Collider Neutrinos:
Opportunities and Perspectives.

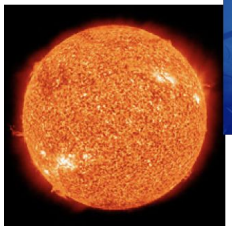
Felix Kling (DESY)
Neutrinos at CERN
24.01.2025

Motivation.

We have detected neutrinos a variety of source across a large energy range.

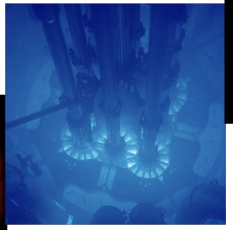
Each detection led to profound insights across the fields of particle physics, nuclear physics, and astrophysics.

Solar



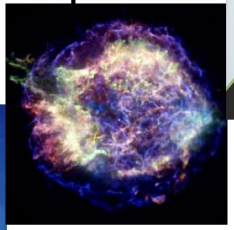
~MeV

Reactor



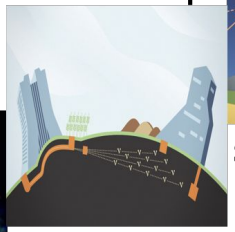
~MeV

Supernova



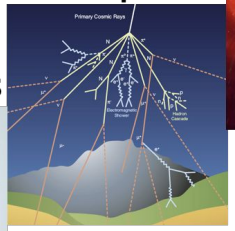
~MeV

Beam Dumps



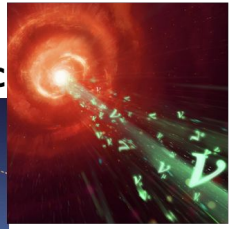
GeV-subTeV

Atmospheric



subGeV-PeV

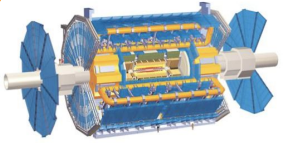
Cosmic



TeV-EeV

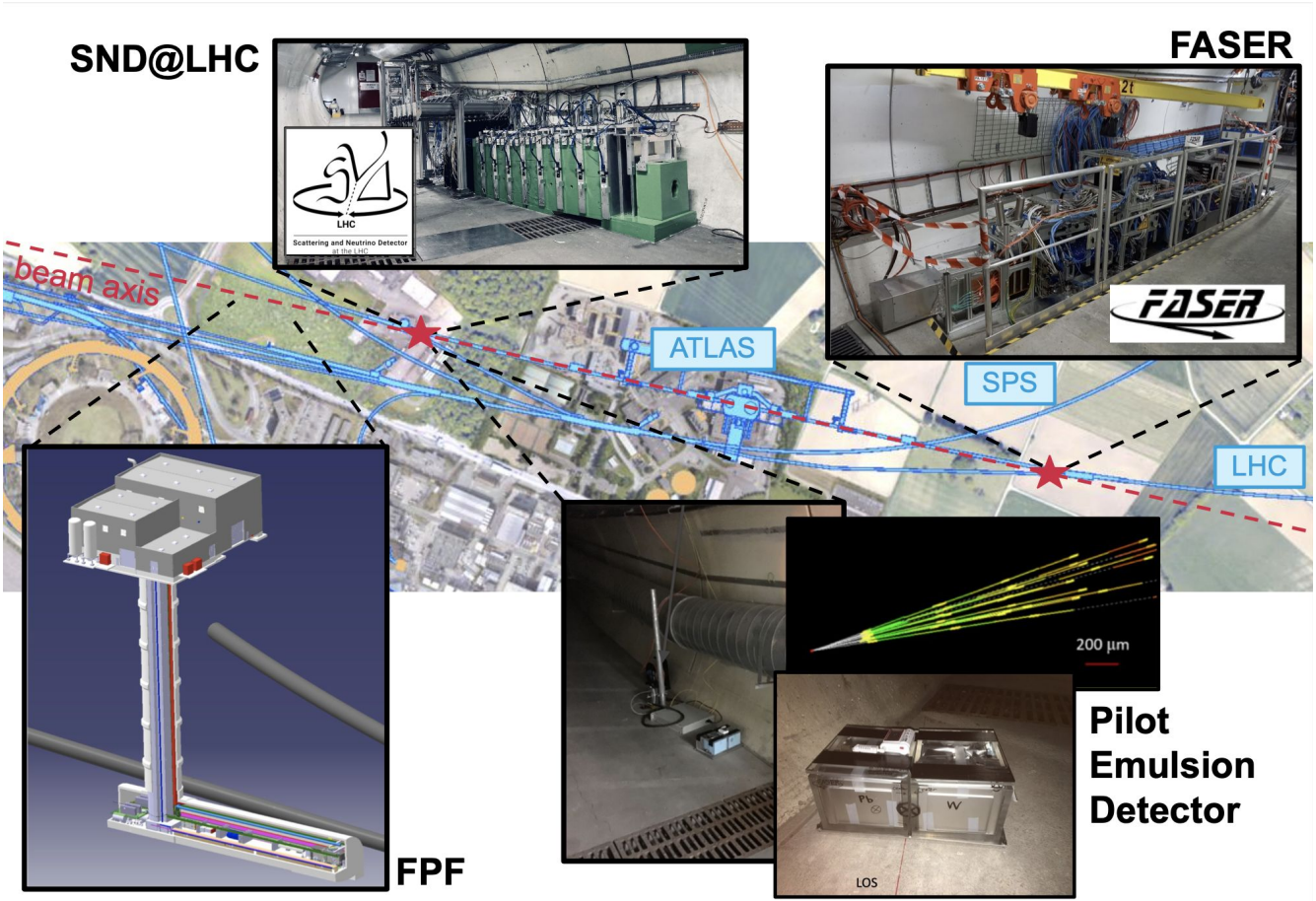
Only recently we observed the first neutrinos from a new source: particle colliders.

Collider

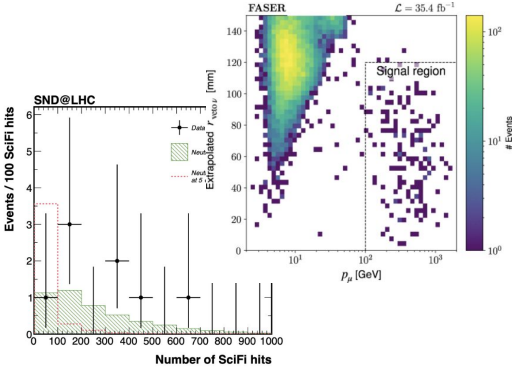


100GeV-multiTeV

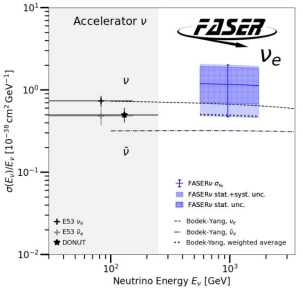
Collider Neutrino Experiments.

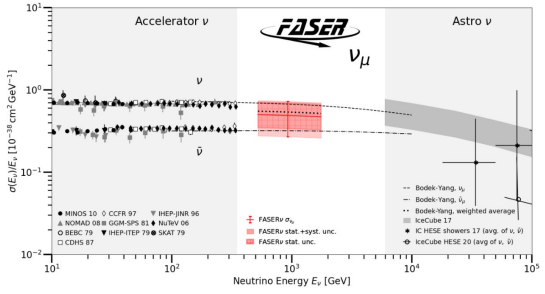


First Experimental Results.

