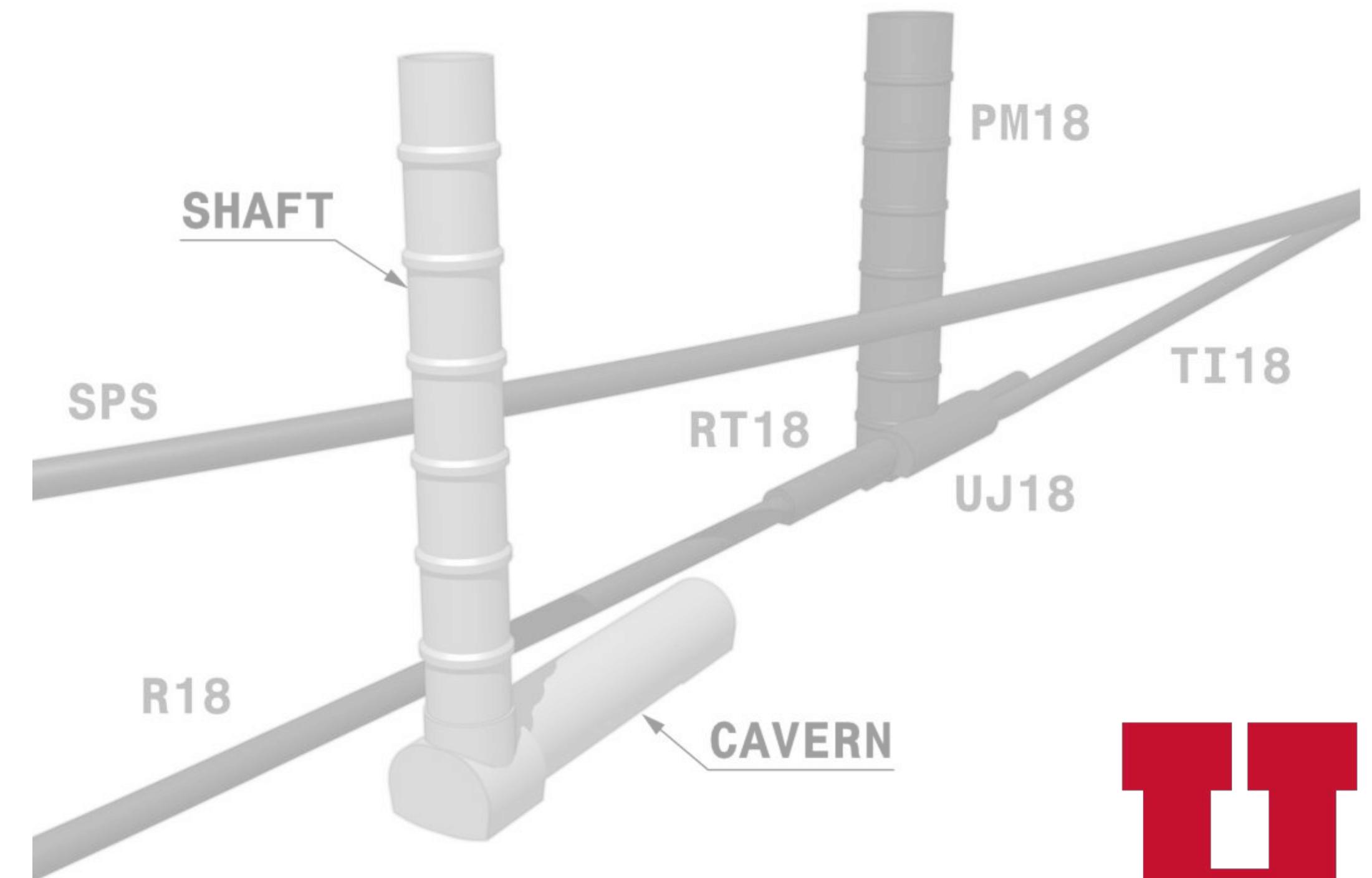


The Forward Physics Facility and its Implications for Astroparticle Physics

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)
- $\sim 30\%$ more muons observed than expected at the highest energies!

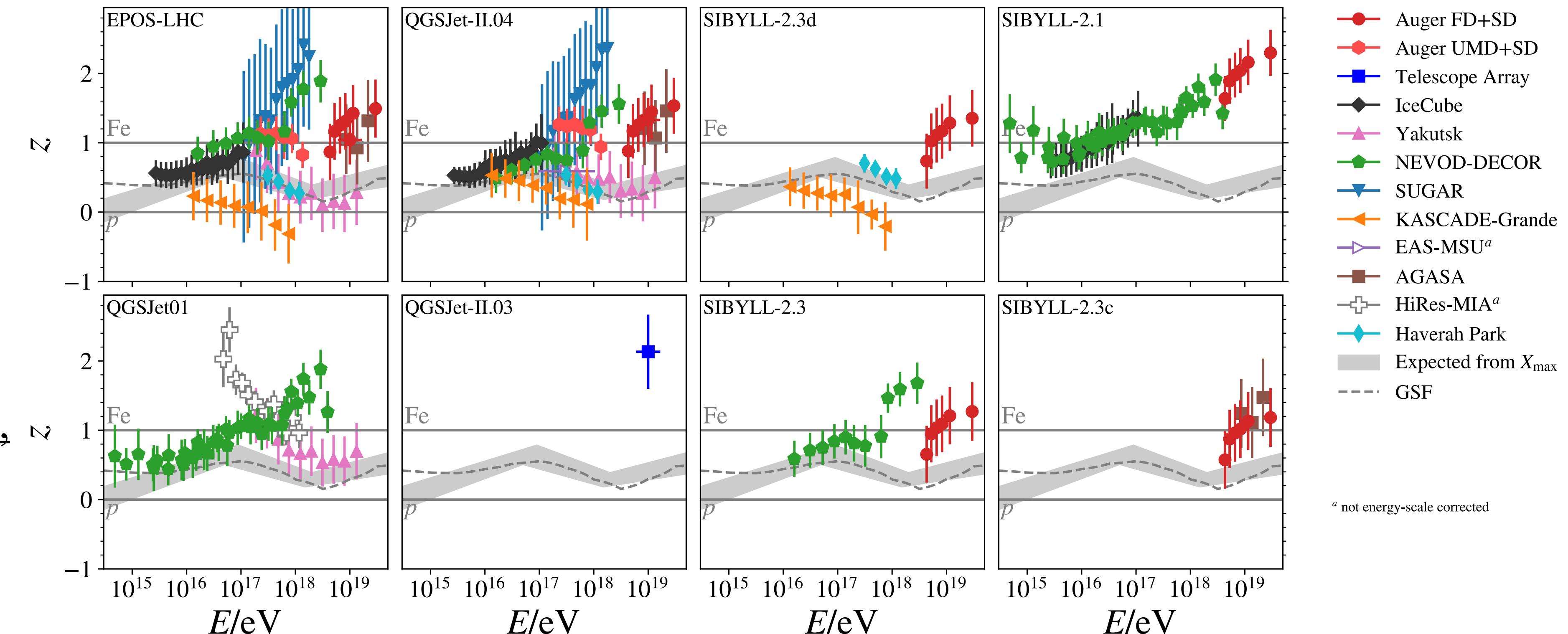
► z-scale:

