Dark-Sector-Origin Anomalous Tau Neutrino Appearance in Neutrino Experiments

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In collaboration with Bhupal Dev, Bhaskar Dutta, and Tao Han, to appear soon

Anomalous Appearance of Tau Neutrinos

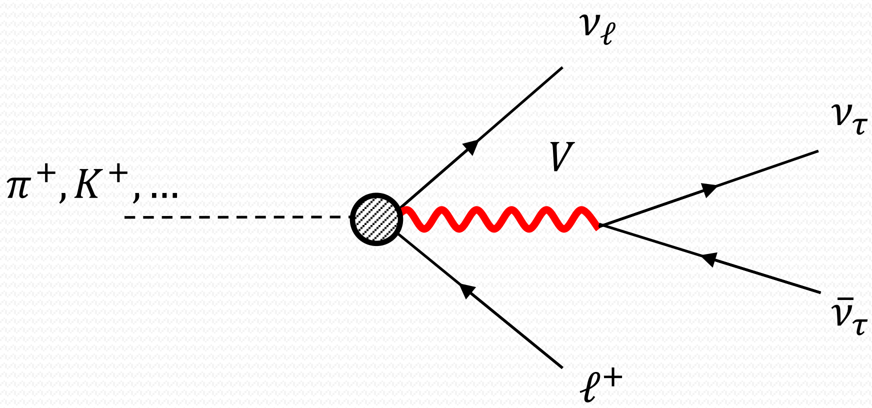
$$P_{\mu\to\tau} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2][\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

- L is too small for ν_μ to oscillate to ν_τ.
- Production rates of D mesons are too small to detect enough ν_τ events.

$\Rightarrow$ **Appearance of tau neutrinos** at the near detectors of neutrino experiments can be considered anomalous and a "smoking-gun" signature of new physics.

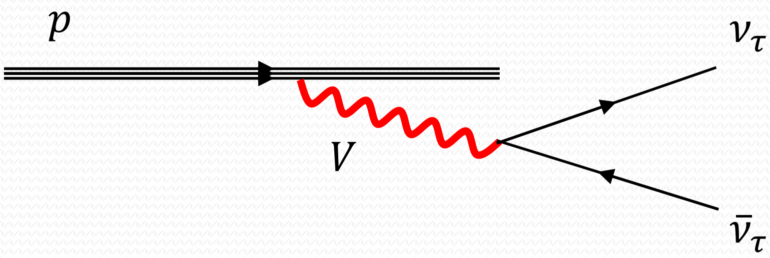
Example BSM case: scenarios involving more than three ν flavors (see Alex Sousa's talk)

Tau Neutrino Appearance under Dark-Sector Scenarios



+ neutral meson decay (for hadrophilic mediators)

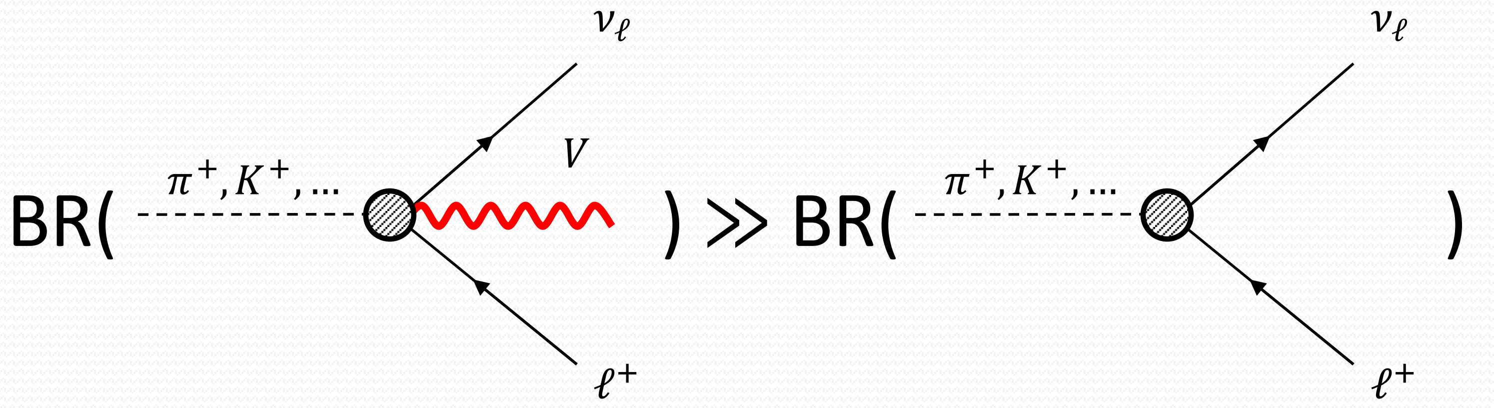
If mediators are hadrophilic



Cf. The vector mediator can be replaced by a scalar or pseudoscalar mediator.

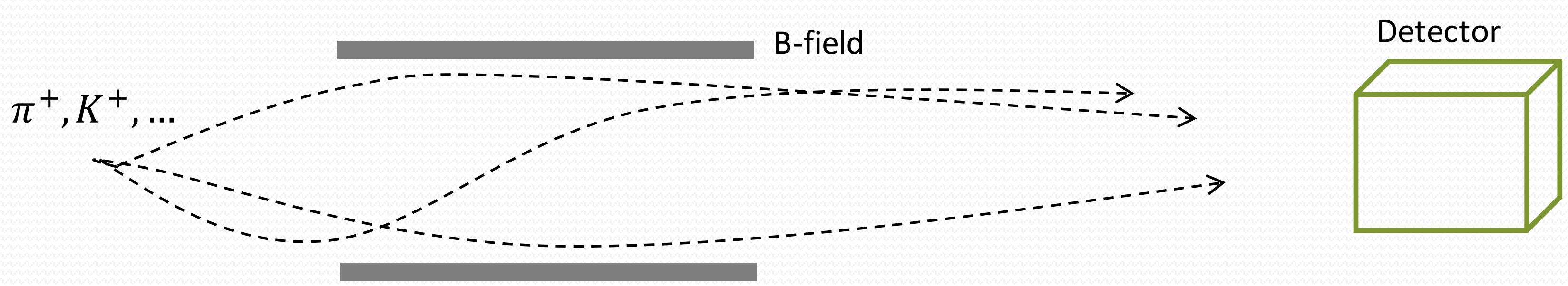
Why Charged-Meson-Induced Tau Neutrino Signals?

