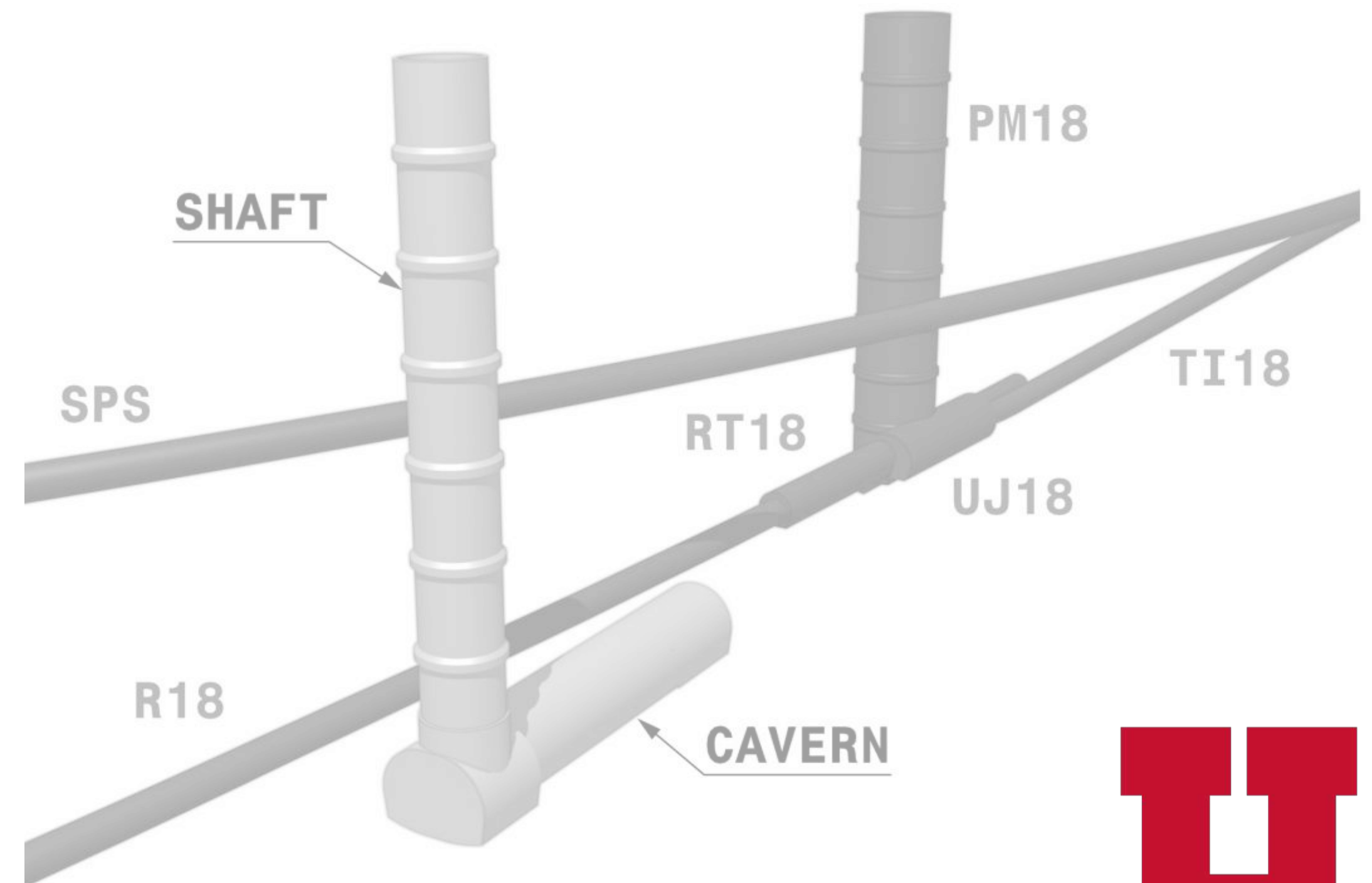


The Forward Physics Facility and its Implications for Astroparticle Physics

Vulcano Workshop 2024
Ischia Island, Italy

Dennis Soldin
University of Utah



Introduction: The Muon Puzzle

▶ Indirect cosmic ray measurements:

▶ Properties of the initial cosmic ray inferred from simulations of extensive air showers (EASs)

▶ ~30% more muons observed than expected at the highest energies!

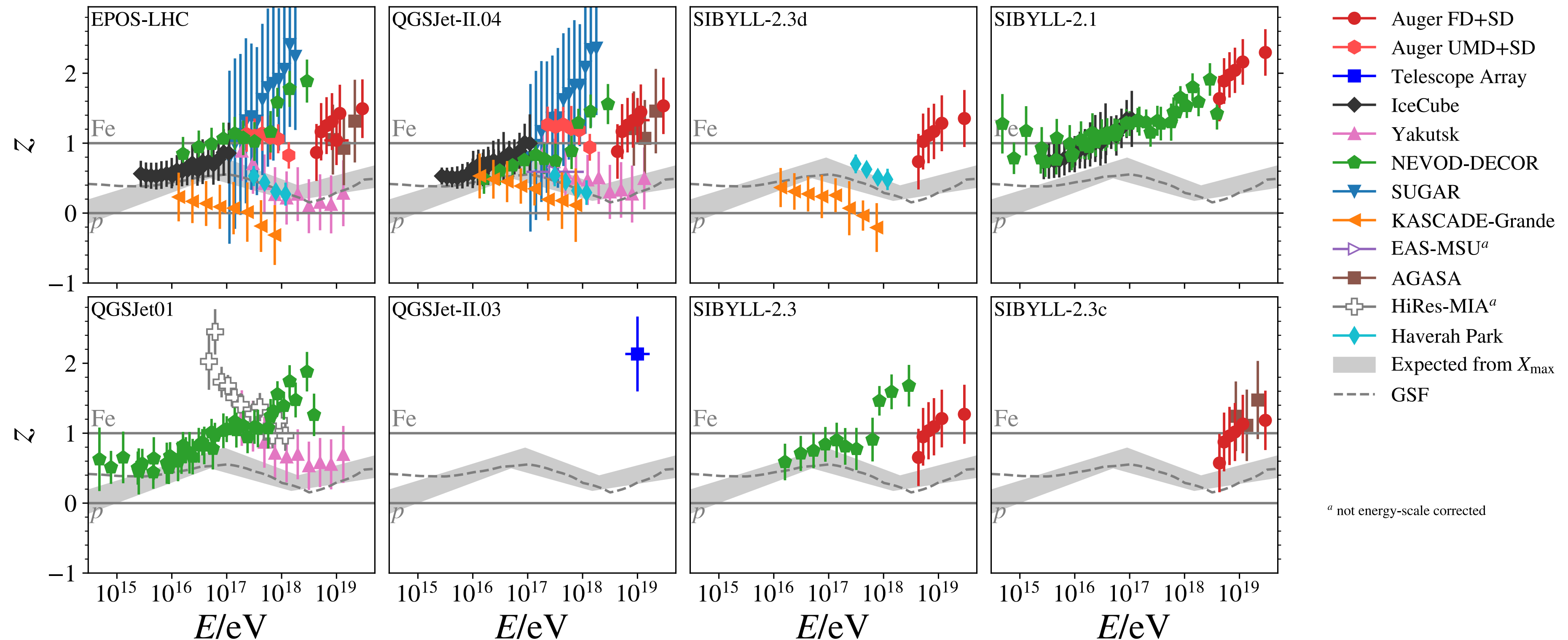
▶ z-scale:

$$z = \frac{\ln(N_\mu) - \ln(N_{\mu,p})}{\ln(N_{\mu,Fe}) - \ln(N_{\mu,p})}$$

▶ $z = 0$: proton

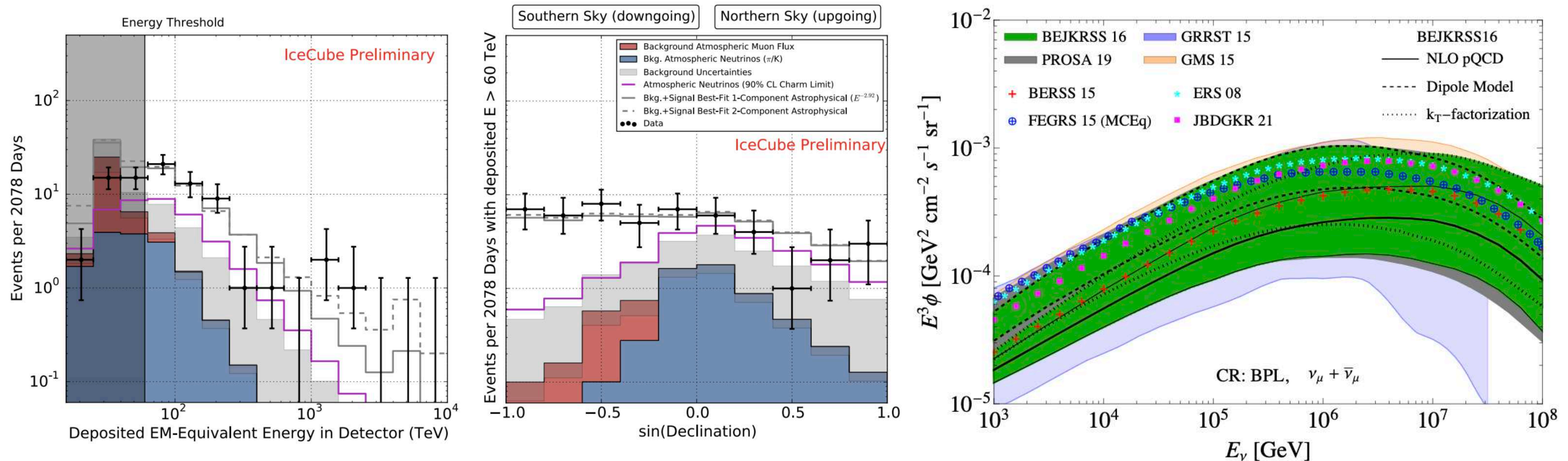
▶ $z = 1$: iron

▶ Large uncertainties in EAS measurements, e.g. composition!



Introduction: Atmospheric Neutrinos

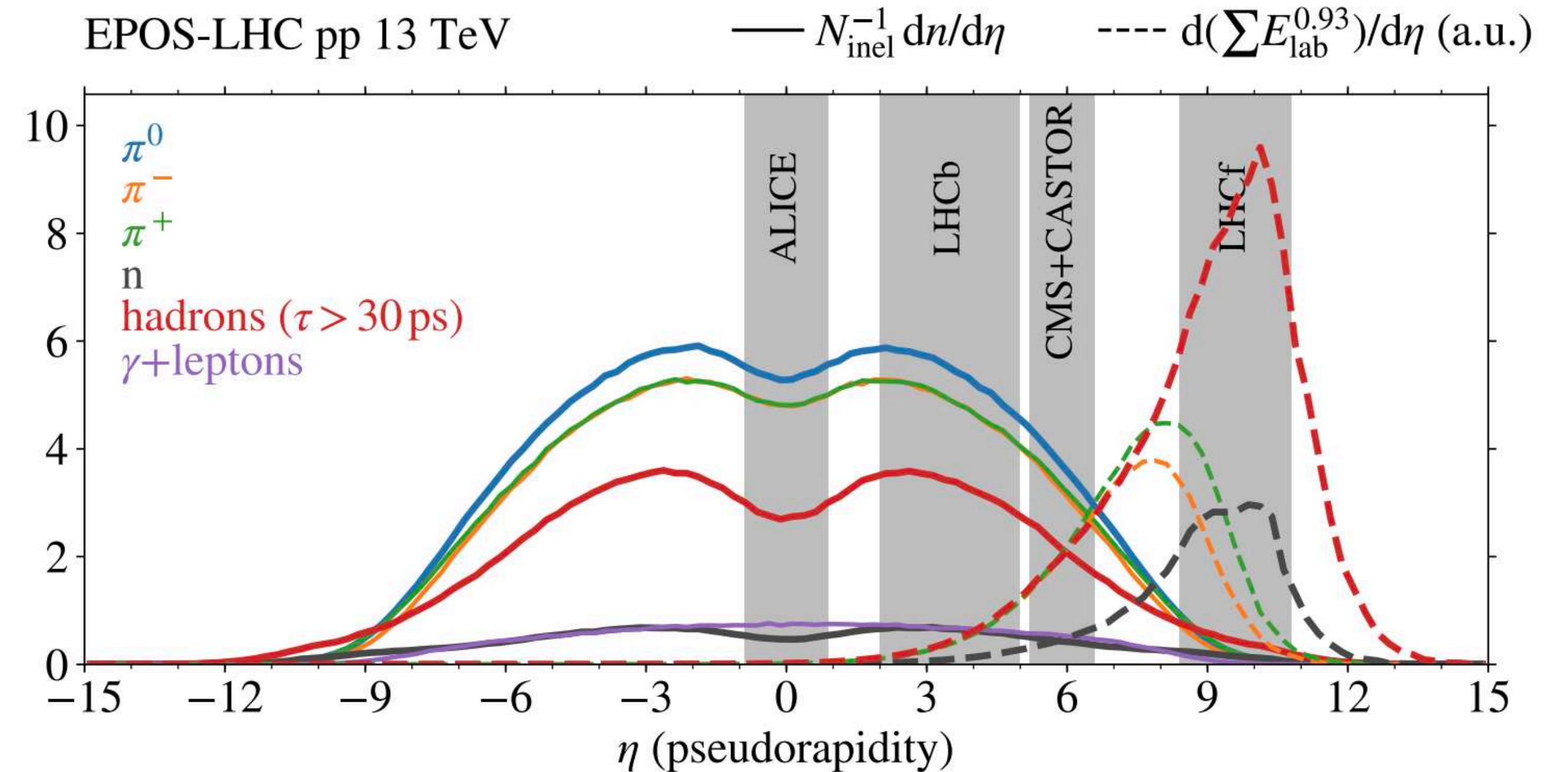
- ▶ Atmospheric high-energy neutrino flux:
 - ▶ Neutrinos from EAS are background for astrophysical neutrino searches, e.g. IceCube / KM3NeT
 - ▶ Prompt neutrino flux (charm) dominates at high energies
 - ▶ Large associated uncertainties for astrophysical neutrino fits!



Introduction: Challenges in EAS Physics

- ▶ Extensive air showers:
 - ▶ Particle production in the far-forward region
 - ▶ Low momentum transfer
 - ▶ (Typically) non-perturbative regime
 - ▶ Complex particle composition
 - ▶ Energies range over many orders of magnitude
- ▶ Modeling of particle interactions in EASs based on phenomenological models

[J. Albrecht et al., *Astrophys. Space Sci.* 367 (2022)]

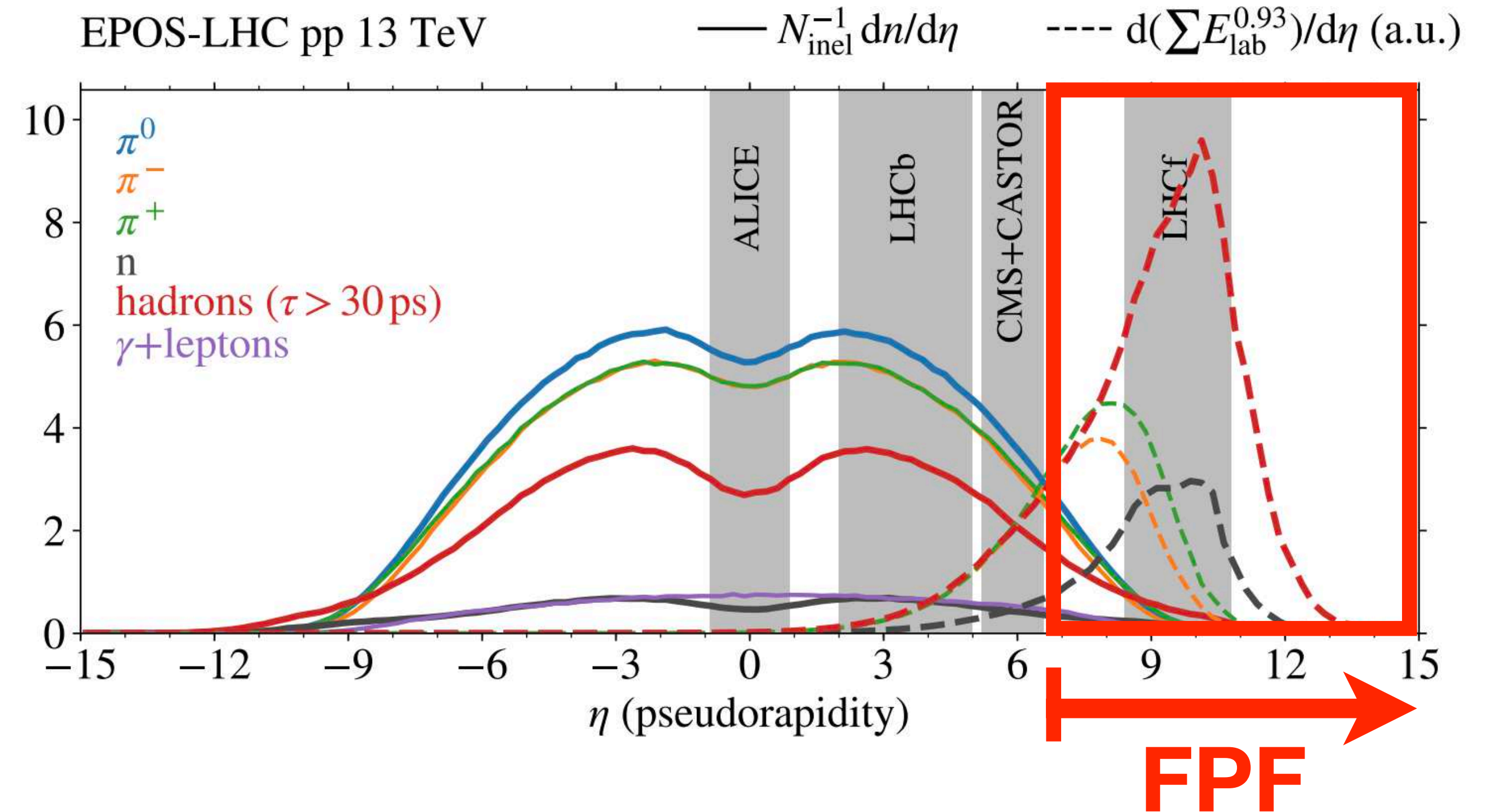


How can we test hadronic interaction models in the far-forward region at accelerators?

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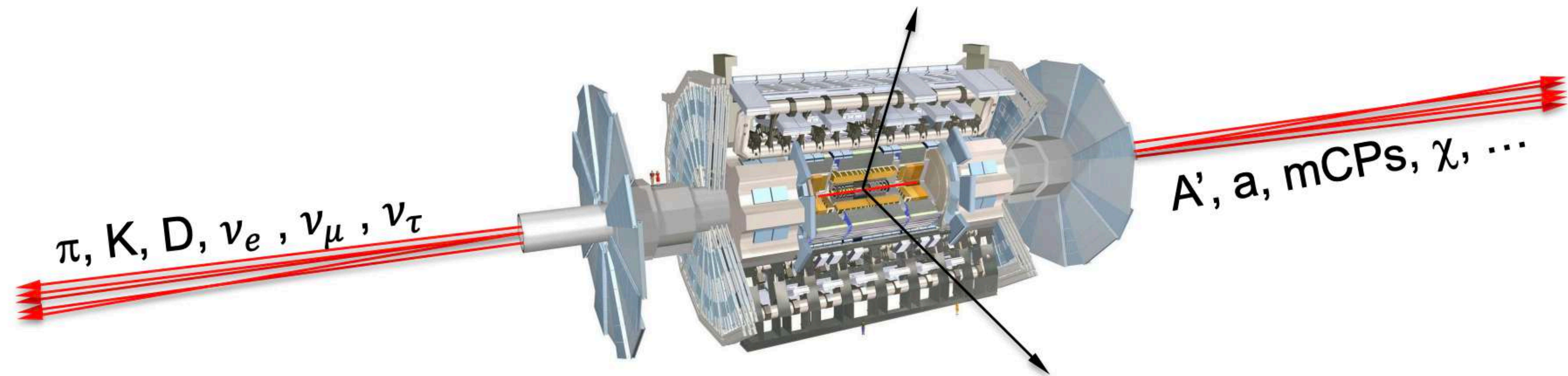


How can we test hadronic interaction models in the far-forward region at accelerators?

The Forward Physics Facility



- ▶ What opportunities are we currently missing from a lack of coverage of far-forward physics at the LHC?
- ▶ How can we test EAS models at accelerators in the forward region?

