SUSY Renormalization Group Effects in Ultra High Energy Neutrinos

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Outline

- Review of Neutrino RGEs
- How to probe Neutrino RGEs
- Theoretical Predictions for Ultra High Energy Neutrinos
- Experimental Prospects

Neutrino RGEs

Neutrino Mass Operator

Dimension-5 Mass Operator:

$$\mathcal{L}_\nu = \frac{1}{4}(\overline{L}_i^c H)\frac{m_{ij}^\nu}{\Lambda_\nu}(L_j H)$$

Neutrino Mass Operator

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Neutrino Mass Matrix:

$$M_{ij}^\nu = \frac{1}{4}\frac{m_{ij}^\nu}{\Lambda_\nu}\,v^2$$

SM

$$M_{ij}^\nu = \frac{1}{4}\frac{m_{ij}^\nu}{\Lambda_\nu}\,v^2\sin^2\beta$$

SUSY

Mass Operator RGEs

At one loop, we have:

$$16\pi^2 \frac{dm^\nu_{ij}}{dx} = C\left((Y_e^\dagger Y_e)^T_{ik} m^\nu_{kj} + m^\nu_{ik}(Y_e^\dagger Y_e)_{kj}\right) + \alpha\, m^\nu_{ij}$$

Babu, Leung, Pantaleone (hep-ph/9309223)
Antusch, Drees, Kersten, Lindner, Ratz (hep-ph/0108005)
Antusch, Drees, Kersten, Lindner, Ratz (hep-ph/0110366)

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$$C = \begin{cases} -\frac{3}{2} \\ 1 \end{cases}$$

$$\alpha = \begin{cases} -3g_2^2 + 2\,\mathrm{Tr}(Y_e^\dagger Y_e) + 6\,\mathrm{Tr}(Y_u^\dagger Y_u) + 6\,\mathrm{Tr}(Y_d^\dagger Y_d) + \lambda \\ -\frac{6}{5}g_1^2 - 6g_2^2 + 6\,\mathrm{Tr}(Y_u^\dagger Y_u) \end{cases}$$

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Mixing Angle RGEs

Still at one loop:

$$\dot{\theta}_{12} = -C\,\frac{y_\tau^2}{32\pi^2}\,\sin 2\theta_{12}\,\sin^2\theta_{23}\,\frac{\left|m_1\,e^{i\phi_1} + m_2\,e^{i\phi_2}\right|^2}{\Delta m_{21}^2} + O(\theta_{13})$$

Antusch, Kersten, Lindner, Ratz (hep-ph/0305273)

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$$\begin{aligned} y_\tau^{SM} &= \sqrt{2} \frac{m_\tau}{v} \\ y_\tau^{SUSY} &= \sqrt{2} \frac{m_\tau}{v \cos \beta} \end{aligned}$$

A large tanβ can enhance running

Antusch, Kersten, Lindner, Ratz (hep-ph/0305273)

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Large neutrino masses can enhance running

WMAP (7 yr) $\Sigma m_i < 1.3\ \text{eV}$ Komatsu *et al* (1001.4538 [hep-ph])

Full Bounds $\Sigma m_i < 0.2\ \text{eV}$ Fogli *et al* (0805.2517 [hep-ph])

Antusch, Kersten, Lindner, Ratz (hep-ph/0305273)

Mixing Angle RGEs

Still at one loop:

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$$m_1^2 + m_2^2 + 2m_1 m_2 \cos(\phi_1 - \phi_2)$$

Majorana phases can enhance running

Antusch, Kersten, Lindner, Ratz (hep-ph/0305273)

Mixing Angle RGEs

Still at one loop:

$$\dot{\theta}_{12} = -C\,\frac{y_\tau^2}{32\pi^2}\,\sin 2\theta_{12}\,\sin^2\theta_{23}\,\frac{\left|m_1\,e^{i\phi_1}+m_2\,e^{i\phi_2}\right|^2}{\Delta m_{21}^2} + O(\theta_{13})$$

$$\begin{aligned}\dot{\theta}_{23} \quad &= \quad -C\frac{y_\tau^2}{32\pi^2}\sin 2\theta_{23}\left(\cos^2\theta_{12}\frac{\left|m_2\,e^{i\phi_2}+m_3\right|^2}{\Delta m_{32}^2}+\sin^2\theta_{12}\frac{\left|m_1\,e^{i\phi_1}+m_3\right|^2}{\Delta m_{31}^2}\right)\\ &\quad +O(\theta_{13})\end{aligned}$$

Antusch, Kersten, Lindner, Ratz (hep-ph/0305273)

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$$\begin{aligned}
\dot{\theta}_{23} &= -C\,\frac{y_\tau^2}{32\pi^2}\,\sin 2\theta_{23}\left(\cos^2\theta_{12}\,\frac{\left|m_2\,e^{i\phi_2} + m_3\right|^2}{\Delta m_{32}^2} + \sin^2\theta_{12}\,\frac{\left|m_1\,e^{i\phi_1} + m_3\right|^2}{\Delta m_{31}^2}\right) \\
&\quad + O(\theta_{13}) \\
\dot{\theta}_{13} &= C\,\frac{y_\tau^2}{32\pi^2}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\times \\
&\quad \times\left(\frac{m_3 m_1}{\Delta m_{31}^2}\cos(\phi_1 - \delta) - \frac{m_3 m_2}{\Delta m_{32}^2}\cos(\phi_2 - \delta) - \frac{\Delta m_{21}^2}{\Delta m_{31}^2\,\Delta m_{32}^2}\,m_3^2\cos\delta\right) \\
&\quad + O(\theta_{13})
\end{aligned}$$

Antusch, Kersten, Lindner, Ratz (hep-ph/0305273)

Probing Neutrino RGEs

How can we probe RGEs?

- If you talk about RGEs, you are talking about a scale μ.
- To avoid large logarithmic corrections, it is customary to set $\mu^2 = Q^2$.

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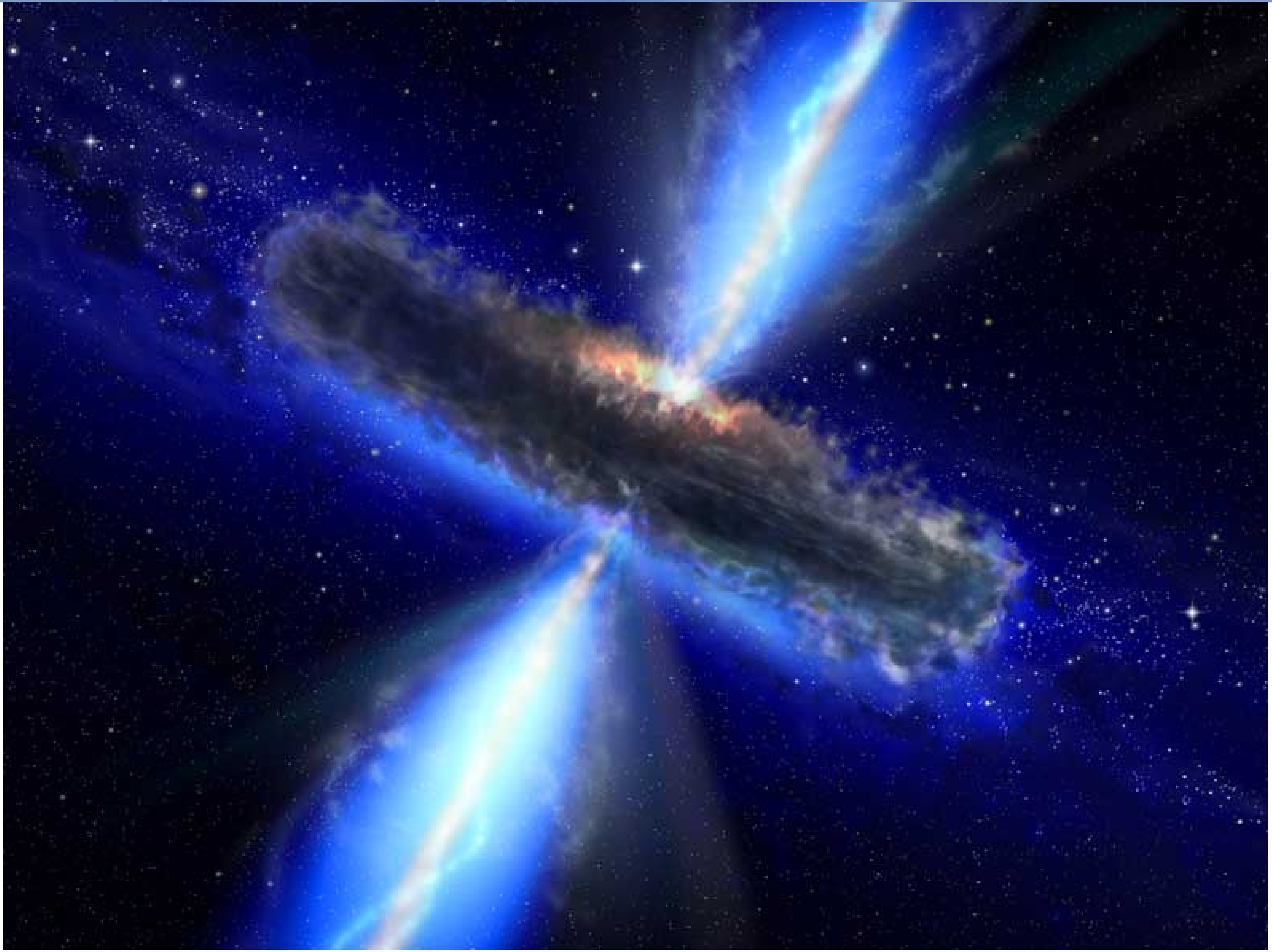
- If you talk about RGEs, you are talking about a scale μ.
- To avoid large logarithmic corrections, it is customary to set $\mu^2 = Q^2$.
- Thus, we need to look for experiments with large Q^2.
- To get large Q^2, we need very high energy neutrinos.

