Tau neutrino as a probe of nonstandard interactions via charged Higgs and W' contribution

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August 15, 2013

Based on: Phys.Rev. D87 (2013) 013002 & arXiv:1303.4332

Session: Neutrino

DPF 2013 Meeting at UC Santa Cruz

Neutrino oscillation

- In vacuum: The transition probability

$$P_{\nu_\alpha \to \nu_\beta}(t) \equiv \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \left| \sum_k U_{\alpha k} U^*_{\beta k} e^{-i\frac{m_k^2 L}{2E}} \right|^2$$

$$i\frac{d}{dt}|\nu_k(t)\rangle = H|\nu_k(t)\rangle, \quad H = \frac{1}{2E} U\, diag\left(0, \Delta m_{21}^2, \Delta m_{31}^2\right) U^+$$

- In matter: Disregarding NC, the effective Hamiltonian

$$\tilde{H}_{\alpha\beta} = H_{\alpha\beta} + a\,\delta_{\alpha e}\delta_{\beta e}, \quad a = \sqrt{2} G_F N_e$$

Non-standard neutrino interactions (NSI)

- At propagation:

$$\tilde{H}_{\alpha\beta} = H_{\alpha\beta} + a\left(\delta_{\alpha e}\delta_{\beta e} + \varepsilon_{\alpha\beta}\right)$$

$$\tilde{H} = \frac{1}{2E}\tilde{U}\, diag\left(\tilde{m}_1^2, \tilde{m}_2^2, \tilde{m}_3^2\right)\tilde{U}^+$$

- At source and detector

$$\left|\nu_\alpha^s\right\rangle = \left|\nu_\alpha\right\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s \left|\nu_\beta\right\rangle$$

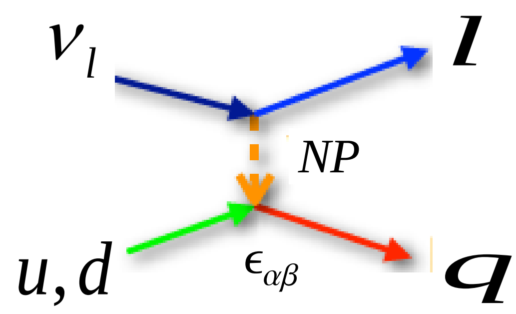
$$\left\langle\nu_\beta^d\right| = \left\langle\nu_\beta\right| + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \left\langle\nu_\alpha\right|$$

- The transition probability

$$P_{\nu_\alpha\to\nu_\beta} = \left|\sum_{\gamma,\delta,k}\left(1+\varepsilon^d\right)_{\gamma\beta}\left(1+\varepsilon^s\right)_{\alpha\delta}\tilde{U}_{\delta k}\tilde{U}_{\gamma k}^* e^{-i\frac{\tilde{m}_k^2 L}{2E}}\right|^2$$

Partonic vs hadronic: NSI parameters

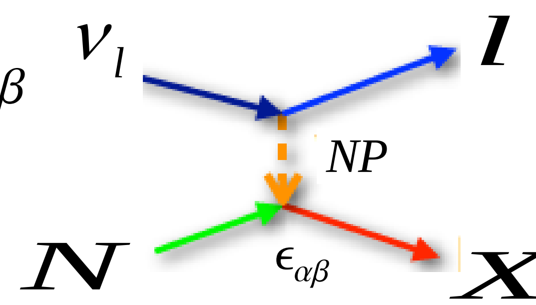
- Partonic level: constant $\epsilon_{\alpha\beta}$



$$\mathscr{L}_{\mathrm{NSI}}^{q} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{qq' P} V_{qq'} [\bar{q}\gamma^{\mu} P q'][\bar{\ell}_{\alpha}\gamma_{\mu} P_L \nu_{\beta}] + \mathrm{h.c.}$$

- Hadronic level: energy dependent $\epsilon_{\alpha\beta}$

  charged hadronic current



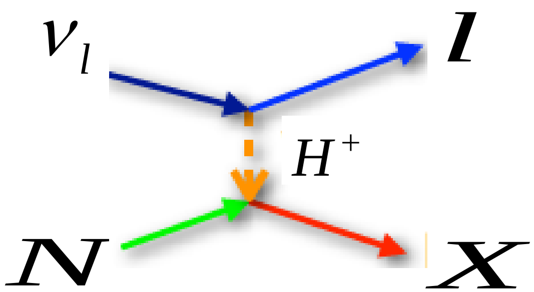
$$\begin{aligned}
\langle p(p')|J_{\mu}^{+}|n(p)\rangle &= V_{ud}\,\langle p(p')|(V_{\mu} - A_{\mu})|n(p)\rangle \\
\langle p(p')|V_{\mu}|n(p)\rangle &= \bar{u}_p(p')\left[\gamma_{\mu} F_1^V + \frac{i}{2M}\sigma_{\mu\nu} q^{\nu} F_2^V + \frac{q_{\mu}}{M} F_S\right] u_n(p), \\
-\langle p(p')|A_{\mu}|n(p)\rangle &= \bar{u}_p(p')\left[\gamma_{\mu} F_A + \frac{i}{2M}\sigma_{\mu\nu} q^{\nu} F_T + \frac{q_{\mu}}{M} F_P\right] \gamma_5 u_n(p).
\end{aligned}$$

