From FASER to the FPF: Looking Forward for Exciting Physics.

Felix Kling (UCI, DESY)

International Workshop on New Opportunities for Particle Physics

July 18th-20th

General Idea

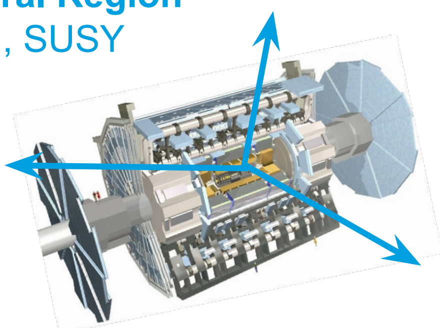
General Idea.

Main focus of LHC are heavy particles: Higgs, SUSY … .

Their decay products have high pT and are distributed almost isotropically.

ATLAS/CMS were constructed to catch them.

Central Region
H, SUSY

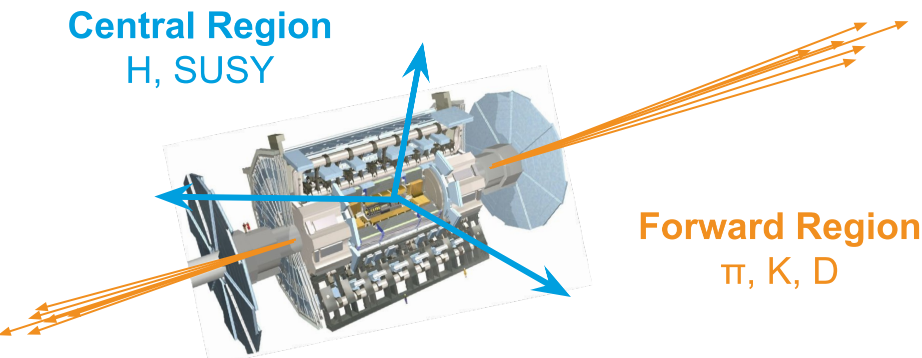


General Idea.

The LHC produces a huge number of hadrons in the forward direction:
10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam.

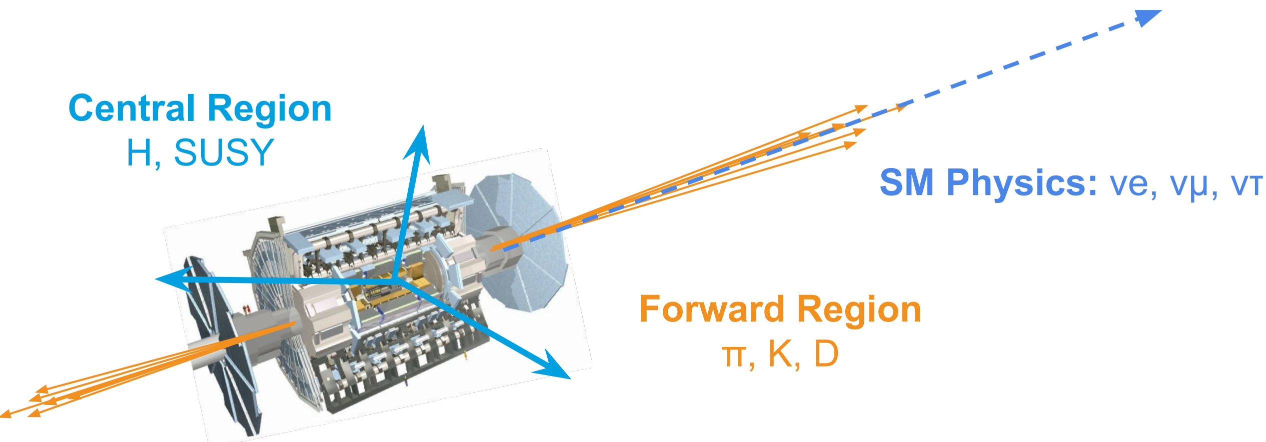
Typically low pT but large energy.

Can we do something with that?



General Idea.

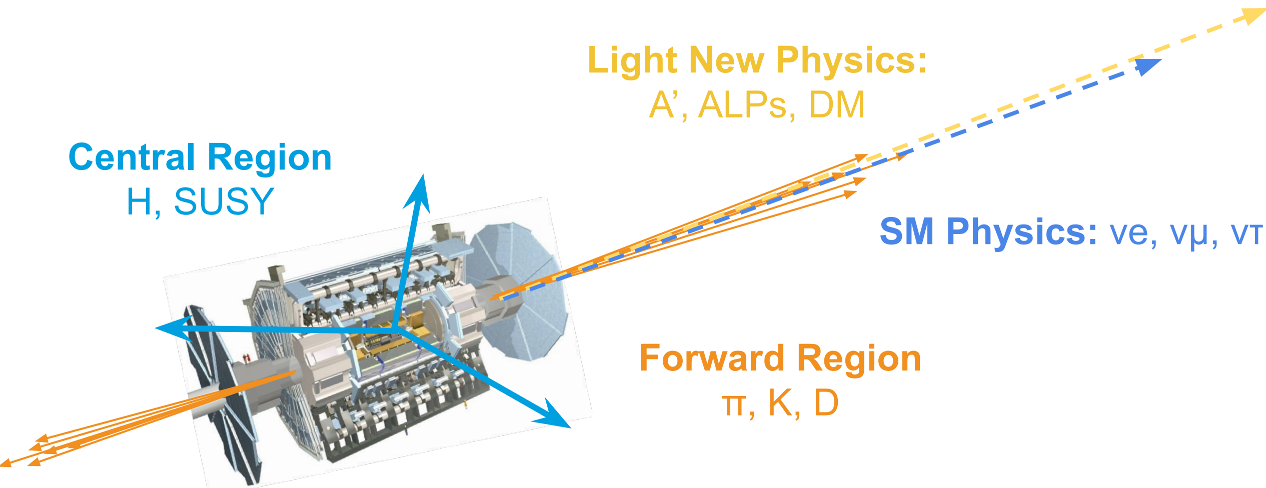
The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.



General Idea.

The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.

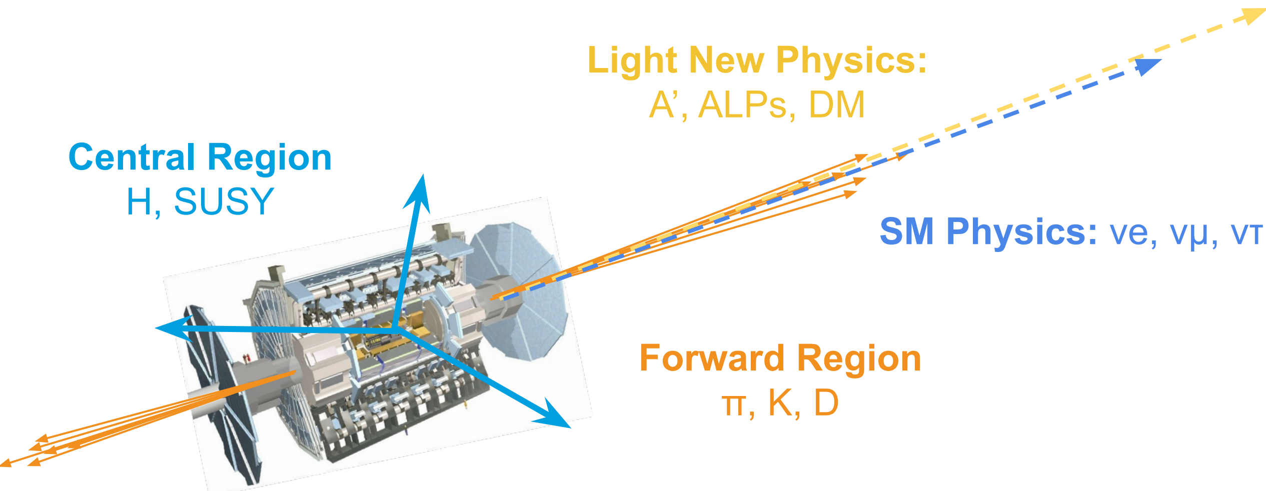
This may also be true for many interesting new particle candidates: dark photons, axion-like particles, dark matter.



General Idea.

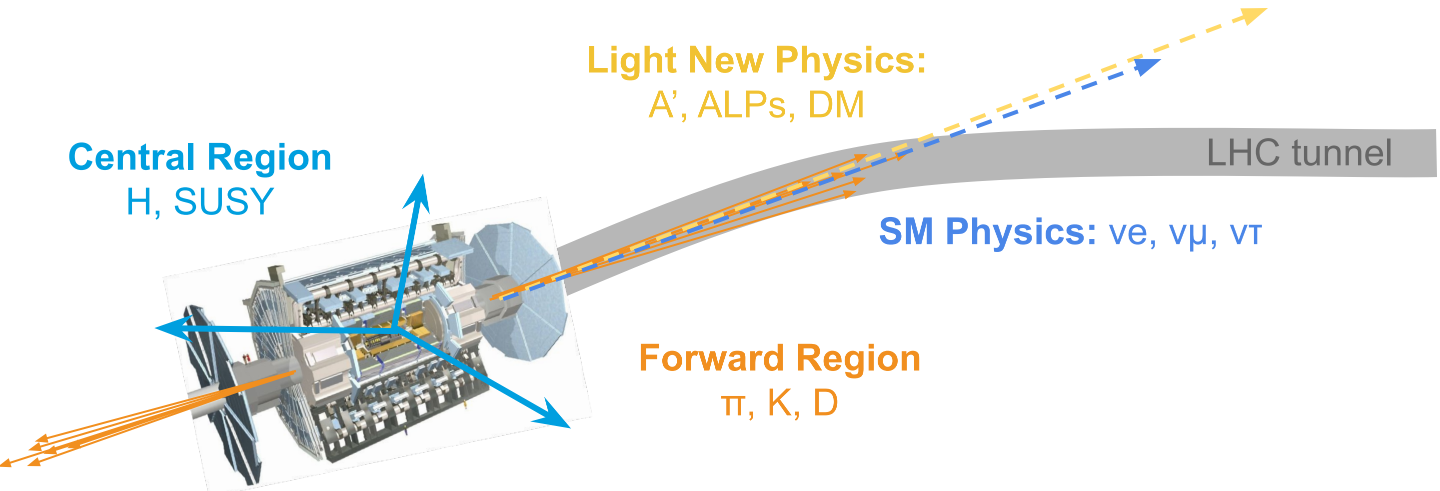
These particles escape down the beam pipe and remain undetected.

Indeed, the existing big LHC detectors are perfectly designed NOT to see them.



General Idea.