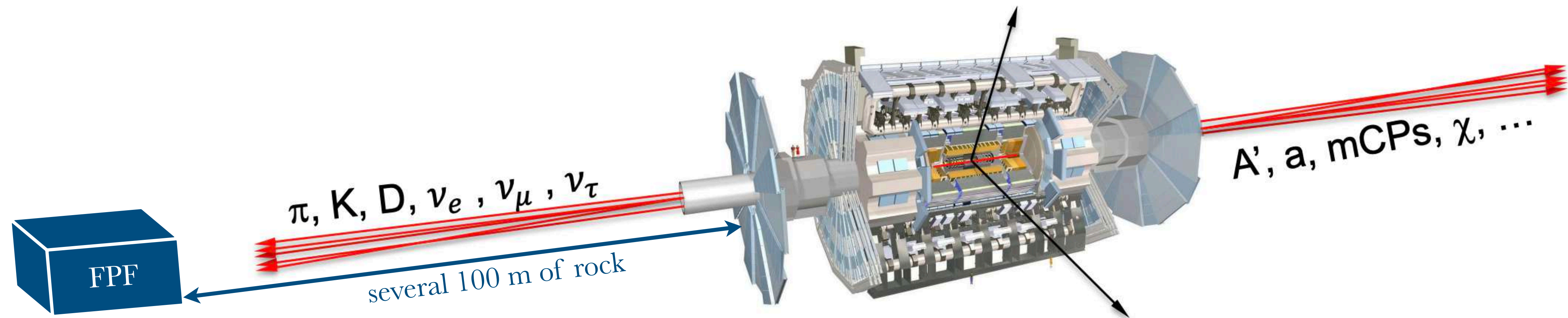


- ▶ By far the largest flux of energetic light particles is in the far-forward direction (mesons, neutrinos, and maybe also dark photons, ALPs, mCPs, DM, ...)
- ▶ Proposal: Forward Physics Facility (FPF) at LHC in ATLAS line-of-sight ($\eta \gtrsim 7$)

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FAR FORWARD EXPERIMENTS AT LHC RUN 3

There are currently 3 detectors in operation to exploit forward physics potential during the LHC Run 3

UJ18

ATLAS

SPS

SND@LHC: approved March 2021

UJ12

LHC

- ▶ Experiments shielded from interaction point by more than 100 m of rock
- ▶ Extremely low background!
- ▶ Ideal to measure rare processes, e.g. exotic physics, neutrino physics, ...

FASER: approved March 2019
FASERv: approved December 2019

LOS

FAR FORWARD EXPERIMENTS AT LHC RUN 3

The FPF is proposed to extend this program into the HL-LHC era!

UJ18

ATLAS

SPS

UJ12

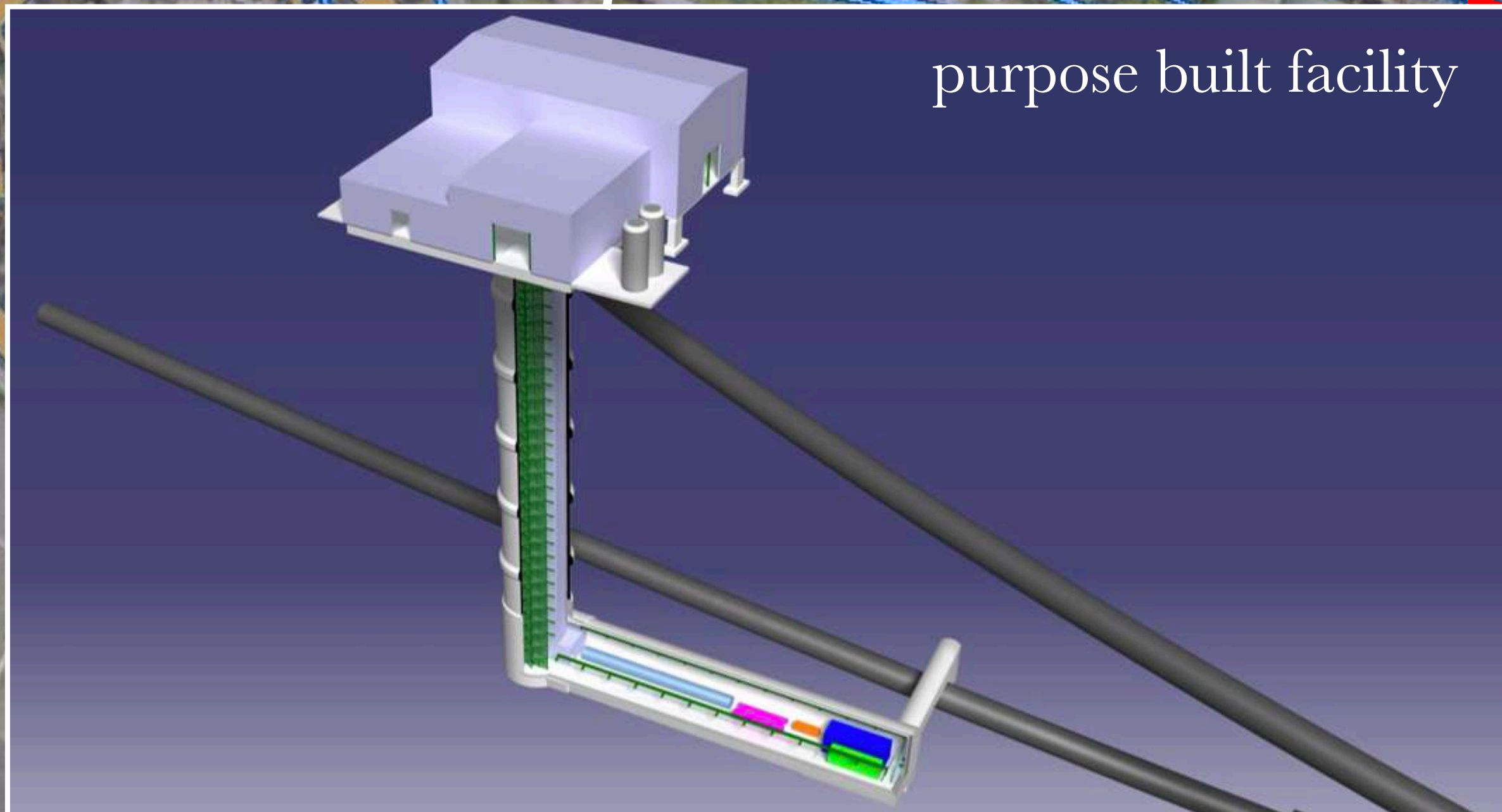
LHC

LOS

FASER: approved March 2019
FASERv: approved December 2019

purpose built facility

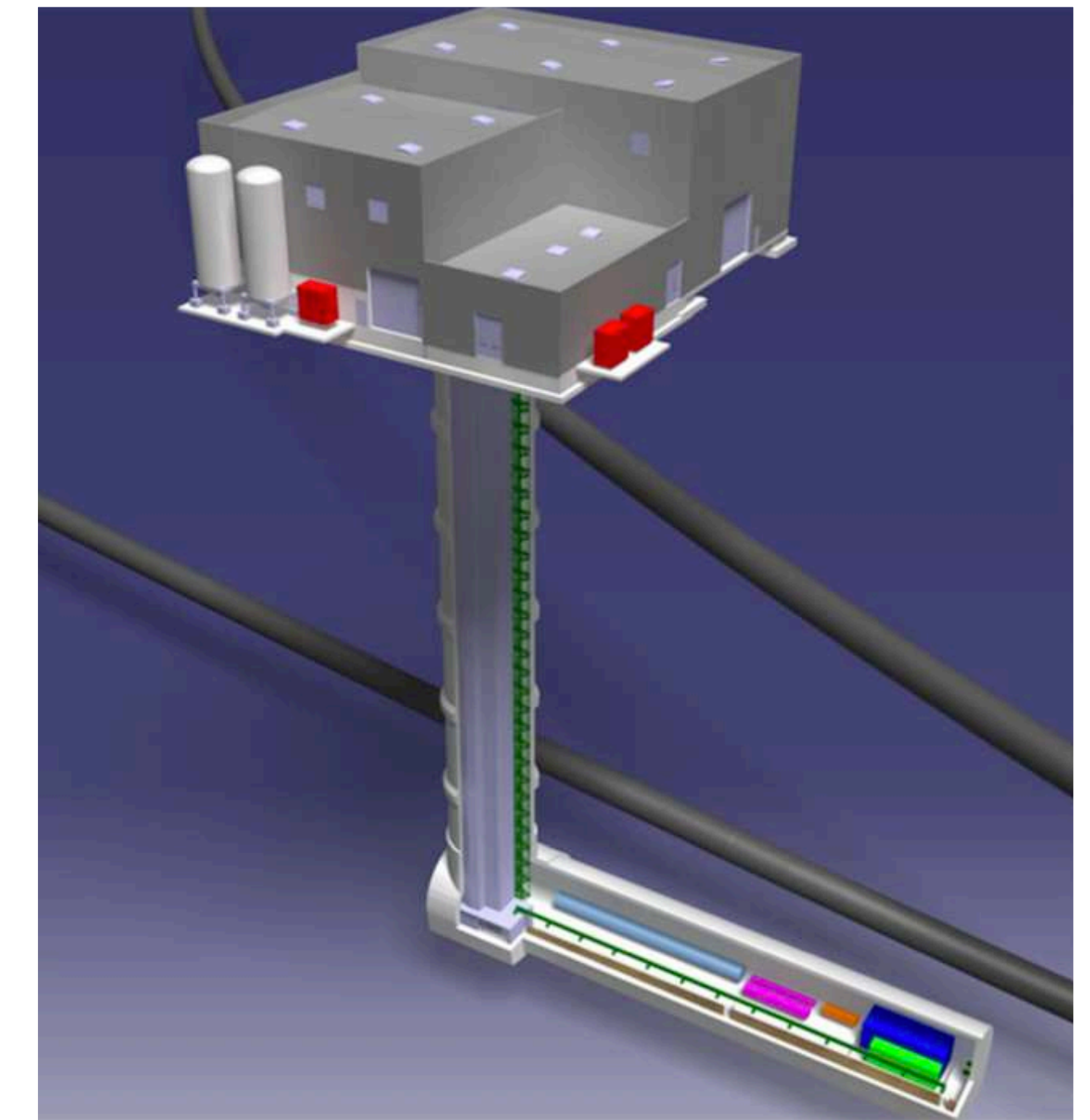
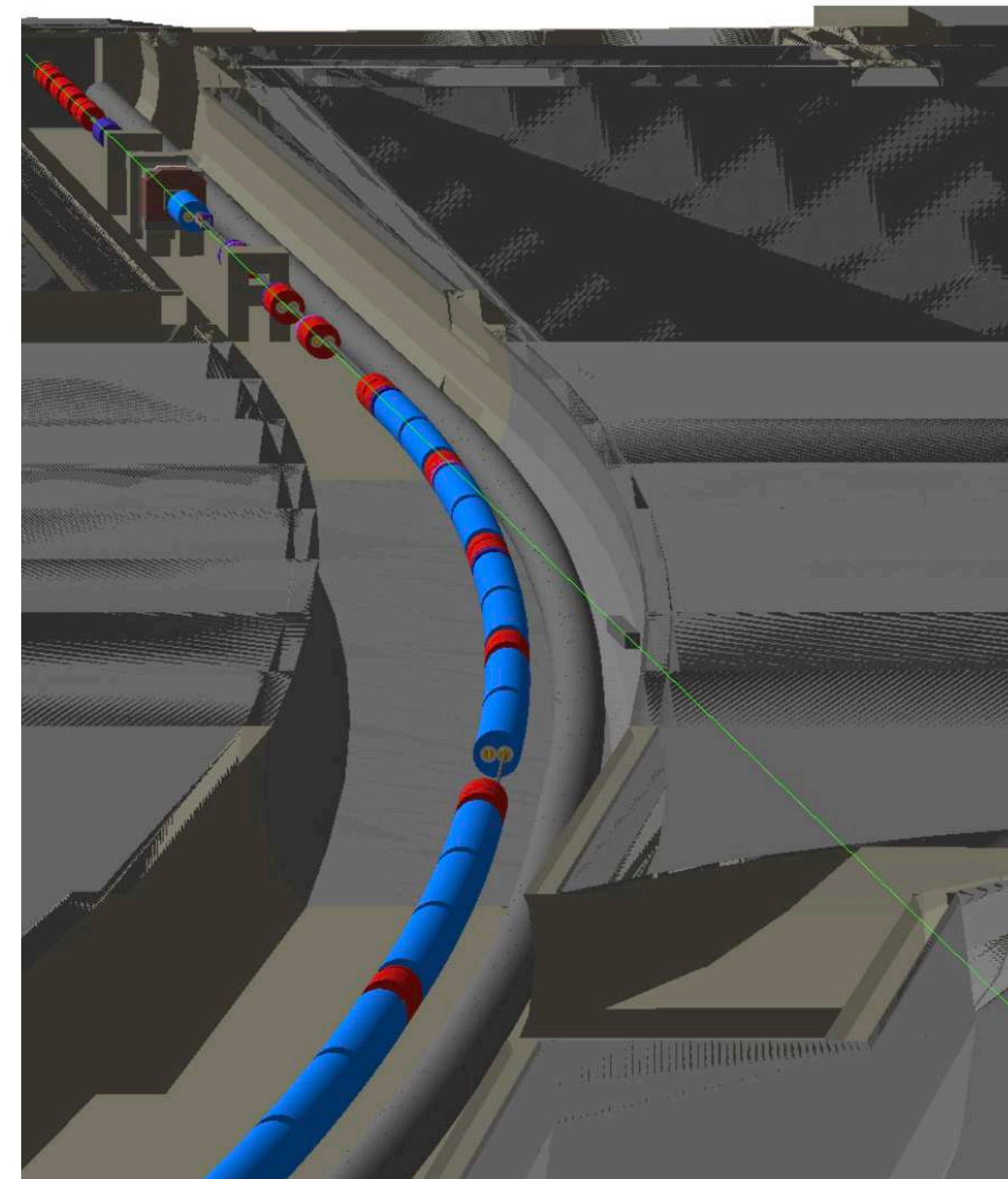
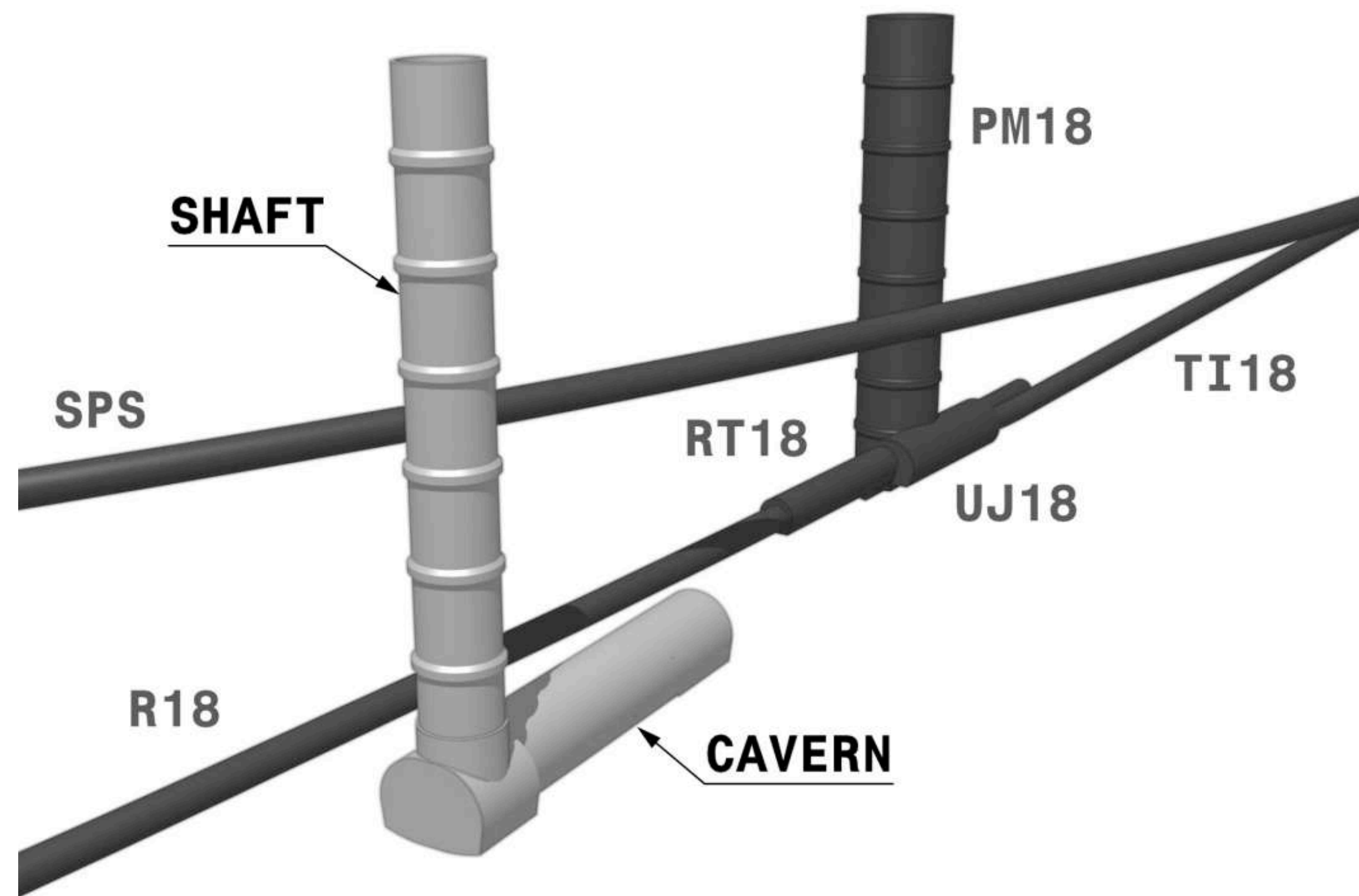
Measures neutrinos (and muons)
produced at ATLAS interaction point!



The Forward Physics Facility



- ▶ Purpose built facility to house dedicated experiments in the far-forward region
- ▶ In line-of-sight to ATLAS interaction point (separated by several 100 m of rock)
- ▶ Currently five proposed experiments*, mainly designed for neutrino detection