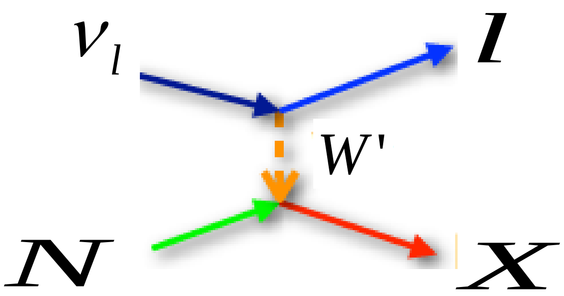
NSI via form factors

- Often in the analysis of NSI, hadronization effects of the quarks via form factors are not included.
- The form factors play an important role in the energy dependence of the NP effects.
- Reasons to consider NSI involving the (ν_τ, τ) sector:
  - Tau-neutrino nucleon cross-section is not well measured
  - Mass dependence of NP non-universal couplings
  - The constraints on NP involving the third generation leptons are weaker allowing for larger NP effects

Charged Higgs and W` model

- Two examples:





- Three subprocesses:

1. Quasi-elastic: Threshold energy 3.5 GeV ($W = M$)
2. Δ-Resonance: 4.35 GeV, ($M + m_\pi < W < W_{\rm cut}$)
3. Deep Inelastic Scattering: Dominant above 10 GeV

$$(\; W_{\rm cut} < W < \sqrt{s} - m_\tau \;)$$

Model independent analysis of NP

- The atmospheric and reactor angles:

$$N(\nu_\tau) = P(\nu_\mu \rightarrow \nu_\tau) \times \Phi(\nu_\mu) \times \sigma(\nu_\tau)$$

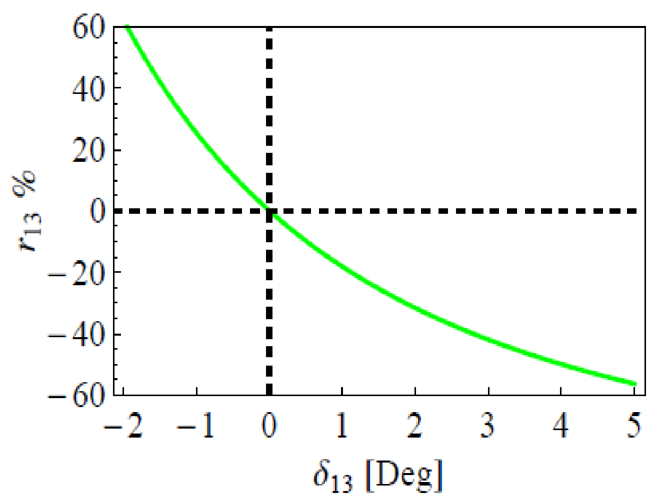
$$N(\bar{\nu}_\tau) = P(\bar{\nu}_e \rightarrow \bar{\nu}_\tau) \times \Phi(\bar{\nu}_e) \times \sigma(\bar{\nu}_\tau)$$

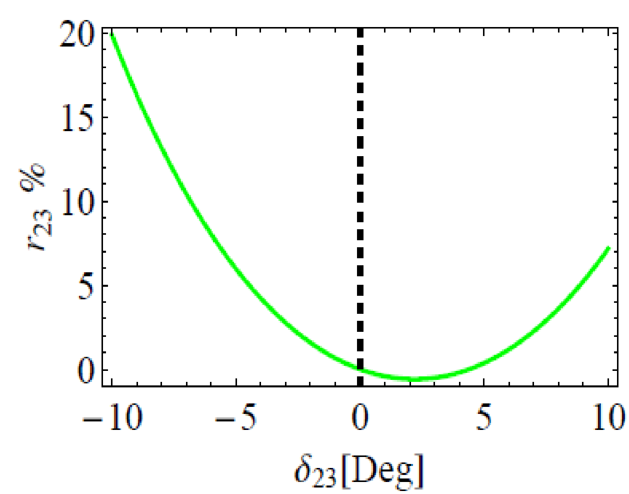
- In the presence of NP

$$r_{23} = \left[\frac{\sin 2(\theta_{23})_{SM}}{\sin 2((\theta_{23})_{SM} + \delta_{23})}\right]^2 - 1 \qquad r_{13} = \left[\frac{\sin 2(\theta_{13})_{SM}}{\sin 2((\theta_{13})_{SM} + \delta_{13})}\right]^2 - 1$$

$$\sigma_{tot} = \sigma_{SM} + \sigma_{NP}$$

$$r = \frac{\sigma_{NP}}{\sigma_{SM}}, \quad \delta = \theta_{ac} - \theta_{SM}$$



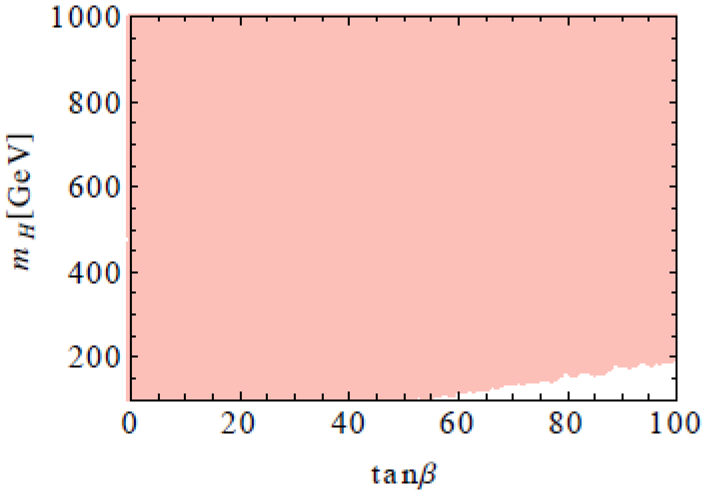


Constraints: Charged Higgs

- Constraint on the size of the operator $\mathcal{O}_{NP} = \bar{u}\Gamma_i d\bar{\tau}\Gamma_j \nu_\tau$ can be obtained from the branching ratio of the decay $\tau^- \to \pi^- \nu_\tau$