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

► $z = 0$: proton

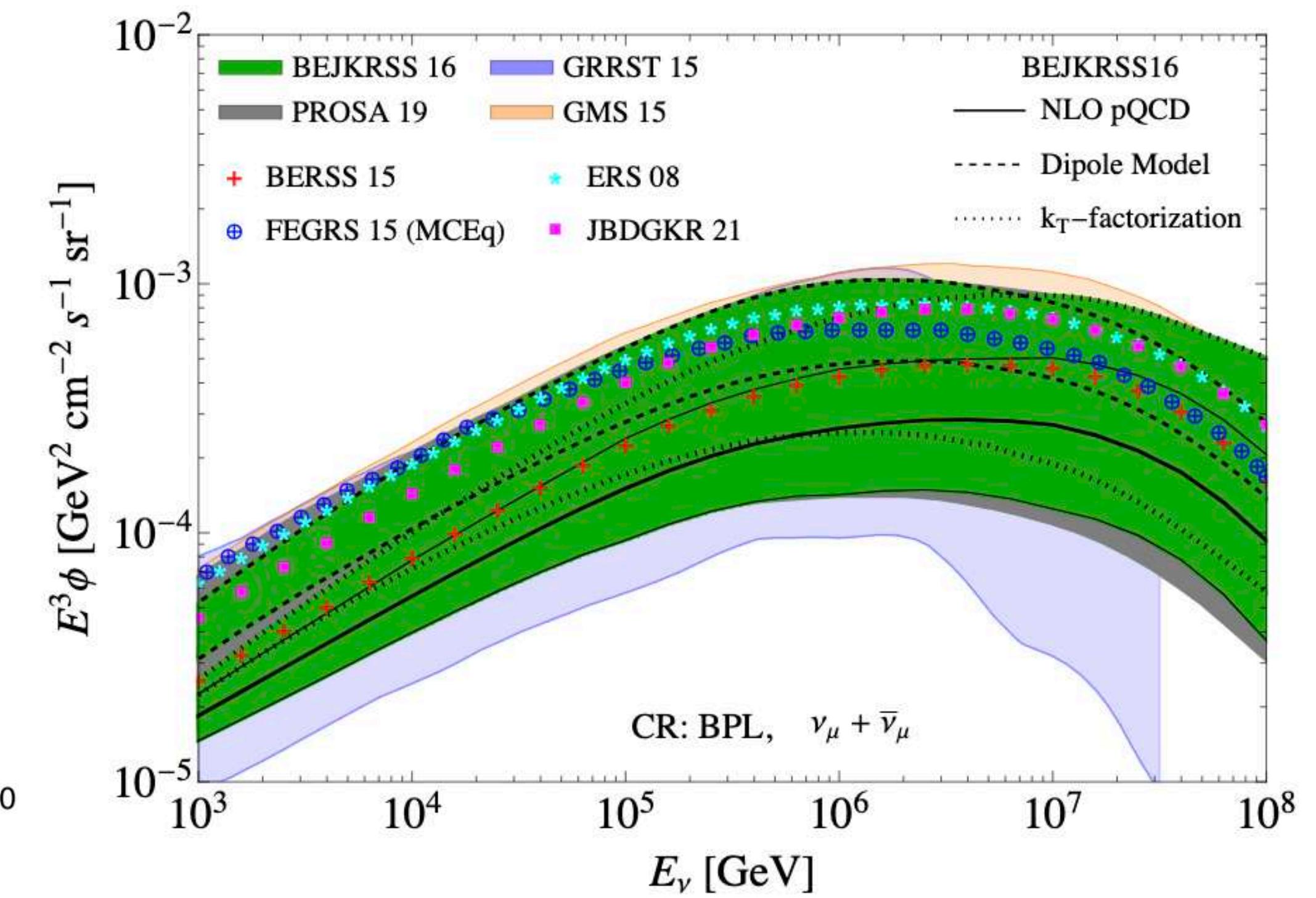
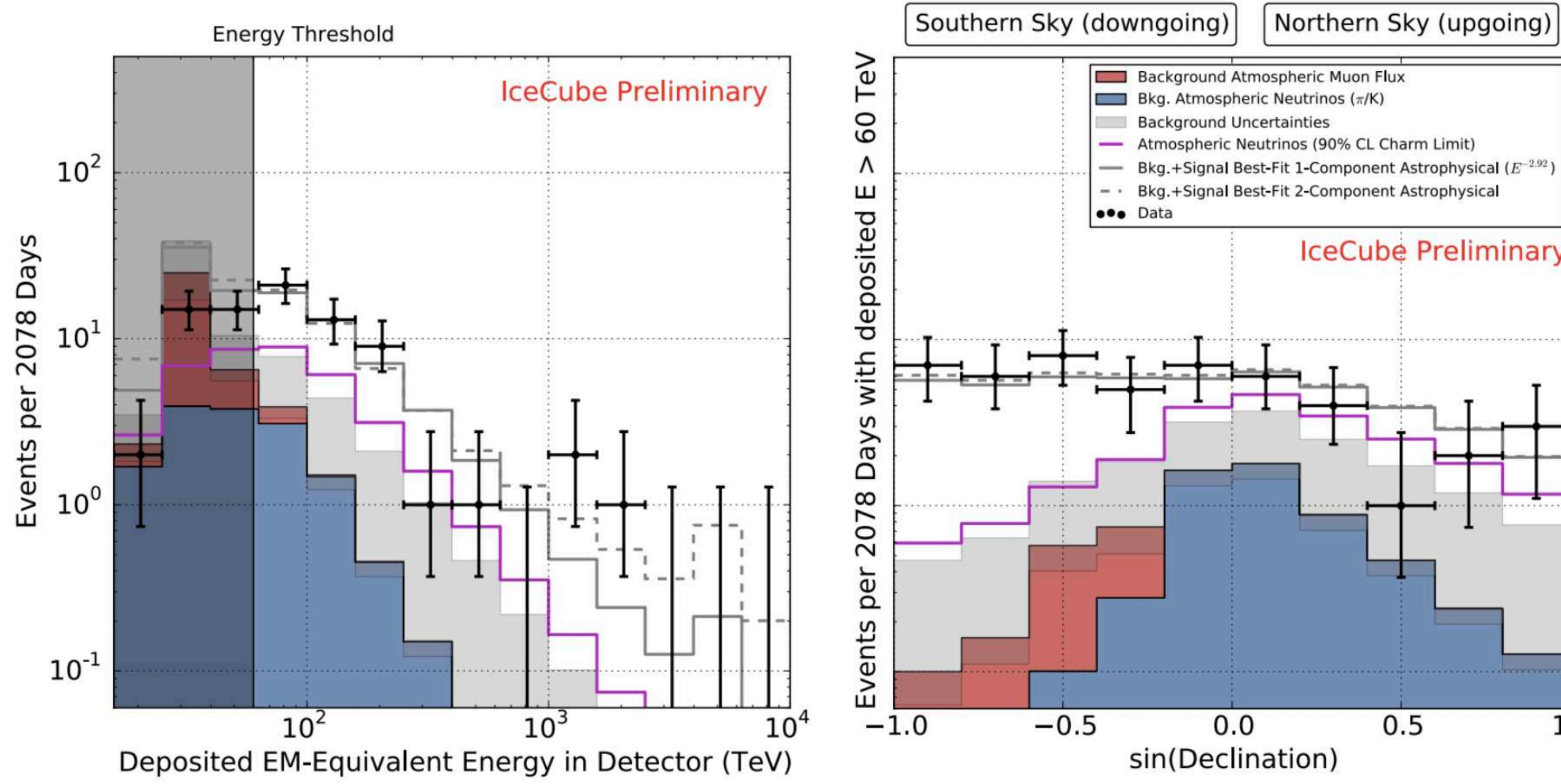
► $z = 1$: iron

