New physics with LHC's forward beam: FASER(ν) and FPF

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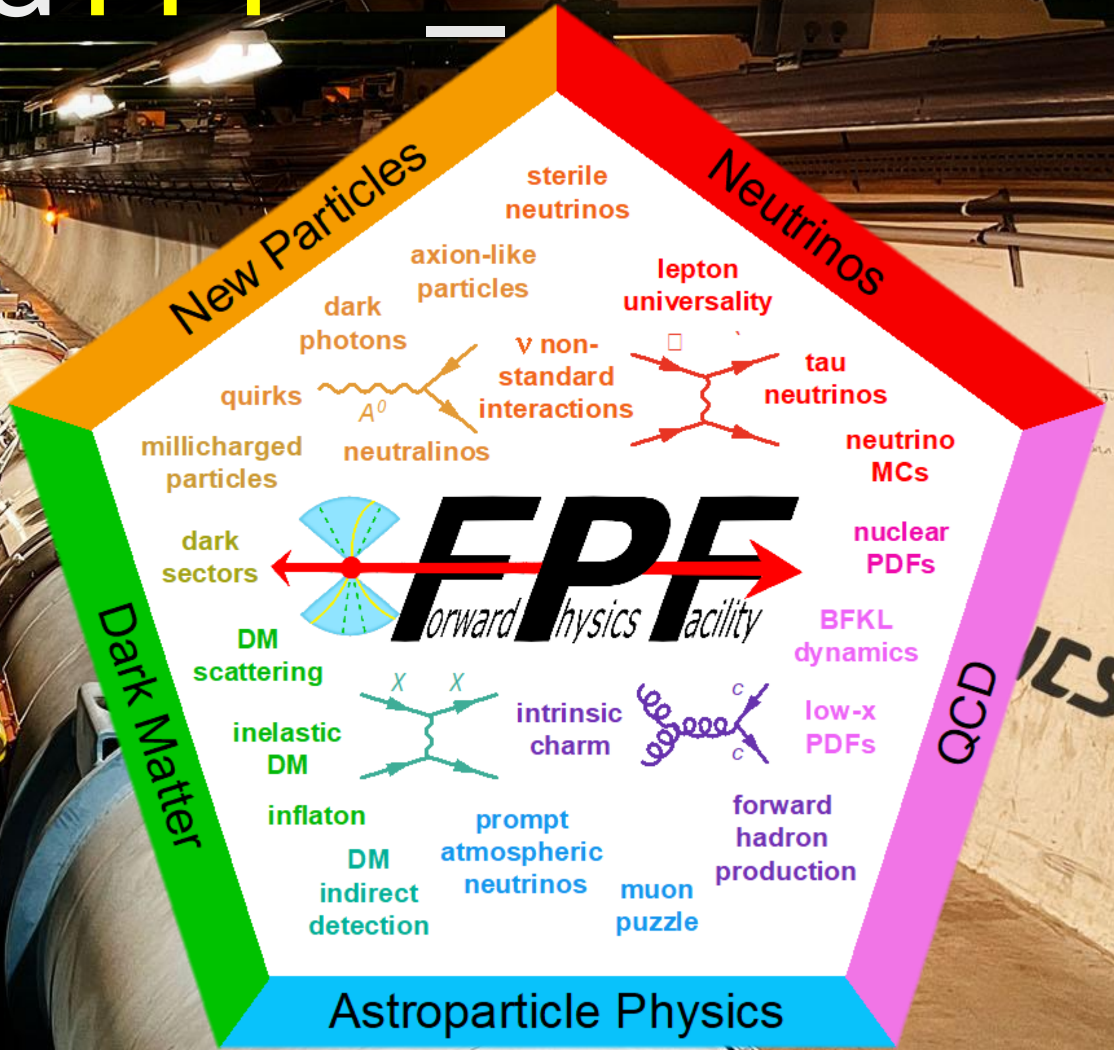
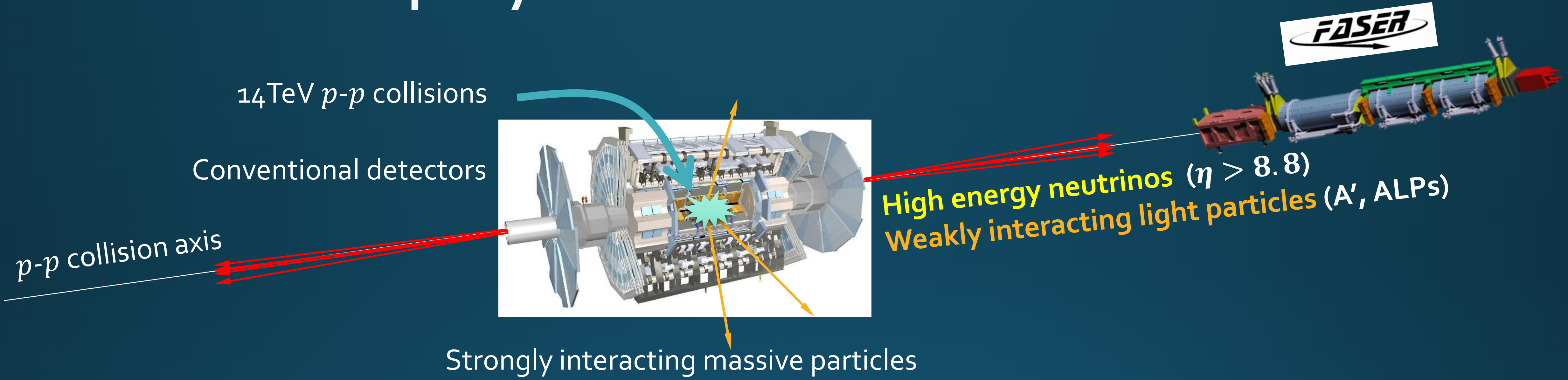


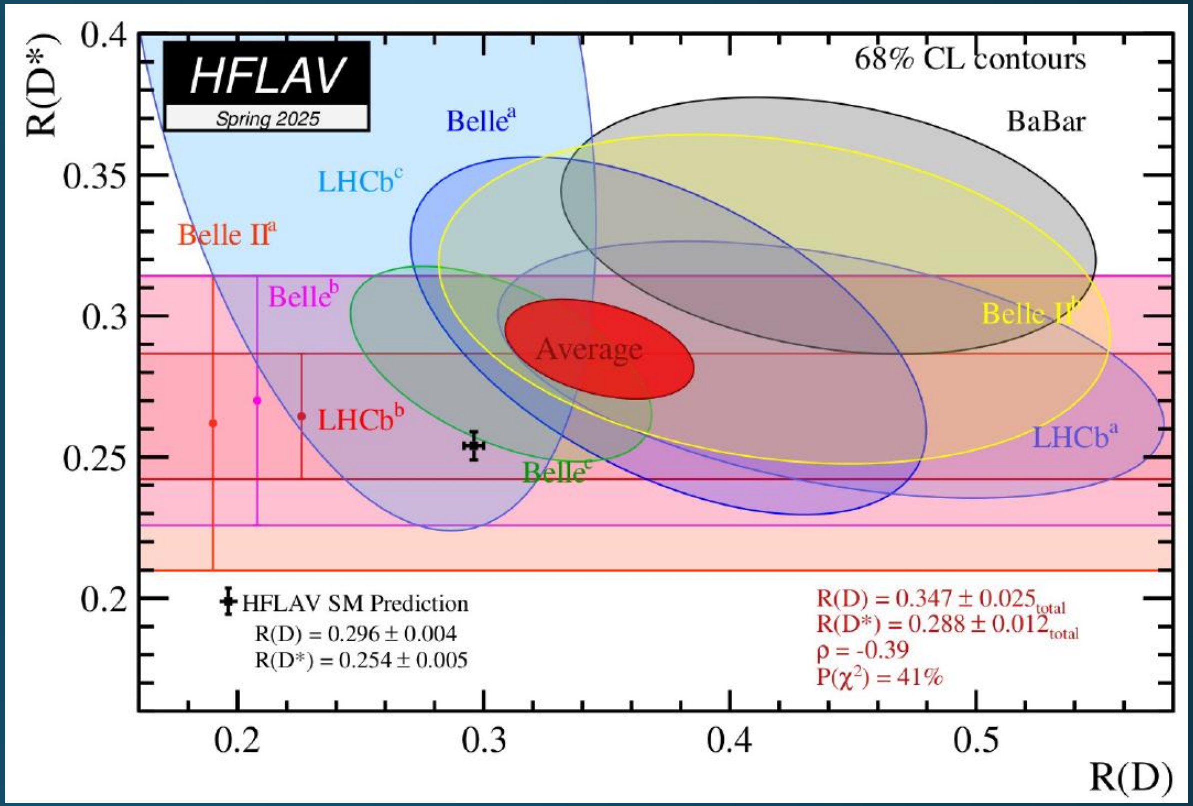
Forward physics at colliders



- In these years, our view of forward physics at colliders has completely changed.
- Forward region holds rich physics, both SM and BSM, addressing all of our top science drivers.
- The discovery of collider neutrinos marks the start of multi-messenger collider physics.
- To fully explore what the LHC can offer, the **Forward Physics Facility (FPF)** is being proposed for the HL-LHC

“Flavor anomaly”

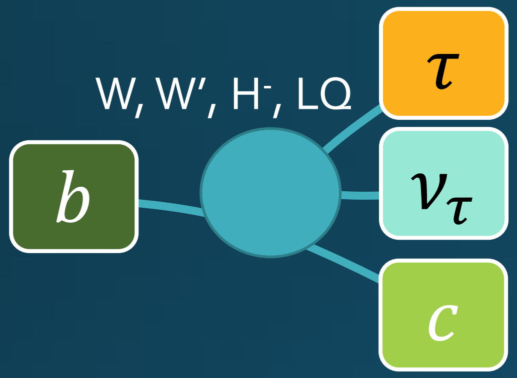
$$R(D) = \frac{\mathcal{B}(B \to \tau \nu_\tau D)}{\mathcal{B}(B \to \mu \nu_\mu D)}$$



3.8 σ. Possible new physics contribution in heavy flavors!?

Flavor anomalies and neutrino scattering

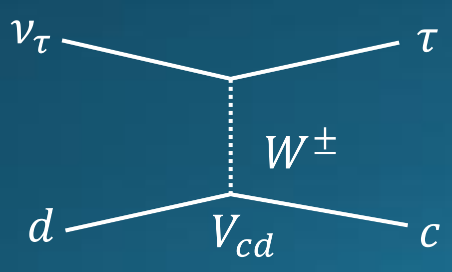
B decays

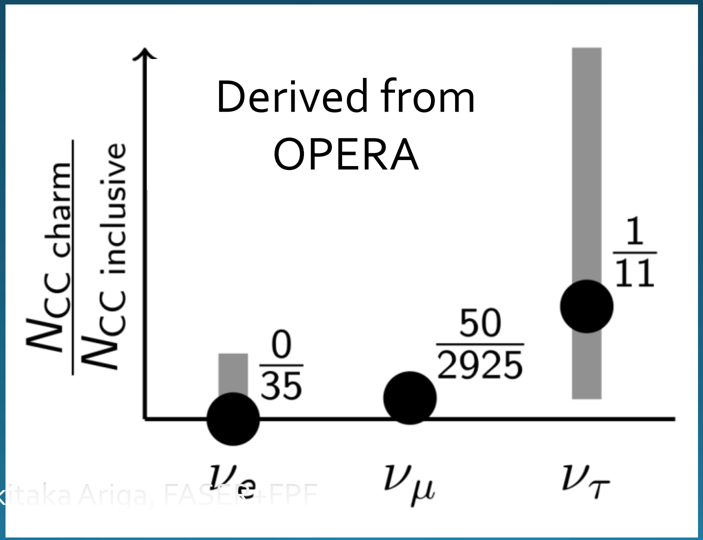


Neutrino scattering

OPERA reported ν_μ, ν_τ CC charm production.
No ν_e CC charm reported, neither in any other neutrino experiments.

Dominant SM process





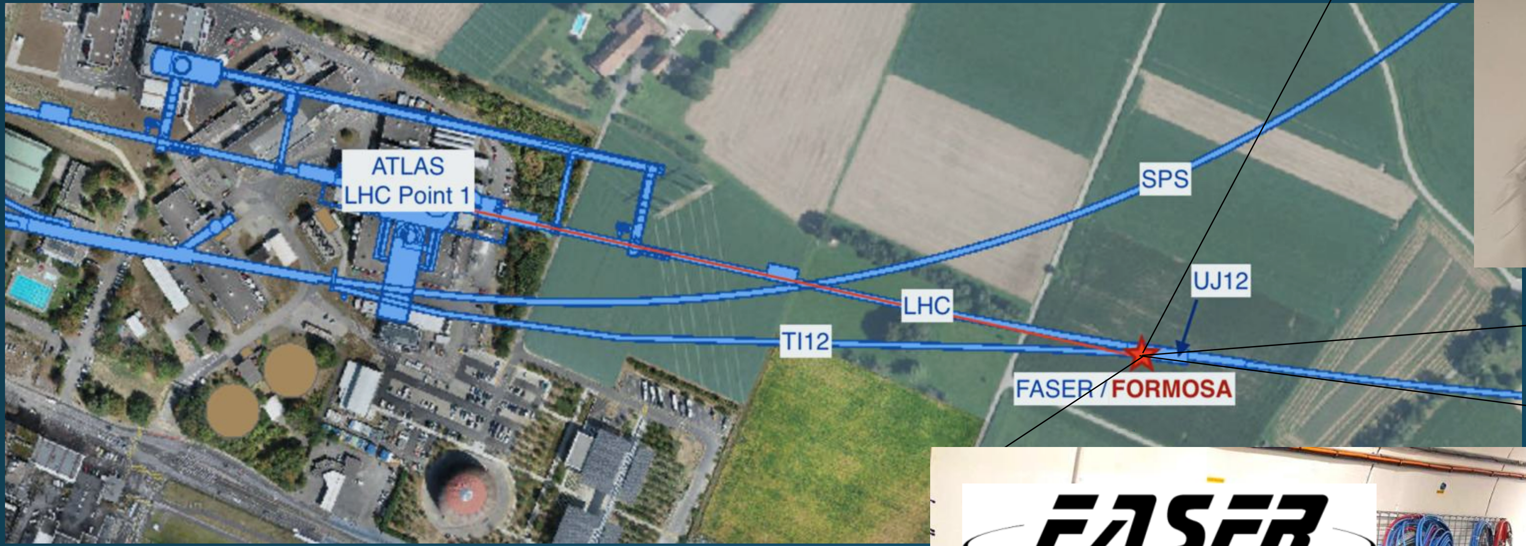
To test LFU, need **high-energy 3-flavor neutrino beam!**

Pathfinder experiments

- *Proof of concepts*: collecting data and validating designs/DAQs through Run 3
  - **FASER (FASERν)**, **SND@LHC**, **FORMOSA demonstrator**

SND@LHC

Milli charged particles



Neutrino

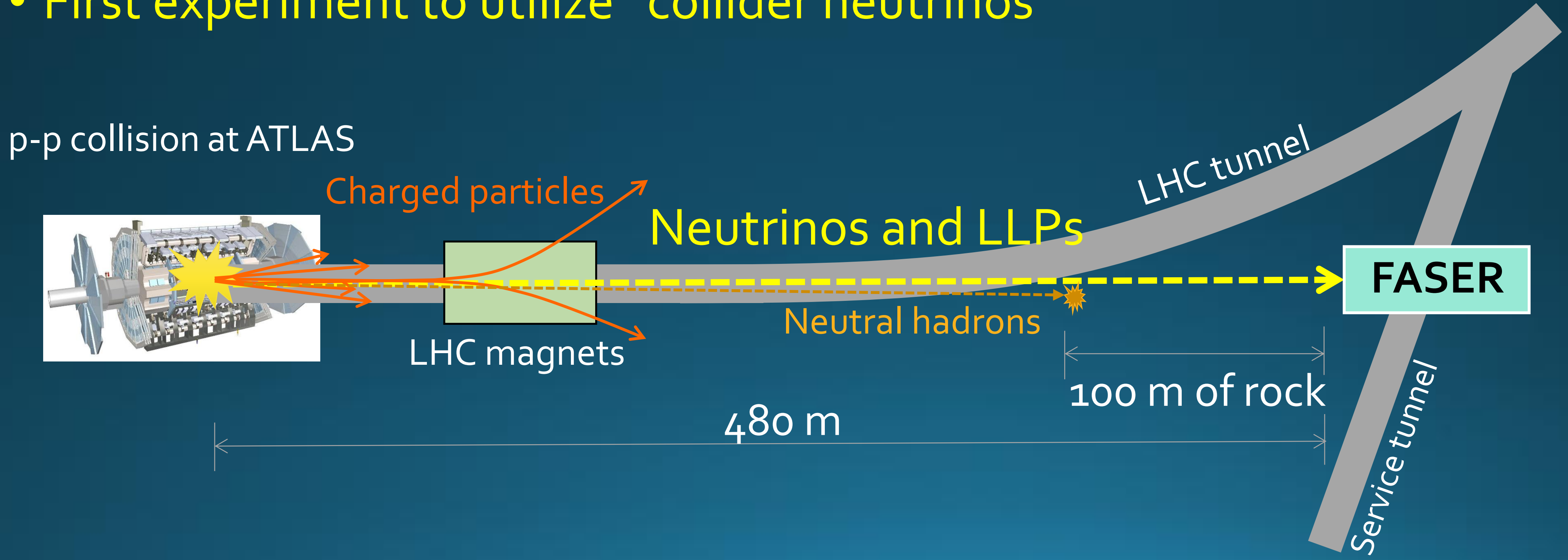
Neutrino and dark sector

The FASER experiment

FORWARD SEARCH EXPERIMENT AT THE LHC

FASER TP arXiv:1812.09139,
FASERν Eur. Phys. J. C (2020) **80**: 61
FASER web page: https://faser.web.cern.ch/

- Targets neutrinos (and μ) and long-lived BSM particles (e.g. A', ALPs)
- First experiment to utilize "collider neutrinos"



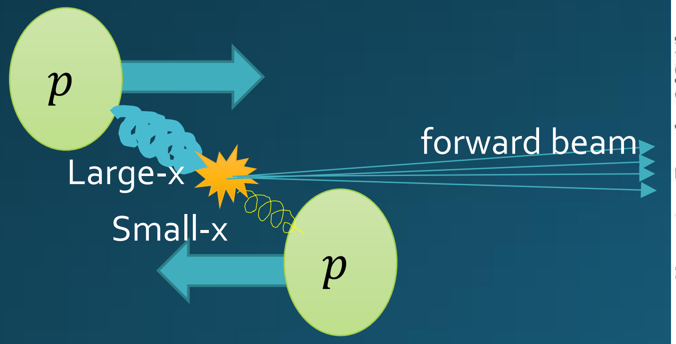
What is special in LHC's forward beam?

