Probing Saturation in LHC Neutrino Experiments

Dr. Felix Kling
Rheinische Friedrich-Wilhelms-Universität Bonn

EMMI Workshop: *Mining for gluon saturation at the LHC and the future EIC*

GSI - July 6-10 2026

UNIVERSITÄT BONN

Idea and Motivation

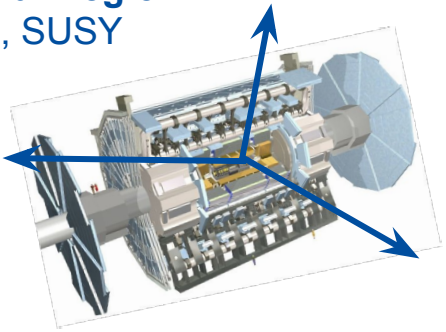
Main focus of LHC are heavy particles: Higgs, SUSY … .

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

ATLAS/CMS were constructed to catch them.

Central Region

H, SUSY



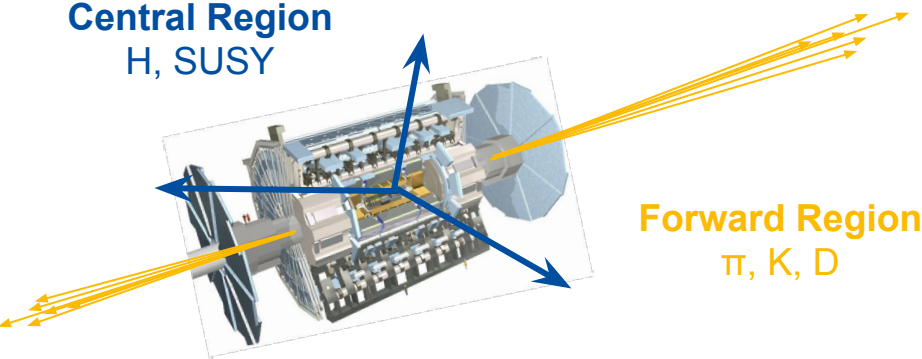
Idea and Motivation

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?

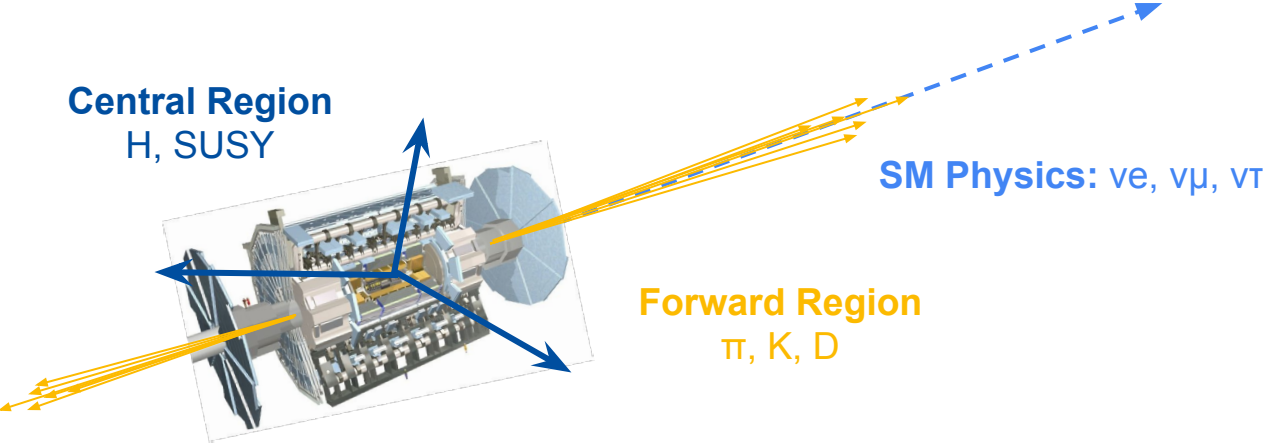
Central Region
H, SUSY



Forward Region
π, K, D

Idea and Motivation

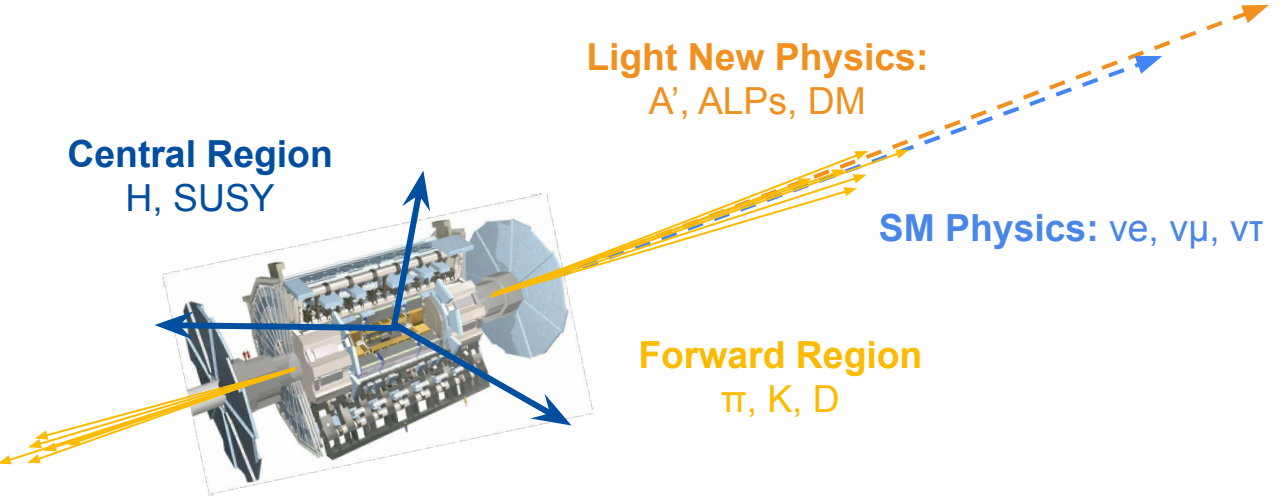
The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction.



Idea and Motivation

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

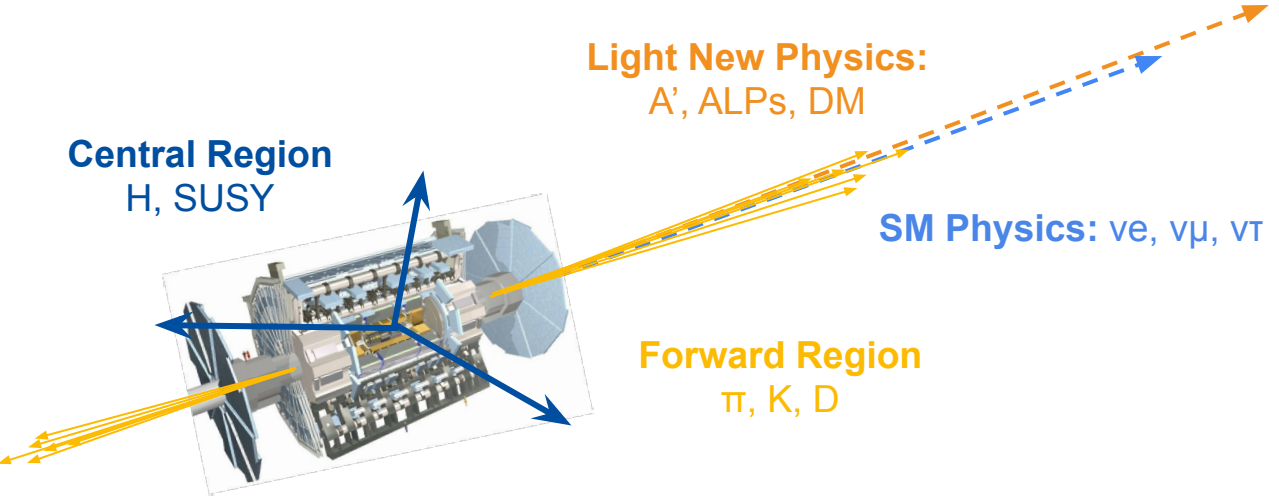
This may also be true for many interesting new particle candidates: dark photons, axion-like particles, dark matter.



