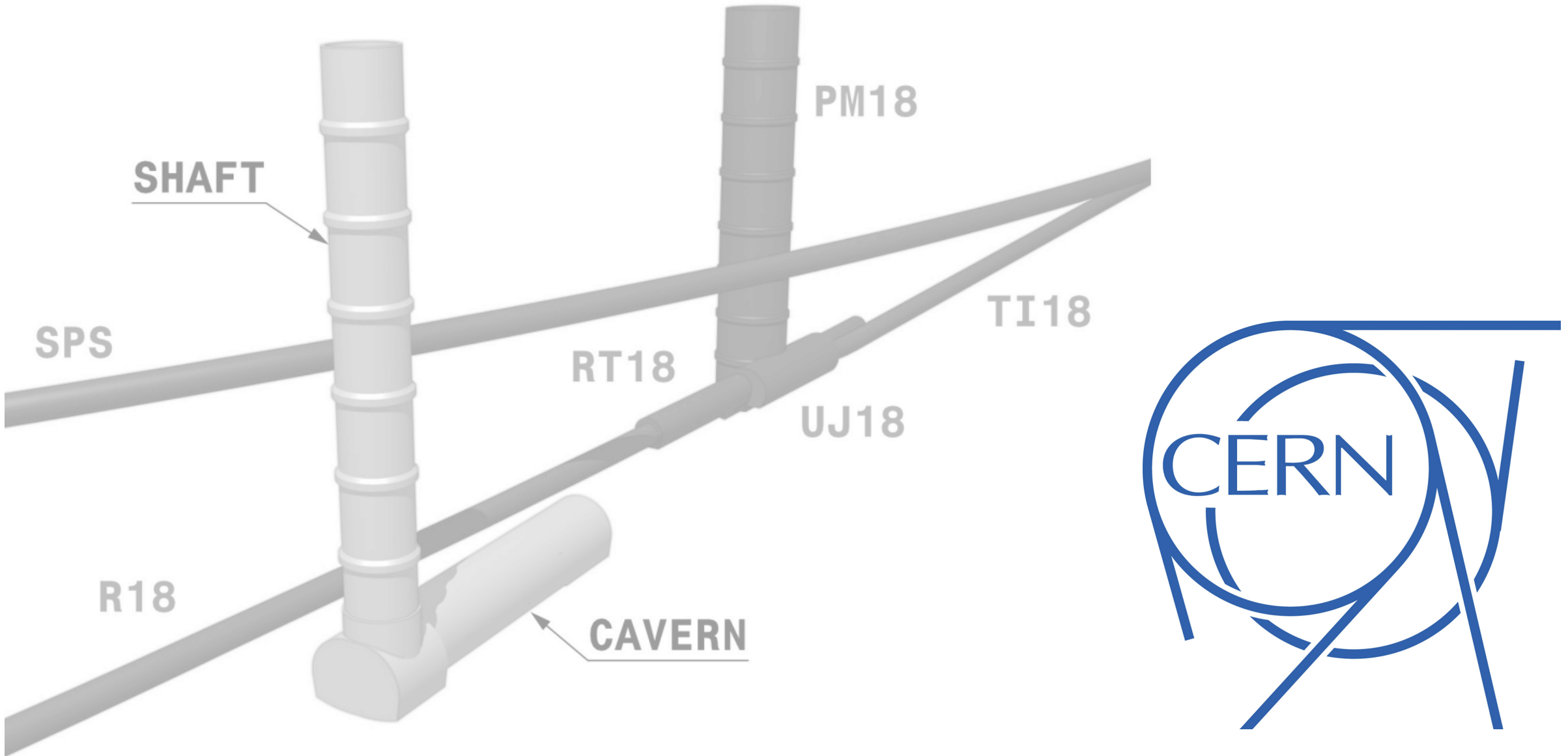


# The Forward Physics Facility at the HL-LHC and its Connection to Astroparticle Physics

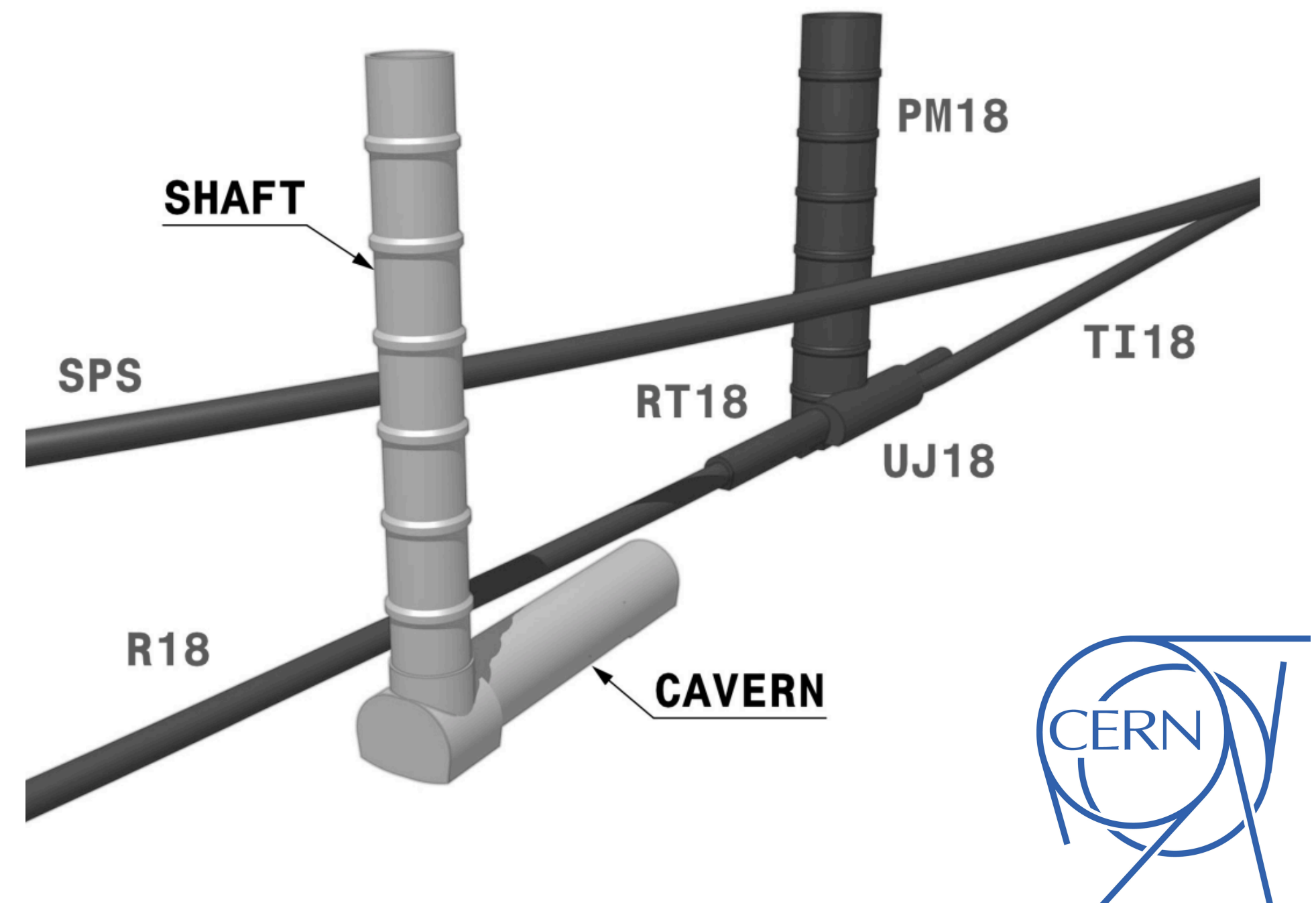
IAP-HEU Seminar, KIT  
May 4, 2023

Dennis Soldin  
ETP / IAP



# Overview

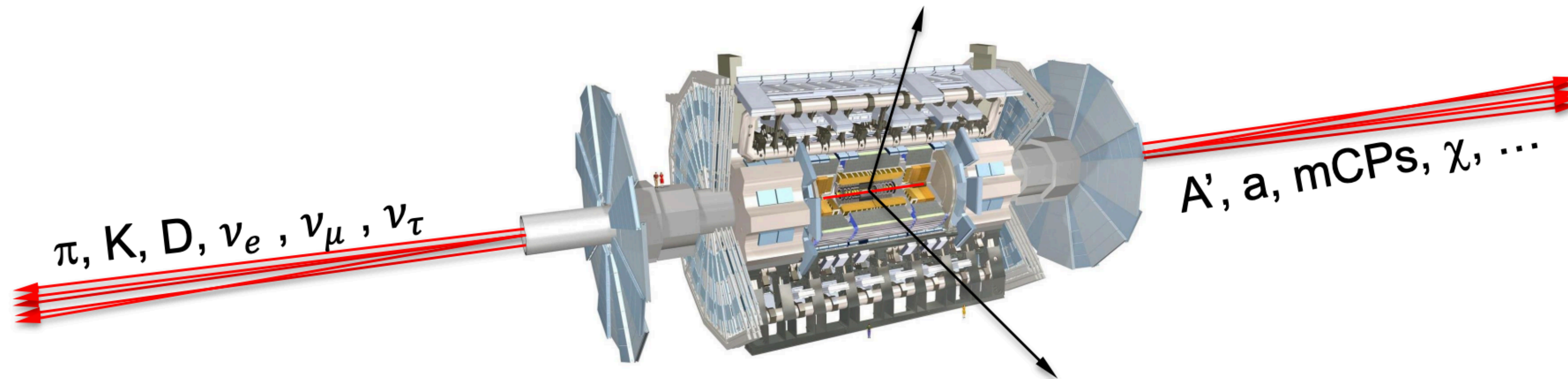
- ▶ Introduction
- ▶ Facility Status Overview
- ▶ Proposed Experiments (short!)
- ▶ Synergies with Astroparticle Physics
  - ▶ Light Hadron Production
  - ▶ Prompt Neutrino Production
  - ▶ (Dark Matter Searches)
- ▶ Summary & Conclusions



# Introduction



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

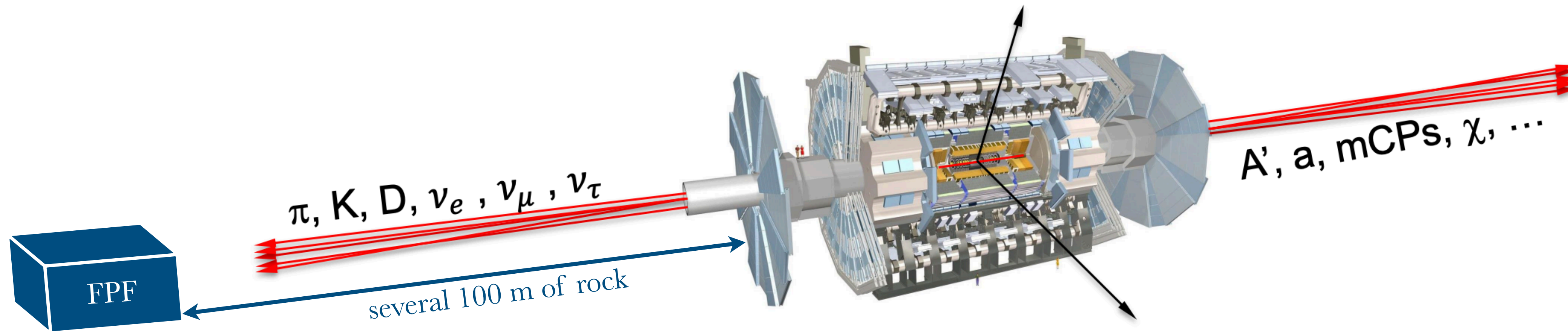


- ▶ By far the largest flux of energetic light particles is in the far-forward direction (mesons, neutrinos, and maybe also dark photons, ALPs, mCPs, DM, ...)
- ▶ Proposal: Forward Physics Facility (FPF) at LHC in ATLAS line-of-sight ( $\eta \gtrsim 7$ )
- ▶ Large synergies between FPF physics and astroparticle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

# Introduction



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

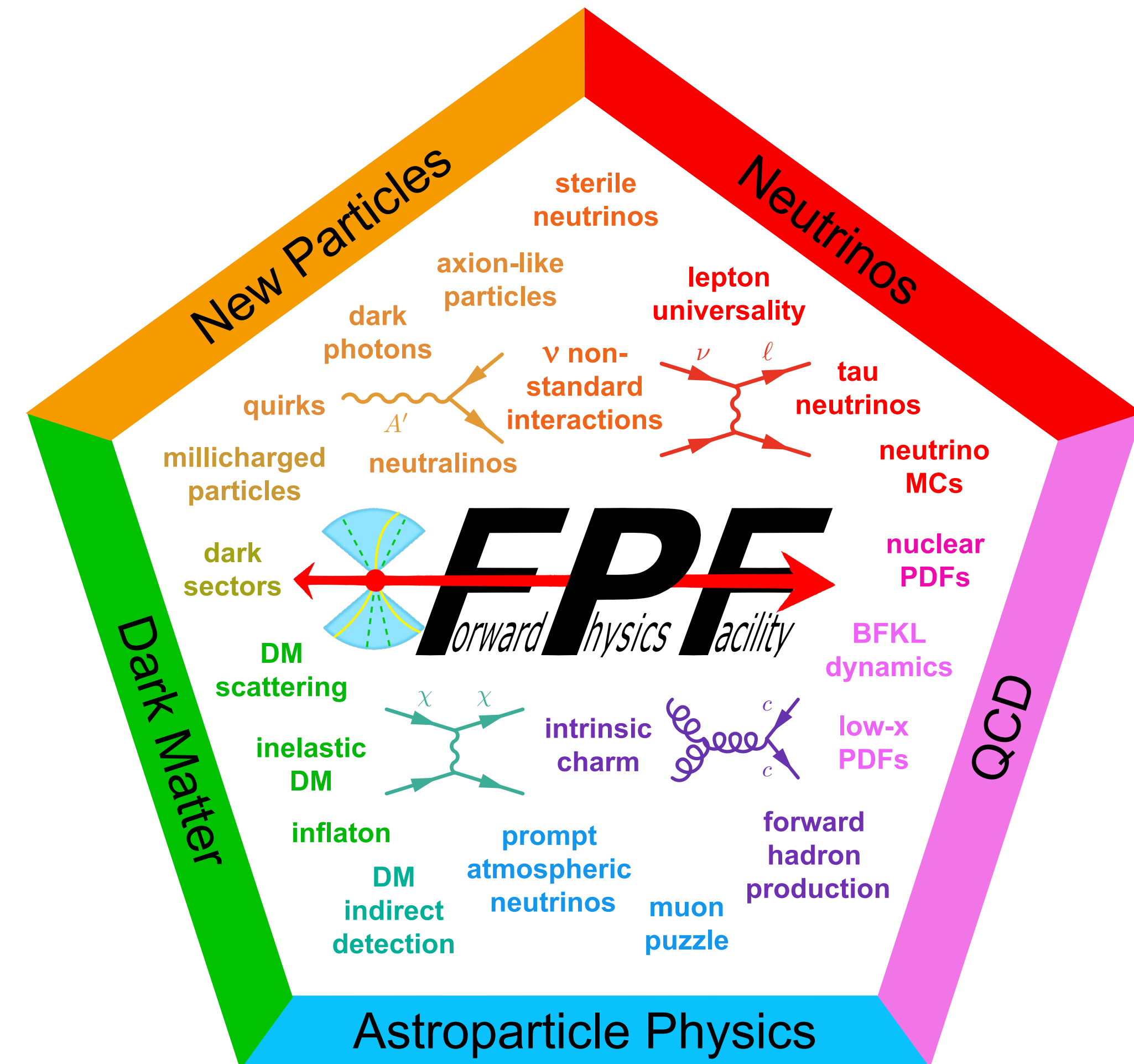


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# Disclaimer



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

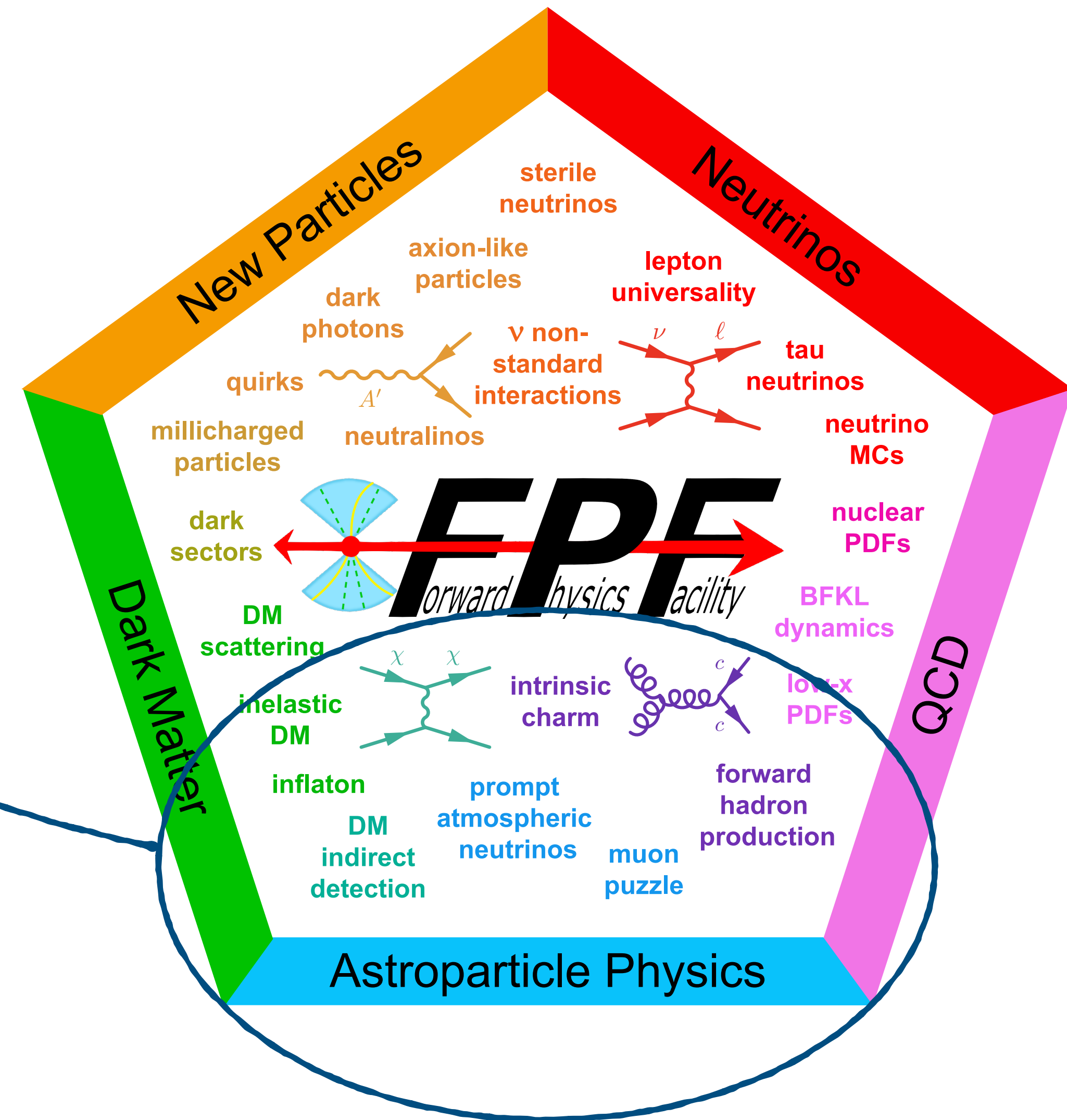


# Disclaimer



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- ▶ Comprehensive physics program
  - ▶ Long-lived particles
  - ▶ Dark Matter and BSM scattering
  - ▶ Quantum Chromodynamics
  - ▶ Neutrino physics
  - ▶ Astroparticle physics
- ▶ This talk's focus:
  - ▶ The facility & organization
  - ▶ Astroparticle physics

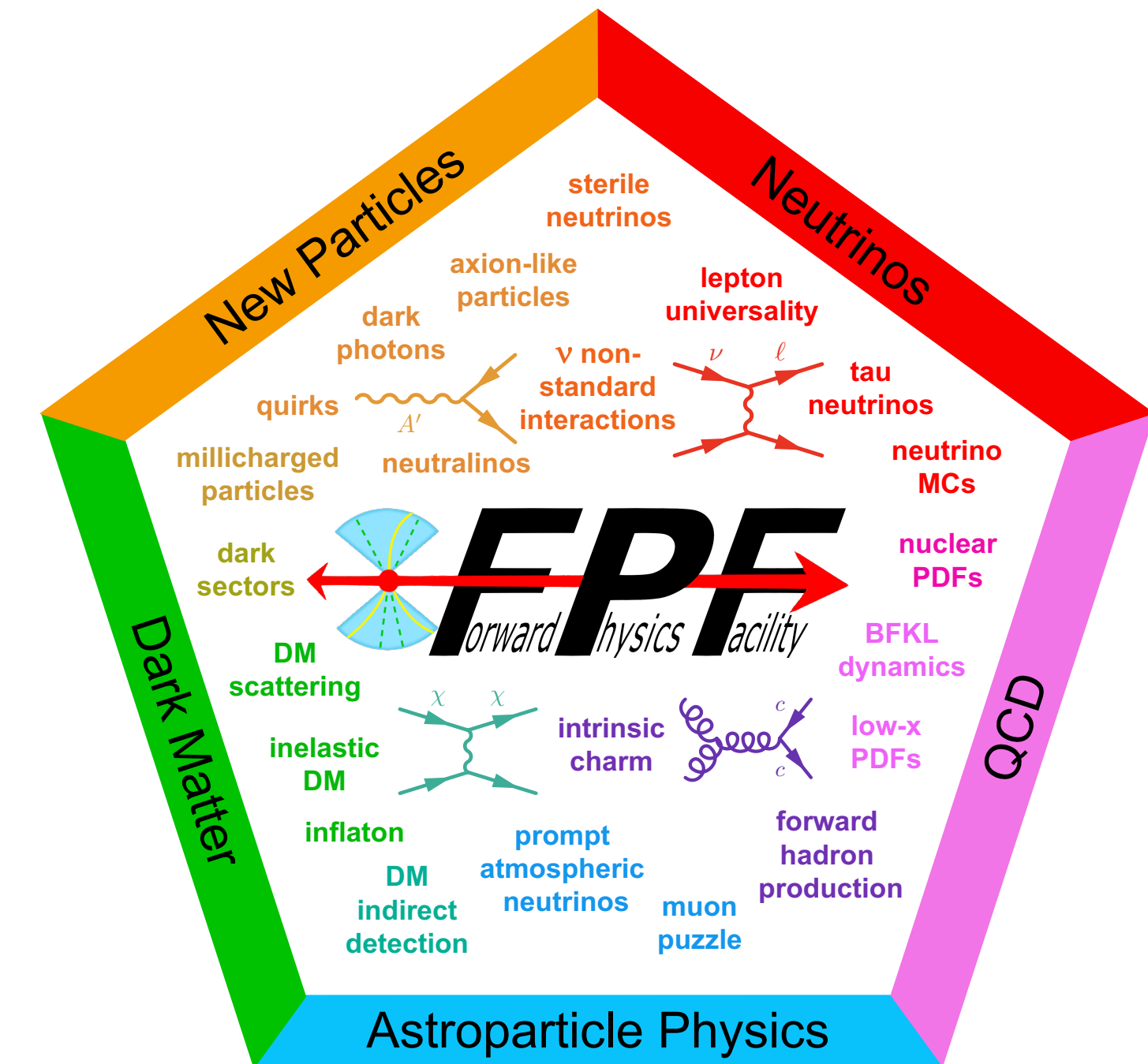
This talk



# FPF Progress



- ▶ Previous FPF Meetings:
  - ▶ FPF Kickoff Meeting, November 9-10, 2020
  - ▶ FPF2 Meeting, May 27-28, 2021
  - ▶ FPF3 Meeting, October 25-26, 2021
  - ▶ FPF4 Meeting, January 31-February 1, 2022
  - ▶ FPF5 Meeting, November 15-16, 2022
- ▶ Next:
  - ▶ FPF6 Meeting, June 8-9, 2023
- ▶ Snowmass 2021 Process:
  - ▶ Meetings embedded in Snowmass 2021 process
  - ▶ Snowmass LoIs, "Short Paper", White Paper



# FPF Short Paper



- ▶ Further reading:
  - ▶ First "real" paper on the FPF
  - ▶ About 80 authors
  - ▶ About 75 pages
  - ▶ First collection of ideas
  - ▶ Reference for future work
  - ▶ Published in Physics Reports 968 (2022)
  - ▶ Pre-print: [arXiv:2109.10905](https://arxiv.org/abs/2109.10905)
  - ▶ 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, UCI-TR-2021-22

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

Luis A. Anchordoqui,<sup>1,\*</sup> Akitaka Ariga,<sup>2,3</sup> Tomoko Ariga,<sup>4</sup> Weidong Bai,<sup>5</sup> Kincso Balazs,<sup>6</sup>  
Brian Batell,<sup>7</sup> Jamie Boyd,<sup>6</sup> Joseph Bramante,<sup>8</sup> Mario Campanelli,<sup>9</sup> Adrian Carmona,<sup>10</sup>  
Francesco G. Celiberto,<sup>11,12,13</sup> Grigorios Chachamis,<sup>14</sup> Matthew Citron,<sup>15</sup> Giovanni De Lellis,<sup>16,17</sup>  
Albert De Roeck,<sup>6</sup> Hans Dembinski,<sup>18</sup> Peter B. Denton,<sup>19</sup> Antonia Di Crescenzo,<sup>16,17,6</sup>  
Milind V. Diwan,<sup>20</sup> Liam Dougherty,<sup>21</sup> Herbi K. Dreiner,<sup>22</sup> Yong Du,<sup>23</sup> Rikard Enberg,<sup>24</sup>  
Yasaman Farzan,<sup>25</sup> Jonathan L. Feng,<sup>26,†</sup> Max Fieg,<sup>26</sup> Patrick Foldenauer,<sup>27</sup>  
Saeid Foroughi-Abari,<sup>28</sup> Alexander Friedland,<sup>29,\*</sup> Michael Fucilla,<sup>30,31</sup> Jonathan Gall,<sup>32</sup>  
Maria Vittoria Garzelli,<sup>33,‡</sup> Francesco Giuliani,<sup>34</sup> Victor P. Goncalves,<sup>35</sup> Marco Guzzi,<sup>36</sup>  
Francis Halzen,<sup>37</sup> Juan Carlos Helo,<sup>38,39</sup> Christopher S. Hill,<sup>40</sup> Ahmed Ismail,<sup>41,\*</sup>  
Ameen Ismail,<sup>42</sup> Richard Jacobsson,<sup>6</sup> Sudip Jana,<sup>43</sup> Yu Seon Jeong,<sup>44</sup> Krzysztof  
Jodłowski,<sup>45</sup> Kevin J. Kelly,<sup>46</sup> Felix Kling,<sup>29,47,§</sup> Fnu Karan Kumar,<sup>20</sup> Zhen Liu,<sup>48</sup> Rafał  
Maciula,<sup>49</sup> Roshan Mammen Abraham,<sup>41</sup> Julien Manshanden,<sup>33</sup> Josh McFayden,<sup>50</sup>  
Mohammed M. A. Mohammed,<sup>30,31</sup> Pavel M. Nadolsky,<sup>51,\*</sup> Nobuchika Okada,<sup>52</sup>  
John Osborne,<sup>6</sup> Hidetoshi Otono,<sup>4</sup> Vishvas Pandey,<sup>53,46,\*</sup> Alessandro Papa,<sup>30,31</sup>  
Digesh Raut,<sup>54</sup> Mary Hall Reno,<sup>55,\*</sup> Filippo Resnati,<sup>6</sup> Adam Ritz,<sup>28</sup> Juan Rojo,<sup>56</sup>  
Ina Sarcevic,<sup>57,\*</sup> Christiane Scherb,<sup>58</sup> Holger Schulz,<sup>59</sup> Pedro Schwaller,<sup>60</sup> Dipan  
Sengupta,<sup>61</sup> Torbjörn Sjöstrand,<sup>62,\*</sup> Tyler B. Smith,<sup>26</sup> Dennis Soldin,<sup>54,\*</sup> Anna Stasto,<sup>63</sup>  
Antoni Szczurek,<sup>49</sup> Zahra Tabrizi,<sup>64</sup> Sebastian Trojanowski,<sup>65,66</sup> Yu-Dai Tsai,<sup>26,46</sup>  
Douglas Tuckler,<sup>67</sup> Martin W. Winkler,<sup>68</sup> Keping Xie,<sup>7</sup> and Yue Zhang<sup>67</sup>

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
  - ▶ More than 230 authors
  - ▶ More than 150 endorsers
  - ▶ Collection of ideas:
    - ▶ The facility
    - ▶ Physics topics
    - ▶ Experiments
- ▶ J. Phys. G: Nucl. Part. Phys. 50 (2023)
- ▶ 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



## ► Comprehensive list of contents:

### Contents

<b>1 Introduction</b>	<b>17</b>
<b>2 The Facility</b>	<b>21</b>
2.1 Purpose-Built Facility	22
2.1.1 Experimental Cavern	23
2.1.2 Access Shaft	25
2.1.3 Safety Gallery	26
2.1.4 Support Buildings and Infrastructure	27
2.2 Services	28
2.3 UJ12 Alcoves Option	30
2.4 Engineering Costs	33
2.5 Choice of Baseline Facility	33
2.6 FLUKA Studies of the FPF Environment and Backgrounds	33
2.6.1 Introduction to FLUKA	34
2.6.2 The FLUKA Model of the ATLAS Insertion	34
2.6.3 Radiation Characterization in the Dispersion Suppressor	36
2.6.4 Validation of FLUKA Estimates	37
2.7 Radiation Protection Studies	38
2.7.1 Radiation Protection at CERN	38
2.7.2 Radiation Protection FLUKA Simulations	38
2.7.3 Radiation Protection Aspects and Constraints	39
2.8 BDSIM Studies of the FPF Environment and Backgrounds	43
2.8.1 Introduction	43
2.8.2 BDSIM Model of the LHC IP1	44
2.8.3 Simulation Procedure	45
2.8.4 Muon and Neutrino Fluxes	48
2.8.5 Outlook	50
2.9 The PROPOSAL Framework For Simulating Particles Fluxes	51
2.10 Sweeper Magnet	52
2.10.1 Sweeper Magnet Location	52
2.10.2 Conceptual Magnet Design	53
<b>3 Experiments</b>	<b>57</b>
3.1 FASER2	57
3.1.1 Physics Goals and Design Considerations	57
3.1.2 Detector Configurations	58
3.1.3 Magnet and Tracker Requirements	59
3.2 FASER $\nu$ 2	62
3.2.1 Physics Goals	62

Contents	14
3.2.2 Detector Requirements	63
3.2.3 Emulsion Film Production	64
3.2.4 Readout and Analysis	66
3.3 AdvSND	68
3.3.1 Physics Goals	68
3.3.2 Detector Layout	71
3.4 FLArE	73
3.4.1 Physics Requirements	74
3.4.2 Detector Design Considerations	75
3.4.3 Cryogenics and Noble Liquid Circulation System	76
3.4.4 Research and Development	77
3.5 FORMOSA	80
3.5.1 Detector Design	81
3.5.2 Backgrounds and Sensitivity	82
<b>4 Long-Lived Particles</b>	<b>85</b>
4.1 Monte Carlo Tools for BSM: FORESEE	87
4.2 Long-Lived Vector Particles	91
4.2.1 Dark Photon	91
4.2.2 $B-L$ Gauge Boson	94
4.2.3 $L_i-L_j$ Gauge Bosons	95
4.2.4 $B-3L_i$ Gauge Bosons	98
4.2.5 $B$ Gauge Boson	100
4.2.6 Production via Proton Bremsstrahlung	104
4.2.7 Additional Production Modes	105
4.2.8 Decays of Light Vector Particles	108
4.3 Long-Lived Scalars	112
4.3.1 Existing Constraints on the Dark Higgs	114
4.3.2 Dark Higgs as Relaxion	115
4.3.3 Dark Higgs as Relaxed Relaxion	116
4.3.4 Dark Higgs and Neutron Star Mergers	117
4.3.5 Dark Higgs as Inflaton	117
4.3.6 Flavor-philic Scalars	120
4.3.7 Two Higgs Doublet Models	122
4.3.8 Sgoldstino	124
4.3.9 Crunching Dilatons	126
4.4 Long-Lived Fermions	129
4.4.1 Heavy Sterile Neutrinos	129
4.4.2 Light Long-lived Sterile Neutrinos in $\nu$ SMEFT	132
4.4.3 Heavy Neutral Leptons with Tau Mixing in Neutrino Mass Models	136
4.4.4 Tree-level Decays of GeV-Scale Neutralinos from $D$ and $B$ Mesons	140
4.4.5 Radiative Decays of Sub-GeV Neutralinos from Light Mesons	143
4.4.6 Fermion Portal Effective Operators	147
4.5 Long-Lived Axion Like Particles	151
4.5.1 Overview on Axion Like Particles	151
4.5.2 Charming ALPs	154
4.5.3 Bremining Enhanced ALP Productions and FPF Sensitivity	157
4.6 Long-Lived Particles in Non-Minimal Models	161
4.6.1 Inelastic Dark Matter	161
4.6.2 Inelastic Dark Matter from Dark Higgs Boson Decays	163

Contents	15
4.6.3 Dynamical Dark Matter	167
4.6.4 Light Dark Scalars through $Z'$ and EFTs	172
4.6.5 Beyond the Minimal Dark Photon Model: Lepton Flavor Violation	175
4.6.6 $U(1)_{T3R}$ Gauge Boson	181
4.6.7 Dark Axion Portal	187
4.6.8 Heavy Neutrino Production via a $B-L$ Gauge Boson	190
4.6.9 Search for Sterile Neutrino with Light Gauge Interactions	193
4.6.10 The $\nu_R$ -philic Dark Photon	196
4.6.11 Secondary Production in BSM and Neutrino Interactions	196
4.6.12 Light Dark Sector Going Through Chain Decay	200
4.6.13 Bound State Formation and Long-Lived Particles	202
<b>5 Dark Matter and BSM Scattering Signatures</b>	<b>205</b>
5.1 Dark Matter Scattering	206
5.1.1 Dark Photon Mediator Models	207
5.1.2 Hadrophilic Dark Matter Models	210
5.1.3 Dark Matter Search in the Advanced SND@LHC Detector	213
5.1.4 Dark States with Electromagnetic Form Factors	217
5.2 Millicharged Particles	222
5.3 Quirks	223
<b>6 Quantum Chromodynamics</b>	<b>229</b>
6.1 Forward Particle Production and QCD in Novel Regimes	233
6.1.1 Introduction	233
6.1.2 Low- $x$ Resummation at the LHC and Its Impact on the FPF Program	234
6.1.3 Charm Production in the Forward Region within $k_T$ Factorisation	238
6.1.4 Forward Charm Production in $k_T$ Factorization and the Role of Intrinsic Charm	240
6.1.5 Charm Production at Very Forward Rapidities in the Color Dipole Formalism	241
6.1.6 Charm Production in the Forward Region and Intrinsic Charm in the CT Framework	243
6.1.7 Probing the Multidimensional Structure of Hadrons at the FPF	244
6.1.8 Monte Carlo Studies of High-energy QCD Reactions at the FPF	247
6.1.9 High-energy QCD via a FPF+ATLAS Timing Coincidence	249
6.1.10 BFKL Phenomenology and Inclusive Forward Processes	253
6.2 Modelling Forward Physics with Monte Carlo Event Generators	253
6.2.1 Introduction	253
6.2.2 Event Generation for Forward Particle Production with <b>Pythia 8</b>	254
6.2.3 Event Generation for Forward Particle Production with <b>Sherpa</b>	257
6.2.4 Improved MC Generation of Forward Particle Production	260
6.2.5 Neutrinos at the FPF from Proton-Lead Collisions	262
6.3 Neutrino-induced Deep Inelastic Scattering: Constraints on Nucleon Structure	264
6.3.1 Introduction	264
6.3.2 Impact of Neutrino-induced DIS within the nCTEQ Framework	265
6.3.3 Impact of Neutrino-induced DIS within the (n)NNPDF Framework	268
6.3.4 Neutrino DIS Cross Sections on a Tungsten Target	271
<b>7 Neutrino Physics</b>	<b>273</b>
7.1 Overview	273
7.2 Neutrino Fluxes	274
7.2.1 Neutrino fluxes from Monte Carlo Generators	274

Contents	16
7.2.2 Neutrino Fluxes from $k_T$ -Factorization	281
7.2.3 Tau Neutrino Fluxes from Heavy Flavor: PDF Uncertainties in NLO Perturbative QCD	281
7.3 Neutrino Cross Sections	287
7.3.1 Deep-Inelastic Scattering	288
7.3.2 Neutral-Current Scattering	291
7.3.3 Quasi-Elastic and Resonance Regions for FPF Physics	293
7.3.4 Interface of Shallow- and Deep-Inelastic Scattering	293
7.3.5 Role of Final State Interactions	297
7.3.6 Scattering with Electrons	298
7.4 Monte Carlo Tools for Neutrino Interactions	299
7.4.1 GENIE	300
7.4.2 NEUT	300
7.4.3 NuWro	302
7.4.4 Generator Comparisons	303
7.4.5 Giessen Model and GiBUU Generator	304
7.5 Beyond Standard Model Physics with Neutrinos	306
7.5.1 Effective Field Theories at the FPF	307
7.5.2 NSI and Effective Field Theories	309
7.5.3 Neutral current cross section and non-standard interactions	313
7.5.4 BSM Interactions in Light of New Mediators	314
7.5.5 Secret Neutrino Interaction	314
7.5.6 Probing Light Gauge Bosons via Tau Neutrinos	315
7.5.7 Neutrino Magnetic Moments	317
7.5.8 Up-scattering through the Neutrino Dipole Portal	319
7.5.9 FASER/FPF Sterile Neutrino Oscillations	322
7.5.10 Neutrinophilic Mediator/Dark Matter Production at the FPF	323
<b>8 Astroparticle Physics</b>	<b>327</b>
8.1 Modelling Cosmic Ray Air Showers	328
8.1.1 The Muon Puzzle and Beyond	329
8.1.2 Probing Hadronic Interaction Models at the FPF	331
8.1.3 Complementary Probes of Strangeness Enhancement: Auger Meets the FPF	334
8.2 Understanding the Atmospheric Background of Astrophysical Neutrinos	336
8.2.1 Atmospheric Backgrounds in Large-Scale Neutrino Telescopes	337
8.2.2 Prompt Atmospheric Neutrino Production	339
8.3 Dark Matter Searches and Their Impact on Astrophysics and Cosmology	342
8.3.1 Dark Matter from Freeze-In Semi-Production	343
8.3.2 Freeze-In Sterile Neutrino Dark Matter	345
8.3.3 Imprints of Scale Invariance and Freeze-In Dark Matter at the FPF	347
8.3.4 Rich Dark Sector and Complementarity with Indirect Searches	351
<b>Acknowledgements</b>	<b>353</b>
<b>References</b>	<b>357</b>



# FPF Status



- ▶ Snowmass process:
- ▶ From the energy frontier executive summary:

“Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.”

- ▶ Also strong endorsements from neutrino, rare processes, and cosmic frontiers!
- ▶ There now appears to be wide acceptance that the physics case is strong!
- ▶ We now have to move toward CDRs for the facility and the experiments
- ▶ Very positive P5 Snowmass report, including budget constraints and recommendations to the DOE and NSF...