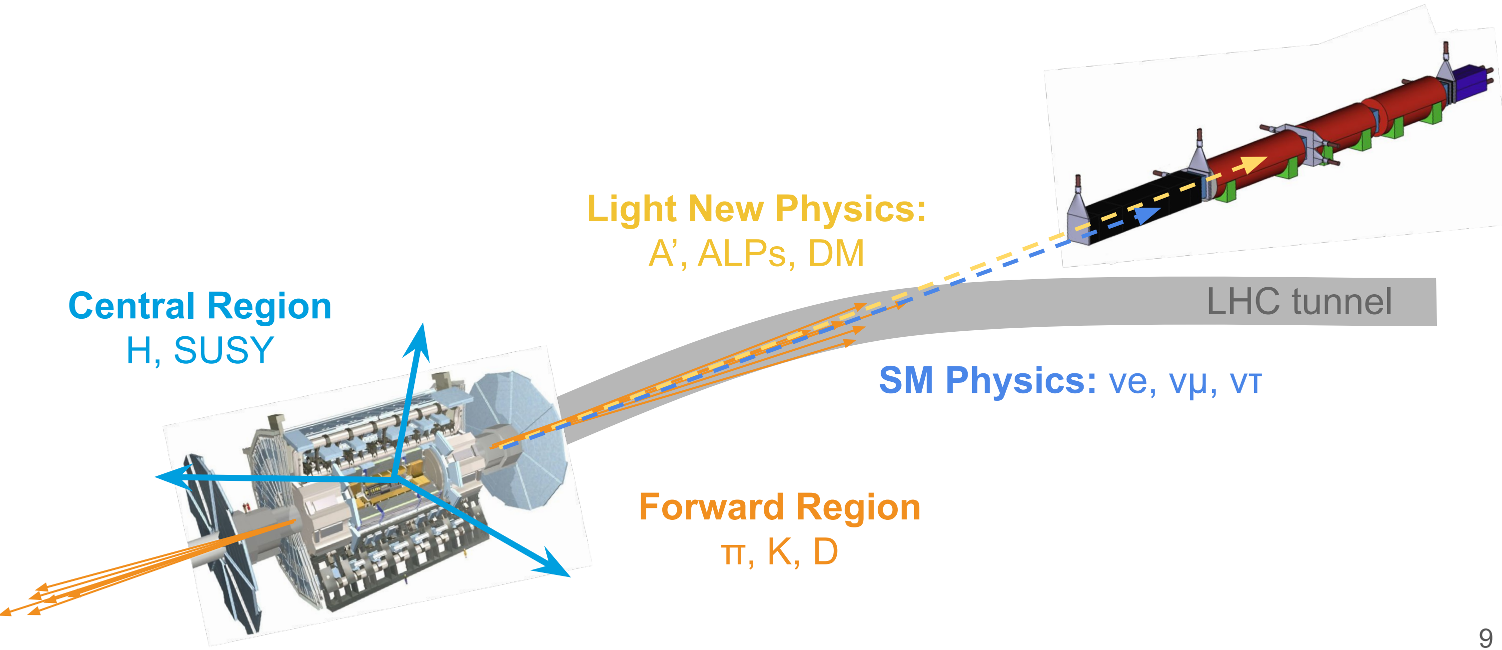
LHC tunnel will eventually curve away, but the beam of neutral particles will continue along the beam collision axis.



General Idea.

LHC tunnel will eventually curve away, but the beam of neutral particles will continue along the beam collision axis.

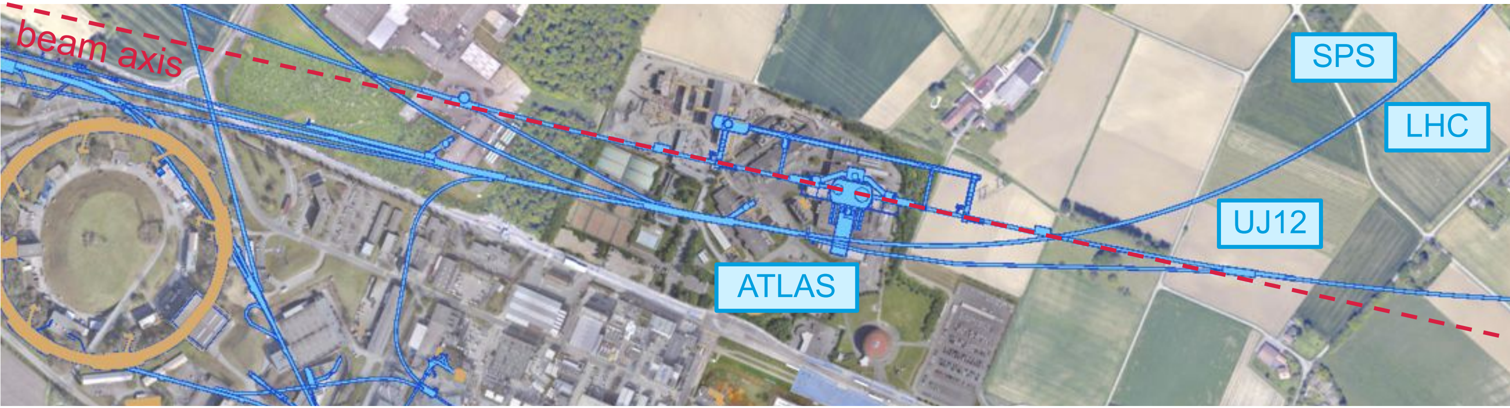
Idea: Placed experiment in this beam to detect them.
[**Feng**, Galon, FK, **Trojanwoski**, 1708.09389]



FASER Experiment

Experimental Program.

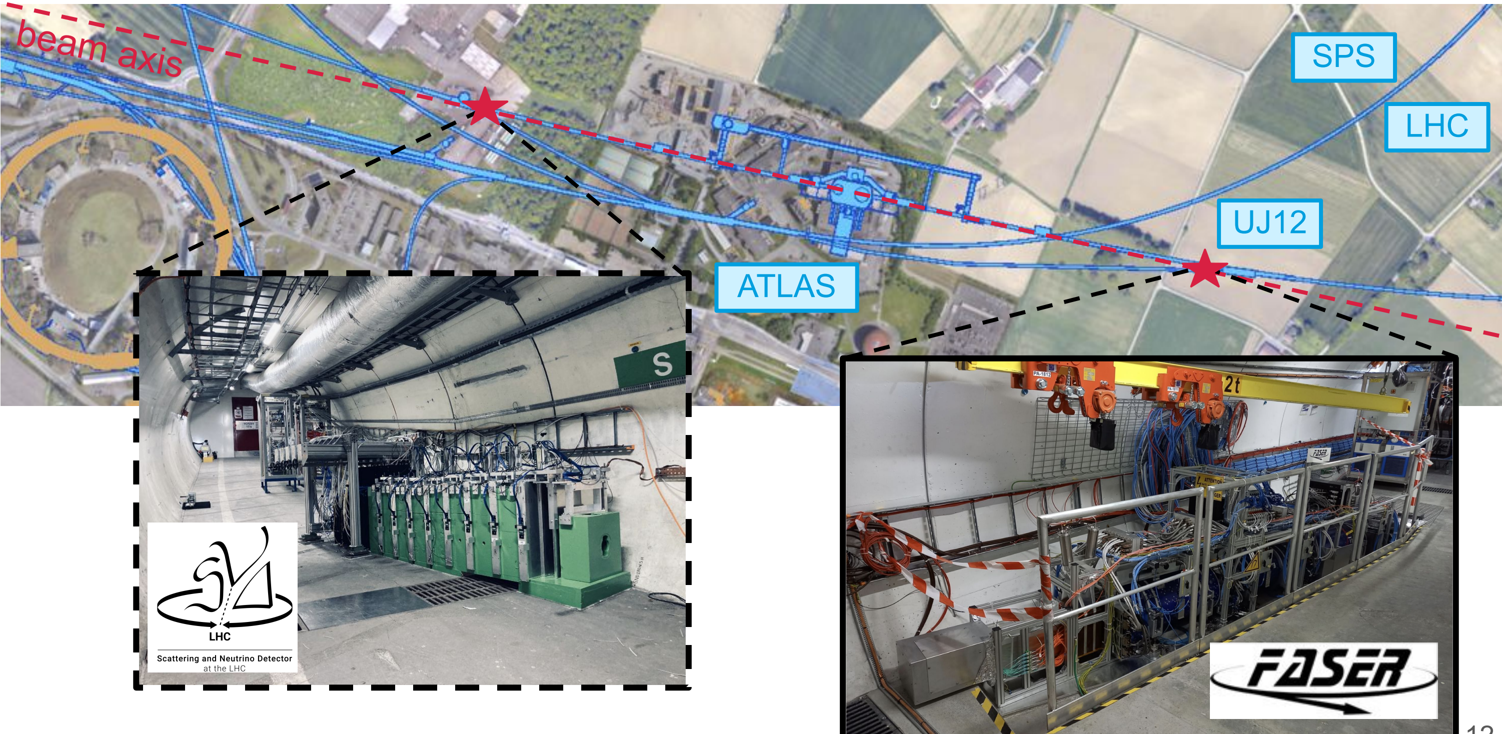
There is potential for forward physics experiments along beam axis.



Experimental Program.

There is potential for forward physics experiments along beam axis.

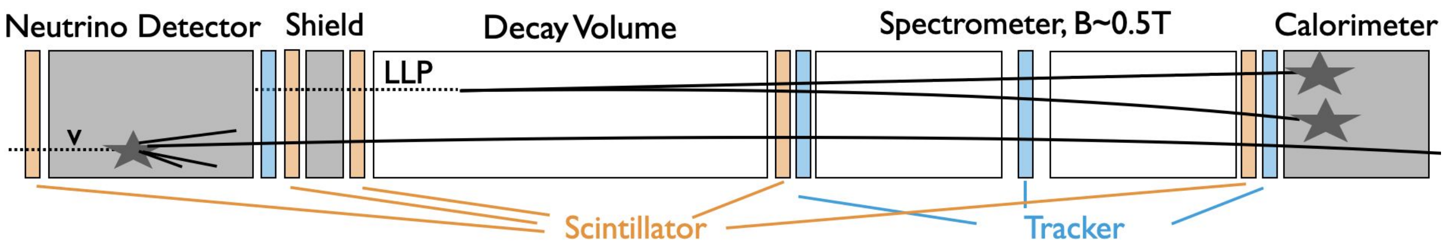
Two new experiments started operation in 2022 to exploit this potential:
SND@LHC and FASER.



FASER Experiment.

