Constraining Neutrinophilic Mediators at Forward Physics Facilities

Jiajun Liao

Sun Yat-Sen University

In collaboration with Weidong Bai and Hongkai Liu
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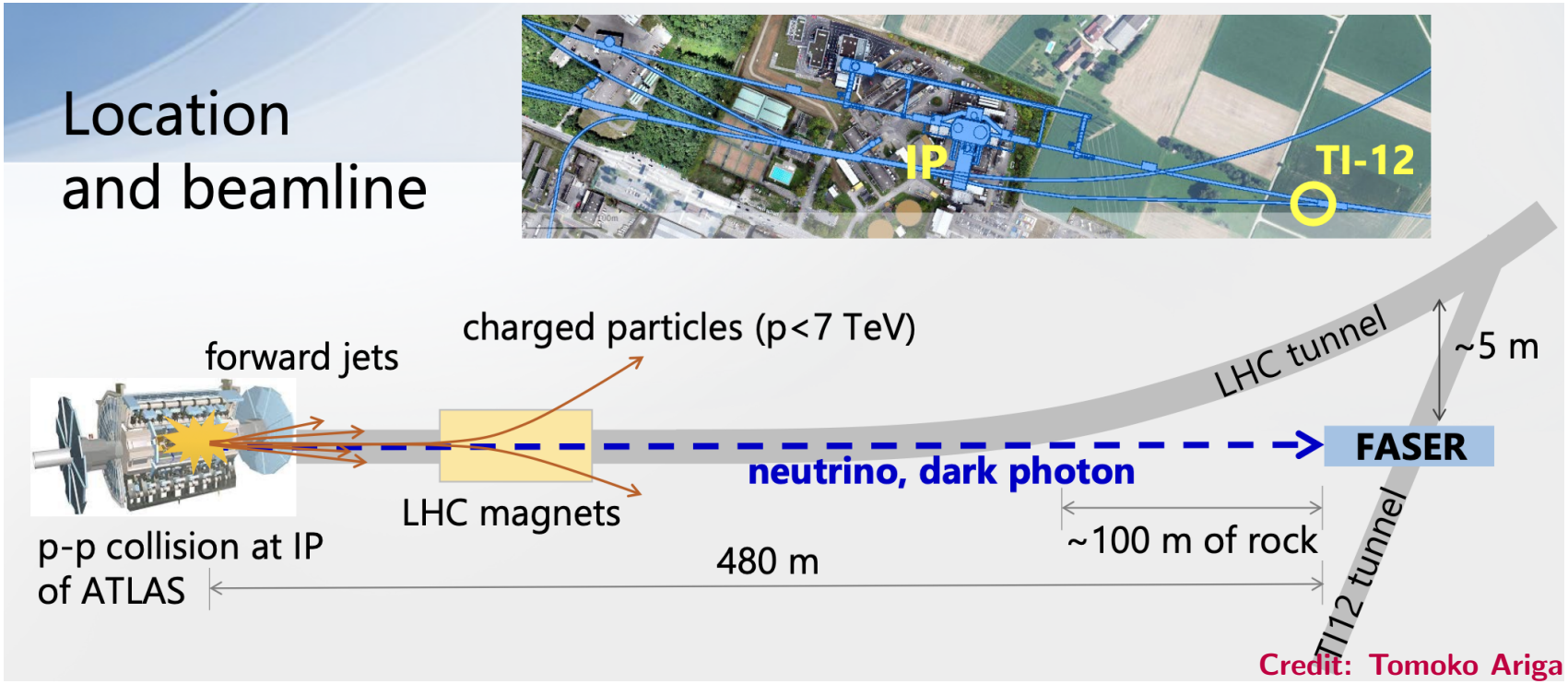
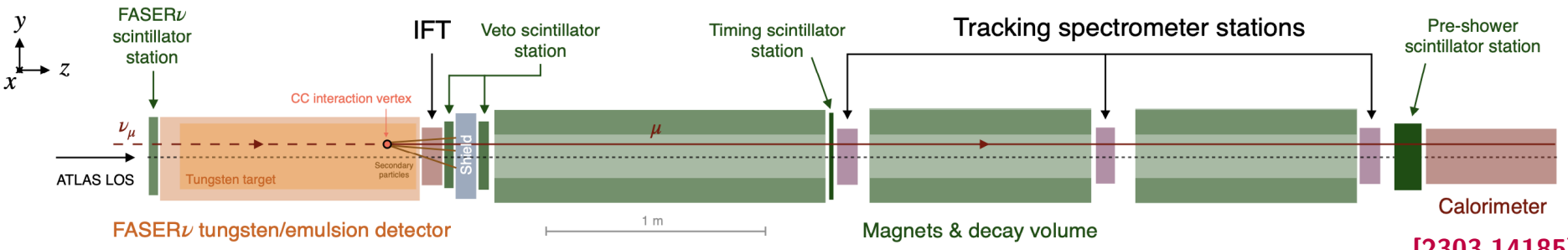
FASER at LHC