# FPF Status



## ▶ News from CERN:

▶ First meeting with CERN directorate (Gianotti, Mnich, Lamont) in June 2022

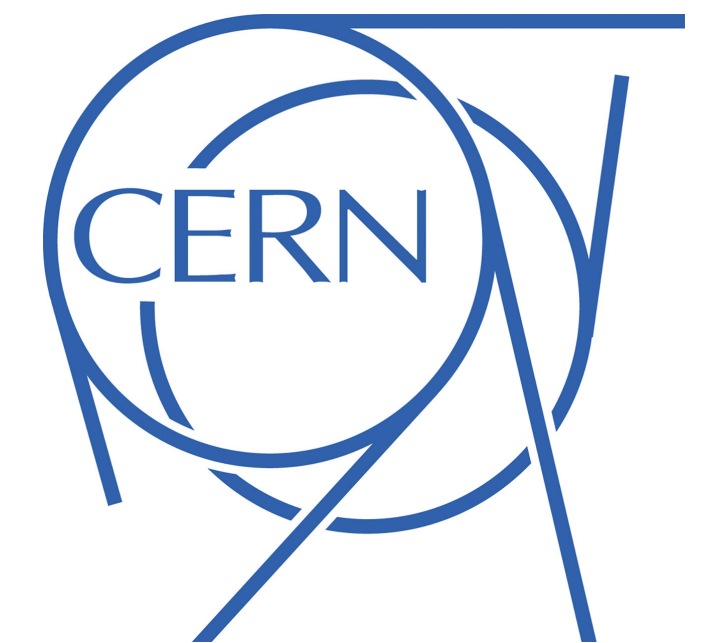
## ▶ Some action items identified:

▶ We should move to the next stage of organizational infrastructure, e.g. webpage with contact names, Slack channels, twikis, etc. ✓

▶ We should contact the LHCC about submitting an EOI ✓

▶ We need stronger commitments from leading experimental groups to work on FPF experiments

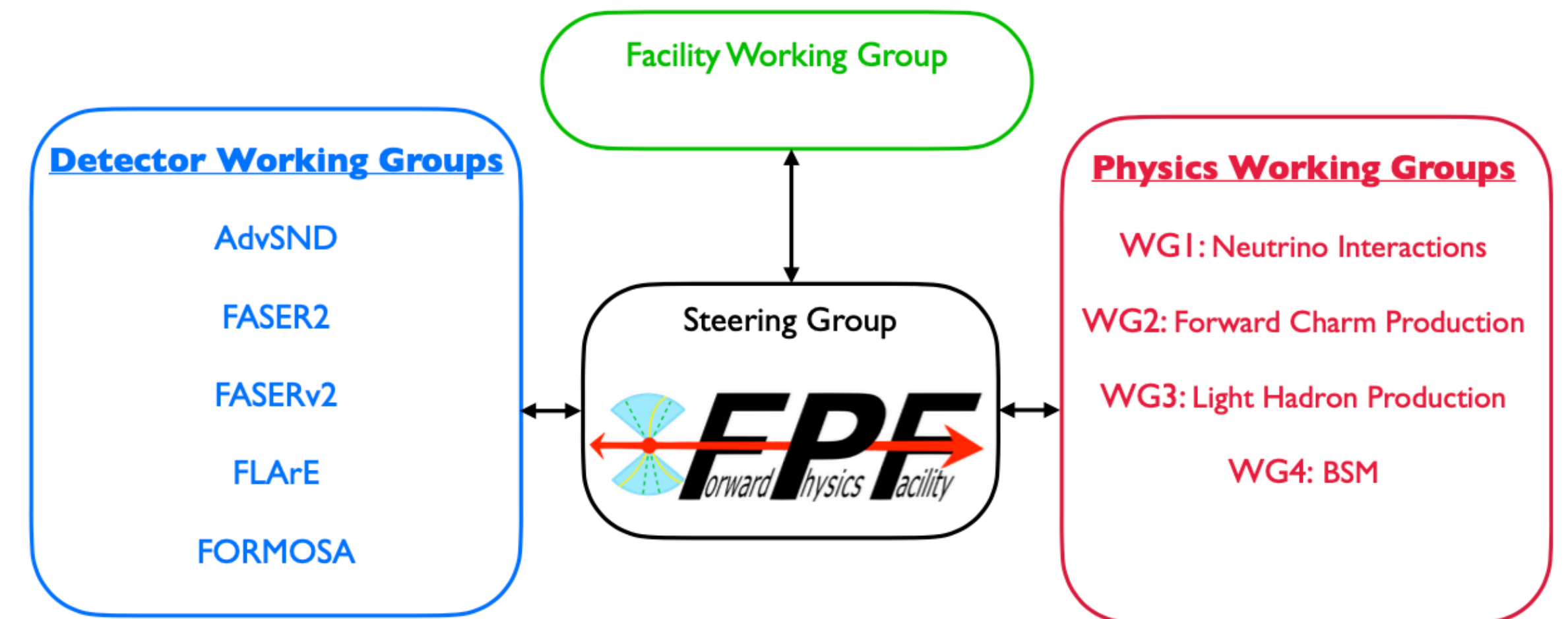
▶ The directorate asked to meet with us again around May 2023



# FPF Organization



- ▶ For the upcoming reviews and CDRs strong physics cases are essential, in particular, more quantitative results are needed!
- ▶ Working group (WG) structures:
  - ▶ 1 facility WG & 4 physics WGs
  - ▶ 5 detector WGs (each experiment)
- ▶ FPF Slack workspace for communication
- ▶ FPF webpage in preparation...



FPF Working Groups

	Facility WG	Physics WGs				Detector WGs				
	WG0	WG1	WG2	WG3	WG4	WG5	WG6	WG7	WG8	WG9
Topic	Facility	Neutrino Interactions	Charm Production	Light Hadron Production	BSM Physics	FASER2	FASERnu2	FLArE	AdvSND	FORMOSA
Contacts	J. Boyd	J. Rojo	M. H. Reno	D. Soldin, L. Anchordoqui	B. Batell, S. Trojanowski	J. McFayden	A. Ariga, T. Arika	J. Bian, M. Diwan	G. De Lellis	M. Citron, C. Hill

Steering committee: J. Boyd, J. Feng, F. Kling

# 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

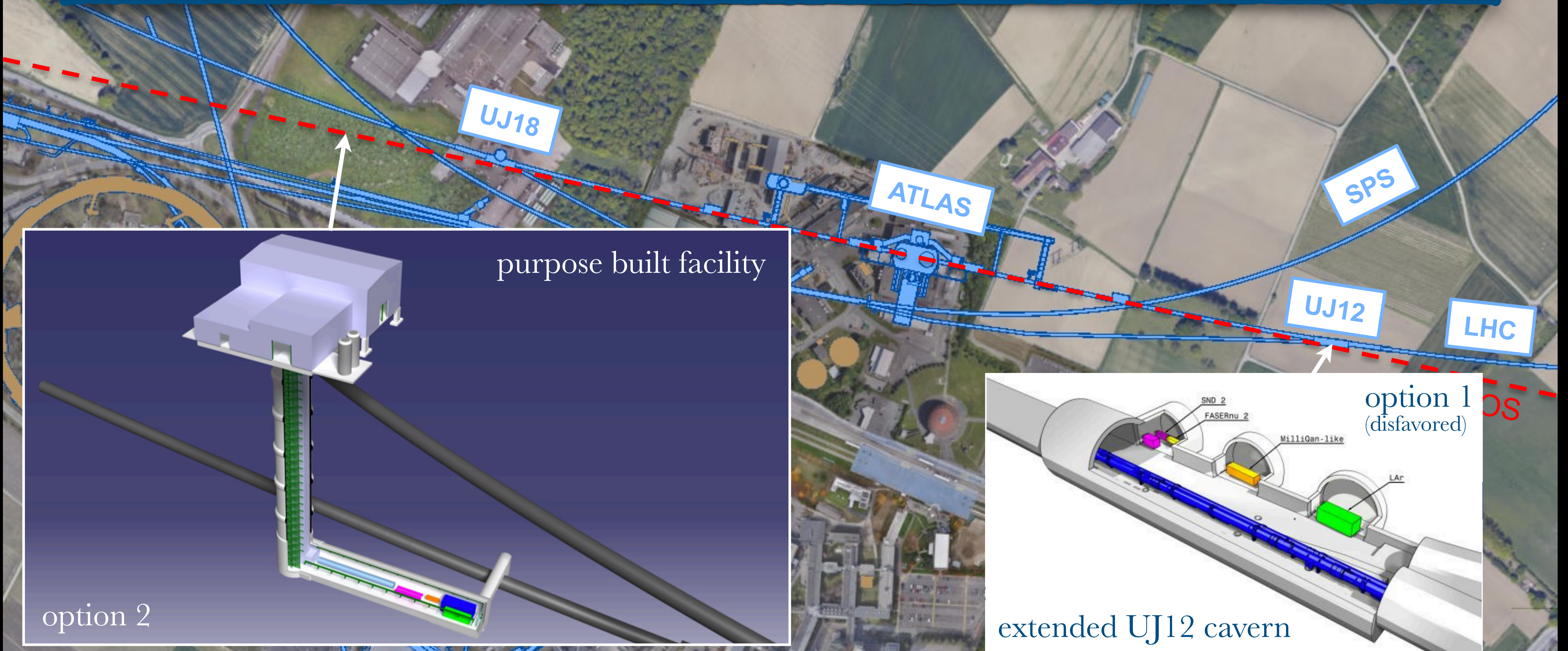
LOS

- ▶ 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, ...

Felix Kling's talk next week!

# 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

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

UJ18

ATLAS

Highly disfavored!

UJ12

LHC

purpose built facility

option 2

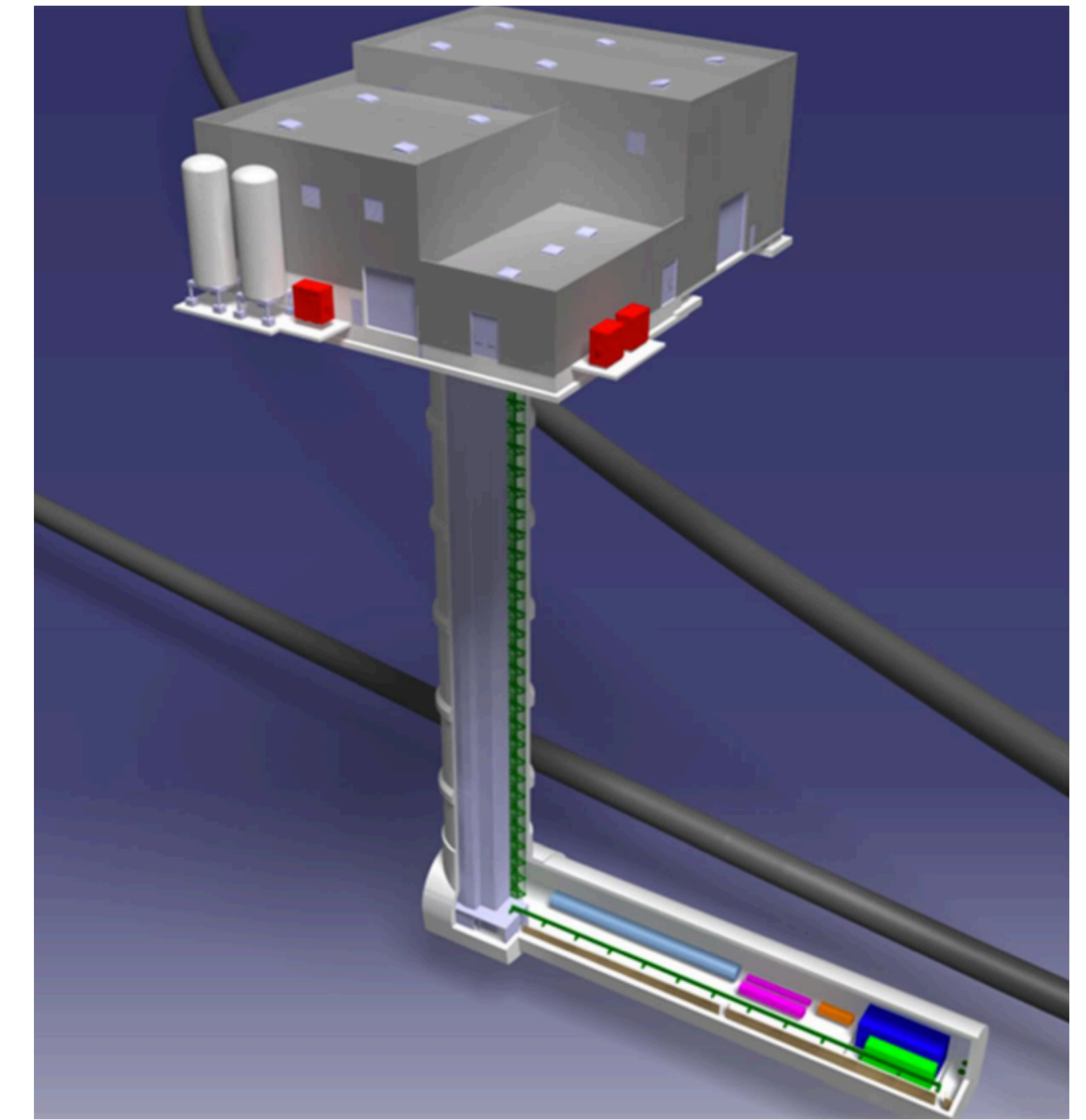
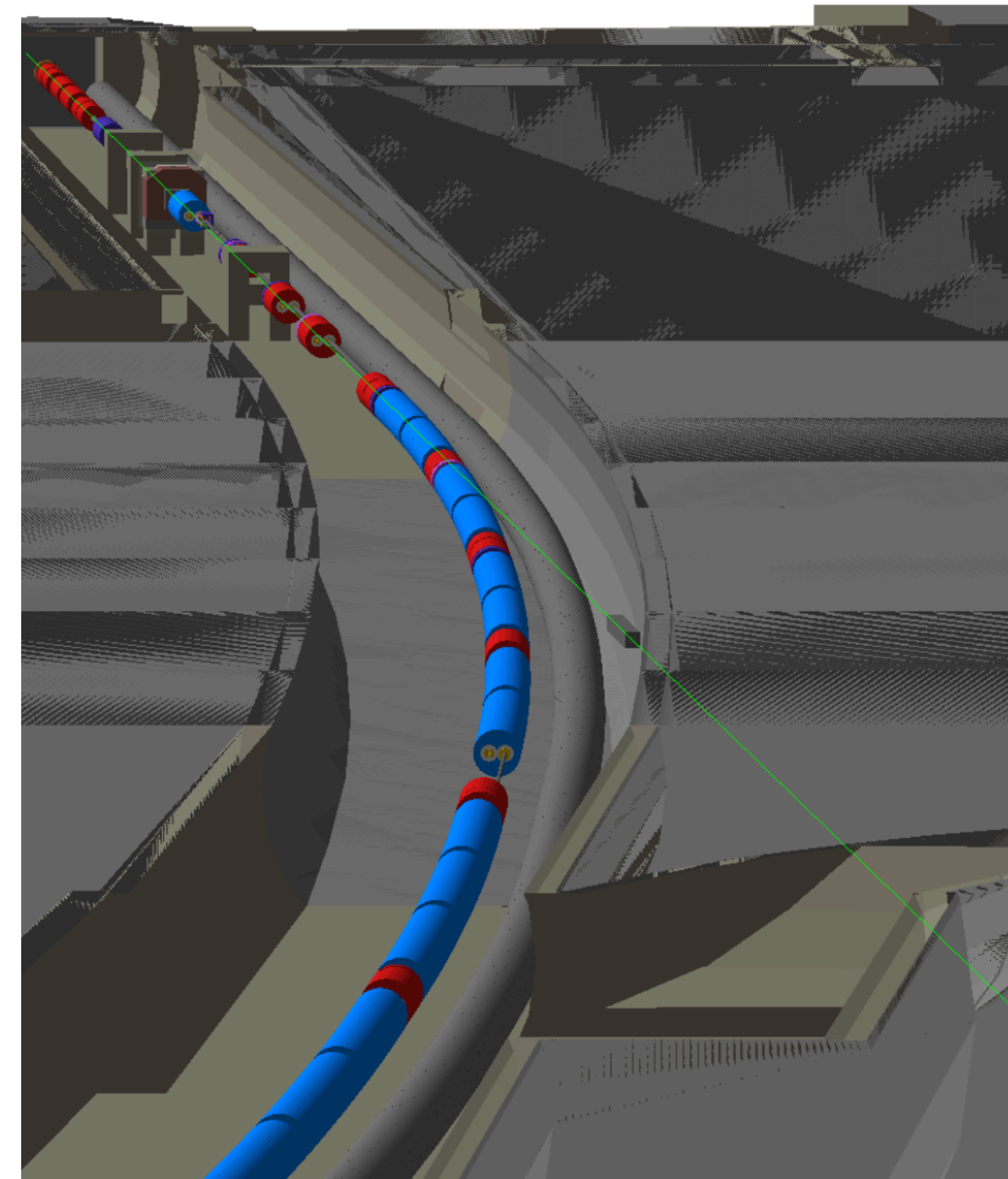
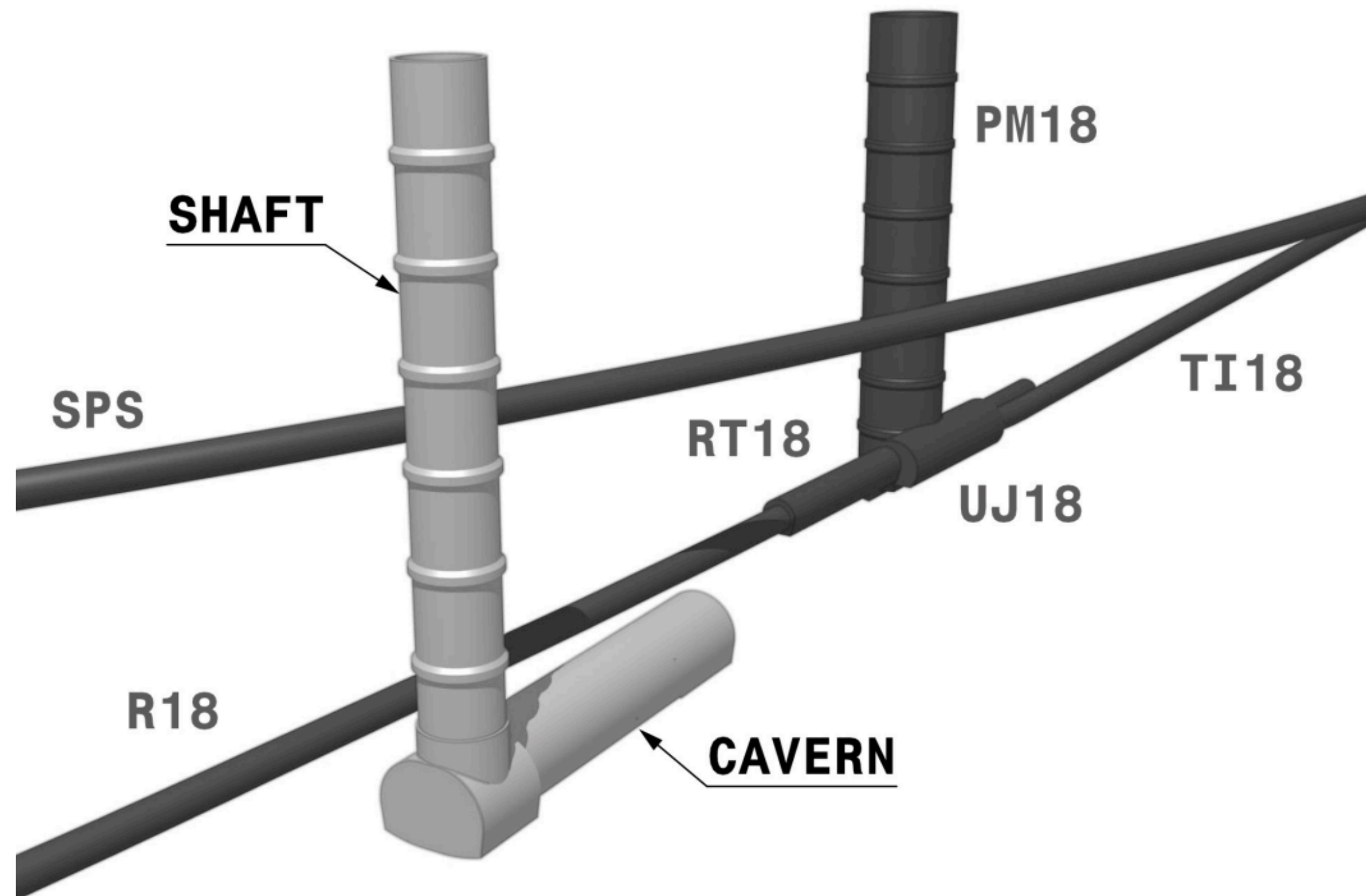
extended 2 caves

option 1  
(disfavored)

# The Facility



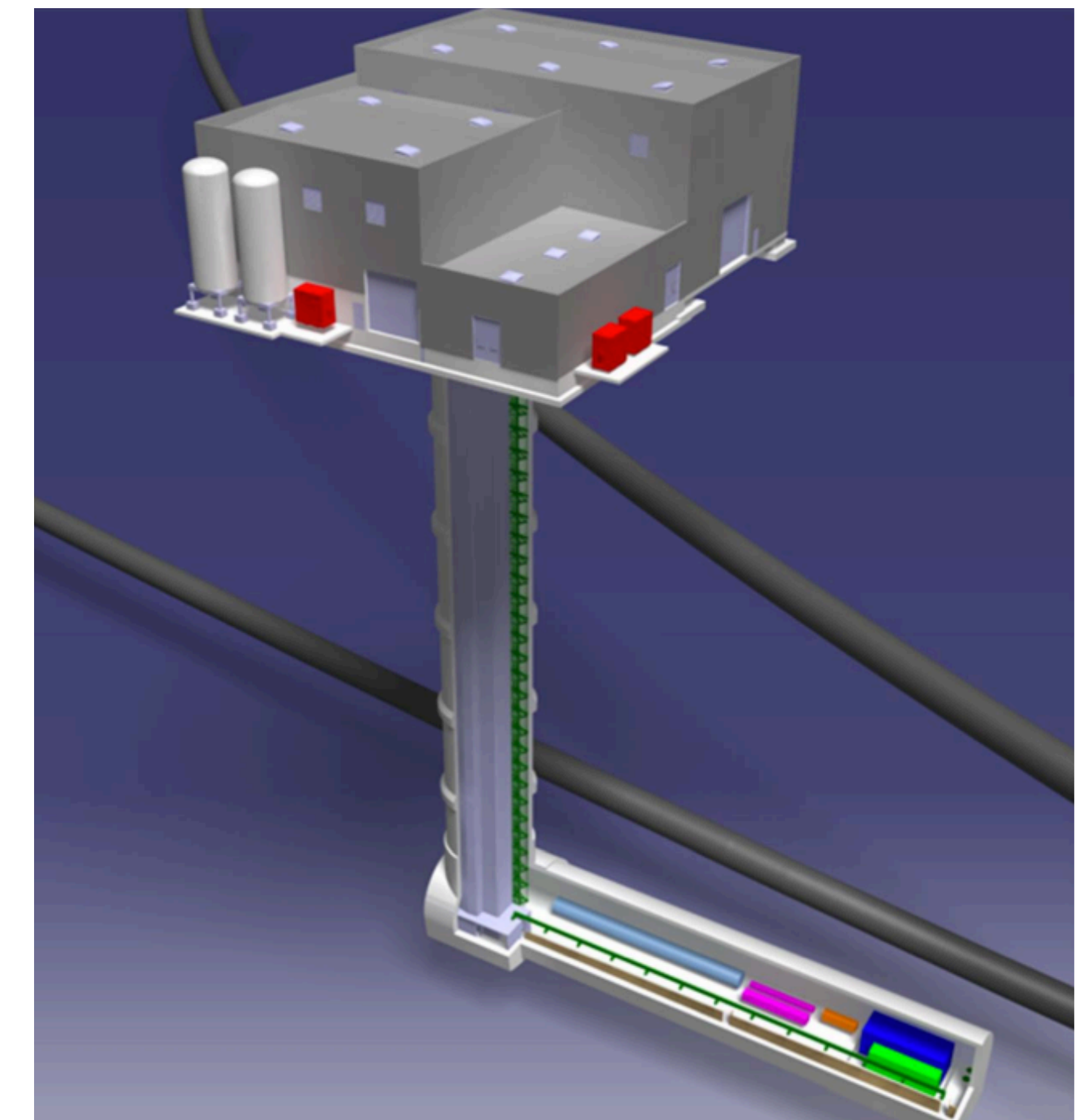
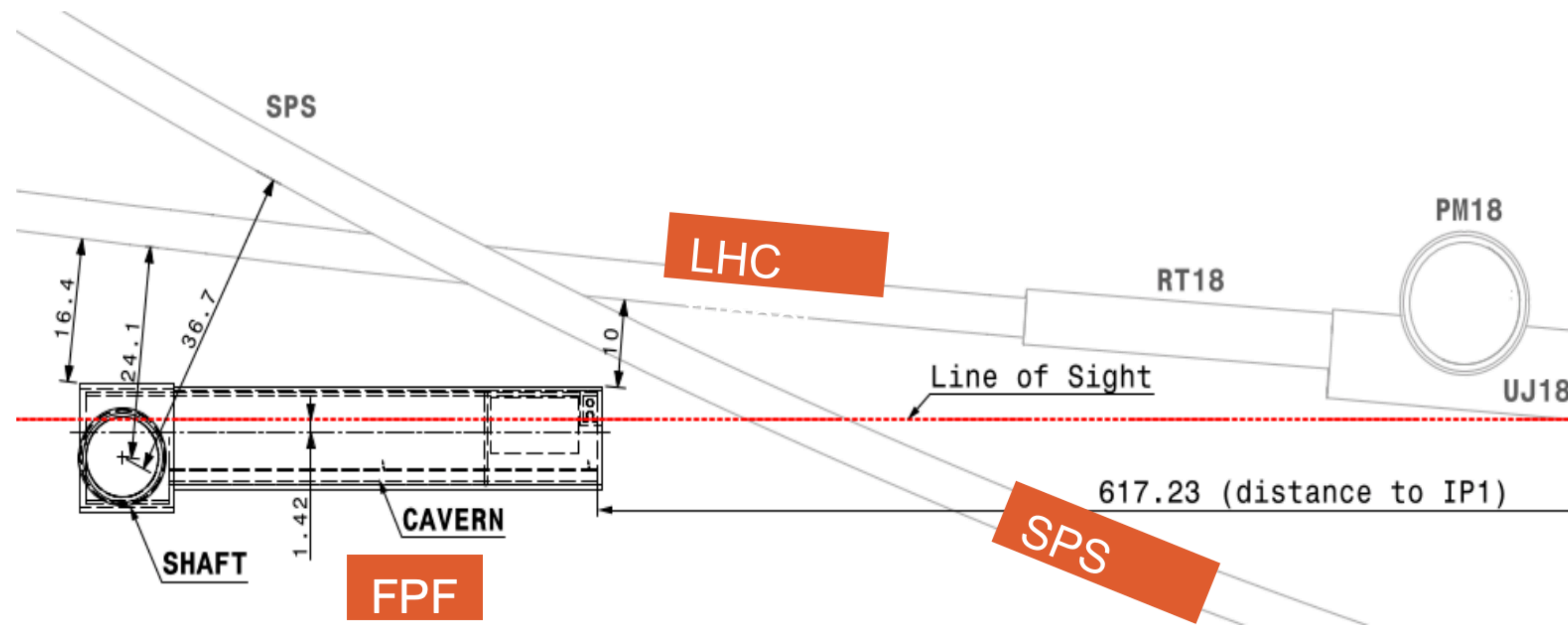
- ▶ Focus of this talk: purpose built facility (favored option!)
- ▶ Extended UJ12 cavern also explored and similar ideas apply (highly disfavored!)
- ▶ Currently five proposed experiments (later slides)



# The Facility



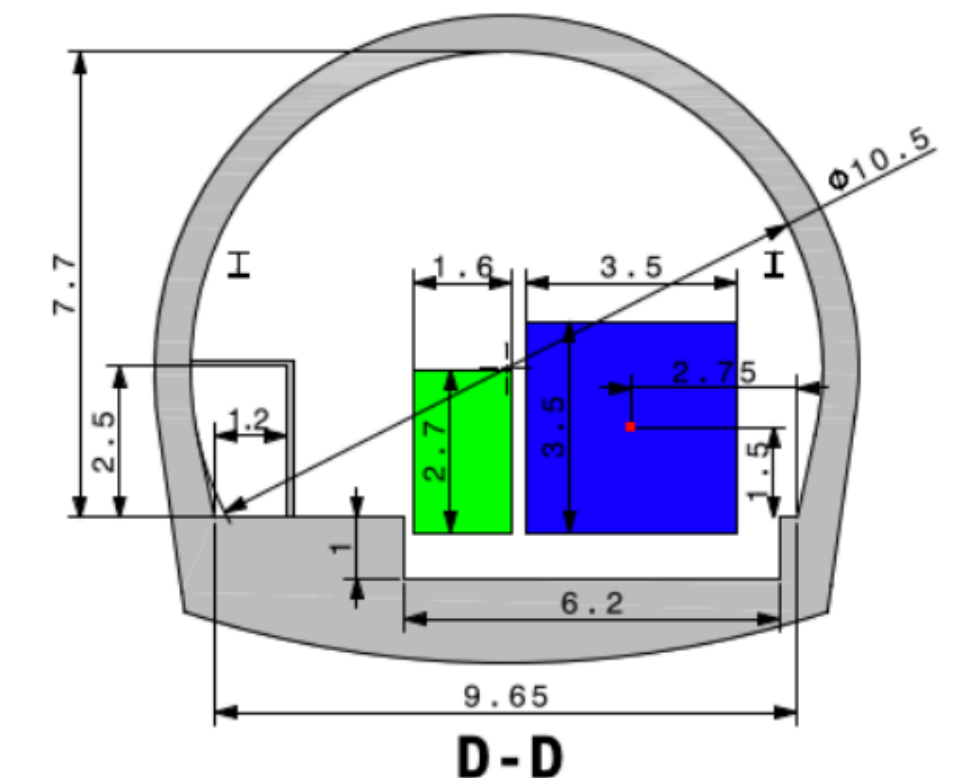
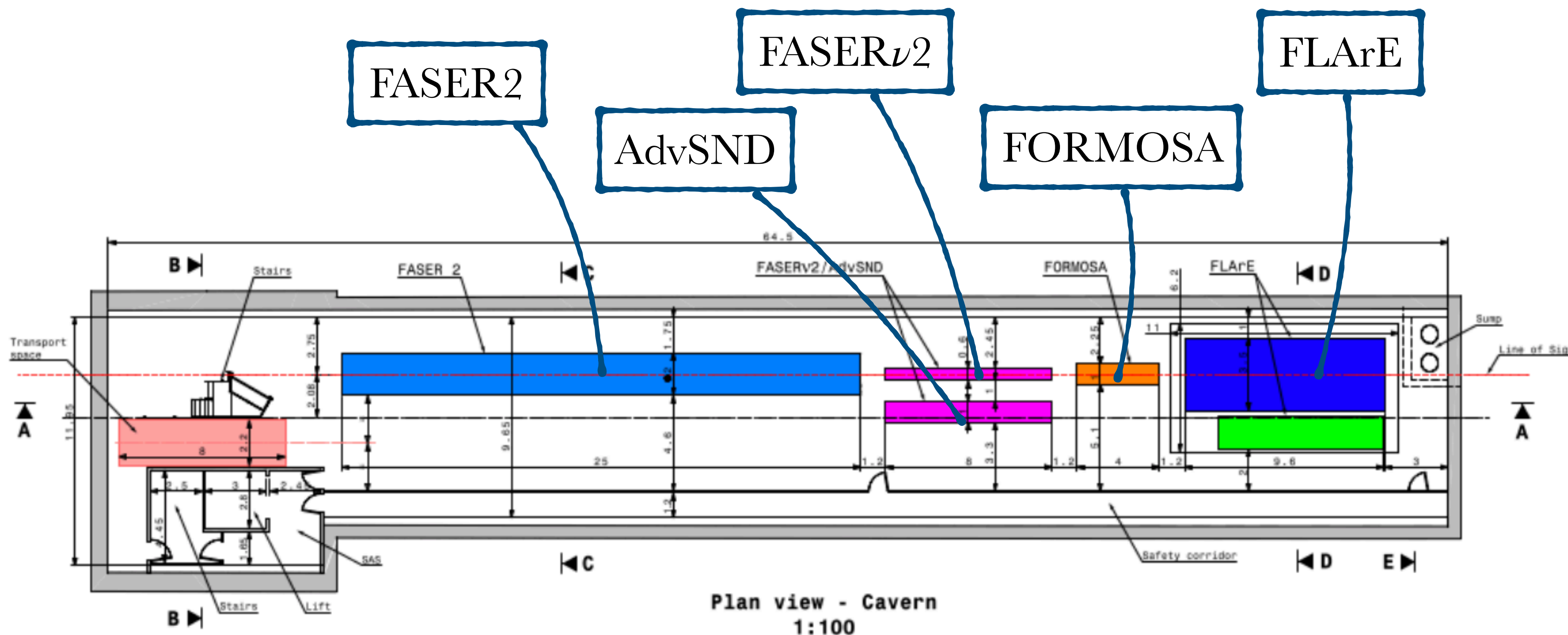
- ▶ Focus of this talk: purpose built facility (favored option!)
- ▶ Extended UJ12 cavern also explored and similar ideas apply (highly disfavored!)
- ▶ Currently five proposed experiments (later slides)



# The Facility



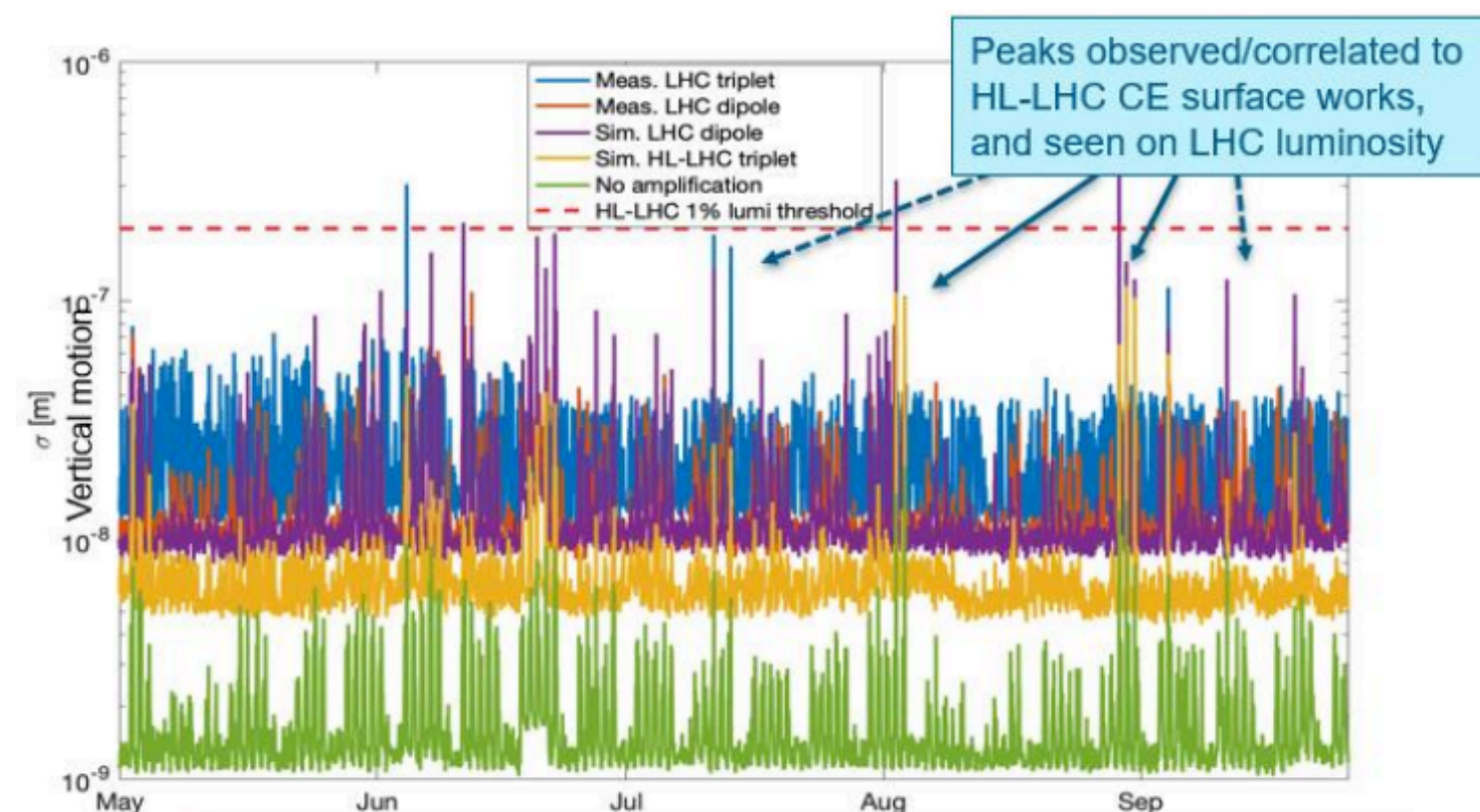
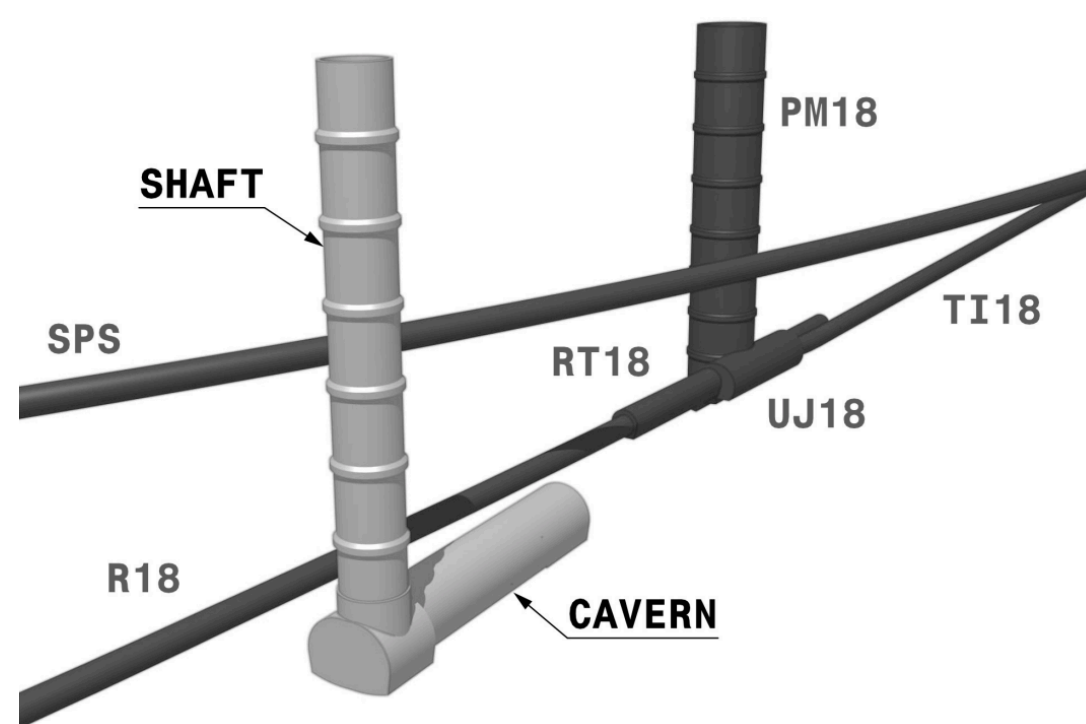
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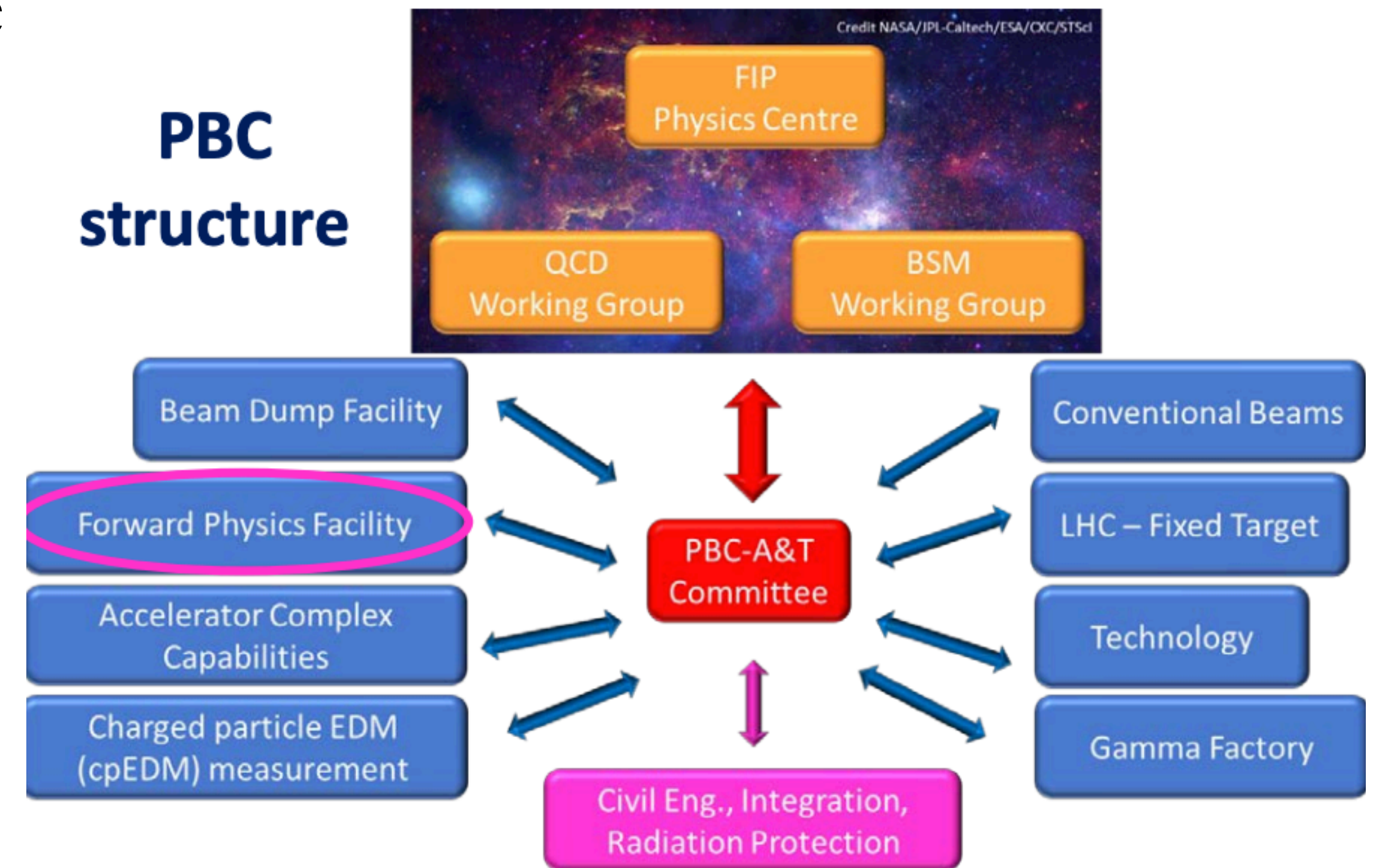
# FPF Status