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



Introduction: Atmospheric Neutrinos

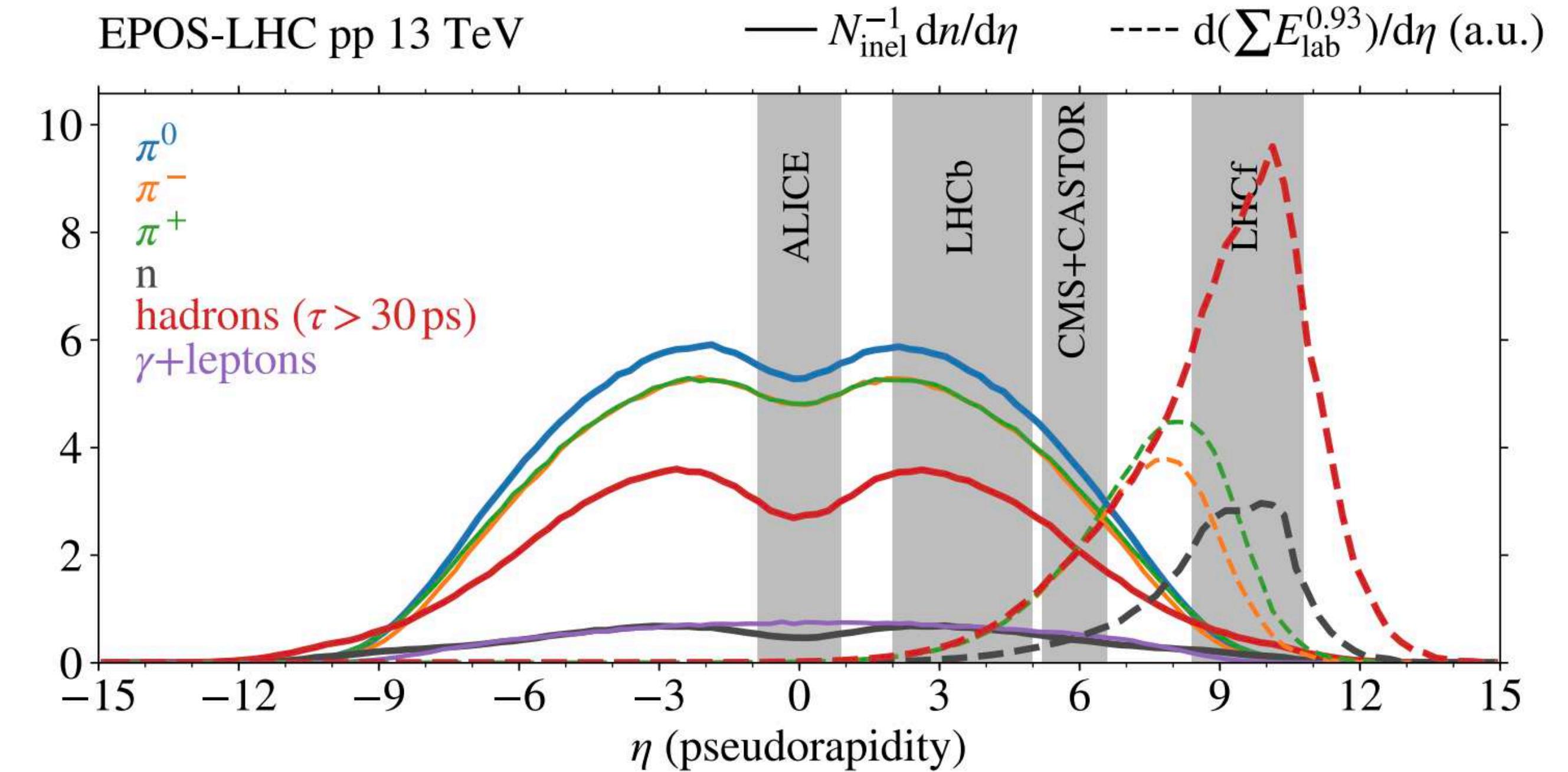
- ▶ Atmospheric high-energy neutrino flux:
 - ▶ Neutrinos from EAS are background for astrophysical neutrino searches, e.g. IceCube / KM3NeT
 - ▶ Prompt neutrino flux (charm) dominates at high energies
 - ▶ Large associated uncertainties for astrophysical neutrino fits!