Idea and Motivation

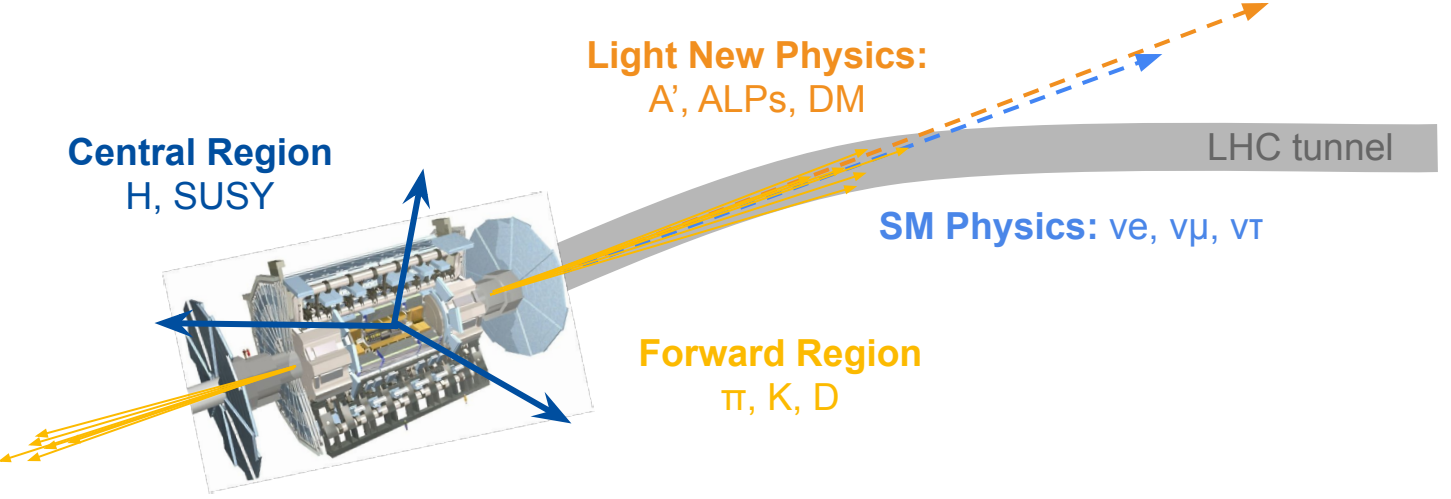
These particles escape down the beam pipe and remain undetected.

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



Idea and Motivation

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

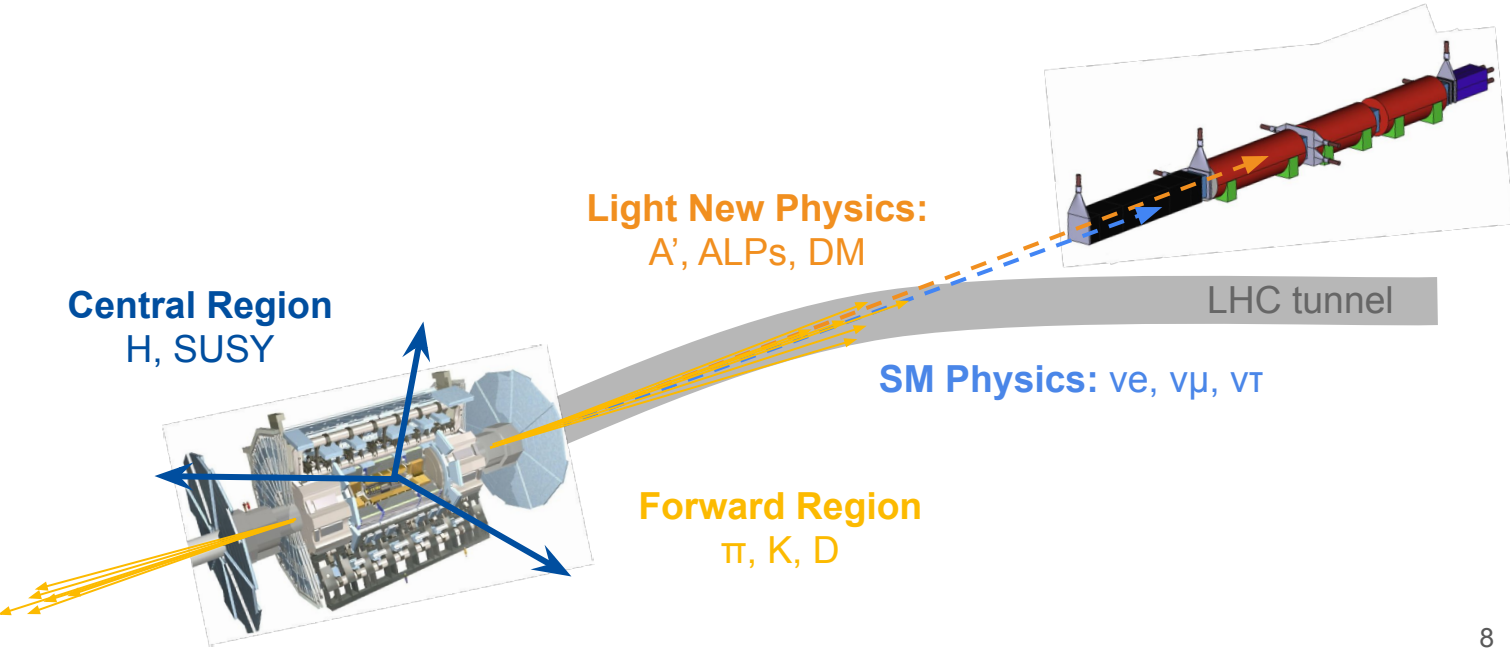


Idea and Motivation

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 there: FASER

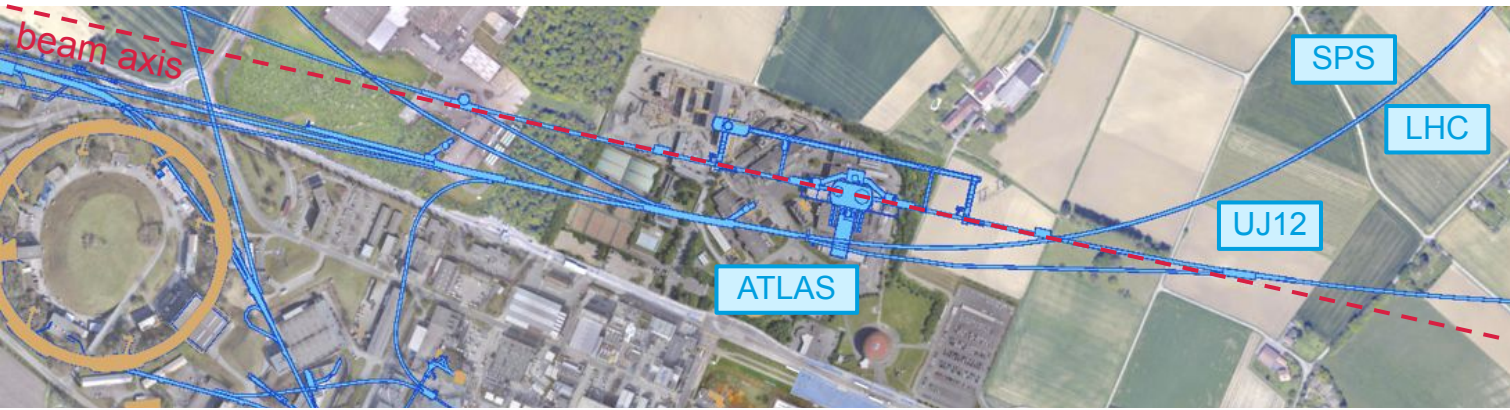
[Feng, Galon, FK, Trojanwoski, 1708.09389]



Experimental Program and First Observation

Experimental Program

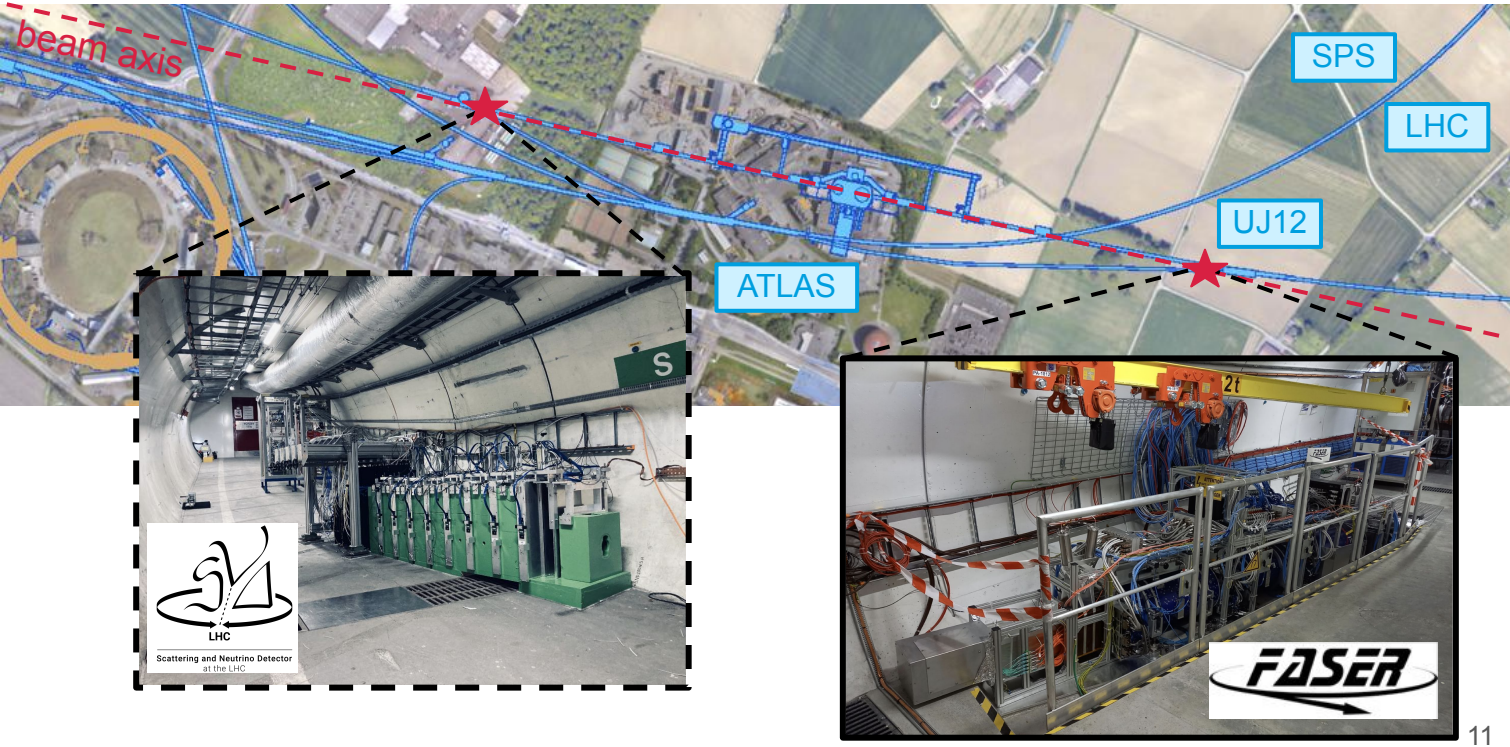
There is potential for forward physics experiments along beam axis.



