatrix}$
  - $\delta H_{LV(\bar{\nu})} = -\begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & 0 & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & 0 \end{pmatrix}^* - \frac{4E}{3}\begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & 0 & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & 0 \end{pmatrix}^*$

Teppei Katori, V. Alan Kostelecký, and Rex Tayloe, Phys. Rev. D **74**, 105009(2006)
V. Alan Kostelecký and Matthew Mewes, Phys. Rev. D **69**, 016005(2004)

INTRODUCTION

- There are two types of astrophysical sources in proton-proton collision and proton-γ collision:

- $PP \rightarrow (\pi^+, \pi^-, \pi^0) + X$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$(\nu_e, \nu_\mu, \nu_\tau) = (\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau) \approx (1,2,0)$$

1. π source(1/3,2/3,0)
2. μ damped source(0,1,0)

- $P\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

$$(\nu_e, \nu_\mu, \nu_\tau) \approx (1,1,0)$$
$$(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau) \approx (0,1,0)$$

1. π source(1/3,2/3,0)
2. μ damped source(0,1,0)

J. P. Rachen and P. Meszaros, 1998

T. Kashti and E. Waxman, Phy. Rev. Lett. 2005

PREVIOUS CONSTRAINT ON LORENTZ VIOLATION PARAMETERS

- The most updated constraint : Super-Kamiokande experiment
  A. path length : 15km - 12800km, E_ν : 100 MeV - 100TeV
  B. with the following Hamiltonian

$$H_{tot(\nu)} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$+ \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & 0 & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & 0 \end{pmatrix}$$

$$H_{tot(\bar{\nu})} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger - \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$- \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix}^* - \frac{4E}{3} \begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & 0 & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & 0 \end{pmatrix}^*$$

K. Abe et al. (Super-Kamiokande Collaboration),Phys. Rev. D 91, 052003(2015)
V. Alan Kostelecký and Neil Russell, Rev. Mod. Phys. 83, 11(2016)

Super-K's result: K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D **91**, 052003(2015)

LV parameter		Limit at 95% C.L.	Best fit	No LV $\Delta\chi^2$	Previous limit
$e\mu$	$\mathrm{Re}(a^T)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [1]
	$\mathrm{Im}(a^T)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	$\mathrm{Re}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [1]
	$\mathrm{Im}(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}		
$e\tau$	$\mathrm{Re}(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [2]
	$\mathrm{Im}(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17} [2]
	$\mathrm{Im}(c^{TT})$	1.0×10^{-24}	3.5×10^{-25}		
$\mu\tau$	$\mathrm{Re}(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	...
	$\mathrm{Im}(a^T)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}(c^{TT})$	4.4×10^{-27}	1.0×10^{-28}	0.1	...
	$\mathrm{Im}(c^{TT})$	4.2×10^{-27}	7.5×10^{-28}		

- real and imaginary parts fit simultaneously
- 6 parameters are fit independently

V. Alan Kostelecký and Neil Russell, Rev. Mod. Phys. **83**, 11(2016)
[1]T. Katori(MiniBooNE Collaboration), Mod. Phys. Lett. A 27, 1230024(2012)
[2]T. Katori and J. Spitz, in CPT and Lorentz Symmetry VI(World scientific, Singapore, 2014)

LORENTZ VIOLATION HAMILTONIAN

$$H_{tot(\nu)} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$+ \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & 0 & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & 0 \end{pmatrix}$$

Standard neutrino oscillation

Lorentz violation

$$H_{tot(\bar{\nu})} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger - \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$- \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix}^* - \frac{4E}{3} \begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & 0 & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & 0 \end{pmatrix}^*$$

Standard neutrino oscillation

Lorentz violation

- Two LV terms with similar structure
- Diagonal terms are not detectable in experiment
- We study $E_\nu \geq 25$TeV (due to IceCube event selection for flavor ratio analysis)
- We will first focus on the "a" term, we will comment c term later

K. Abe et al. (Super-Kamiokande Collaboration),Phys. Rev. D **91**, 052003(2015)
V. Alan Kostelecký and Neil Russell, Rev. Mod. Phys. **83**, 11(2016)

SIMPLE NUMERICAL TEST

$$H_{std} = 10^{-26}(GeV)\begin{pmatrix} 0.16 & 0.05+0.47i & -0.04+0.54i \\ 0.05-0.47i & 2.11 & 2.27-0.01i \\ -0.04-0.54i & 2.27+0.01i & 2.68 \end{pmatrix}$$

$$\delta H_{LV(\nu)} = +\,10^{-23}(GeV)\begin{pmatrix} 0 & 1.8+1.8i & 4.1+2.8i \\ 1.8-1.8i & 0 & 0.65+0.51i \\ 4.1-2.8i & 0.65-0.51i & 0 \end{pmatrix}$$

- Global fit ν oscillation parameters are used
- Super-Kamiokande's 95% C.L. bound is applied
- E_ν=25TeV(due to IceCube event selection for flavor ratio analysis)
- Standard oscillation term is negligible
- Higher E_ν, "a" term dominates more

K. Abe et al. (Super-Kamiokande Collaboration),Phys. Rev. D **91**, 052003(2015)
F. Capozzi et al.,Phys. Rev.D89,093018(2014)
M. G. Aartsen *et al*. (IceCube Collaboration), Astrophys.J. 809 (2015) no.1, 98

SIMPLE LORENTZ VIOLATION HAMILTONIAN

$$H_{tot} = \begin{pmatrix} 0 & a_{e\mu} & 0 \\ a^*_{e\mu} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow P = \begin{pmatrix} 1/2 & 1/2 & 0 \\ 1/2 & 1/2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

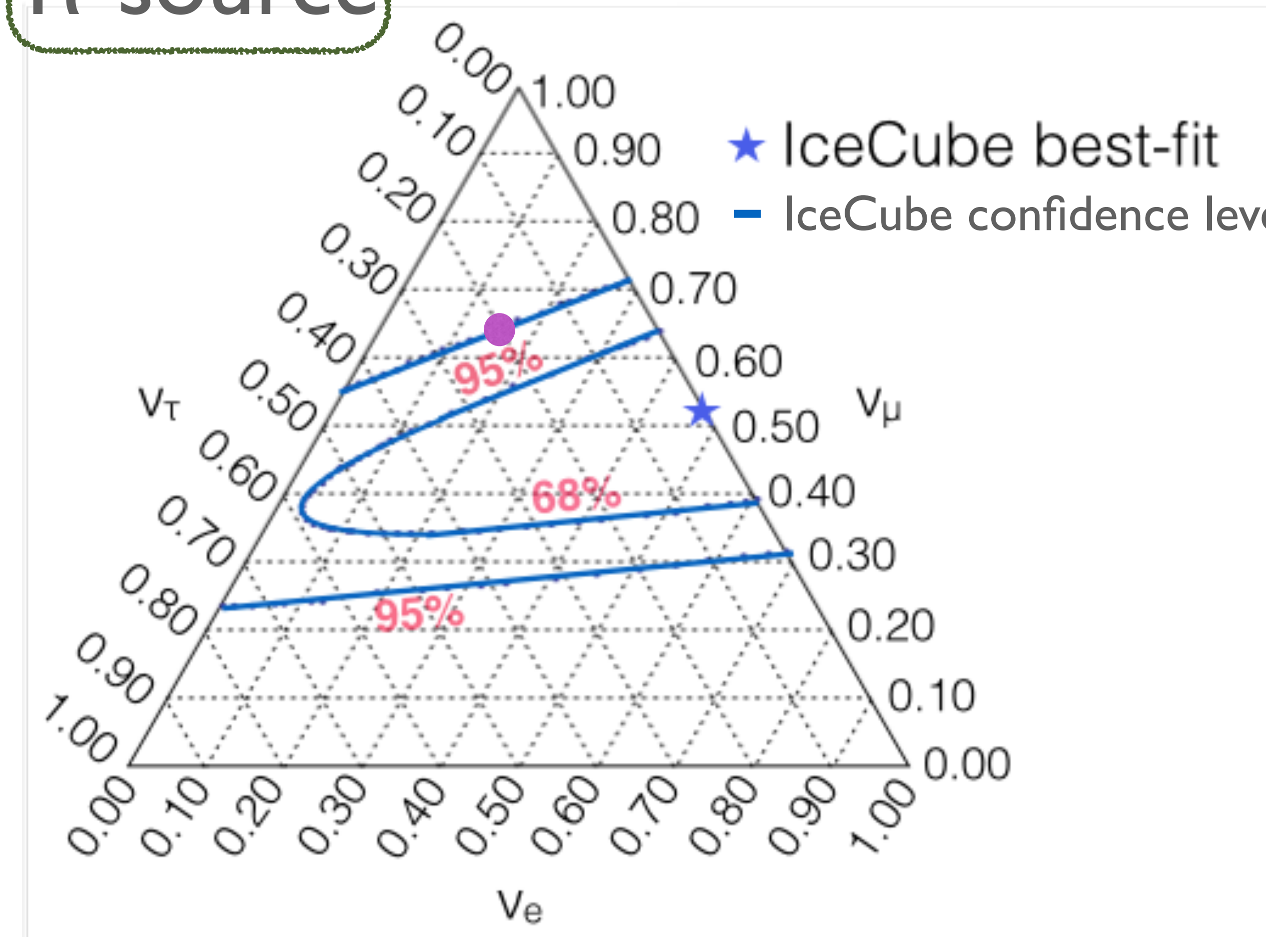
$$H_{tot} = \begin{pmatrix} 0 & 0 & a_{e\tau} \\ 0 & 0 & 0 \\ a^*_{e\tau} & 0 & 0 \end{pmatrix} \Rightarrow P = \begin{pmatrix} 1/2 & 0 & 1/2 \\ 0 & 1 & 0 \\ 1/2 & 0 & 1/2 \end{pmatrix}$$

$$H_{tot} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & a_{\mu\tau} \\ 0 & a^*_{\mu\tau} & 0 \end{pmatrix} \Rightarrow P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{pmatrix}$$

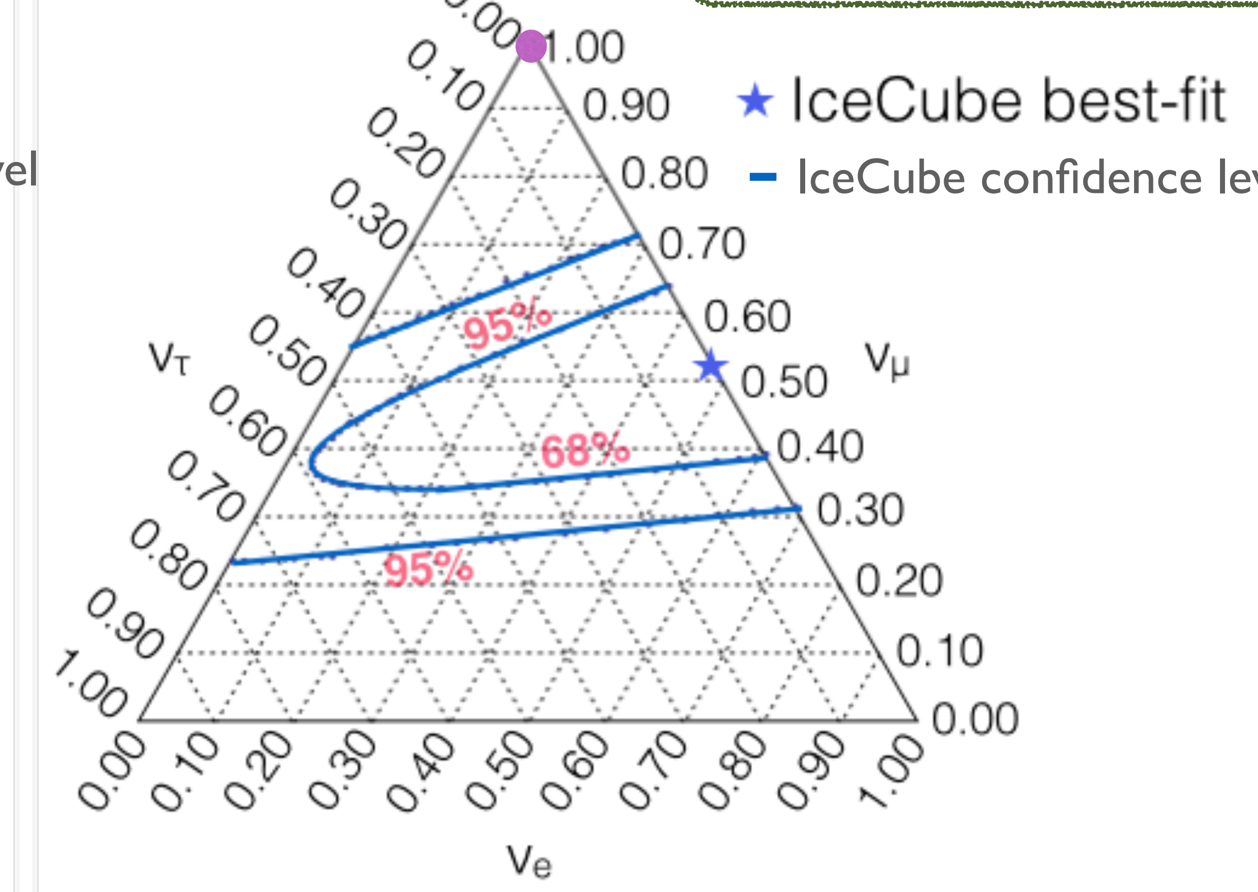
Recall: $(\Phi_e:\Phi_\mu:\Phi_\tau)=P_{\alpha\beta}(\Phi_e^0:\Phi_\mu^0:\Phi_\tau^0)$

$a_{e\tau}$ dominant scenario is the most interesting

π source



μ damped source



- The other scenarios give rise to flavor ratios in the IceCube 95% allowed region

New constraints on Lorentz violation parameters from IceCube flavor ratio analysis

In general, we can have

$$H_{LV} = \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix} = \begin{pmatrix} 0 & r_1 e^{i\psi_1} & r_2 e^{i\psi_2} \\ r_1 e^{-i\psi_1} & 0 & r_3 e^{i\psi_3} \\ r_2 e^{-i\psi_2} & r_3 e^{-i\psi_3} & 0 \end{pmatrix}$$

$$= r_2 \begin{pmatrix} 0 & x e^{i\psi_1} & e^{i\psi_2} \\ x e^{-i\psi_1} & 0 & y e^{i\psi_3} \\ e^{-i\psi_2} & y e^{-i\psi_3} & 0 \end{pmatrix}$$

$$x = \frac{r_1}{r_2}, \quad y = \frac{r_3}{r_2}$$

$\Phi = \psi_2 - \psi_1 - \psi_3$ (physical phase)

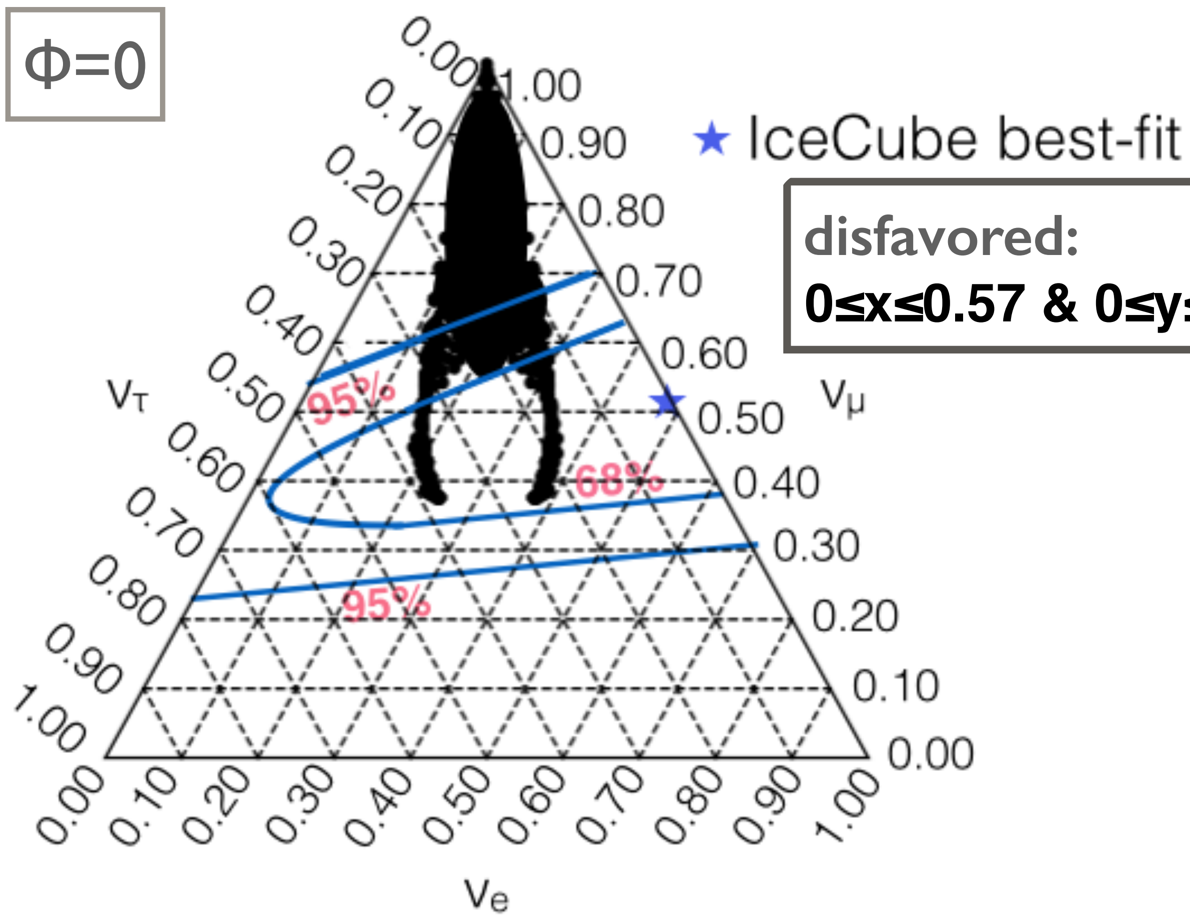
- When $a_{e\tau}$ dominants in H_{LV}, we can set better limit from IceCube flavor ratio analysis
- We scan x and y between 0 and 1 to set the limit

NUMERICAL RESULTS :Pγ collisions (μ damped)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV ,
$|a_{\mu\tau}|=8.26\times10^{-24}$GeV

first take $|a_{e\tau}|=4.96\times10^{-23}$ GeV

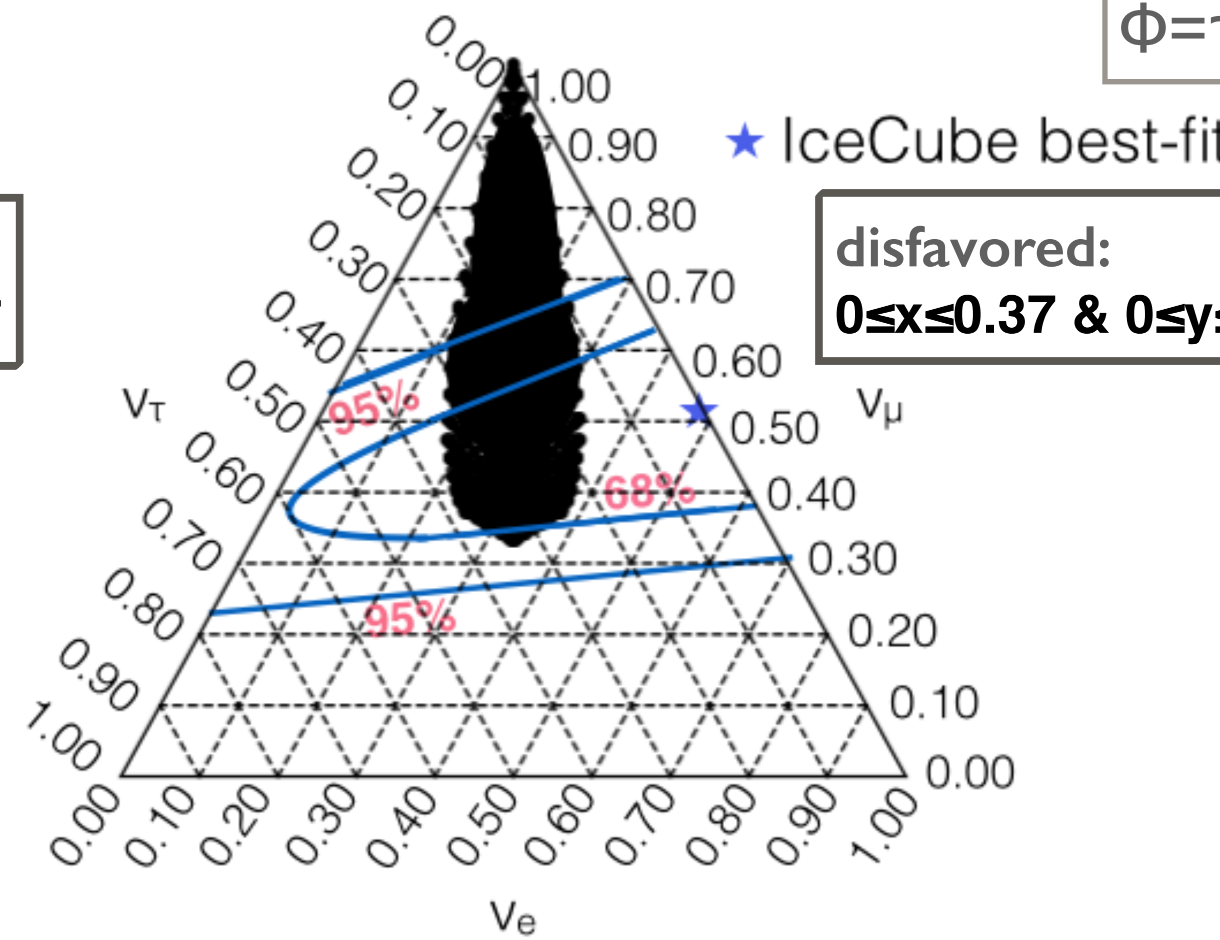
Φ=0



disfavored:
0≤x≤0.57 & 0≤y≤0.47

disfavored:
$0\leq|a_{e\mu}|\leq2.83\times10^{-23}$GeV &
$0\leq|a_{\mu\tau}|\leq2.33\times10^{-23}$GeV