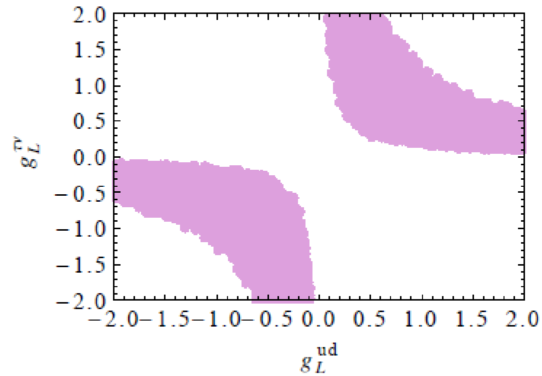
- Constraint at 95%CL,

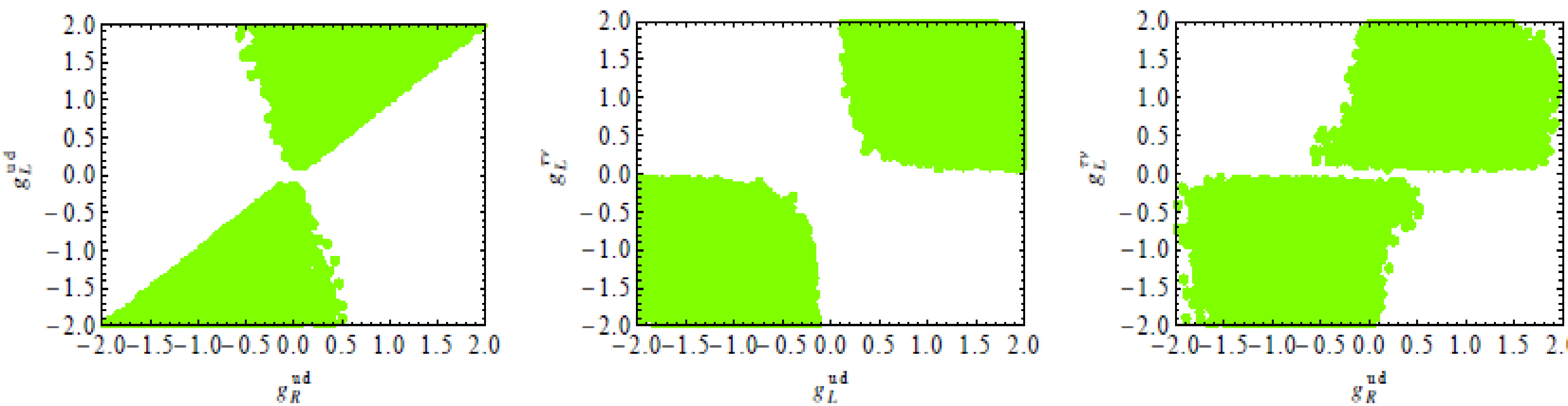
The colored region is allowed.



Constraints: W` model

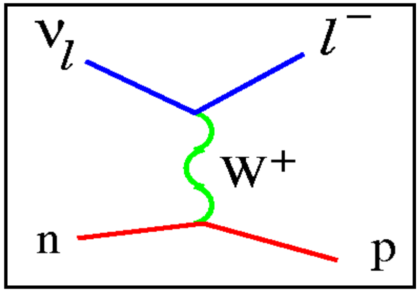
- Constraint on the size of the operator $\mathcal{O}_{NP} = \bar{u}\Gamma_i d \bar{\tau}\Gamma_j \nu_\tau$ can be obtained from the branching ratio of the decay $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ at 1σ with/without RH couplings





Quasi-elastic - SM

- We define the charged hadronic current for the process $\nu_l(k) + n(p) \to l(k') + p(p')$



$$\langle p(p')|J_\mu|n(p)\rangle = V_{ud}\langle p(p')|(V_\mu - A_\mu)|n(p)\rangle$$

$$\langle p(p')|V_\mu|n(p)\rangle = \bar{u}_p(p')\left[\gamma_\mu F_1^V + \frac{i}{2M}\sigma_{\mu\nu}q^\nu F_2^V\right]u_n(p),$$

$$-\langle p(p')|A_\mu|n(p)\rangle = \bar{u}_p(p')\left[\gamma_\mu F_A + \frac{q_\mu}{M}F_P\right]\gamma_5 u_n(p).$$

- The SM differential cross section for the reaction

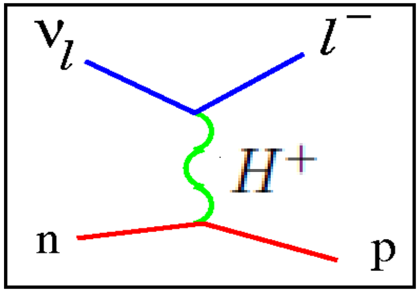
$$\frac{d\sigma_{SM}}{dt} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A_{SM} + B_{SM}\frac{(s-u)}{M^2} + C_{SM}\frac{(s-u)^2}{M^4}\right]$$

