EXCESS OF TAU EVENTS AT SND@LHC, FASERν AND FASERν2

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HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

This talk is based on

Saeed Ansarifard and YF, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799

ν_e	Direct discovery announcement: 1956	Cowan and Reines
ν_μ	Direct discovery announcement: 1962	Lederman, Schwartz, Steinberger
ν_τ	Direct discovery announcement: 2000	DONUT

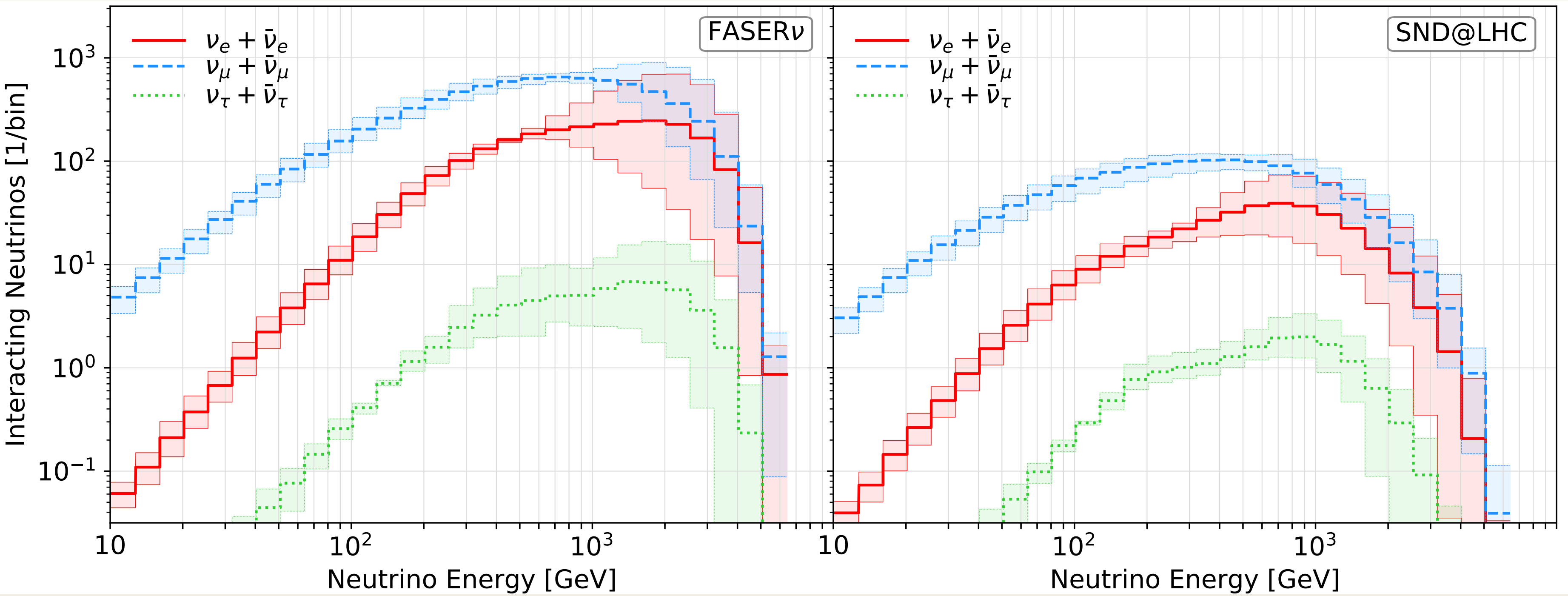
Sources

- Beta decay: $\bar{\nu}_e$
- Fusion in stars: ν_e
- Pion and Kaon decay: $\nu_\mu, \bar{\nu}_\mu$
- Muon decay: $\nu_\mu, \bar{\nu}_\mu$

Reactor neutrinos, solar neutrinos, Earth neutrinos, atmospheric neutrinos, short baseline and long baseline neutrinos

Moreover, the detection of tau neutrinos is far more challenging than the detection of muon and electron neutrinos

Tau neutrino interaction at FP experiments



Kling, "Forward Neutrino fluxes at the LHC," PRD 104 (21) 11, 113008

Standard model prediction

$\nu_\tau + \bar{\nu}_\tau$ events at FASERν : $21.6^{+12.5}_{-6.9}$

$\nu_\tau + \bar{\nu}_\tau$ events at SND@LHC : $8.8^{+2.7}_{-1.5}$

Kling, "Forward Neutrino fluxes at the LHC," PRD 104 (21) 11, 113008

Excess due to New Physics?

$(1)\ \pi^+ \rightarrow \mu^+ \nu_\tau;$ Lepton number conserving

$(2)\ \pi^+ \rightarrow \mu^+ \bar{\nu}_\tau$ Lepton number violating

$(3)\ \nu_e + \text{nucleus} \rightarrow \tau + X.$

S. Ansarifard and Y. Farzan, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799.

Pion decay universality

$$R_{e/\mu} = \frac{\Gamma[(\pi^+ \to e^+\nu) + (\pi^+ \to e^+\nu\gamma)]}{\Gamma[(\pi^+ \to \mu^+\nu) + (\pi^+ \to \mu^+\nu\gamma)]}$$

PIENU collaboration:

$$R_{e/\mu} = (1.2344 \pm 0.0023(stat) \pm 0.0019(syst)) \times 10^{-4}$$

PiENu Collaboration, A. Aguilar-Arevalo et al., *Phys. Rev. Lett.* 115 (2015) 7, 071801

$$R_{e/\mu} = (1.2344 \pm 0.0023(stat) \pm 0.0019(syst)) \times 10^{-4}$$

$$Br(\pi^+ \to e^+\nu_\tau) < 2.4 \times 10^{-3} Br(\pi^+ \to e^+\nu_e) = 2.8 \times 10^{-7}$$

$$Br(\pi^+ \to \mu^+\nu_\tau) < 2.4 \times 10^{-3} Br(\pi^+ \to \mu^+\nu_\mu) = 2.4 \times 10^{-3}.$$

$$Br(\pi^+ \to \mu^+\bar{\nu}_\tau) < 2.4 \times 10^{-3} Br(\pi^+ \to \mu^+\nu_\mu) = 2.4 \times 10^{-3}$$

Unless $\dfrac{Br(\pi^+ \to e^+\nu_\tau)}{Br(\pi^+ \to e^+\nu_e)} = \dfrac{Br(\pi^+ \to \mu^+\nu_\tau)}{Br(\pi^+ \to \mu^+\nu_\mu)}$

