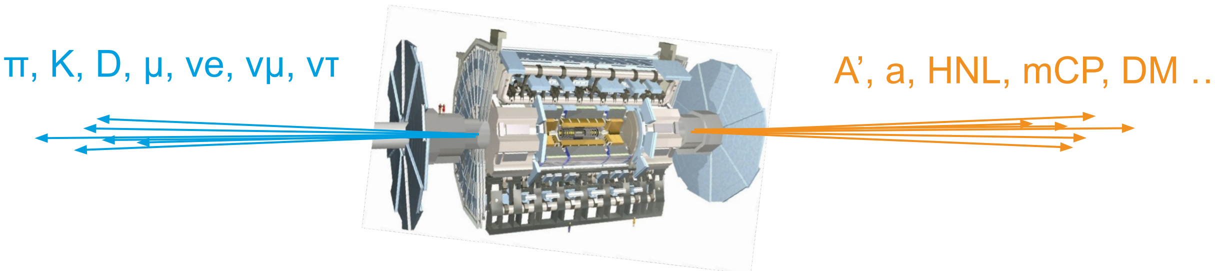
The Forward Physics Facility at the LHC.

Felix Kling
LLP 14 Workshop
05/07/2024

Introduction

Motivation and Introduction.

LHC collisions produce an enormous number of particles along the beam collision axis, which escape existing LHC detectors.

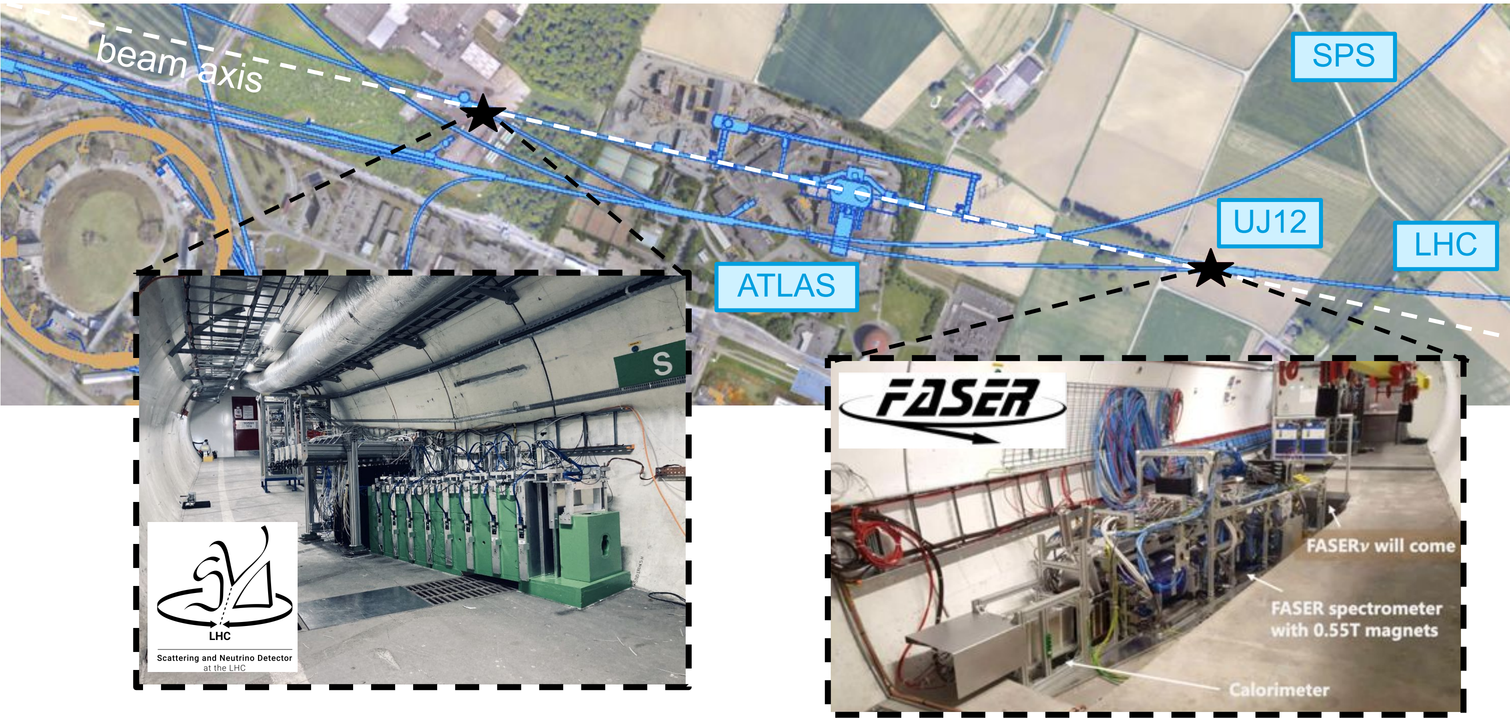


In recent years it became very clear that there is a broad program of SM and BSM physics associated to these particles.

Without dedicated detectors in the far-forward direction, the LHC would be blind to this beautiful physics program.

FASER and SND@LHC.

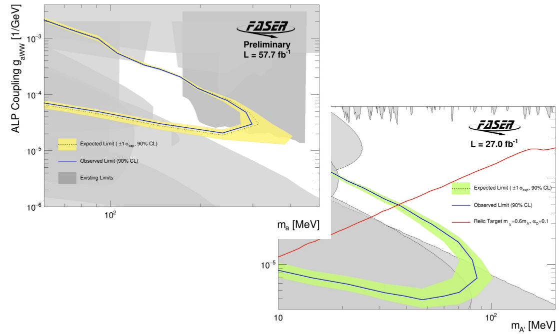
Two new experiments have started their operation with the start of LHC Run 3:
SND@LHC and **FASER**.

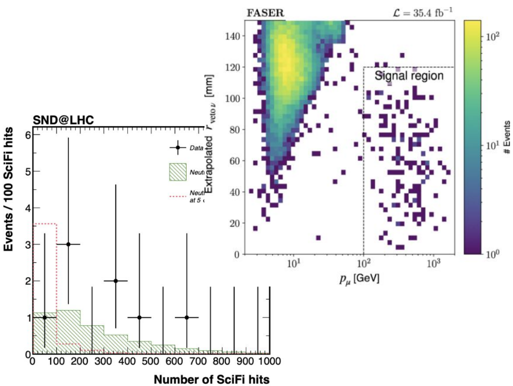


FASER and SND@LHC.

First experimental results from pathfinder experiments are already available!

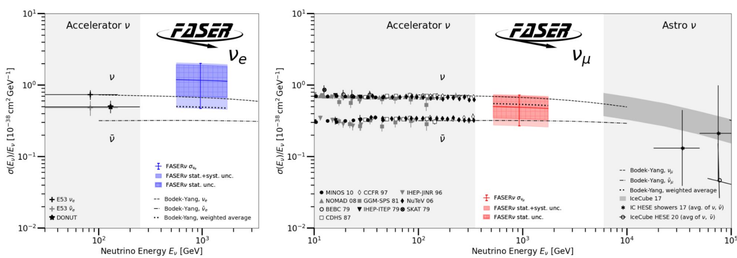
First search results on dark photons and ALPs
[FASER, 2308.05587] [FASER, CERN-FASER-CONF-2024-001]





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

First measurement of TeV energy neutrino cross sections.
[FASER, 2403.12520]



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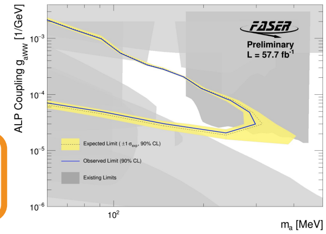
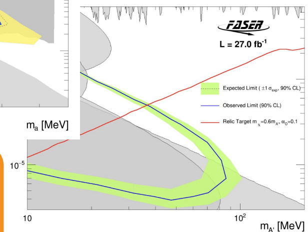
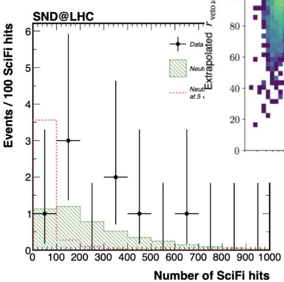
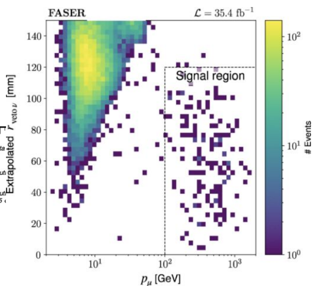




Yuxiao Wang
FASER BSM results

Masahiro Komatsu
Recent results from the SND@LHC experiment





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Motoya Nonaka
New neutrino results from the FASER experiment at the LHC

