Constraining neutrinophilic interactions at FASER(ν) experiments

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Neutrino Scattering: Theory, Experiment, Phenomenology (νSTEP 2024)

Neutrinophilic mediators

We study the sensitivities of high-energy ν scattering experiments (Faser(ν), Faser(ν)2, FLArE) to neutrinophiclic mediators (predominantly coupled to neutrinos) of the form

$$\mathscr{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi + h.c.,$$

or

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

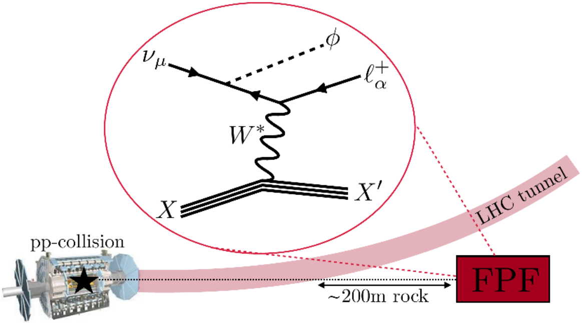
with $m_{\phi,Z'} \sim$GeV.

- Theoretical motivation: SM extensions related to the generation of the light neutrino mass and the production of dark matter;
- These interactions can be significantly larger than those provided by SM and have impact on cosmological, astrophysical, and laboratory observables.

Signal process of interest

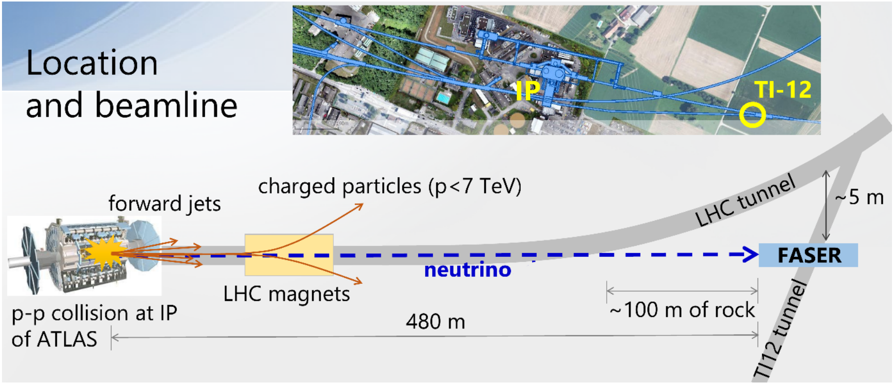
Laboratory processes:

- produced along with neutrinos;
- or through neutrino beamstrahlung happening along with a CC interaction inside a neutrino detector:
  - missing transverse momentum
  - charged lepton with wrong sign for ϕ



(arXiv:2111.0586)

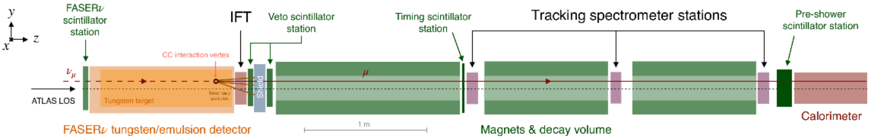
Far-forward neutrinos at LHC



(slide from Tomoko Ariga)

The energy is high, the flux is large in the forward region.

First direct observation of $\nu_\mu(\bar{\nu}_\mu)$ interactions with FASER at the LHC



Using FASER electronic detectors (with charge identification):

$$n_\nu = 153^{+12}_{-13} \text{ of } \nu_\mu + \bar{\nu}_\mu$$

at 13.6 TeV. (arXiv:2303.14185).

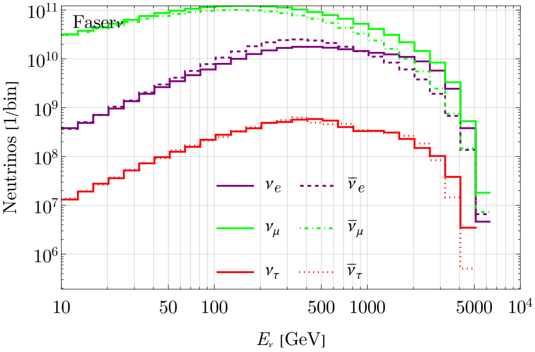
Neutrino CC event numbers

$$dN = \frac{1}{m_A} \frac{d\sigma_{\nu A}}{d^3 p} \left(\int_t \int_S \phi_\nu(E_\nu, 0) dS^{'} dt^{'} \right) e^{-X'/\lambda_\nu} dX^{'} dE_\nu d^3 p,$$