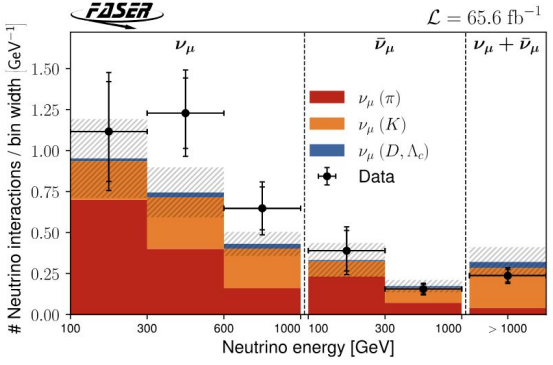


First observation of collider neutrinos:
153 events (FASER) + 8 events (SND@LHC)
[FASER, 2303.14185] [SND@LHC, 2305.09383]



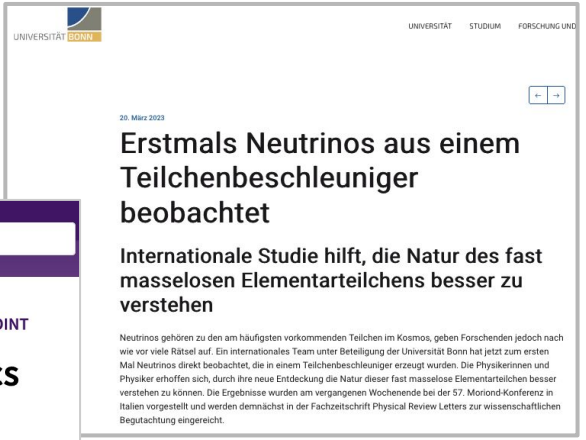


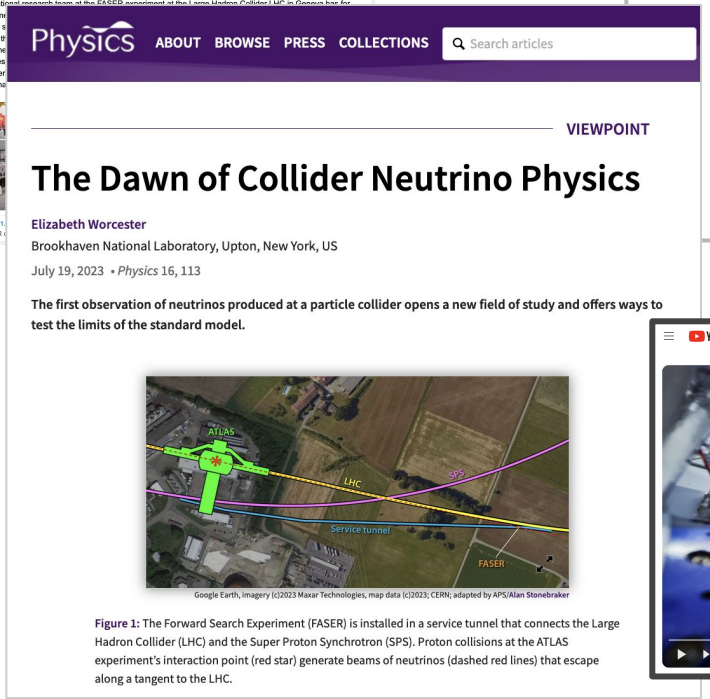
first cross sections measurement
[FASER, 2403.12520]

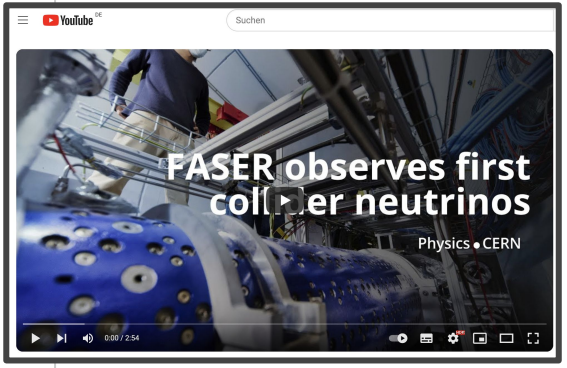


first flux measurement
[FASER, 2412.03186]

The Dawn of Collider Neutrino Physics.

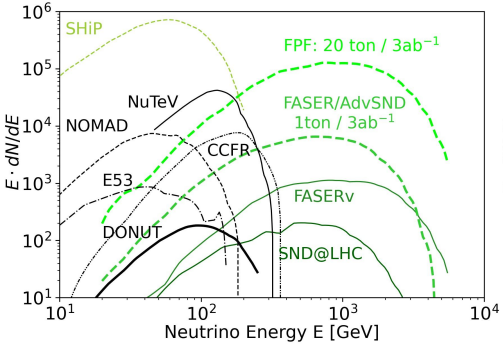


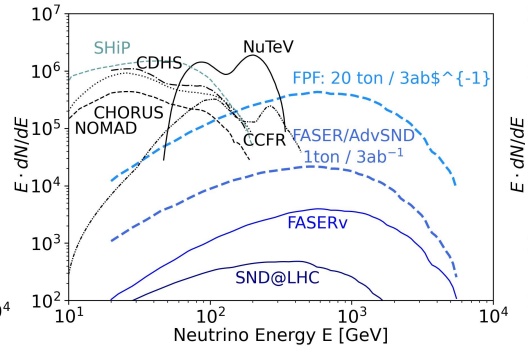


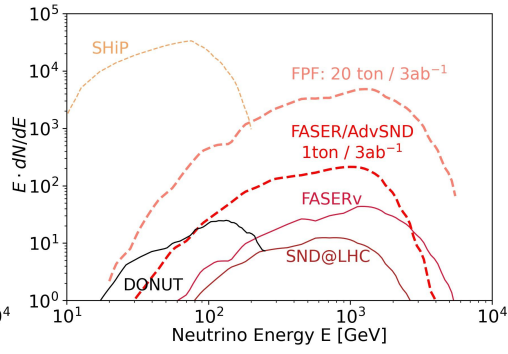


Neutrino Fluxes.

LHC is source of most energetic human made neutrinos.