Φ=π/2



disfavored:
0≤x≤0.37 & 0≤y≤0.35

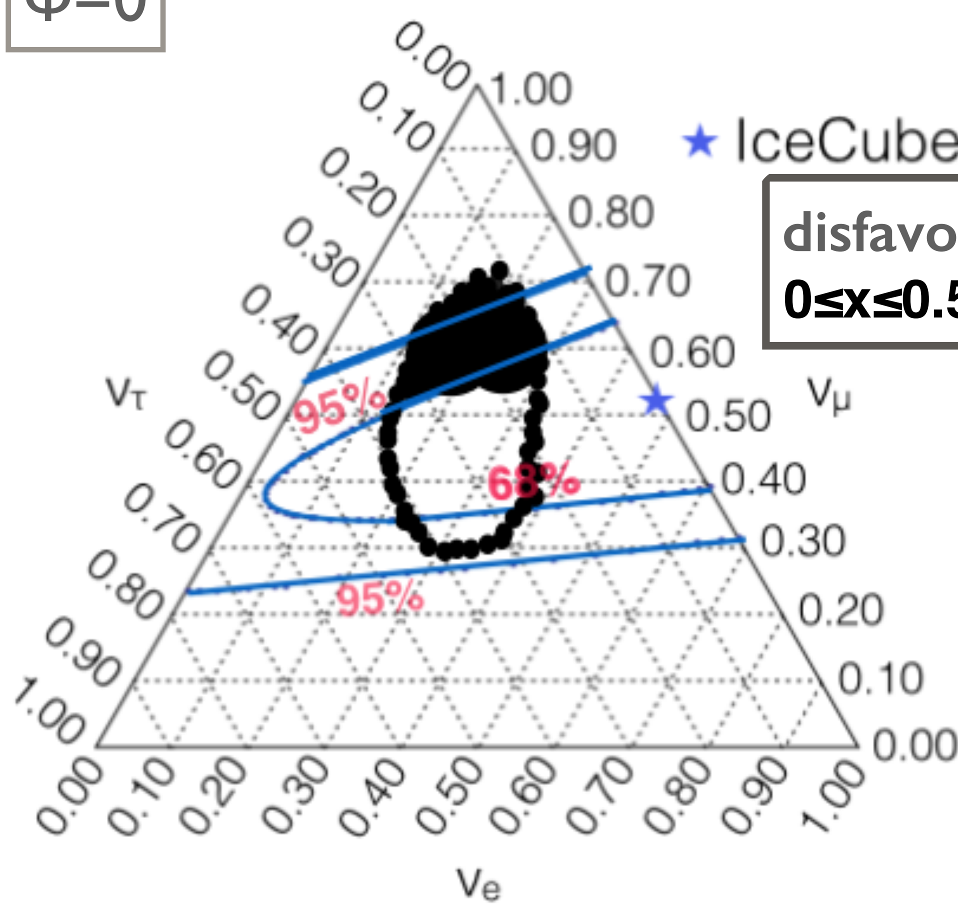
disfavored:
$0\leq|a_{e\mu}|\leq1.84\times10^{-23}$GeV &
$0\leq|a_{\mu\tau}|\leq1.74\times10^{-23}$GeV

NUMERICAL RESULTS :Pγ collisions (μ damped)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV ,
$|a_{\mu\tau}|=8.26\times10^{-24}$GeV

$|a_{e\tau}|=4.96\times10^{-26}$ GeV(lower 3-orders by Super-K)

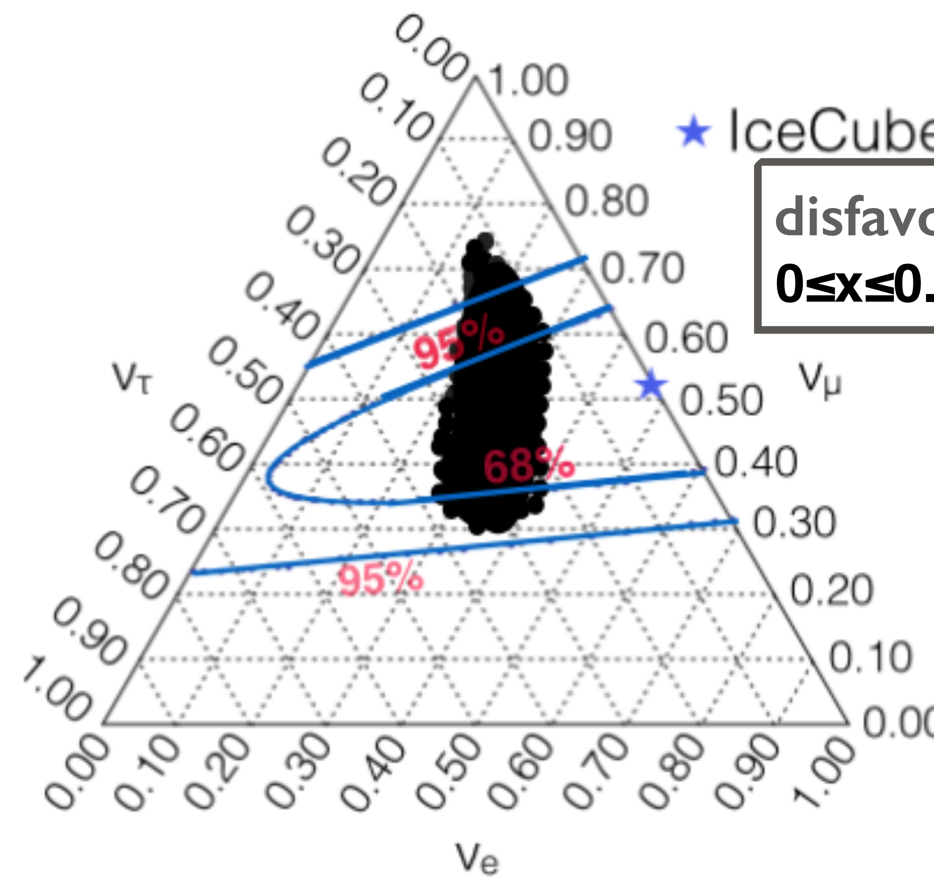
Φ=0



disfavored:
0≤x≤0.5 & 0≤y≤0.03

disfavored:
$0\leq|a_{e\mu}|\leq2.48\times10^{-26}$GeV &
$0\leq|a_{\mu\tau}|\leq1.49\times10^{-27}$GeV

Φ=π/2



disfavored:
0≤x≤0.3 & 0≤y≤0.09

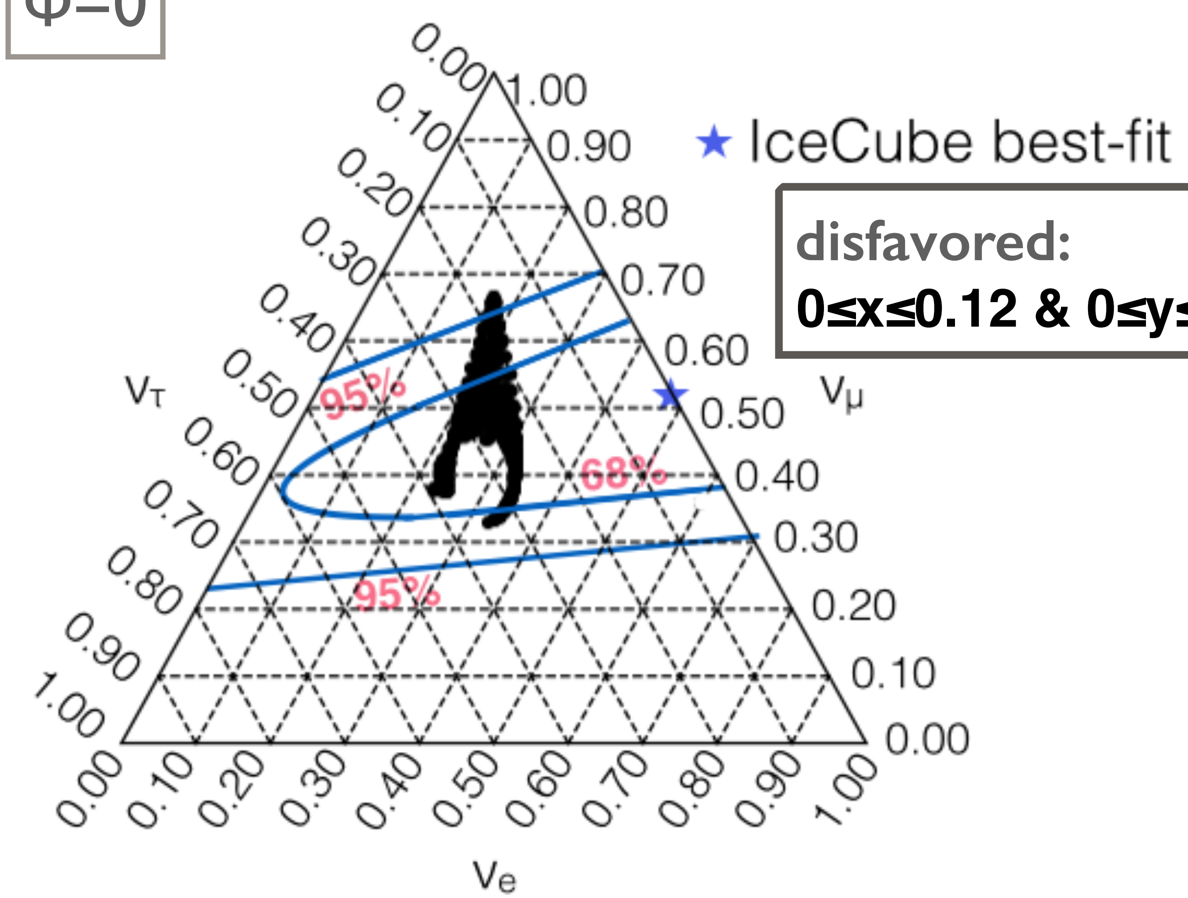
disfavored:
$0\leq|a_{e\mu}|\leq1.49\times10^{-26}$GeV &
$0\leq|a_{\mu\tau}|\leq4.47\times10^{-27}$GeV

NUMERICAL RESULTS :Pγ collisions (π source)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV , $|a_{\mu\tau}|=8.26\times10^{-24}$GeV

first take $|a_{e\tau}|=4.96\times10^{-23}$ GeV

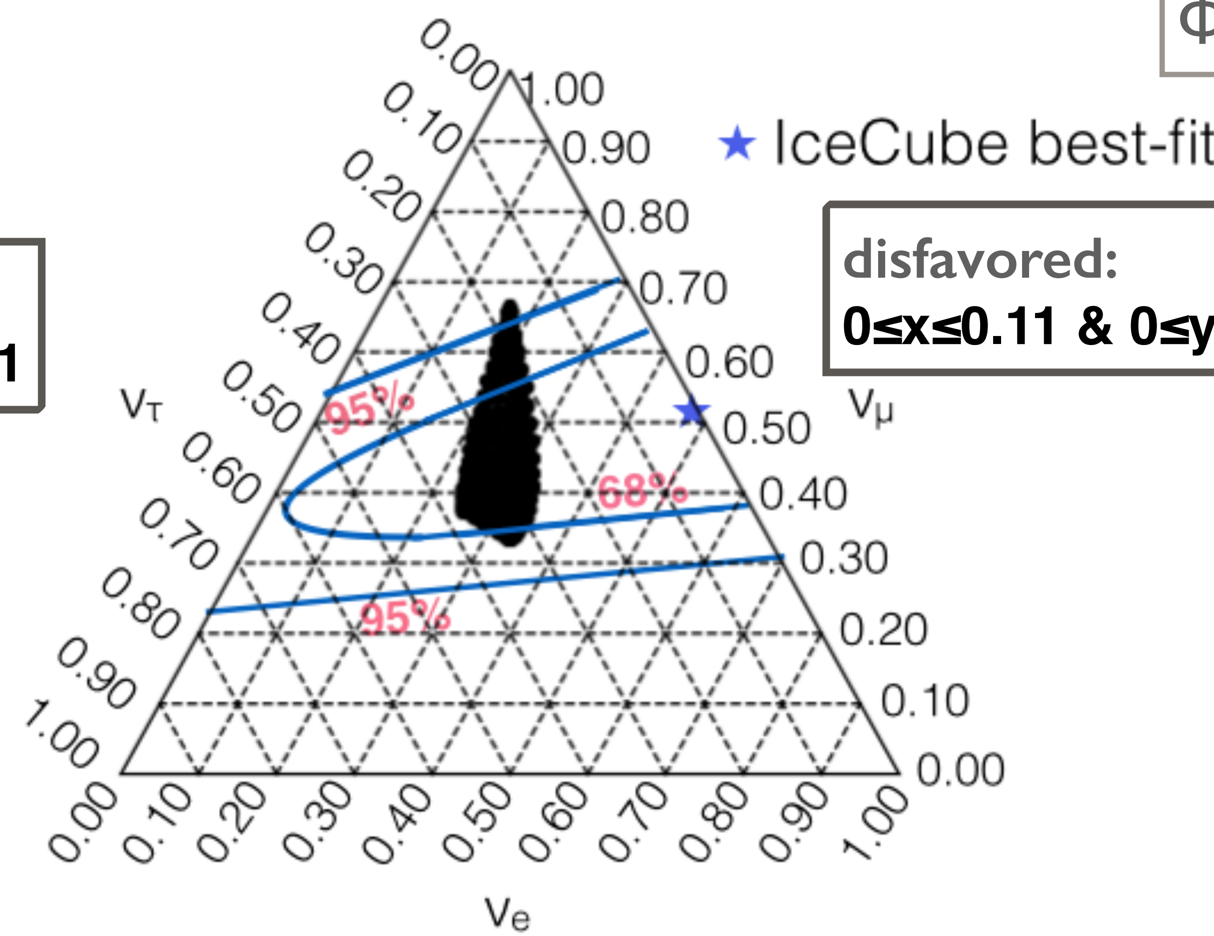
Φ=0



disfavored:
$0\leq x\leq0.12$ & $0\leq y\leq0.11$

disfavored:
$0\leq|a_{e\mu}|\leq5.96\times10^{-24}$GeV & $0\leq|a_{\mu\tau}|\leq5.46\times10^{-24}$GeV

Φ=π/2



disfavored:
$0\leq x\leq0.11$ & $0\leq y\leq0.12$

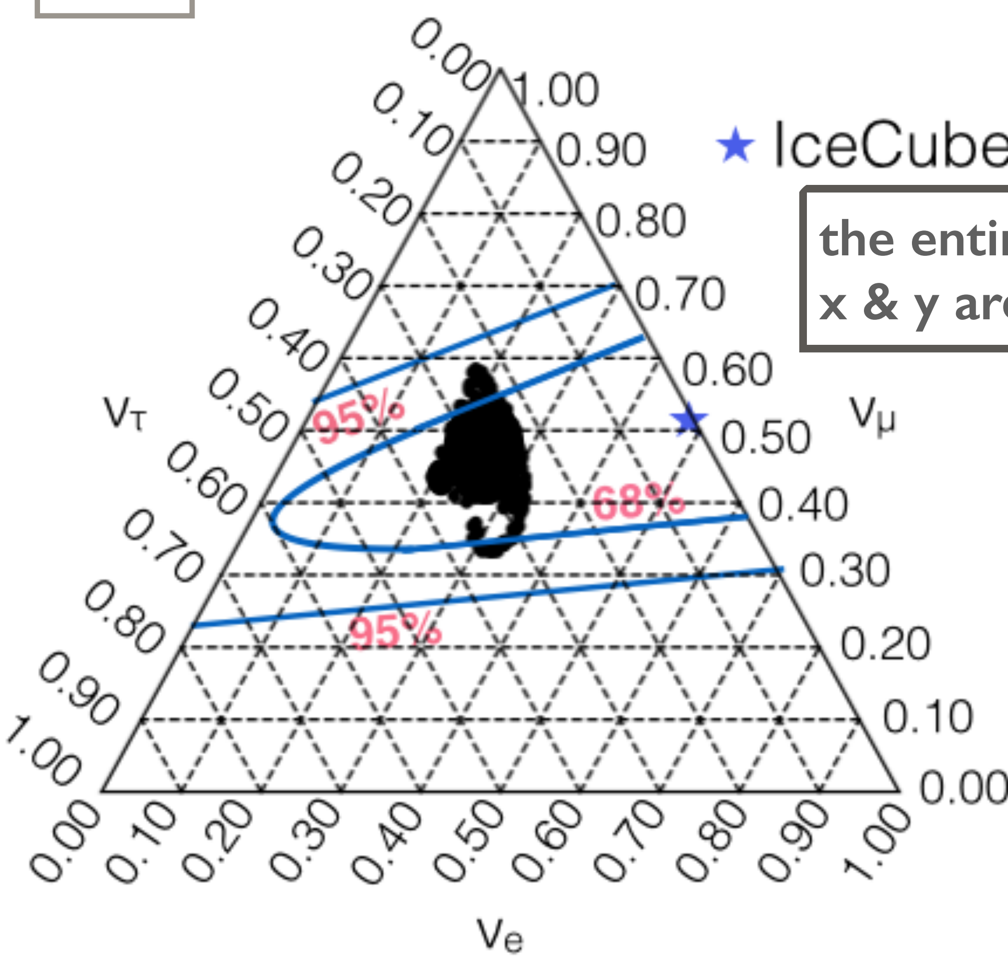
disfavored:
$0\leq|a_{e\mu}|\leq5.46\times10^{-24}$GeV & $0\leq|a_{\mu\tau}|\leq5.96\times10^{-24}$GeV

NUMERICAL RESULTS :Pγ collisions (π source)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV ,
$|a_{\mu\tau}|=8.26\times10^{-24}$GeV

$|a_{e\tau}|=4.96\times10^{-26}$ GeV(lower 3-orders by Super-K)

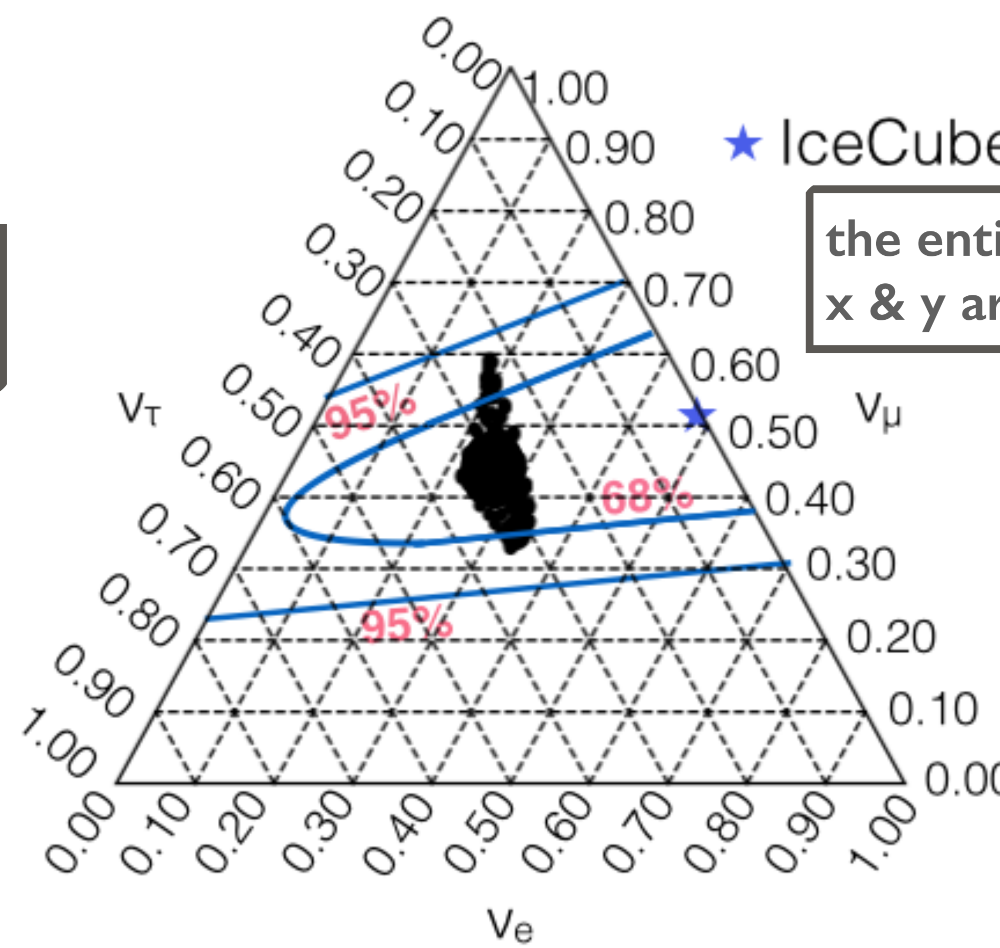
Φ=0



the entire range of x & y are allowed

Any values of $|a_{e\mu}|$ and $|a_{\mu\tau}|$ that are less than $|a_{e\tau}|$ are allowed

Φ=π/2



the entire range of x & y are allowed

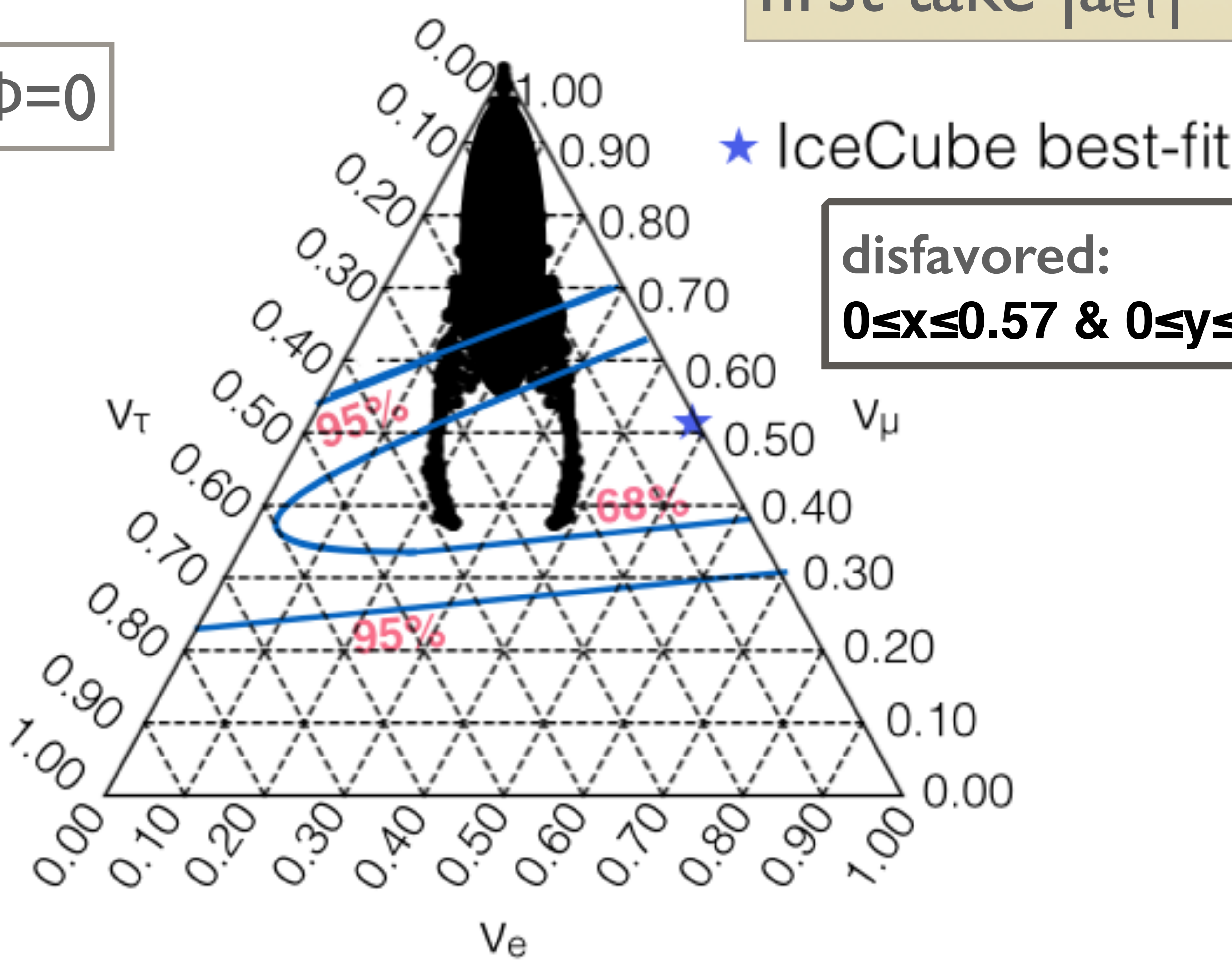
Any values of $|a_{e\mu}|$ and $|a_{\mu\tau}|$ that are less than $|a_{e\tau}|$ are allowed