Reason-1) **Large BR enhancement**

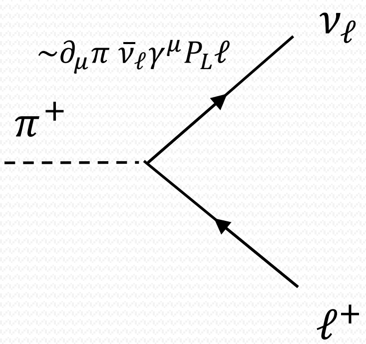


(assuming an $\mathcal{O}(1)$ dark-sector coupling for purposes of comparison)

Reason-2) **Focusing of charged mesons**



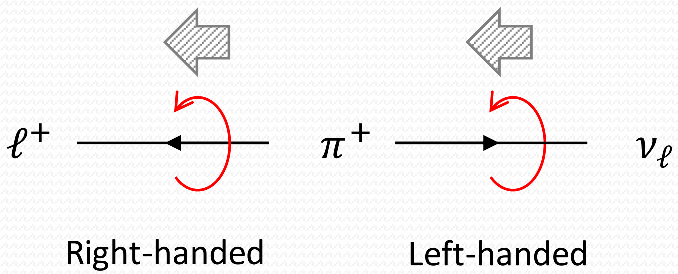
Reason-1: Two-Body Decay of a Charged Meson



$$\Rightarrow \mathcal{M} \sim f_\pi m_\ell \bar{u}_\ell (1-\gamma_5) v_\nu \Rightarrow \Gamma_{\pi\to\ell\nu} \sim \frac{f_\pi^2}{m_\pi^3} m_\ell^2 (m_\pi^2 - m_\ell^2)^2$$

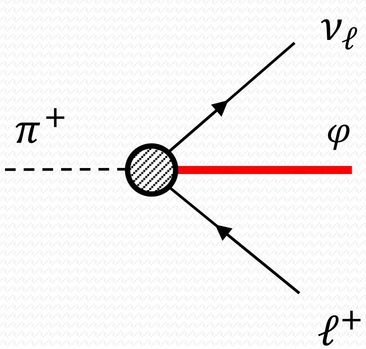
(vs. $\Gamma_{\pi\to\ell\nu} \sim (m_\pi - m_\ell)$ by a naïve guess)

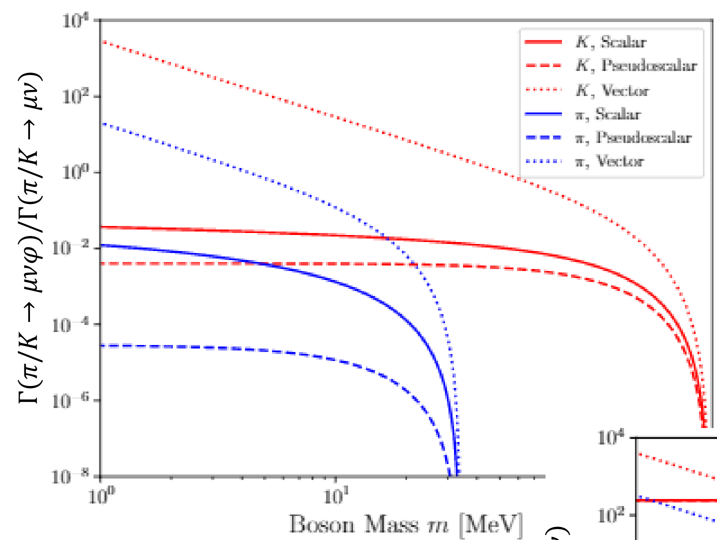
Suppressed by a "wrong" helicity assignment



Angular momentum conservation highly suppresses the decay of scalar mesons in this way.

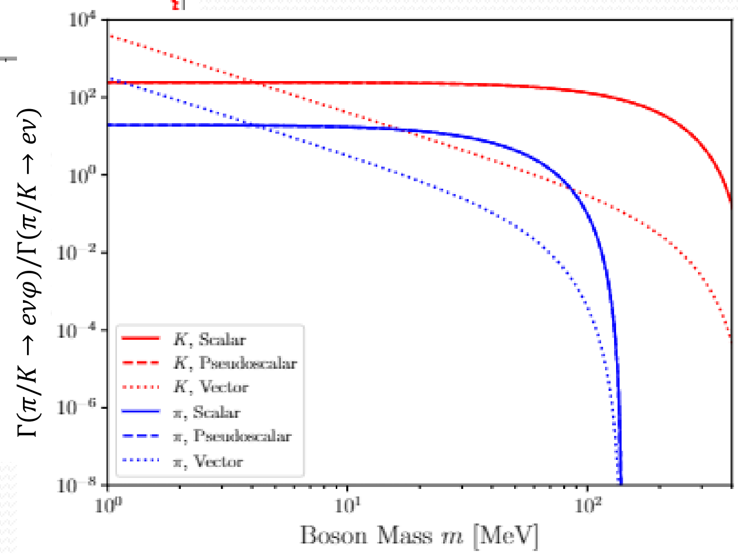
Reason-1: Three-Body Decay of a Charged Meson





- φ is assumed to couple to the charged lepton only and the associated couplings are set to be unity for comparison.