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)]

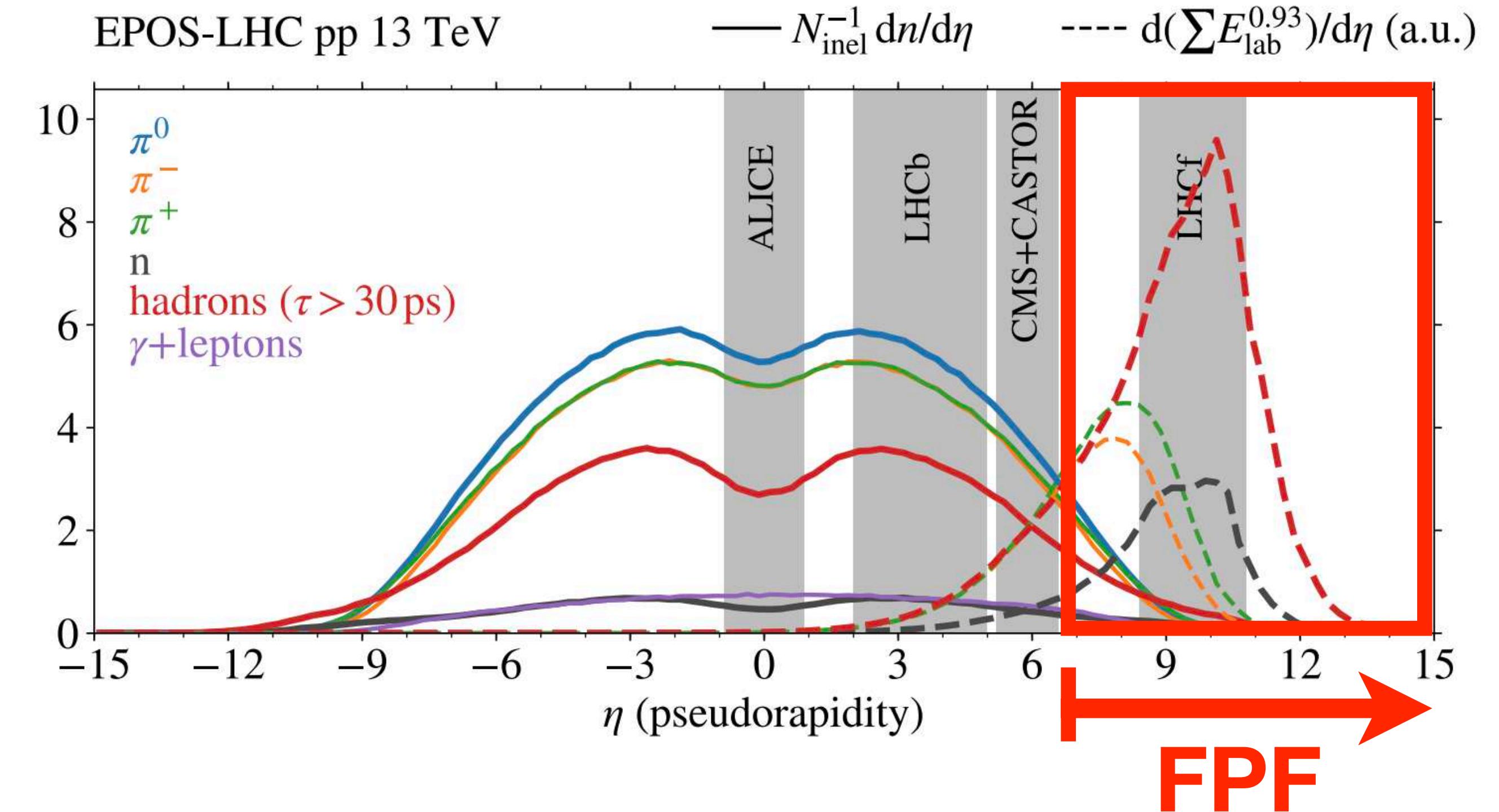


How can we test hadronic interaction models in the far-forward region at accelerators?

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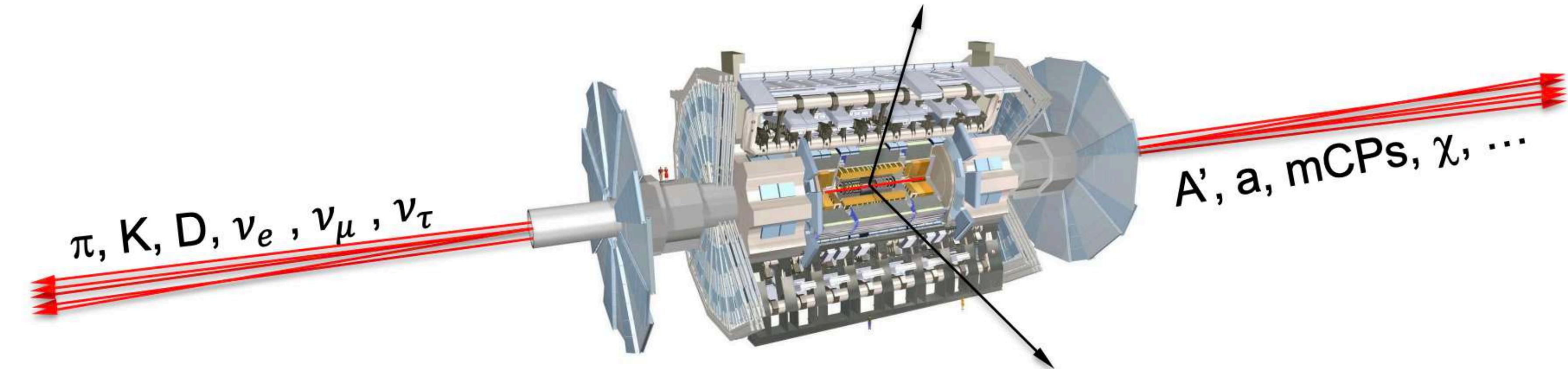


How can we test hadronic interaction models in the far-forward region at accelerators?

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?

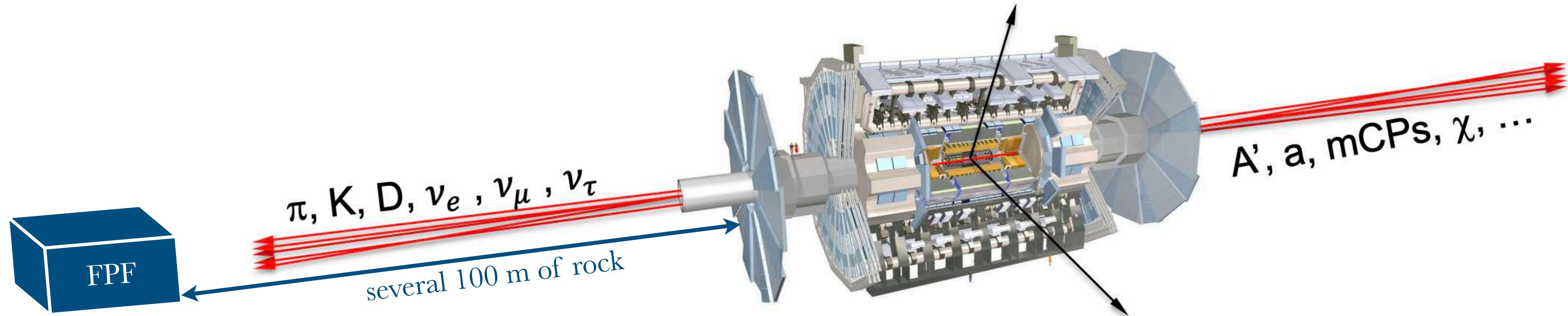


- ▶ By far the largest flux of energetic light particles is in the far-forward direction (mesons, neutrinos, and maybe also dark photons, ALPs, mCPs, DM, ...)
- ▶ Proposal: Forward Physics Facility (FPF) at LHC in ATLAS line-of-sight ($\eta \gtrsim 7$)