(as imagined by a theorist)

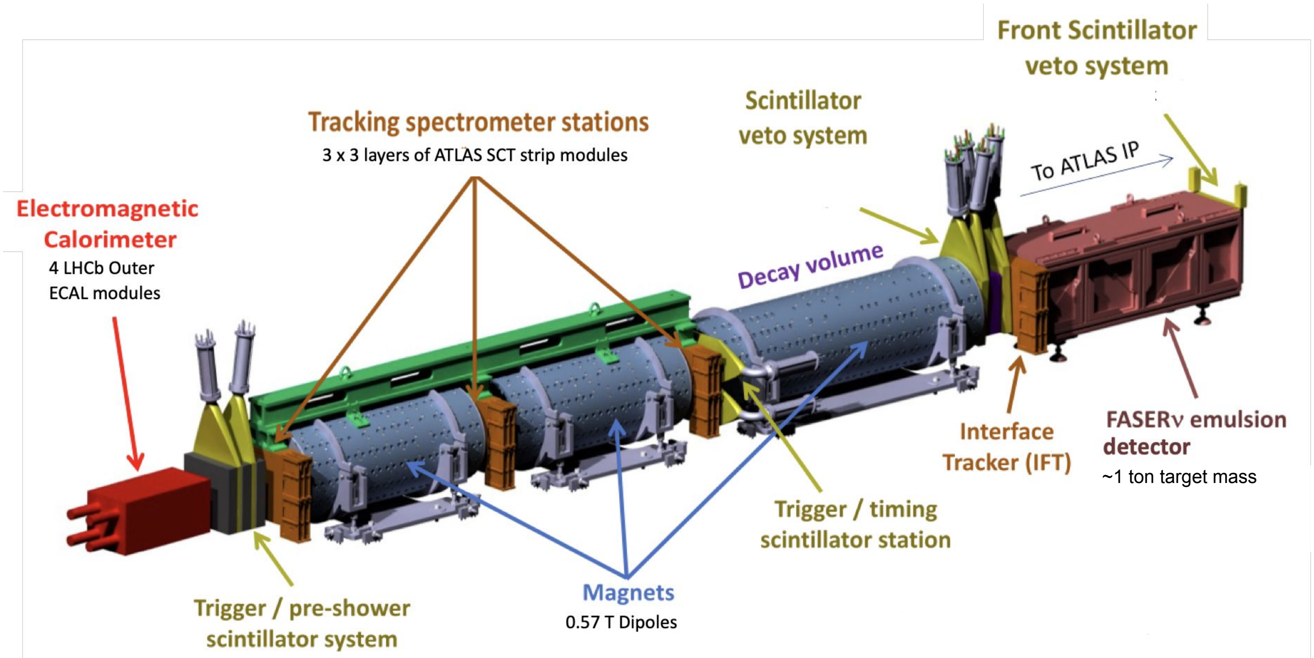
Goal 1: Search for New Physics:
- decay of long-lived particles, e.g. A’ → e e
- highly energetic particles emerge from empty decay volume
- need front veto, tracker, calorimeter

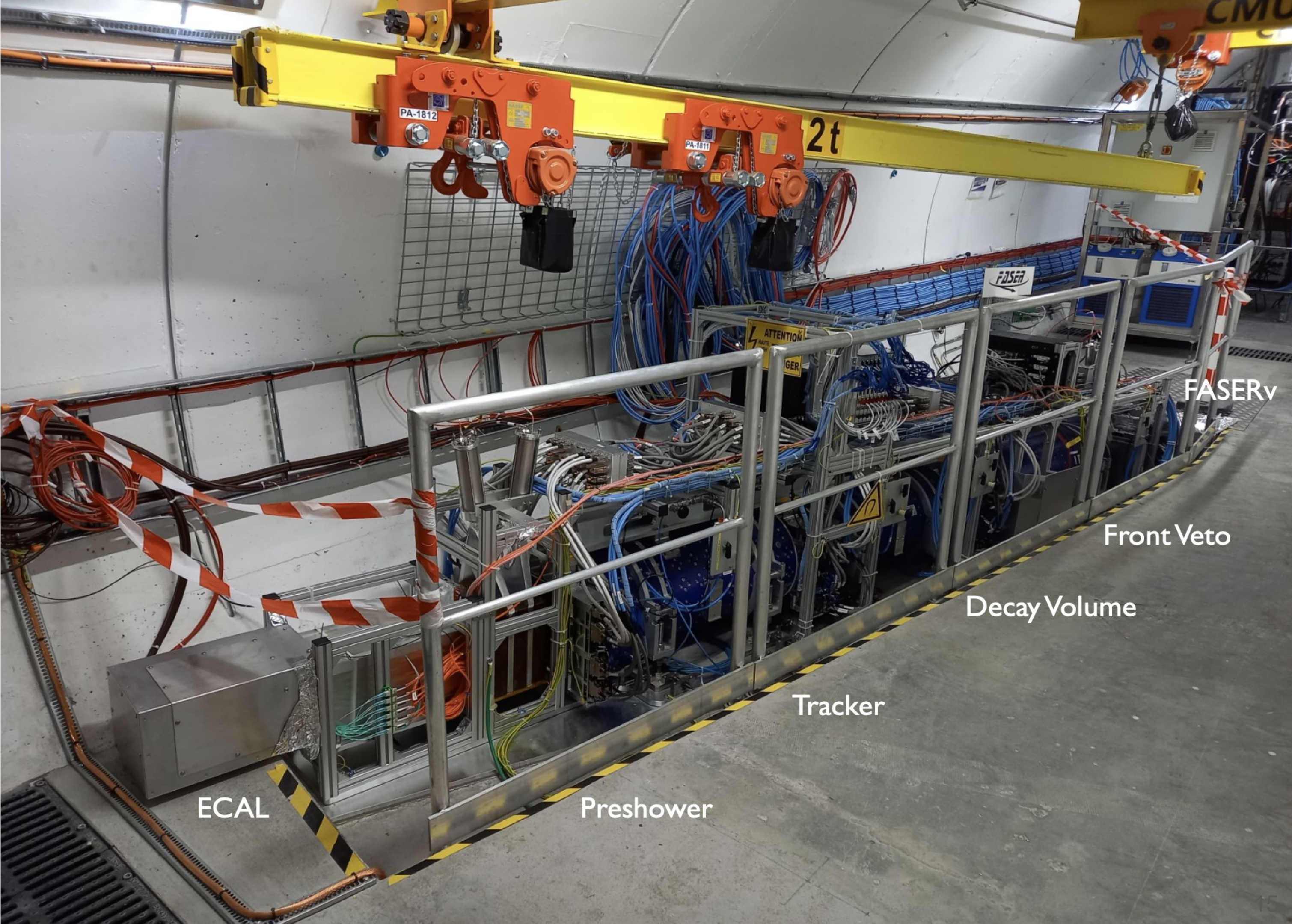


Goal 2: Neutrino Measurements
- interactions of collider neutrinos, e.g. ν N → μ + hadrons
- highly energetic particles emerge from dense material
- dedicated emulsion neutrino detector in front

FASER Experiment.

(as realized by the experimentalists)
[FASER, arXiv:2207.11427]





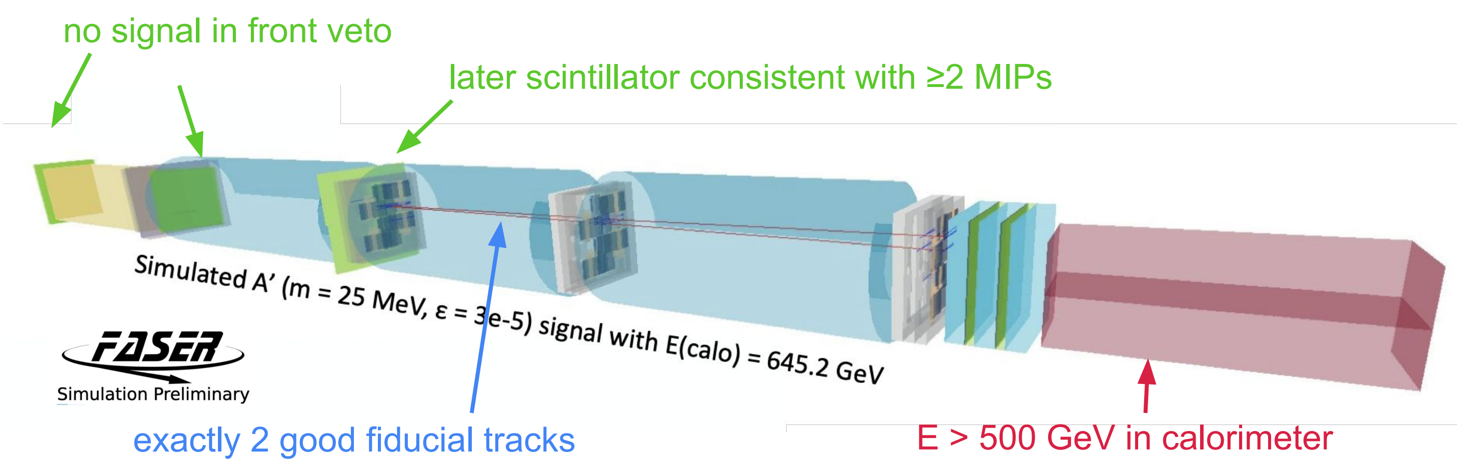
PA-1812
PA-1811
2t
ATTENTION
FASER
FASERν
Front Veto
Decay Volume
Tracker
Preshower
ECAL

FASER: First Results

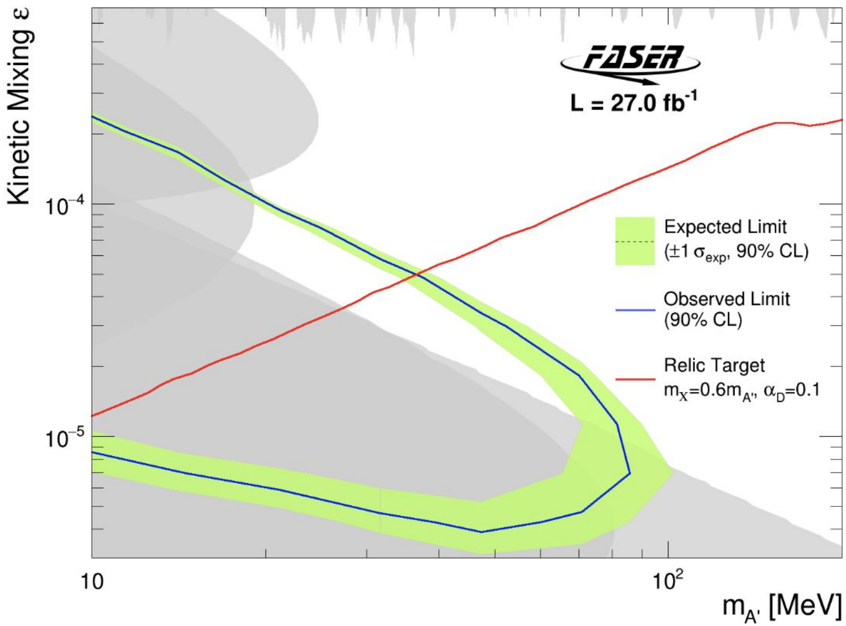
FASER Dark Photon Search.

In 2023, FASER performed a first search for dark photons.
[FASER, arXiv:2308.05587]

simple and robust A’ e+e- selection, optimised for discovery
expected background: $(2.0 \pm 2.7) \times 10^{-3}$ events (mainly neutrinos)



FASER Dark Photon Search.



No events found in signal region.