The Forward Search ExpeRiment (FASER) is designed to study new light and weakly coupled particles and high energy collider neutrinos produced in the forward region of the pp collision at the LHC.

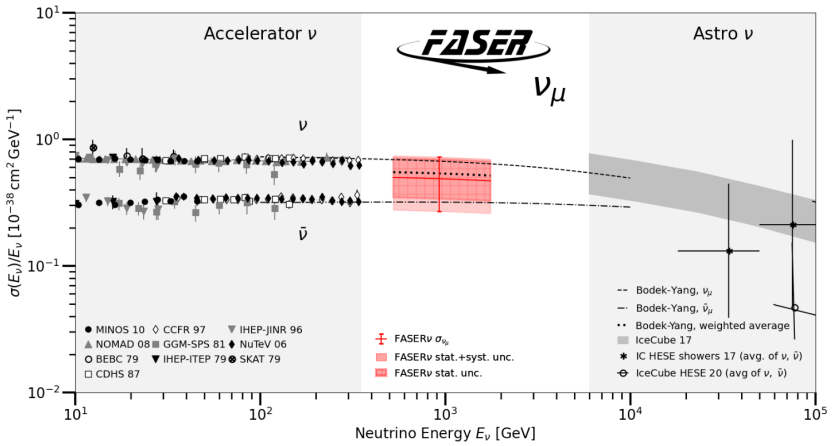


First observation of collider neutrinos

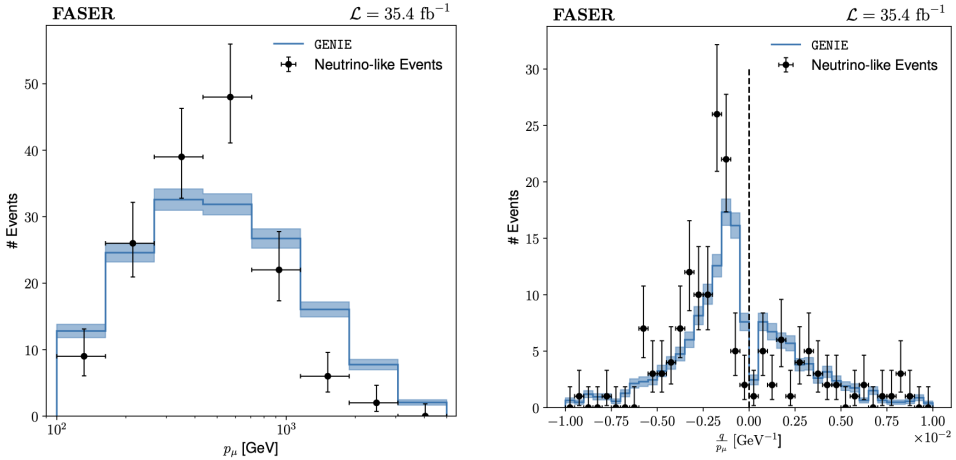
FASERν experiment has made the first observation of collider neutrinos using the active electronic components of the FASER spectrometer.