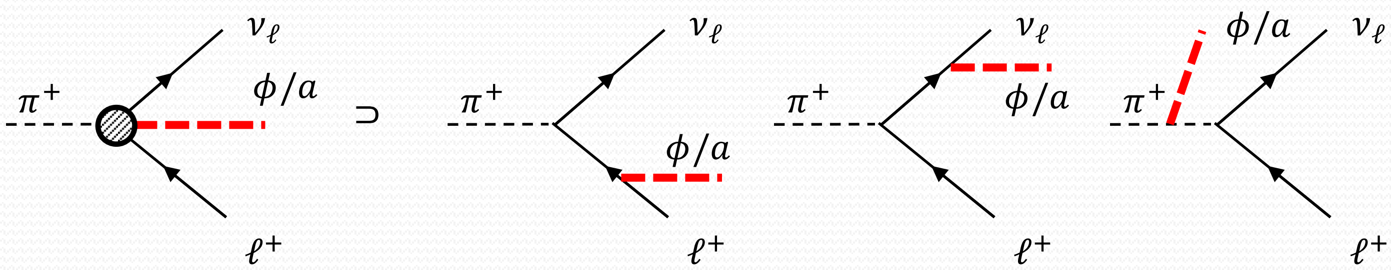
By adding the third particle φ (e.g., scalar, pseudoscalar, vector, etc), the helicity suppression can be evaded, i.e., 3-body decays can be **hugely enhanced**. The decay to a massive vector is even more enhanced due to the longitudinal polarization. [e.g., Carlson, Rislow, arXiv:1206.3587]



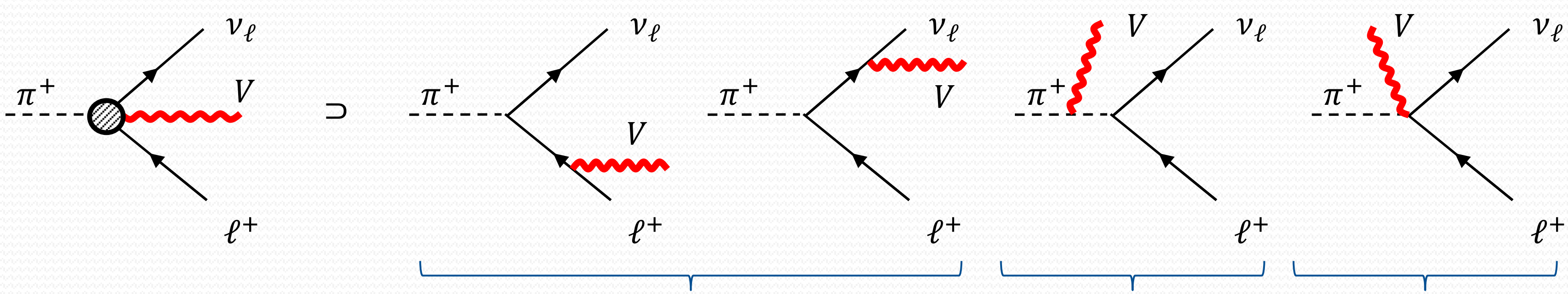
(See also Bhaskar Dutta's and Adrian Thompson's talks)

Reason-1: Various Dynamics in the Three-Body Decay

(Pseudo)scalar case



Vector case



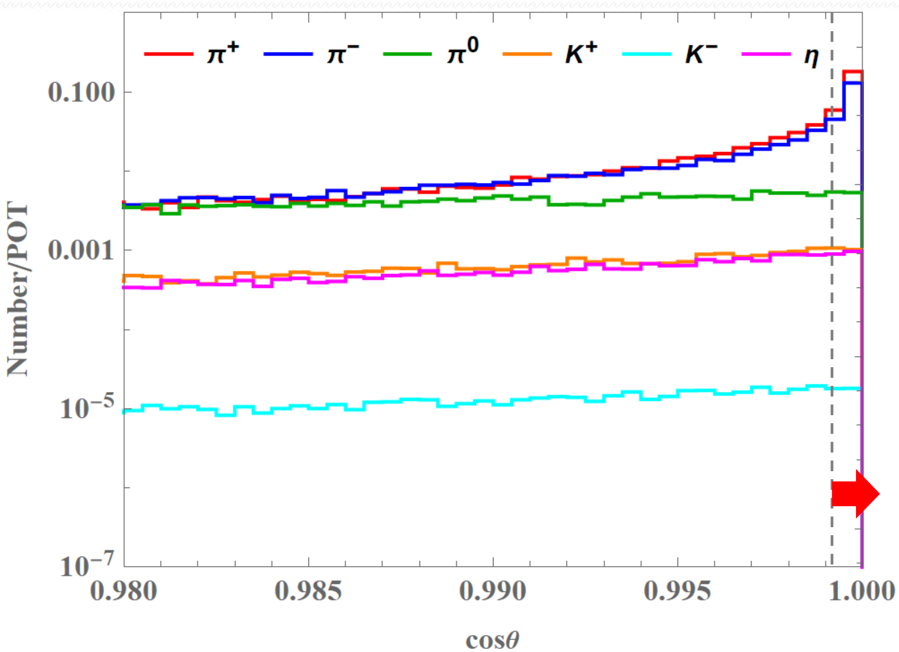
- Typically, IB3 contributions ≫ IB2 ≈ IB1

Cf. For models having couplings to the quark contents inside the meson, (QCD-origin) structure-dependent (SD) terms may arise.
See also [Khodjamirian, Wyler, arXiv:hep-ph/0111249] for more details.

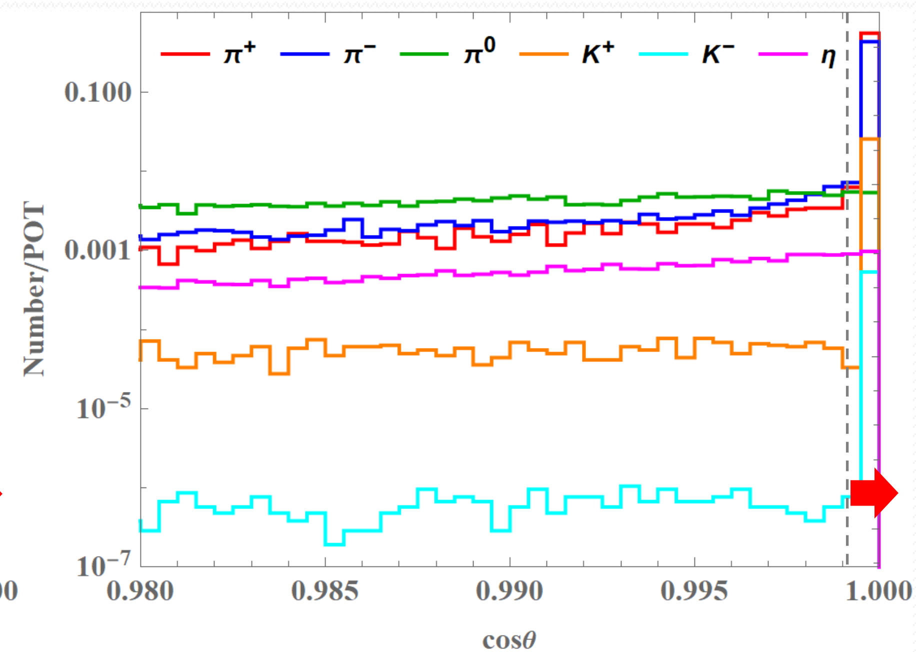
Reason-2: Angular Distributions of Mesons

