

Astroparticle Physics with the Forward Physics Facility at the High-Luminosity LHC

Dennis Soldin on behalf of the FPF initiative

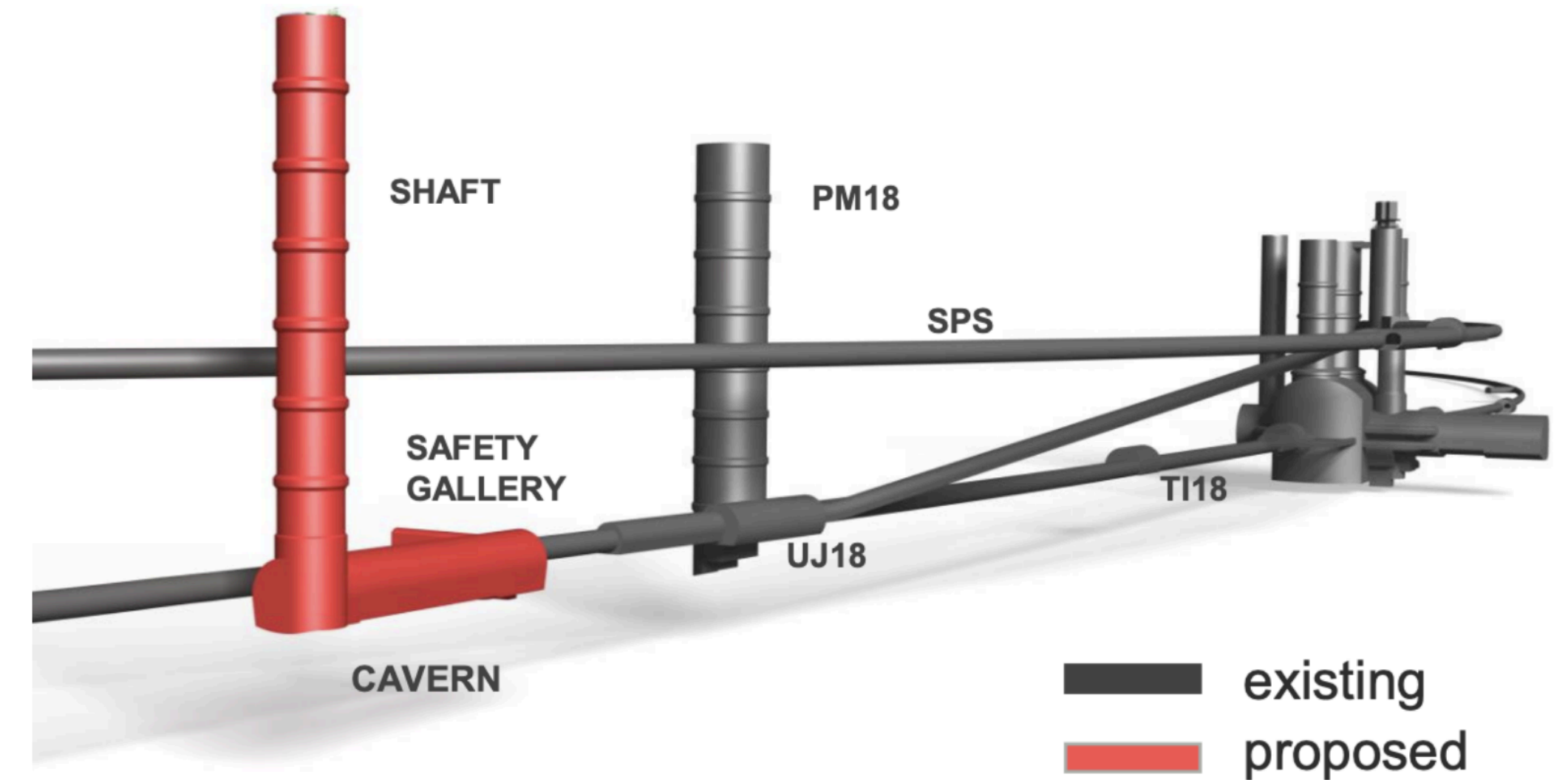


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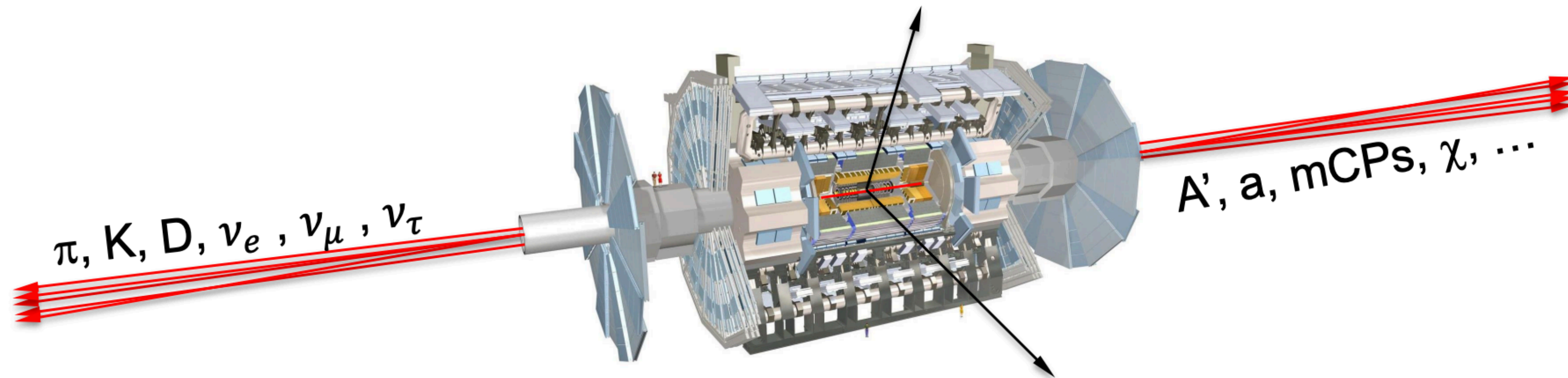
Overview

- ▶ Introduction
- ▶ Facility & Timeline
- ▶ Experiments
- ▶ Astroparticle Physics with the FPF
- ▶ Summary & Conclusions



Introduction

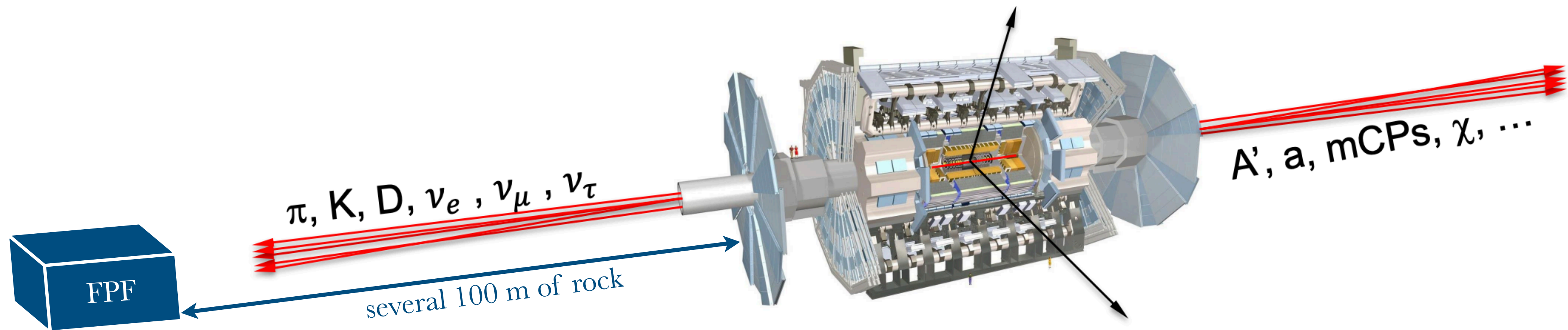
- ▶ Question: What opportunities are we currently missing from a lack of coverage of far-forward physics at the LHC?



- ▶ 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 ($\eta \gtrsim 7$)
- ▶ Synergies between FPF physics and astroparticle physics!

Introduction

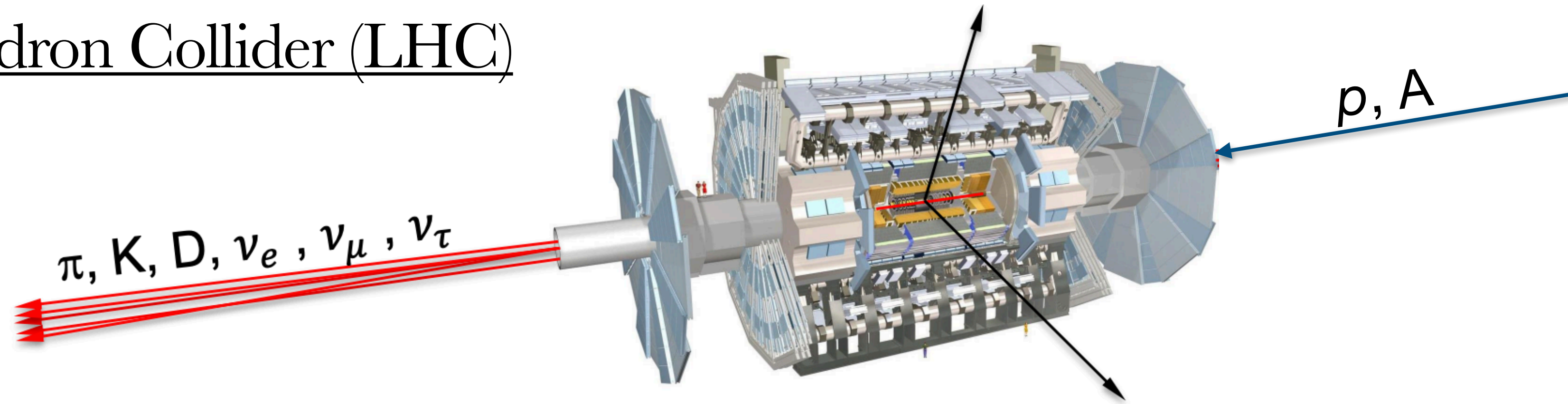
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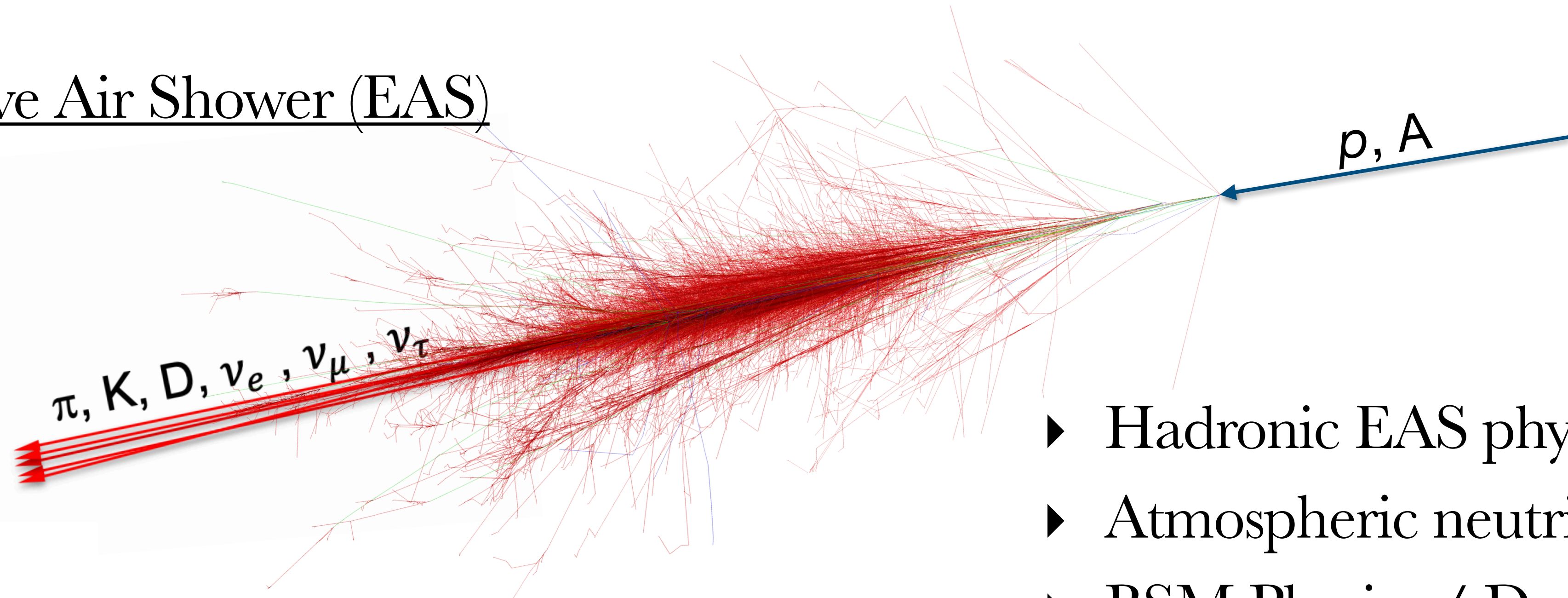
- ▶ By far the largest flux of energetic light particles is in the far-forward direction (mesons, neutrinos, and maybe also dark photons, ALPs, mCPs, DM, ...)
- ▶ Proposal: Forward Physics Facility (FPF) at LHC in ATLAS line-of-sight ($\eta \gtrsim 7$)
- ▶ Synergies between FPF physics and astroparticle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

Introduction

- ▶ Large Hadron Collider (LHC)



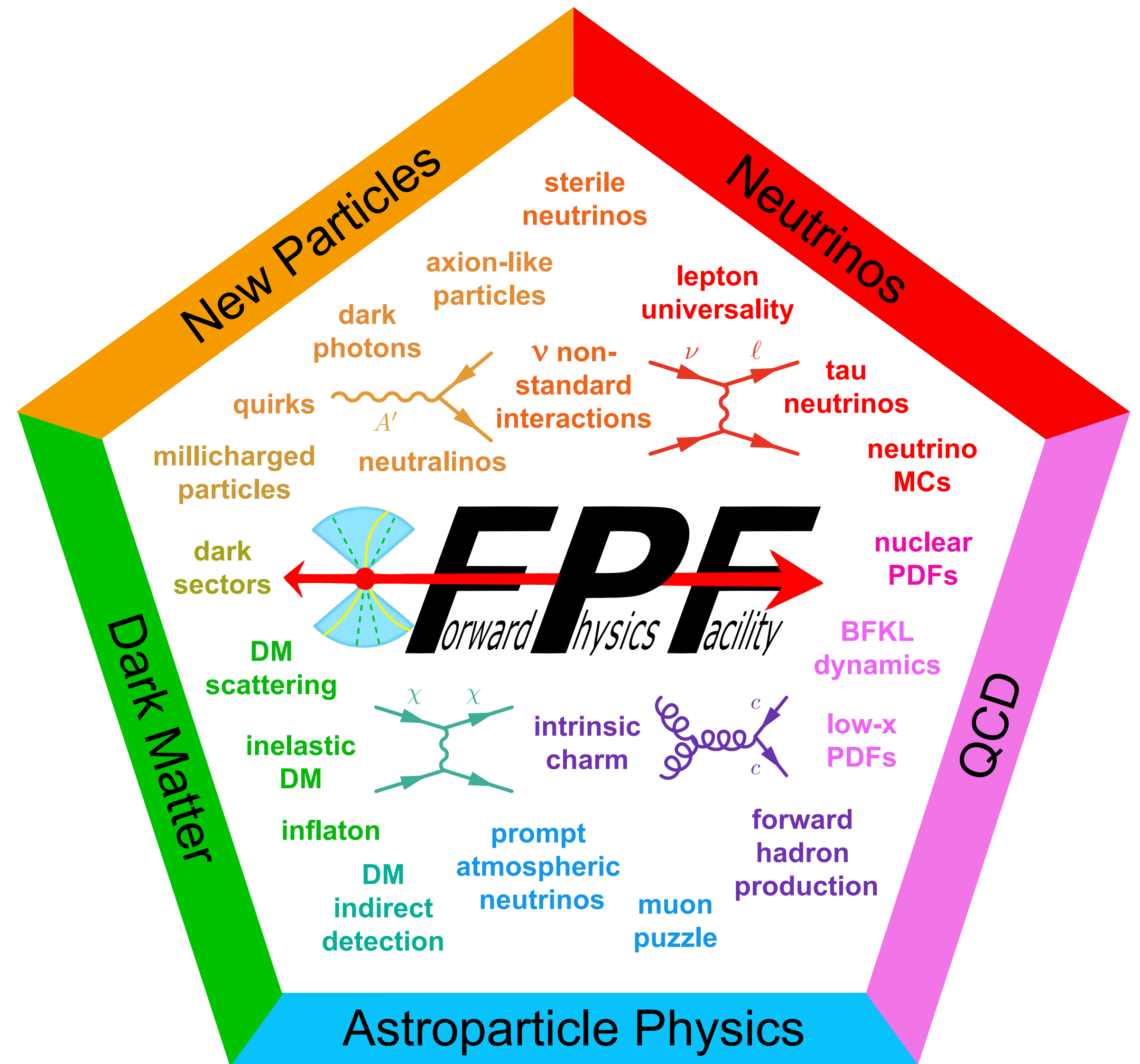
- ▶ Extensive Air Shower (EAS)



- ▶ Hadronic EAS physics
- ▶ Atmospheric neutrino production
- ▶ BSM Physics / Dark Matter

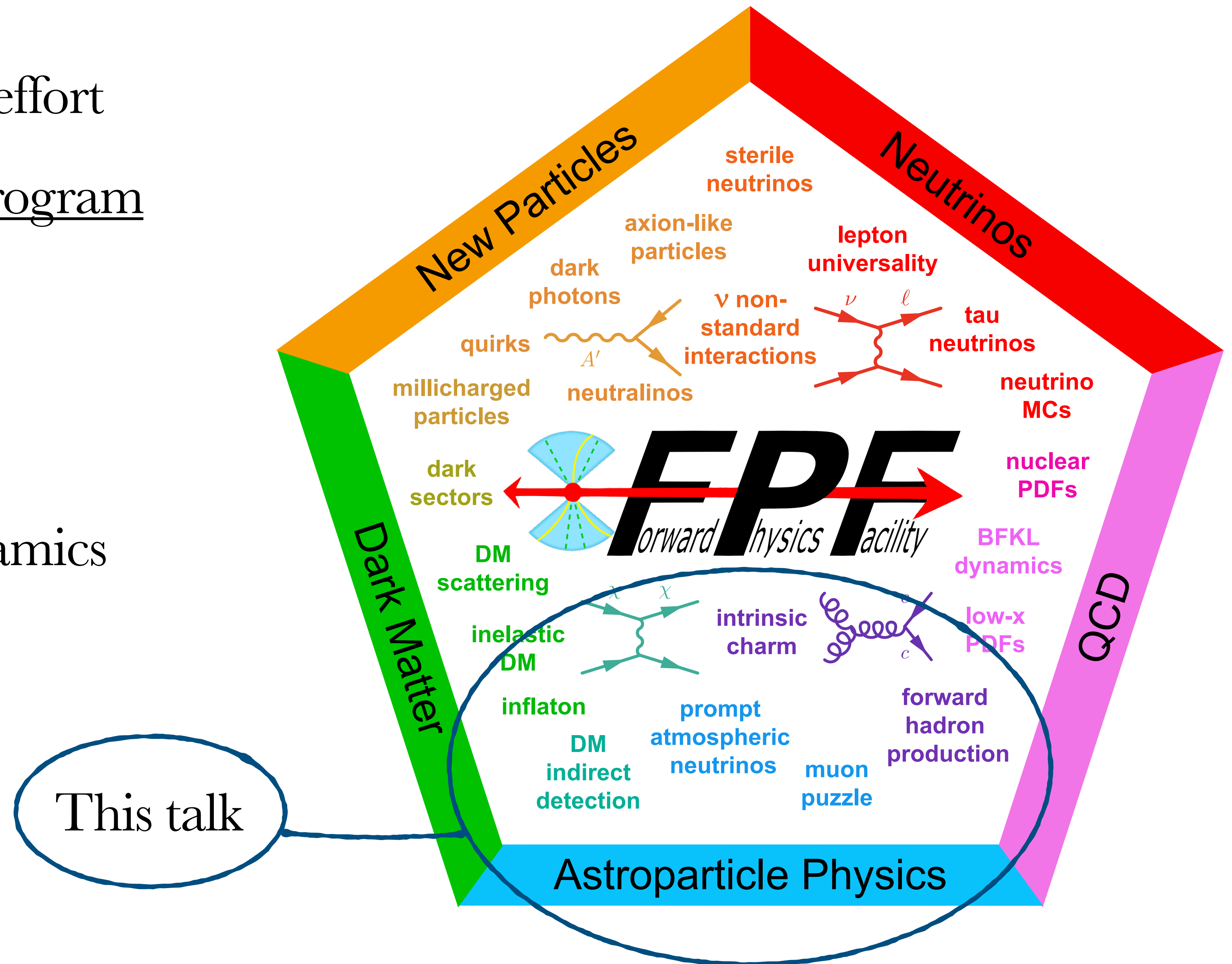
Disclaimer

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



Disclaimer

- ▶ Large (multi-)community effort
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FPF Short Paper

- ▶ Further reading:
 - ▶ First "real" paper on FPF
 - ▶ About 80 authors
 - ▶ About 75 pages
 - ▶ Physics Reports 968 (2022)
[arXiv:2109.10905](https://arxiv.org/abs/2109.10905)
 - ▶ Collection of ideas
 - ▶ Reference for future work
 - ▶ Basis for Snowmass White Paper...

BNL-222142-2021-FORE, CERN-PBC-Notes-2021-025, DESY-21-142, FERMILAB-CONF-21-452-AE-E-ND-PPD-T
KYUSHU-RCAPP-2021-01, LU TP 21-36, PITT-PACC-2118, SMU-HEP-21-10, UCL-TR-2021-22

The Forward Physics Facility: Sites, Experiments, and Physics Potential

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The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era. Located along the beam collision axis and shielded from the interaction point by at least 100 m of concrete and rock, the FPF will house experiments that will detect particles outside the acceptance of the existing large LHC experiments and will observe rare and exotic processes in an extremely low-background environment. In this work, we summarize the current status of plans for the FPF, including recent progress in civil engineering in identifying promising sites for the FPF and the experiments currently envisioned to realize the FPF's physics potential. We then review the many Standard Model and new physics topics that will be advanced by the FPF, including searches for long-lived particles, probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of all three flavors, aspects of perturbative and non-perturbative QCD, and high-energy astroparticle physics.