[2303.14185]



FASER w/ emulsion detector [2403.12520]



FASER w/electronic detector [2303.14185]

Neutrinophilic mediators

- Neutrino self-interactions (νSI) have been proposed as a means of easing the disagreement between late-and early time cosmological measurements (the Hubble and S_8 tensions).

Kreisch, Cyr-Racine, Dore [1902.00534]

Blinov, Kelly, Krnjaic, McDermott [1905.02727]

- To avoid strong constraints from interactions with charged SM fermions, it is often to make mediator neutrinophilic. We focus on the case with a scalar mediator:

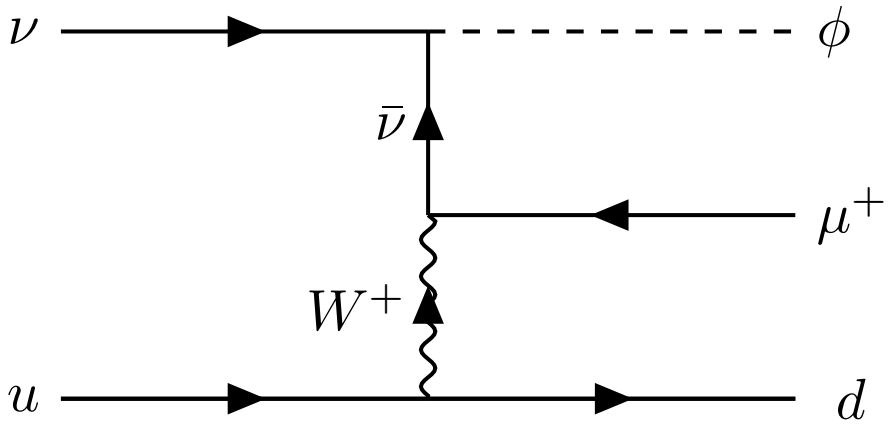
$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\overline{\nu_\alpha^c}\nu_\beta\phi + h.c.\,,$$

or a vector mediator:

$$\mathcal{L} \supset g_{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta Z'_\mu\,,$$

Snowmass White Paper [2203.01955]

Signatures of a scalar mediator at FASERν



The presence of a neutrinophilic mediator will lead to an initial state radiation when neutrinos scatter off nucleus in the detector via the CC process. The radiation of scalar ϕ from neutrino bremsstrahlung will

- modify the energy spectrum due to the missing energies in the event reconstruction.
- produce a wrong sign for the final leptons.

Cross sections of scalar mediators

- To calculate the cross section of the 2-to-3 process $\nu u \to \phi d \mu^+$, we factorize the full process into a neutrino splitting process $\nu(p) \to \bar{\nu}(k)\phi(q)$ and a neutrino scattering process $\bar{\nu} u \to d\mu^+$.