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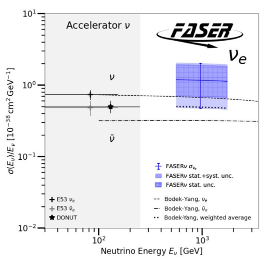
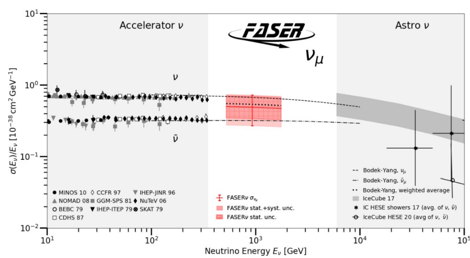
[FASER, 2403.12520]



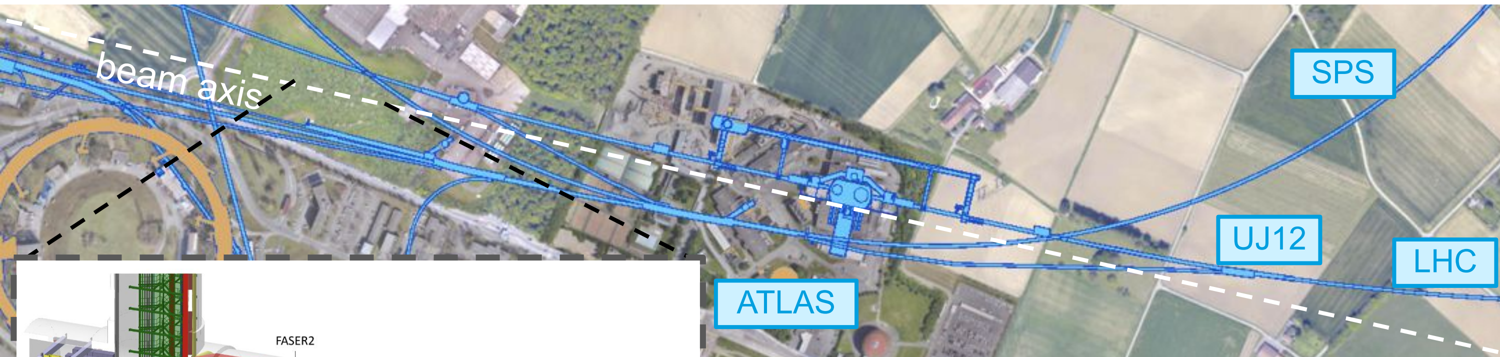


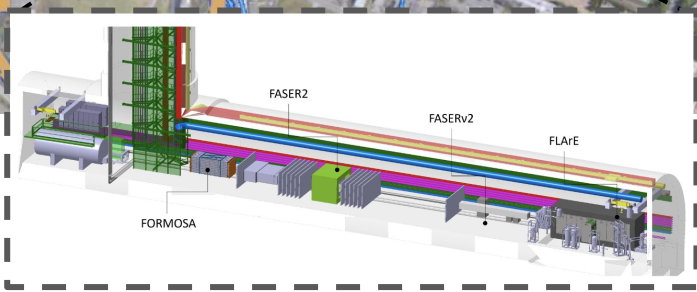
Forward Physics Facility.

FASER and SND@LHC have demonstrated the ability to detect TeV energy neutrinos and carry out background-free BSM searches with far-forward experiments.

They have opened a new window at the energy frontier.

Similar to other discoveries in physics, such as those of gravitational waves, the appropriate question is not whether we should follow up on these discoveries, but how can we best exploit this new way of learning about the Universe.





Forward Physics Facility (FPF)
to house a suite of dedicated forward experiments to exploit this physics potential.

Strongly Reviewed in Snowmass.

Executive Summary (10 pages)

LHC

The Energy Frontier (Science Drivers 1 – 3 & 5): The Energy Frontier currently has a top-notch program with the Large Hadron Collider (LHC) and its planned High Luminosity upgrade (HL-LHC) at CERN, which sets the basis for the Energy Frontier vision. The fundamental lessons learned from the LHC thus far are that a Higgs-like particle exists at 125 GeV and there is no obvious and unambiguous signal of BSM physics. This implies that new physics either occurs at scales higher than we have probed, must be weakly coupled to the SM, or is hidden in backgrounds at the LHC. The immediate goal for the Energy Frontier is to continue to take and analyze the data from LHC Run 3, which will go on for about three more years, and carry out the 2014 P5 recommendations to complete the HL-LHC Upgrade and execute its physics program. The HL-LHC will measure the properties of the Higgs Boson more precisely, probe the boundaries of the SM further, and possibly observe new physics or point us in a particular direction for discovery.

A new aspect of the proposed LHC program is the emergence of a variety of auxiliary experiments that can use the interactions already occurring in the existing collision regions during the normal LHC and HL-LHC running of the ATLAS, CMS, LHCb, and ALICE experiments to explore regions of discovery space that are not currently accessible. These typically involve observing particles in the far forward direction or long-lived particles produced at larger angles but decaying far outside the existing detectors. These are mid-scale detectors in their own right and provide room for additional innovation and leadership opportunities for younger physicists at the LHC. The EF supports continued strong U.S. participation in the success of the LHC, and the HL-LHC construction, operations, and physics programs, including auxiliary experiments.

future collider

New colliders are the ultimate tools to extend the EF program into the next two decades thanks to the broad and complementary set of measurements and searches they enable. With a combined strategy of precision measurements and high-energy exploration, future lepton colliders starting at energies as low as the Z-pole up to a few TeV can shed substantial light on some of these key questions. It will be crucial to find a way to carry out experiments at higher energy scales, directly probing new physics at the 10 TeV energy scale and beyond. The EF supports a fast start for the construction of an e^+e^- Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs Factory will require an immediate, vigorous, and targeted accelerator and detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.

Finally, the U.S. EF community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the U.S., while maintaining its international collaborative partnerships and obligations with, for example, CERN.

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FPF Updates

FPF Documentation.

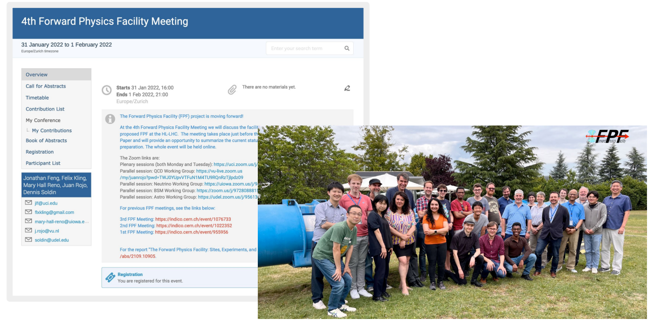
FPF workshop series:
FPF1, FPF2, FPF3, FPF4, FPF5,
FPF6, FPF7, FPF Theory Day

FPF Paper:
2109.10905
~75 pages, ~80 authors

Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors

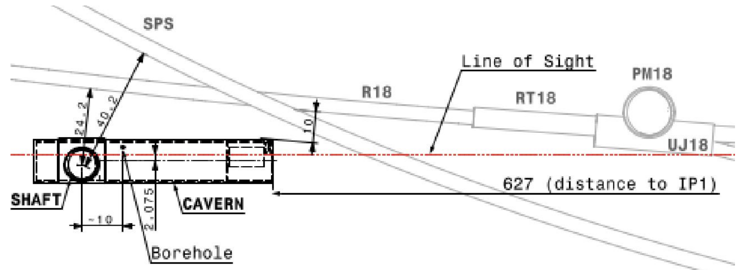
Recent Summary:
FPF Update

Technical Documents:
Facility Technical Study
Muon Flux Study
Vibration Study
Geotechnical Report



FPF: Facility.