with

- $\sigma_{\nu A}(E_\nu) = Z\sigma_{\nu p}(E_\nu) + (A - Z)\sigma_{\nu n}(E_\nu)$;
- flux $\phi_\nu(E_\nu, 0)$ taken from FastNeutrinoFluxSimulation (arXiv:2105.08270);
- differential cross section $d\sigma_{\nu A}/d^3 p$ from MadGraph.

Neutrino flux



(arXiv:2105.08270)

- Muon neutrinos (ν_μ and $\bar{\nu}_\mu$) are mostly produced: consider $\lambda_{\mu\mu}$ or $g_{\mu\mu}$ at first;
- Neutrino energies are high (10′s to 10^3 GeV): DIS, cross section computed at parton level.

Neutrino interaction cross section

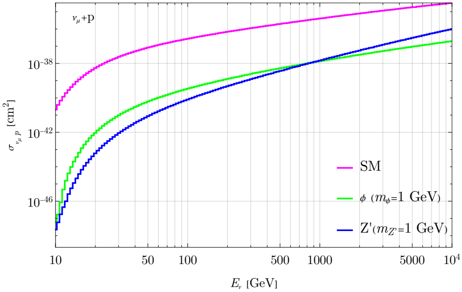
The presence of ϕ or $Z^{'}$ modifies the cross section of SM CC process, e.g.,

$$\frac{d\sigma_{\nu_\mu u\to\phi d\mu^+}}{dp_{T\phi}} = \frac{3\lambda^2 G_F^2 s p_{T\phi}^3}{8\pi^3 m_\phi^4}\left[\left(1+\frac{2p_{T\phi}^2}{m_\phi^2}\right)\log\left(1+\frac{m_\phi^2}{p_{T\phi}^2}\right)-2\right],$$

$$\frac{d\sigma_{\nu_\mu d\to Z' u\mu^-}}{dp_{TZ'}} = \frac{3g'^2 G_F^2 s^3 p_{TZ'}}{\pi^3 m_{Z'}^6}\left[\frac{1}{20}+\frac{3p_{TZ'}^4}{m_{Z'}^4}\log\left(1+\frac{m_{Z'}^2}{p_{TZ'}^2}\right)\right].$$

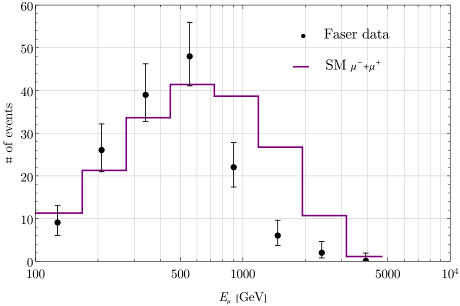
Cross sections with ϕ or $Z^{'}$,

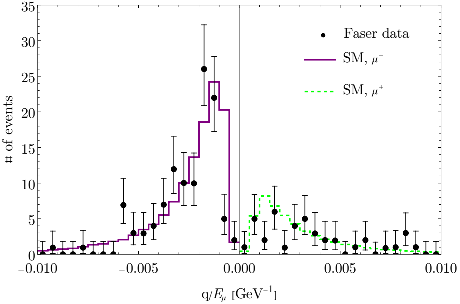
- decrease with mediator mass, constraints will be weak as mass increases;
- $\sim 10^3$ times lower than those of SM, constraints will be weak unless statistics is large enough.