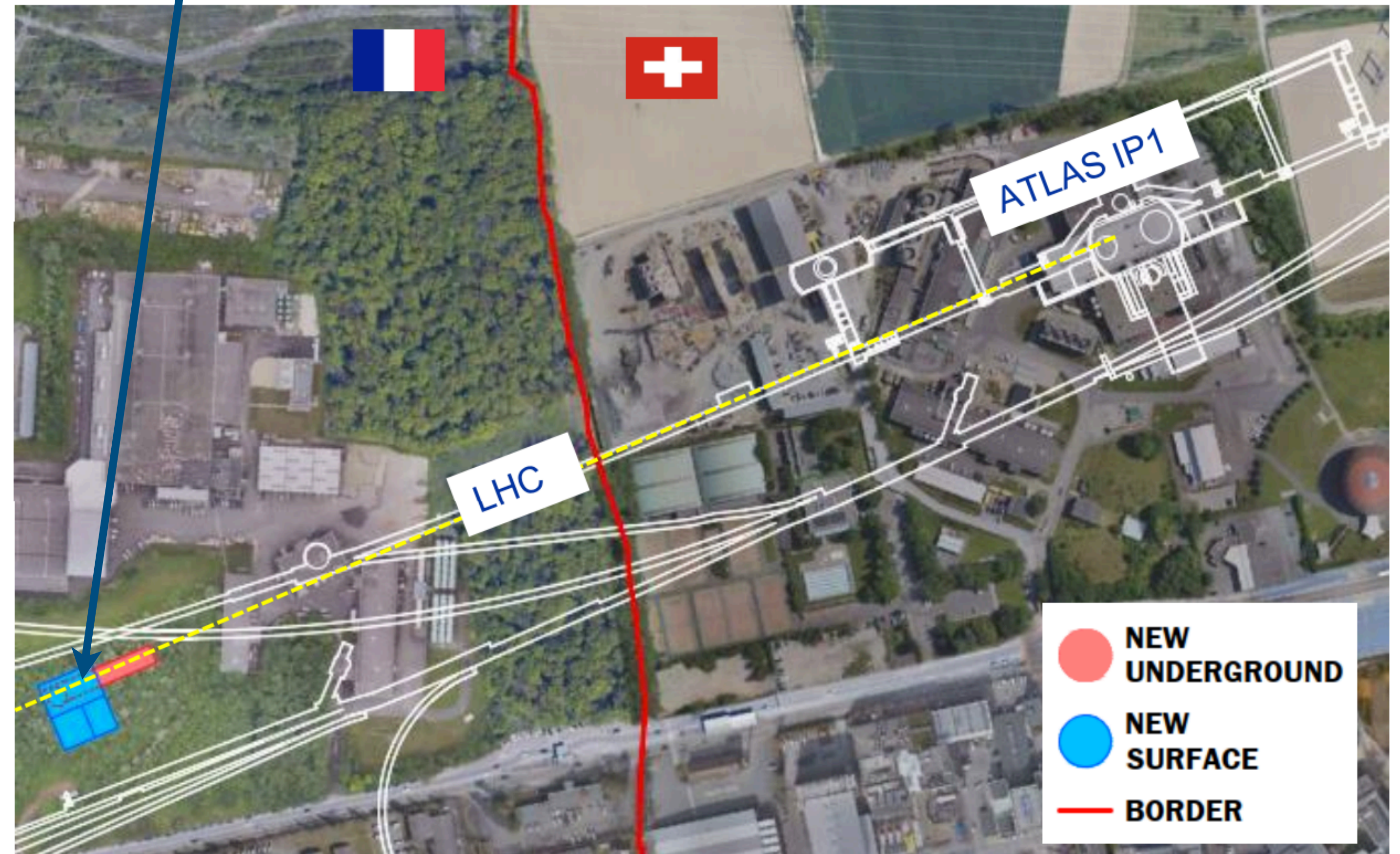
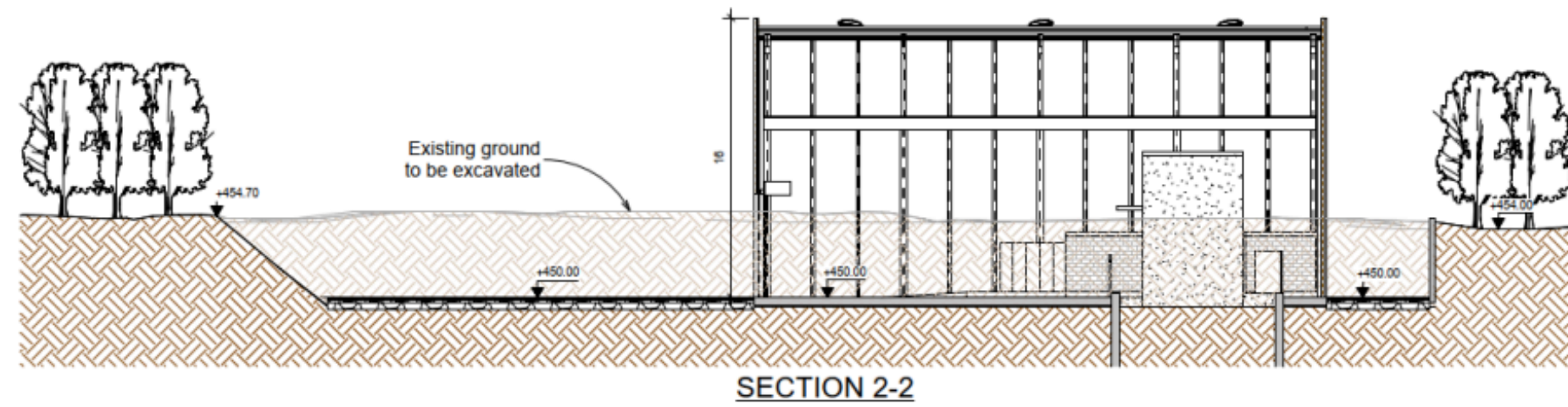
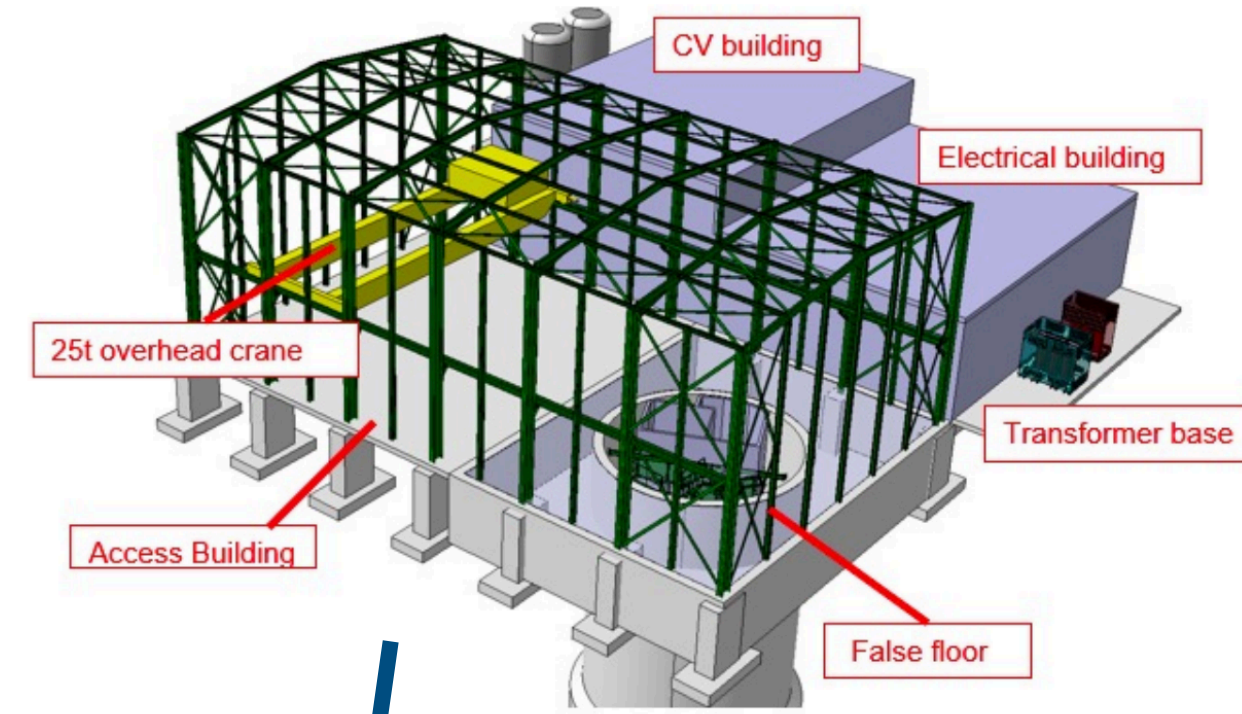
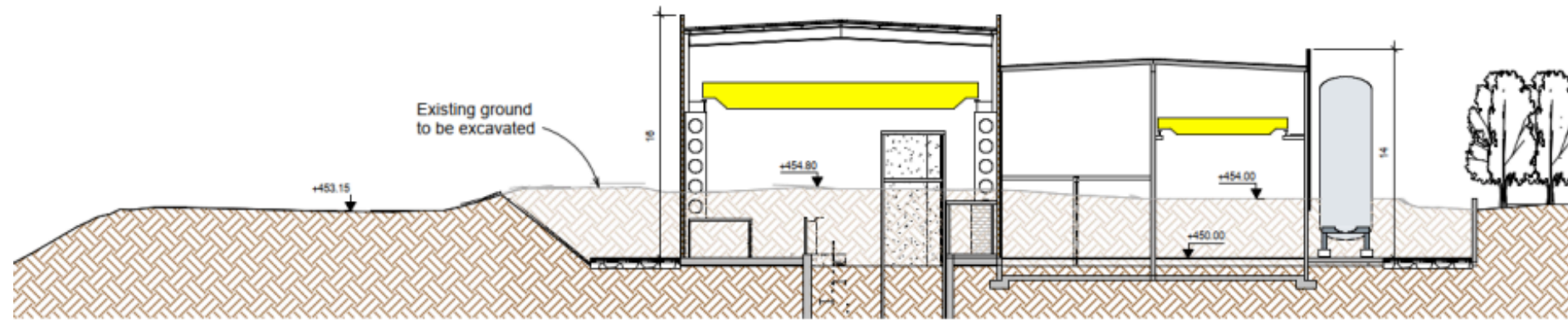
- ▶ Latest news from facility / civil engineering:
  - ▶ Safety corridor between FPF and LHC tunnel no longer needed
  - ▶ Vibration studies indicate that construction of the FPF, installation of services and experiments, will not interfere with LHC operations
  - ▶ FPF is one of the major new projects supported by the Physics Beyond Collider (PBC) committee
  - ▶ The PBC has allocated 75k CHF for a site investigation study to take a core



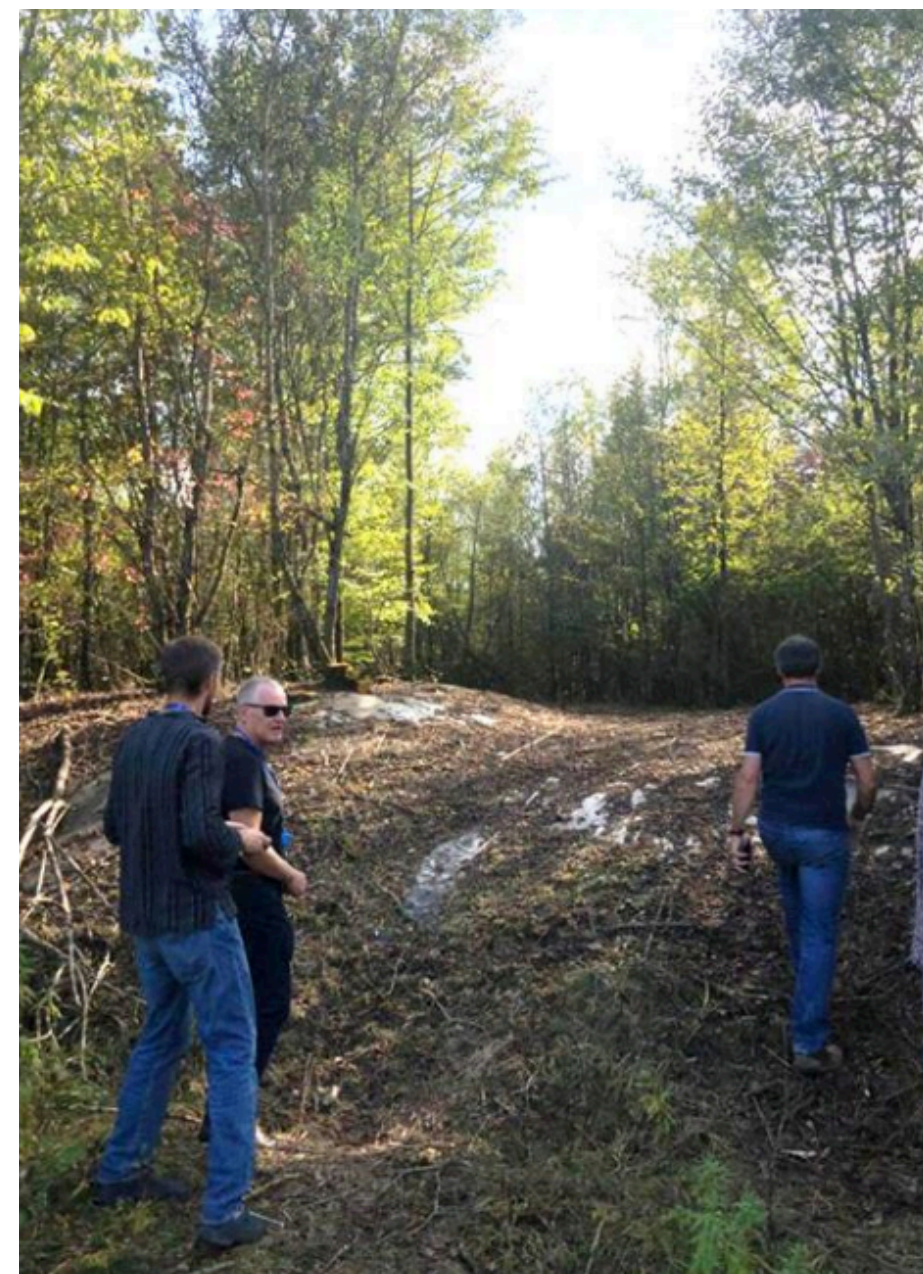
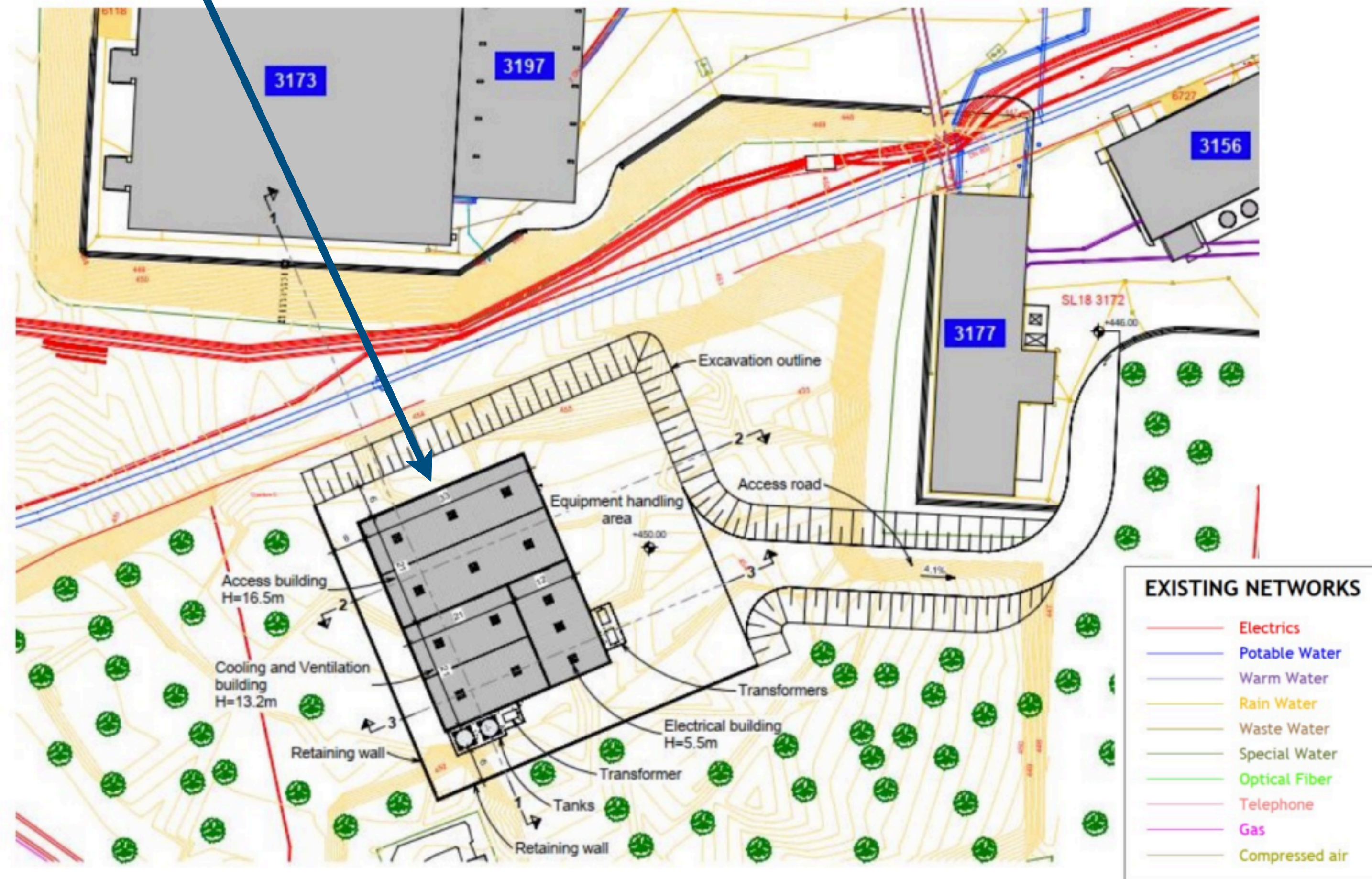
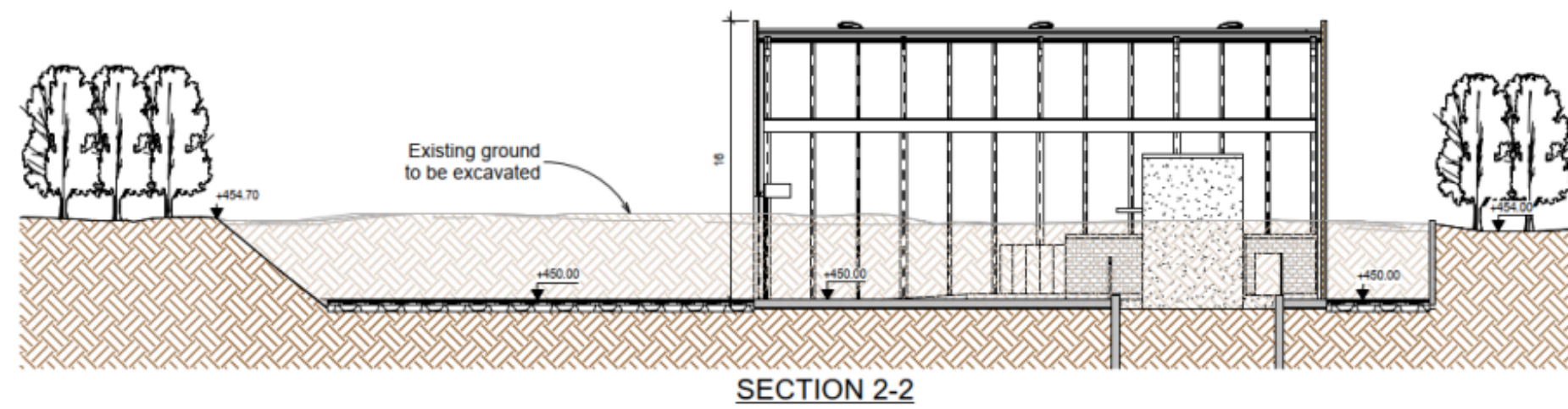
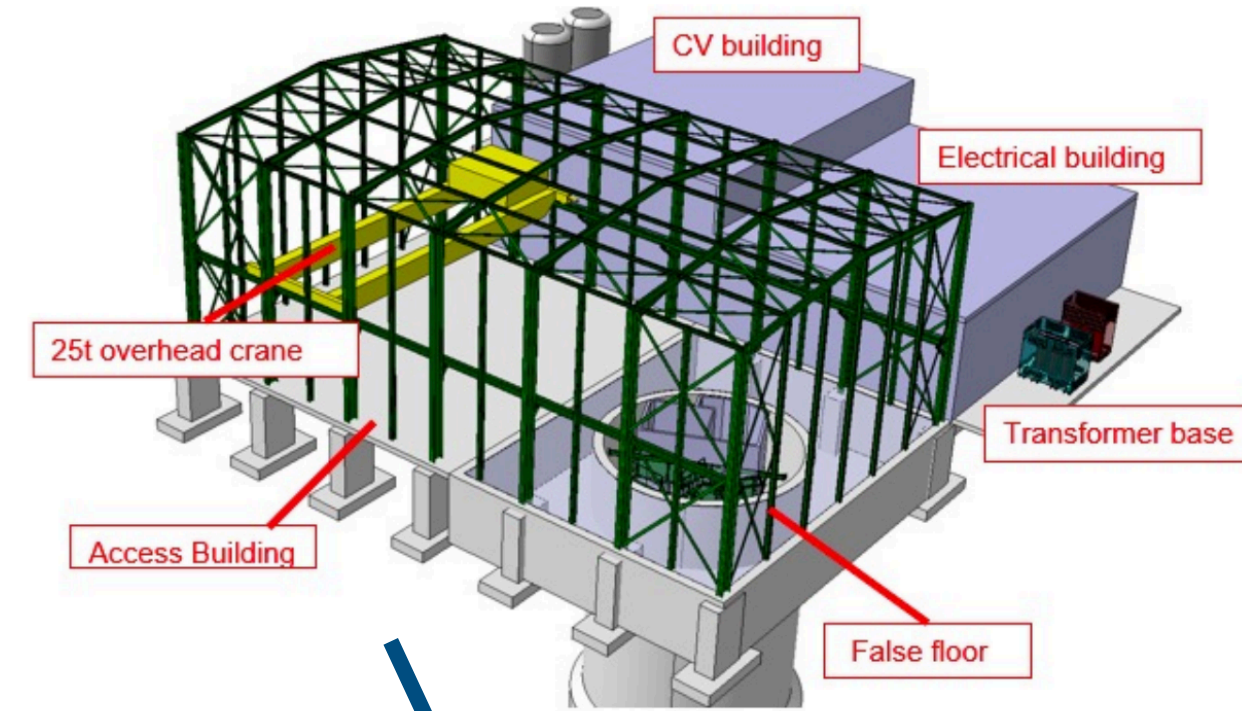
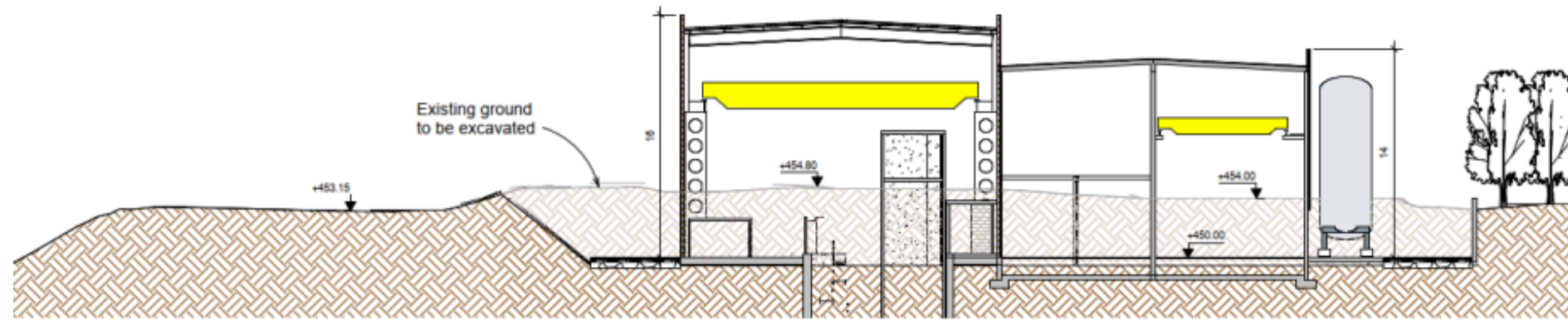
## PBC structure



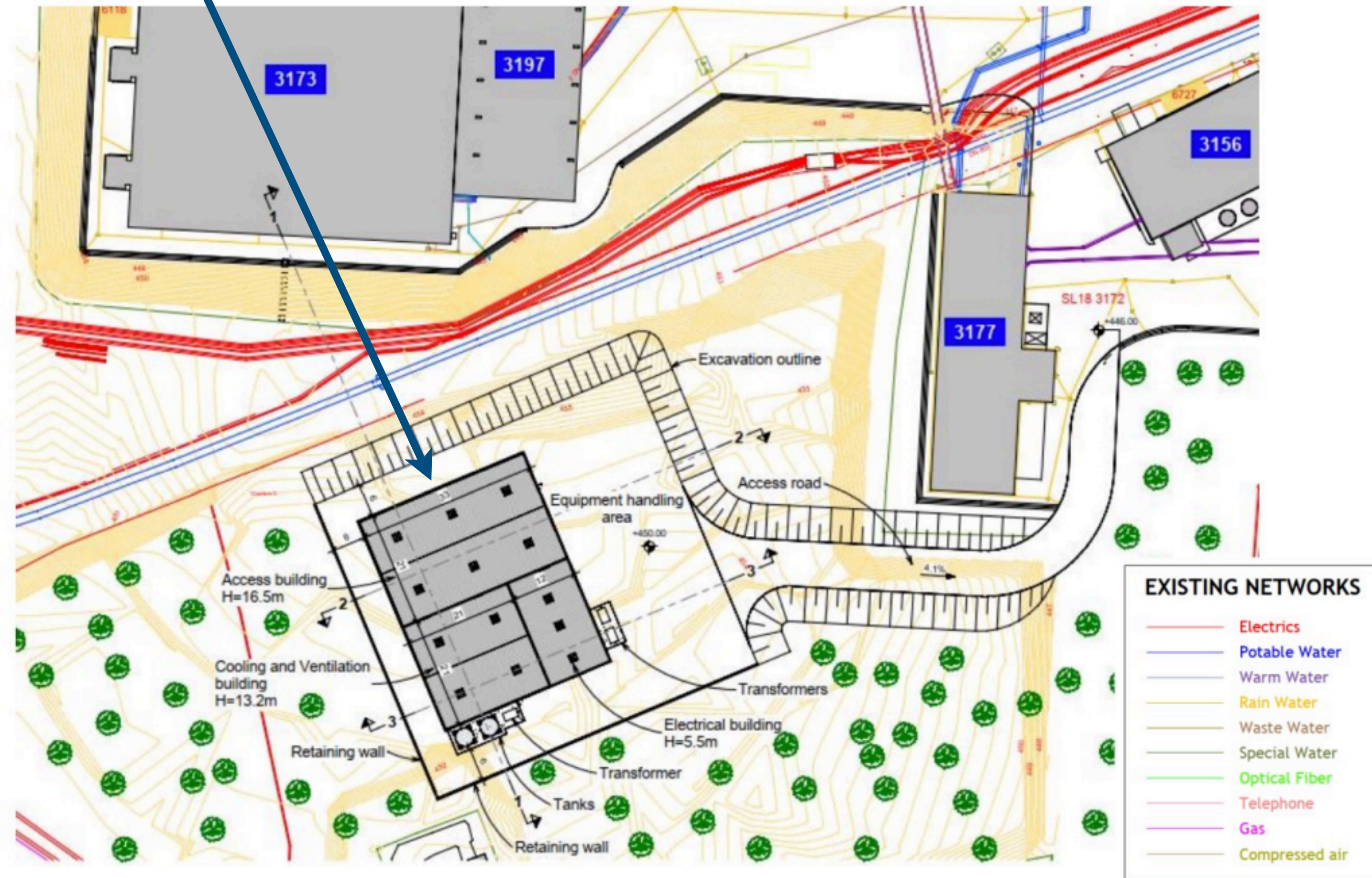
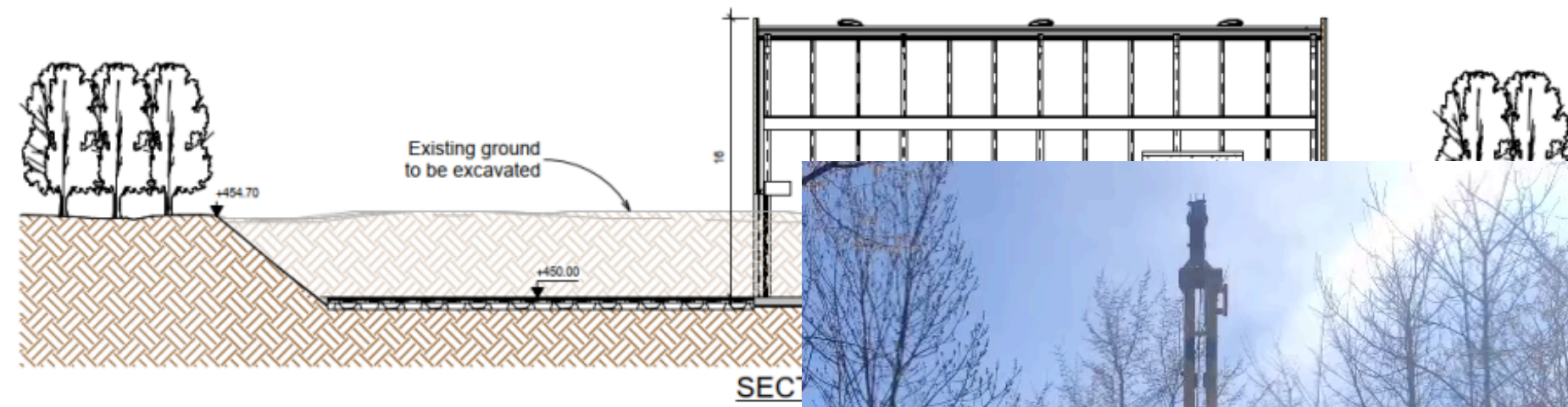
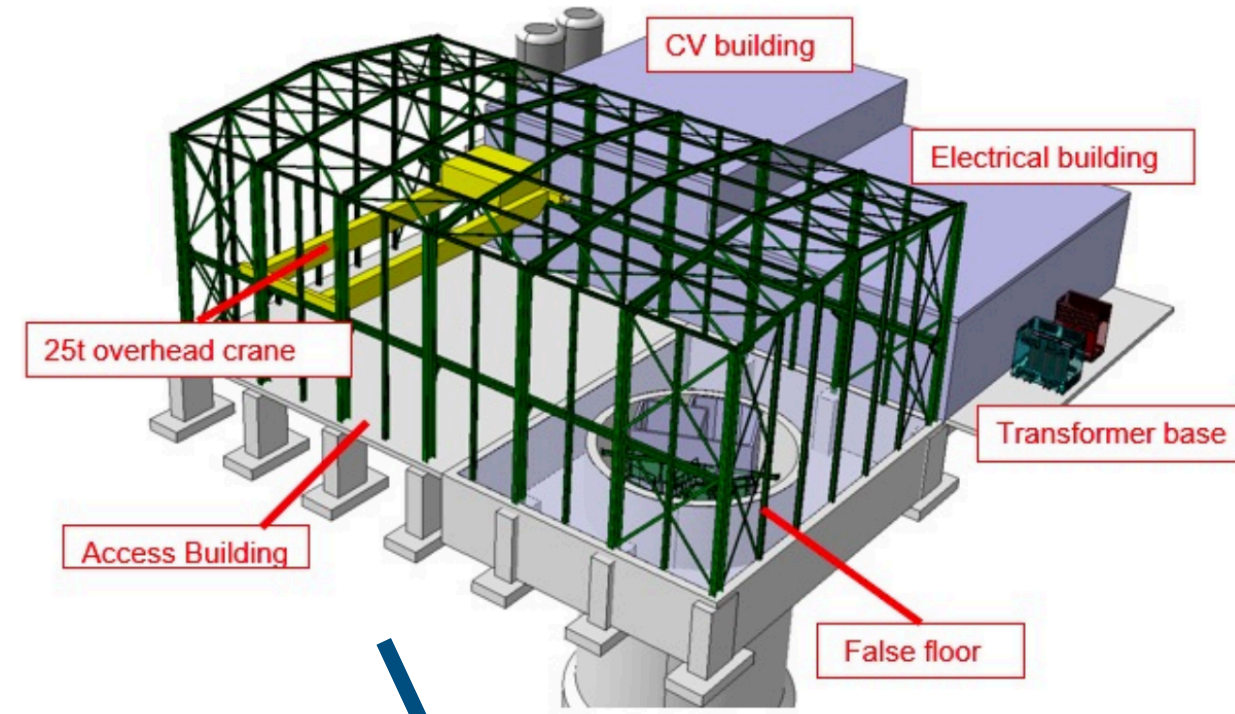
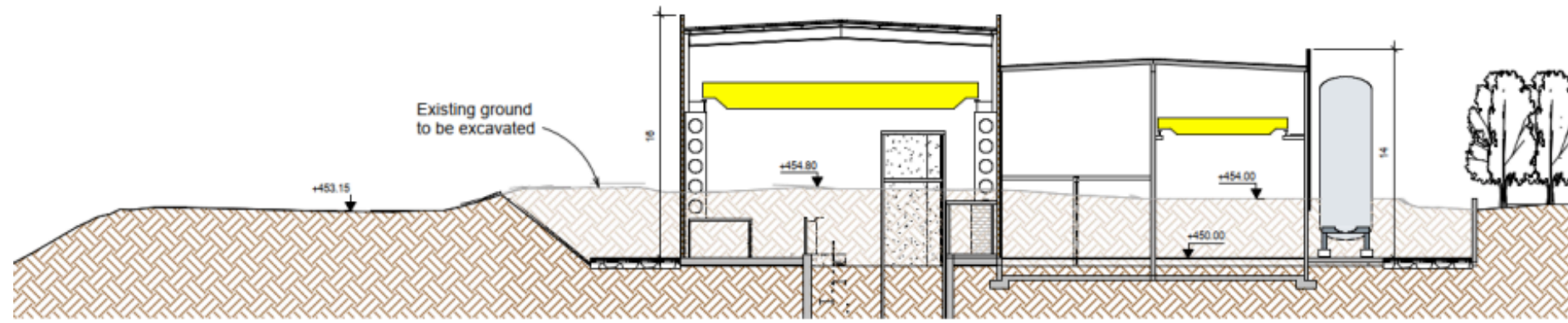
# The Facility