Snowmass White Paper

- ▶ Even further reading:
 - ▶ Comprehensive 429-page document
 - ▶ 236 authors
 - ▶ 156 endorsers
 - ▶ Accepted by Journal of Physics G
 - ▶ Pre-print: [arXiv:2203.05090](https://arxiv.org/abs/2203.05090)

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)



The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

Snowmass White Paper

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Focus of this talk

Facility & Timeline

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

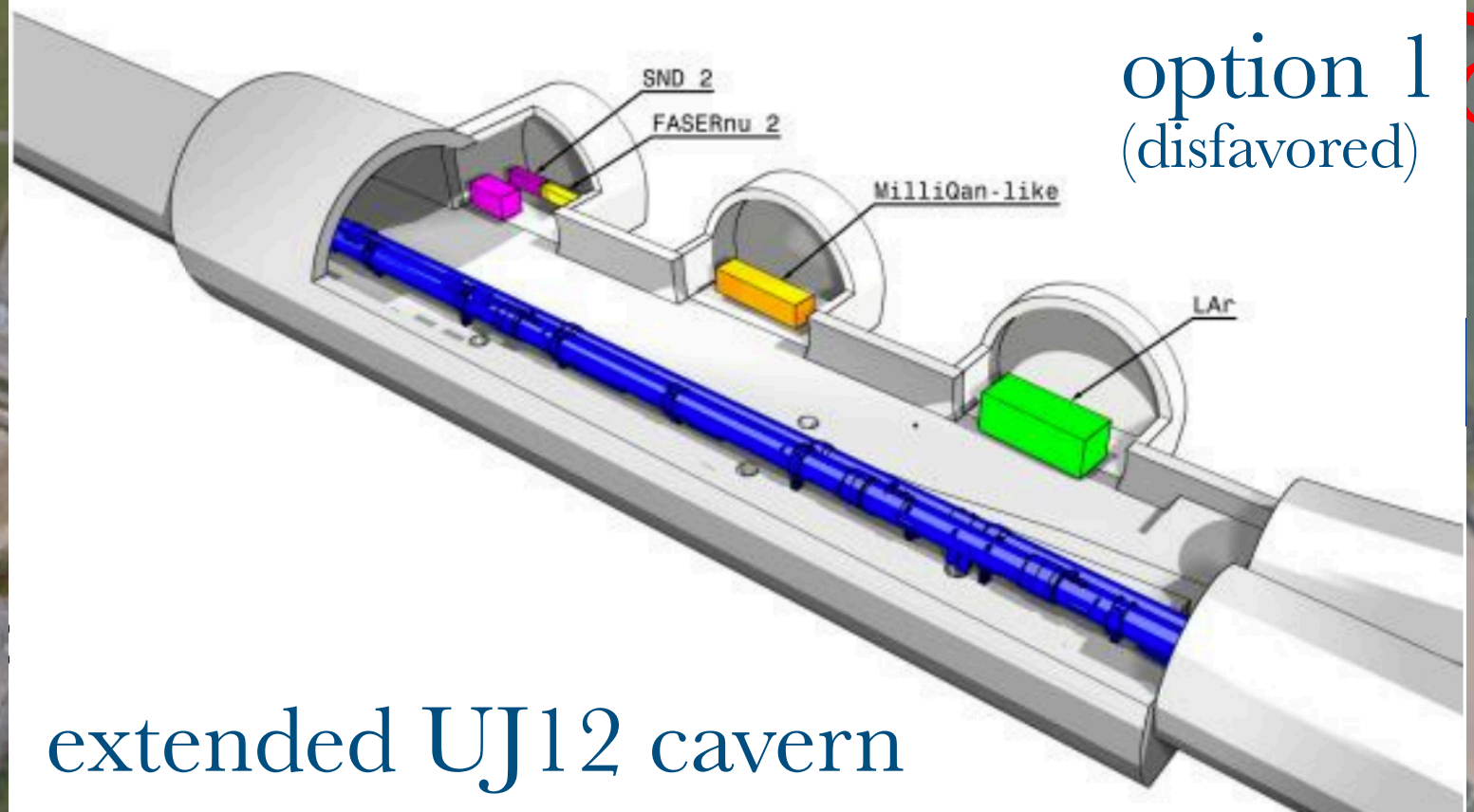
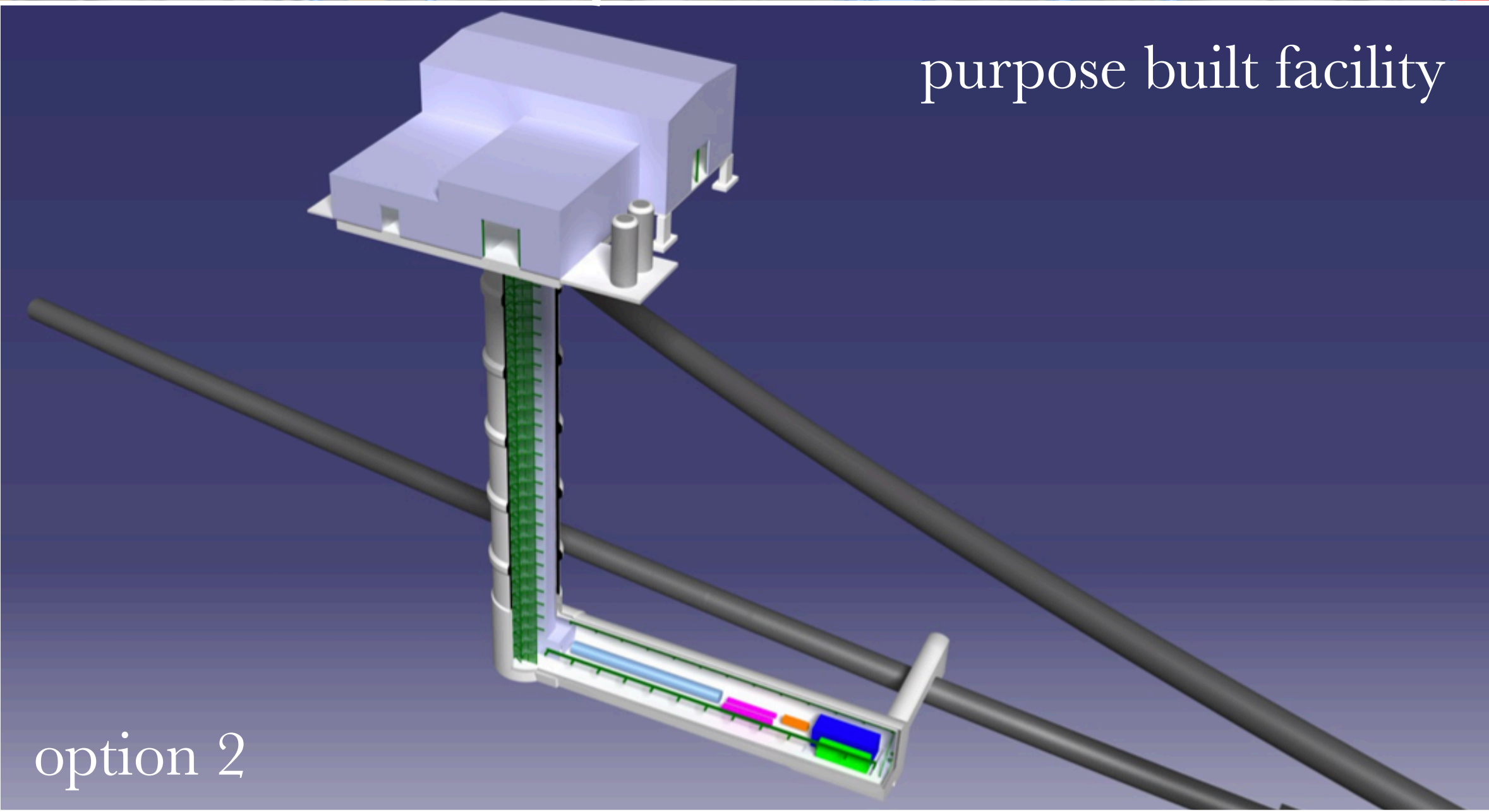
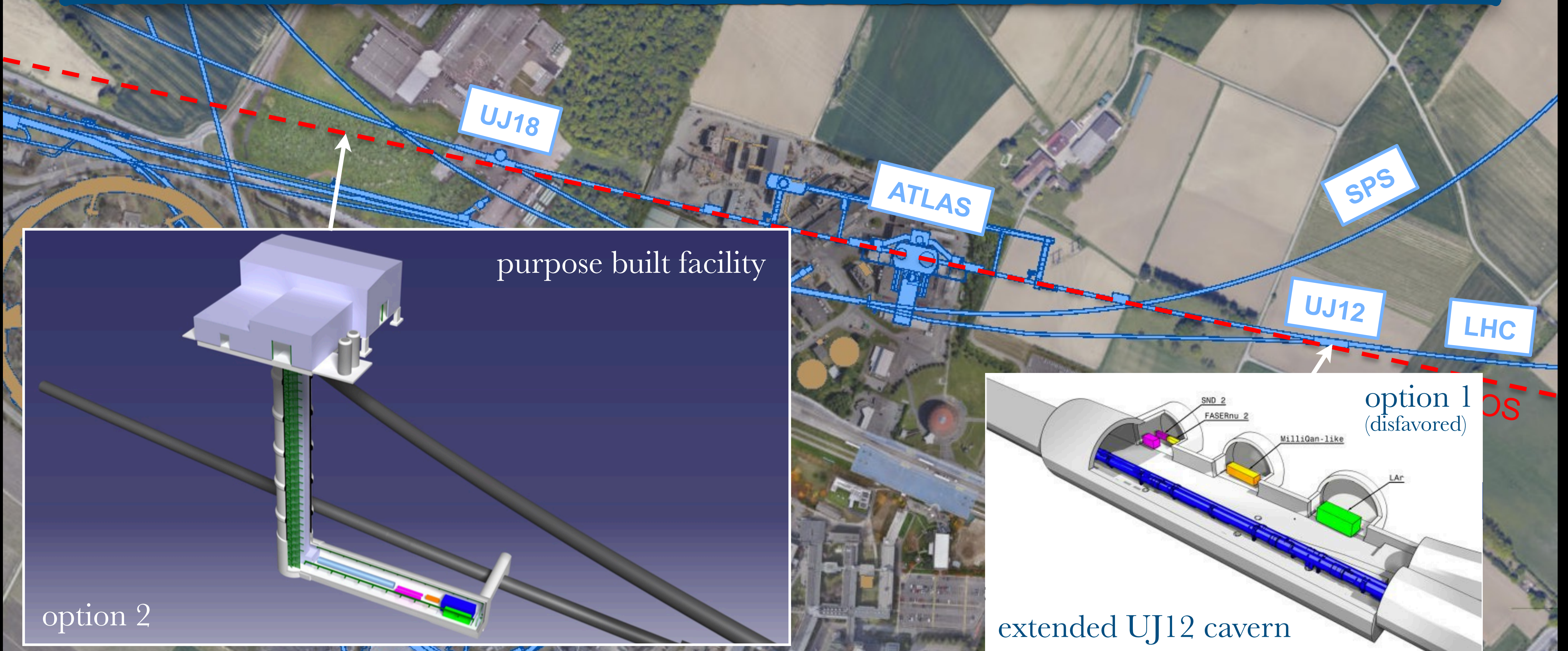
FASER: approved March 2019
FASERv: approved December 2019

LOS

- ▶ 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, ...

FAR FORWARD EXPERIMENTS AT LHC RUN 3

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



FAR FORWARD EXPERIMENTS AT LHC RUN 3

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UJ18

ATLAS

Highly disfavored!

UJ12

LHC

purpose built facility

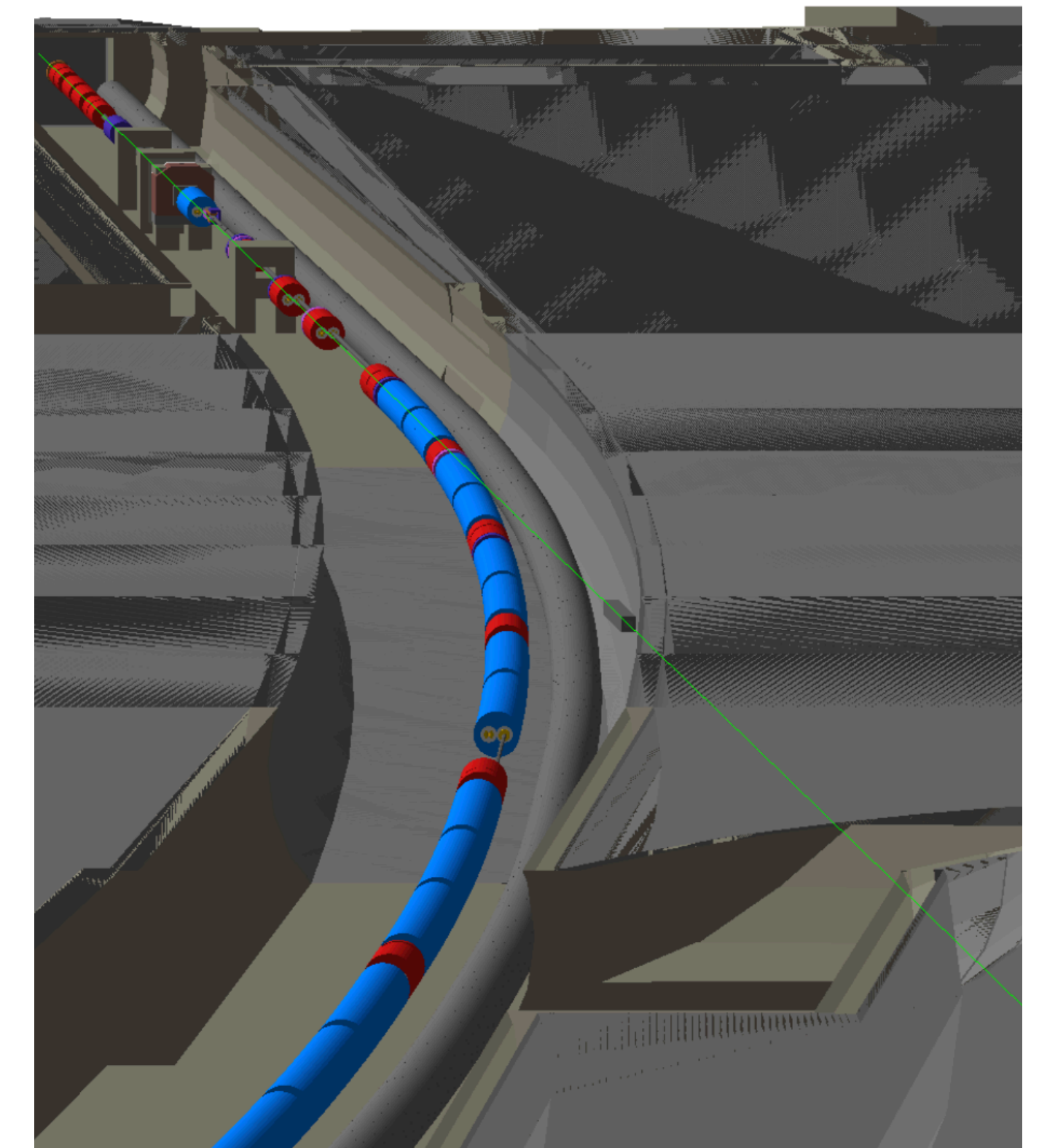
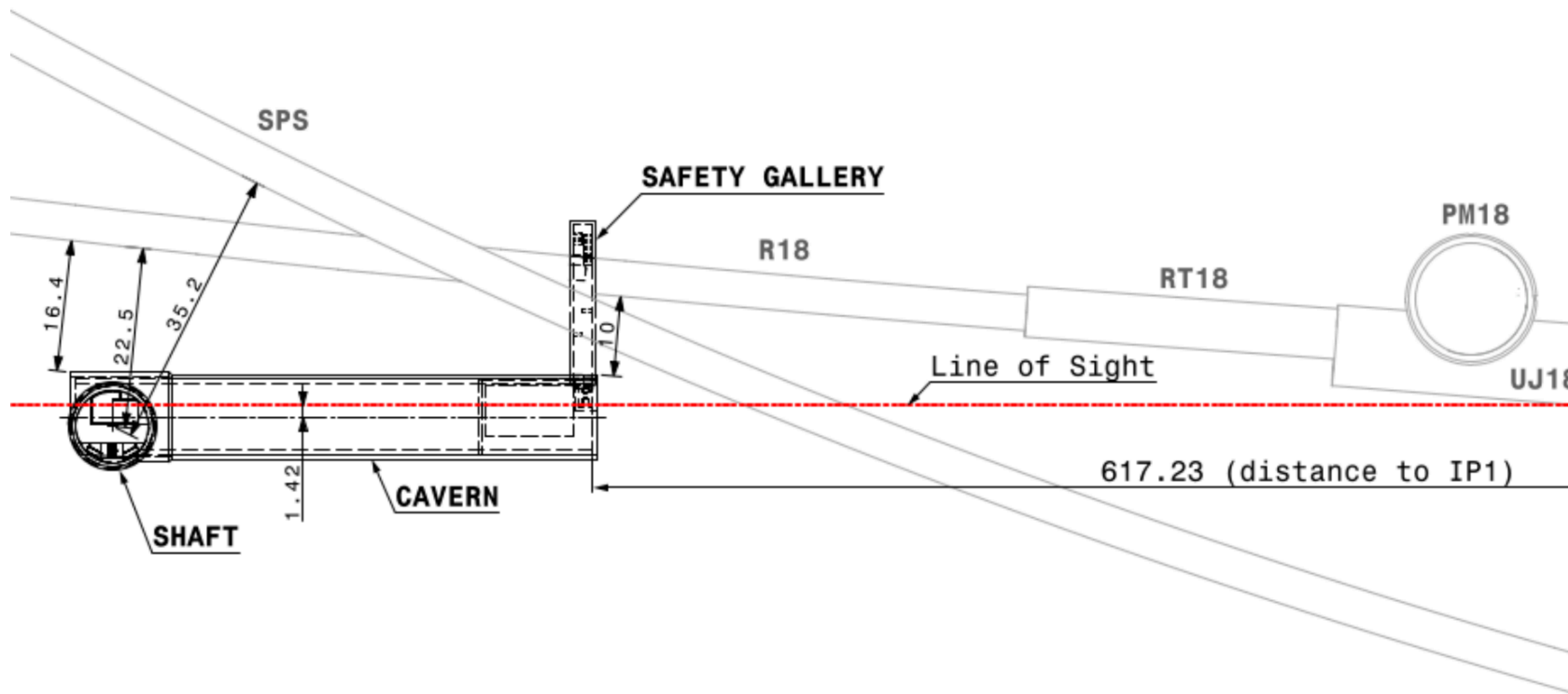
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extended 2 caves

option 1
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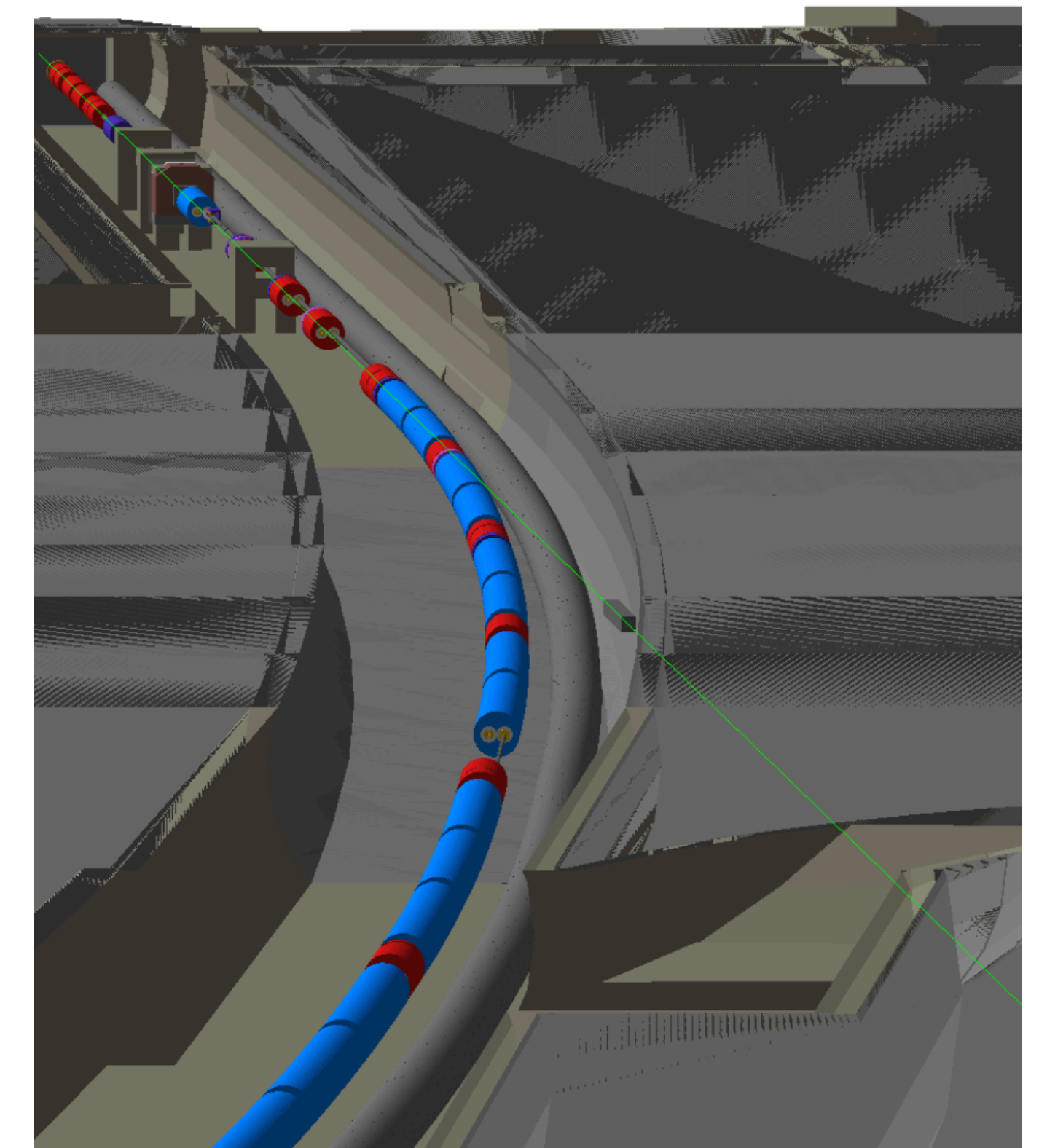
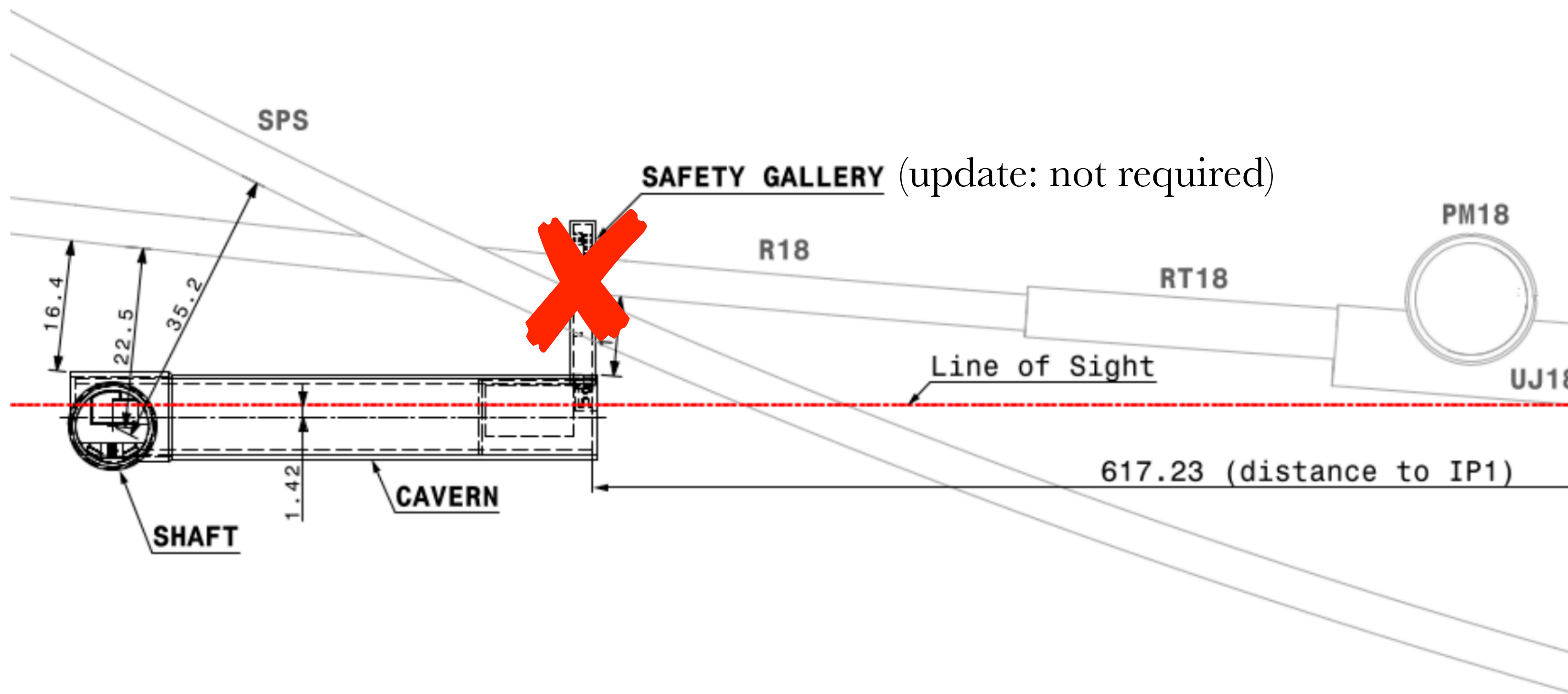
Facility

