Probing neutrino flavor transition mechanism with cosmogenic neutrinos

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KCL, G.-L. Lin, T.-C. Liu, PRD 82, 89

Outline

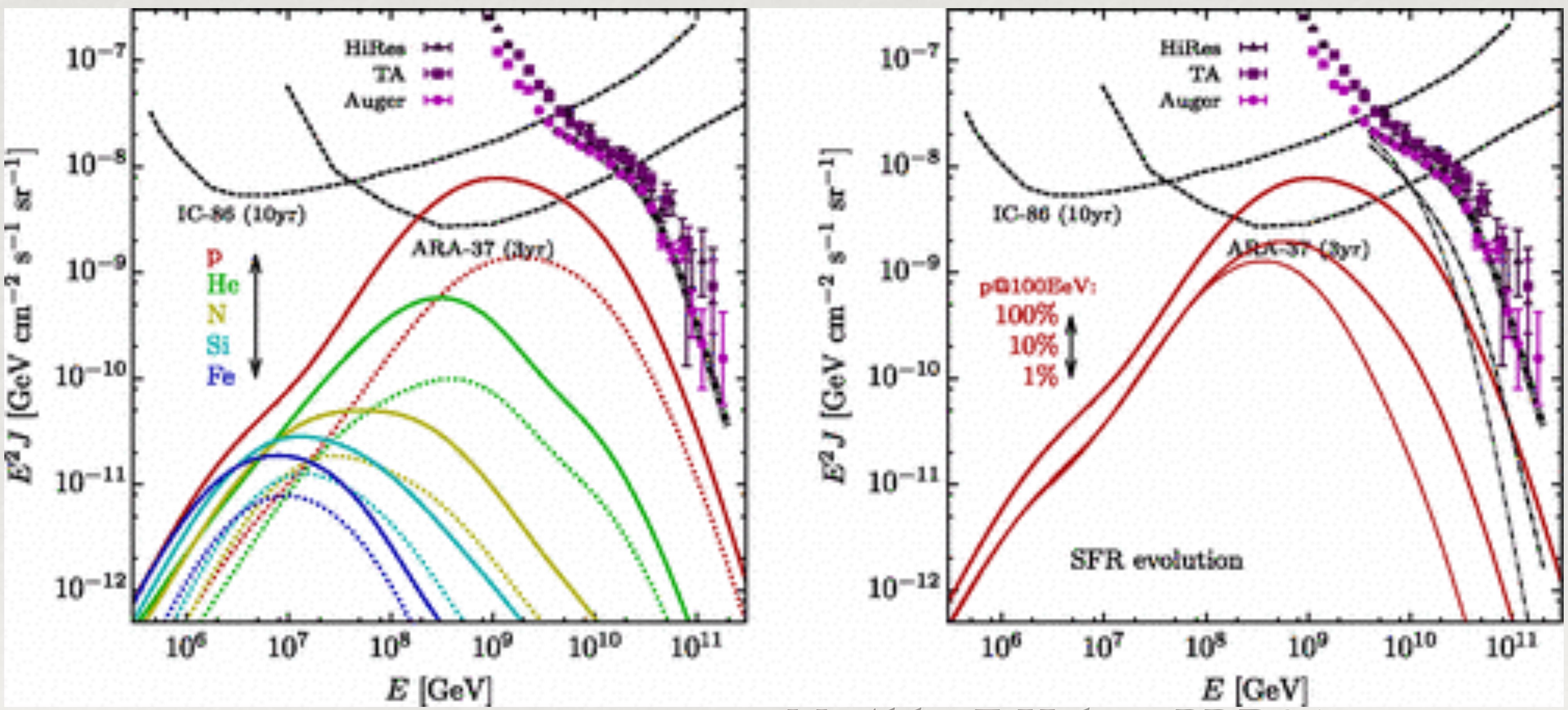
- *Cosmogenic neutrino*
- *Neutrino flavor transition*
- *Neutrino signals in neutrino telescopes*
- *Test of transition models*

Cosmogenic neutrino

originated from UHECR interacting with CMB, IRB…

expected flavor composition of $\nu_e:\nu_\mu:\nu_\tau=1:1:1$ ← pion source

muon energy loss in situ → $\nu_e:\nu_\mu:\nu_\tau=0:1:0$, damped-muon source



M. Ahler, F. Halzen, PRD86

Astrophysical neutrino

$$P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{E})$$
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{E})$$

"Astrophysical" means $\Delta m^2_{ij} \frac{L}{E} >> 1$

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Flavor transition

- *Q-representation*
- *Standard oscillation*
- *Neutrino decay*
- *Quantum decoherence*
- *Pseudo-Dirac neutrino*

Q-representation

Tri-bimaximal matrix and its eigenvectors

$$P^{\text{TBM}} = \frac{1}{18}\begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}, \begin{cases} V_1 = (1,\ 1,\ 1) \\ V_2 = (0,\ -1,\ 1) \\ V_3 = (2,\ -1,\ -1) \end{cases}, A = \begin{pmatrix} 1 & 0 & 2 \\ 1 & -1 & -1 \\ 1 & 1 & -1 \end{pmatrix}$$

neutrino on Earth $\rightarrow \phi = P\phi_0 \leftarrow$ neutrino at the source

$$\phi_0 = (\phi_0(\nu_e),\ \phi_0(\nu_\mu),\ \phi_0(\nu_\tau)) = 1/3 V_1 + a V_2 + b V_3$$

$$\phi = \varkappa V_1 + \varrho V_2 + \lambda V_3 \qquad (\varkappa,\ \varrho,\ \lambda)^T = Q(1/3,\ a,\ b)^T$$

$$\Longrightarrow Q \equiv A^{-1} P A$$

Q-representation

$$Q = \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix}$$

Flux-conservation ➔ $(Q_{11}, Q_{12}, Q_{13}) = (1,0,0)$

ν_μ - ν_τ symmetry ➔ $(Q_{21}, Q_{22}, Q_{23}) \approx (0,0,0)$
$(Q_{12}, Q_{22}, Q_{32}) \approx (0,0,0)$

$\Rightarrow$ Q_{31} and Q_{33} classify possible flavor transition models

Standard oscillation

Expand probability transition matrix
with respect to TBM values of the mixing angles

$$P^{\mathrm{osc}} = P_0^{\mathrm{osc}} (= P^{\mathrm{TBM}}) + P_1^{\mathrm{osc}} + P_2^{\mathrm{osc}} + \ldots$$

$$Q_0^{\mathrm{osc}} = A^{-1} P^{\mathrm{TBM}} A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/3 \end{pmatrix},$$

$$Q_1^{\mathrm{osc}} = A^{-1} P_1^{\mathrm{osc}} A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -3\varepsilon \\ 0 & -\varepsilon & 1/3 \end{pmatrix}, \ \varepsilon = 2\cos\theta_{23}/9 + \sqrt{2}\sin\theta_{13}\cos\delta/9$$

Neutrino decay

$$P_{\alpha\beta} = \sum_{f\ stable} \left(|U_{\alpha f}|^2 + \sum_{i\ unstable} |U_{\alpha i}|^2\ \mathrm{Br}_{i \to f} \right) |U_{\beta f}|^2$$

Normal hierarchy

	One stable state			One unstable state		
Scenario	$\not{3}\not{2}1$	$\not{3}2\not{1}$	$3\not{2}\not{1}$	$\not{3}21$	$3\not{2}1$	$32\not{1}$
Branching ratio	Br_{31}=a Br_{21}=b	Br_{32}=a	Br_{ij}=0 all i, j	Br_{32}=a, Br_{31}=b	Br_{21}=a	Br_{ij}=0 all i, j

TABLE I: Decay scenarios for normal mass hierarchy.