NUMERICAL RESULTS :PP collisions (μ damped)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV , $|a_{\mu\tau}|=8.26\times10^{-24}$GeV

first take $|a_{e\tau}|=4.96\times10^{-23}$ GeV

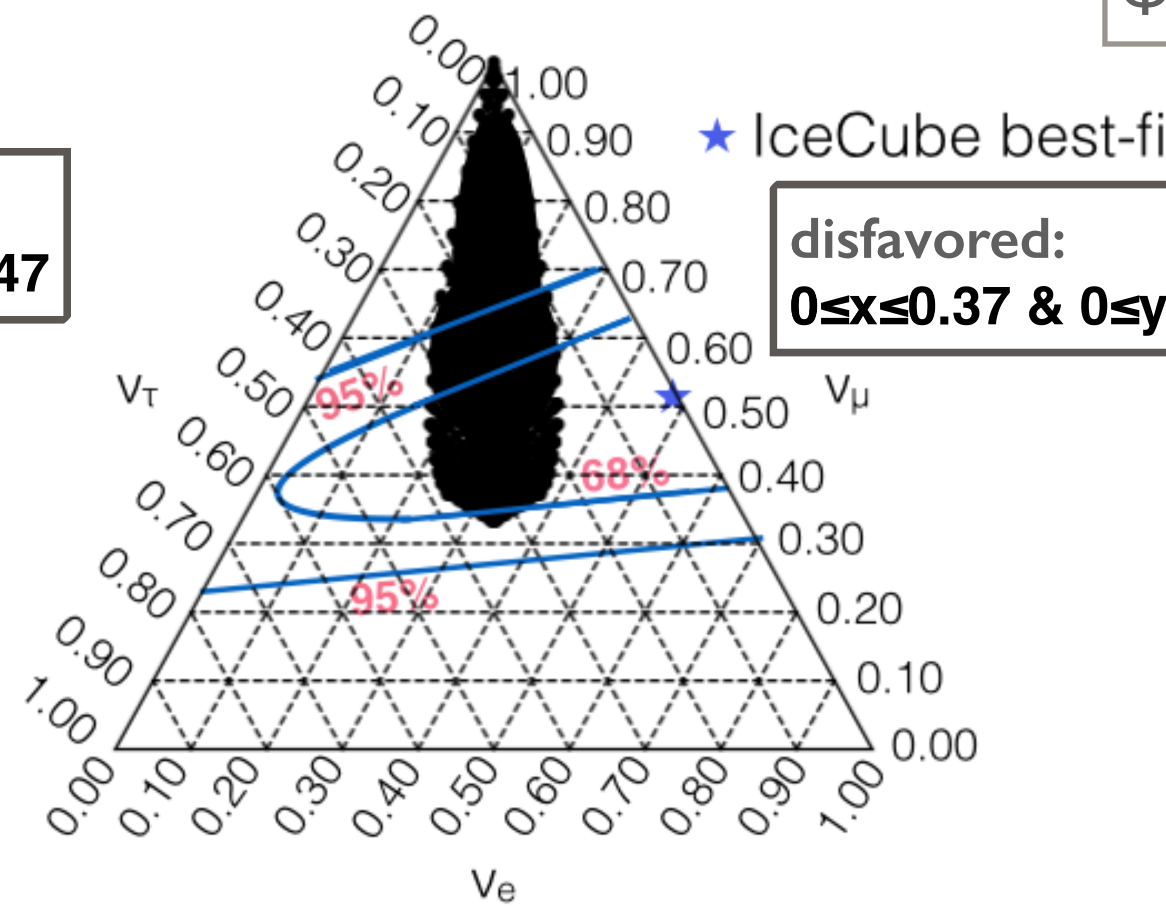
$\Phi=0$



disfavored:
$0\leq x\leq0.57$ & $0\leq y\leq0.47$

disfavored:
$0\leq|a_{e\mu}|\leq2.83\times10^{-23}$GeV &
$0\leq|a_{\mu\tau}|\leq2.33\times10^{-23}$GeV

$\Phi=\pi/2$



disfavored:
$0\leq x\leq0.37$ & $0\leq y\leq0.35$

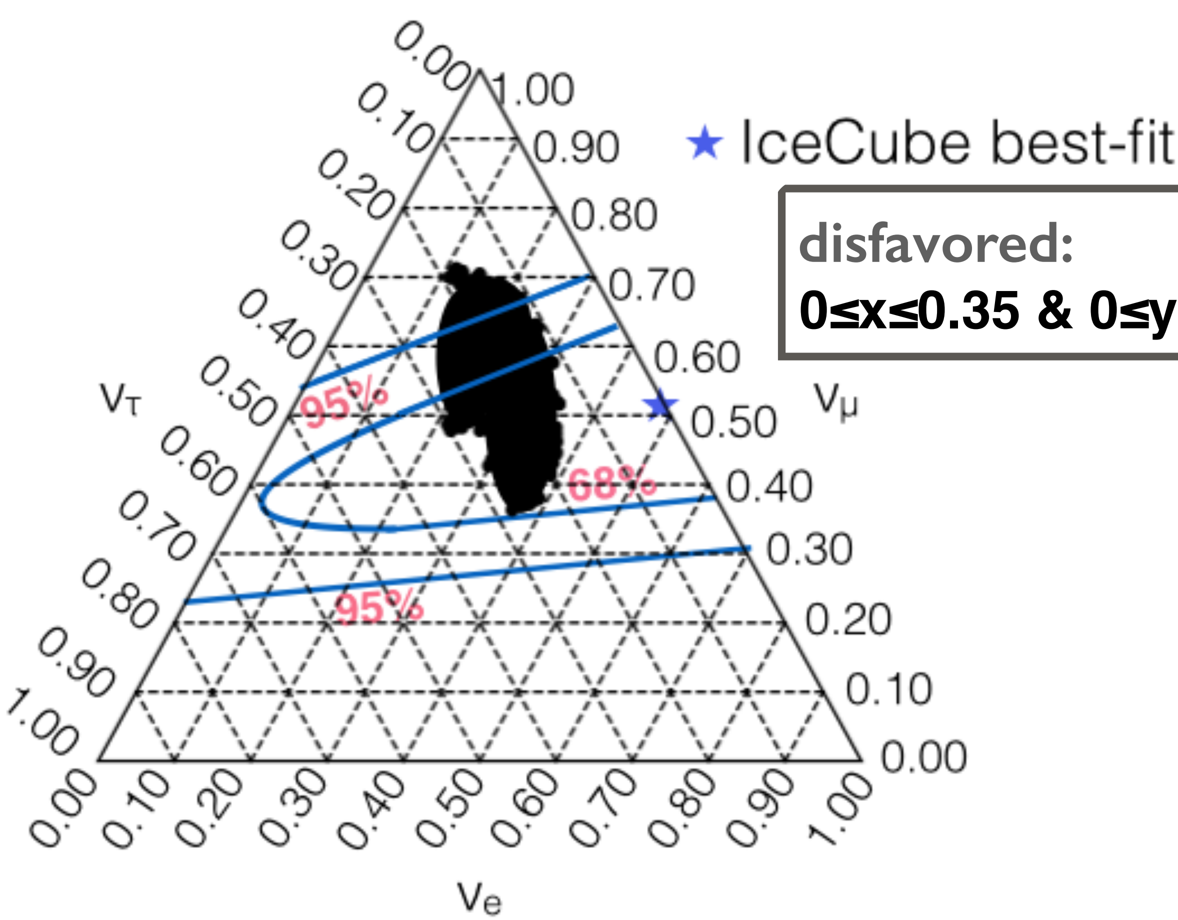
disfavored:
$0\leq|a_{e\mu}|\leq1.84\times10^{-23}$GeV &
$0\leq|a_{\mu\tau}|\leq1.74\times10^{-23}$GeV

NUMERICAL RESULTS :PP collisions (μ damped)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV ,
$|a_{\mu\tau}|=8.26\times10^{-24}$GeV

$|a_{e\tau}|=4.96\times10^{-26}$ GeV(lower 3-orders by Super-K)

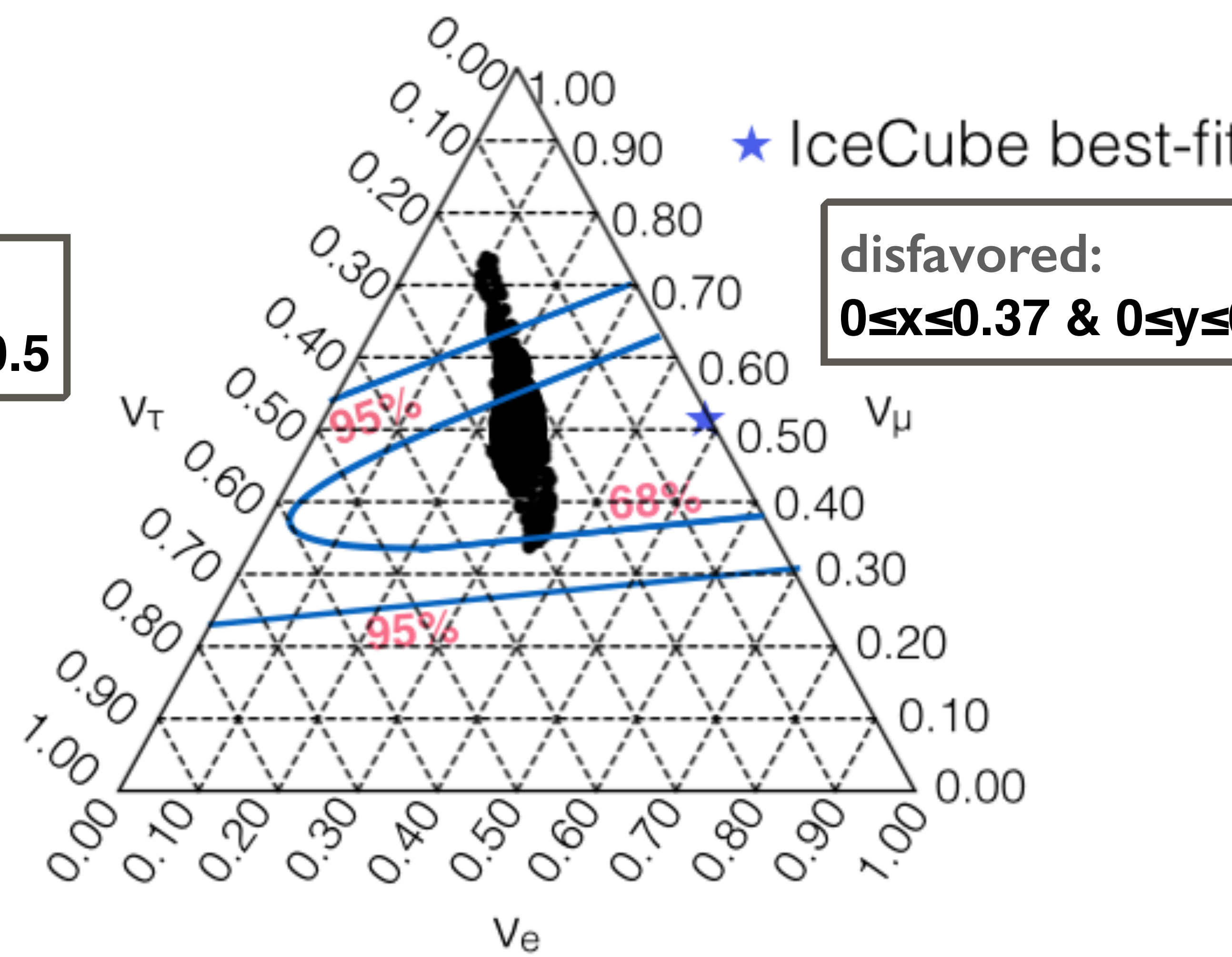
Φ=0



disfavored:
$0\leq x\leq0.35$ & $0\leq y\leq0.5$

disfavored:
$0\leq|a_{e\mu}|\leq1.74\times10^{-26}$GeV &
$0\leq|a_{\mu\tau}|\leq2.48\times10^{-26}$GeV

Φ=π/2



disfavored:
$0\leq x\leq0.37$ & $0\leq y\leq0.35$

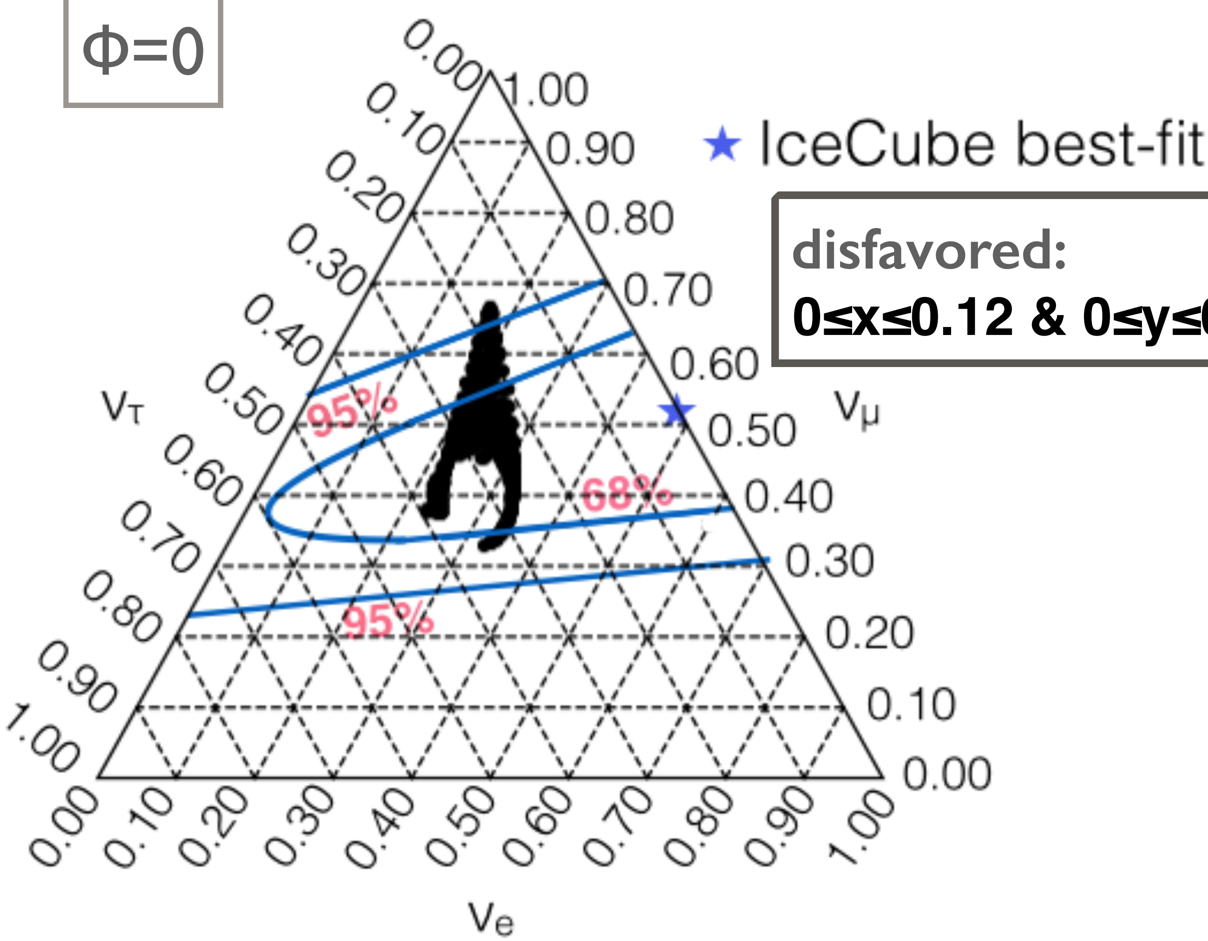
disfavored:
$0\leq|a_{e\mu}|\leq1.54\times10^{-26}$GeV &
$7.94\times10^{-27}\text{GeV}\leq|a_{\mu\tau}|\leq1.69\times10^{-26}$GeV

NUMERICAL RESULTS :PP collisions (π source)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV , $|a_{\mu\tau}|=8.26\times10^{-24}$GeV

first take $|a_{e\tau}|=4.96\times10^{-23}$ GeV

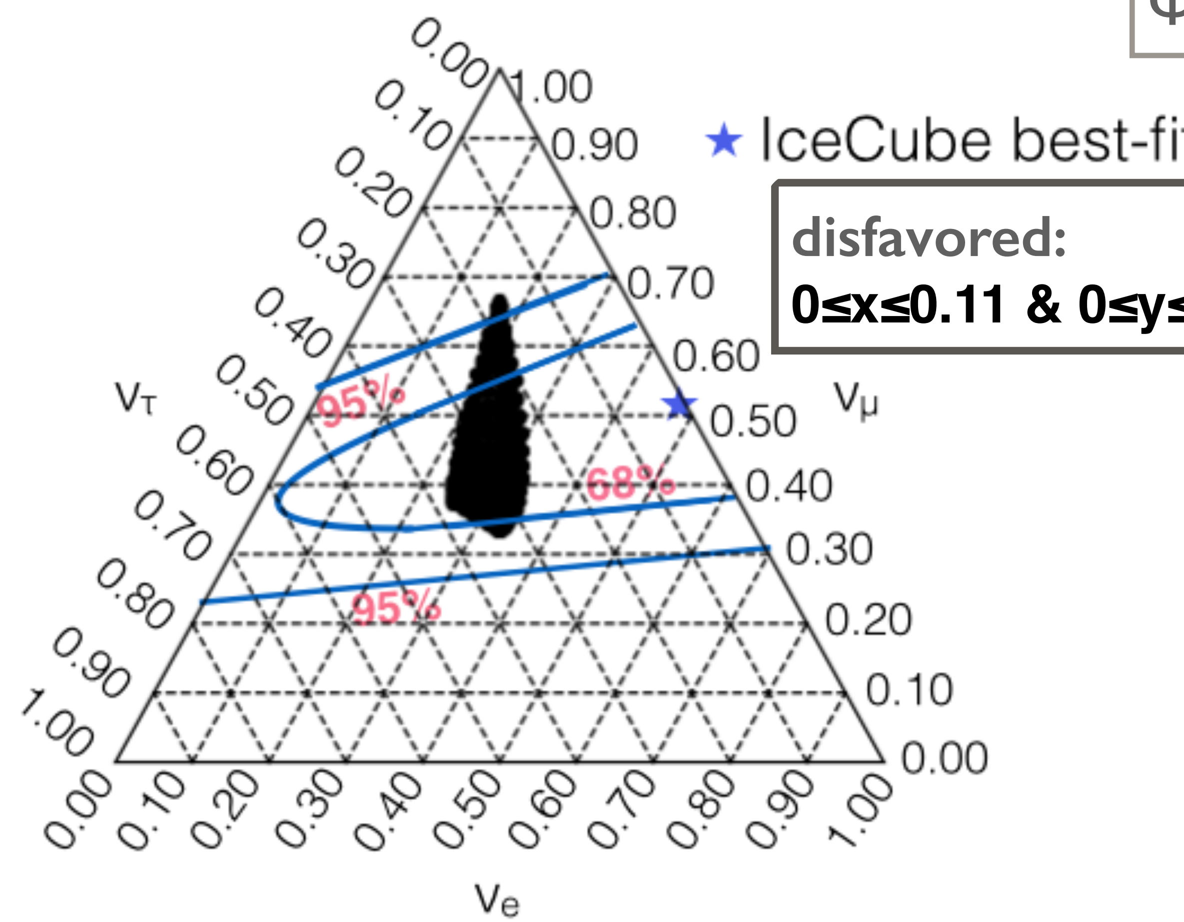
$\Phi=0$



disfavored:
$0\le x\le0.12$ & $0\le y\le0.11$

disfavored:
$0\le|a_{e\mu}|\le5.96\times10^{-24}$GeV &
$0\le|a_{\mu\tau}|\le5.46\times10^{-24}$GeV

$\Phi=\pi/2$



disfavored:
$0\le x\le0.11$ & $0\le y\le0.12$

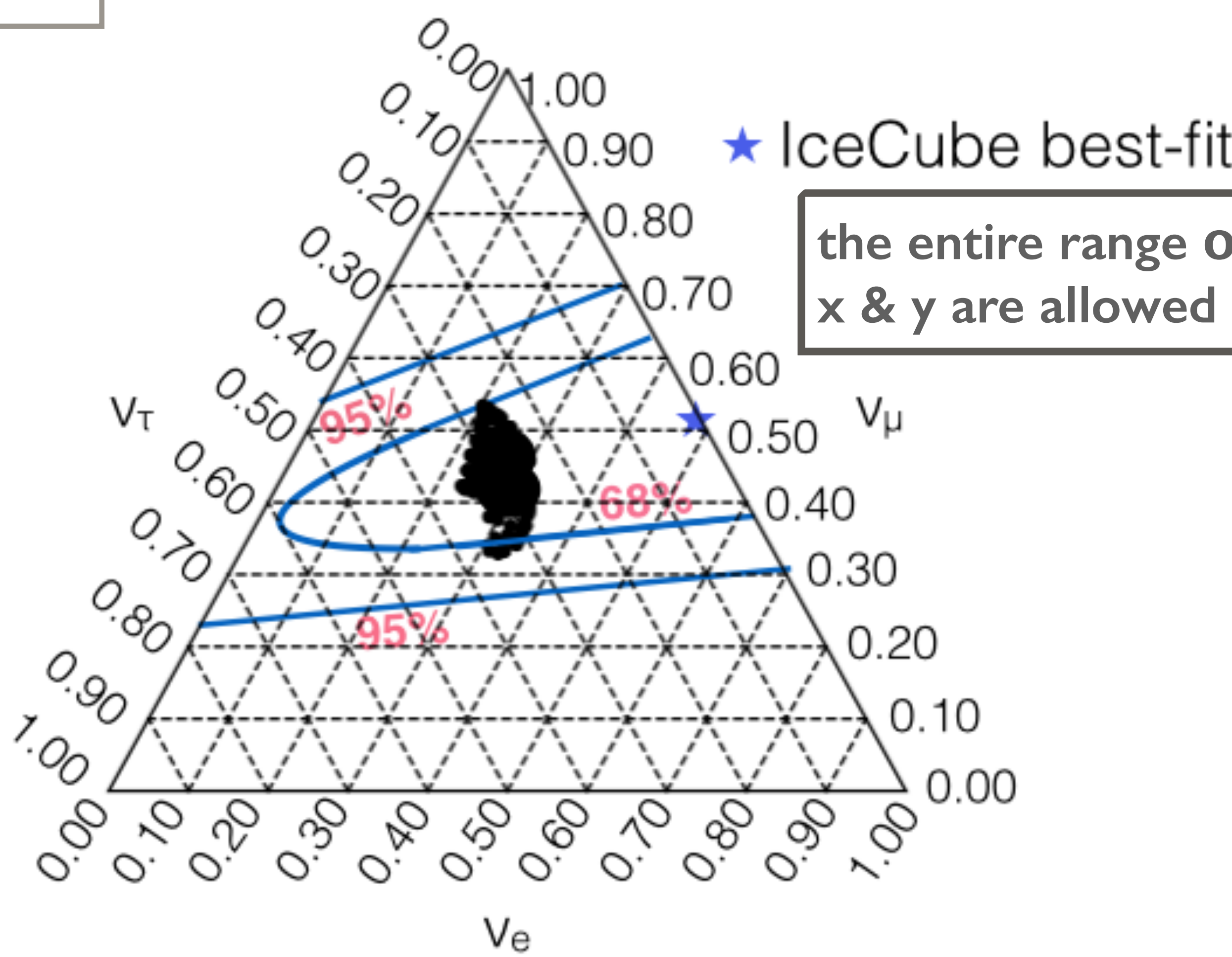
disfavored:
$0\le|a_{e\mu}|\le5.46\times10^{-24}$GeV &
$0\le|a_{\mu\tau}|\le5.96\times10^{-24}$GeV

NUMERICAL RESULTS :PP collisions (π source)

Super-K 95% C.L. :
$|a_{e\tau}|=4.96\times10^{-23}$ GeV, $|a_{e\mu}|=2.55\times10^{-23}$GeV , $|a_{\mu\tau}|=8.26\times10^{-24}$GeV

$|a_{e\tau}|=4.96\times10^{-26}$ GeV(lower 3-orders by Super-K)