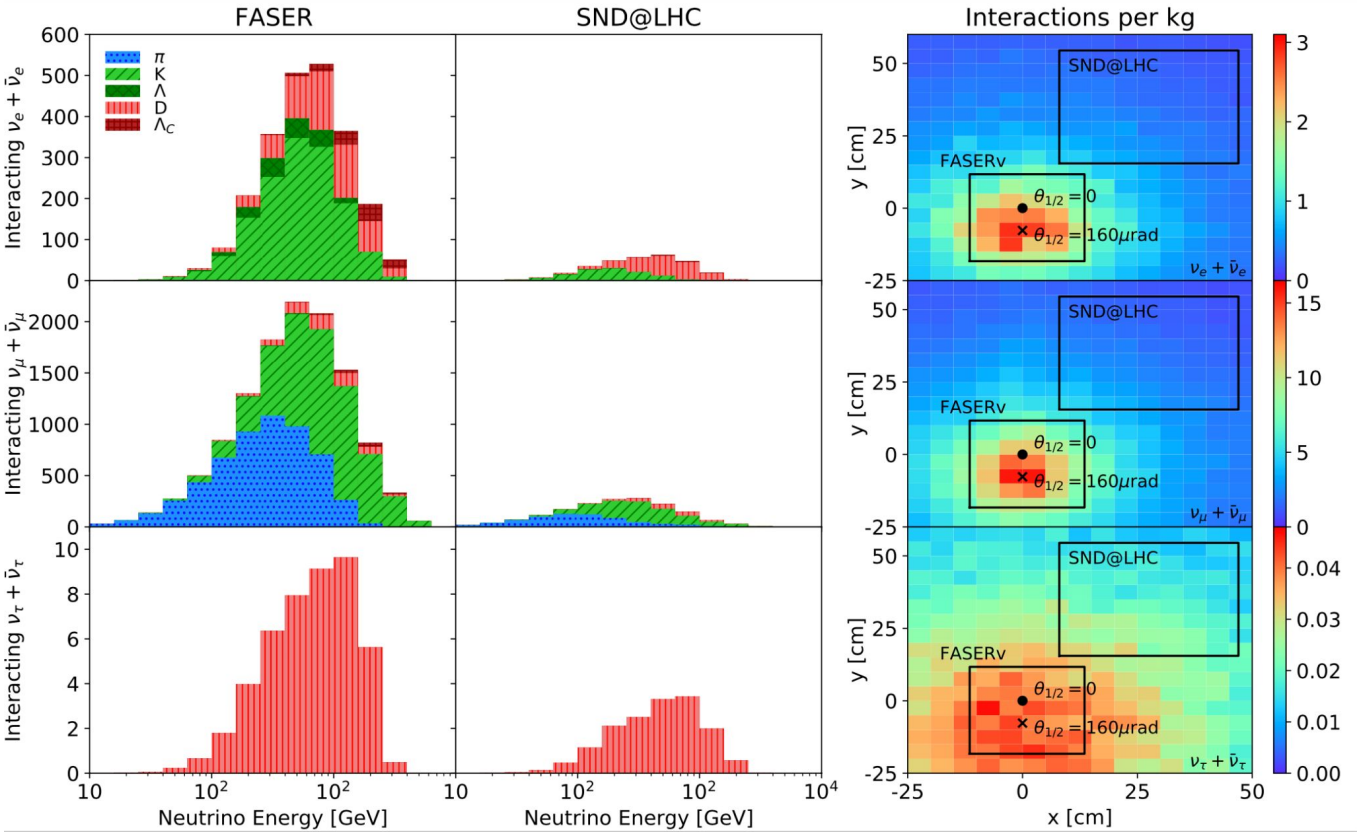


Current LHC experiments will detect thousands of neutrinos
The FPF experiments will detect millions of neutrinos.

What physics can we probe with them?

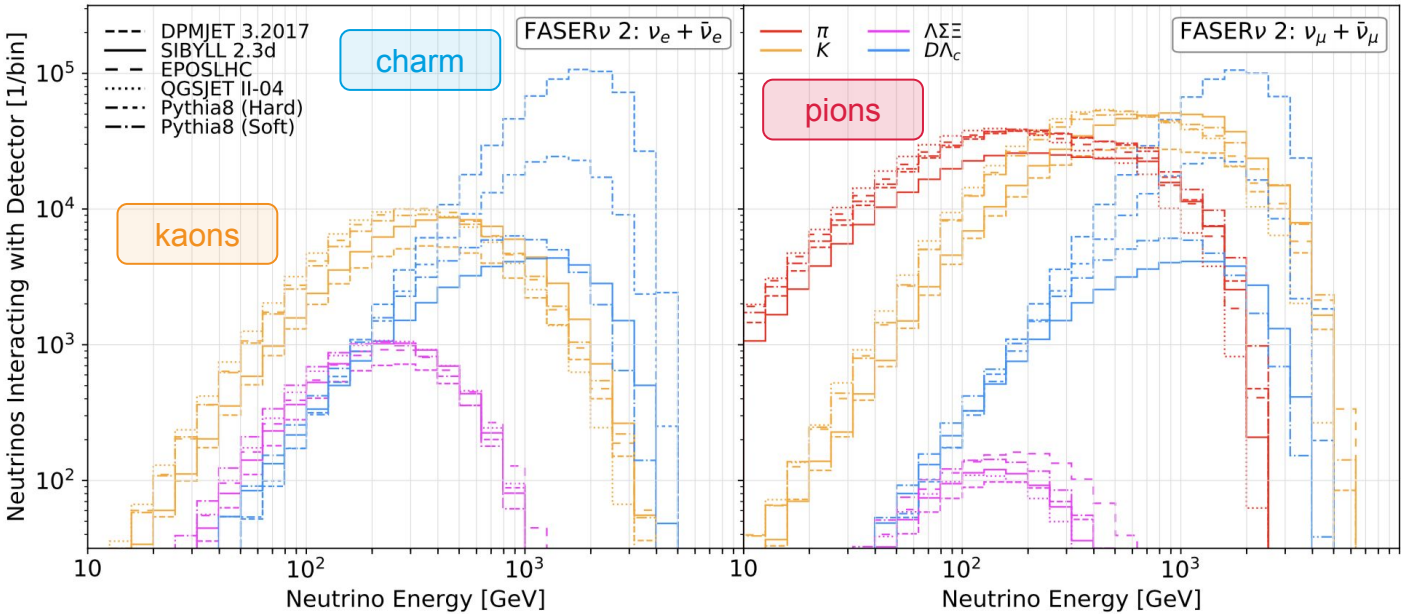
Neutrino Production.

Neutrino Fluxes.



Collider neutrinos are a novel probe of forward particle production.

Neutrino Fluxes.



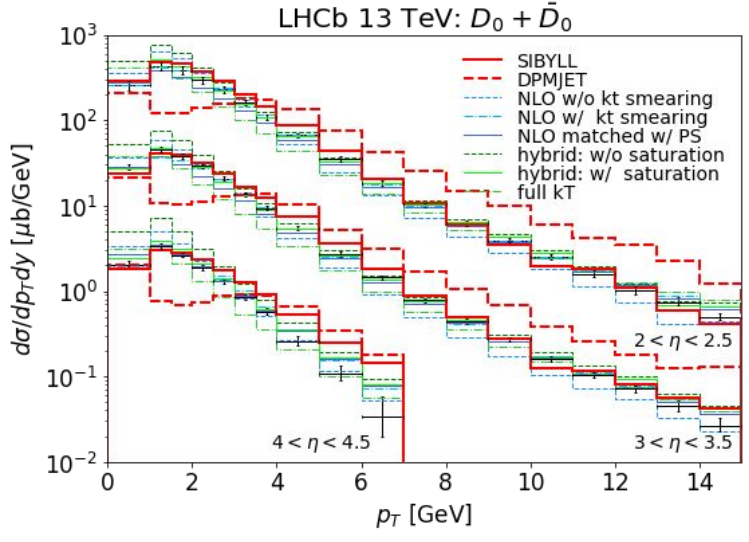
Collider neutrinos are a novel probe of forward particle production.

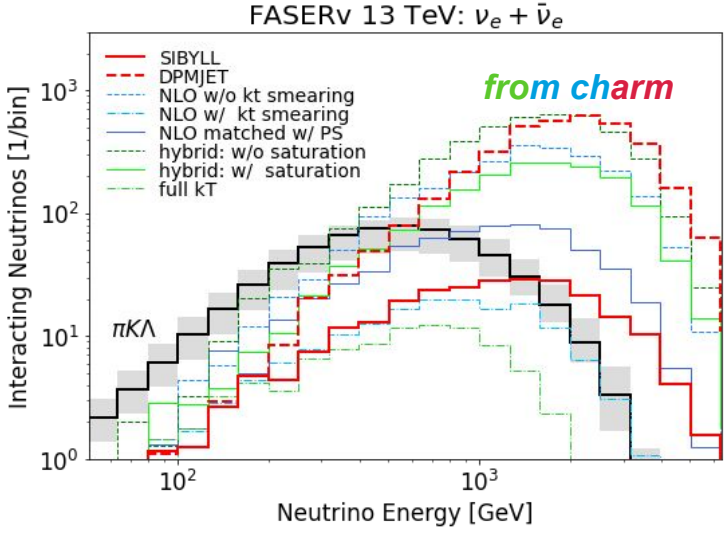
Neutrinos from Charm Hadrons.