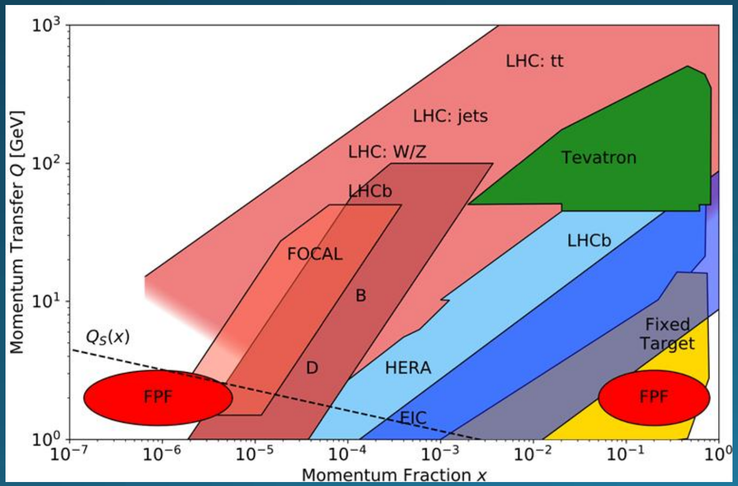
Neutrino production

- Forward hadron production in p-p collisions at $\sqrt{s} = 13.6$ TeV
  - Equivalent to 100 PeV p fixed-target interactions
  - Neutrinos from π, K, D decays
- Asymmetric gluon-gluon interaction: small-x × large-x
  - Unexplored kinematical region

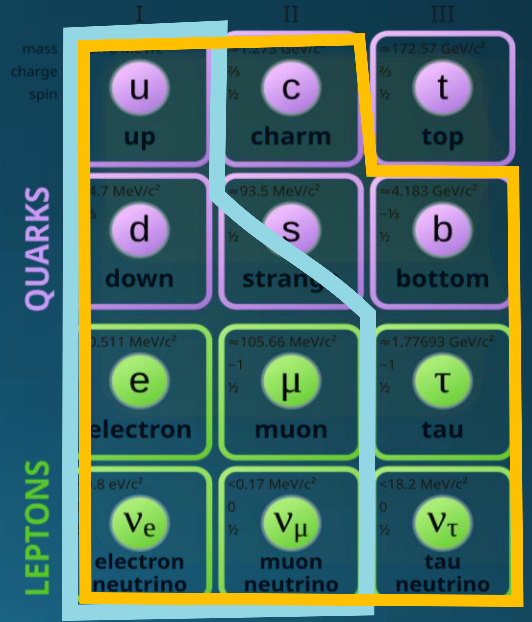
Neutrino beam

- 3 flavor neutrinos; $\nu_e,\ \nu_\mu,\ \nu_\tau$ and $\bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau$
- TeV energies, dominated by DIS
  - Access to heavy flavor particles, such as tau/charm/beauty, $\simeq 15\%$ charm production rate
- Collimated neutrino beam
  - $O(10)$ cm radius at 500 m





$x \sim 10^{-6}$

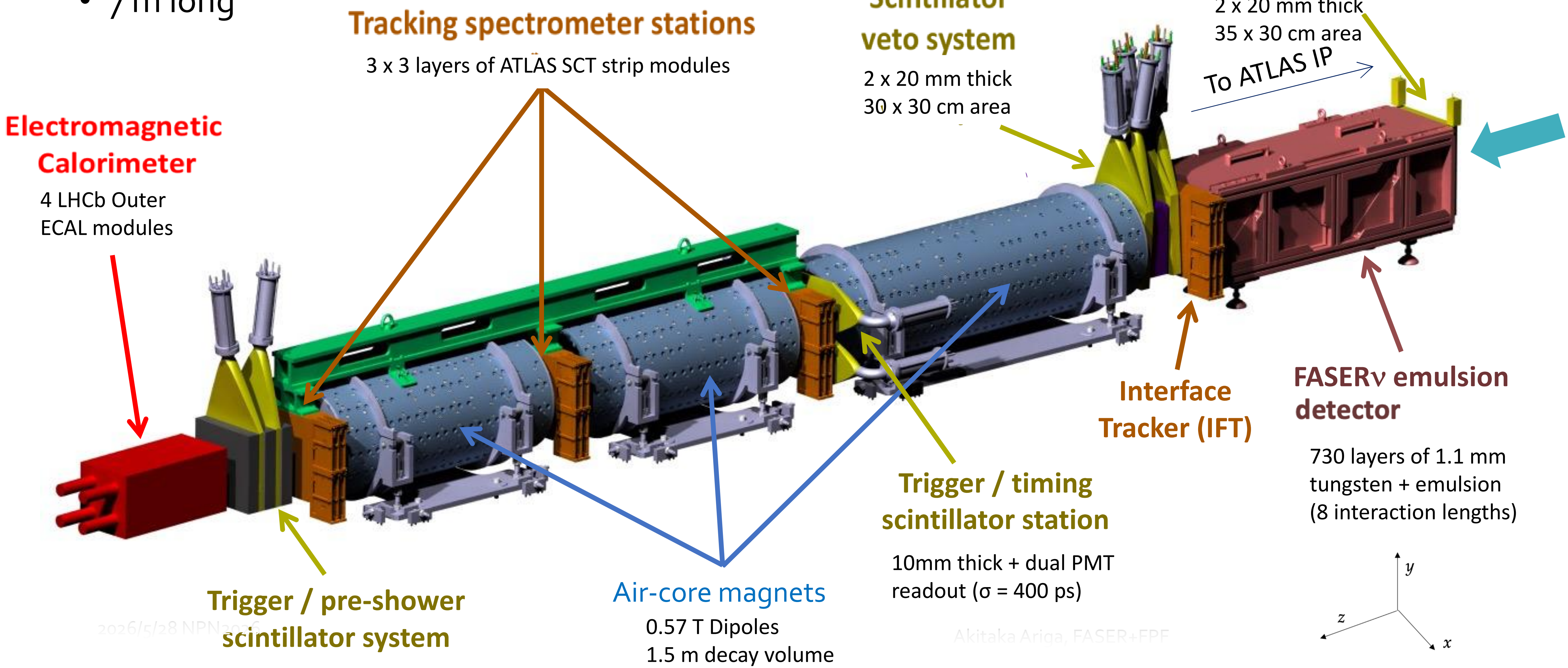


GeV experiments

LHC ν

FASER detector

- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long

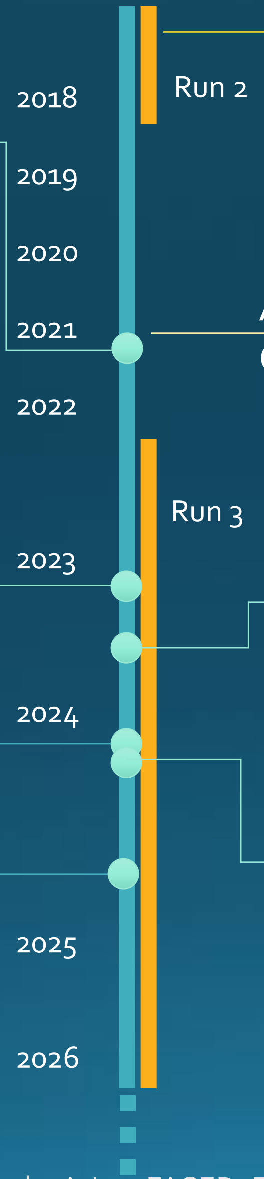


FASERν installation
3 times / year

Results from the FASER experiment

SM

- Neutrino candidates with Run2 data
  - PhysRevD.104.L091101
- Neutrino detection with electronic detectors with 2022 data
  - PhysRevLett.131.031801
- First ν_e, ν_μ cross sections with emulsion detector
  - PhysRevLett.133.021802
- Differential ν_μ, $\bar{\nu}_\mu$ cross sections with electronic detectors with 2022-23 data
  - PhysRevLett.134.211801
- Further new results
  - CERN-FASER-CONF-2025-004 Forward hadron production
  - CERN-FASER-CONF-2026-002 Updated nue / numu results
  - CERN-FASER-CONF-2026-003 Neutrino-induced charm
  - CERN-FASER-CONF-2026-004 ν_e with calorimeter
  - CERN-FASER-CONF-2026-005 ν_μ double-differential measurement



Pilot detector

Approved in 2019
Constructed by 2021

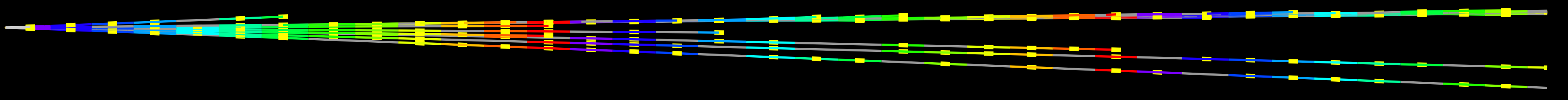
BSM

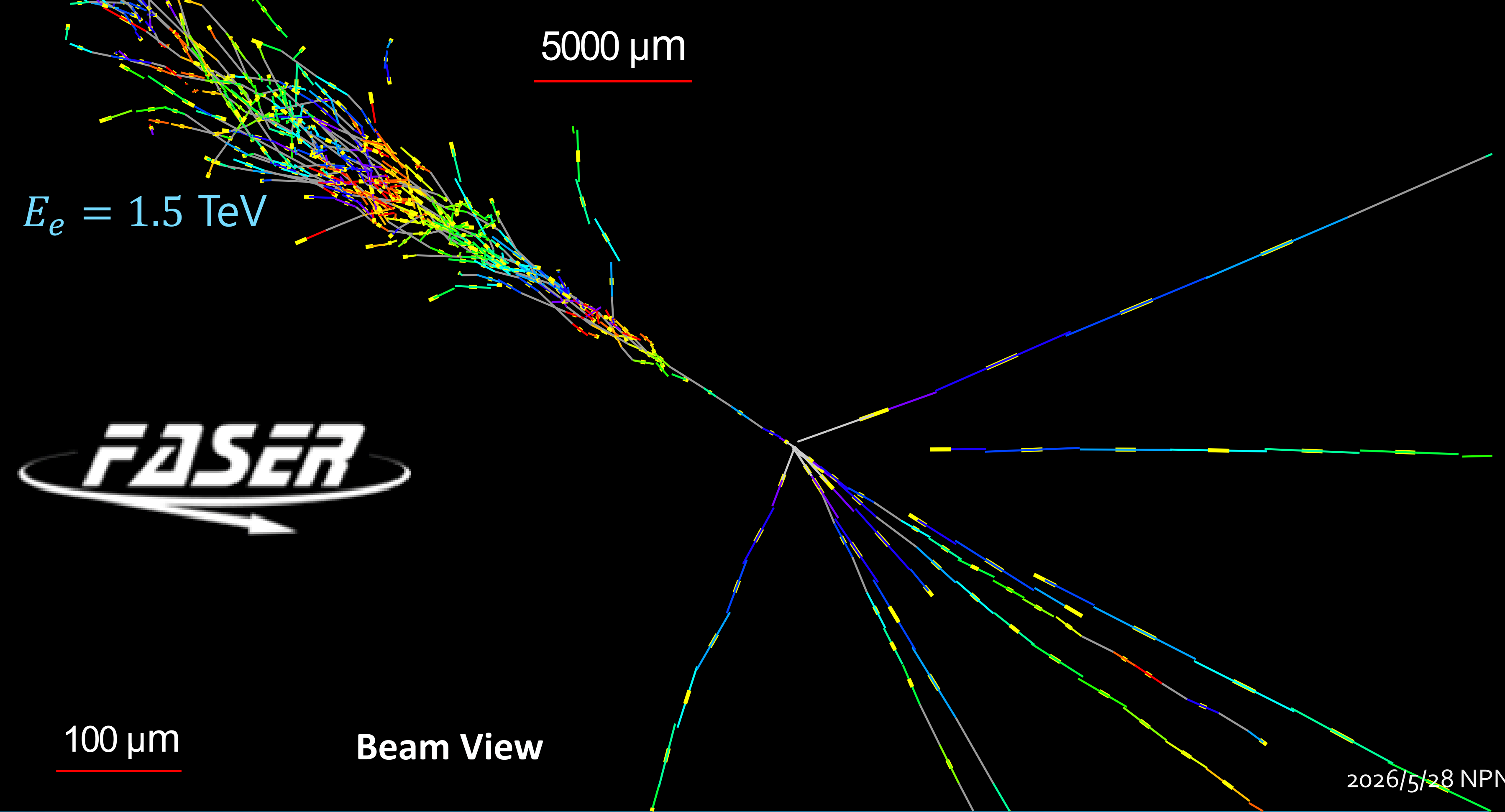
- Dark photon with 2022 data
  - 10.1016/j.physletb.2023.138378
- Axion-Like-Particles (ALPs) with 2022, 2023 data
  - 10.1007/JHEP01(2025)199
- CERN-FASER-CONF-2026-001 Updated dark photon result

Electron neutrino observation in FASERν

ν_e CC event, “Pika-ν“ event

Enjoy an interactive 3D display here!

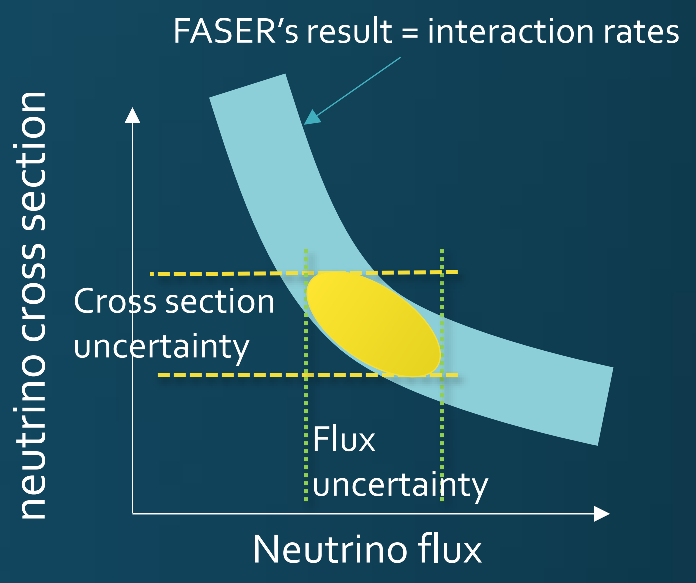


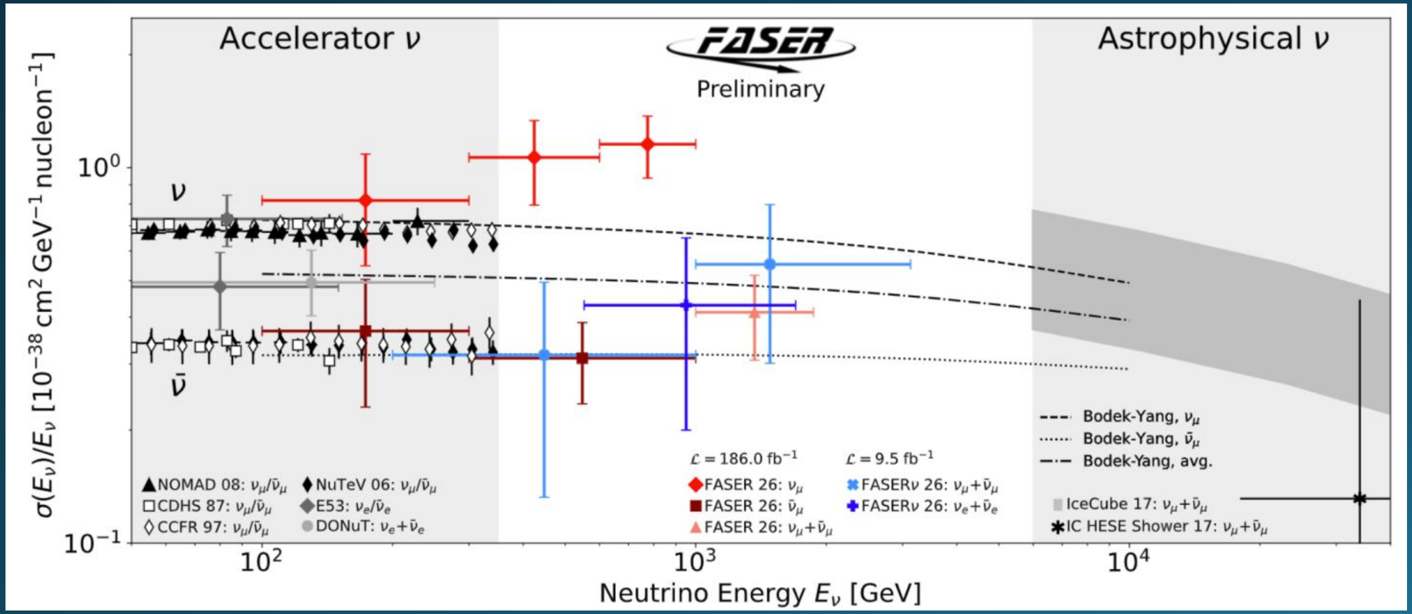


- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

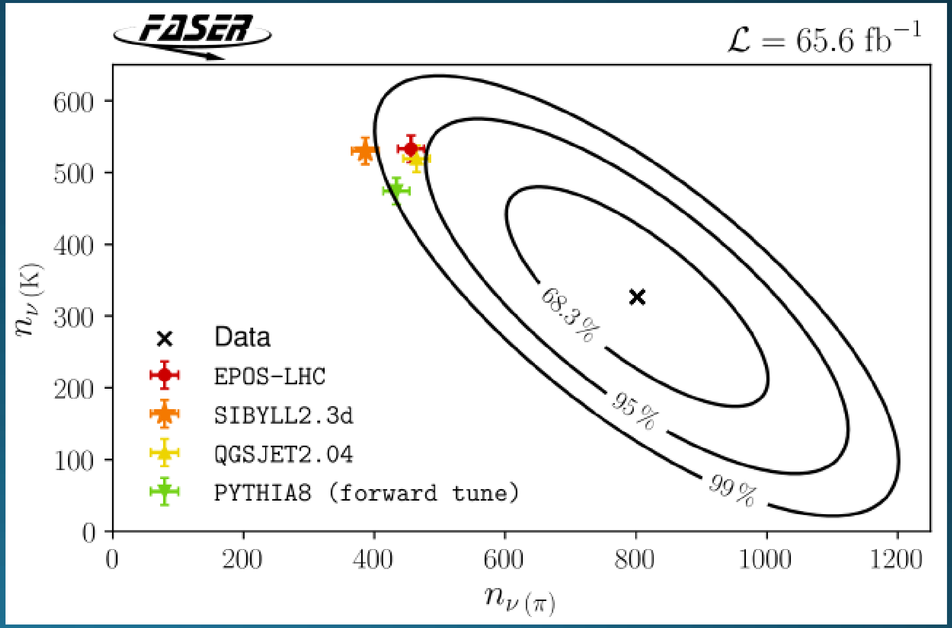
Interpretations of ν_μ interaction rate

- FASER's result can be interpreted in two ways
  - Neutrino cross sections
  - Flux measurement → hadron production model study