In the example of BNB,

Before focusing



After focusing

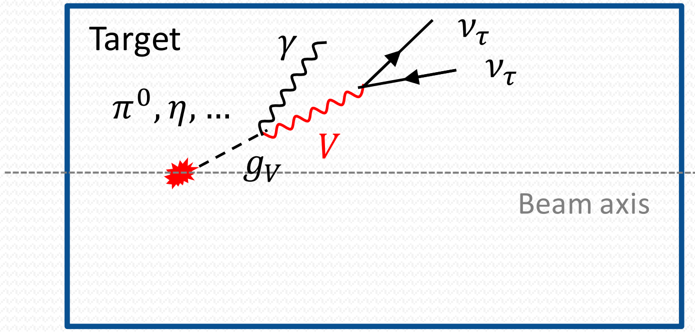


: ~SBN detector coverage

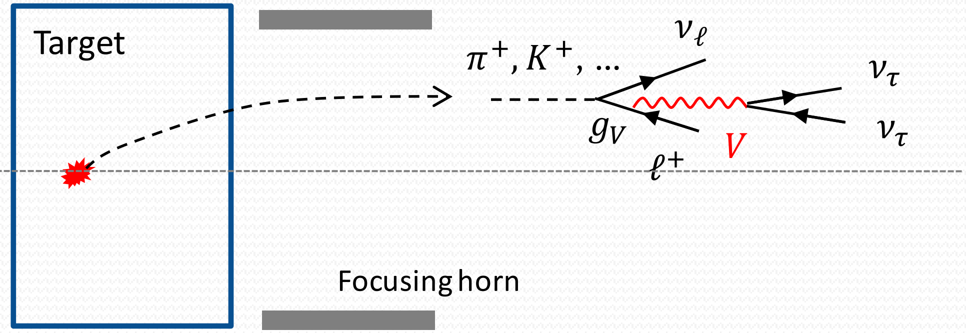
Charged Meson vs. Neutral Meson

In the example of hadrophilic mediators,

Production via neutral meson



Production via charged meson

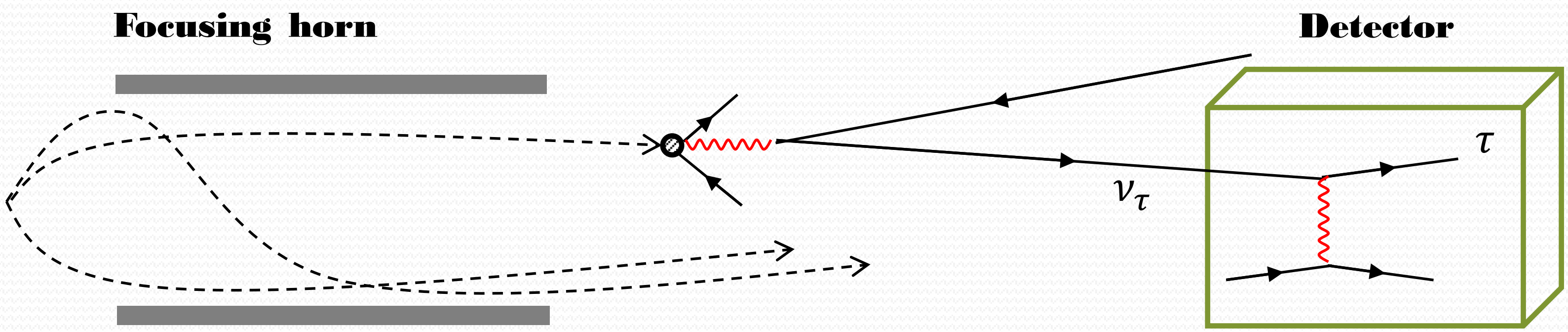


$$N^{\nu_\tau}_{\pi^0-\mathrm{ind}} = N_{\pi^0} \cdot \mathrm{BR}(\pi^0 \to V \to \nu_\tau) \cdot f^{\nu_\tau}_{\pi^0-\mathrm{ind}} \ll N^{\nu_\tau}_{\pi^\pm-\mathrm{ind}} = N_{\pi^\pm} \cdot \mathrm{BR}(\pi^\pm \to V \to \nu_\tau) \cdot f^{\nu_\tau}_{\pi^\pm-\mathrm{ind}}$$

- Comparable production rate: $\pi^0 : \pi^+ : \pi^- \approx 10^{22} : 10^{22} : 10^{22}$ per year $\Rightarrow N_{\pi^0} \approx N_{\pi^\pm}$
- No BR enhancement vs. Large BR enhancement $\Rightarrow \mathrm{BR}(\pi^0 \to V \to \nu_\tau) \ll \mathrm{BR}(\pi^\pm \to V \to \nu_\tau)$
- Unfocused π^0 vs. Focused $\pi^\pm$
- Wider spreading π^0-induced flux vs. Forward-directed $\pi^\pm$-induced flux $\Rightarrow f^{\nu_\tau}_{\pi^0-\mathrm{ind}} < f^{\nu_\tau}_{\pi^\pm-\mathrm{ind}}$

Production via **charged meson** can be more efficient than production via **neutral meson**!