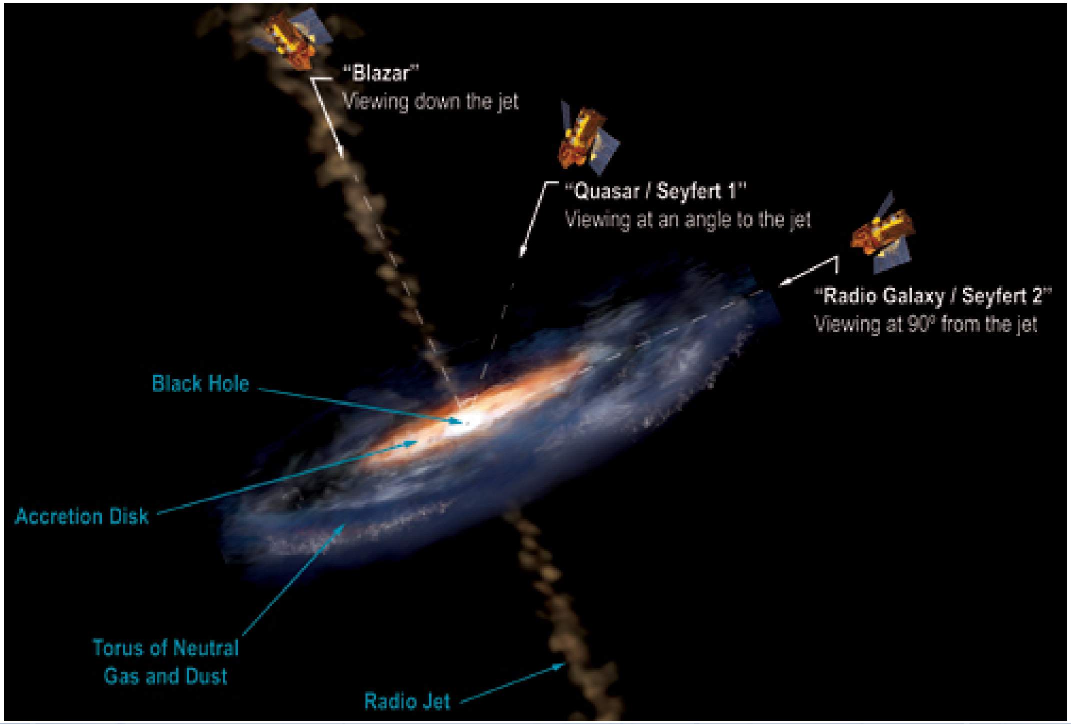


Credit: ESA/NASA/AVO/Paolo Padovani

Active Galactic Nuclei

From NASA Webpage:

“AGN - extraordinarily energetic cores of galaxies powered by accreting supermassive black holes. AGN such as quasars, blazars, and Seyfert galaxies are among the most luminous objects in our Universe, often pouring out the energy of billions of stars from a region no larger than our solar system.”



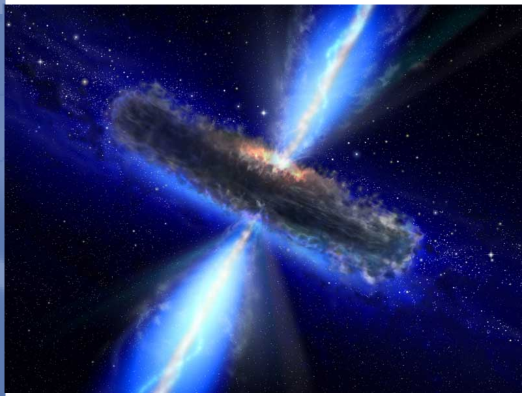
Stecker *et al*:

(Phys. Rev. Lett. 66, 2697–2700 (1991))

“Collectively, AGN produce the dominant isotropic ν background between 10^4 and 10^{10} GeV, detectable with current instruments.”

Credit: Aurore Simonnet, Sonoma State University

Two Scales: Two Mixing Matrices



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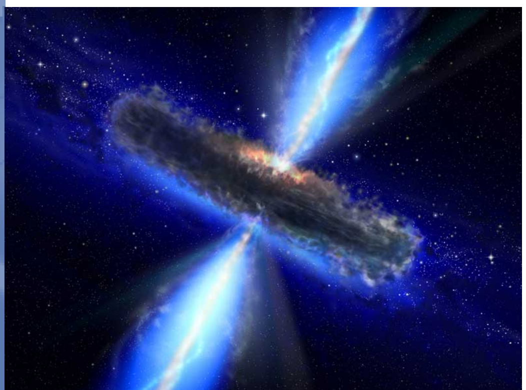

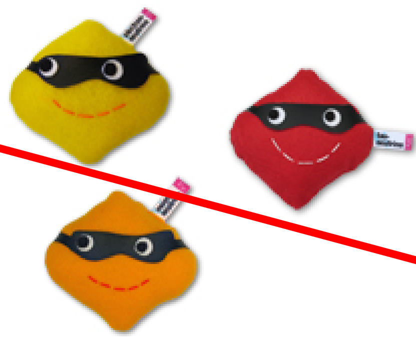

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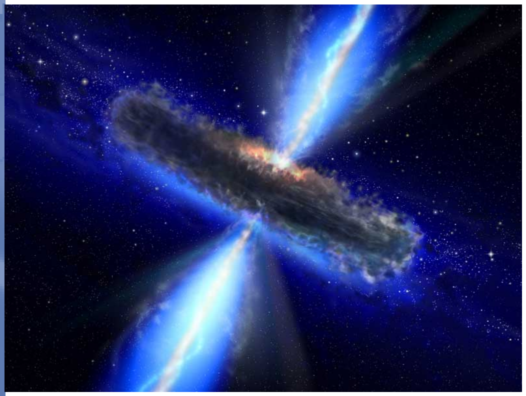
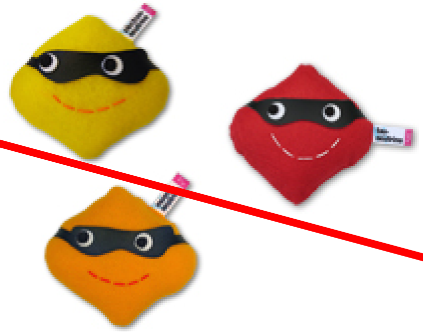


$$\mu = m_\pi$$
$$U_\nu = U_{\mathrm{PMNS}}$$



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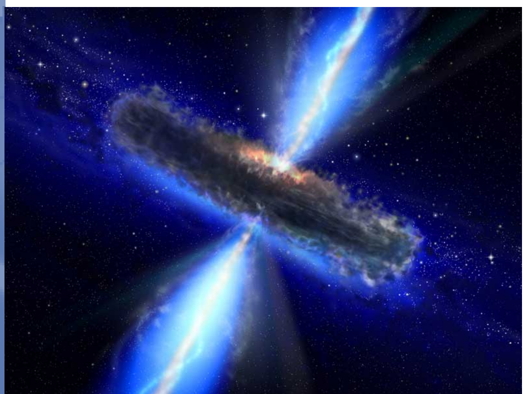

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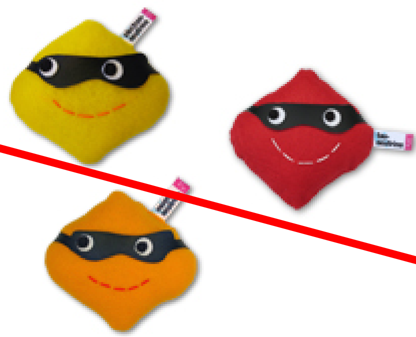
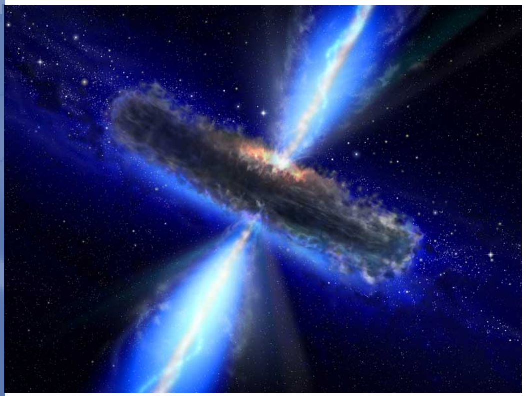
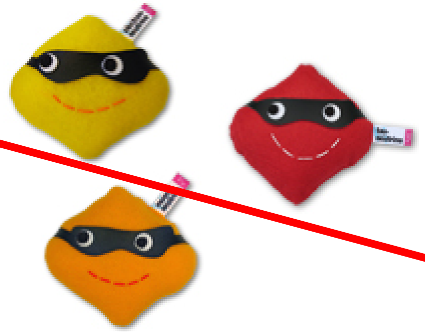


$$\mu \sim 10^4 \ \mathrm{GeV?}$$
$$U_\nu \neq U_{\mathrm{PMNS}}$$

Two Scales: Two Mixing Matrices





$$\mu = m_\pi$$
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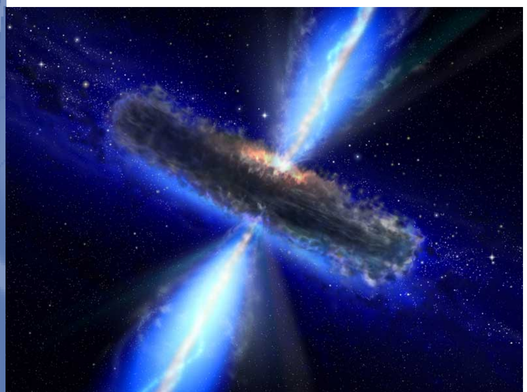
$$\mu \sim 10^4 \text{ GeV?}$$
$$U_\nu \neq U_{\rm PMNS}$$

$$P_{\alpha\beta}(Q) = \sum_{i=1}^{3} \left|(U_\nu)_{\alpha i}\right|^2 \left|(U'_\nu(Q))_{\beta i}\right|^2$$