A model for $\pi^+ \to \mu^+ \nu_\tau$

The effective four-Fermi coupling

$$G_{\nu\mu}(\bar{\mu}\frac{1-\gamma_5}{2}\nu_\tau)(\bar{d}\frac{1\pm\gamma_5}{2}u)$$

$$\Gamma(\pi^+ \to \mu^+\nu_\tau) = G_{\nu\mu}^2 \frac{m_\pi}{32\pi}\frac{F_\pi^2}{(m_u+m_d)^2}(m_\pi^2 - m_\mu^2)^2.$$

With $G_{\nu\mu} \sim 4\times 10^{-8}\ \mathrm{GeV}^{-2}$, $Br(\pi^+ \to \mu^+\nu_\tau) \sim 10^{-3}$

Model for $\pi^+ \to \mu^+ \nu_\tau$

$$\lambda_d \bar{d} \Phi_1^\dagger Q_1 + \lambda_u \bar{u} \Phi_1^T c Q_1 + \lambda_\mu \bar{\mu} \Phi_2^\dagger L_\tau + \text{H.c.},$$

$$\Phi_1 = (\phi_1^+ \ \phi_1^0)^T$$

$$\Phi_2 = (\phi_2^+ \ \phi_2^0)^T$$

$$L_\tau = (\nu_\tau \ \tau_L)^T$$

$$Q_1 = (u_L \ d_L)^T$$

$$c = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

Why $\Phi_1 \neq \Phi_2$?

$$\lambda_d \bar{d} \Phi_1^\dagger Q_1 + \lambda_u \bar{u} \Phi_1^T c Q_1 + \lambda_\mu \bar{\mu} \Phi_2^\dagger L_\tau + \text{H.c.},$$

$\lambda_u - \lambda_d$

$$\Phi_1 = \Phi_2 \Rightarrow \begin{cases} G_\pi (\bar{\mu}_R \tau_L)(\bar{u}\gamma_5 u - \bar{d}\gamma_5 d) \\ G_\eta (\bar{\mu}_R \tau_L)(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d) \end{cases} \Rightarrow \begin{cases} \tau \to \mu \pi^0 \\ \tau \to \mu \eta^0 \end{cases}$$

$\lambda_u + \lambda_d$

$$\Rightarrow \begin{cases} G_\pi < 5 \times 10^{-9} \quad \text{GeV}^{-2} \\ G_\eta < 4 \times 10^{-10} \quad \text{GeV}^{-2}. \end{cases} \Rightarrow \Phi_1 \neq \Phi_2$$

The $U_1(1) \times U_2(1)$ charges of the fields.

charges	Φ_1	Φ_2	L_τ, τ_R	L_μ, μ_R	Q	d_R
$U_1(1)$	1	0	0	0	β	$\beta - 1$
$U_2(1)$	0	1	α	$1+\alpha$	0	0

~~$\bar{d}H^\dagger Q_1$~~ ~~$\bar{u}H^T c Q_1$~~

Explaining smallness of u and d quark masses as bonus

Breaking the global $U_1(1) \times U_2(1)$

$$\lambda_{12}(H^T c\Phi_1)(\Phi_2^\dagger c H^*)$$

$$U_1(1) \times U_2(1) \Longrightarrow U(1)$$

Charged components mix but not the neutral components.

$$G_{\nu\mu} = \frac{\lambda_\mu \lambda_d}{m^2_{\phi_1^+}} \frac{\lambda_{12} v^2/2}{m^2_{\phi_2^+}} = 4 \times 10^{-8}\ \text{GeV}^{-2} \frac{\lambda_\mu}{0.3} \frac{\lambda_d}{0.3} \frac{\lambda_{12}}{0.12} \frac{(300\ \text{GeV})^2}{m^2_{\phi_1^+}} \frac{(300\ \text{GeV})^2}{m^2_{\phi_2^+}}.$$