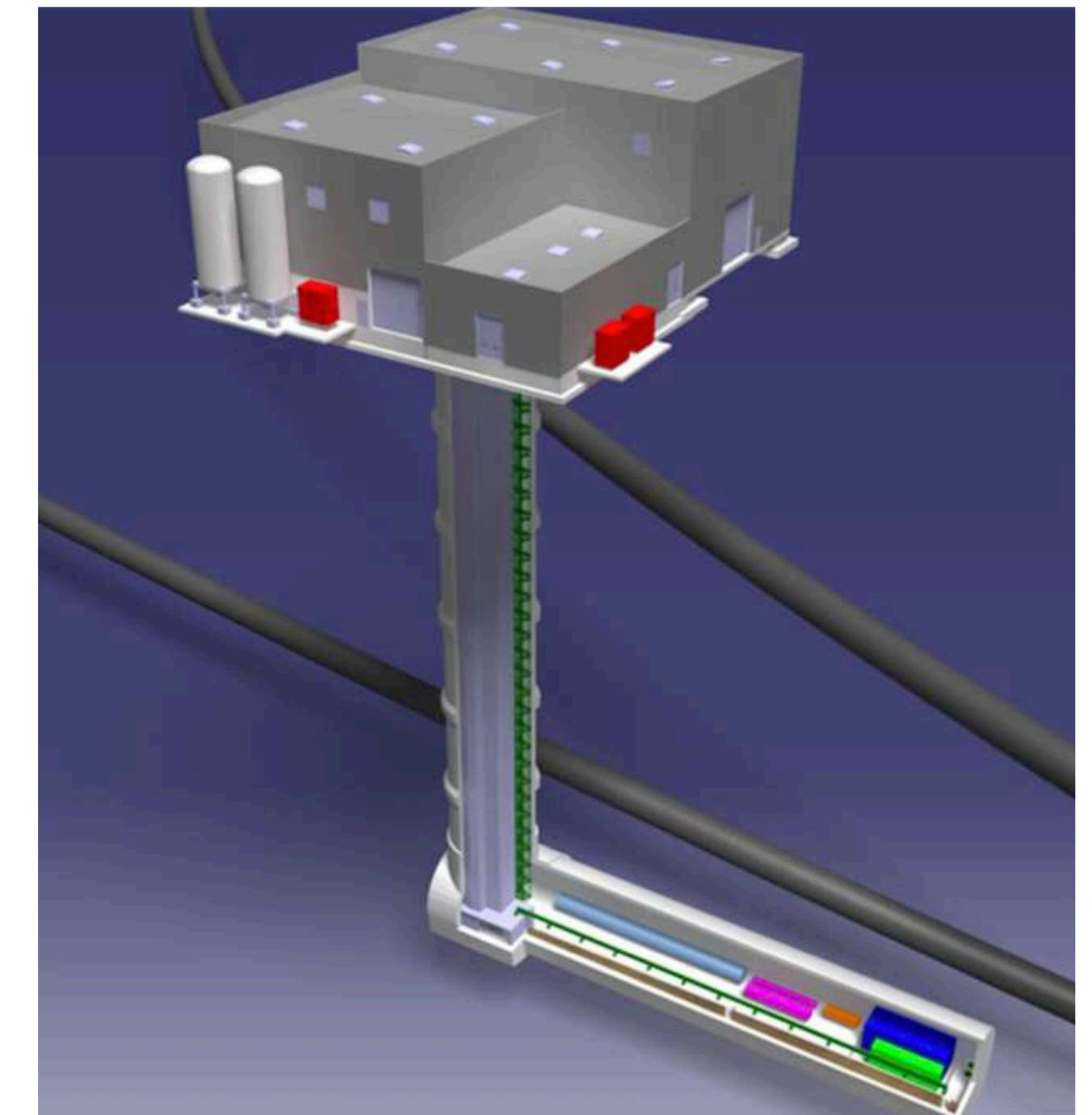
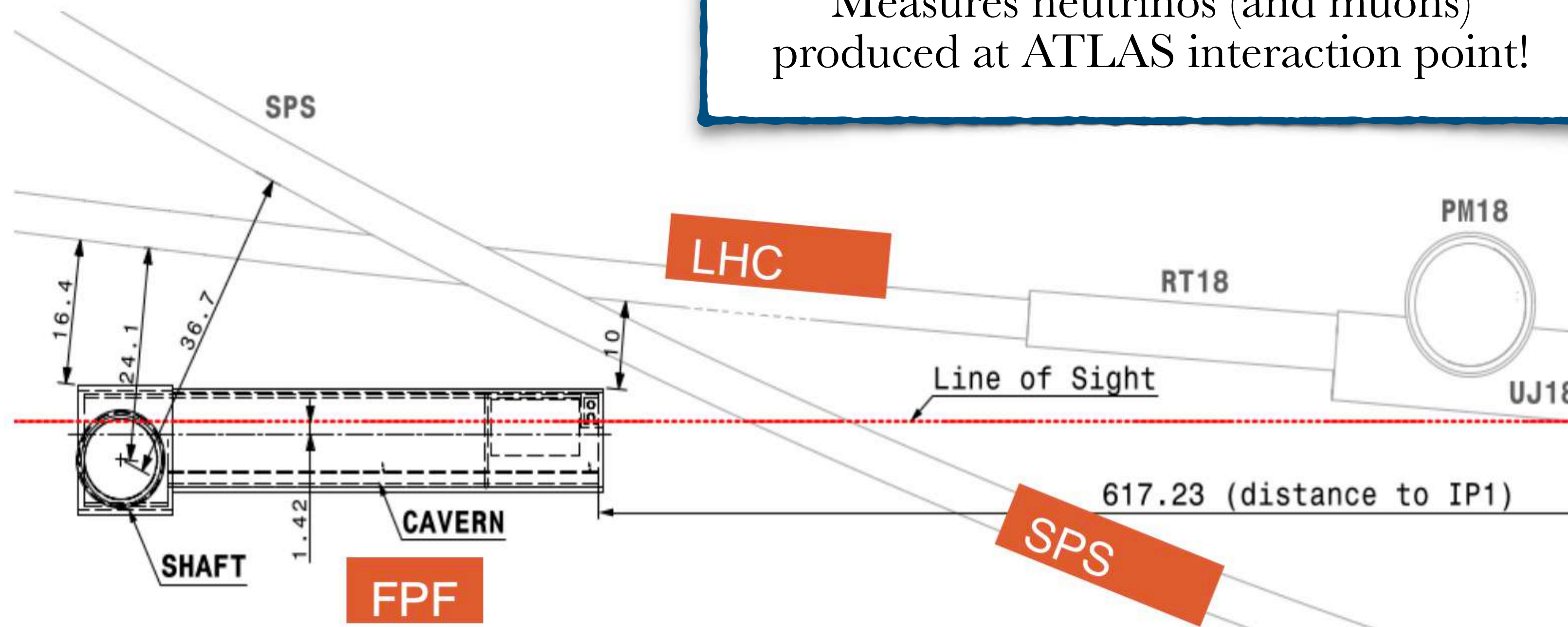
* for a complete description of the experiments, please see [J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

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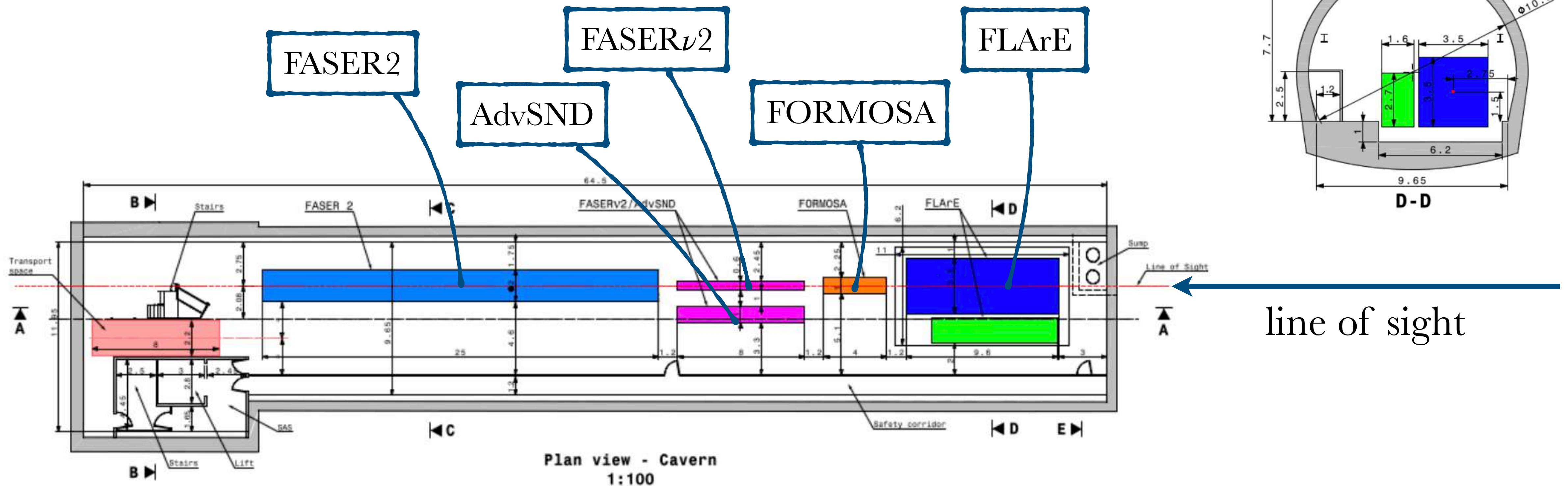


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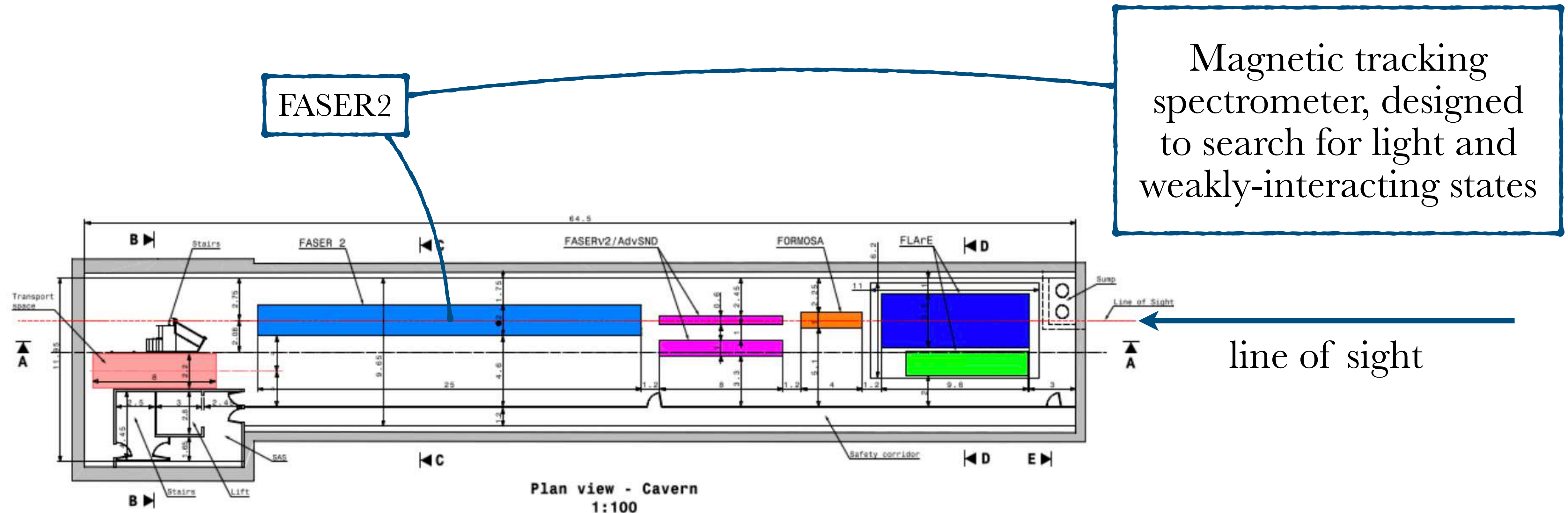


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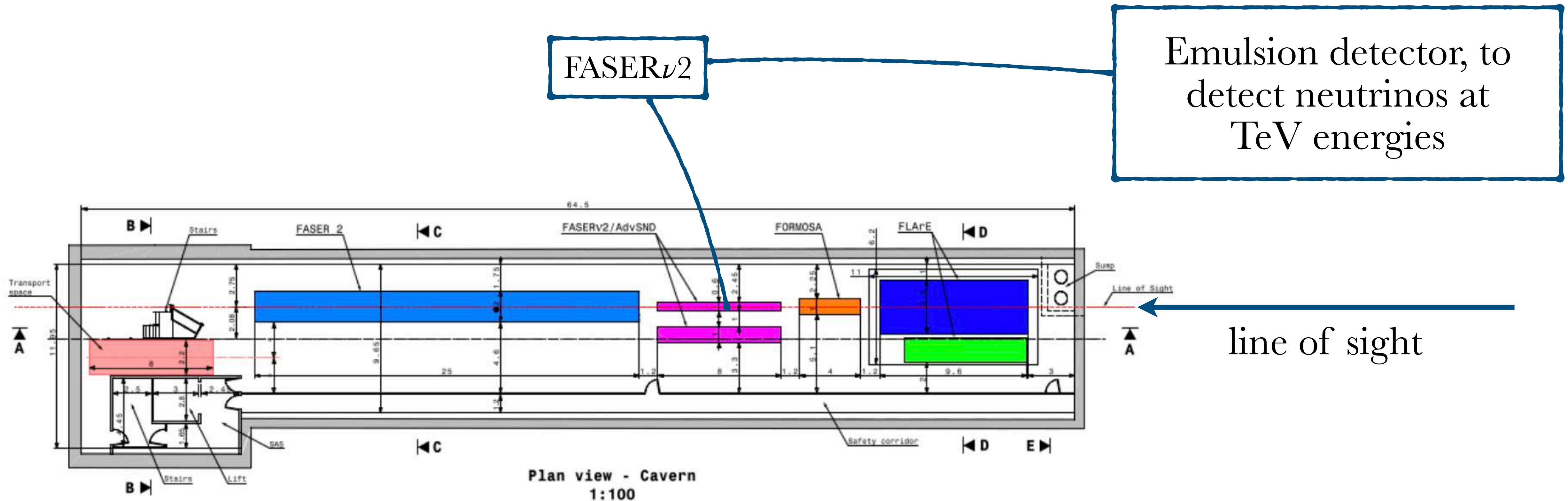
Magnetic tracking spectrometer, designed to search for light and weakly-interacting states

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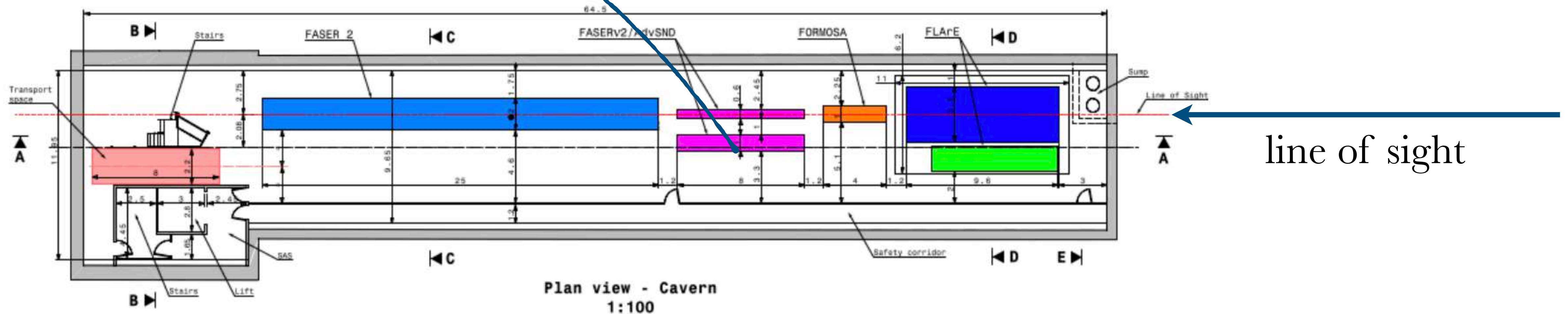
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AdvSND

Off-axis detector to study neutrinos from charm decay and neutrino interactions

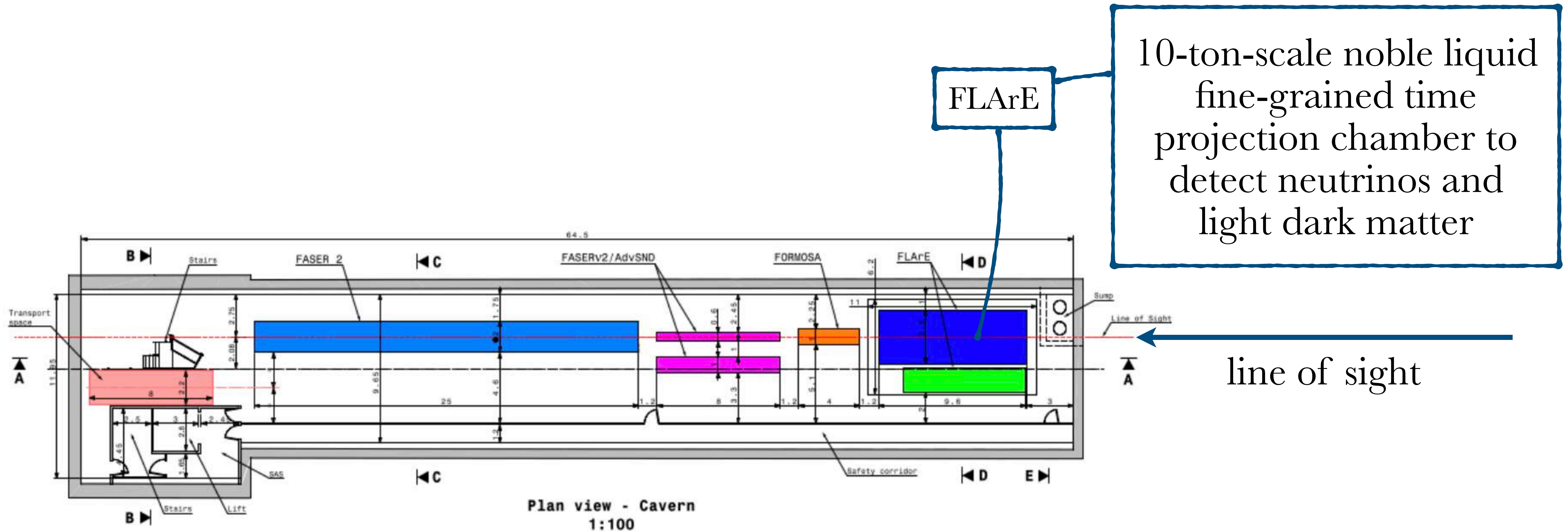


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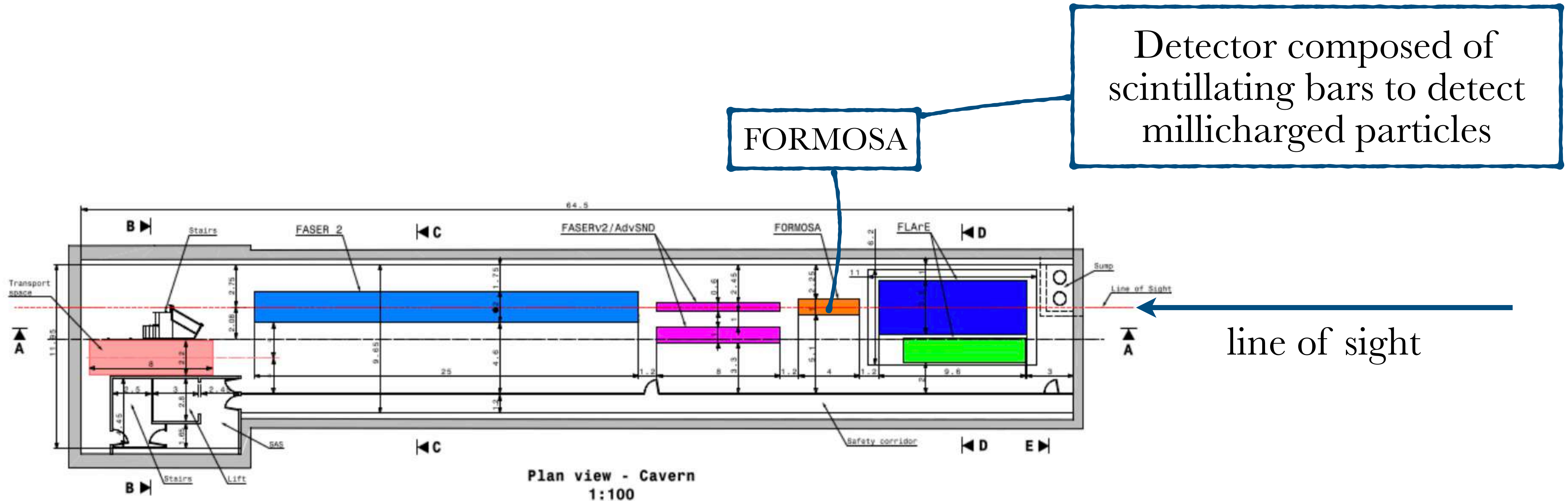


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FPP Physics Potential



▶ Example:

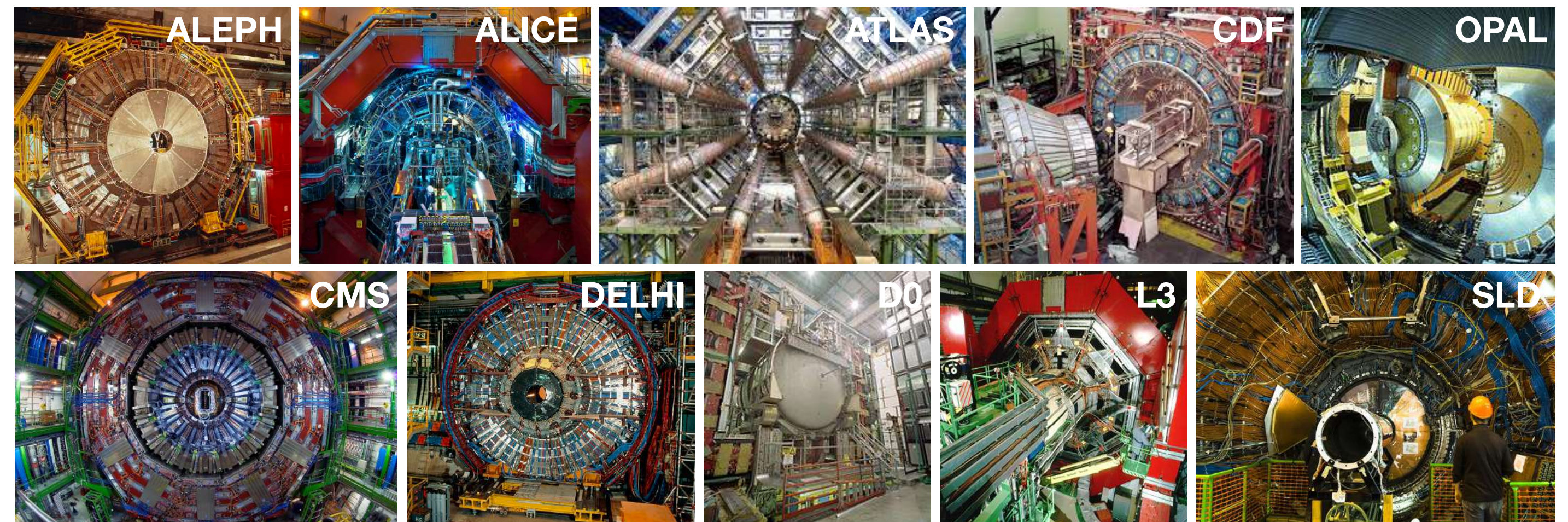
FASER ν pilot detector

vs.