Experimental Program

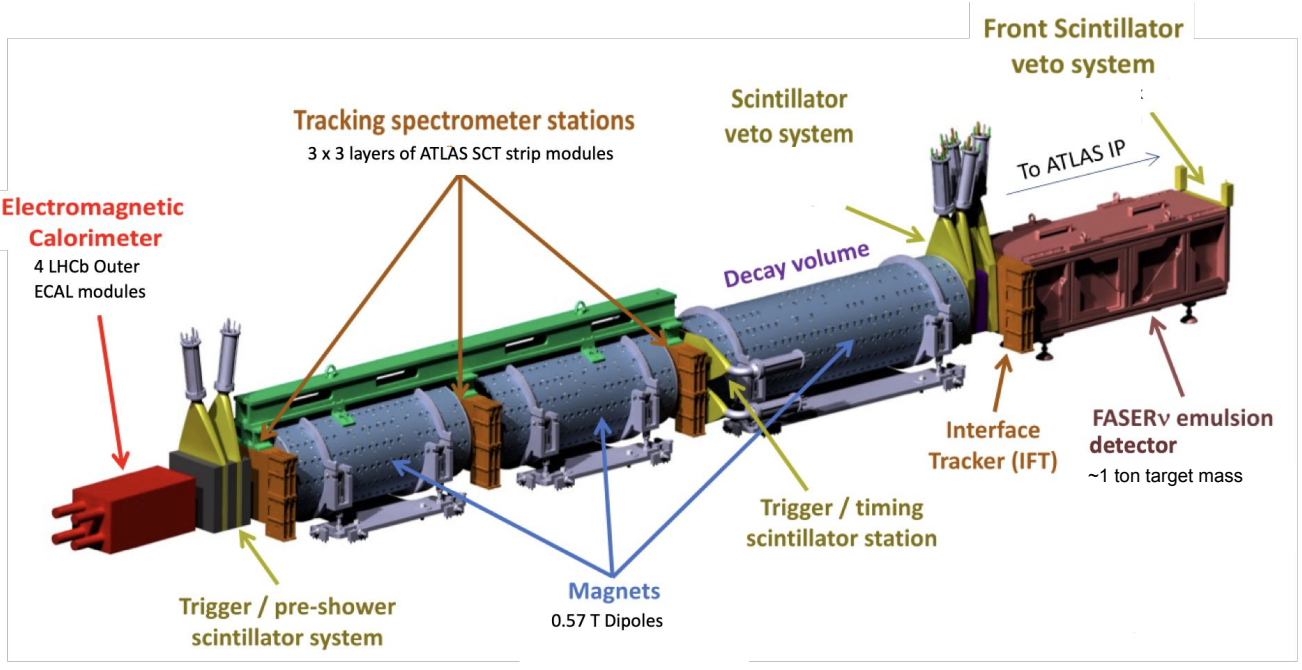
There is potential for forward physics experiments along beam axis.

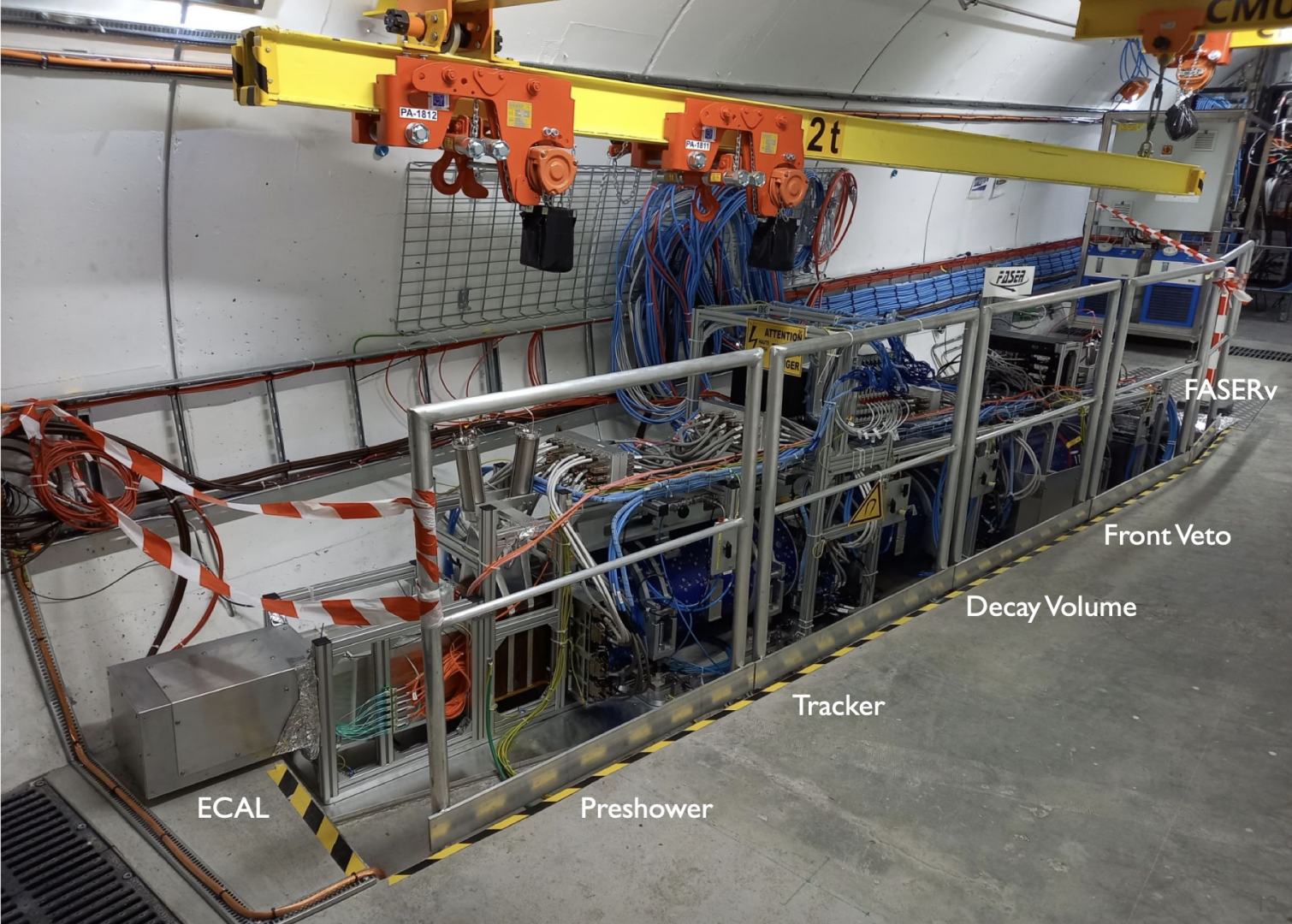
Two new experiments started operation in 2022 to exploit this potential:
SND@LHC and FASER.