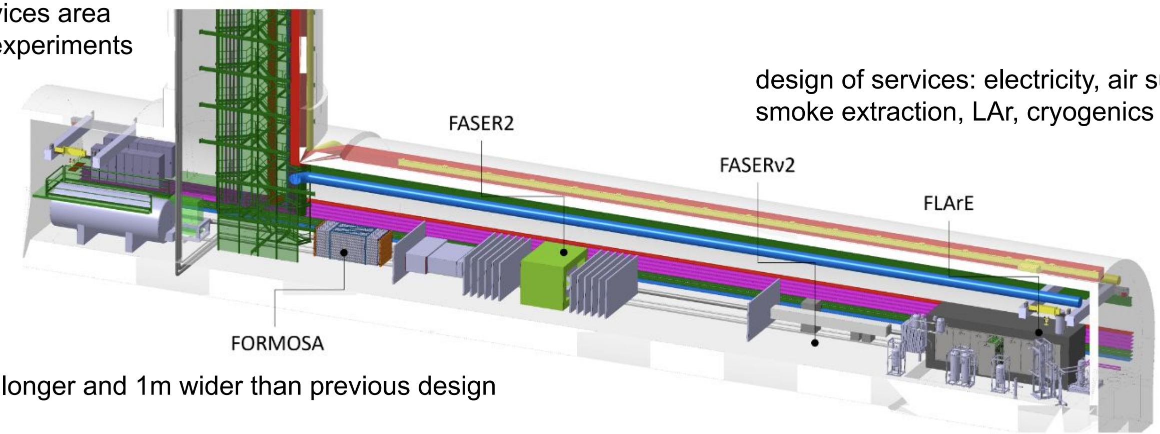
Location:
- several sites considered by the CERN civil engineering team
- preferred location on CERN land in France, 627 m west of the ATLAS IP



Cavern design:
- 75 m-long and 12 m-wide cavern, cover η > 5.1
- 10 m from the LHC and disconnected from it

10m added to back of cavern: services area away from experiments

design of services: electricity, air supply, smoke extraction, LAr, cryogenics

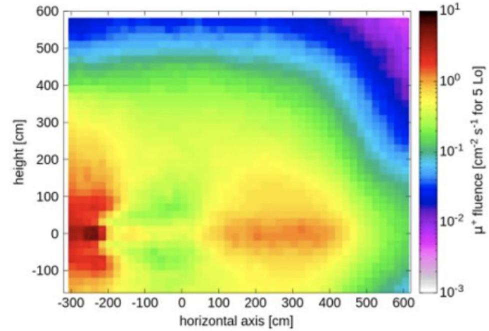


10m longer and 1m wider than previous design

FPF: Technical Progress.

Excavation works during beam operation? (CERN beam physics group)
- vibrations / tunnel-movement not expected to be an issue

Access to cavern during beam operation? (CERN Radioprotection group)
- access cavern for people classified as radiation workers.



Muons background flux Simulation (CERN FLUKA team)
- expected muon flux O(1Hz/cm2) within 1m or LOS.
- generally OK for experiments.
- study if flux can be reduced with sweeper magnet

Geological Conditions (CERN civil engineering group)
- site investigation (single core sample drilled) in 2023
- geological conditions look good for proposed works

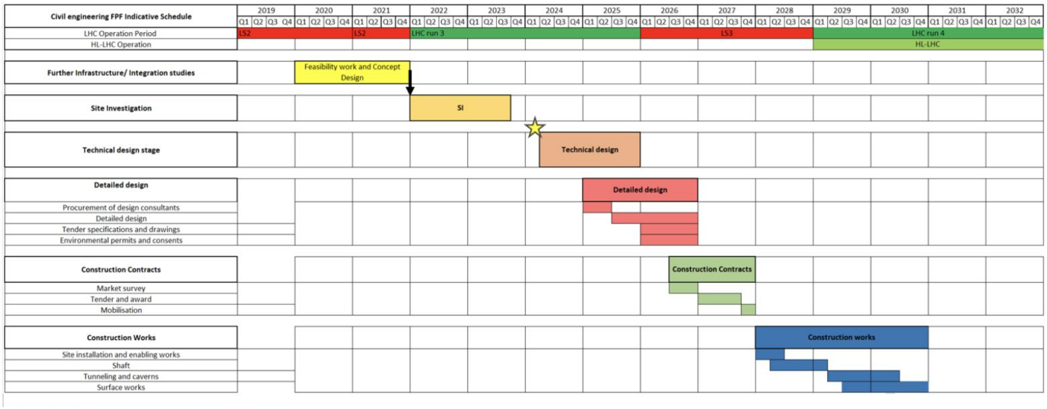
Is one access point OK for safety? (CERN safety team)
- Addition of safety corridor along the facility length allows only one access point.

Transport and Installation Study (CERN handling group)
- all large components can be transported into the facility

FPF: Timeline and Cost.

vibration study indicates that construction of the FPF possible during LHC operations

radiation protection studies indicate work in FPF possible while the LHC is running



Ref.	Work Package	Cost [CHF]
1.	Underground Works	10,000,000.00
1.1	Preliminary activities	1,600,000.00
1.2	Access shaft	3,900,000.00
1.3	Experimental Cavern	4,500,000.00
2.	Surface Works	6,120,000.00
2.1	General items	640,000.00
2.2	Topsoil and earthworks	660,000.00
2.3	Roads and network	730,000.00
2.4	Buildings	4,090,000.00
2.4.1	Access building	2,000,000.00
2.4.2	Cooling and ventilation building	1,400,000.00
2.4.3	Electrical Building	490,000.00
2.4.5	External platforms	200,000.00
3.	General items	10,000,000.00
4.	Miscellaneous	4,000,000.00
	TOTAL CE WORKS	30,120,000.00

Cost table shown for previous cavern design, current design cost expected to be 10% higher

Timeline: construct in LS3/early Run 4, physics starts in late Run 4.
Capture as much HL-LHC luminosity as possible.

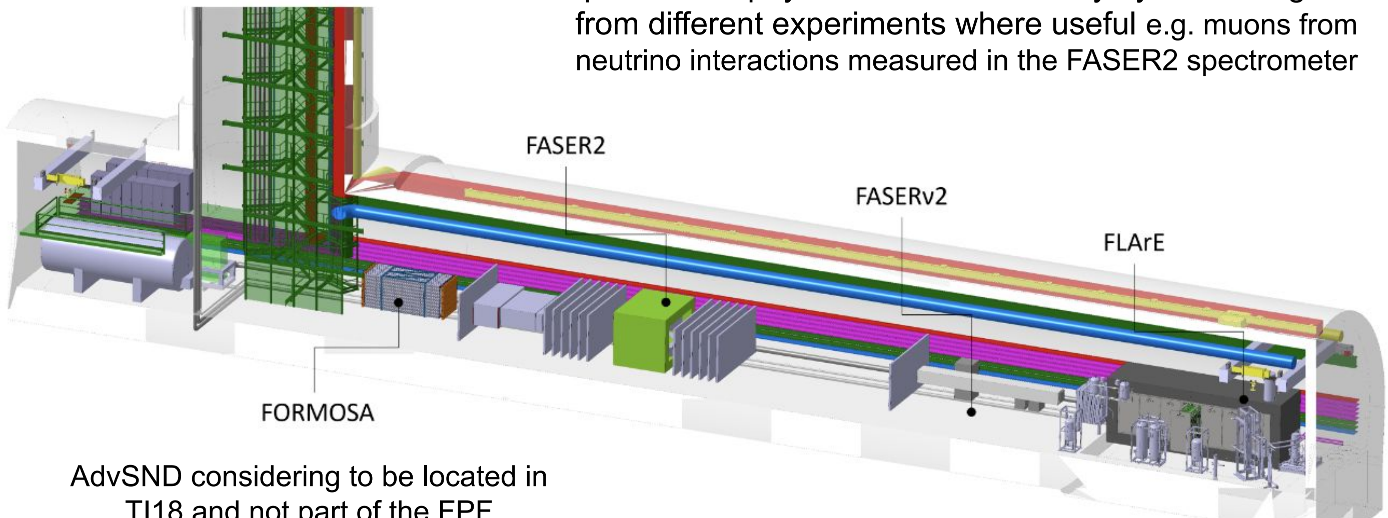
Physics case summary by October 2024,
EPPSU input and LHCC LOI in early 2025.

Cost Estimate: 30 MCHF (class 4)

FPF: Experiments.

Much progress across all FPF experiments:

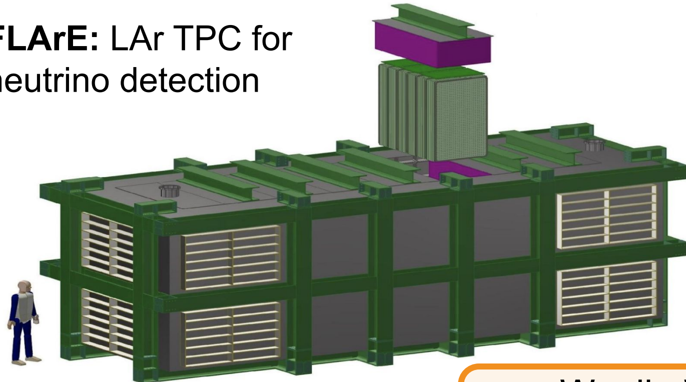
optimize the physics across the facility by combining info from different experiments where useful e.g. muons from neutrino interactions measured in the FASER2 spectrometer



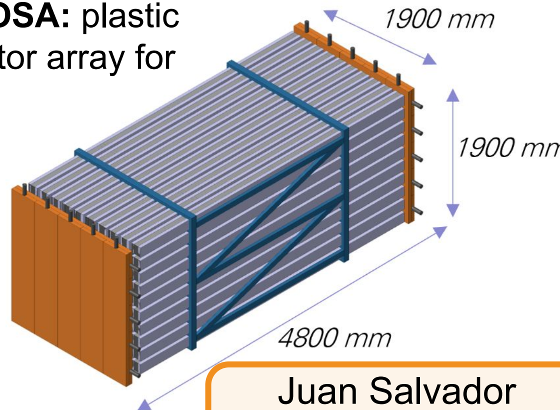
AdvSND considering to be located in TI18 and not part of the FPF

FPF: Experiments.