Inverted hierarchy

	One stable state			One unstable state		
Scenario	$\not{2}\not{1}3$	$\not{2}1\not{3}$	$2\not{1}\not{3}$	$\not{2}13$	$2\not{1}3$	$21\not{3}$
Branching ratio	Br_{23}=a Br_{13}=b	Br_{21}=a	Br_{ij}=0 all i, j	Br_{21}=a Br_{23}=b	Br_{13}=a	Br_{ij}=0 all i, j

TABLE II: Decay scenario for inverted mass hierarchy

Neutrino decay

- *The heaviest and middle states decay into the lightest one.-dec1*
- *The heaviest state decays into the middle and lightest ones.-dec2*

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ -3(|U_{\mu j}|^2 - |U_{\tau j}|^2)/2 & 0 & 0 \\ |U_{ej}|^2 - (|U_{\mu j}|^2 + |U_{\tau j}|^2)/2 & 0 & 0 \end{pmatrix}$$

$$Q_0^{I\,\mathrm{dec}} = \frac{1}{6}\begin{pmatrix} 4+2(r+s) & 0 & 2-2(r+s) \\ 0 & 0 & 0 \\ 1+s & 0 & 1-s \end{pmatrix}$$

$$Q_0^{II\,\mathrm{dec}} = \frac{1}{6}\begin{pmatrix} 4+2(r+s) & 0 & 0 \\ 0 & 0 & 0 \\ r-s & 0 & 2 \end{pmatrix}$$

	Elements of subleading matrices $Q_1^{I\,\mathrm{dec}}$ and $Q_1^{II\,\mathrm{dec}}$			
	12	21	23	32
$Q_1^{I\,\mathrm{dec}}$	$-2(1-r-s)(\epsilon_1+\epsilon_2)/3$	$-(1+r)\epsilon_1-(1+s)\epsilon_2$	$r\epsilon_1-(1-s)\epsilon_2$	$[s(\epsilon_1+\epsilon_2)-\epsilon_2]/3$
$Q_1^{II\,\mathrm{dec}}$	$2(1-r-s)\epsilon_1/3$	$(1+s)\epsilon_1-(r-s)\epsilon_2$	$-\epsilon_1-2\epsilon_2$	$-[(1+r-s)\epsilon_1+2\epsilon_2]/3$

$\varepsilon_1=\cos 2\vartheta_{23}-(\sqrt{2}/3)\sin\vartheta_{13}$, $\varepsilon_2=(1/2)\cos 2\vartheta_{23}-\varepsilon_1$

Quantum decoherence

$$P_{\alpha\beta}^{\mathrm{dc}} = \frac{1}{3} + \left[\frac{1}{2}e^{-\gamma_3 d}(U_{\beta 1}^2 - U_{\beta 2}^2)(U_{\alpha 1}^2 - U_{\alpha 2}^2)\right.$$
$$\left. + \frac{1}{6}e^{-\gamma_8 d}(U_{\beta 1}^2 + U_{\beta 2}^2 - 2U_{\beta 3}^2)(U_{\alpha 1}^2 + U_{\alpha 2}^2 - 2U_{\alpha 3}^2)\right]$$

$$Q_0^{\mathrm{dc}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & e^{-\gamma d}/3 \end{pmatrix} \qquad Q_1^{\mathrm{dc}} = e^{-\gamma d}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -3\epsilon_0 \\ 0 & -\epsilon_0 & 0 \end{pmatrix}$$

- *propagation distance dependent*
- $\gamma \to 0$ *or* $d \to \infty$, $Q^{dc} = Q^{osc}$

Pseudo-Dirac neutrino

$$P^{\mathrm{pd}}_{\alpha\beta} = \sum_{i=1}^{3} |U_{\beta i}|^2 |U_{\alpha i}|^2 \cos^2\left[\frac{\Delta m_i^2}{4E_\nu} L(z)\right]$$

Δm_i^2: the mass-squared difference between active and sterile states.

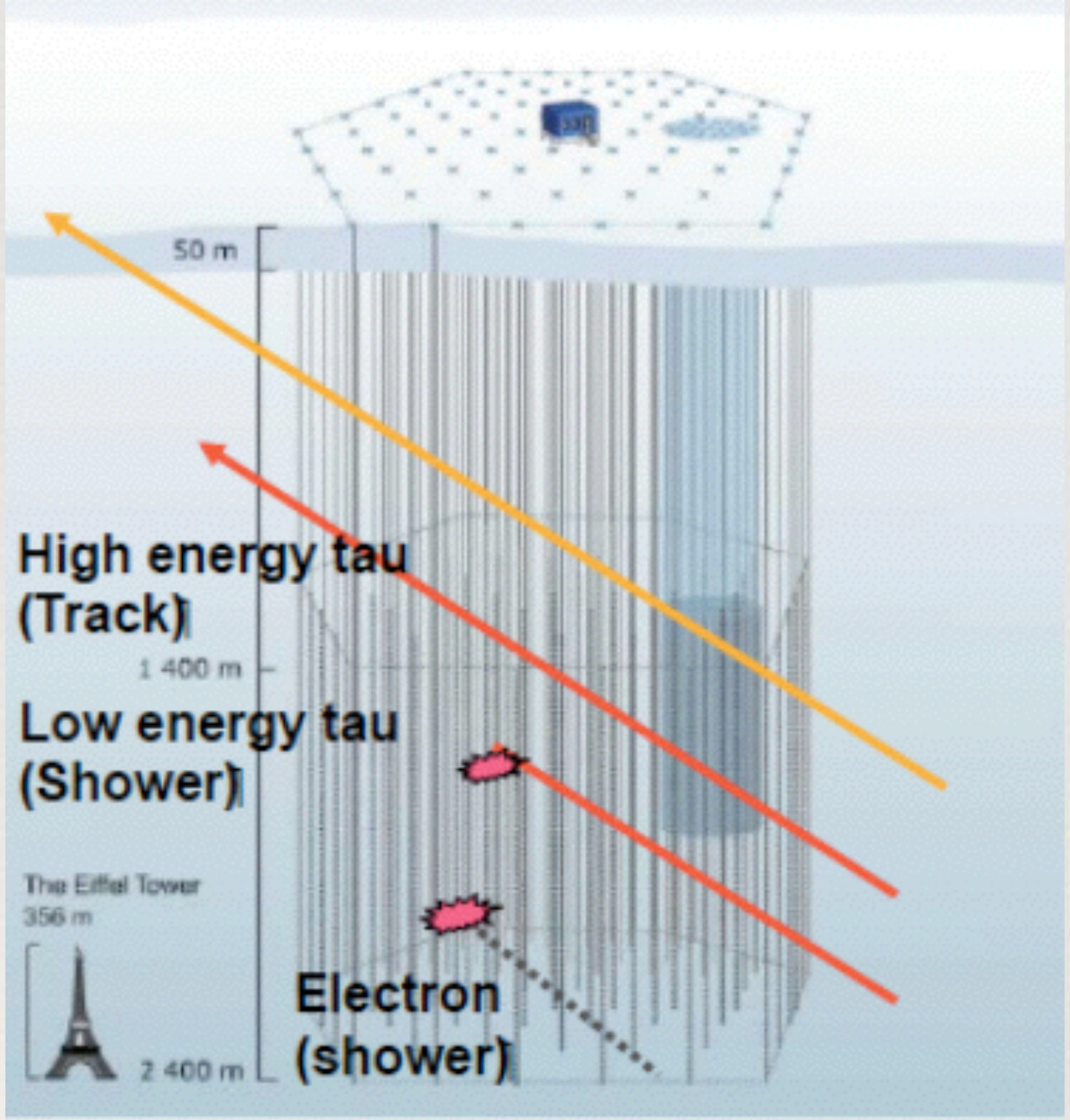
$$L(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{(1+z')^2\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

