# Muon-decay parameters at COHERENT

## New horizons for CE$\nu$NS experiments

**Sergio Cruz-Alzaga**

based on 2502.18175 in collaboration with
Martín González-Alonso (IFIC), Suraj Prakash (IFIC) and Victor Bresó-Pla (ITP Heidelberg)

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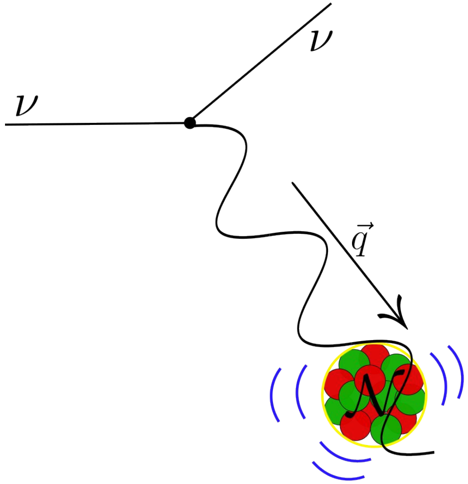
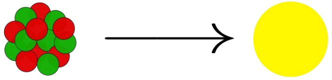
AGENCIA ESTATAL DE INVESTIGACIÓN

Flavour Symmetries and Consequences in Accelerators and Cosmology-FLASY 2025 5th July 2025

# CEνNS (Coherent Elastic Neutrino-Nucleus Scattering)





$\mathrm{sw}^2 = 0.23$

$$\propto Q_W = Z(1 - 4\sin^2\theta_W) - N \simeq -N$$

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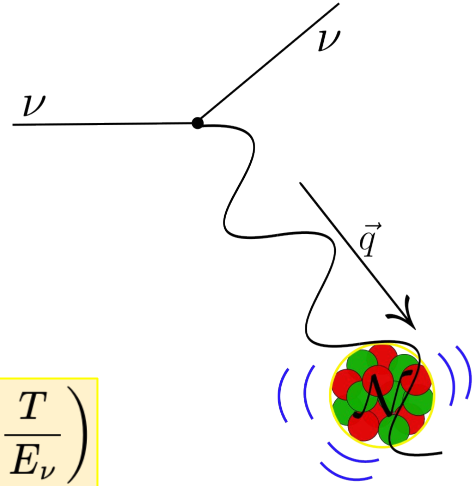

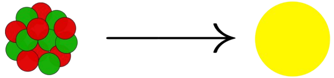

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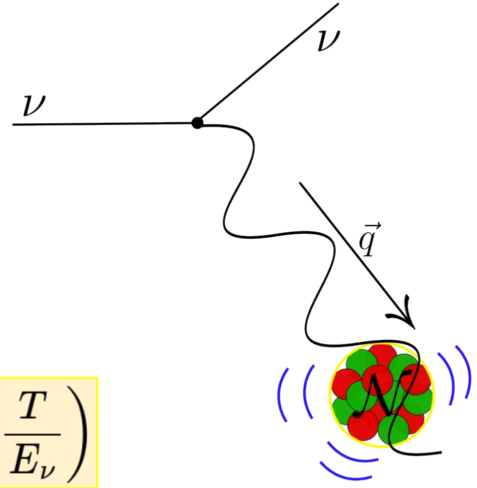

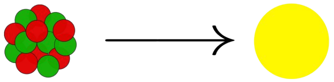

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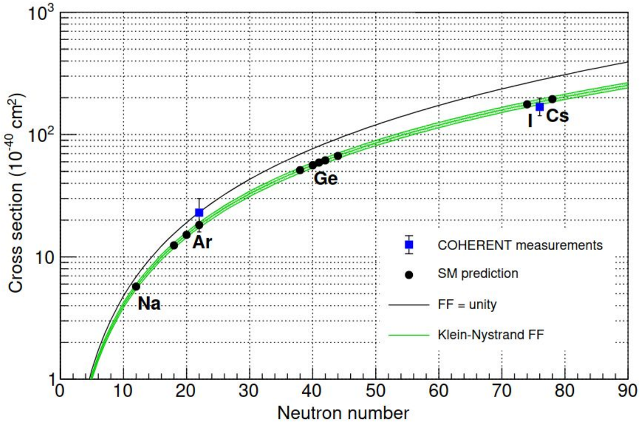
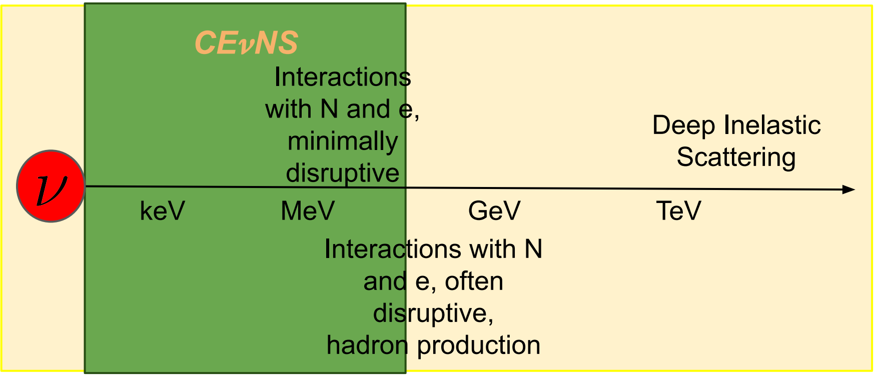


From P. S. Barbeau, et al. Ann. Rev. Nucl. Part. Sci. 73, 41–68 (2023)



CEνNS

Interactions with N and e, minimally disruptive

ν

keV MeV GeV TeV

Deep Inelastic Scattering

Interactions with N and e, often disruptive, hadron production

Adapted from De Romeri

# The COHERENT Experiment

*Spallation Neutron Source*
*(Oak Ridge National Laboratory)*

source https://neutrons.ornl.gov/sns

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  Targets → CsI, LAr, Ge

  D. Akimov et al. (COHERENT) Science 357, 1123–1126 (2017)
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- Neutrino production

prompt: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

delayed: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

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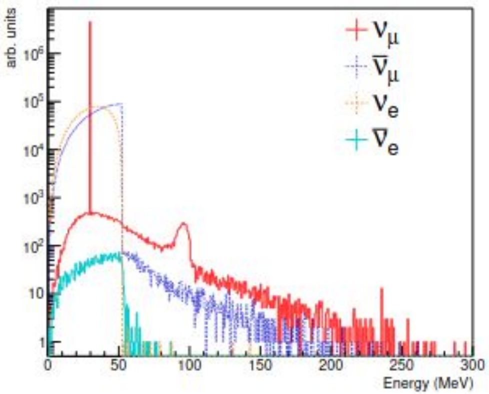