FLArE: LAr TPC for neutrino detection



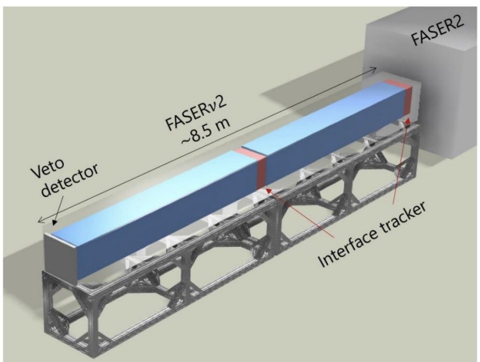
FORMOSA: plastic scintillator array for MCPs



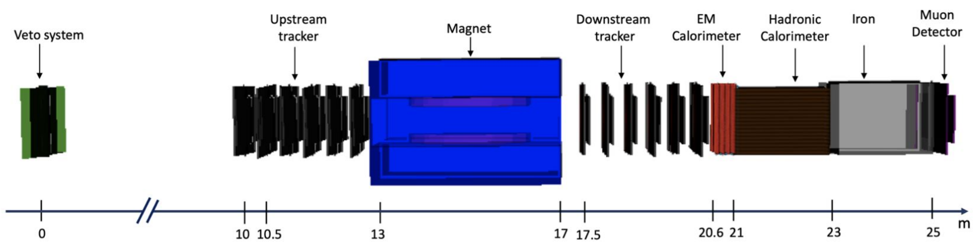
Wenjie Wu
Forward Liquid Argon Experiment at the High Luminosity LHC

Juan Salvador Tafoya Vargas
FORMOSA

FASERv2: emulsion detector for neutrinos



FASER2: tracking spectrometer for LLP searches and muon charge ID



FPF Physics

LLPs at the FPF.

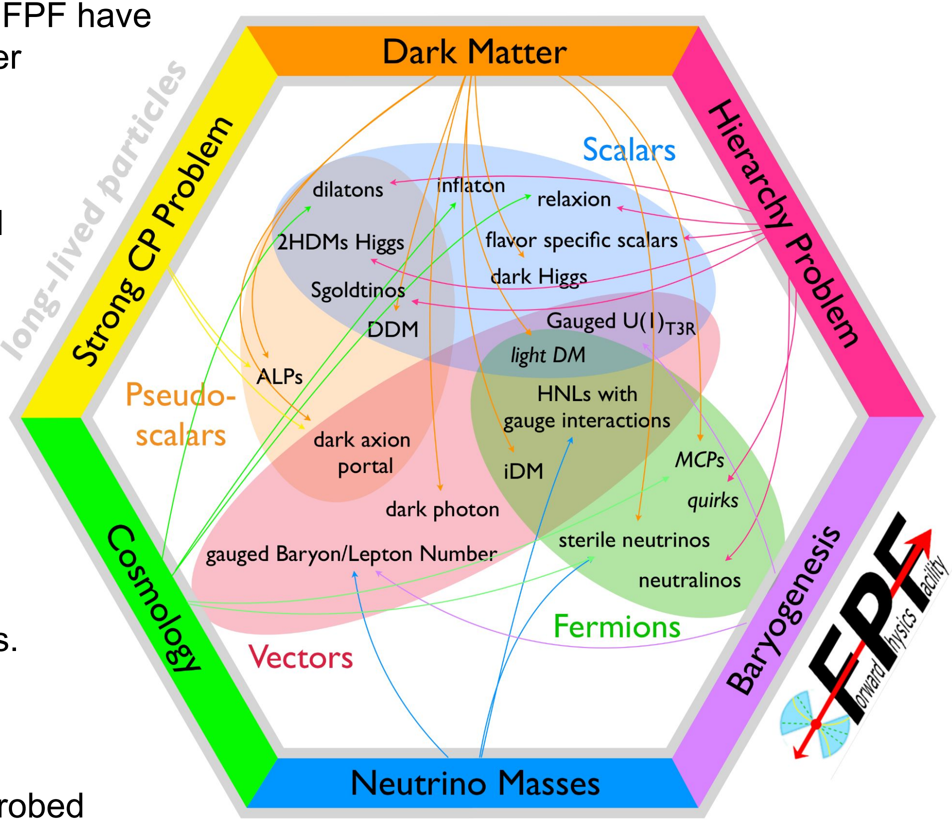
Discovery prospects for LLPs at FPF have been analyzed for a huge number of models.

Many of them related to various outstanding fundamental questions in particle and astro-particle physics.

Youhei Nakashima
Dark photon pair production via off-shell dark higgs at FASER

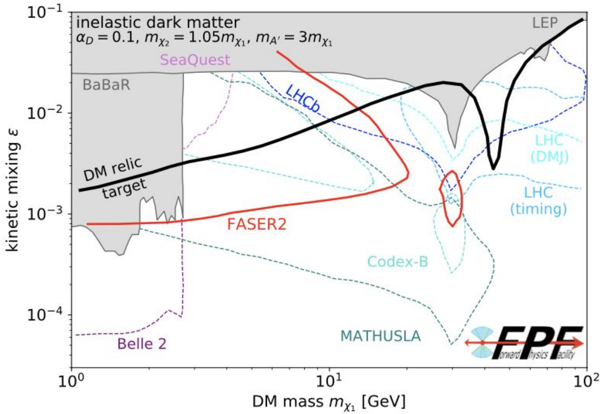
FPF experiments have discovery potential in every one of the PBC benchmark scenarios.

There are many other scenarios in which the high LHC energy is essential and which cannot be probed at fixed target experiments.

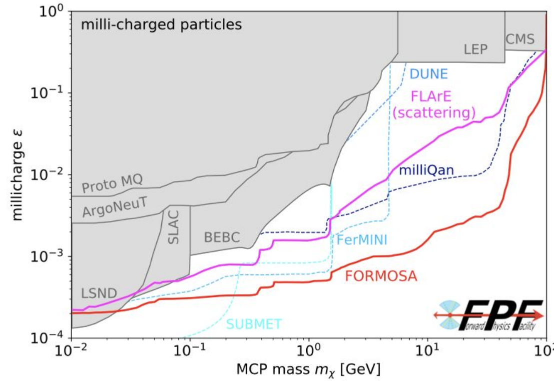


LLPs at the FPF.

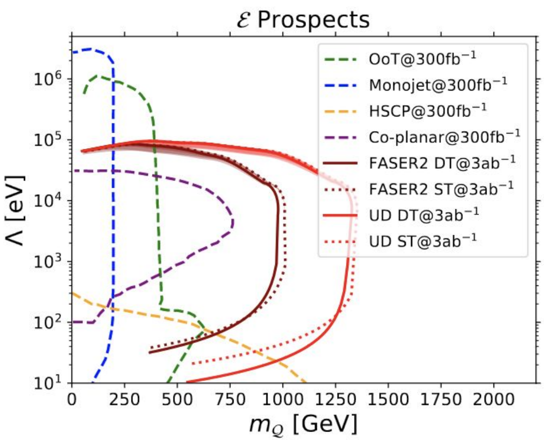
Three examples of heavy LLPs at the FPF



Inelastic Dark Matter (at FASER2)
- dark sector with compressed spectrum
- pp → X1 X2
- X2 > X1 e e