Pair production at LHC

$$\phi_2^0 \to \mu^+\tau^- \text{ and } \phi_2^+ \to \mu^+\nu_\tau.$$

$\phi_2^+(\phi_2^0)^\dagger$ → $\mu^+\nu_\tau\mu^-\tau^+$

$\phi_2^-\phi_2^0$ → $\mu^-\bar{\nu}_\tau\mu^+\tau^-$

$\phi_2^+\phi_2^-$ → $\mu^+\nu_\tau\mu^-\bar{\nu}_\tau$

$(\phi_2^0)^\dagger\phi_2^0$ → $\mu^-\tau^+\mu^+\tau^-$

Invariant mass $= m_{\phi_2^0}$

Enhancement in decay rate

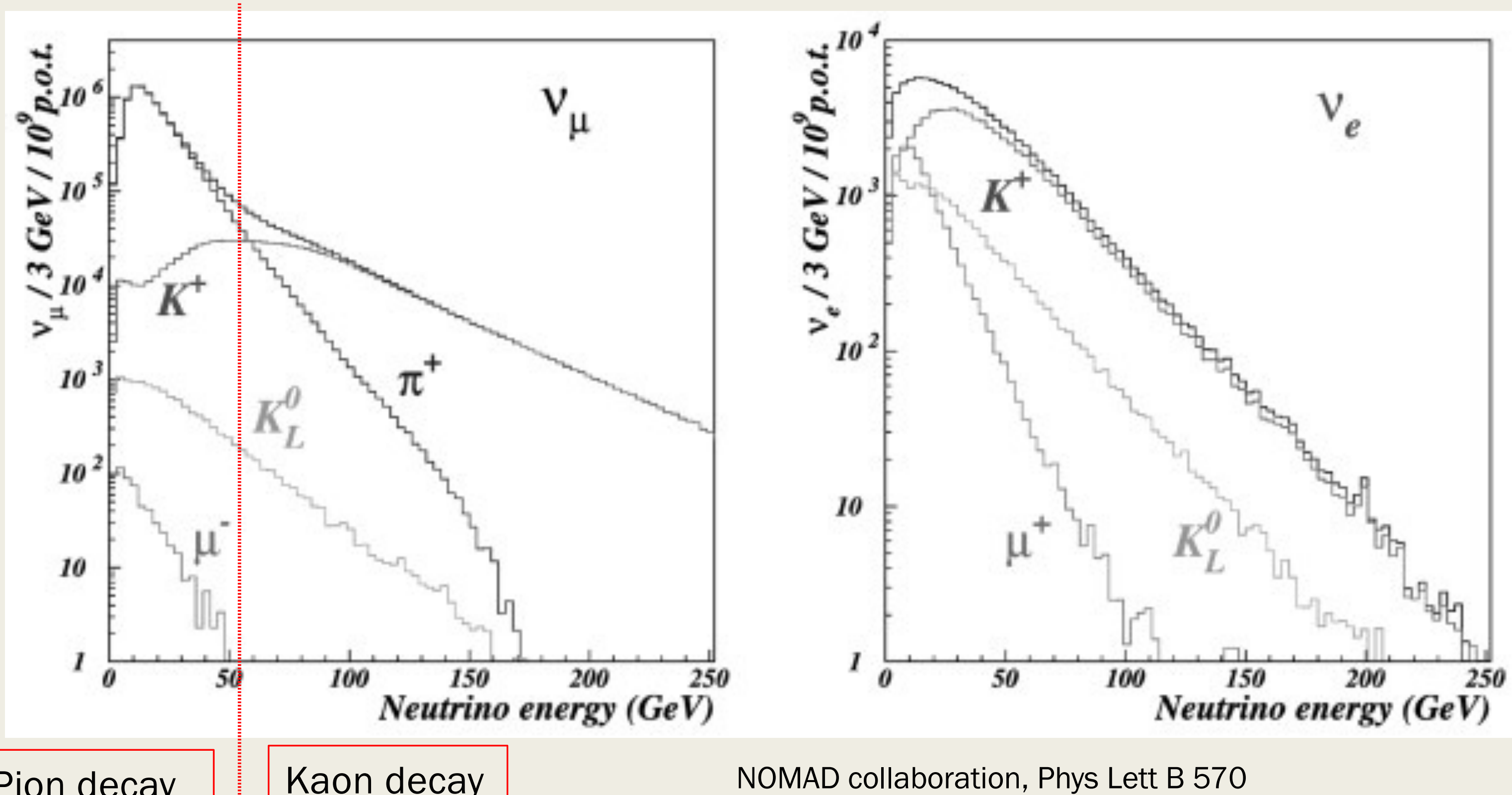
$$G_{\nu\mu}(\bar{\mu}\frac{1-\gamma_5}{2}\nu_\tau)(\bar{d}\frac{1\pm\gamma_5}{2}u)$$

$$\Gamma(\pi^+ \to \mu^+\nu_\tau) = G_{\nu\mu}^2 \frac{m_\pi}{32\pi} \frac{F_\pi^2}{(m_u+m_d)^2}(m_\pi^2 - m_\mu^2)^2.$$

Enhancement

No such enhancement in $\nu_\tau + \mathrm{nucleus} \to \mu + X$

NOMAD bounds



Pion decay domination

Kaon decay domination

NOMAD collaboration, Phys Lett B 570 (2003) 19

Bound on

$K^+ \to \mu^+ \nu_\tau$

and on

$K^+ \to \mu^+ \bar{\nu}_\tau$

The energy of tau from $\pi^+ \to \nu_\tau \mu^+$ or $\pi^+ \to \bar{\nu}_\tau \mu^+$ will be too low to be detectable.

A model for $\pi^+ \to \bar{\nu}_\tau \mu^+$ with a connection to observed anomalies in τ decay

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \left(\lambda_{ij}/2\, \bar{L}^c_{a,i}\, \varepsilon_{ab}\, L_{b,j}\, \Phi^+ + {\rm h.c.}\right)$$

$$\delta(\ell_i \to \ell_j \nu\nu) = \frac{\mathcal{A}_{NP}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}{\mathcal{A}_{SM}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} = \frac{\left|\lambda^2_{ij}\right|}{g_2^2} \frac{m_W^2}{m_\phi^2}\,.$$

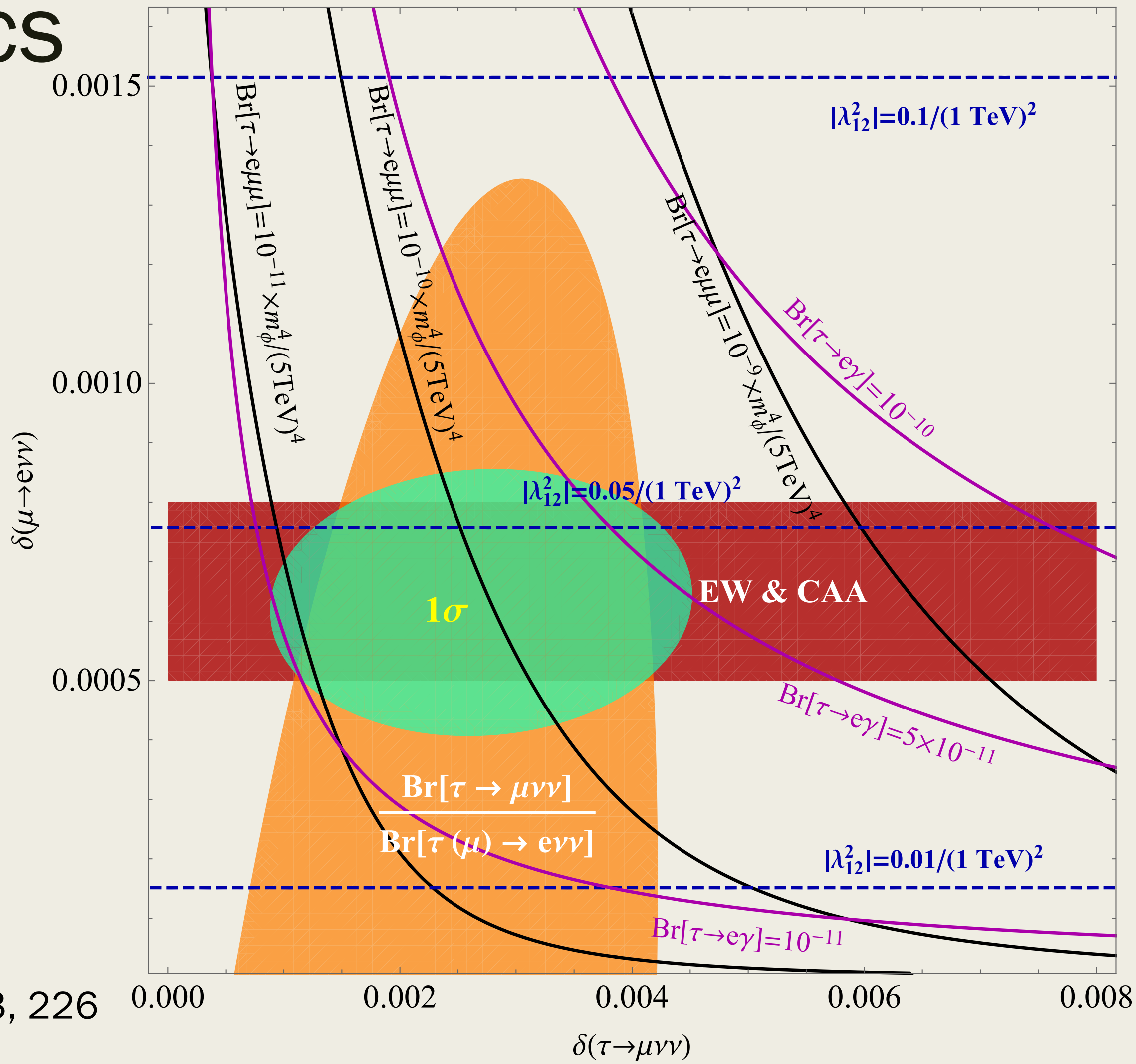
Crivellin et al, PRD 103 (2021) 7, 073002