$\Delta m_i^2 = \Delta m^2$

$$Q^{\mathrm{pd}}_{\alpha\beta} = \cos^2\left[\frac{\Delta m^2}{4E_\nu} L(z)\right] Q_{\alpha\beta}.$$

In the limit of $L(z)/4E_\nu \gg 1/\Delta m_i^2$, $Q^{pd} = 1/2\ Q^{osc}$

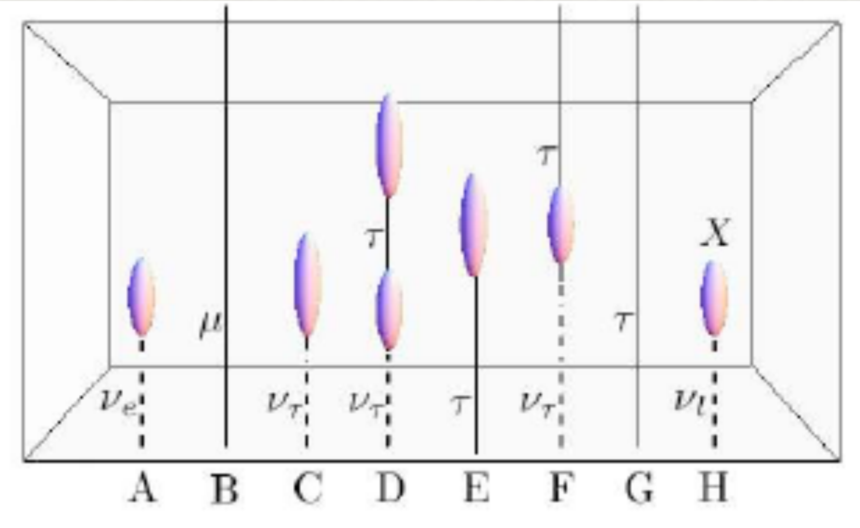
Neutrino signals



- *Tracks and showers*
- *Muon neutrinos produce track events through constant energy loss.*
- *Electron neutrinos produce shower events via charge-current interactions.*
- *Signals of tau neutrinos depends on their energies.*

Neutrino events

particle	major processes	signal type	symbol in Fig.1
e	EM shower	shower	A
μ	energy loss	track	B
$\tau(E_\nu < 3.3$ PeV)	CC int. and τ-decay	shower	C
τ(3.3 PeV$< E_\nu <$ 33 PeV)	CC int. and τ-decay	2 separate showers	D (double-bang event)
$\tau(E_\nu > 3.3$ PeV)	energy loss and decay	track and shower	E (lollipop event)
$\tau(E_\nu > 3.3$ PeV)	CC int. and energy loss	shower and track	F (inverted lollipop event)
$\tau(E_\nu > 33$ PeV)	energy loss	track	G
X	hadron shower	shower	H



125m corresponds to the decay length of a 2.5 PeV tau lepton.-dist. between strings

≈1km corresponds to the decay length of a 25 PeV tau lepton.-size of IceCube

M. A. Huang, G.-L. Lin, T.-C. Liu, 1054.5154

Observables

Case I:
$E_\nu < 33$PeV

Case II:
$E_\nu > 33$PeV

$R^{I} = \phi(\nu_\mu)/(\phi(\nu_e) + \phi(\nu_\tau))$
$S^{I} = \phi(\nu_e)/\phi(\nu_\tau)$

$R^{II} = \phi(\nu_e)/(\phi(\nu_\mu) + \phi(\nu_\tau))$
$S^{II} = \phi(\nu_\mu)/\phi(\nu_\tau)$

R^{I}: track-to-shower ratio; R^{II}:shower-to-track ratio

Observables

- $\phi_0=(\phi(\nu_e), \phi(\nu_\mu), \phi(\nu_\tau))=1/3\ V_1+aV_2+bV_3$.

- for non-ν_τ sources, a=-1/3+b and let $R^{II}\equiv R$.

- flux conservation assumed

$$R(b) = -1 + \frac{3}{2}[1-(Q_{31}-Q_{32})-3(Q_{32}+Q_{33})b]^{-1}, \\ = -1 + \frac{3}{2}[1-f_{12}-3f_{23}b]^{-1},$$

$$f_{12} = Q_{31} - Q_{32}, \\ f_{23} = Q_{32} + Q_{33}.$$

- for pion and damped-muon sources

$$R_\pi = -1 + \frac{3}{2}(1-f_{12})^{-1}, \\ R_\mu = -1 + \frac{3}{2}\left(1-f_{12}+\frac{1}{2}f_{23}\right)^{-1}.$$

Statistical analysis

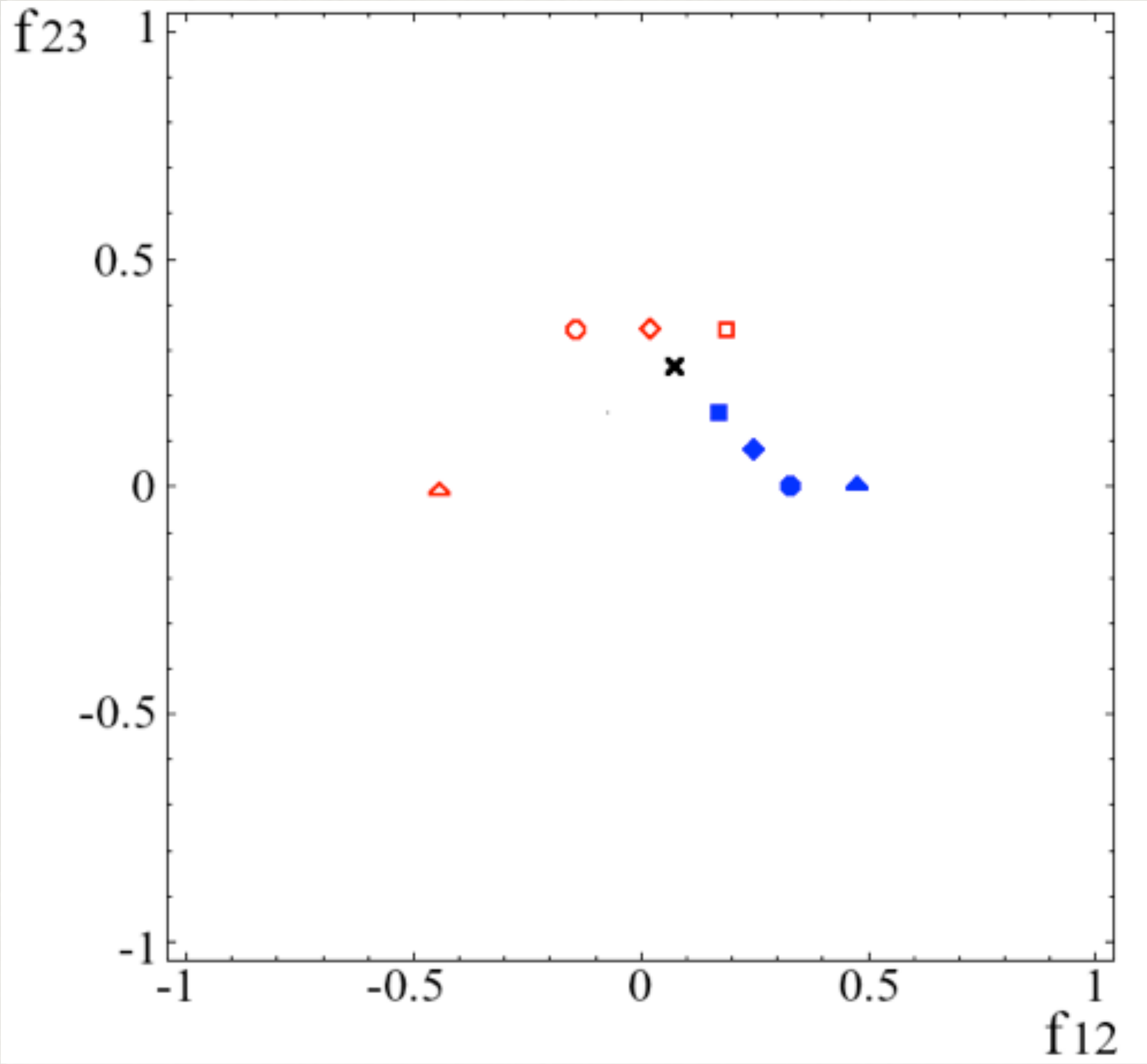
$$\chi^2 = \sum_i \chi_i^2 = \sum_i \left(\frac{R_{i,\mathrm{th}} - R_{i,\exp}}{\sigma_{R_{i,\exp}}} \right)^2$$