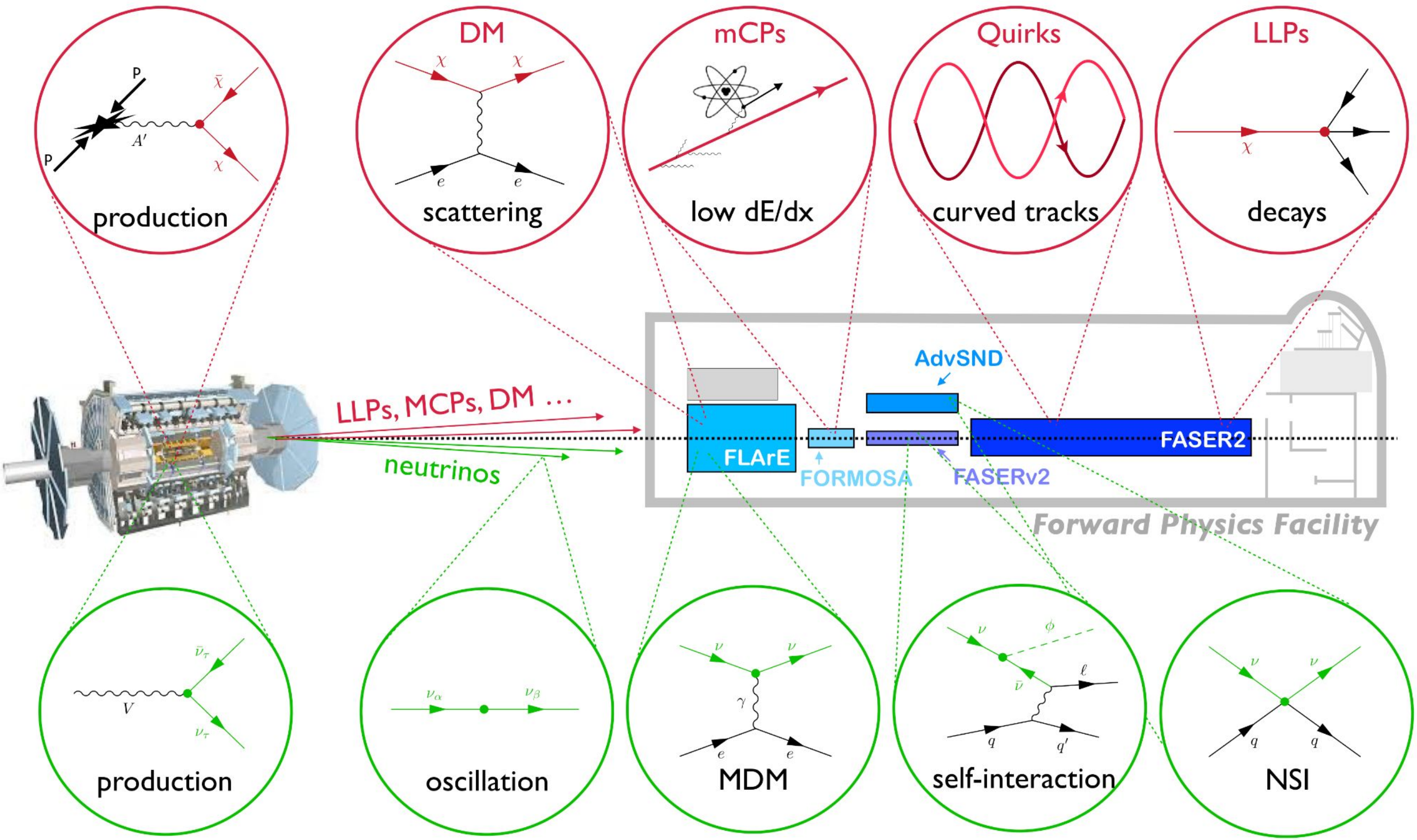


Millicharged Particles (at FORMOSA)
unique sensitivity at >GeV masses



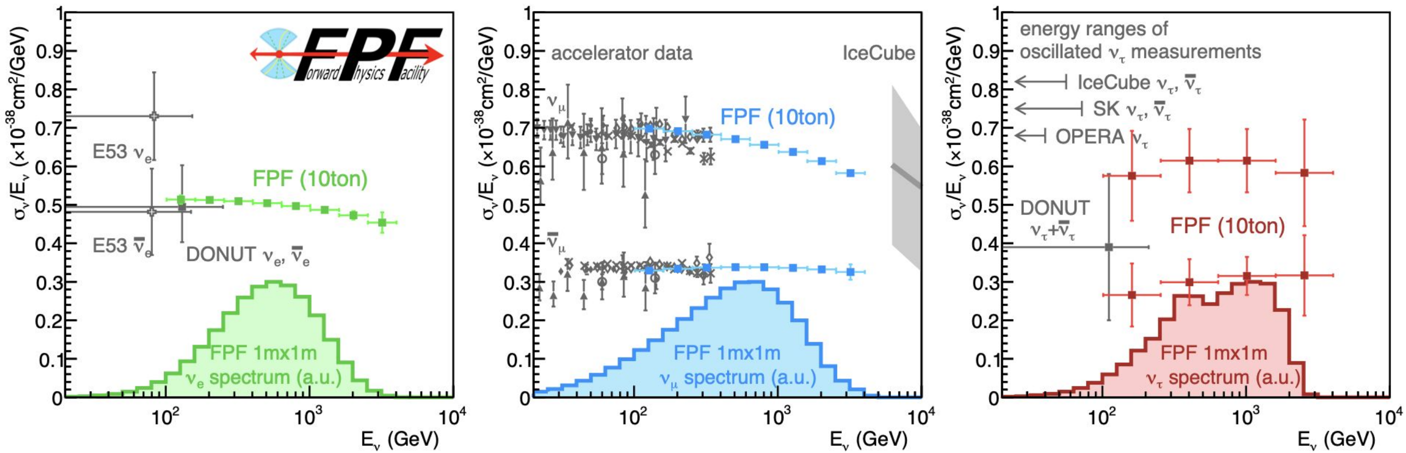
Quirks (at FASER2)
- 100s GeV-TeV masses motivated by hierarchy problem
- quirk pair bound by hidden QCD, highly forward peaked
- delayed/slow tracks [Feng et al. 2404.13814]

More Searches for BSM Physics



Collider Neutrinos.

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.



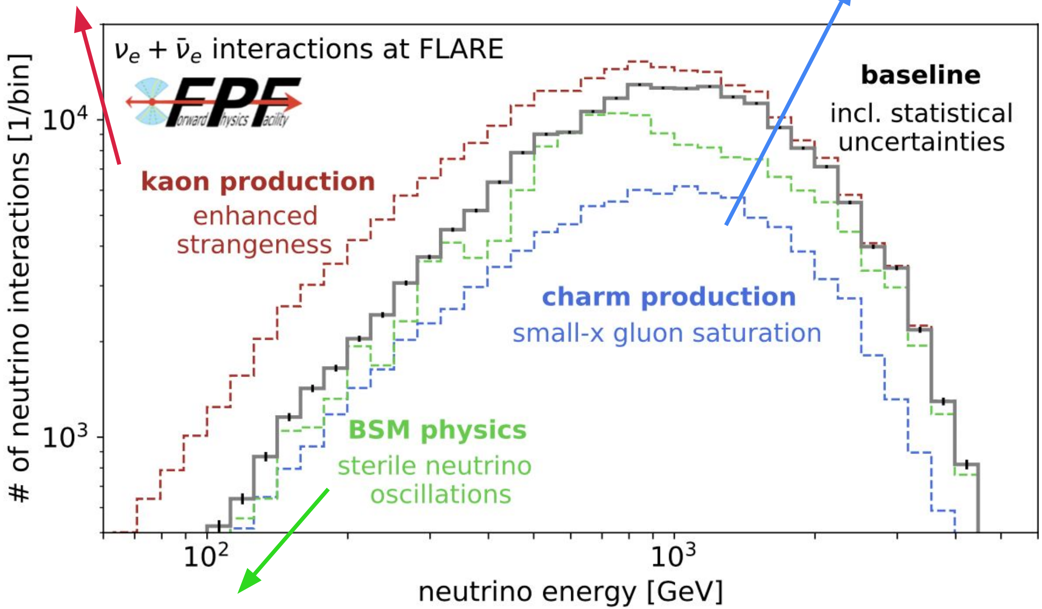
Proposed FPF experiment have potential to detect O(1M) neutrinos.

Collider Neutrinos: Fluxes.

Neutrinos are produced by forward hadron production (π, K, D). There spectra contains information on a variety of phenomena.

PDFs as x~10^{-7} and x~1:
intrinsic charm, small-x gluon saturation, …

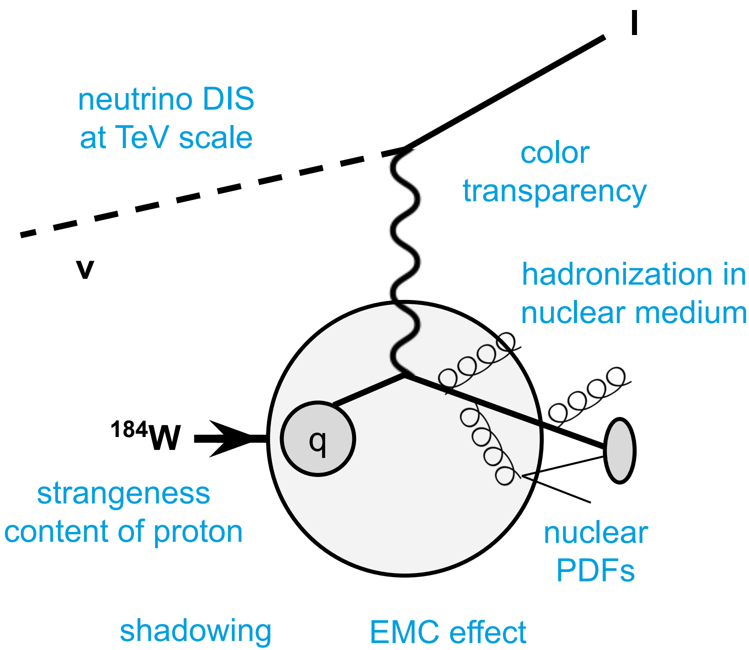
understand cosmic ray muon puzzle



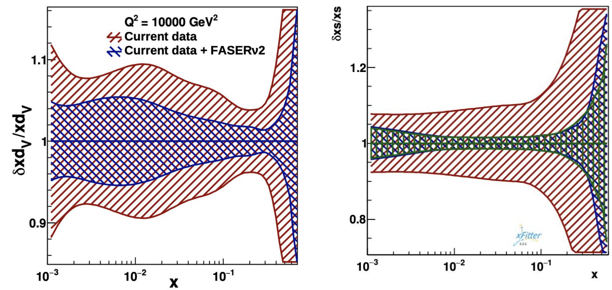
sterile neutrinos with m~10eV

Collider Neutrinos: Interactions.