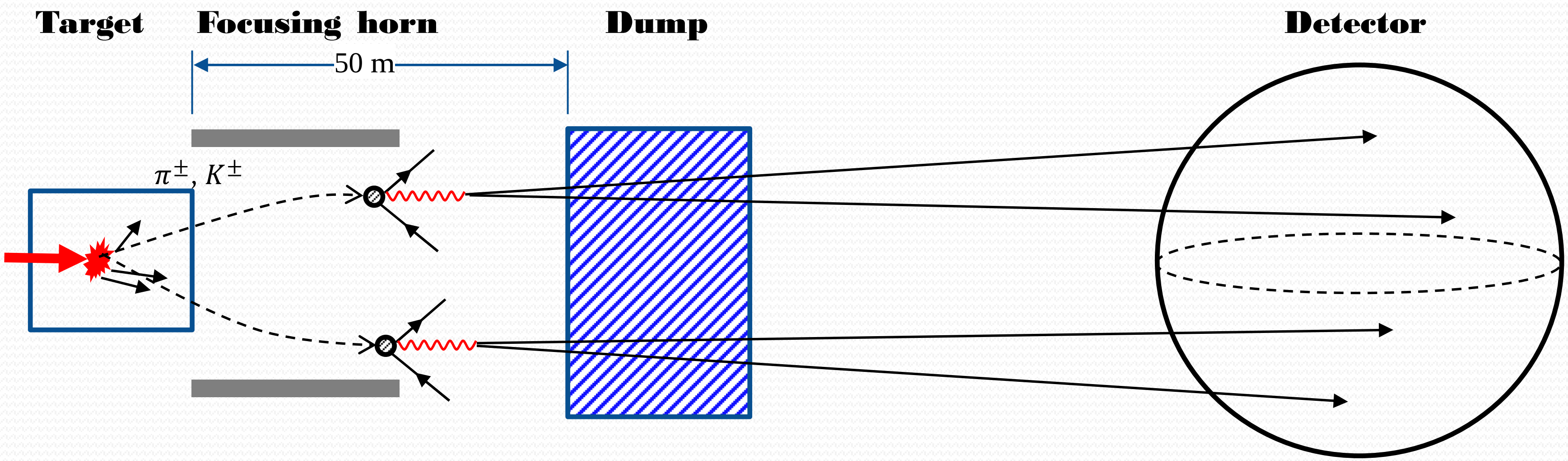
Necessary Components of Tau Neutrino Appearance



- Tau neutrinos entering the detector fiducial volume should be energetic enough to upscatter to tau leptons. ⇒ High energy beams are preferred.
- Focusing of energetic charged mesons should be described as precisely as possible.
- It is desirable to have a horn configuration that preferentially focuses the energetic charged meson on the detector (cf. tau-neutrino-optimized mode of DUNE).

Beam-Focusing at Low-Energy Beam Experiments

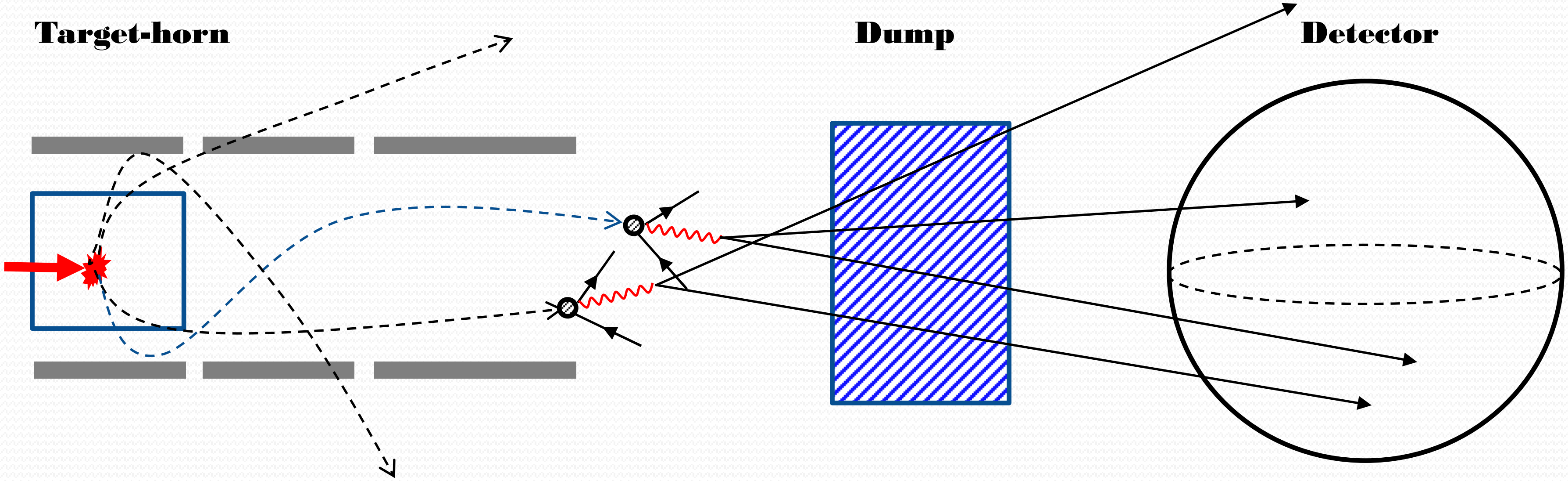
Example: BNB beam



- Charged mesons are assumed to be focused and aligned to the beam axis if they satisfy $\theta \in (30, 210)$ mrad and $E > 0.85$ GeV [Schmitz, PhD Thesis] (See also Adrian Thompson's talk).
- Beam energy is small, hence behaviors of produced charged mesons are relatively less diversified.

Beam-Focusing at High-Energy Beam Experiments

Example: DUNE beam



- Beam energy is large, hence behaviors of produced charged mesons and responses to the focusing horn (e.g., decay position, direction) are rather diversified.
- A single empirical model may not describe the focusing-horn effects reasonably well. ⇒ FastSim package development and/or publicly available information of detector-level simulation needed!