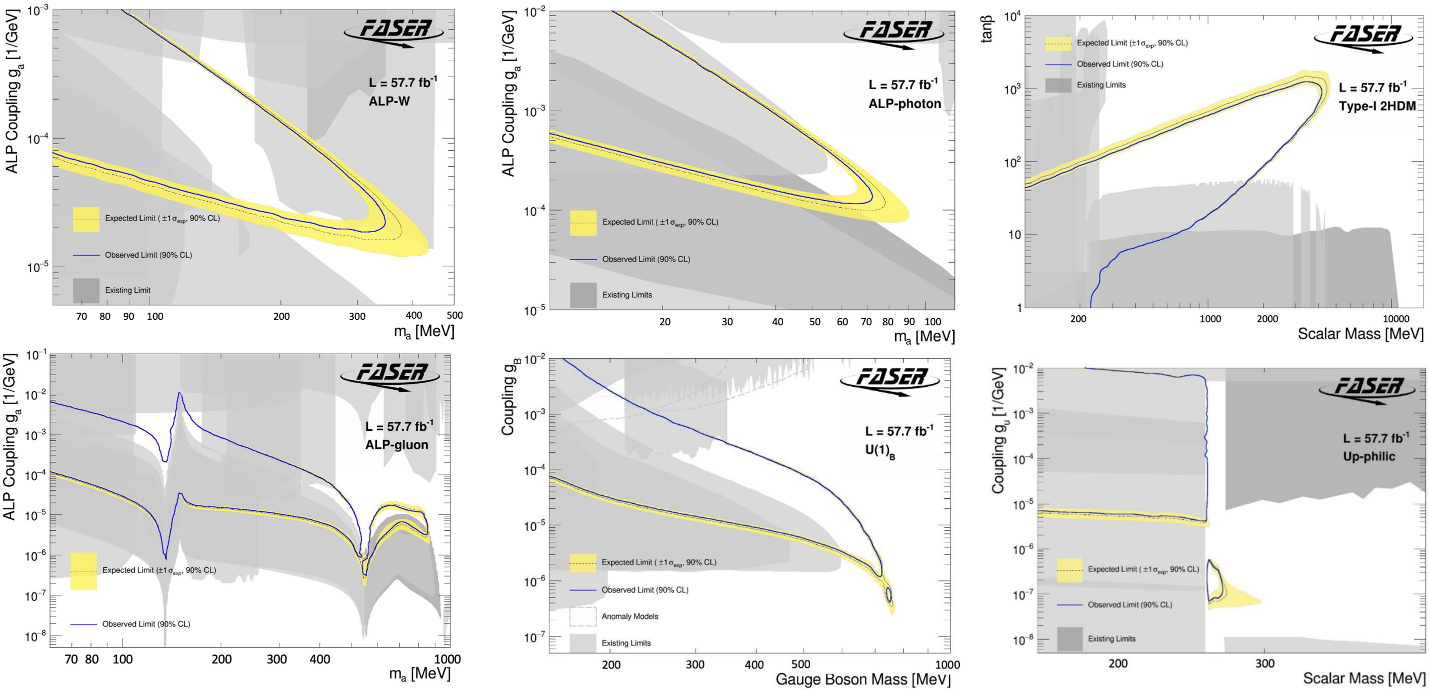
Based on this null results, FASER sets limits in previously unexplored parameter space

Probing region interesting from thermal relic target.

FASER ALP Search.

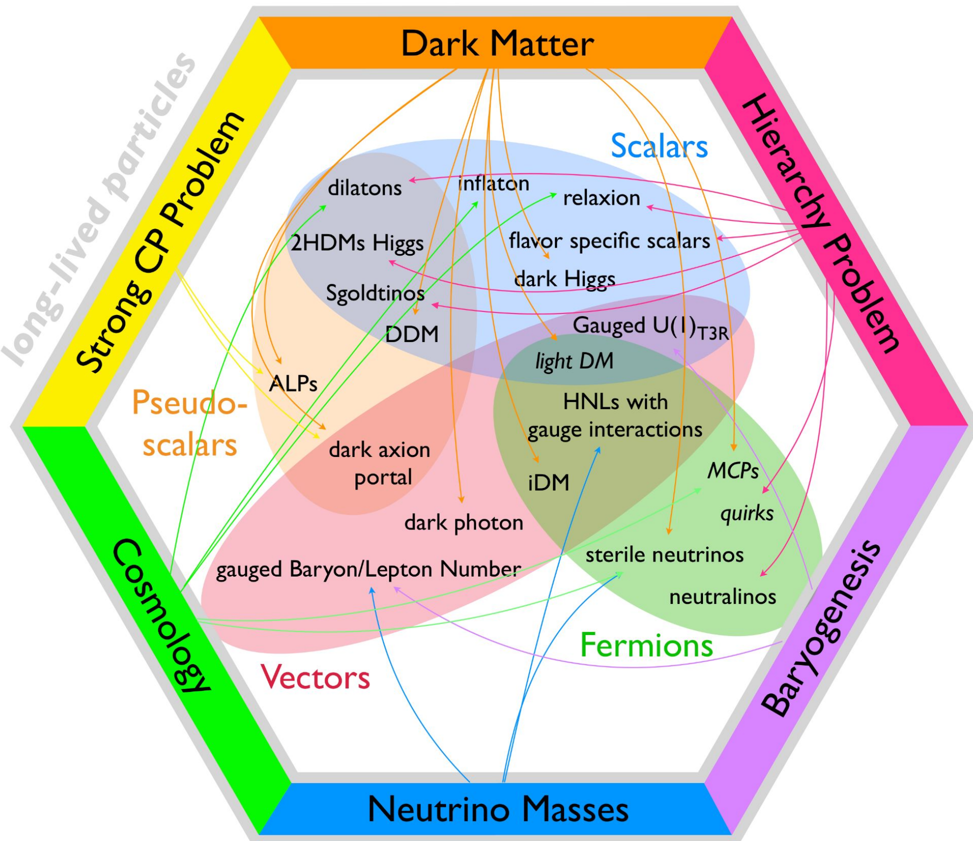
More recently, FASER also searched for LLPs decaying to photons. FASER, 2203.05090]

This constrained a variety of models, such as ALPs, 2HDM scalars, U(1)B gauge bosons, up-philic scalars. Many of those benchmarks were suggested by the community.



More Long-Lived Particles.

More analyses ongoing / planned.



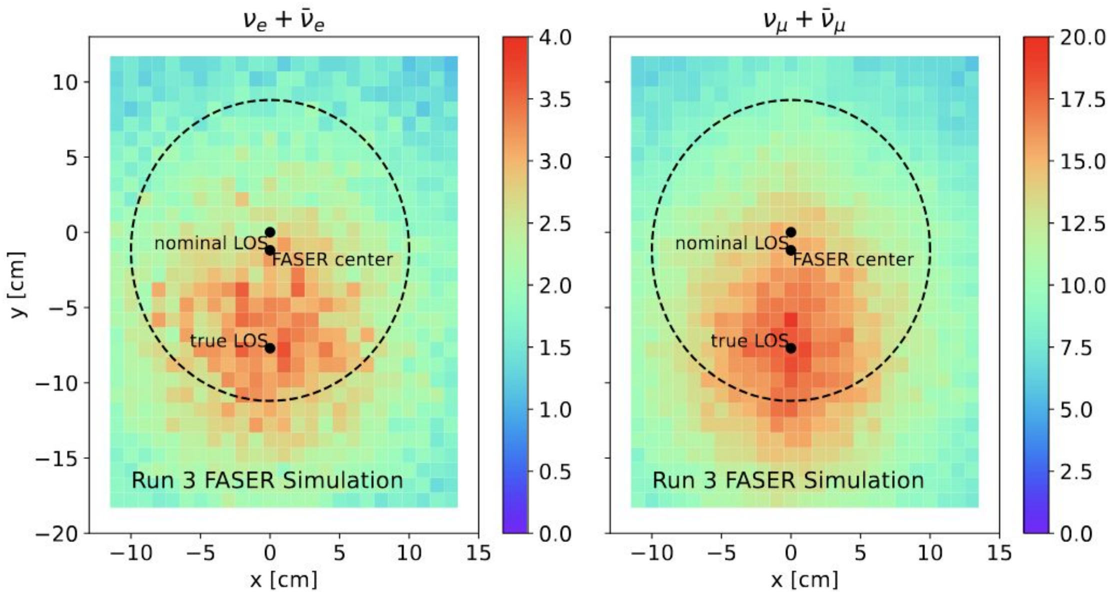
Light new physics models can address many outstanding problems in particle physics

[Feng, FK, Reno, Rojo, Soldin et al. 2203.05090]

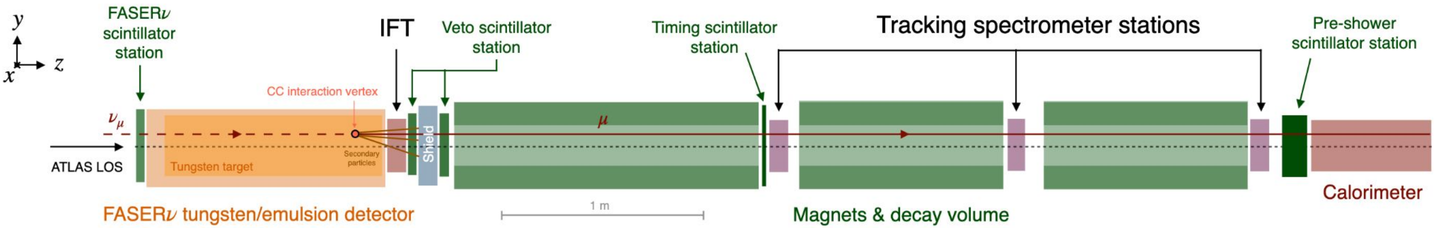
Collider Neutrino Observation.

The LHC produces a huge flux of TeV energy neutrinos of all three flavours in the forward direction, mainly from π, K and D meson decays. [De Rujula et al. (1984)]

FASER is ideally located to exploit this beam.



Collider Neutrino Observation.



first observation of collider νμ

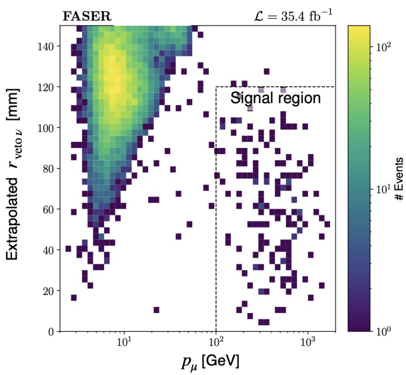
search for charged current νμ events through muon appearance: 153 events (16σ)

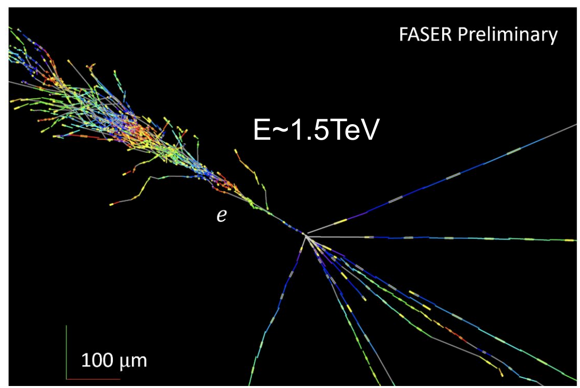
[FASER, 2303.14185]

first observation of collider νe

search for charged current νe events in emulsion detector: 4 events (5σ)

[FASER, 2403.12520]





The Dawn of Collider Neutrino Physics.