- *i*=π, *only pion source*
- *i*=π *and* μ, *both pion and damped-muon sources*
- σ=*10% assumed*

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

G. Fogli, et al., PRD86

Statistical analysis



- *Legend:*

  ×: oscillation

  △: dec1-n, ▲:dec1-i

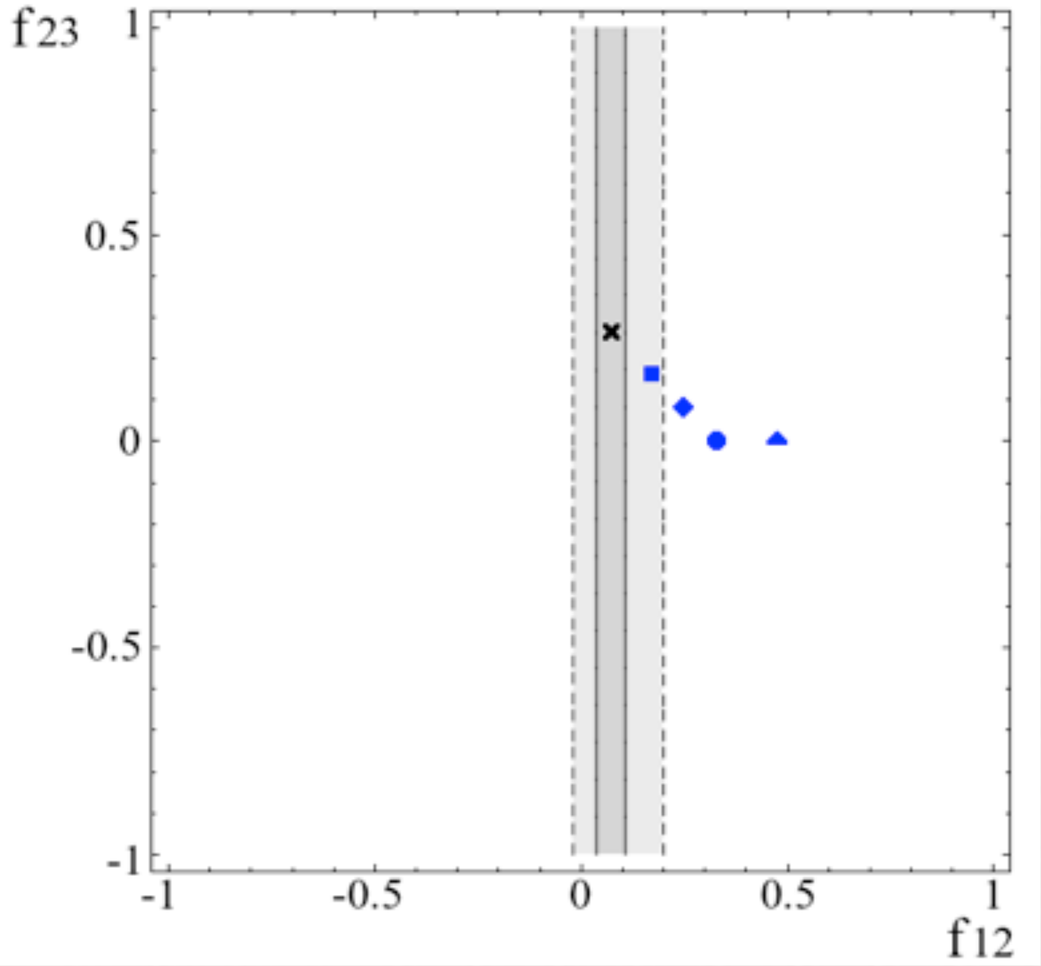
  ○, ◇, □ : dec2-n

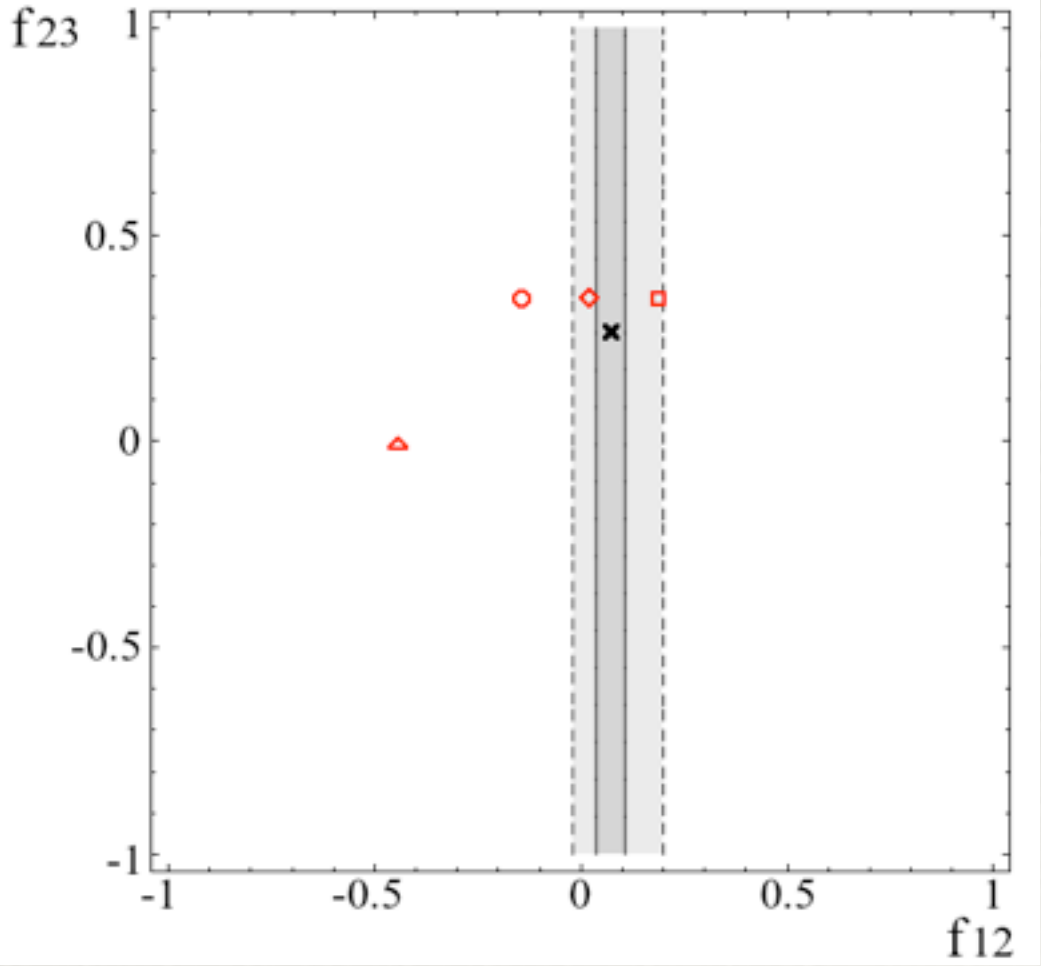
  ●, ◆, ■: dec2-i

Pion source only

1σ region