forward charm hadron production can be calculated using perturbative QCD

several predictions for FPF based on hadronic interaction models, NLO collinear factorization and kT factorization: guided by LHCb data

[Bai, Diwan, Garzelli, Jeong, Reno, 2002.03012] [Maciula, Szczurek, 2210.08890] [Bhattacharya, FK, Sarcevic, Stasto, 2306.01578] [Buonocore, FK, Rottoli, Sominka, 2309.12793]



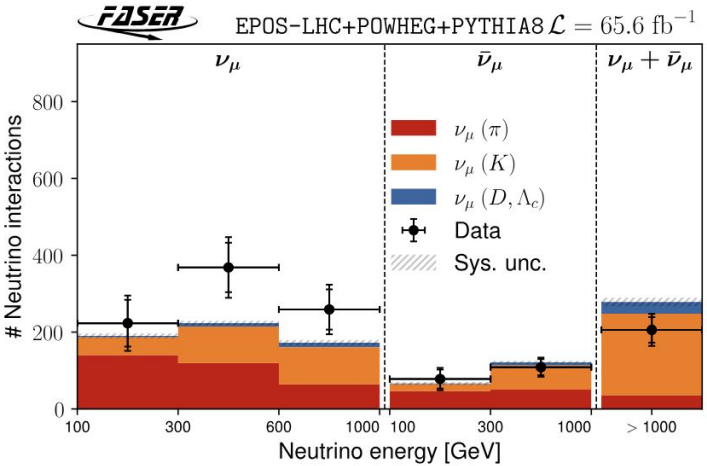


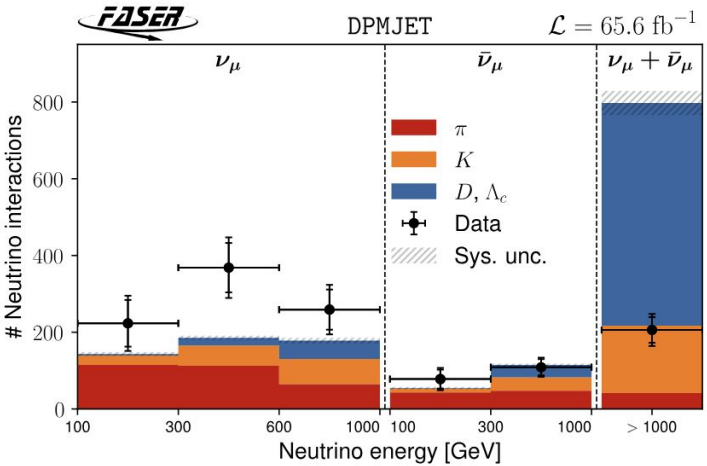
Collider neutrinos will be able to distinguish predictions that LHCb cannot.

Neutrinos from Charm Hadrons.

FASER data already ruled out some models.

[FASER, 2412.03186]

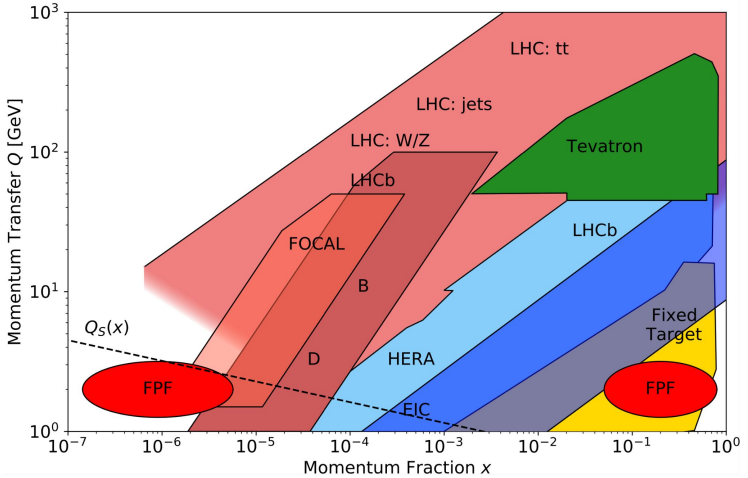


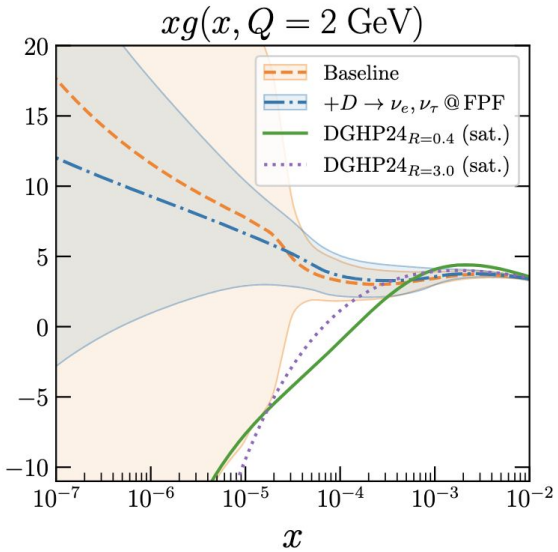


Neutrinos from Charm Hadrons.

Neutrinos from forward charm production probe uncharted kinematic regimes in QCD. [FPF 2203.05090]

$Q \sim 2m_c$, $x_1 \sim 1$, $x_2 \sim 4m_c^2/s \sim 10^{-6}$





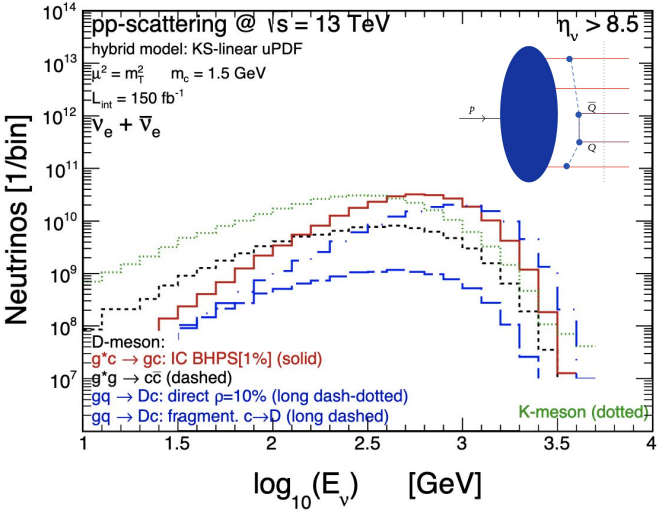
Unique ability to constrain gluon PDF at x~10^-7

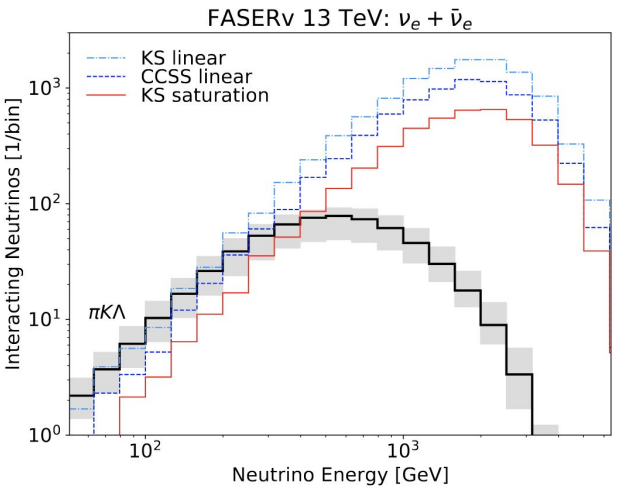
[FPF 2411.04175]

Neutrinos from Charm Hadrons.