DESY.

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

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2023/03/21

Back

Research team detects first neutrinos made by a particle collider

The discovery promises to help physicists understand the nature of the elusive particle

An international research team at the FASER experiment at the Large Hadron Collider LHC in Geneva has for
the first time
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The FASER

UNIVERSITÄT BONN

UNIVERSITÄT STUDIUM FORSCHUNG UND

20. März 2023

Erstmals Neutrinos aus einem Teilchenbeschleuniger beobachtet

Internationale Studie hilft, die Natur des fast masselosen Elementarteilchens besser zu verstehen

Neutrinos gehören zu den am häufigsten vorkommenden Teilchen im Kosmos, geben Forschenden jedoch nach wie vor viele Rätsel auf. Ein internationales Team unter Beteiligung der Universität Bonn hat jetzt zum ersten Mal Neutrinos direkt beobachtet, die in einem Teilchenbeschleuniger erzeugt wurden. Die Physikerinnen und Physiker erhoffen sich, durch ihre neue Entdeckung die Natur dieser fast masselosen Elementarteilchen besser verstehen zu können. Die Ergebnisse wurden am vergangenen Wochenende bei der 57. Moriond-Konferenz in Italien vorgestellt und werden demnächst in der Fachzeitschrift Physical Review Letters zur wissenschaftlichen Begutachtung eingereicht.

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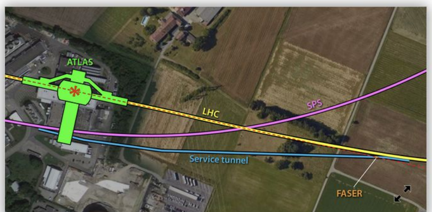
VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester
Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.



Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker

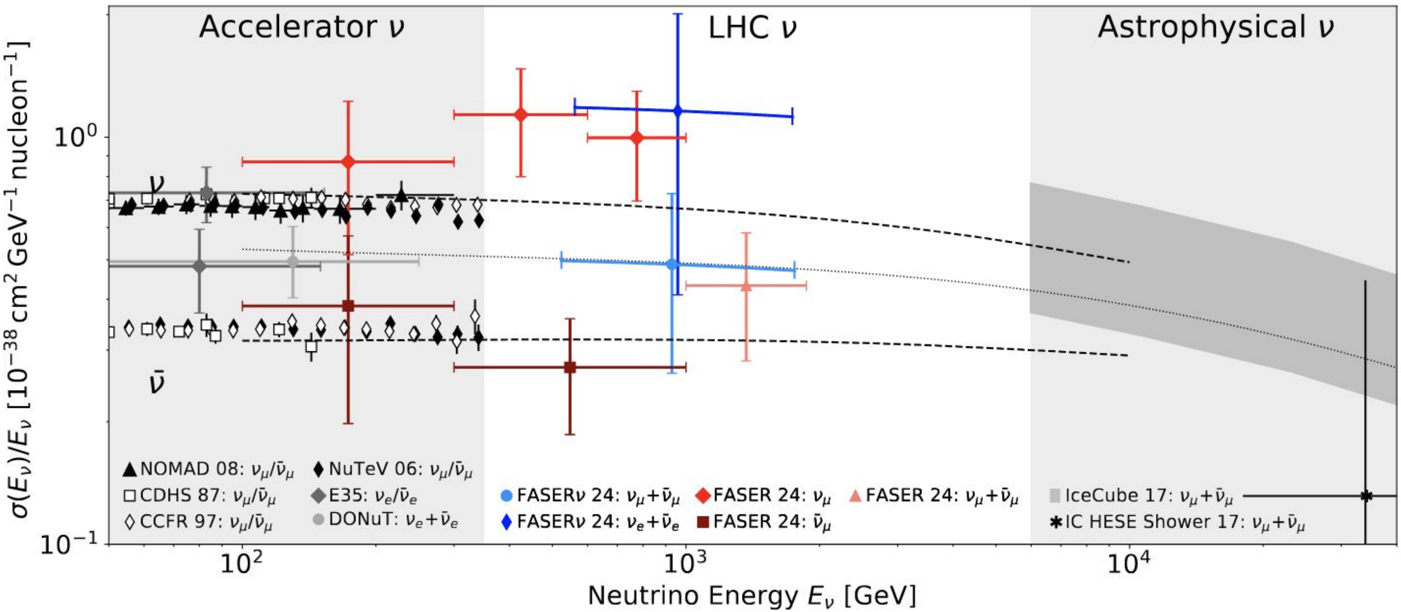
Figure 1: The Forward Search Experiment (FASER) is installed in a service tunnel that connects the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS). Proton collisions at the ATLAS experiment's interaction point (red star) generate beams of neutrinos (dashed red lines) that escape along a tangent to the LHC.

YouTube DE Suchen

Neutrinos Interactions Measurements.

first measurements of the neutrino interaction cross section

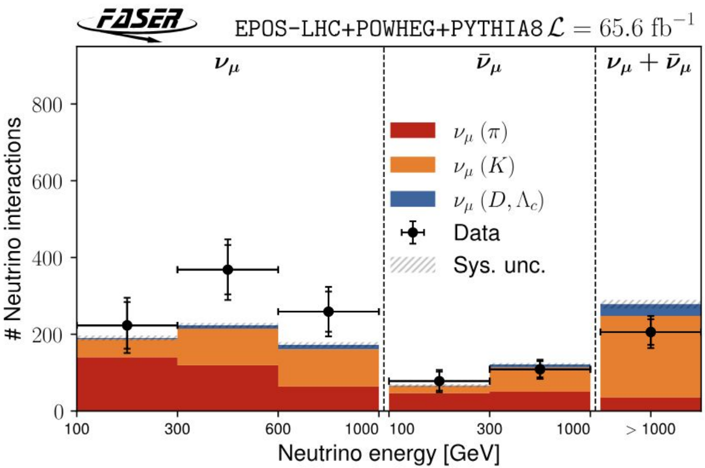
[FASER, 2412.03186], [FASER, 2403.12520]

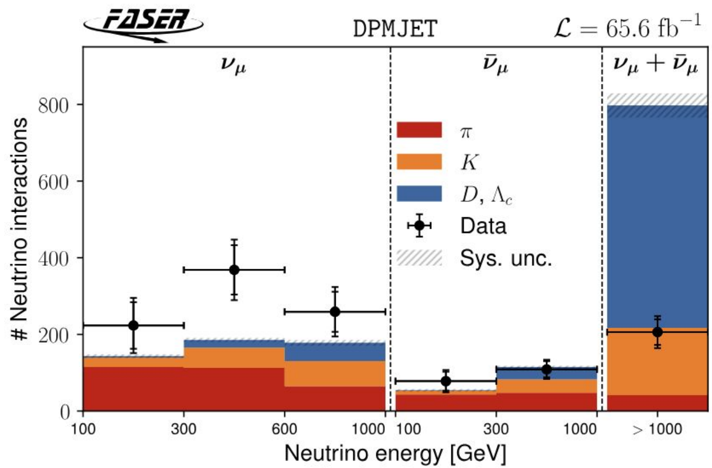


Neutrino Flux Measurements.

FASER data can test forward particle models.

[FASER, 2412.03186]





mild excess compared to theory prediction

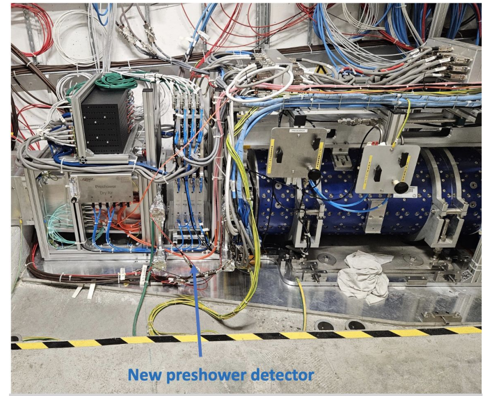
already ruled out some models with first data

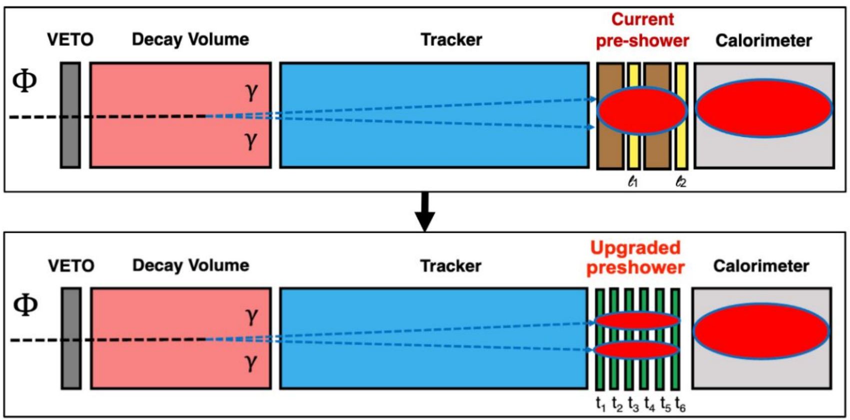
Future Plans and Perspectives

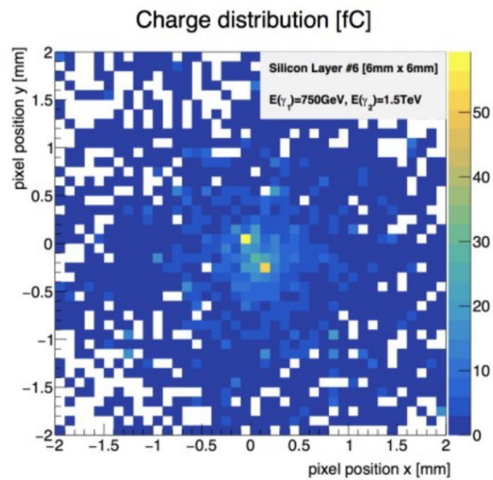
Preshower Upgrade.

A few month ago FASER has installed a preshower detector upgrade, designed to distinguish very closely spaced high energy photons.

This will allow to further improve searches for ALPs.





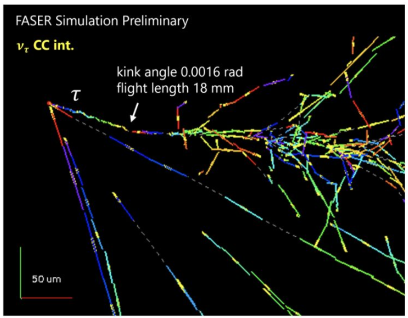


FASER in Run 4.

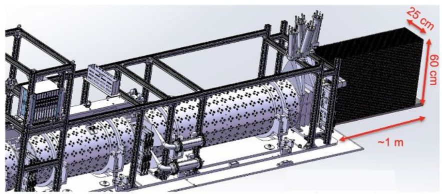
FASER has been approved to continue operation in LHC Run 4 (starting 2030).