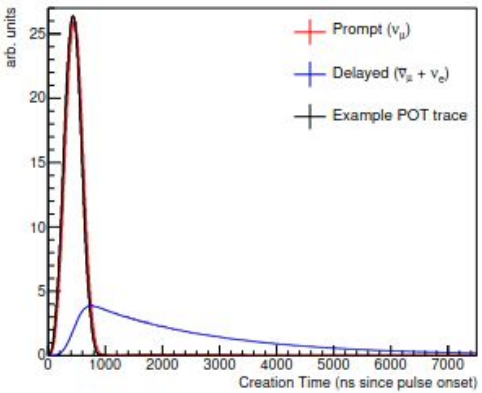

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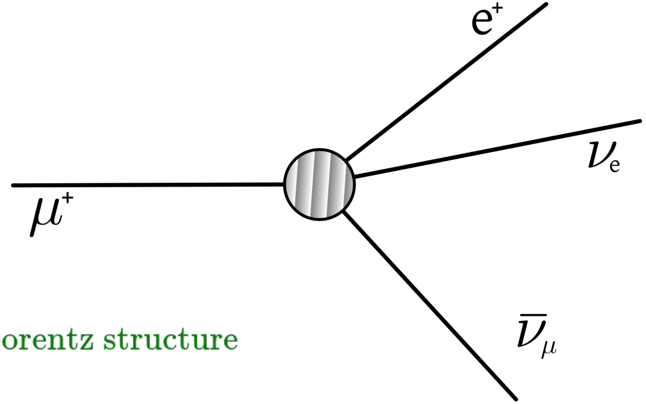
# Muon decay parameters



$$\mathcal{L} \supset -\frac{4\,G_F}{\sqrt{2}} \sum_{X,\eta,\epsilon} g^X_{\epsilon\eta}(\bar{e}_\epsilon \Gamma^X (\nu_e)_\rho)((\bar{\nu}_\mu)_\gamma \Gamma_X \mu_\eta) \,+\, h.\,c.$$

$$\Gamma_X = \{1, \gamma_\lambda, \sigma_{\lambda\omega}/\sqrt{2}\}$$

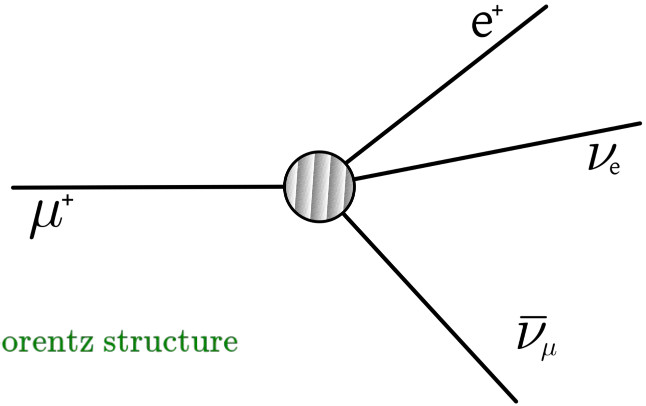
$$X = \{S, V, T\}$$

$g^X_{\epsilon\eta}$

$X$ ← Lorentz structure

$\epsilon\eta$ ← $e$, $\mu$ chirality

# Muon decay parameters



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← Lorentz structure

← $e,\ \mu$ chirality

- $\underset{\text{measurement}}{\Gamma_\mu \longrightarrow G_F} \Longrightarrow \sum_{\epsilon,\eta}\left[\frac{1}{4}\,|g^S_{\epsilon\eta}|^2 \,+\, |g^V_{\epsilon\eta}|^2 \,+\, 3\,|g^T_{\epsilon\eta}|^2\right] = 1$

- SM limit → $g^V_{LL} = 1,\ \text{rest} = 0$

(PDG collaboration), Review of particle physics, vol. 110, pp. 826–828, Phys. Rev. D (2024)

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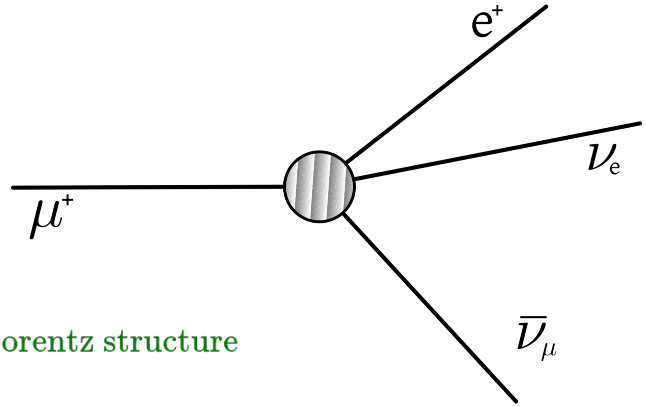

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Lorentz structure

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- $\Gamma_\mu \xrightarrow[\text{measurement}]{} G_F \Longrightarrow \sum_{\epsilon,\eta} \left[ \frac{1}{4}\,|g^S_{\epsilon\eta}|^2 \; + \; |g^V_{\epsilon\eta}|^2 \; + \; 3\,|g^T_{\epsilon\eta}|^2 \right] = 1$
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Usually measured from the e$^+$/e$^-$ detection

Flat direction

$$(g^V_{LL})^2 + \frac{1}{4}(g^S_{LL})^2$$

(PDG collaboration), Review of particle physics, vol. 110, pp. 826–828, Phys. Rev. D (2024)

B. Balke et al., Phys. Rev. D 37, 587 (1988)
R. P. MacDonald et al. (TWIST), Phys. Rev. D 78, 032010 (2008)
A. Hillairet et al. (TWIST), Phys. Rev. D 85, 092013 (2012)

# Muon decay parameters

- For left-handed neutrinos:

$$\frac{d\Gamma_{\nu_L}}{dE_\nu} = \frac{24\Gamma_\mu}{m_\mu} P_{\nu_L} \left[ y^2 (1-y) + \frac{8}{9} w_{\nu_L} y^2 \left( y - \frac{3}{4} \right) \right],$$

- For left-handed anti-neutrinos

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$$P_{\nu_L} = |g^V_{LL}|^2 + |g^V_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + \frac{1}{4}|g^S_{RL}|^2 + 3|g^T_{RL}|^2$$

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$$P_{\nu_L} w_{\nu_L} = \frac{3}{16}\left(4|g^V_{LR}|^2 + |g^S_{RR}|^2 + |g^S_{RL} + 2\, g^T_{RL}|^2\right)$$

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$$(g^V_{LL})^2 + \frac{1}{4}(g^S_{LL})^2 \;???$$

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Extraction suggested in **Phys. Rev. D 49, 5945 (1994)**.