All previous collider experiments

- ▶ Suitcase size, 4 weeks of data
- ▶ Costs: \$0 (recycled parts)
- ▶ 6 TeV neutrino candidates
[\[FASER Collaboration, Phys. Rev. D 104 \(2021\)\]](#)

- ▶ Building size, decades of data
- ▶ Costs: $\sim \$10^9$
- ▶ 0 TeV neutrino candidates



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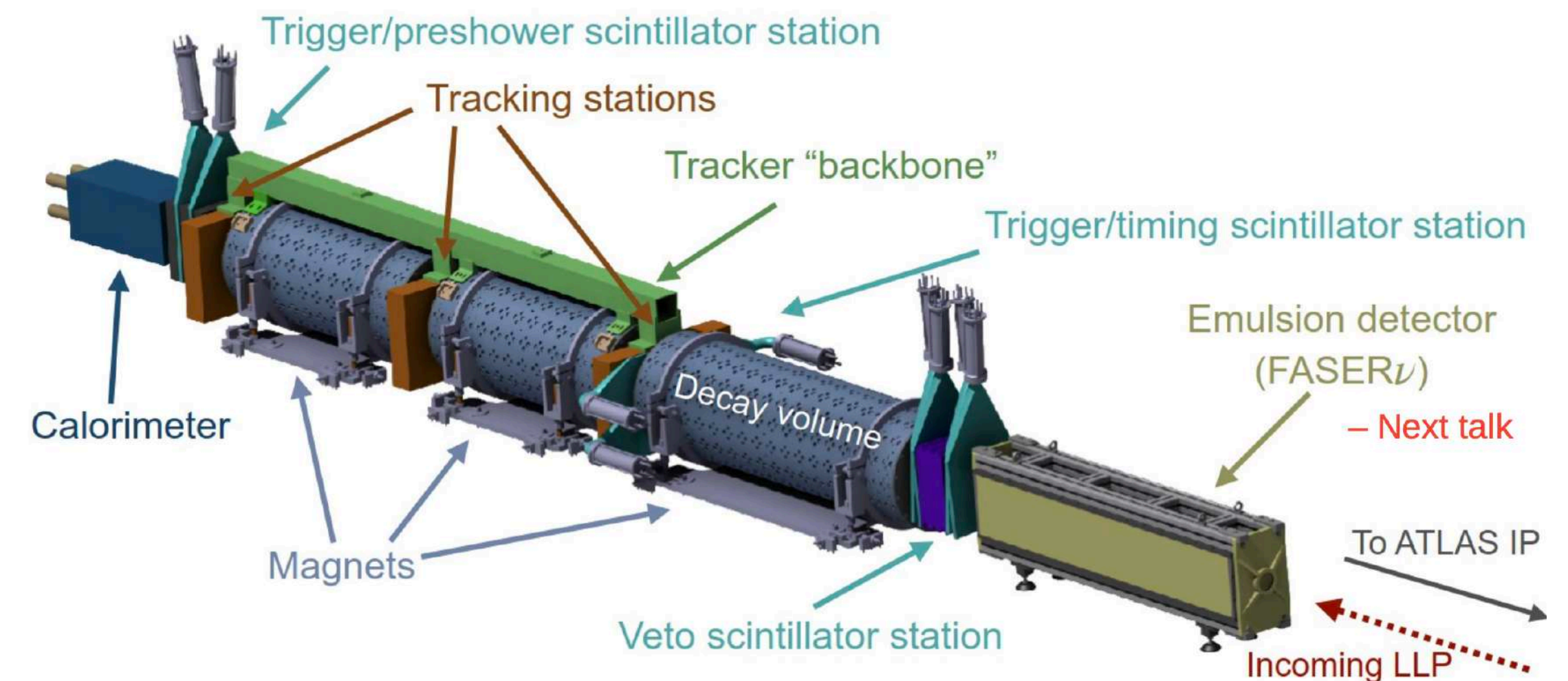
▶ First 153 neutrino candidates reported

[[FASER Collaboration, Phys. Rev. Lett. 131 \(2023\)](#)]

▶ Significance of $\sim 16\sigma$

▶ ~ 10000 ν candidates expected

($\sim 10^9$ muons*)



*origin not well understood, further studies needed (see later slides)

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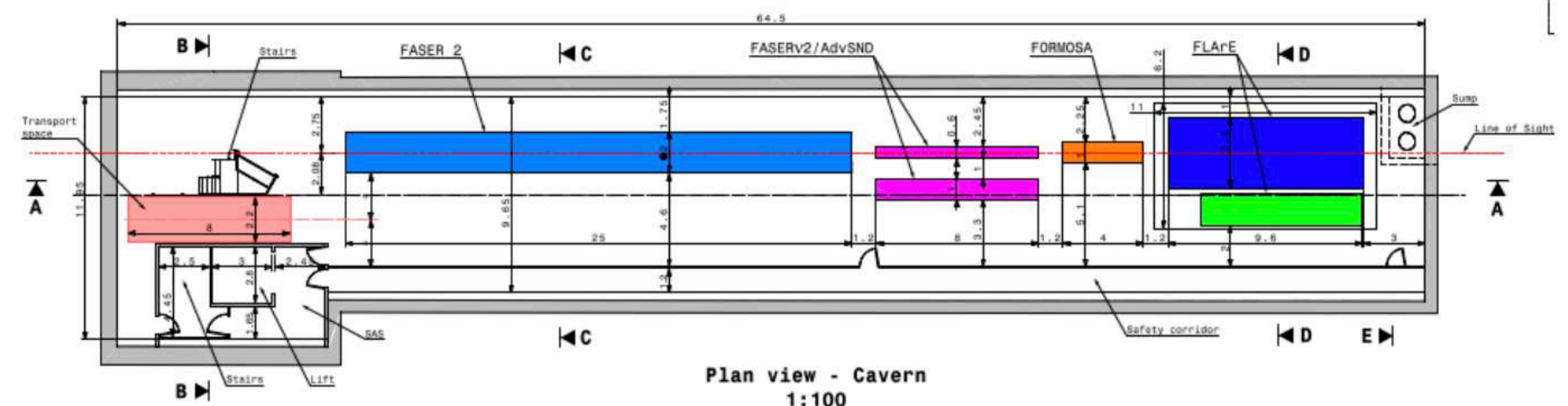
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▶ Forward Physics Facility:

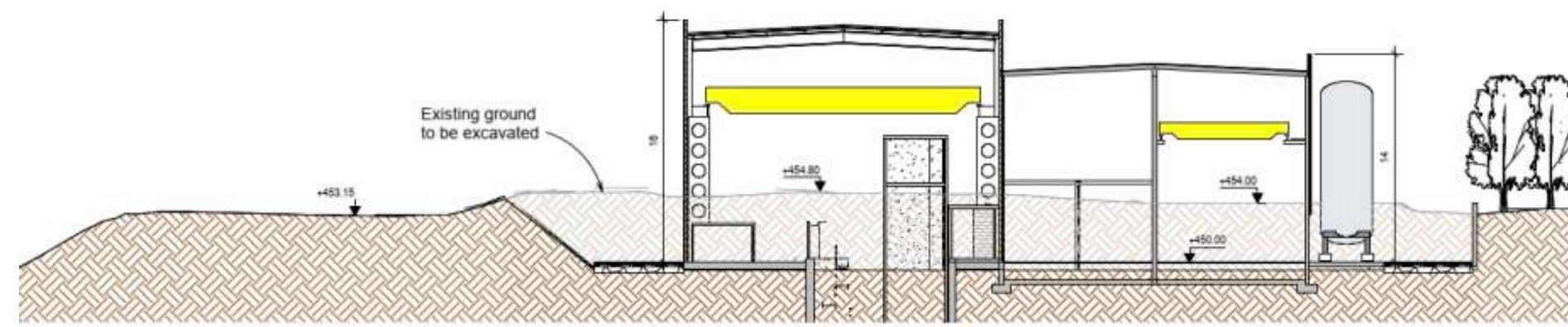
▶ $\sim 10^6 \nu$ candidates expected!

($\sim 10^{12}$ muons*)

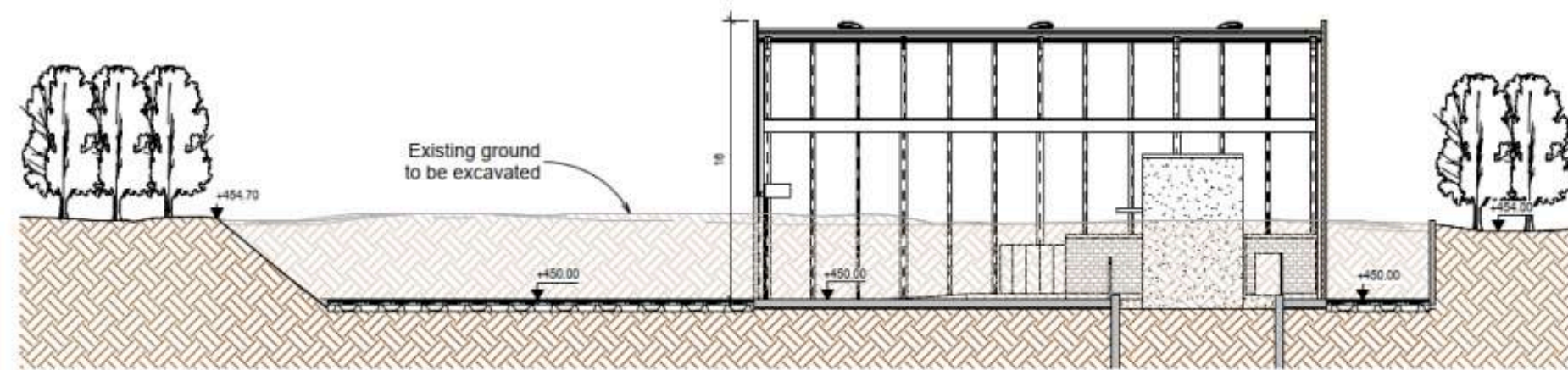


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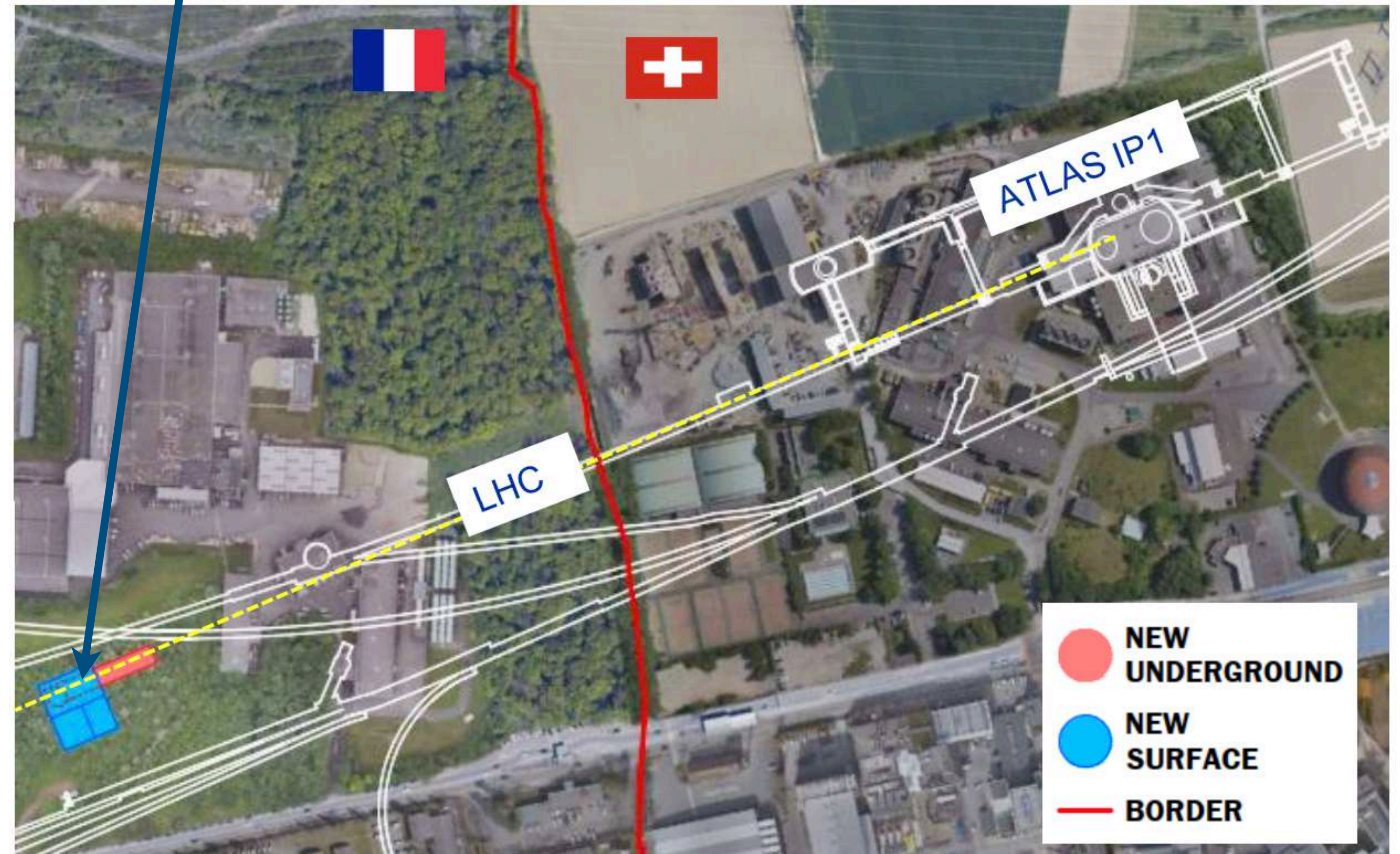
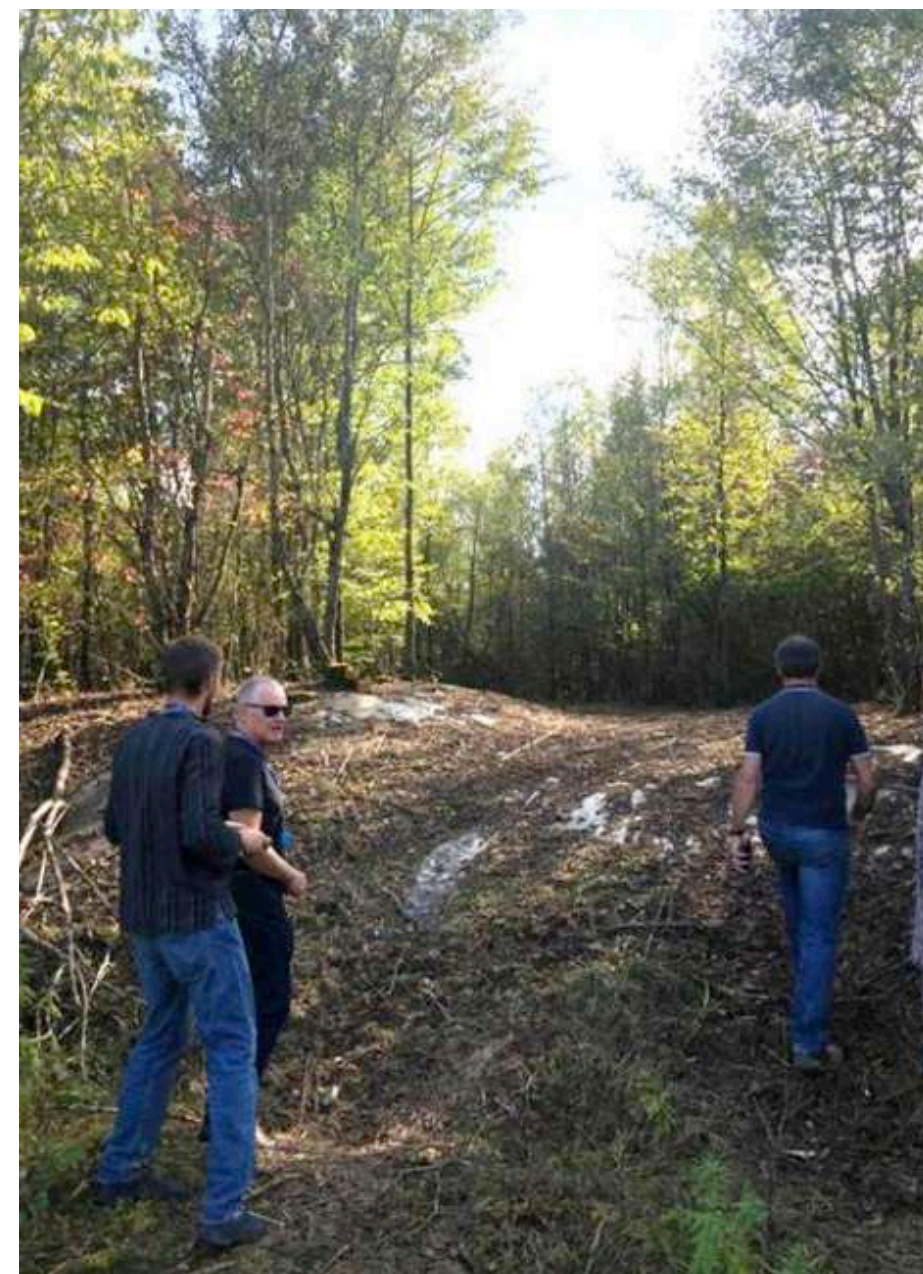
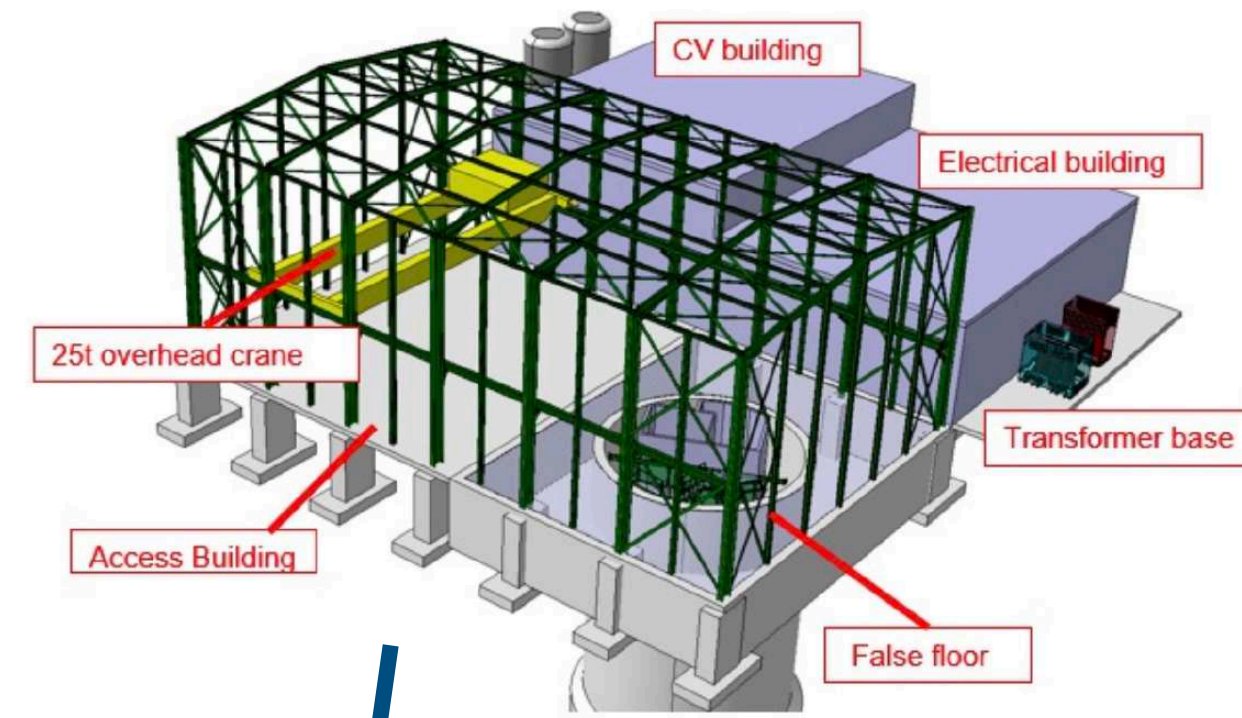
The Facility