probe of intrinsic charm at high-x

[Maciula, Szczurek 2210.08890]





study of gluon saturation at low-x

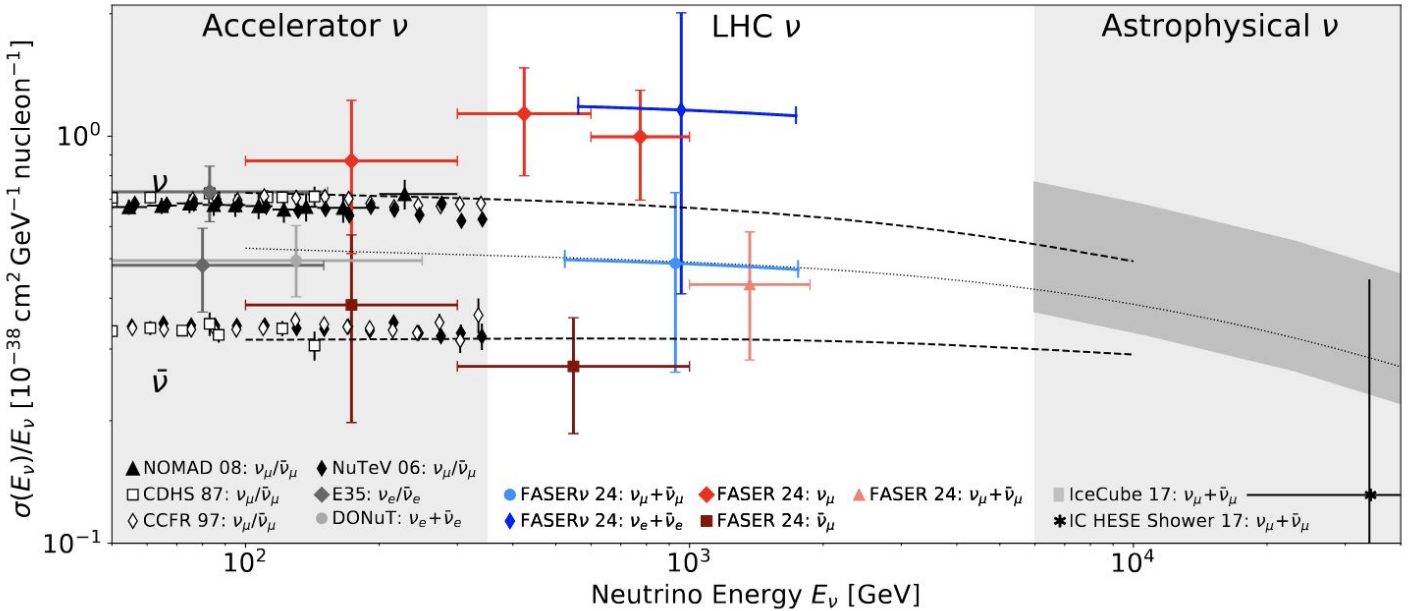
[Bhattacharya, FK, Stato, Sarcevic: 2306.01578]

Neutrino Interaction.

Neutrino Interactions.

first measurements of the neutrino interaction cross section

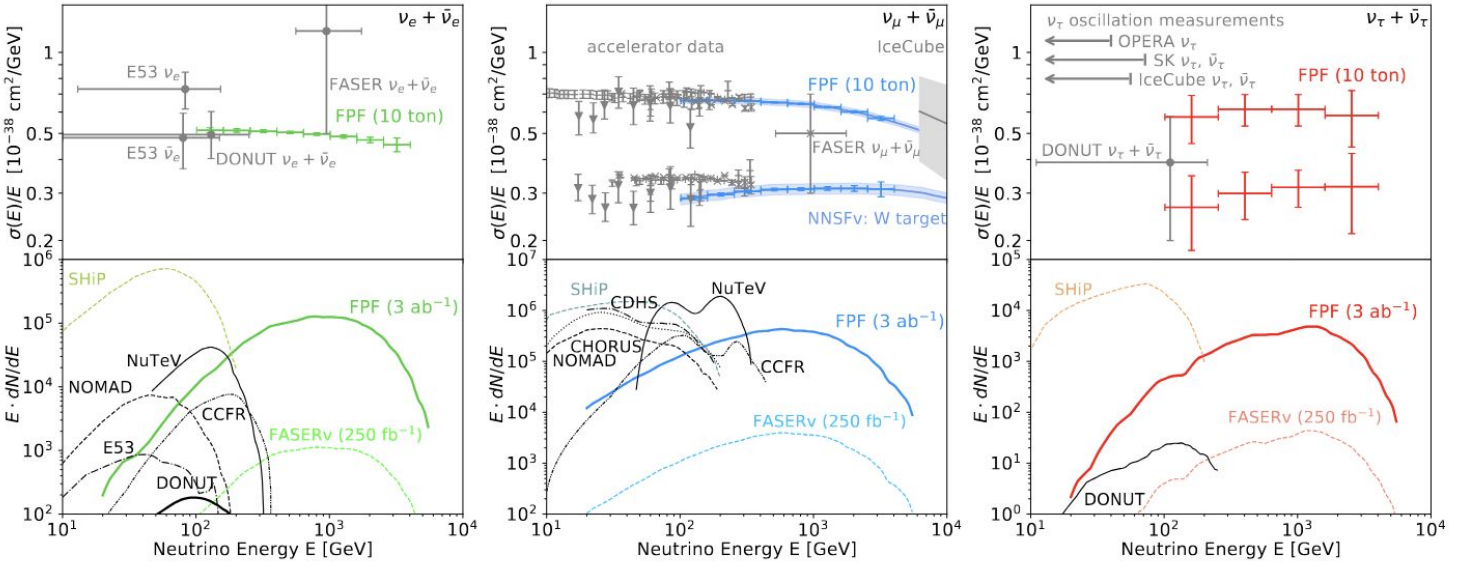
[FASER, 2412.03186], [FASER, 2403.12520]



Neutrino Interactions.

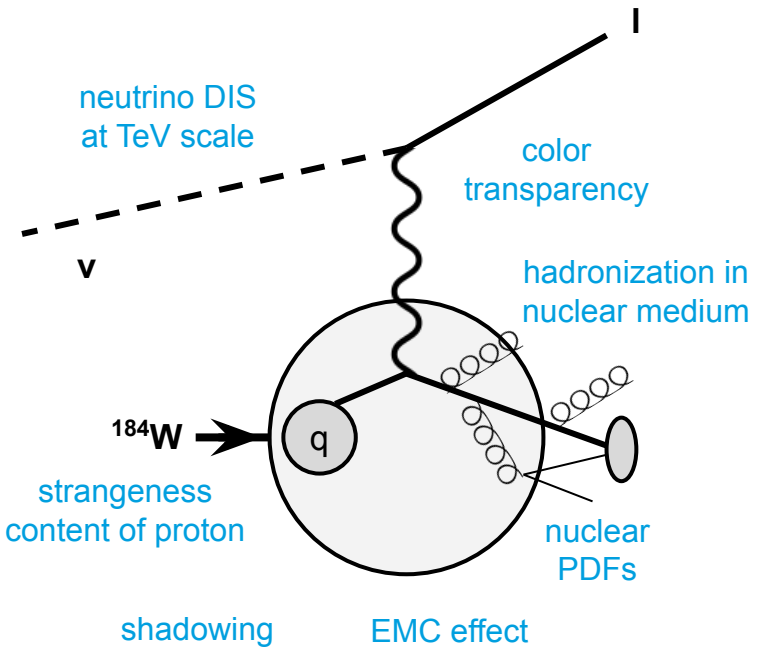
more precise measurements possible at FPF

[FPF, 2411.04175]



Neutrino Interactions.