Performed by the KARMEN collaboration, Phys. Rev. Lett. 81, 520 (1998)

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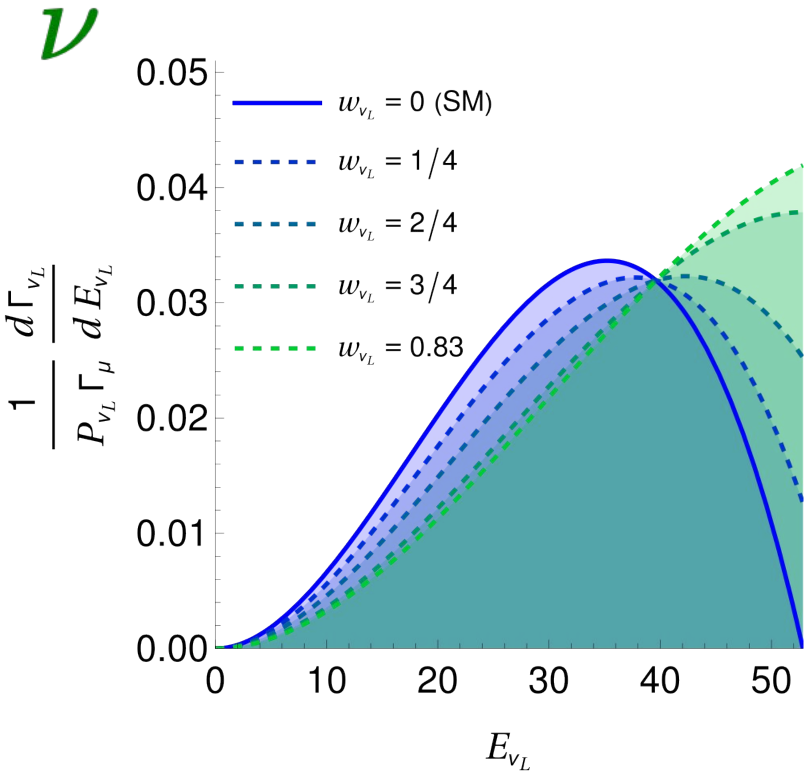
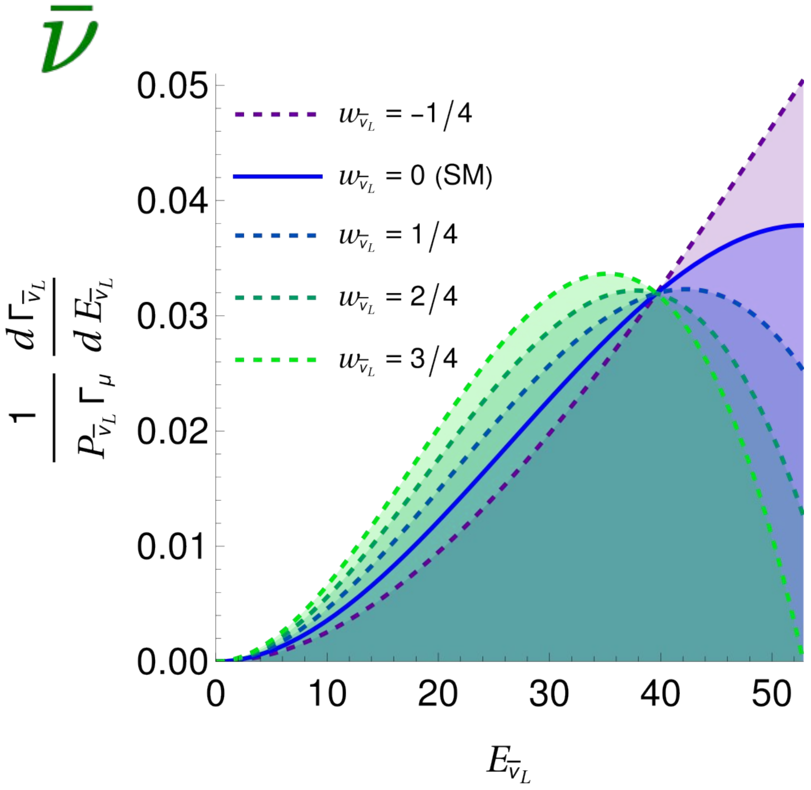
In our work, we show the sensitivity of COHERENT-like experiments to these parameters and propose their first phenomenological extraction.

# The (anti)neutrino flux





# Rates

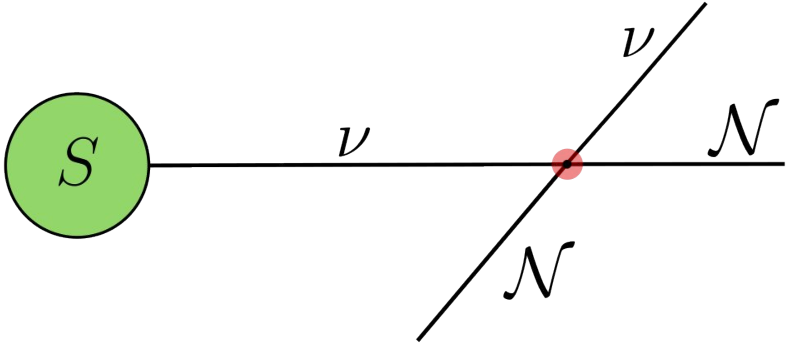
The rate per recoil energy T, per time t is:

$$\frac{dN}{dtdT} = g_\pi(t)\frac{dN^{\text{prompt}}}{dT} + g_\mu(t)\frac{dN^{\text{delayed}}}{dT} \ ,$$

where

$$\frac{dN^{\text{prompt}}}{dT} = N_T \int dE_\nu \frac{d\phi_{\nu_\mu}}{dE_\nu}\frac{d\,\sigma_{\nu_\mu}}{d\,T} \ , \qquad \frac{dN^{\text{delayed}}}{dT} = N_T \int dE_\nu \left(\frac{d\phi_{\nu_e}}{dE_\nu}\frac{d\,\sigma_{\nu_e}}{d\,T} + \frac{d\phi_{\bar{\nu}_\mu}}{dE_\nu}\frac{d\,\sigma_{\bar{\nu}_\mu}}{d\,T}\right) .$$

# Rates



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time dependence of the source

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$\phi_\nu$ — neutrino flux

$\sigma$ — CE$\nu$NS cross-section

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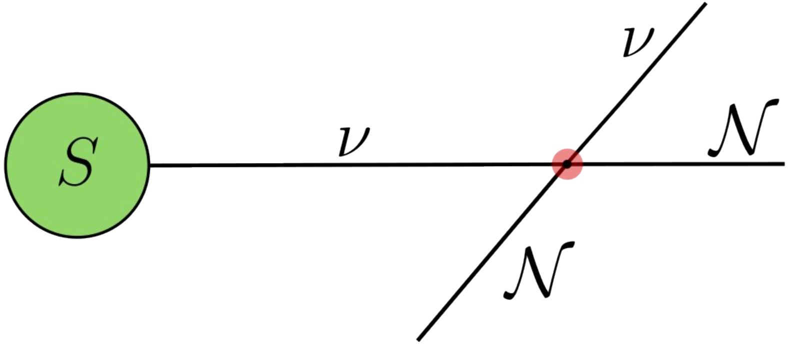

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This setup has been widely used in many different CE$\nu$NS analysis (electroweak precision proves, nuclear studies and NP searchers).