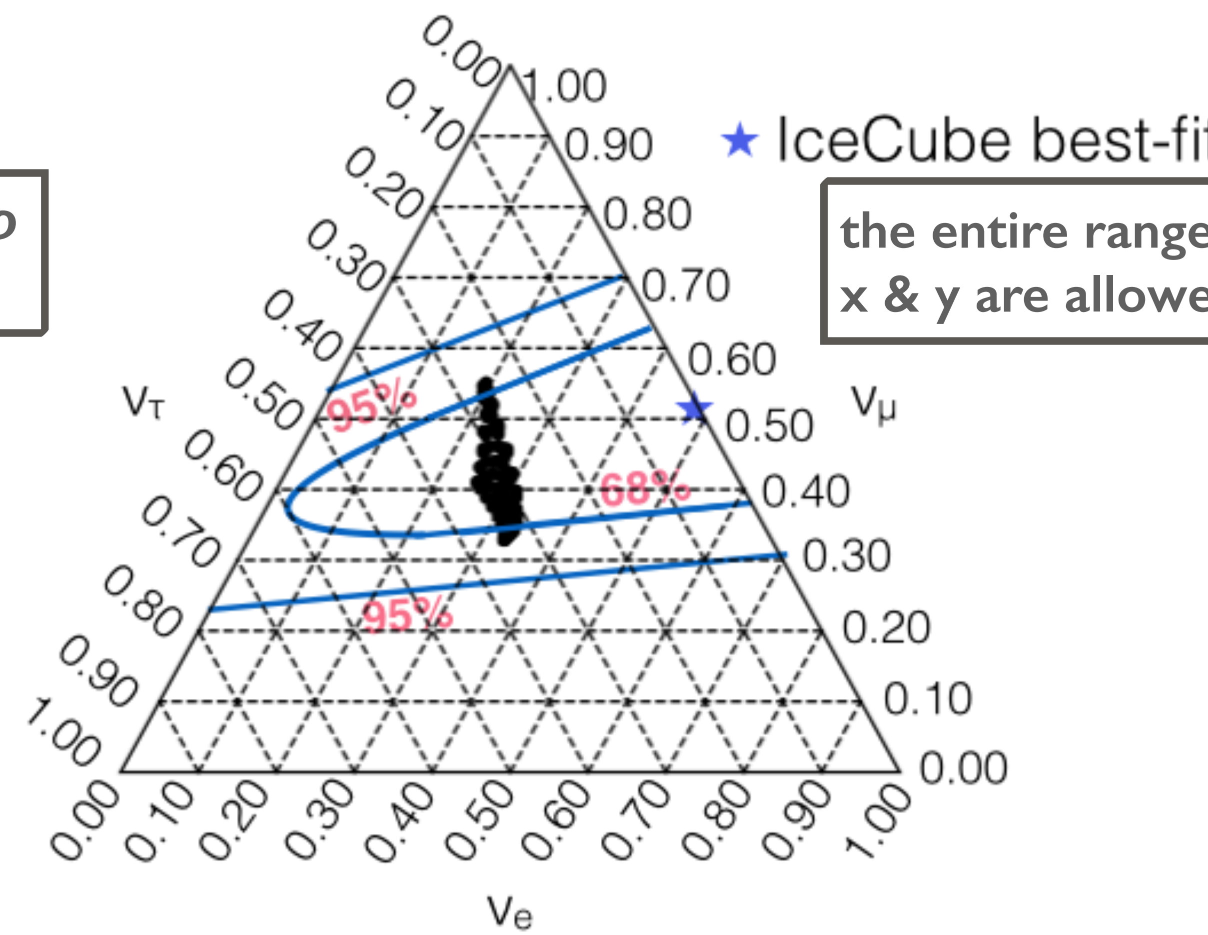
$\Phi=0$



the entire range oφ x & y are allowed

Any values of $|a_{e\mu}|$ and $|a_{\mu\tau}|$ that are less than $|a_{e\tau}|$ are allowed

$\Phi=\pi/2$



the entire range oφ x & y are allowed

Any values of $|a_{e\mu}|$ and $|a_{\mu\tau}|$ that are less than $|a_{e\tau}|$ are allowed

The limits on “c” terms

$$H_{tot(\nu)} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
$$+ \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & 0 & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & 0 \end{pmatrix}$$

$$H_{tot(\bar{\nu})} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger - \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
$$- \begin{pmatrix} 0 & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & 0 & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & 0 \end{pmatrix}^* - \frac{4E}{3} \begin{pmatrix} 0 & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & 0 & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & 0 \end{pmatrix}^*$$

- If we turn off the “a” term, the limits on $E \times C_{e\mu, e\tau, \mu\tau}$ are similar to those on $a_{e\mu, e\tau, \mu\tau}$

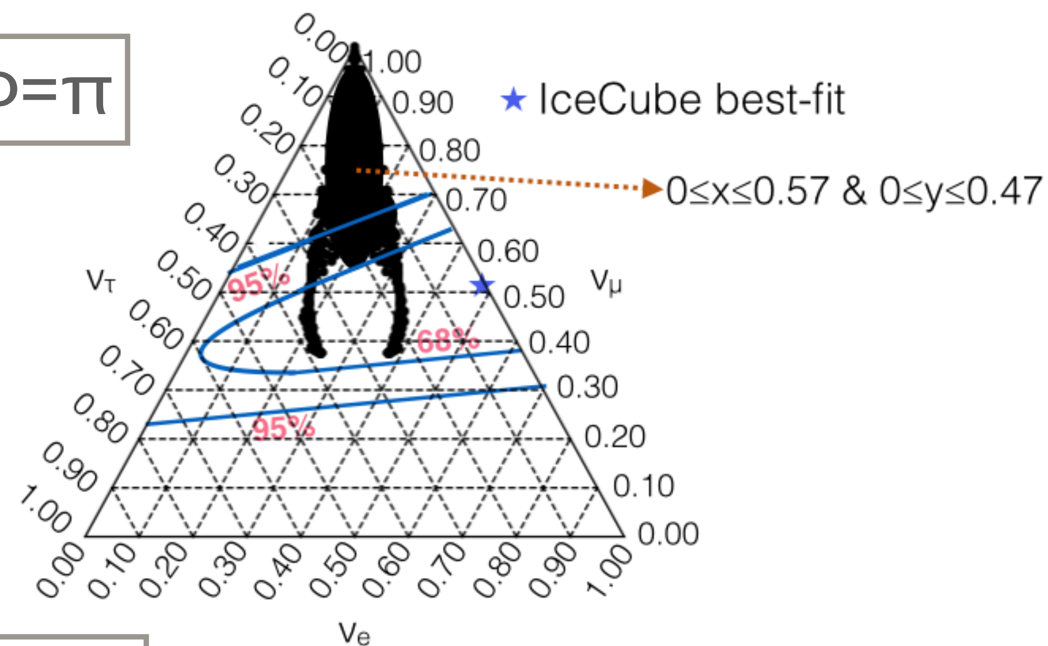
SUMMARY

- We computed the flavor ratio at the detector which includes the standard oscillation and "a" term of Lorentz violation at $E_\nu \geq 25$TeV.
- In the $a_{e\tau}$ dominant scenario, we can set better limit on Lorentz violation parameters by using IceCube high energy neutrino flavor analysis.
- If the IceCube detected high energy neutrinos are due to μ damped source, then the limits on the Lorentz violation parameters are more stringent than the case of π source.