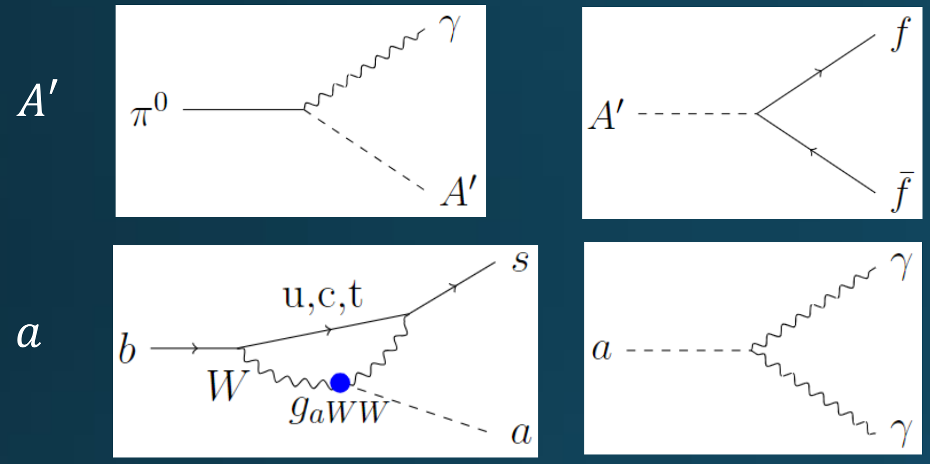
Neutrino cross sections



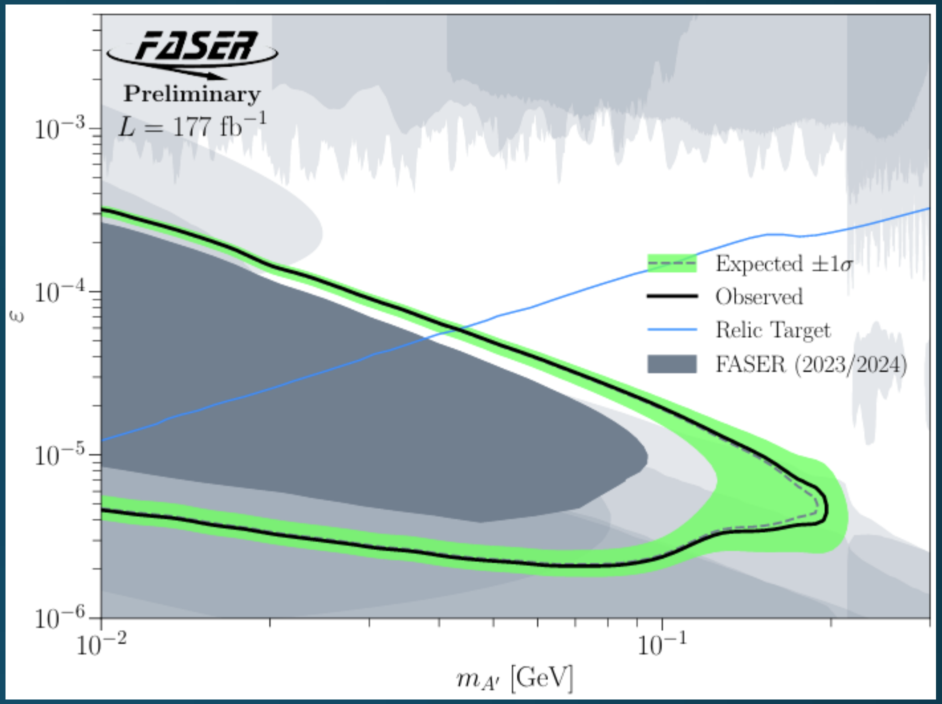
Analysis in π/K production ratio at p-p collisions

BSM particle searches

CERN-FASER-CONF-2026-001

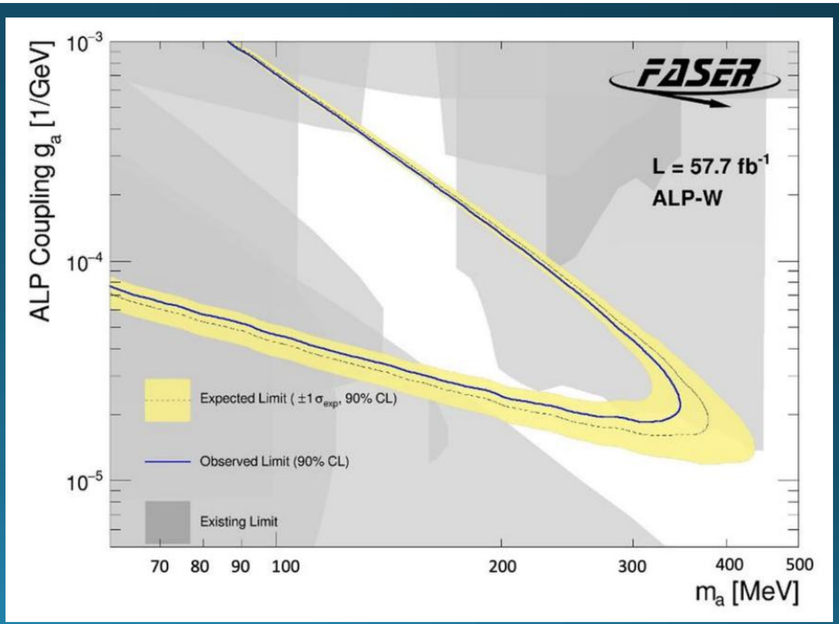


Dark photon (A')



Axion-like particles search with 2022/2023 data (57.7 fb^{-1})

JHEP01(2025)199



Phase of experiments

- **Run 3** (2022-2026, 250 fb^{-1})
  - Proof of principle
- **Run 4** (2030-2034, 780 fb^{-1})
  - Physics-driven expansion in HL-LHC.
- **Forward Physics Facility** Run 4/5 (2033-, 2000 fb^{-1})
  - High statistics measurements & precision physics

- $1\ \mathrm{fb}^{-1} \leftrightarrow 10^{14}$ pp interactions
- Peak luminosity in Run 3
  $= 3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \leftrightarrow 6.5\ \mathrm{kW}$

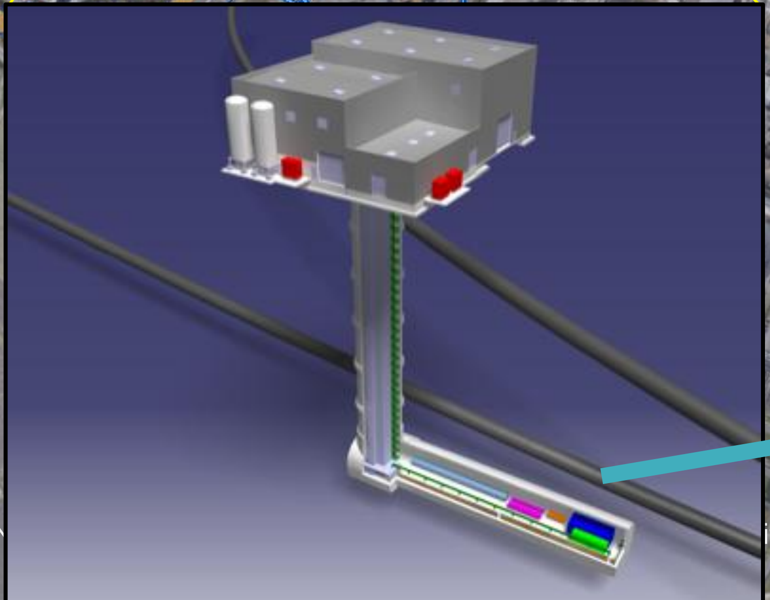
- The phase of pathfinding has been over. Move to high precision physics.

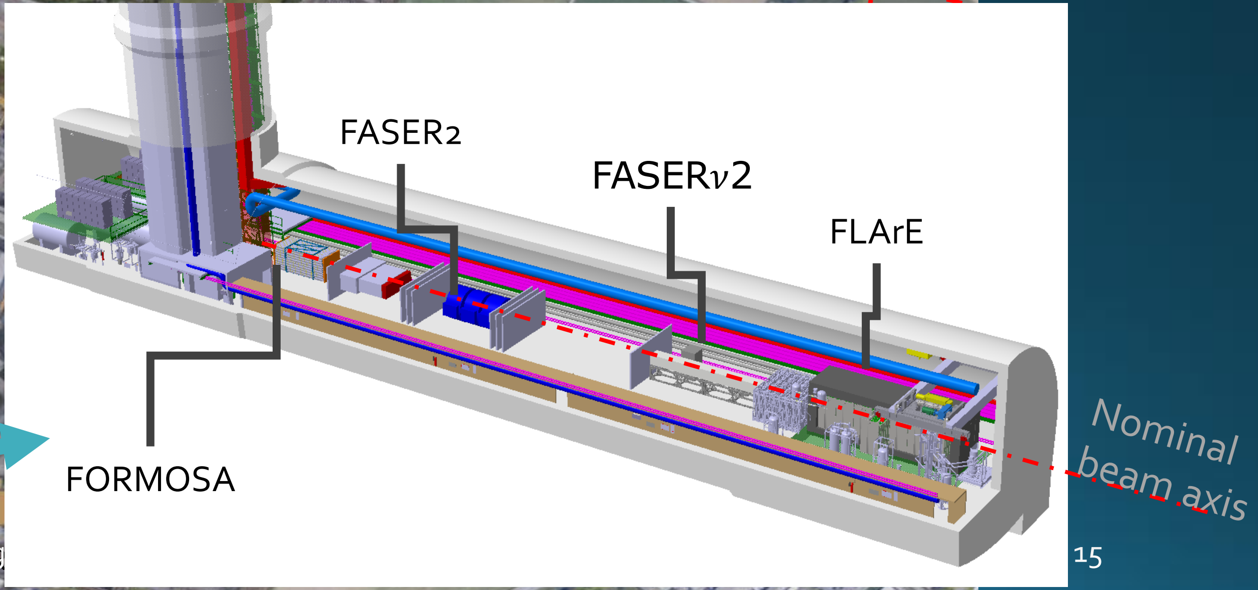
Forward Physics Facility at the HL-LHC

HL-LHC provides x20 proton collisions

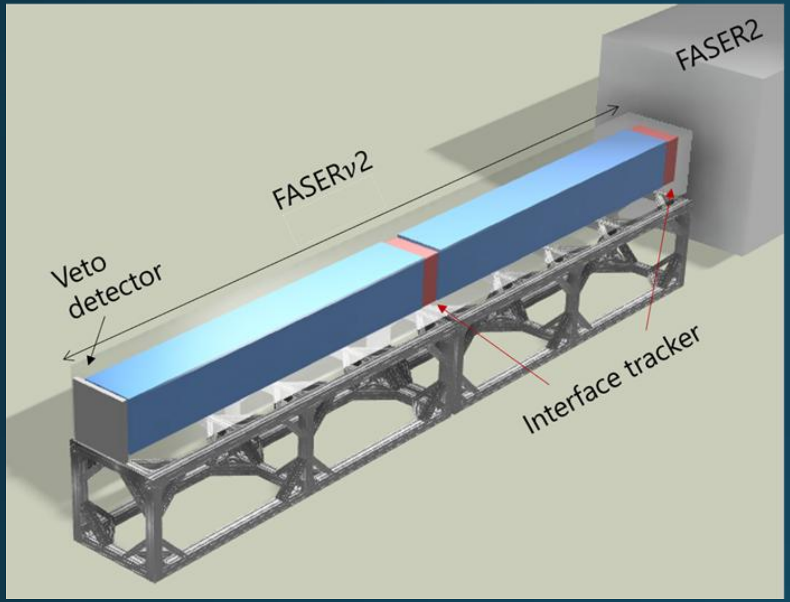
Extending sensitivities for new particle searches and neutrino physics by **2 to 4 orders of magnitude**

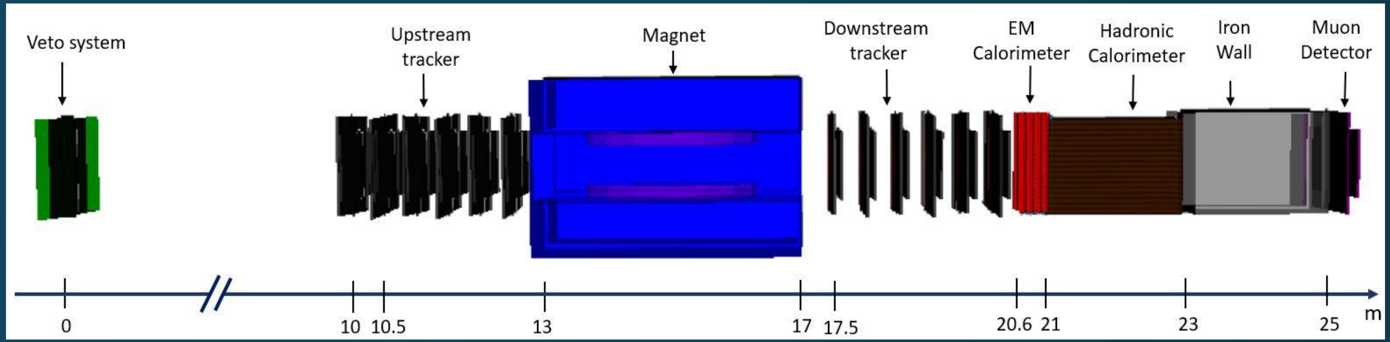
New shaft and hall





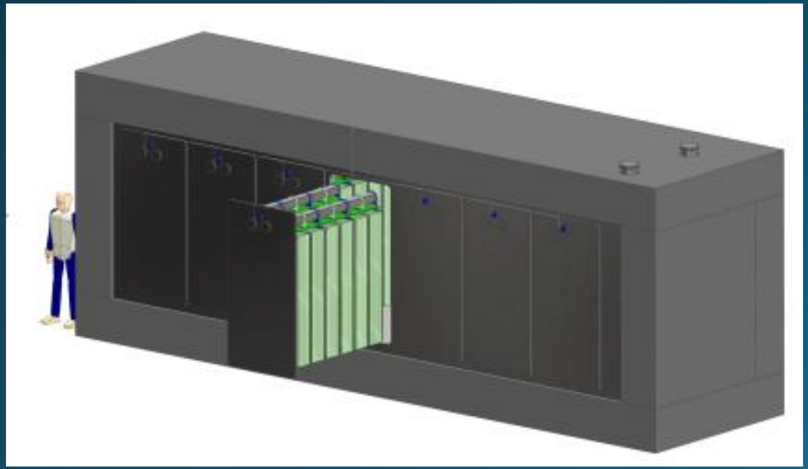
Tailored detectors at the FPF



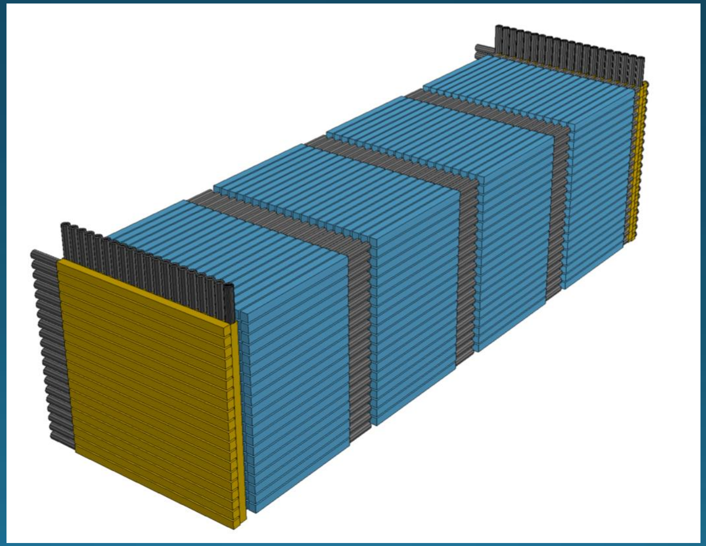


FASER2: tracking spectrometer for LLP searches and muon charge ID

FASERν2: emulsion detector for three-flavor neutrinos



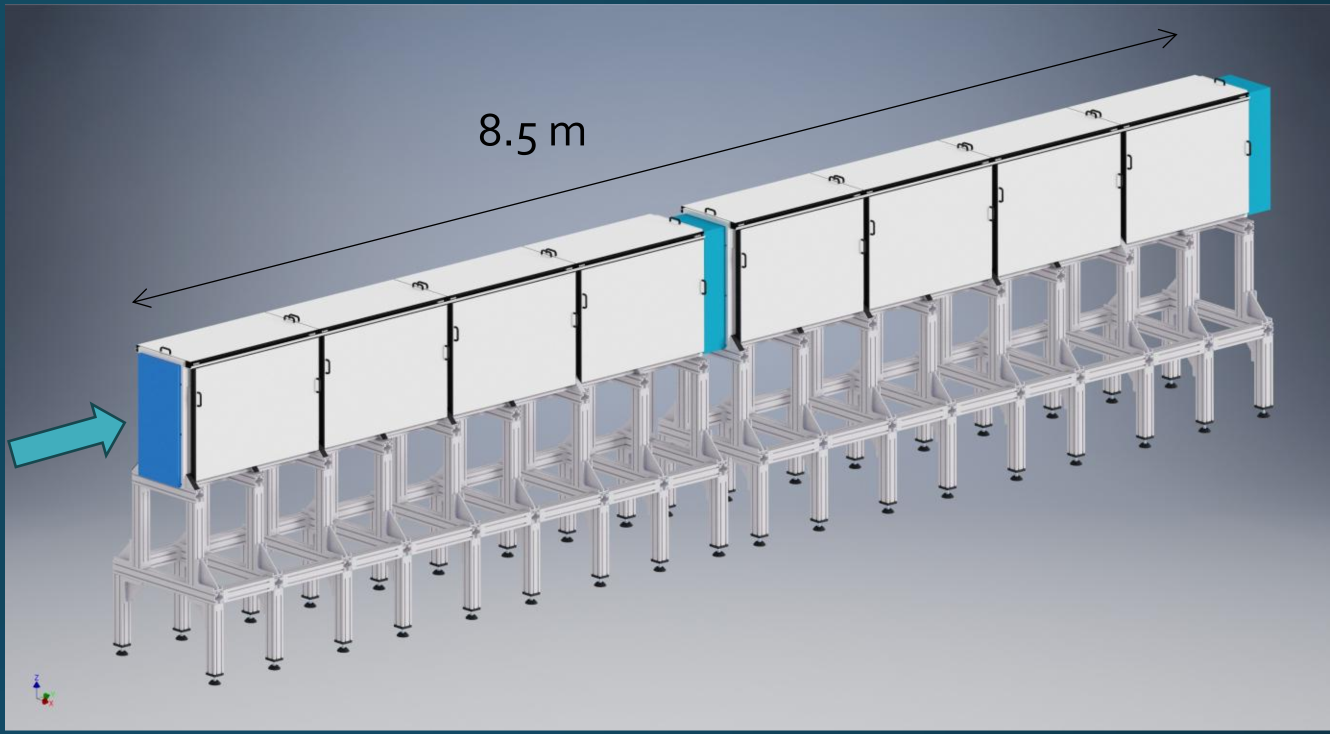
FLArE: LAr TPC for neutrinos

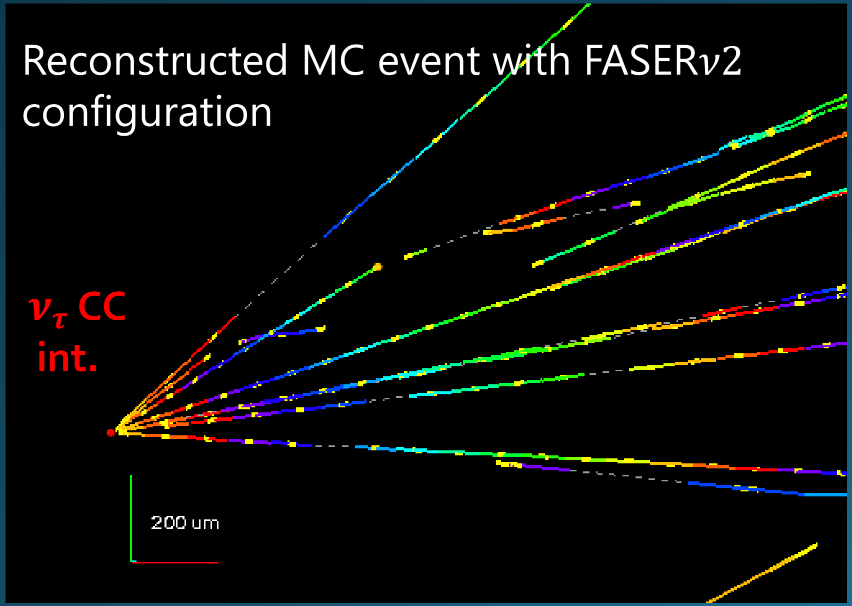


FORMOSA: plastic scintillator array for mCPs

FASERν2

- 20-ton tungsten-emulsion detector
  - Tungsten target: 64 cm x 25 cm x **2 mm** x 3300 plates
  - Sensitivity to ν_e, ν_μ, ν_τ
  - $\mu^\pm$ charge ID with FASER2
- Performance proven by FASERν
- High statistics ν_τ studies and test lepton flavor universality