# The Facility

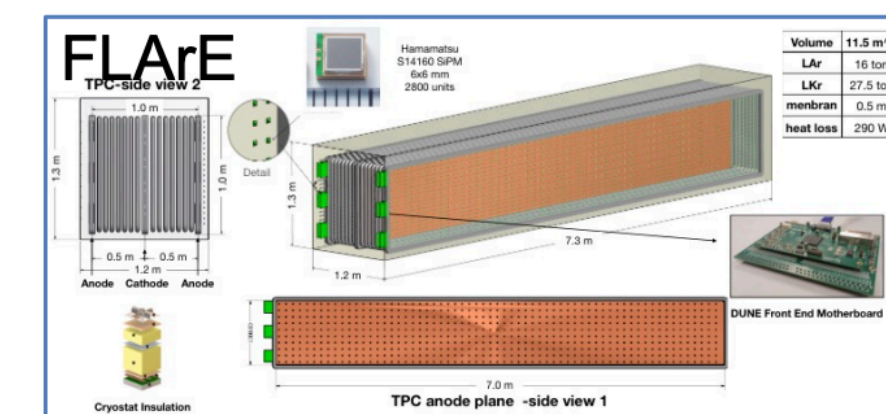
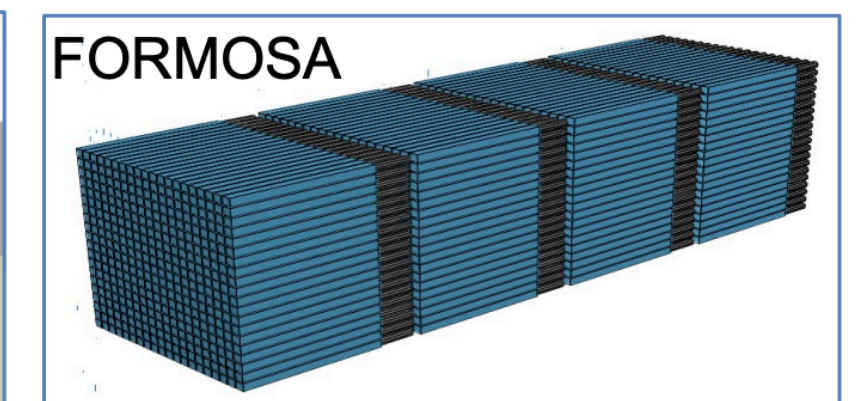
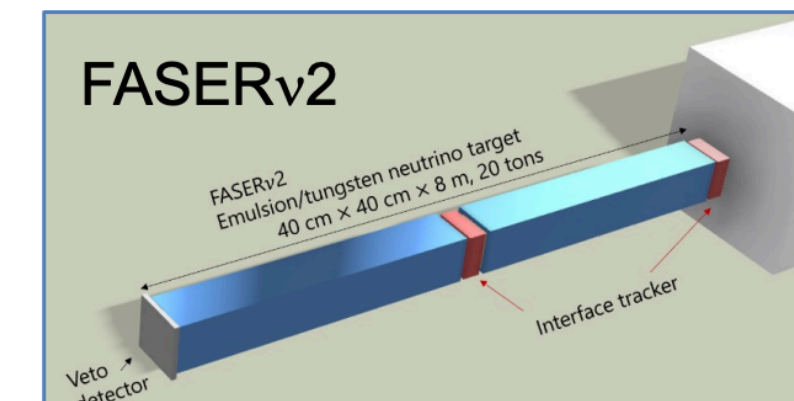
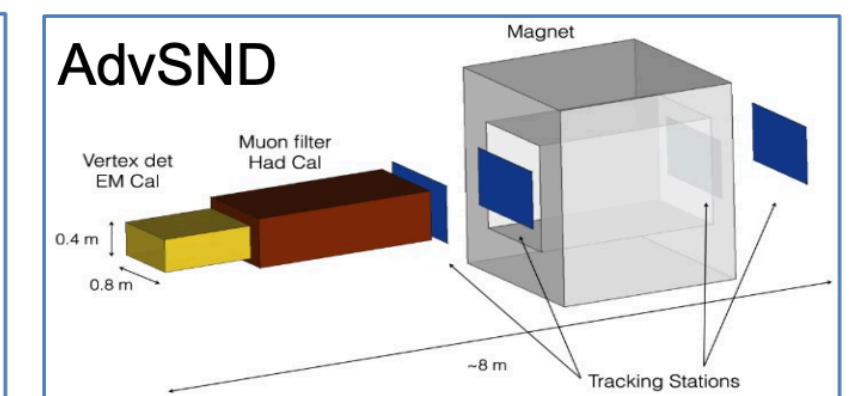
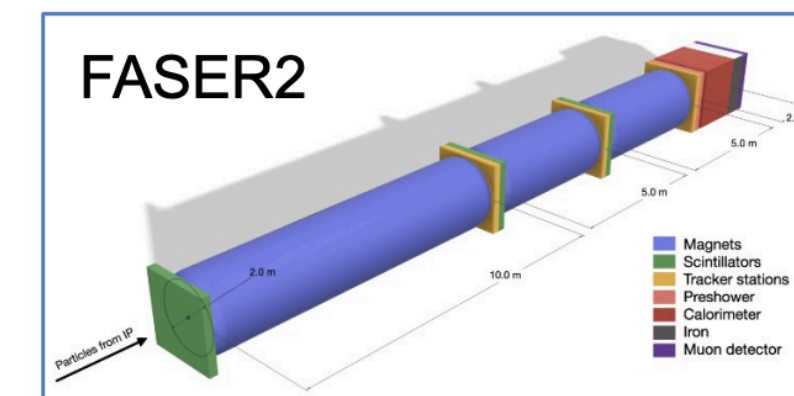
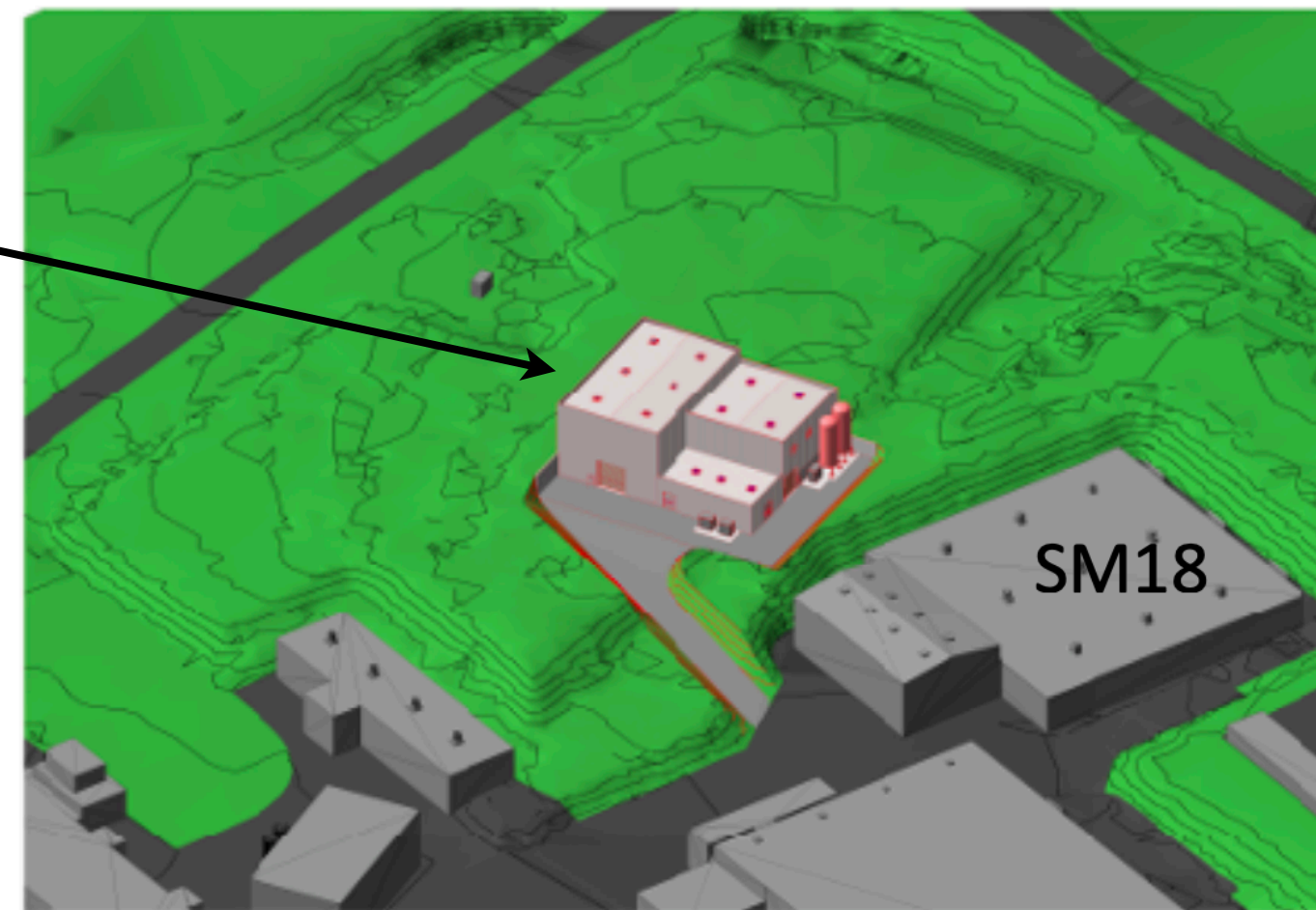
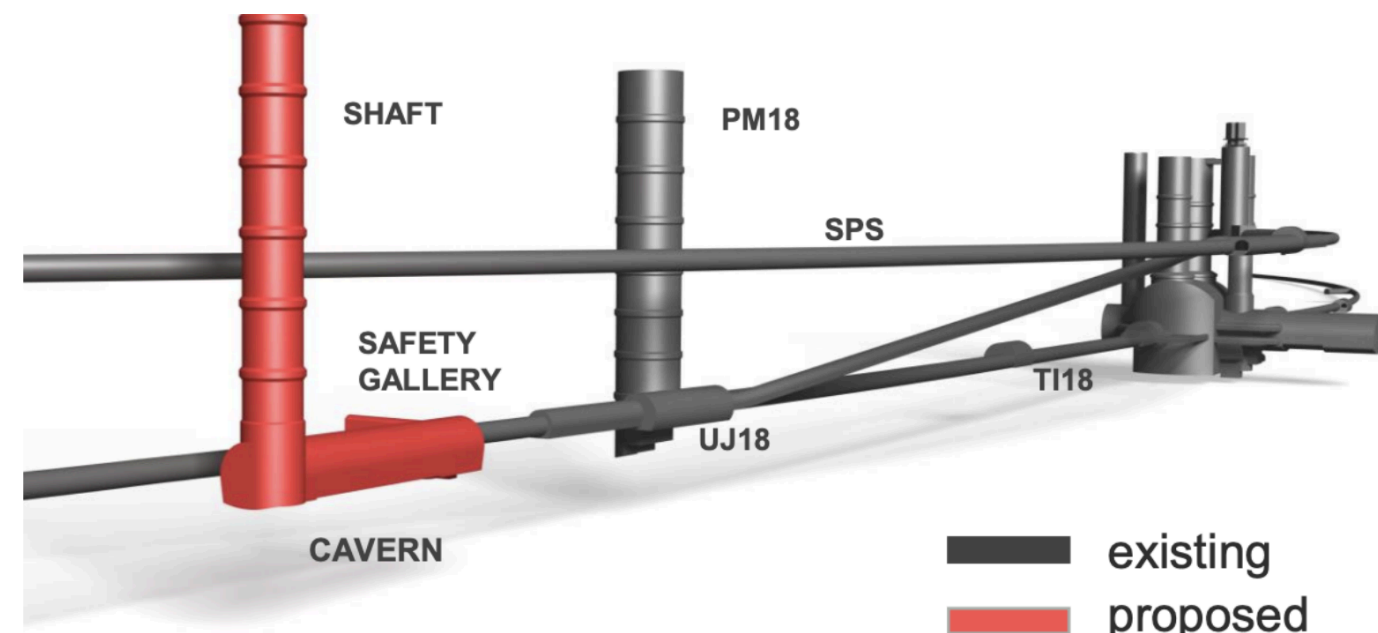
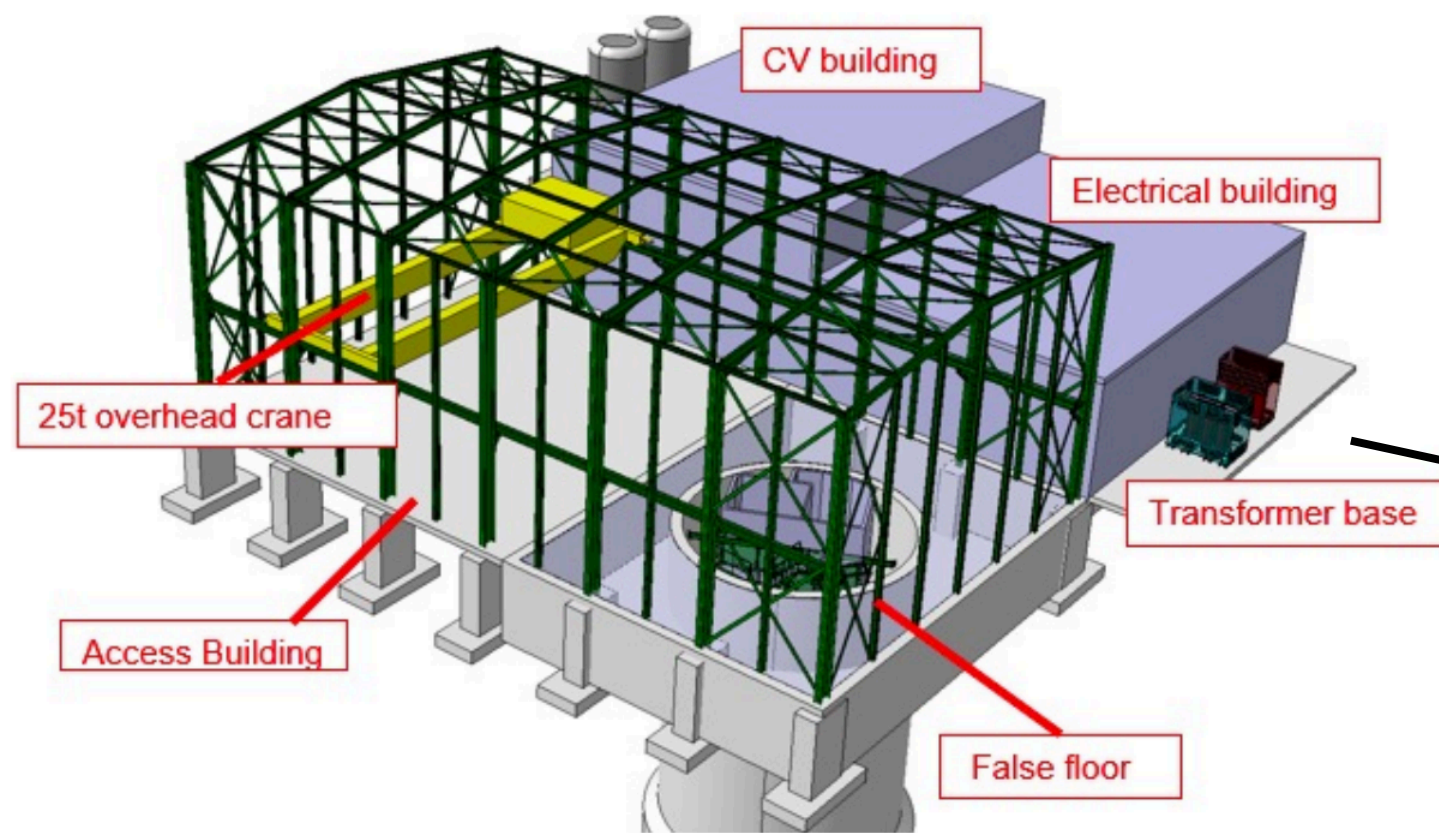
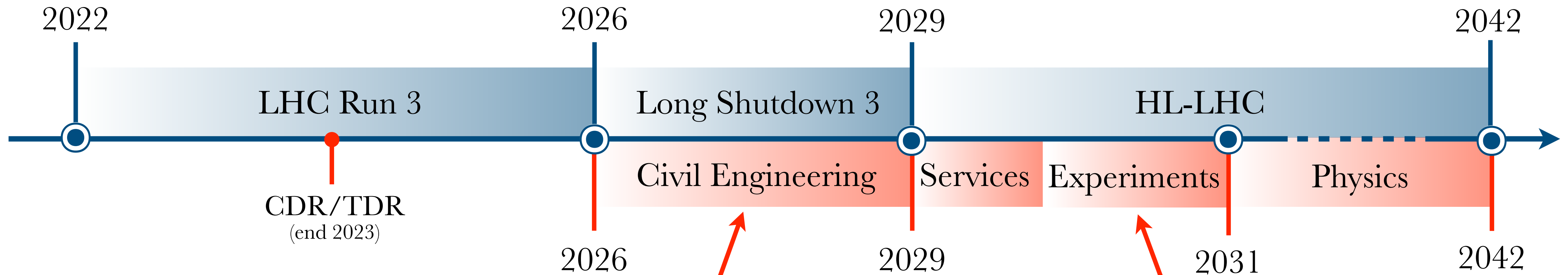


# The Facility





# FPF Timeline



# Proposed Experiments

# FPF Physics Potential



## ▶ Example:

FASER $\nu$  pilot detector

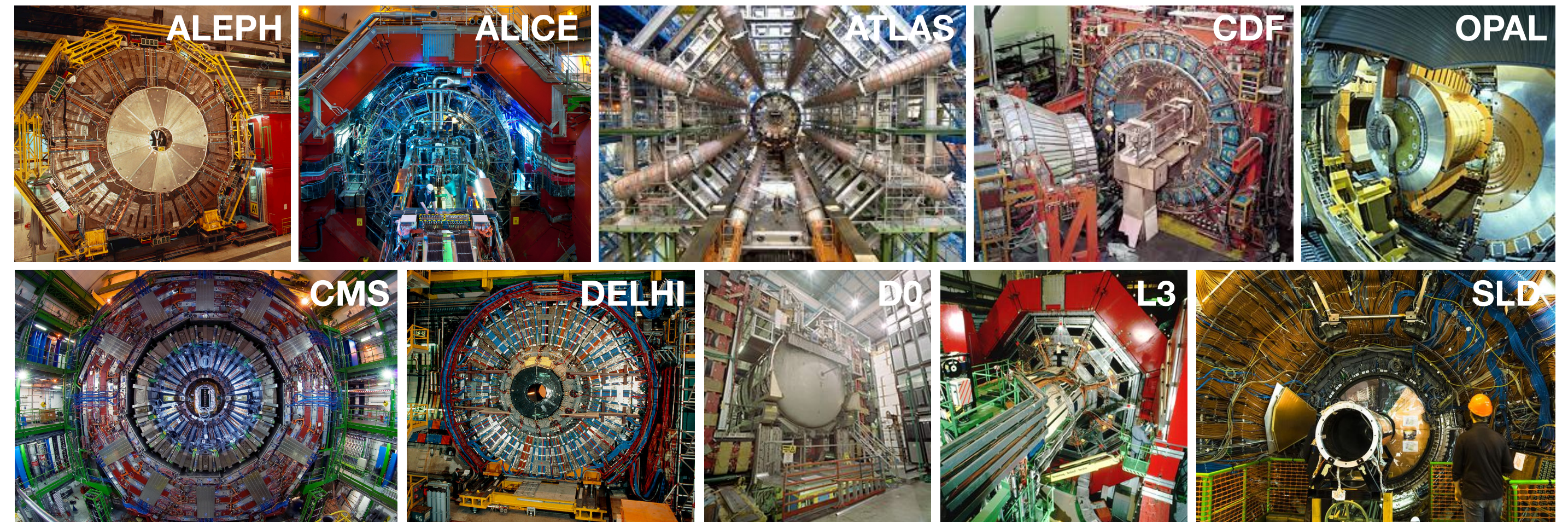
vs.

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



# FPP Physics Potential



## ▶ Example:

FASER $\nu$  pilot detector

vs.

All previous collider experiments

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▶ 6 TeV neutrino candidates

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

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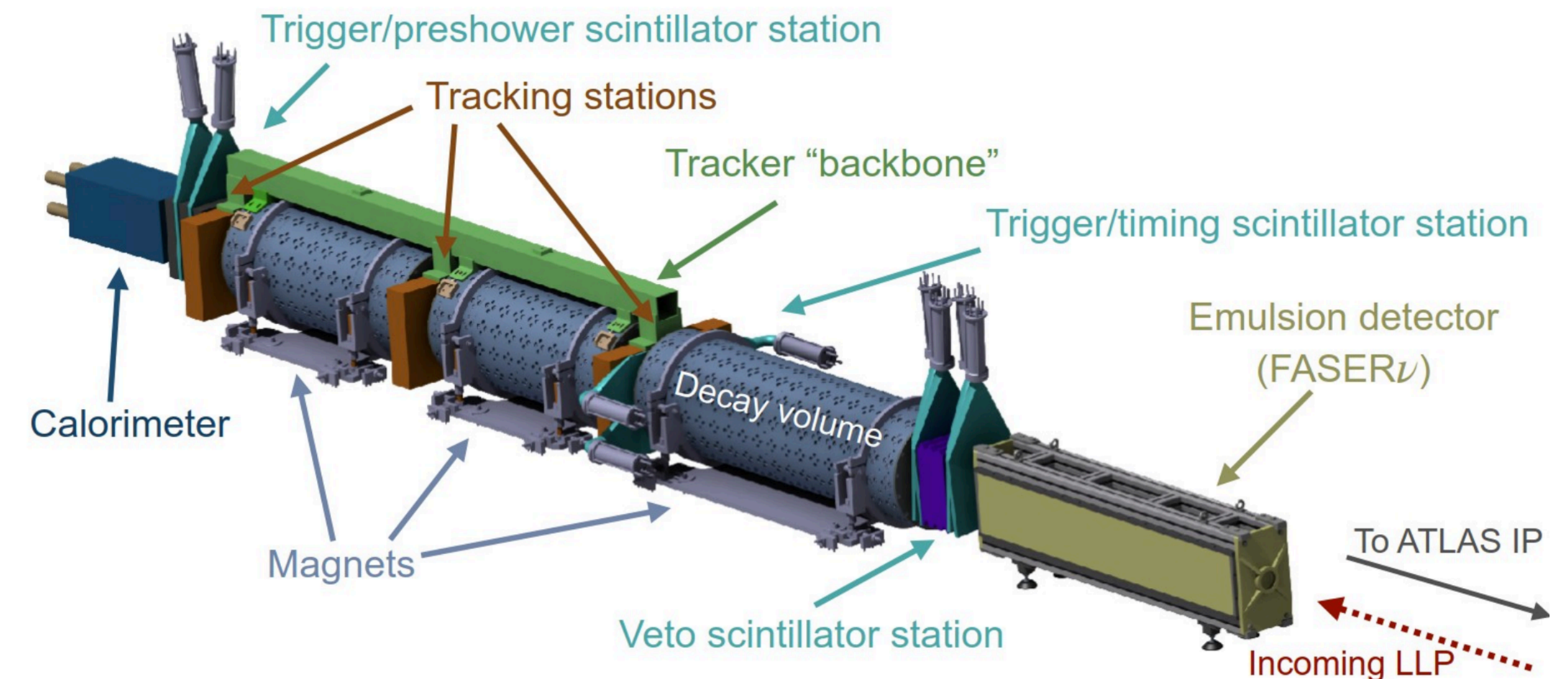
▶ 0 TeV neutrino candidates

## ▶ FASER $\nu$ years 2022-2024:

▶  $\sim 10000$   $\nu$  candidates expected  
( $\sim 10^9$  muons\*)

## ▶ Forward Physics Facility, FASER $\nu$ 2:

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



\*origin not well understood, further studies needed

# FPF Physics Potential



## ▶ Example:

FASER $\nu$  pilot detector

vs.

All previous collider experiments

- ▶ Suitcase size, 4 weeks of data
- ▶ Costs: \$0 (recycled parts)
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## ▶ Forward Physics Facility, FASER $\nu$ 2:

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

**See Felix Kling's  
talk next week!**

# Proposed FPF Experiments



▶ Five proposed experiments\* with different (main) physics goals:

▶ FASER2

▶ Long-lived particles

▶ FASER $\nu$ 2

▶ TeV neutrinos

▶ AdvSND

▶ TeV neutrinos

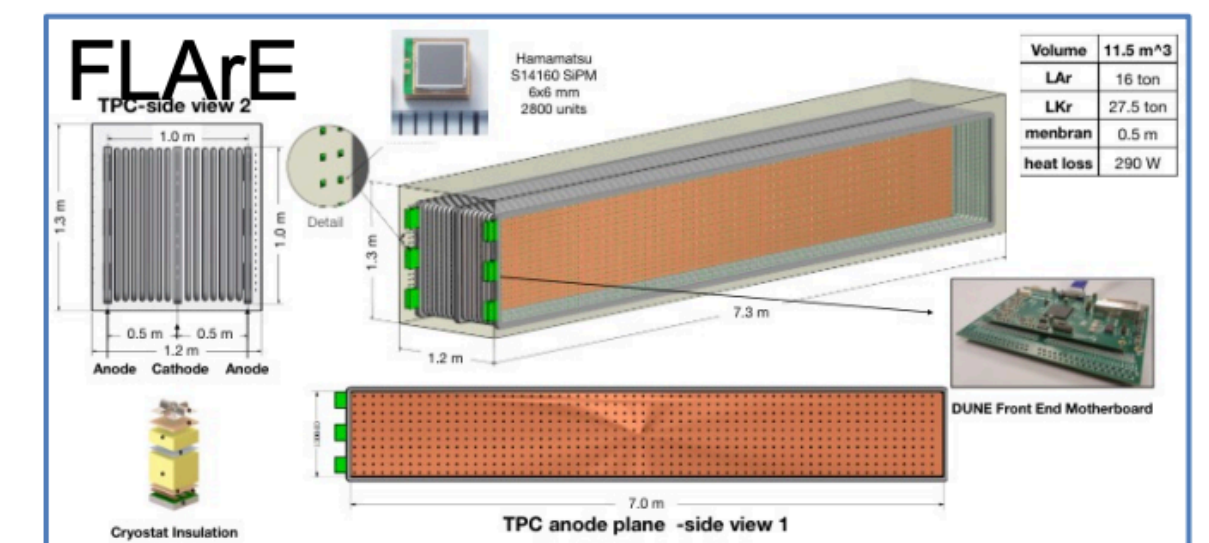
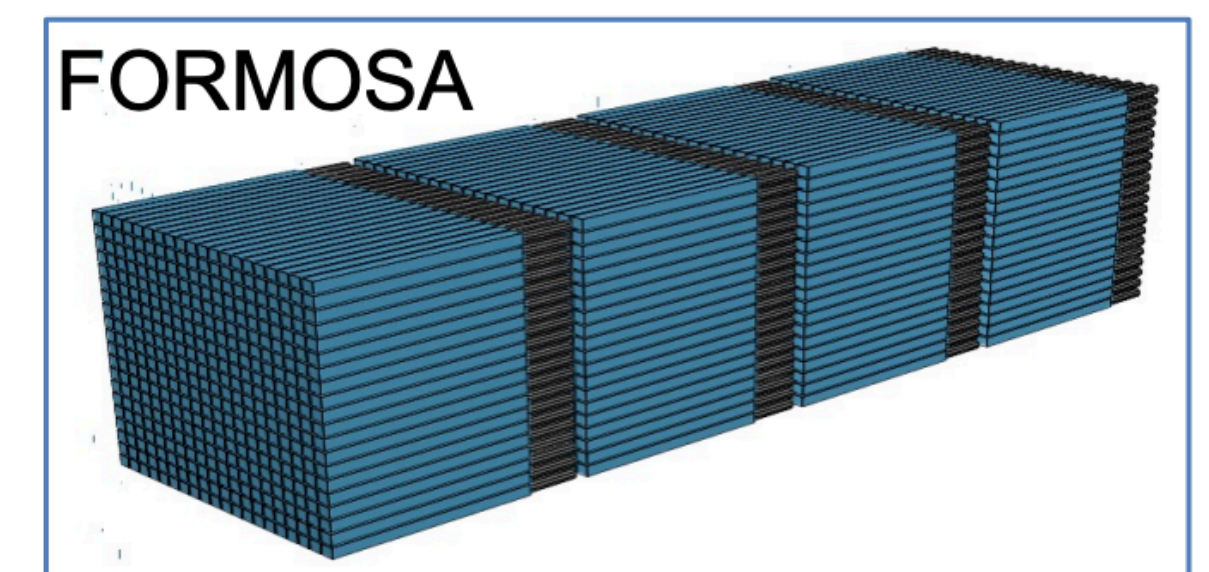
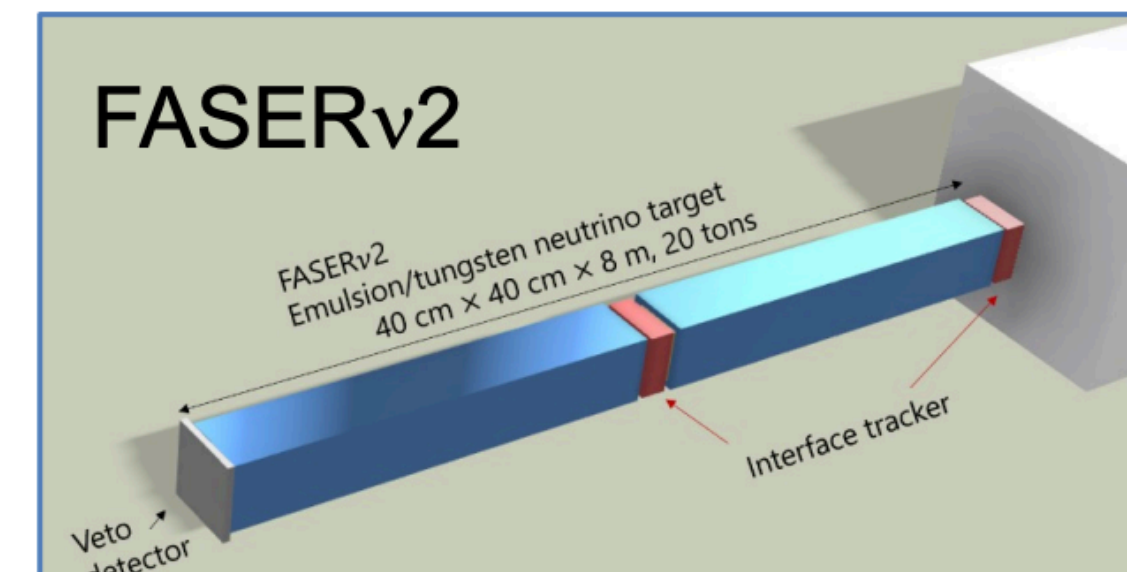
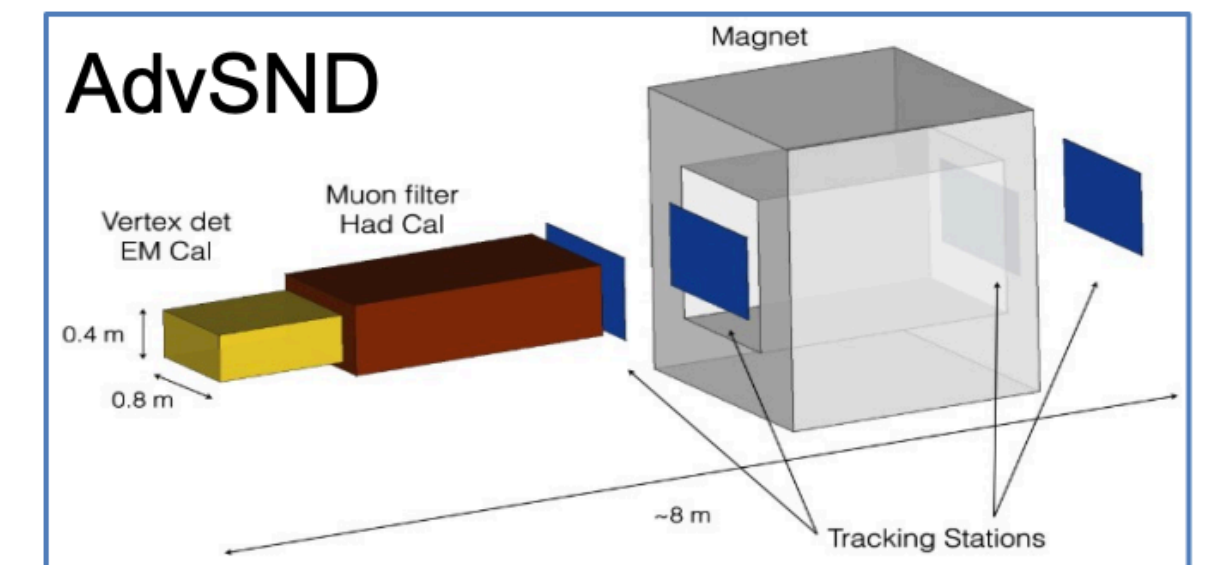
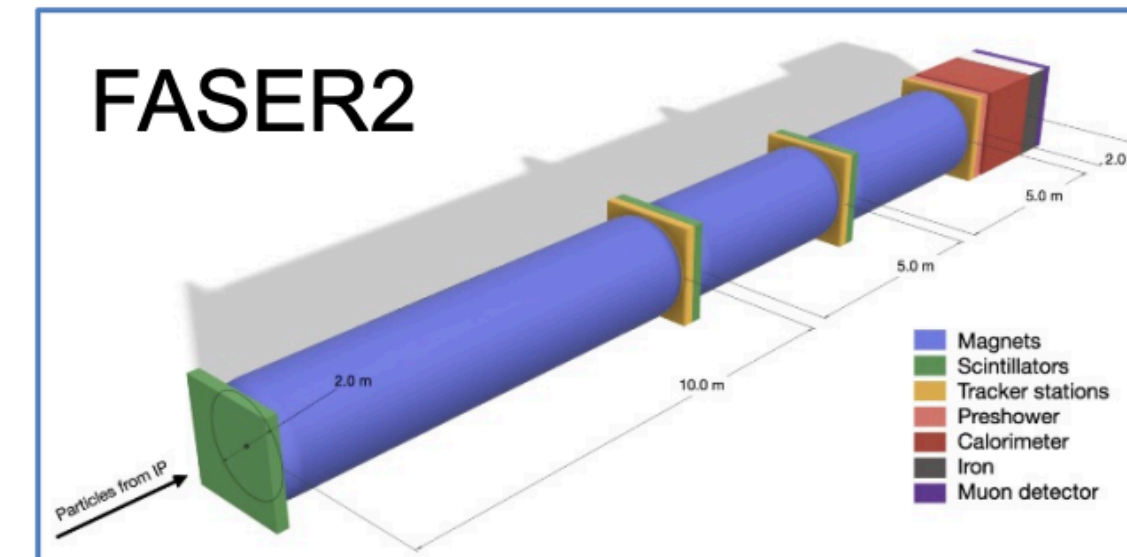
▶ FORMOSA

▶ BSM physics: millicharged particles

▶ FLArE

▶ TeV neutrinos & light dark matter

▶ Details of detector designs under investigation...

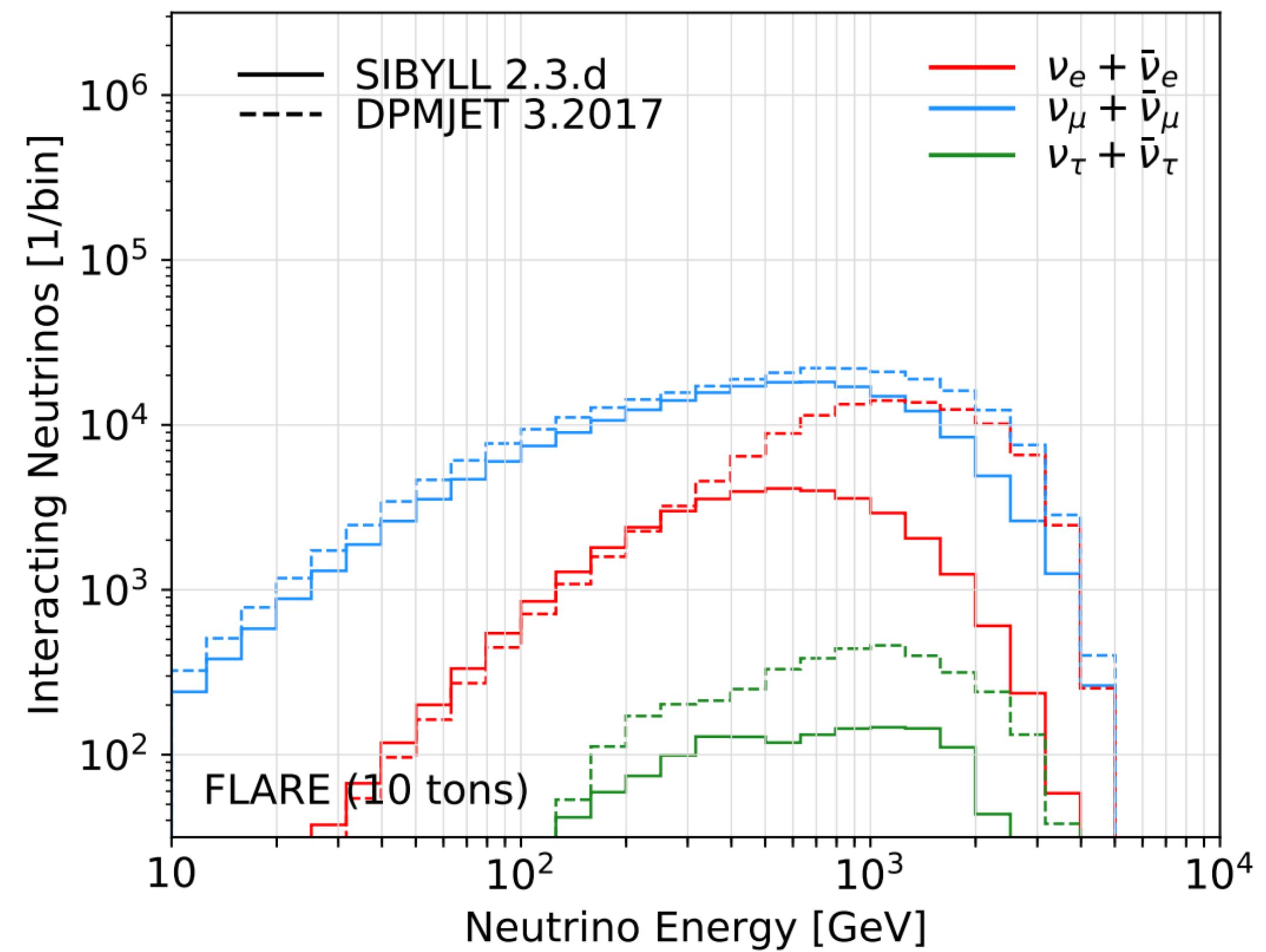
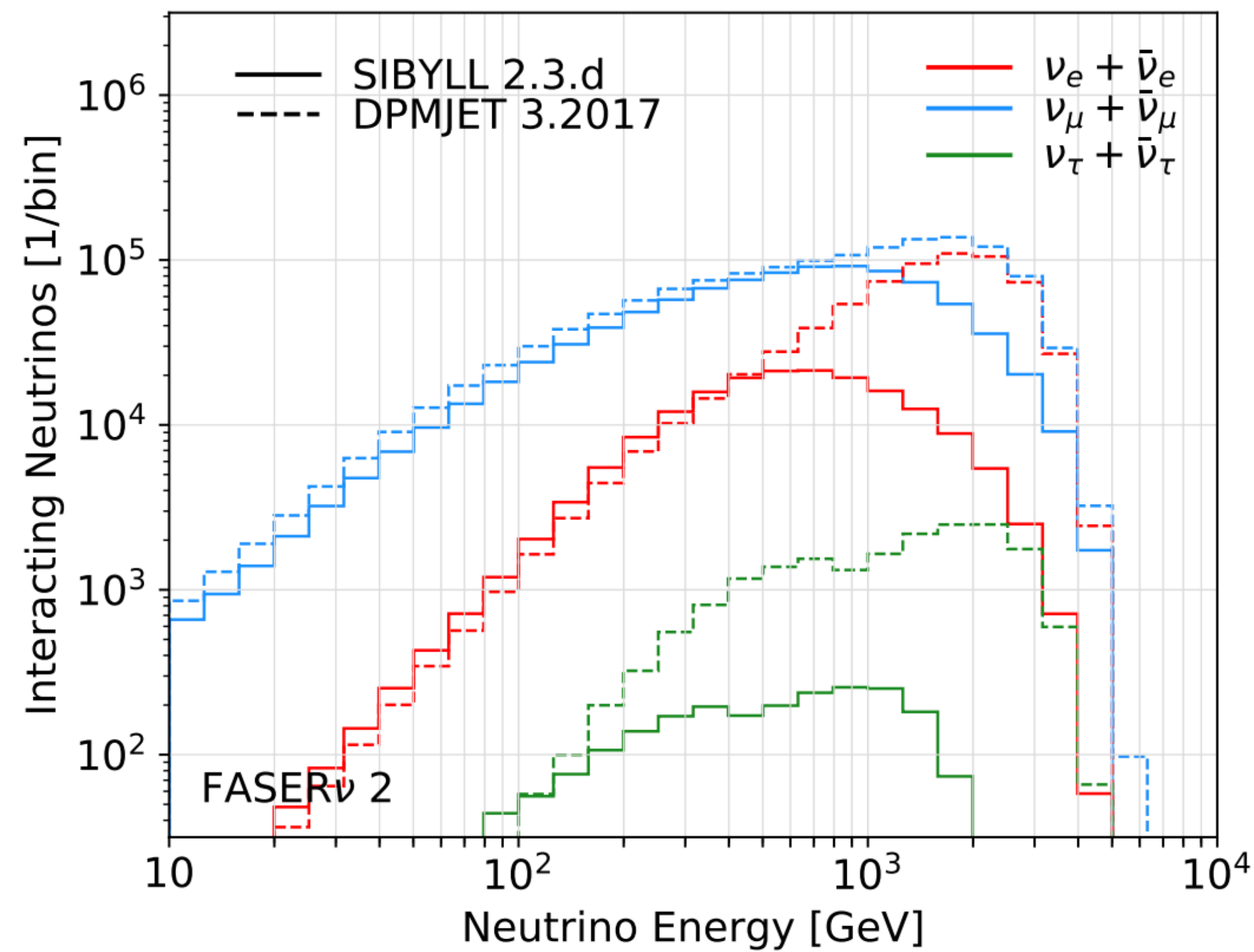