Back up

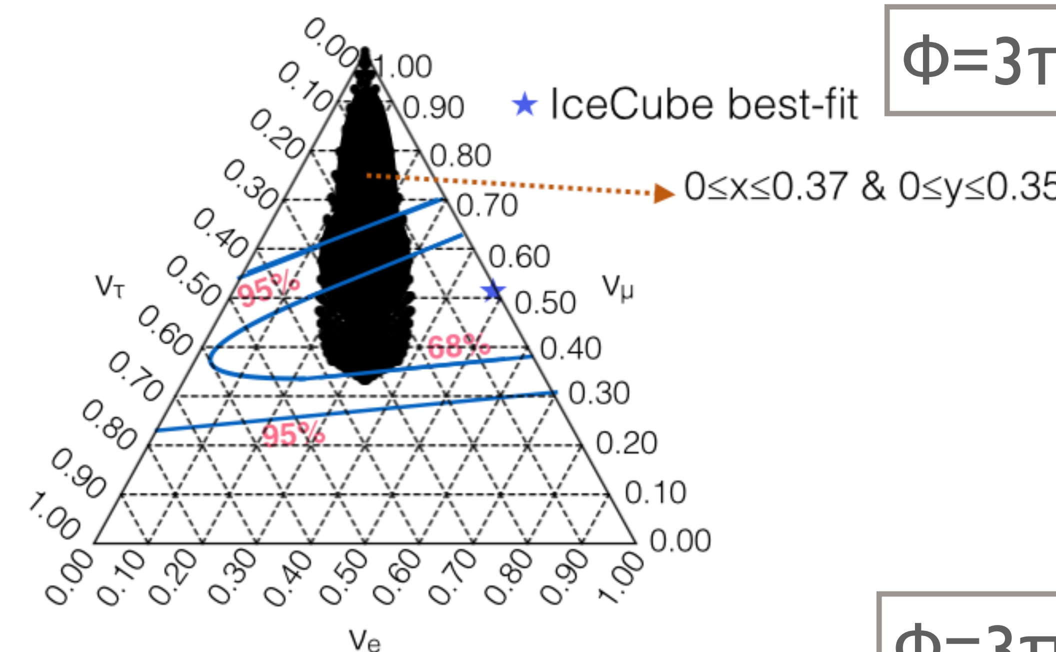
NUMERICAL RESULTS OF Pγ

$\Phi=\pi$

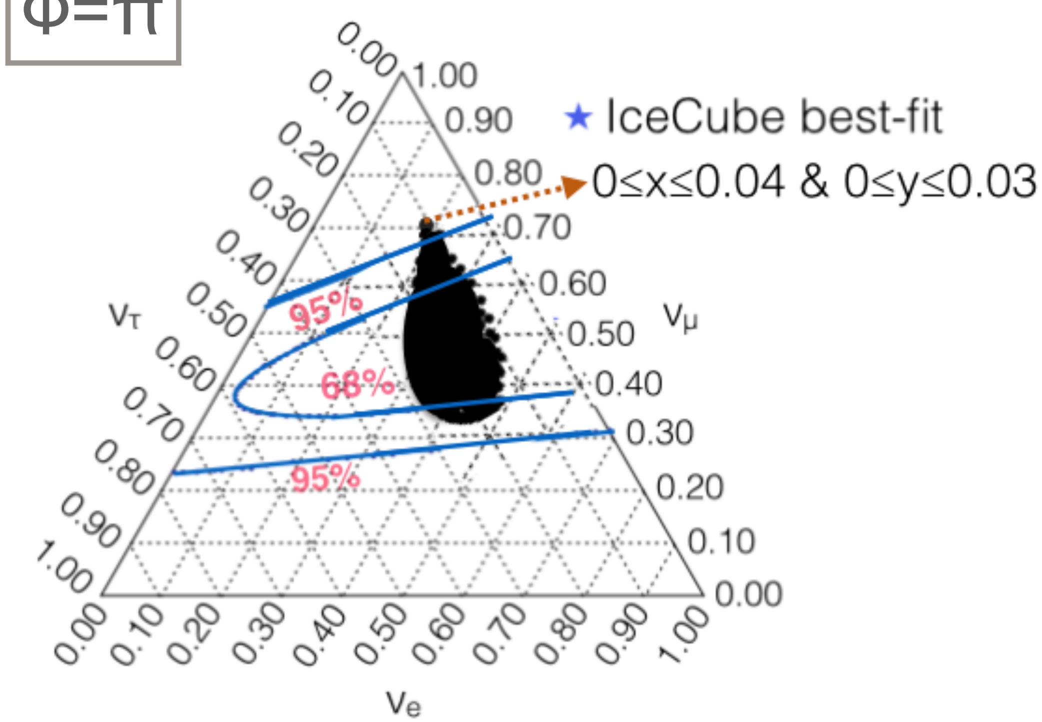


$a_{e\tau}=10^{-14}$

$\Phi=3\pi/2$

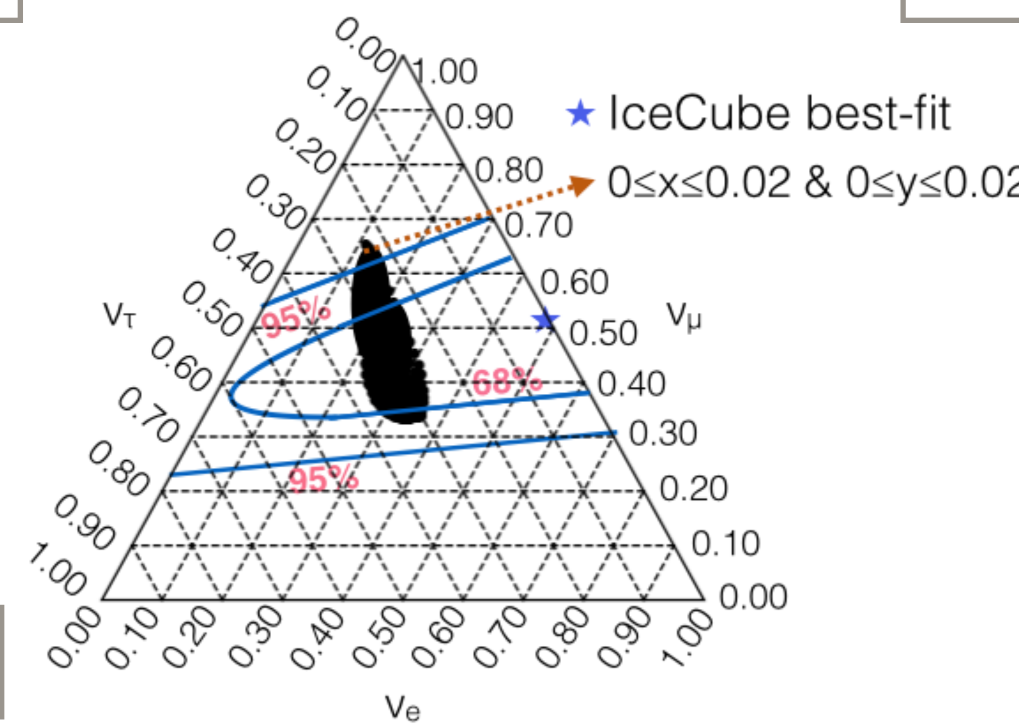


$\Phi=\pi$



μ damped

$\Phi=3\pi/2$

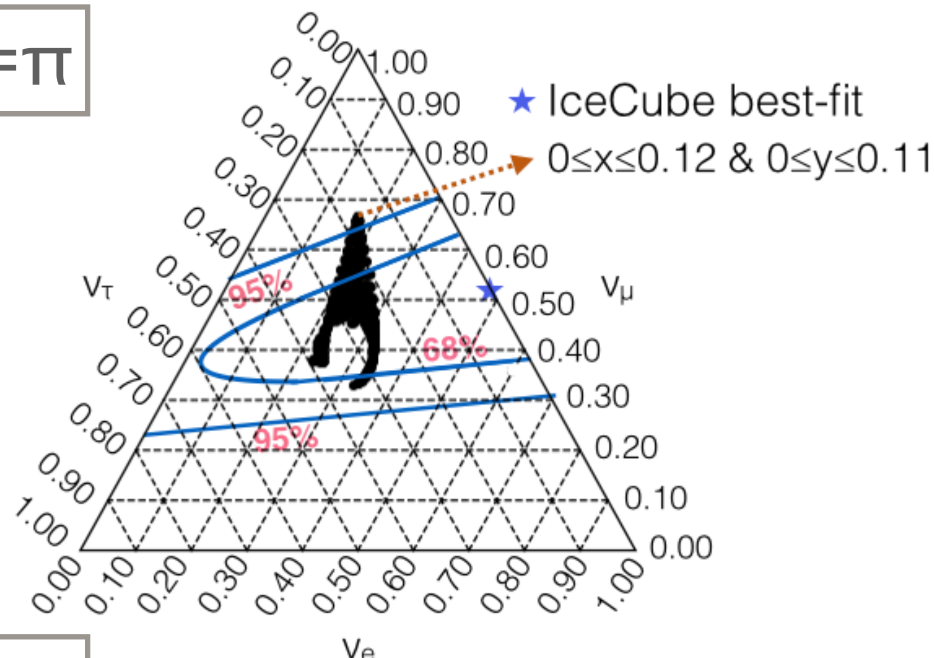


$a_{e\tau}=10^{-17}$

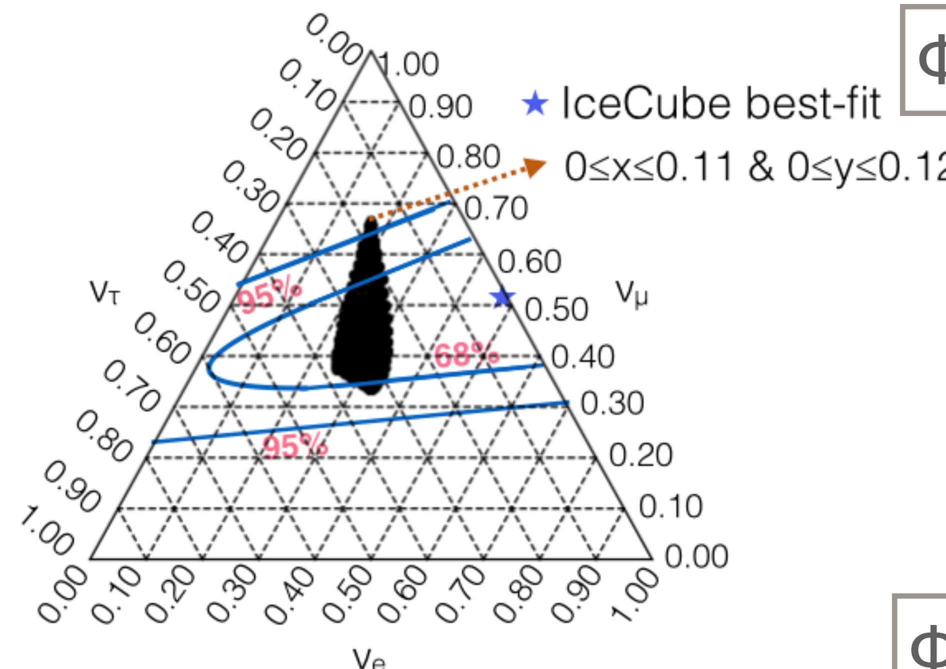
NUMERICAL RESULTS OF Pγ

$a_{e\tau}=10^{-14}$

Φ=π

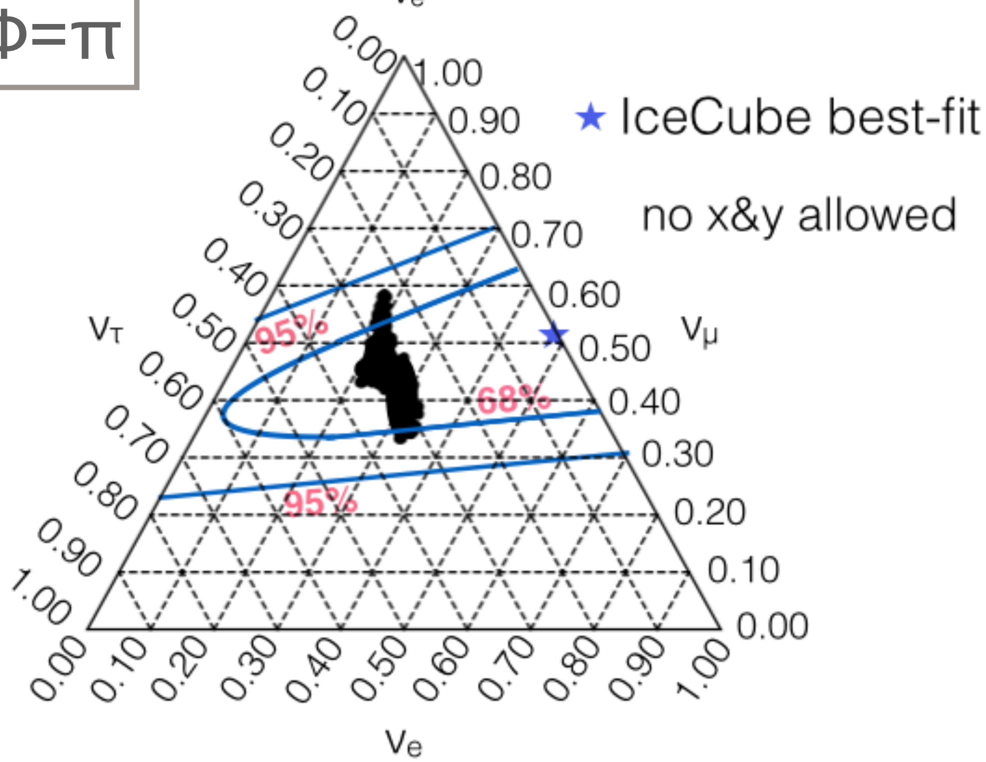


Φ=3π/2

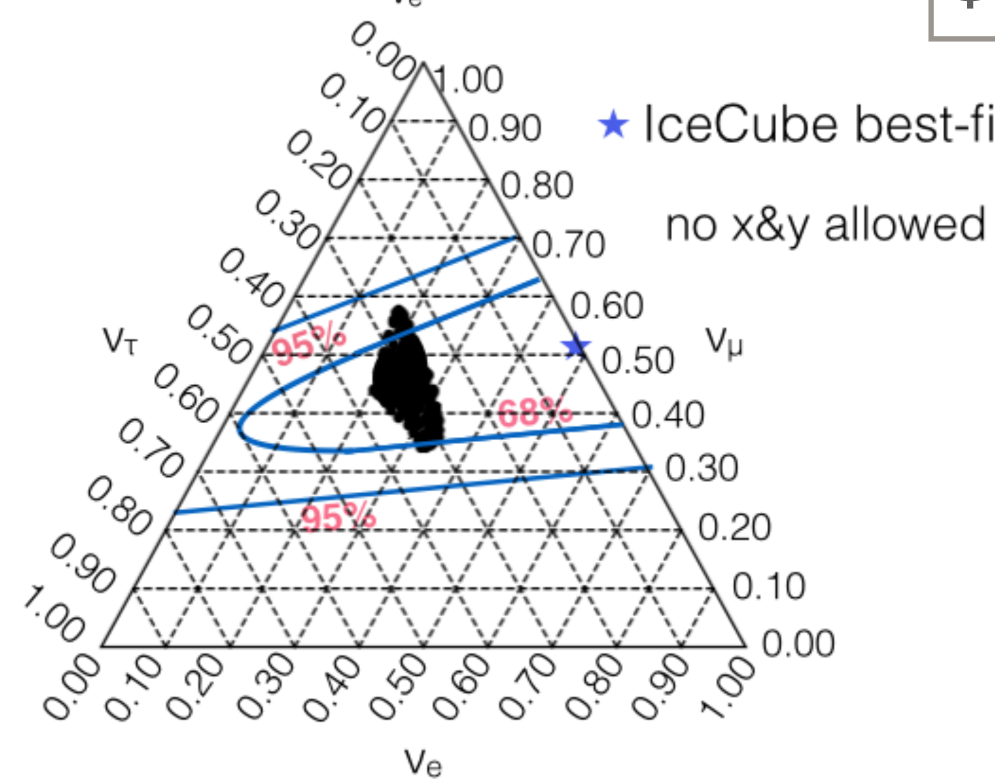


π source

Φ=π



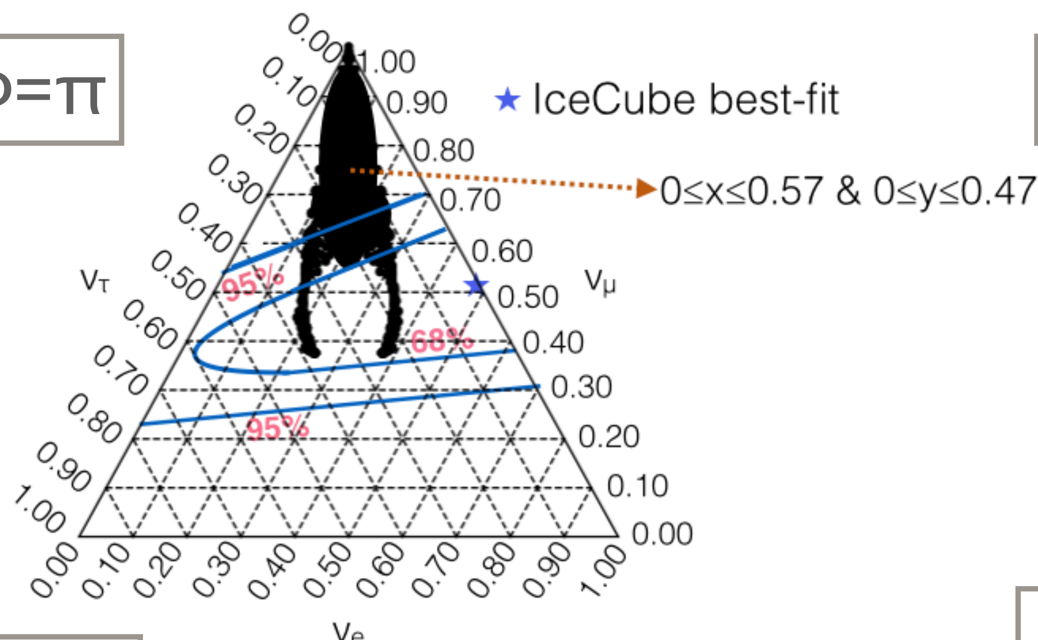
Φ=3π/2



$a_{e\tau}=10^{-17}$

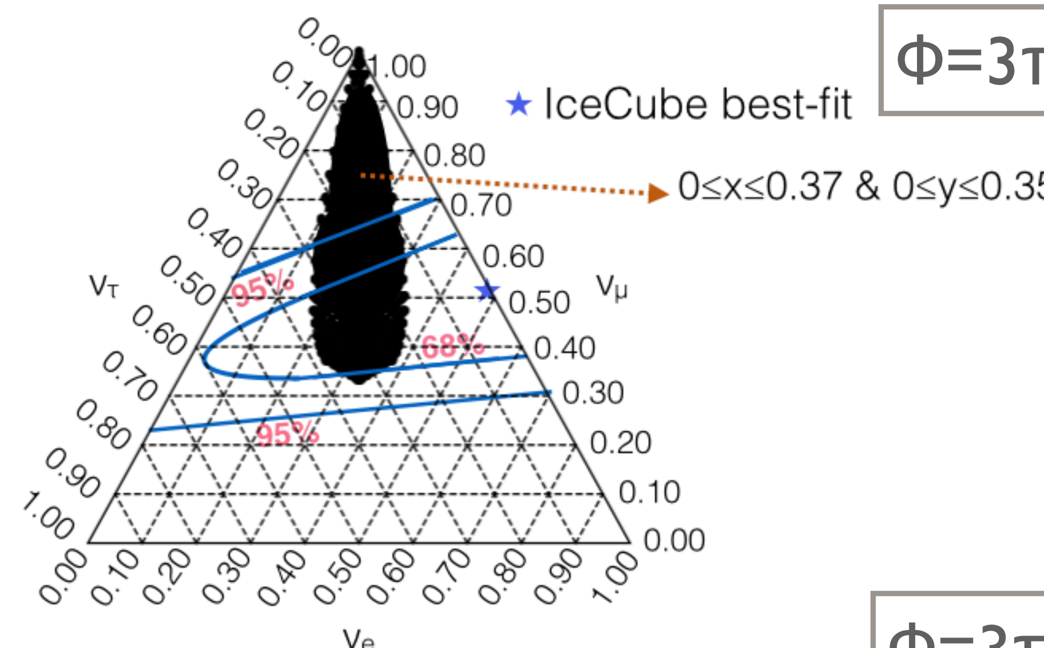
NUMERICAL RESULTS OF PP

Φ=π



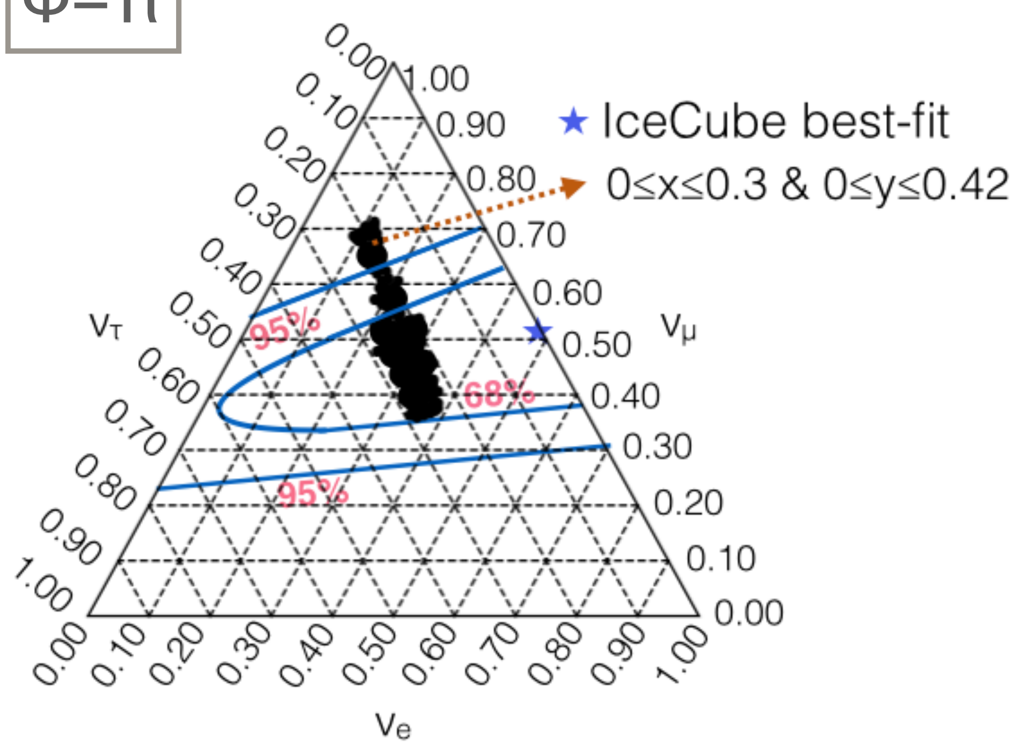
$a_{e\tau}=10^{-14}$

Φ=3π/2

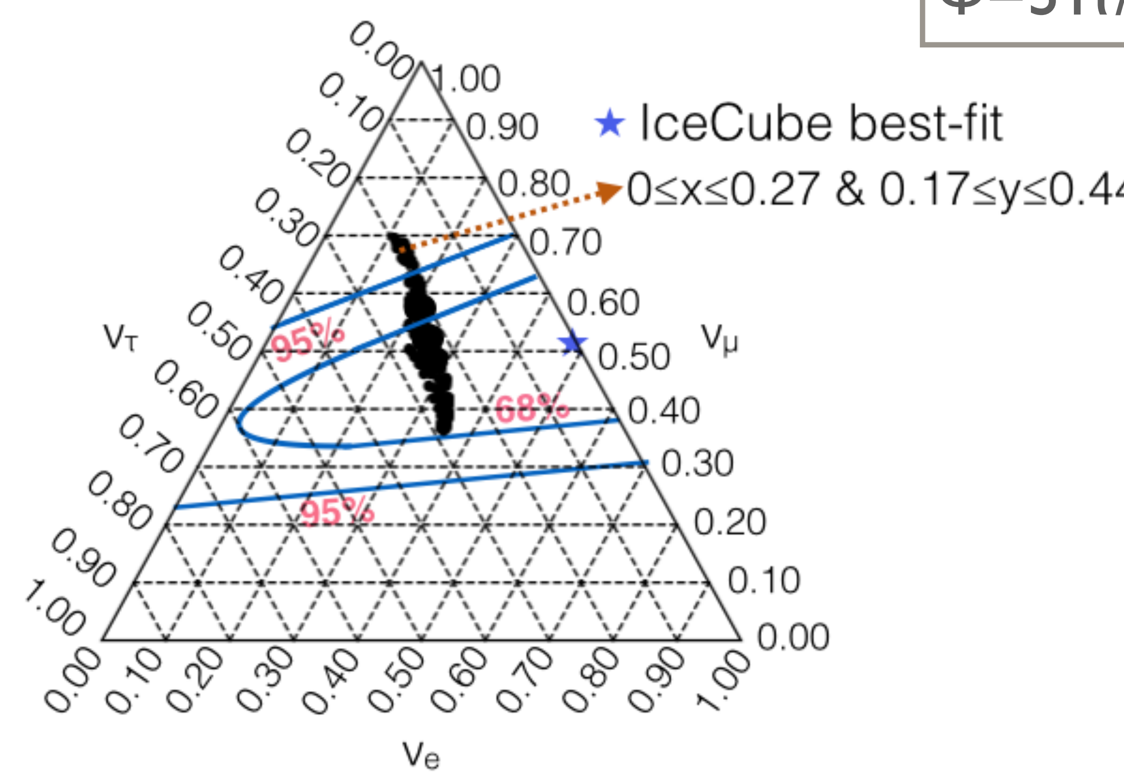


μ damped

Φ=π



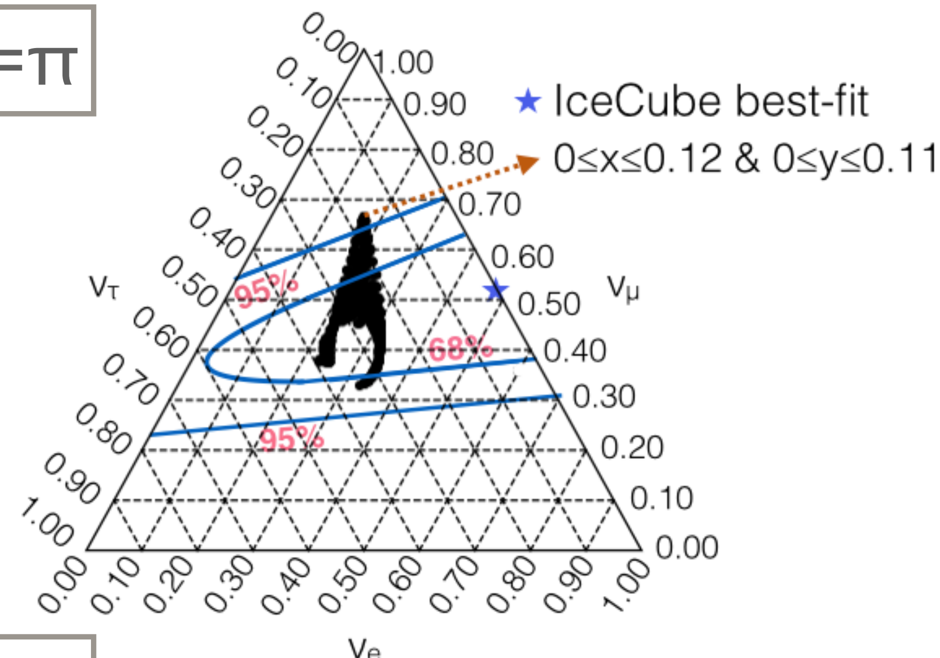
Φ=3π/2



$a_{e\tau}=10^{-17}$