Two Scales: Two Mixing Matrices



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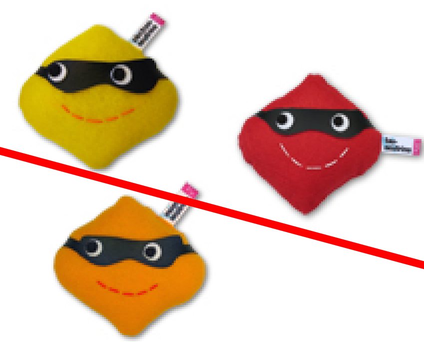


$$\mu \sim 10^4 \text{ GeV?}$$
$$U_\nu \neq U_{\mathrm{PMNS}}$$

REAP
hep-ph/0501272

$$m^\nu_{ij}$$

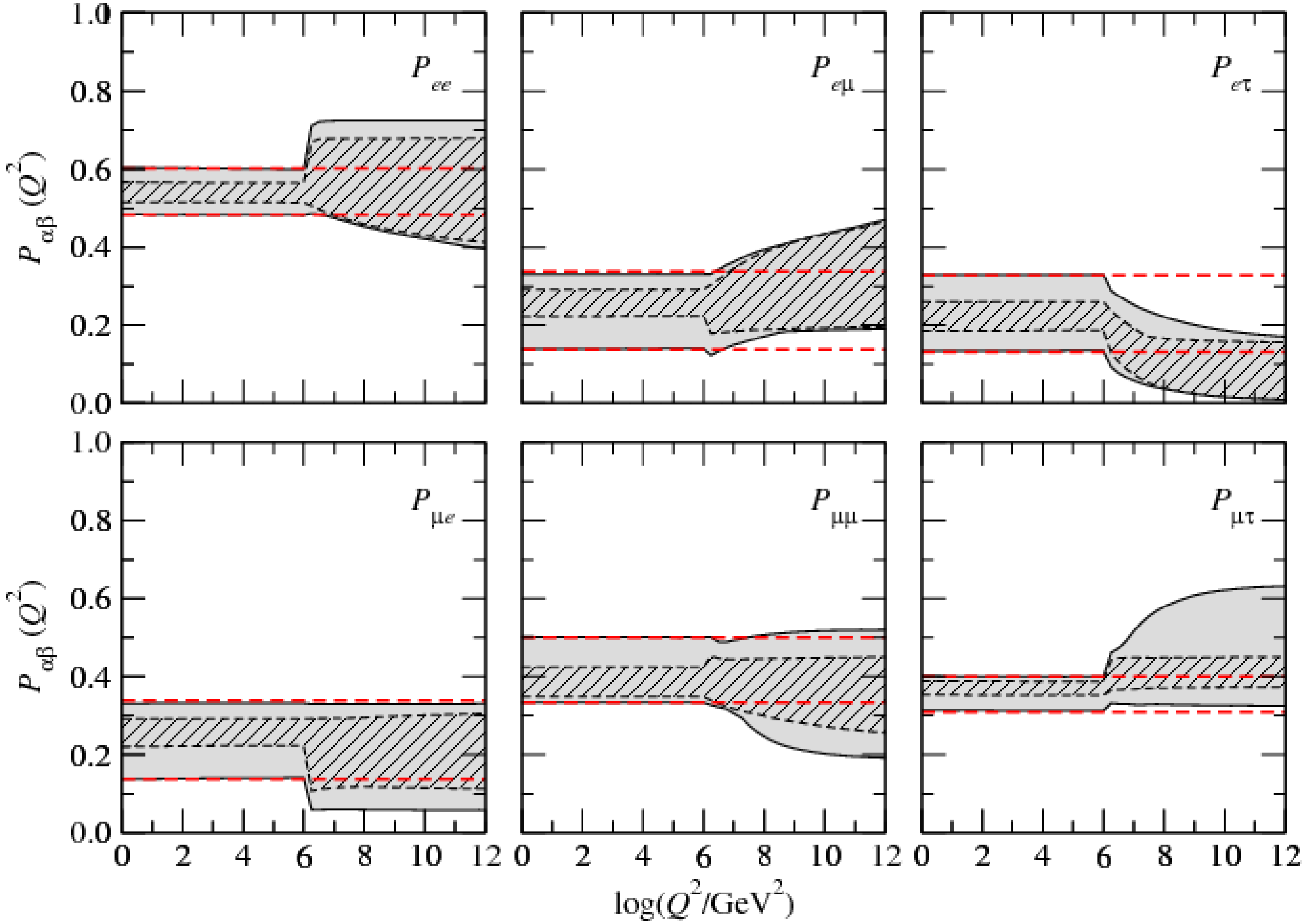
$$P_{\alpha\beta}(Q) = \sum_{i=1}^{3} \left| (U_\nu)_{\alpha i} \right|^2 \left| (U'_\nu(Q))_{\beta i} \right|^2$$

Transition Probability

No running

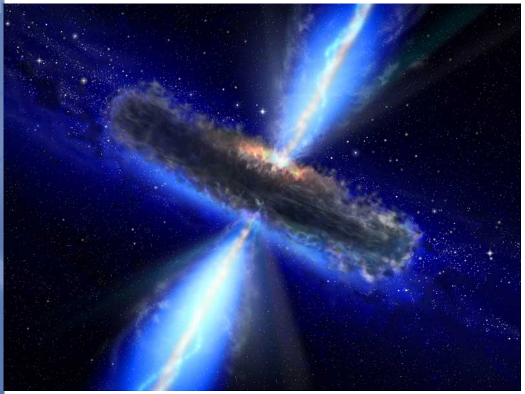
3σ variation

Only θ_{13} and phases



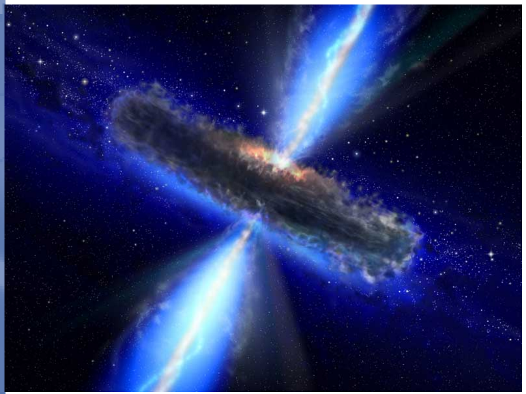
Theoretical Predictions

Production Ratios



$$(\nu_e : \nu_\mu : \nu_\tau)$$

Production Ratios

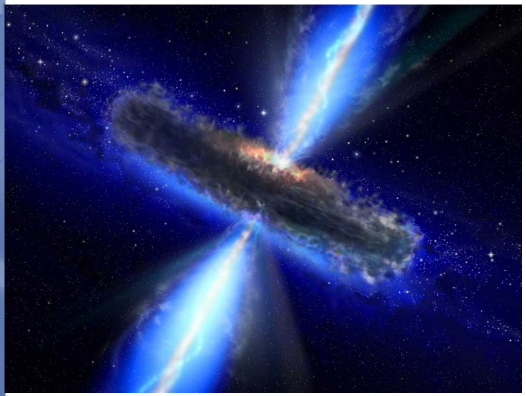


$$(\nu_e : \nu_\mu : \nu_\tau)$$

$(1:2:0)$ Pion + Muon Decay

$(0:1:0)$ Pion Decay

Production Ratios



$$(\nu_e : \nu_\mu : \nu_\tau)$$

$(1:2:0)$ Pion + Muon Decay

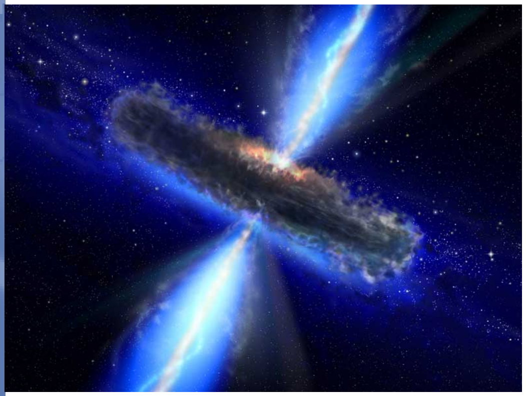
$(0:1:0)$ Pion Decay

$(1:0:0)$ Neutron Decay

$(1:1:0)$ Charm Decay

Production Ratios

$$(\nu_e : \nu_\mu : \nu_\tau)$$



$(1:2:0)$ Pion + Muon Decay

$(0:1:0)$ Pion Decay

$(1:0:0)$ Neutron Decay

$(1:1:0)$ Charm Decay

SM

$(1:0.9:0.9)$

$(1:1.4:1.4)$

$(1:0.5:0.3)$

$(1:0.8:0.7)$

Useful Ratios

$$T = \frac{\Phi_{\nu_\mu+\bar{\nu}_\mu}}{\Phi_{\nu_e+\bar{\nu}_e} + \Phi_{\nu_\mu+\bar{\nu}_\mu} + \Phi_{\nu_\tau+\bar{\nu}_\tau}}$$

Useful Ratios

$$T = \frac{\Phi_{\nu_\mu + \bar{\nu}_\mu}}{\Phi_{\nu_e + \bar{\nu}_e} + \Phi_{\nu_\mu + \bar{\nu}_\mu} + \Phi_{\nu_\tau + \bar{\nu}_\tau}}$$

$(1:2:0)$	$(0:1:0)$	$(1:0:0)$	$(1:1:0)$
0.32	0.37	0.28	0.32

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$$T = \frac{\Phi_{\nu_\mu + \bar{\nu}_\mu}}{\Phi_{\nu_e + \bar{\nu}_e} + \Phi_{\nu_\mu + \bar{\nu}_\mu} + \Phi_{\nu_\tau + \bar{\nu}_\tau}}$$

$(1:2:0)$	$(0:1:0)$	$(1:0:0)$	$(1:1:0)$
0.32	0.37	0.28	0.32

$$R = \frac{\Phi_{\nu_e + \bar{\nu}_e}}{\Phi_{\nu_\tau + \bar{\nu}_\tau}}.$$

$(1:2:0)$	$(0:1:0)$	$(1:0:0)$	$(1:1:0)$
1.1	0.71	3.3	1.4

Useful Ratios

$$T = \frac{\Phi_{\nu_\mu+\bar{\nu}_\mu}}{\Phi_{\nu_e+\bar{\nu}_e} + \Phi_{\nu_\mu+\bar{\nu}_\mu} + \Phi_{\nu_\tau+\bar{\nu}_\tau}}$$

$(1:2:0)$	$(0:1:0)$	$(1:0:0)$	$(1:1:0)$
0.32	0.37	0.28	0.32

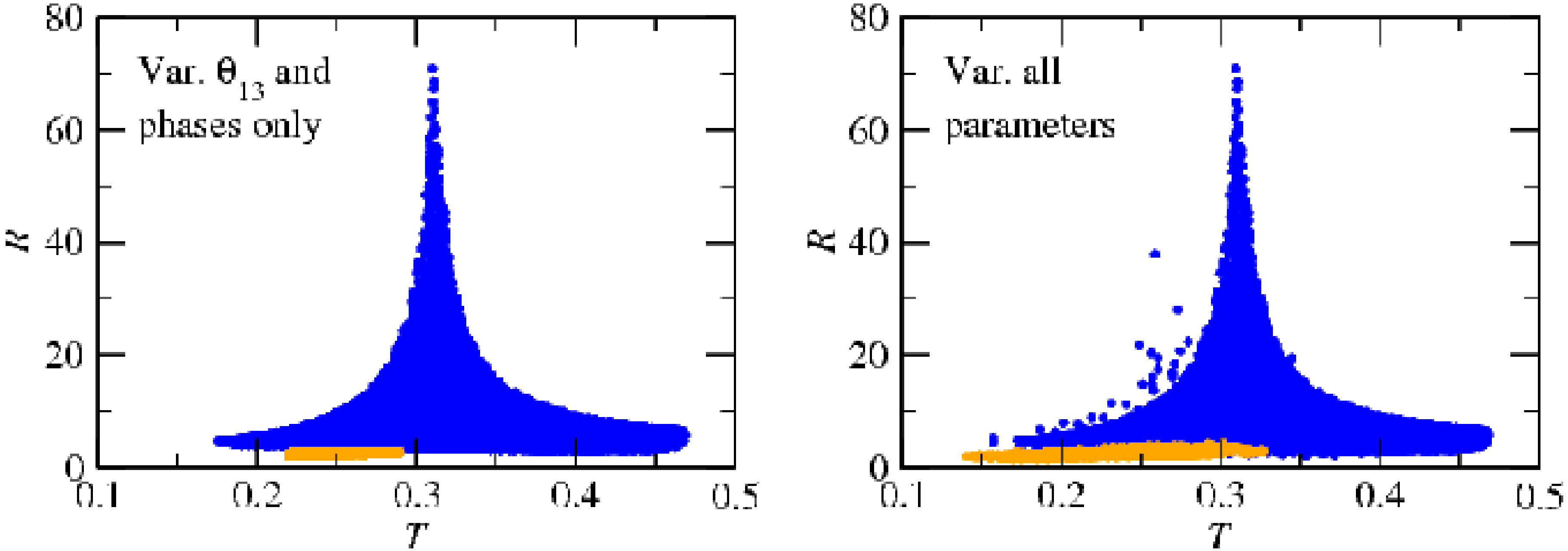
$$R = \frac{\Phi_{\nu_e+\bar{\nu}_e}}{\Phi_{\nu_\tau+\bar{\nu}_\tau}}.$$

$(1:2:0)$	$(0:1:0)$	$(1:0:0)$	$(1:1:0)$
1.1	0.71	3.3	1.4

What happens when one includes RGE effects?