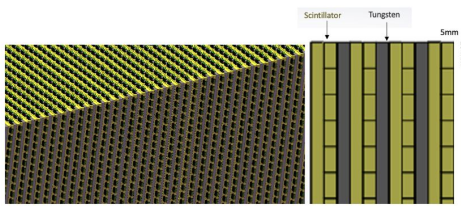
FASER is planning to continue its neutrino program during the HL-LHC.
Several detector options are being investigated [2503.19775].

Emulsion

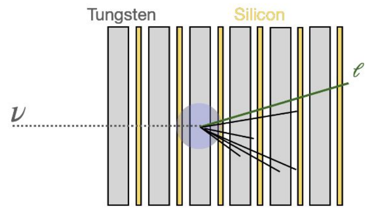


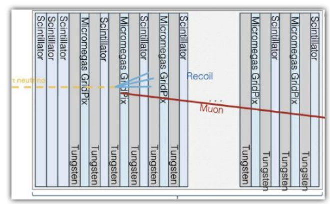
Scintillators





Precision Tracking





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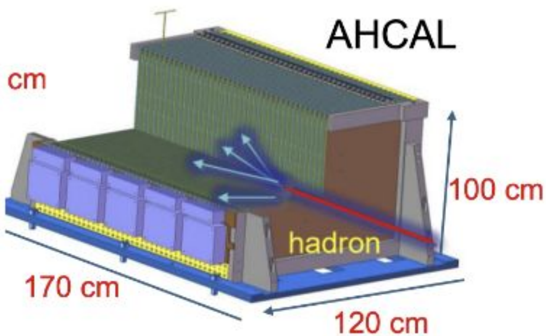
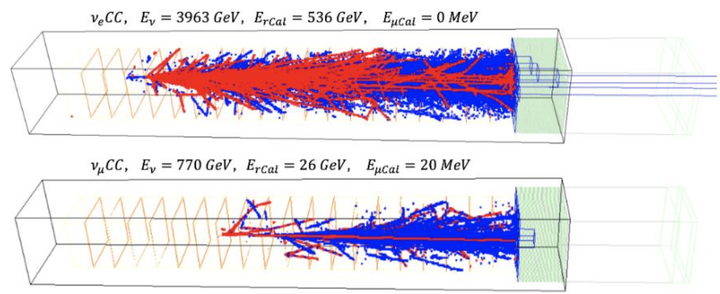


FASERCal: 3D Scintillator Cubes

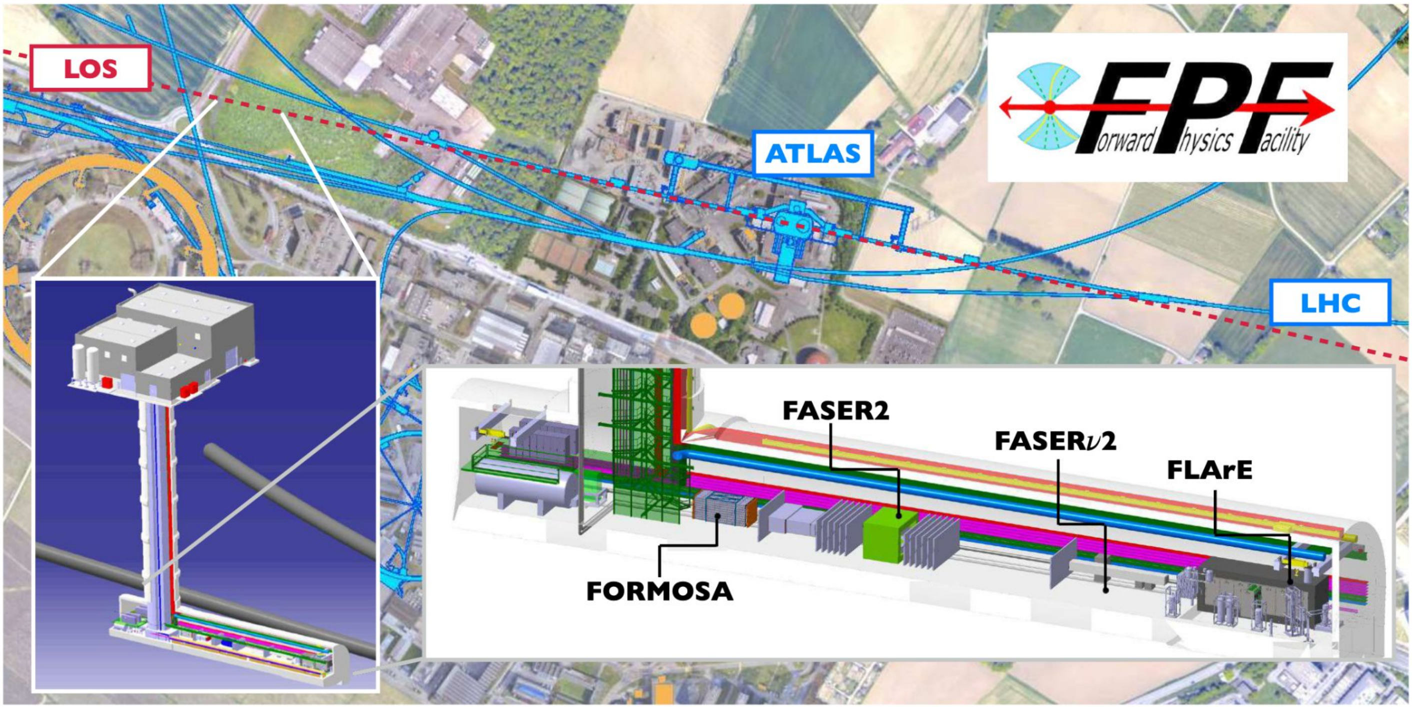


Prototypes of AHCAL and FASERCal planned already for 2026

Forward Physics Facility.

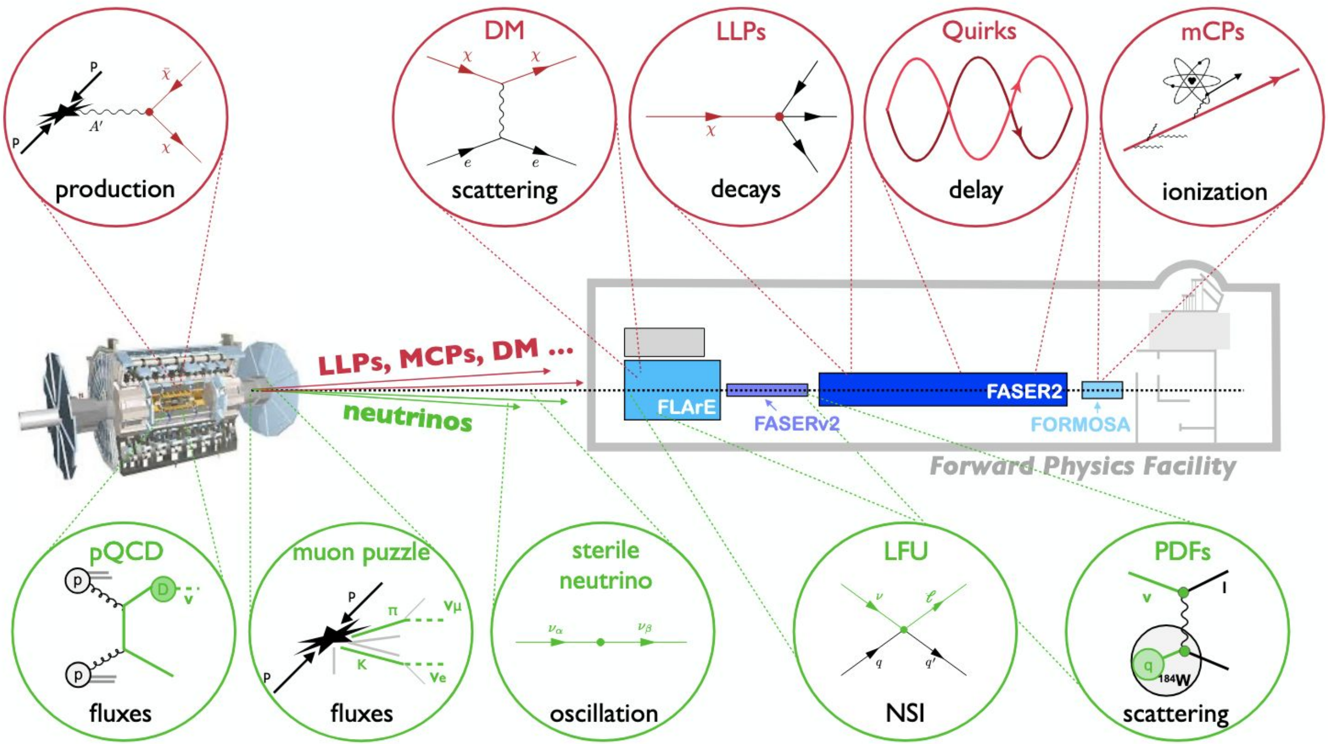
Current infrastructure at FASER side strongly constraints possible experiments.

Expansion of this program envisioned for HL-LHC era (2030s): the FPF.



Physics Opportunities

Physics Opportunities.

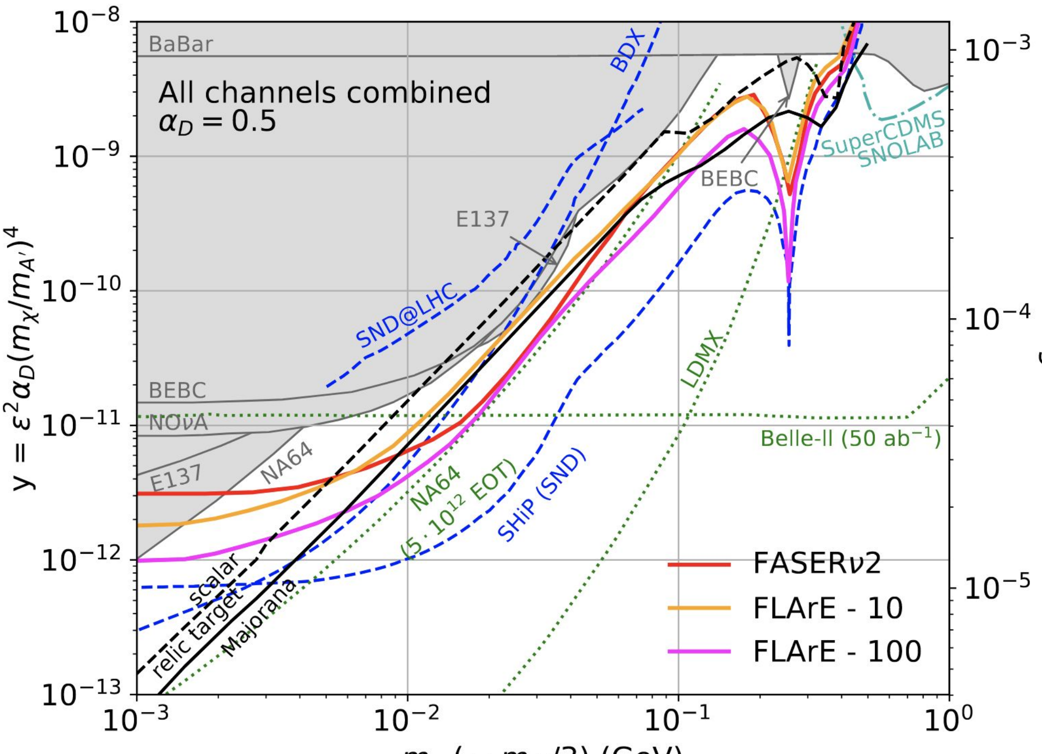


Dark Matter Scattering.

if mA’ > 2mX : A’ decays to DM

→ LHC produces energetic DM beam [**Batell**, **Feng**,**Trojanowksi**: 2101.10338]

DM scatters in **FLArE** and **FASERv2** neutrino detector: X e → X e.