Liao and Marfatia, Phys. Lett. B 775 (2017) 54
C. Giunti, Phys. Rev. D 101 (2020) 035039
Papoulias and Kosmas, Phys. Rev. D 97 (2018) 033003
Aristizabal-Sierra, et. al., Phys. Rev. D 98 (2018) 075018
Skiba and Xia, JHEP 10 (2022) 102
De Romeri, et. al., JHEP 04 (2023) 035
Bresó-Pla, et.al., JHEP 05 (2023) 074

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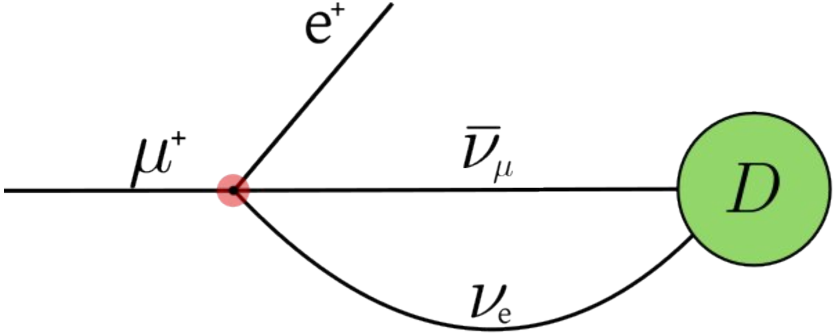

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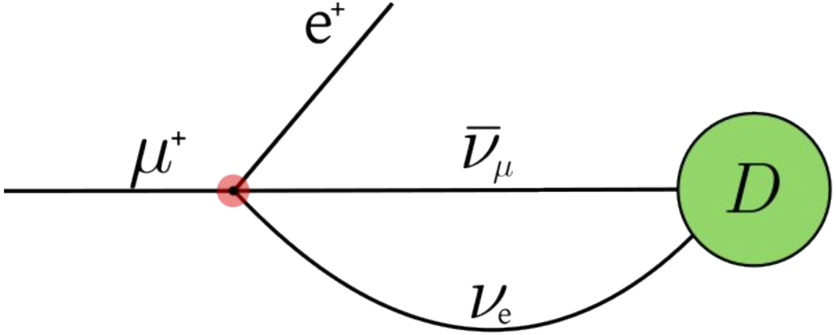

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time dependence of the source

where

$$\boxed{\frac{dN^{\text{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu\, x_f\, \frac{d\phi_f^{\text{SM}}}{dE_\nu}\frac{d\sigma^{\text{SM}}}{dT}}$$

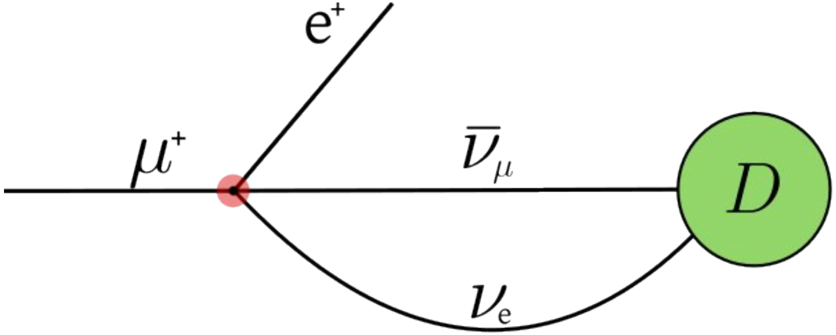
$$\begin{aligned}
x_{\nu_\mu} &= 1\ ,\\
x_{\bar{\nu}_\mu} &= P_{\bar{\nu}_L} - \frac{4}{3}P_{\bar{\nu}_L}w_{\bar{\nu}_L} + \frac{4}{3}P_{\nu_L}w_{\nu_L}\ ,\\
x_{\nu_e} &= P_{\nu_L} - \frac{4}{3}P_{\nu_L}w_{\nu_L} + \frac{4}{3}P_{\bar{\nu}_L}w_{\bar{\nu}_L}\ .
\end{aligned}$$

# Rates

The rate per recoil energy T, per time t is:

$$\frac{dN}{dtdT} = g_\pi(t)\,\frac{dN^{\text{prompt}}}{dT} + g_\mu(t)\,\frac{dN^{\text{delayed}}}{dT}\ ,$$

time dependence of the source



where

$$\boxed{\frac{dN^{\text{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu\, x_f\, \frac{d\phi_f^{\text{SM}}}{dE_\nu}\,\frac{d\sigma^{\text{SM}}}{dT}}$$

prompt $\{x_{\nu_\mu} = 1\ ,$

delayed
$$\begin{cases} x_{\bar{\nu}_\mu} = P_{\bar{\nu}_L} - \frac{4}{3}P_{\bar{\nu}_L}w_{\bar{\nu}_L} + \frac{4}{3}P_{\nu_L}w_{\nu_L}\ , \\ x_{\nu_e} = P_{\nu_L} - \frac{4}{3}P_{\nu_L}w_{\nu_L} + \frac{4}{3}P_{\bar{\nu}_L}w_{\bar{\nu}_L}\ . \end{cases}$$

$$\frac{d\sigma^{\text{SM}}}{dT} = \frac{m_\mathcal{N} G_F^2 \mathcal{F}^2(T)}{4\,\pi} Q_{\text{W}}^2 \left(1 - \frac{m_\mathcal{N}\,T}{2E_\nu^2} - \frac{T}{E_\nu}\right)$$

$$\frac{d\phi_{\nu_\mu}^{\text{SM}}}{dE_\nu} = \frac{N_{\nu_\mu}}{4\pi L^2}\delta(E_\nu - E_{\nu,\pi})\ ,$$

$$\frac{d\phi_{\nu_e}^{\text{SM}}}{dE_\nu} = \frac{N_{\nu_e}}{4\pi L^2}\frac{192 E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)\ ,$$

$$\frac{d\phi_{\bar{\nu}_\mu}^{\text{SM}}}{dE_\nu} = \frac{N_{\bar{\nu}_\mu}}{4\pi L^2}\frac{64 E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right)\ .$$

# Muon decay

$$\frac{dN^{\text{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu \, x_f \, \frac{d\phi_f^{\text{SM}}}{dE_\nu} \frac{d\sigma^{\text{SM}}}{dT}$$

with

$$\begin{aligned} x_{\nu_\mu} &= 1 \,, \\ x_{\bar\nu_\mu} &= P_{\bar\nu_L} - \frac{4}{3} P_{\bar\nu_L} w_{\bar\nu_L} + \frac{4}{3} P_{\nu_L} w_{\nu_L} \,, \\ x_{\nu_e} &= P_{\nu_L} - \frac{4}{3} P_{\nu_L} w_{\nu_L} + \frac{4}{3} P_{\bar\nu_L} w_{\bar\nu_L} \,. \end{aligned}$$

$$\begin{aligned} x_{\bar\nu_\mu} &= -1.5(1.3) \,, \\ x_{\nu_e} &= 4.6(2.1) \,, \\ \rho &= -0.98 \,. \end{aligned}$$