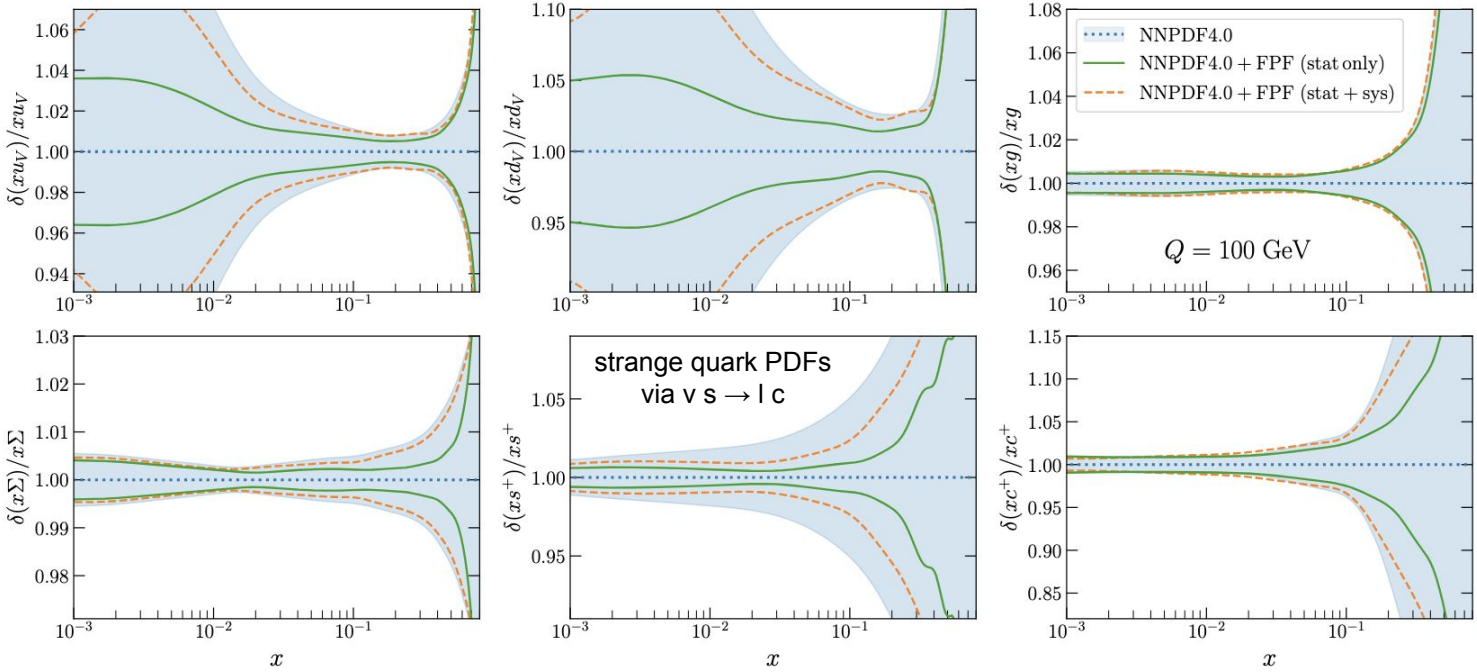
Collider Neutrino Experiments
are a Neutrino-Ion Collider
at EIC center of mass energies



Collider Neutrinos: Interactions.

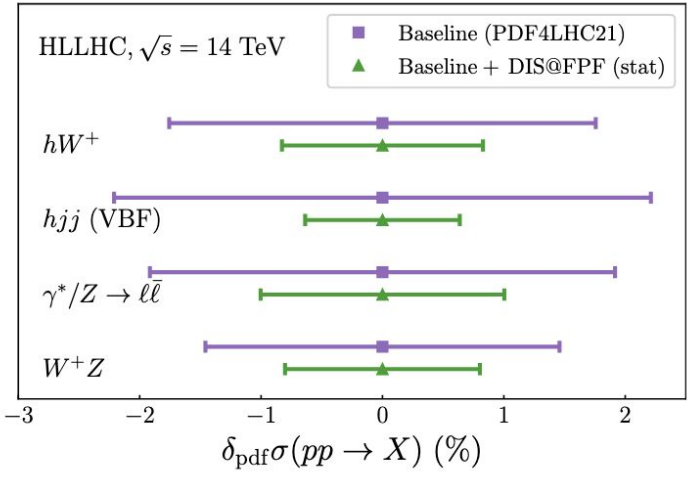
neutrino DIS data will improve PDFs

[FPF, P5 Input] [Cruz-Martinez et al. 2309.09581]

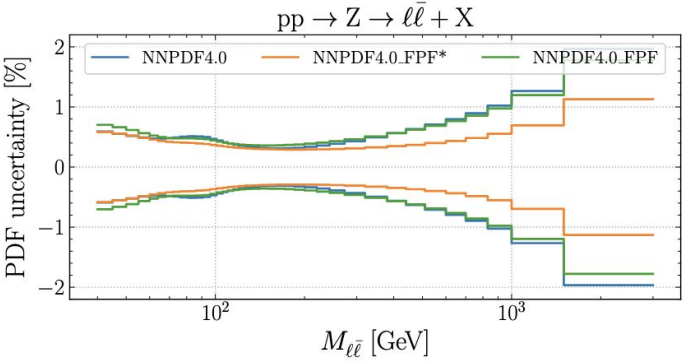


Collider Neutrinos: Interactions.

reduced PDF uncertainties for many key LHC processes



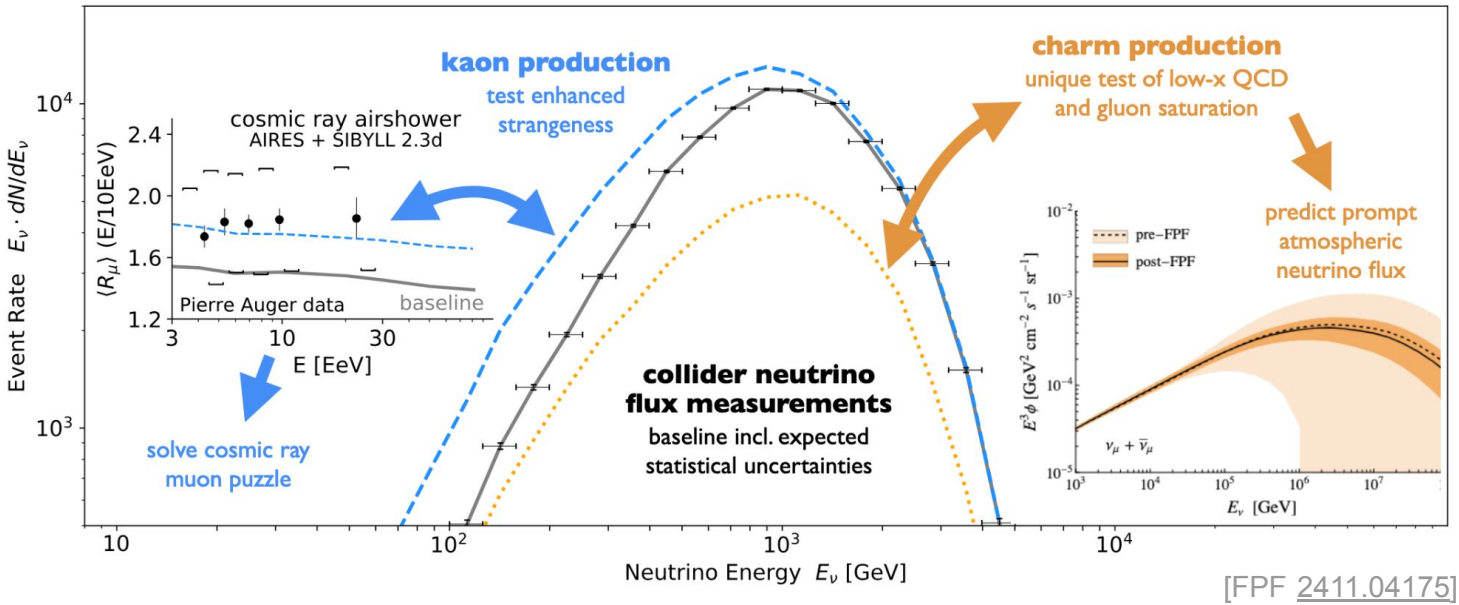
[FPF, 2411.04175]



[Cruz-Martinez et al. 2309.09581]

Astroparticle Physics

Input for Astroparticle Physics.