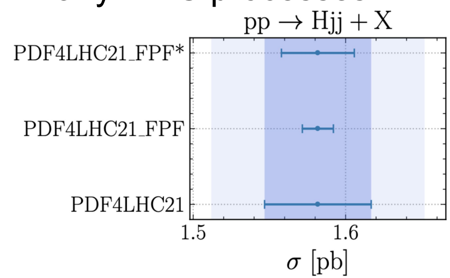
Collider Neutrino Experiments
are a Neutrino-Ion Collider
at EIC center of mass energies



neutrino DIS data will improve PDFs
[FPF, P5 Input] [Cruz-Martinez et al. 2309.09581]



reduced PDF uncertainties for
many LHC processes



breaks PDF/BSM degeneracy
[Rojo, FPF7 Talk]

Summary

Summary.

With FASER and SND@LHC, a novel forward physics program emerged to fully exploit potential of the LHC.

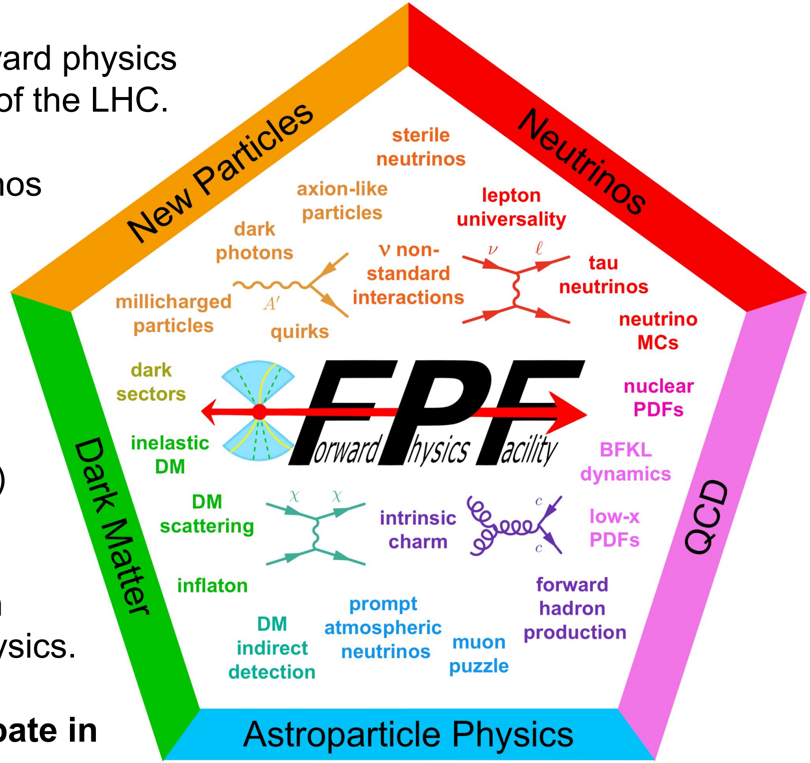
Already success: discovery the first neutrinos in the 50+ years of collider physics.

The FPF is proposed to continue this program during the HL LHC era.

Searches for various light (and also heavy) feebly interacting BSM particles

Study of TeV energy collider neutrinos with implications for QCD and astroparticle physics.

We invite the LLP community to participate in this program. You are welcome to join!