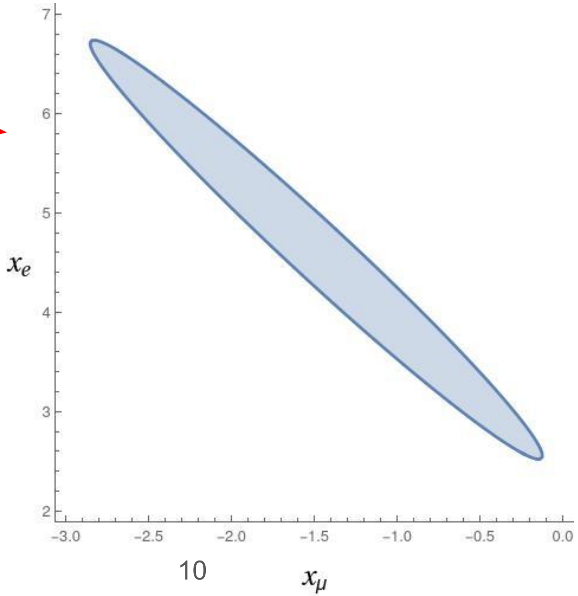
# Muon decay

$$\frac{dN^{\text{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu \, x_f \, \frac{d\phi_f^{\text{SM}}}{dE_\nu} \frac{d\sigma^{\text{SM}}}{dT}$$

with

$$\begin{aligned} x_{\nu_\mu} &= 1\,, \\ x_{\bar{\nu}_\mu} &= P_{\bar{\nu}_L} - \frac{4}{3} P_{\bar{\nu}_L} w_{\bar{\nu}_L} + \frac{4}{3} P_{\nu_L} w_{\nu_L}\,, \\ x_{\nu_e} &= P_{\nu_L} - \frac{4}{3} P_{\nu_L} w_{\nu_L} + \frac{4}{3} P_{\bar{\nu}_L} w_{\bar{\nu}_L}\,. \end{aligned}$$

$$\left.\begin{aligned} x_{\bar{\nu}_\mu} &= -1.5(1.3)\,, \\ x_{\nu_e} &= 4.6(2.1)\,, \\ \rho &= \boxed{-0.98\,.} \end{aligned}\right\}$$



# Muon decay

$$\frac{dN^{\mathrm{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu \, x_f \, \frac{d\phi_f^{\mathrm{SM}}}{dE_\nu} \frac{d\sigma^{\mathrm{SM}}}{dT}$$

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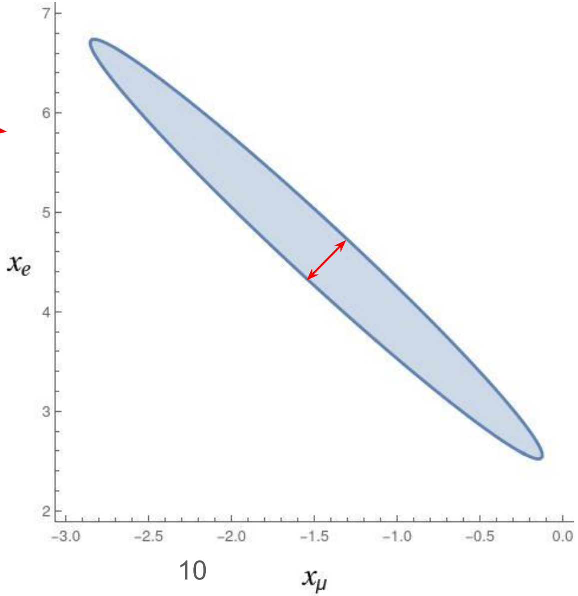
$$\left. \begin{aligned} x_{\bar{\nu}_\mu} &= -1.5(1.3) \, , \\ x_{\nu_e} &= 4.6(2.1) \, , \\ \rho &= \boxed{-0.98 \, .} \end{aligned} \right\} \longrightarrow$$



# Muon decay

$$\frac{dN^{\mathrm{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu \, x_f \, \frac{d\phi_f^{\mathrm{SM}}}{dE_\nu} \frac{d\sigma^{\mathrm{SM}}}{dT}$$

with

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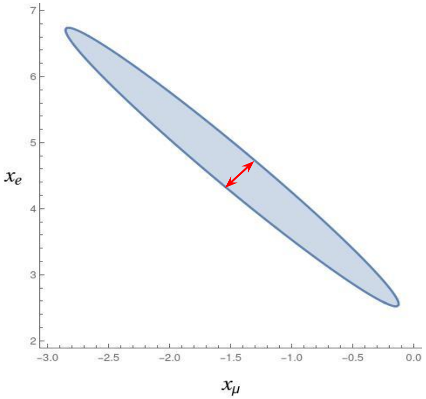


$$\boxed{0.84 \, x_{\bar{\nu}_\mu} + 0.54 \, x_{\nu_e} = 1.25(21) \, ,}$$

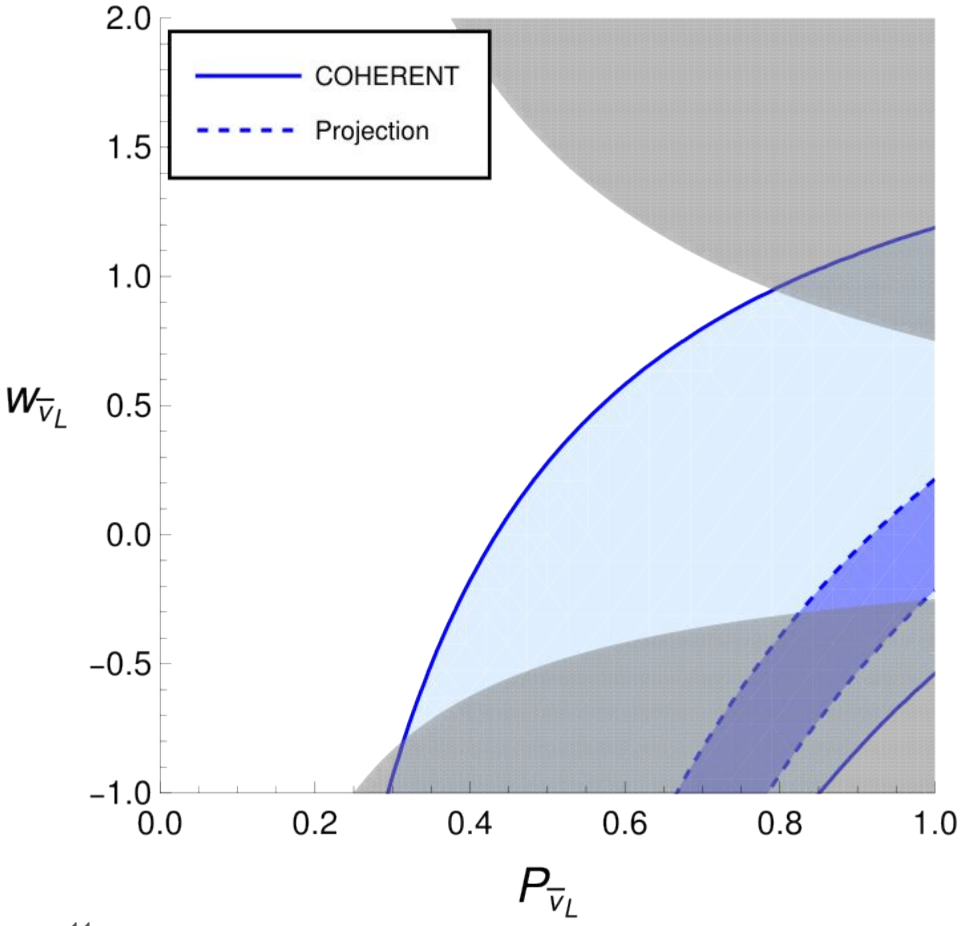
$$\downarrow$$

$$0.54 \, P_{\nu_L} + 0.84 \, P_{\bar{\nu}_L} + 0.40 \, (P_{\nu_L} w_{\nu_L} - P_{\bar{\nu}_L} w_{\bar{\nu}_L}) = 1.25 \pm 0.21 \, .$$