- ▶ Focus of this talk: purpose built facility (favored option!)
- ▶ Extended UJ12 cavern also explored and similar ideas apply (highly disfavored!)
- ▶ Currently five proposed experiments



Facility

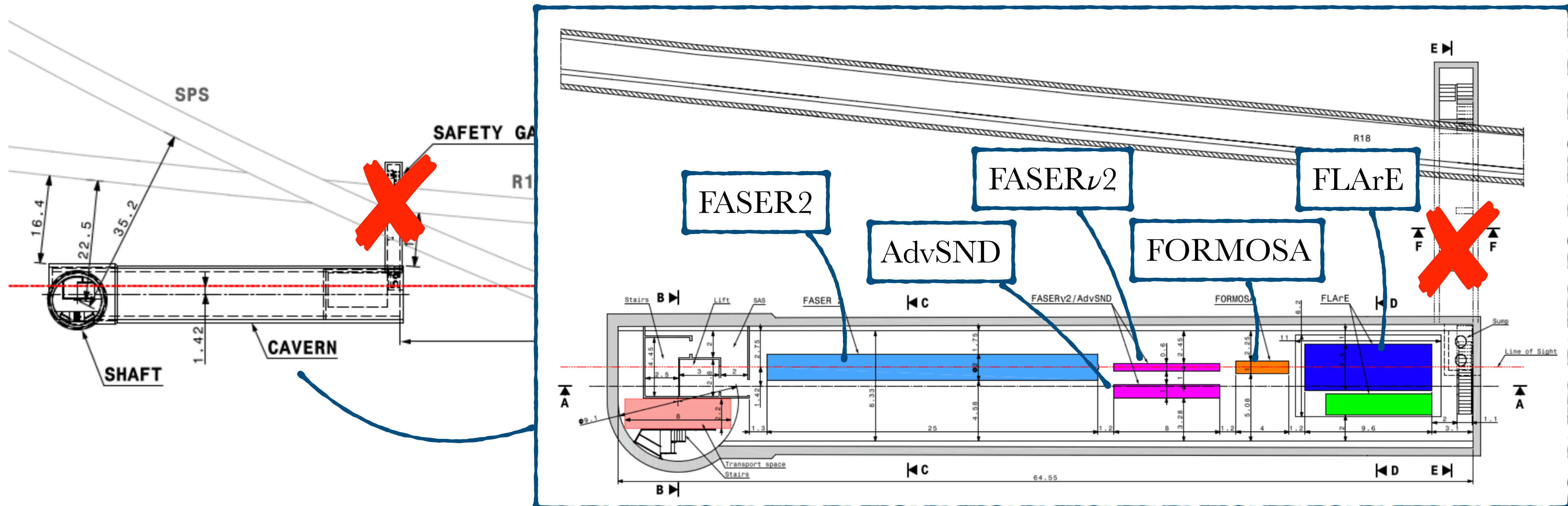
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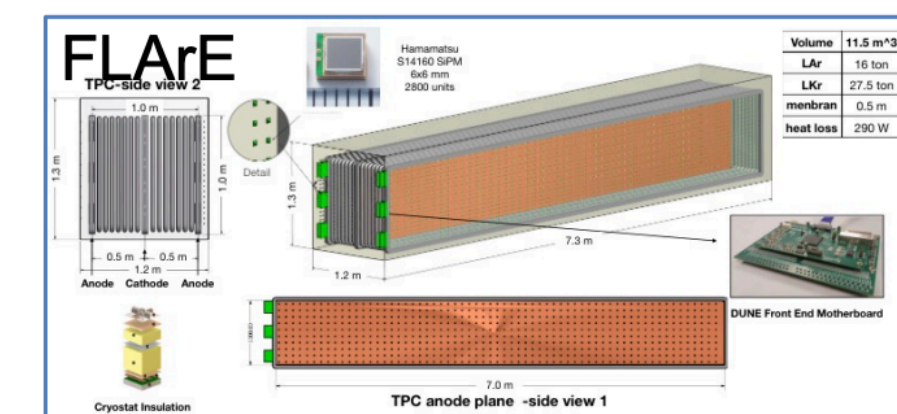
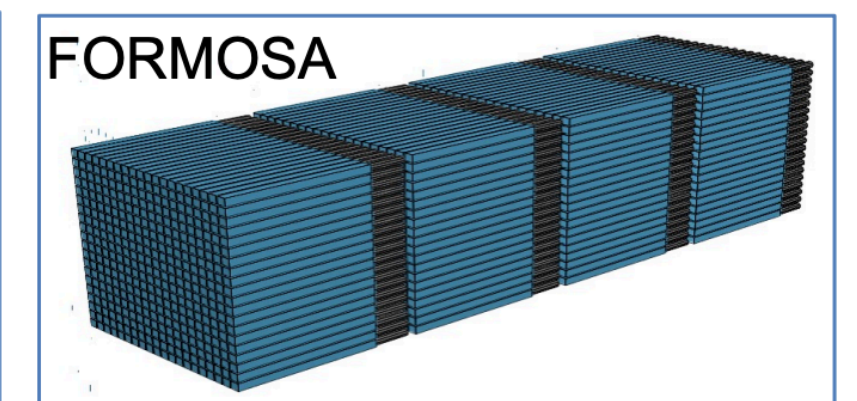
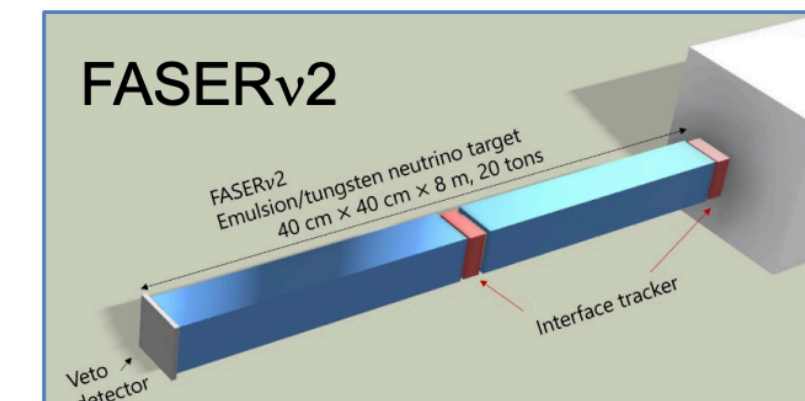
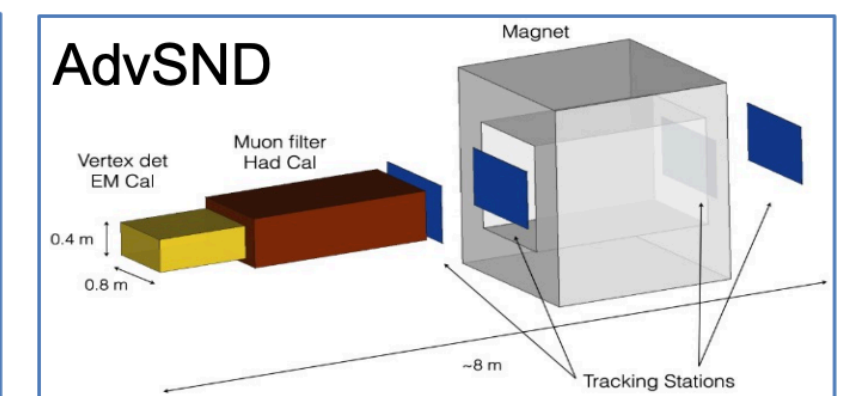
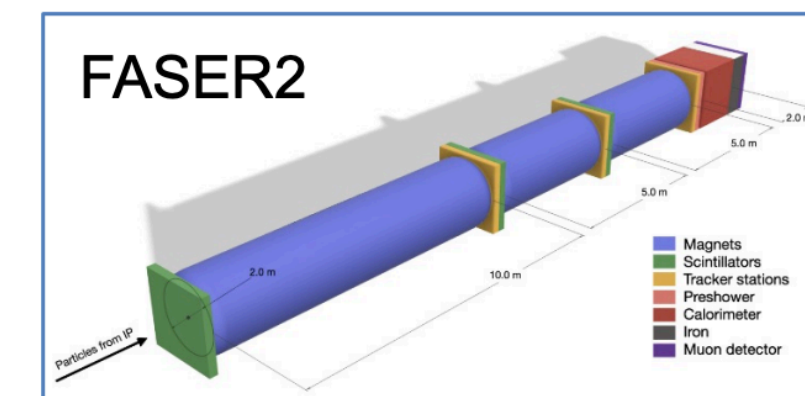
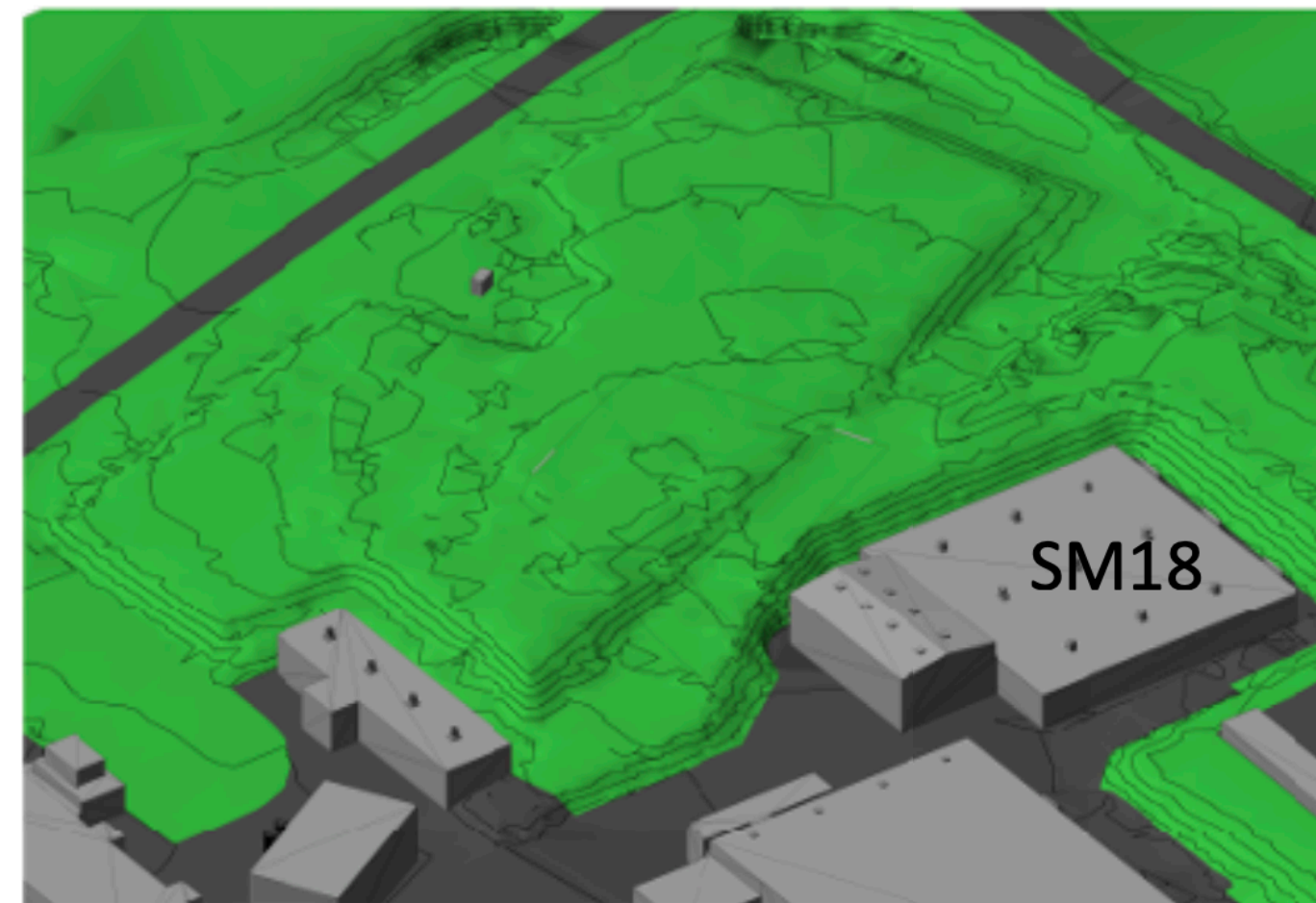
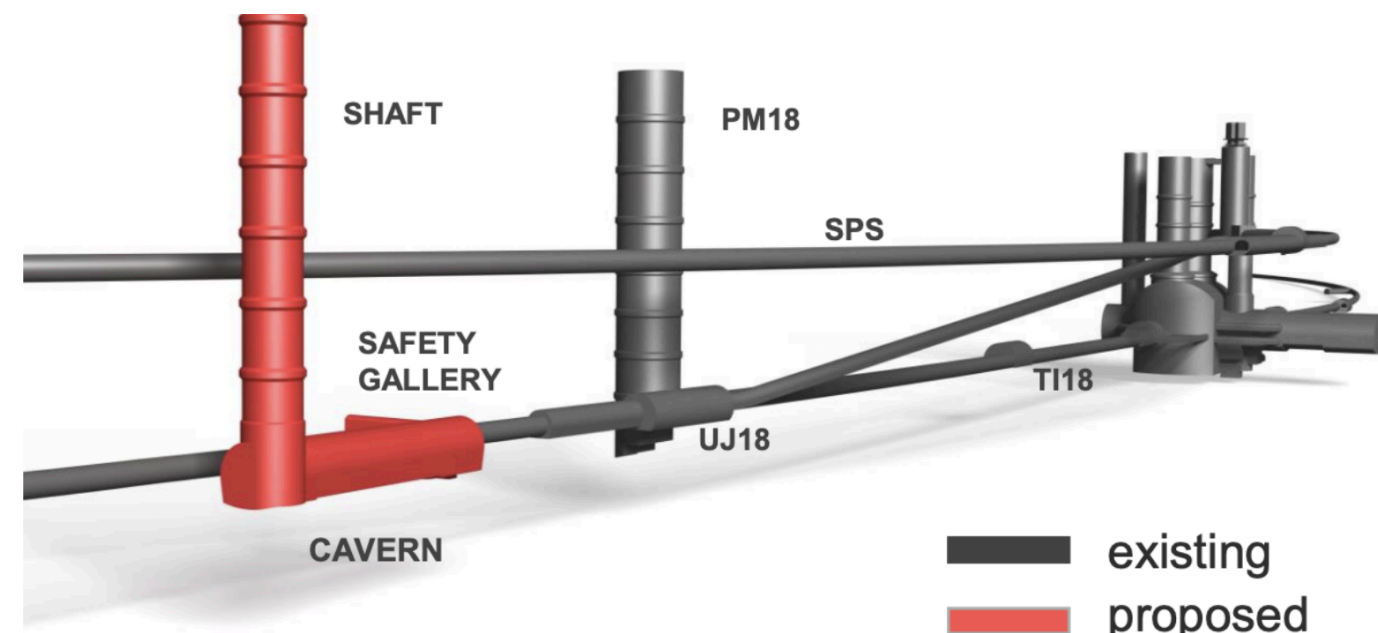
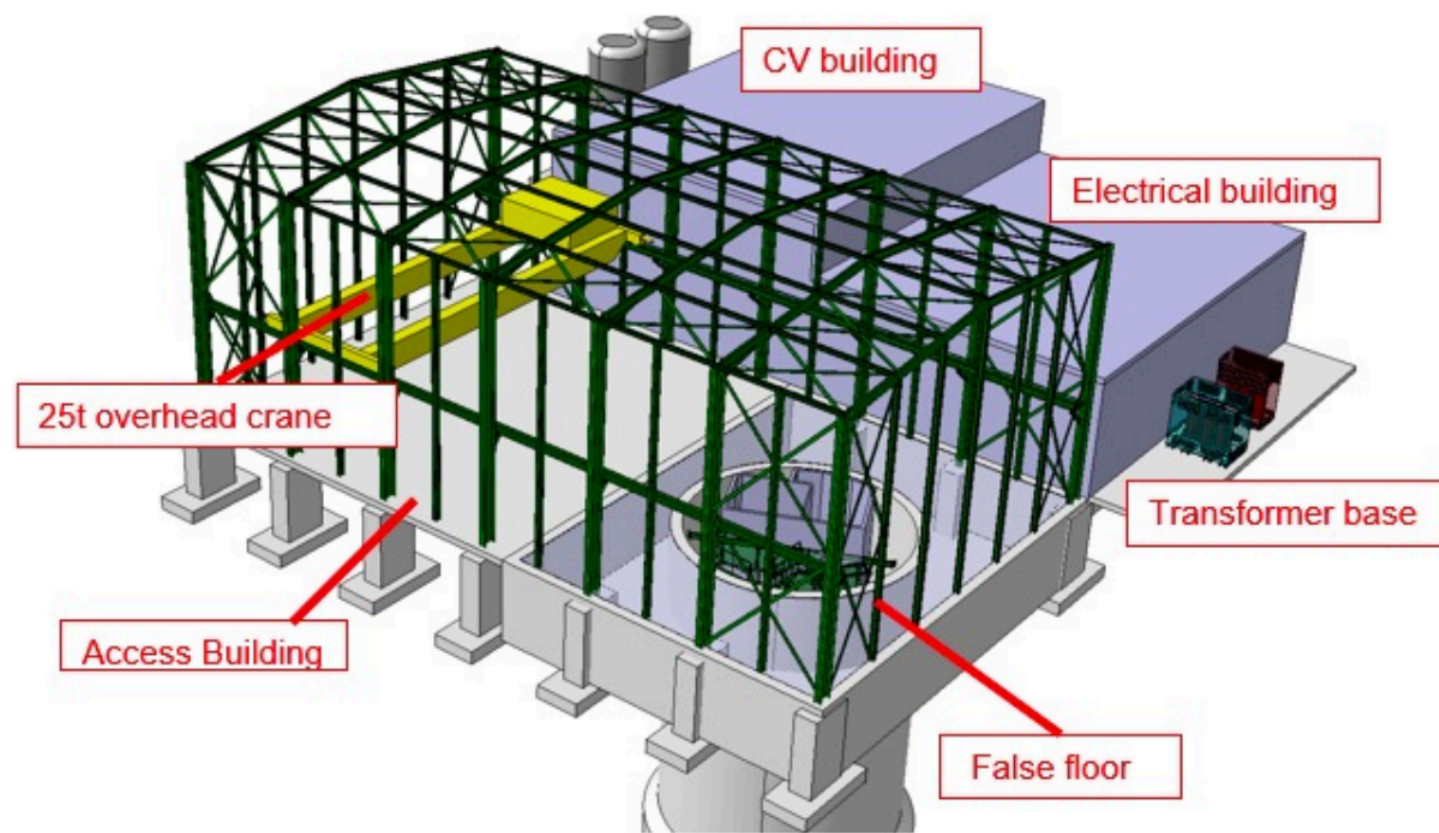
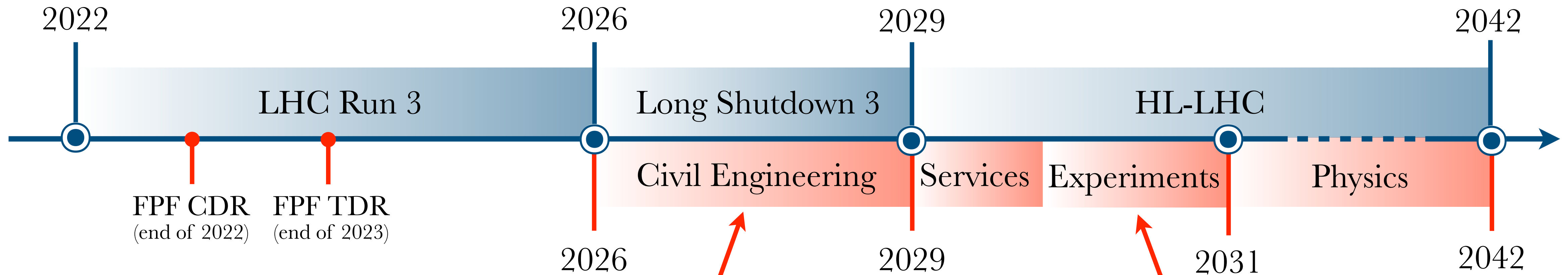
Facility