Neutron Decay Production (1:0:0)

$$T = P_{e\mu} \qquad R = \frac{P_{ee}}{P_{e\tau}}$$

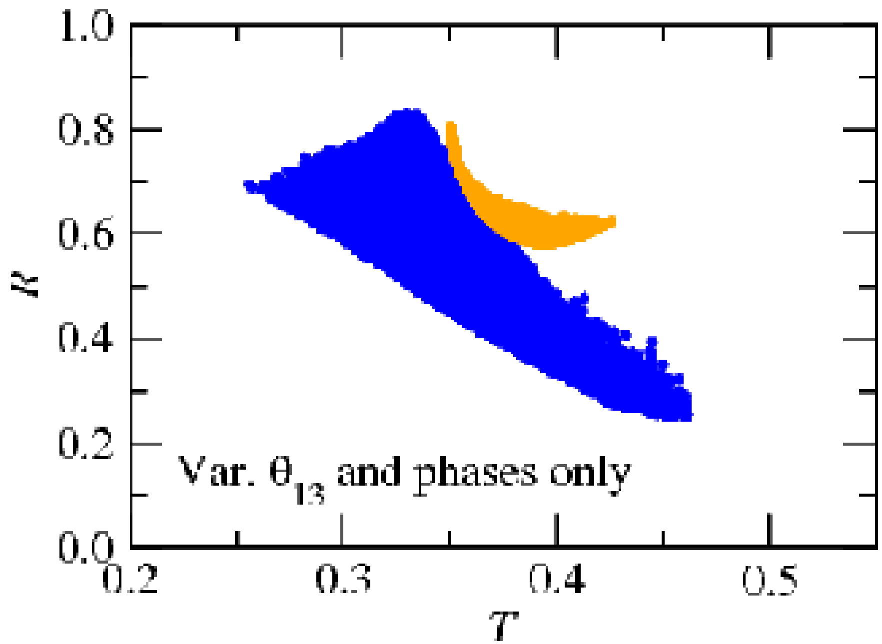


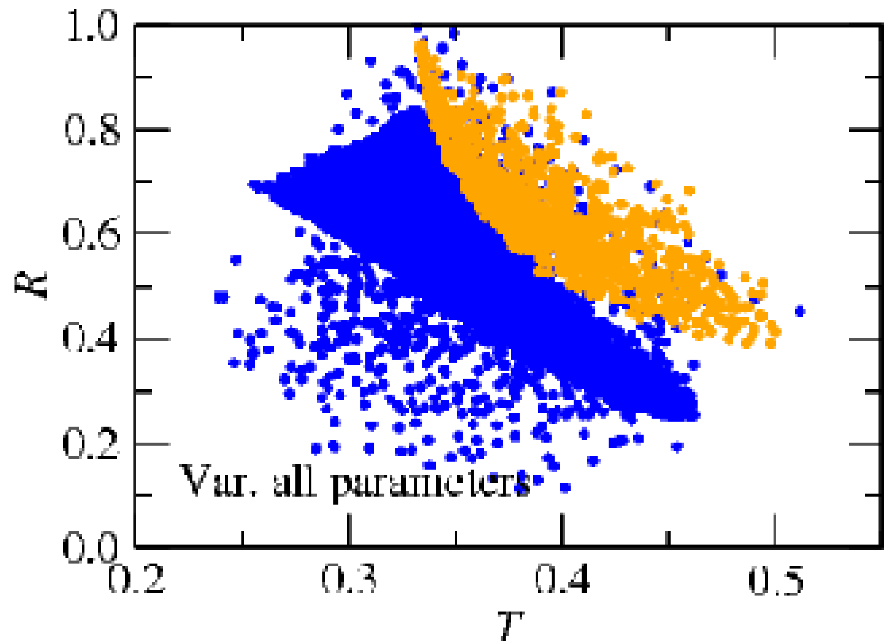
SM

SUSY

Pion Decay Production (0:1:0)