[FPF 2411.04175]

cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

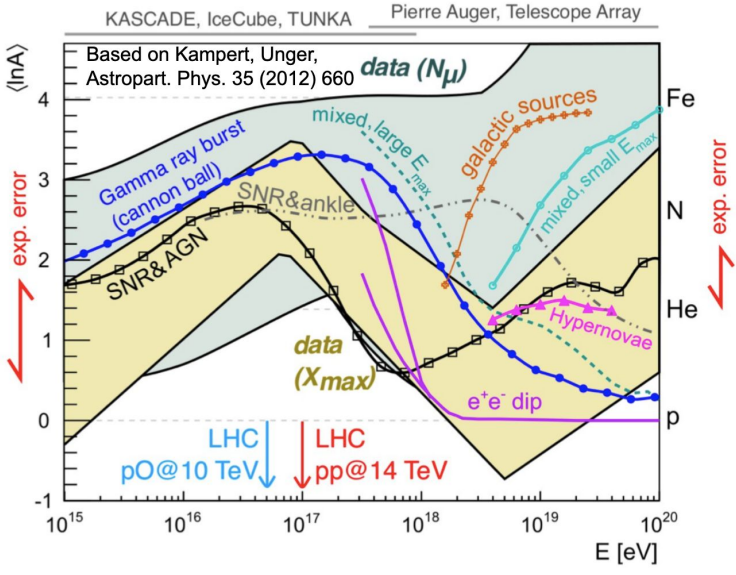
forward charm production at the LHC constraints on **prompt atmospheric neutrino flux** at IceCube

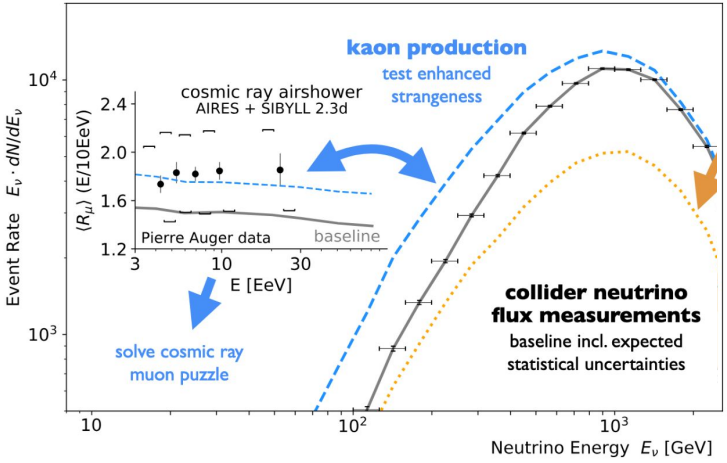
collider neutrino program is endorsed/supported by the astroparticle community

Light Hadrons and Muon Puzzle.

cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

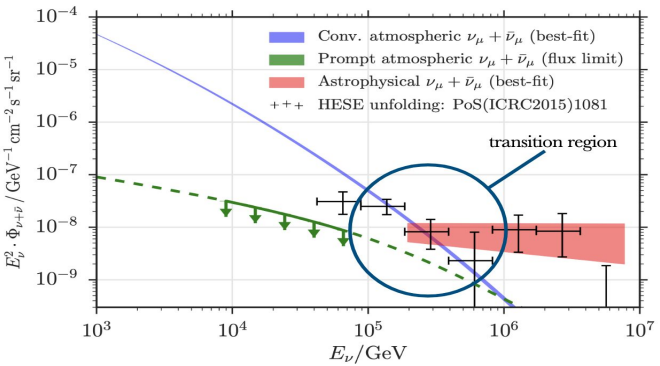
prevents extracting flux composition and origin of cosmic rays





strangeness enhancement: solves puzzle and can lead to large differences at LHC

Charm Astroparticle Physics.

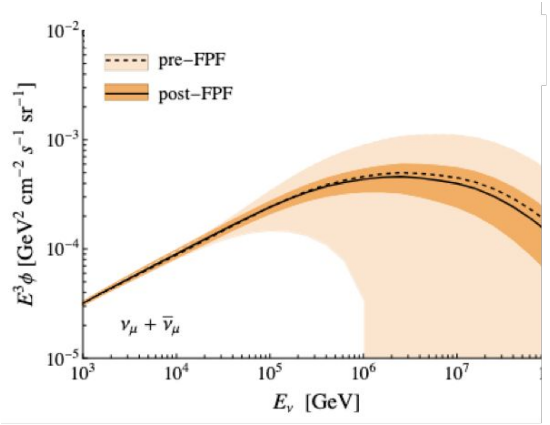


forward charm production at the LHC

↓

constraints on prompt atmospheric neutrino flux at IceCube

(currently very poorly constrained/understood)

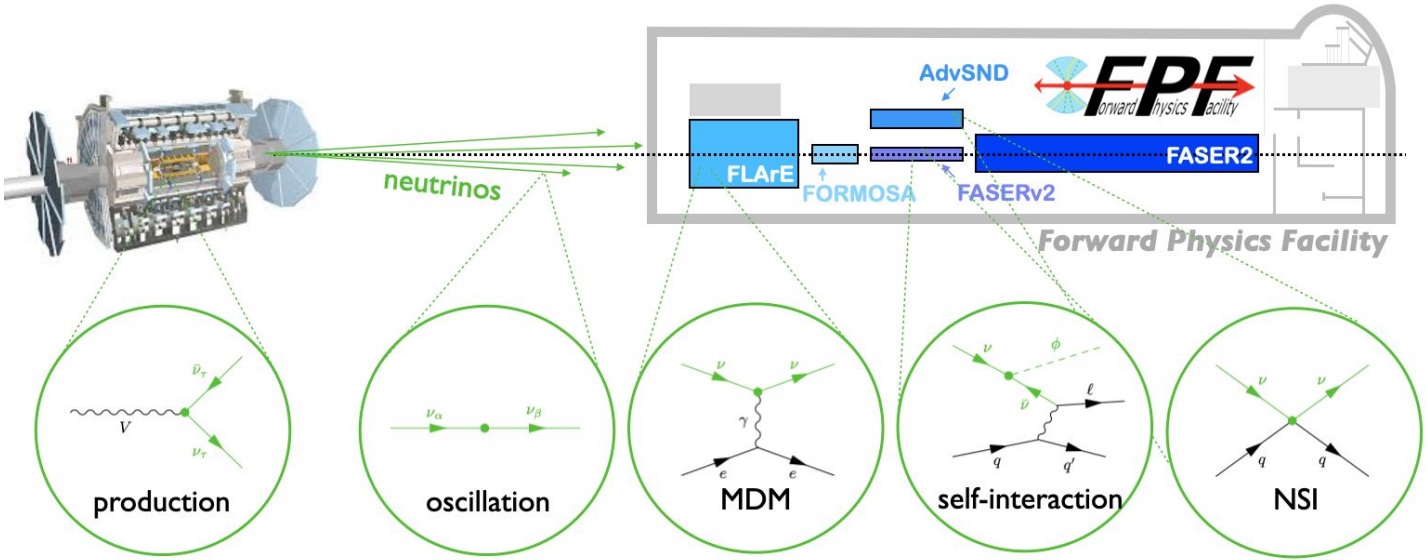


FPF data will improve flux predictions!