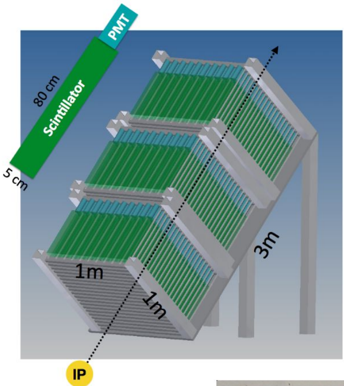


Millicharged Particles.

millicharge Q=εe → search for minimum ionizing particle with very small dE/dx

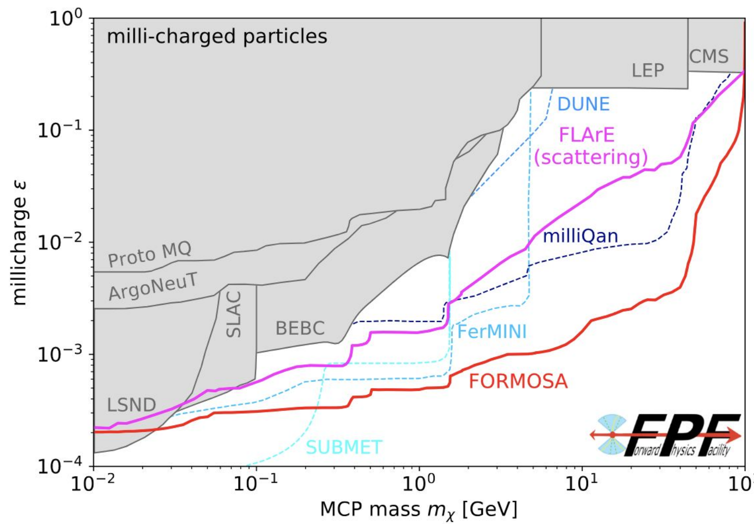
MilliQan was proposed as dedicated LHC experiment to search for MCPs near CMS

Flux is ~100 times larger in forward direction: **FORMOSA** [Abari, FK, Tsai, 2010.07941]



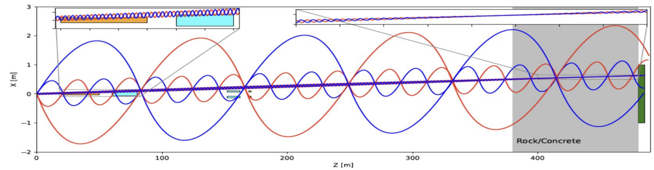
[MilliQan, 1607.04669]

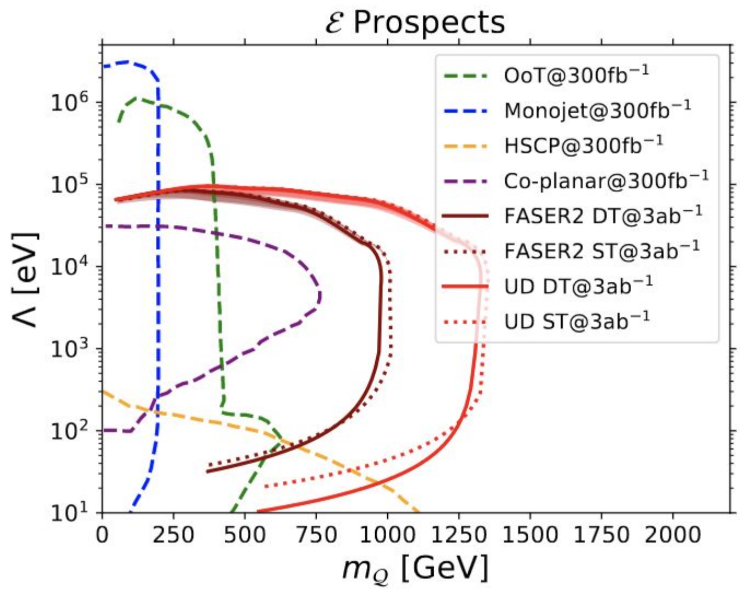
Demonstrator installed last year.



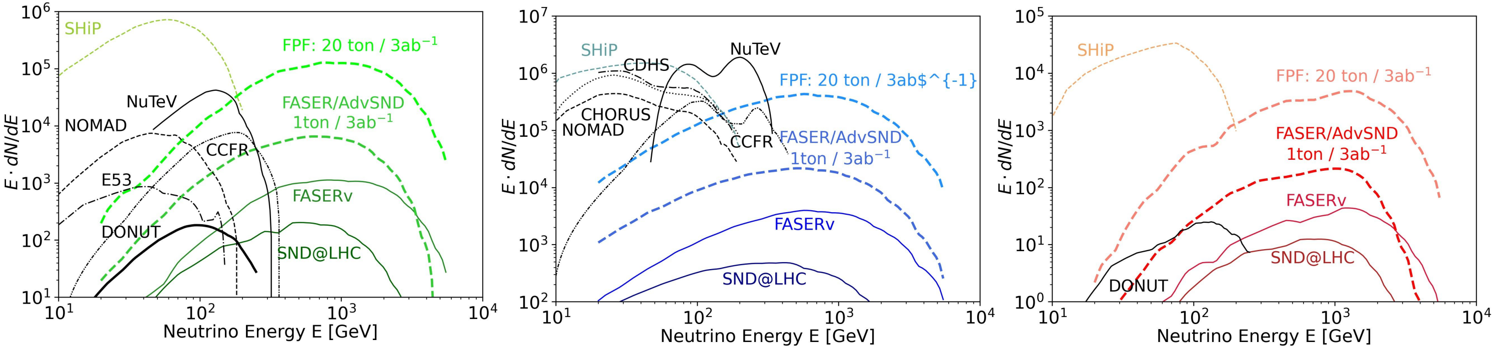
Quirks.

FASER and **FASER2** may also be able to probe quirks
- mass range of 100s GeV - TeV motivated by hierarchy problem, neutral naturalness
- quirk-anti-quirk system bound by hidden QCD, highly forward peaked
- signature: delayed/slow tracks [**Feng**, Li, Liao, Ni, Pei; 2404.13814]





Collider Neutrino Physics.

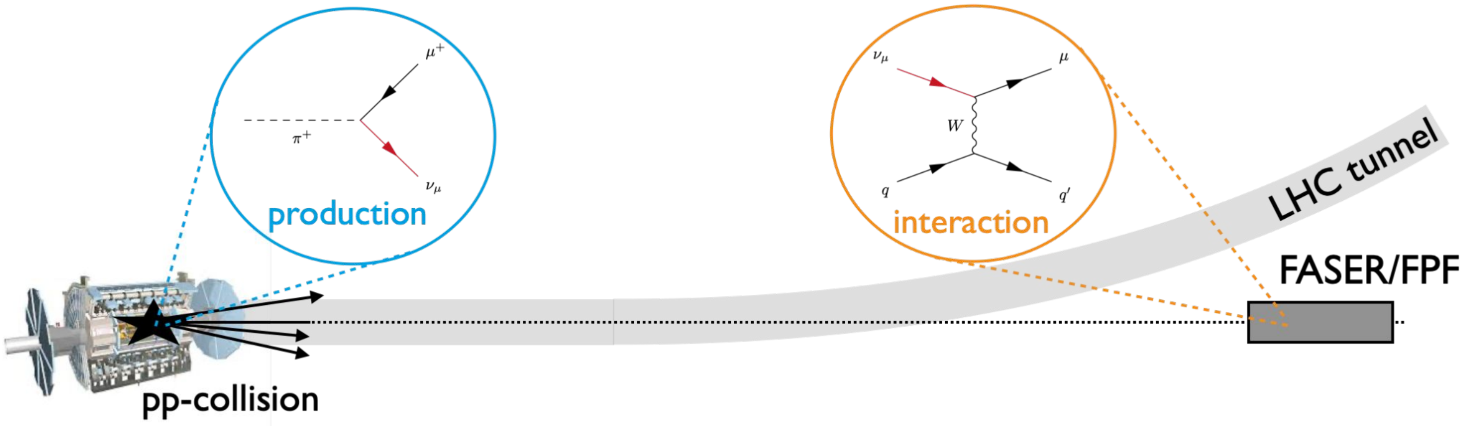


LHC neutrinos uniquely cover unexplored TeV energy range.

Thousands of neutrino interactions in current detectors.

Millions of neutrino interactions expected at FPF detectors, including several thousands of tau neutrinos.

Collider Neutrino Physics.



complementary probe of
forward particle production

light and charm hadrons

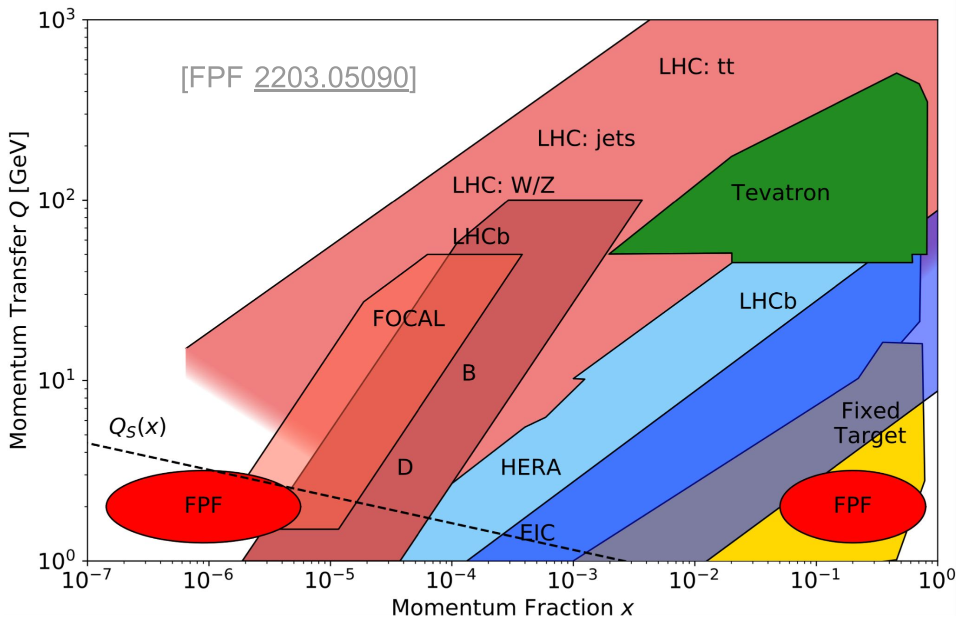
unique laboratory probe of
TeV energy neutrino interactions

cross sections and nuclear structure

Implications for QCD.