Comparison to Faser data

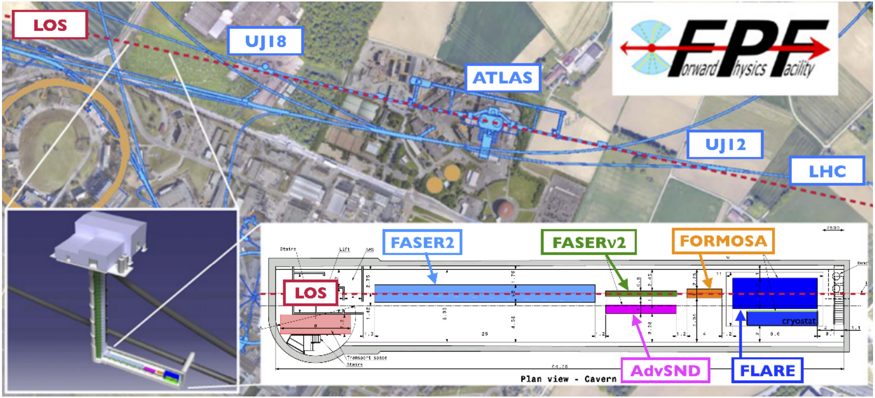
- Generate 4-momentum of final state particles (ϕ, μ, quark) using MadGraph;
- Event selection:
  - Muons traversing the entire length of the FASER detector;
  - Track in fiducial tracking volume with $r < 95$ mm;
  - Track extrapolation with $r < 120$ mm in front veto scintillator;
  - Track polar angle $\theta < 25$ mrad;





- Constraints on ϕ: $\lambda_{\mu\mu} = 12.1 @ m_\phi = 1$ GeV.

Faserν2 and FLArE at Forward Physics Facility



(arxiv:2203.05090)

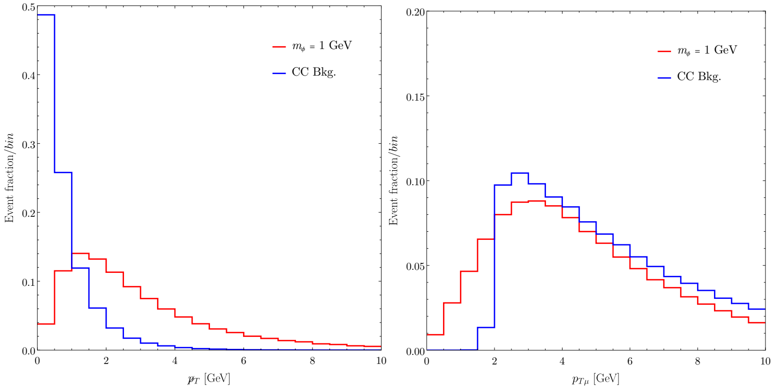
Faserν2 and FLArE Simulation

Detector			
Name	Mass	Coverage	Luminosity
FASERν	1.1 ton	$\eta \gtrsim 8.5$	34.5$\rightarrow$150 fb^{-1}
FASERν2	20 ton	$\eta \gtrsim 8.5$	3 ab^{-1}
FLArE	10 ton	$\eta \gtrsim 7.5$	

Faserν2 and FLArE Simulation

- Flux $\phi_\nu(E_\nu, 0)$ taken from FastNeutrinoFluxSimulation, as before;
- Generate 4-momentum of final state particles (ϕ, μ, quark) using MadGraph;
- Smear final state momenta to approximate the effects of a finite detector resolution:
  - muon energy resolution: 5%;
  - final state quark energy resolution: 15%;
- kinematic observables for signal-background comparison:
  - $p_{T\mu}$: transverse momentum of muon;
  - $\not{p}_T$: missing transverse momentum, $\not{p}_T = p_{T\phi} = |\vec{p}_{T\mu} + \vec{p}_{Tq}|$.

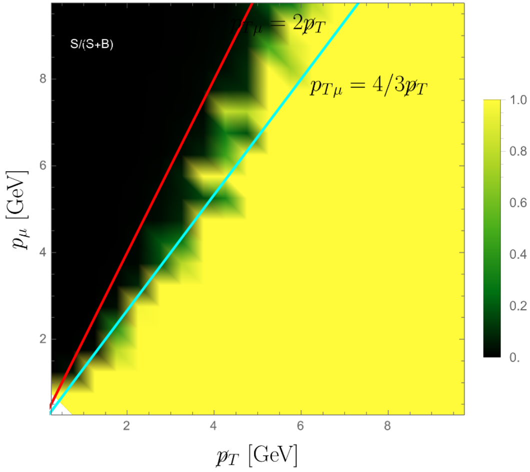
Signal-background comparison: 1D distribution and cuts



- Signal is more pronounced for large $\not{p}_T$, but small $p_{T\mu}$;
- Cut could be applied on these distributions, but results are not significant.