- In the limit $p_T, m_\phi \ll E_\nu$, the cross section can be evaluated as

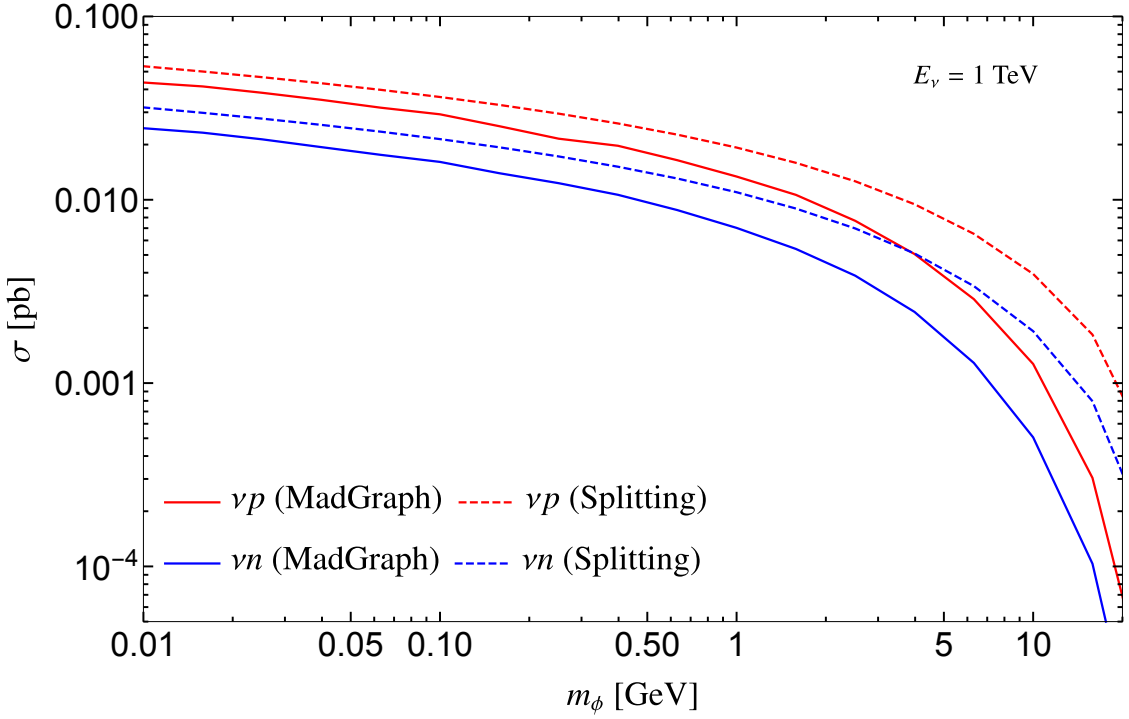
$$\sigma_{\nu u \to \phi d \mu^+} \simeq \int dz dp_T^2 \frac{1}{16\pi^2 z} |M_{\nu \to \bar{\nu}\phi}|^2 \left[\frac{1}{(p-q)^2}\right]^2 (1-z)\sigma_{\bar{\nu} u \to d\mu^+}(\hat{s})$$

with $|M_{\nu \to \bar{\nu}\phi}|^2 = \lambda^2 \frac{p_T^2}{1-z}$, and $\sigma_{\bar{\nu} u \to d\mu^+} = G_F^2 \hat{s}/(3\pi)$. The differential cross section of the 2-to-3 process to the transverse momentum p_T becomes [1]

$$\frac{d\sigma_{\nu u \to \phi d \mu^+}}{dp_T} \simeq \frac{G_F^2 s}{3\pi} \frac{\lambda^2 p_T^3}{8\pi^2 m_\phi^4} \left[\left(1 + \frac{2p_T^2}{m_\phi^2}\right) \log\left(1 + \frac{m_\phi^2}{p_T^2}\right) - 2\right]$$

[1] Our result differs by a factor of 9 compared to Eq. (6) in 2111.05868.

Comparison with the MadGraph simulation



The total cross section of neutrino bremsstrahlung at the hadron level is

$$\sigma_{\nu N \to \phi \mu^+ X} = \sigma_{\nu u \to \phi d \mu^+} \langle x u_N \rangle + \sigma_{\nu \bar{d} \to \phi \bar{u} \mu^+} \langle x \bar{d}_N \rangle,$$

where $\langle x q_N \rangle \equiv \int_0^1 x q_N(x) dx$ and $\langle x \bar{q}_N \rangle \equiv \int_0^1 x \bar{q}_N(x) dx$ denote the fraction of nucleon momentum carried by quark u and antiquark $\bar{d}$.