$$T = P_{\mu\mu} \qquad R = \frac{P_{\mu e}}{P_{\mu\tau}}$$



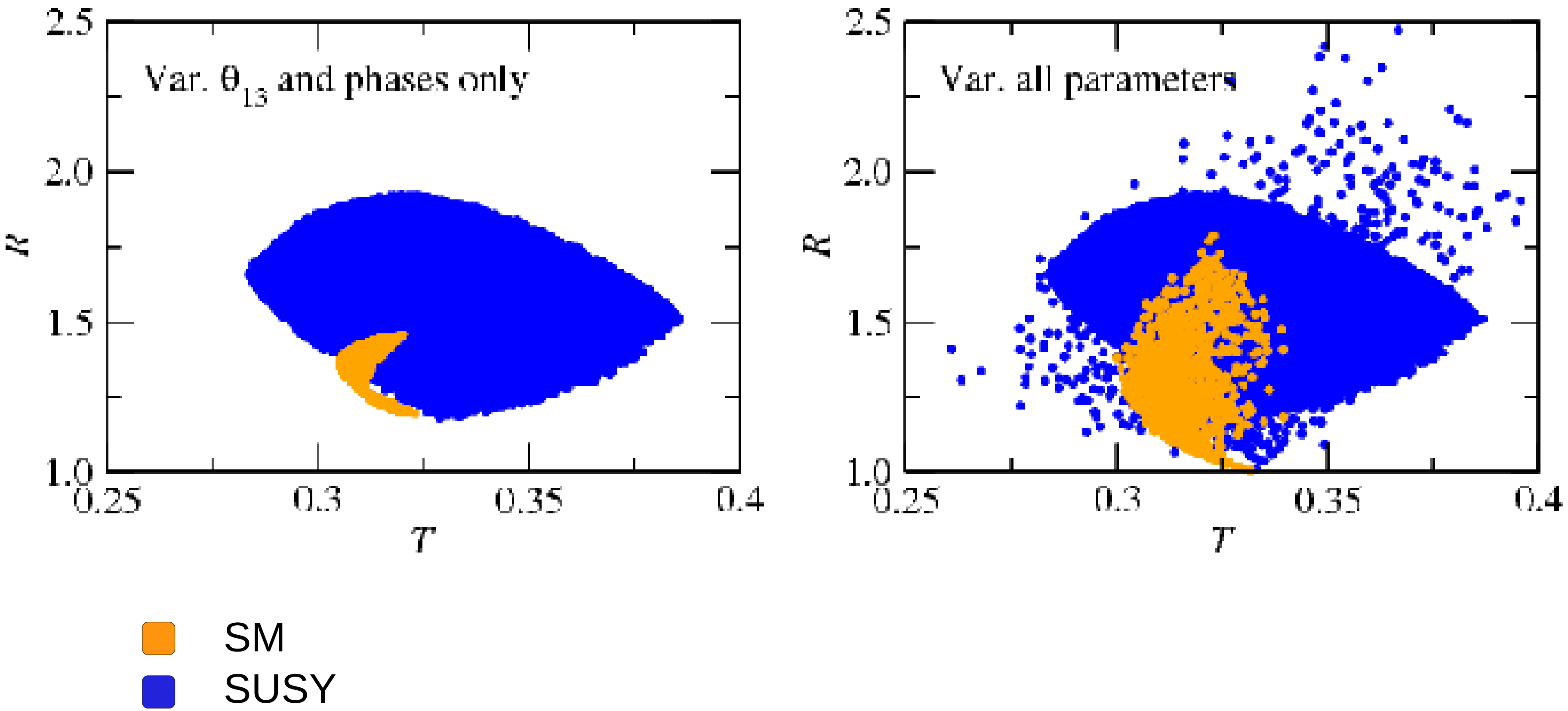


SM

SUSY

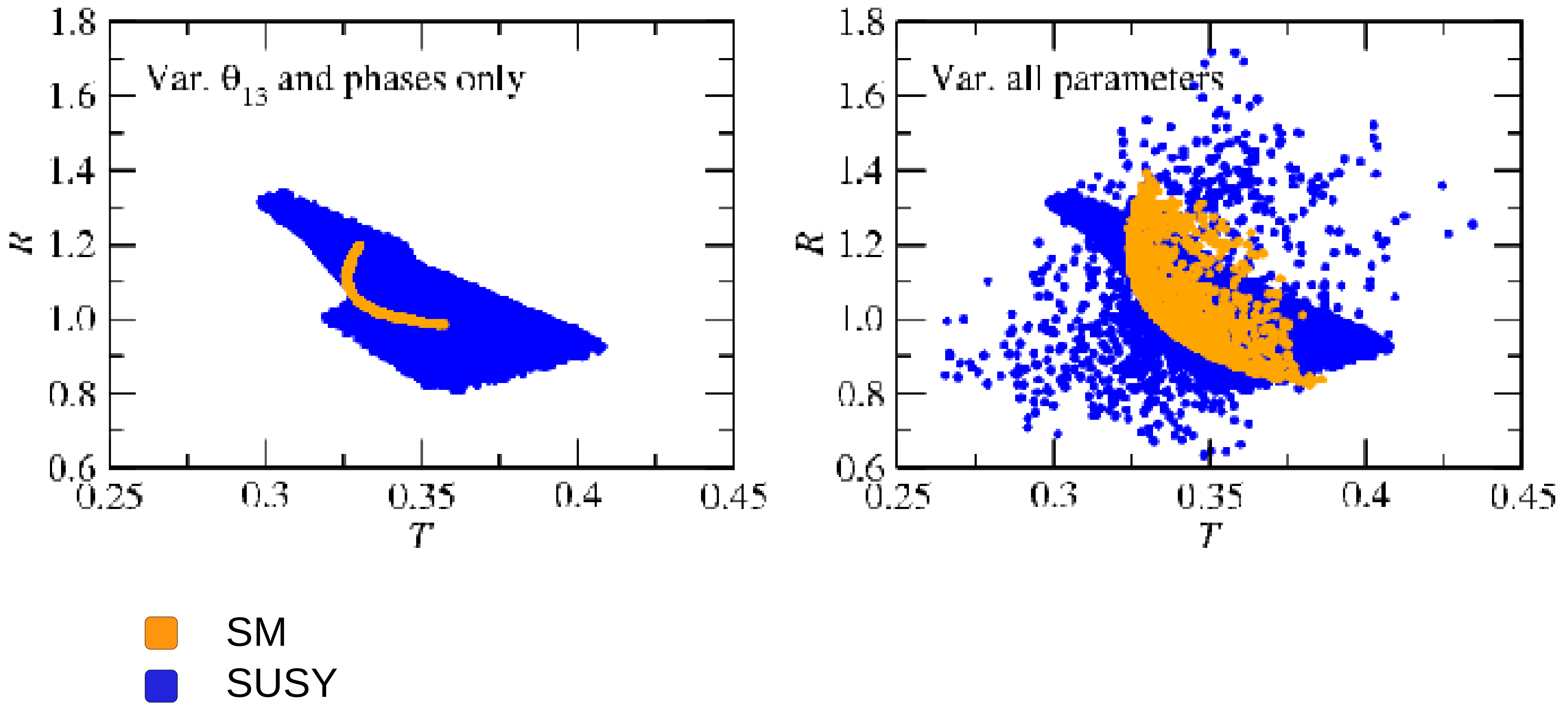
Charm Decay Production (1:1:0)

$$T = \frac{1}{2}\left(P_{e\mu} + P_{\mu\mu}\right) \qquad R = \frac{P_{ee} + P_{\mu e}}{P_{e\tau} + P_{\mu\tau}}$$

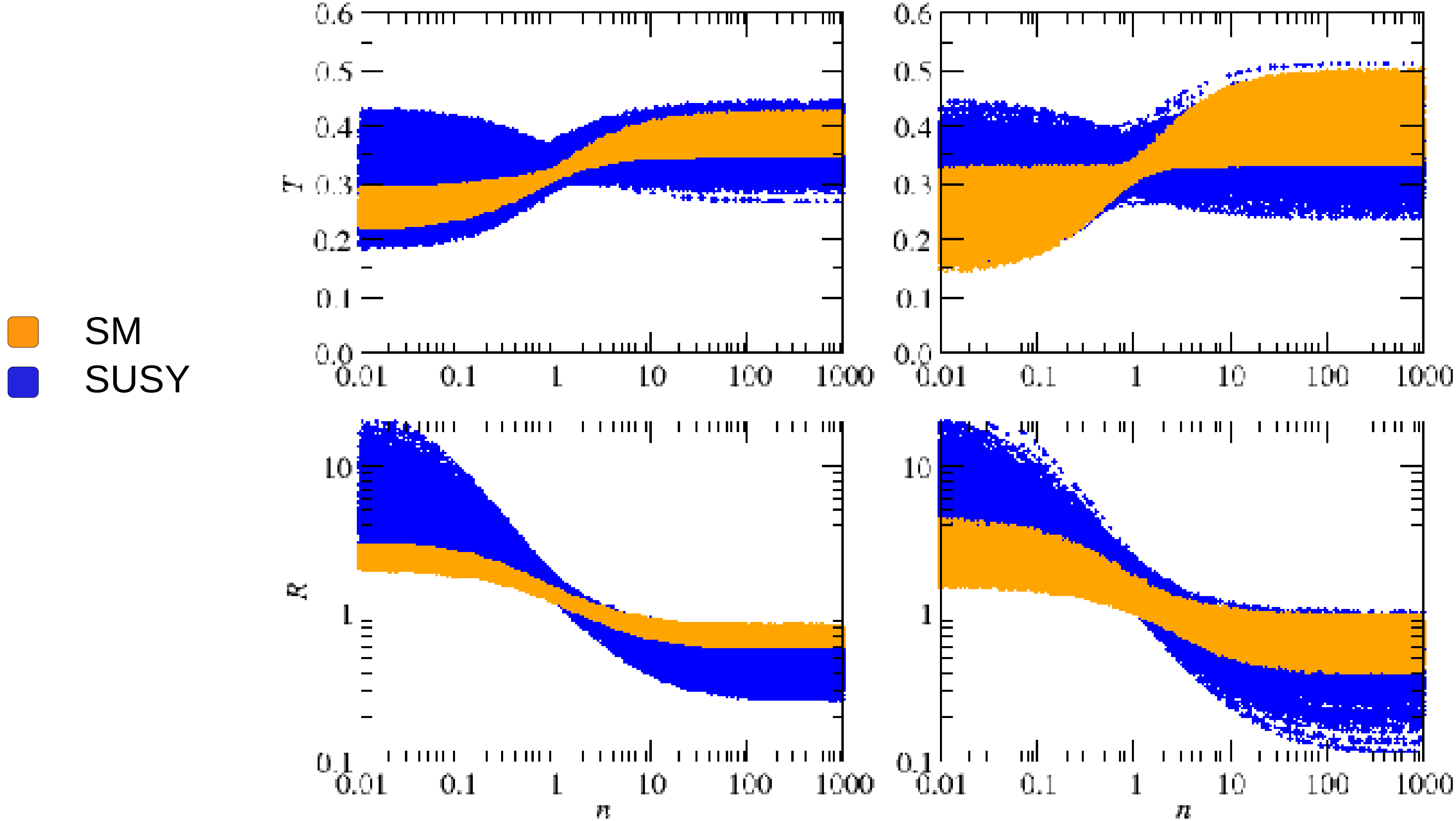


Pion + Muon Decay Production (1:2:0)

$$T = \frac{1}{3}\left(P_{e\mu} + 2P_{\mu\mu}\right) \qquad R = \frac{P_{ee} + 2P_{\mu e}}{P_{e\tau} + 2P_{\mu\tau}}$$



Unknown Production (1:n:0)



θ_{13} and phases.

3σ variation.

Experimental Prospects (Preliminary)

Step 1: Average Probability

Neutrino-nucleon interactions are through Deep Inelastic Scattering:

$$\langle P_{\alpha\beta}(E_\nu)\rangle^{\overset{(-)}{\nu}} = \frac{1}{\sigma_{\mathrm{CC}}^{\overset{(-)}{\nu}}(E_\nu)} \int_0^1 dx \int_0^1 dy \frac{d^2\sigma_{\mathrm{CC}}^{\overset{(-)}{\nu}}}{dxdy}(E_\nu, x, y)\, P_{\alpha\beta}\left(Q^2\right)$$

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Deep Inelastic Scattering:

$$\left\langle P_{\alpha\beta}\left(E_{\nu}\right)\right\rangle^{\overset{(-)}{\nu}} = \frac{1}{\sigma_{\mathrm{CC}}^{\overset{(-)}{\nu}}\left(E_{\nu}\right)} \int_{0}^{1} dx \int_{0}^{1} dy \frac{d^{2}\sigma_{\mathrm{CC}}^{\overset{(-)}{\nu}}}{dx\,dy}\left(E_{\nu}, x, y\right) P_{\alpha\beta}\left(Q^{2}\right)$$

Bjorken variables

Diferential cross-section

Step 1: Average Probability

Neutrino-nucleon interactions are through
Deep Inelastic Scattering:

Transition Probability

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Bjorken variables

Total cross-section

Diferential cross-section

Step 1: Average Probability

Neutrino-nucleon interactions are through Deep Inelastic Scattering:

Transition Probability

$$\langle P_{\alpha\beta}(E_\nu)\rangle^{\overset{(-)}{\nu}} = \frac{1}{\sigma_{\mathrm{CC}}^{\overset{(-)}{\nu}}(E_\nu)} \int_0^1 dx \int_0^1 dy \frac{d^2\sigma_{\mathrm{CC}}^{\overset{(-)}{\nu}}}{dx\,dy}(E_\nu, x, y)\, P_{\alpha\beta}(Q^2)$$