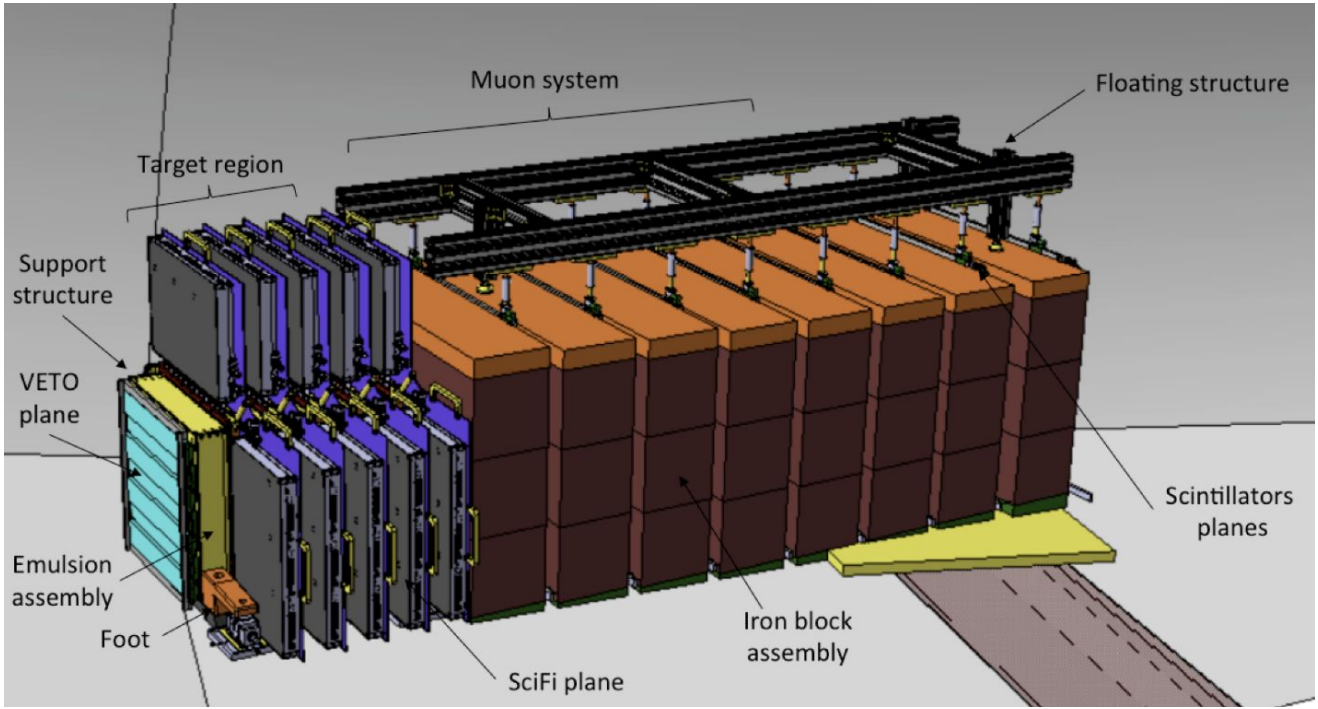
FASER

[FASER, arXiv:2207.11427]

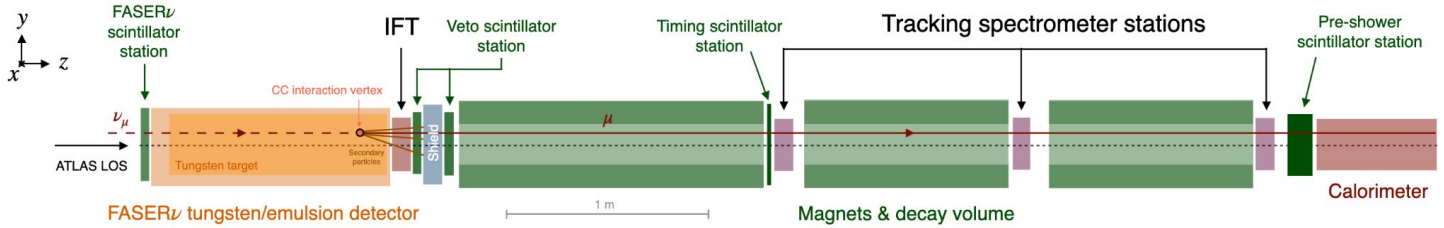



FASERν
Front Veto
Decay Volume
Tracker
Preshower
ECAL

SND@LHC


Muon system
Floating structure
Target region
Support structure
VETO plane
Scintillators planes
Emulsion assembly
Foot
Iron block assembly
SciFi plane

First Collider Neutrino Observation

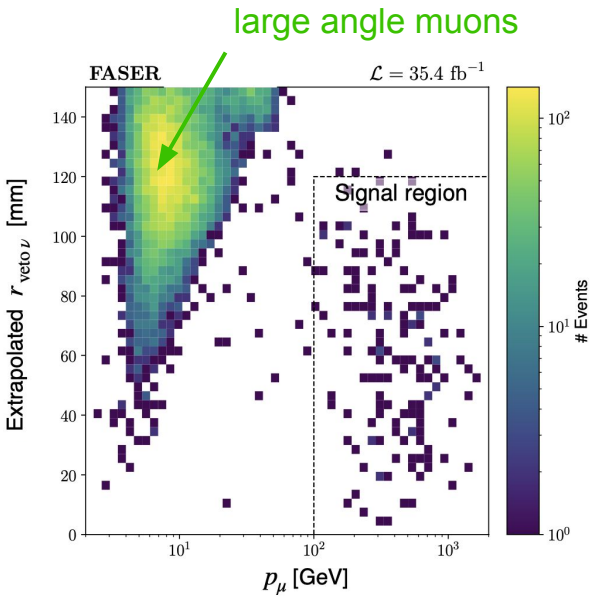


Strategy
- search for charged current νμ events through muon appearance
- use only electronic detector

Selection
- 1 good track with p>100GeV
- front veto not activated

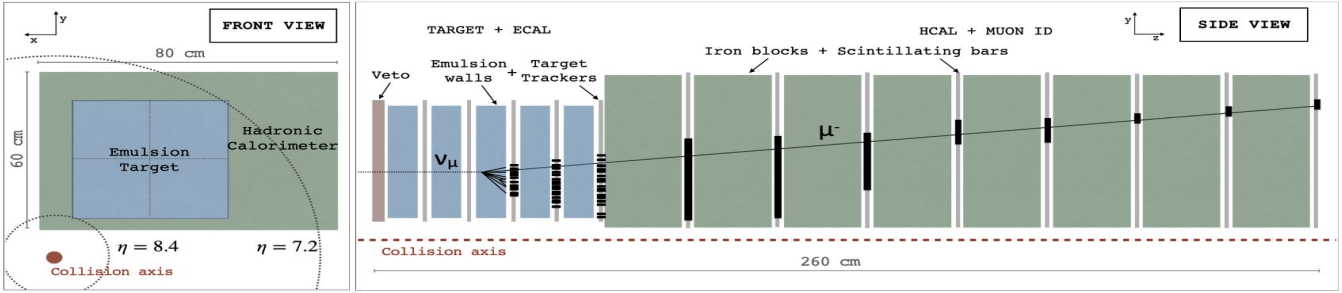
Background
- neutral hadrons (0.11±0.06 from MC)
- large-angle muons (0.08±1.83 from data)

Result
- 153 νμ events: 16σ!
- first direct observation of collider neutrinos



[FASER, 2303.14185]

First SND@LHC Analysis



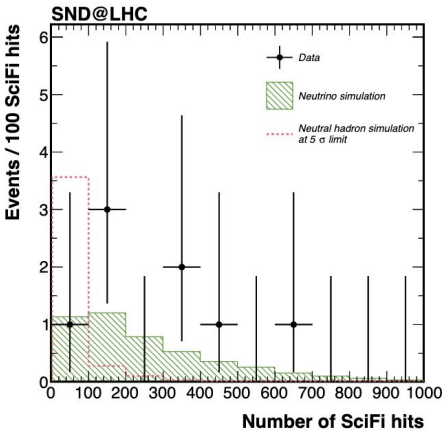
Strategy
- search for CC νμ events
- use only electronic detector components

Selection
- long track with muon ID
- high number of hits in SciFi station
- front veto not activated

Background: 0.086

Result: 8 events in 2022 (6σ)

Update: 32 events in 2023



[SND@LHC, 2305.09383]

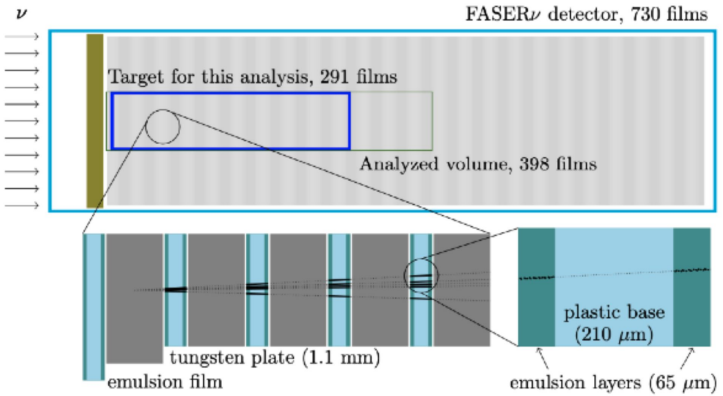
First FASERν Analysis

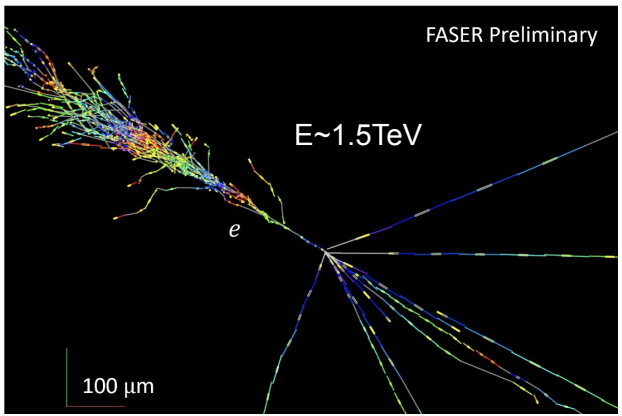
FASERν emulsion detector
- 1.1 ton tungsten target with 730 emulsion planes
- sub μm spatial resolution

Data Set
- 9.5 fb-1 in 2022 run
- analyzed target mass of 128.6 kg
- ~1.7% of data collected so far