Cross sections of vector mediators

- The differential cross section for the vector boson Z' radiation is

$$\frac{d\sigma_{\nu_\mu d \to Z' u \mu^-}}{dz dp_T^2} = \frac{G_F^2 s}{\pi} g'^2 \frac{(1-z)}{32\pi^2 z} \frac{p_T^4/m_{Z'}^2 + m_{Z'}^2(1-z)^2 + 2p_T^2(1-z+z^2)}{[p_T^2 + m_{Z'}^2(1-z)]^2}$$

  For the Z' case, there is an infrared divergence for $z \to 0$.

  Chen, Han, Tweedie, [1611.00788]

- The cross section of the pseudoscalar (axial vector) case is similar to the scalar (vector) case. This is because in the massless limit of SM neutrinos ν_L, we have

$$\bar{u}_\nu \Gamma u_\nu + \bar{u}_\nu \Gamma \gamma^5 u_\nu = \bar{u}_\nu \Gamma (1+\gamma^5) u_\nu = 0\,,$$

  which does not depend on the Lorentz structure of Γ.

  Y.-S. Tsai, Phys. Rev. D 34, 1326 (1986)

Analysis of the FASERν data

The number of events per unit neutrino energy per unit muon energy can be calculated by

$$\frac{dN}{dE_\nu dE_\mu} \approx \frac{1}{m_A}\left(\frac{d\mathcal{N}}{dE_\nu}\right)_0 \left(\frac{1}{S_0}\int dS' dX' \frac{d\sigma_{\nu A}}{dE_\mu} e^{-X'/\lambda_\nu}\right)$$

- We use MadGraph to simulate the neutrino-nucleon interactions, the 4-momentum of final state leptons and quarks for the SM and NP cases.
- The neutrino energy spectra for the FASERν 2023 is

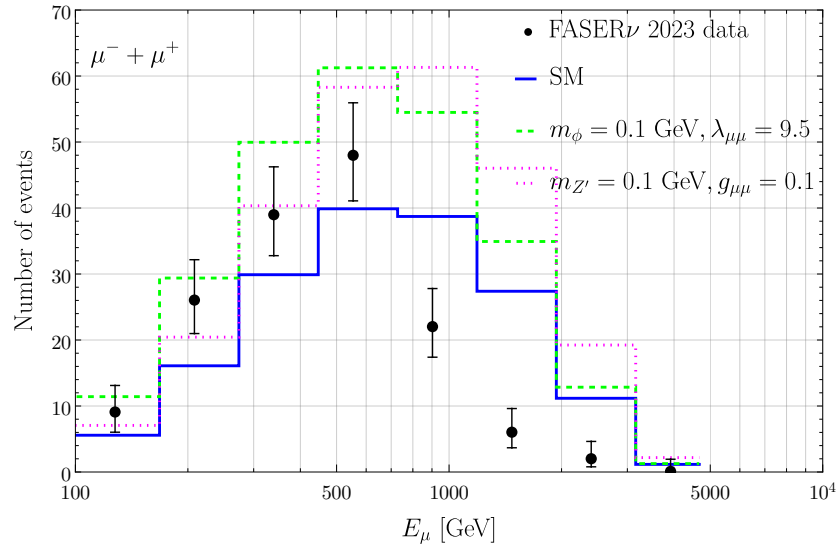
$$\left(\frac{d\mathcal{N}}{dE_\nu}\right)_0 \approx \left(\frac{d\mathcal{N}}{dE_\nu}\right)\frac{S_0}{S}\frac{\mathcal{L}_{\rm int0}}{\mathcal{L}_{\rm int}},$$