Hint for new physics

Crivellin et al, PRD 103 (2021) 7, 073002

$$0.052\frac{m_{\Phi^+}}{300\ \mathrm{GeV}} < \lambda_{23} < 0.148\frac{m_{\Phi^+}}{300\ \mathrm{GeV}}.$$

Amhis et al., [HFLAV], Eur. Phys. J. C81 (2021) No3, 226



Our model

$$\mathcal{L} = -\frac{\lambda_{23}}{2} L_{a,\mu}\epsilon_{ab}L_{b\tau}\Phi^+ + \text{H.c} = -\frac{\lambda_{23}}{2}(\nu_\mu^T c\tau_L - \mu_L^T c\nu_\tau)\Phi^+ + \text{H.c}$$

charges	Φ_1	Φ^+	L_τ, τ_R	L_μ, μ_R	Q	d_R
$U(1)$	1	1	$-1/2-\alpha$	$-1/2+\alpha$	β	$\beta - 1$

$$A\Phi^- H^T c\Phi_1 \qquad \sin 2\theta = \frac{2A\ v/\sqrt{2}}{m^2_{\phi_1^+} - m^2_{\Phi^+}}$$

$$G_{\bar\nu\mu}(\bar d \frac{1-\gamma_5}{2} u)(\nu_\mu^T c\tau_L - \mu_L^T c\nu_\tau) + \text{H.c.} \qquad G_{\bar\nu\mu} = \frac{\lambda_d \lambda_{23}}{2}\frac{Av/\sqrt{2}}{m^2_{\Phi^+} m^2_{\phi_1^+}}.$$

$$\Gamma(\tau^- \to \bar\nu_\mu \pi^-) \sim \frac{G^2_{\bar\nu\mu}}{4\pi}\frac{F_\pi^2 m_\pi^2}{(m_u+m_d)^2} m_\tau$$

Our model

$$\mathcal{L} = -\frac{\lambda_{23}}{2} L_{a,\mu}\epsilon_{ab}L_{b\tau}\Phi^+ + \text{H.c} = -\frac{\lambda_{23}}{2}(\nu_\mu^T c\tau_L - \mu_L^T c\nu_\tau)\Phi^+ + \text{H.c}$$

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$G_{\bar{\nu}\mu} \sim 5\times 10^{-8}\ \text{GeV}^{-2}$, ⇒ $Br(\pi^+ \to \bar{\nu}_\tau\mu^+) \sim 10^{-3}$

Non-standard τ production at the detector

$$\lambda_e \bar{\tau}_R \Phi_2^\dagger L_e$$

$$G_e(\bar{\tau}_R \nu_e)(\bar{u}_L d_R) \qquad \nu_e + \text{nucleus} \to \tau + X$$

$$G_e = \lambda_d \lambda_e \lambda_{12} v^2/(2m^2_{\phi_1^+} m^2_{\phi_2^+})$$

uncertainty on $\tau^+ \to \pi^+ \nu$ gives the constraint $G_{e(\mu)} < 5 \times 10^{-7}$ GeV^{-2}

Connection to the Charged Current Non-Standard Interaction formalism

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma\in\{e,\mu,\tau\}} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle$$

$|\nu_\alpha^s\rangle$ is the eigenstate produced in the source along with the charged lepton of flavor α

$$\langle\nu_\alpha^d| = \langle\nu_\alpha| + \sum_{\gamma\in\{e,\mu,\tau\}} \epsilon_{\gamma\alpha}^d \langle\nu_\gamma|$$

$|\nu_\alpha^d\rangle$ is the eigenstate which can produce the charged lepton of flavor α in the detector.

SM: $|\nu_\alpha^s\rangle = |\nu_\alpha^d\rangle = |\nu_\alpha\rangle$

$\pi^+ \to \mu^+\nu_\tau$ in terms of CC NSI

$$|\nu_\mu^s\rangle = \frac{\mathcal{M}_1|\nu_\mu\rangle + \mathcal{M}_2|\nu_\tau\rangle}{\sqrt{|\mathcal{M}_1|^2 + |\mathcal{M}_2|^2}} \simeq |\nu_\mu\rangle + \mathcal{M}_2/\mathcal{M}_1|\nu_\tau\rangle,$$