Quasi-elastic - Charged Higgs

- The most general coupling of the charged Higgs

$$\mathcal{L} = \frac{g}{2\sqrt{2}}\left[V_{u_i d_j}\bar{u}_i(g_S^{u_i d_j} + g_P^{u_i d_j}\gamma^5)d_j + \bar{\nu}_i(g_S^{\nu_i l_j} + g_P^{\nu_i l_j}\gamma^5)l_j\right] H^+$$

$$g_S^{u_i d_j} = \left(\frac{m_{d_j}\tan\beta + m_{u_i}\cot\beta}{m_W}\right), \quad g_P^{u_i d_j} = \left(\frac{m_{d_j}\tan\beta - m_{u_i}\cot\beta}{m_W}\right), \quad g_S^{\nu_i l_j} = g_P^{\nu_i l_j} = \frac{m_{l_j}\tan\beta}{m_W}.$$



- The modified differential cross section

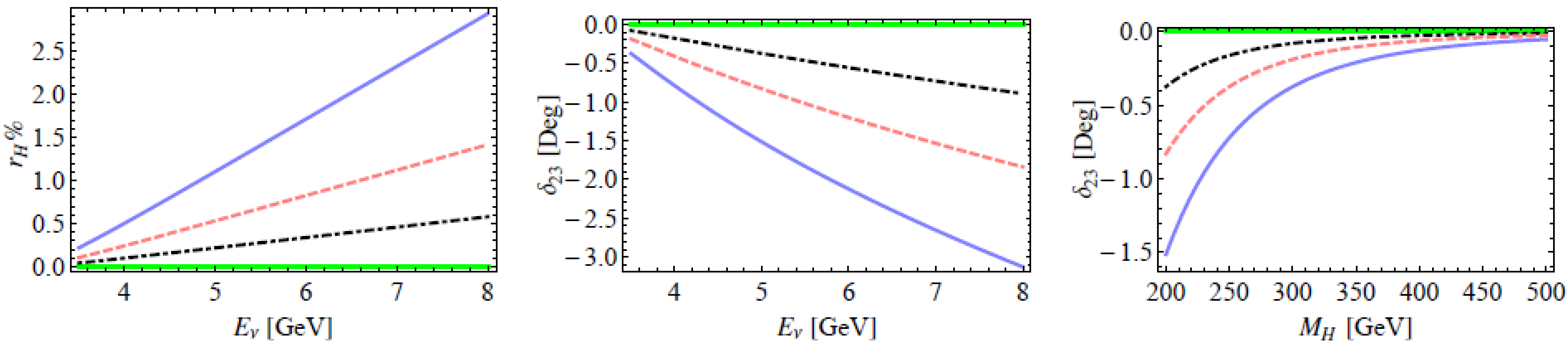
$$\frac{d\sigma_{SM+H}}{dt} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A_H + B_H\frac{(s-u)}{M^2} + C_{SM}\frac{(s-u)^2}{M^4}\right]$$

$$A_H = A_{SM} + 2x_H Re(A_H^I) + x_H^2 A_H^P, \text{ and } B_H = B_{SM} + 2x_H Re(B_H^I)$$

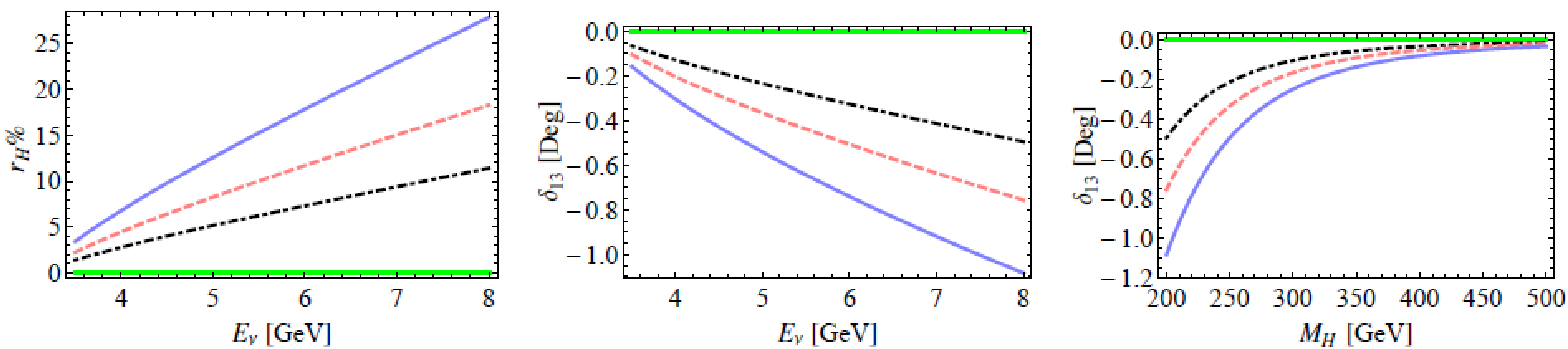
$$x_H = m_W^2/M_H^2$$

Results

- Atm: M_H=200GeV, E_ν=5GeV, tanβ=40,50,60

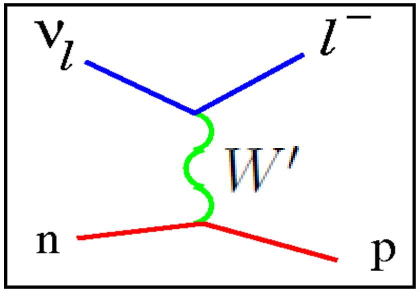


Reactor: M_H=200GeV, E_ν=8GeV, tanβ=80,90,100



Quasi-elastic - W′ model

- The lowest dimension effective Lagrangian for W′ interactions to the SM fermions