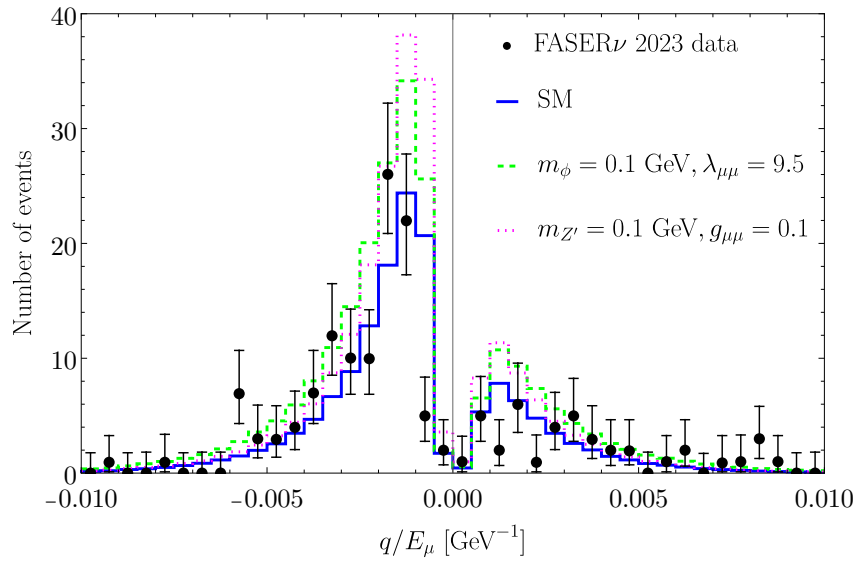
where $d\mathcal{N}/dE_\nu$, S and $\mathcal{L}_{\rm int}$ are taken from the previous FASERν simulation in 2105.08270.

Comparison of the measured FASERν 2023 data

Apply event selection criteria in [2303.14185] for reconstructed track:

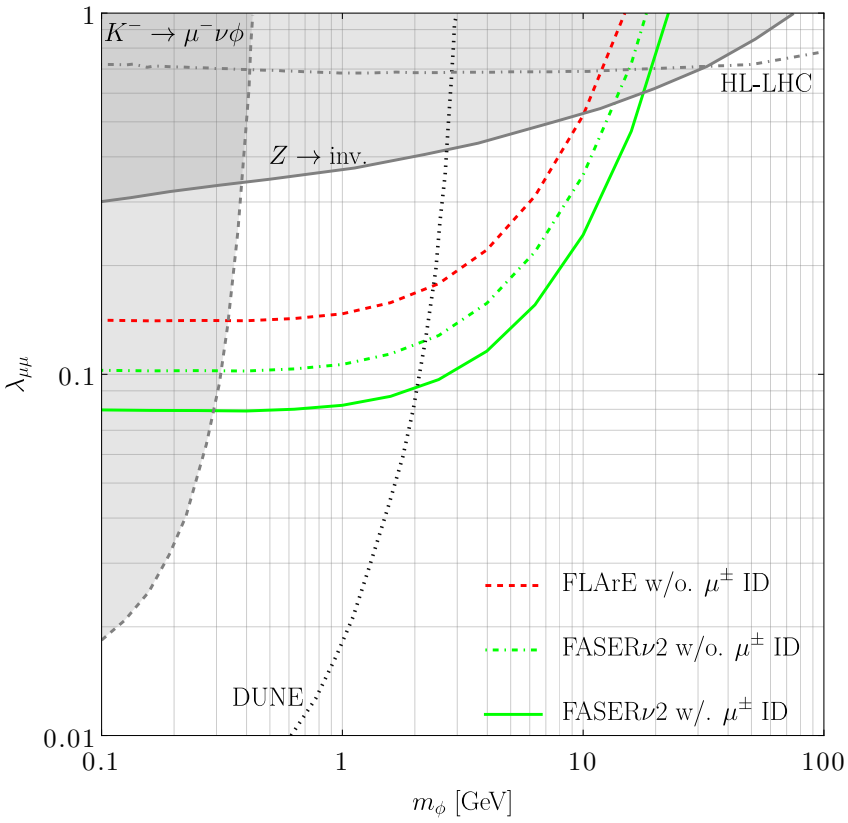
- The polar angle θ is required to satisfy $\theta < 25$ mrad;
- extrapolation to the FASERν scintillator must be at a distance of $r_{\text{veto}\nu} < 120$ mm from the FASERν scintillator center;
- extrapolation to the interface tracking station must lie within 95 mm of detector's central axis;
- must traverses the three tracking spectrometer stations with an diameter of 200 mm.