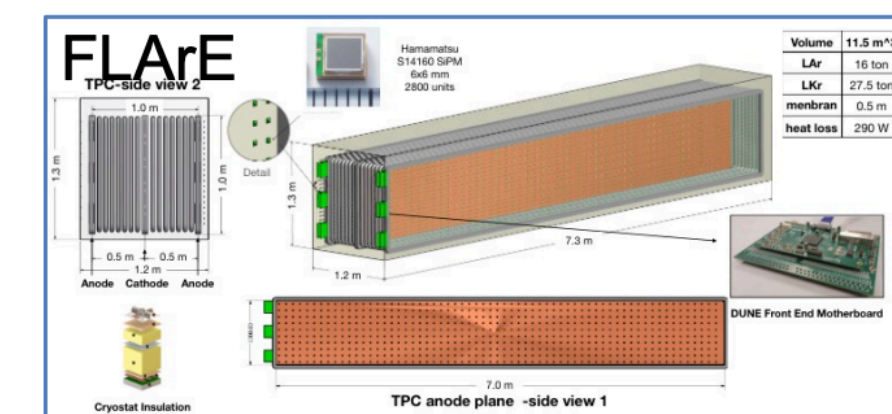
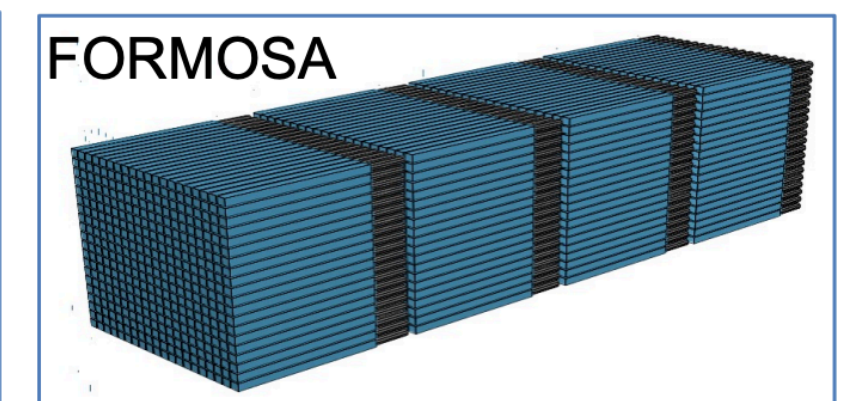
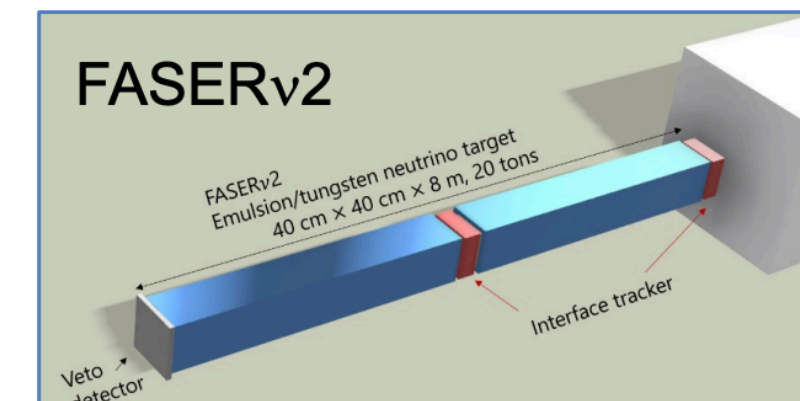
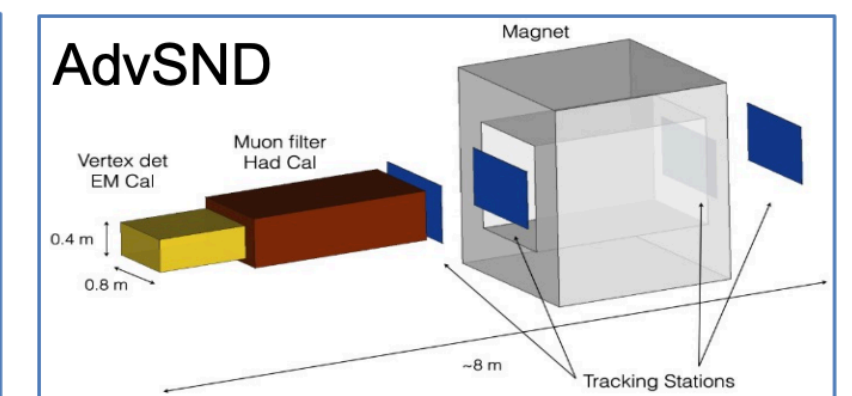
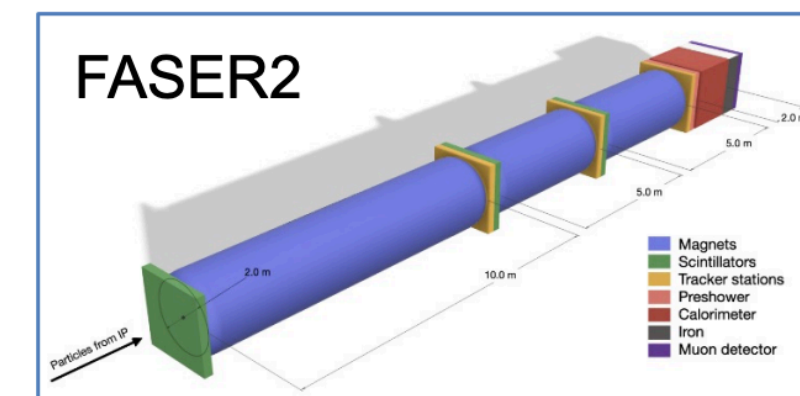
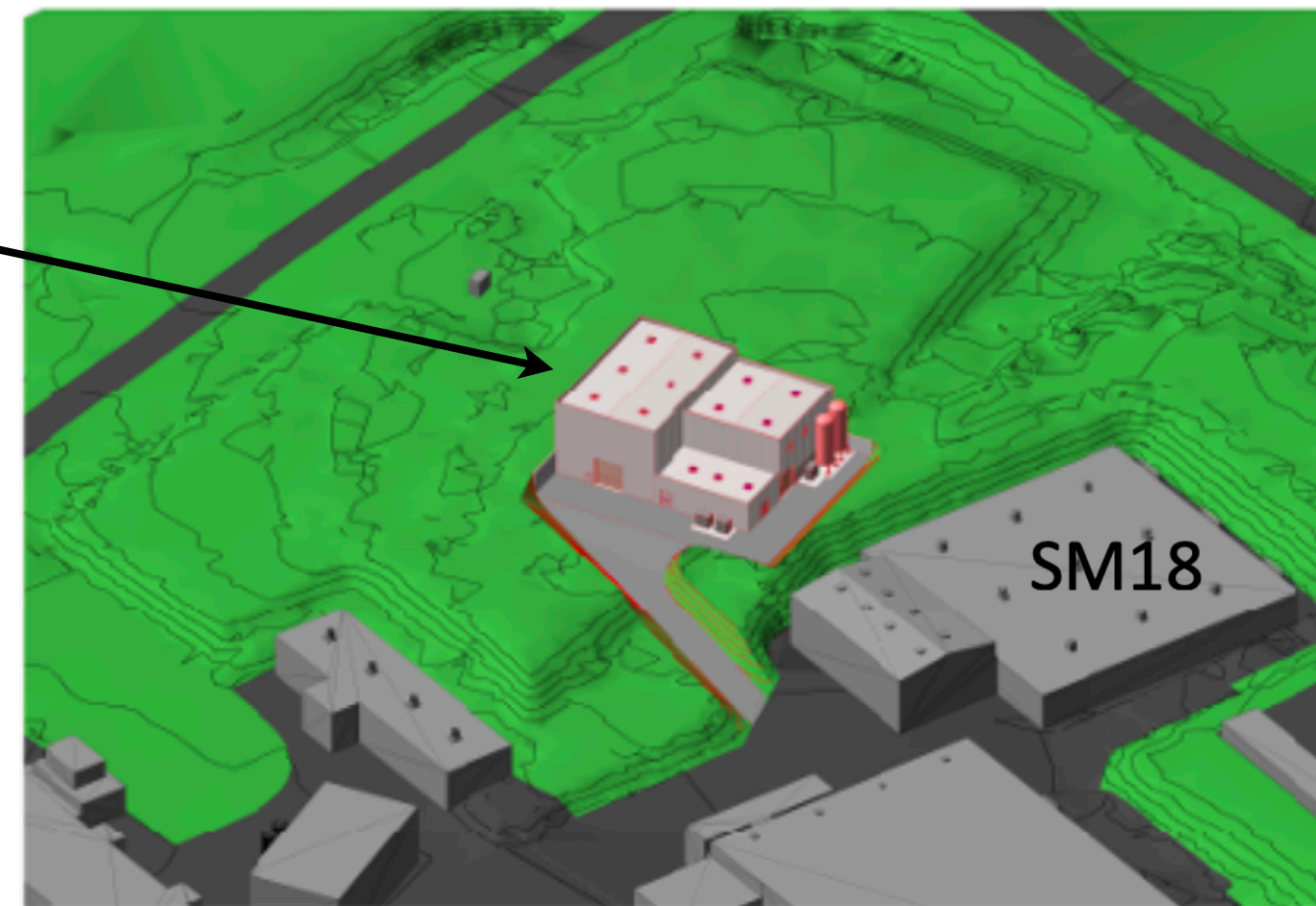
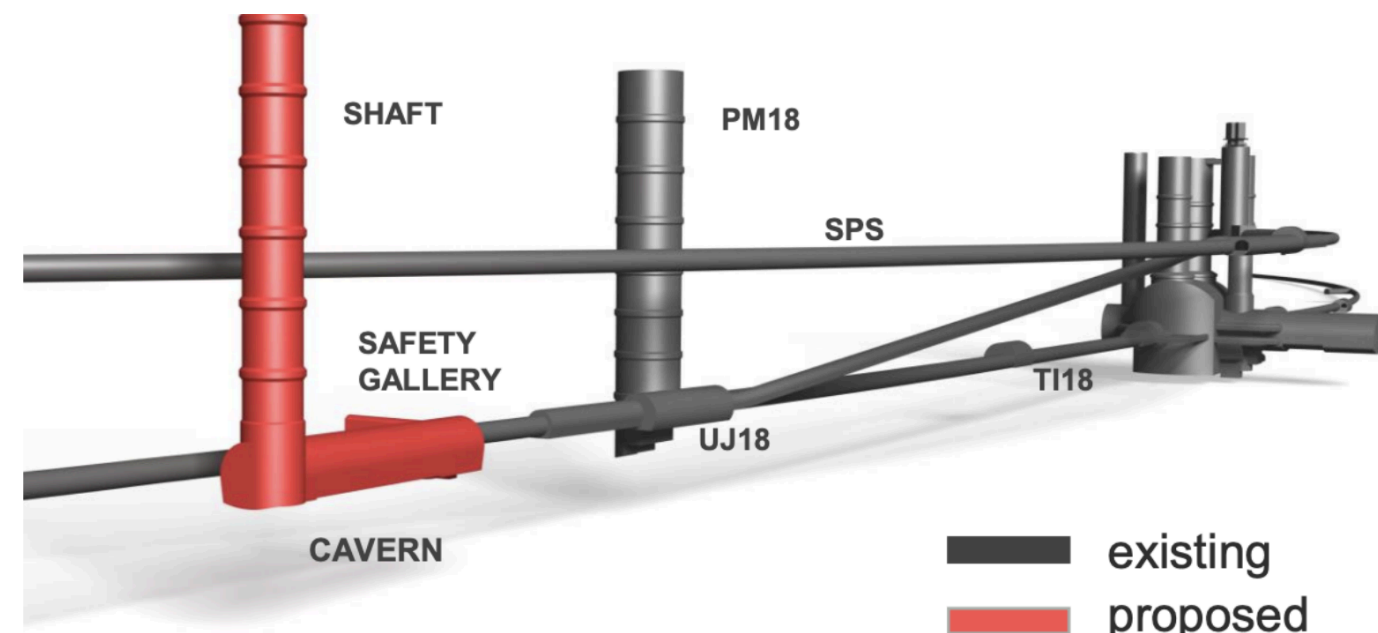
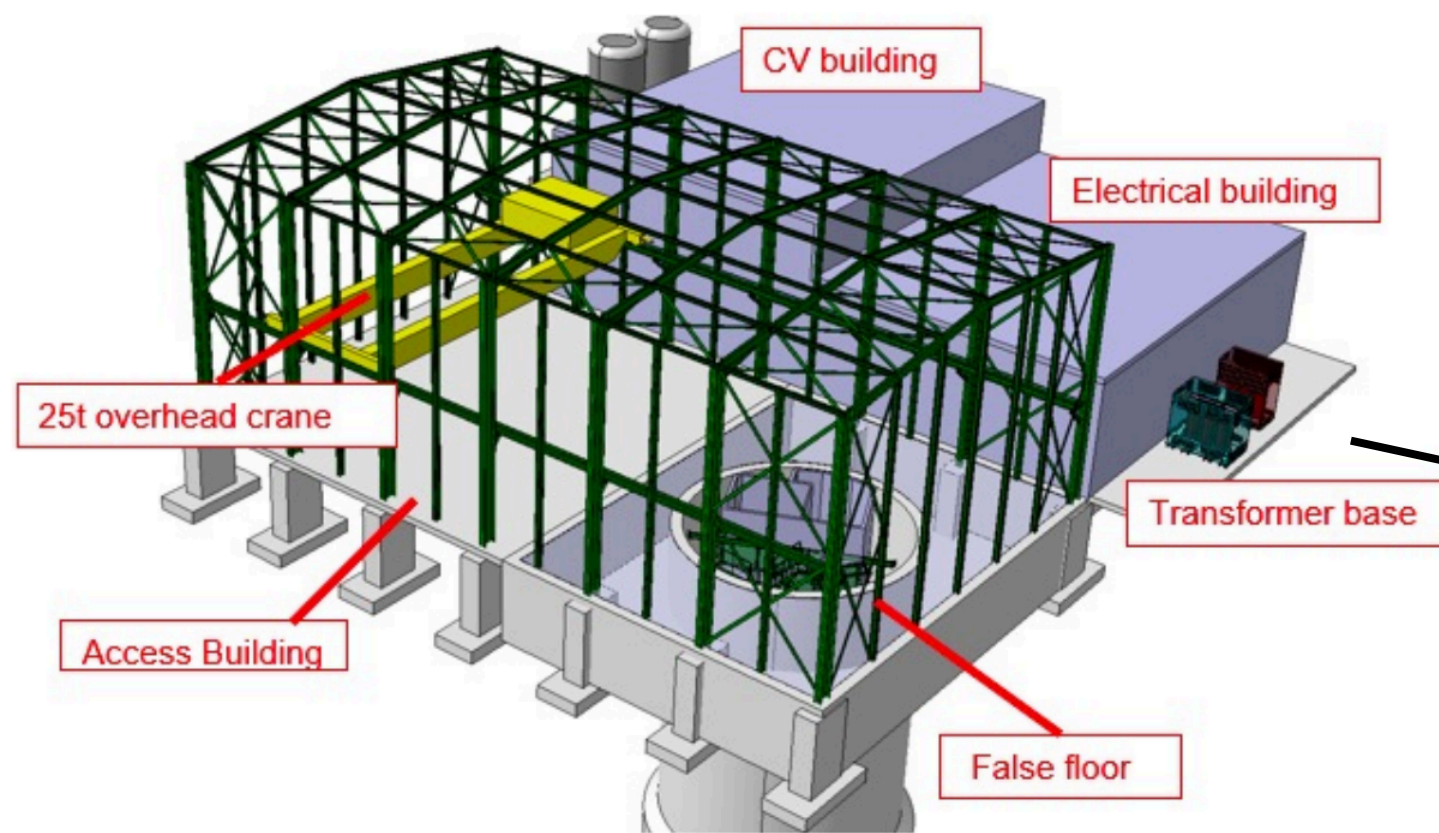
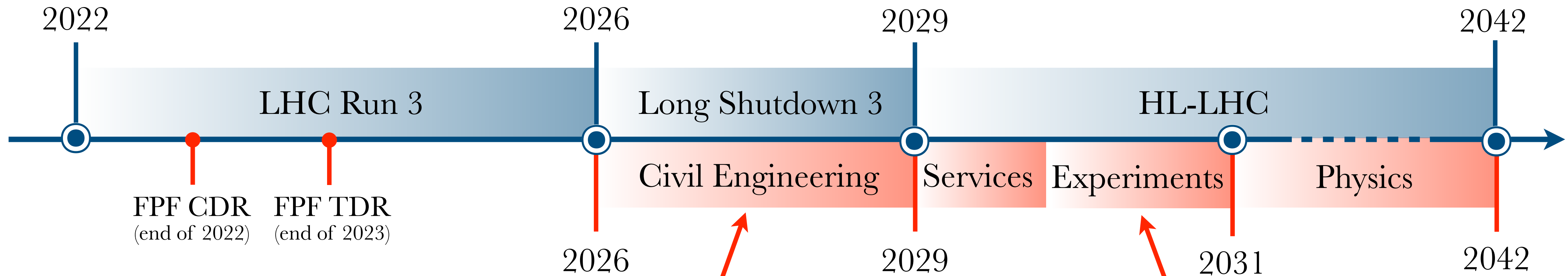
- ▶ Focus of this talk: purpose built facility (favored option!)
- ▶ Extended UJ12 cavern also explored and similar ideas apply (highly disfavored!)
- ▶ Currently five proposed experiments



FPF Timeline



FPF Timeline



Proposed Experiments

Introduction: FPF Physics Potential

▶ Example:

FASER ν pilot detector

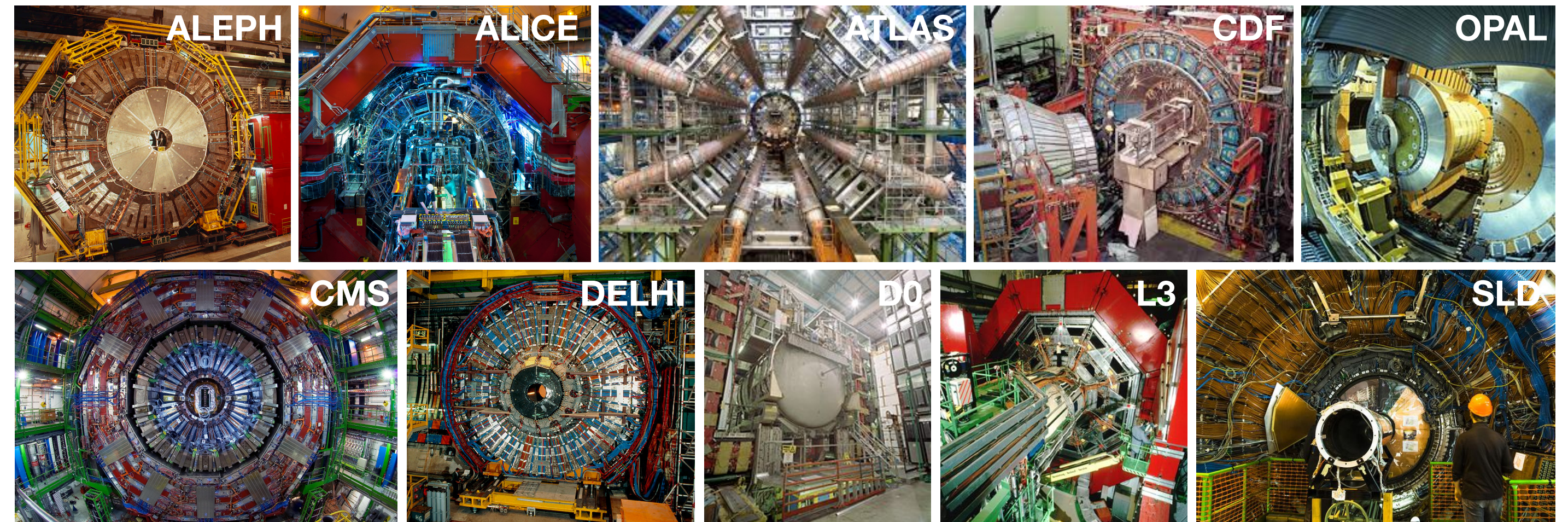
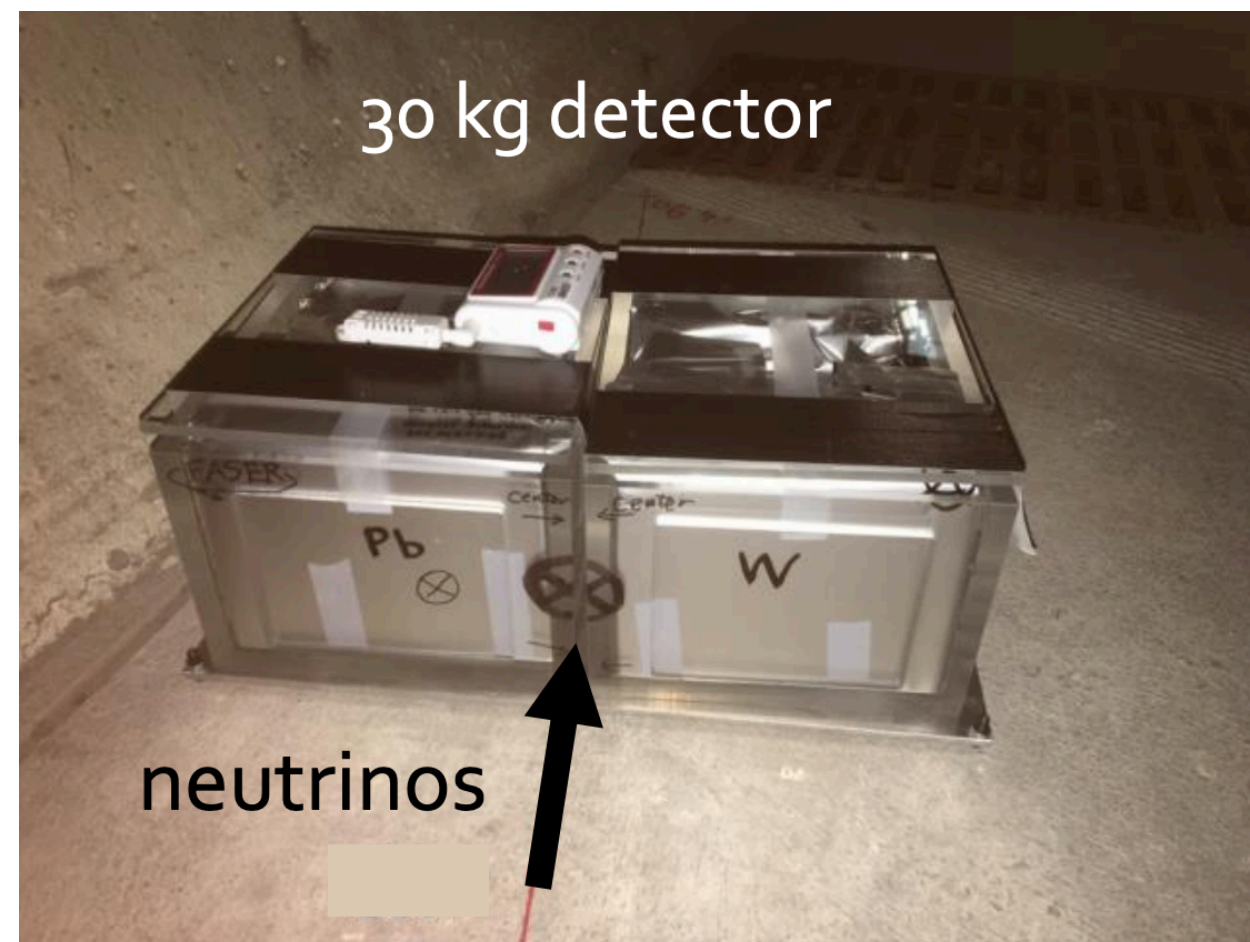
vs.

All previous collider experiments

- ▶ Suitcase size, 4 weeks of data
- ▶ Costs: \$0 (recycled parts)
- ▶ 6 neutrino candidates

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

[FASER Collaboration, Phys. Rev. D 104 (2021)]



Introduction: FPF Physics Potential

▶ Example:

FASER ν pilot detector

vs.