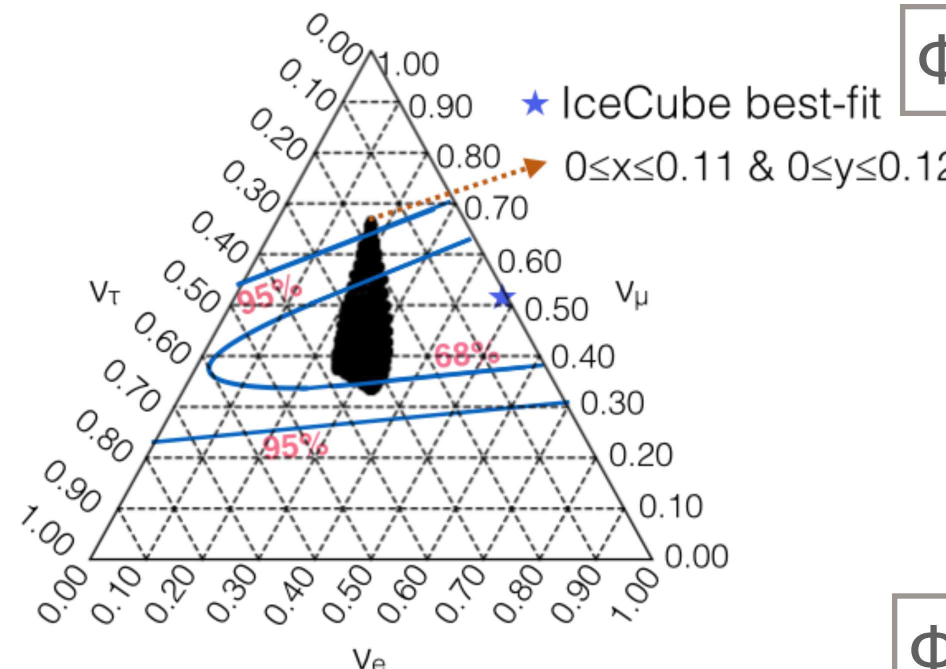
NUMERICAL RESULTS OF PP

Φ=π



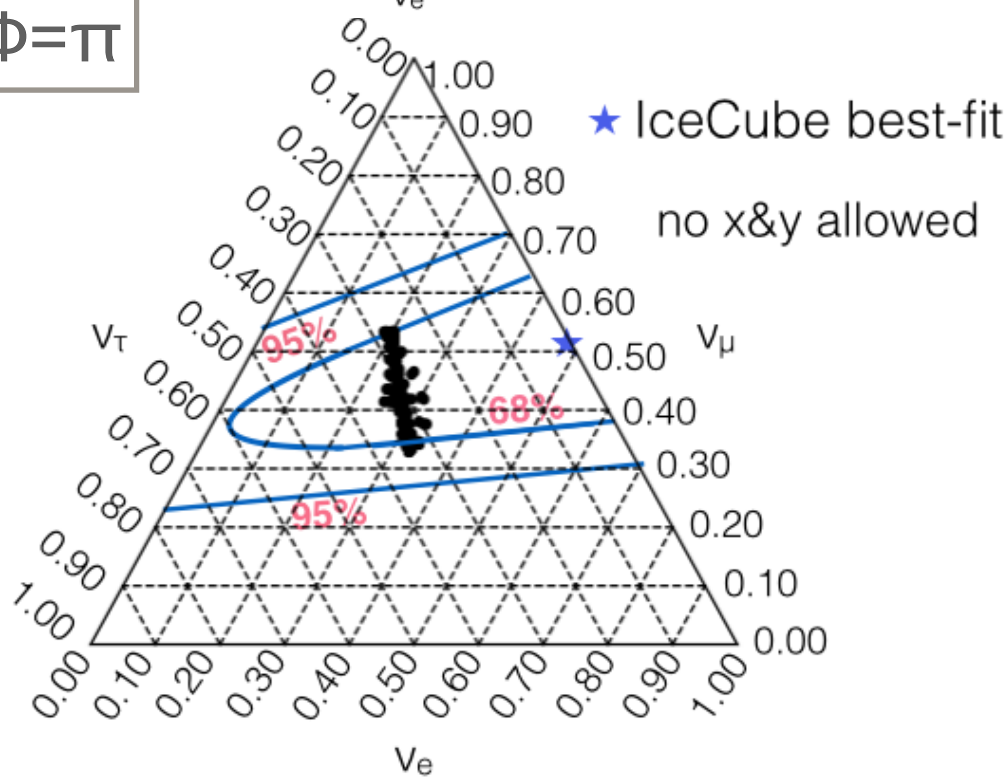
$a_{e\tau}=10^{-14}$

Φ=3π/2

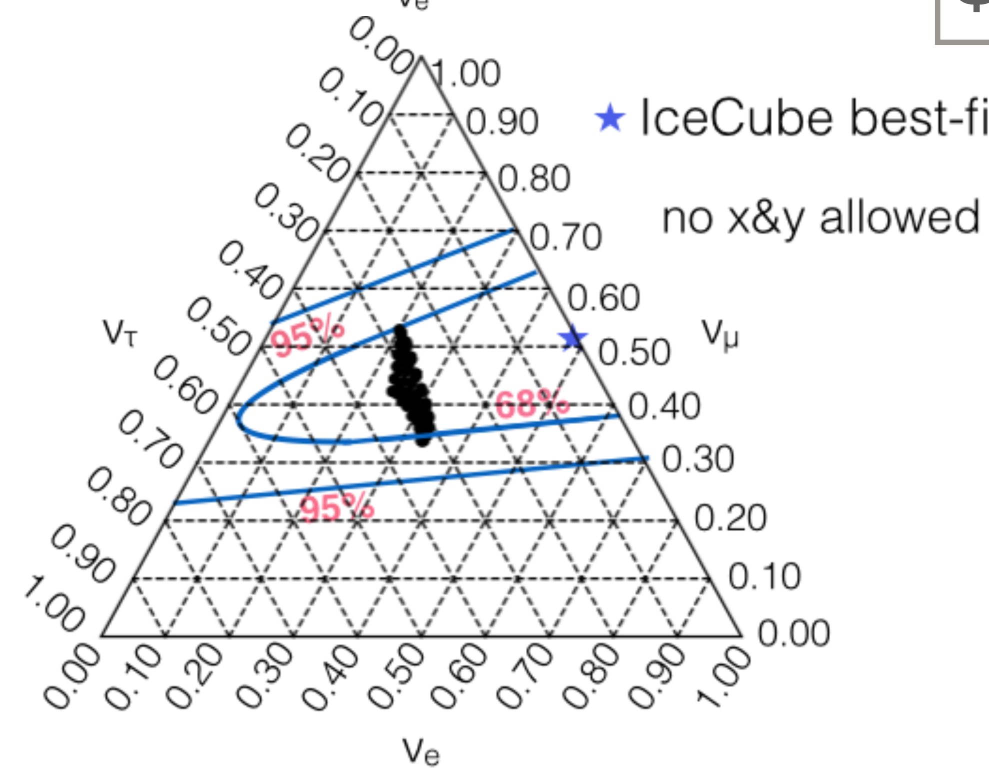


π source

Φ=π



Φ=3π/2



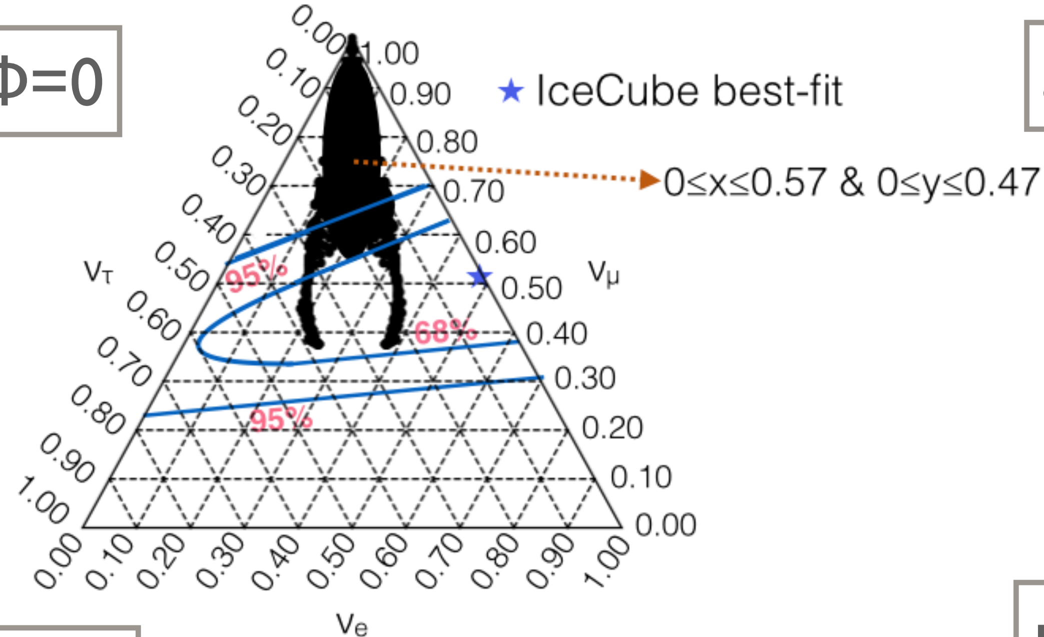
$a_{e\tau}=10^{-17}$

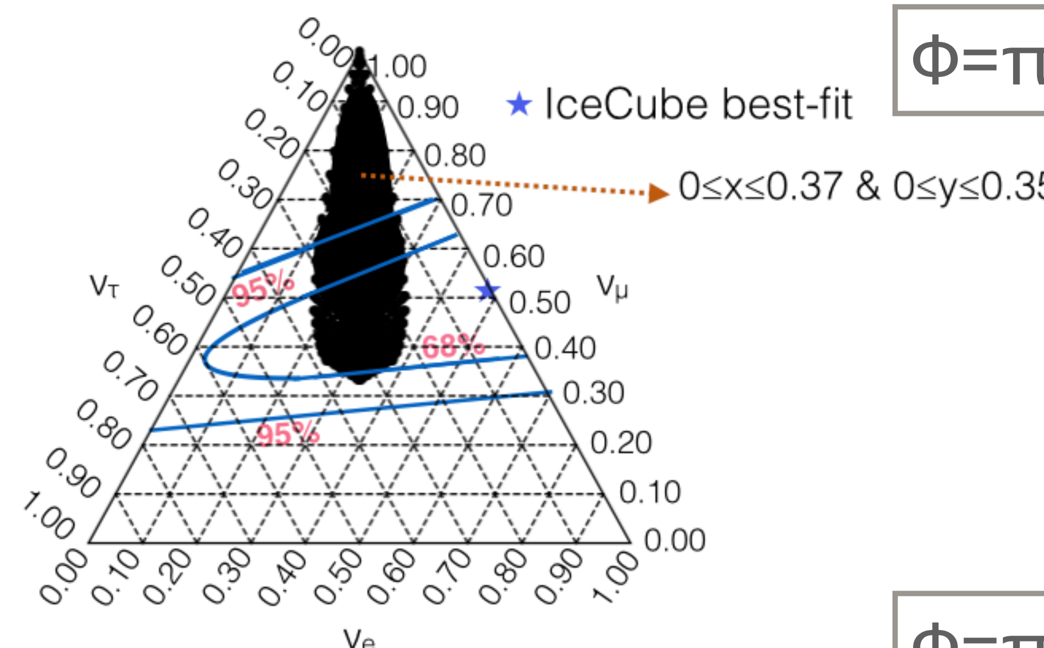
NUMERICAL RESULTS OF Pγ

$\Phi=0$

$a_{e\tau}=10^{-15}$

$\Phi=\pi/2$

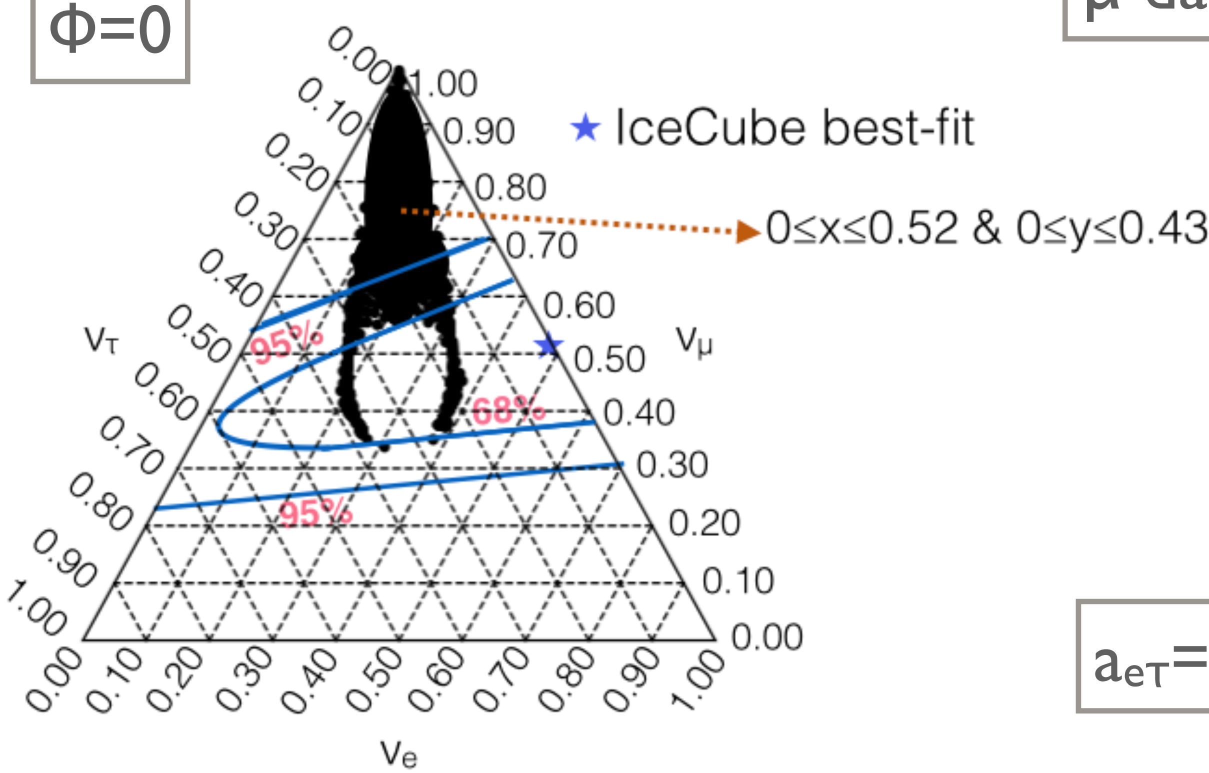


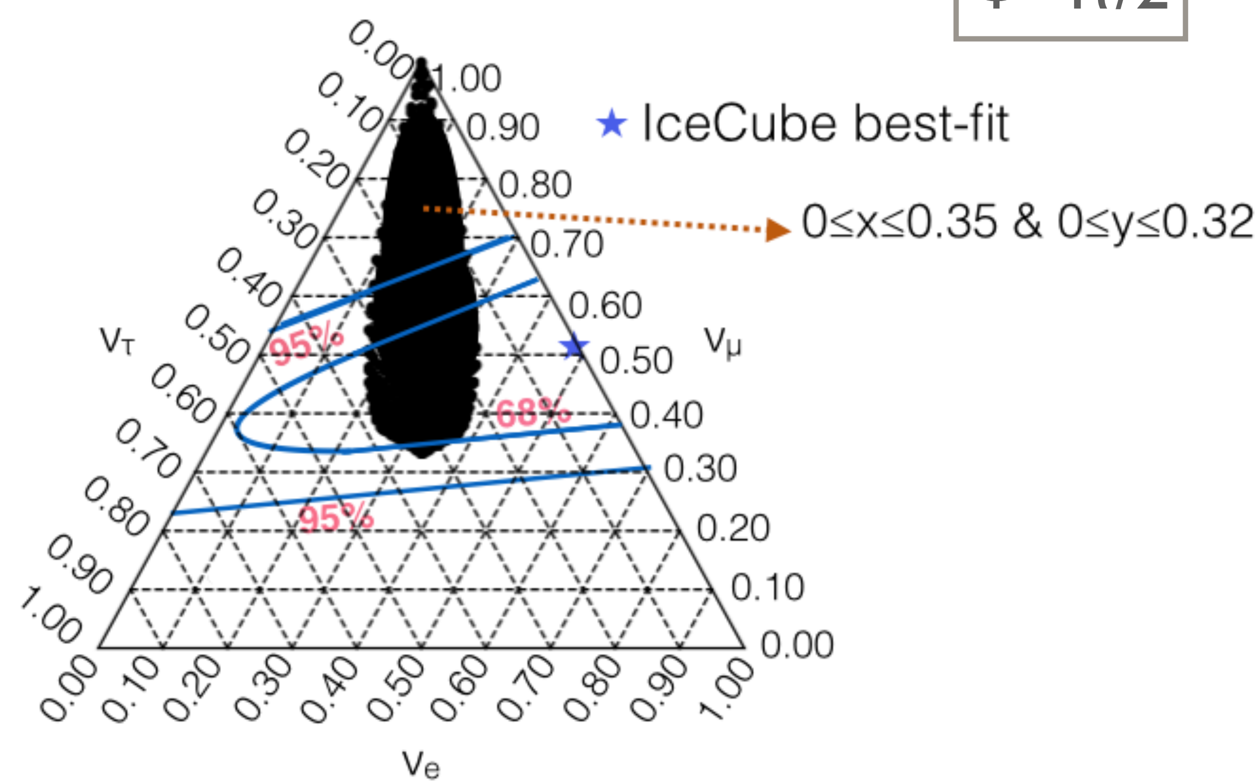


μ damped

$\Phi=0$

$\Phi=\pi/2$



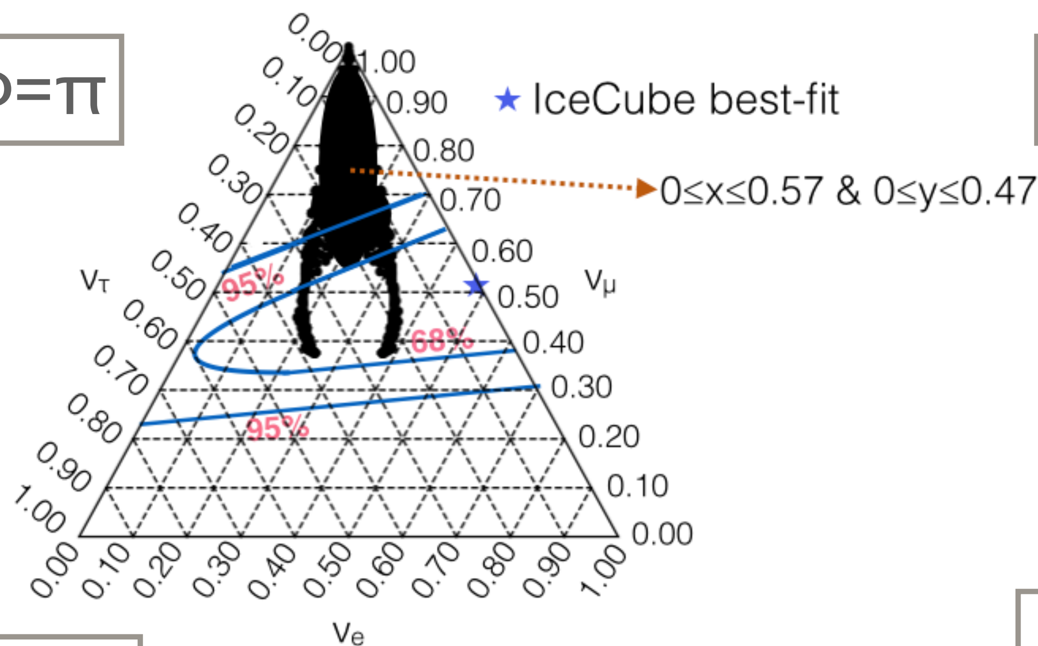


$a_{e\tau}=10^{-16}$

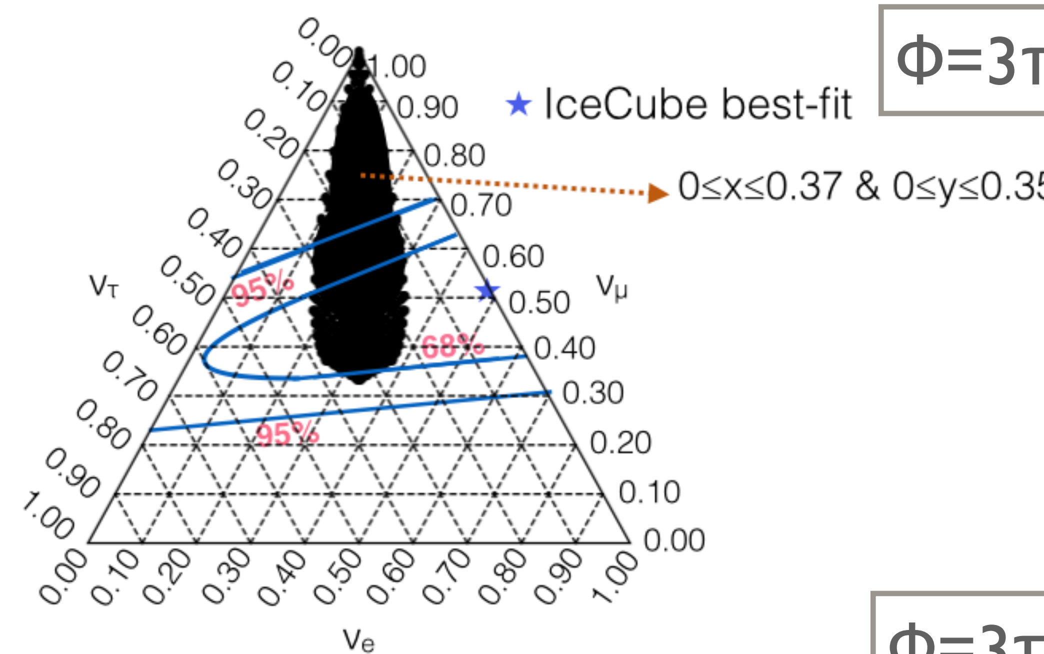
NUMERICAL RESULTS OF Pγ

$\Phi=\pi$

$a_{e\tau}=10^{-15}$

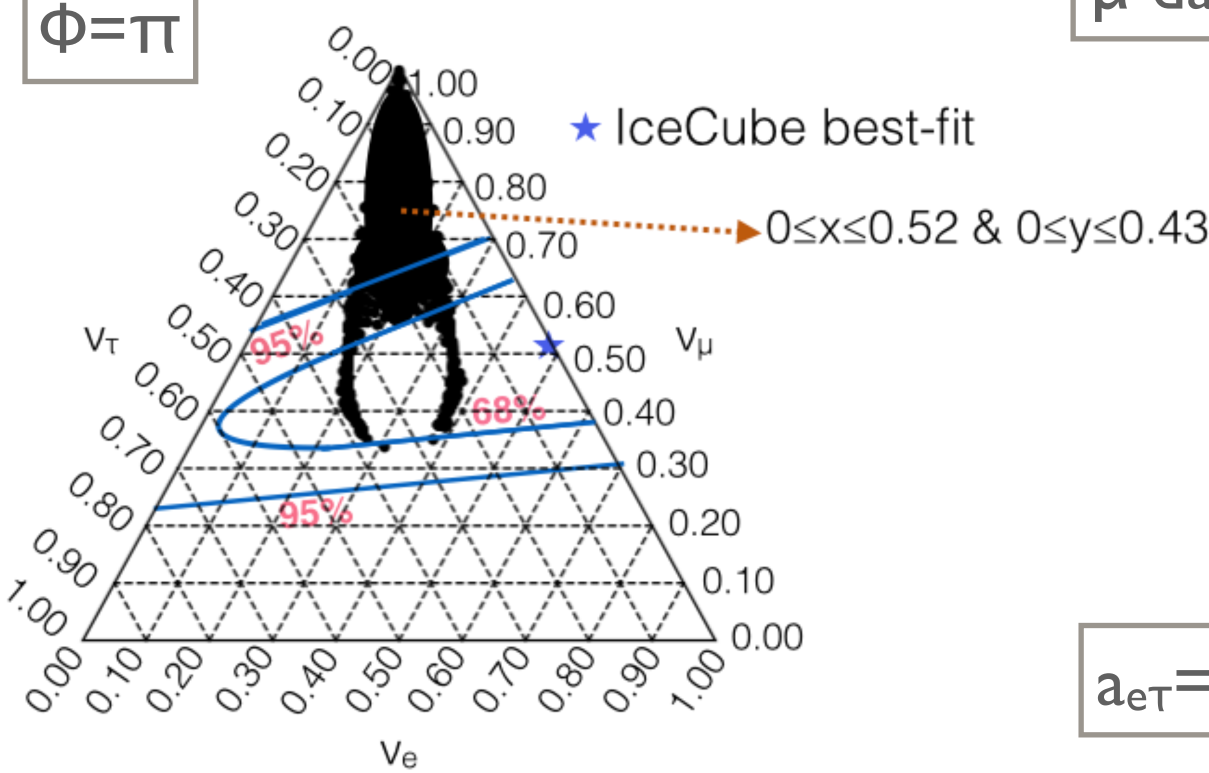


$\Phi=3\pi/2$

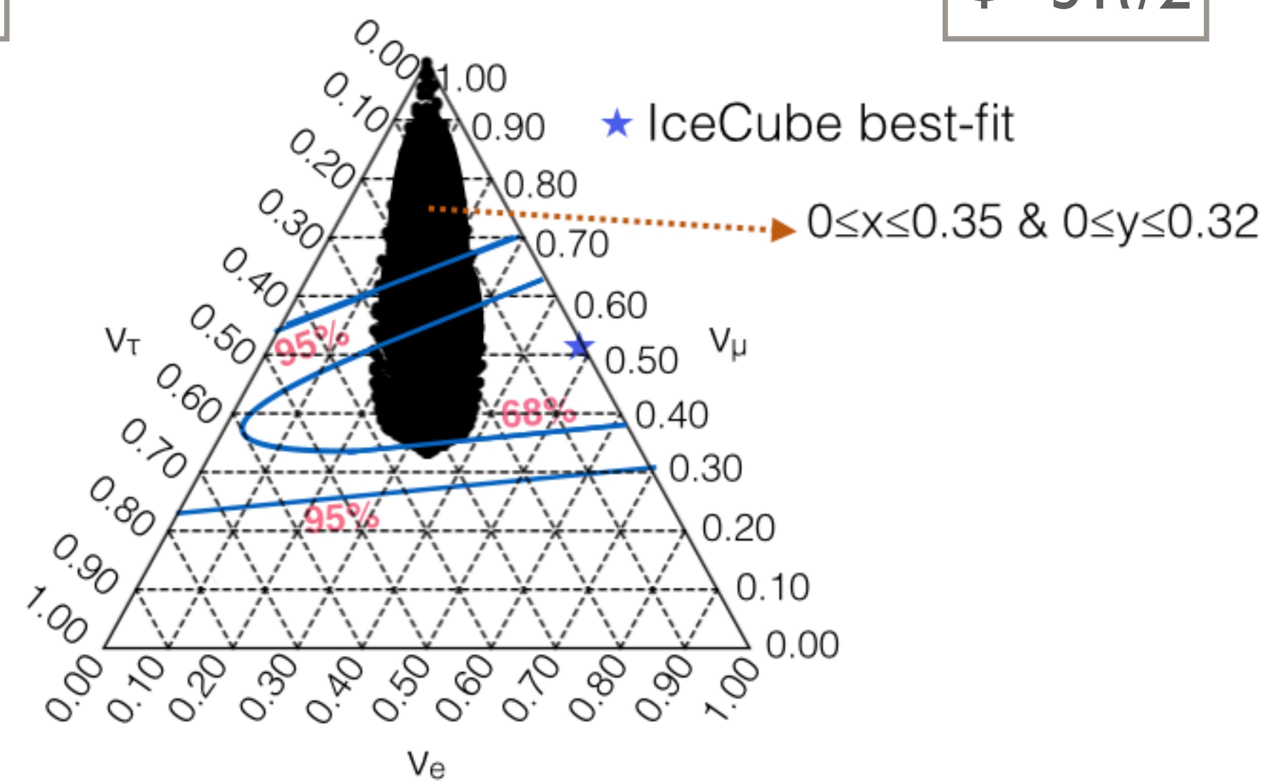


μ damped

$\Phi=\pi$



$\Phi=3\pi/2$



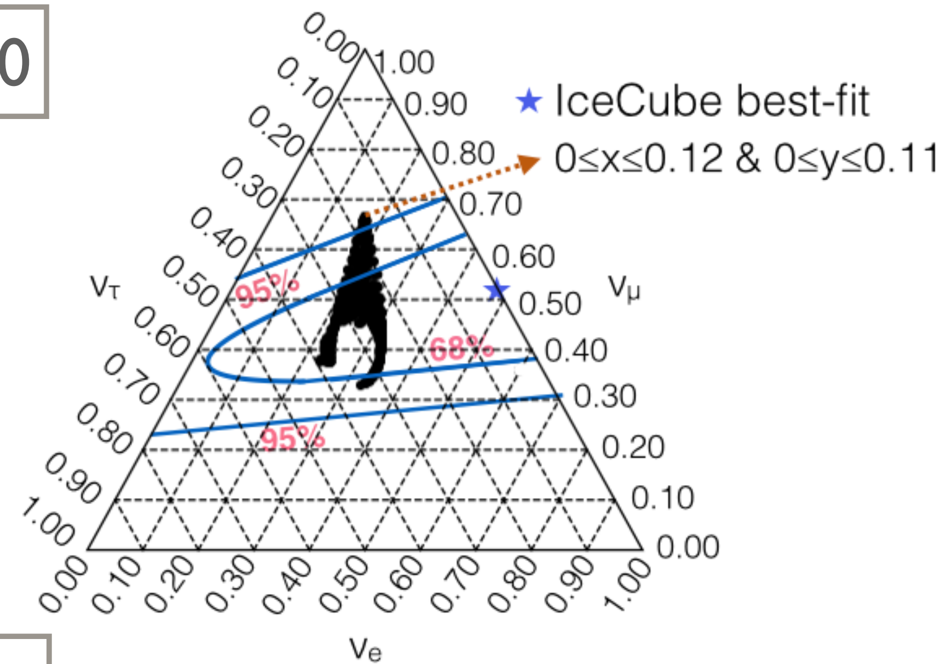
$a_{e\tau}=10^{-16}$