[Reno, Jeong, FPF 2411.04175]

BSM Physics

Collider Neutrinos: BSM Physics.



[FK, 2005.03594]

[FASER, 1908.02310]

[Abraham, Abari, FK, Tsai, 2301.10254]

[Kelly, FK, Tuckler, Zhang, 2111.05868]

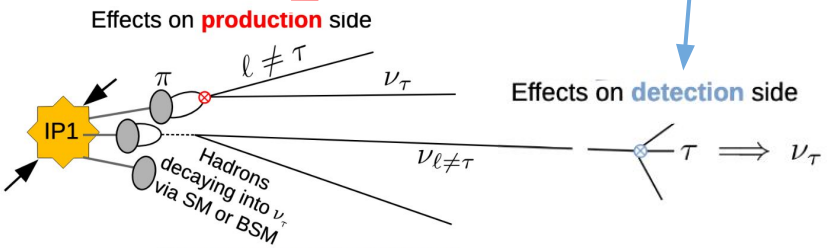
[Abraham, Ismail, FK, 2012.10500]

Collider Neutrinos: BSM Physics.

Non Standard Interactions associated can modify tau neutrino flux

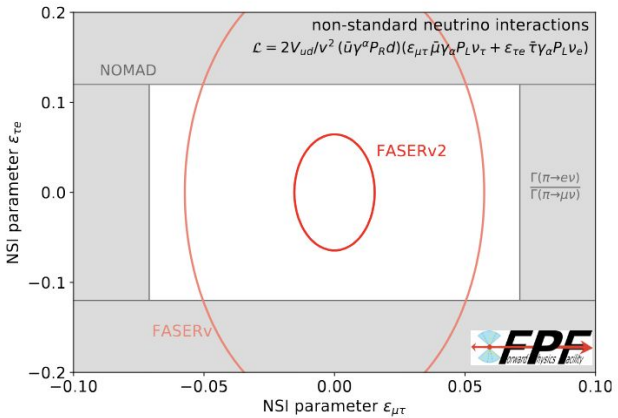
[Falkowski et al, 2105.12136]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{2V_{ud}}{v^2} \times (\bar{u}\gamma^\kappa P_R d) \times \left[\epsilon_R^{\mu\tau}(\bar{\ell}_\mu \gamma_\kappa P_L \nu_\tau) + \epsilon_R^{\tau e}(\bar{\ell}_\tau \gamma_\kappa P_L \nu_e)\right]$$



Can be probed at FPF!

[FK, Mäkelä, Trojanowski, 2309.10417]



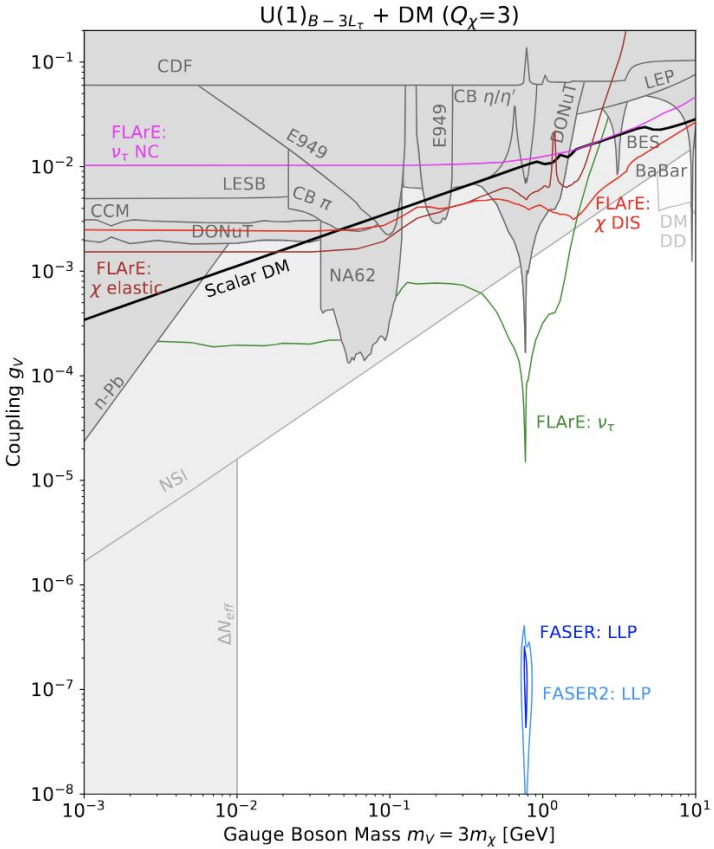
Collider Neutrinos: BSM Physics.

new light weakly coupled particles could decay into tau neutrinos.

$$\pi^0 \to V\gamma, \quad V \to \nu_\tau \nu_\tau$$

Excess of tau neutrinos
[FK, 2005.03594]

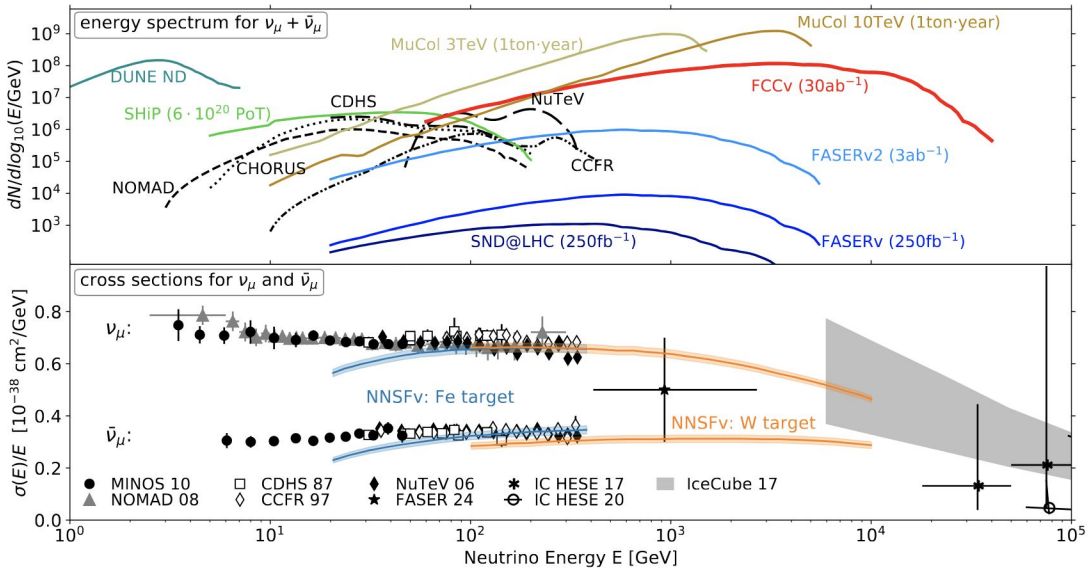
Can be probed at FPF!
[Batell et al 2111.10343]



Summary and Outlook

Future Colliders.

Great potential for forward neutrino measurements and searches also muon collider [IMCC, 2407.12450] and FCC-hh [Abraham et al, 2409.02163]



1B neutrinos will allow many precision studies:
PDFs at x~10^{-9}, polarized PDFs, nuclear PDFs, neutrinos from heavy ions

Summary.

There is lots of interesting and unique physics that can be done with collider neutrinos.