$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{f'f} \bar{f}' \gamma^\mu (g_L^{f'f} P_L + g_R^{f'f} P_R) f W'_\mu + \ h.c.$$

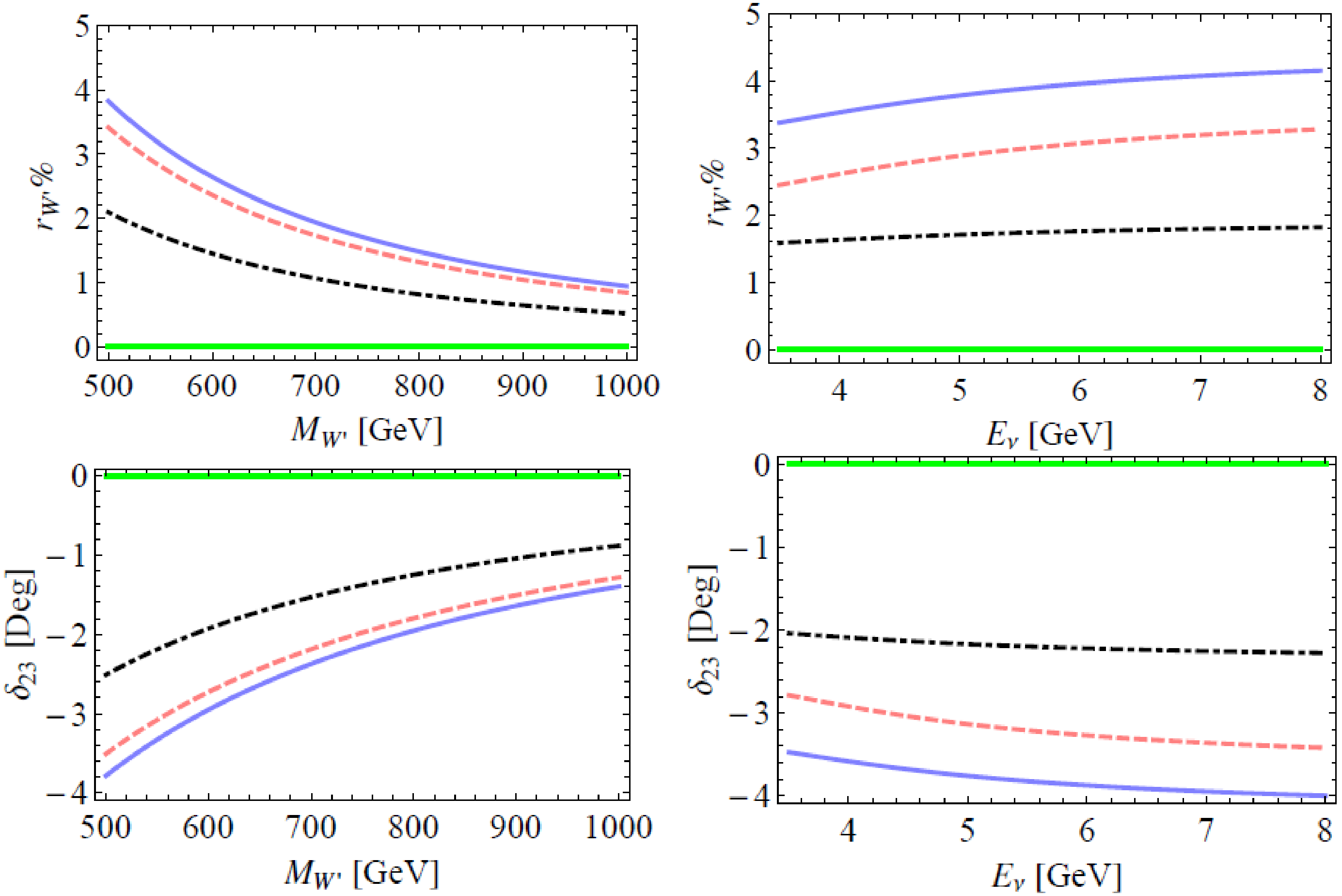
- The modified differential cross section

$$\frac{d\sigma_{SM+W'}}{dt} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2} \left[A' + B' \frac{(s-u)}{M^2} + C' \frac{(s-u)^2}{M^4} \right]$$

$f' = f_{SM} + 2x_{W'} Re(f_{W'}^I) + x_{W'}^2 f_W^P$, $x_{W'} = M_W^2 / M_{W'}^2$, $f = A, B, C$