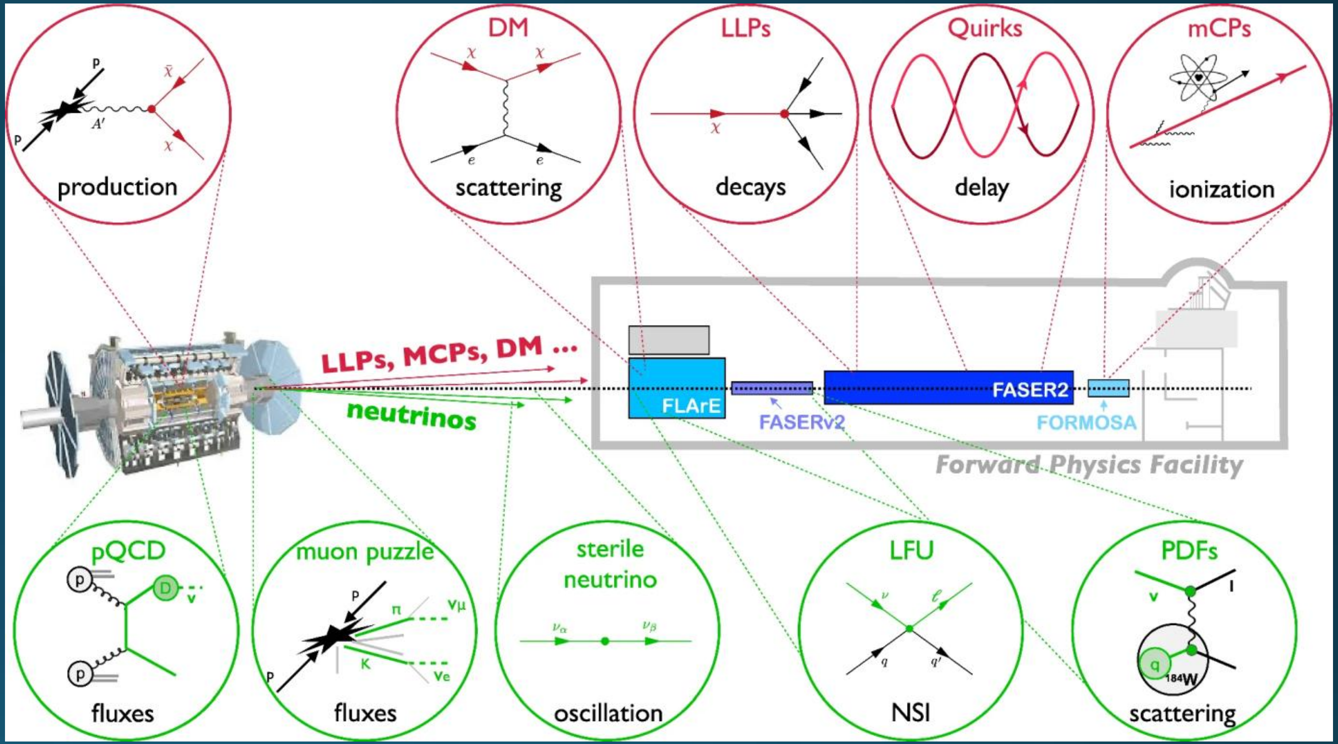


ν int. rate estimated based on **Sibyll 2.3d**

Detector				CC Interactions		
Name	Mass	Luminosity	Rapidity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν at Run 3	1.1 t	350 fb^{-1}	$\eta > 8.8$	2.3k	12k	40
SND@LHC at Run 3	0.8 t	350 fb^{-1}	$7.2 < \eta < 8.4$	300	1.5k	12
FASER at HL-LHC	1.1 t	3 ab^{-1}	$\eta > 8.8$	19k	102k	360
SND@HL-LHC	1.3 t	3 ab^{-1}	$6.9 < \eta < 7.6$	2.9k	15k	143
FASERν2 at FPF	20 t	2 ab^{-1}	$\eta > 8.5$	127k	647k	2.3k
FLArE at FPF	10 t	2 ab^{-1}	$\eta > 7.5$	34.7k	167k	1.0k
FLArE HCAL at FPF	41 t	2 ab^{-1}	$\eta > 6.5$	34.0k	180k	1.5k
FASER2 veto at FPF	0.9 t	2 ab^{-1}	$\eta > 6.7$	1.6k	6.8k	54

Physics objectives and experiments

- Neutrino physics at TeV energies
- Neutrino precision physics
- FPF as neutrino-ion collider
- Unique probe of small-x QCD
- Impact for Astroparticle Physics
- Dark matter and mediators
- Millicharged particles
- Other opportunities for new particle searches
- See the Letter of Intent submitted to CERN!



Physics objectives and experiments

- Neutr
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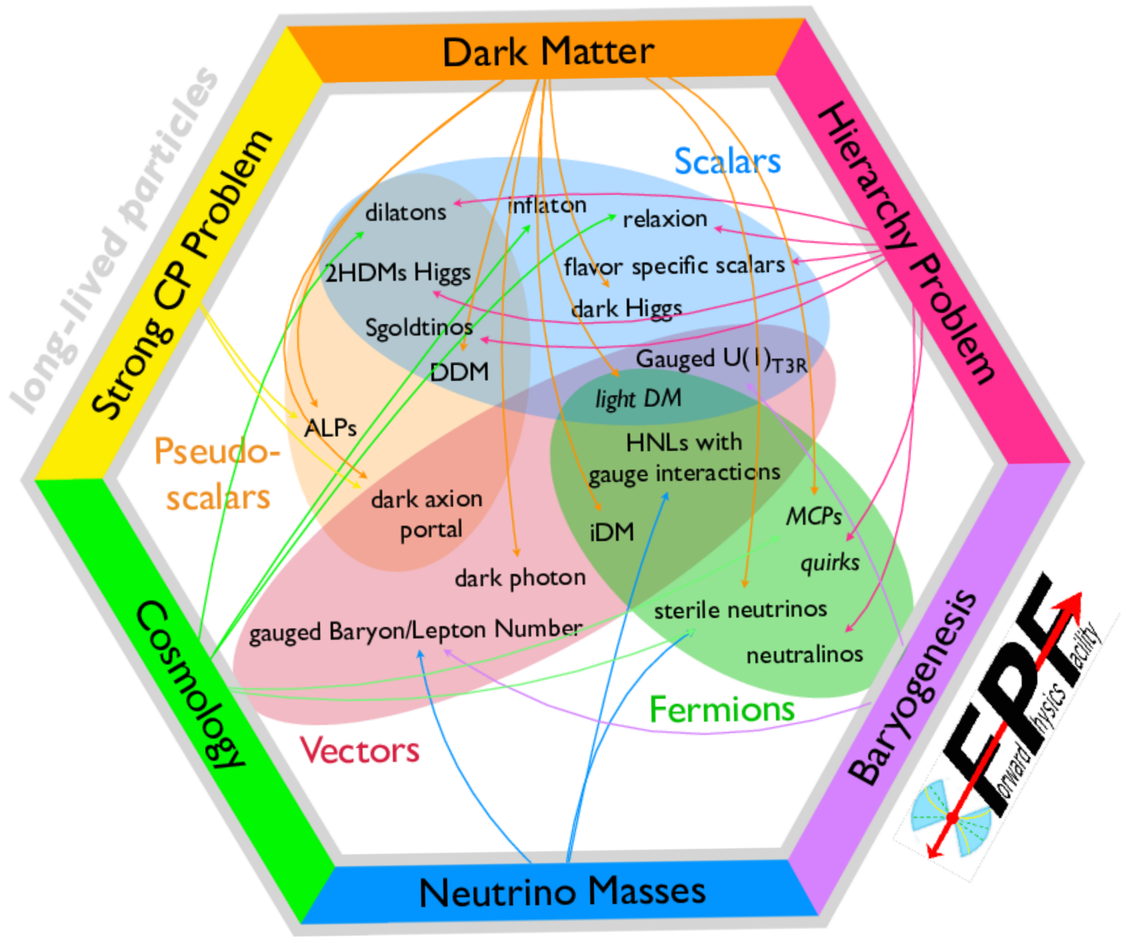
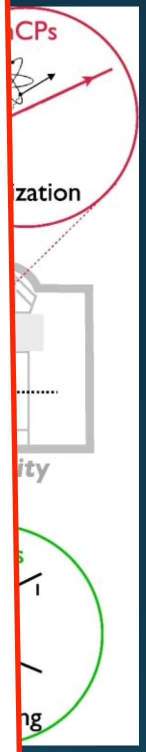
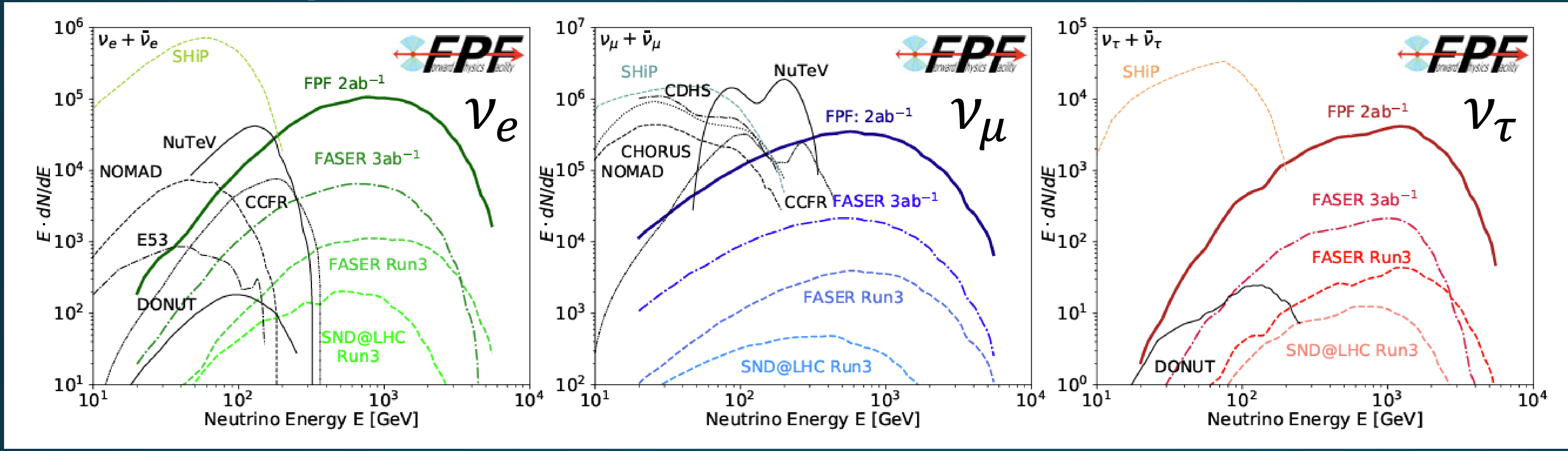
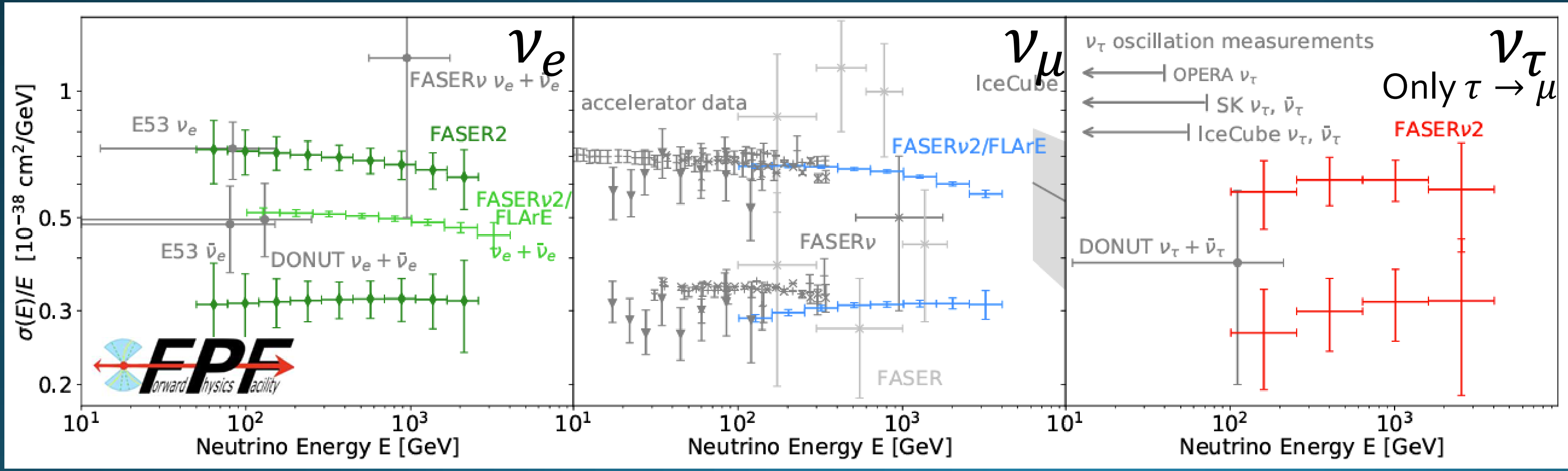
FPF experiments have discovery potential in every one of the PBC benchmark scenarios!