SECTION 1-1



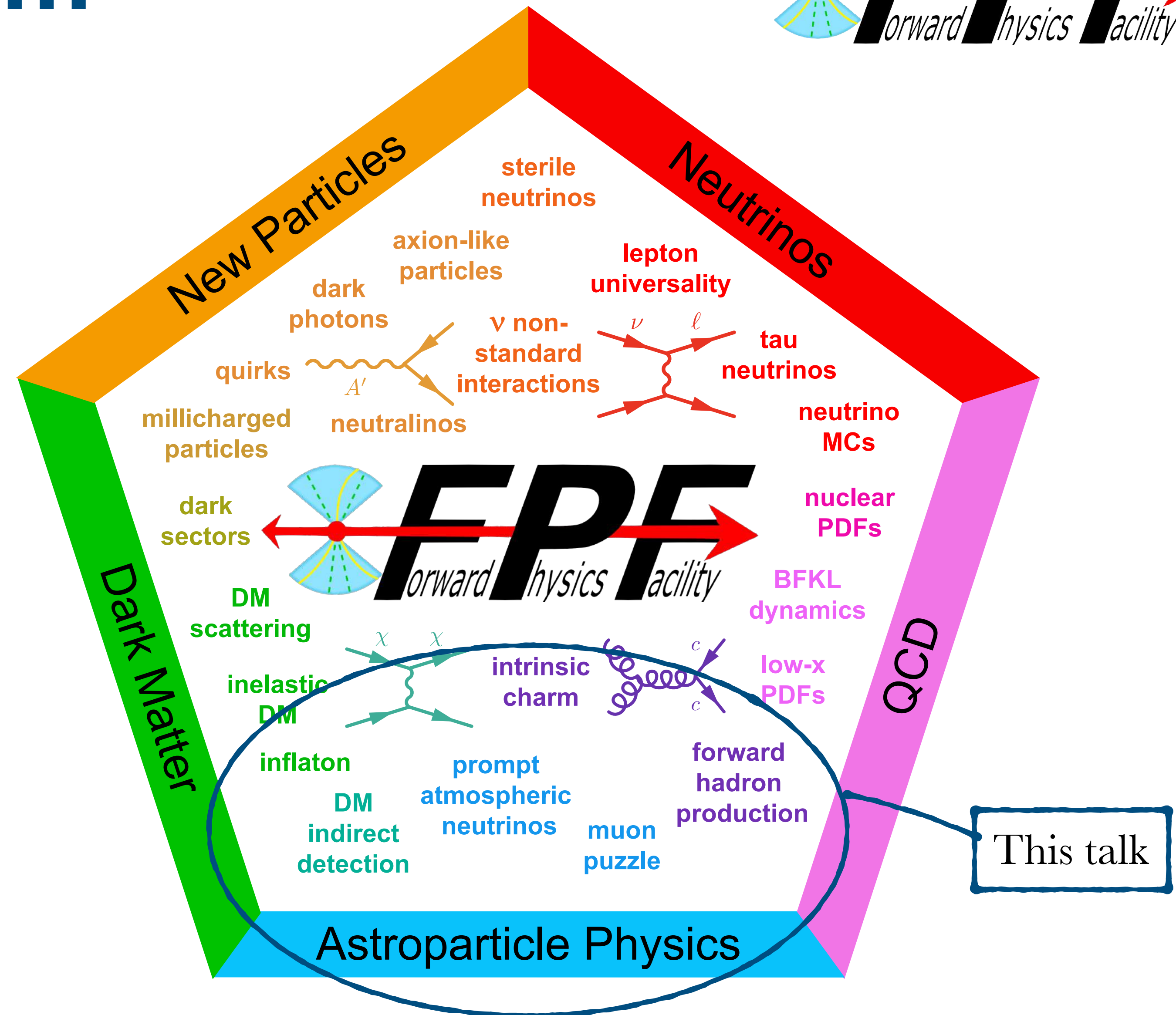
SECTION 2-2



FPF Physics Program



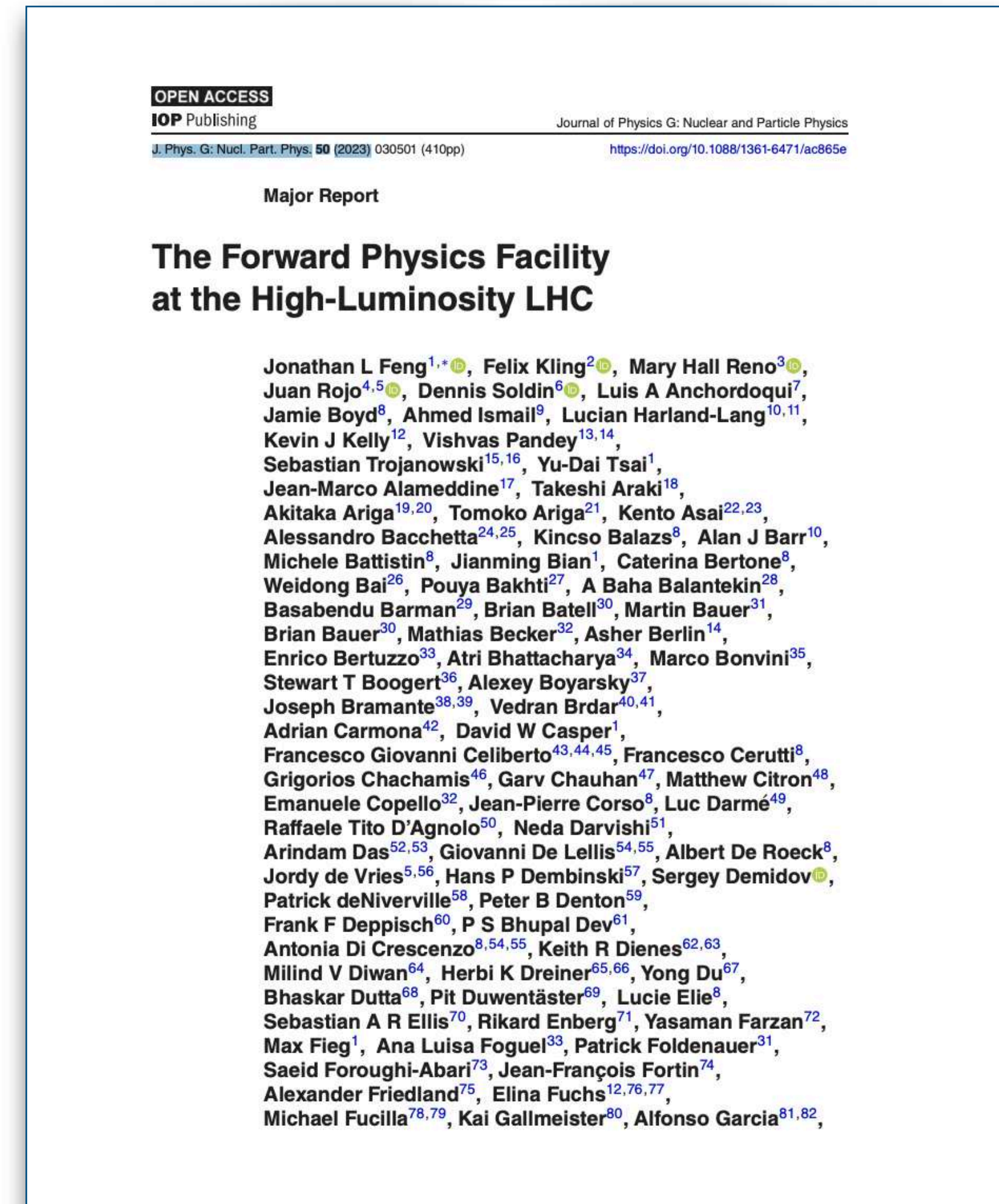
- ▶ Large (multi-)community effort!
- ▶ Comprehensive physics program:
 - ▶ Long-lived particles
 - ▶ Dark Matter and BSM scattering
 - ▶ Quantum Chromodynamics
 - ▶ Neutrino physics
 - ▶ Astroparticle physics



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- ▶ Comprehensive physics program:
 - ▶ Long-lived particles
 - ▶ Dark Matter and BSM scattering
 - ▶ Quantum Chromodynamics
 - ▶ Neutrino physics
 - ▶ Astroparticle physics
- ▶ Comprehensive description of the FPF:
 - ▶ "Short paper" (77 pages):
 - ▶ Phys. Rep. 968 (2022)
 - ▶ Snowmass White Paper (~430 pages):
 - ▶ J. Phys. G: Nucl. Part. Phys. 50 (2023)
- ▶ See also <https://fpf.web.cern.ch/>



FPF Physics Program



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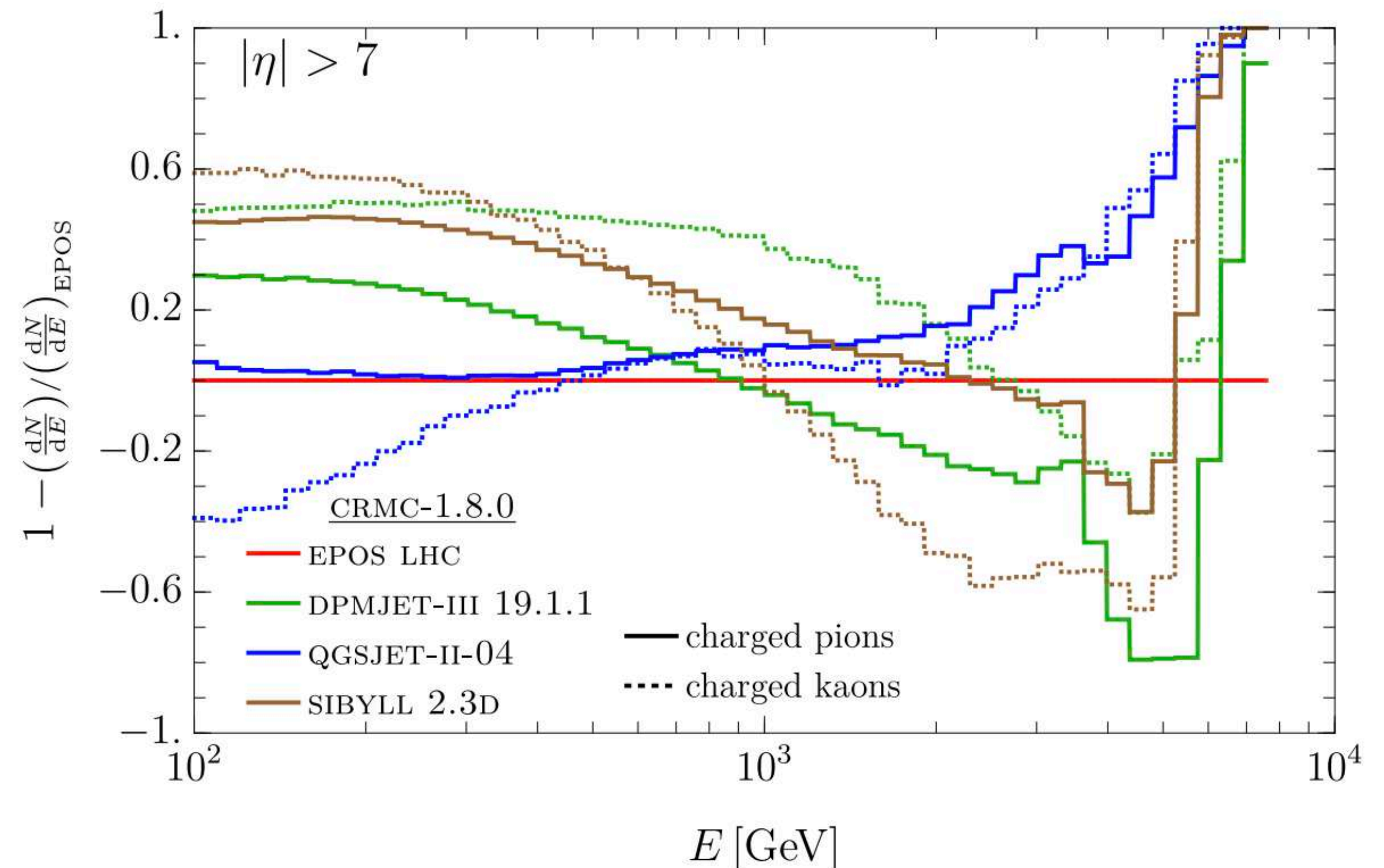
Astroparticle physics

Neutrino Fluxes at the FPF



- ▶ Most muons in EAS are produced by the decay of pions and kaons
- ▶ Ratio of electron and muon neutrinos is a proxy for the ratio of charged pions and kaons
- ▶ Electron and muon neutrino fluxes populate different energy regions which will help to disentangle them
- ▶ Neutrinos from pion and kaon decays have different rapidity distributions which will help to disentangle them
- ▶ Measurements of neutrino fluxes as tests of hadronic interaction models and prompt neutrino production models

[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]



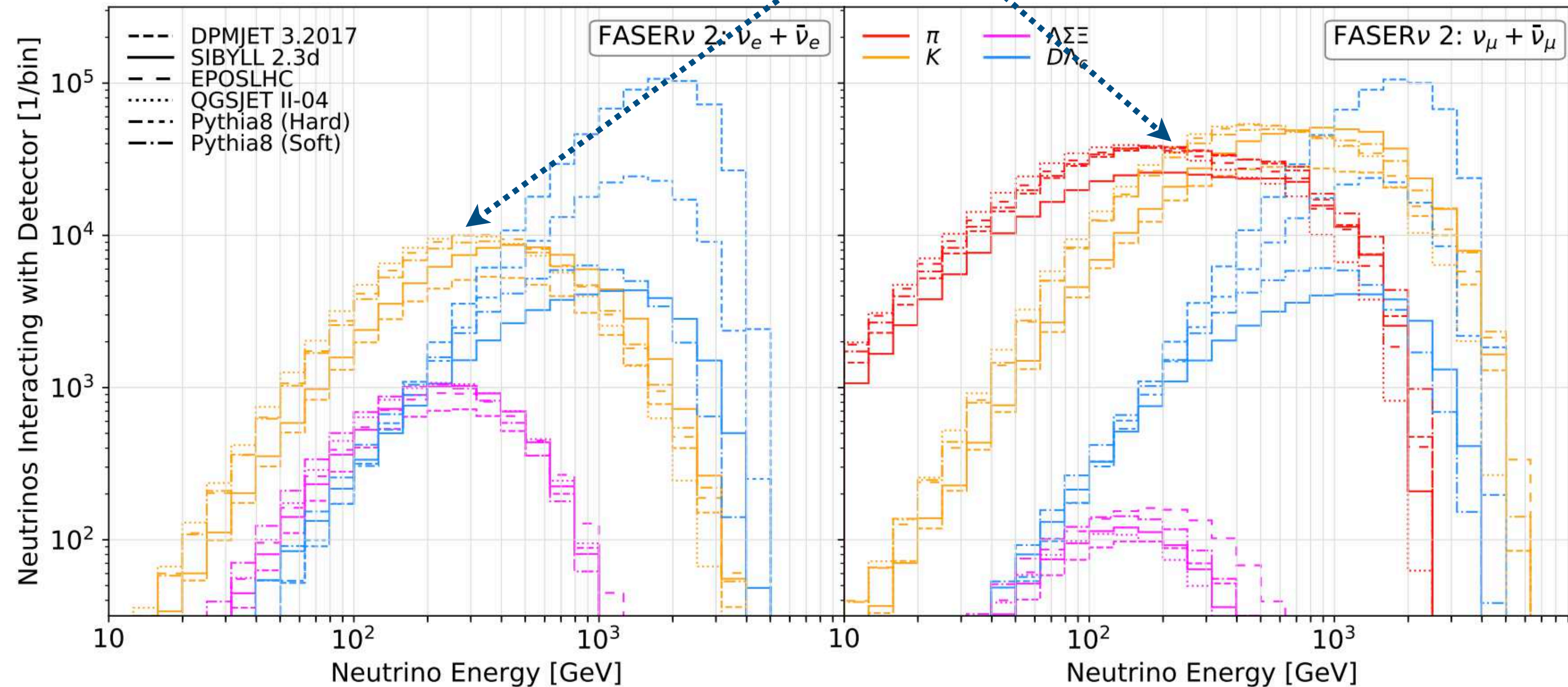
Light Hadron Production



- ▶ Example: Neutrino fluxes at FASER ν 2

low-energy region relevant!

[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]



- ▶ Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties!

Light Hadron Production



- ▶ Indications for strangeness enhancement in the mid rapidity region reported by ALICE

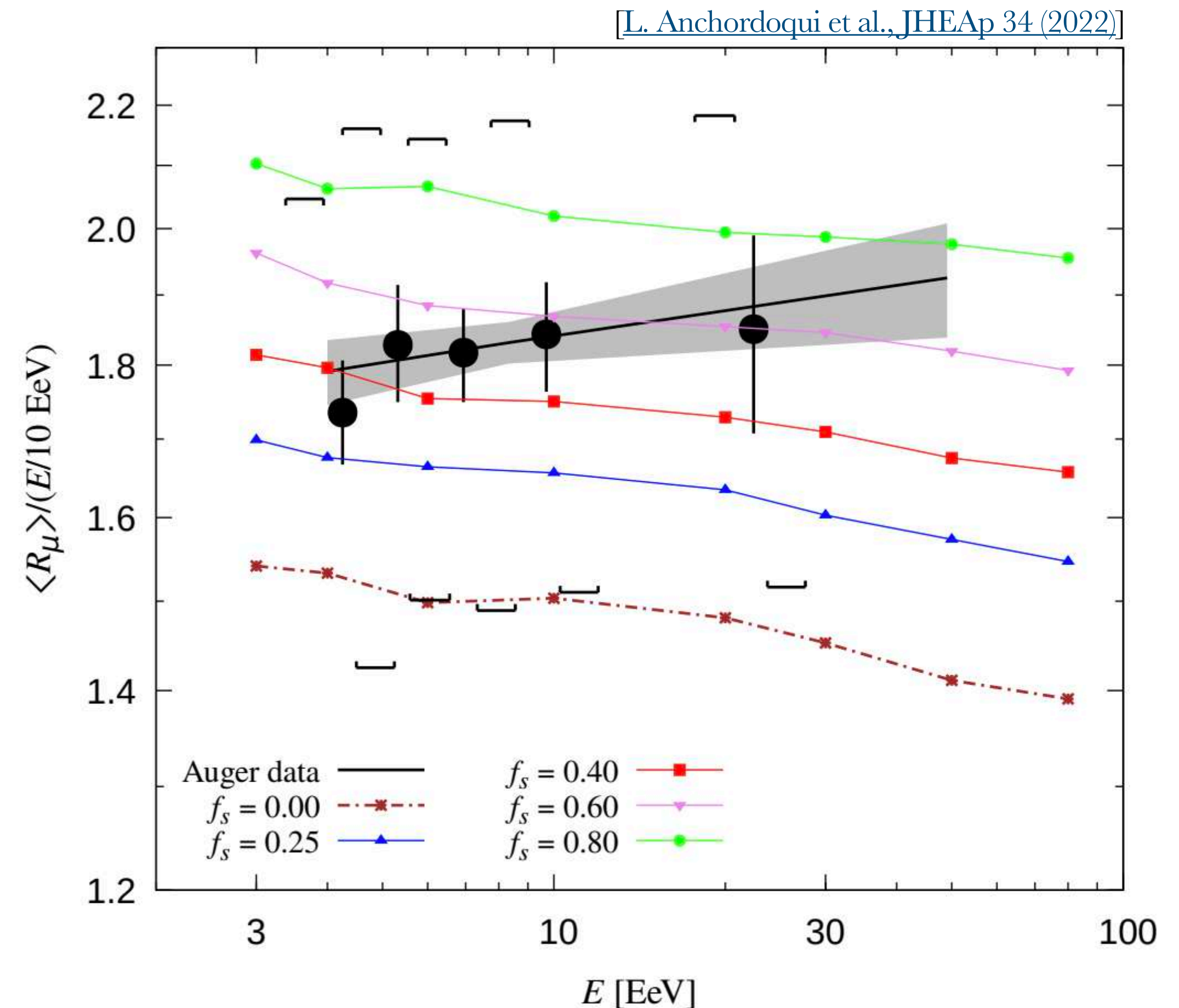
[J. Adam et al. (ALICE), *Nature Phys.* 13, 535 (2017)]

- ▶ Can this effect also be seen in hadrons produced at forward rapidities?

- ▶ Simple toy model:

[L. Anchordoqui et al., *JHEAp* 34 (2022)]

- ▶ Strangeness enhancement realized by $\pi \leftrightarrow K$ swapping
- ▶ Swapping fraction f_s
- ▶ Possible explanation for the Muon Puzzle in EAS!
- ▶ FPF provides unique opportunities for testing the forward rapidity region!