Devising/Validating Simulation Scheme

$$\frac{d\Phi_\nu^{DUNE}}{dE_\nu} \approx \sum_i c_i \frac{d\Phi_\nu^i}{dE_\nu}$$

Neutrino (e.g., ν_μ) flux at ND [DUNE TDR Vol. II]

Fit to find coefficient c_i

Combination of ν fluxes predicted with different focusing schemes

(1) Standard mode

$$\frac{d\Phi_\nu^{\rm DUNE}}{dE_\nu} \approx 3\frac{d\Phi_\nu^1}{dE_\nu} + 0.2\frac{d\Phi_\nu^2}{dE_\nu}$$

with

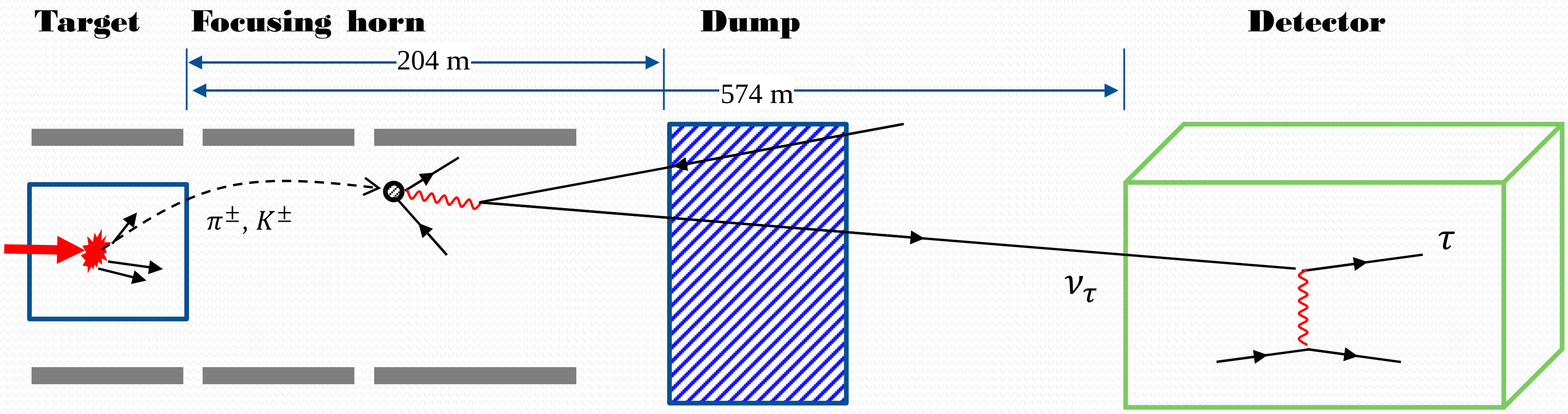
$$\Phi_\nu^1 \;:\; E_{\pi/K} < 10 \text{ GeV}, \;\theta_{\pi/K} \in [0.01, 1] \text{ rad},$$
$$\Phi_\nu^2 \;:\; E_{\pi/K} < 120 \text{ GeV}, \;\theta_{\pi/K} \in [0.01, 1] \text{ rad}.$$

(2) ν_τ-optimized mode [DUNE TDR Vol. II]

$$\frac{d\Phi_\nu^{DUNE}}{dE_\nu} \approx 1.5\frac{d\Phi_\nu}{dE_\nu}$$

with $\Phi_\nu: E_{\pi/K} \in [5, 120]$ GeV, $\theta_{\pi/K} \in [0.01, 1]$ rad

Flow of Simulation



- GEANT-described meson production
- Cf. Production of proton bremsstrahlung [Foroughi-Abari, Ritz, 2108.05900] is included, when needed.

- Focused and aligned to the beam axis as per prescriptions in the previous slide
- Meson decay probability (within 204 m) according to the decay law
- Three-body decay of mesons described by MadGraph

- ν_τ upscattering in the detector fiducial volume via C.C. processes [Jeong, Reno, 1007.1966]
- Ideal detection efficiency is assumed to find the maximal potential.

Example Scenarios

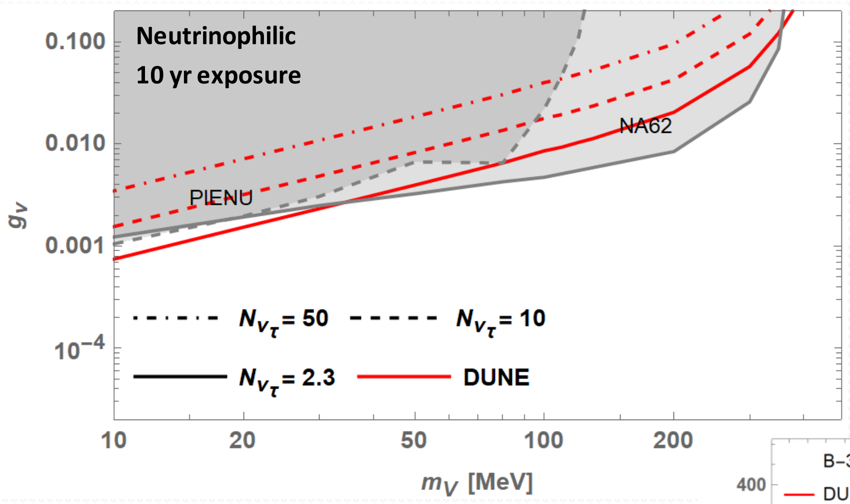
$$\mathcal{L}_{\text{int}} \supset \sum_f g_V x_f V_\mu \bar{f} \gamma^\mu f$$

g_V: coupling of vector boson V, x_f: $U(1)_V$ charge of SM fermion f

V could be dark photon, pure neutrinophilic, $B-L$, $B-3L_\tau$, $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$, …