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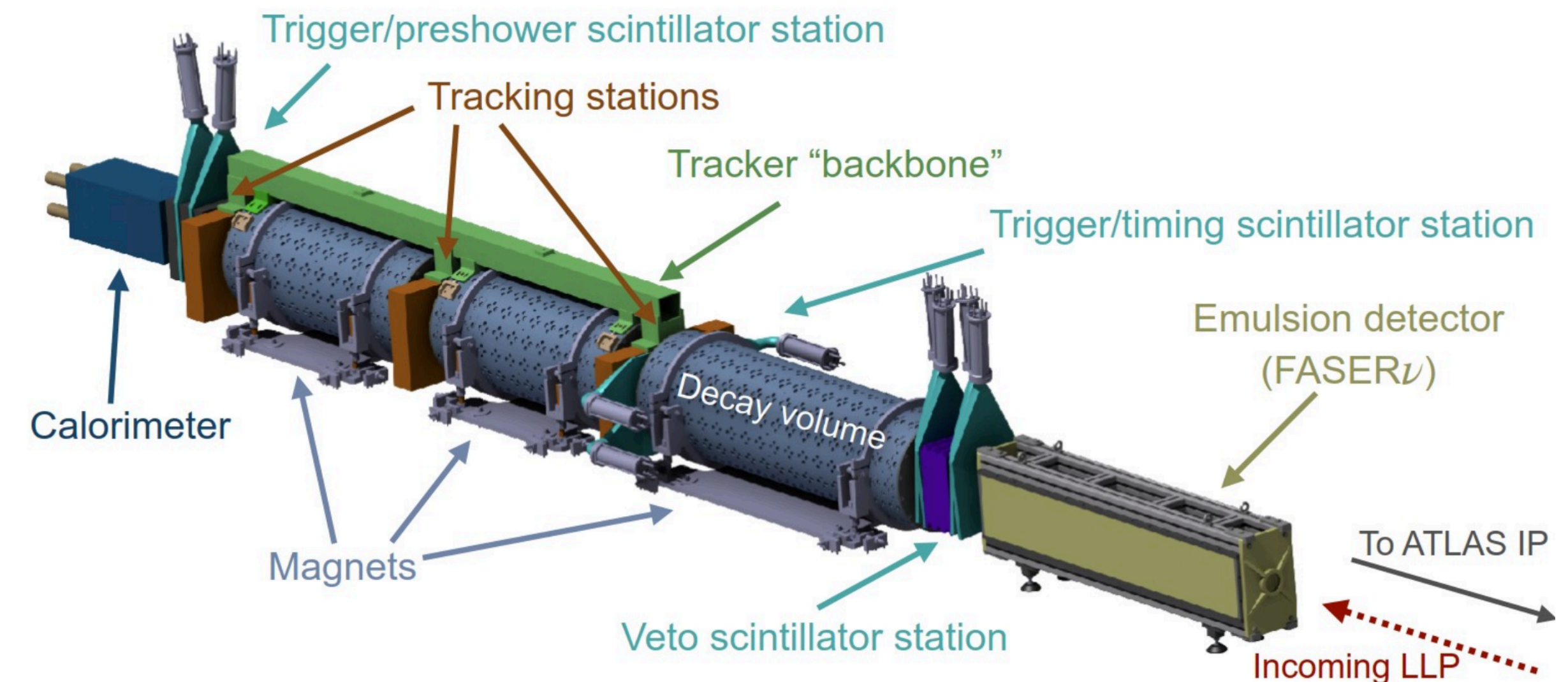
[FASER Collaboration, Phys. Rev. D 104 (2021)]

▶ FASER ν years 2022-2024:

- ▶ ~ 10000 ν candidates expected
($\sim 10^9$ muons*)

▶ Forward Physics Facility:

- ▶ $\sim 10^6$ ν candidates expected!
($\sim 10^{12}$ muons*)



*origin not well understood, further studies needed

Proposed FPF Experiments

▶ Currently 5 proposed experiments* with different (main) physics goals:

▶ FASER2

▶ Long-lived particles (LLPs)

▶ FASER ν 2

▶ TeV neutrinos

▶ AdvSND

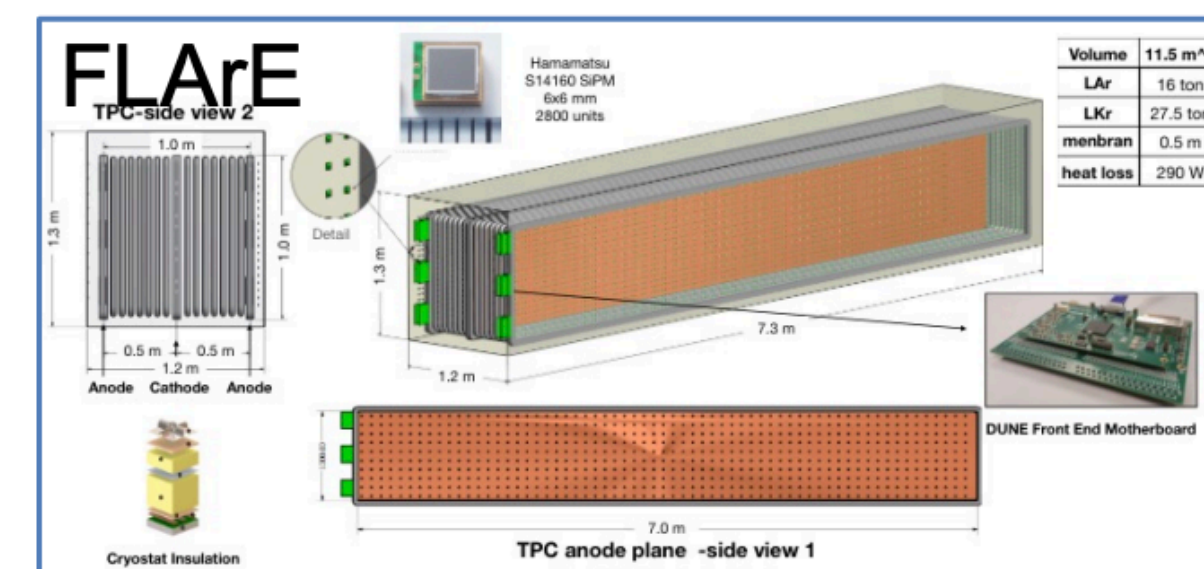
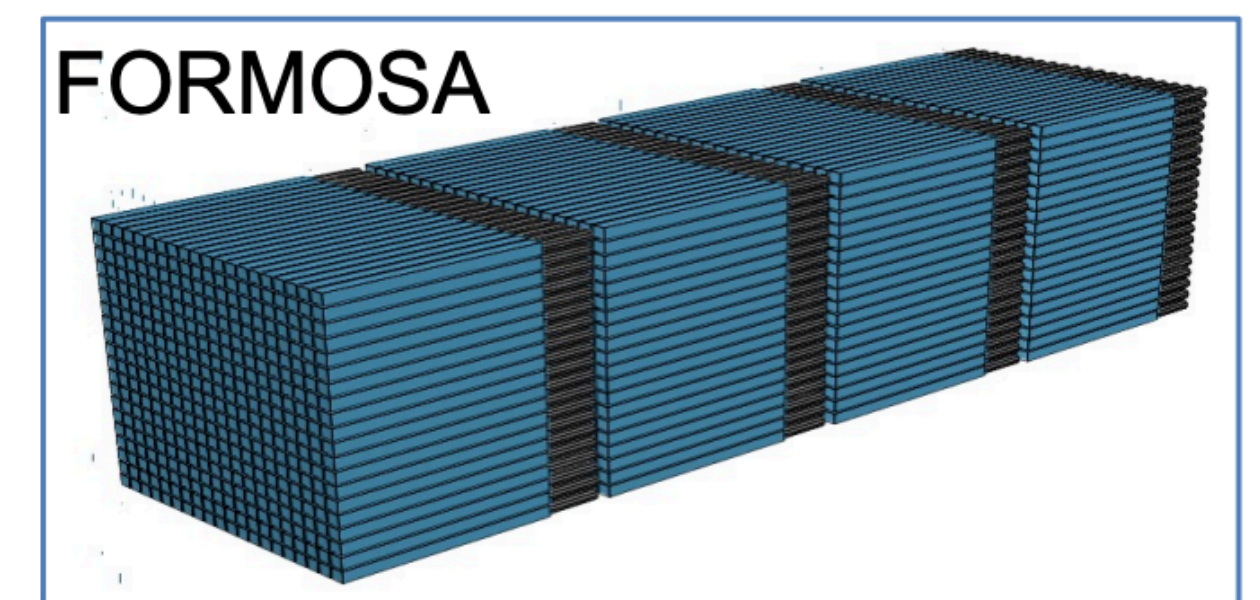
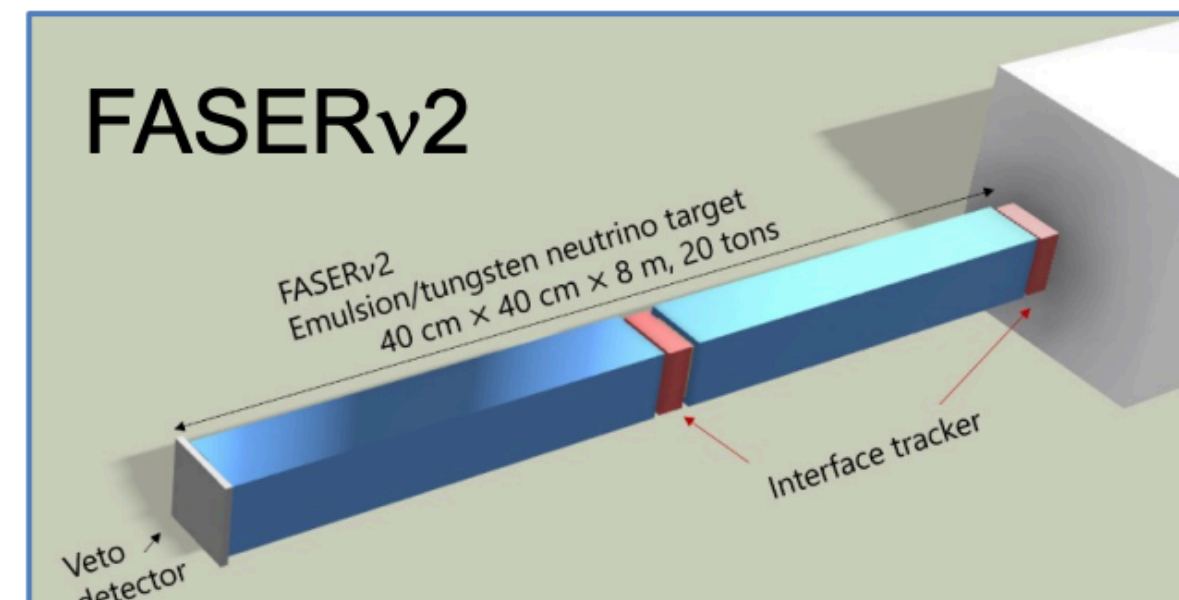
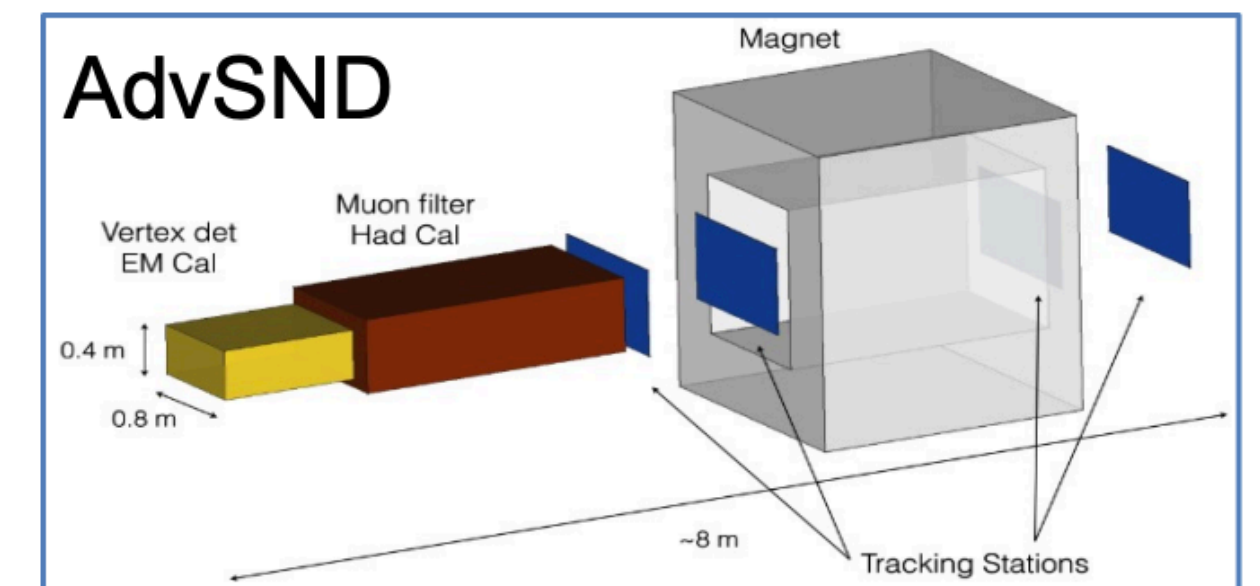
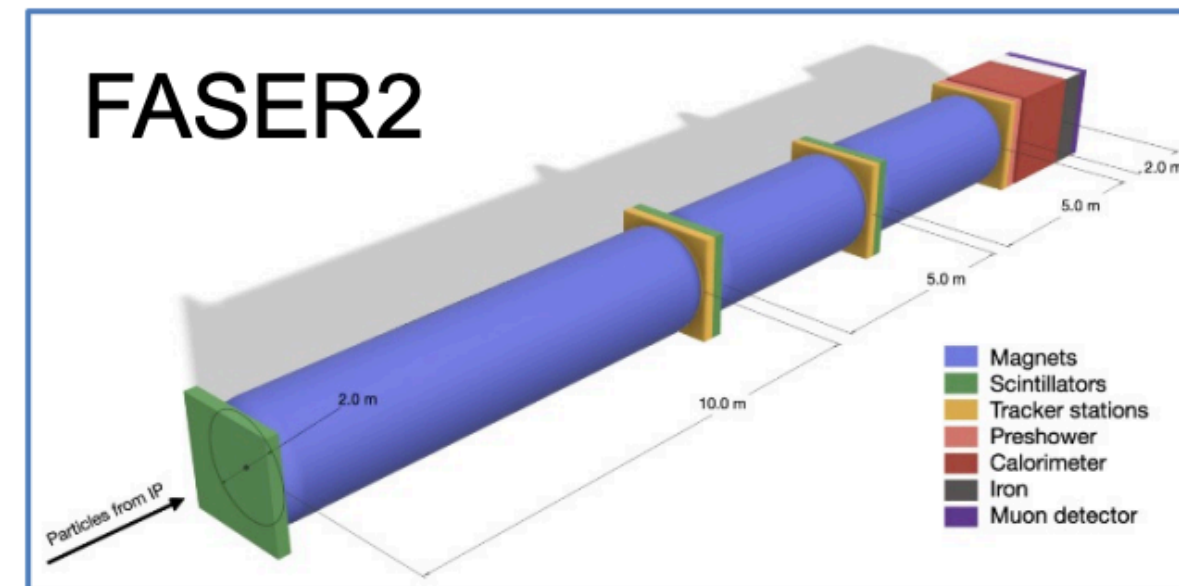
▶ TeV neutrinos

▶ FORMOSA

▶ BSM physics: millicharged particles

▶ FLArE

▶ TeV neutrinos & light dark matter

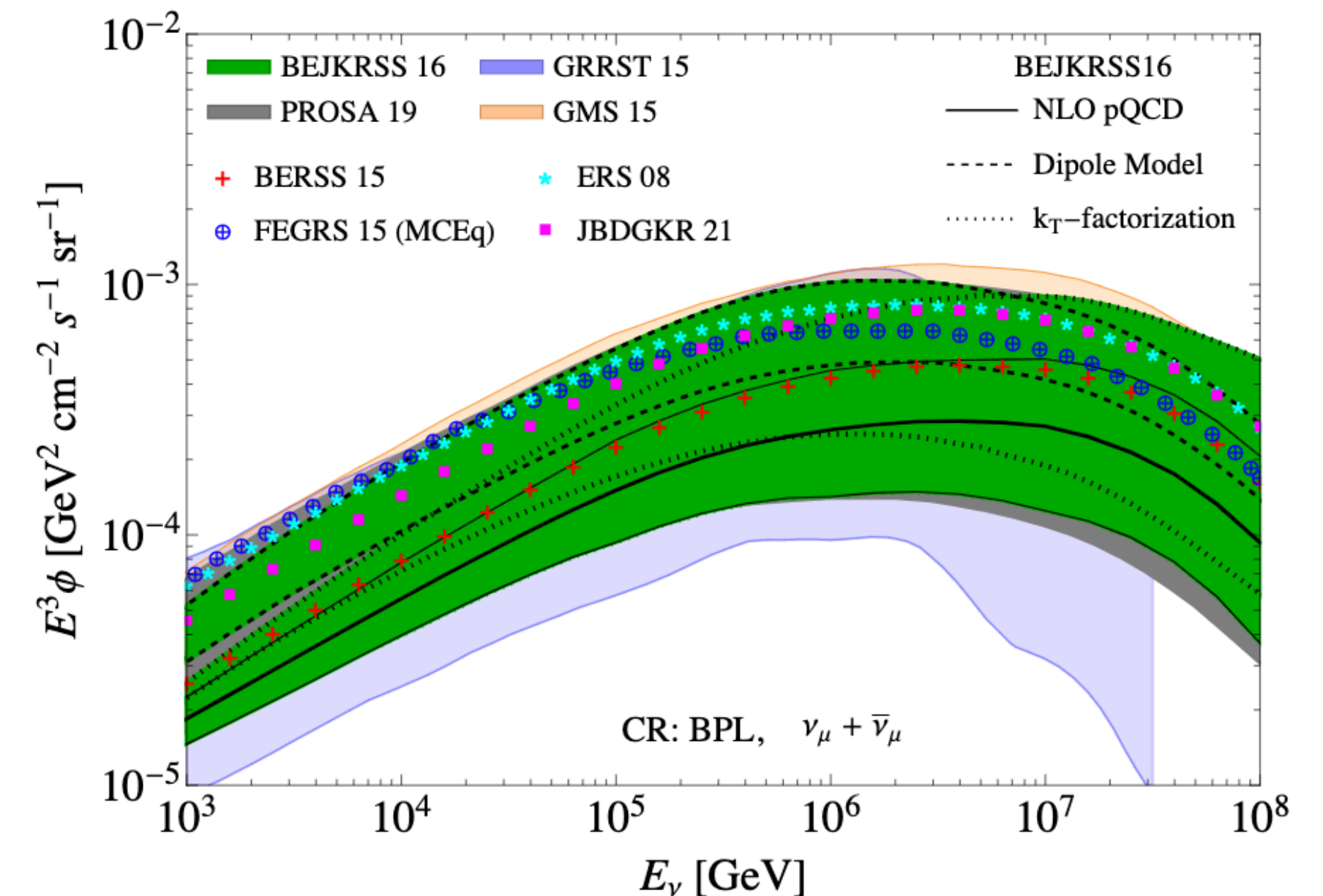
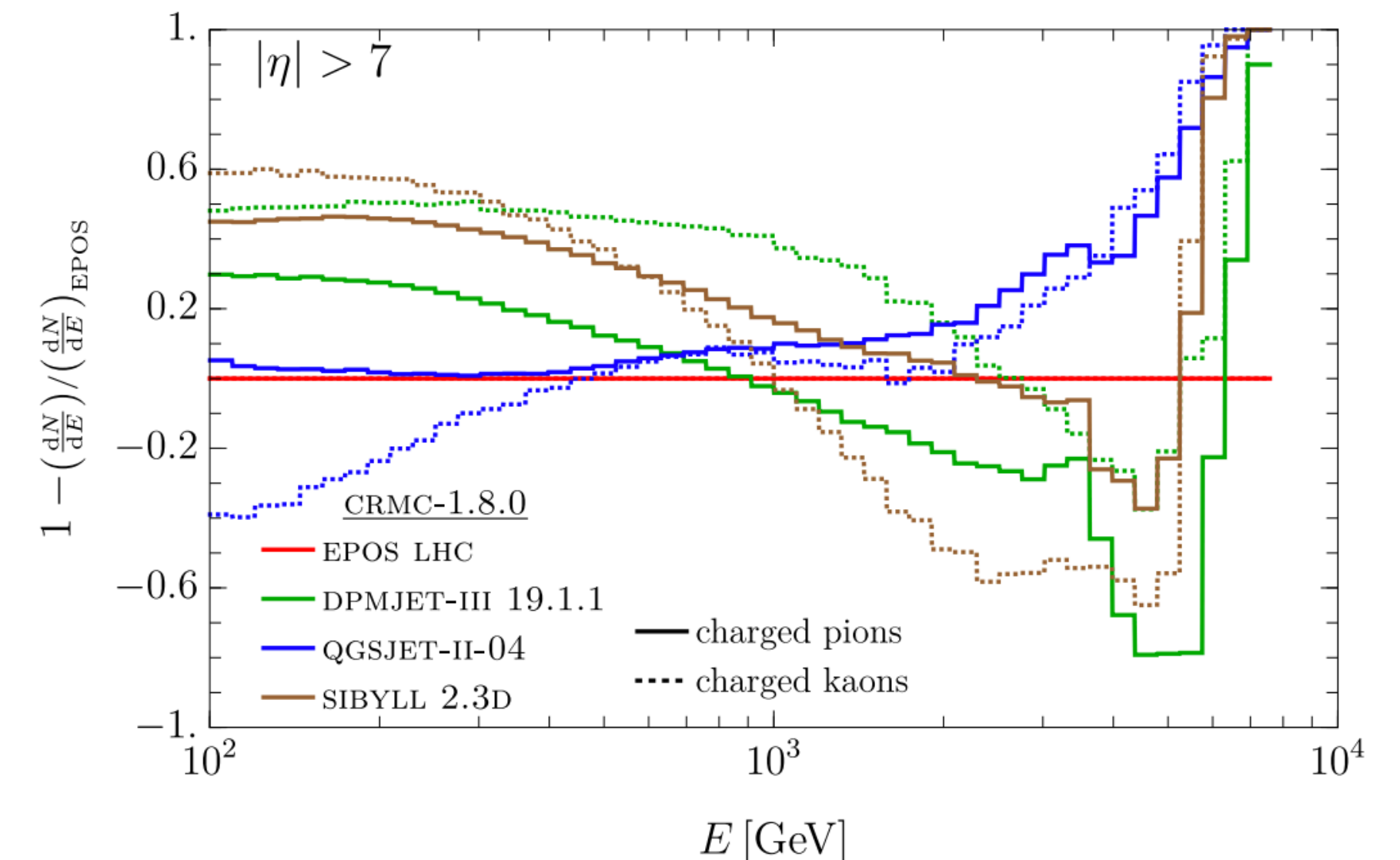


* for a complete description of the experiments, please see FPF white paper

Astroparticle Physics with the FPF

Overview: Astroparticle Physics at the FPF

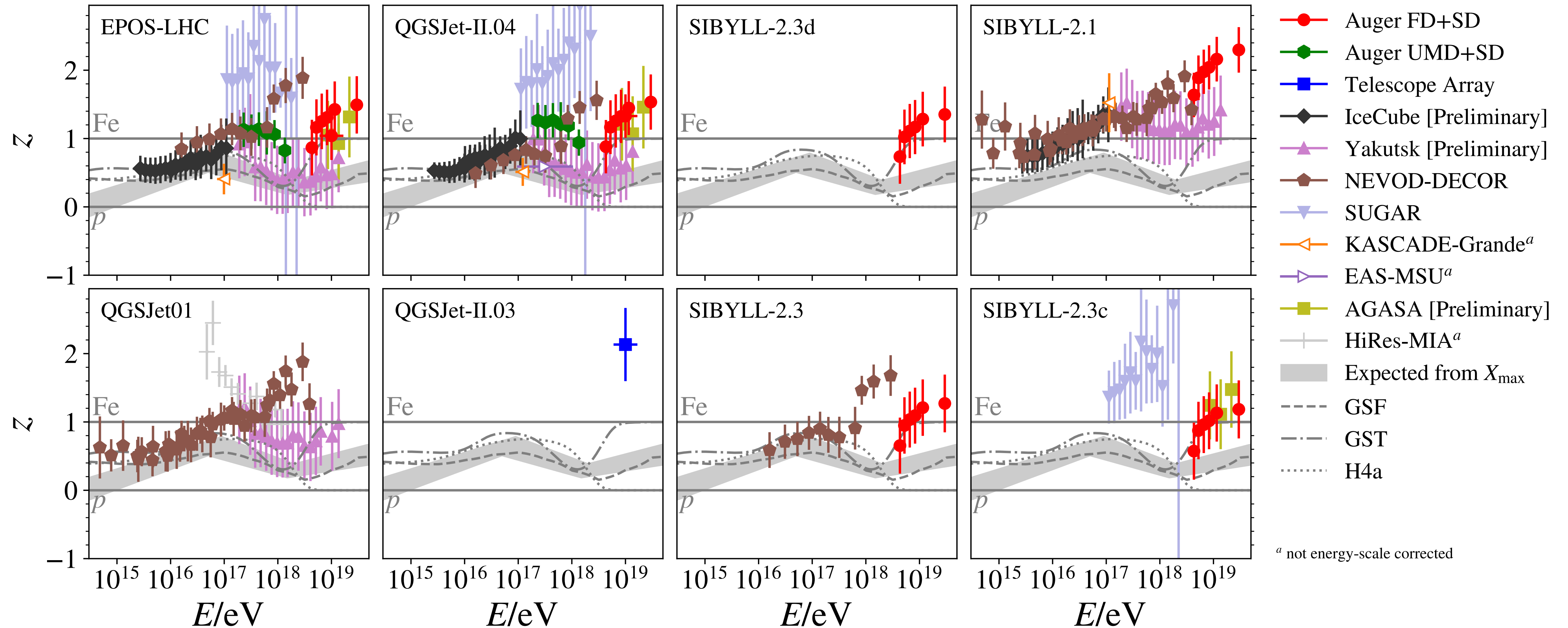
- ▶ Extensive air shower (EAS) physics
 - ▶ Tests of forward multi-particle production
 - ▶ Muon Puzzle in EAS
 - ▶ Hadronic interaction models
- ▶ Atmospheric neutrino fluxes
 - ▶ Prompt neutrino fluxes and uncertainties
 - ▶ Background for neutrino observatories
- ▶ Dark Matter & BSM physics
 - ▶ Large variety of BSM scenarios can be tested
 - ▶ Tests of dark matter scenarios