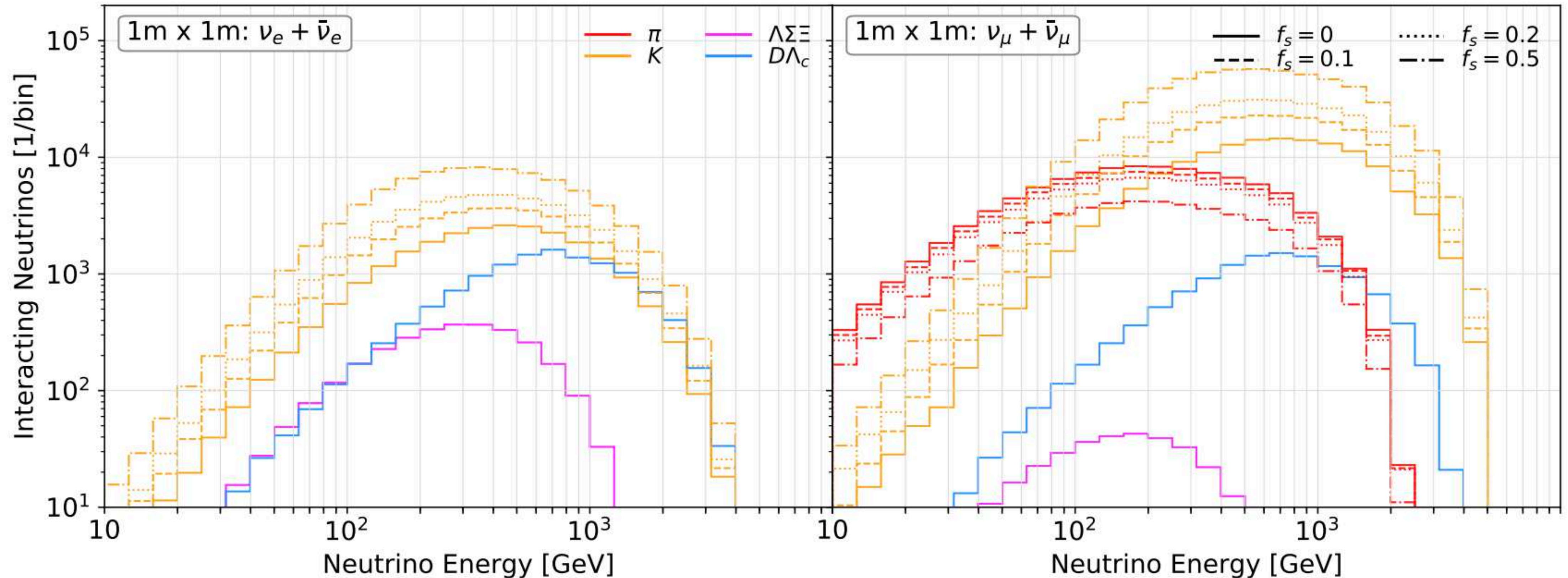


Light Hadron Production



- ▶ Example: Neutrino fluxes at FLArE

[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]



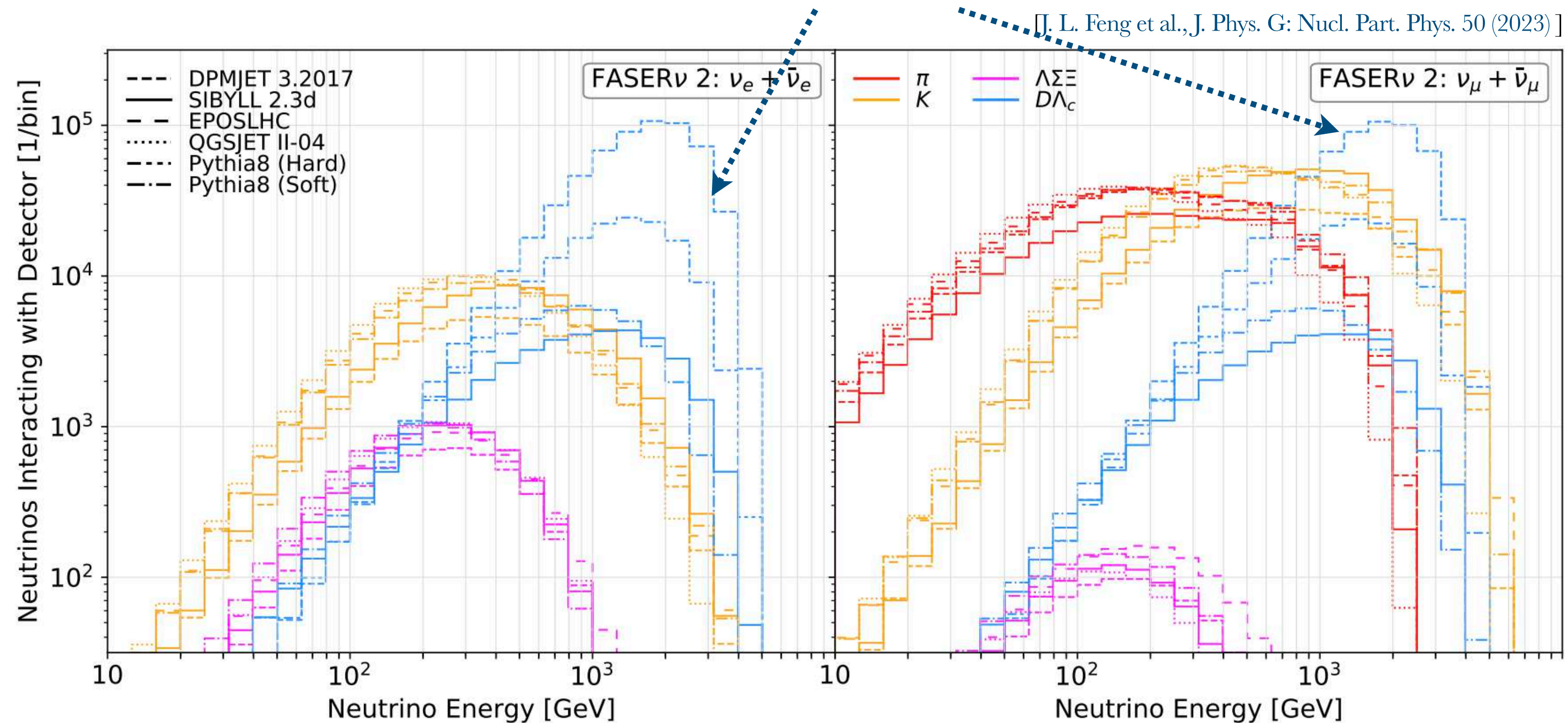
- ▶ Model comparison: strangeness enhancement toy model as an example [L. Anchordoqui et al., JHEAp 34 (2022)]

Prompt Hadron Production



- ▶ Example: Neutrino fluxes at FASER ν 2

high-energy region relevant!



- ▶ Measurements of charm production will reduce uncertainties in atmospheric prompt flux

Muon Fluxes at the FPF

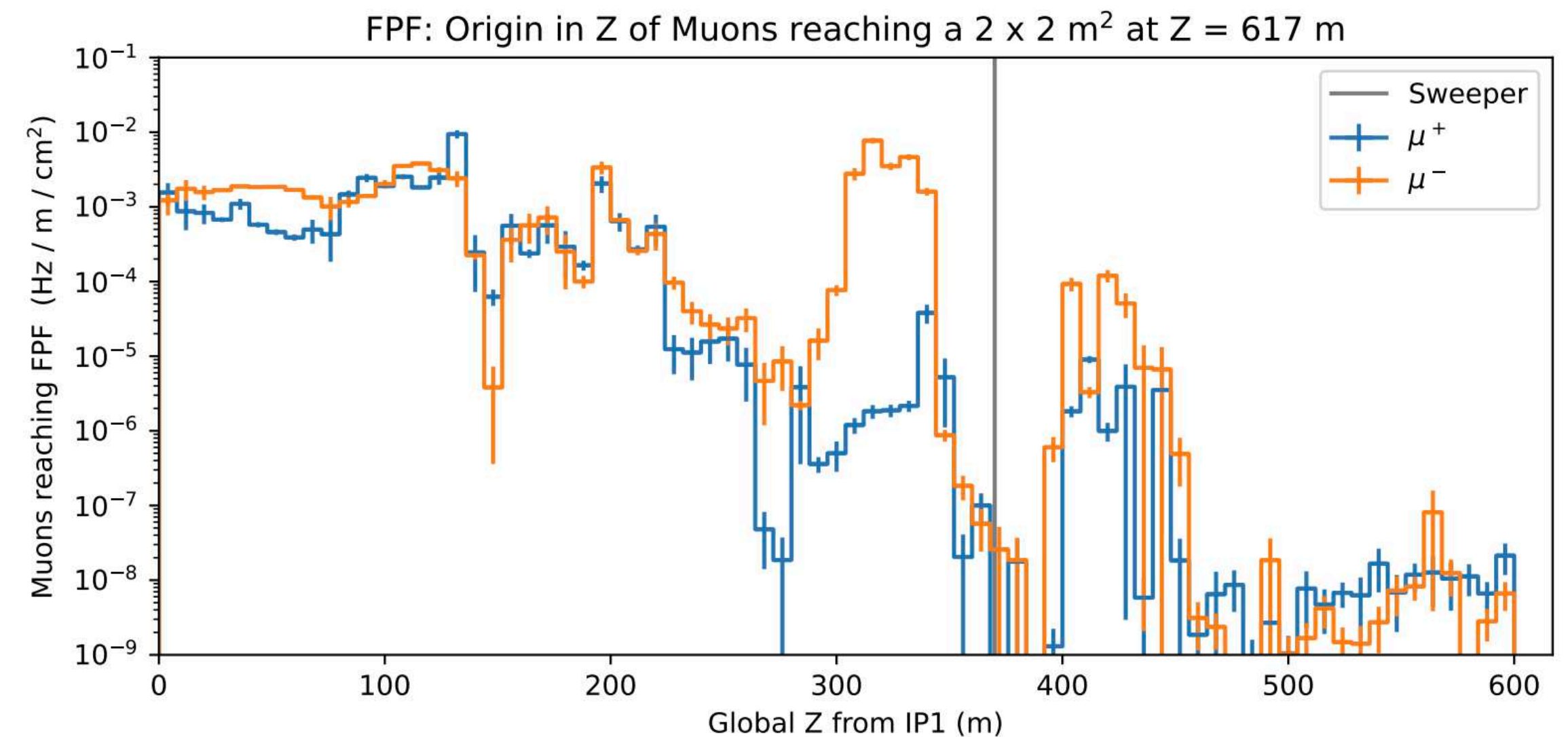


▶ Muon fluxes at the FPF:

- ▶ Large muon flux at the FPF, e.g. ~ 1 Hz per cm^2 in FASER
- ▶ While we know the origin of neutrinos in the FPF (ATLAS interaction point), studies of muons at the FPF are challenging as the origin of production is uncertain...

▶ Open questions:

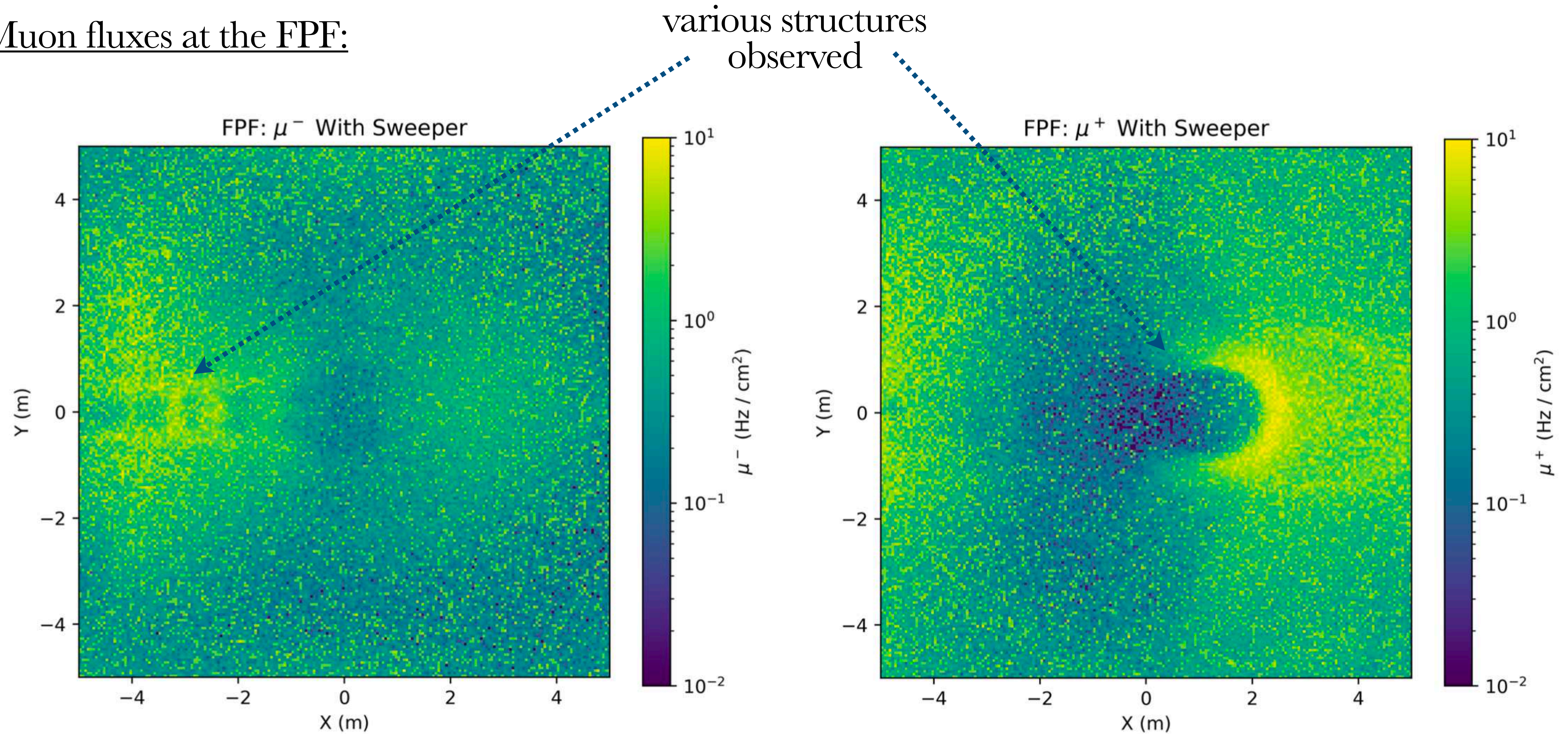
- ▶ Can we use muons to study light hadron production?
- ▶ Can we measure the muon charge ratio?
- ▶ Can temporary detectors help to understand the muons fluxes at the FPF?
- ▶ What can we learn from muon fluxes measured at FASER and SND@LHC?
- ▶ Dedicated studies of the muon yield at the FPF are ongoing...



Muon Fluxes at the FPF



- ▶ Muon fluxes at the FPF:



- ▶ Temporary detectors? Simulation studies ongoing...

BSM Physics & Dark Matter



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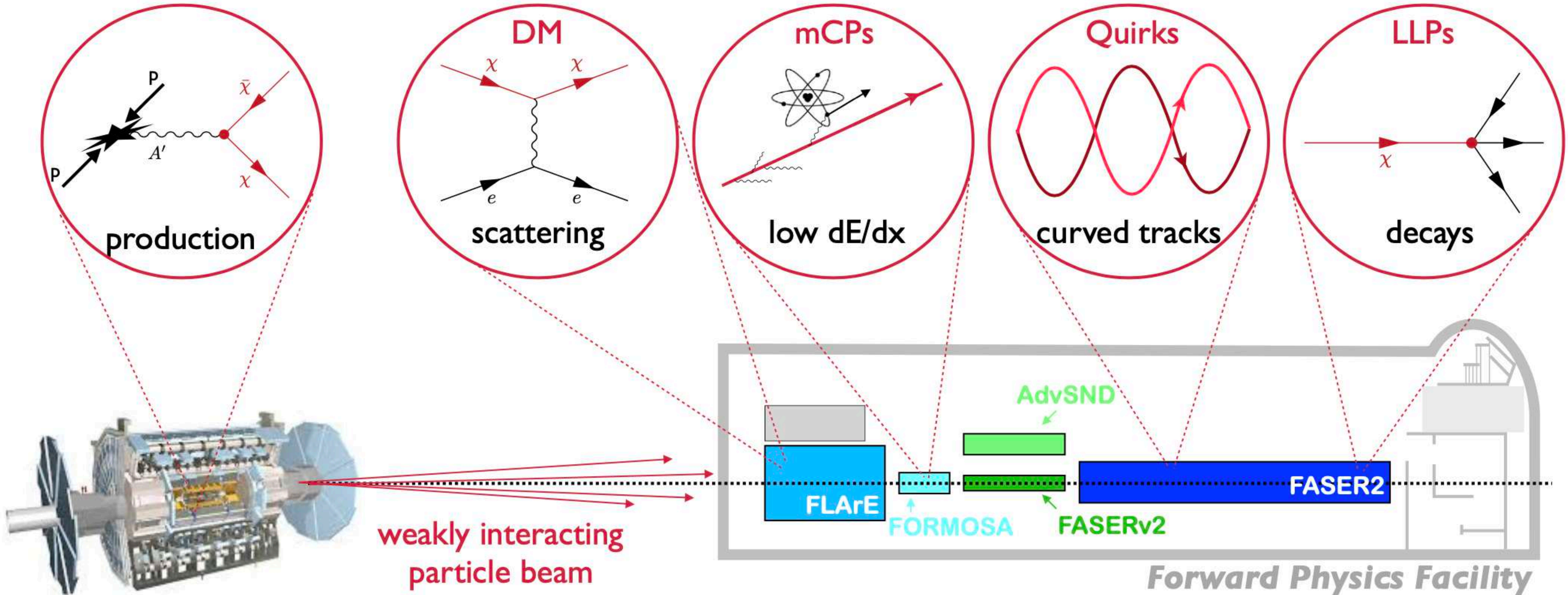
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BSM physics & dark matter

Dark Matter Searches



- ▶ Huge variety of BSM and dark matter models can be tested at the FPF!