\* for a complete description of the experiments, please see the FPF white paper

# Expected Neutrino Interactions



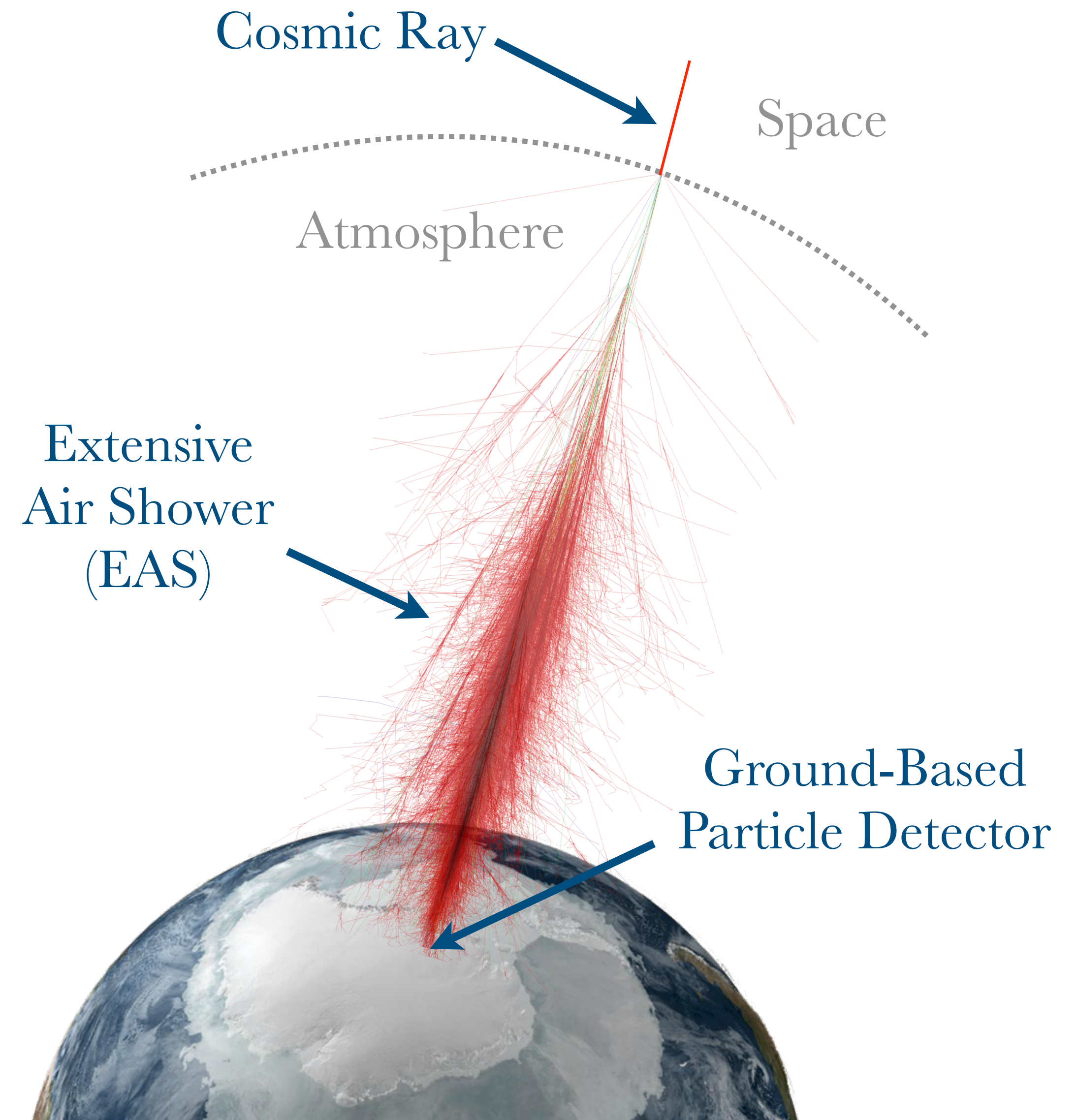
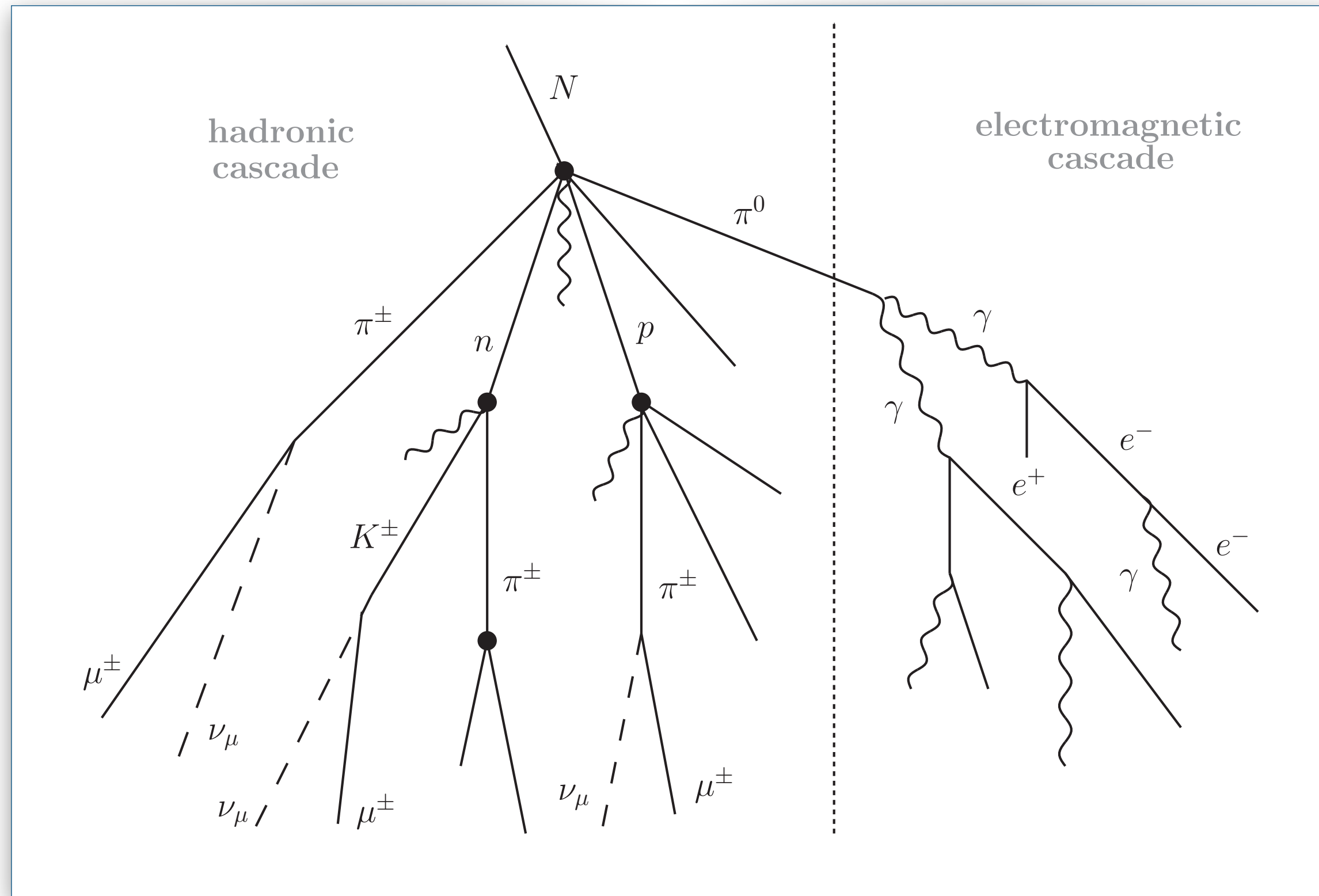
- ▶ FASER $\nu$ 2 (20 ton) and FLArE (10 ton) during HL-LHC era (3000 fb $^{-1}$  integrated luminosity)



# **Astroparticle Physics and Light Hadron Production at the FPF**



# Extensive Air Showers



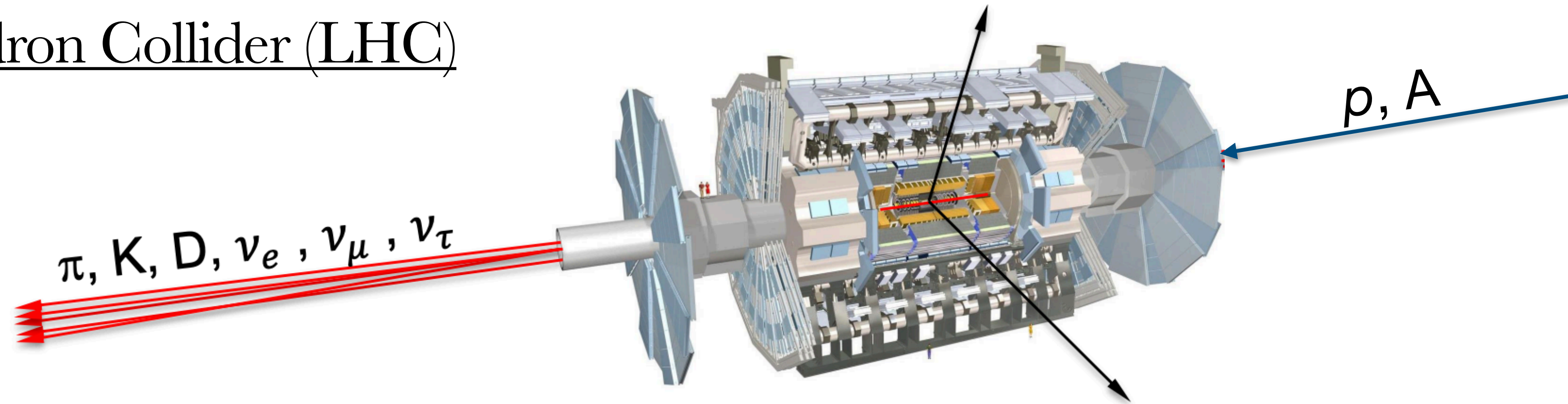
- ▶ EAS are driven by (light) hadron production
- ▶ EAS are the connection between cosmic ray and particle physics!

not to scale!

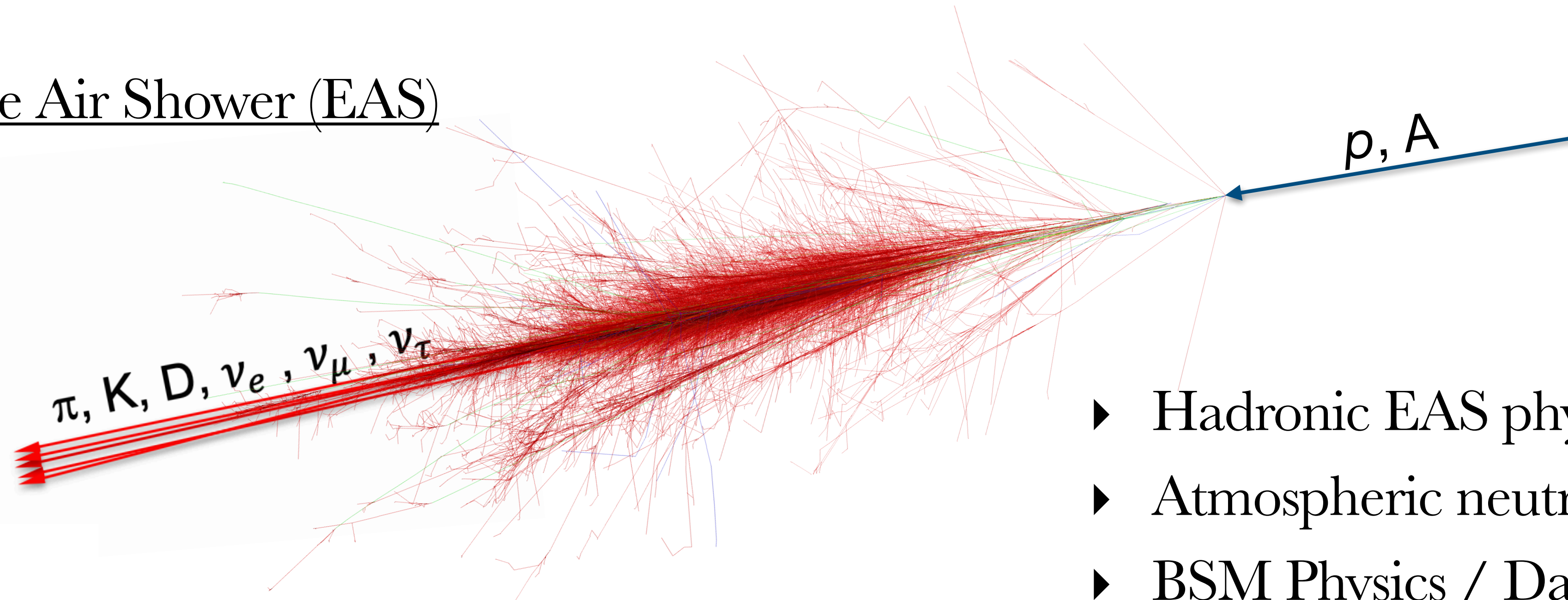
# EAS vs. Collider



- ▶ Large Hadron Collider (LHC)



- ▶ Extensive Air Shower (EAS)



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

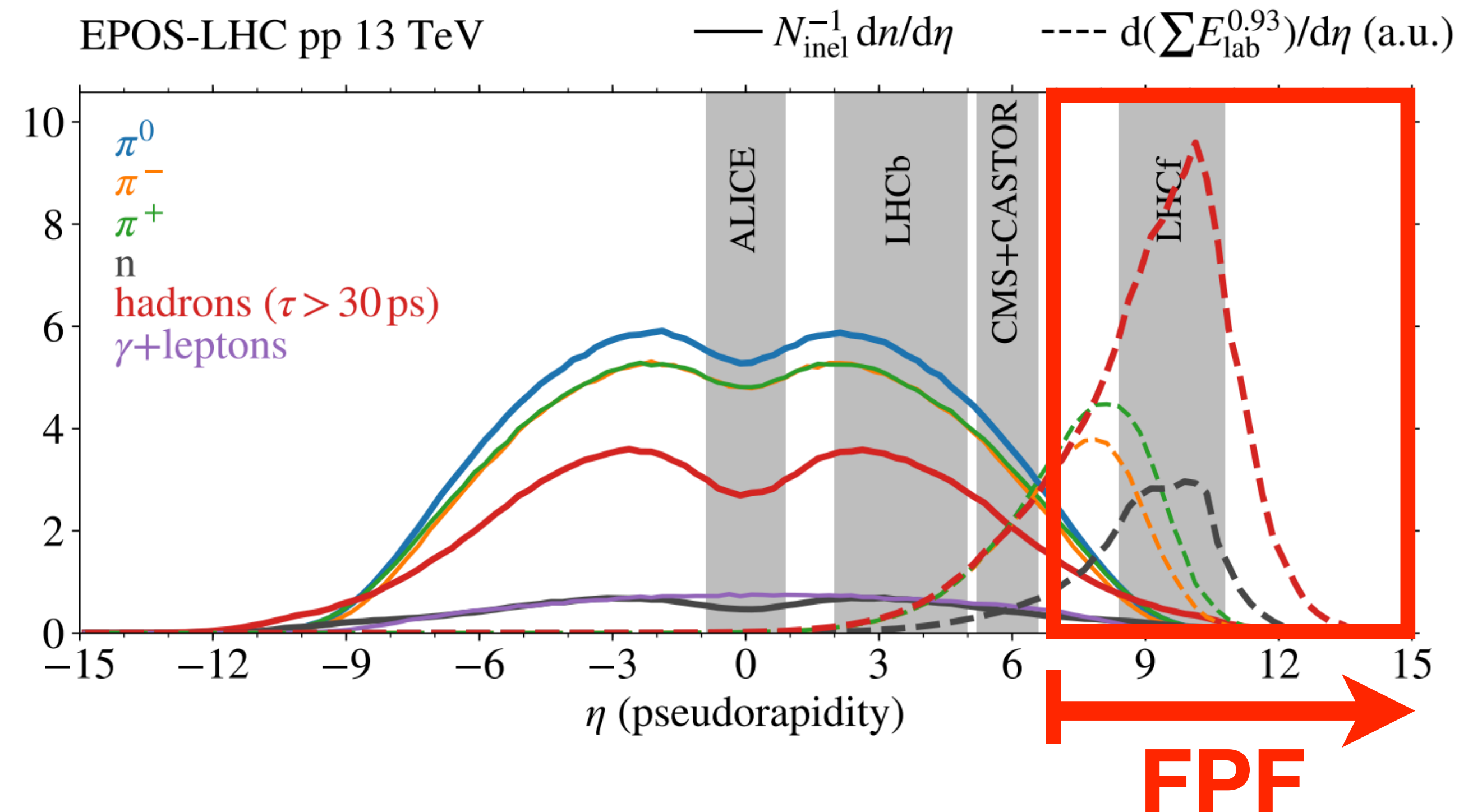
# Motivation I



- ▶ Extensive air showers:

- ▶ Particle production in the far-forward region
- ▶ Low momentum transfer
- ▶ Non-perturbative regime
- ▶ Complex particle composition
- ▶ Energies range over many orders of magnitude
- ▶ Modeling of particle interactions based on phenomenological models developed for EAS simulations
- ▶ FPF will provide unique opportunities to test hadronic interaction models

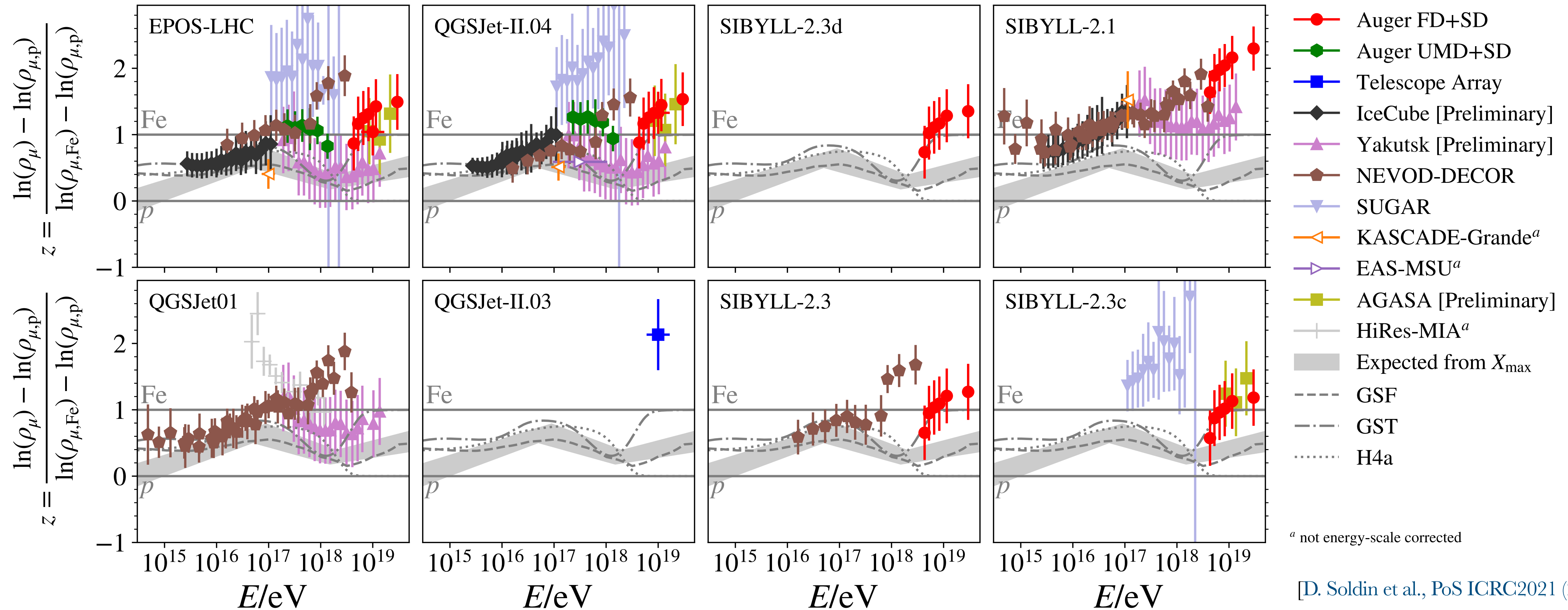
[J. Albrecht, D. Soldin, et al., *Astrophys. Space Sci.* 367 (2022)]



# Motivation I



- ▶ Large discrepancies between data and MC observed in EAS



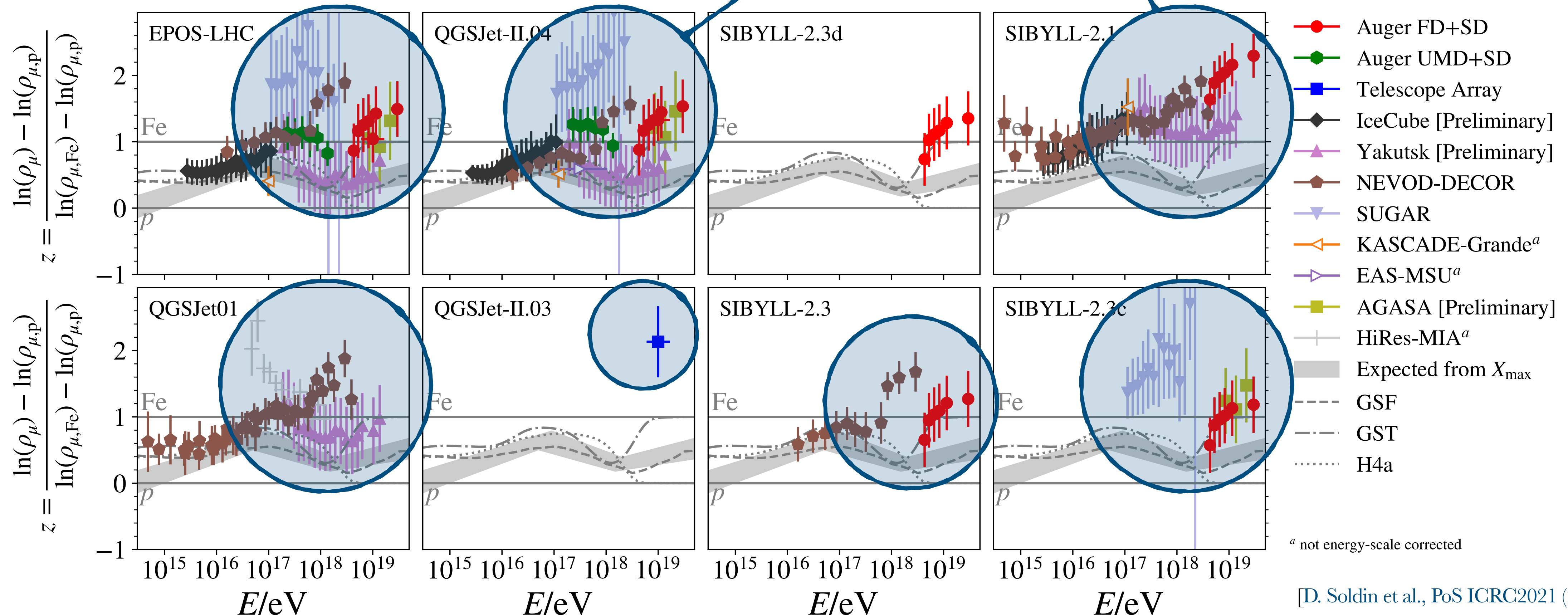
- ▶ Muon measurements and models indicate composition heavier than iron at high energies!

# Motivation I

## Muon Puzzle



- ▶ Large discrepancies between data and MC observed in EAS



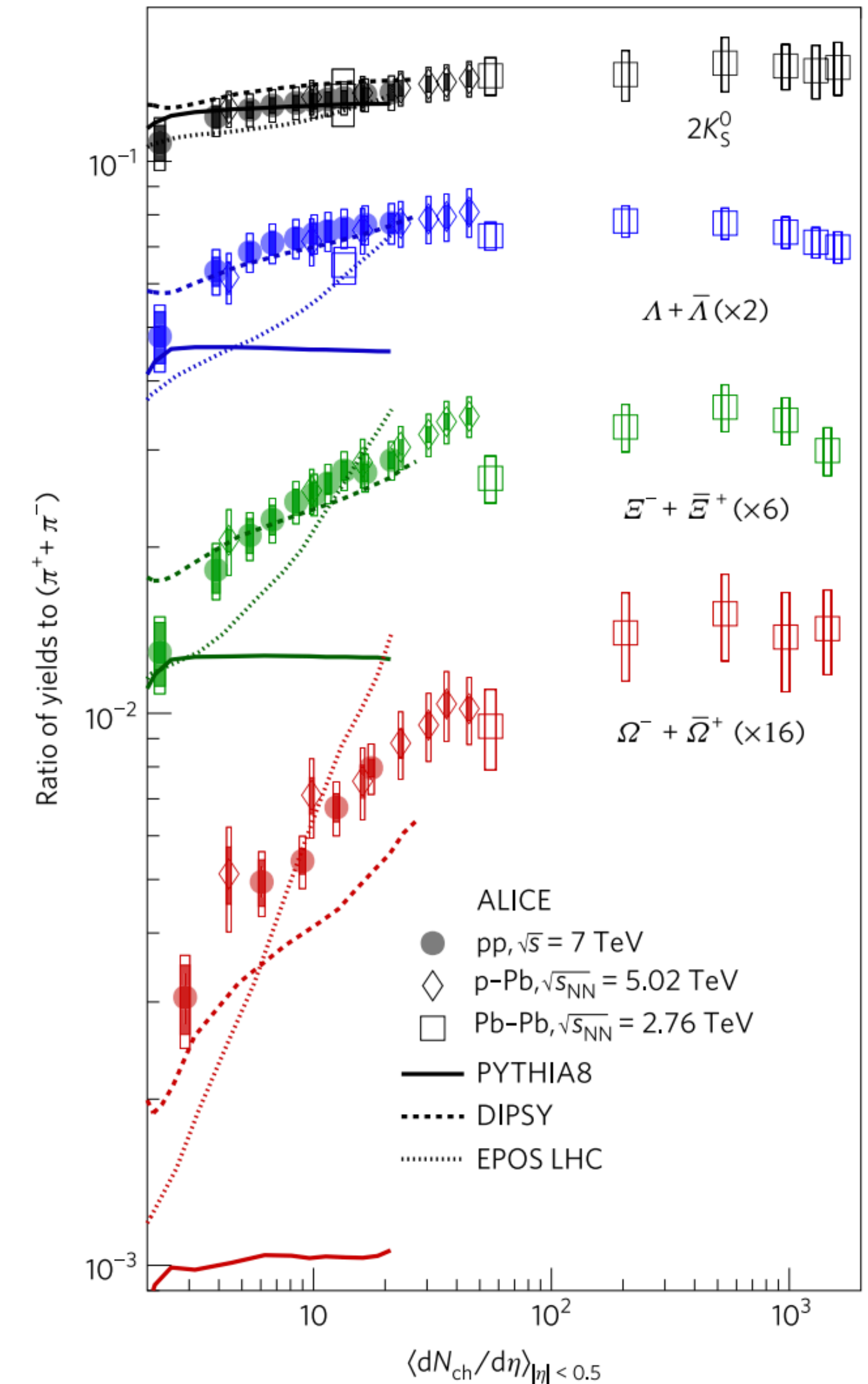
- ▶ Muon measurements and models indicate composition heavier than iron at high energies!

# Motivation II

- ▶ Evidence for strangeness enhancement reported by ALICE
- ▶ Universal enhancement of strangeness production in high-multiplicity events at mid-rapidity ( $|y| < 2$ )
- ▶ Depends on the multiplicity of the event at mid-rapidity, not on the details of the collision system!
- ▶ Can this effect also be seen in hadrons produced at forward rapidities?
- ▶ Possible explanation for the Muon Puzzle in EAS...?
- ▶ FPF provides unique opportunities for testing the forward rapidity region!



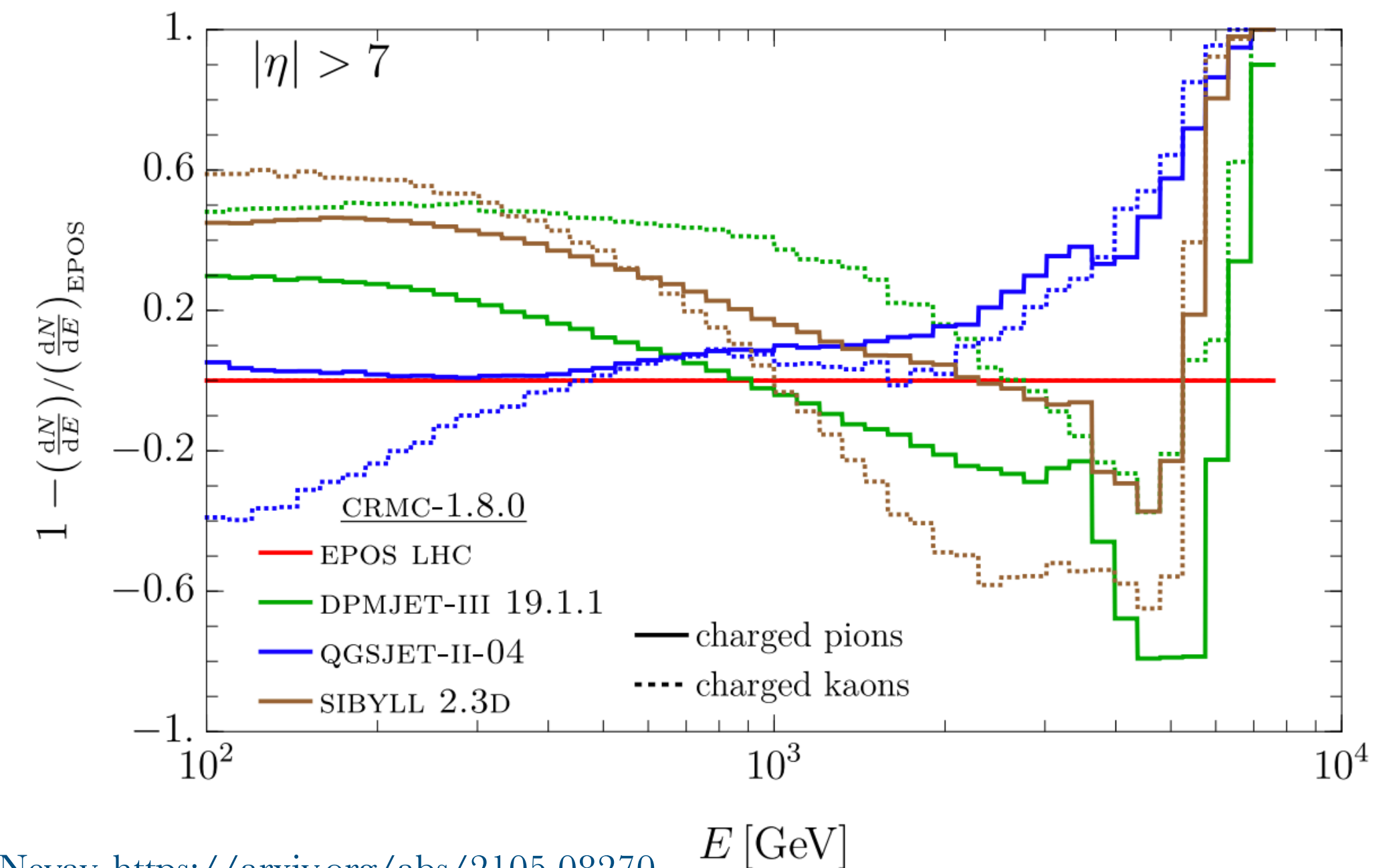
[ALICE Collaboration, Nature Phys. 13, 535 (2017)]



# Light Hadron Production



- ▶ Neutrino fluxes at the FPF:
  - ▶ 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
  - ▶ Fast simulation package\* available! (F. Kling)
  - ▶ Further studies needed:
    - ▶ MC based on different generators
    - ▶ Neutrino fluxes in different detectors
    - ▶ Tests of dedicated strangeness (muon) enhancement models, sensitivities



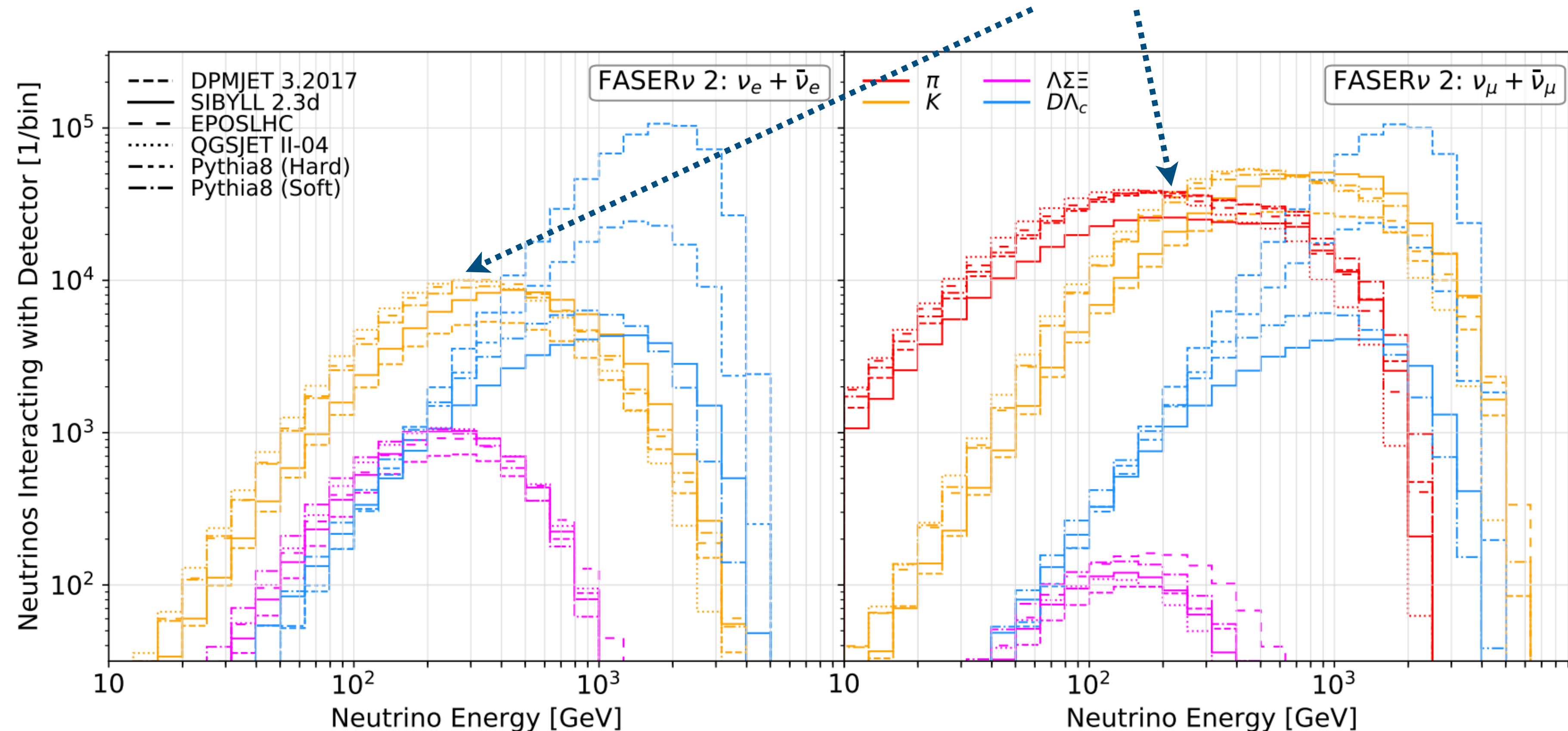
\* Simulation code available at: <https://github.com/KlingFelix/FastNeutrinoFluxSimulation>, see also F. Kling, L. Nevay, <https://arxiv.org/abs/2105.08270>

# Light Hadron Production



- ▶ Example: Neutrino fluxes at FASER $\nu$ 2

low-energy region relevant!



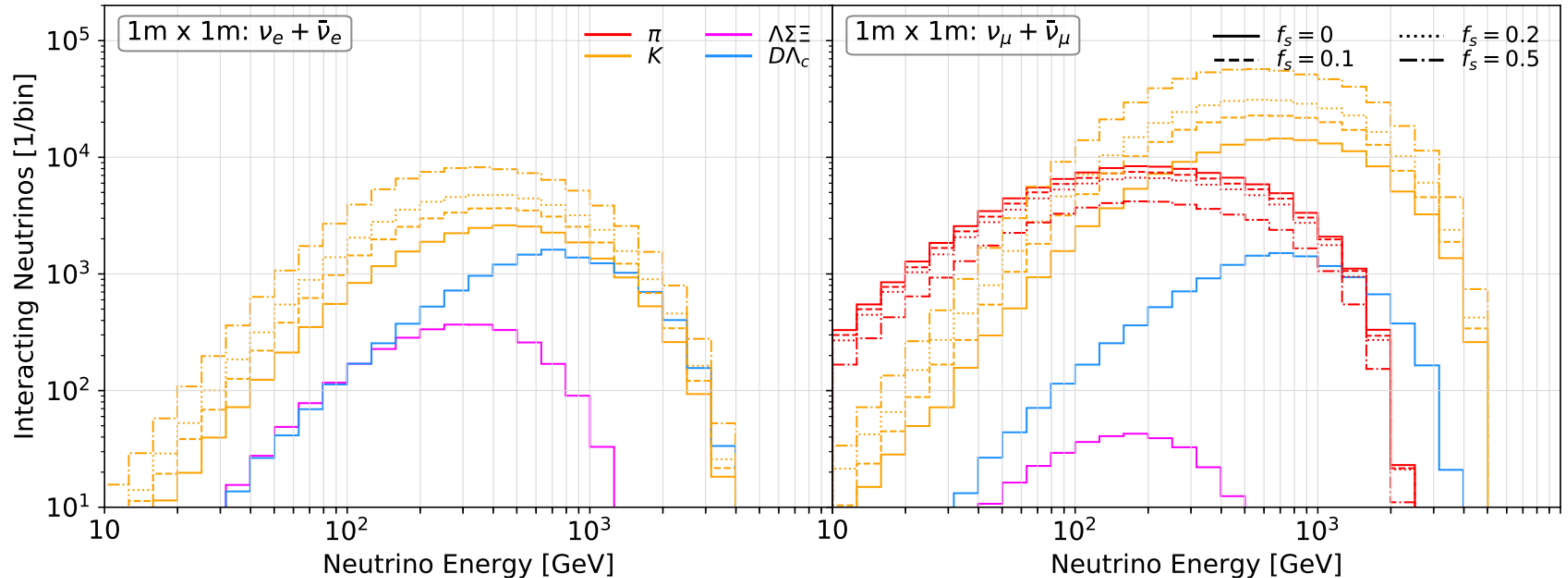
- ▶ Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties!



# Light Hadron Production



- ▶ Example: Neutrino fluxes at FLArE

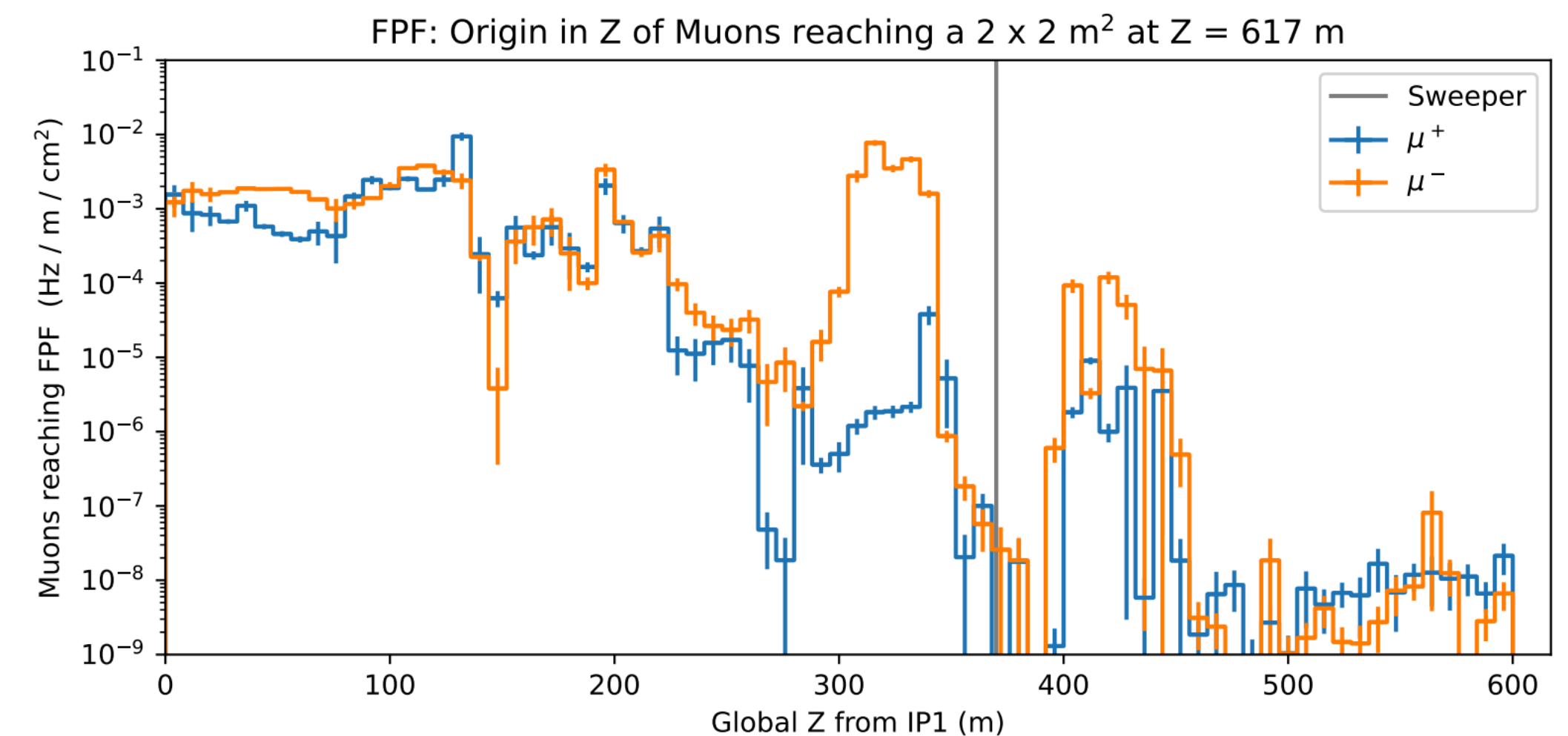


- ▶ Model comparison: strangeness enhancement toy model [L. Anchordoqui et al., JHEAp 34 (2022)]

# Light Hadron Production



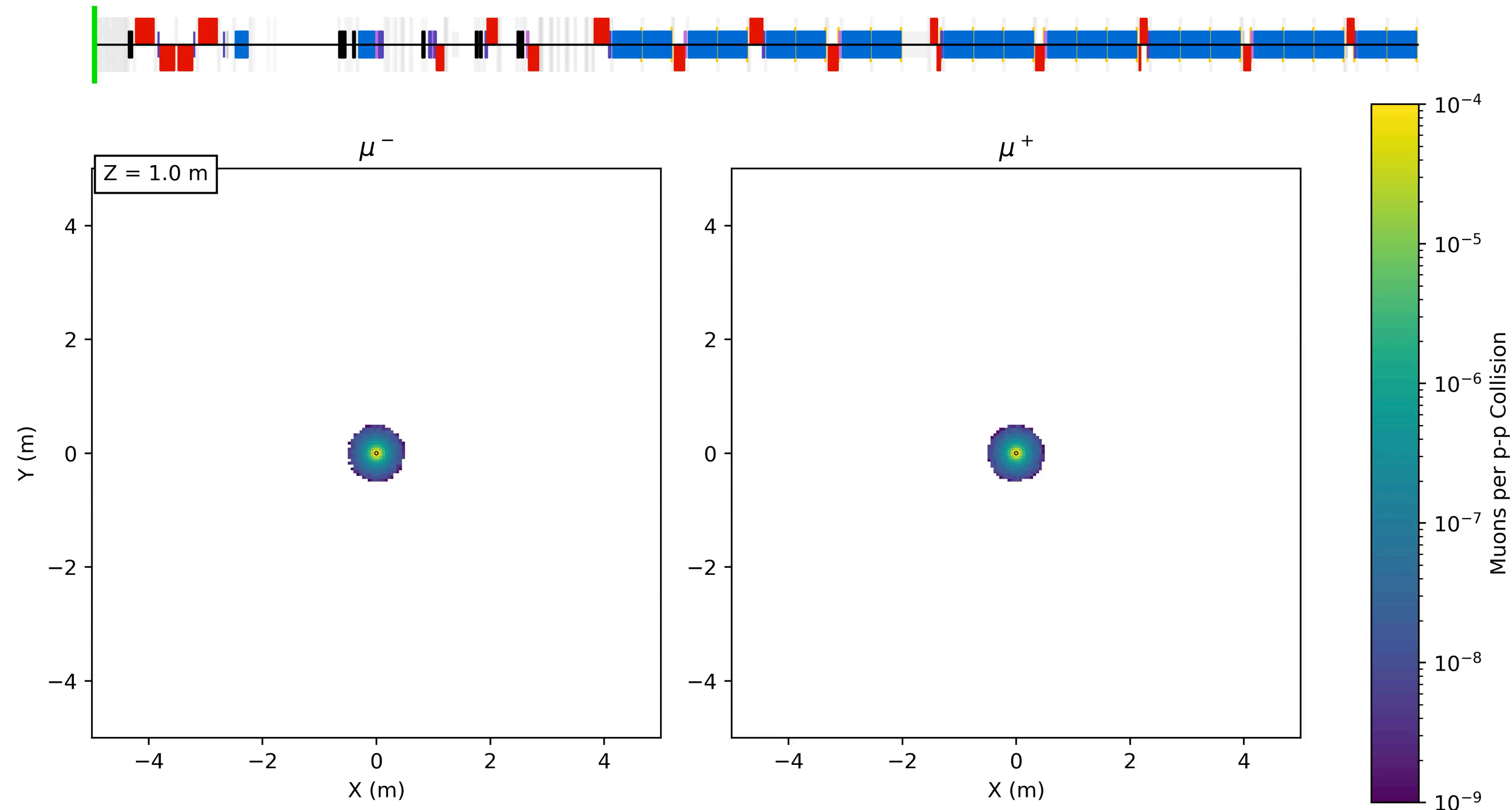
- ▶ Muon fluxes at the FPF:
  - ▶ Large muon flux at the FPF, e.g.  $\sim 1$  Hz per  $\text{cm}^2$  in FASER2
  - ▶ Challenging to study as the origin of production is uncertain...
  - ▶ BDSIM/Geant4 simulations available, including full muon history (L. Nevay)
- ▶ Open questions:
  - ▶ Can we use muons to study light hadron production?
  - ▶ Can we measure the muon charge ratio?
  - ▶ Do sweeper magnets help our physics case?
  - ▶ What can we learn from muon fluxes measured at FASER and SND@LHC?
- ▶ Dedicated studies of the muon yield at the FPF (incl. full muon history) needed!