# Muon decay

$$P_{\nu_L} = 0.98 \left(\begin{smallmatrix}+02\\-37\end{smallmatrix}\right) , \qquad w_{\nu_L} = 0.00 \left(\begin{smallmatrix}+23\\-00\end{smallmatrix}\right) ,$$
$$P_{\bar{\nu}_L} = 0.90 \left(\begin{smallmatrix}+10\\-24\end{smallmatrix}\right) , \qquad w_{\bar{\nu}_L} = 0.51 \left(\begin{smallmatrix}+24\\-51\end{smallmatrix}\right) .$$

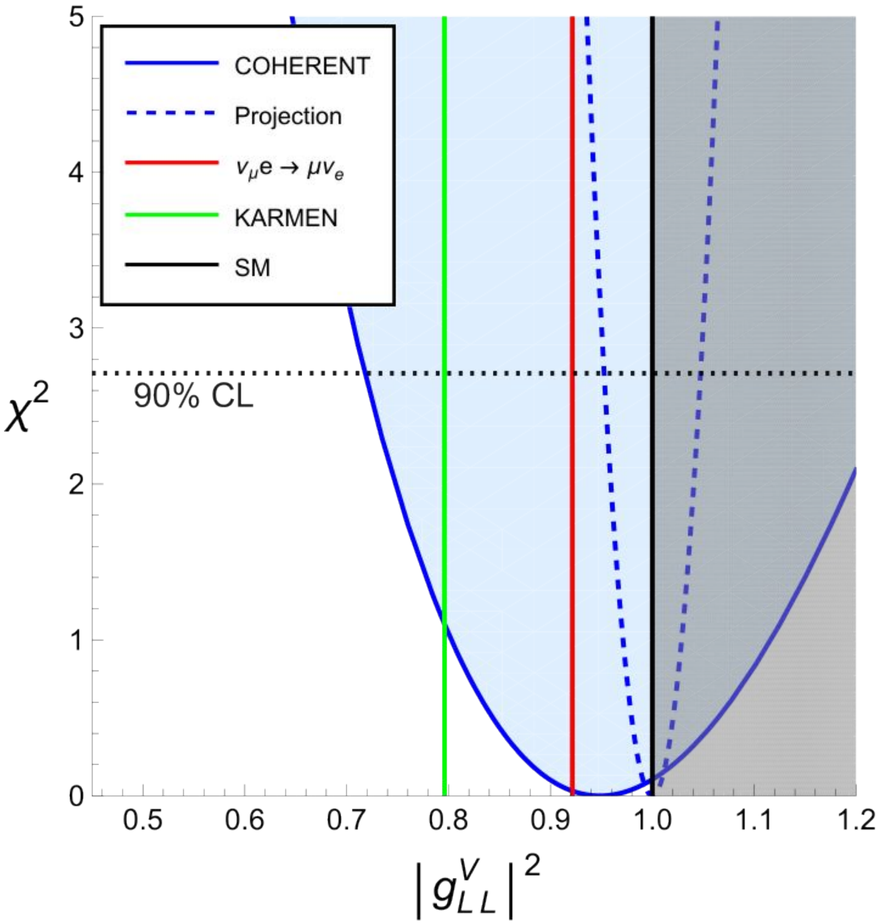
first constraint



# Muon decay full $\chi^2$

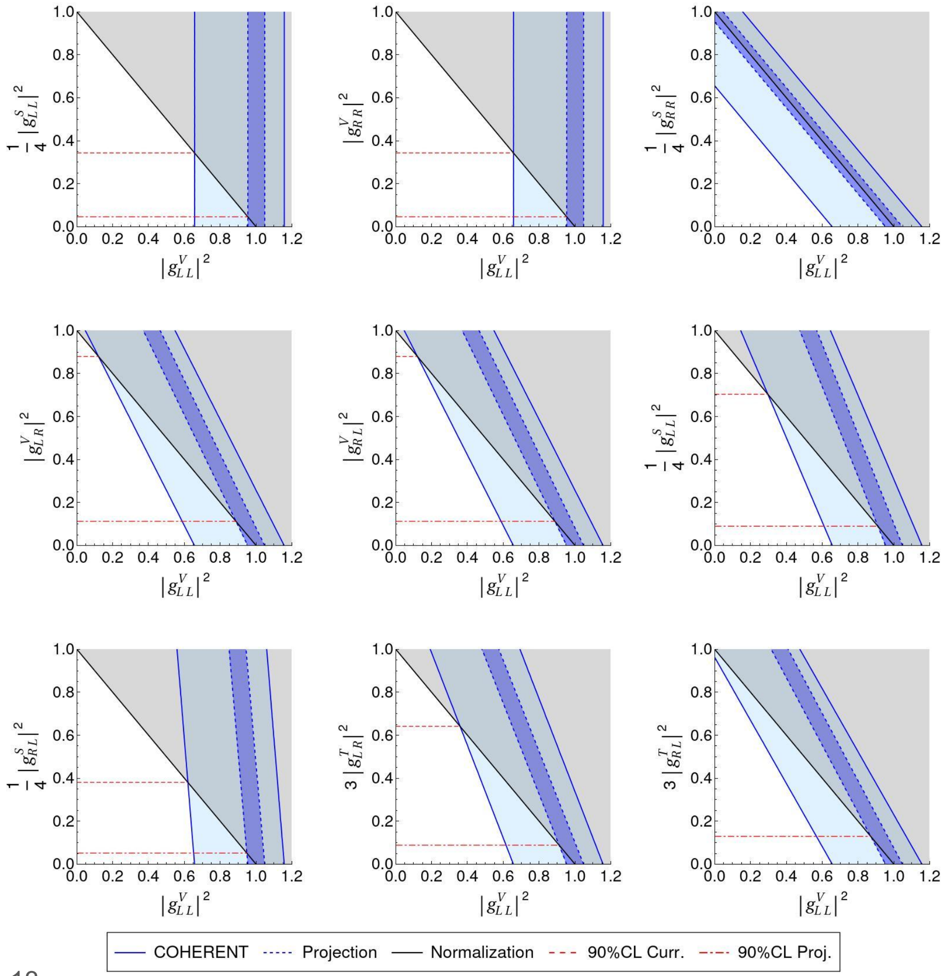
$$|g_{LL}^V|^2 = 0.95^{+0.05}_{-0.15}$$

independent of $g_{LL}^S$



# Muon decay

| Coefficient | Bound (90% C.L.) | | |
|---|---|---|---|
| | Current | Projected | PDG ($\alpha = \mu, \beta = e$) |
| $\lvert g^V_{LL}\rvert$ | $>0.848$ | $>0.976$ | $>0.960$ |
| $\lvert g^V_{LR}\rvert$ | 0.79 | 0.34 | 0.023 |
| $\lvert g^V_{RL}\rvert$ | 0.79 | 0.34 | 0.105 |
| $\lvert g^S_{LR}\rvert$ | 1.4 | 0.57 | 0.050 |
| $\lvert g^S_{RL}\rvert$ | 1.6 | 0.67 | 0.420 |
| $\lvert g^T_{LR}\rvert$ | 0.47 | 0.21 | 0.015 |
| $\lvert g^T_{RL}\rvert$ | 0.42 | 0.17 | 0.105 |
| $\lvert g^V_{RR}\rvert$ (*) | 0.53 | 0.22 | 0.017 |
| $\lvert g^S_{LL}\rvert$ (*) | 1.07 | 0.44 | 0.550 |