The Forward Physics Facility



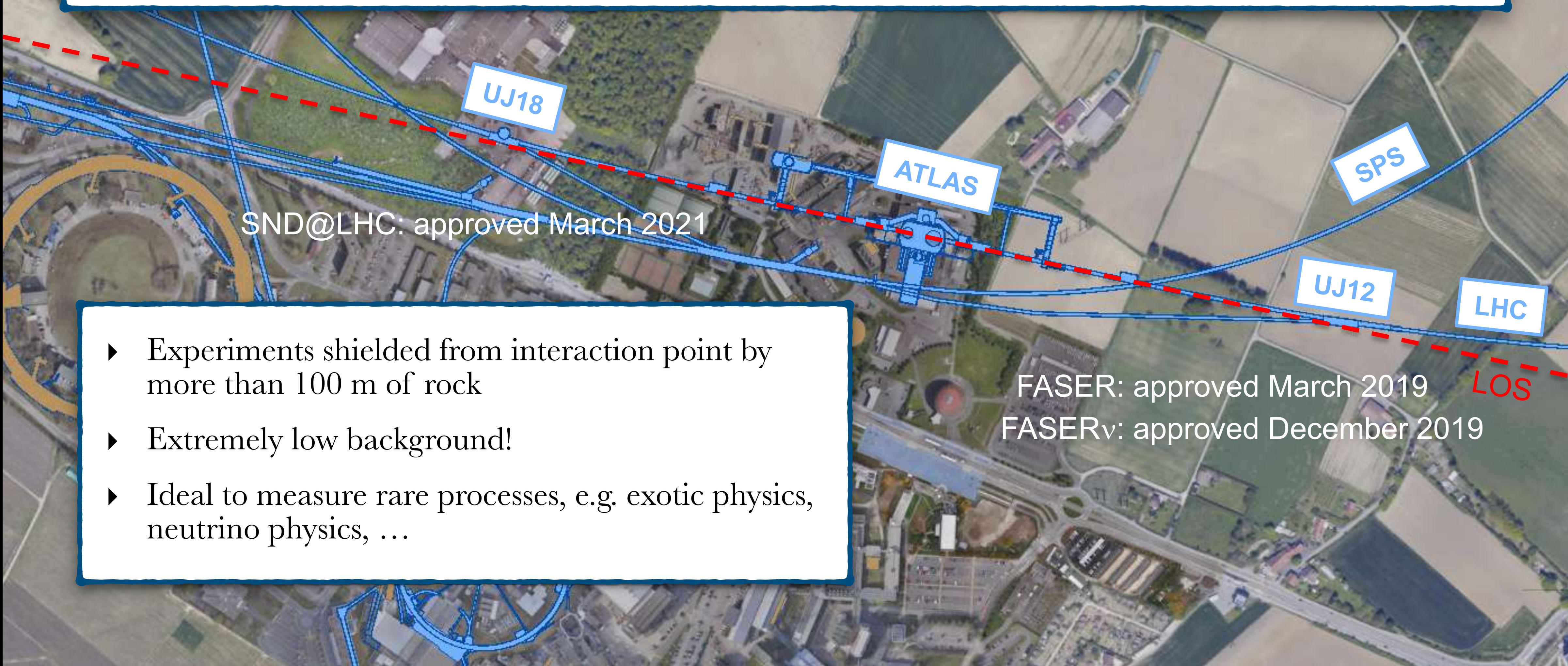
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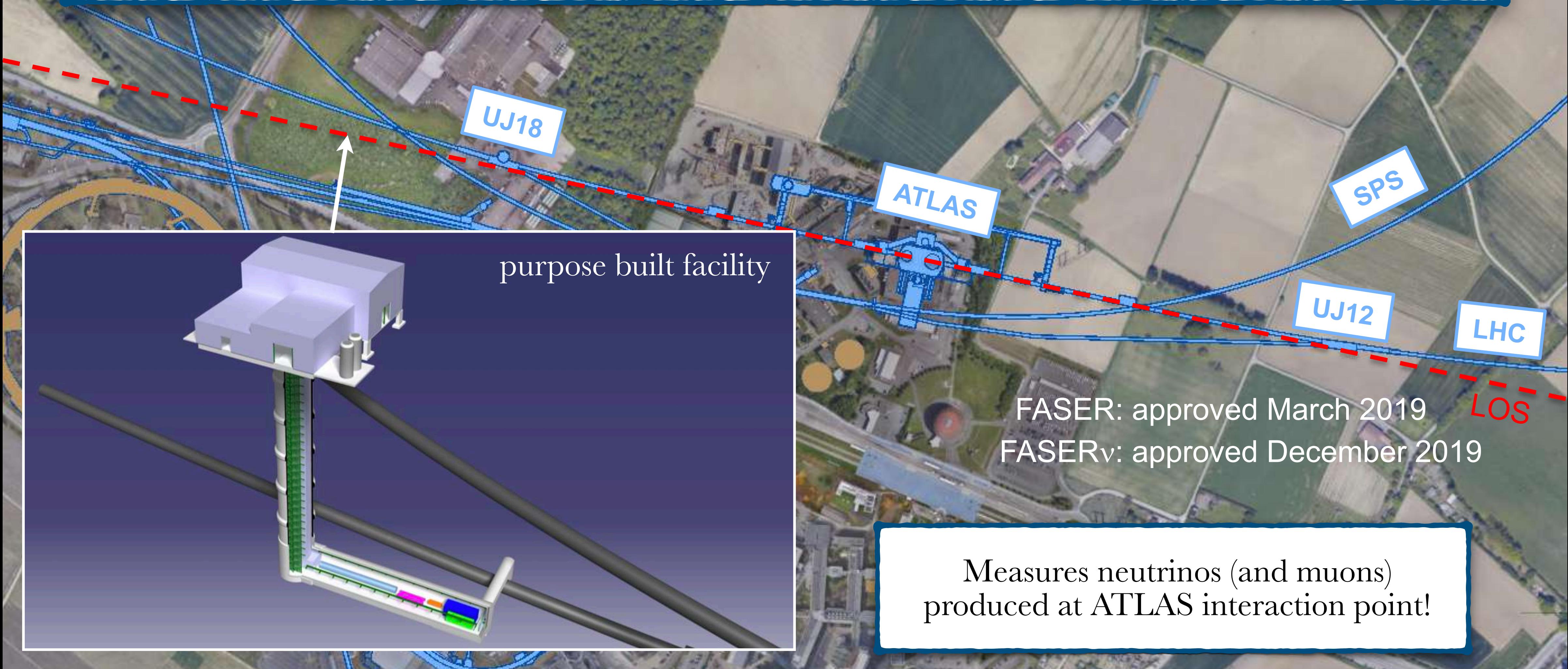
FAR FORWARD EXPERIMENTS AT LHC RUN 3