$$\mathcal{M}_1 = \mathcal{M}(\pi^+ \to \mu^+\nu_\mu)$$

$$\mathcal{M}_2 = \mathcal{M}(\pi^+ \to \mu^+\nu_\tau)$$

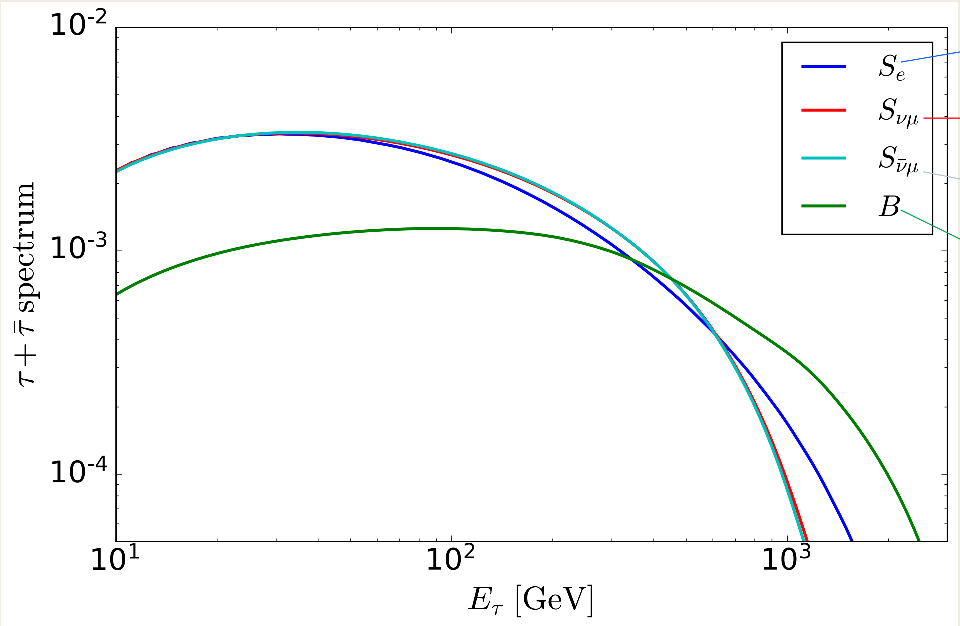
$$\epsilon^s_{\mu\tau} = \frac{\mathcal{M}_2}{\mathcal{M}_1} \qquad |\epsilon^s_{\mu\tau}|^2 = |\mathcal{M}_2|^2/|\mathcal{M}_1|^2 \simeq \mathrm{Br}(\pi^+ \to \mu^+\nu_\tau)$$

Short baseline experiments

$$2Re[U_{\mu i}U^*_{\mu i}U^*_{\mu j}U_{\tau j}(\epsilon^s_{\mu\tau})^* e^{i(m_i^2-m_j^2)L/(2E_\nu)}] << 1$$

$$2Re[U_{\tau i}U^*_{\mu i}U^*_{\tau j}U_{\tau j}(\epsilon^s_{\mu\tau})^* e^{i(m_i^2-m_j^2)L/(2E_\nu)}] << 1$$

Spectra of $\tau + \bar{\tau}$ produced at FASERν normalized to 1.



ν_e + nucleus $\rightarrow \tau + X$.

$\pi^+ \rightarrow \mu^+ \nu_\tau$

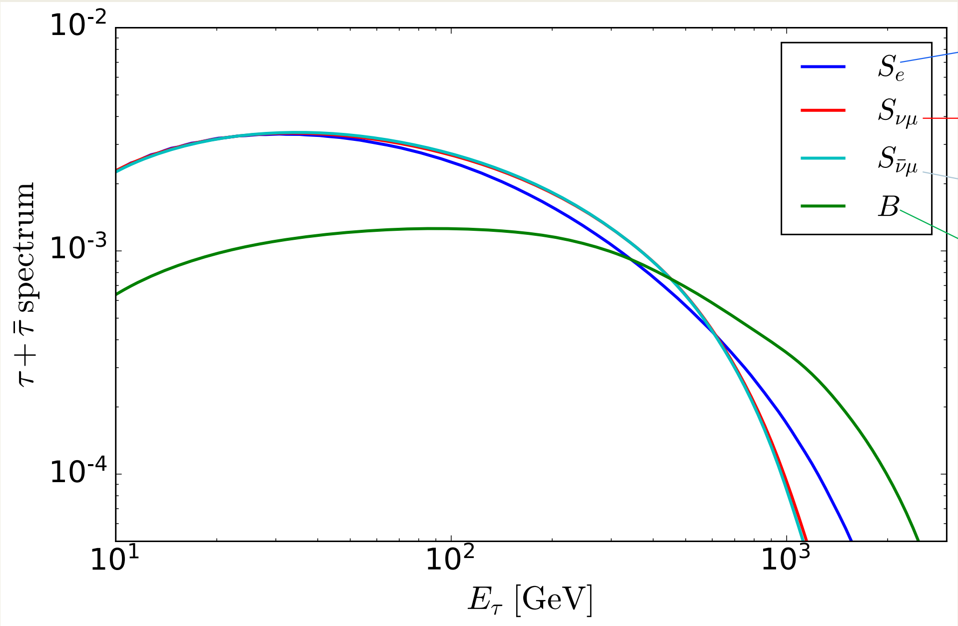
$\pi^+ \rightarrow \mu^+ \bar{\nu}_\tau$

SM prediction

$$B = \frac{\int_{E_\tau} [F_{\nu_\tau}(E_\nu) \frac{d\sigma_\nu^{SM}}{dE_\tau} + F_{\bar{\nu}_\tau}(E_\nu) \frac{d\sigma_{\bar{\nu}}^{SM}}{dE_\tau}] dE_\nu}{\int [F_{\nu_\tau}(E_\nu) \sigma_\nu^{SM} + F_{\bar{\nu}_\tau}(E_\nu) \sigma_{\bar{\nu}}^{SM}] dE_\nu}.$$

S. Ansarifard and YF, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799

Spectra of $\tau + \bar{\tau}$ produced at FASERν normalized to 1.



ν_e + nucleus $\to \tau + X$.

$\pi^+ \to \mu^+ \nu_\tau$

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SM prediction

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Pythia 8 (hard)

Kling, "Forward Neutrino fluxes at the LHC," PRD 104 (21) 11, 113008

S. Ansarifard and YF, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799

CHARACTERISTICS OF FASERν, SND@LHC AND FASERν2

number of τ events at the ith bin

No of W nuclei

$$B_i^J = \epsilon_\tau N_W \int_{E^i_{min}}^{E^i_{max}} \int_{m_\tau} \int_{E_\tau} \Big[F^J_{\nu_\tau}(E_\nu) \frac{d\sigma_{CC}}{dE_\tau}(\nu_\tau + \text{nucleus} \to \tau + X) + F^J_{\bar{\nu}_\tau}(E_\nu) \frac{d\sigma_{CC}}{dE_\tau}(\bar{\nu}_\tau + \text{nucleus} \to \tau^+ + X) \Big] f(E'_\tau, E_\tau) dE_\nu dE_\tau dE'_\tau,$$

$\epsilon_\tau = 0.67$ is the efficiency of the ν_τ detection

$f(E'_\tau, E_\tau)$ is the energy resolution function which we take to be a Gaussian with a 30 % width.

(E^i_{min}, E^i_{max}) determine the limits of the ith energy bin.