Dark Matter Searches



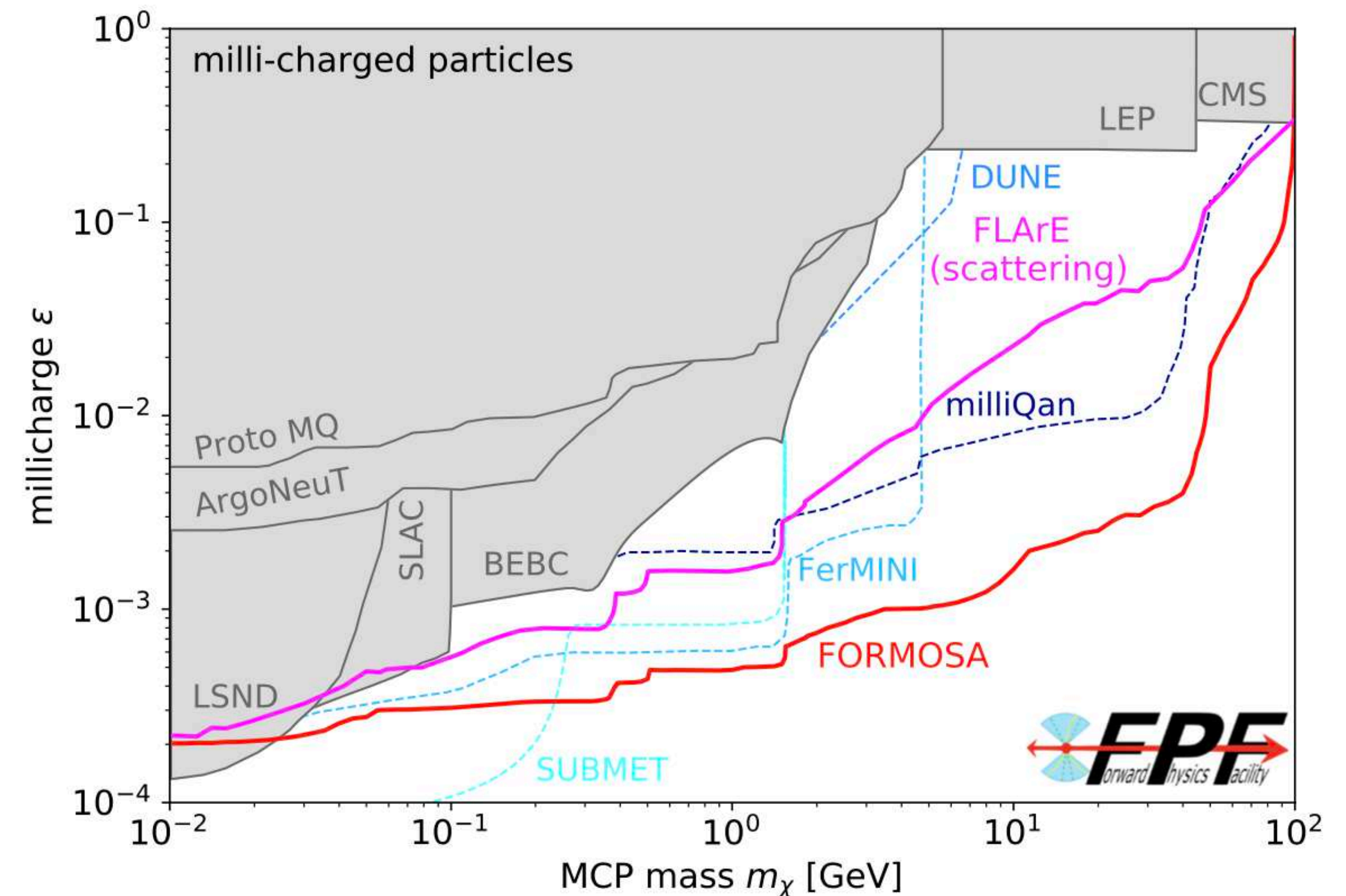
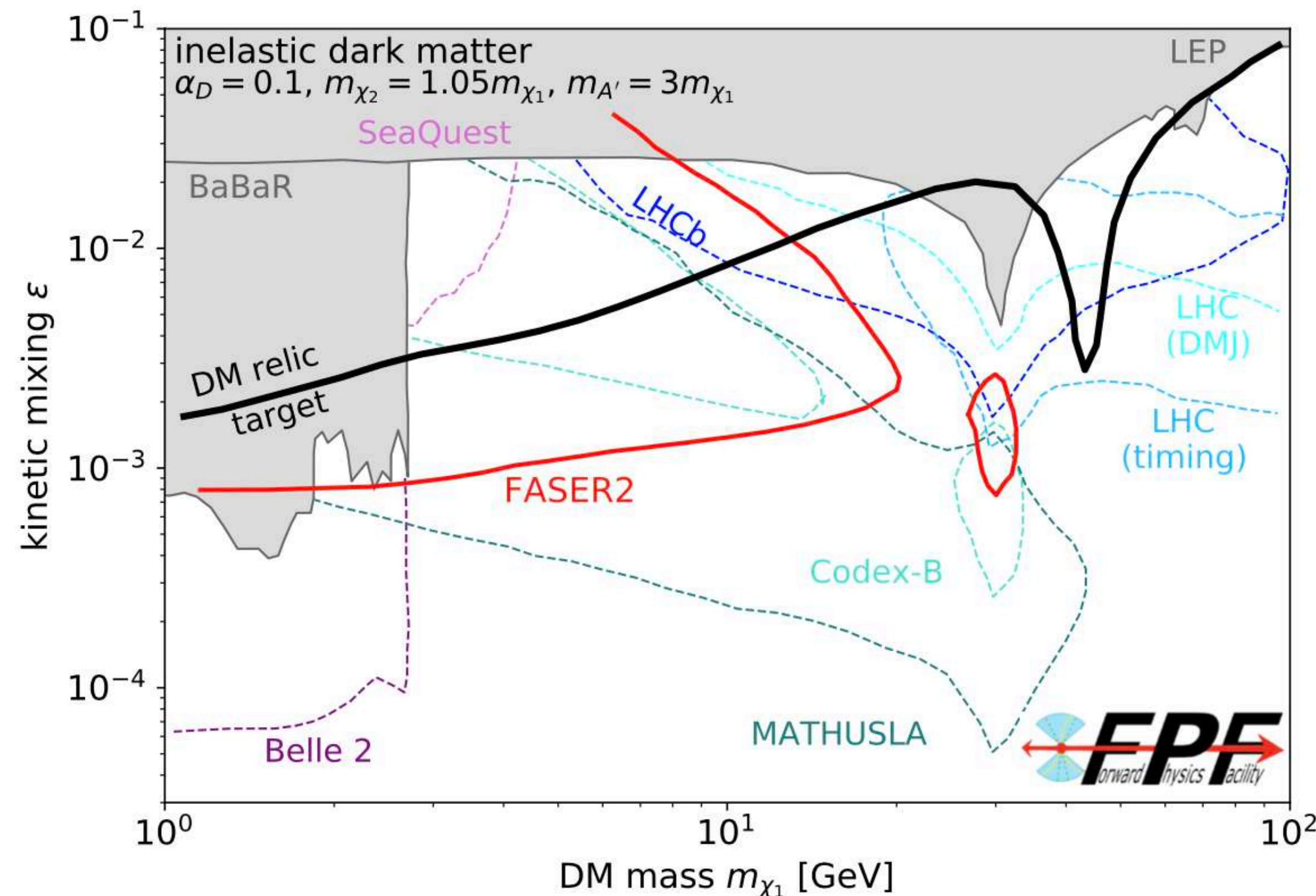
► Examples:

► Search for displaced decays of highly-boosted excited DM states produced in pp collisions

► Millicharged particle searches as a candidate for a strongly interacting sub-component of DM

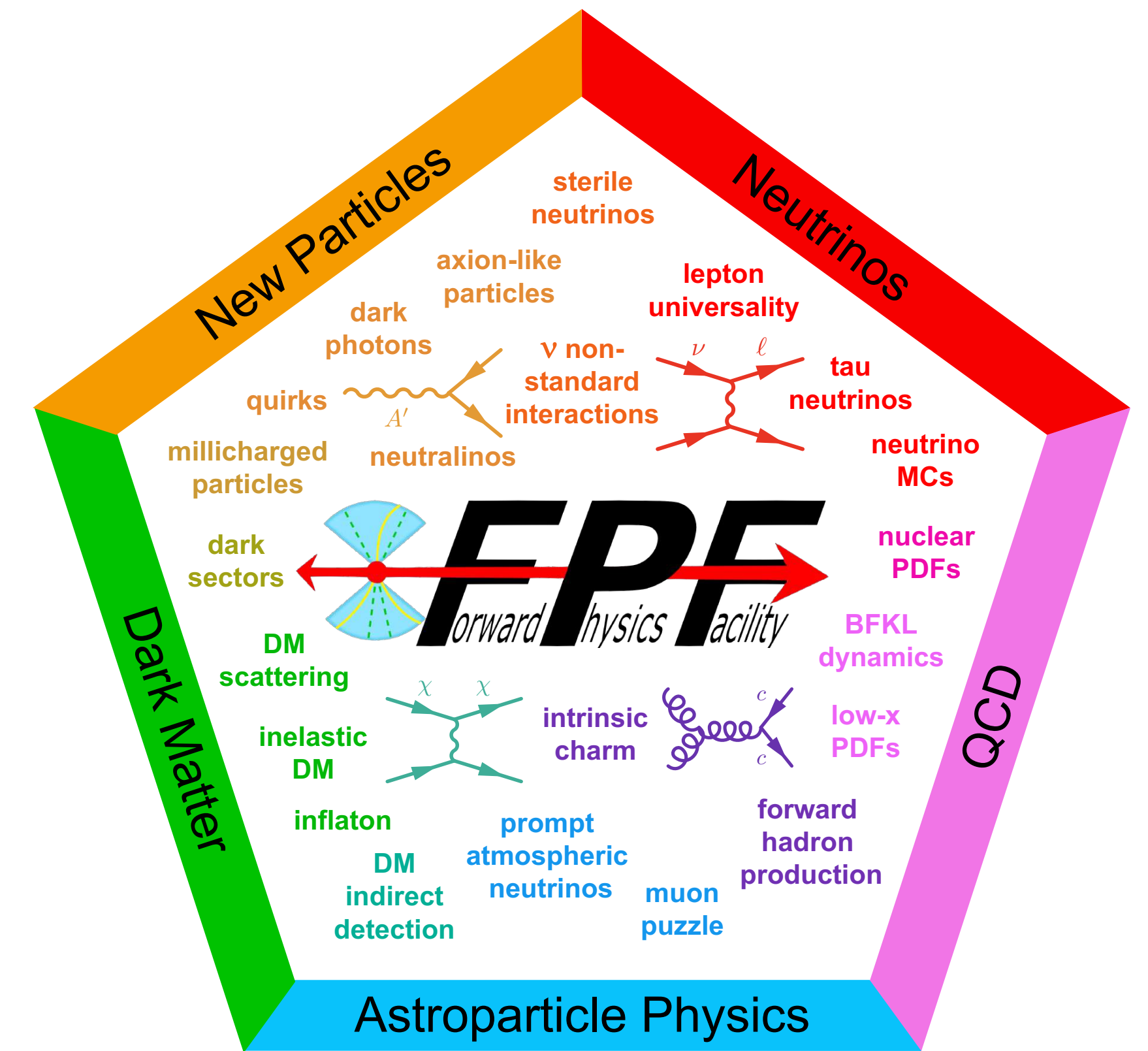
[A. Berlin, F. Kling, Phys. Rev. D99 (2019)]

[S. Foroughi-Abari, F. Kling, Phys. Rev. D104 (2021)]



Summary

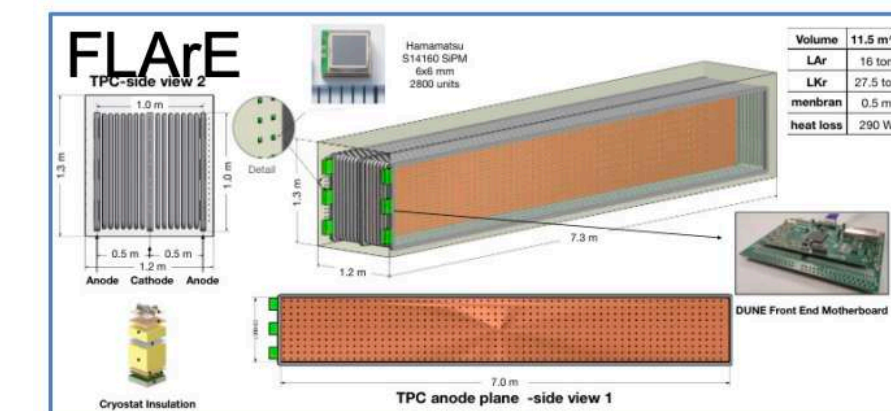
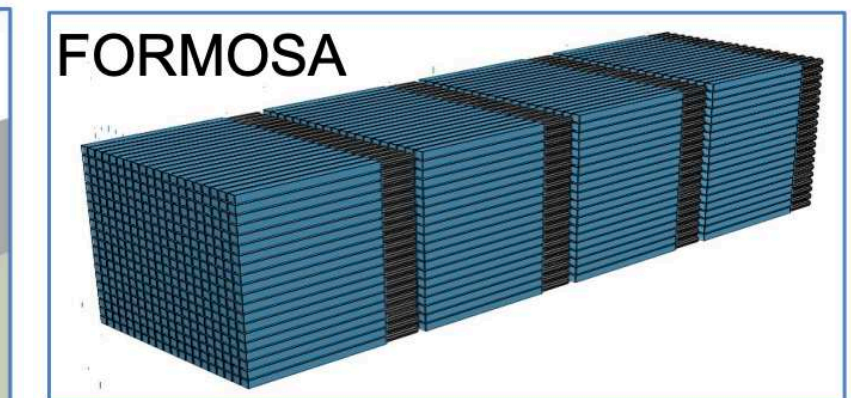
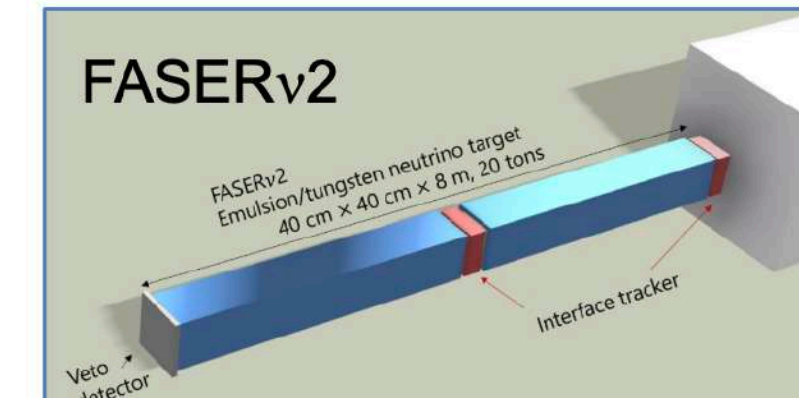
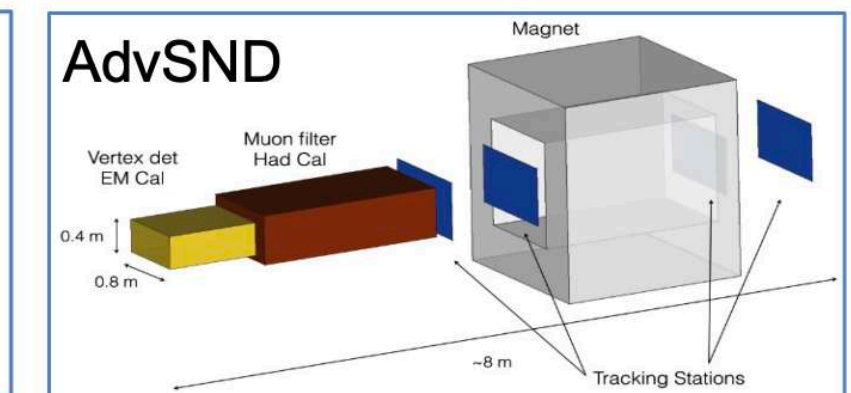
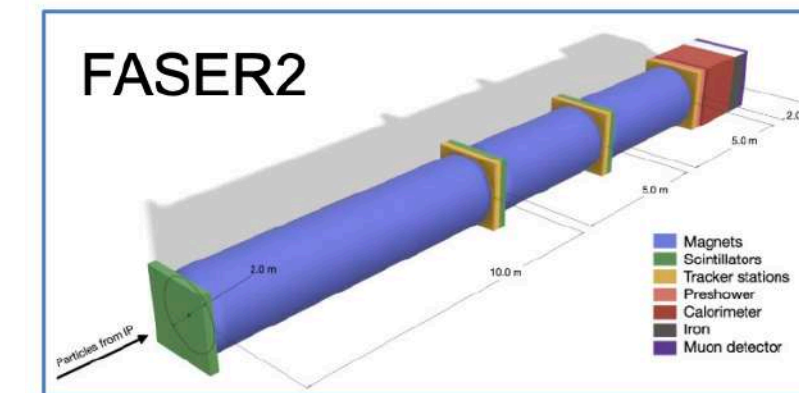
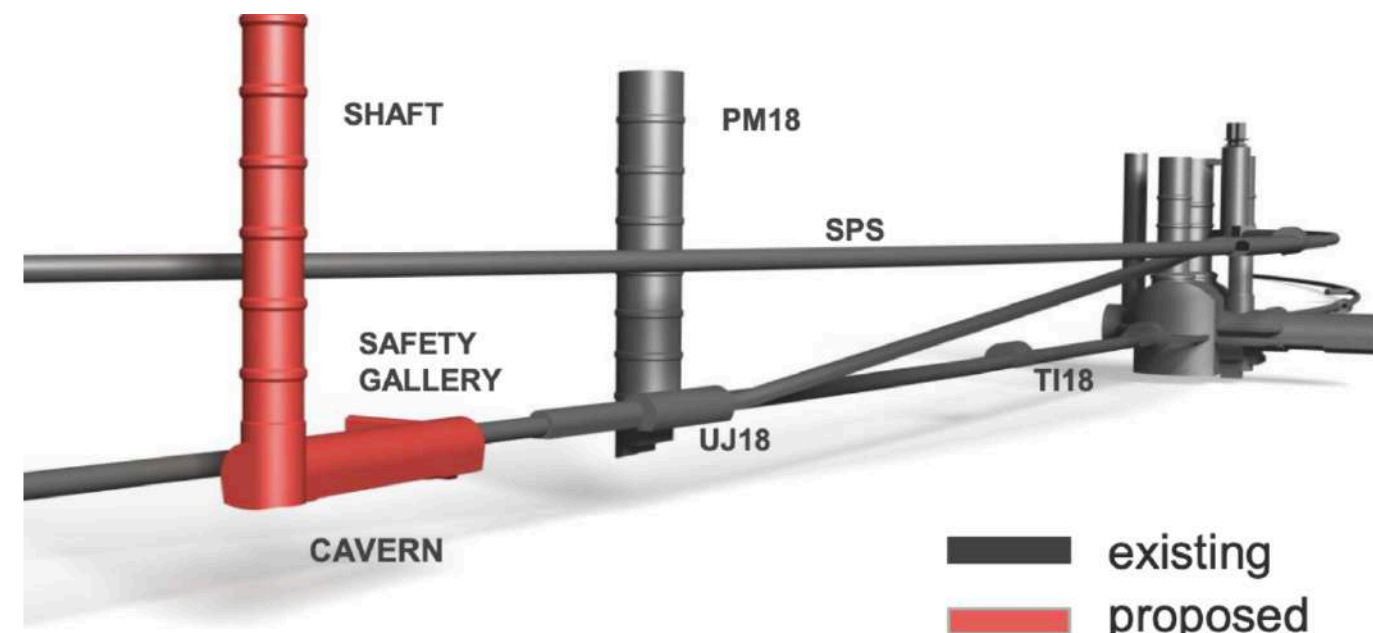
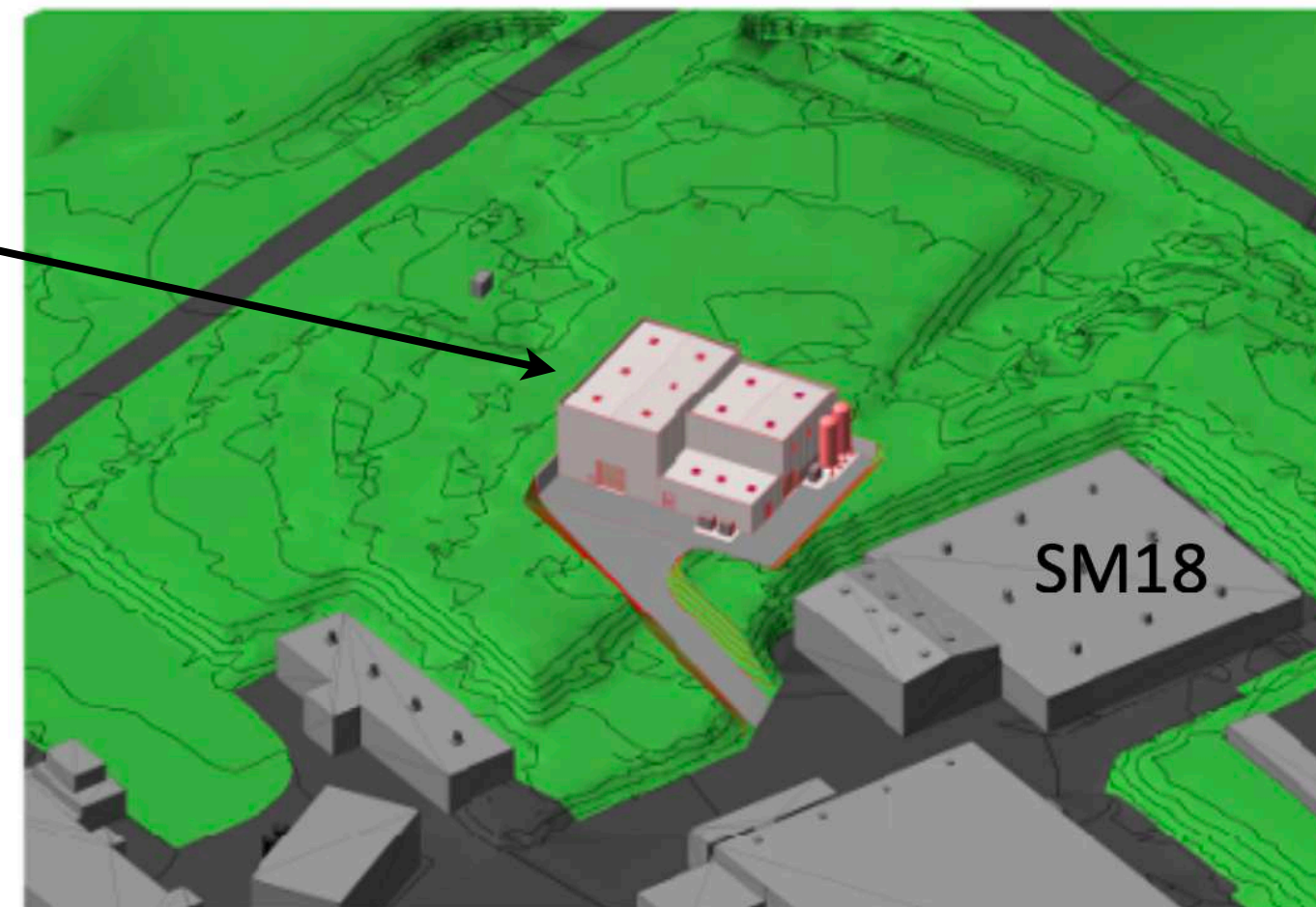
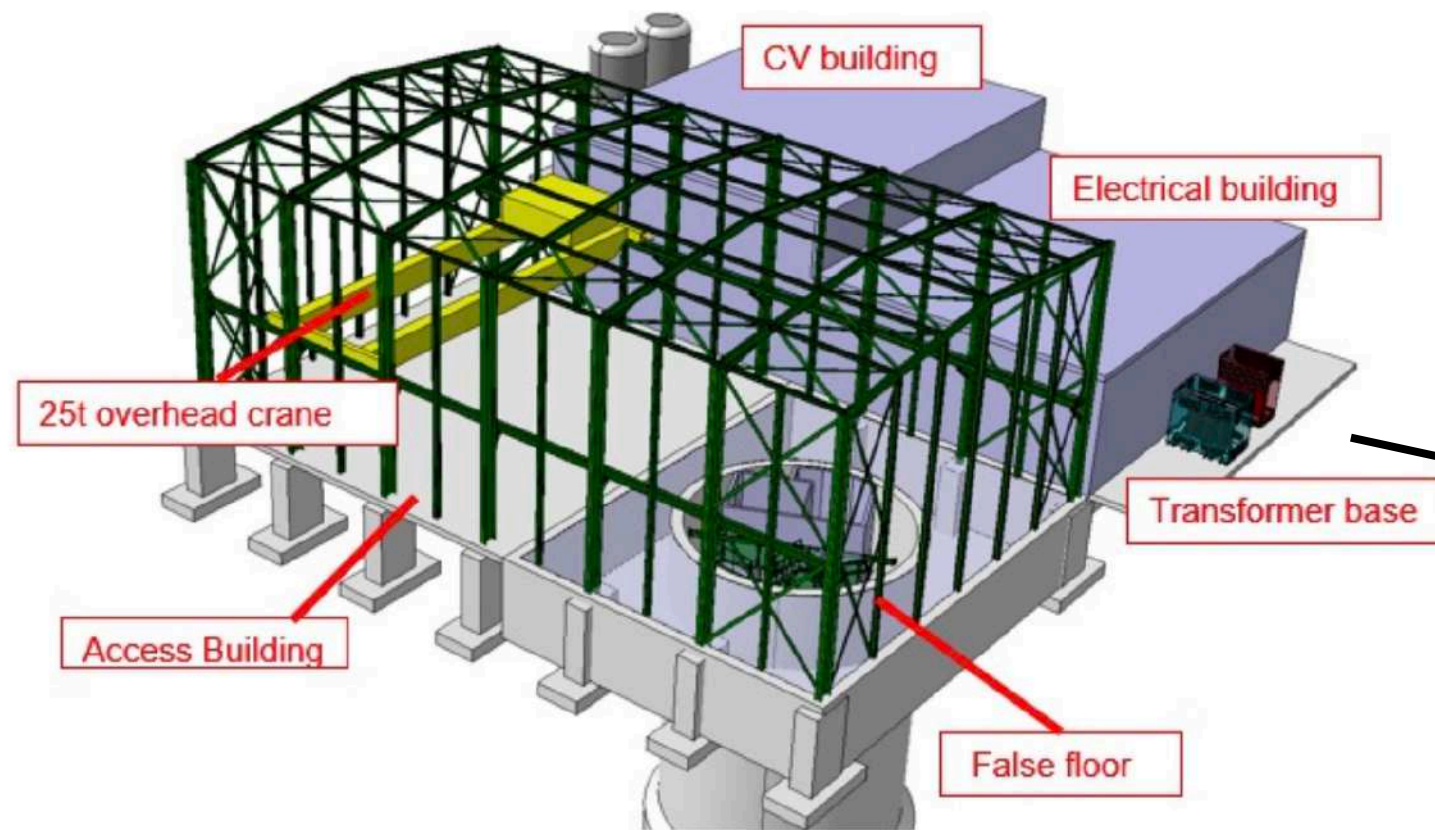
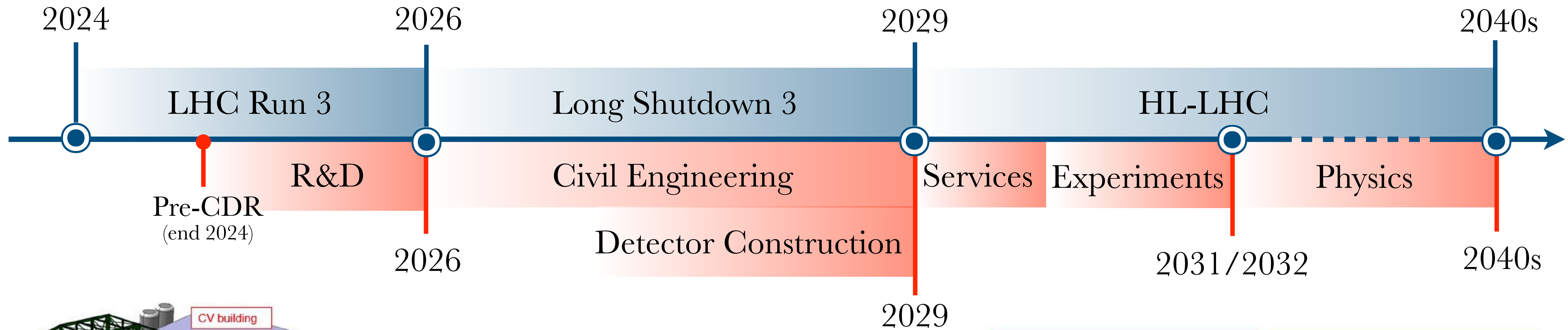
- ▶ Cosmic ray measurements highly rely on interpretation based on MC simulations of EASs
 - ▶ Large discrepancies observed in the muon content of EAS
- ▶ High-energy neutrinos from EASs are background for astrophysical neutrino searches
 - ▶ Prompt neutrino flux not well understood
- ▶ The FPF is a proposal to measure particle production at the HL-LHC in the ATLAS line-of-sight ($\eta \gtrsim 7$)
- ▶ Comprehensive and diverse physics program
- ▶ Reduced uncertainties for astroparticle physics measurements, i.e. cosmic rays & neutrinos
- ▶ Various BSM & dark matter searches
- ▶ More information: <https://fpf.web.cern.ch/>