# Light Hadron Production



- ▶ Simulated muon fluxes at the FPF:

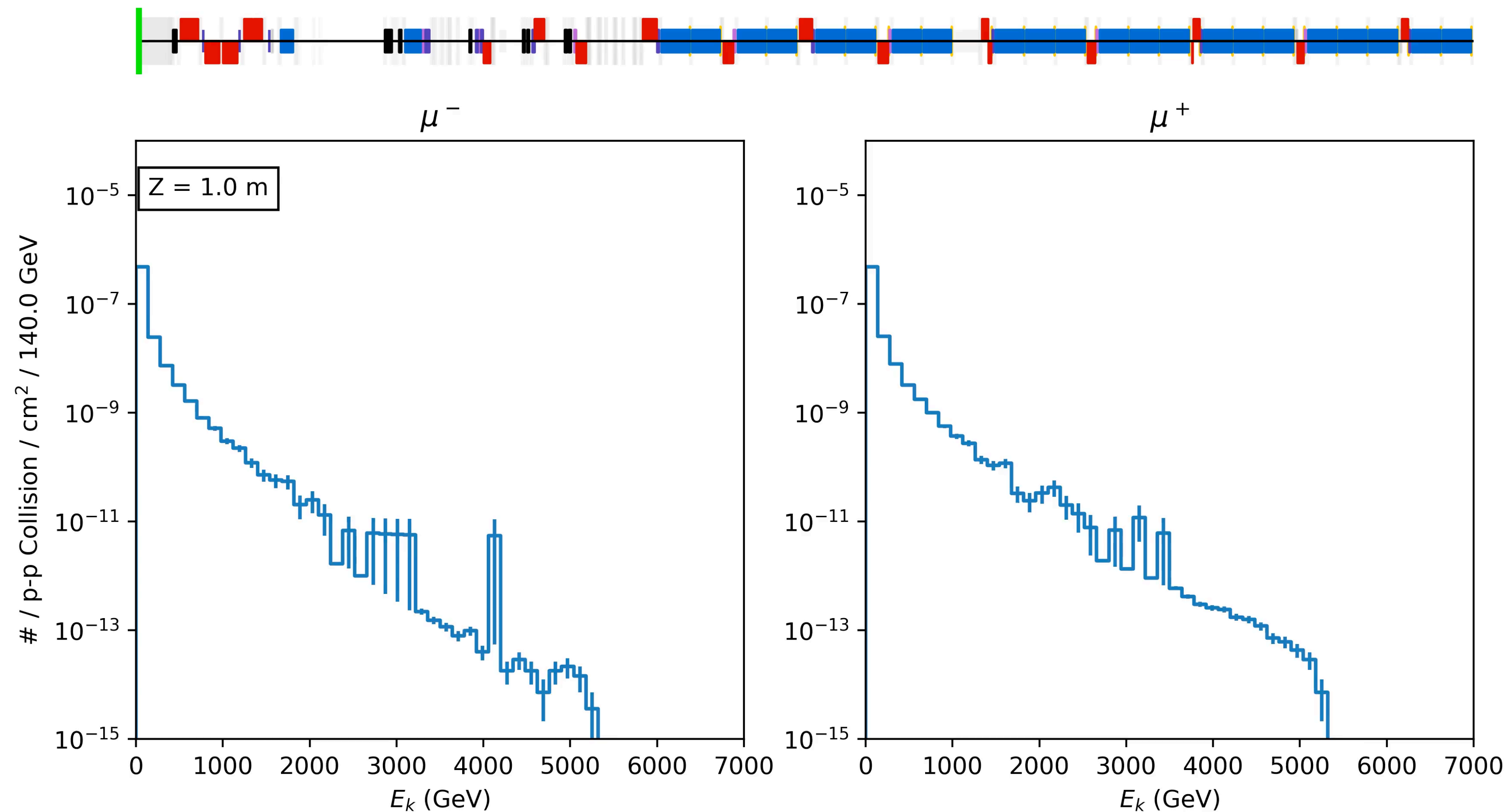


by L. Nevay

# Light Hadron Production



- ▶ Simulated muon spectra at the FPF:



by L. Nevay

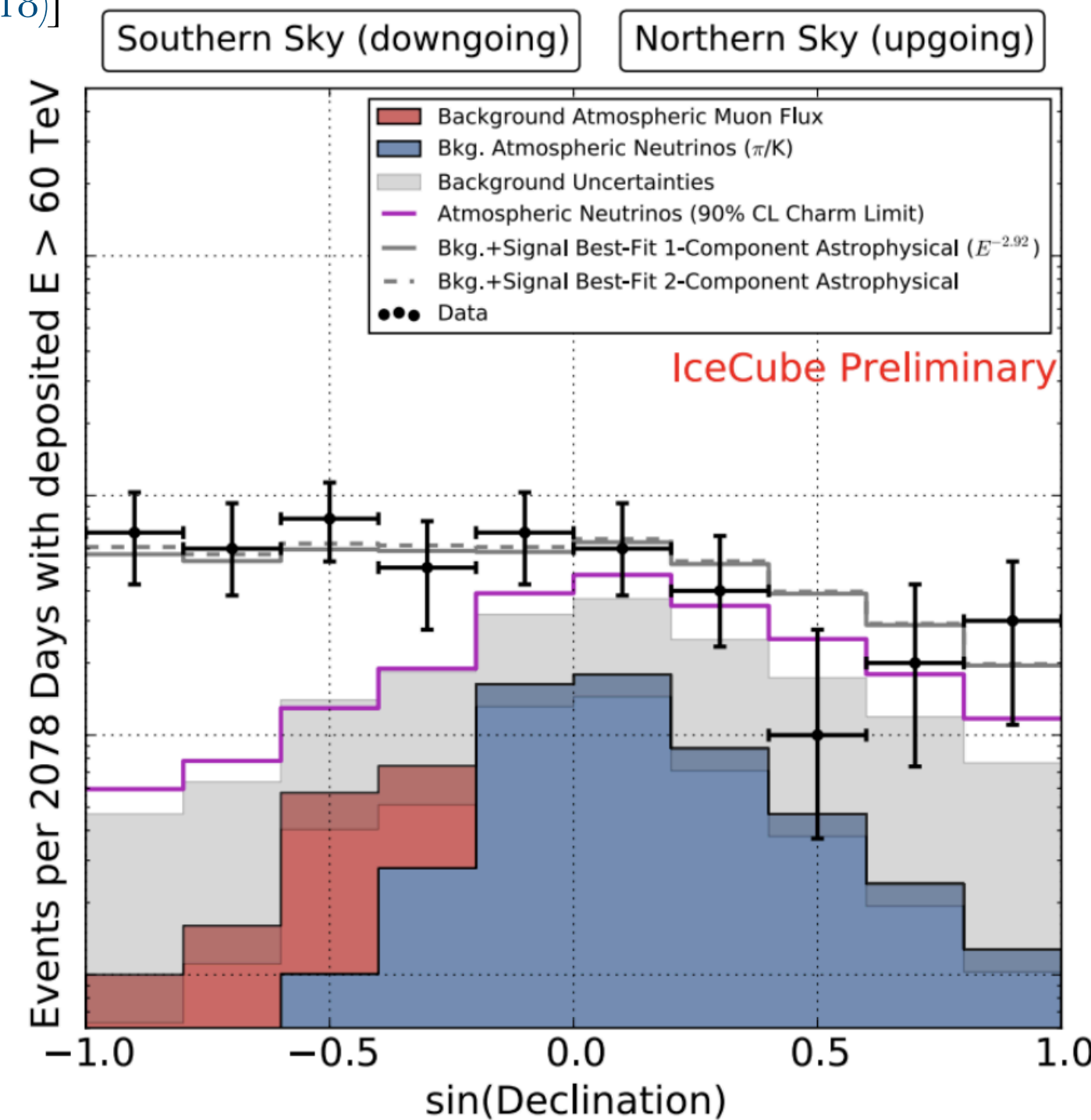
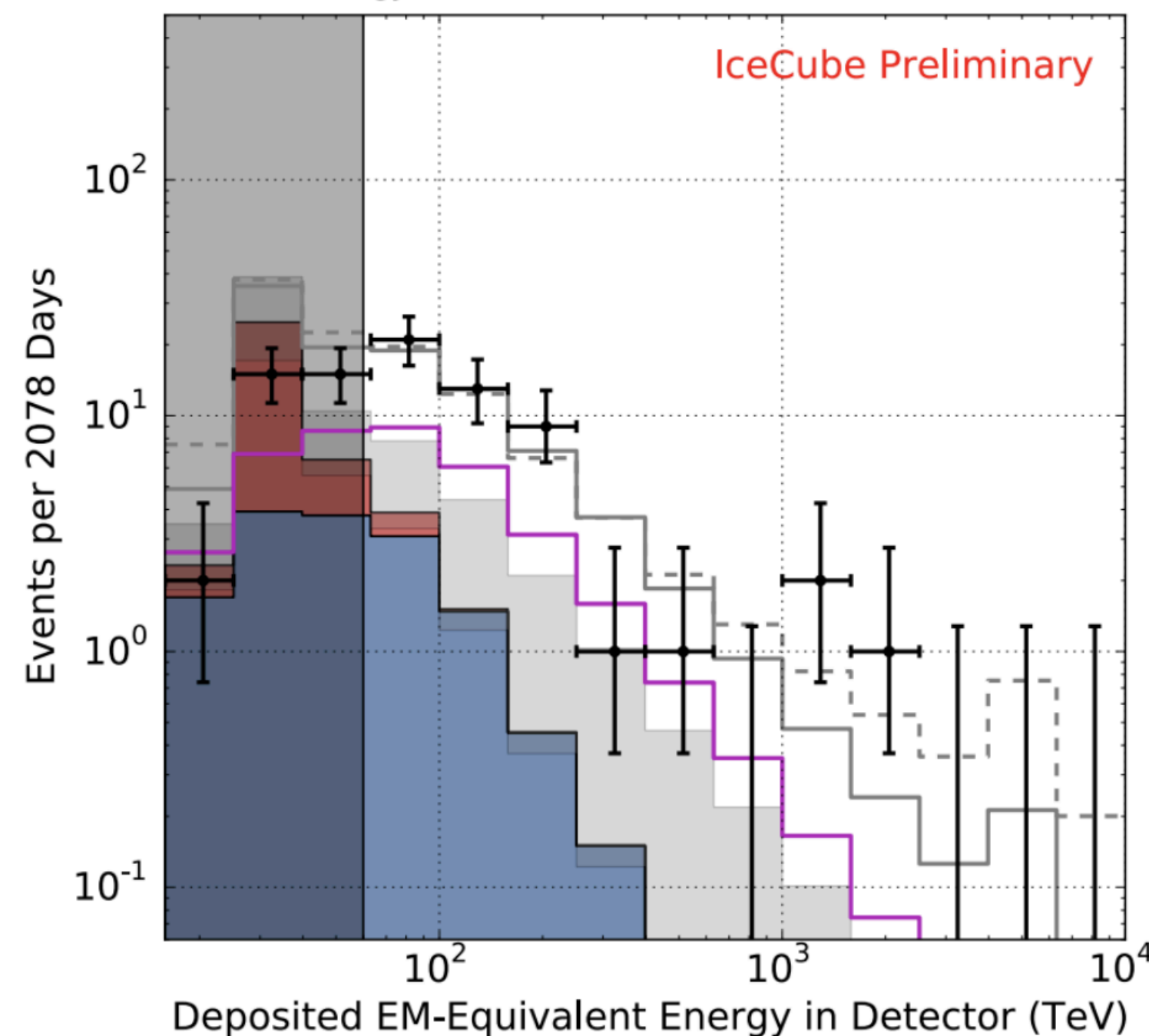
# **Astroparticle Physics and Neutrino Production at the FPF**

# Motivation III

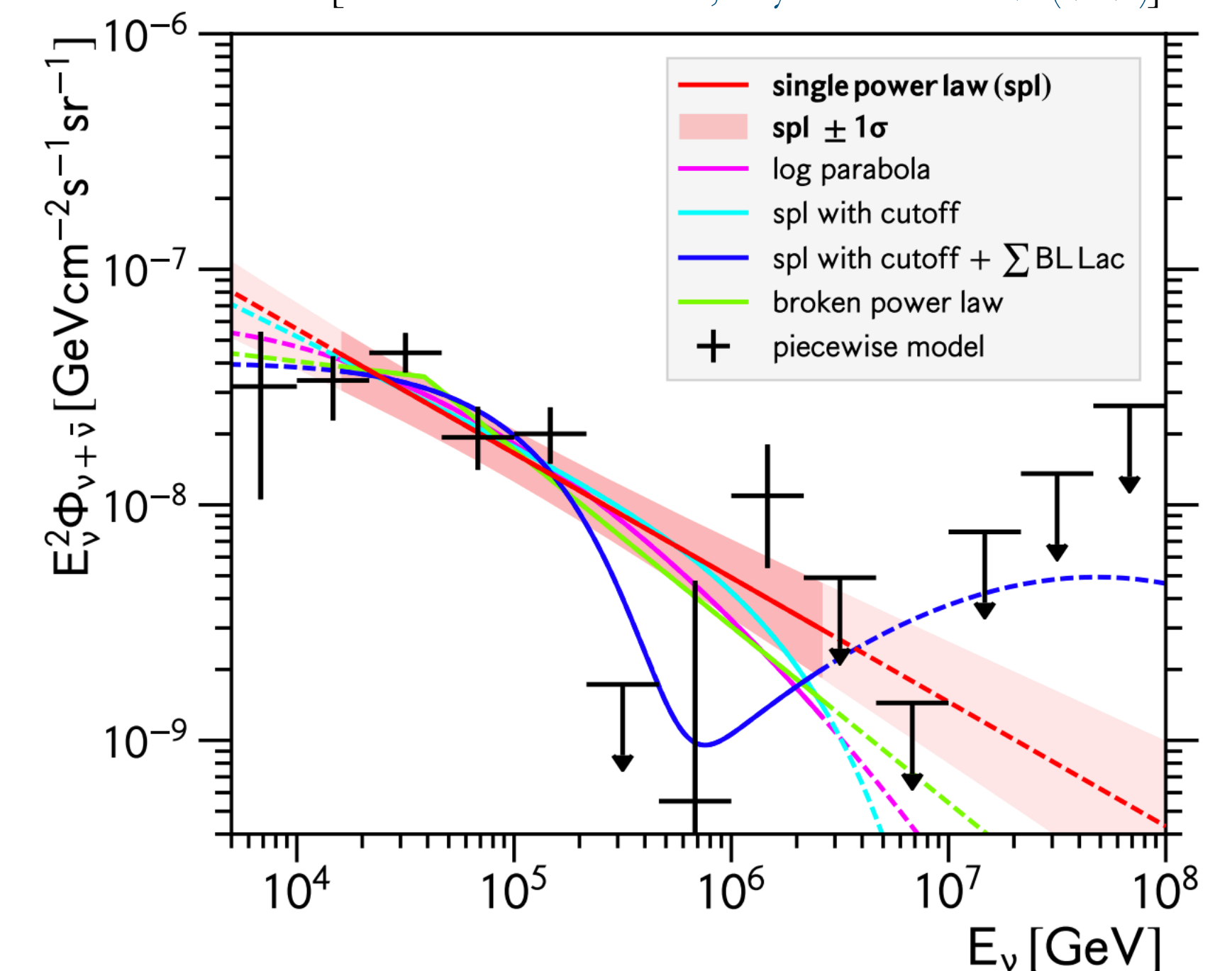


- ▶ Atmospheric muons (in particular prompt) are dominant background for astrophysical neutrino searches
- ▶ Large uncertainties in prompt neutrino flux calculations
- ▶ FPF experiments will directly measure TeV neutrino production

[C. Kopper (IceCube Collaboration), PoS(ICRC2017)981 (2018)]



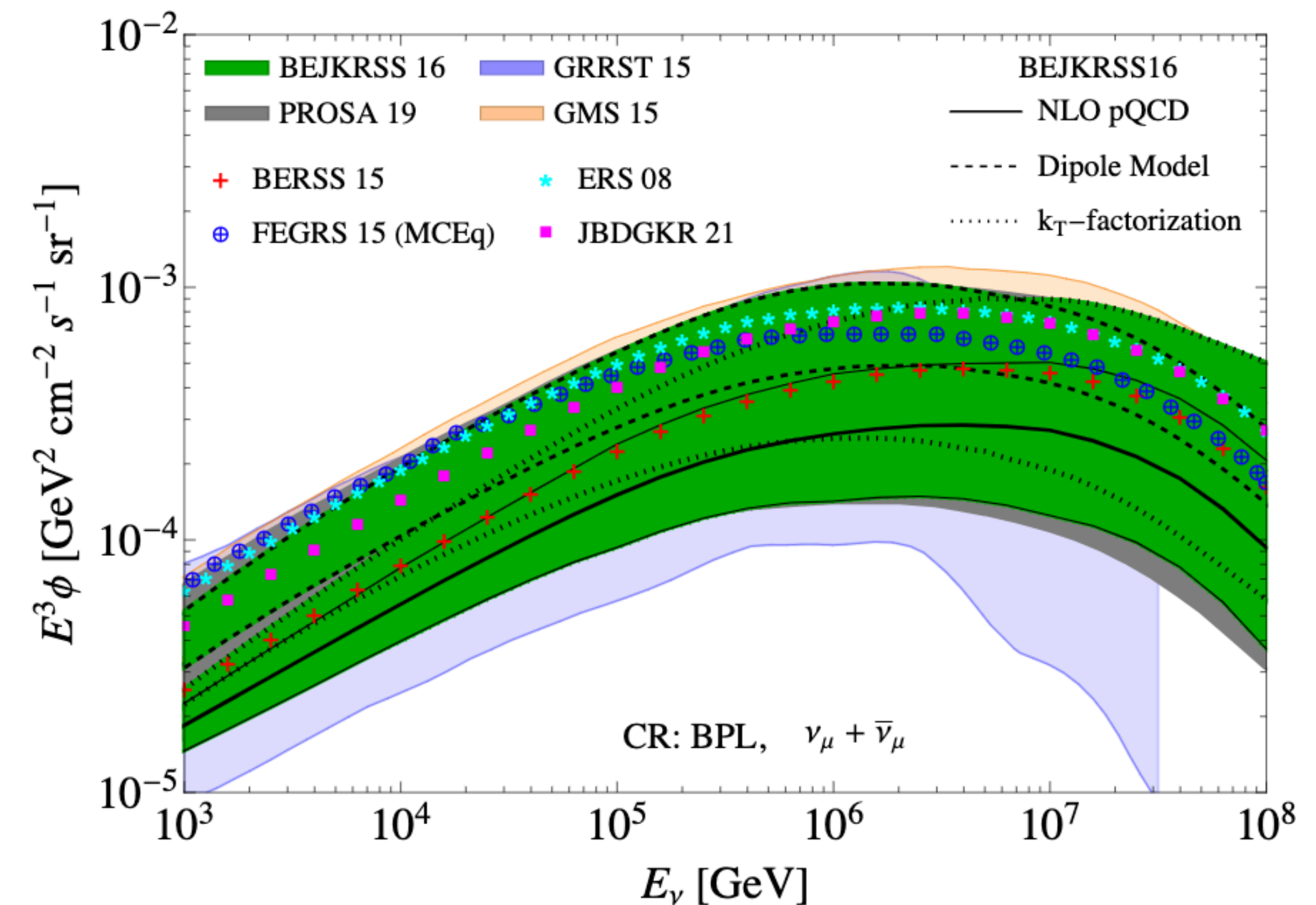
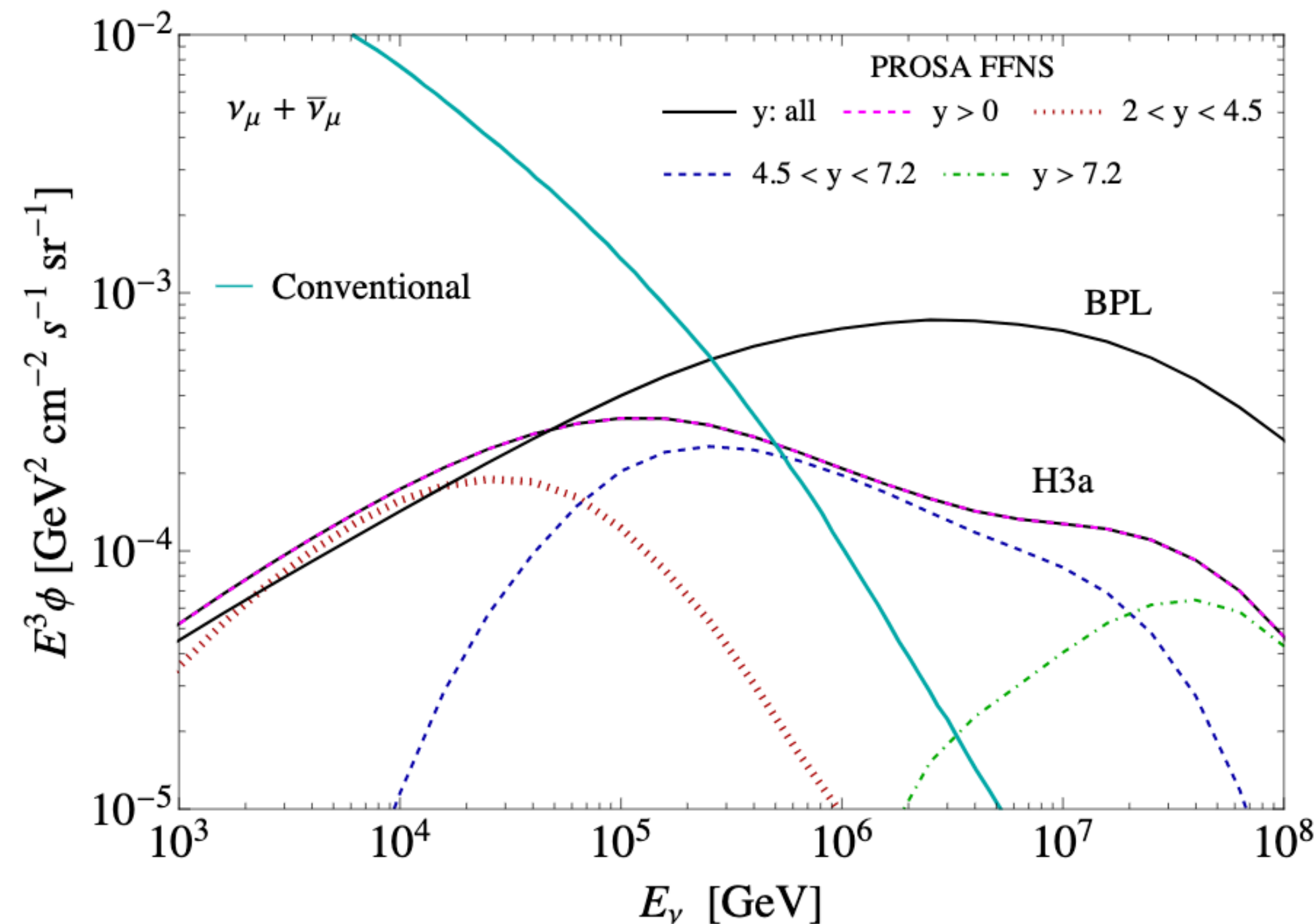
[IceCube Collaboration, Phys. Rev. Lett. 125 (2020)]



# 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)

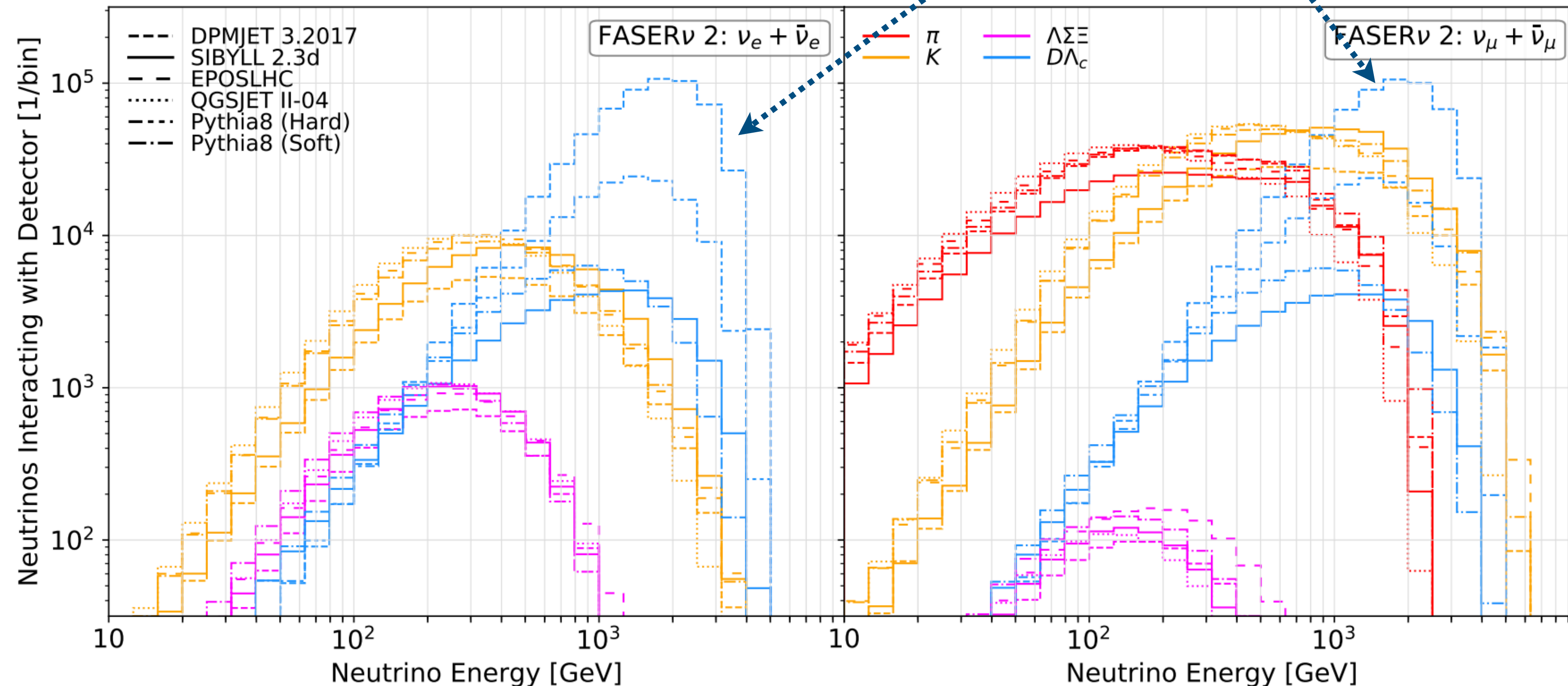


# Prompt Neutrino Production



► Example: Neutrino fluxes at FASER $\nu$ 2

high-energy region  
relevant!



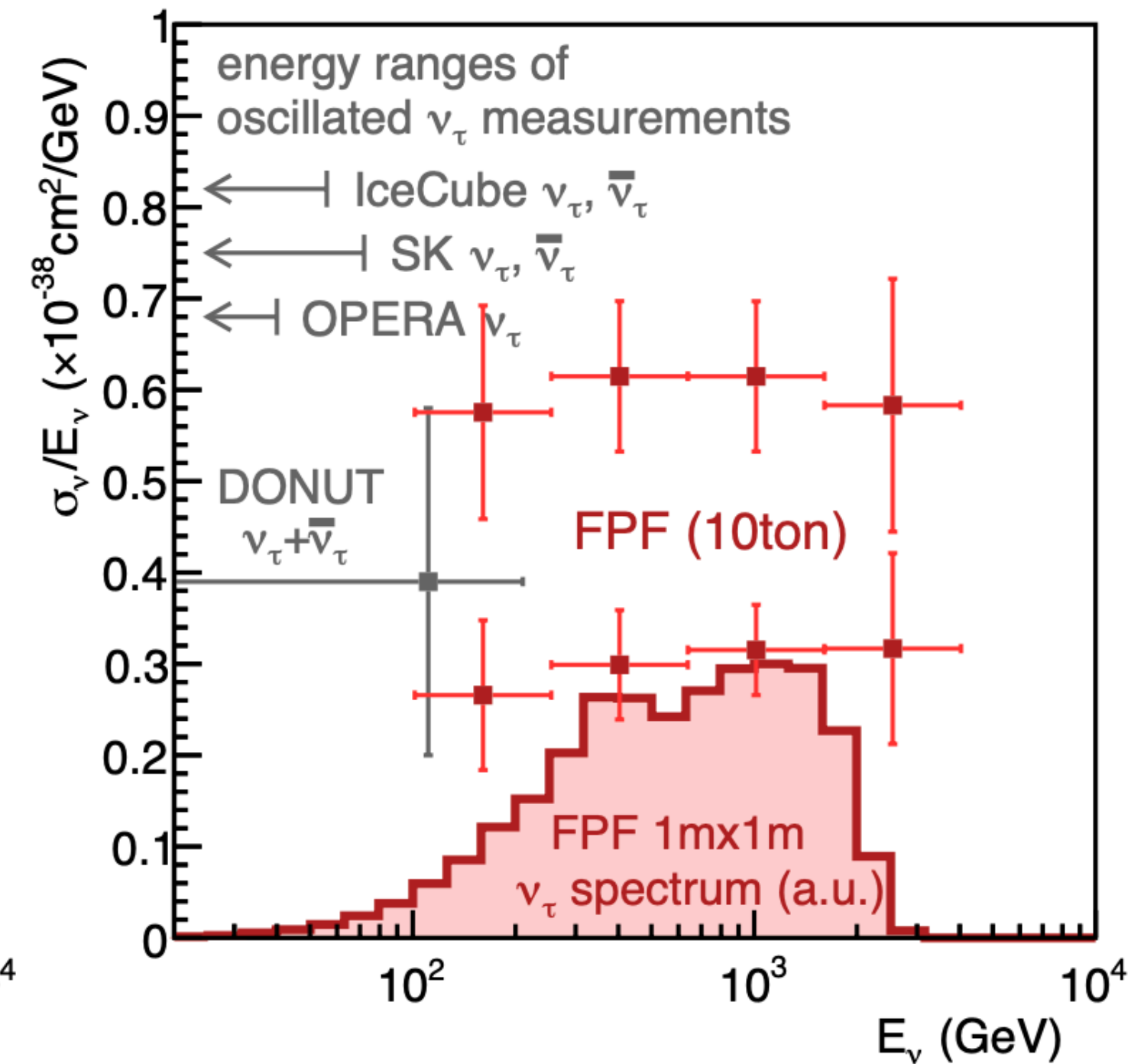
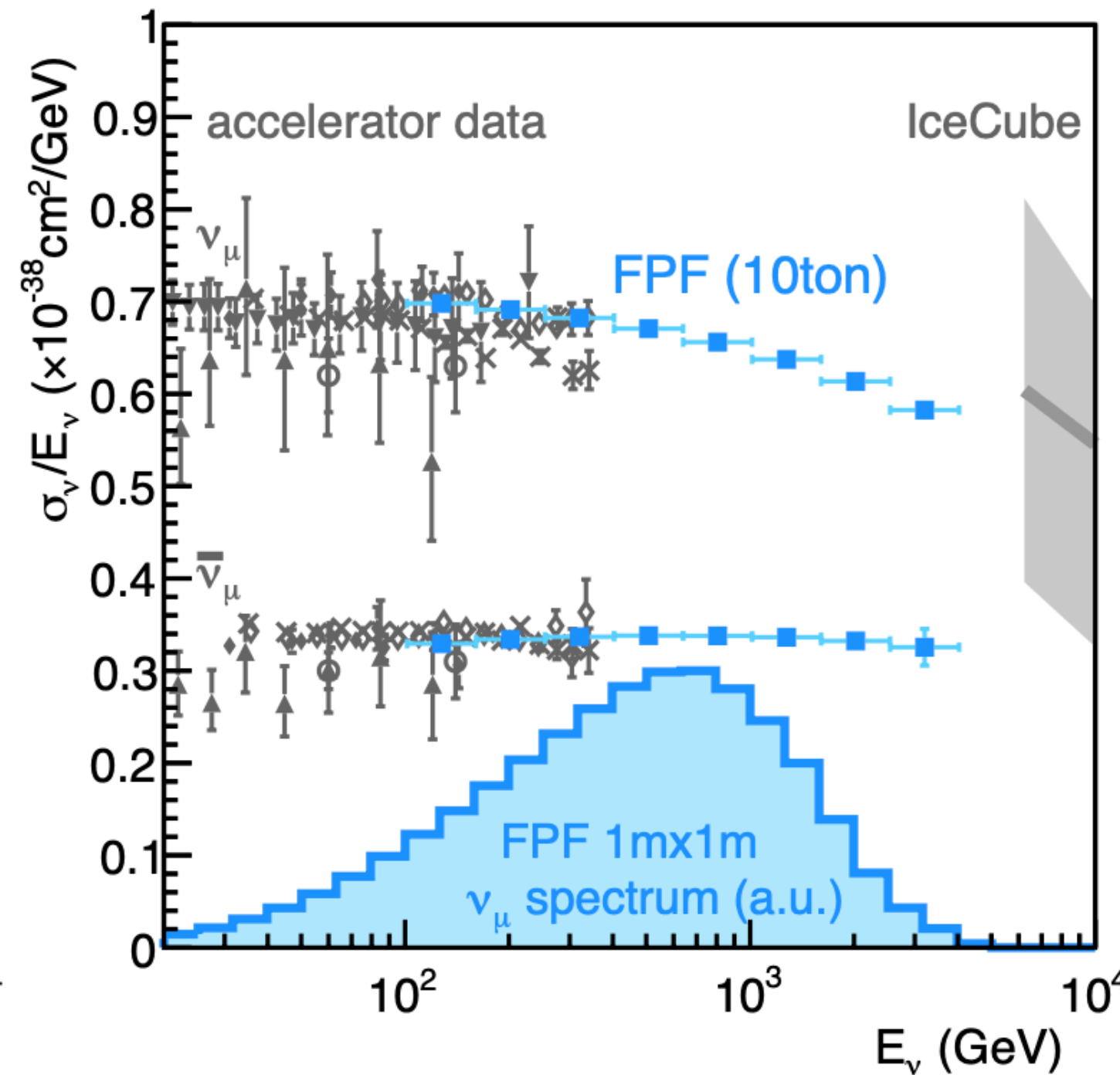
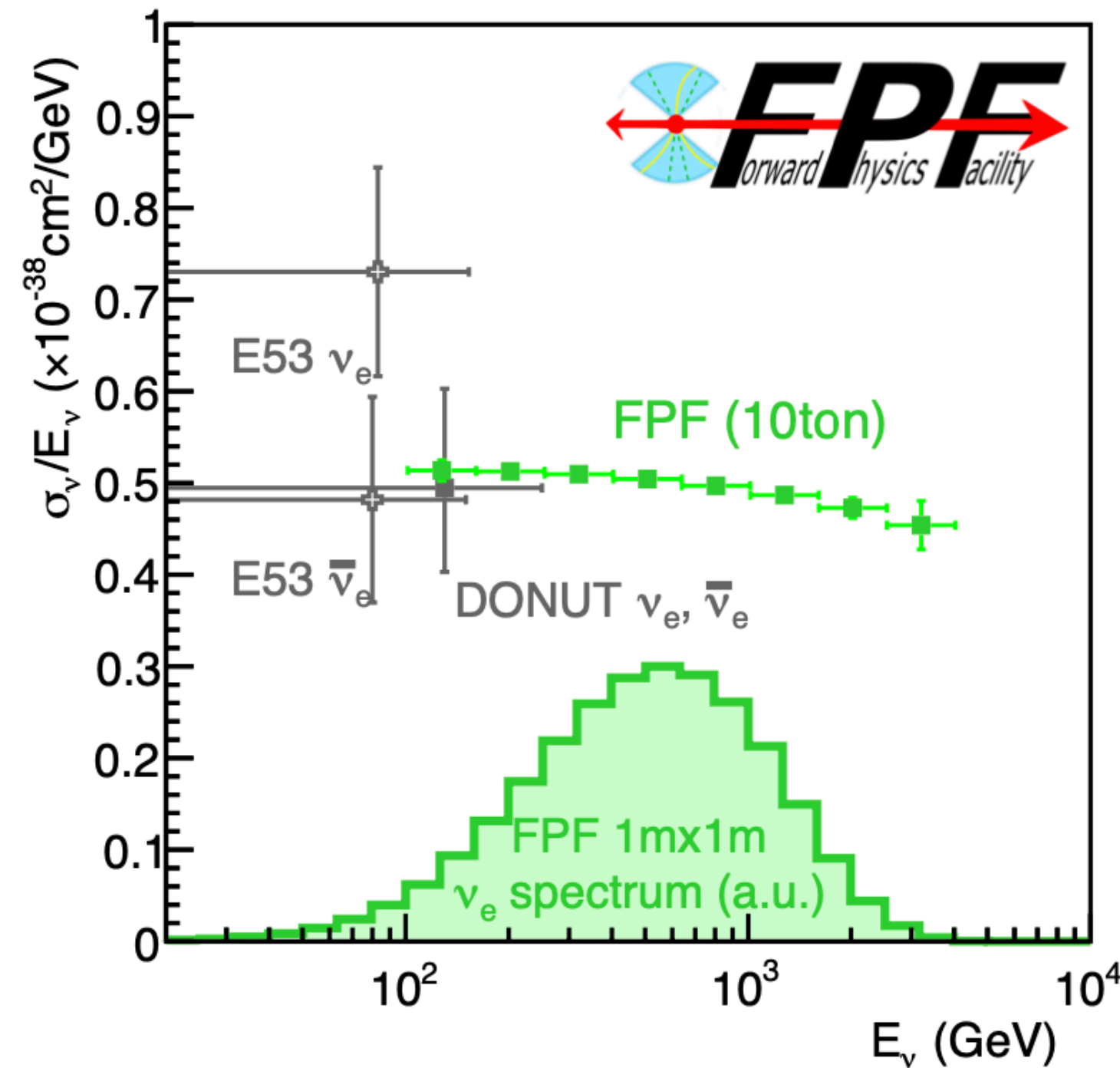
► Prompt neutrino fluxes!