CHARACTERISTICS OF FASERν, SND@LHC AND FASERν2

number of τ events at the ith bin

$$B_i^J = \epsilon_\tau N_W \int_{E_{min}^i}^{E_{max}^i} \int_{m_\tau} \int_{E_\tau} \Big[F_{\nu_\tau}^J(E_\nu) \frac{d\sigma_{CC}}{dE_\tau}(\nu_\tau + \text{nucleus} \to \tau + X) + F_{\bar{\nu}_\tau}^J(E_\nu) \frac{d\sigma_{CC}}{dE_\tau}(\bar{\nu}_\tau + \text{nucleus} \to \tau^+ + X) \Big] f(E'_\tau, E_\tau) dE_\nu dE_\tau dE'_\tau,$$

$$\chi^2_{rel} = \sum_i \left[\frac{[(1+f)B_i^{true} - N_i^J]^2}{B_i^{true}} + \frac{f^2}{\sigma_\eta^2} \right]$$

$\sigma_\eta = 15\%$

CHARACTERISTICS OF FASERν, SND@LHC AND FASERν2

number of τ events at the ith bin

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Simulator	bin limits in GeV					χ^2_{rel}
	< 50	$50-100$	$100-500$	$500-1000$	$1000 <$	
Pythia8 (Hard)	0.9	1.8	8.1	9.7	4.8	0.0
DPMJET 3.2017	1.5	3.1	16.2	23.3	14.5	43.7
SIBYLL 2.3c	0.7	1.1	3.7	3.1	0.7	9.6

Kling, "Forward Neutrino fluxes at the LHC," PRD 104 (21) 11, 113008

CHARACTERISTICS OF FASERν, SND@LHC AND FASERν2

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By end of run III (2024), FASERν will determine the tau neutrino spectrum.

Prediction of New physics for the tau excess

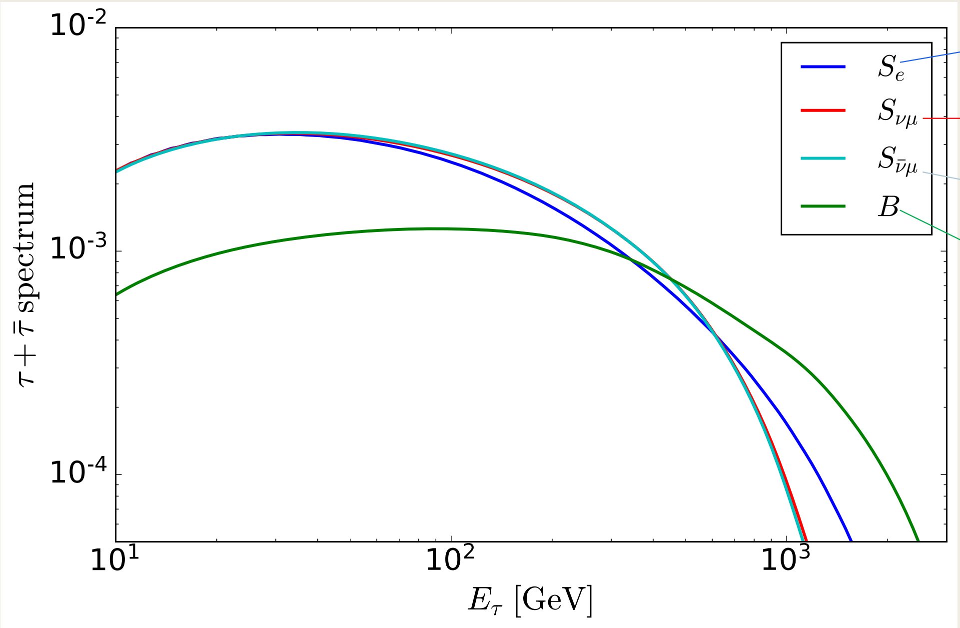
Saturating the bounds

$\nu_e + \text{nucleus} \to \tau + X.$

Detector	$Br(\pi^+ \to \nu_\tau \mu^+)$	$Br(\pi^+ \to \bar{\nu}_\tau \mu^+)$	G_e	SM
SND@LHC	1.0	0.9	0.003	6.6
FASERν	4.9	4.3	0.027	25.3
FASERν 3.6	1125.9	938.0	9.6	3403.3

S. Ansarifard and YF, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799

Spectra of $\tau + \bar{\tau}$ produced at FASERν normalized to 1.



$\nu_e + \text{nucleus} \to \tau + X$.

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SM prediction

$$B = \frac{\int_{E_\tau} [F_{\nu_\tau}(E_\nu) \frac{d\sigma_\nu^{SM}}{dE_\tau} + F_{\bar{\nu}_\tau}(E_\nu) \frac{d\sigma_{\bar{\nu}}^{SM}}{dE_\tau}] dE_\nu}{\int [F_{\nu_\tau}(E_\nu) \sigma_\nu^{SM} + F_{\bar{\nu}_\tau}(E_\nu) \sigma_{\bar{\nu}}^{SM}] dE_\nu}.$$

S. Ansarifard and YF, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799

$$\pi^+ \to \mu^+ \nu_\tau$$

$$\mathcal{N}_s^i = \epsilon_\tau N_W Br(\pi^+ \to \mu^+ \nu_\tau) \int_{E^i_{min}}^{E^i_{max}} \int_{m_\tau} \int_{E_\tau} \Big[F^\pi_{\nu_\mu}(E_\nu) \frac{d\sigma_{CC}}{dE_\tau}(\nu_\tau + \text{nucleus} \to \tau + X) + F^\pi_{\bar{\nu}_\mu}(E_\nu) \frac{d\sigma_{CC}}{dE_\tau}(\bar{\nu}_\tau + \text{nucleus} \to \tau^+ + X) \Big] f(E'_\tau, E_\tau) dE_\nu dE_\tau dE'_\tau$$