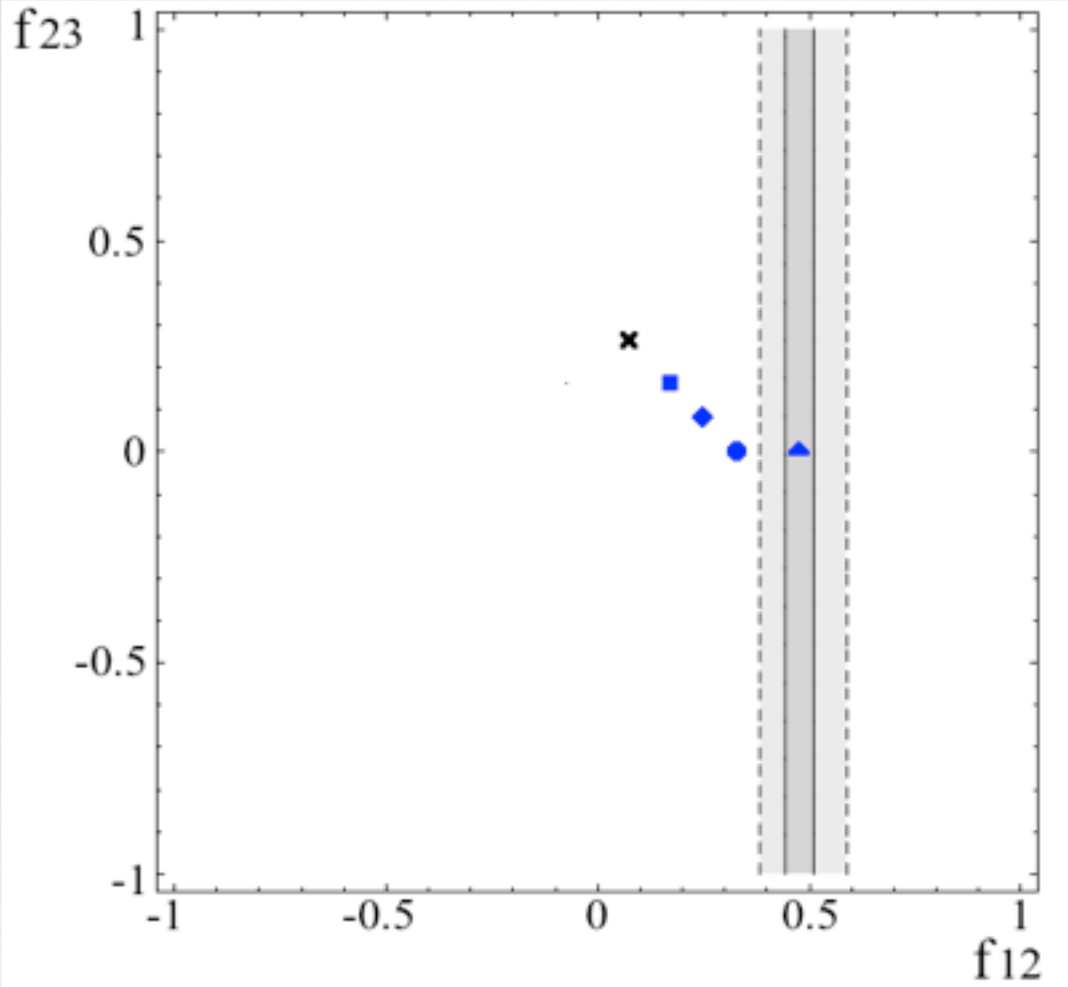
3σ region

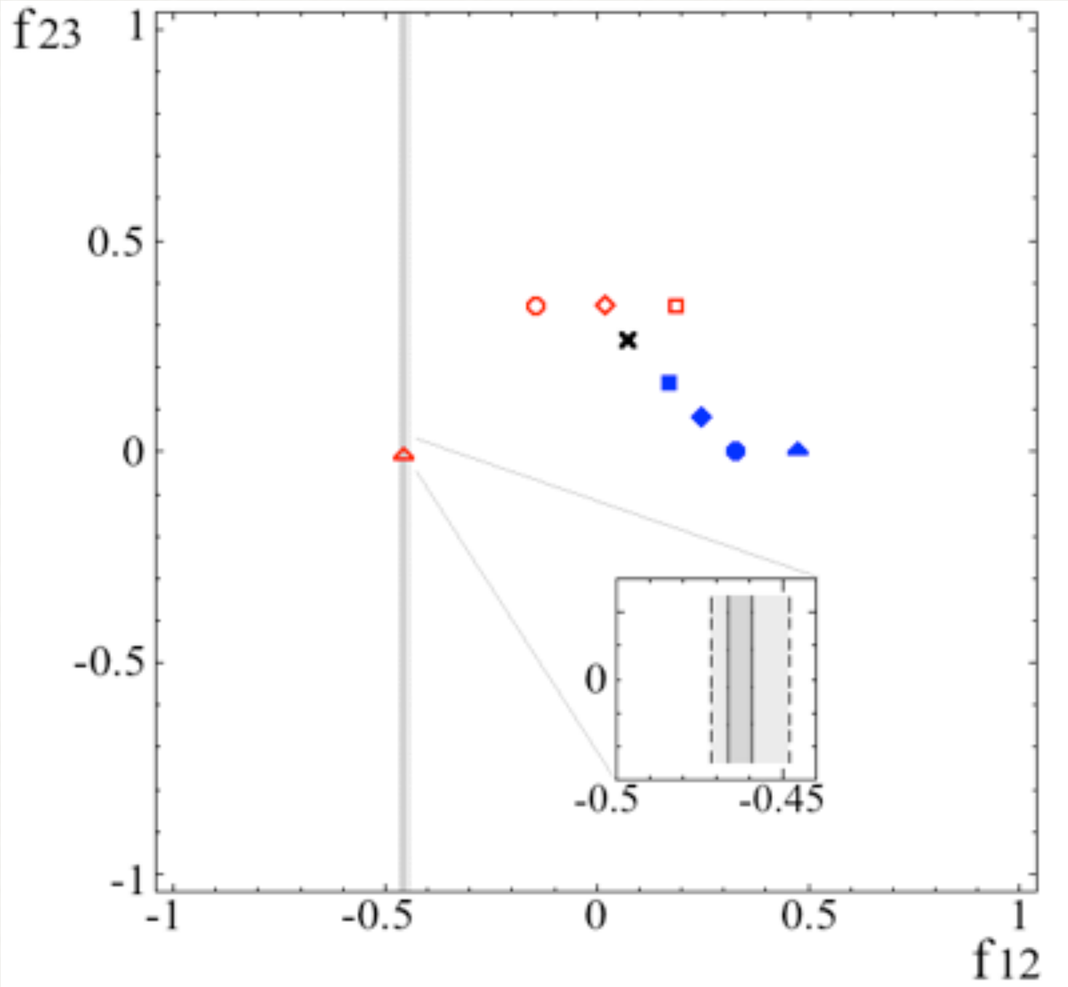




Pion source only

1σ region — 3σ region

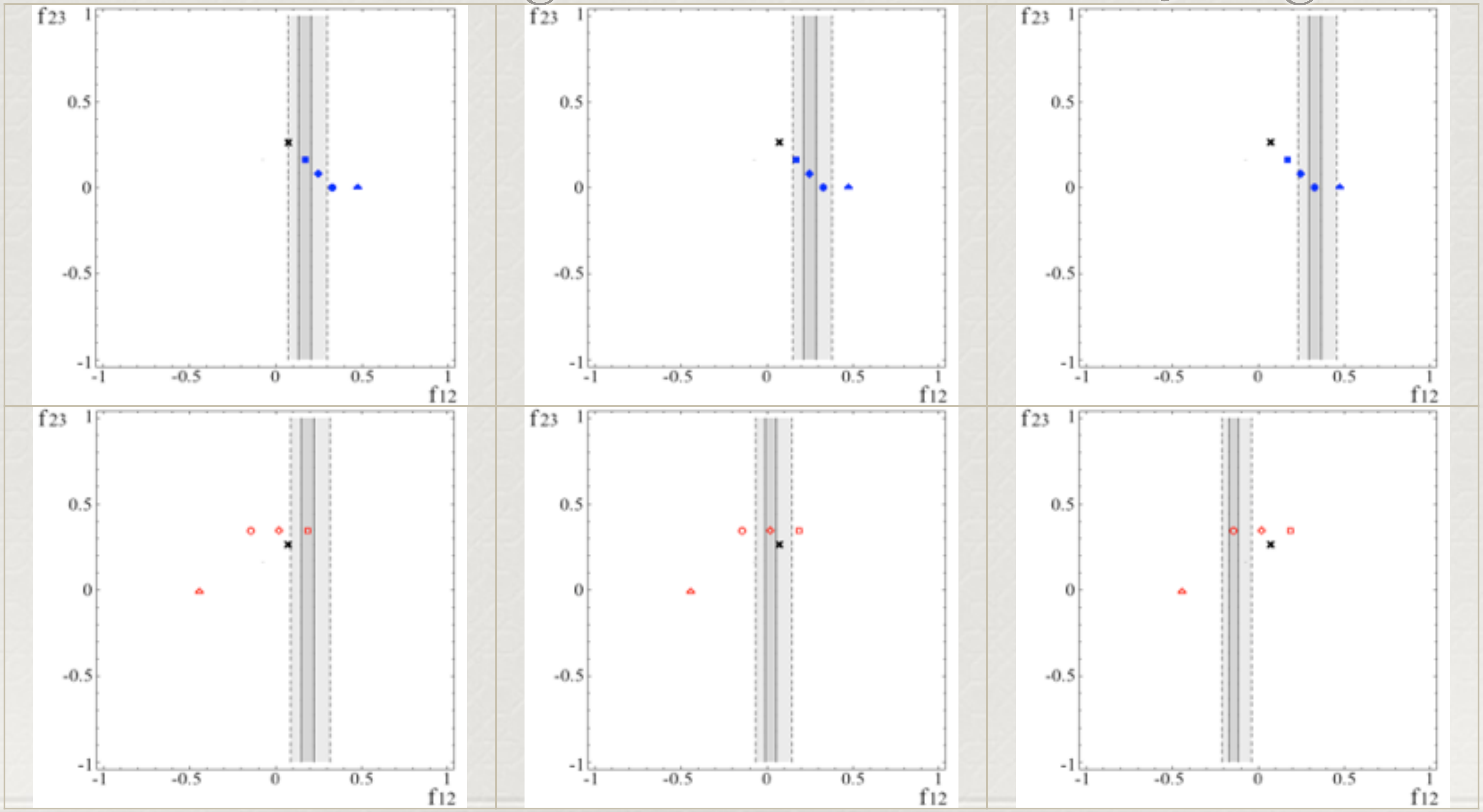




Pion source only