Please don't hesitate to contact us if you want to contribute!

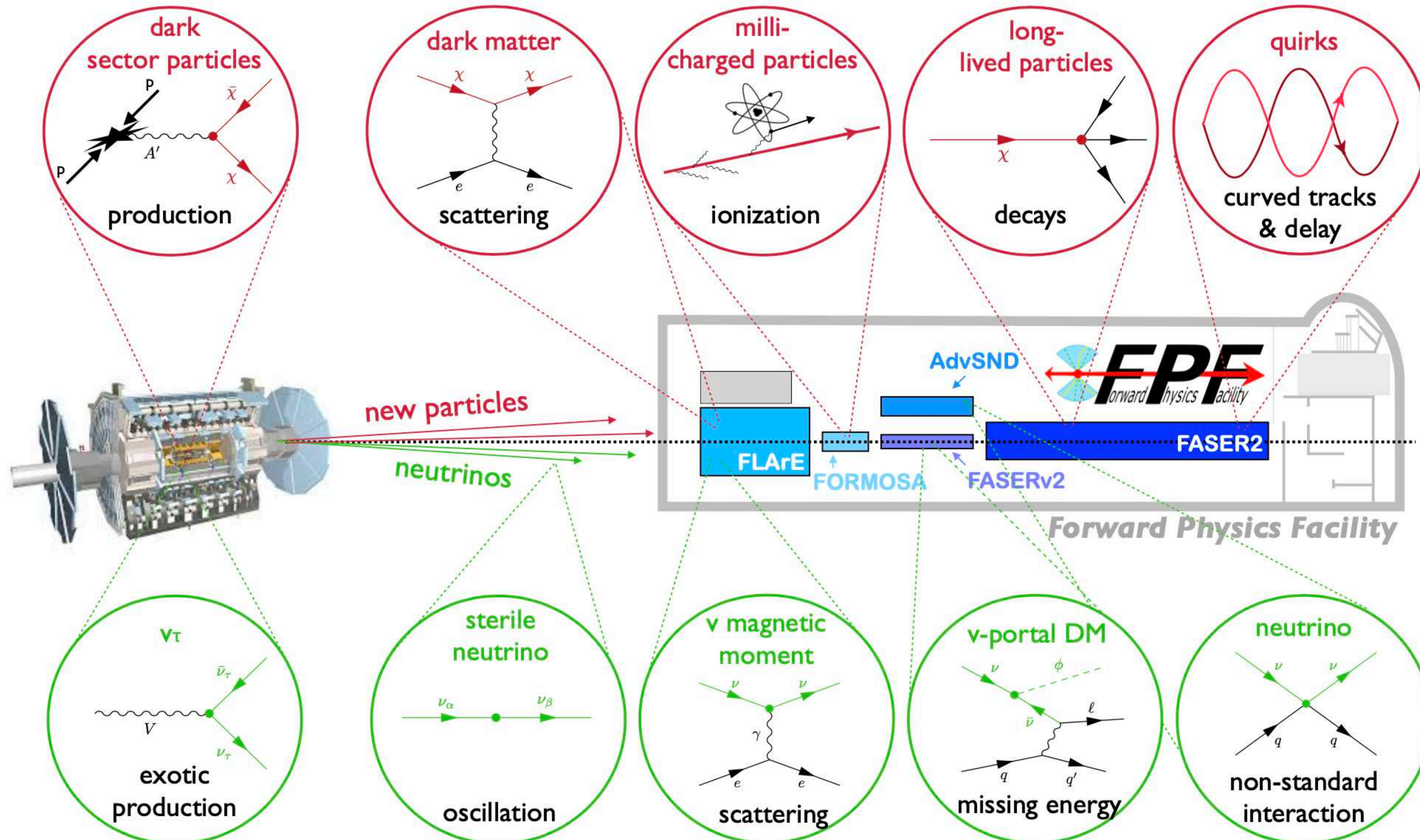
Backup

FPP Timeline

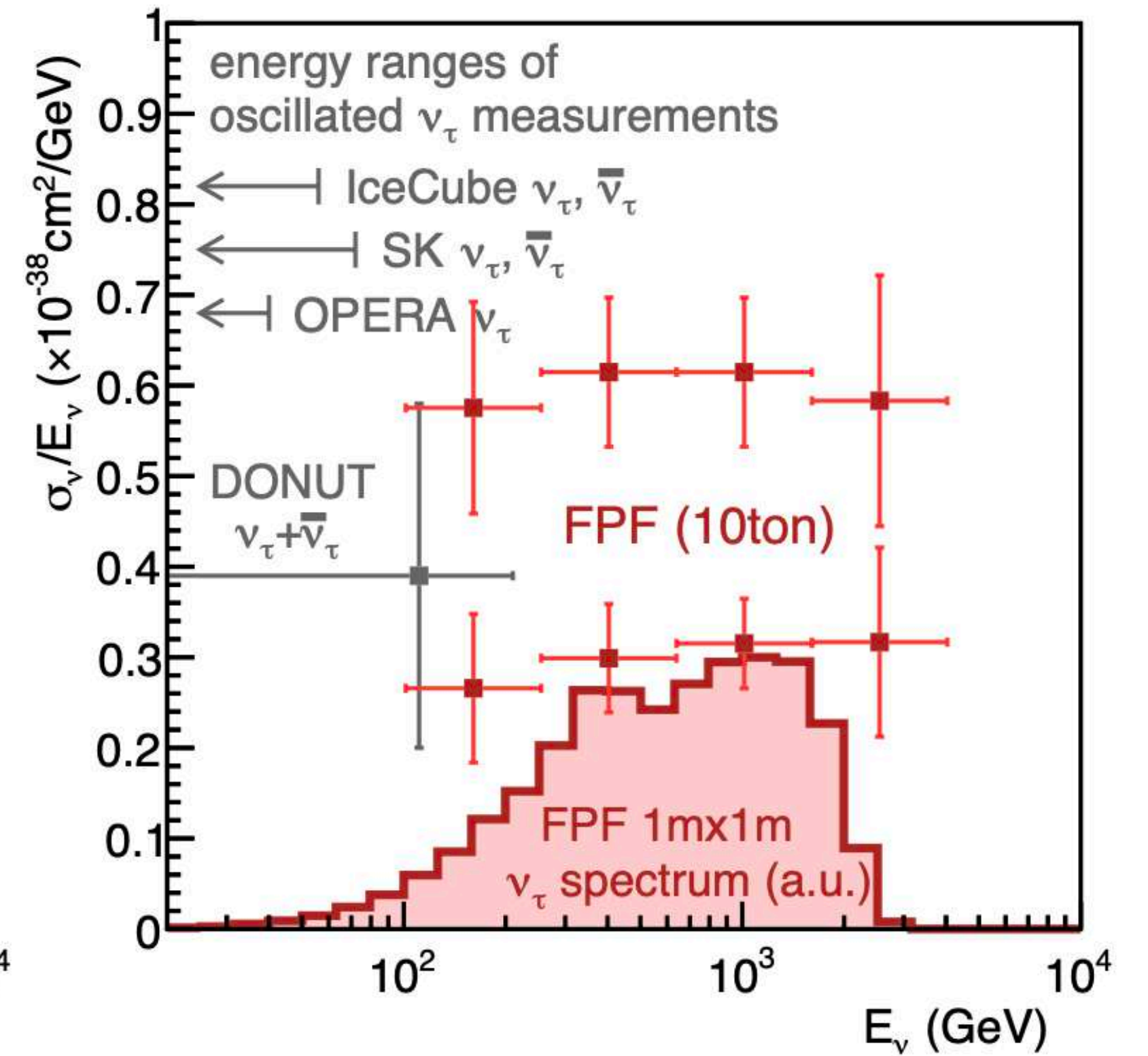
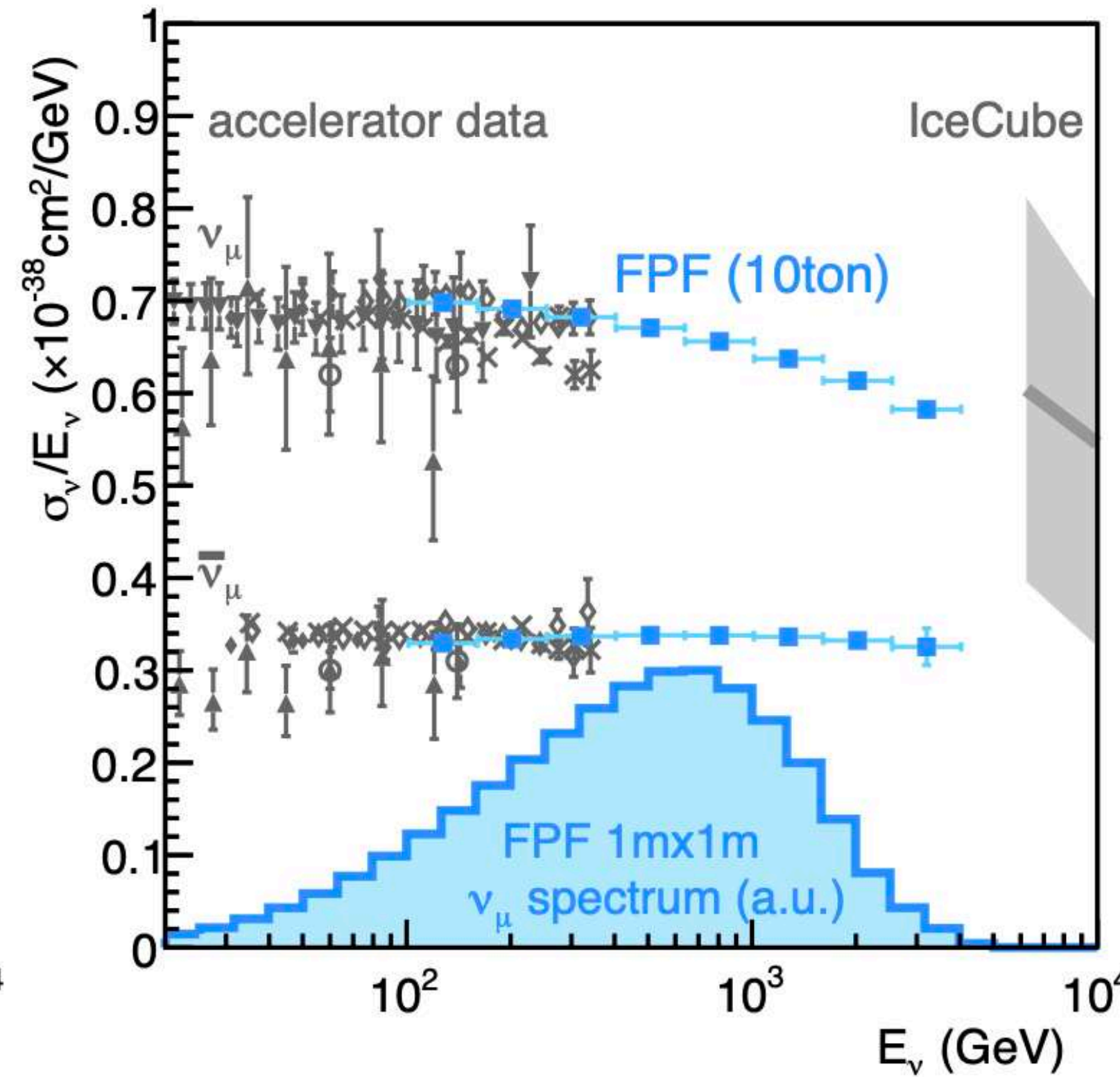
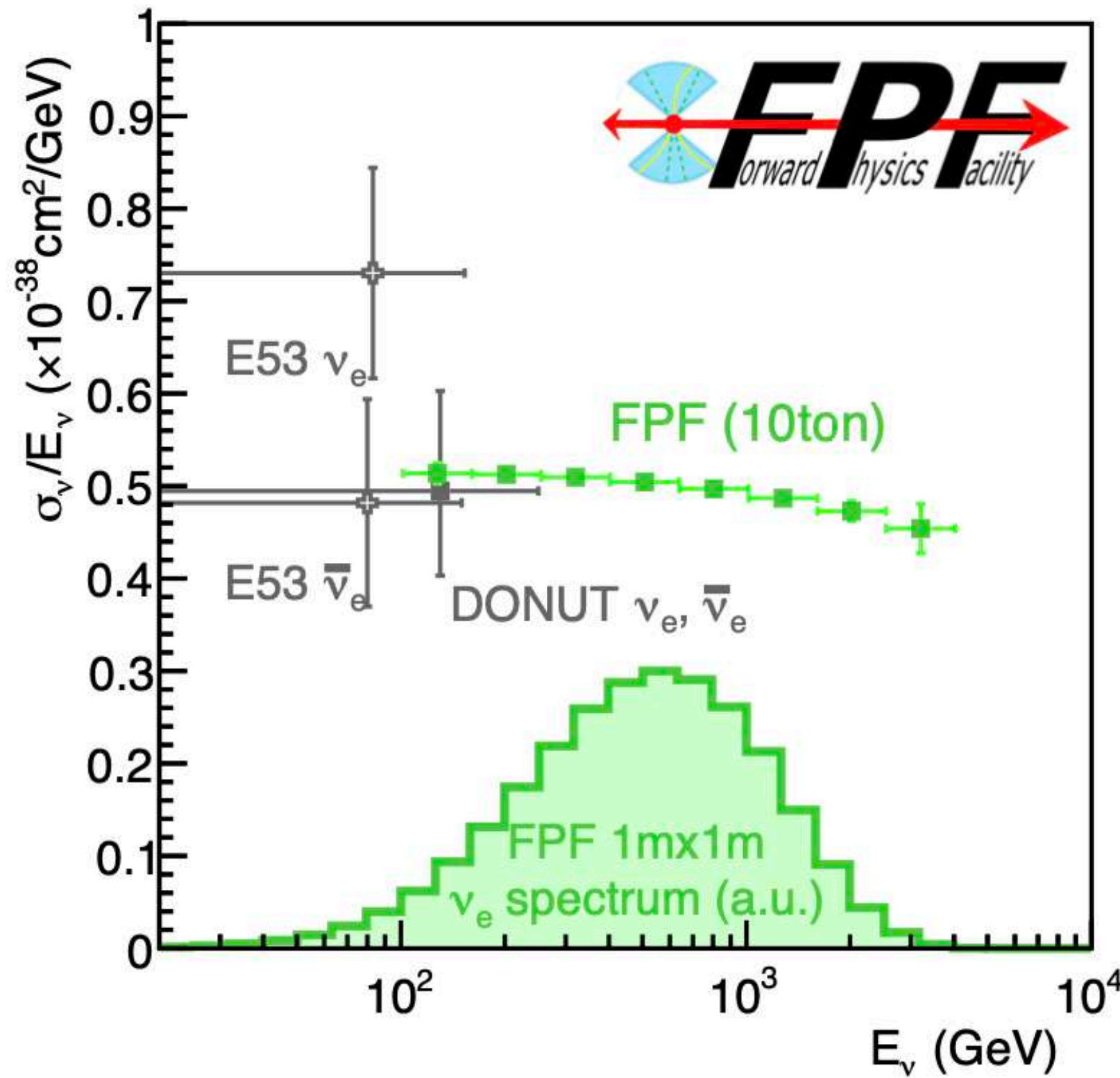


[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Neutrino / DM Overview



Neutrino Fluxes at the FPF



- ▶ Neutrino fluxes (ν_e, ν_μ, ν_τ) as a function of energy through a 1×1 m area at the FPF
- ▶ Expected precision of the neutrino interaction cross section with nucleons (statistical errors only)