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



FAR FORWARD EXPERIMENTS AT LHC RUN 3

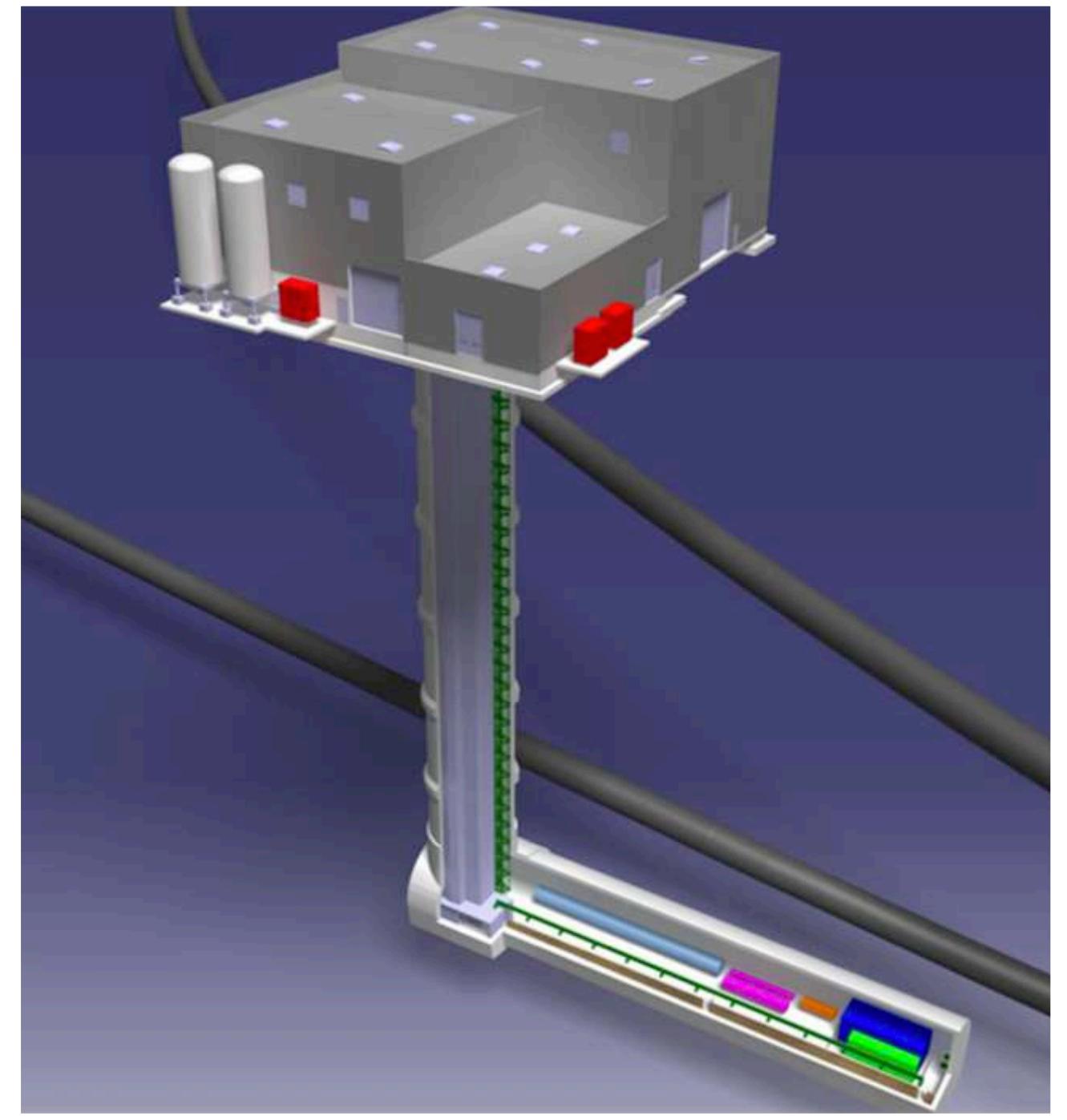