Analysis
- developing and scanning emulsion films
- align and reconstruct tracks
- find candidate CC vertices
- electron energy from shower multiplicity
- muon momentum from MCS

Observed events:
- electron neutrino: 4 (5.2σ)
- muon neutrino: 8 (5.7σ)





[FASER, 2303.14185]

The Dawn of Collider Neutrino Physics

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

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Research team detects first neutrinos made by a particle collider

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

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 masselose 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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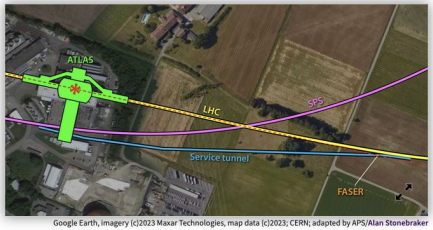
VIEWPOINT

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

FASER observes first collider neutrinos

Physics • CERN

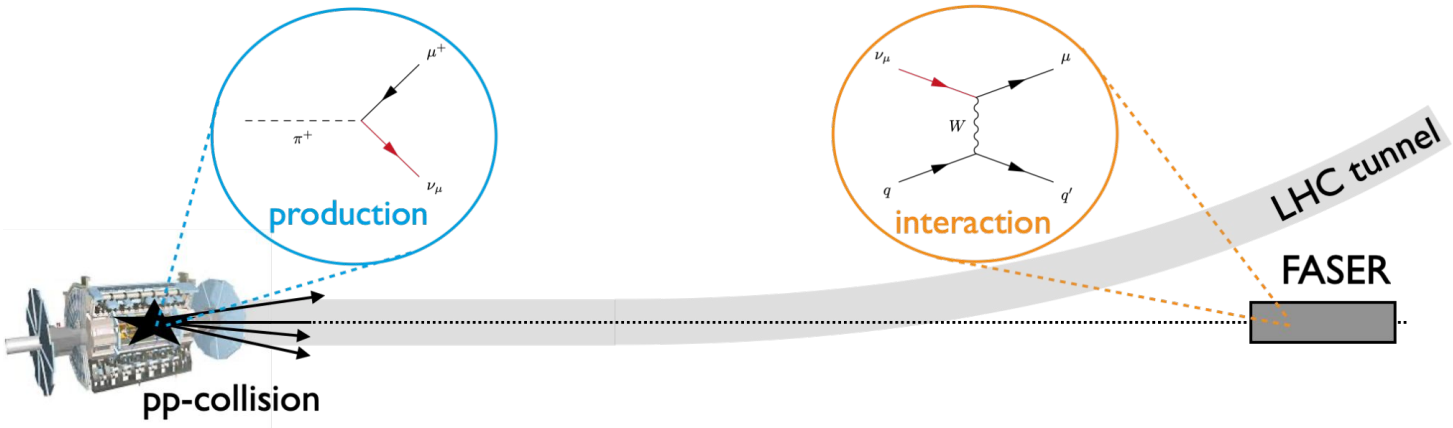
0:00 / 2:54

Collider Neutrino Physics and Saturation

Neutrino Flux Measurements

Current LHC experiments will detect thousands of neutrinos
Plans for larger detectors which could detect millions of neutrinos.

What physics can we probe with them?



complementary probe of
forward particle production

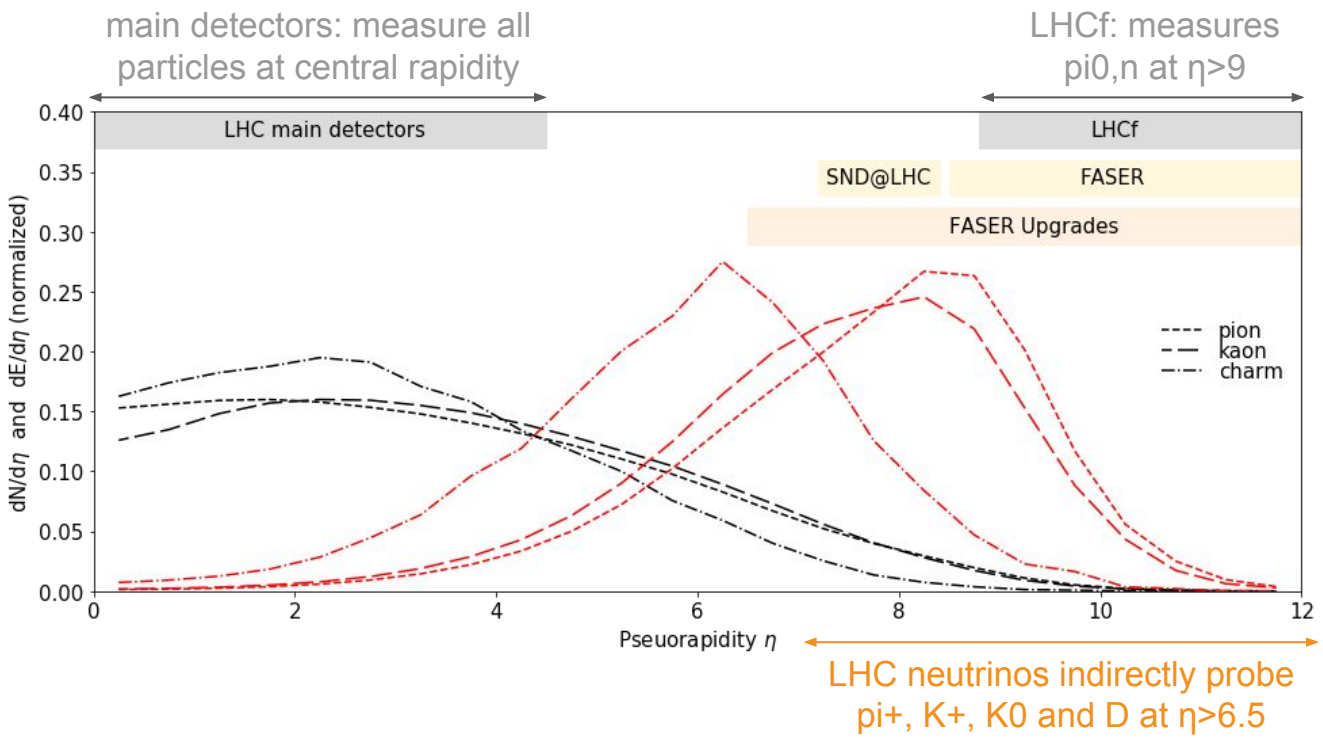
light and charm hadrons

unique laboratory probe of
TeV energy neutrino interactions

cross sections and nuclear structure

Neutrino Flux Measurements

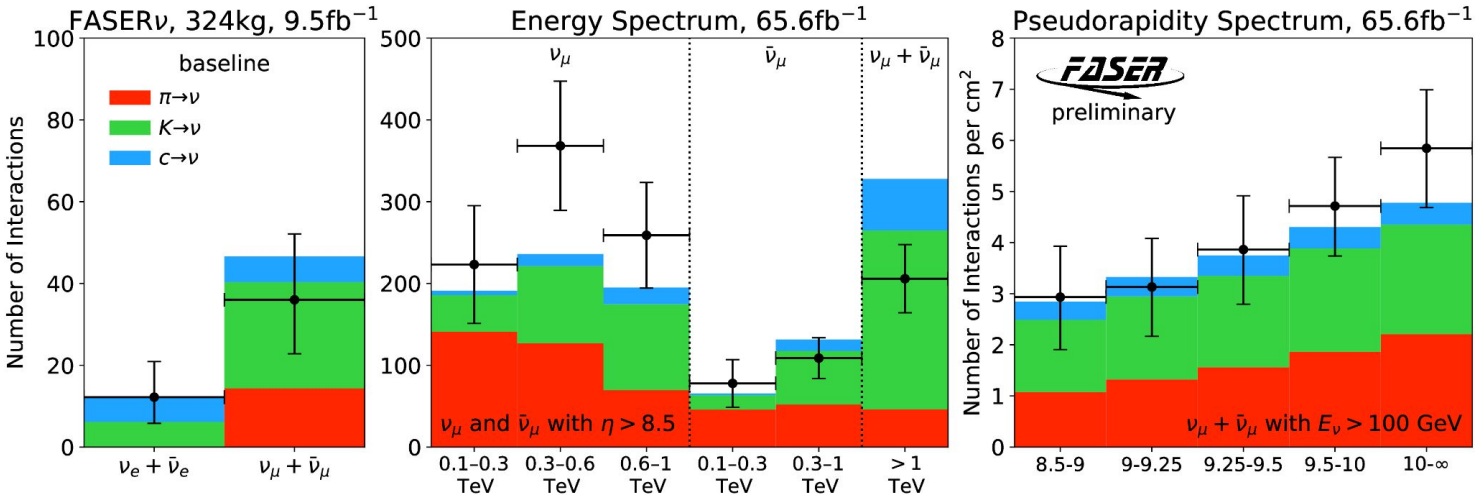
Most of the energy of event is carried by pion/kaons with η~8.5 and charms with η~6. So measuring these particles at higher η>5 is well motivated.



Neutrino Flux Measurements

FASER data can test forward particle models.