# A more general case (2505.01275)

- Flavour general interactions

$$g^X_{\mu\epsilon} \longrightarrow \left[h^X_{\mu\epsilon}\right]_{\alpha\beta} \quad \nu \text{ flavour}$$

- NP in detections and in π decay

$$(\bar{u}\gamma^\mu d)(\bar{l}_\alpha\gamma_\mu P_H\nu_\beta)$$
$$(\bar{u}\gamma^\mu\gamma^5 d)(\bar{l}_\alpha\gamma_\mu P_H\nu_\beta)$$
$$(\bar{u}d)(\bar{l}_\alpha P_H\nu_\beta)$$
$$(\bar{u}i\gamma^5 d)(\bar{l}_\alpha P_H\nu_\beta)$$
$$(\bar{u}\sigma^{\mu\nu}P_H d)(\bar{l}_\alpha\sigma_{\mu\nu}P_H\nu_\beta)$$

$$(\bar{q}\gamma^\mu q)\,(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$(\bar{q}\gamma^\mu\gamma^5 q)\,(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$(\bar{q}\gamma^\mu q)(\bar{\nu}_\alpha\gamma_\mu P_R\nu_\beta)$$
$$(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\nu}_\alpha\gamma_\mu P_R\nu_\beta)$$
$$(\bar{q}q)(\bar{\nu}_\alpha P_R\nu_\beta) + h.c.$$
$$(\bar{q}i\gamma^5 q)(\bar{\nu}_\alpha P_R\nu_\beta) + h.c.$$
$$(\bar{q}\sigma^{\mu\nu}q)(\bar{\nu}_\alpha\sigma_{\mu\nu}P_R\nu_\beta) + h.c.$$
$$(\bar{\nu}_\alpha\sigma^{\mu\nu}P_R\nu_\beta)F_{\mu\nu} + h.c.$$

- A consistent EFT framework

$$\frac{1}{N_T}\frac{dN^S_\alpha}{dt\,dE_\nu\,dT} = \frac{N_S(t)}{32\pi L^2 m_S m_{\mathcal{N}} E_\nu}\sum_{j,k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}}\int d\Pi_{P'}\mathcal{M}^P_{\alpha k}\bar{\mathcal{M}}^P_{\alpha l}\int d\Pi_{D'}\mathcal{M}^D_{jk}\bar{\mathcal{M}}^D_{jl}$$

**A. Falkowski et al., JHEP 11 (2020) 048** and **V. Bresó-Pla et al., JHEP 05 (2023) 074**

# A more general case (2505.01275)

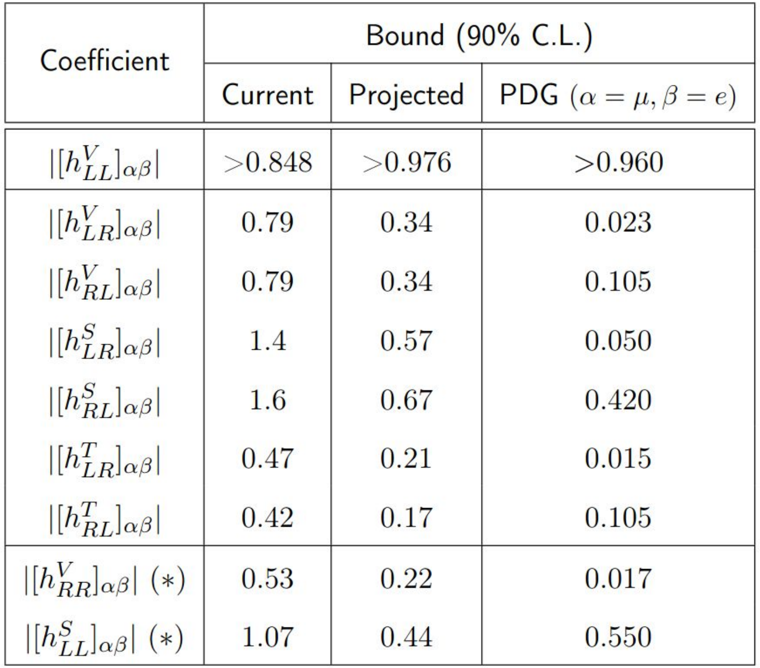
- Flavour general interactions
- NP in detections and in π decay
- A consistent EFT framework

$$\frac{dN^{\text{prompt/delayed}}}{dT} = N_T \int dE_\nu \, \frac{d\phi^{\text{SM}}_{\nu_f}}{dE_\nu} \frac{d\widetilde{\sigma}_{\nu_f}}{dT}$$

$$\begin{aligned}\frac{d\widetilde{\sigma}_{\nu_f}}{dT} = \frac{m_\mathcal{N}\mathcal{F}^2(q^2)}{8\pi v^4}\Bigg\{ & (\widetilde{Q}^f_{V})^2\left(1-\frac{m_\mathcal{N}T}{2E_\nu^2}-\frac{T}{E_\nu}\right) \\ & + (\widetilde{Q}^f_{S})^2\frac{m_\mathcal{N}T}{2E_\nu^2} + (\widetilde{Q}^f_{F})^2\frac{v^2}{2m_\mathcal{N}T}\left(1-\frac{T}{E_\nu}\right) \\ & + (\widetilde{Q}^f_{SF})^2\frac{v}{2E_\nu}\left(1-\frac{T}{2E_\nu}\right)\Bigg\}\end{aligned}$$

$$\begin{aligned}\frac{d\phi^{\text{SM}}_{\nu_\mu}}{dE_\nu} &= \frac{N_{\nu_\mu}}{4\pi L^2}\delta(E_\nu - E_{\nu,\pi})\,, \\ \frac{d\phi^{\text{SM}}_{\nu_e}}{dE_\nu} &= \frac{N_{\nu_e}}{4\pi L^2}\frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2}-\frac{E_\nu}{m_\mu}\right), \\ \frac{d\phi^{\text{SM}}_{\bar{\nu}_\mu}}{dE_\nu} &= \frac{N_{\bar{\nu}_\mu}}{4\pi L^2}\frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4}-\frac{E_\nu}{m_\mu}\right).\end{aligned}$$