Prediction of SM for neutrino flux from the pion decay

$$N_i^{obs} = B_i + \mathcal{N}_s^i$$

$$\chi^2 = \sum_i \left[\frac{\left(B_i(1+\eta) - N_i^{obs}\right)^2}{B_i} + \frac{\eta^2}{\sigma_\eta^2} \right]$$

$$\sigma_\eta = 15\%$$

Binning schemes at FASERν2

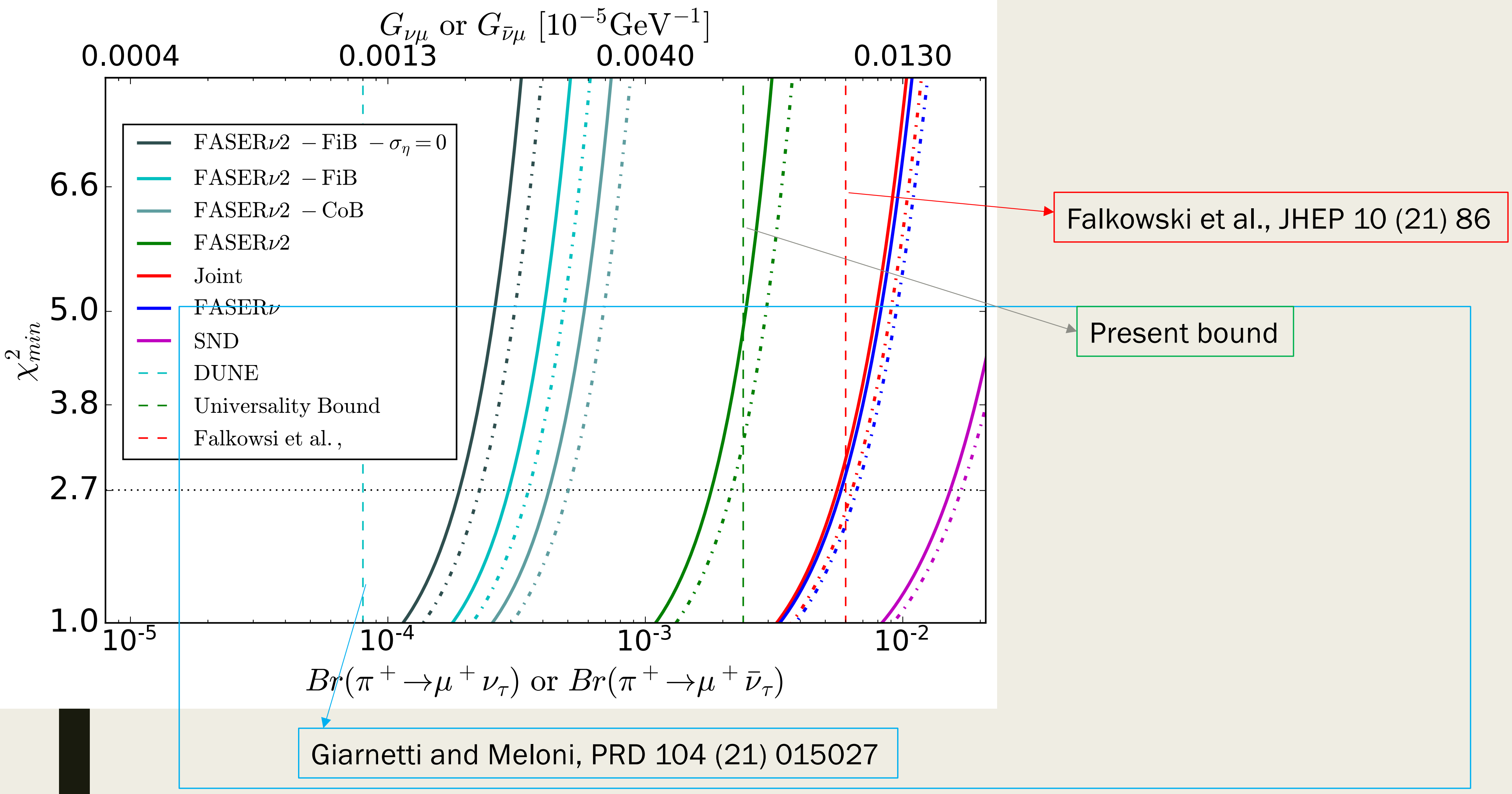
(1) no binning;

(2) coarse binning with bins divided as

$E_\tau < 50$ GeV,

50 GeV $< E_\tau <$ 100 GeV, 100 GeV $< E_\tau <$ 500 GeV, 500 GeV $< E_\tau <$ 1 TeV and 1 TeV $< E_\tau$;

(3) fine binning with three bins at each energy decade.



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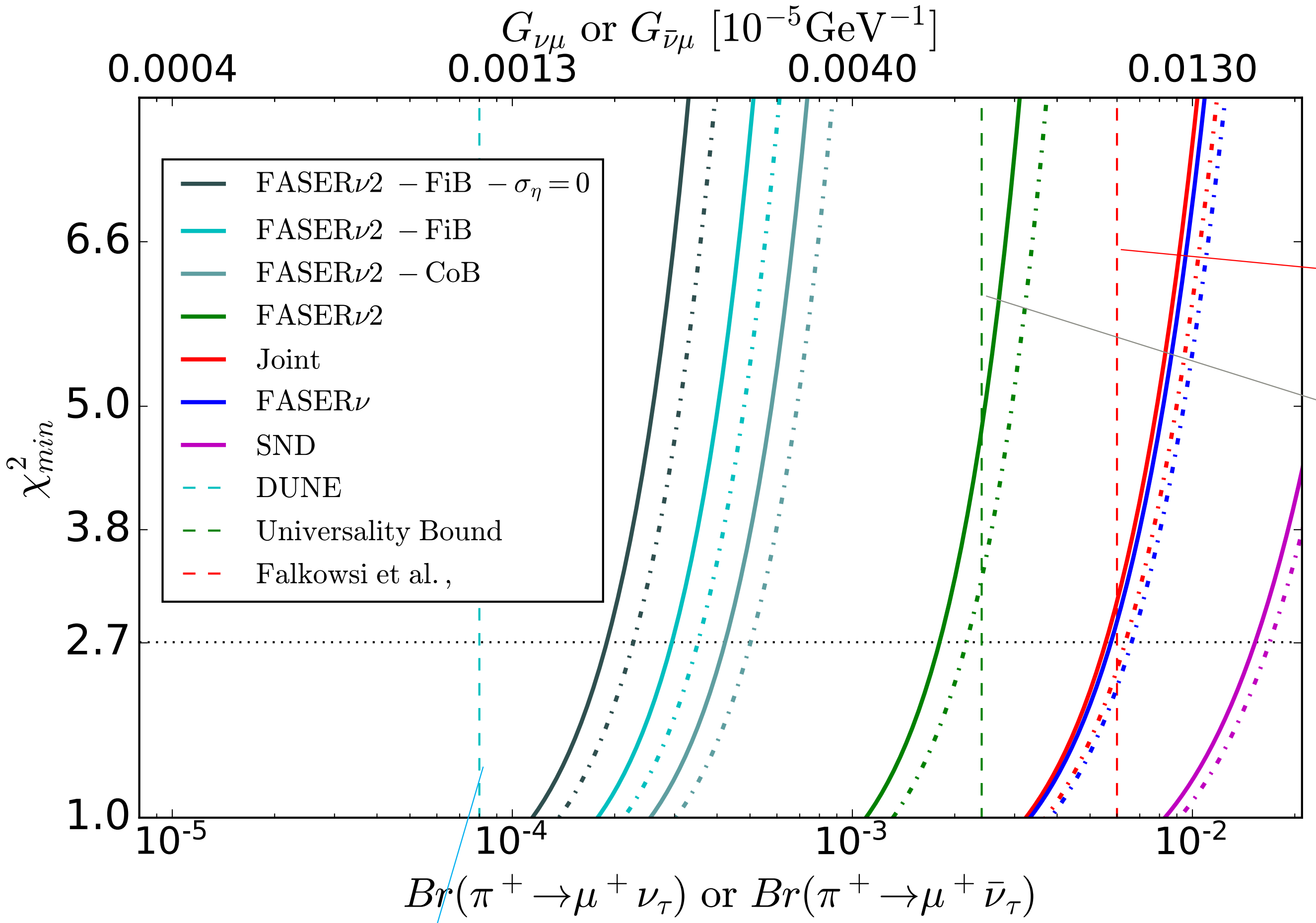