[FASER, 2412.03186], [FASER 2507.23552]

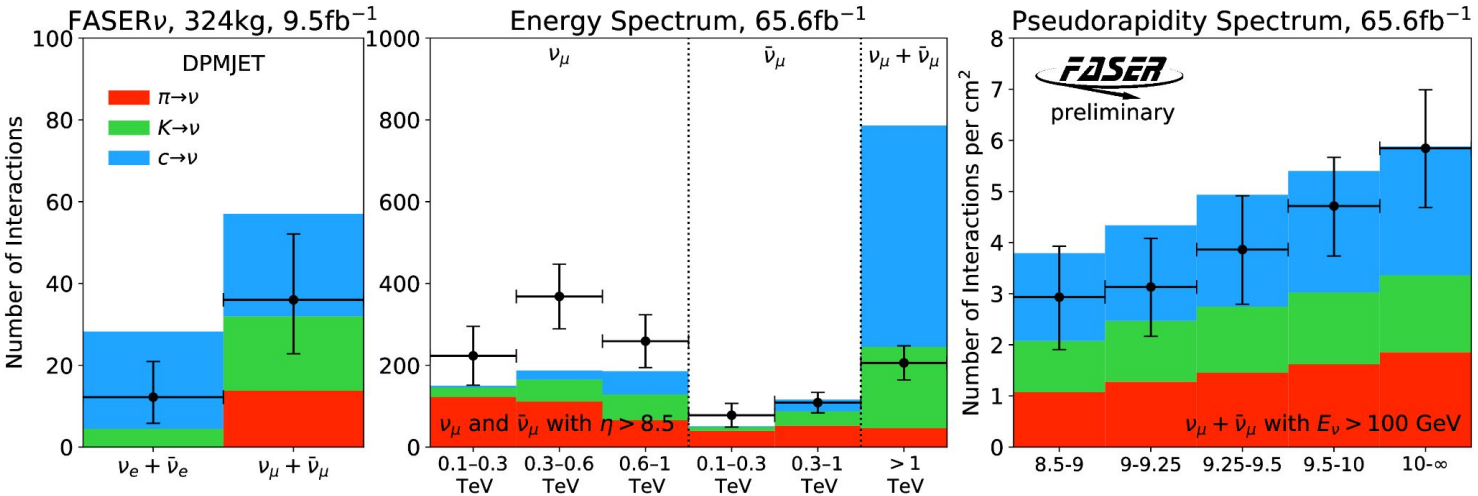


EPOS-LHC+ POWHEG: mild excess compared to theory predictions

Neutrino Flux Measurements

FASER data can test forward particle models.

[FASER, 2412.03186], [FASER 2507.23552]

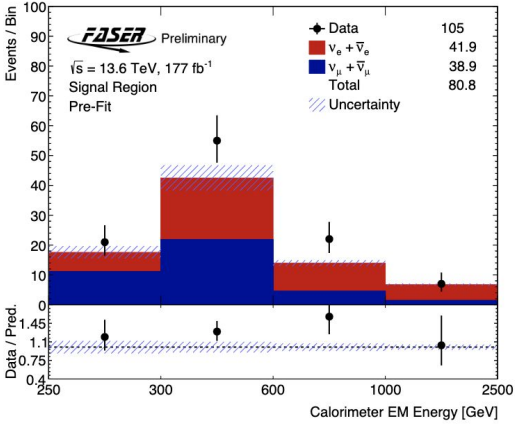


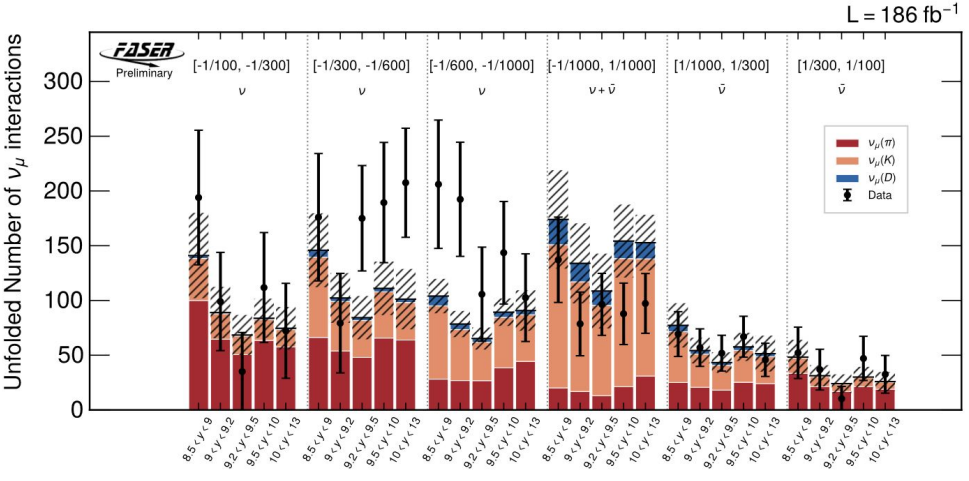
DPMJET: already ruled out some models with first data

Neutrino Flux Measurements

New preliminary results

[FASER, CDS:2956617], [FASER CDS:2956447]

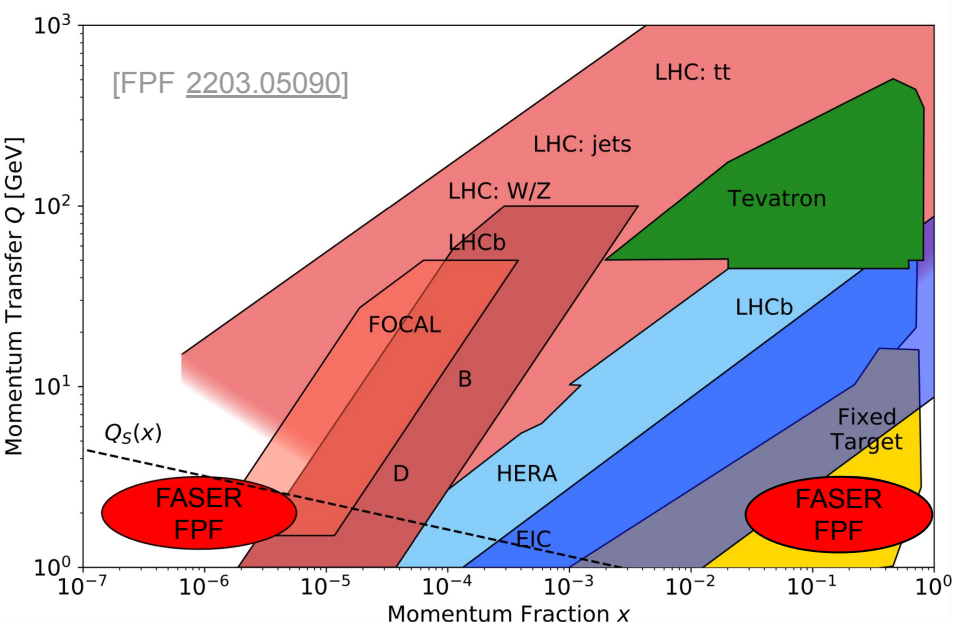




Implications for QCD

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

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



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

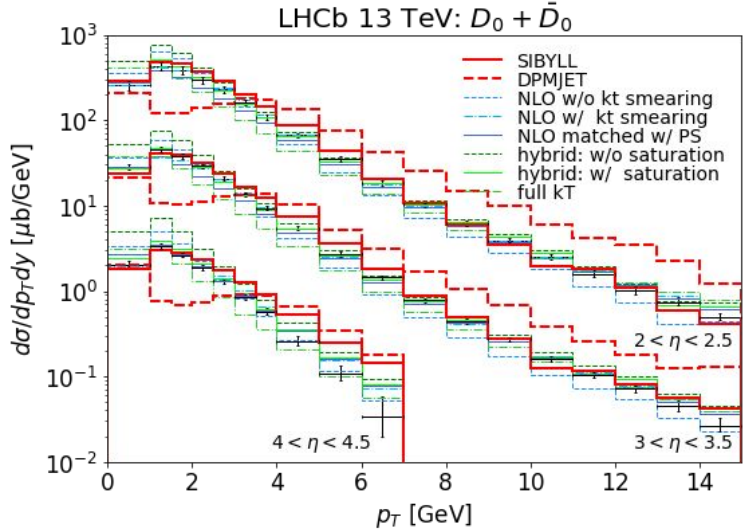
Sensitivity to gluon saturation and intrinsic charm.