The Muon Puzzle in EAS

$$z = \frac{\ln\langle\rho_\mu\rangle - \ln\langle\rho_{\mu,p}\rangle}{\ln\langle\rho_{\mu,Fe}\rangle - \ln\langle\rho_{\mu,p}\rangle}$$

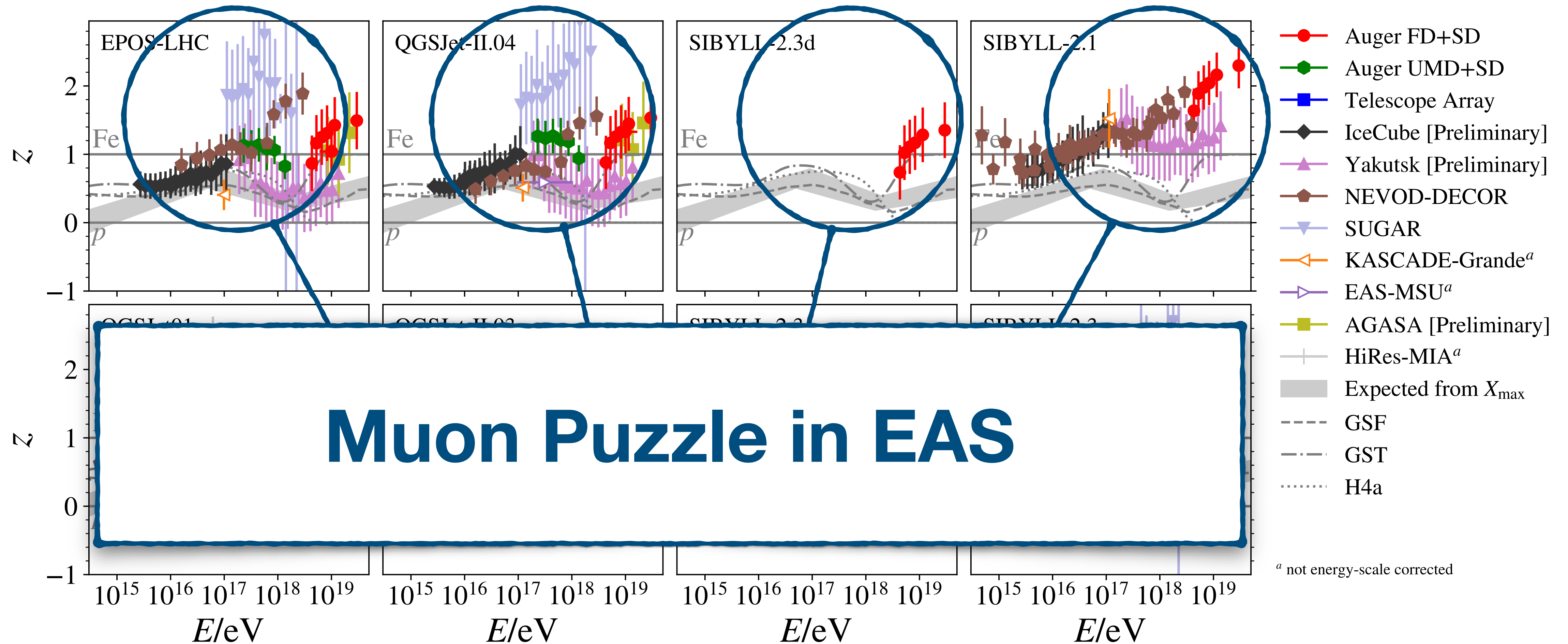
- Muon density in EAS after cross-calibration of the energy-scales



The Muon Puzzle in EAS

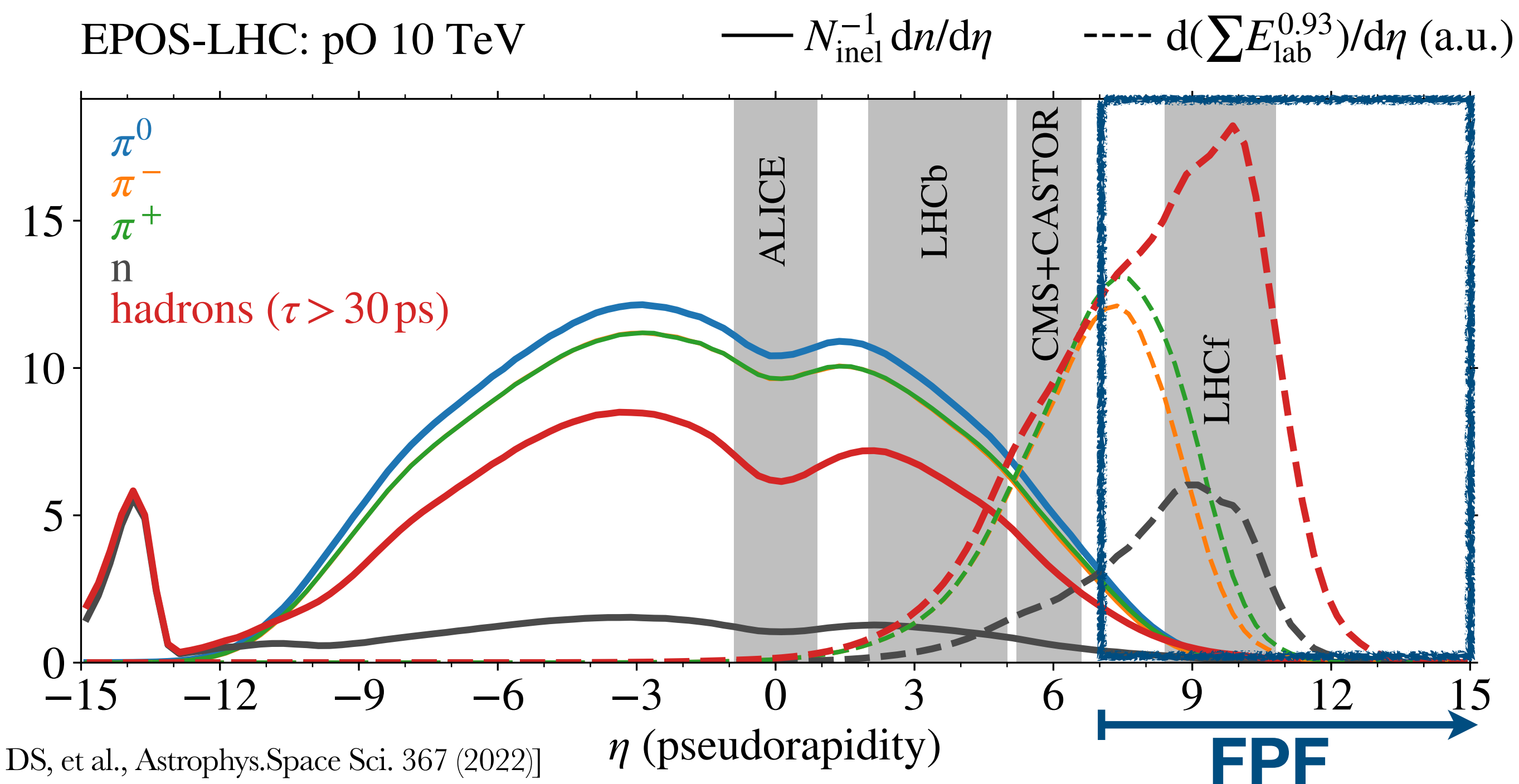
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► Muon density in EAS after cross-calibration of the energy-scales

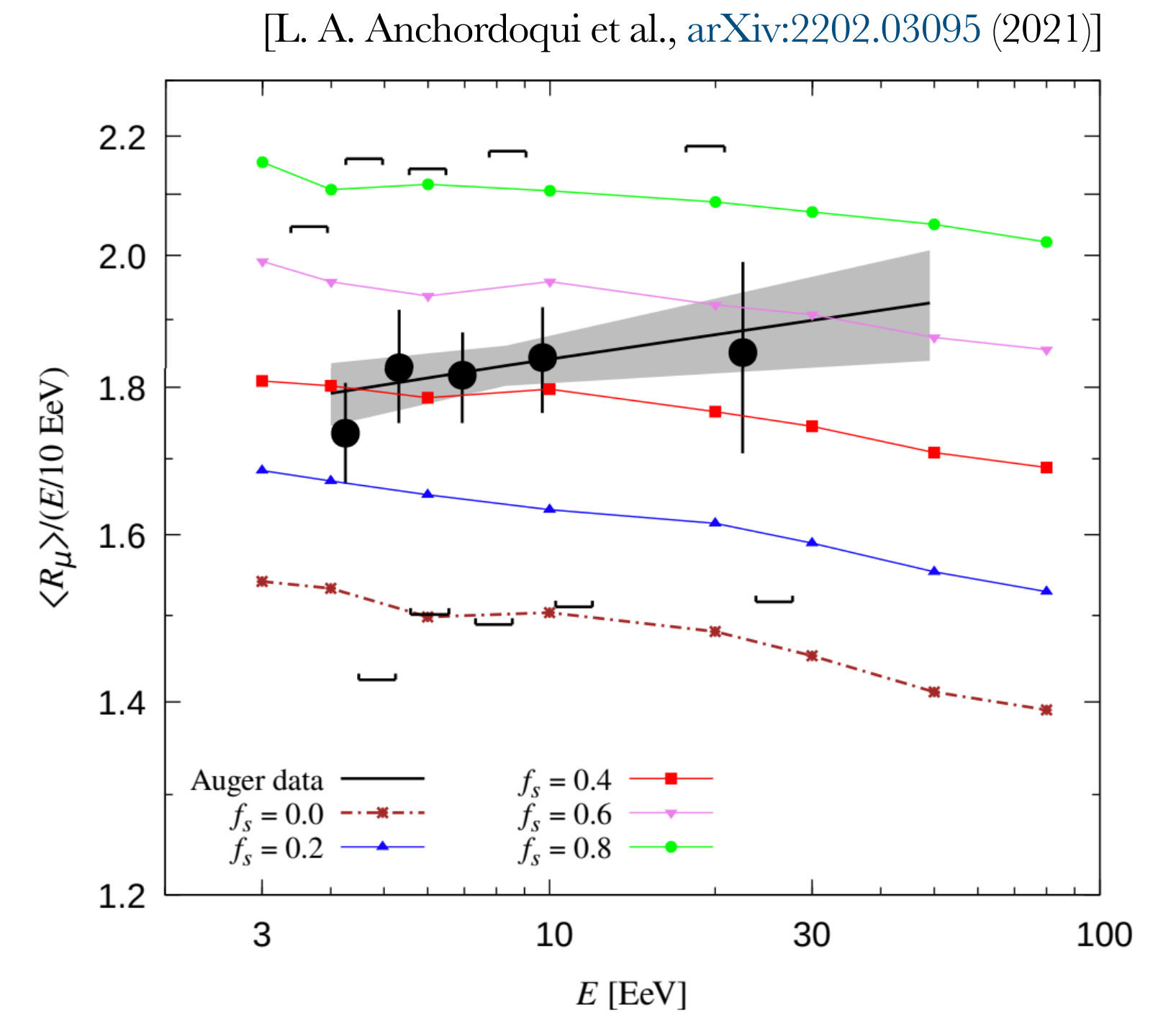


Modeling Cosmic Ray Air Showers

- ▶ Muons from hadrons produced in the far forward region
- ▶ Complex hadron composition, i.e. mesons, heavy hadrons, ...
- ▶ No calculations based on first principles, very limited accelerator data
- ▶ Evidence for strangeness enhancement in ALICE measurement [ALICE Collaboration, Nature Phys. 13 (2017)]

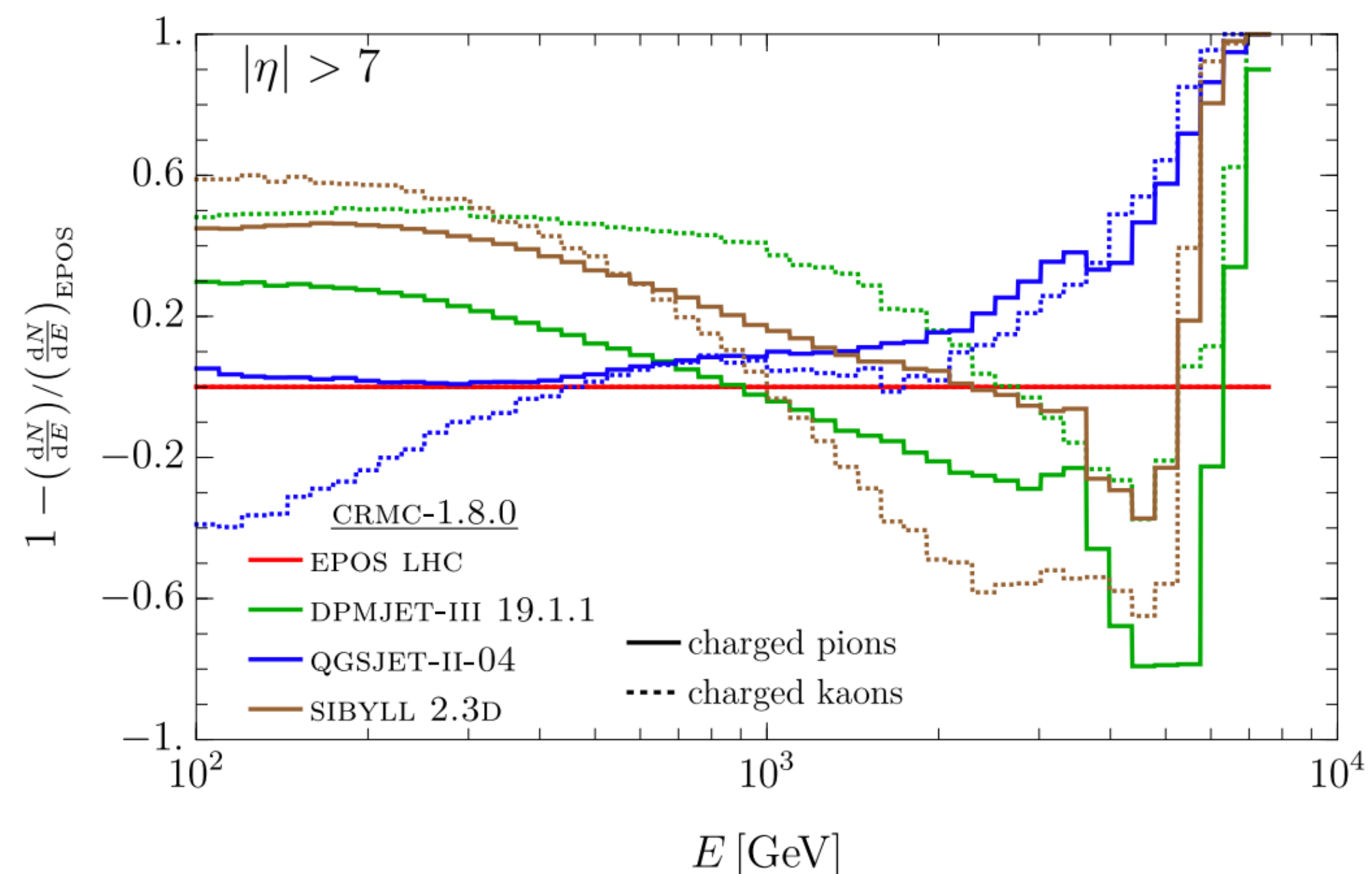
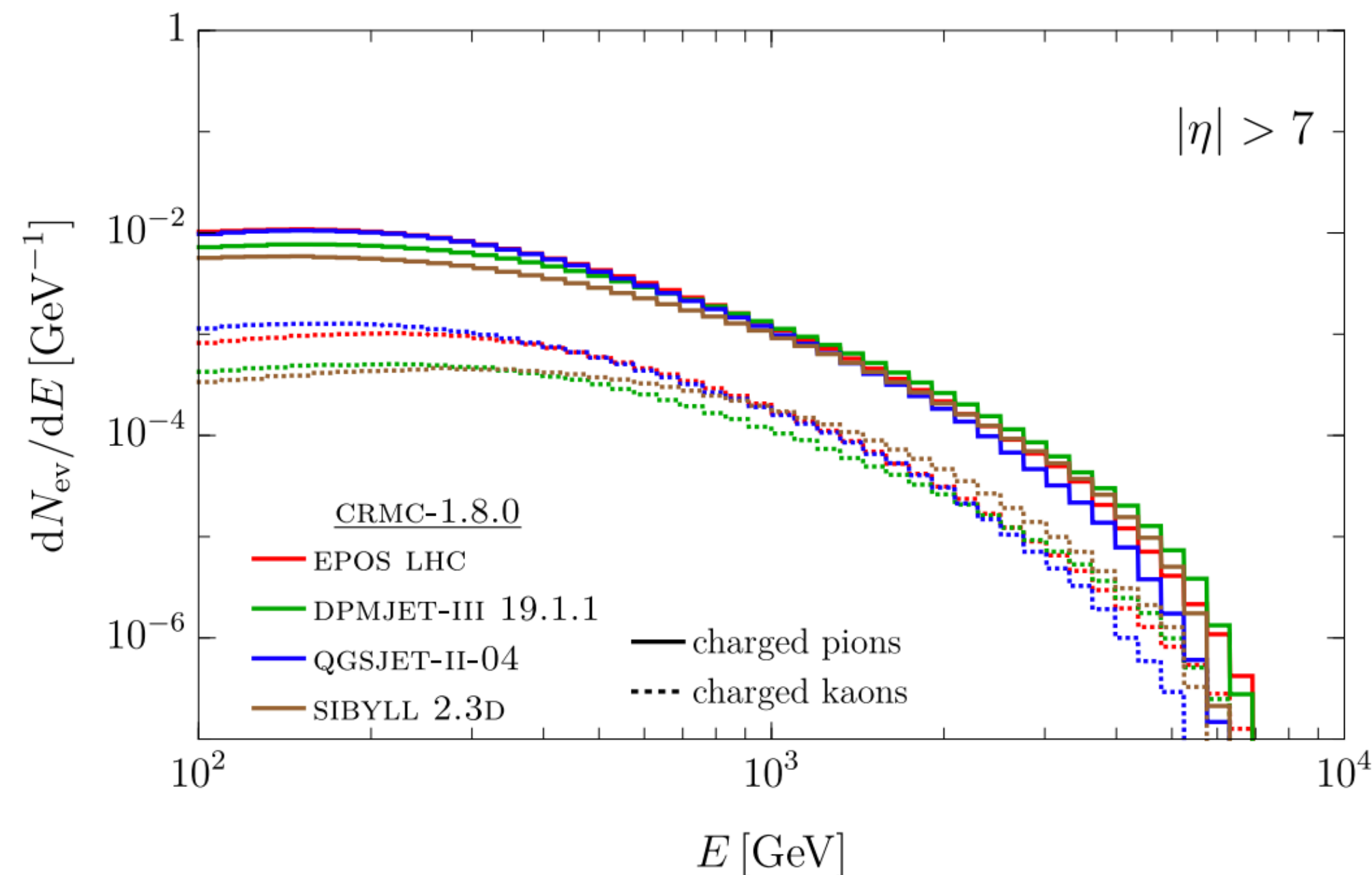


[J. Albrecht, DS, et al., Astrophys.Space Sci. 367 (2022)]



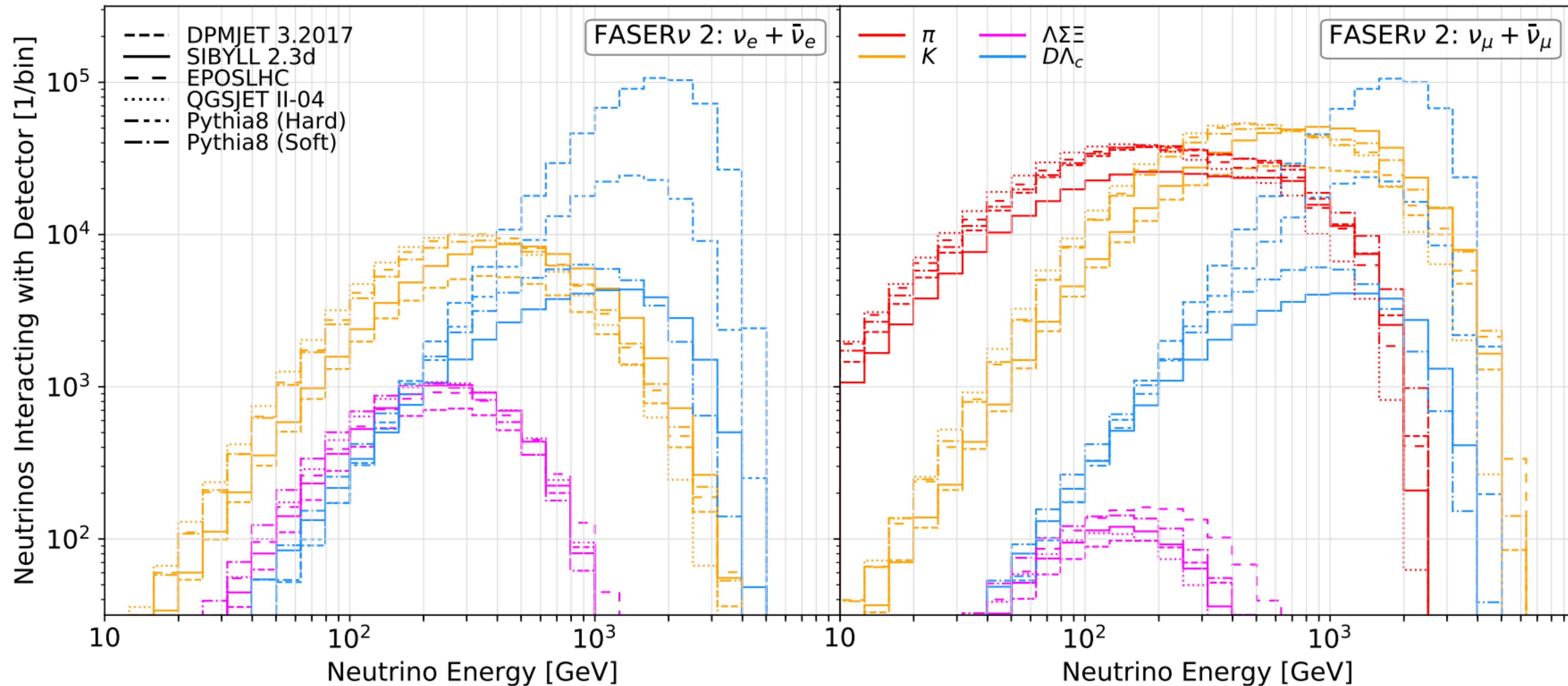
Modeling Cosmic Ray Air Showers

- ▶ Electron/muon neutrinos at the FPF are proxies for pion/kaon distributions
- ▶ Muons can also possibly constrain pion/kaon production (challenging due to secondary scattering, deployment of sweeper magnets under investigation)
- ▶ Test of EAS models → reduced uncertainties in EAS/neutrino measurements
- ▶ Complementary data to IceCube's neutrino and muon measurements