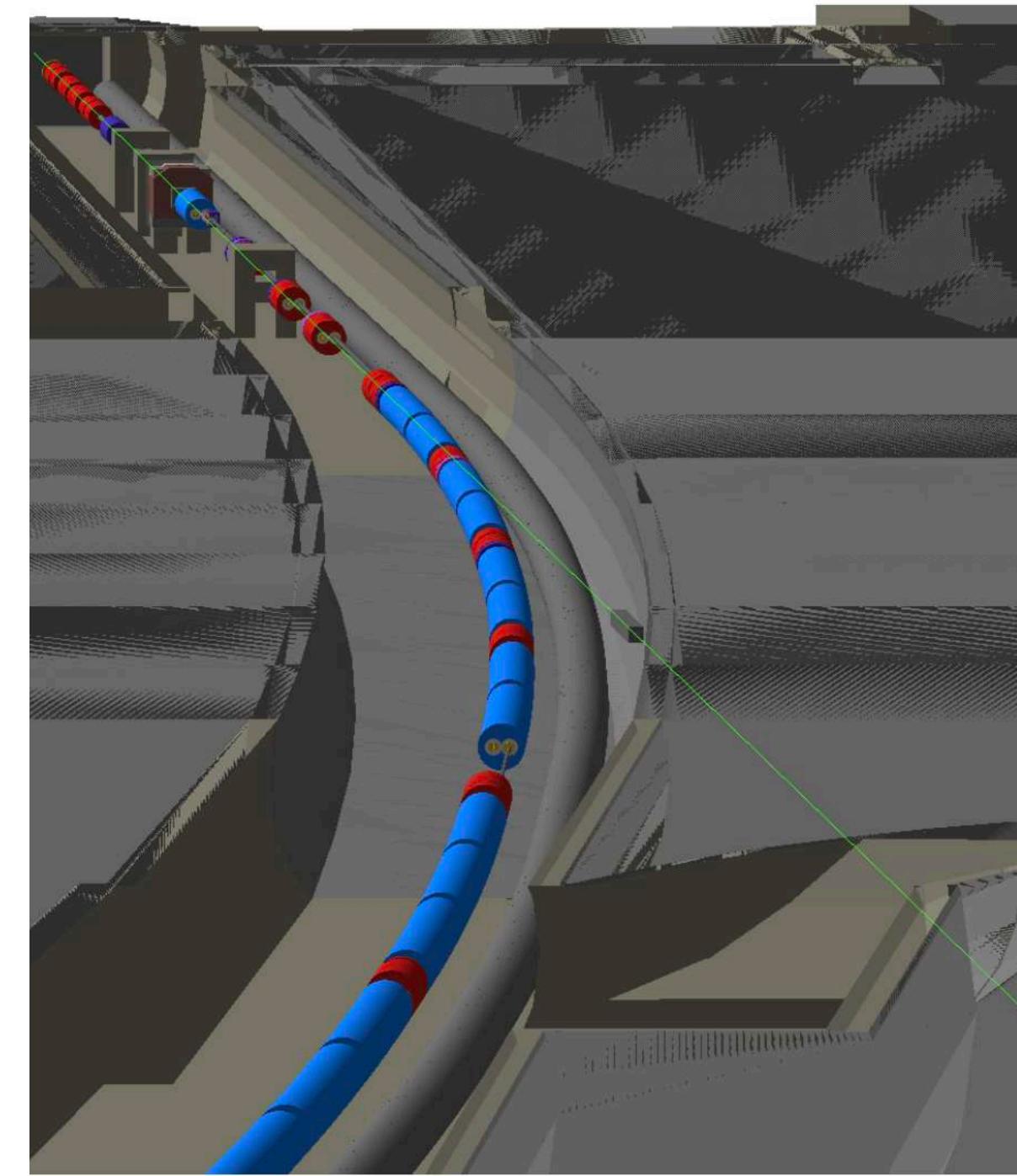
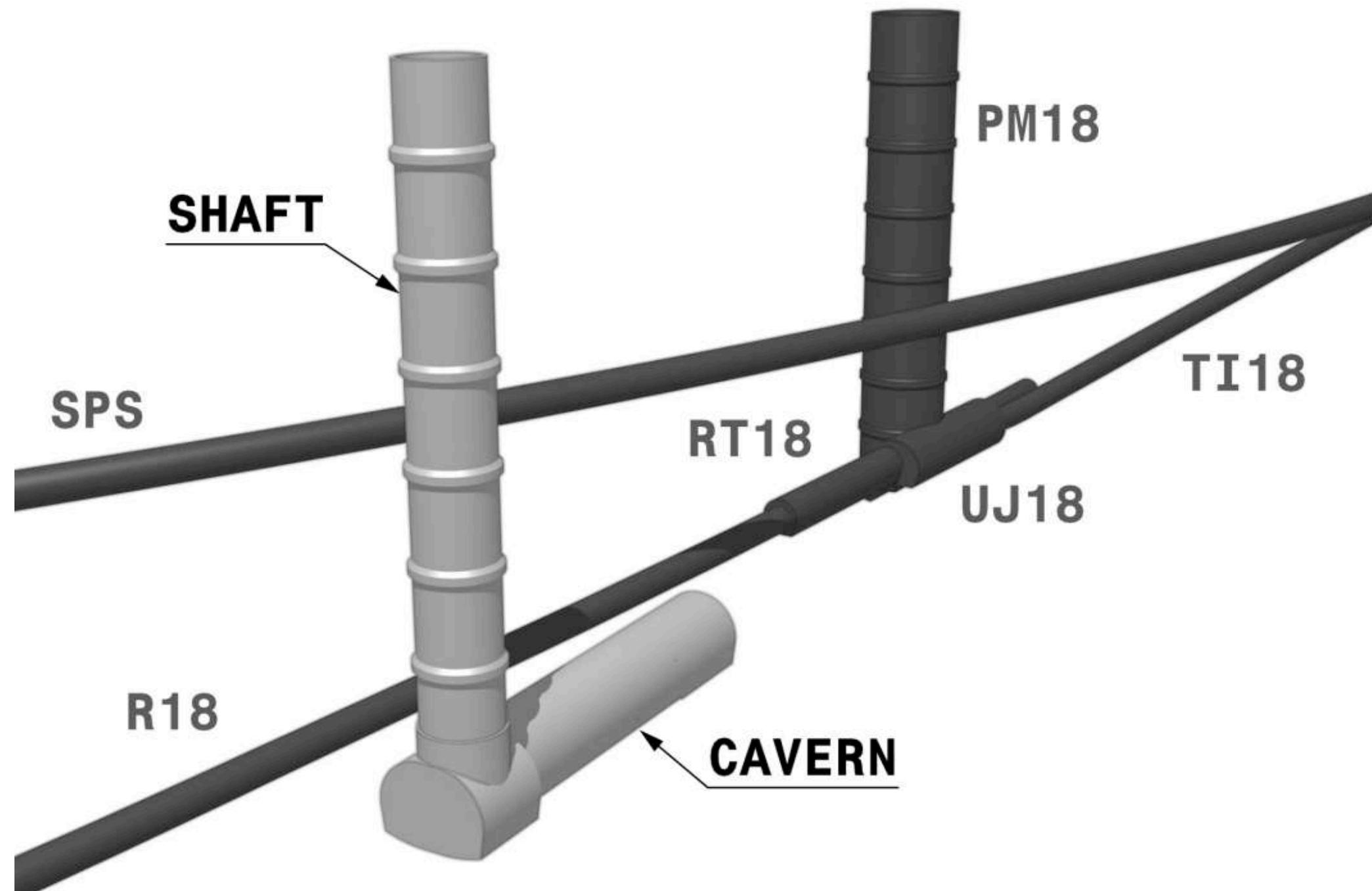
The FPF is proposed to extend this program into the HL-LHC era!