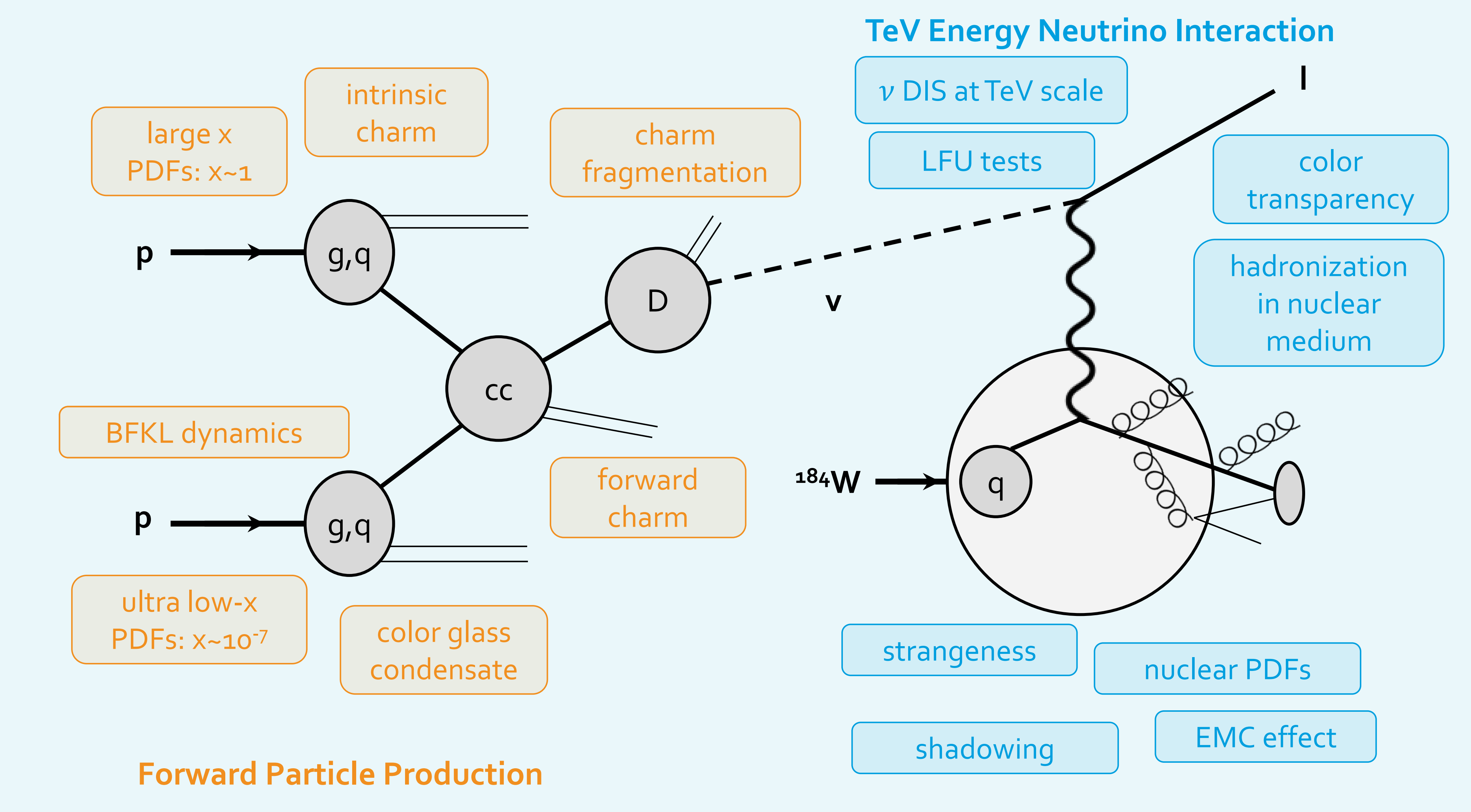


Neutrino yields and cross-section sensitivities at FPF





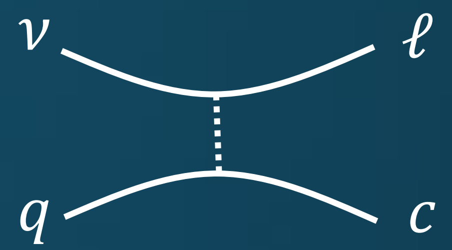
Neutrinos as a probe

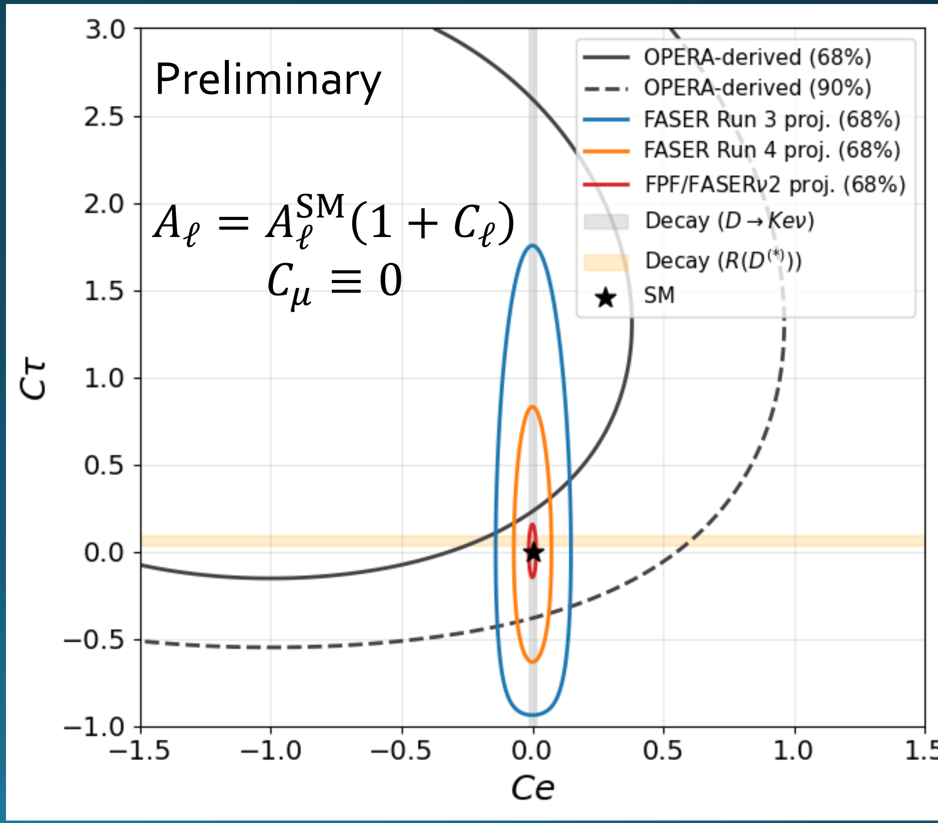


Lepton Flavor Universality in charm production

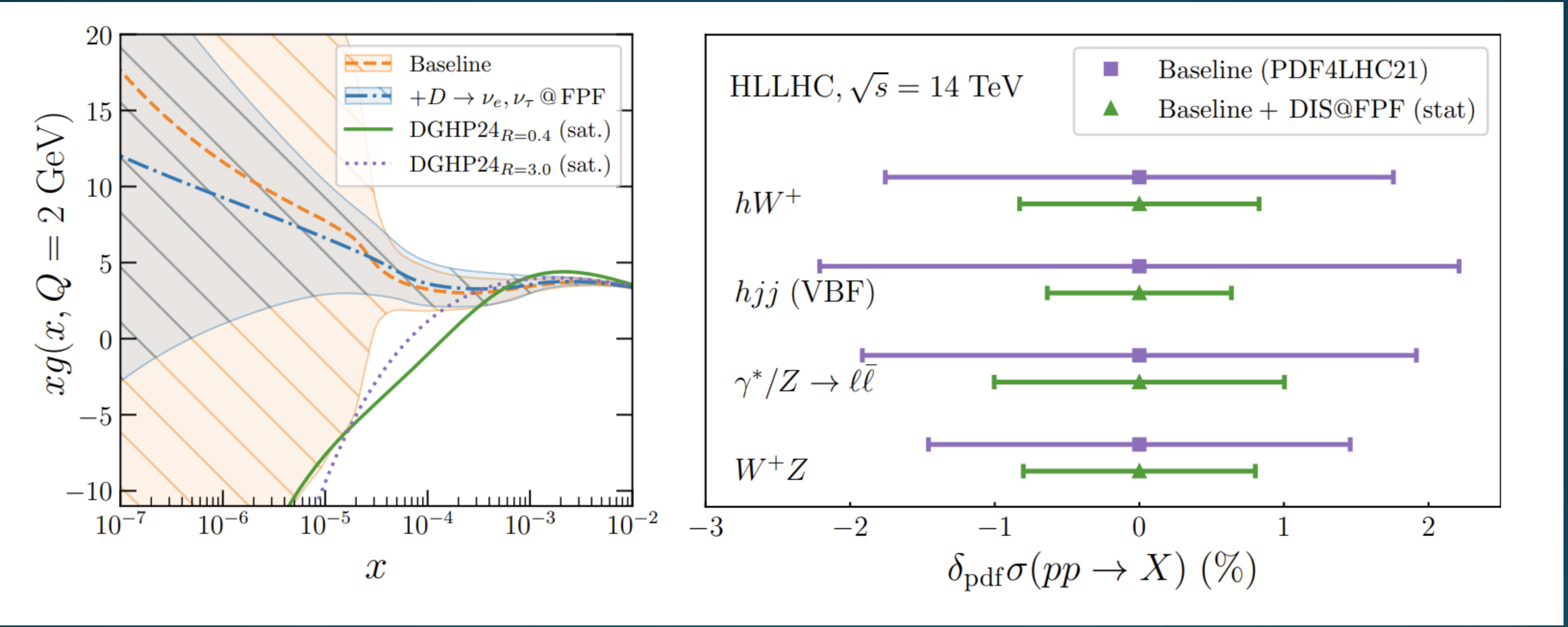
- LFU test in neutrino scattering
  - Complementary approach wrt decays, but poorly measured so far, even inclusive CC channels
  - OPERA's results can be interpreted as $\sim 1.5\ \sigma$ away from the SM
- FASER/FPF can constrain the effective couplings C_e, C_τ by double ratio measurement, canceling flux uncertainty
  - 10-20% of CC produce charmed hadrons

$$R^{\nu_\ell}_{\text{charm}} = \frac{\sigma^{\nu_\ell}_{\text{CC charm}}}{\sigma^{\nu_\ell}_{\text{CC inclusive}}} \Big/ \frac{\sigma^{\nu_\mu}_{\text{CC charm}}}{\sigma^{\nu_\mu}_{\text{CC inclusive}}} = |1 + C_\ell|^2, \qquad (\ell = e, \tau)$$





QCD and enhancing HL-LHC discovery potential



FPF measures the **gluon probability (PDF)** at low momentum fractions

Improves predictions of **Higgs-** and **weak gauge-boson** cross sections at the HL-LHC

LLPs searches at the FPF

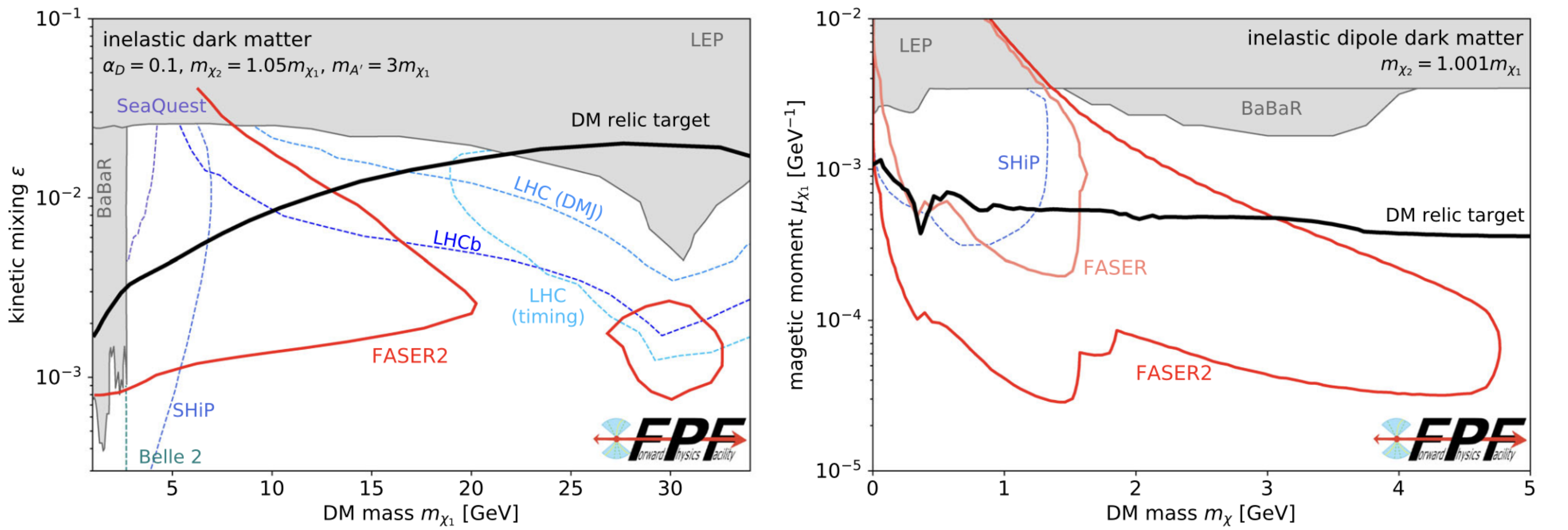


Fig. 4 Inelastic dark matter searches at the FPF. The discovery potential of FASER2 and other experiments for two different realizations of inelastic DM. The left panel considers a the case of heavy inelastic DM interacting via a dark photon portal, as introduced in [15], where the high energy of the LHC allows FASER2 to probe masses up to tens of GeV. The right panel considers the case of light inelastic DM with very small mass splittings that is mediated by a dipole portal as introduced in Ref. [16], where the large LHC energy boosts the signal to observable energies. In both scenarios, the reach of FASER2 extends beyond all other experiments, including direct and indirect DM searches, LHC experiments, and beam dump experiments, such as SHiP. It also covers the thermal DM relic target (solid black lines), that is the cosmologically-favored parameter space where the model predicts the observed dark matter relic abundance as produced through thermal freeze-out. For comparison, we have shown the leading constraints provided by BaBaR [17] and LEP [18,19], as well as projections from a number of other proposed searches, including those for displaced muon jets (DMJ) and delayed particles (timing) at the main LHC experiments [20,21] as well as displaced particle searches at LHCb [22–24], SHiP [25], Belle 2 [26], and SeaQuest [27]

From FPF's input to **ESPPU**

LLPs with unusual propagation patterns

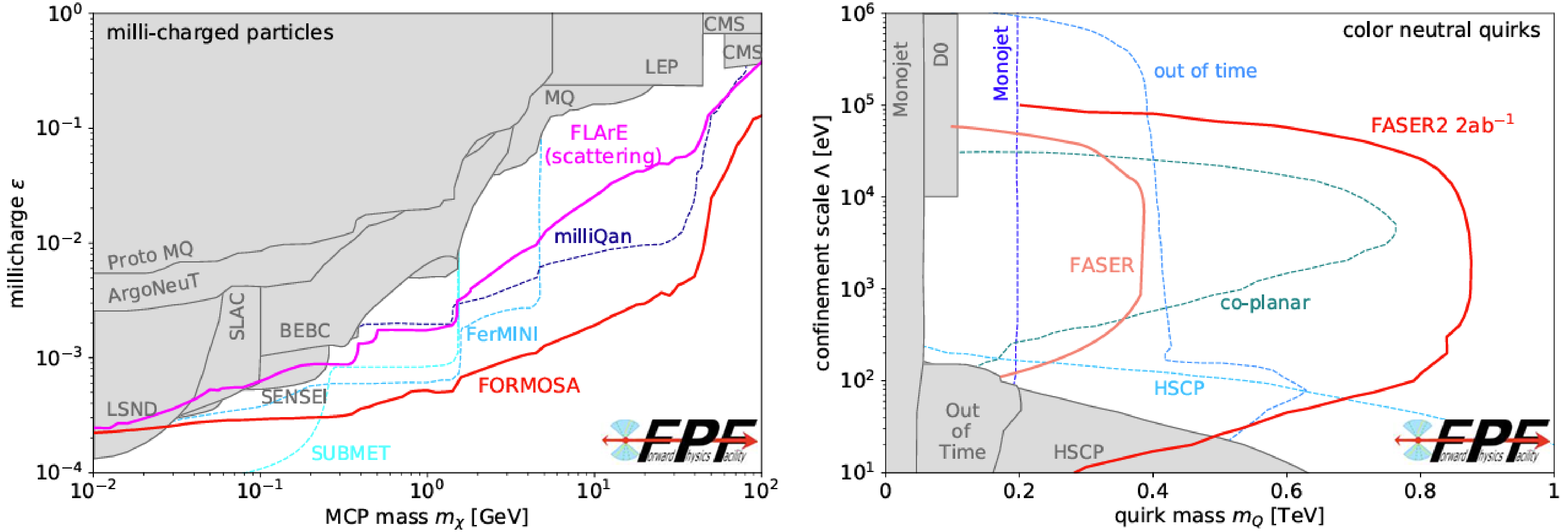


FIG. 21. **New Particle Searches at the FPF.** Left: The discovery reach of FORMOSA and FLArE with 2 ab^{-1} for millicharged particles [227, 229]. Right: The discovery reach of FASER and FASER2 for colour-neutral quirks [230]. In both panels, we also show existing bounds (gray shaded regions) and projected sensitivities of other experiments (dashed contours), including millicharged particle searches at BEBC [231], SLAC [232], LEP [233, 234], CMS [235–237], LSND [238], ArgoNeuT [239], milliQan [240–242], FerMINI [243], SUBMET [244], and SENSEI [245], as well as quirk searches at D0 [246], monojet searches [247–249], heavy stable charged particle searches (HSCP) [247, 250, 251], co-planar hits searches [252], and out-of-time searches [253, 254].

FPF documentation

- **FPF workshop series:**
  - FPF1, FPF2, FPF3, FPF4, FPF5, FPF6, FPF7, FPF theory day, FPF8, FPF9
- **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

ESPPU scientific program:

doi.org/10.1140/epjc/s10052-025-14048-6

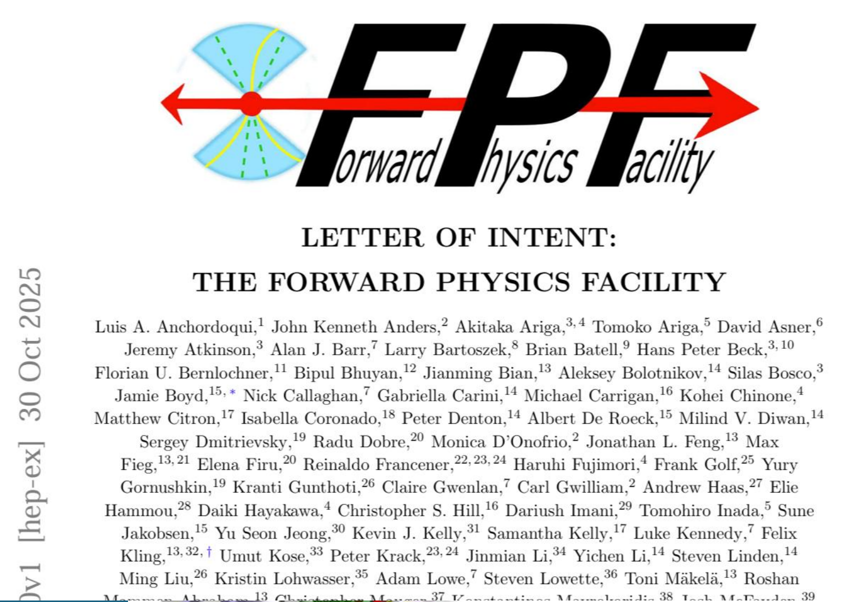
~25 pages, ~26 authors

LoI submitted to CERN

10.1016/j.nuclphysb.2026.117398

Oct 2025

73 pages, 114 authors



30 Oct 2025 [hep-ex] v1

LETTER OF INTENT:

THE FORWARD PHYSICS FACILITY

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trinos at colliders are ideal messengers of the inner structure of protons and nuclei. The FPF neutrino program will refine our understanding of forward hadron production, uniquely probe QCD in uncharted re-

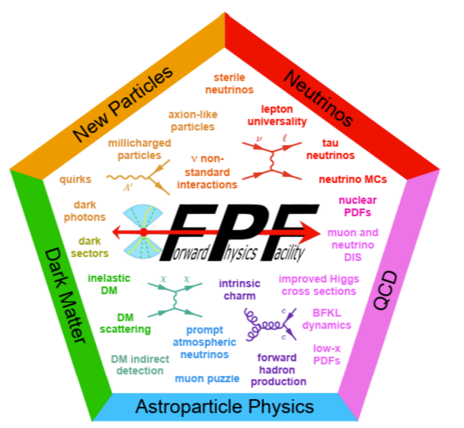


FIG. 1. **Physics Overview.** The FPF will probe topics that span multiple frontiers, including new particles, neutrinos, dark matter, QCD, and astroparticle physics.

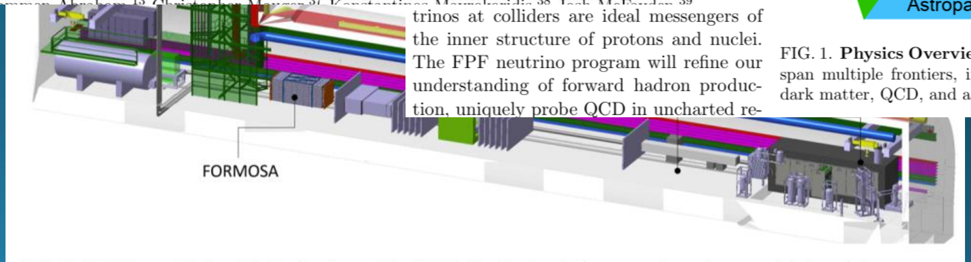


FIG. 24. **FPF Cavern Design.** The baseline layout of the FPF facility, showing the four proposed experiments and the large infrastructure.

Summary

- Forward physics has proven to be a rich playground for exciting physics
  - Pathfinder experiments have already reported results from Run 3
- The Forward Physics Facility (FPF) has been proposed to fully exploit the potential of the HL-LHC
  - 4 complementary experiments; FASER2, FASERν2, FLArE, FORMOSA
  - The physics program is rich and diverse, spanning neutrino physics and searches for BSM particles
- A Letter of Intent (LoI) has been submitted to CERN (see here)

FPF timeline and cost

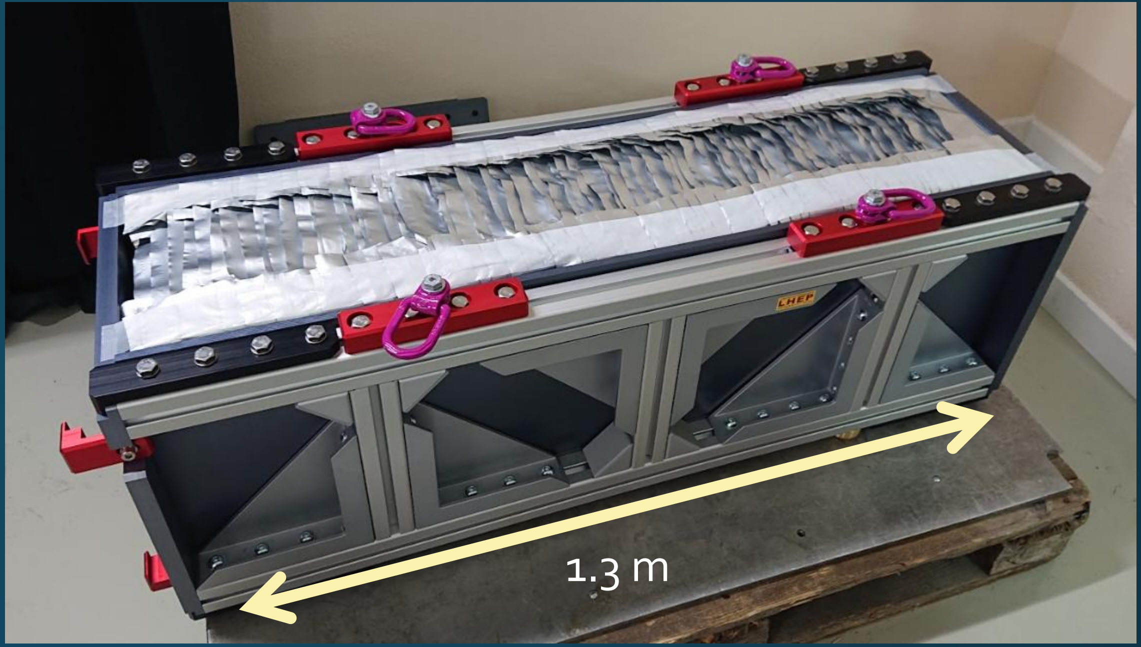
- Vibration study indicates that construction of the FPF possible during LHC operations
- Radiation protection studies indicate work in FPF possible while the LHC is running