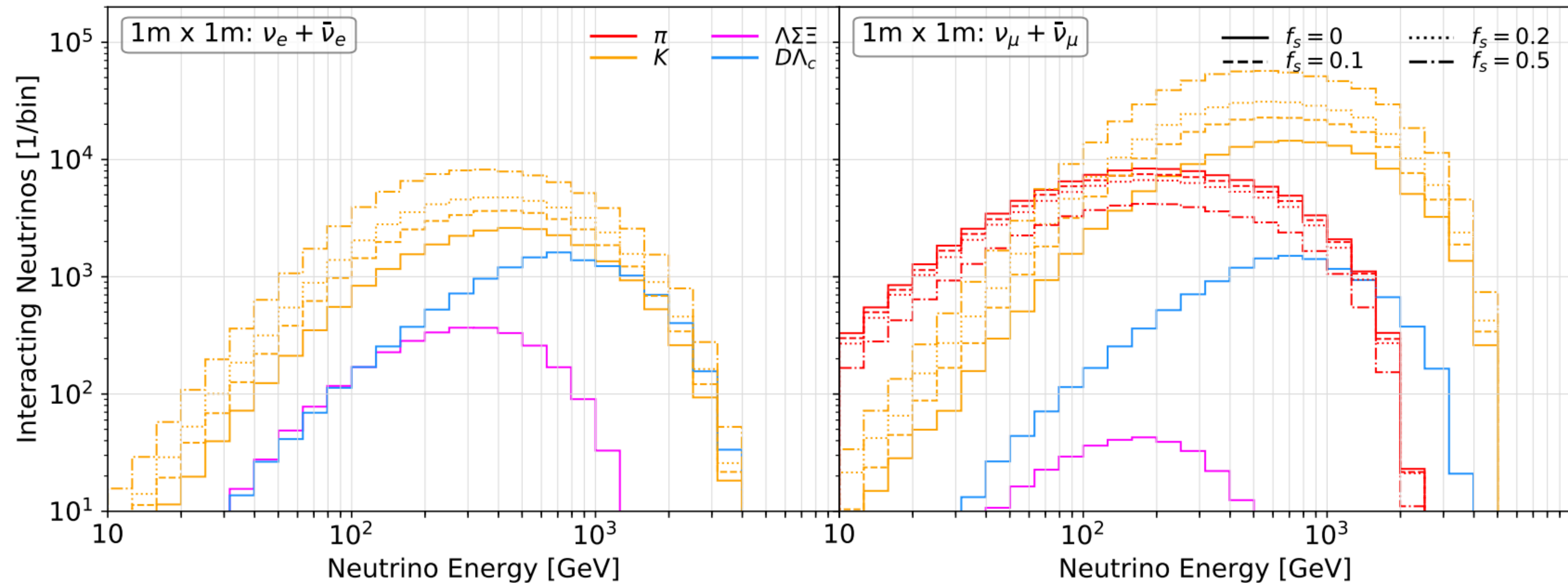
Modeling Cosmic Ray Air Showers

- ▶ Expected neutrino fluxes in FASER ν 2:



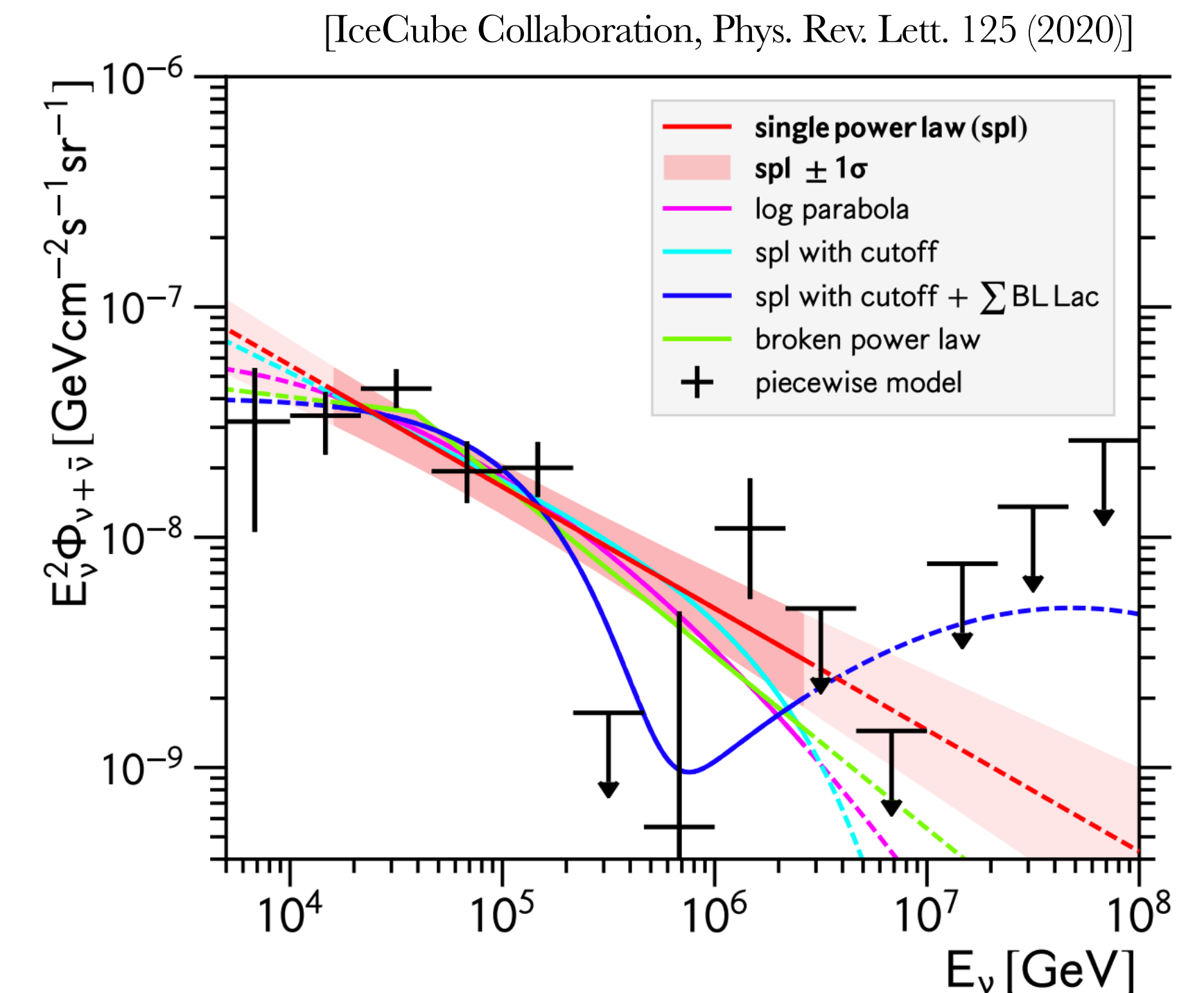
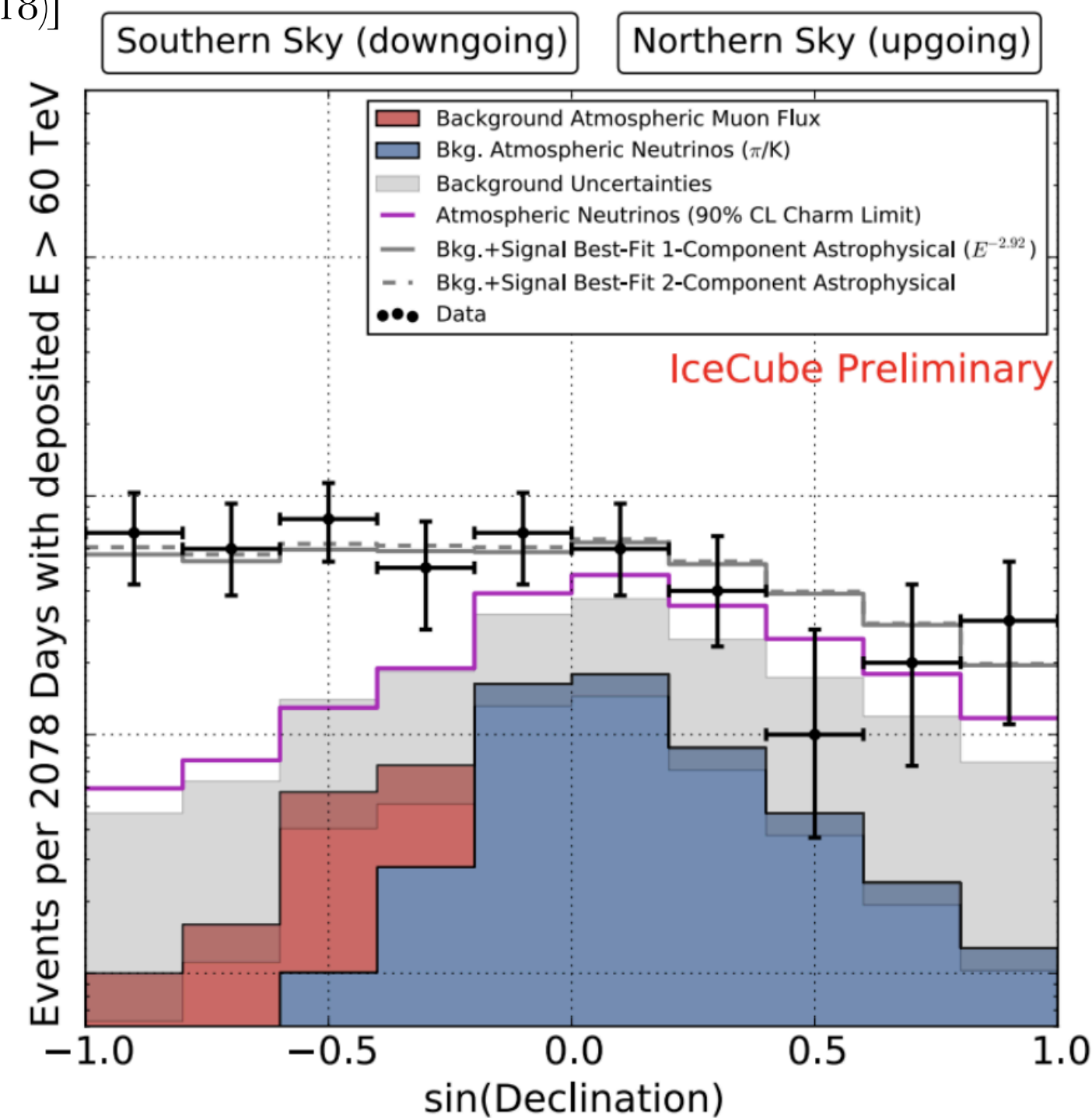
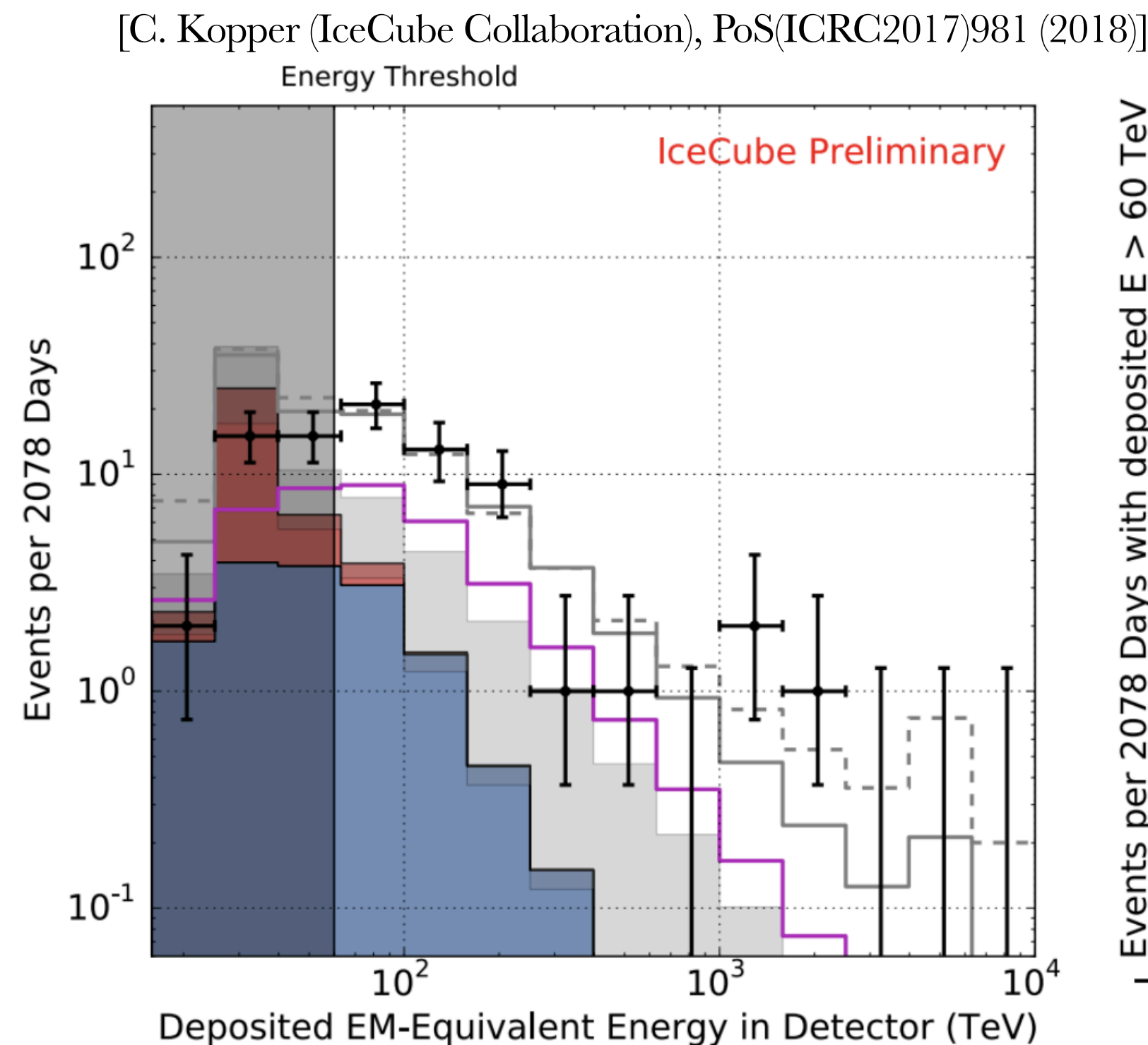
Modeling Cosmic Ray Air Showers

- ▶ Expected neutrino fluxes in FLArE (incl. strangeness enhancement toy model):



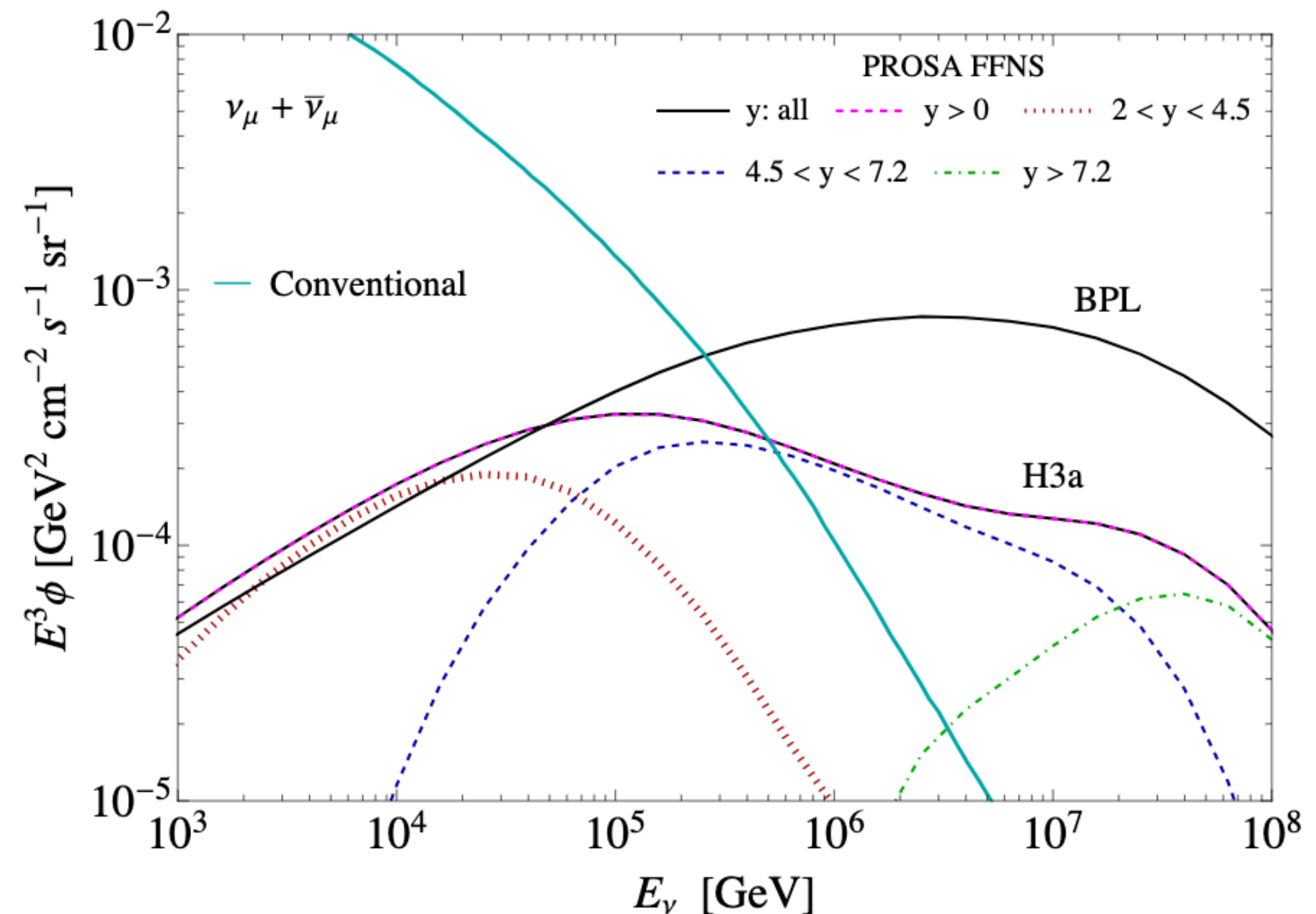
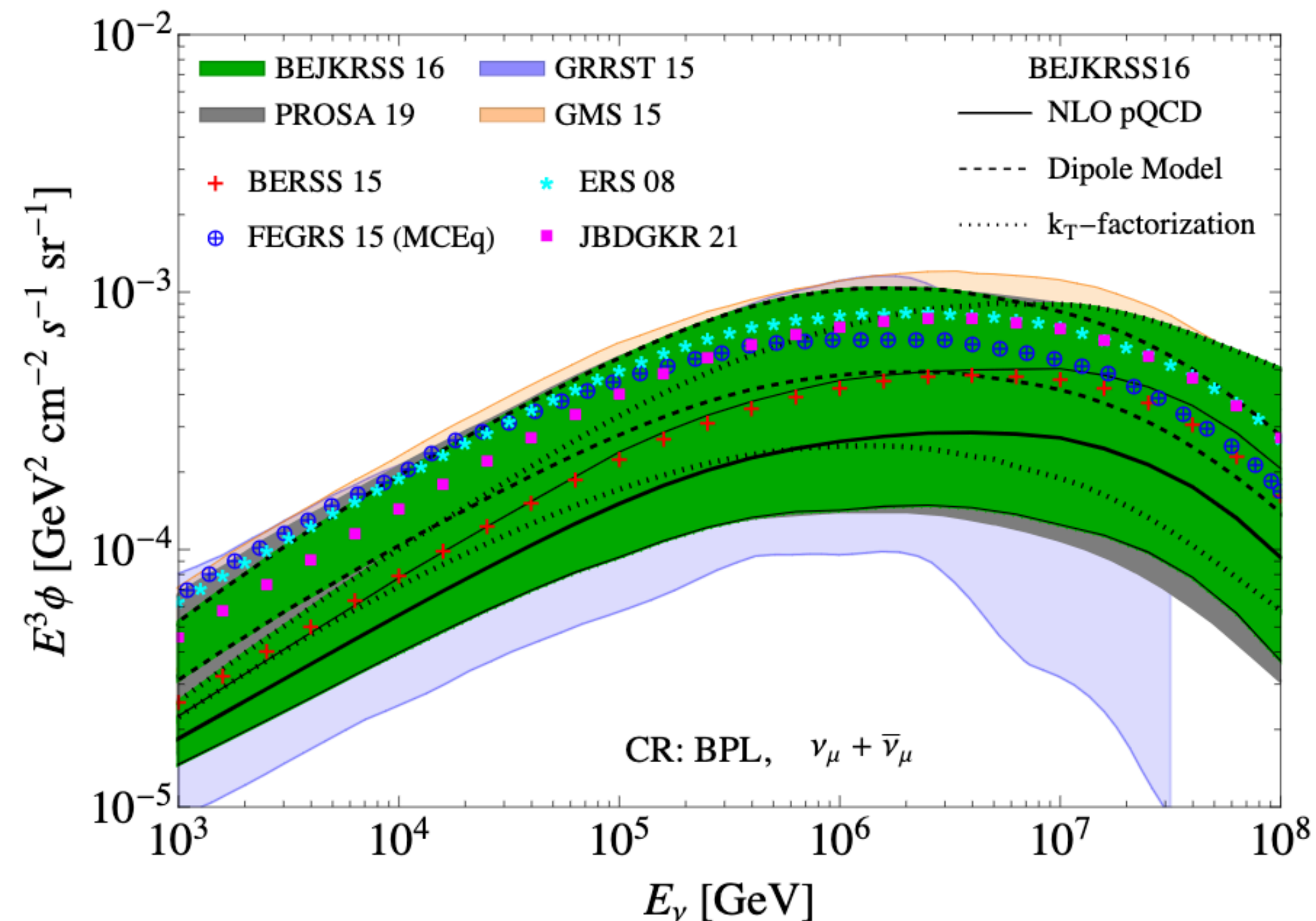
Understanding Atmospheric Neutrinos

- ▶ Atmospheric muons (in particular prompt) are dominant background for astrophysical neutrino searches
- ▶ Large uncertainties in prompt neutrino flux calculations
- ▶ FPF experiments will directly measure TeV neutrino production



Understanding Atmospheric Neutrinos

- ▶ FPF can provide high-statistics neutrino data over forward rapidity ranges
- ▶ Strong constraints on prompt (charmed) neutrino production
- ▶ Improvement of prompt atmospheric neutrino models
- ▶ Reduced uncertainties of astrophysical neutrino searches (e.g. spectral fits)



[PROSA Collaboration, JHEP 04 (2020)]

Dark Matter Searches

- ▶ BSM searches at the FPF towards understanding dark matter in the Universe
- ▶ Various BSM models can be tested:
 - ▶ Long-lived vector particles, e.g. dark photons, gauge bosons, ...
 - ▶ Long-lived scalars, e.g. dark Higgs, two Higgs doublets, flavor-philic scalars, ...
 - ▶ Long-lived fermions, e.g. sterile neutrinos, heavy neutral leptons, ...
 - ▶ Other long-lived particles, e.g. axion-like particles, inelastic dark matter, ...
 - ▶ Even more: Dark matter scattering, millicharged particles, Quirks, ...
- ▶ In the following, a few example dark matter scenarios which can be tested at the FPF
- ▶ For a complete description, please see FPF white paper