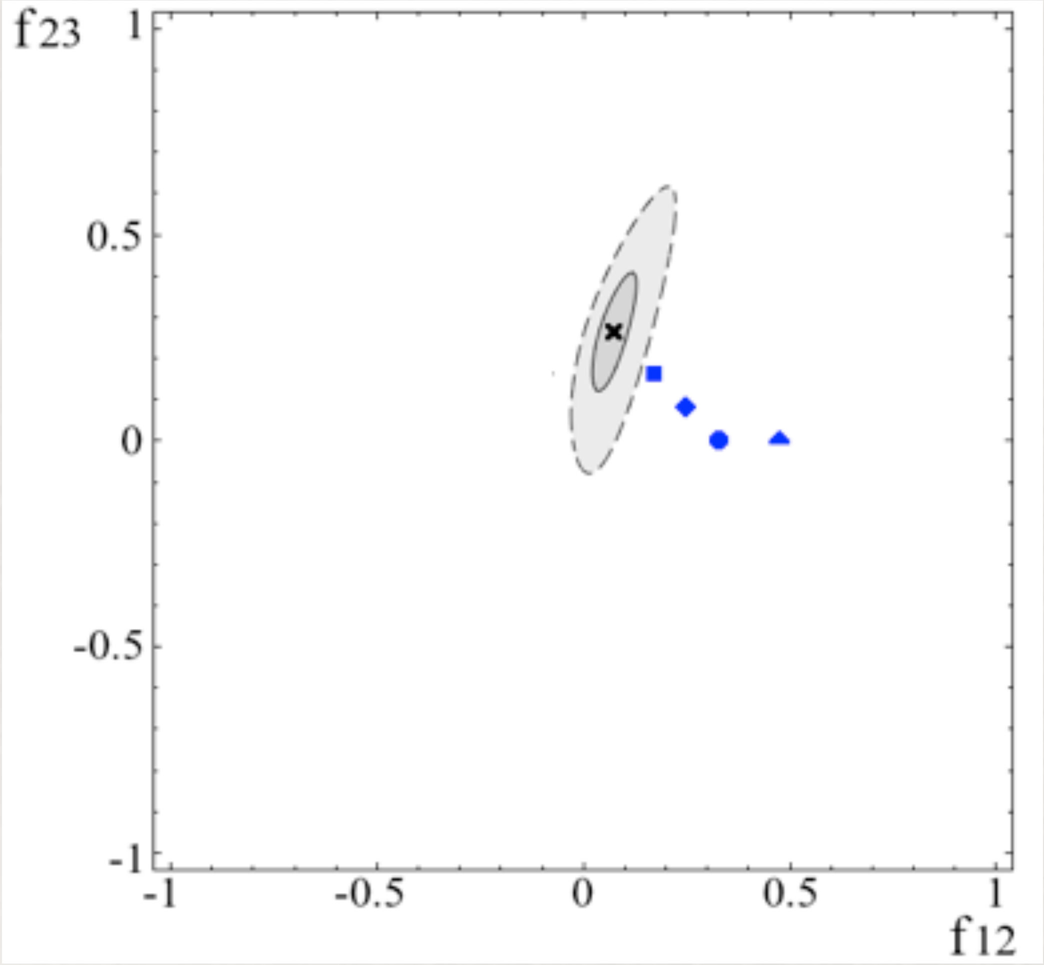
1σ region

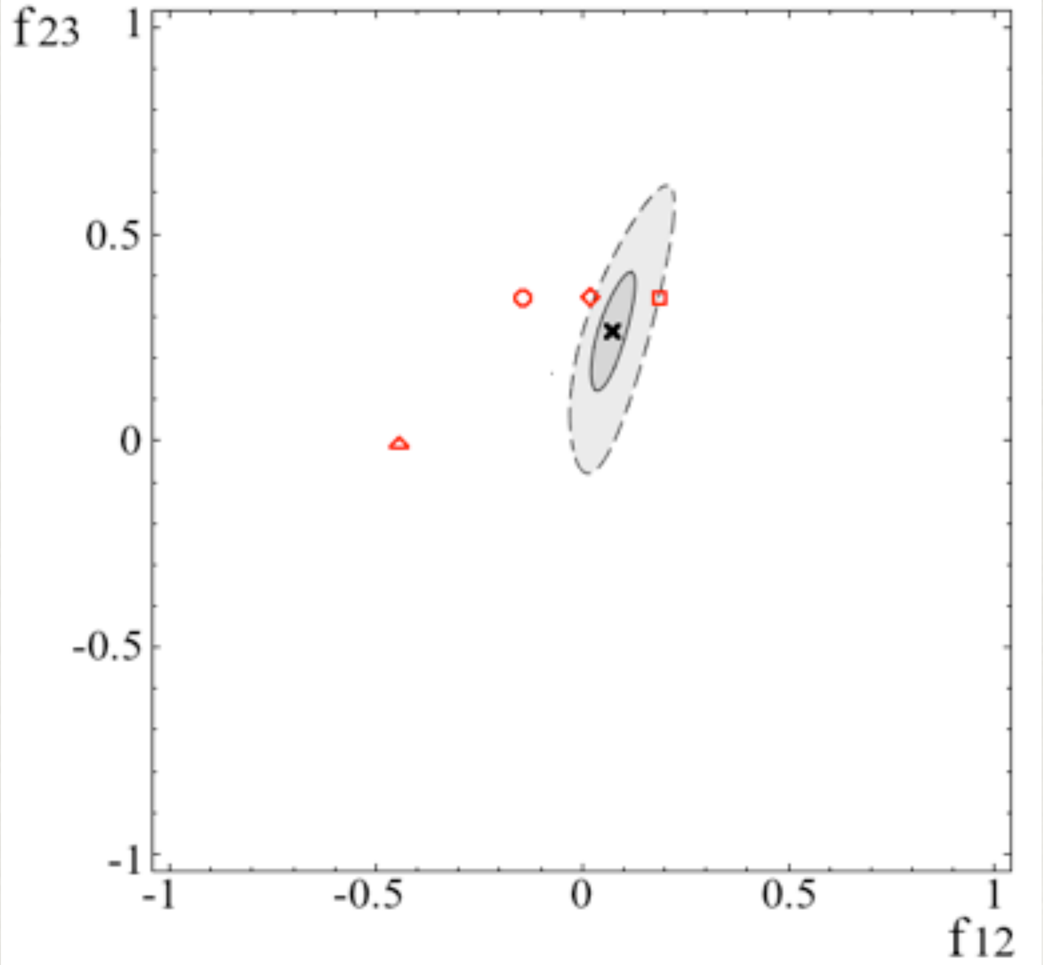
3σ region



Pion and damped-muon sources

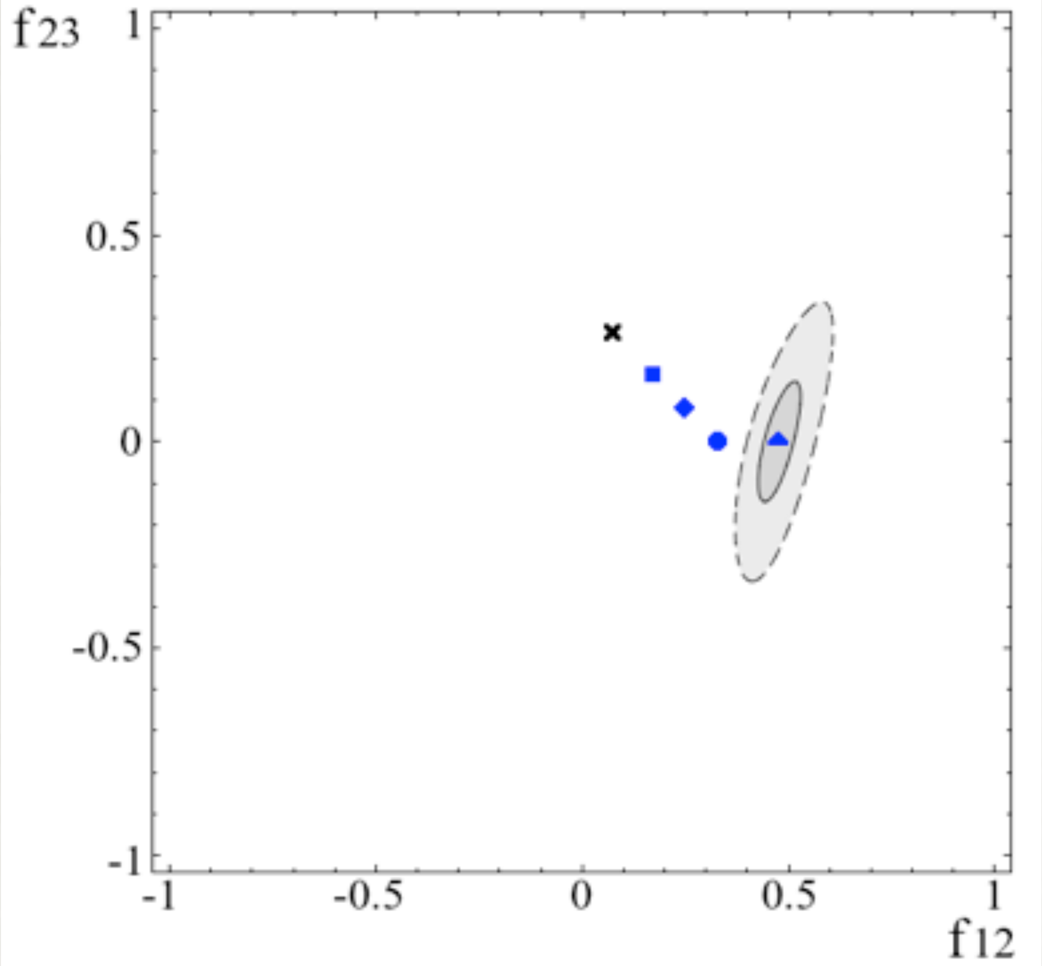
1σ region (solid line) *3σ region* (dashed line)