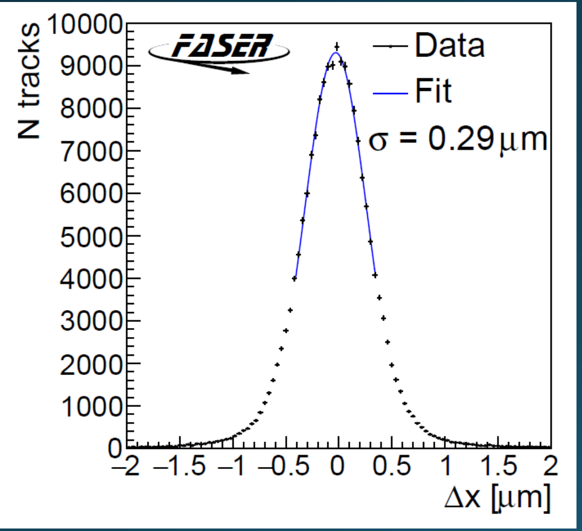
  → not restricted to LS!
- Timeline: construct in LS3/early Run 4, physics starts in late Run 4.
- Capture as much HL-LHC luminosity as possible.
- Cost Estimate: 35 MCHF (class 4)

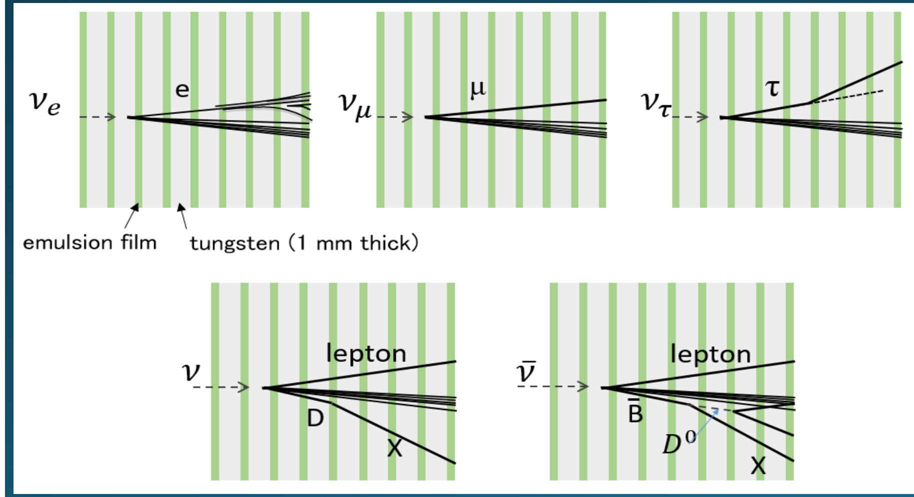
Ref.	Work Package	Cost [CHF]	Percentage of the CE Works
1.	Underground Works	12,392,344.00	35%
1.1	Preliminary activities	1,845,000.00	5.2%
1.2	Access shaft	4,424,143.00	12.5%
1.3	Experimental Cavern	6,123,201.00	17.3%
2.	Surface Works	6,727,231.00	19%
2.1	General items	720,776.00	2.0%
2.2	Topsoil and earthworks	702,227.00	2.0%
2.3	Roads and network	796,122.00	2.3%
2.4	Buildings	4,508,106.00	12.8%
2.4.1	Access building	2,224,786.00	6.3%
2.4.2	Cooling and ventilation building	1,497,350.00	4.2%
2.4.3	Electrical Building	563,689.00	1.6%
2.4.5	External platforms	222,281.00	0.6%
3.	General items	11,815,899.00	33.4%
4.	Miscellaneous	4,397,504.00	12.4%
	TOTAL CE WORKS	35,332,978.00	100.0%

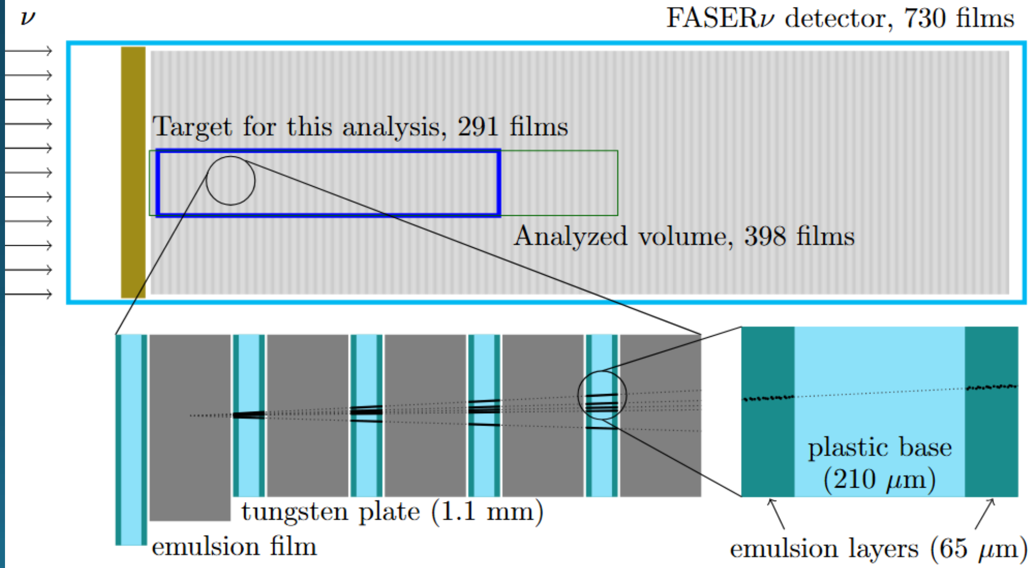
FASERν and current sample

- Emulsion/tungsten neutrino detector
  - 730 emulsion films ~ an exa-channel detector
  - Target mass of 1.1 tons (8 λ_{int}, 220X_0)
  - Typical position resolution, 300 nm
- Data set for the published result:
  - 9.5 fb^{-1} in 2022 run, target mass of 128.6 kg
  - ~1.7% of data collected by 2023



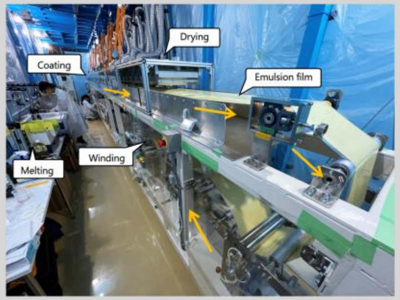






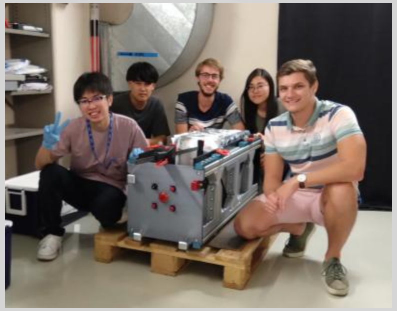
FASERν steps, 3 detectors per year

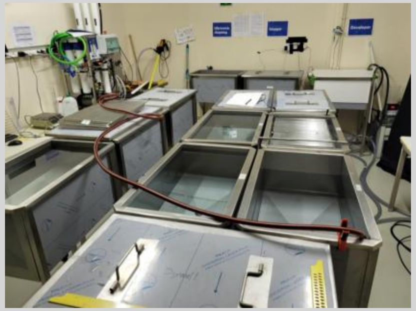
Japan



Film production

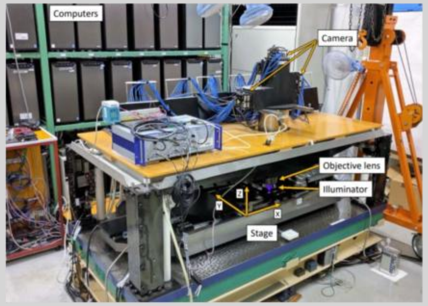
CERN





Assembly → Exposure → Disassembling → Development →

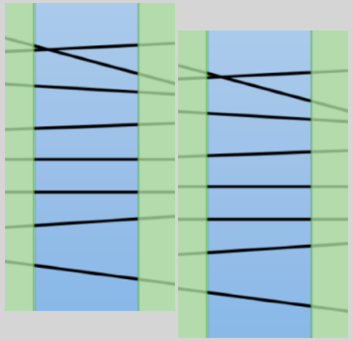
Japan

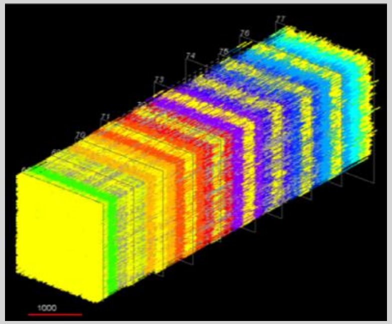


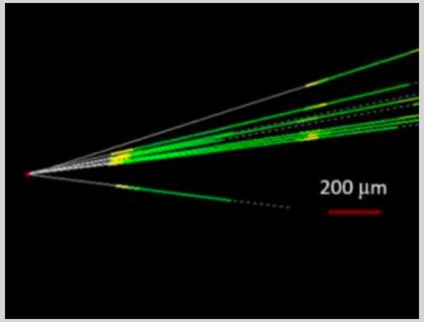
Readout

Offline analysis

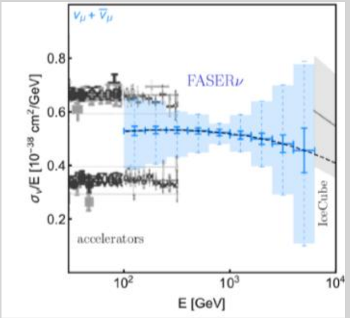
Alignment → Track reconstruction → Vertex reconstruction → e, μ ID, τ decay search, charge ID, Eν reco, charm/beauty, etc. → Physics analysis







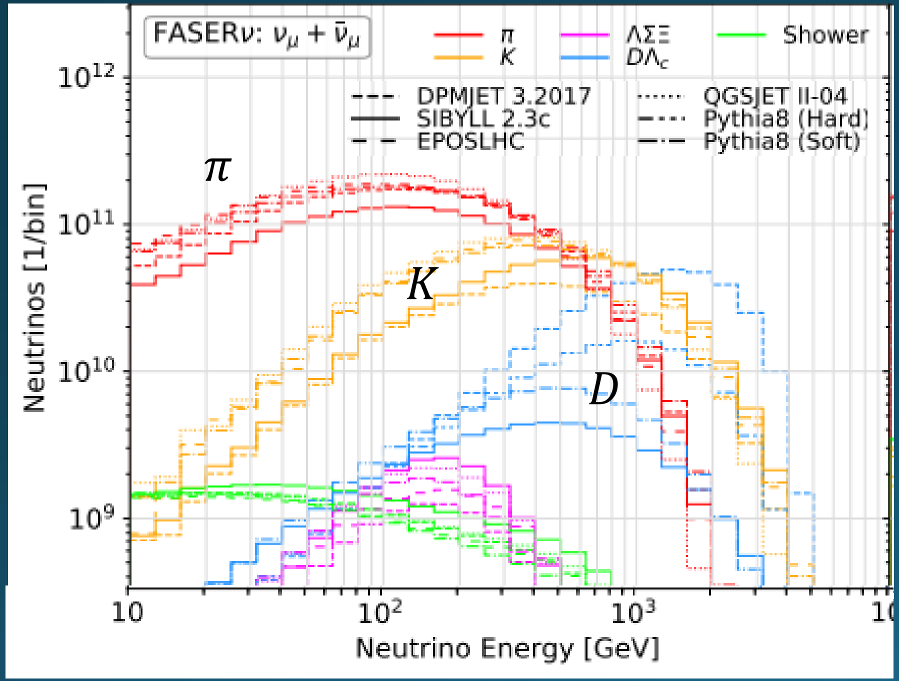
e, μ ID
τ decay search
charge ID
Eν reco
charm/beauty
etc.



Neutrinos = proxy of forward hadron production

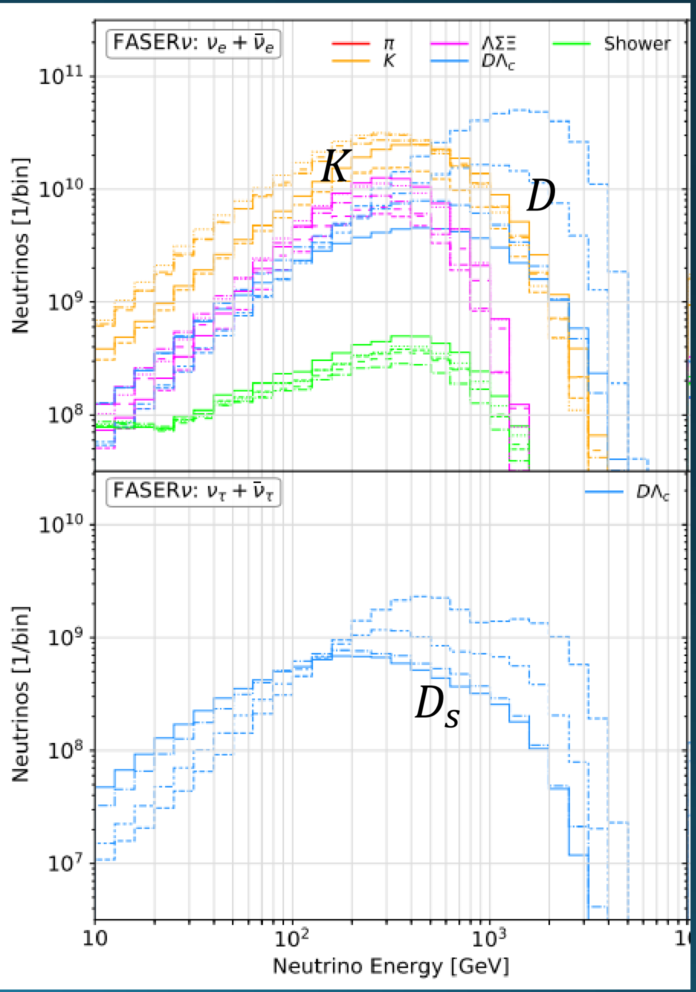
- Pion, Kaon, charm contribute to different part of energy spectra and flavor

ν_μ



ν_e

ν_τ

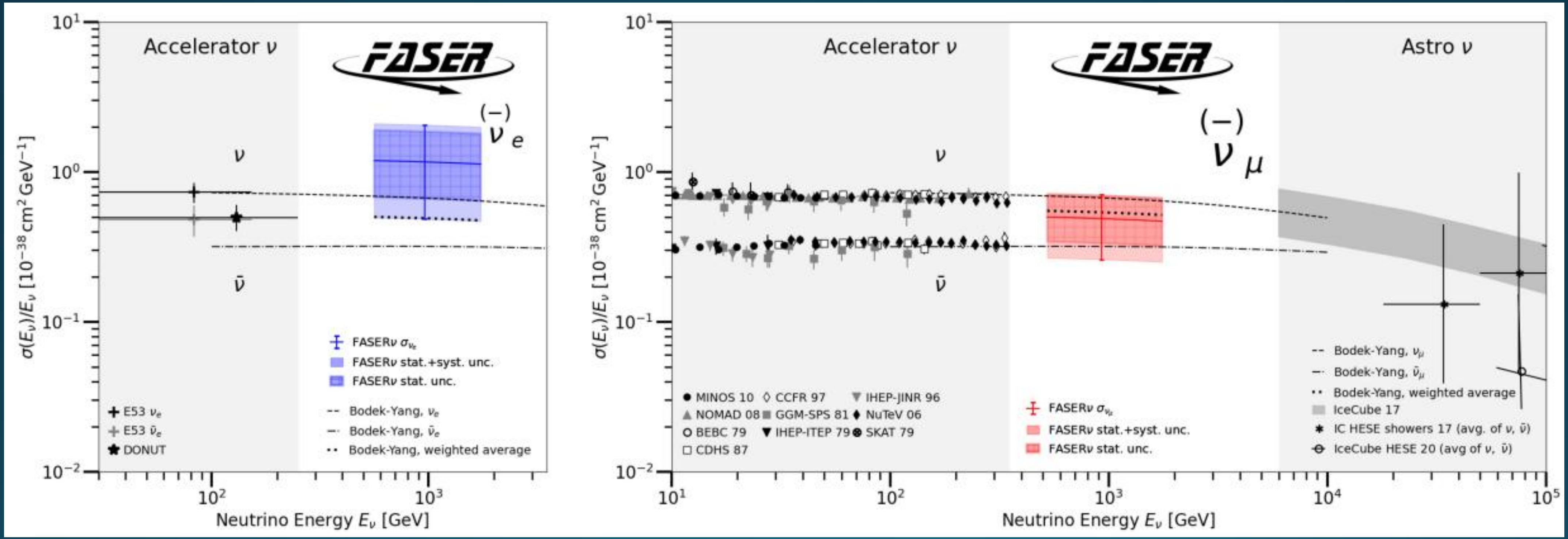


- FASERν/FPF provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

First cross section measurements at TeV energies

PhysRevLett.133.021802

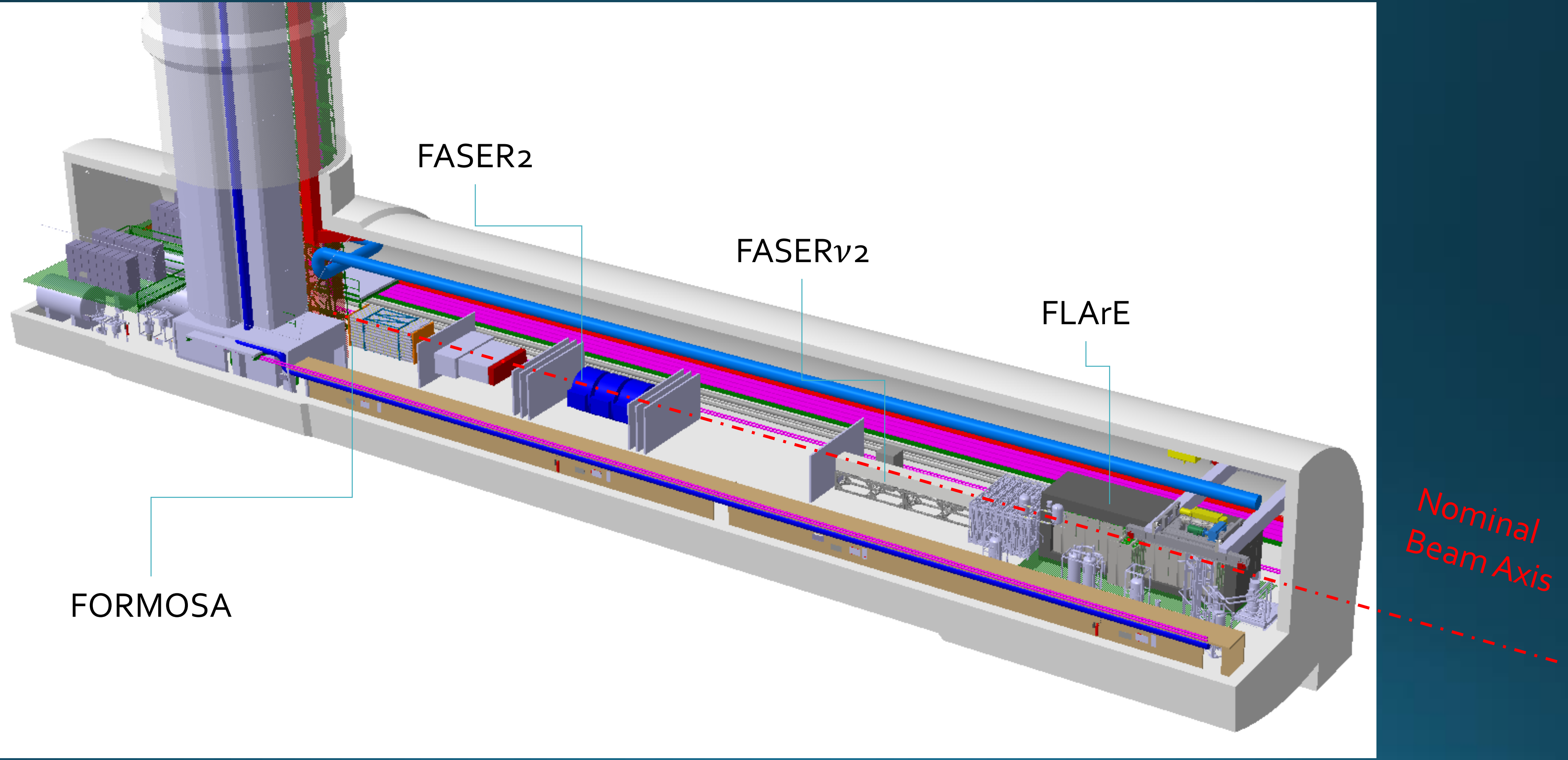
$4\ \nu_e$ and $8\ \nu_\mu$ observed events with negligible BG, both above $5\ \sigma$



Relative measurement wrt theoretical curve.