# A more general case



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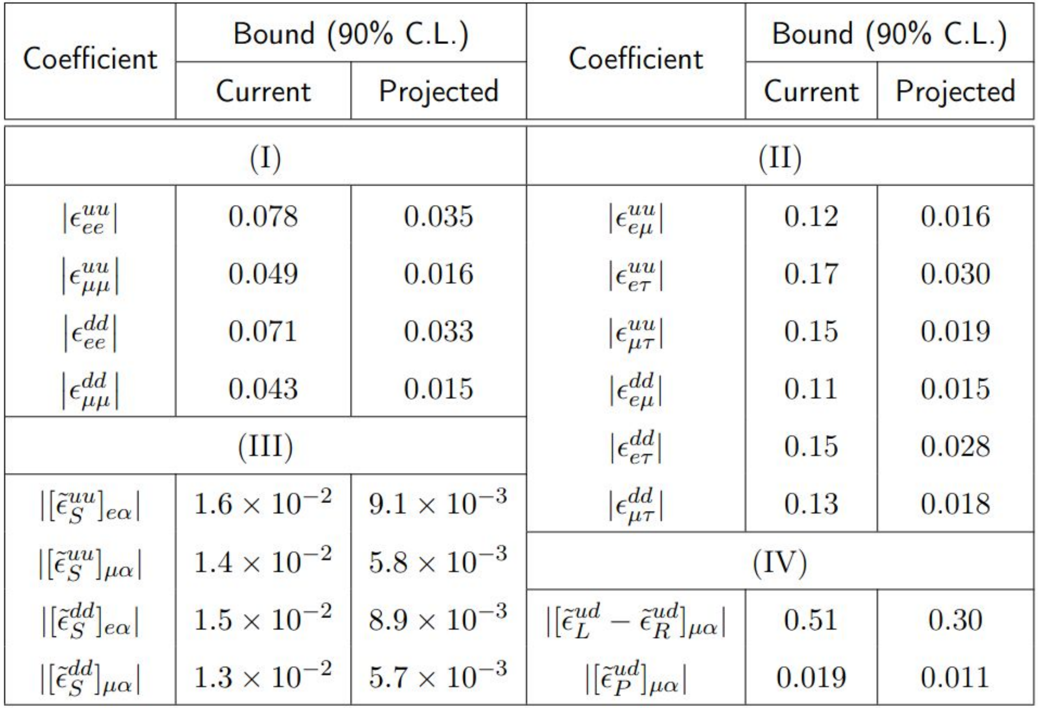

| Coefficient | Bound (90% C.L.) | | Coefficient | Bound (90% C.L.) | |
|---|---|---|---|---|---|
| | Current | Projected | | Current | Projected |
| (I) | | | (II) | | |
| $\lvert\epsilon^{uu}_{ee}\rvert$ | 0.078 | 0.035 | $\lvert\epsilon^{uu}_{e\mu}\rvert$ | 0.12 | 0.016 |
| $\lvert\epsilon^{uu}_{\mu\mu}\rvert$ | 0.049 | 0.016 | $\lvert\epsilon^{uu}_{e\tau}\rvert$ | 0.17 | 0.030 |
| $\lvert\epsilon^{dd}_{ee}\rvert$ | 0.071 | 0.033 | $\lvert\epsilon^{uu}_{\mu\tau}\rvert$ | 0.15 | 0.019 |
| $\lvert\epsilon^{dd}_{\mu\mu}\rvert$ | 0.043 | 0.015 | $\lvert\epsilon^{dd}_{e\mu}\rvert$ | 0.11 | 0.015 |
| (III) | | | $\lvert\epsilon^{dd}_{e\tau}\rvert$ | 0.15 | 0.028 |
| $\lvert[\tilde{\epsilon}^{uu}_S]_{e\alpha}\rvert$ | $1.6 \times 10^{-2}$ | $9.1 \times 10^{-3}$ | $\lvert\epsilon^{dd}_{\mu\tau}\rvert$ | 0.13 | 0.018 |
| $\lvert[\tilde{\epsilon}^{uu}_S]_{\mu\alpha}\rvert$ | $1.4 \times 10^{-2}$ | $5.8 \times 10^{-3}$ | (IV) | | |
| $\lvert[\tilde{\epsilon}^{dd}_S]_{e\alpha}\rvert$ | $1.5 \times 10^{-2}$ | $8.9 \times 10^{-3}$ | $\lvert[\tilde{\epsilon}^{ud}_L - \tilde{\epsilon}^{ud}_R]_{\mu\alpha}\rvert$ | 0.51 | 0.30 |
| $\lvert[\tilde{\epsilon}^{dd}_S]_{\mu\alpha}\rvert$ | $1.3 \times 10^{-2}$ | $5.7 \times 10^{-3}$ | $\lvert[\tilde{\epsilon}^{ud}_P]_{\mu\alpha}\rvert$ | 0.019 | 0.011 |

# Summary

- We have performed the first extraction of the **anti-neutrino** emission probability and the corresponding spectrum shape parameter.
- EFTs (Low Energy in our case) provide a suitable frame to study NP phenomenology in a **model independent** way.
- Neutrino experiments are required inputs in the **EW precision fits.**
- COHERENT-like experiments are entering the **precision era** and will become relevant precision EW inputs in the near future.

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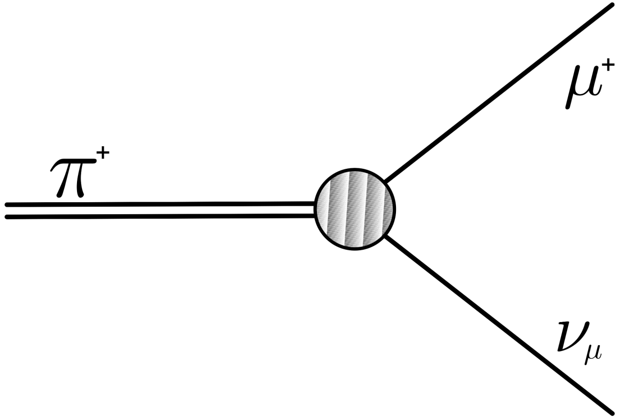
## Thank you!

# Pion decay (pseudoscalar coupling)



$$\Delta\mathcal{L} = \sqrt{2}\, G_F\, V_{ud}\ \Big\{ \epsilon_P (\bar{u}\gamma^5 d)(\bar{\mu}\, P_L\, \nu_\mu) \\ + \tilde{\epsilon}_P (\bar{u}\gamma^5 d)(\bar{\mu}\, P_R\, \nu_\mu) \Big\} + \ h.\, c.\, ,$$

---

$$\frac{dN^{\text{pr./del.}}}{dT} = \sum_f N_T \int dE_\nu\, x_f \frac{d\phi_f^{\text{SM}}}{dE_\nu} \frac{d\sigma^{\text{SM}}}{dT}$$

prompt $\left\{ x_{\nu_\mu} \approx 1 - |\tilde{\epsilon}_P|^2 \frac{m_{\pi^\pm}^4}{m_\mu^2 (m_u + m_d)^2} \right. ,$

delayed $\left\{ \begin{array}{l} x_{\bar{\nu}_\mu} = 1\, , \\ x_{\nu_e} = 1\, . \end{array} \right.$

---

- COHERENT data (projection) ——→ $\tilde{\epsilon}_P = 0.000 \pm 0.012\ (0.009)$ $\quad 2.3\ (2.6)\ \text{TeV}$