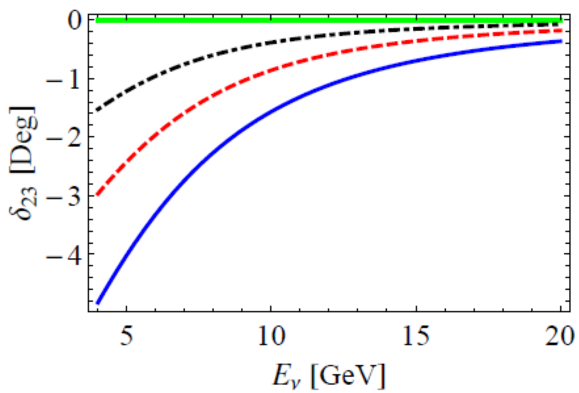
Results

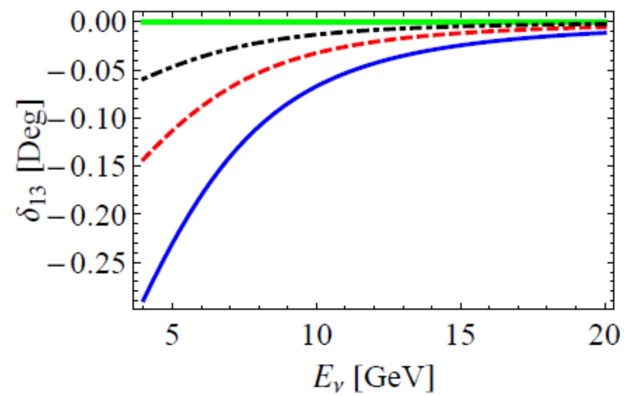
- Atm: $M_{W`}$=500GeV, E_ν=5GeV, $(g_L^{\tau\nu_\tau}, g_L^{ud}, g_R^{ud})$



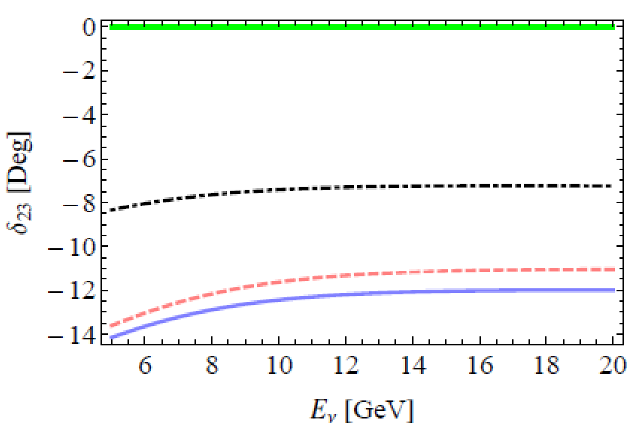
Δ Resonance - Results

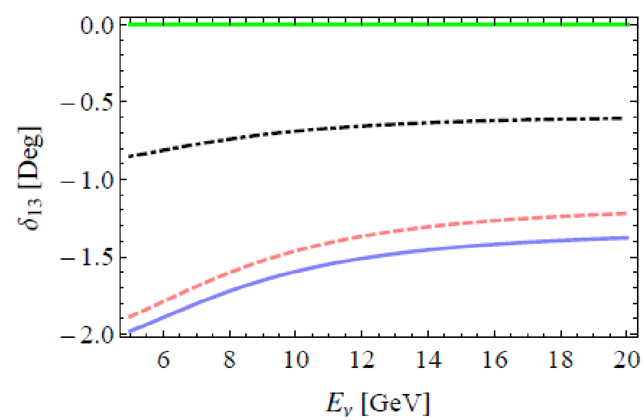
- Charged Higgs: M_H=200GeV, tanβ=40,50,60





- W' model: $M_{W'}$=200GeV $(g_L^{\tau\nu_\tau}, g_L^{ud}, g_R^{ud}) = (1.23\ ,\ 0.84\ ,\ 0.61)$

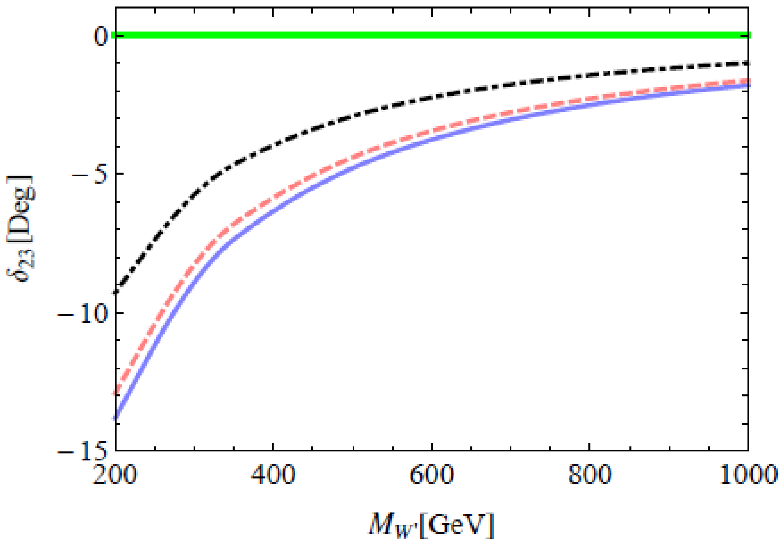


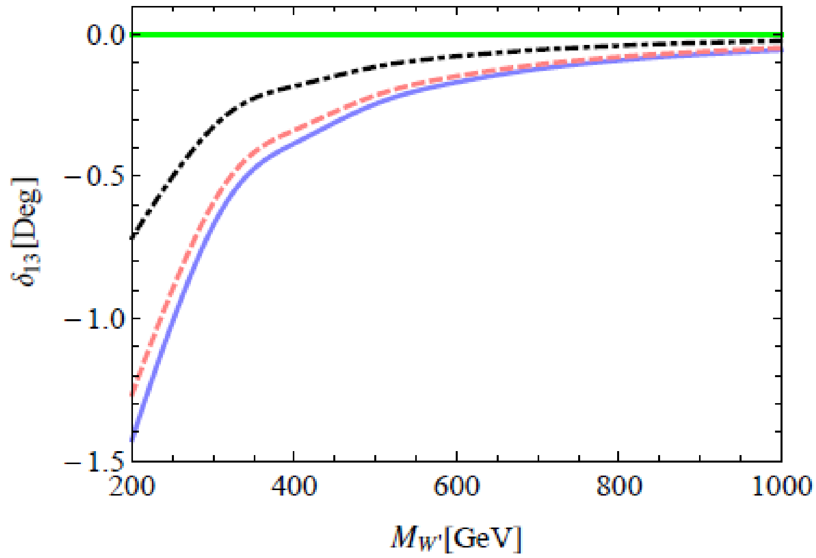


Deep Inelastic Scattering- Results

- Charged Higgs: The deviations of the mixing angles are negligibly within the kinematical interval.