Bjorken variables

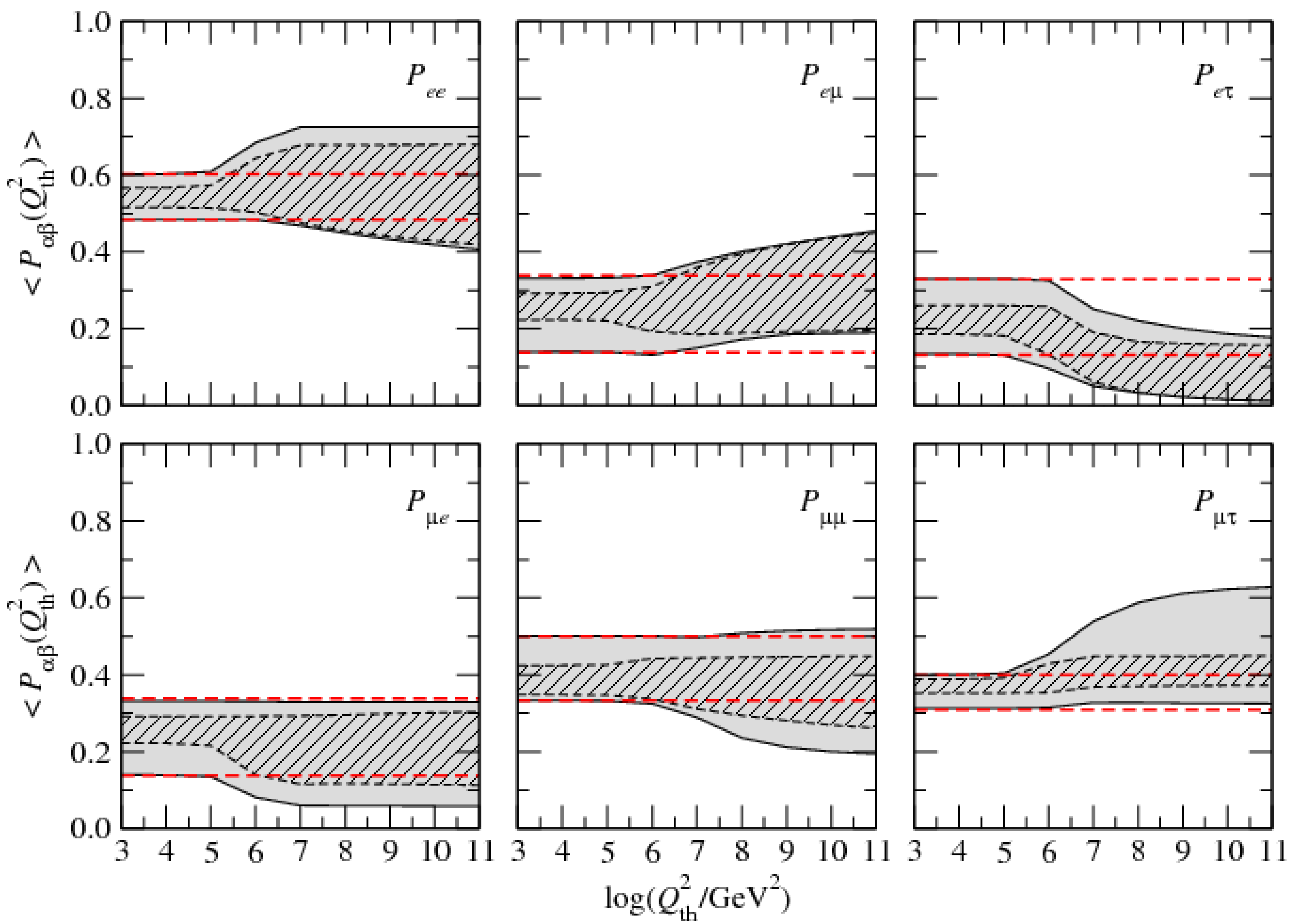
Total cross-section

Diferential cross-section

pdfs prefer low values of Q^2!

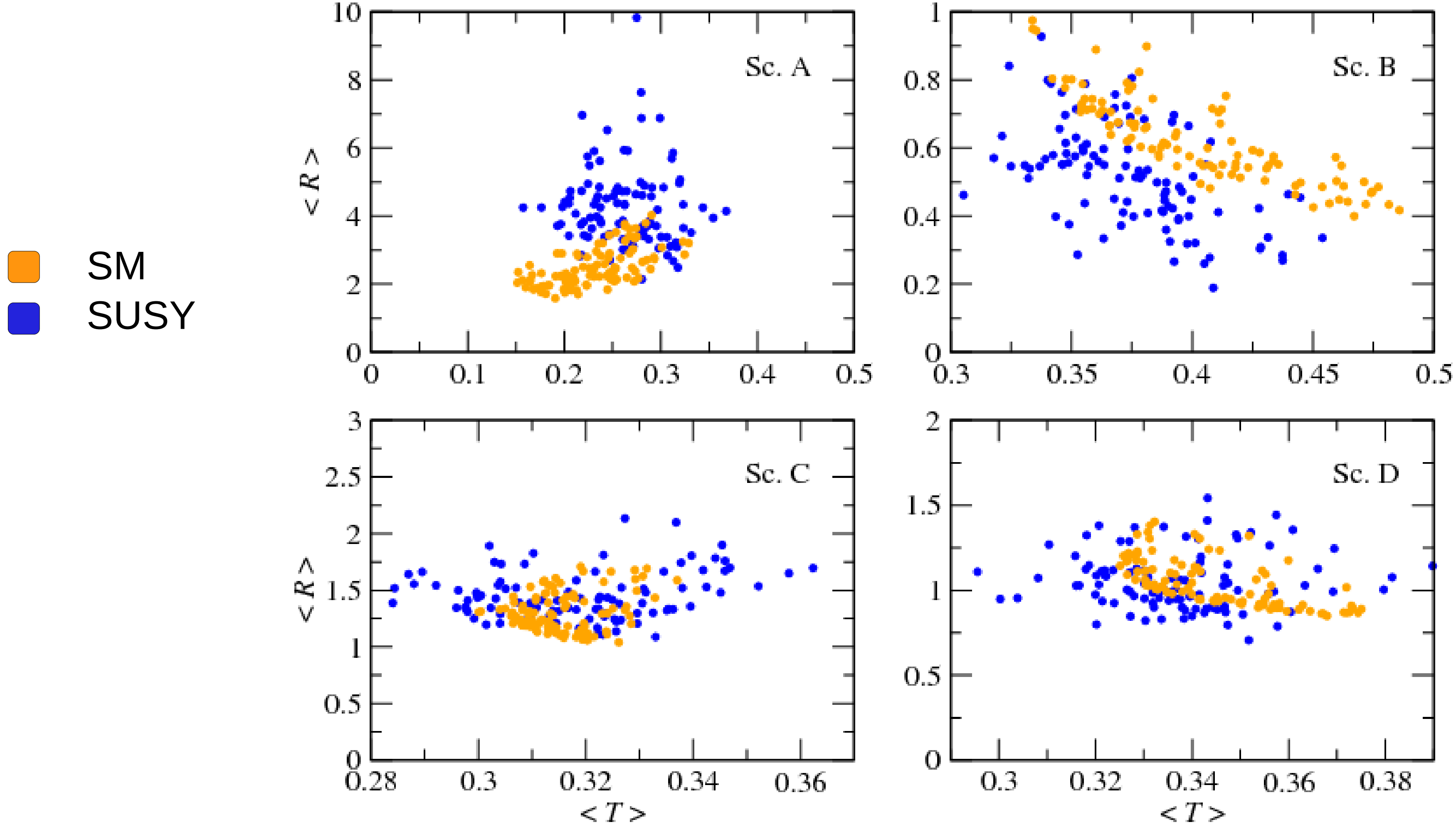
Step 1: Average Probability

Cutoff Q_{th}:



Step 1: Average Probability

Probability-Averaged Ratios:



Step 2: Number of Events

Need to add fluxes:

$$N^{\mathrm{CC}}_{\overset{(-)}{\nu}_\alpha} = t\, n_T V_{\mathrm{eff}} \Omega \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \int_0^1 dx \int_0^1 dy \frac{d^2\sigma^{\overset{(-)}{\nu}}_{\mathrm{CC}}}{dx\,dy}\left(E_\nu, x, y\right) \times$$

$$\times \left[\sum_{\beta=e,\mu,\tau} P_{\beta\alpha}\left(Q^2\right) \tilde{\Phi}^0_{\overset{(-)}{\nu}_\beta}\right] \Phi_{\nu_{\mathrm{all}}}\left(E_\nu\right)$$

Step 2: Number of Events

Need to add fluxes:

Diferential Cross-Section

$$N^{\mathrm{CC}}_{\overset{(-)}{\nu}_\alpha} = t\, n_T V_{\mathrm{eff}} \Omega \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \int_0^1 dx \int_0^1 dy \frac{d^2\sigma^{\overset{(-)}{\nu}}_{\mathrm{CC}}}{dx\,dy} (E_\nu, x, y) \times$$

$$\times \left[\sum_{\beta=e,\mu,\tau} P_{\beta\alpha}\left(Q^2\right) \tilde{\Phi}^0_{\overset{(-)}{\nu}_\beta} \right] \Phi_{\nu_{\mathrm{all}}}\left(E_\nu\right)$$

Transition Probability

Step 2: Number of Events

Need to add fluxes:

Diferential Cross-Section

$$
\begin{aligned}
N^{\mathrm{CC}}_{\overset{(-)}{\nu}_\alpha} &= t\, n_T V_{\mathrm{eff}} \Omega \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \int_0^1 dx \int_0^1 dy \, \frac{d^2\sigma^{\overset{(-)}{\nu}}_{\mathrm{CC}}}{dx\,dy}\left(E_\nu, x, y\right) \times \\
&\times \left[\sum_{\beta=e,\mu,\tau} P_{\beta\alpha}\left(Q^2\right) \tilde{\Phi}^0_{\overset{(-)}{\nu}_\beta} \right] \Phi_{\nu_{\mathrm{all}}}\left(E_\nu\right)
\end{aligned}
$$

Transition Probability

Total neutrino flux

Production Ratio

Step 2: Number of Events

Need to add fluxes:

Number density of target

Time

Opening solid angle

Diferential Cross-Section

$$N^{\mathrm{CC}}_{\overset{(-)}{\nu}_\alpha} = t\, n_T V_{\mathrm{eff}} \Omega \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \int_0^1 dx \int_0^1 dy \frac{d^2\sigma^{\overset{(-)}{\nu}}_{\mathrm{CC}}}{dx\,dy}(E_\nu, x, y) \times$$

$$\times \left[\sum_{\beta=e,\mu,\tau} P_{\beta\alpha}\left(Q^2\right) \tilde{\Phi}^0_{\overset{(-)}{\nu}_\beta} \right] \Phi_{\nu_{\mathrm{all}}}\left(E_\nu\right)$$

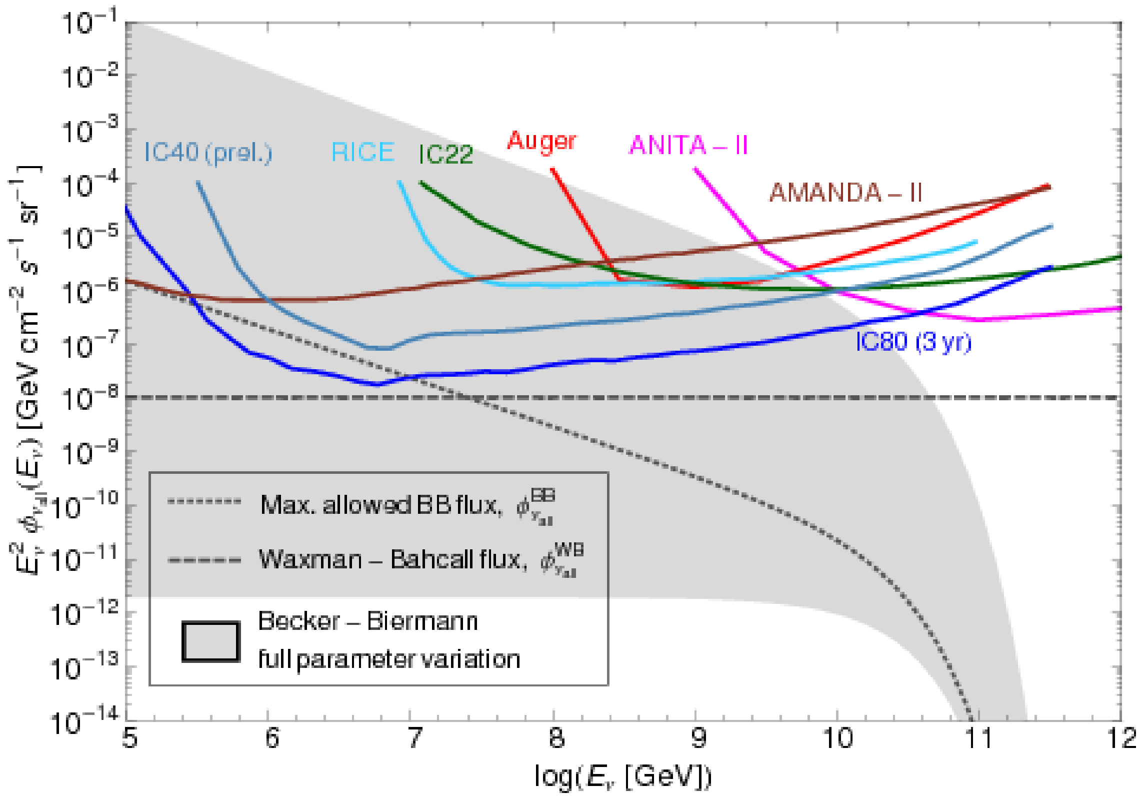
Effective Volume

Transition Probability

Production Ratio

Total neutrino flux

Fluxes are too low!