Falkowski et al., JHEP 10 (21) 86

Present bound

15 % uncertainty in the normalization of the flux

energy resolution of 30 %

Giarnetti and Meloni, PRD 104 (21) 015027

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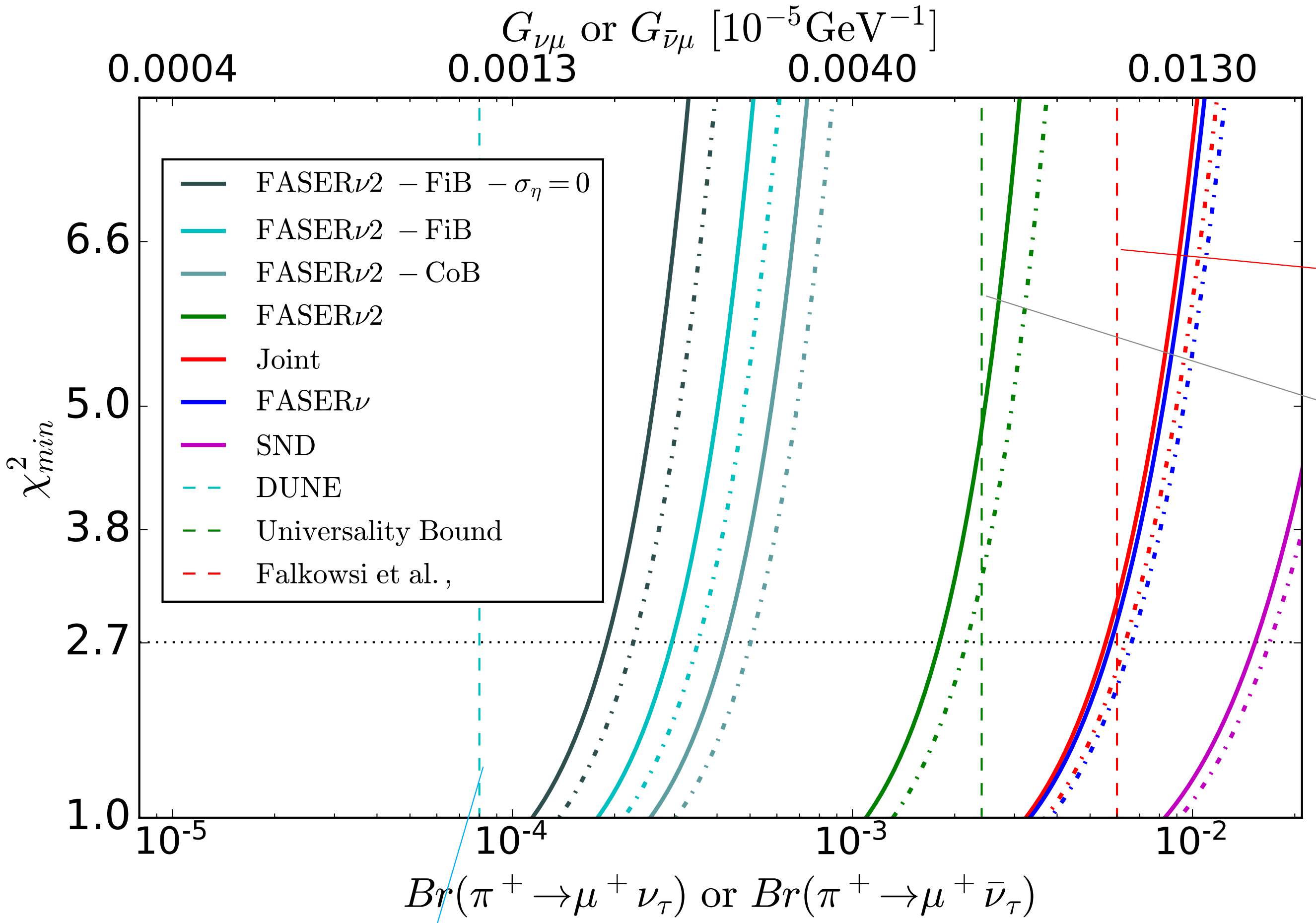

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15 % uncertainty in the normalization of the flux

energy resolution of 30 %

Robust against variation

Giarnetti and Meloni, PRD 104 (21) 015027

S. Ansarifard and YF, "Excess of Tau events at SND@LHC, FASERν and FASERν2," arXiv:2112.08799

Summary and Conclusions

- We have built three viable BSMs for tau excess at forward experiments leading to

$$(1)\ \pi^+ \to \mu^+\nu_\tau;\ (2)\ \pi^+ \to \mu^+\bar{\nu}_\tau\quad (3)\ \nu_e + \text{nucleus} \to \tau + X.$$

- SND@LHC and FASERν cannot improve the bounds but can significantly reduce the uncertainty in the SM prediction for the tau events.

- FASERν2 can probe the new physics by looking for tau excess.

- Reconstructing the energy spectrum of detected tau (binning the data) can significantly enhance the potential of FASERν2 to probe new physics.