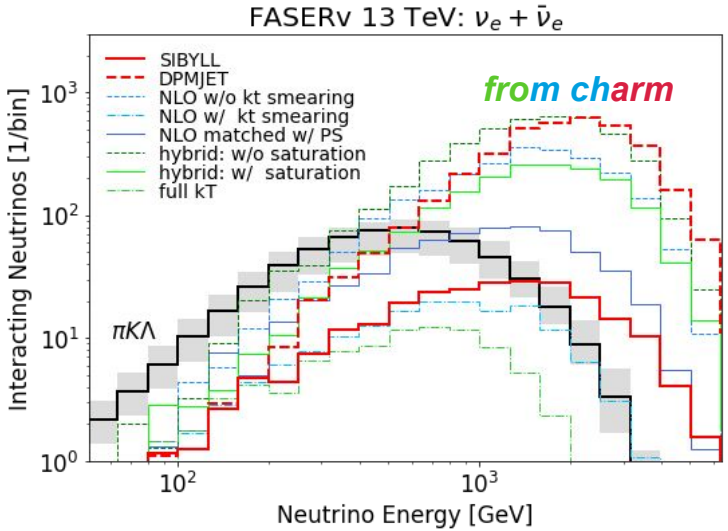
Neutrinos from Charm Hadrons

forward charm hadron production can, in principle, be calculated using perturbative QCD

several predictions available 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]





large spread of predictions at FASER

approximate descriptions of hard scattering/hadronization may affect reliability

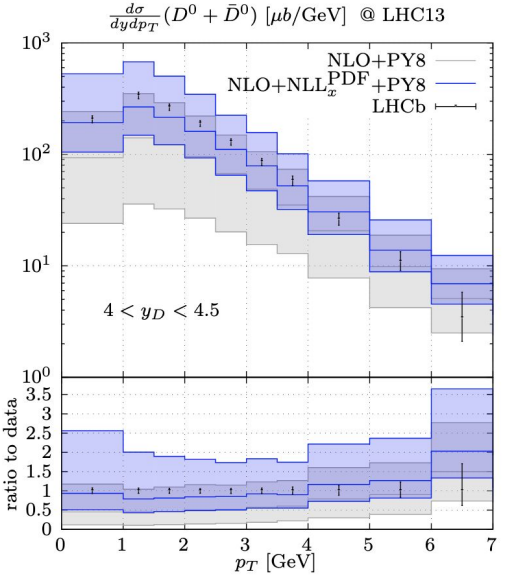
Neutrinos from Charm Hadrons

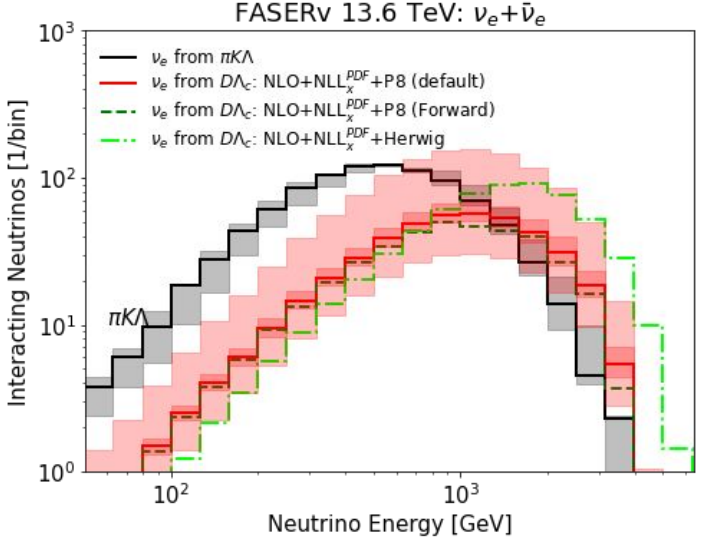
state-of-the-art QCD predictions for charm an bottom using POWHEG+Pythia: NLO+NLLx accuracy

[Buonocore, FK, Rottoli, Sominka, 2309.12793]

NNPDF3.1sx + LHCb PDF set: includes small-x resummation at NLLx and fit to LHCb D-meson data

[Ball et al. 1710.05935] [Bertone, Gauld, Rojo, 1808.02034]





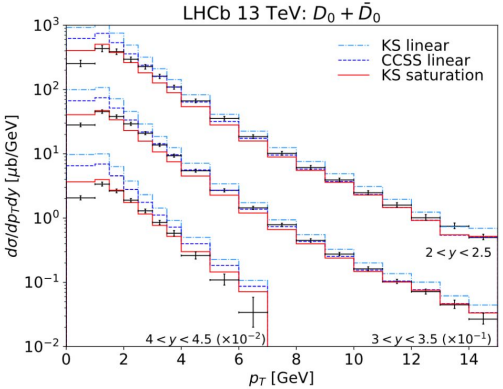
matching with Pythia for shower and hadronization

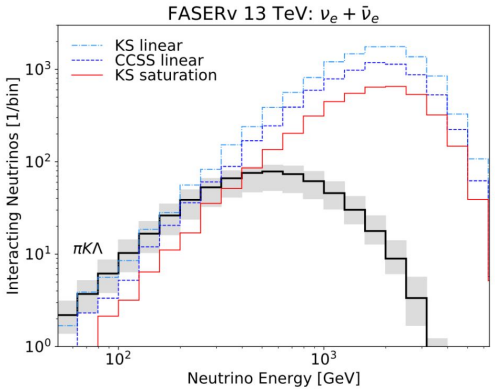
scale uncertainties dominate: roughly factor 2

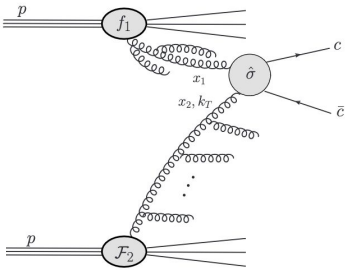
Implications for Saturation

Prediction using kT-factorization (hybrid approach)

[Bhattacharya, FK, Stato, Sarcevic: 2306.01578]







study of **gluon saturation** at low-x

Implications for Saturation

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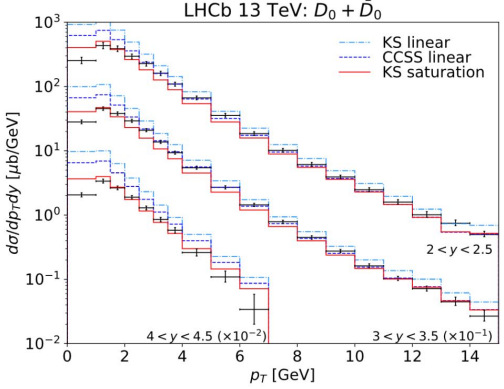
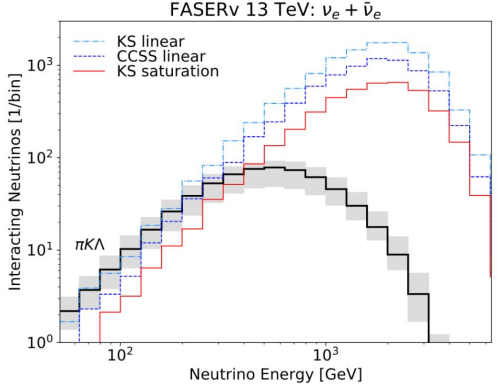
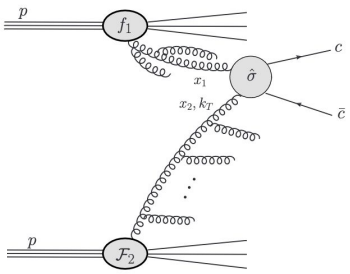
[Bhattacharya, FK, Stato, Sarcevic: 2306.01578]