Neutrinos from forward charm production probe uncharted kinematic regimes in QCD.

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



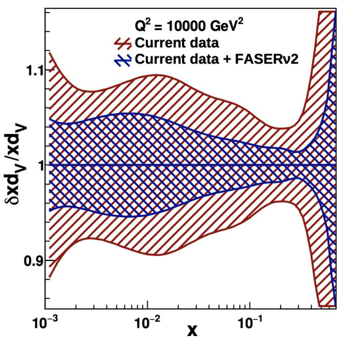
Unique ability to constrain gluon PDF at $x \sim 10^{-7}$ [FPF 2411.04175]

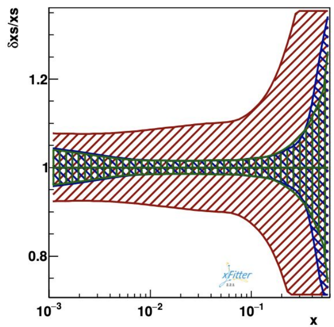
Sensitivity to gluon saturation and intrinsic charm.

Implications for QCD.

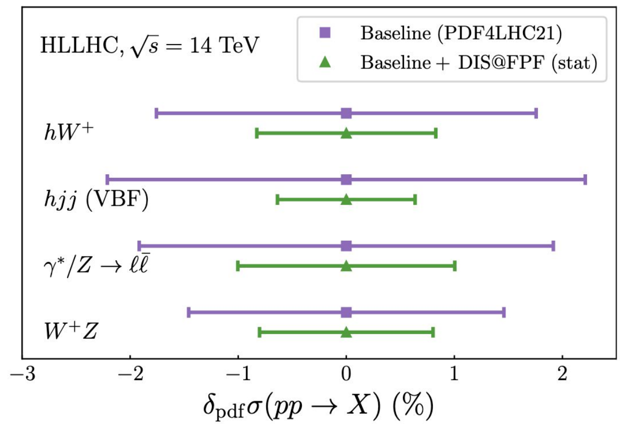
Collider Neutrino Experiments are a Neutrino-Ion Collider
at EIC center of mass energies

neutrino DIS data will improve PDFs
[Cruz-Martinez et al. 2309.09581]

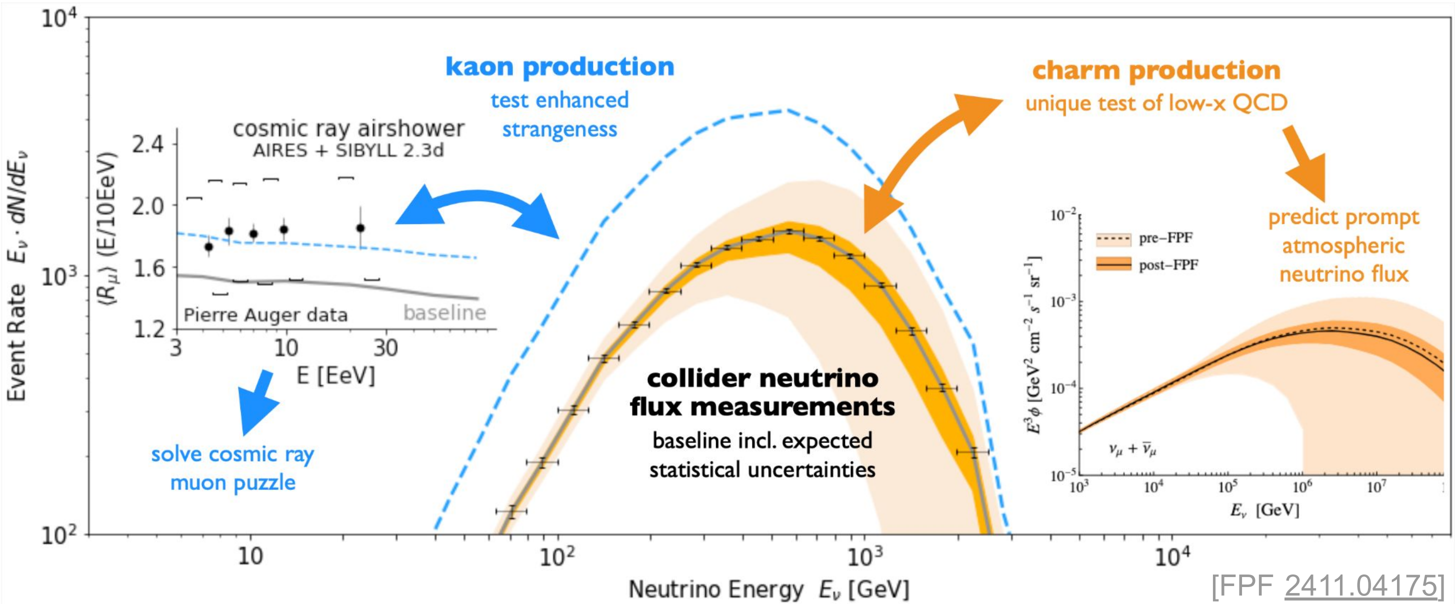




reduced PDF uncertainties for
many LHC processes and breaks
PDF/BSM degeneracy [FPF 2411.04175]



Implications for Astroparticle Physics.



[FPF 2411.04175]

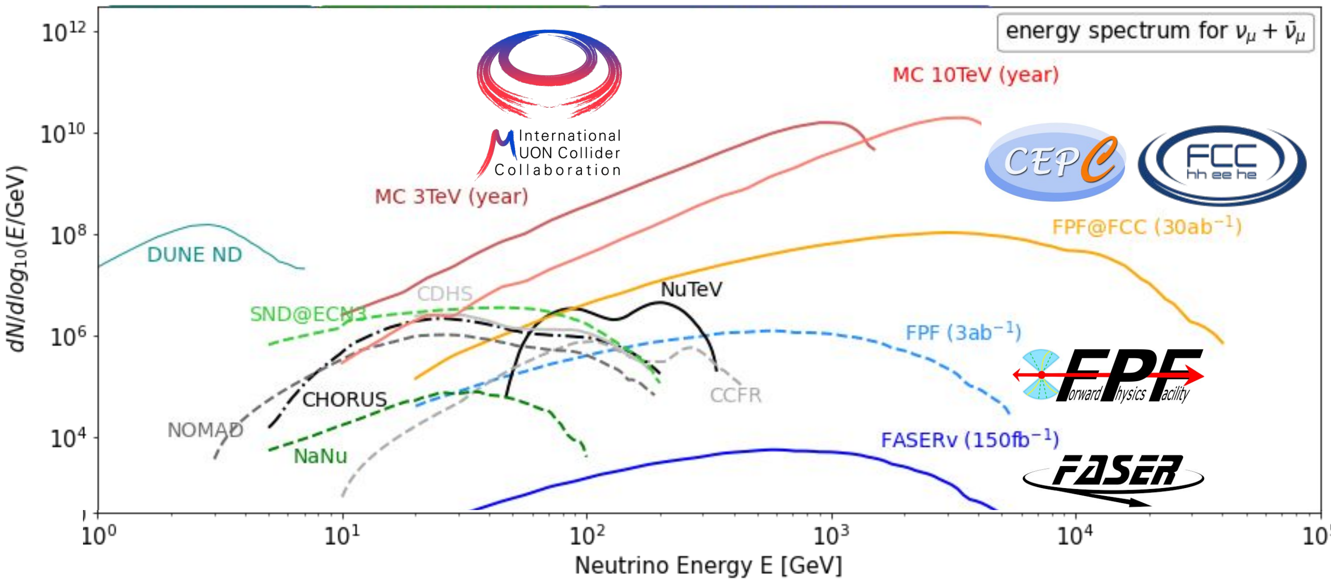
cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

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

Outlook: Far Future

Forward Physics beyond LHC.

The same ideas also apply to future colliders!



[FPF, 2203.05090] [Abraham, Adhikary, Feng, Fieg, FK, Rojo, Trojanowski, 2409.02163]] [MuCol Interim report, 2407.12450]

Summary

Summary.

A novel forward physics program emerged to fully exploit the LHC.

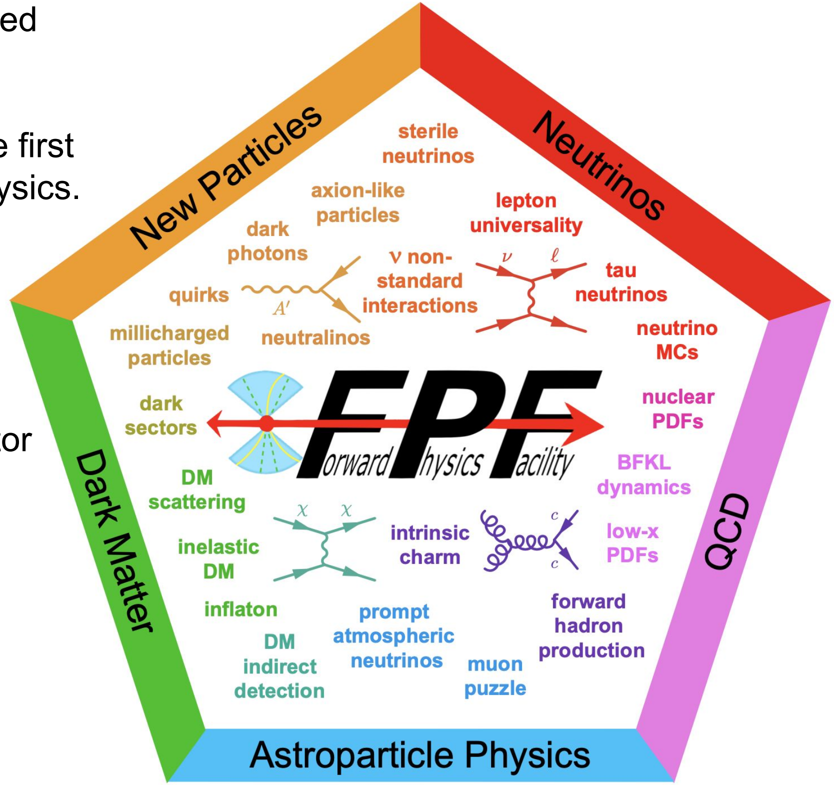
Already success: FASER discovered the first neutrinos in the 50+ years of collider physics.

This is just the beginning of a time of multi-messenger collider physics
- neutrinos: messenger to QCD
- new particles: messenger to dark sector

Many more exciting results to come.

Program heavily benefited from good ideas in the community.

Let's come up with some new ideas!



[Feng, FK, Reno, Rojo, Soldin et al. 2203.05090]