- W' model : E_ν=17GeV, $(g_L^{\tau\nu_\tau}, g_L^{ud}, g_R^{ud}) =$ (-0.94 , -1.13 , -0.85)

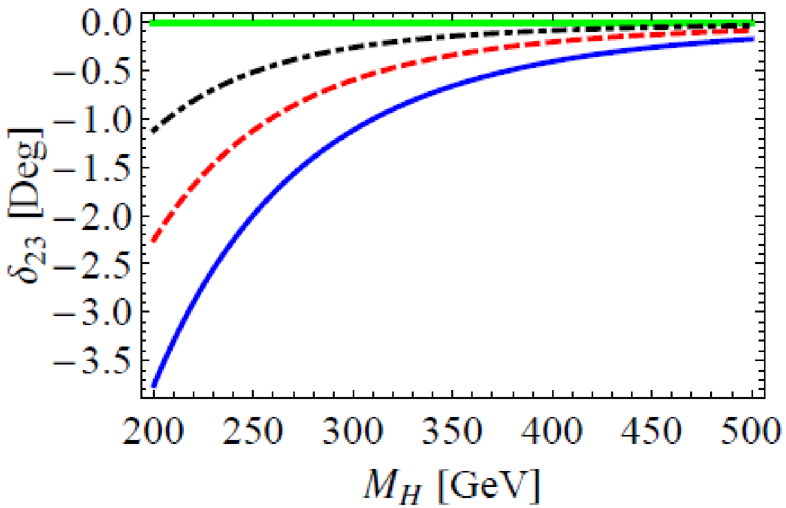


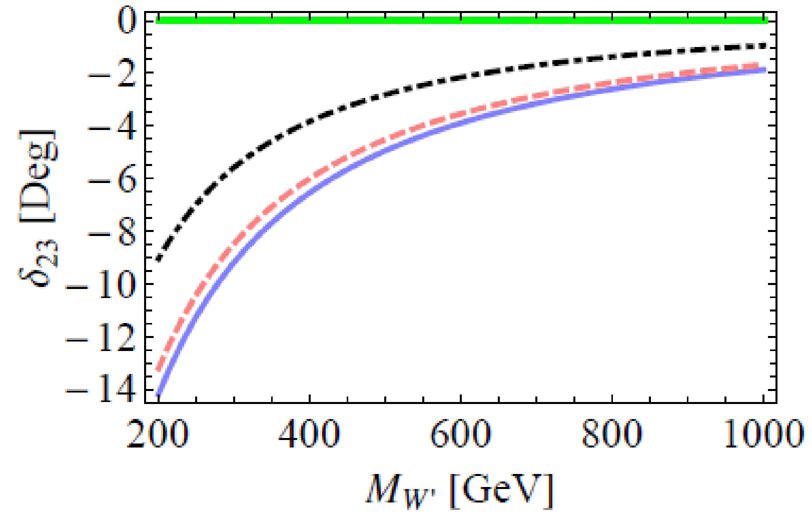


Flux effect

$$\frac{N_\tau^{SM+NSI}}{N_\tau^{SM}}(E_\nu) \sim \frac{\int \Phi^{SM}_{\nu_\mu,\nu_e} \times \sin^2(2\tilde{\theta}^{SM+NSI}_{ij}) \times \frac{d\sigma^{SM+NSI}_{\nu_\tau N}}{dE_\nu}\, dE_\nu}{\int \Phi^{SM}_{\nu_\mu,\nu_e}(E_\nu) \times \sin^2(2\tilde{\theta}^{SM}_{ij}) \times \frac{d\sigma^{SM}_{\nu_\tau N}}{dE_\nu}\, dE_\nu}$$