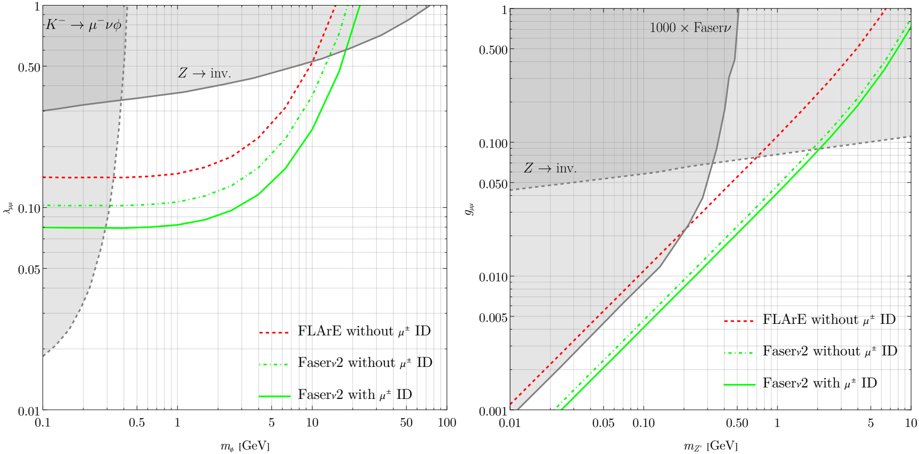
Signal-background comparison: 2D distribution and cuts

- Plot of
$$\frac{S}{S+B}$$
with S the signal and B background;
- With cut $p_{T\mu} \lesssim 4\not{p}_T/3$ applied, constraints improve significantly.



Constraints on NP parameters

Preliminary results:



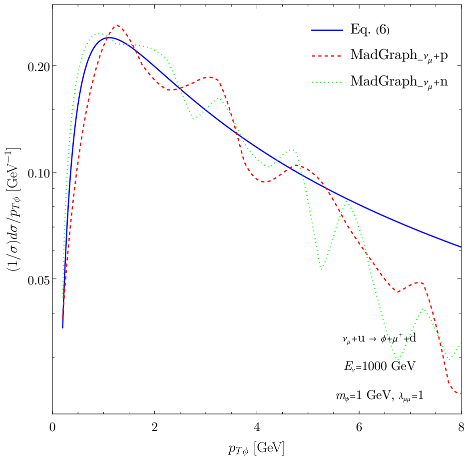
Summary

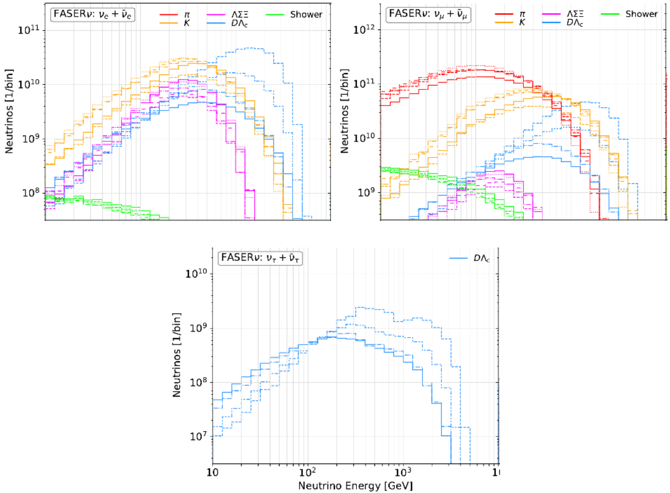
- Present Faser data put very weak constraints on ϕ: $\lambda_{\mu\mu} = 12.1@m_\phi = 1$ GeV, more data is needed;
- Appropriate cuts and charge identification is helpful in improving the constraints;
- Faser(ν)2 may be able to improve the constraints at around $m_{\phi,Z'} = 1$ GeV.

Thanks

Backup slides

Consistency of MadGraph results and analytical formula




FASERν: $\nu_e + \bar{\nu}_e$
π
K
$\Lambda\Sigma\Xi$
$D\Lambda_c$
Shower
Neutrinos [1/bin]
FASERν: $\nu_\mu + \bar{\nu}_\mu$
FASERν: $\nu_\tau + \bar{\nu}_\tau$
Neutrino Energy [GeV]