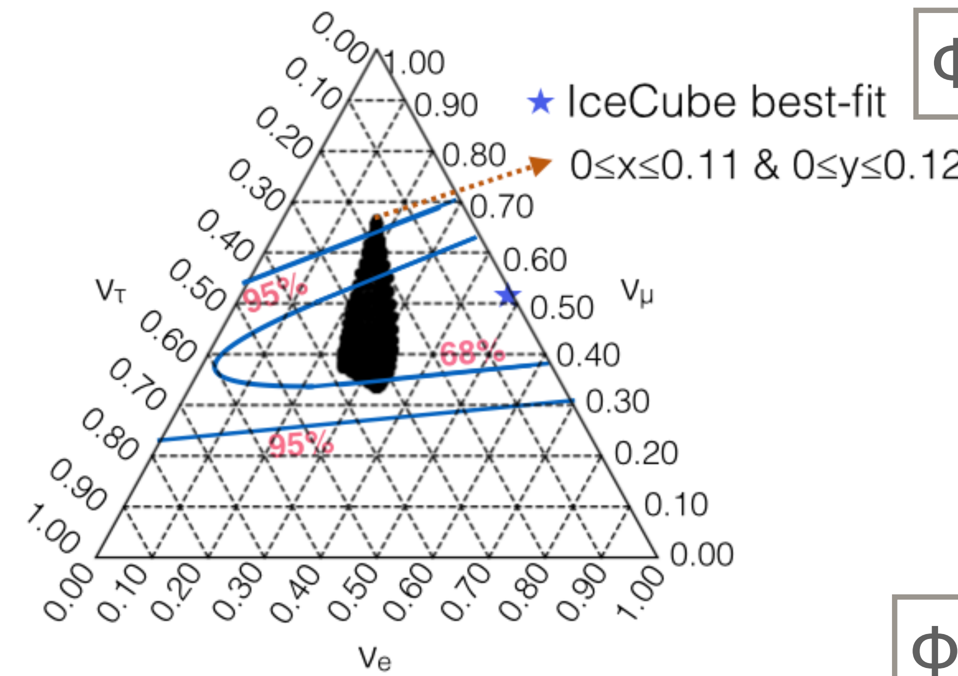
NUMERICAL RESULTS OF Pγ

$\Phi=0$

$a_{e\tau}=10^{-15}$

$\Phi=\pi/2$

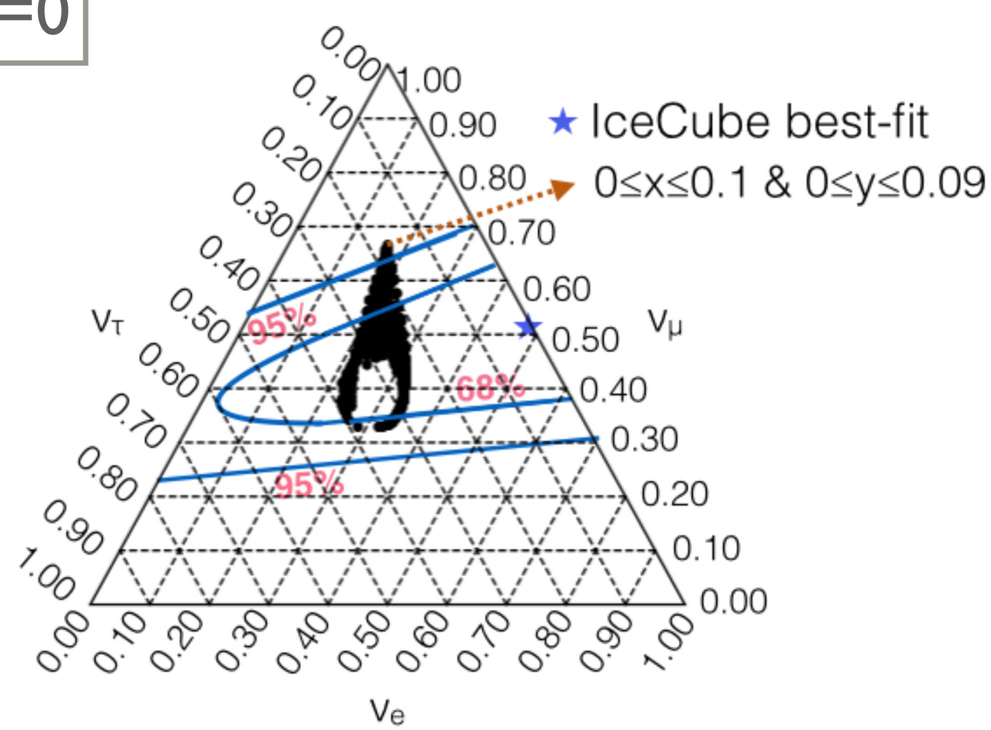


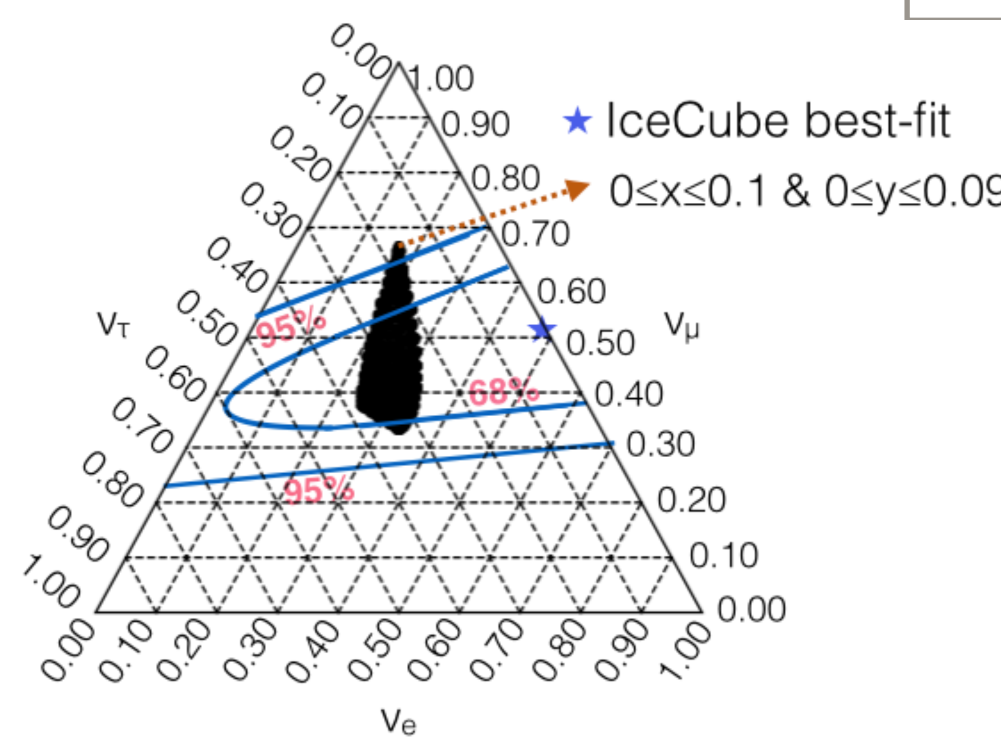


π source

$\Phi=0$

$\Phi=\pi/2$

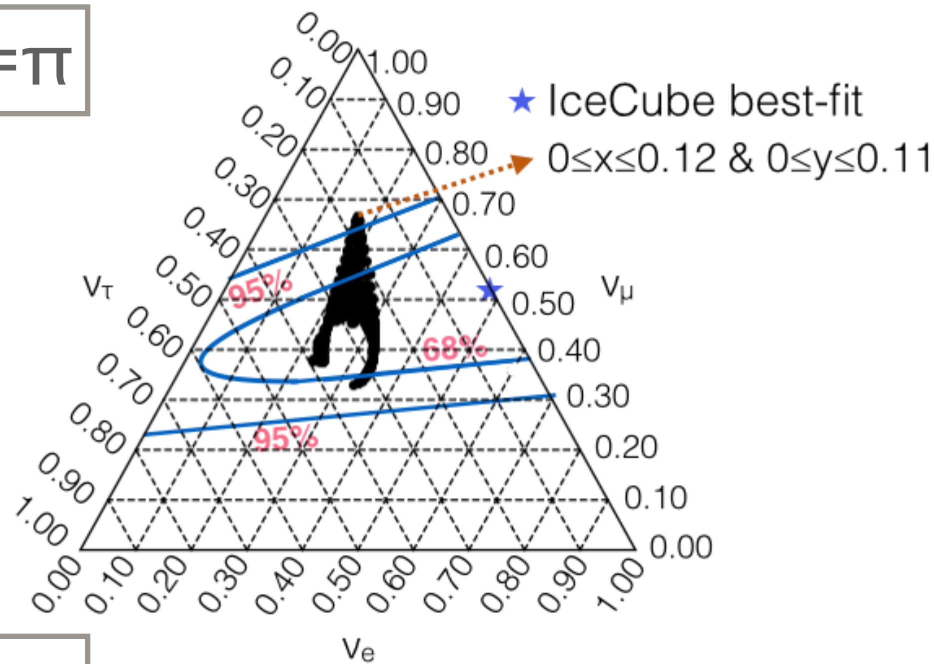




$a_{e\tau}=10^{-16}$

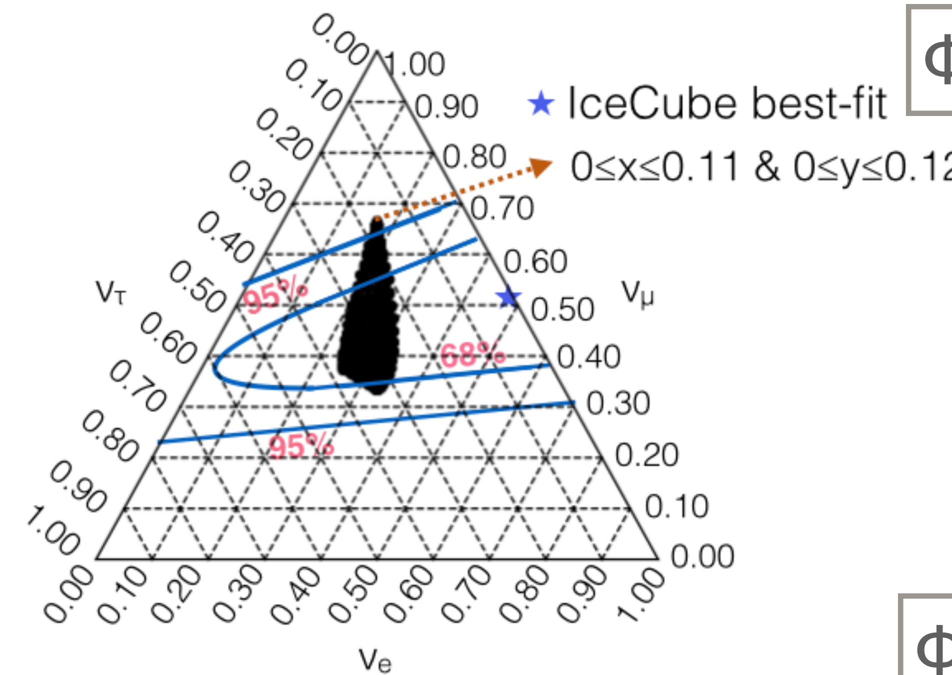
NUMERICAL RESULTS OF Pγ

$\Phi=\pi$



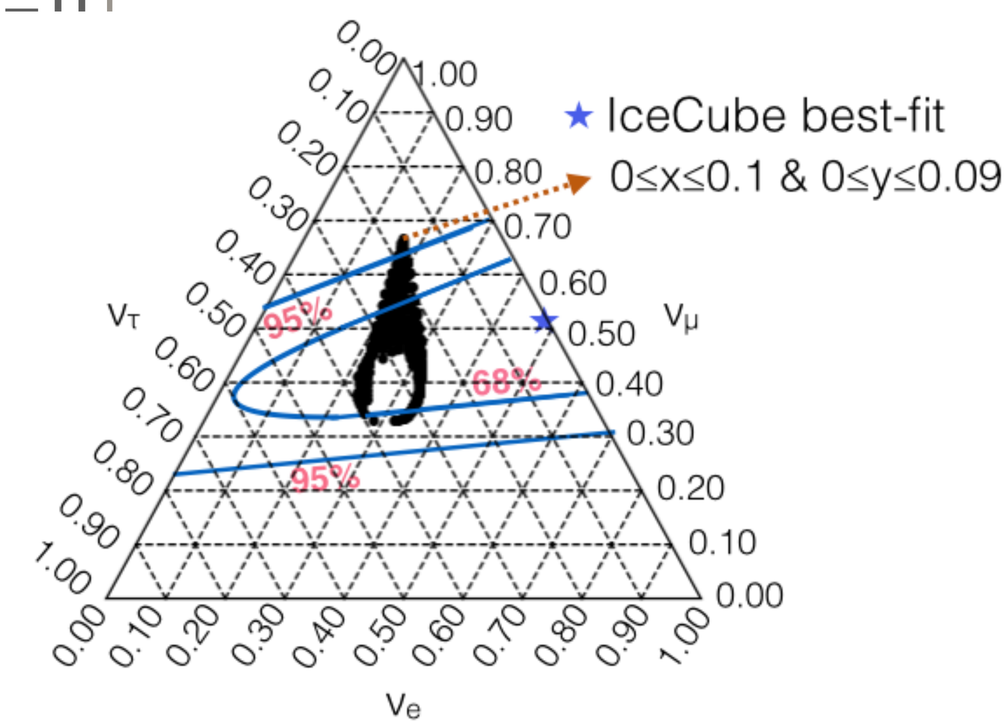
$a_{e\tau}=10^{-15}$

$\Phi=3\pi/2$

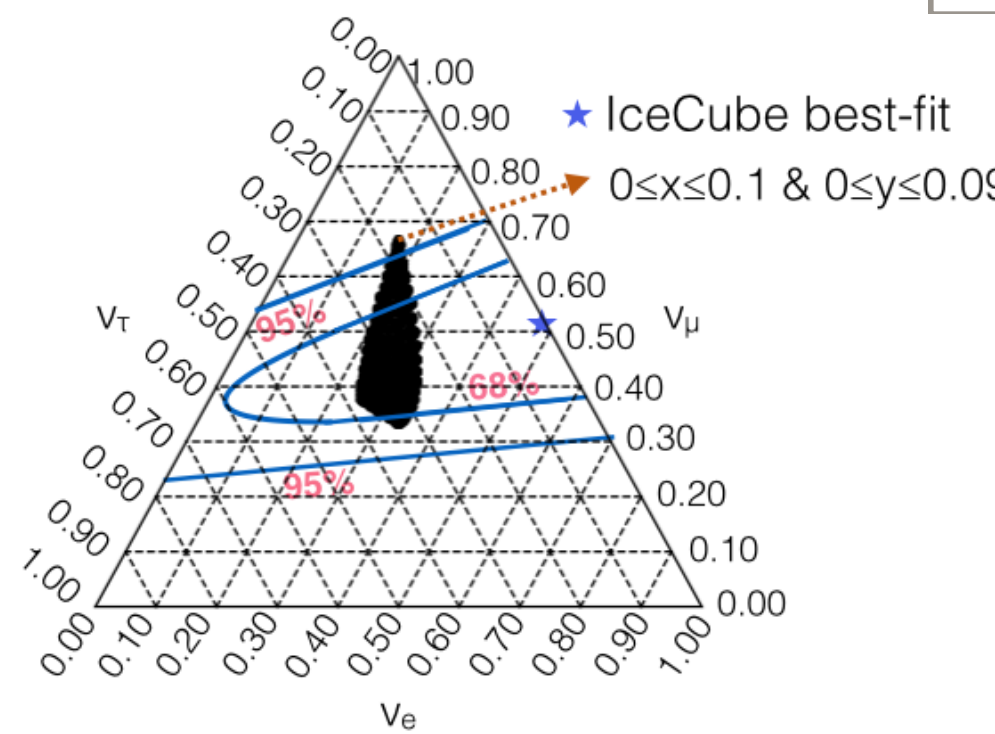


π source

$\Phi=\pi$



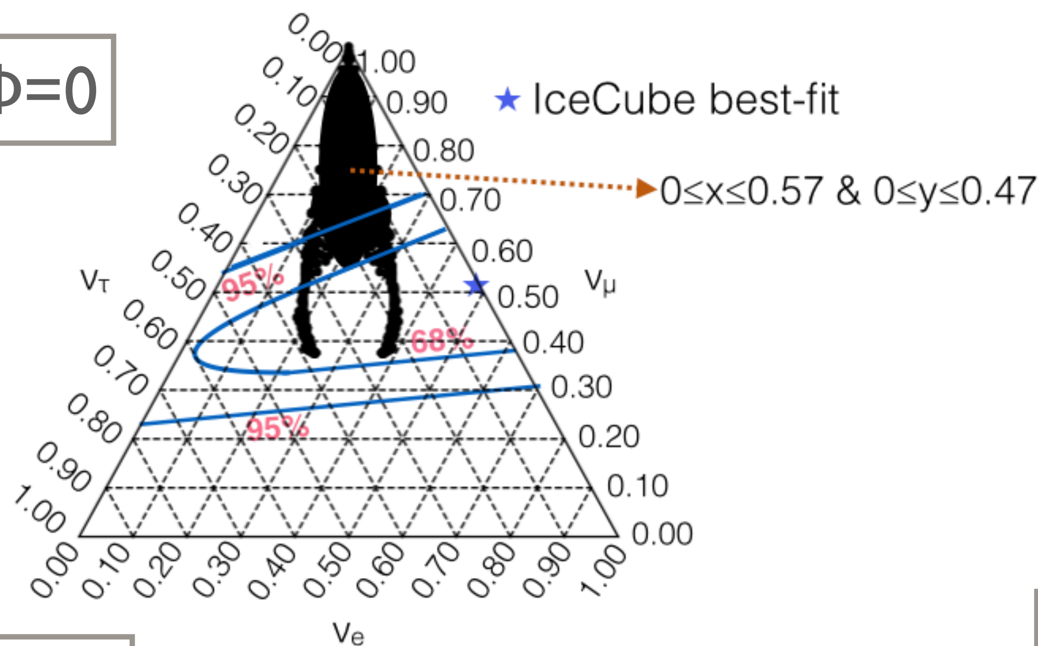
$\Phi=3\pi/2$



$a_{e\tau}=10^{-16}$

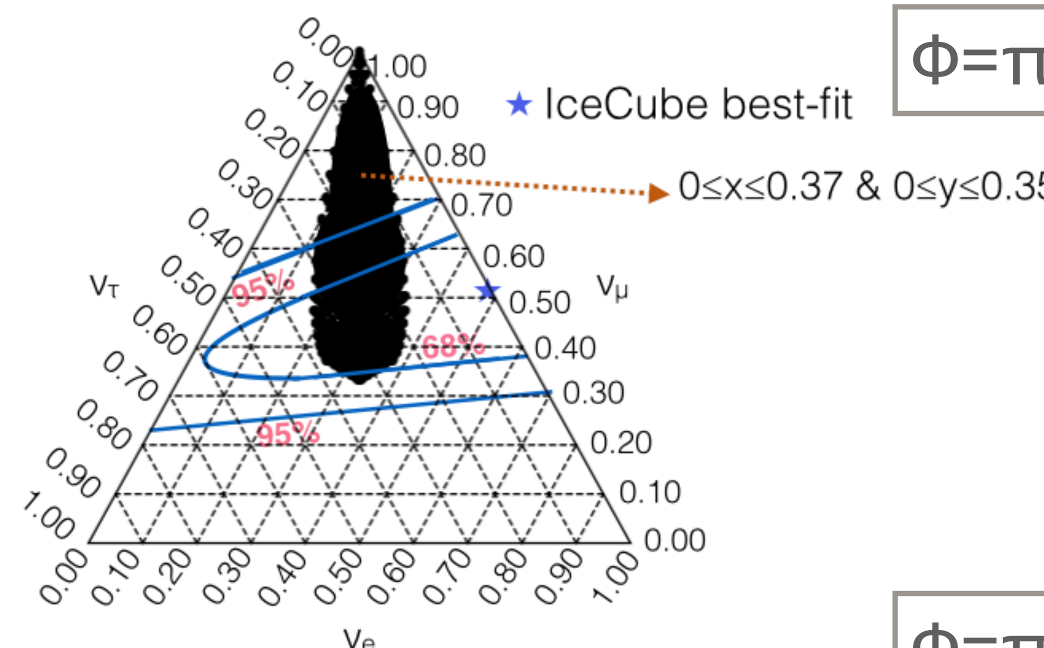
NUMERICAL RESULTS OF PP

Φ=0



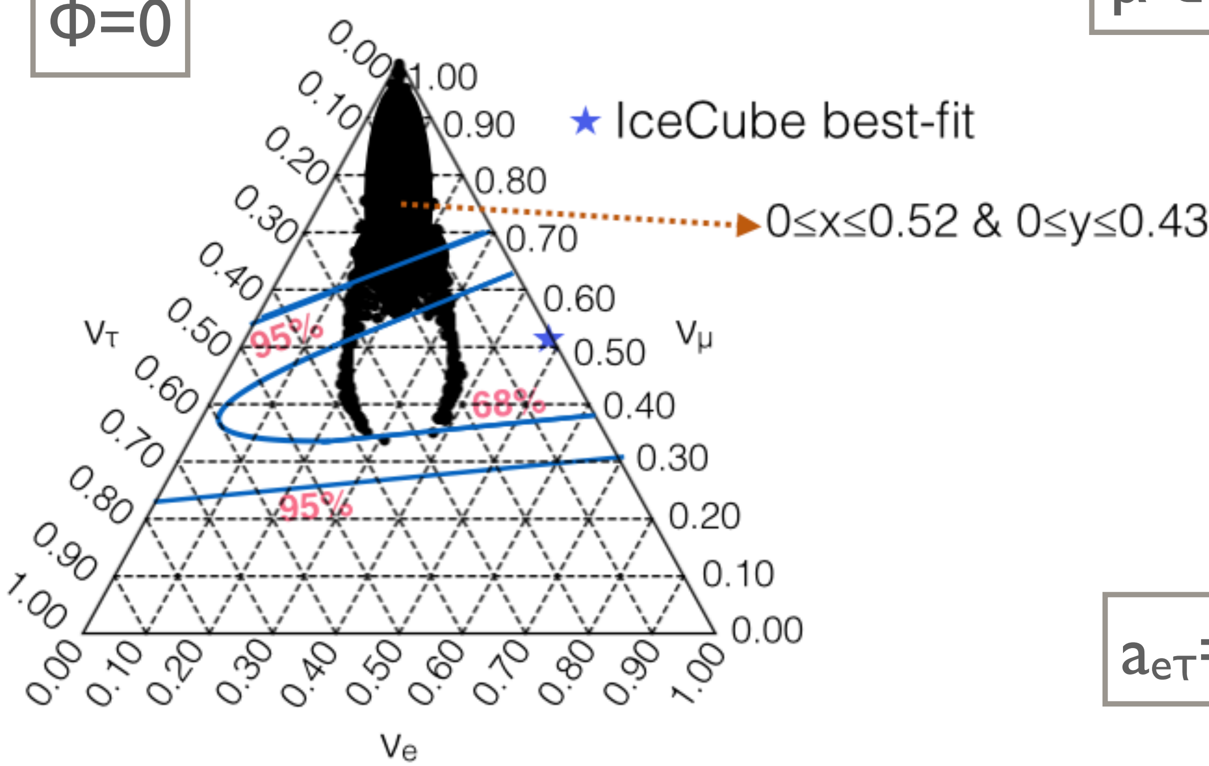
$a_{e\tau}=10^{-15}$

Φ=π/2

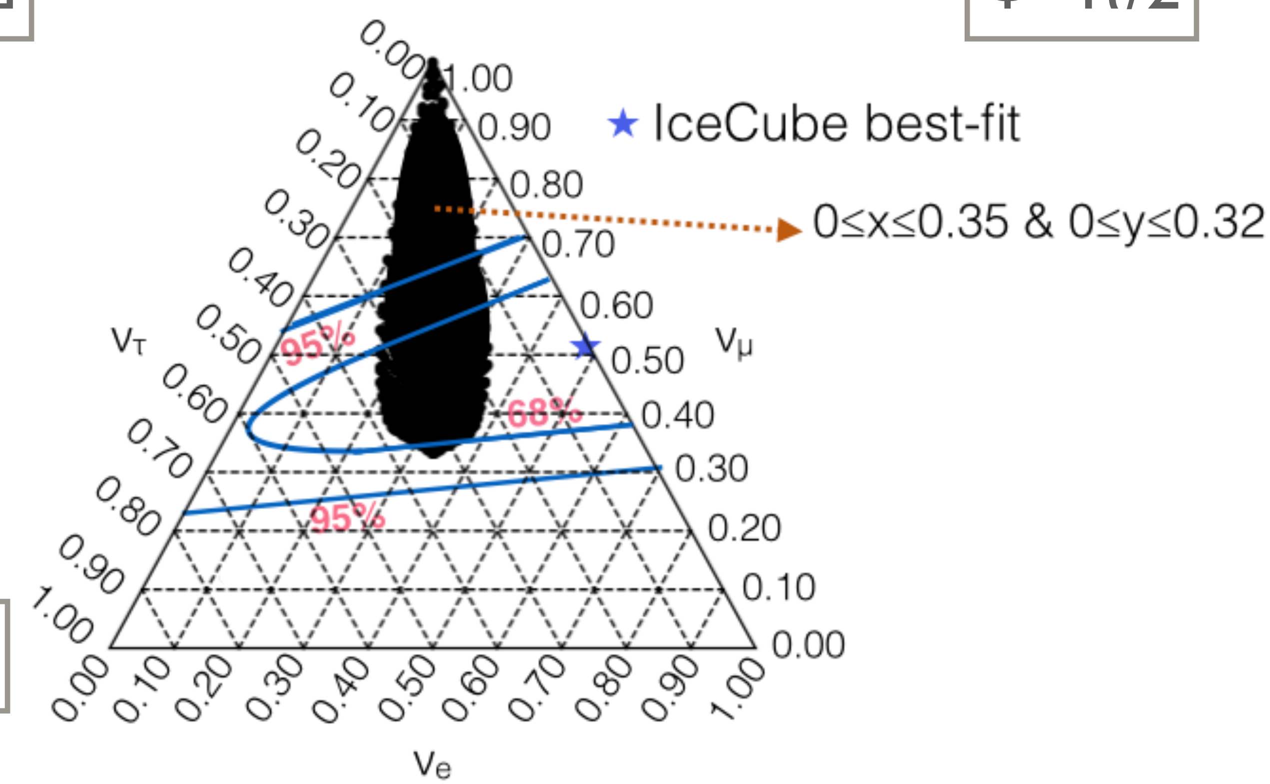


μ damped

Φ=0



Φ=π/2

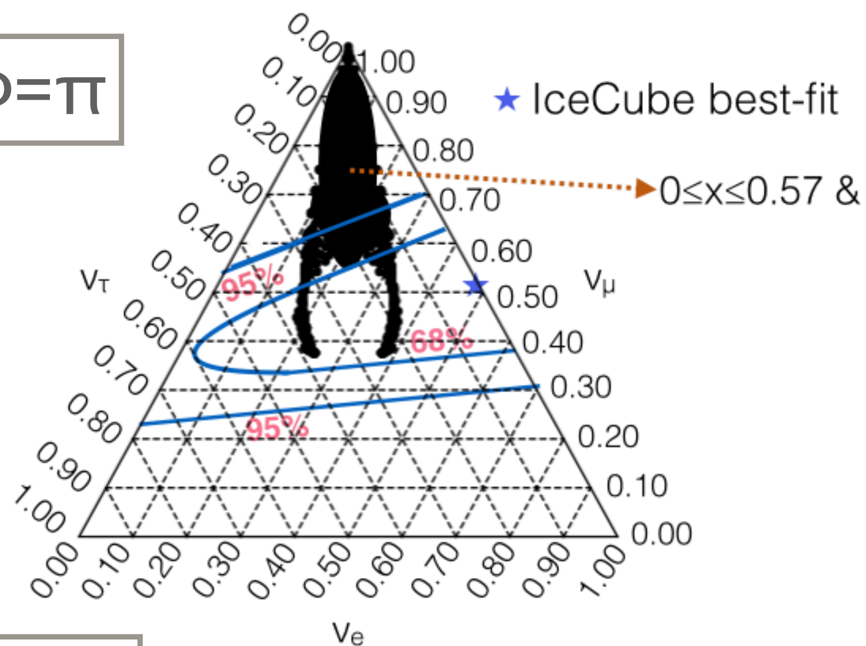


$a_{e\tau}=10^{-16}$

NUMERICAL RESULTS OF PP