- Resonance - Charged Higgs & W\` model



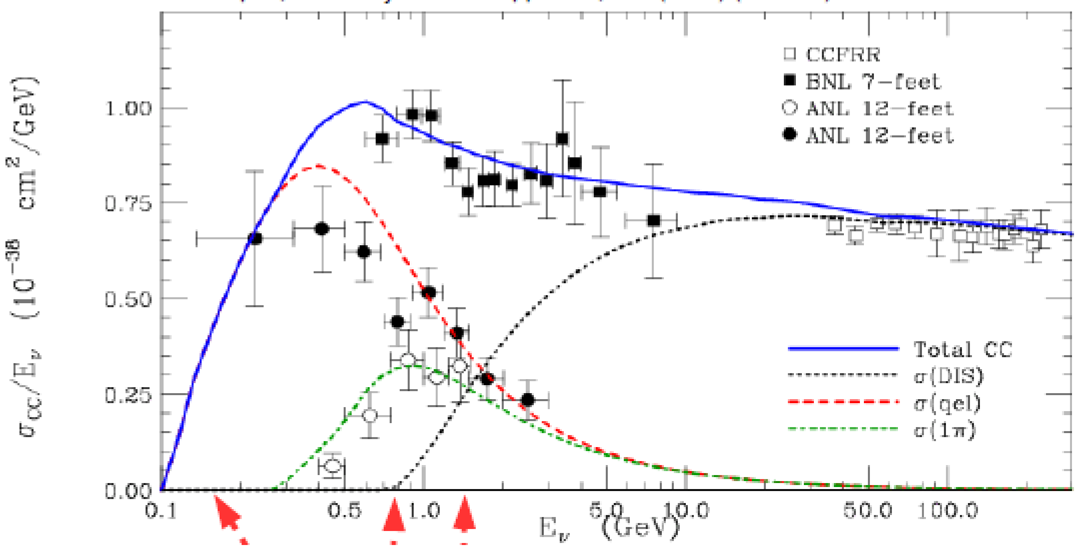


Number of events

- Super-K estimated $180.1 \pm 44.3\,(stat)\,^{+17.8}_{-15.2}\,(syst)$ produced in the 22.5 kton fiducial volume of the detector by tau neutrinos during the 2806 day.
- The ν_τ cross section can be parametrized as

$$\sigma_{\nu_\tau}^{\mathrm{SM}} = \sigma_{\nu_\tau}^{\mathrm{const}} E K(E)$$

P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



Number of events (Cont.)

- From the SM universality: $\sigma_{\nu_\tau}^{\text{const}} = \sigma_{\nu_\mu}^{\text{const}}$
- Within neutrino energy 30-100 GeV

Using Honda model for the atmospheric neutrino flux

Using vertically upward going neutrinos ($\cos\theta = -1$)

SM results: $N_{SM} = 30.7 \pm 3.37$

NP results: $N_{NSI} = 30.08$ @ zero W` couplings

$N_{NSI} = 41.49$ @ $M_{W`}$=200GeV

NSI is potentially detectable

Conclusion

- We calculated the effect of a charged Higgs and a W' contribution to the neutrino-nucleon scattering.
- Both models can produce significant corrections to the measured mixing angle θ_{23} and θ_{13}.
- The deviation in the charged Higgs model is more sensitive to energy variation than in the W' model.

Conclusion

- We calculated the effect of a charged Higgs and a W' contribution to the neutrino-nucleon scattering.
- Both models can produce significant corrections to the measured mixing angle θ_{23} and θ_{13}.
- The deviation in the charged Higgs model is more sensitive to energy variation than in the W' model.

THANK YOU

BACKUP SLIDES

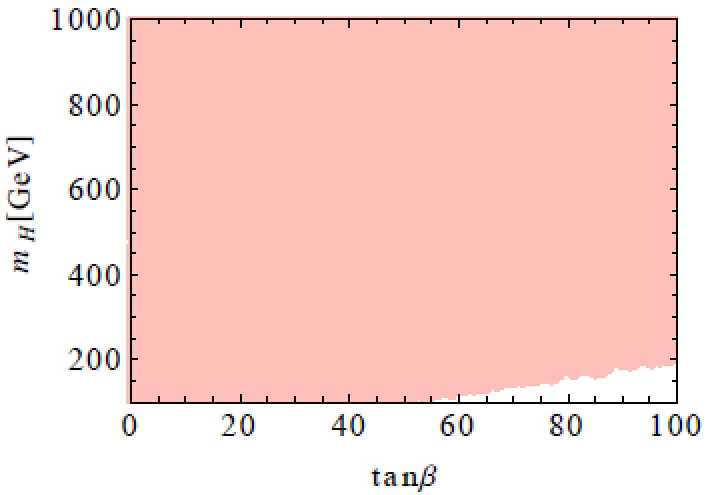
Constraints: Charged Higgs

- Constraint on the size of the operator $\mathcal{O}_{NP} = \bar{u}\Gamma_i d\bar{\tau}\Gamma_j\nu_\tau$ can be obtained from the branching ratio of the decay $\tau^- \to \pi^-\nu_\tau$ ($Br(\tau^- \to \pi^-\nu_\tau)_{exp} = (10.91 \pm 0.07)\%$)

$$\Gamma^{SM}_{\tau^-\to\pi^-\nu_\tau} = \frac{G_F^2}{16\pi}|V_{ud}|^2 f_\pi^2 m_\tau^3\left(1-\frac{m_\pi^2}{m_\tau^2}\right)^2\delta_{\tau/\pi} = 10.82 \pm .02\%$$

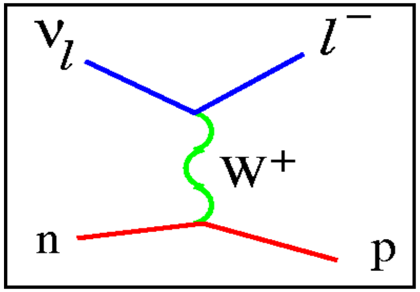
- Constraint at 95%CL,

The colored region is allowed.



Quasi-elastic neutrino scattering

- Quasi-elastic scattering makes up the largest single component of the total ν–N interaction rate in the threshold regime $E_\nu \leq 2$ GeV.



- Llewellyn-Smith formalism for differential cross section

$$\frac{d\sigma}{dQ^2}\begin{pmatrix} \nu_l + n \to l^- + p \\ \bar{\nu}_l + p \to l^+ + n \end{pmatrix} = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

- Q.E. form factors

$$\{f_1, f_2\} = \frac{\{1-(1+\xi)t/4M^2, \xi\}}{(1-t/4M^2)(1-t/M_V^2)^2}, \quad g_1 = \frac{g_1(0)}{(1-t/M_A^2)^2}, \quad g_2 = \frac{2M^2 g_1}{m_\pi^2 - t}$$

Thank you