L=9.5 fb^{-1}, m=128.6 kg

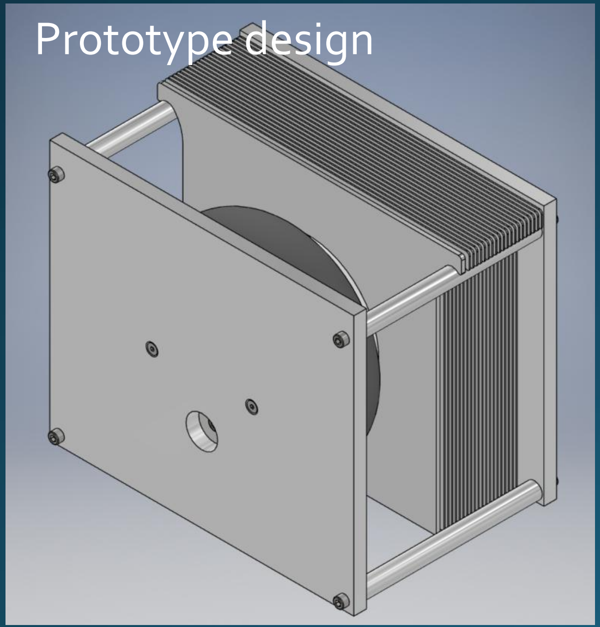
4 proposed FPF experiments, diverse detectors for a broad physics program



FASERν2 detector structure

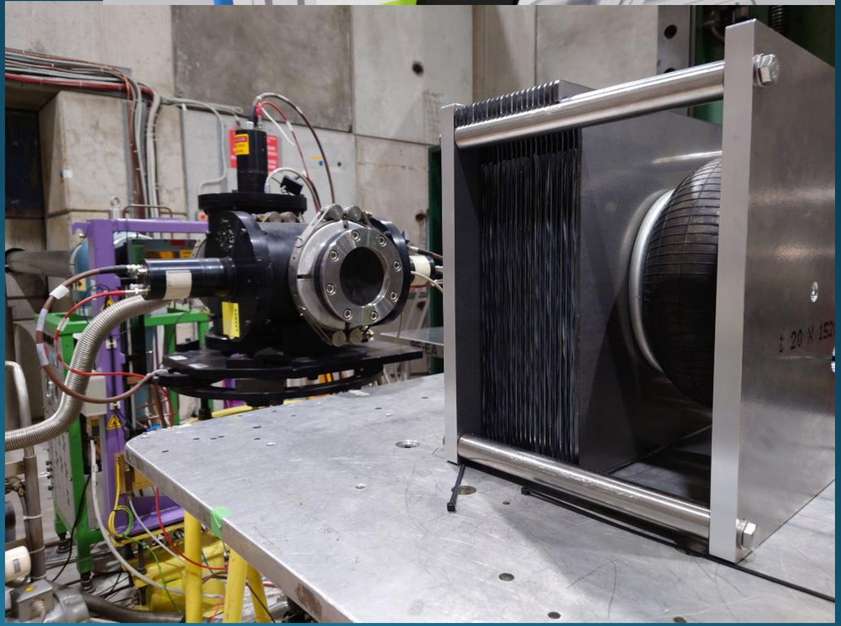
Prototype design, T-shirt shape iron plates on a rail, pushed by compressed-air pressure

- Assembling a 20-ton detector in dark is technically challenging → Assembling in FPF
  - Light-tight-packed emulsion film
- The scheme was tested in test beam at SPS-H8 in 2024

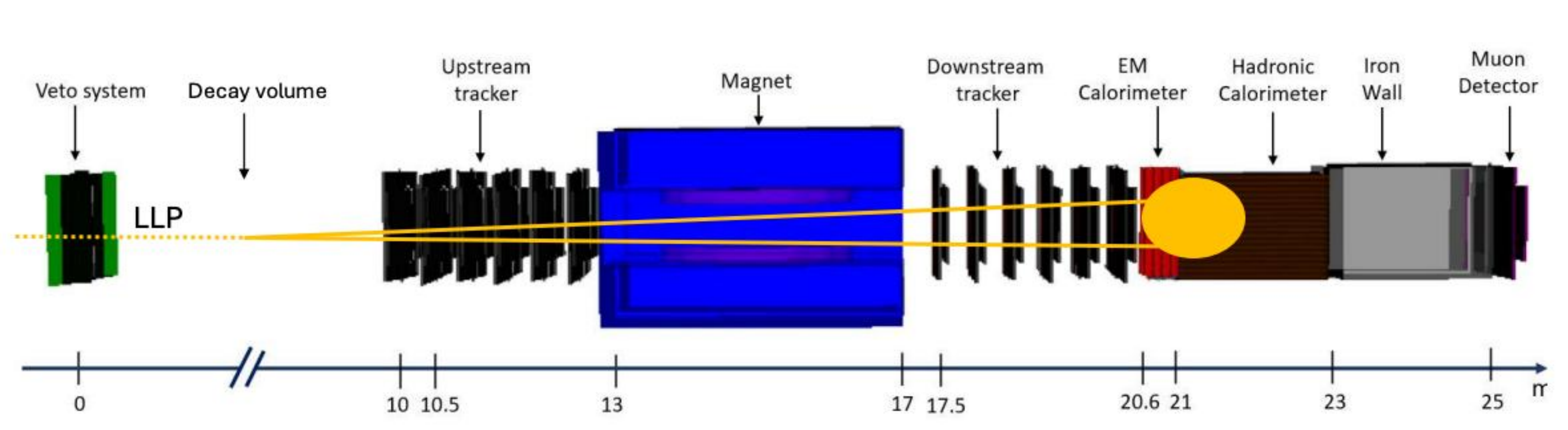


Prototype design

Test at SPS-H8



FASER2



Decay volume:

- 10 m long decay volume

Tracker:

- Based on LHCb's SciFi tracker
- SiPM and scintillating fiber design
- Detector resolution: ~ 100 µm

Magnet:

- Large aperture
- 3m wide X 1m gap (*)
- Superconducting technology
- Magnetic Field : 2 Tm
- Based on the SAMURAI magnet

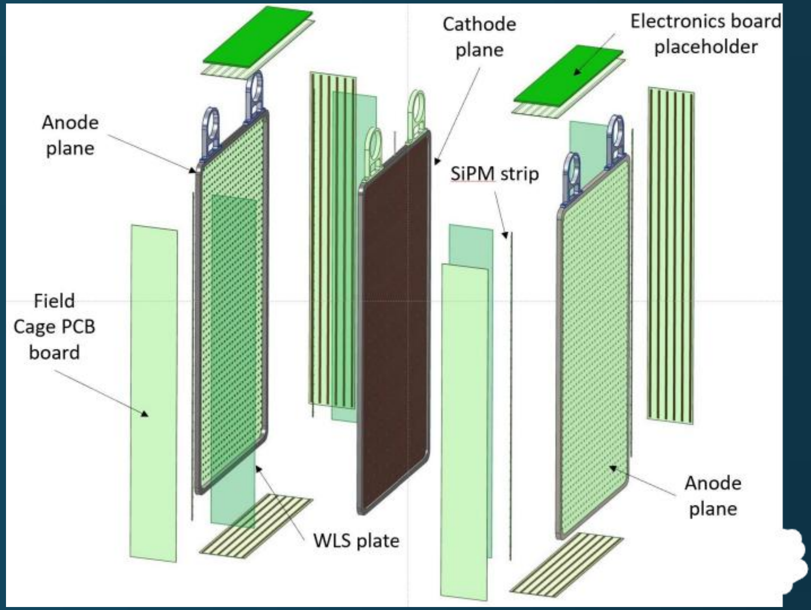
Calorimeter:

- Based on dual-readout calorimetery
- Spatial resolution: 1-10 mm

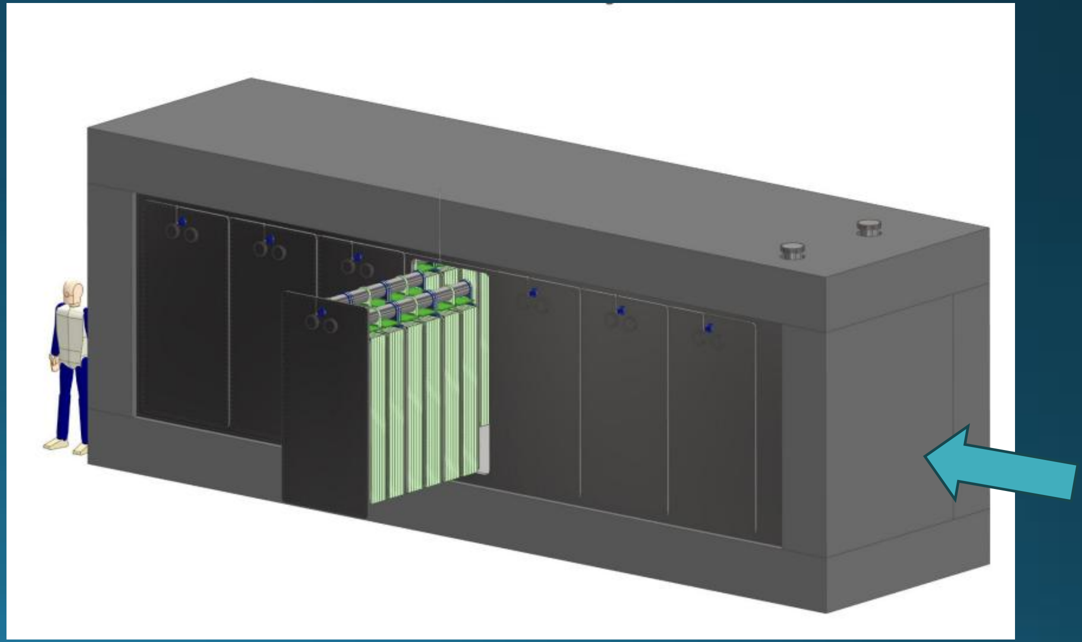
All possible with existing detector technologies

FLArE

Inspired by the DUNE near detector concept (photo in Bern)

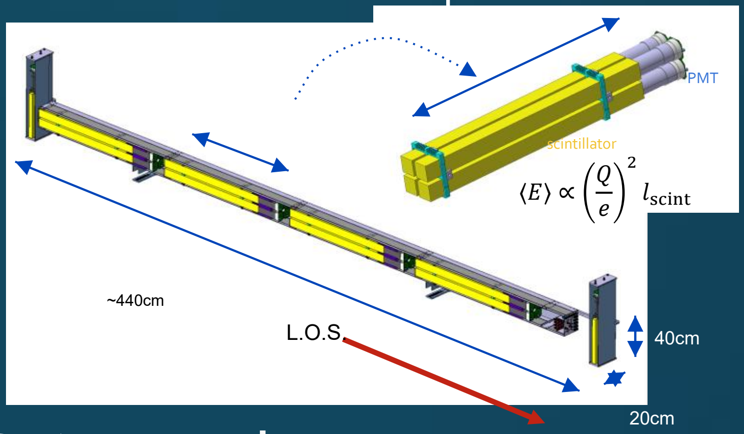


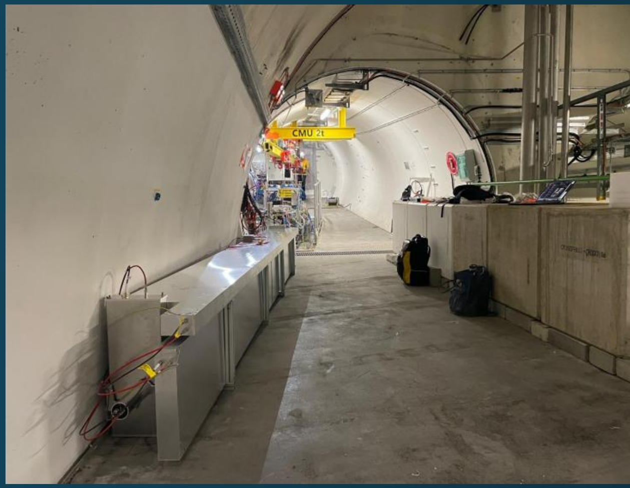
- Liquid Argon neutrino detector
  - Based on DUNE near detector concept
  - 3 x 7 = 21 TPCs
  - 30 tons active volume, 10 tons fiducial volume
- LAr works as precision tracker and calorimeter
- Particle ID, energy measurements from MeV – O(100) GeV
- Study ν_e, ν_μ, ν_τ (statistically)
- $\mu^\pm$ charge ID with FASER2



FORMOSA

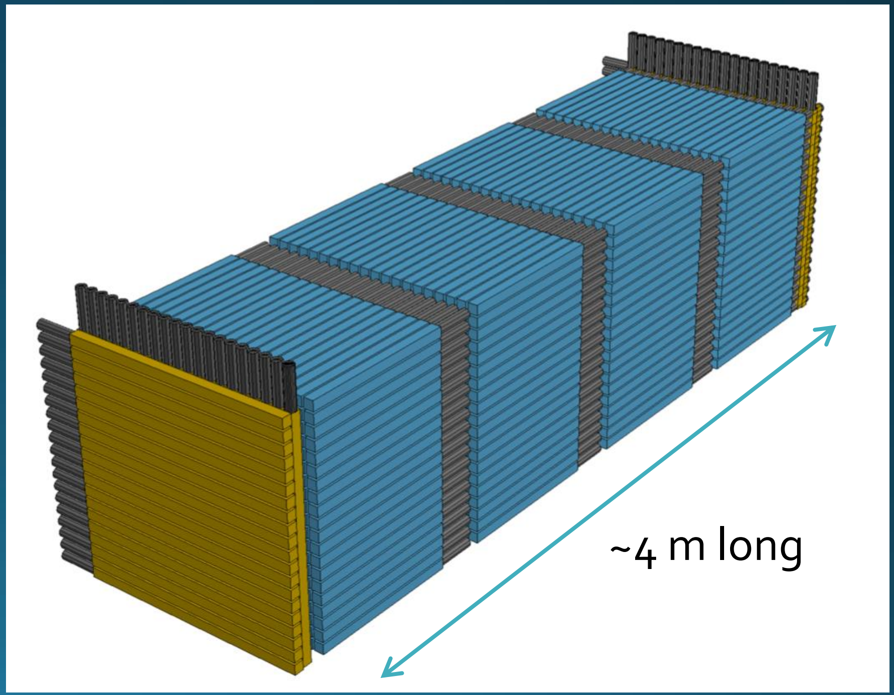
2024





FORMOSA demonstrator as of 2025

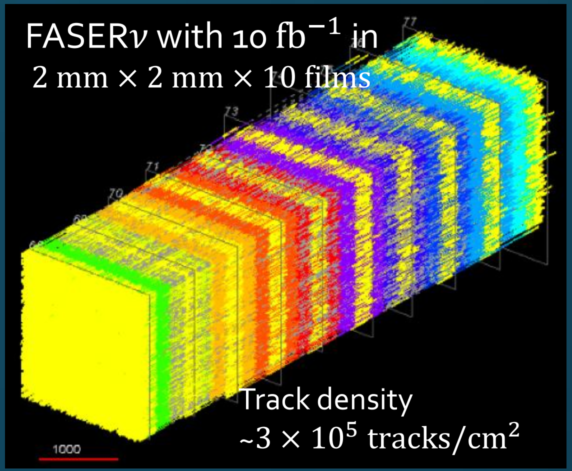
- Direct millicharged particle (mCP) searches at the LHC
- Core concept: Use array of efficient long scintillator bars + PMTs to detect ionization from mCPs.
- Small scale prototype in 2025:
  - 16 scintillator bars
  - Front+back muon panels

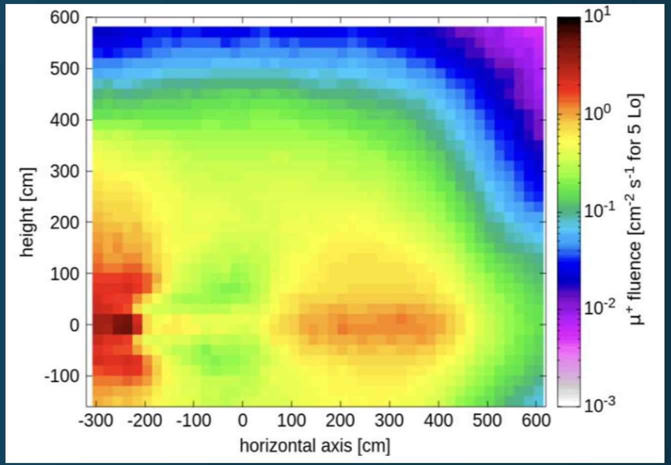


BG muon measures

- Background muon limits sensitivities
  - Impacts FASERν2, FLArE, FORMOSA
  - Estimated to be O(1) Hz/cm²
- Reducing muon background would be beneficial for the FPF experiments (particularly FASERnu2)

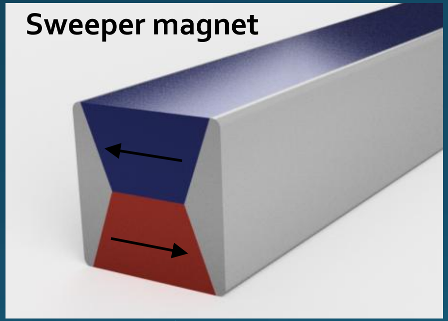
→Investigating the feasibility of implementing a Sweeper magnet