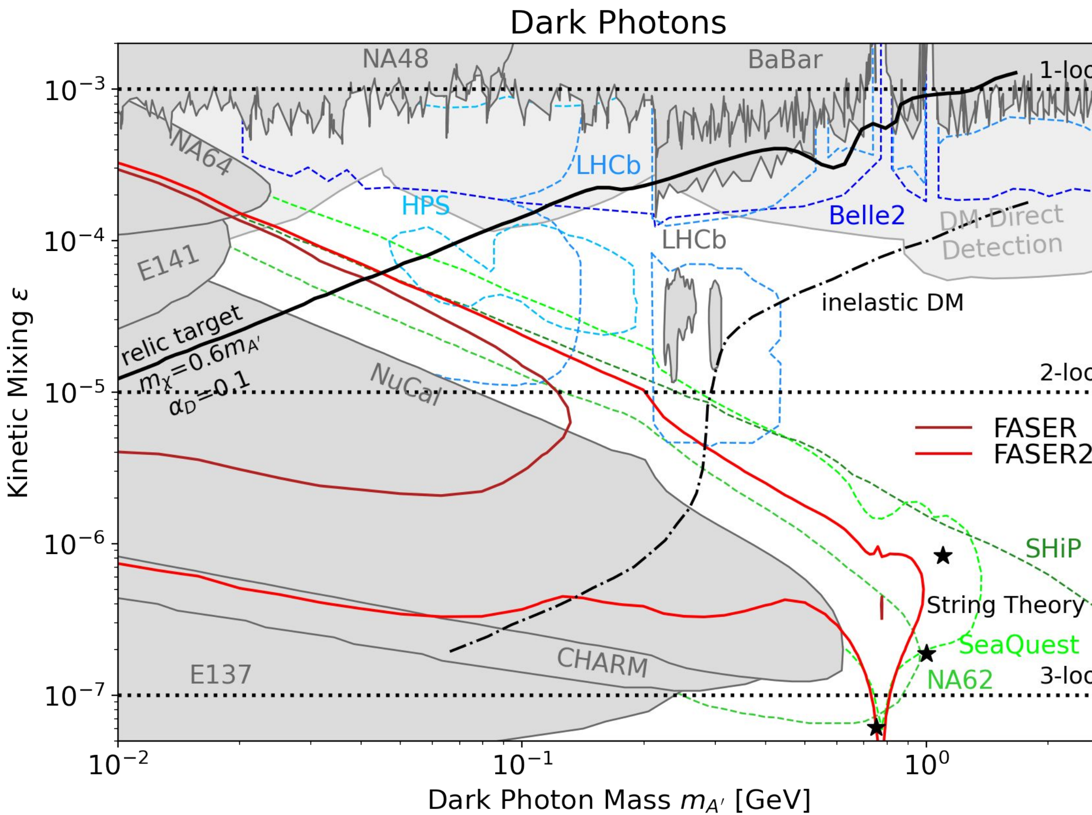


For questions and comments, please contact me via felix.kling@desy.de

Backup

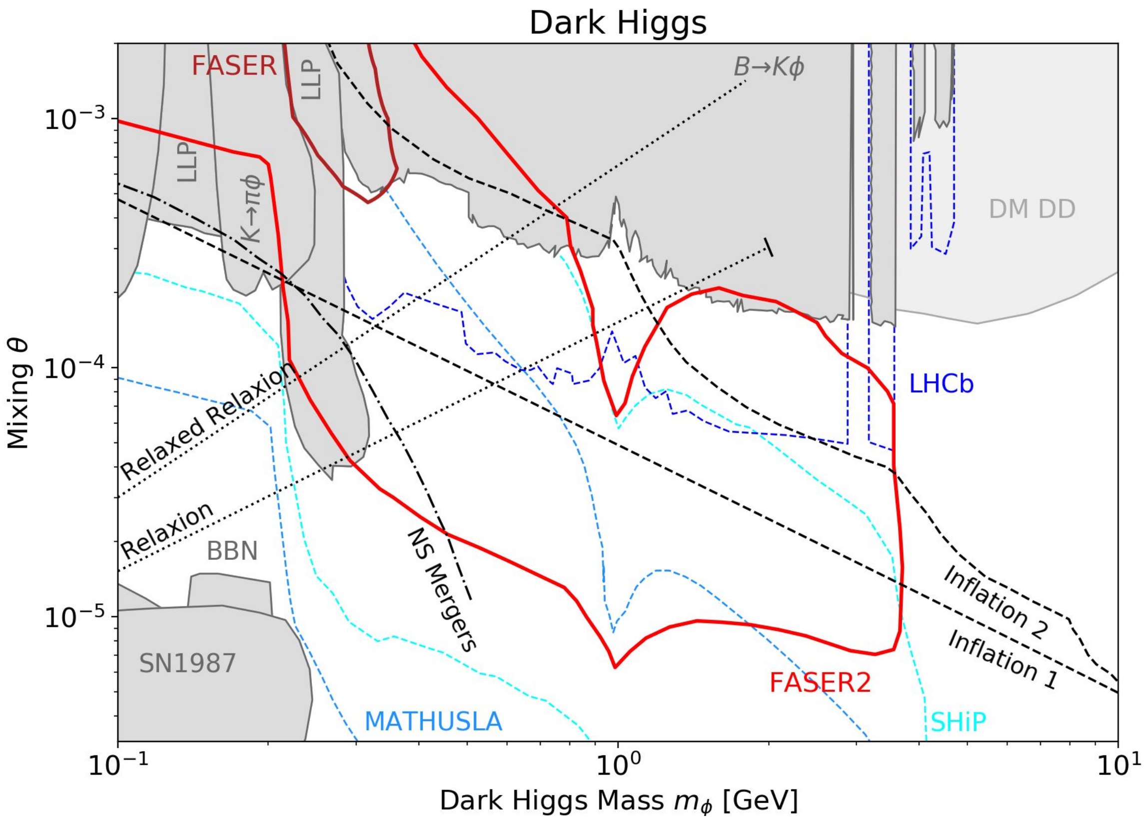
Long-Lived Particles: Dark Photon.

Dark Photon = gauge boson mixing with photon: $\mathcal{L} \sim -\frac{1}{2} m_{A'}{}^2 A'^2 - \epsilon e q_f \bar{f} \not{A}' f$



Long-Lived Particles: Dark Higgs.

Dark Higgs = light scalar mixing with SM Higgs: $\mathcal{L} \supset {m_\phi}^2 \phi^2 + \sin\theta \, y_f \phi \bar{f} f$



Dark Matter Scattering.

mA’ > 2mX

↓

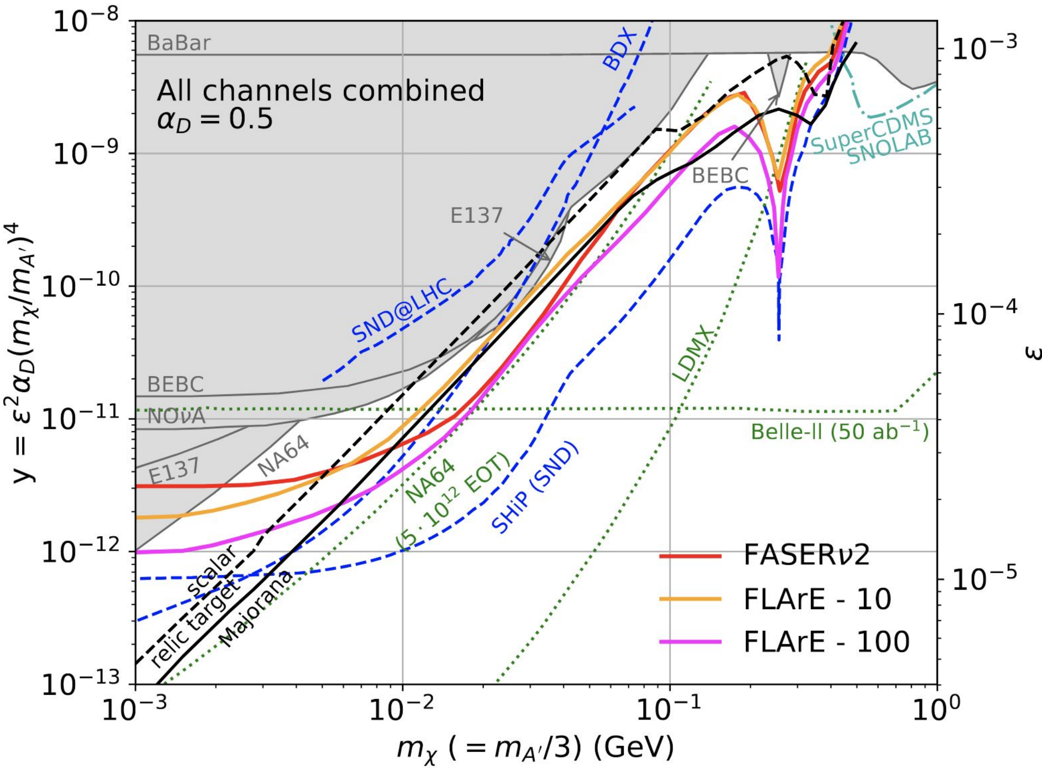
dark photon promptly decays in DM

↓

LHC produces DM beam

↓

DM scattering in neutrino detector



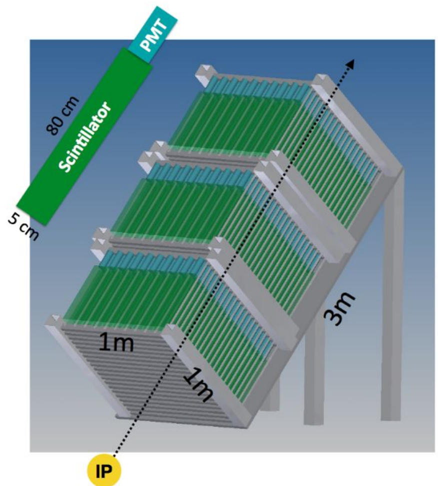
for more details see: [2101.10338](2101.10338)

MilliCharged Particles.

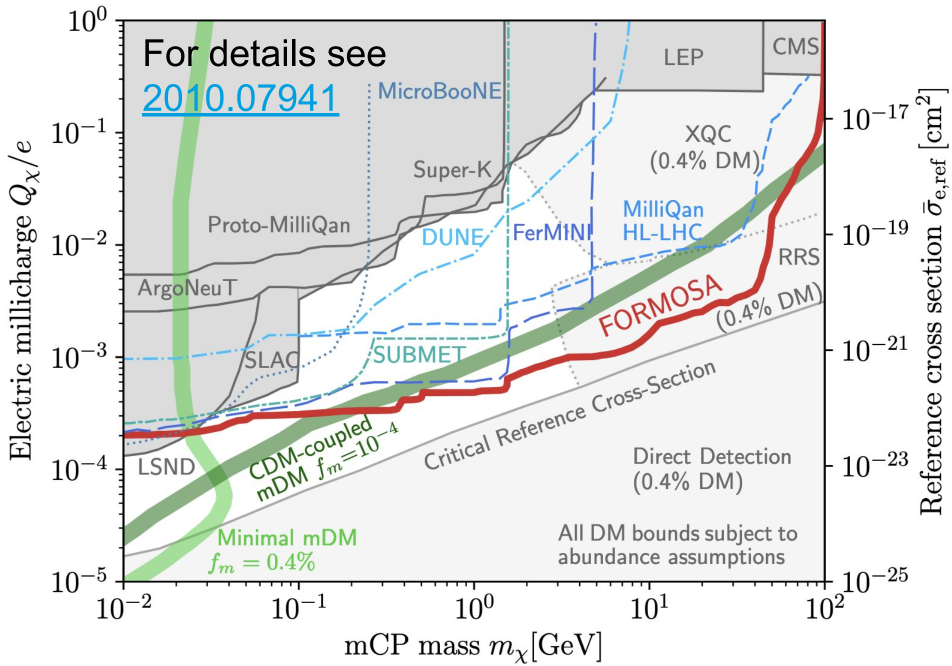
If mA'=0: X is effectively milli-charged with Q=εe → search for minimum ionizing particle with very small dE/dx

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

But it was noted that sigal flux is ~100 times larger in forward direction.