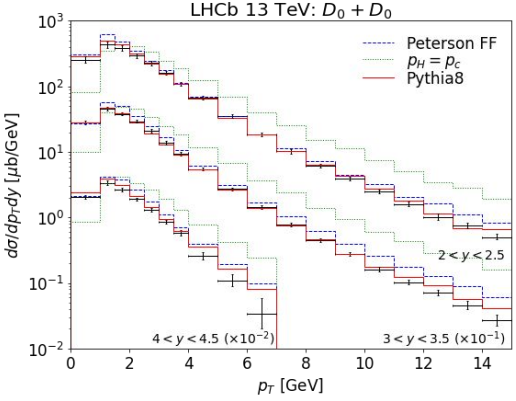


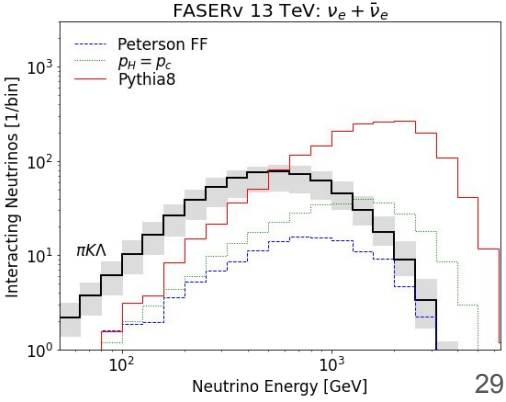




study of **gluon saturation** at low-x

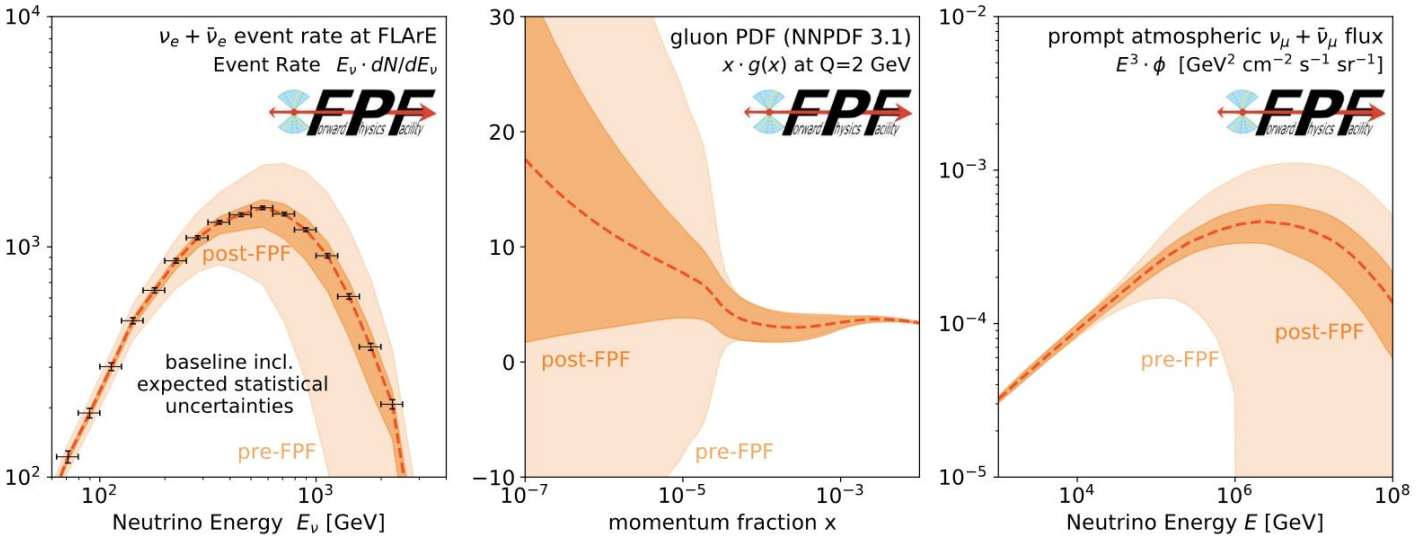
dominating modelling uncertainty at the moment: **hadronization**





Implications for Astroparticle Physics

FLArE at FPF = proposed bigger version of FASER



forward charm production at the LHC will constrain the **low-x gluon PDFs** and thus **prompt atmospheric neutrino fluxes** at IceCube

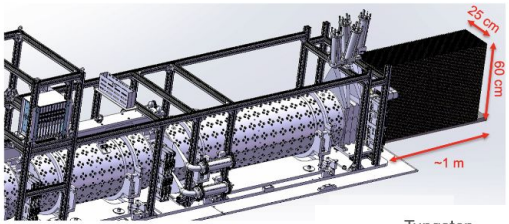
[FPF 2510.26260]

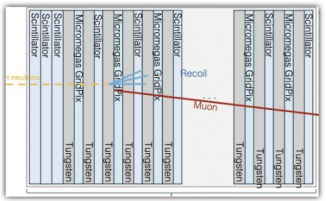
Outlook

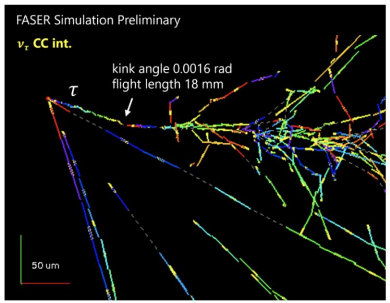
FASER at the HL-LHC

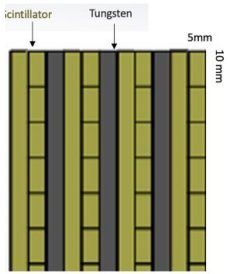
FASER has been approved to continue operation in LHC Run 4 (starting 2030).

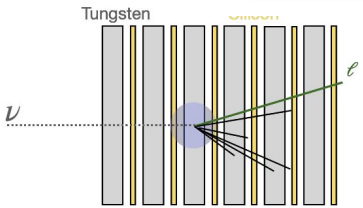
FASER is planning to continue its neutrino program during the HL-LHC. Several detector options are being investigated [2503.19775].

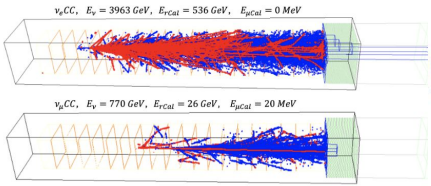


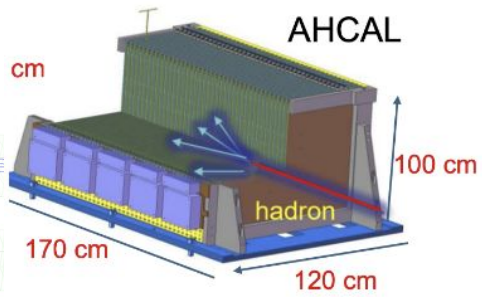








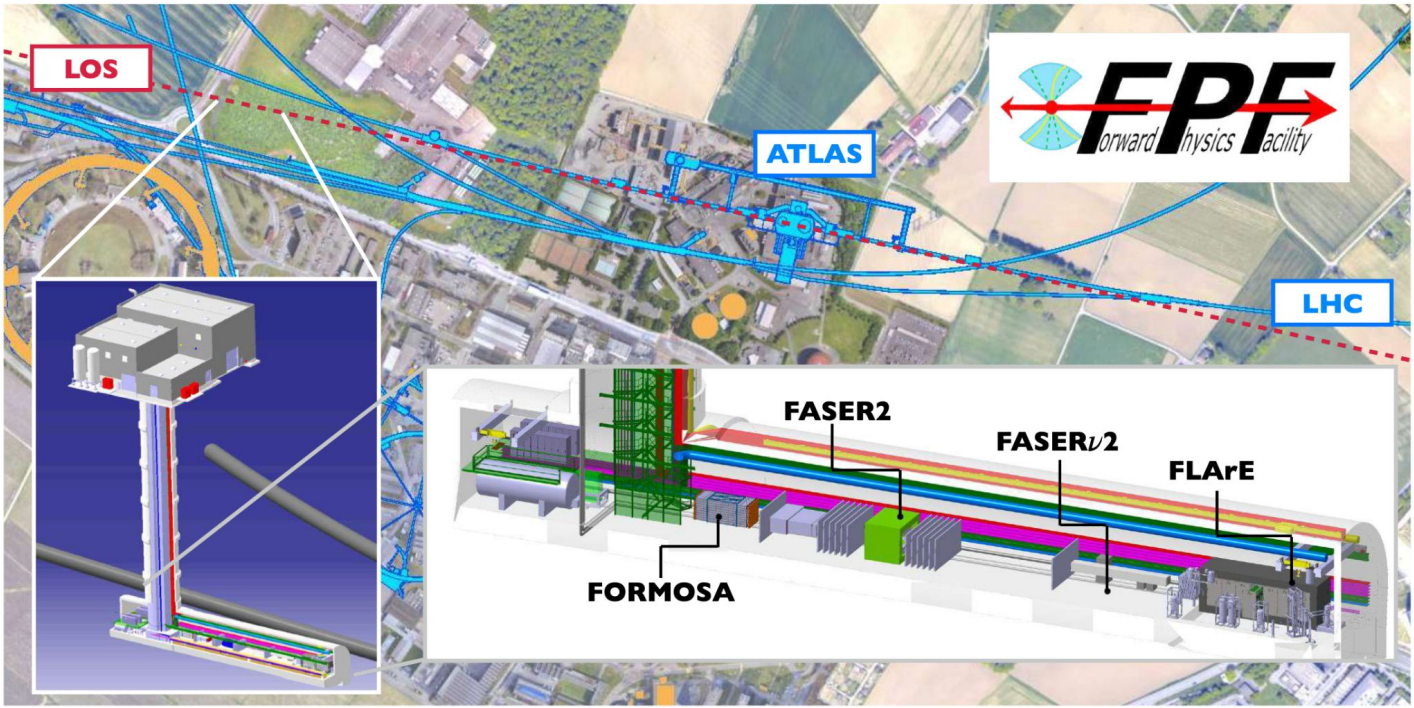




Forward Physics Facility

Proposal to create a dedicated **Forward Physics Facility (FPF)** for the HL-LHC: suite of experiments that will greatly enhance the LHC's physics potential.

Millions of neutrinos expected, including thousands of tau neutrinos.



Summary

Summary

A novel collider neutrino program emerged to fully exploit the LHC.

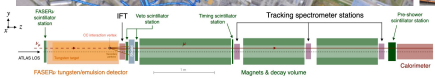
FASER discovered the first neutrinos in the 50+ years of collider physics.

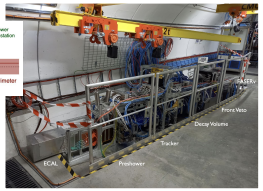
First measurements of the neutrino interaction cross section and neutrino flux were performed, that allowed to test theoretical predictions and models.

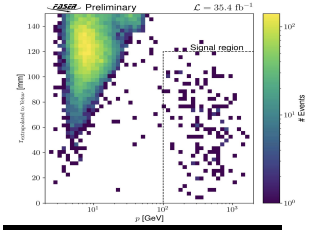
Neutrinos are an interesting tool to study QCD, including saturation.

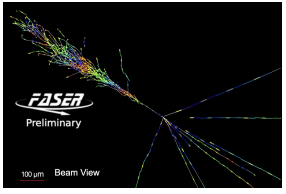
Plans to expand program at LHC.

Also applicable to future colliders.









The Dawn of Collider Neutrino Physics

Elizabeth Worcester
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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.