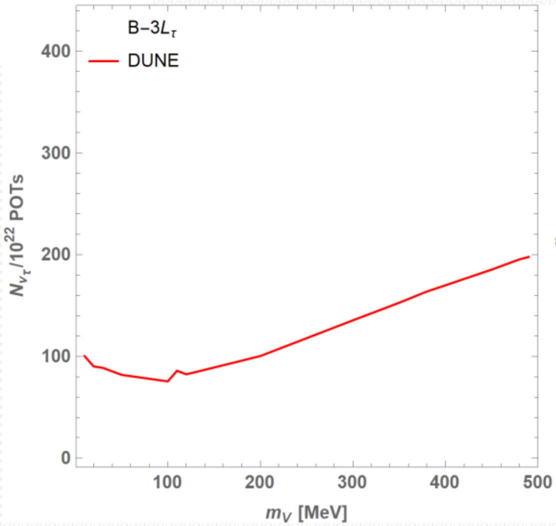
Example cases for illustration

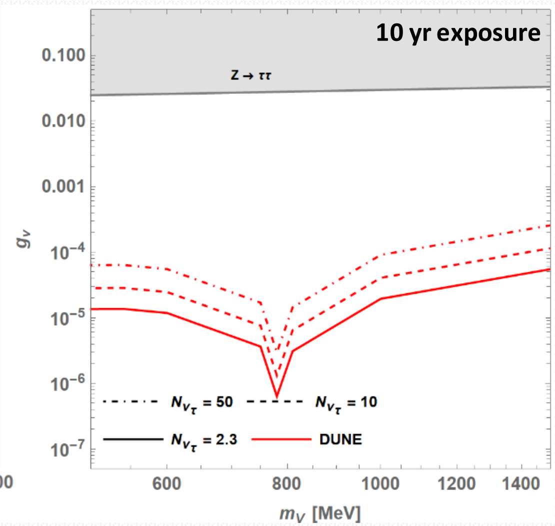
Results: Standard Mode



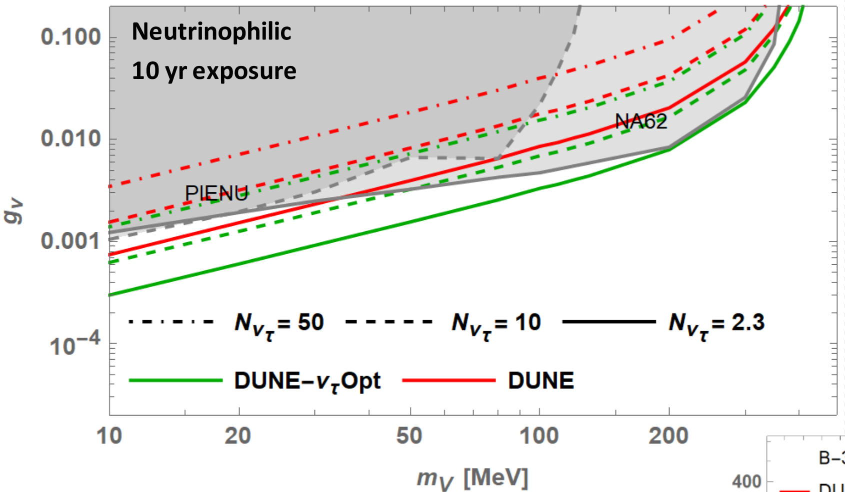
- Stringent limits are from recent measurements of exotic three-body charged pion [PIENU Collaboration, arXiv:2101.07381] and kaon [NA62 Collaboration, arXiv:2101.12304] decays.

- Below ~500 MeV, the production from charged mesons are maximized up to the allowed BRs, and above 500 MeV, proton bremsstrahlung is the main channel.



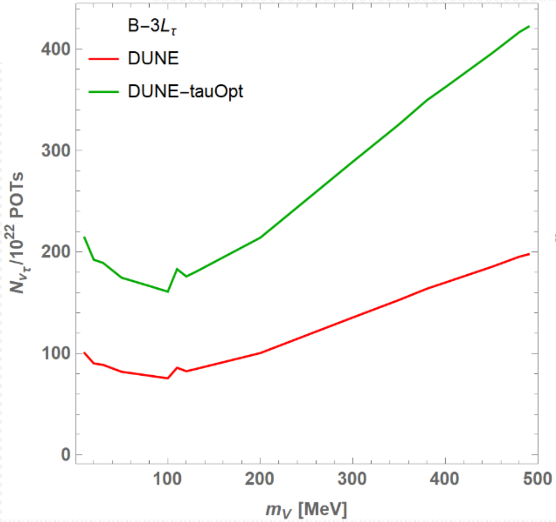


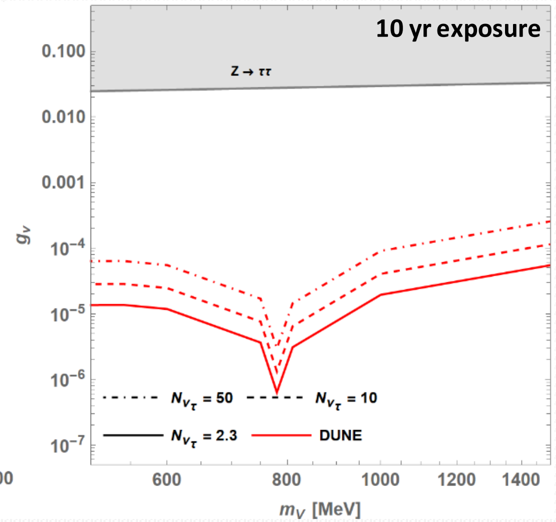
Result: Tau-Neutrino-Optimized Mode



- Tau neutrino-optimized mode allows us to explore a wider range of parameter space over the entire mass range.

- Production via proton bremsstrahlung is irrelevant to standard vs ν_τ-optimized mode measurements .