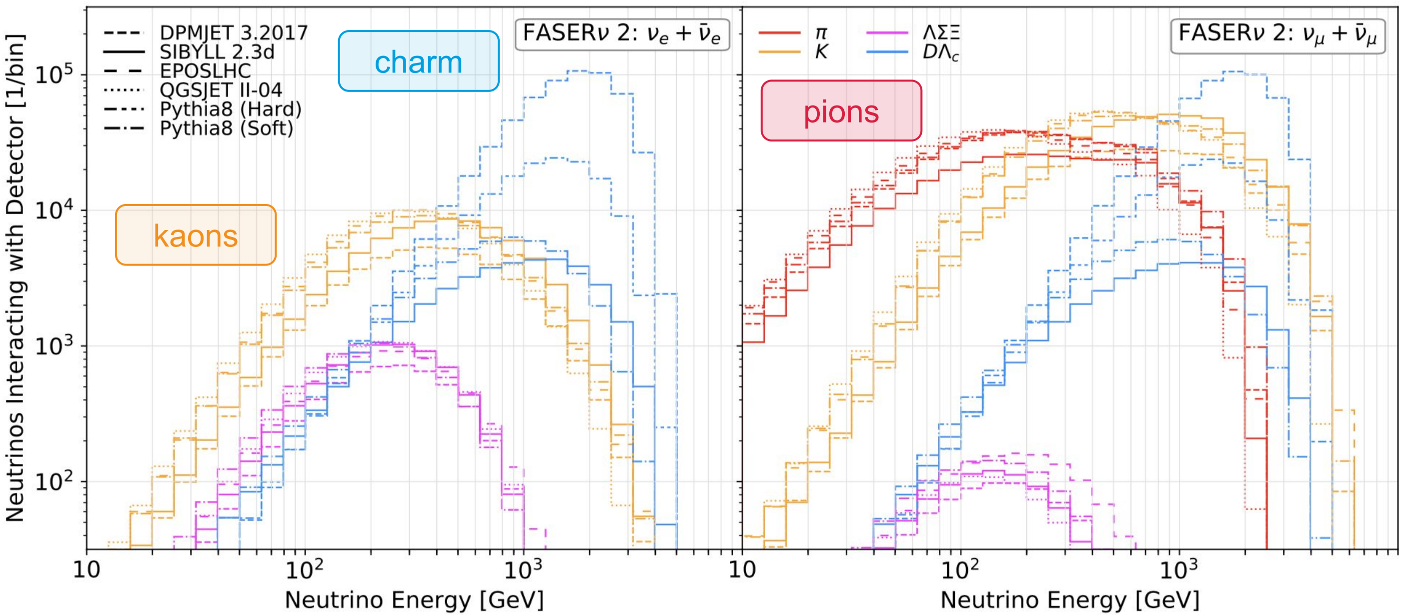


milliQan detector: 1607.04669



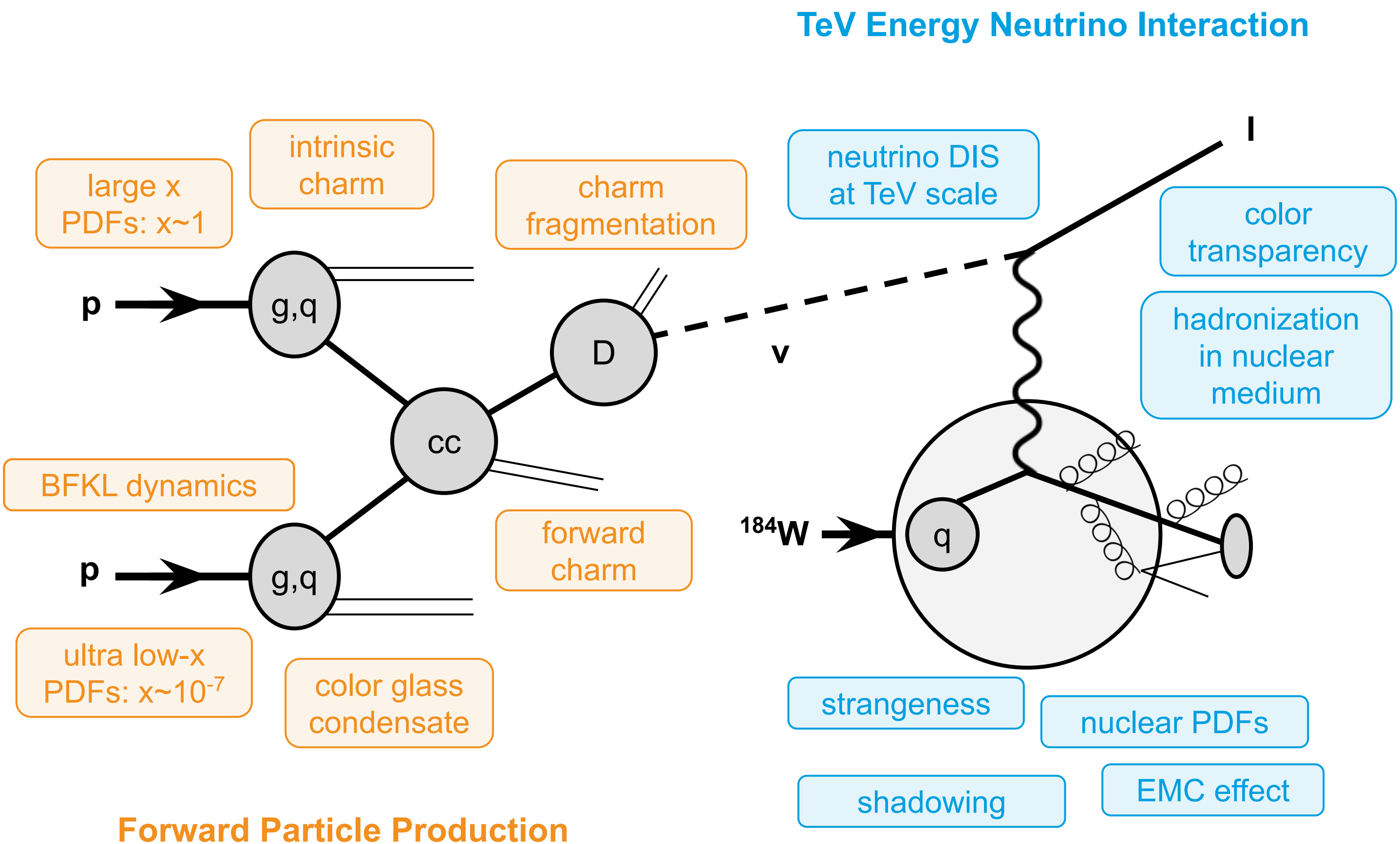
Application: QCD.

Where do the LHC neutrinos come from?



LHC neutrinos = probe of forward particle production

Application: QCD.

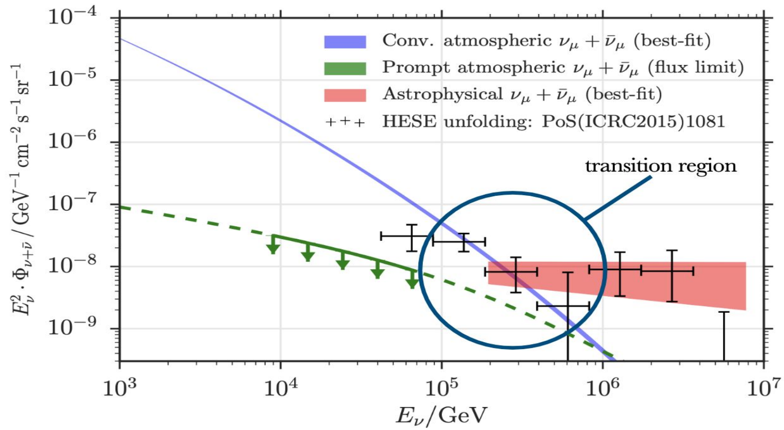


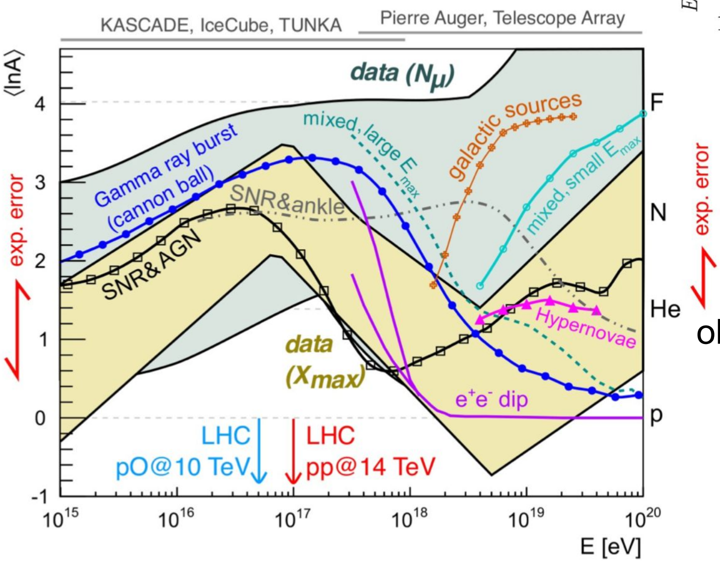
Application: Astroparticle Physics.

forward charm production at the LHC

↓

constraints on prompt atmospheric neutrino flux at IceCube





cosmic ray muon puzzle:

observed excess of muons compared to hadronic interaction models

forward pion/kaons fluxes will provide crucial input

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660