# Neutrino Interactions



- ▶ Example: Neutrino-nucleon cross sections, FLArE (10 ton, 1mx1m)



- ▶ Many more precision measurements of neutrino properties, e.g. PDFs, charm, BSM physics
- ▶ Will improve modeling of neutrino fluxes in IceCube, Km3NET, etc.

# **Astroparticle Physics and Dark Matter Searches at the FPF**

# Dark Matter Searches

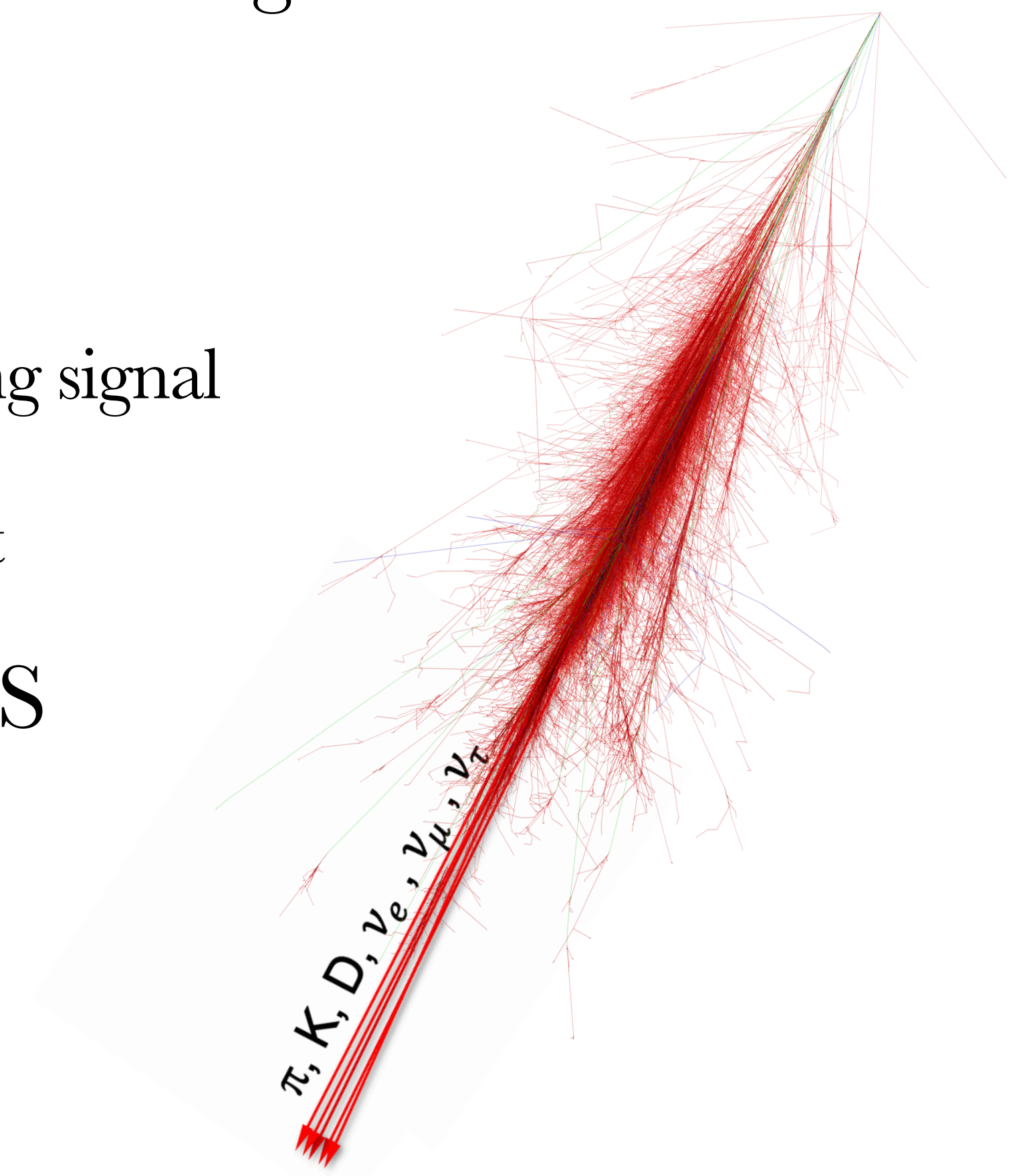


- ▶ BSM searches at the FPF towards understanding dark matter in the Universe
- ▶ Various BSM models can be tested:
  - ▶ Long-lived vector particles, e.g. dark photons, gauge bosons, ...
  - ▶ Long-lived scalars, e.g. dark Higgs, two Higgs doublets, flavor-philic scalars, ...
  - ▶ Long-lived fermions, 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 backup, a few example dark matter scenarios to be tested at the FPF
- ▶ For a complete description, please see FPF white paper...

# 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

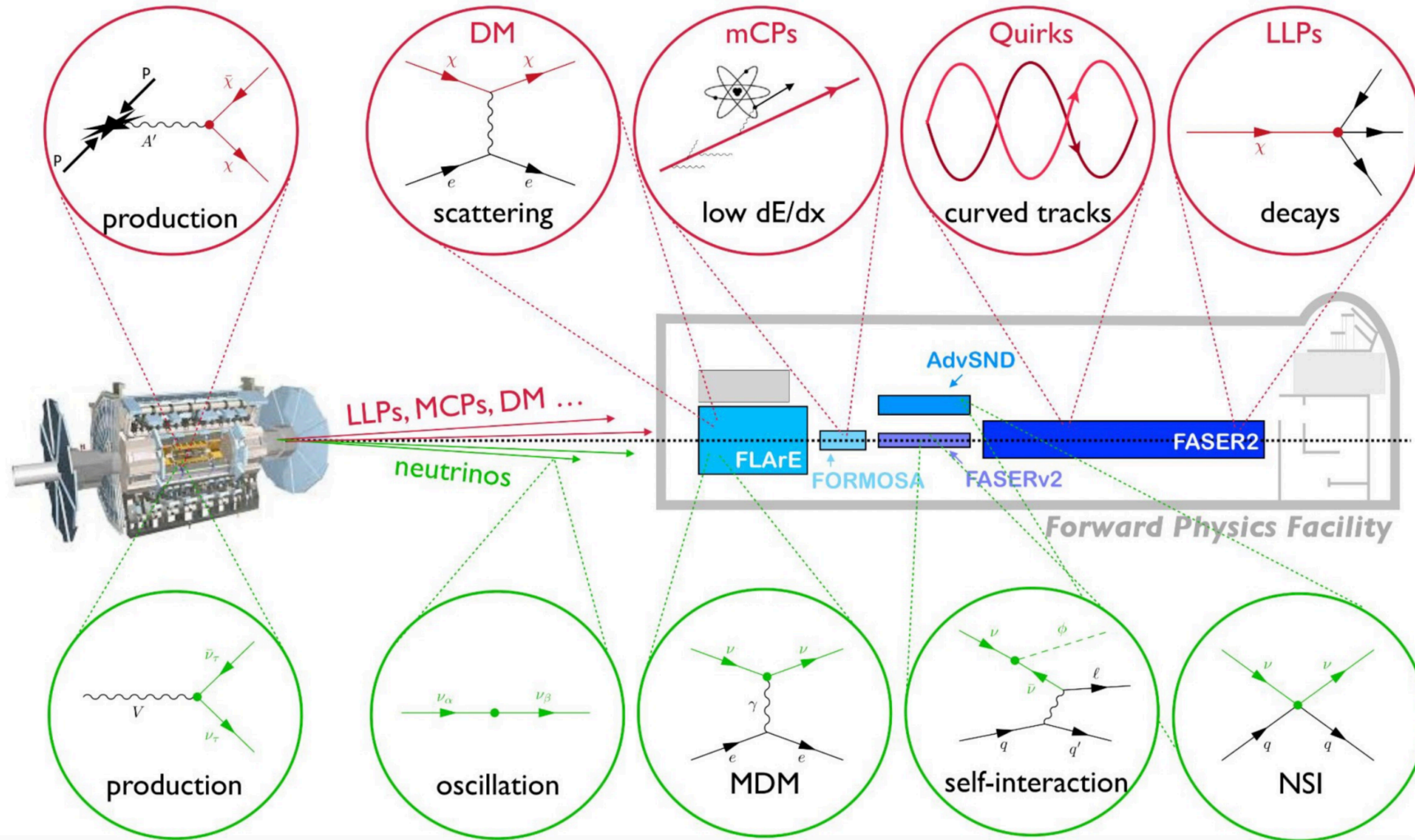


# Summary & Conclusions



FPF Short Paper:  
[arXiv:2109.10905](https://arxiv.org/abs/2109.10905)

FPF White Paper:  
[arXiv:2203.05090](https://arxiv.org/abs/2203.05090)

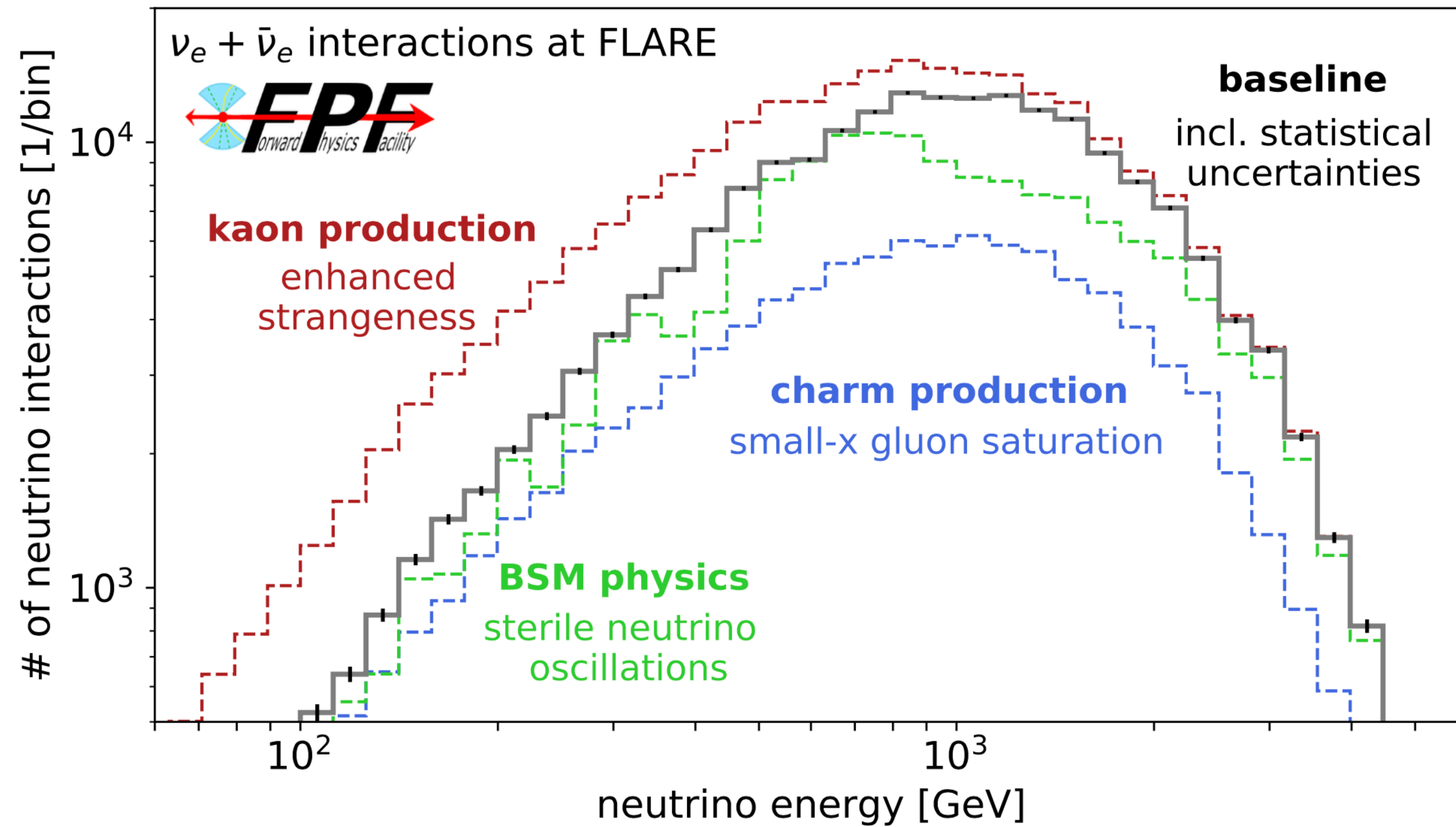


Thank you!



**Backup**

# Summary & Conclusions



FPF Short Paper:  
[arXiv:2109.10905](https://arxiv.org/abs/2109.10905)

FPF White Paper:  
[arXiv:2203.05090](https://arxiv.org/abs/2203.05090)

Thank you!

# FPF Costs



Component	Cost Range	Comments
<b>Facility Costs</b>		
FPF civil construction	20-35 MCHF	Construction of shaft and cavern
FPF outfitting costs	7-15 MCHF	Electrical, safety, and other services
<b>Total</b>	<b>27-50 MCHF</b>	Total including integration
<b>Int'l Experiment Costs</b>		Labor, overhead, contingency not included
FASER2	17 MCHF	Non-US portion
FASER $\nu$ 2	16 MCHF	
ADV-SND	12 MCHF	
<b>Total</b>	<b>45 MCHF</b>	
<b>US Experiment Costs</b>		Labor, overhead, contingency included
FLArE	\$39-65 M	Contingency 40%
FORMOSA	\$7-8 M	Contingency 20%
FASER2	\$6-10.5 M	Contingency 50%, US portion
<b>Total</b>	<b>\$52-83.5 M</b>	

TABLE II. Cost ranges for components of the FPF and the experimental program. Costs of the infrastructure at CERN are Class 4 estimates according to international standards; they have a range (+50% and -30%). The costs for experimental components other than FLArE and FORMOSA are estimated as core costs, which consist of direct costs of materials and contracts only. The US costs include the costs for FLArE, FORMOSA, and portions of FASER2 appropriate for the US. The US costs include engineering and labor rates from either US laboratories or universities and include contingency (see text). Escalation over the construction period was added for US costs also. As described in the text the cost ranges result from technical or management choices that will be made in the future. All cost ranges are in FY2023 dollars.



# FPF Costs



Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033-34
(HL)-LHC nominal schedule	Run3	Run3	Run3	Run3	LS3	LS3	LS3	Run4	Run4	Run4	Run4	LS4
FPF/FLARE milestones		Pre-CDR and physics proposal	R&D and detector prototypes	CDR- long lead item magnet	Start of civil constr. TDR for detectors	Detector construction start	Long lead items for detector	End of civil constr. Install services	Detector install	Detector Commissioning and physics start	Physics running with full complement of detectors	
US-DOE FLARE (kUS\$)						9750	19500	19500	13000	3250		
US-DOE FORMOSA (kUS\$)						800	1600	4000	1600			
US-DOE-FASER2 (kUS\$)			875	1750	3500	2625	1750					
<b>Total US-DOE (kUS\$)</b>			<b>875</b>	<b>1750</b>	<b>3500</b>	<b>13175</b>	<b>22850</b>	<b>23500</b>	<b>14600</b>	<b>3250</b>		

TABLE III. Proposed funding profile for the US DOE portion of the FPF experimental program using the upper ranges from Table II. The main components are FLArE, FORMOSA, and US contributions to FASER2. The estimates include all technical components and laboratory and university labor with appropriate overhead factors. The FLArE estimate has a 40% contingency applied, and the FORMOSA estimate has a 20% contingency applied. Cost numbers are in FY2023 dollars.

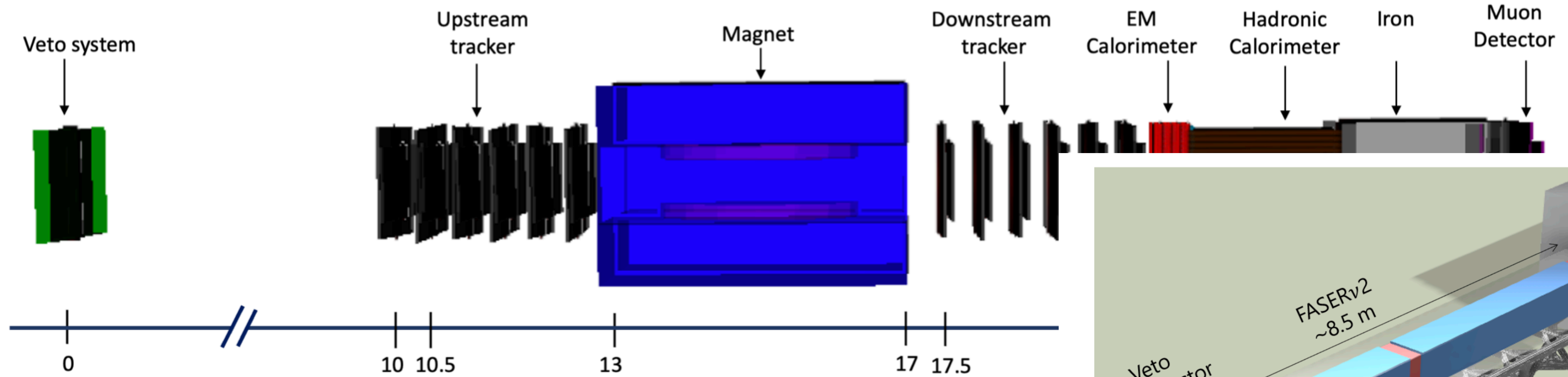


FIG. 10. Schematic diagram of the full FASER2 detector, showing the decay volume, tracker, magnet, electromagnetic calorimeter, hadronic calorimeter, and muon detector.

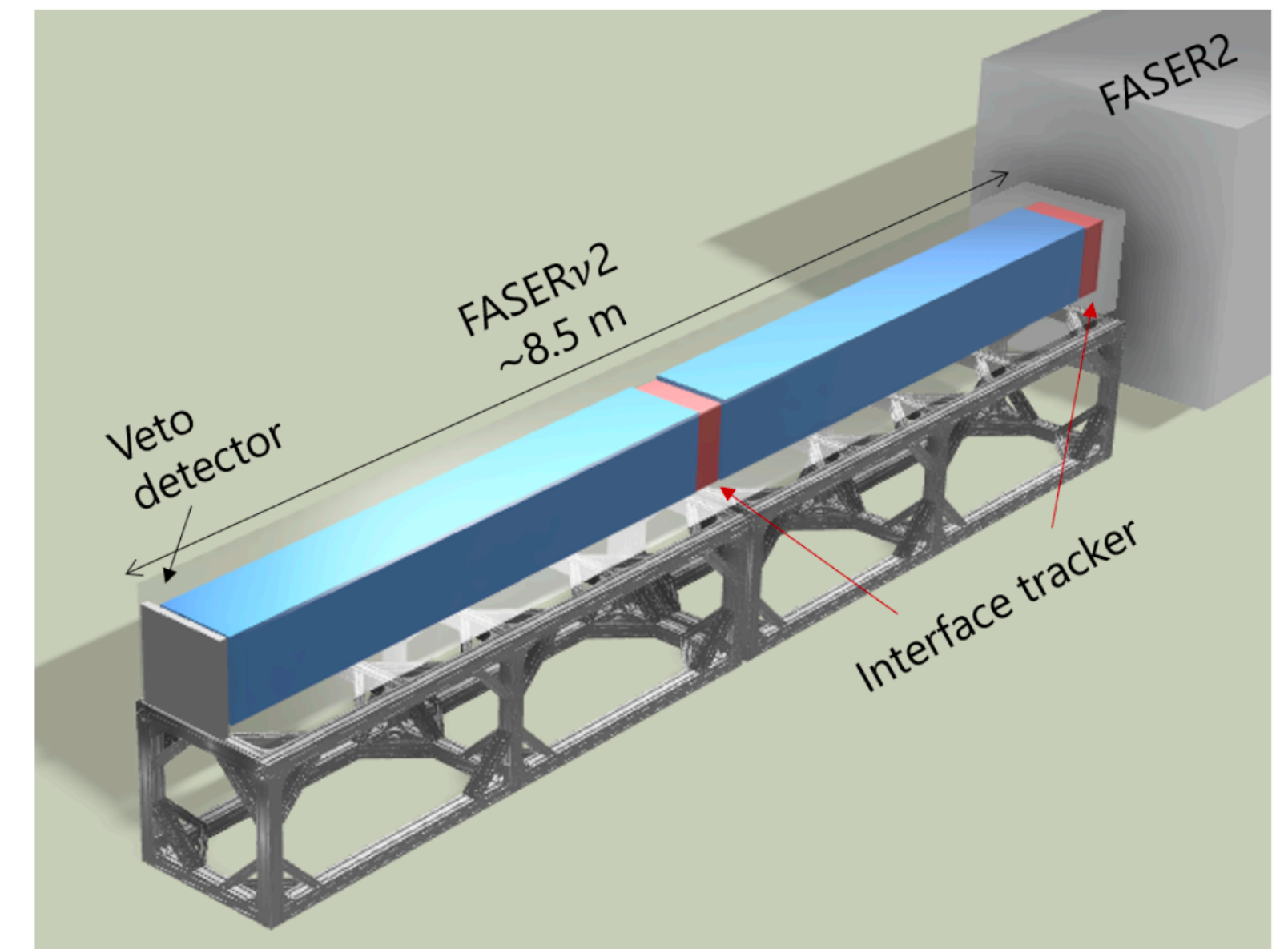


FIG. 11. Conceptual design of the FASERν2 detector.

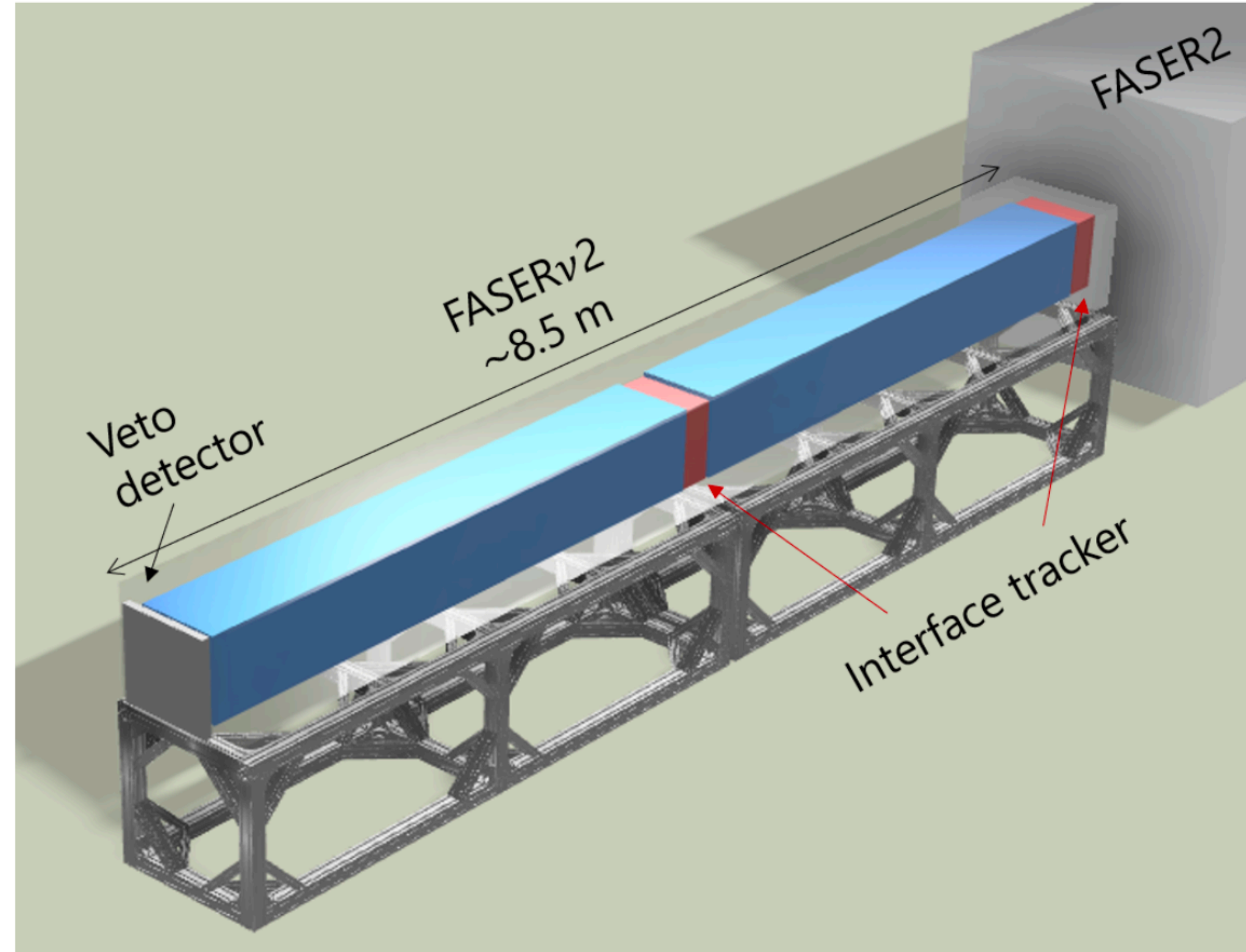


FIG. 11. Conceptual design of the FASER $\nu$ 2 detector.

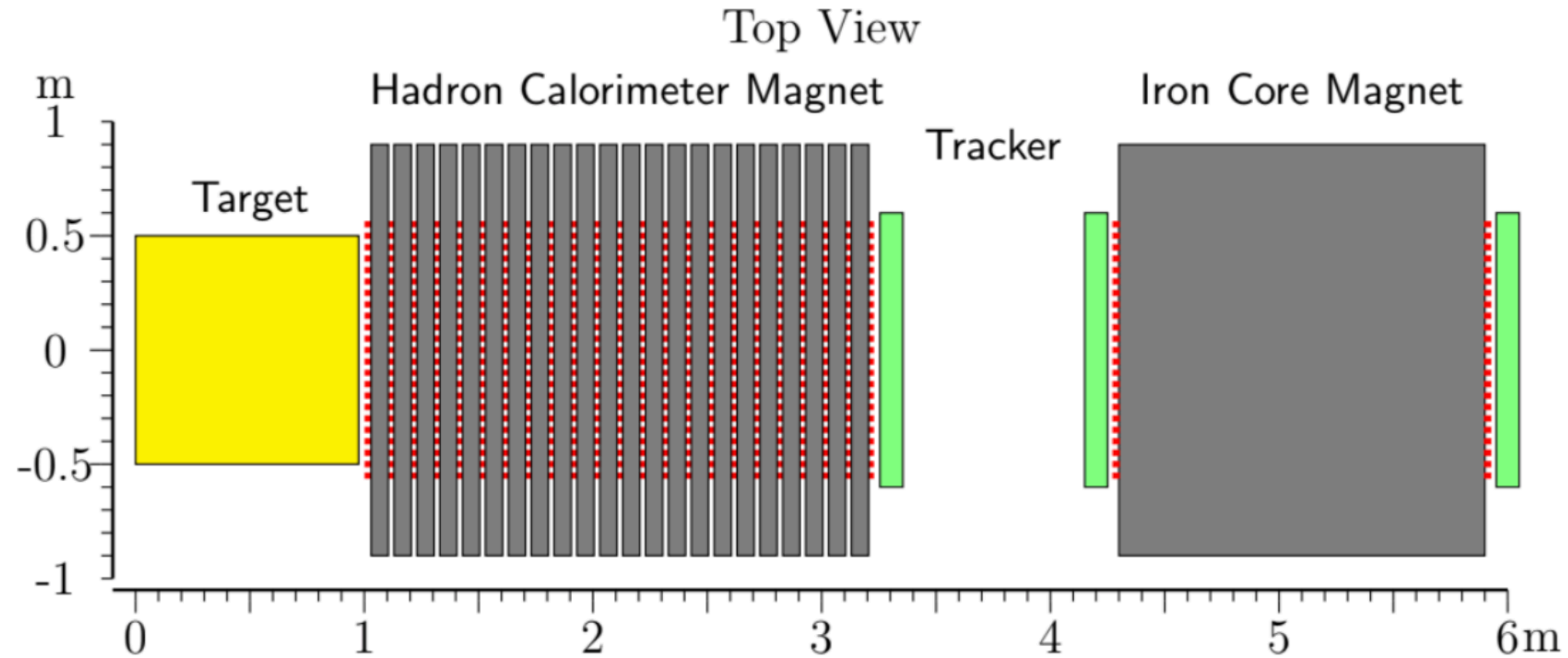


FIG. 12. Layout of the Advanced SND – FAR detector proposed for the FPF.

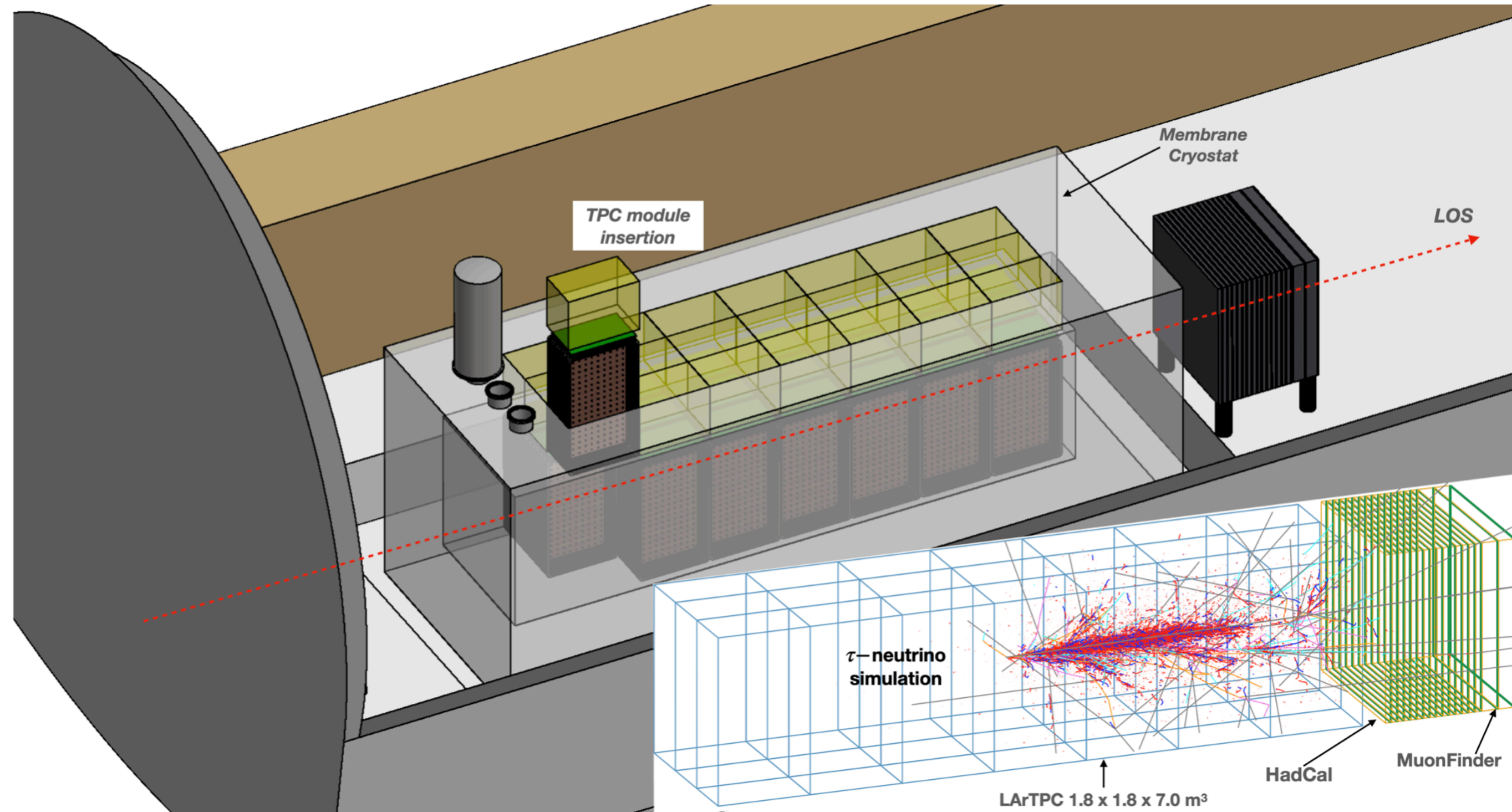


FIG. 13. Layout of FLArE detector in the FPF cavern with a simulated neutrino event inset. The detector is shown with an example of a TPC module being inserted from the top.

# FORMOSA

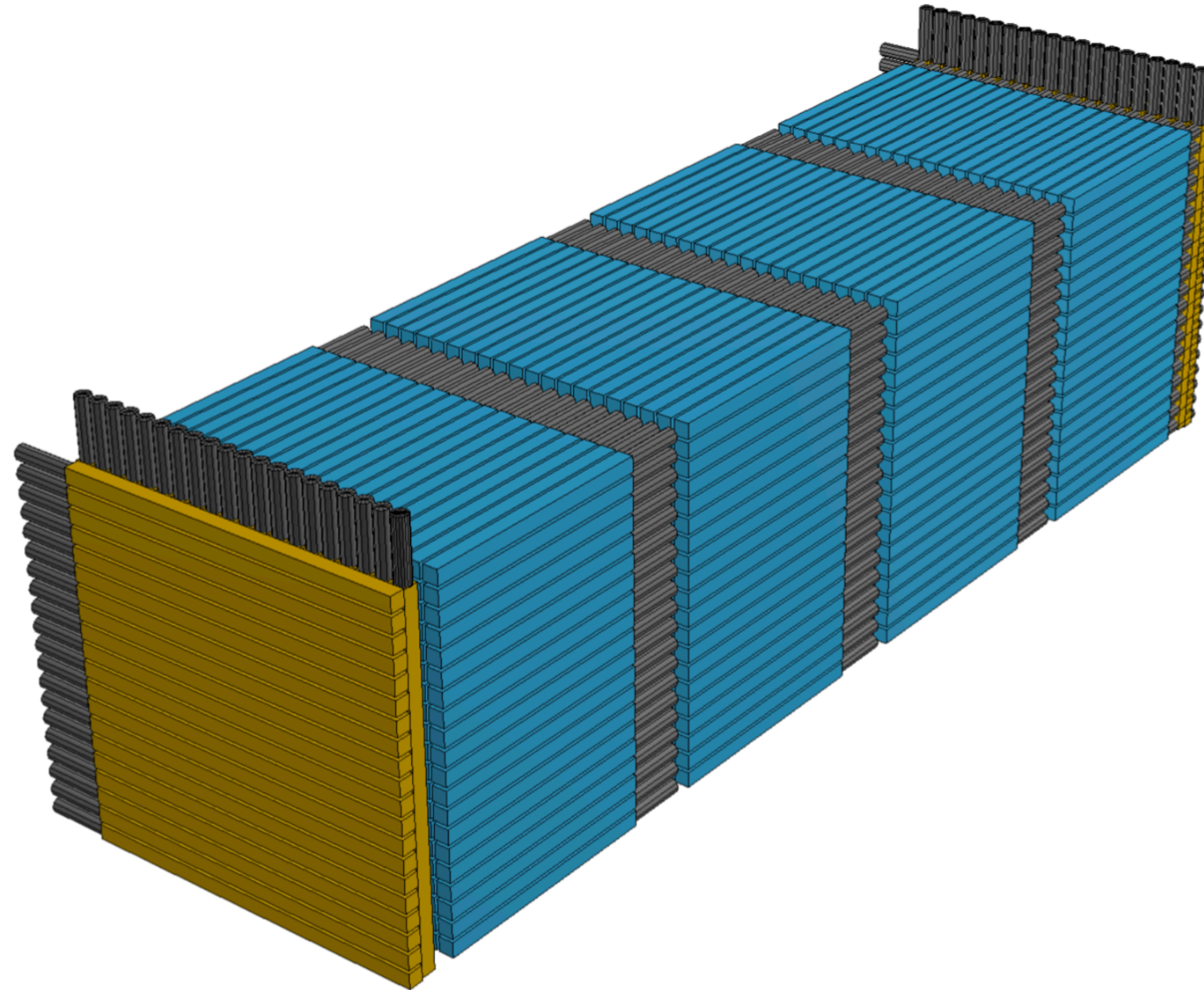


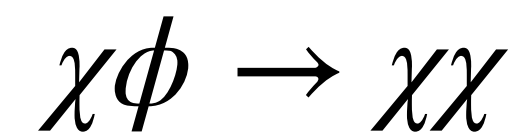
FIG. 14. A diagram of the FORMOSA detector components. The scintillator bars are shown in blue connected to PMTs in black.