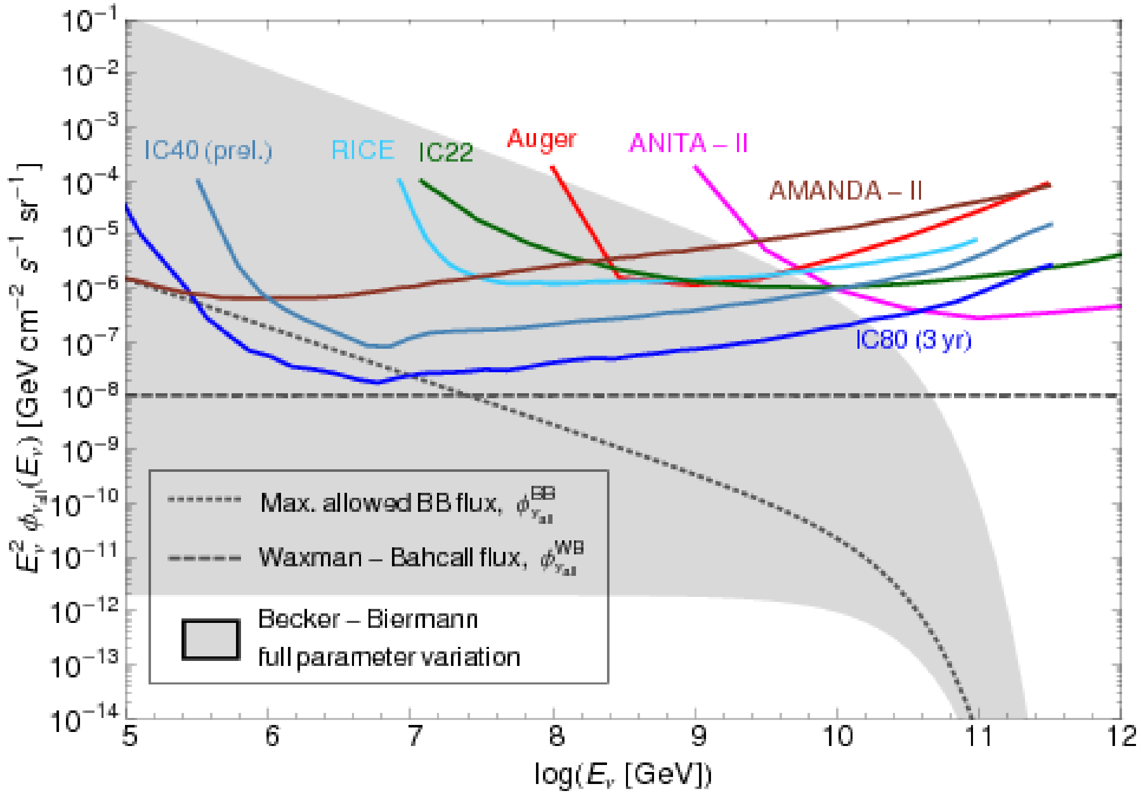


$$\Phi^{\mathrm{WB}}_{\nu_{\mathrm{all}}}(E_\nu) = 10^{-8}\,(E_\nu/\mathrm{GeV})^{-2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

$$\Phi^{\mathrm{BB}}_{\nu_{\mathrm{all}}}(E_\nu) \simeq 5\times 10^{-2}\,(E_\nu/\mathrm{GeV})^{-2.9}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

Waxman, Bahcall (hep-ph/9807282)
Becker, Bierman (0805.1498 [astro-ph])

Fluxes are too low!



$$N^{\mathrm{WB}}_{\overset{(-)}{\nu}_\alpha} \sim 3 \times 10^{-8} \text{ events/yr}$$

$$N^{\mathrm{BB}}_{\overset{(-)}{\nu}_\alpha} \sim 2 \times 10^{-7} \text{ events/yr}$$

Experimentally Unobservable?

Experiment requires:

- Sensitivity to high energy
- Neutrino flavour distinction
- Transferred momentum reconstruction
- 10^8 times number of targets of IceCube.

Experimentally Unobservable?

Experiment requires:

- Sensitivity to high energy
- Neutrino flavour distinction
- Transferred momentum reconstruction
- 10^8 times number of targets of IceCube.

  - Academic exercise?
  - Breakthrough in neutrino detection techniques????

Conclusions

- SUSY RGEs can modify transition probability in neutrino experiments.
- Effects depend on neutrino mass, tanβ and Majorana phases.
- Theoretically, R and T ratios for AGNs can distinguish a SUSY from a SM scenario.
- Low neutrino fluxes and cross-section pdfs seem to make observation currently unfeasible.

Backups

Probability

$$
\begin{aligned}
P_{\alpha e} &= g_{\alpha 3} + c^2_{\zeta_{13}} \left[(g_{\alpha 1} - g_{\alpha 3}) - s^2_{\zeta_{12}} (g_{\alpha 1} - g_{\alpha 2}) \right] \\
P_{\alpha \mu} &= g_{\alpha 2} + s^2_{\zeta_{12}} (g_{\alpha 1} - g_{\alpha 2}) \\
&\quad + s^2_{\zeta_{23}} \left[(g_{\alpha 3} - g_{\alpha 2}) - s^2_{\zeta_{12}} \left(1 + s^2_{\zeta_{13}}\right) (g_{\alpha 1} - g_{\alpha 2}) + s^2_{\zeta_{13}} (g_{\alpha 1} - g_{\alpha 3}) \right] \\
&\quad + \left(\frac{g_{\alpha 1} - g_{\alpha 2}}{2} \right) c_{\delta_1} s_{2\zeta_{12}} s_{2\zeta_{23}} s_{\zeta_{13}} \\
P_{\alpha \tau} &= g_{\alpha 2} + s^2_{\zeta_{12}} (g_{\alpha 1} - g_{\alpha 2}) \\
&\quad + c^2_{\zeta_{23}} \left[(g_{\alpha 3} - g_{\alpha 2}) - s^2_{\zeta_{12}} \left(1 + s^2_{\zeta_{13}}\right) (g_{\alpha 1} - g_{\alpha 2}) + s^2_{\zeta_{13}} (g_{\alpha 1} - g_{\alpha 3}) \right] \\
&\quad - \left(\frac{g_{\alpha 1} - g_{\alpha 2}}{2} \right) c_{\delta_1} s_{2\zeta_{12}} s_{2\zeta_{23}} s_{\zeta_{13}}
\end{aligned}
$$