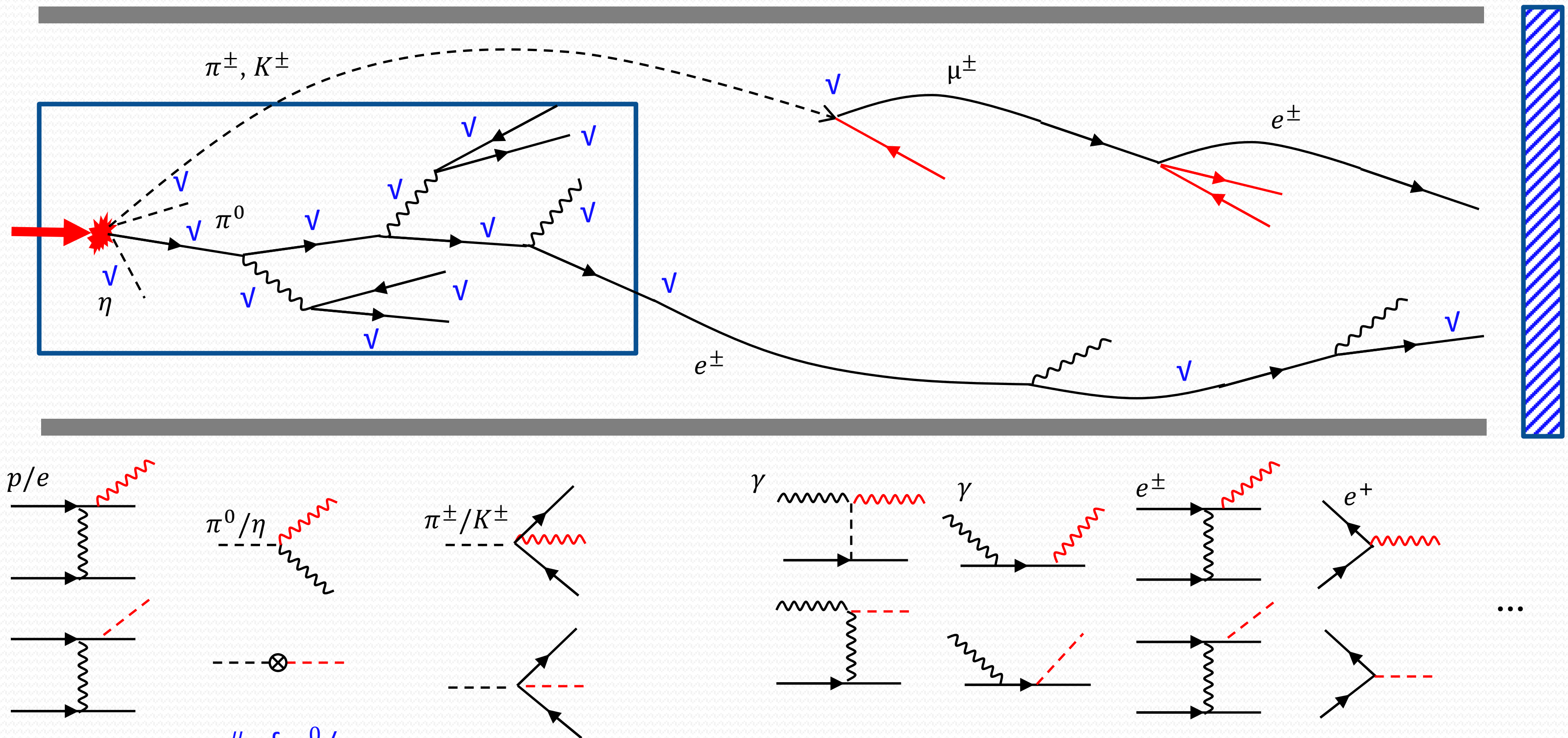




Conclusions

- Anomalous **appearance of tau neutrinos** at the near detectors of beam-focused neutrino experiments can be a **"smoking-gun" signature of new physics**.
- Dark-sector scenarios involving charged mesons are plausible scenarios to give tau neutrino signals due to
  - ✓ **Focused flux** of charged mesons → dark-sector mediators → tau neutrinos
  - ✓ **Enhanced BRs of three-body** meson decays
- Dedicated studies of **signal production in the target-horn system** and **tau identification at the detectors** will allow us to estimate tau-neutrino signals more precisely.

Wish List



p^μ of π^0/η

p^μ, $\vec{x}$ of $\pi^\pm/K^\pm$ at decay point

p^μ, step length of every single γ

p^μ, step length of Every single $e^\pm$

Back-up

Pion Dark Radiative Decay

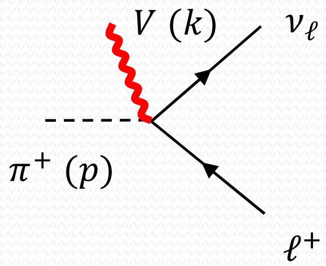
$$\mathcal{M} = ig_\pi \varepsilon^\mu \left[\bar{u}_\ell \gamma_\rho (1-\gamma_5) \nu_\nu\right] \left[\int d^4x e^{iqx} \langle 0 | T\{j_\mu(x) \bar{d}\Gamma^\rho u(0)\} | \pi^+ \rangle\right]$$

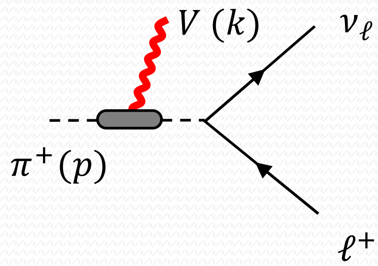
$$j_\mu = \bar{q}\gamma_\mu q$$

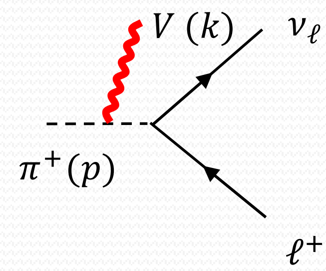
The hadronic part of the matrix element can be decomposed into a generic gauge-invariant form:

$$T_{\mu\rho} = \alpha g_{\mu\rho}(p-k)\cdot k + \beta (p-k)_\mu k_\rho + i[g_{\mu\rho}(p-k)\cdot k - (p-k)_\mu k_\rho] F_A + \epsilon_{\rho\mu\lambda\sigma} p^\lambda k^\sigma F_V + \frac{i(2p-k)_\mu (p-k)_\rho}{2p\cdot k - m_X^2} f_\pi$$

Contact interaction | Structure-dependent contributions | IB2







If we wish to satisfy the Ward Identity for our dark current, we require $\alpha + \beta = \dfrac{if_\pi}{(p-k)\cdot k}$.

We can choose a family of (unknown) solutions for α and β.

See also more detailed discussions in [Khodjamirian, Weiler, arXiv:hep-ph/0111249].