# Dark Matter Searches



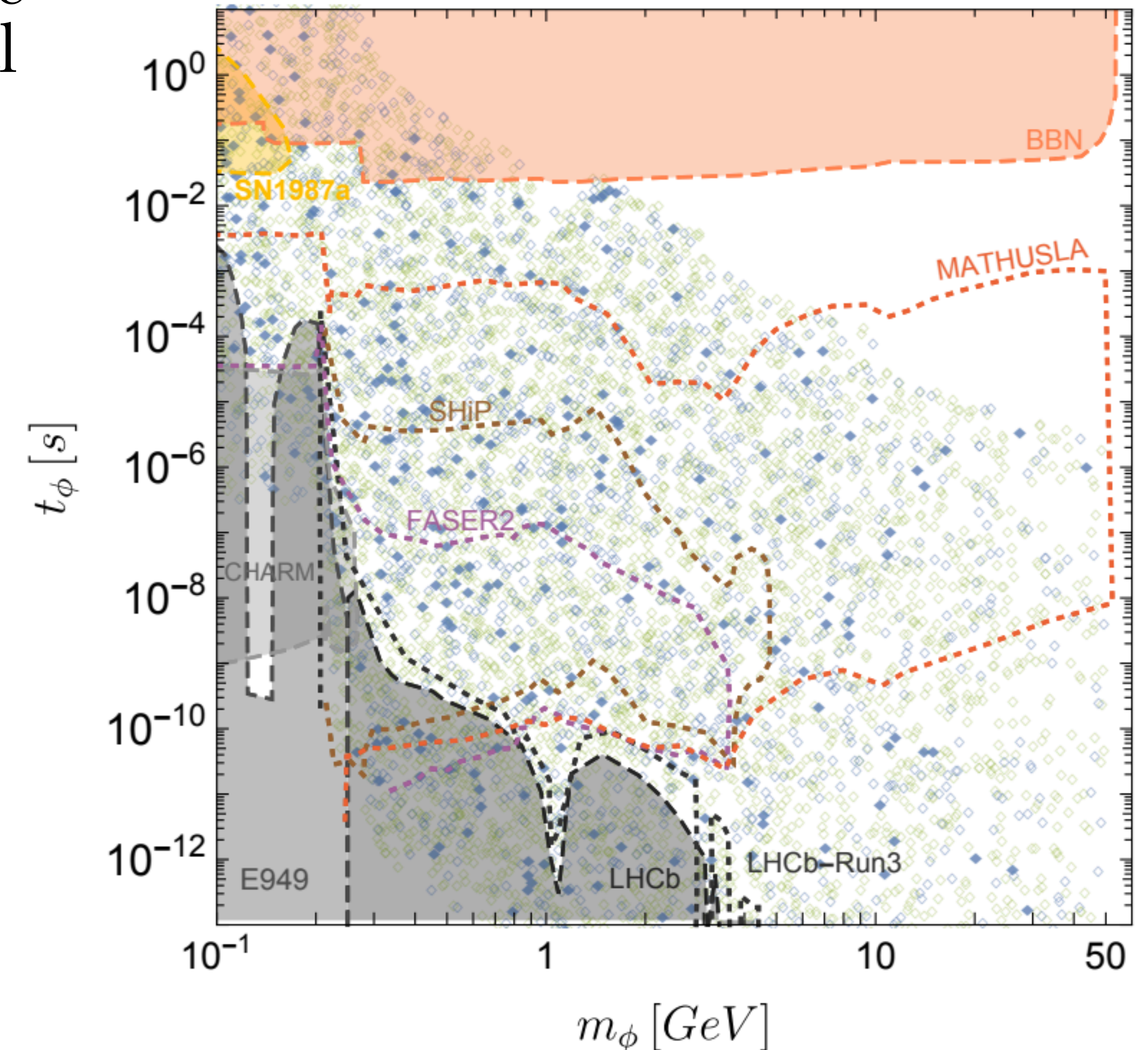
## Example: Dark Matter from Freeze-In Semi-Production

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



- ▶ Constraints on the mediator mass  $m_\phi$  and lifetime  $t_\phi$
- ▶ For details of the model, please see A. Hryczuk, M. Laletin, JHEP 06 (2021)

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

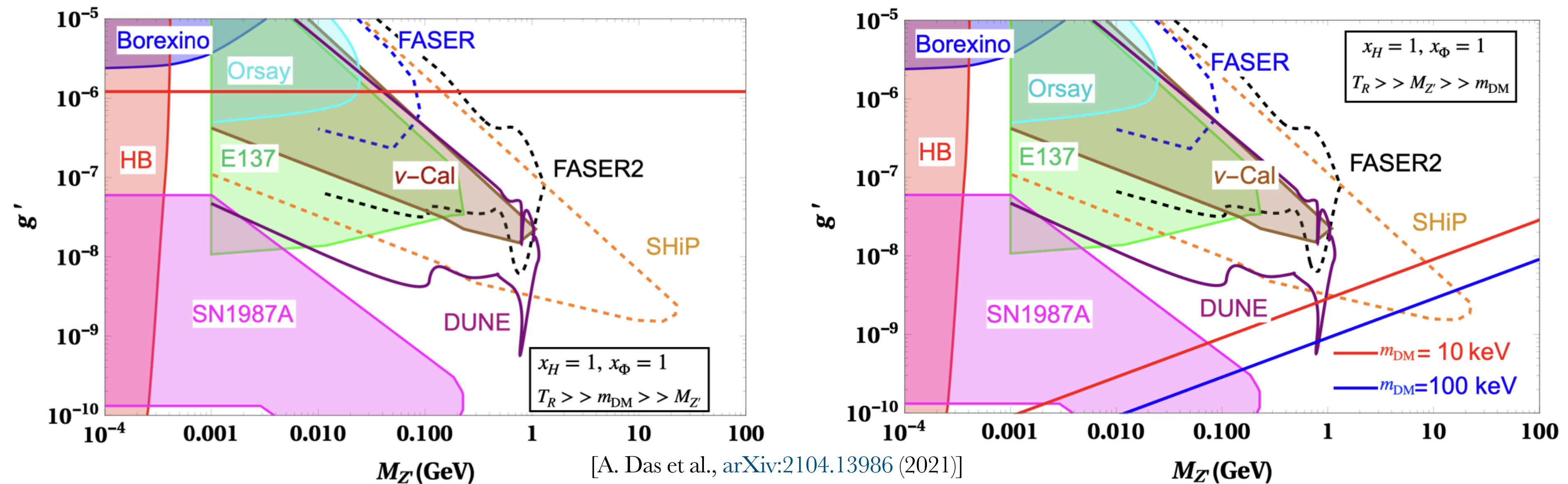


# Dark Matter Searches



## 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)



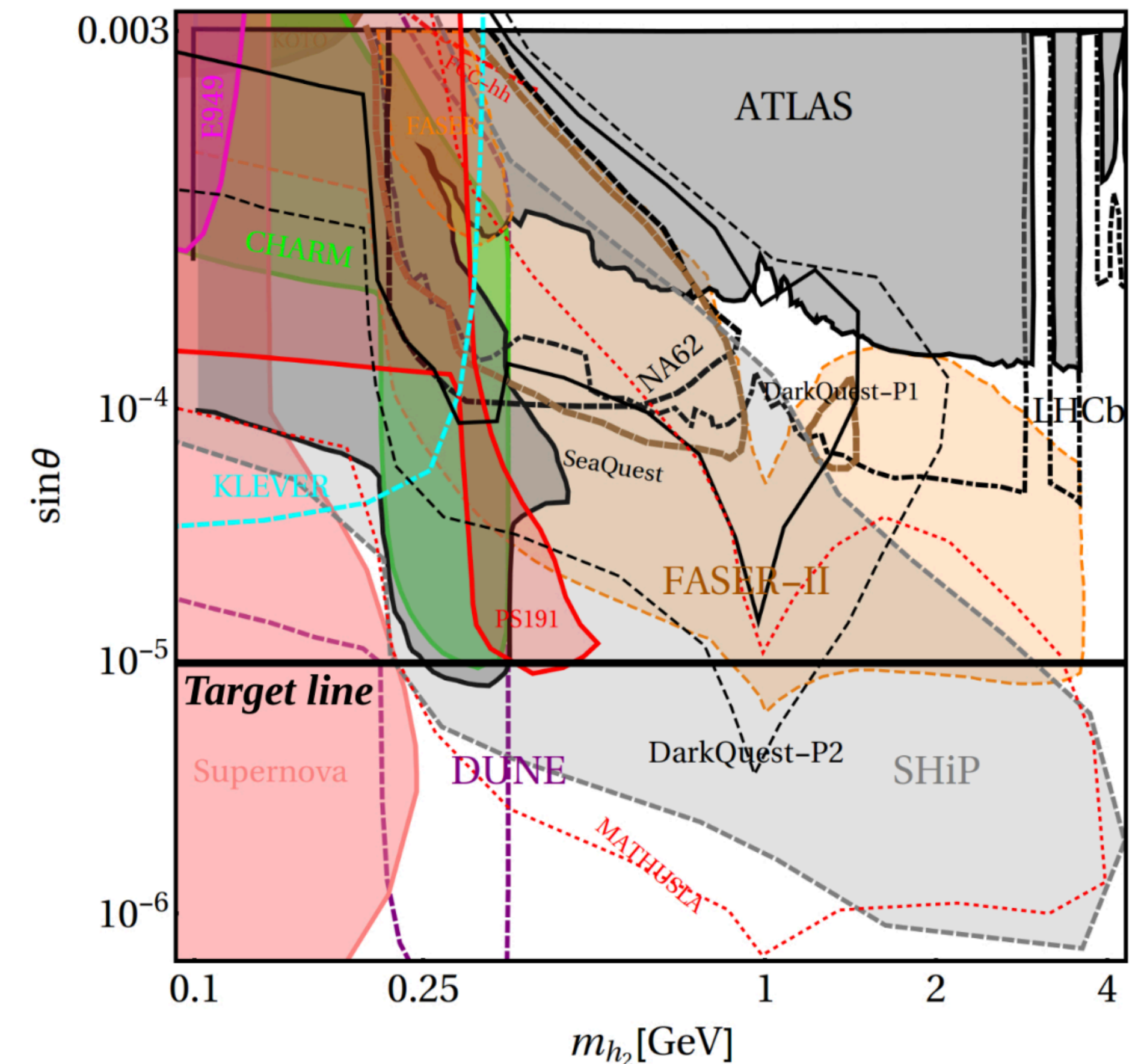
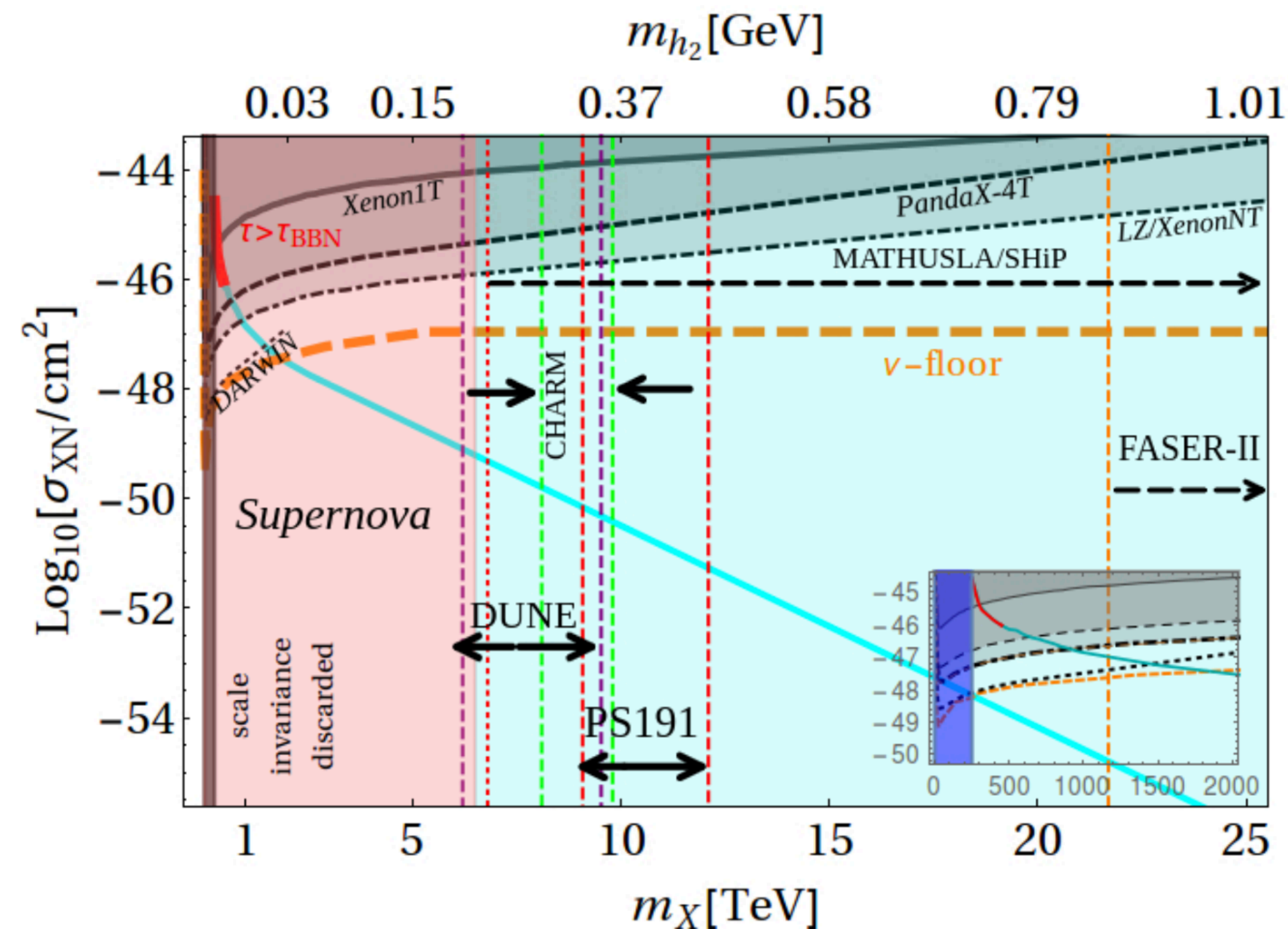


# Dark Matter Searches



## 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  $\theta$

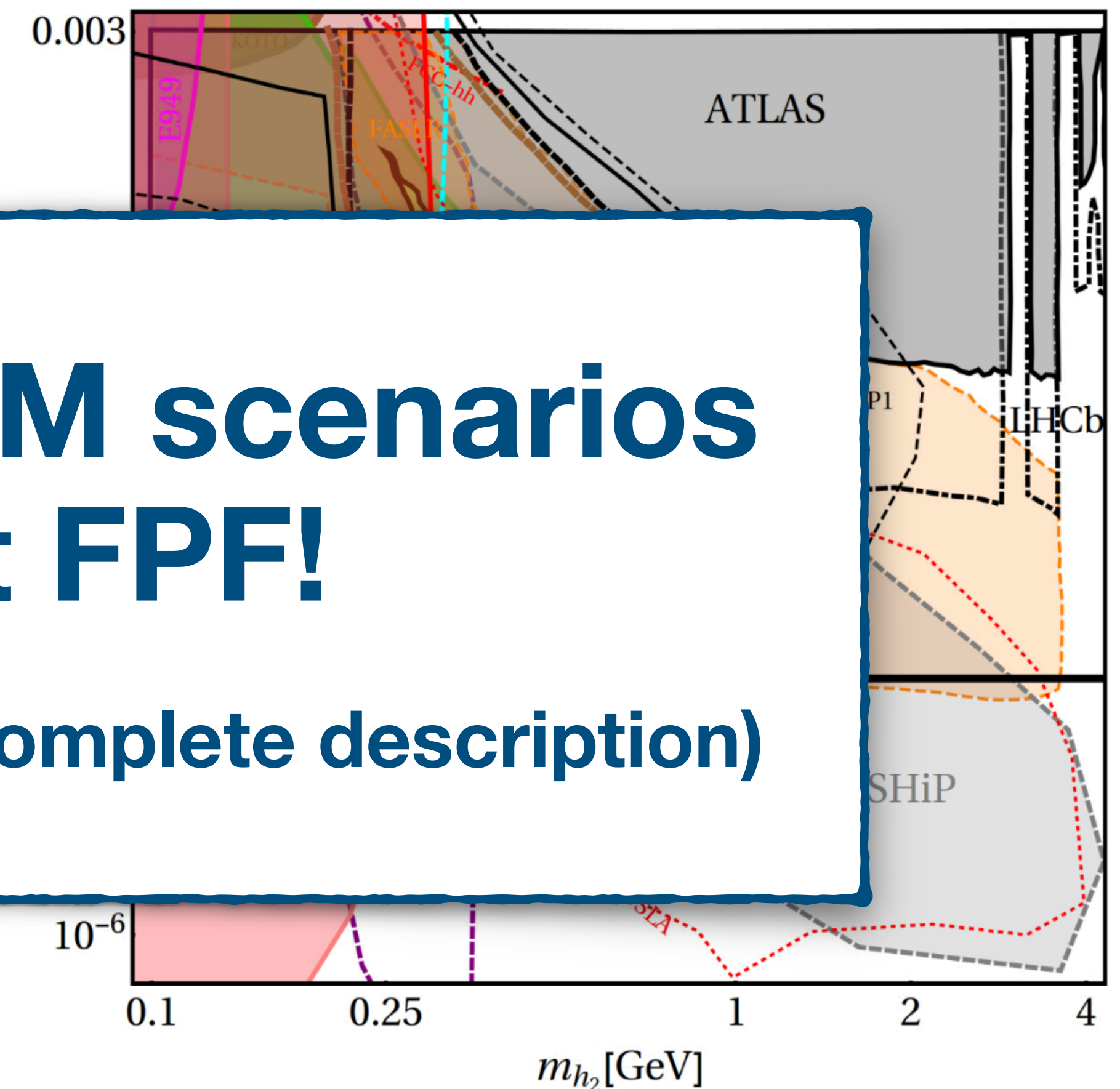


# Dark Matter Searches



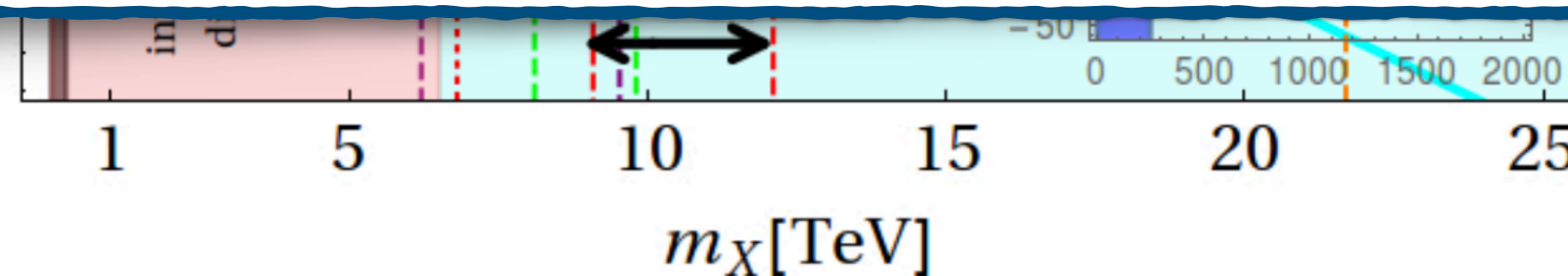
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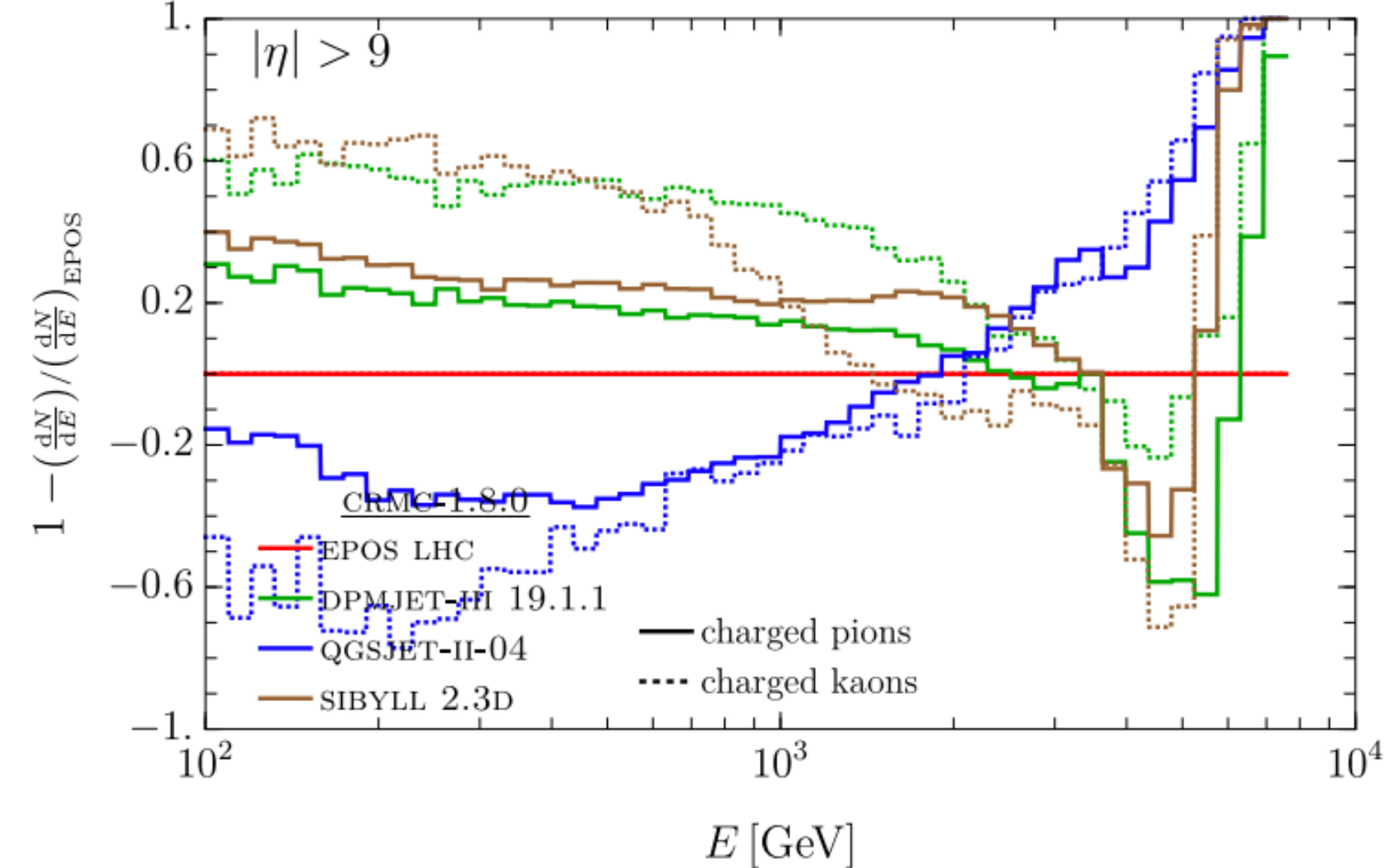
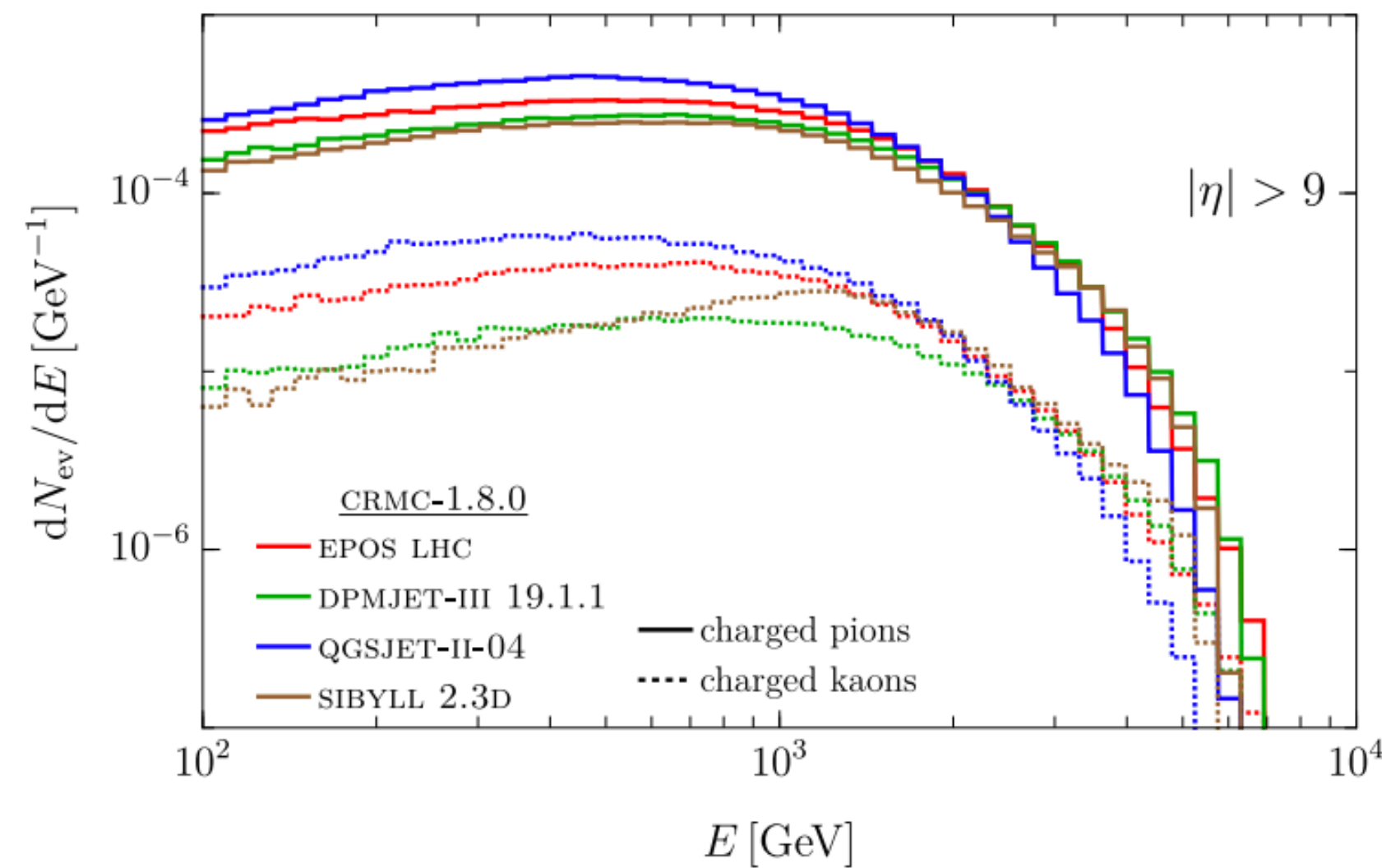
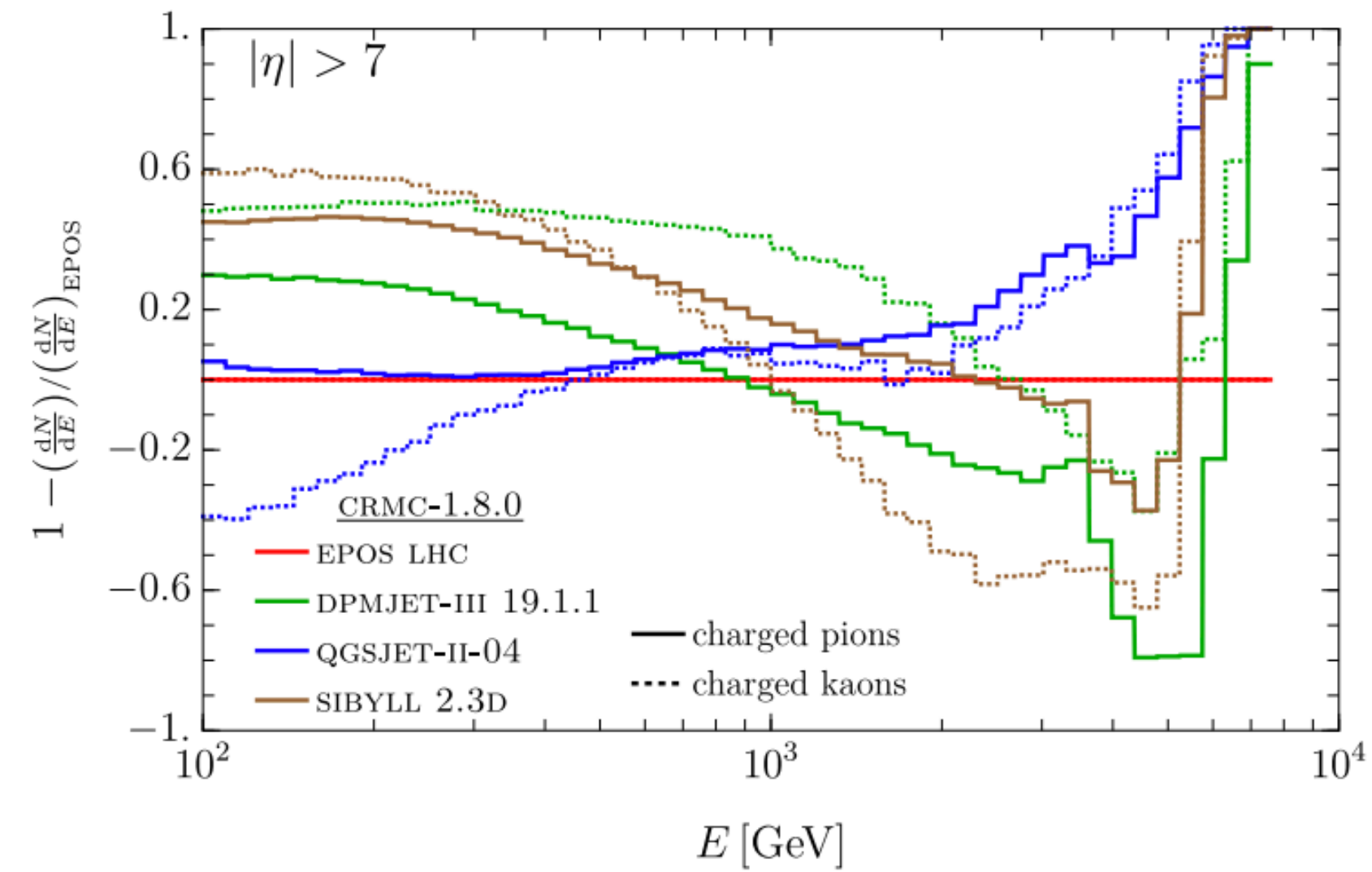
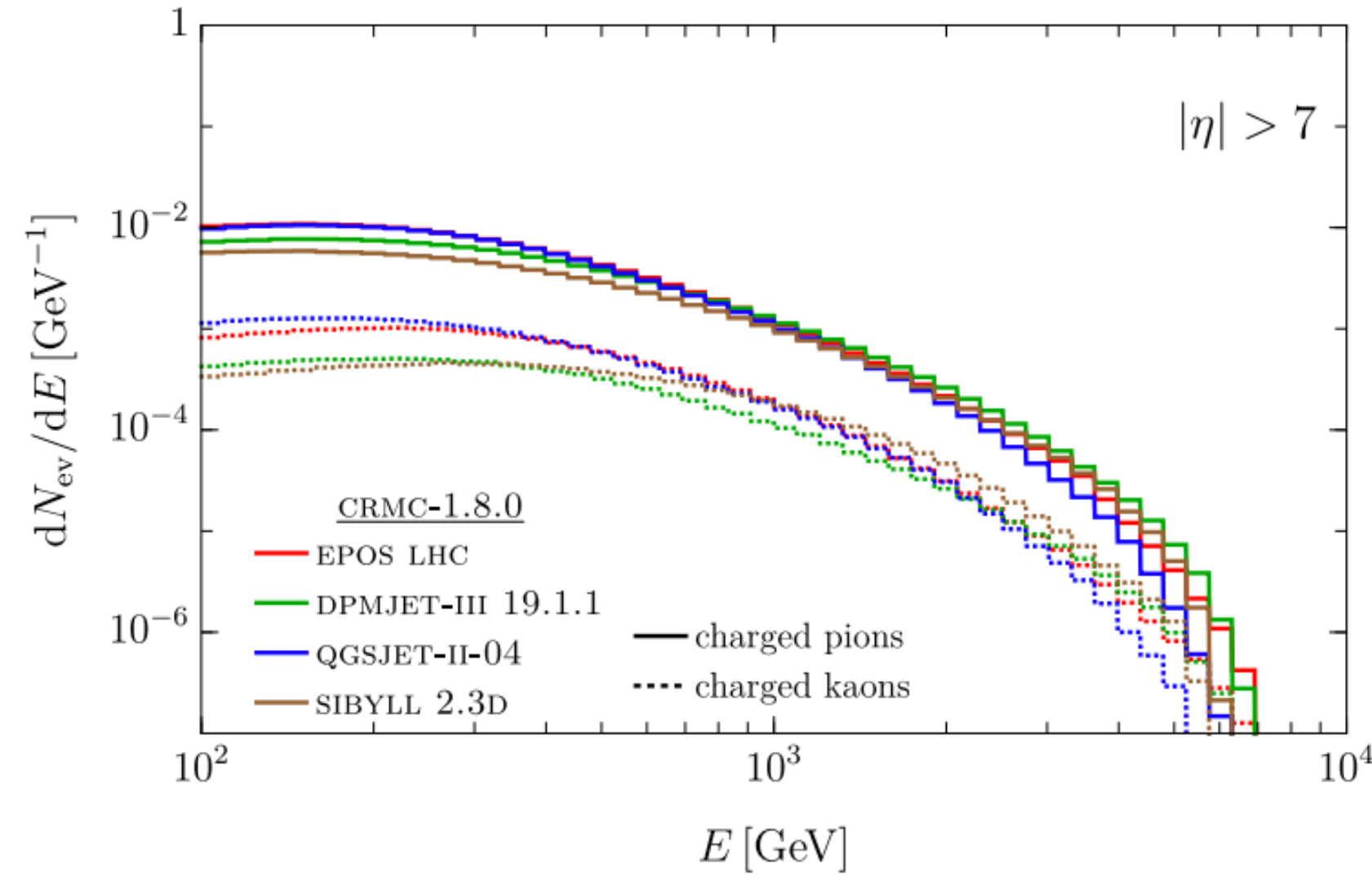


**Many, many more BSM scenarios  
to be tested at FPF!**

**(please see FPF white paper for a complete description)**



# Light Hadron Production



# Summary & Conclusions



- ▶ Further reading:
  - ▶ FPF Short Paper: Physics Reports 968 (2022), [arXiv:2109.10905](https://arxiv.org/abs/2109.10905)
  - ▶ FPF White Paper: Accepted by Journal of Physics G, [arXiv:2203.05090](https://arxiv.org/abs/2203.05090)
- ▶ If you want to become WG3 member, please sign up at:
  - ▶ [https://docs.google.com/spreadsheets/d/1SKCB0uE\\_EX2sWJNPajjPXg9xohsX6SqjDeUS-ypYICk/edit?usp=sharing](https://docs.google.com/spreadsheets/d/1SKCB0uE_EX2sWJNPajjPXg9xohsX6SqjDeUS-ypYICk/edit?usp=sharing)
- ▶ If you have any further questions or input, please don't hesitate to contact us:
  - ▶ Jamie Boyd: [jamie.boyd@cern.ch](mailto:jamie.boyd@cern.ch)
  - ▶ Jonathan Feng: [jlf@uci.edu](mailto:jlf@uci.edu)
  - ▶ Felix Kling: [flxkling@gmail.com](mailto:flxkling@gmail.com)
  - ▶ Mary Hall Reno: [mary-hall-reno@uiowa.edu](mailto:mary-hall-reno@uiowa.edu)
  - ▶ Juan Rojo: [j.rojo@vu.nl](mailto:j.rojo@vu.nl)
  - ▶ Dennis Soldin: [soldin@kit.edu](mailto:soldin@kit.edu)

# WG3 Organization



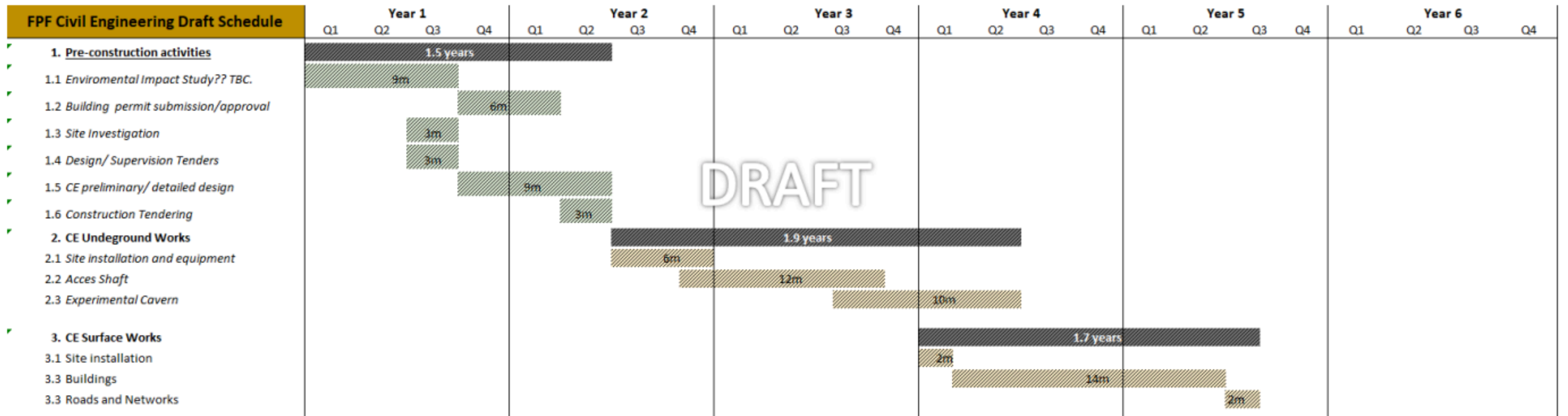
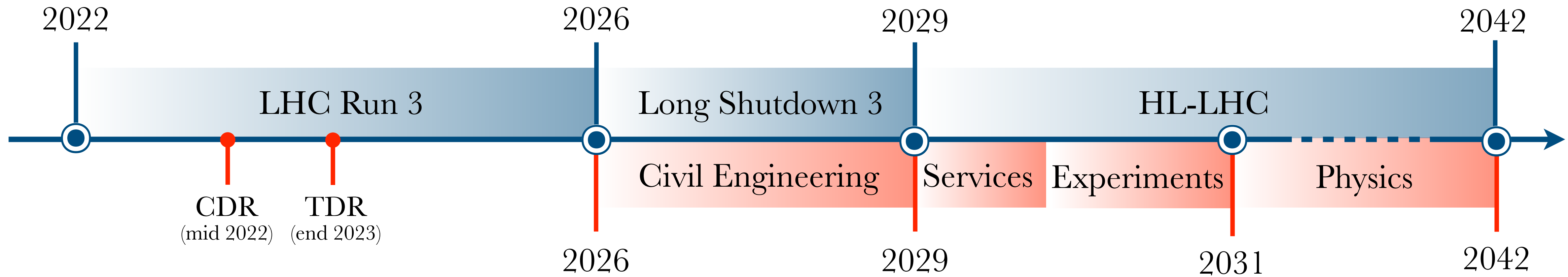
- ▶ First email to become part of WG3 on Oct. 19
- ▶ Sign-up sheet for WG3 members:
  - ▶ [https://docs.google.com/spreadsheets/d/1SKCB0uE\\_EX2sWJNPajjPXg9xohsX6SqjDeUS-ypYICk/edit?usp=sharing](https://docs.google.com/spreadsheets/d/1SKCB0uE_EX2sWJNPajjPXg9xohsX6SqjDeUS-ypYICk/edit?usp=sharing)
- ▶ In the future, we will only contact members on this list!
- ▶ Please feel free to contact/add further interested candidates!

## FPF Working Group "Light Hadron Production"

List of members of the FPF working group on light hadron production which includes all topics that are related to forward pion/kaon production, e.g. non-perturbative physics, hadronic interaction models, cosmic rays, the cosmic muon puzzle, etc.

	First Name	Last Name	Affiliation	Email Address	Comments
1	Dennis	Soldin	Karlsruhe Institute of Technology	soldin@kit.edu	Working Group Lead
2	Luis	Anchordoqui	Lehman College, City University of New York	luis.anchordoqui@gmail.com	Working Group Lead
3	Felix	Riehn	Instituto Galego de Física de Altas Enerxías, USC, Spain	friehn@lip.pt	
4	Felix	Kling	DESY	felix.kling@desy.de	
5	Spencer	Klein	LBNL & UC Berkeley	srklein@lbl.gov	
6	Carlos	García Canal	Universidad Nacional de La Plata-IFLP CONICET	cgarciacanal@fisica.unlp.edu.ar	
7	Max	Fieg	UC Irvine	mfig@uci.edu	
8	Hans	Dembinski	TU Dortmund	hans.dembinski@tu-dortmund.de	
9	Sergio	Sciutto	Universidad Nacional de La Plata - IFLP CONICET	sciutto@fisica.unlp.edu.ar	
10	Jorge	Fernandez Soriano	Lehman College, City University of New York	jorge.soriano@lehman.cuny.edu	
11	Laurie	Nevay	CERN	laurie.nevay@cern.ch	
12	Ralph	Engel	Karlsruhe Institute of Technology	ralph.engel@kit.edu	
13	Tanguy	Pierog	Karlsruhe Institute of Technology	tanguy.pierog@kit.edu	

# FPF Timeline



# WG3 Goals



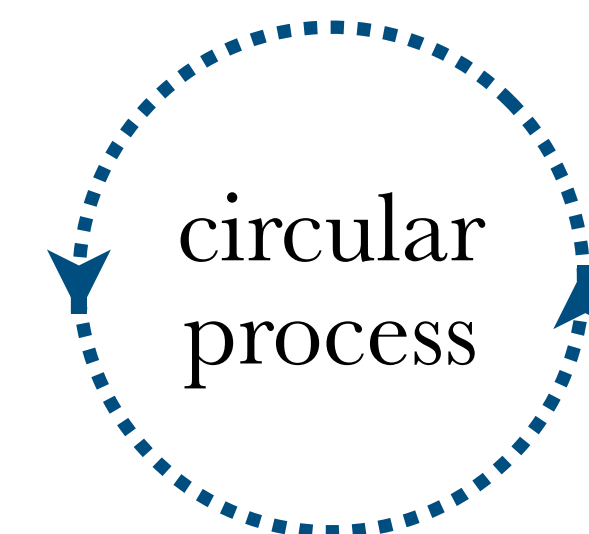
## ▶ Short-term goals:

- ▶ Identify interested people and organize WG3 ✓
- ▶ Define physics goals (✓)
- ▶ Identify some action items (✓)
- ▶ Finalize statement of scope and goals (✓)
  - ▶ Dennis & Luis will draft a first document to be circulated to WG3 for feedback
  - ▶ Assign volunteers (students?) to work on specific topics based on the existing simulations ✗
- ▶ Any open issues/questions will be discussed during the next WG3 meeting (Nov./Dec.)

# WG3 Goals



- ▶ Long-term goals (~February):
  - ▶ Define analyses of FPF data that can help to understand light hadron production
  - ▶ Quantify how well we can test/constrain certain models/generators
  - ▶ Define detector requirements, e.g.
    - ▶ Rapidity ranges, e.g.  $\eta > 7$
    - ▶ Energy resolution (i.e. low energy region)
    - ▶ Angular/spacial resolution
    - ▶ Requirements on flavor ID efficiency
    - ▶ ...
  - ▶ Give feedback to experimentalists about detector requirements
  - ▶ Include realistic detector description in simulations





# FPF Status



- ▶ FPF was discussed at the LHCC meeting last September:
- ▶ From the LHCC minutes:

“A proposal on the Forward Physics Facility (FPF), a large underground experimental facility, well shielded in the line of sight of the ATLAS interaction point, is being put forward. First informal discussions about the next steps with this proposal have taken place between the proponents and the LHCC chair.”

“Given the scope of the proposed facility and the scientific overlap with projects that fall into the responsibility of other committees, the LHCC proposes to discuss the FPF together with other proposals, in an appropriate forum such as the Physics Beyond Colliders study group, prior to moving towards reviews by the scientific committees to ensure a comprehensive and aligned view of the strategy for CERN moving forward. Considering the implications for the long-term scientific strategy and the future development of the CERN infrastructure, a discussion in the SPC may be appropriate to help define priorities prior to further steps.”

- ▶ Takeaway: FPF will be reviewed in conjunction with other proposals, particularly HIKE + SHADOWS and SHiP@ECN3, this year