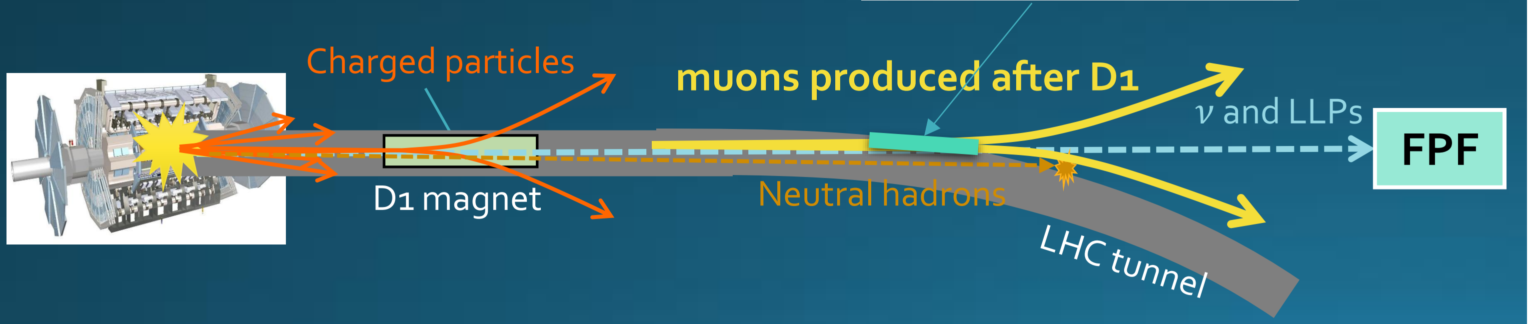




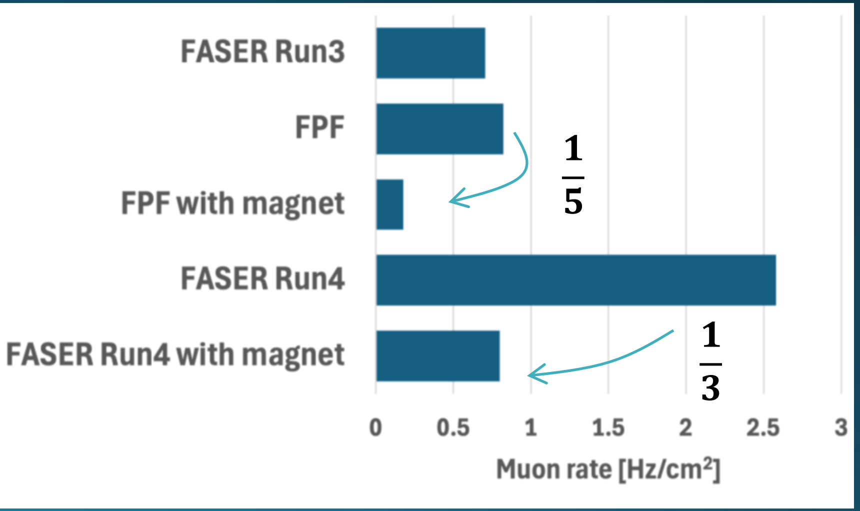
μ^+ fluence expected in FPF
~O(1) Hz/cm²

Place a permanent magnet along the wall of the LHC tunnel
1 T x 40 m long



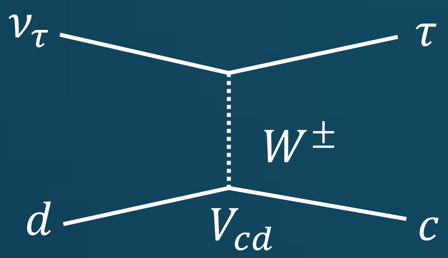


Simulated muon rates with/without sweeper magnet (preliminary)

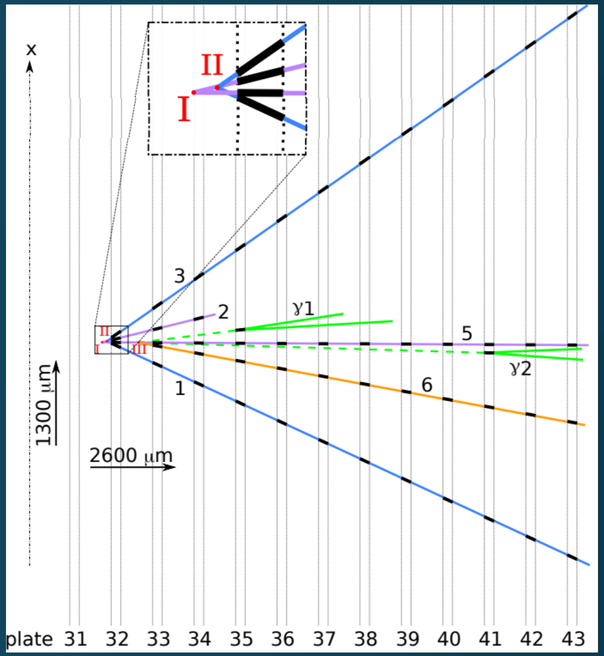


OPERA's ν_τ induced charm production event

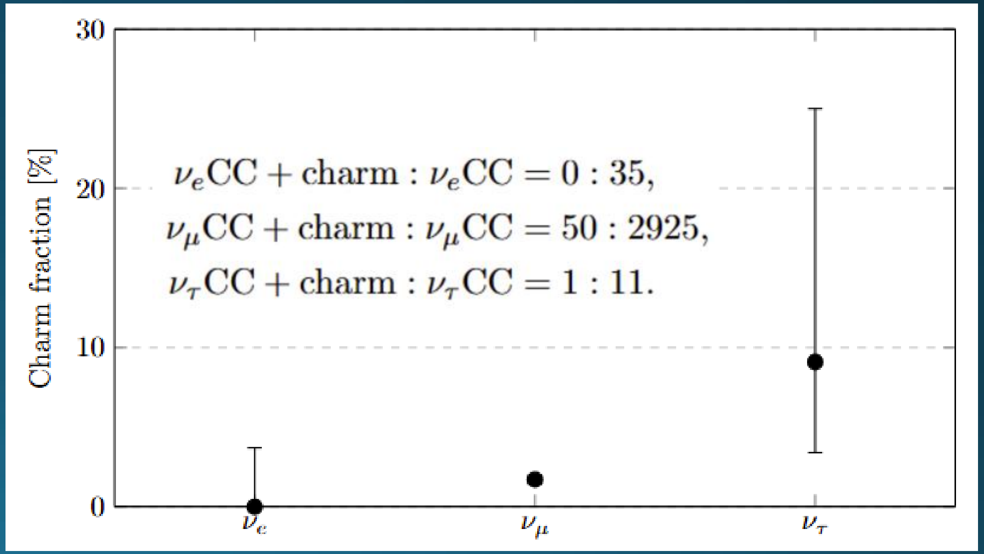
SM process,
charm production
via mixing



Well measured for ν_μ



- 1 event was observed <u>with surprise</u>
- Expectation:
  - Signal 0.04
  - Background <0.05
- Could also be a hint of new physics!?
- No ν_eCC+charm has ever been reported



Looks like LFU is very broken in ν scattering

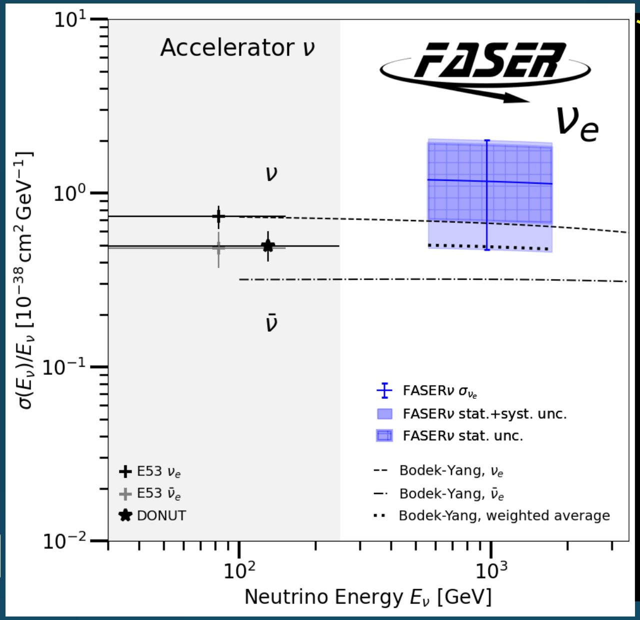
New physics parameterization

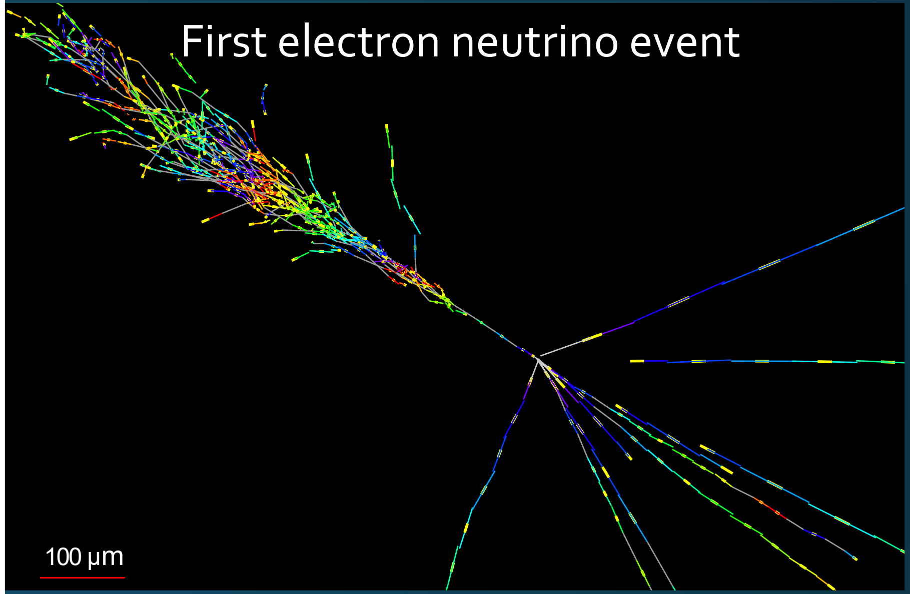
- We parameterize new physics contributions to the CC amplitude as
$$A_\ell = A_{SM}(1 + C_\ell)$$
- $C\ell = 0$ corresponds to the SM, $C_\ell \neq 0$ represents flavor-dependent new physics
- The observable charm production rate is modified as
$$R_\ell = |1 + C_\ell|^2$$
- This effective description approximately captures possible contributions from W', $H^\pm$, scalar/vector LQ, non-standard CC
- We fix $C_\mu = 0$

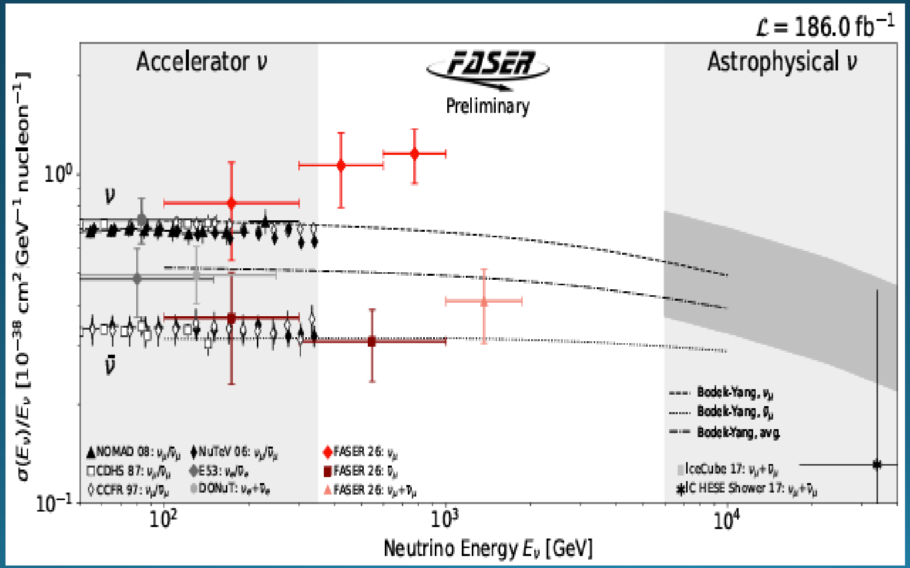
$$R^{\nu_\ell}_{\text{charm}} = \frac{\sigma^{\nu_\ell}_{\text{CC charm}}}{\sigma^{\nu_\ell}_{\text{CC inclusive}}} \Bigg/ \frac{\sigma^{\nu_\mu}_{\text{CC charm}}}{\sigma^{\nu_\mu}_{\text{CC inclusive}}} = |1 + C_\ell|^2, \qquad (\ell = e, \tau)$$

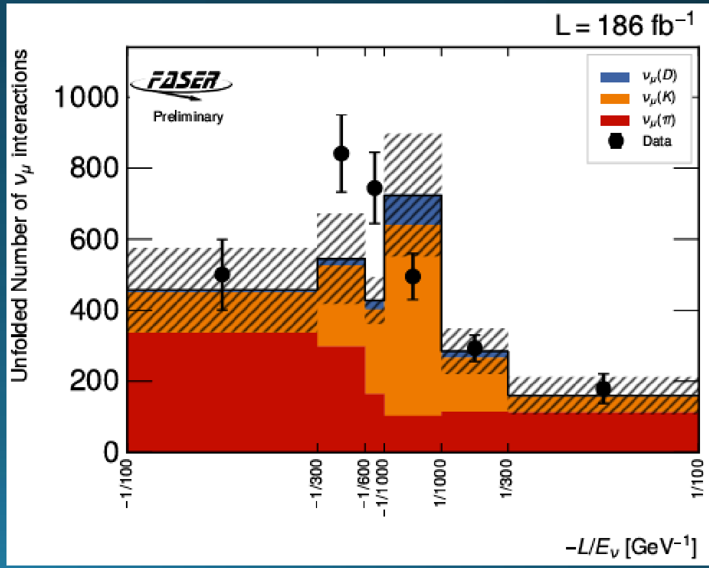
Collider neutrino results

- ν candidates in 2021 [PhysRevD.104.L091101]
- Collider ν detection established in 2023 [PhysRevLett.131.031801]
- ν_e and ν_μ cross sections in 2024 [PhysRevLett.133.021802] [nature]
  - Selected as PRL Collection 2024!
- Differential measurements 2024 [PhysRevLett.134.211801]









CERN-FASER-CONF-2026-005

FASER measures ν_ℓ interaction rates, and then?

Precise knowledge of flux

- Hadron production models
- External validation data

FASER's interaction rate measurements

Neutrino cross section measurements

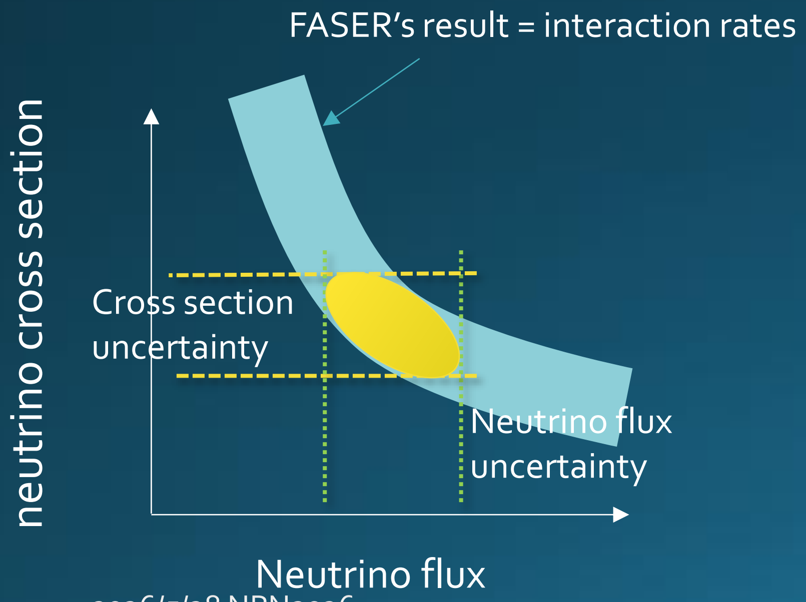
- Test Lepton Flavor Universality
- Search for new interactions

SM neutrino cross section is decent

- Assuming LFU is valid

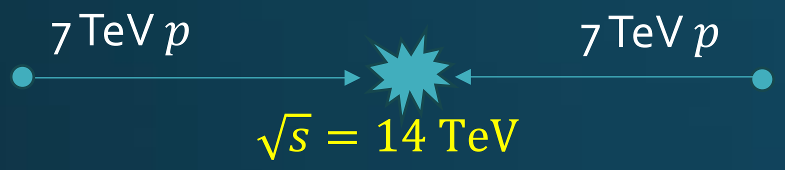
Neutrino flux measurement

- Study hadron/neutrino production at very high-energy
- Prompt neutrinos
- QCD at small x

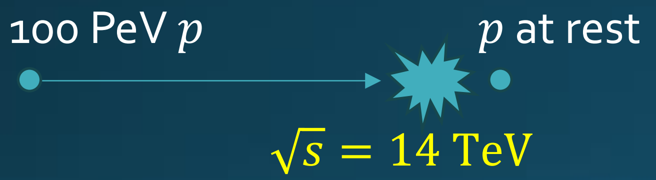


LHC's forward neutrino beam… Is it special?

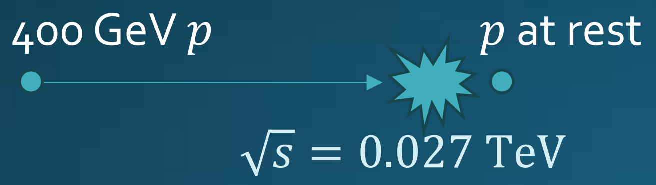
FASERν: Hadron production in p-p collision at



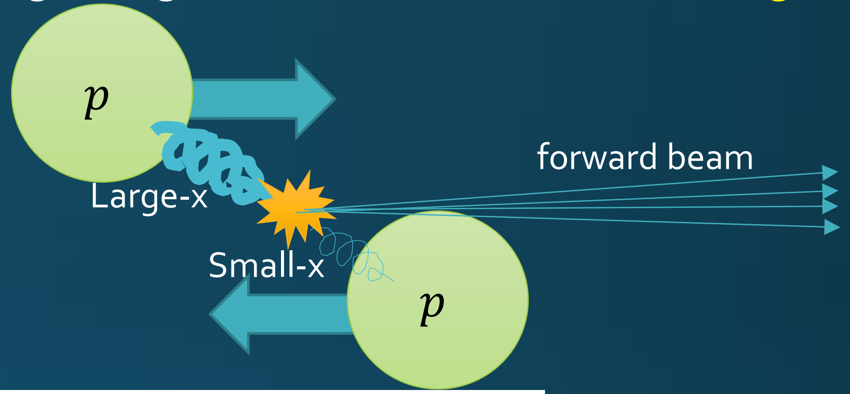
IceCube: 100 PeV fixed target

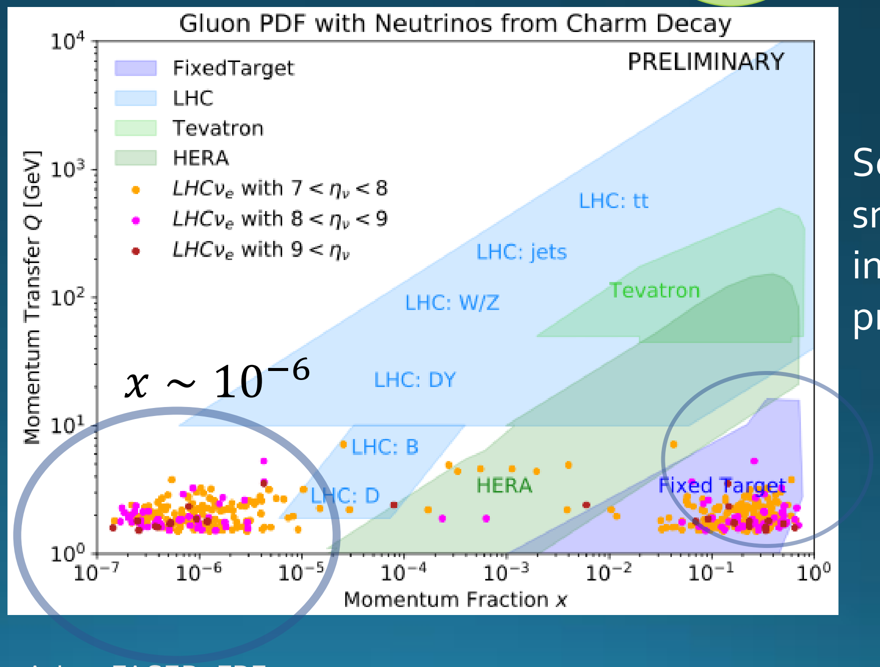


Accelerator ν with conventional fixed target:
e.g. CERN-SPS (OPERA, SHiP)



Asymmetric gluon-gluon interaction: small-x × large-x.





Sensitive to QCD studies; small-x factorization, probe intrinsic charm, and prompt neutrinos.