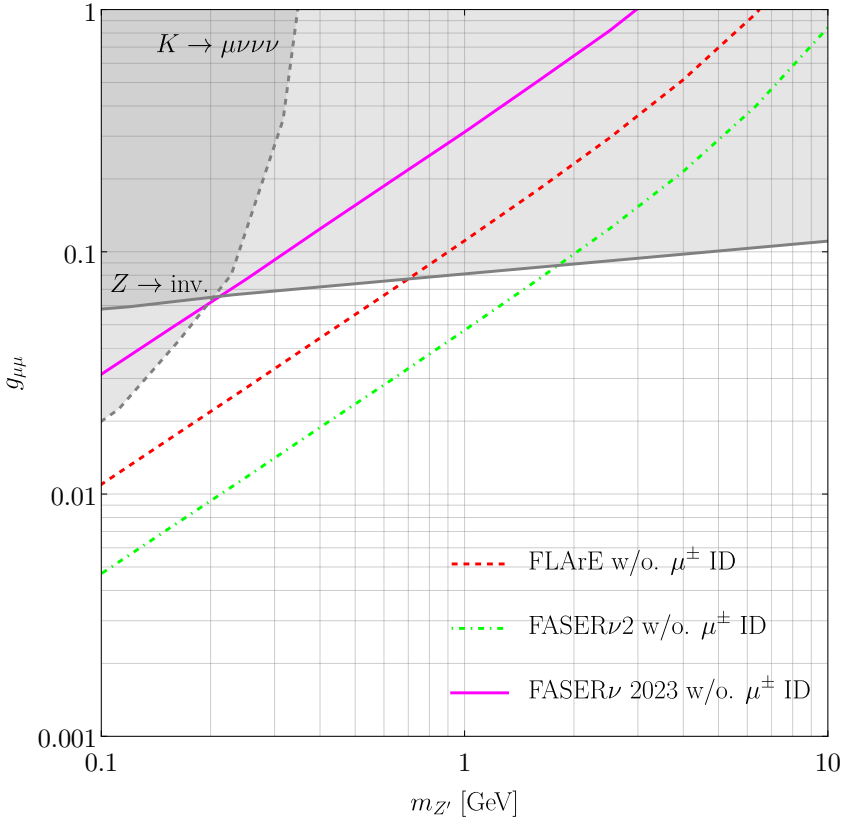




Constraints on neutrinophilic mediators

Detector	Mass [tonne]	S [cm^2]	$\mathcal{L}_{\rm int}$ [fb^{-1}]
FASERν 2021 simulation	1.2	25×25	150
FASERν 2023 data	1.1	25×30	35.4
FLArE	10	100×100	3000
FASERν2	20	40×40	3000





Summary

- The first observation of collider neutrinos by FASERν opens a new window into high energy neutrino interactions.
- The data can be used to probe neutrinophilic mediator. Constraints on a pseudoscalar (axial vector) mediator are close to the scalar (vector) mediator due to similar cross sections.
- Bounds on the scalar mediator from the current FASERν data are weaker than the existing limits. Constraints on the vector mediator from the current data are comparable to the existing limits at $m_{Z'} \approx 0.2$ GeV.
- Future FLArE and FASERν2 can impose much stronger bounds on both the scalar and vector mediators than existing bounds at GeV-scale masses.
- Constraints on the scalar mediator can reach 0.08 (0.1) for $m_\phi \lesssim 1$ GeV with (w/o) muon charge identification at FASERν2.

Thanks for your attention