Dark Matter Searches

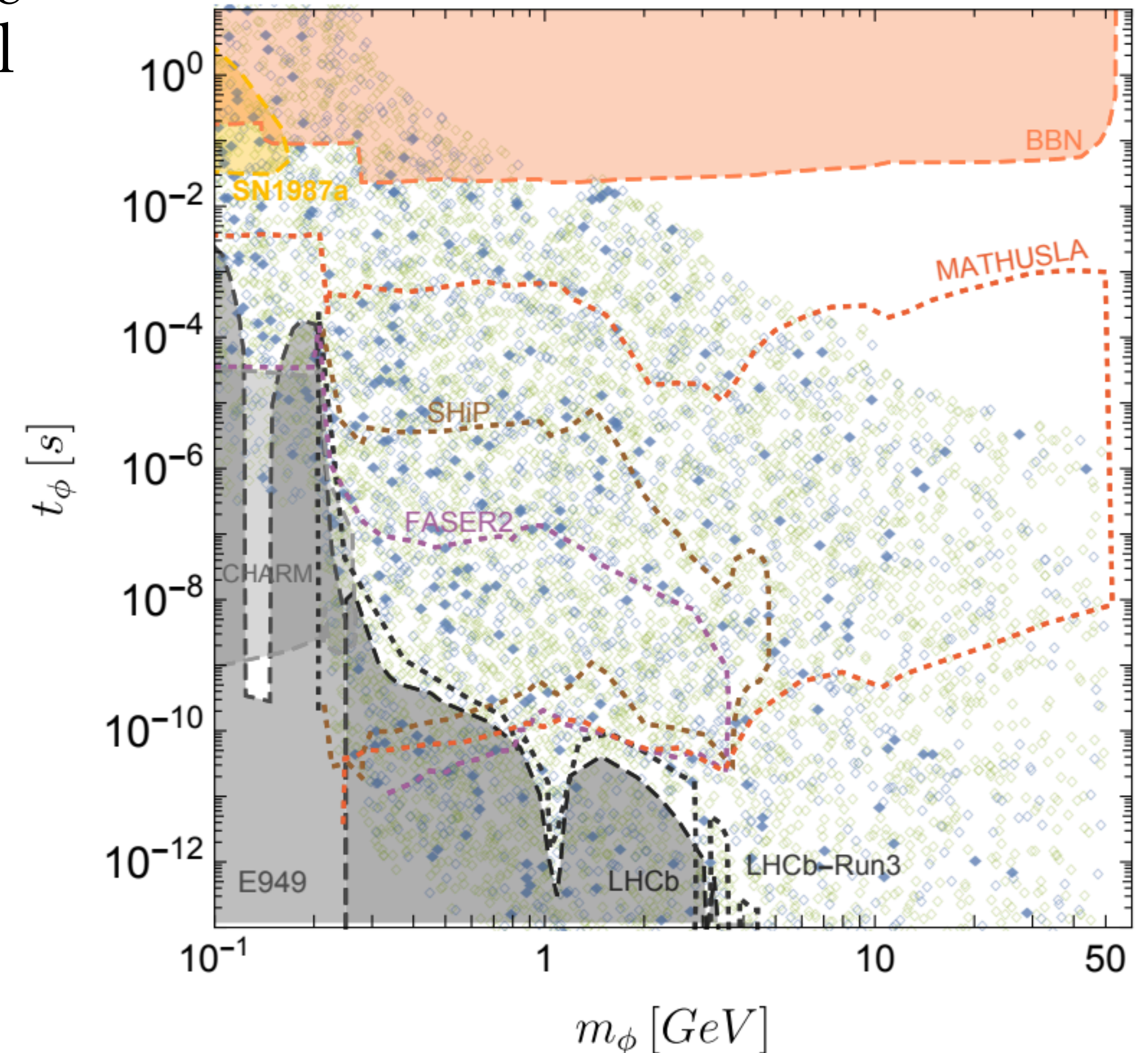
Example: Dark Matter from Freeze-In Semi-Production

- ▶ Interactions between the dark sector and the SM sector takes place through an additional mediator field, ϕ
- ▶ Semi-production, i.e. reaction of the dark matter candidate χ with the mediator ϕ :

$$\chi\phi \rightarrow \chi\chi$$

- ▶ Constraints on the mediator mass m_ϕ and lifetime t_ϕ
- ▶ For details of the model, please see A. Hryczuk, M. Laletin, JHEP 06 (2021)

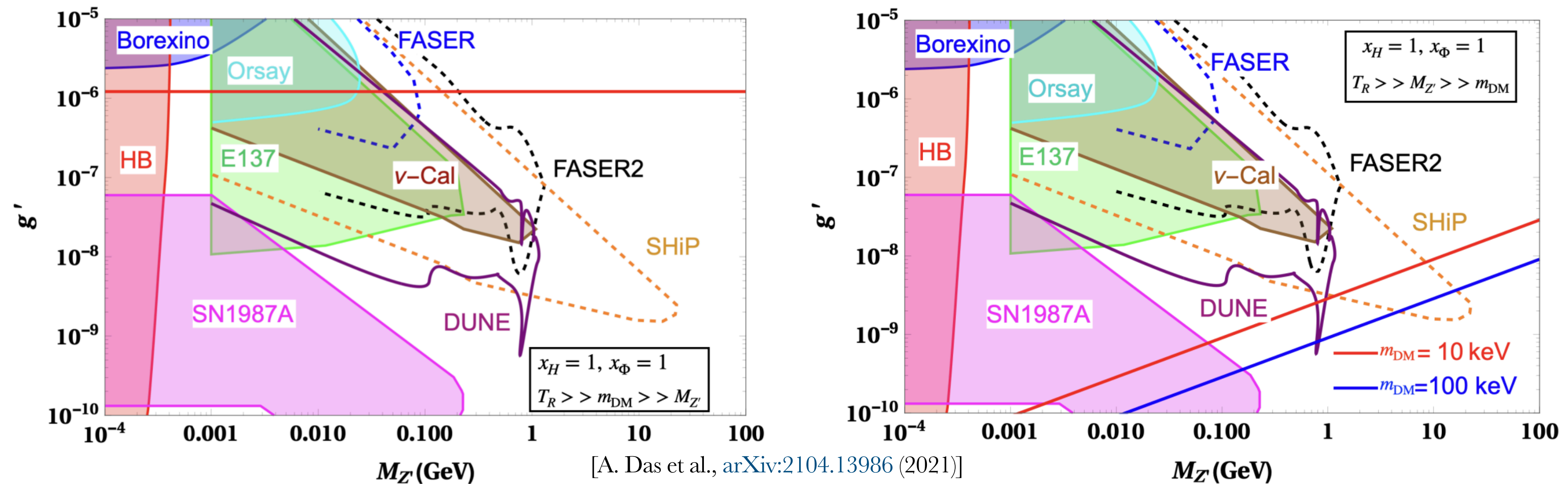
[A. Hryczuk, M. Laletin, JHEP 06 (2021)]



Dark Matter Searches

Example: Freeze-In Sterile Neutrino Dark Matter

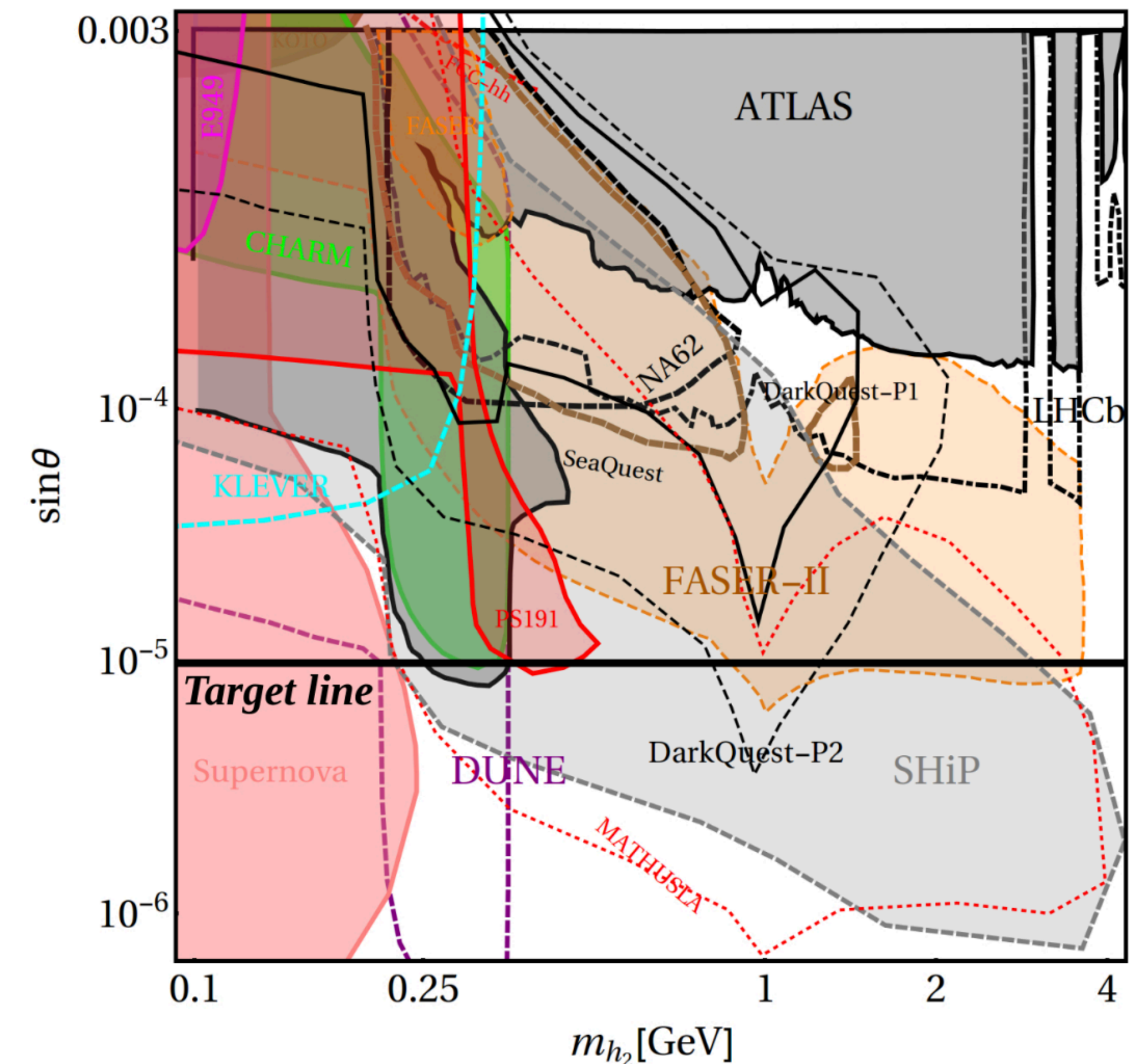
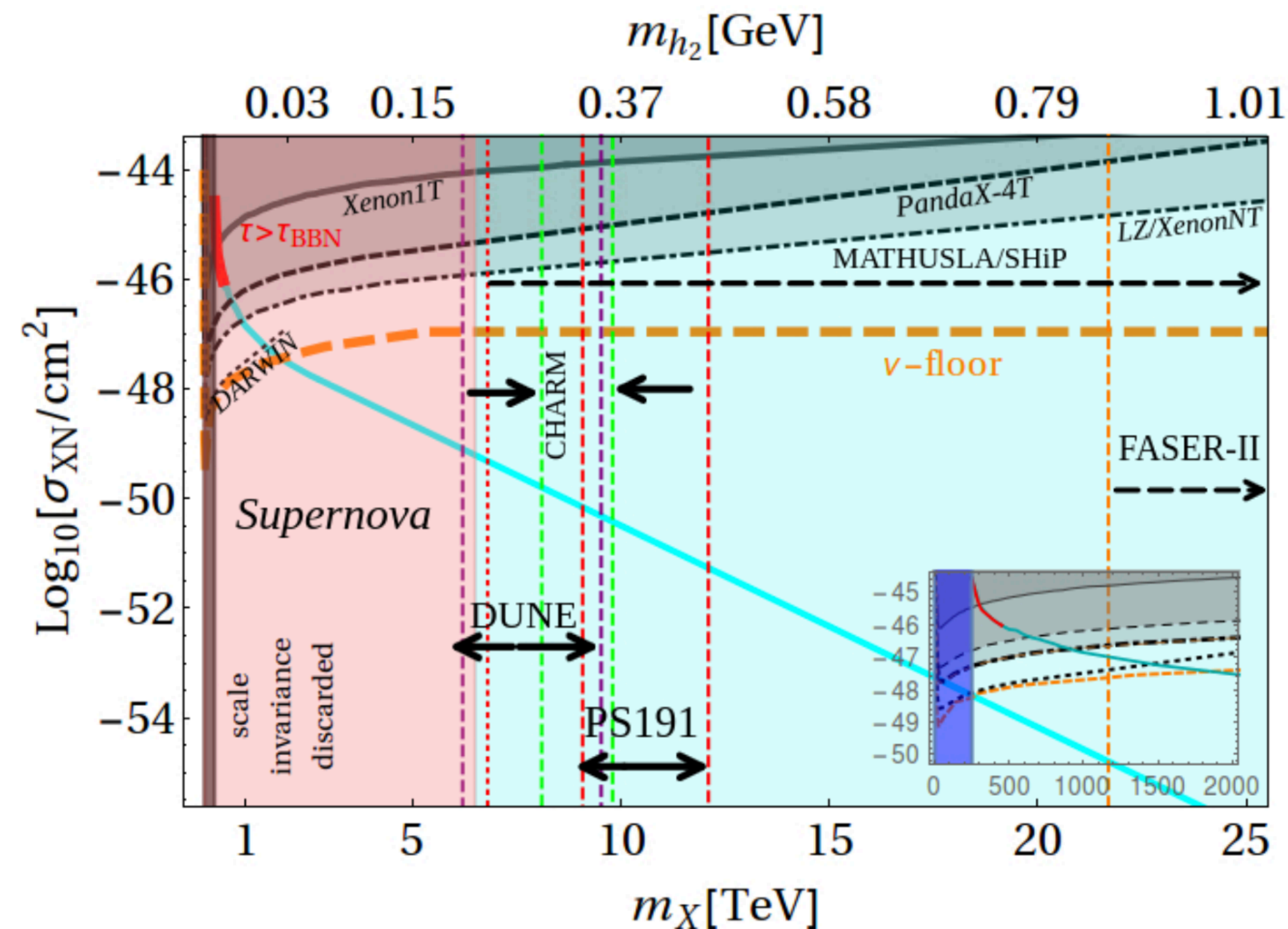
- ▶ Inverse seesaw mechanism allows for mixing between light and heavy states
- ▶ $U(1)'$ extended framework: 3 SM singlet right-handed neutrinos and 3 gauge singlet Majorana fermions are introduced to generate the light neutrino mass
- ▶ Extra Z' which gets mass, $M_{Z'}$, when the $U(1)'$ symmetry is broken
- ▶ For details of the model, please see A. Das et al., [arXiv:2104.13986](https://arxiv.org/abs/2104.13986) (2021)



Dark Matter Searches

Example: Imprints of Scale Invariance and Freeze-In Dark Matter

- ▶ Scale-invariant $U(1)_X$ extension of the SM with gauge boson X (dark matter particle)
- ▶ New gauge coupling g_X , dark matter mass m_X , and mixing angle θ



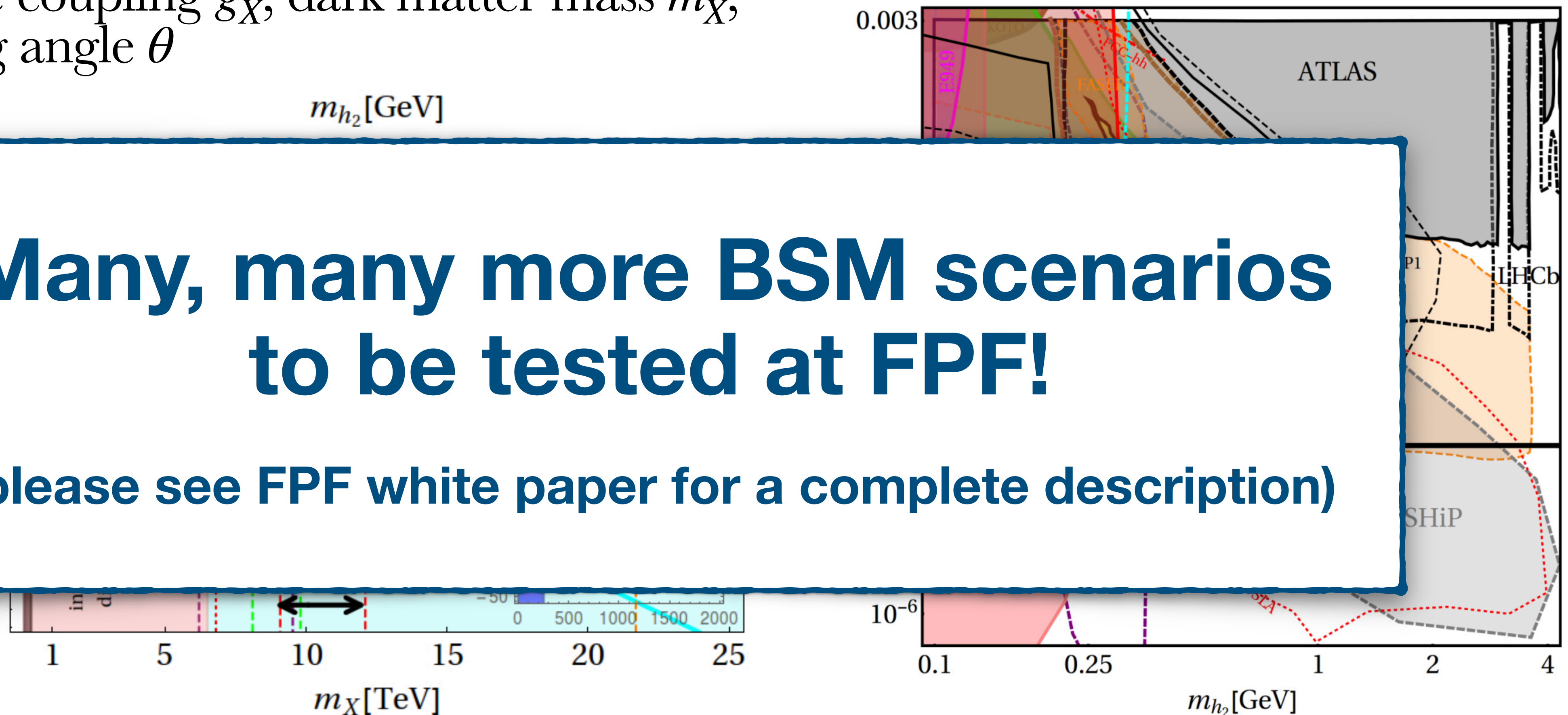
Dark Matter Searches

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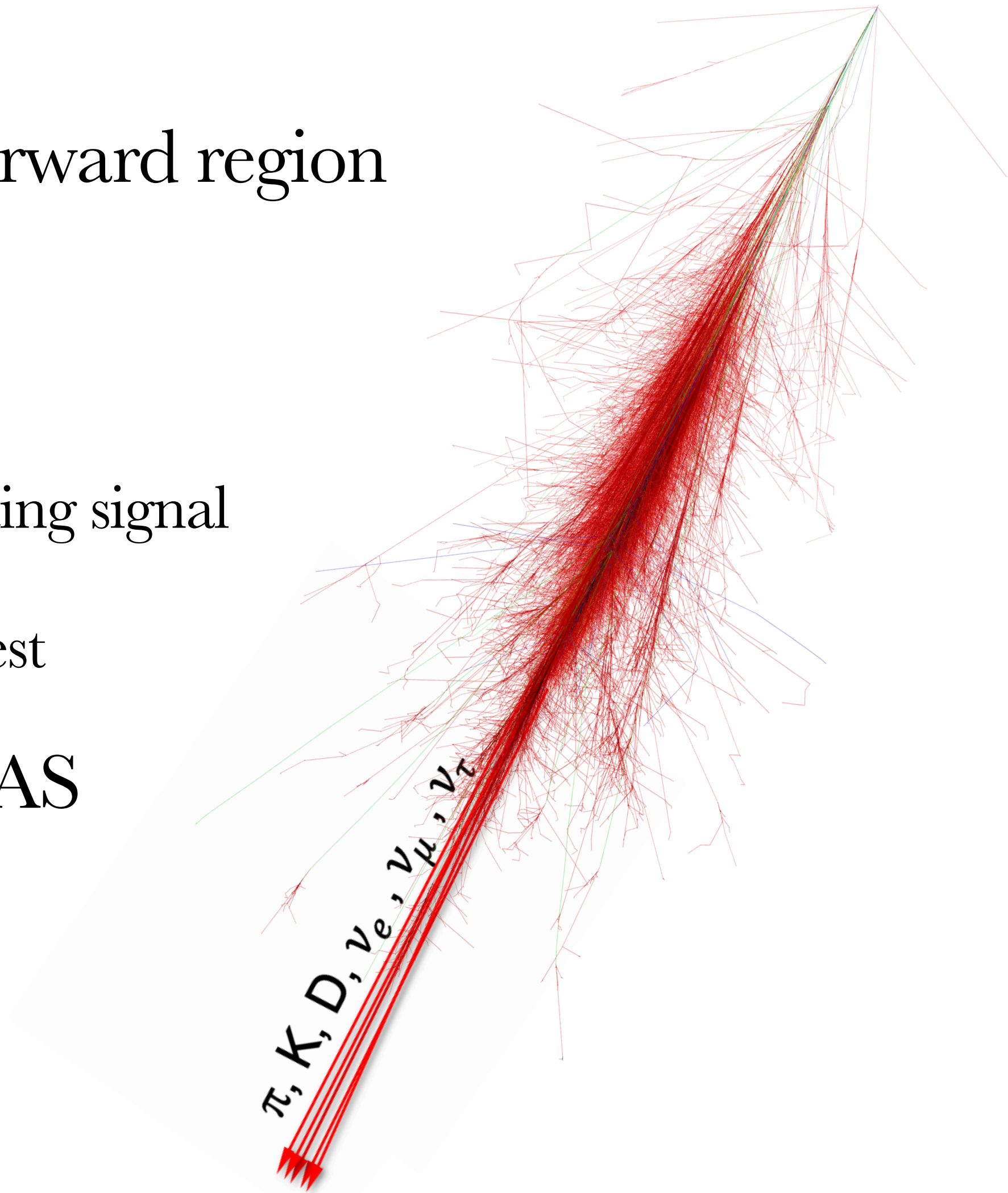
**Many, many more BSM scenarios
to be tested at FPF!**

(please see FPF white paper for a complete description)



Summary & Conclusions

- ▶ Understanding high-energy particle production in the forward region is an important aspect in astroparticle physics
 - ▶ Multi-particle production in extensive air showers (EAS)
 - ▶ The Muon Puzzle in EAS
 - ▶ Lepton fluxes in large-scale neutrino telescopes are both an interesting signal and background for astrophysical neutrino searches
 - ▶ Prompt atmospheric neutrino (muon) fluxes are of particular interest
- ▶ The FPF will help to understand lepton production in EAS
- ▶ Reduced associated uncertainties for astrophysical measurements, e.g.
 - ▶ Cosmic ray mass composition
 - ▶ Astrophysical neutrino searches
- ▶ Complementary constraints for indirect dark matter searches from the FPF



Summary & Conclusions



- ▶ Further reading:
 - ▶ FPF Short Paper: Physics Reports 968 (2022), [arXiv:2109.10905](#)
 - ▶ FPF White Paper: Accepted by Journal of Physics G, [arXiv:2203.05090](#)
- ▶ Many thanks to all contributors and conveners!
- ▶ If you have any further questions or input, please don't hesitate to contact us:
 - ▶ Jonathan Feng: jlf@uci.edu
 - ▶ Felix Kling: flxkling@gmail.com
 - ▶ Mary Hall Reno: mary-hall-reno@uiowa.edu
 - ▶ Juan Rojo: j.rojo@vu.nl
 - ▶ Dennis Soldin: soldin@kit.edu

Thank You!