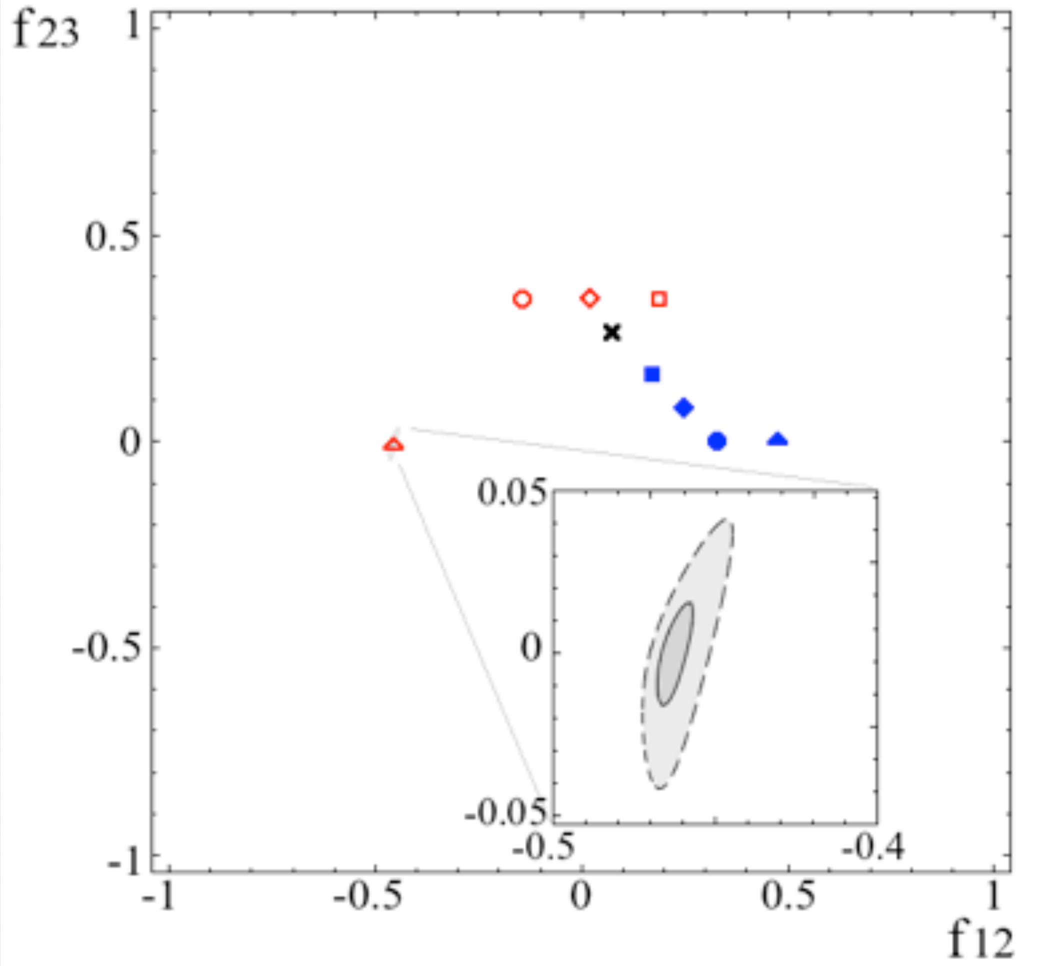




Pion and damped-muon sources

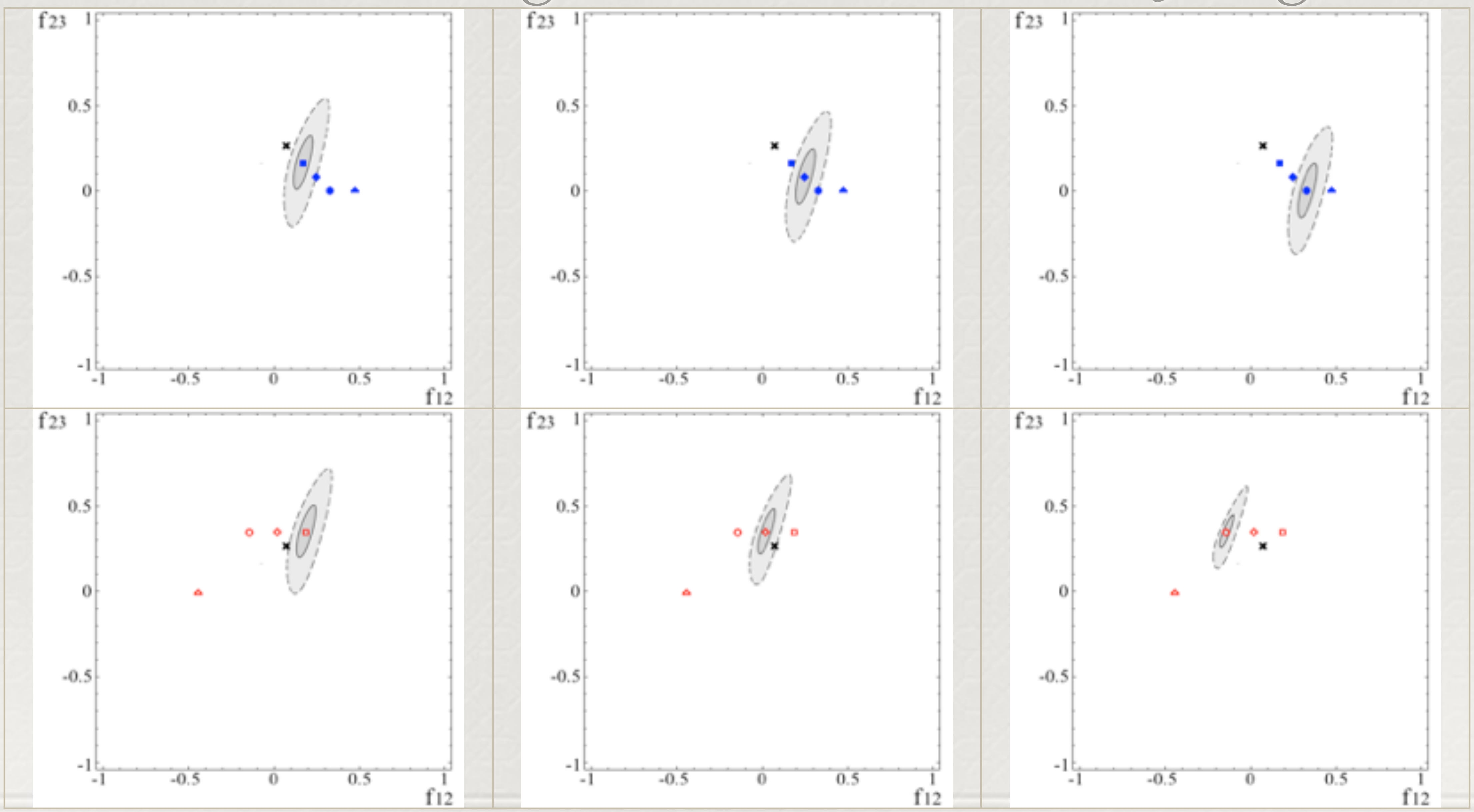
1σ region — *3σ region*





Pion and damped-muon sources

1σ region 3σ region



Summary

- *Astrophysical neutrinos have been observed.*
  - *37 events detected and more on the way*
  - *cosmogenic events expected*
- *Flavor transition can be probed.*
  - *Q-representation proposed*
  - *flavor-ratio observables defined*
  - *χ^2-analysis performed*