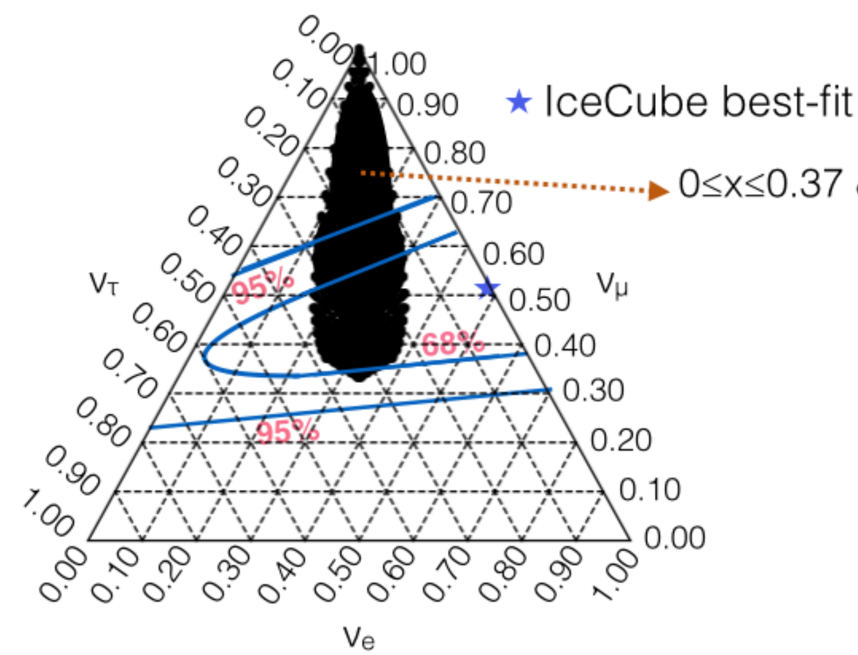
Φ=π

$a_{e\tau}=10^{-15}$



0≤x≤0.57 & 0≤y≤0.47

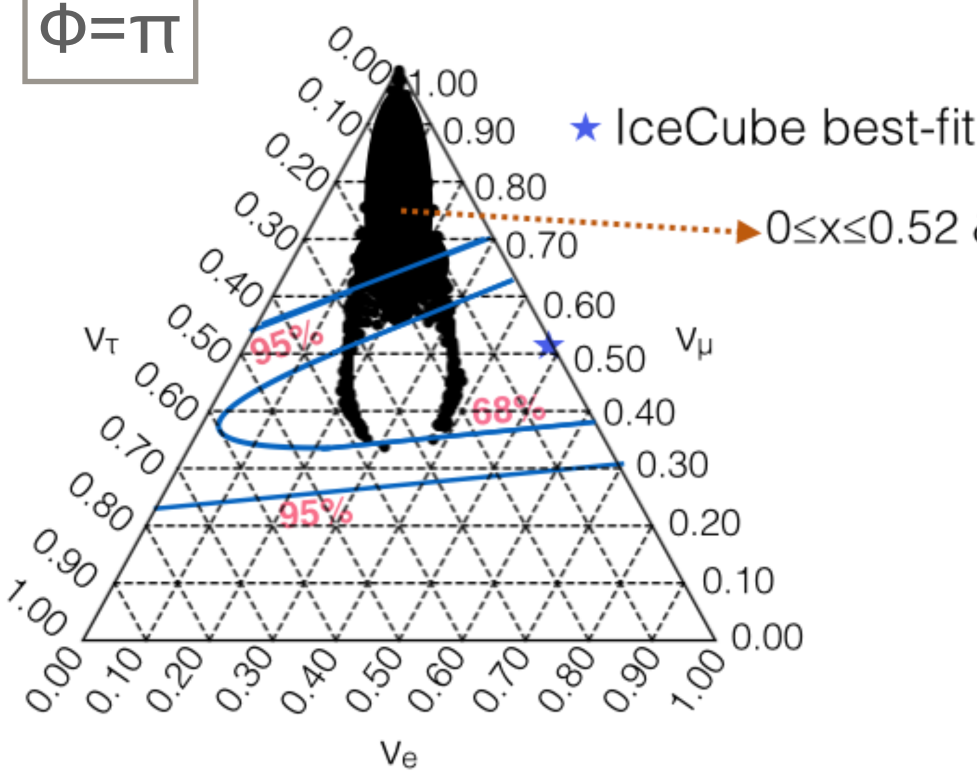
Φ=3π/2



0≤x≤0.37 & 0≤y≤0.35

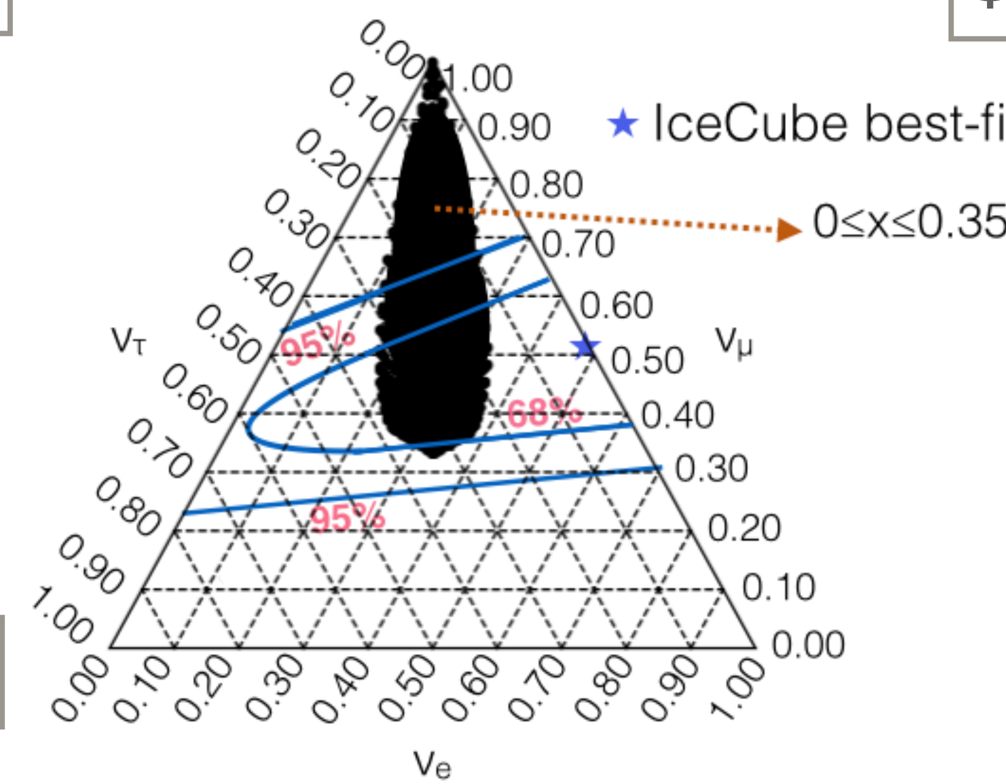
μ damped

Φ=π



0≤x≤0.52 & 0≤y≤0.43

Φ=3π/2



0≤x≤0.35 & 0≤y≤0.32

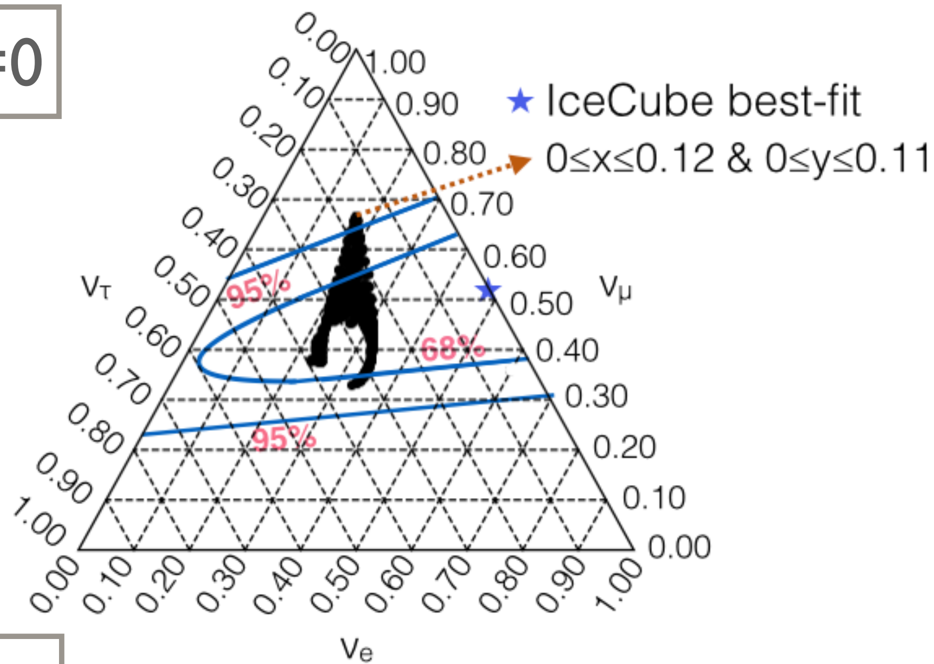
$a_{e\tau}=10^{-16}$

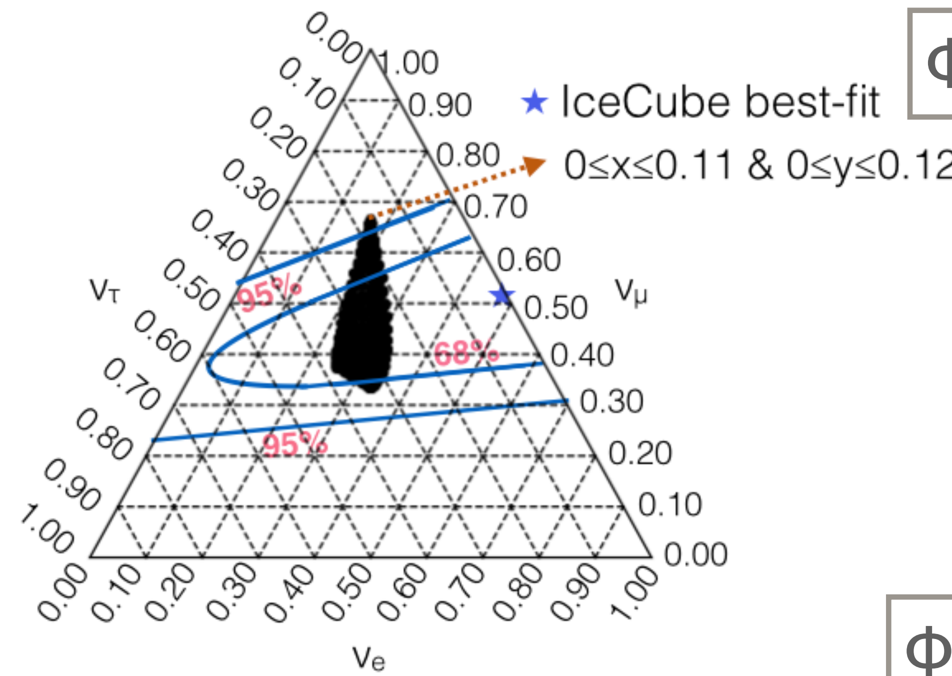
NUMERICAL RESULTS OF PP

$\Phi=0$

$a_{e\tau}=10^{-15}$

$\Phi=\pi/2$

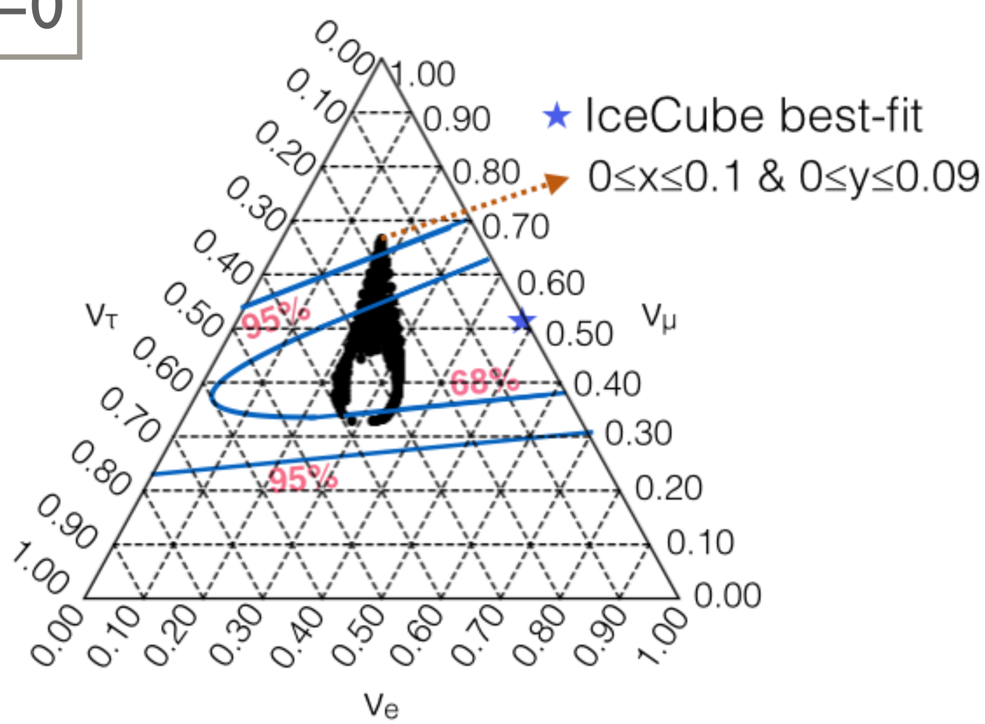


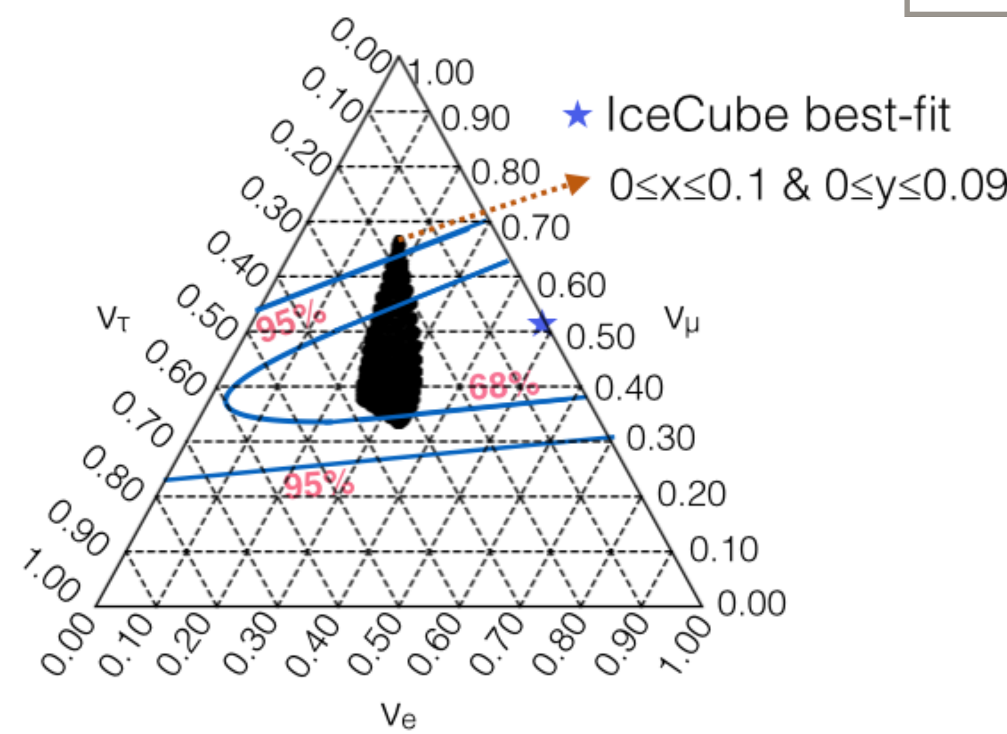


$\Phi=0$

π source

$\Phi=\pi/2$

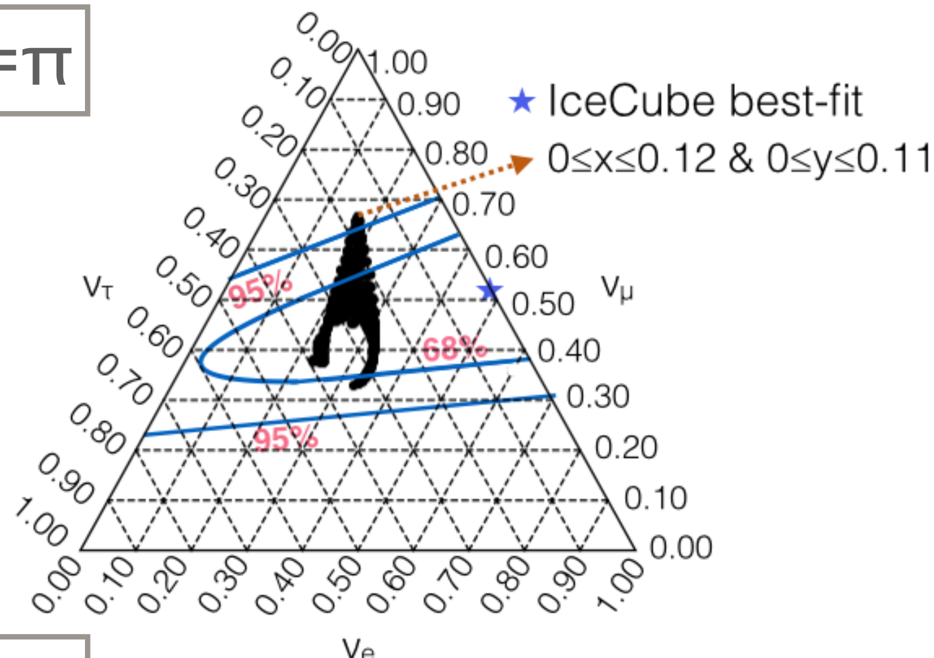




$a_{e\tau}=10^{-16}$

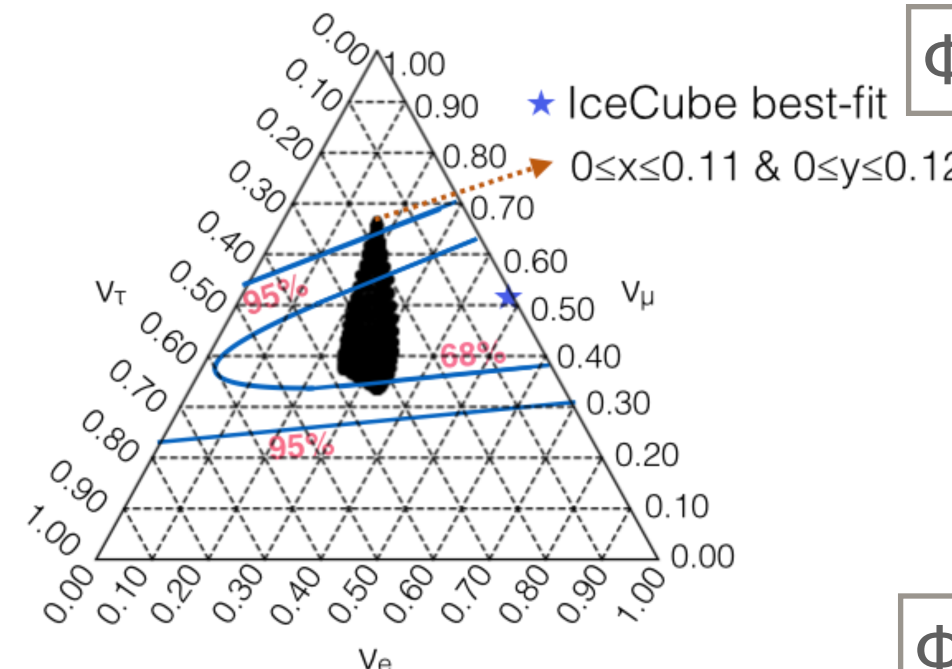
NUMERICAL RESULTS OF PP

Φ=π



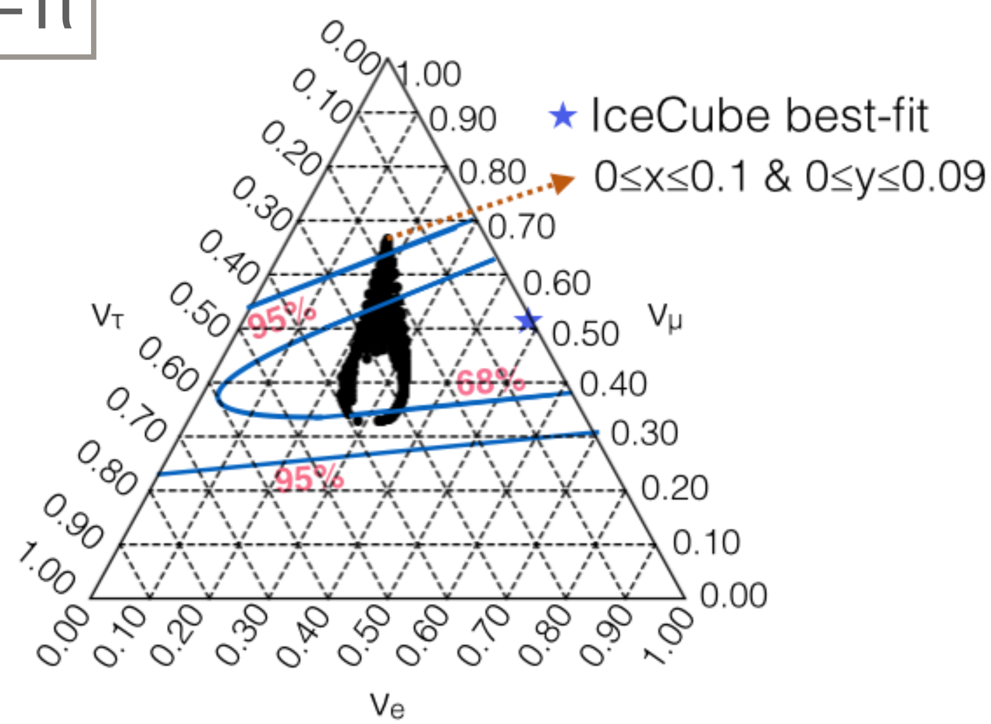
$a_{e\tau}=10^{-15}$

Φ=3π/2

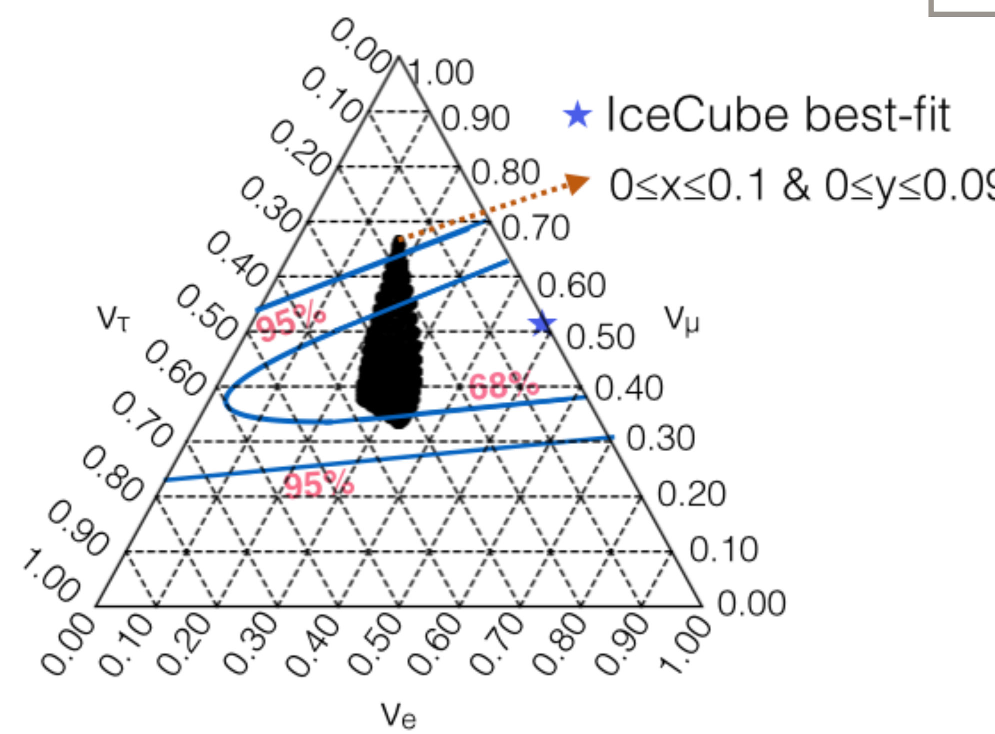


π source

Φ=π



Φ=3π/2



$a_{e\tau}=10^{-16}$