Transition Probability

P_{ee} $P_{\mu e}$

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

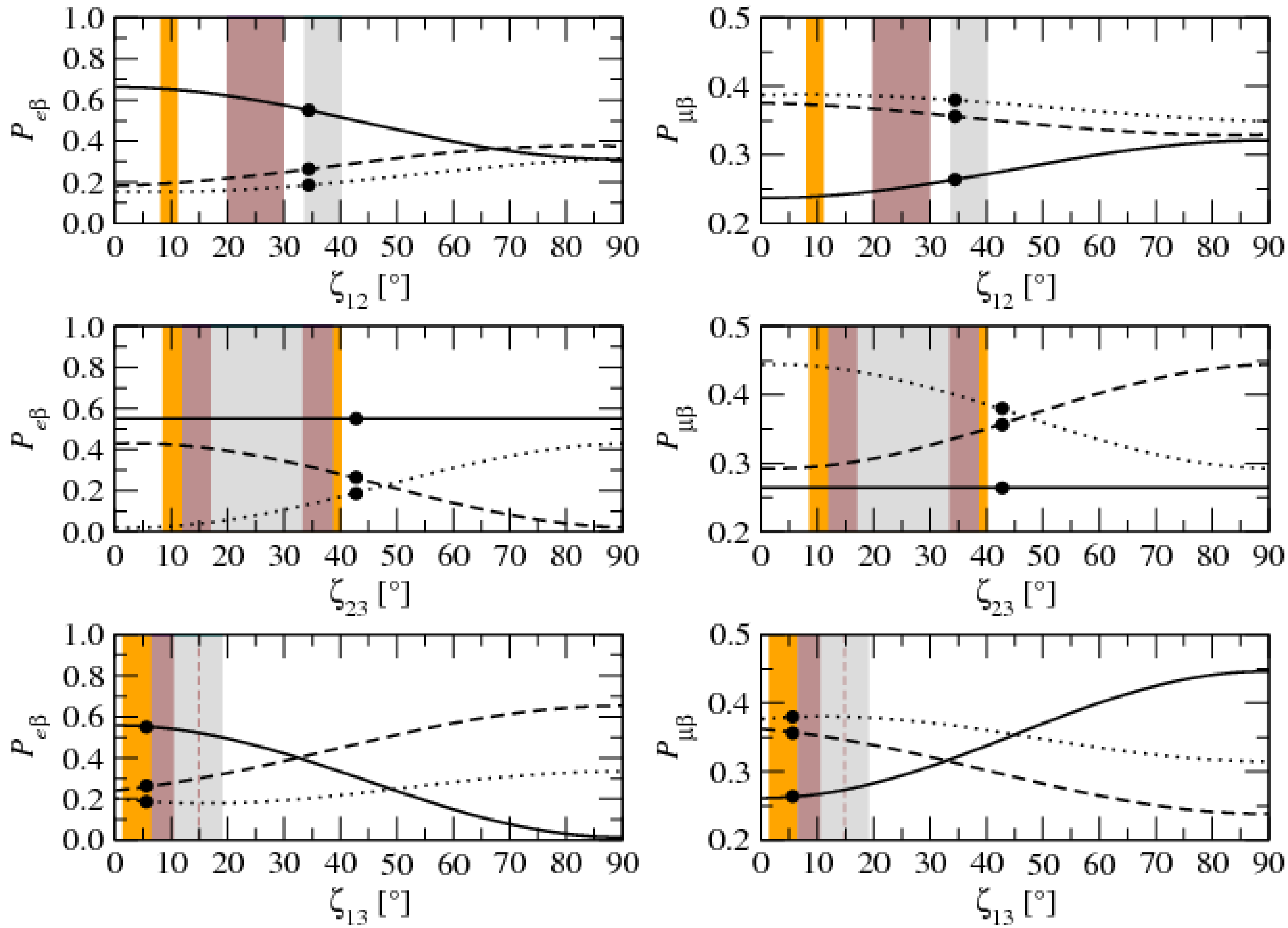
$P_{e\tau}$ $P_{\mu\tau}$

● No running

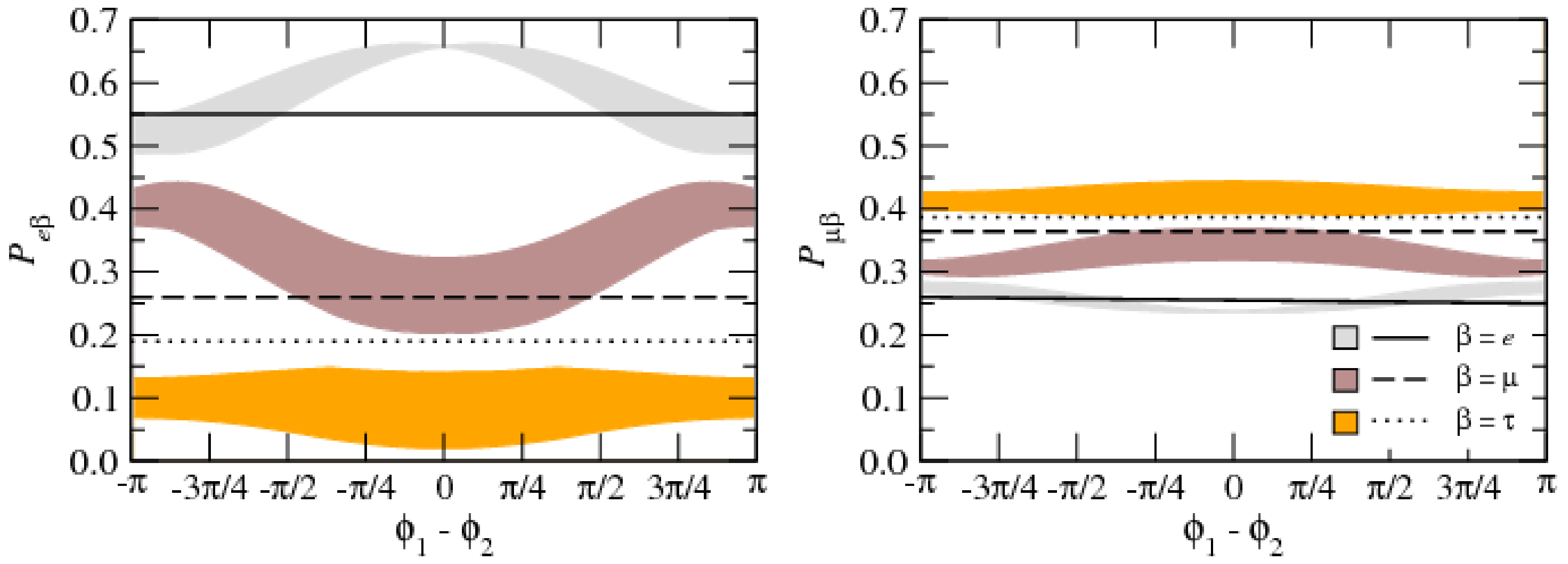
$\phi_1 - \phi_2 = 0°$

$\phi_1 - \phi_2 = 90°$

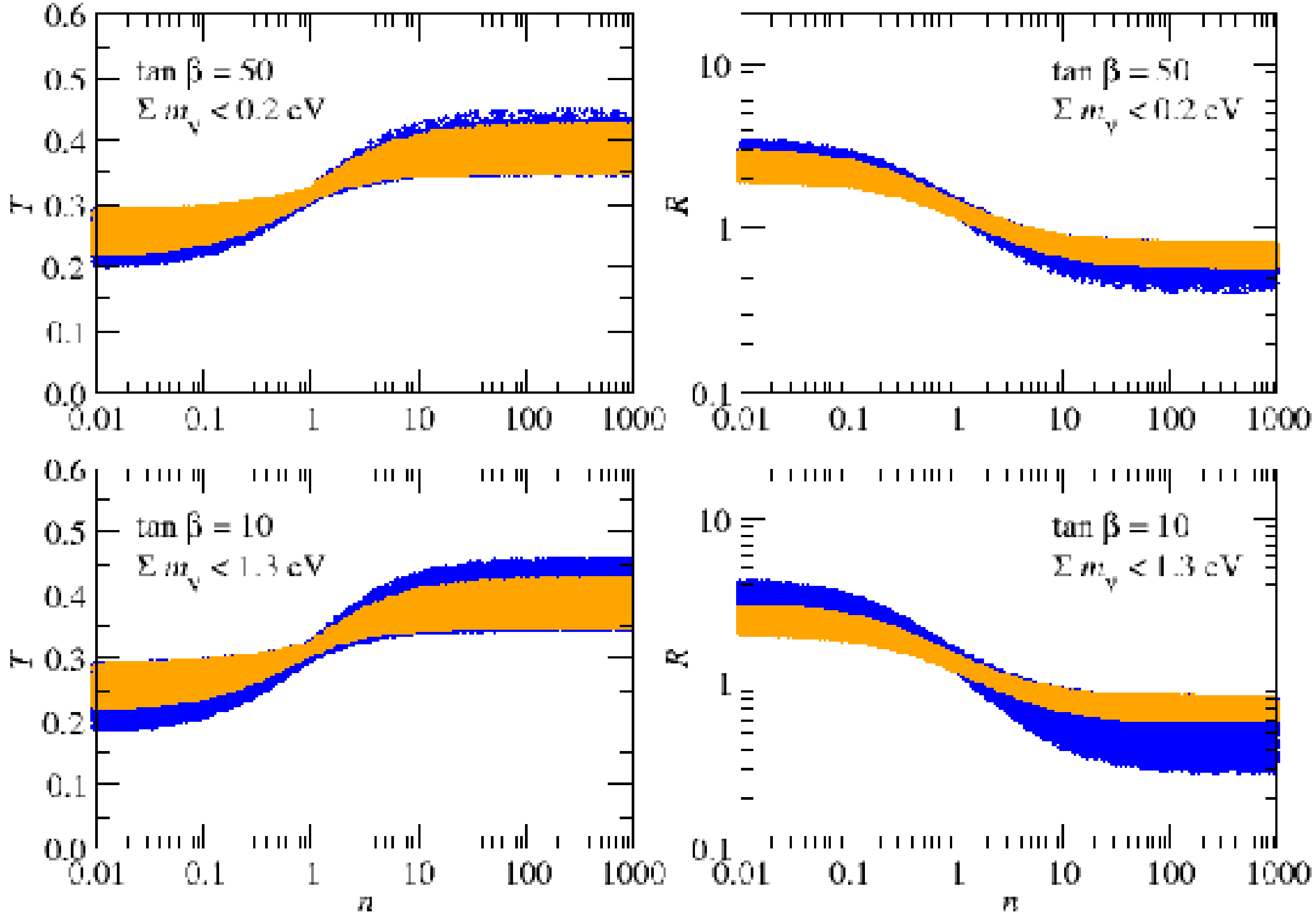
$\phi_1 - \phi_2 = 180°$



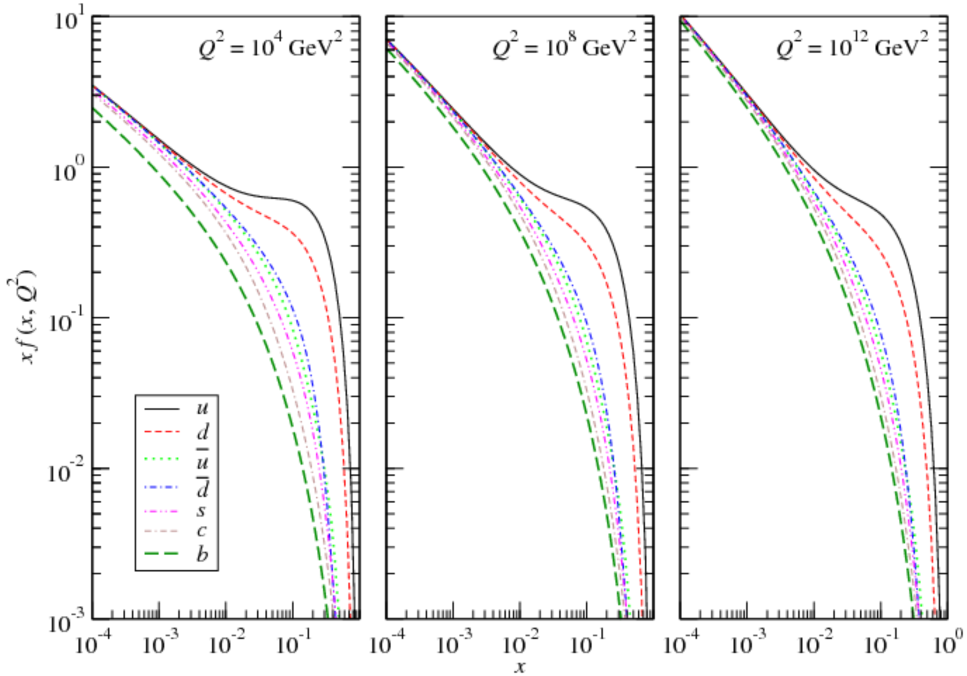
Majorana Phase Dependence



Non-Enhanced Scenarios



Particle Distribution Functions



$$\frac{d^2\sigma_{\rm CC}^{\nu N}}{dx\,dy} = 2x\sigma_{\rm CC}^0(Q^2)\left[\sum_{q=d,s,b} f_q^N(x,Q^2) + (1-y)^2 \sum_{\bar{q}=\bar{u},\bar{c},\bar{t}} f_{\bar{q}}^N(x,Q^2)\right]$$

$$\frac{d^2\sigma_{\rm CC}^{\bar{\nu} N}}{dx\,dy} = 2x\sigma_{\rm CC}^0(Q^2)\left[\sum_{\bar{q}=\bar{d},\bar{s},\bar{b}} f_{\bar{q}}^N(x,Q^2) + (1-y)^2 \sum_{q=u,c,t} f_q^N(x,Q^2)\right]$$