The Forward Physics Facility



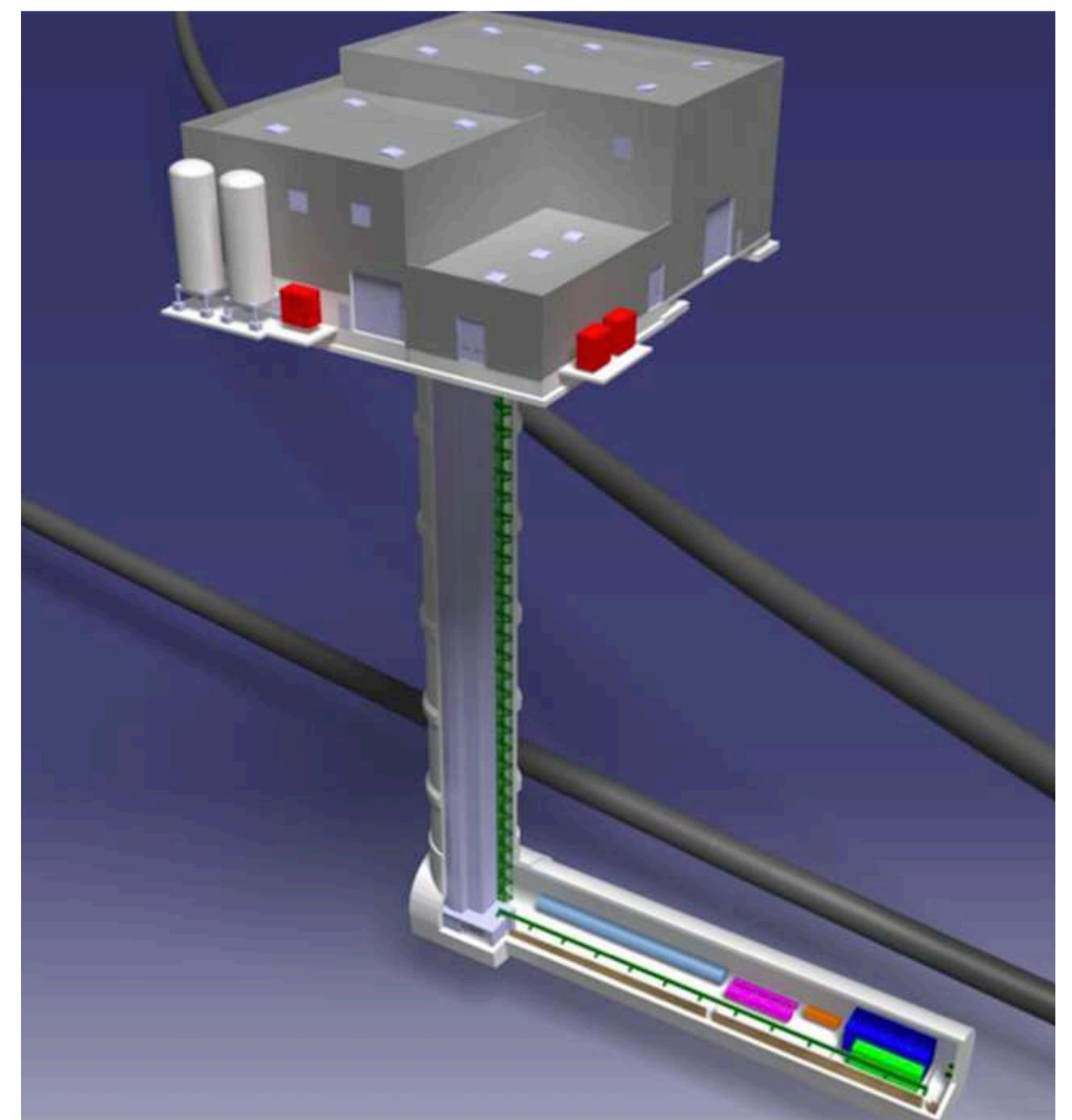
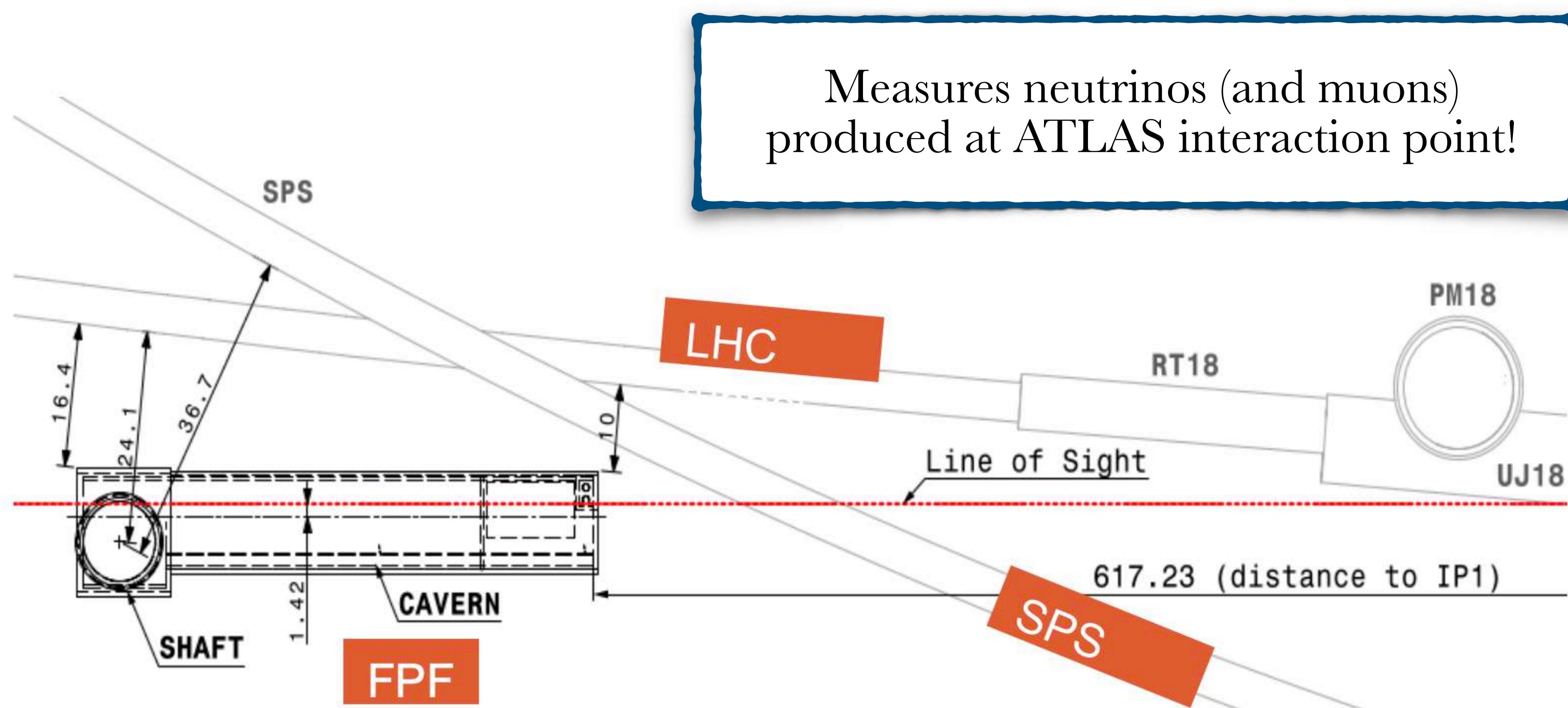
- ▶ Purpose built facility to house dedicated experiments in the far-forward region
- ▶ In line-of-sight to ATLAS interaction point (separated by several 100 m of rock)
- ▶ Currently five proposed experiments*, mainly designed for neutrino detection



The Forward Physics Facility



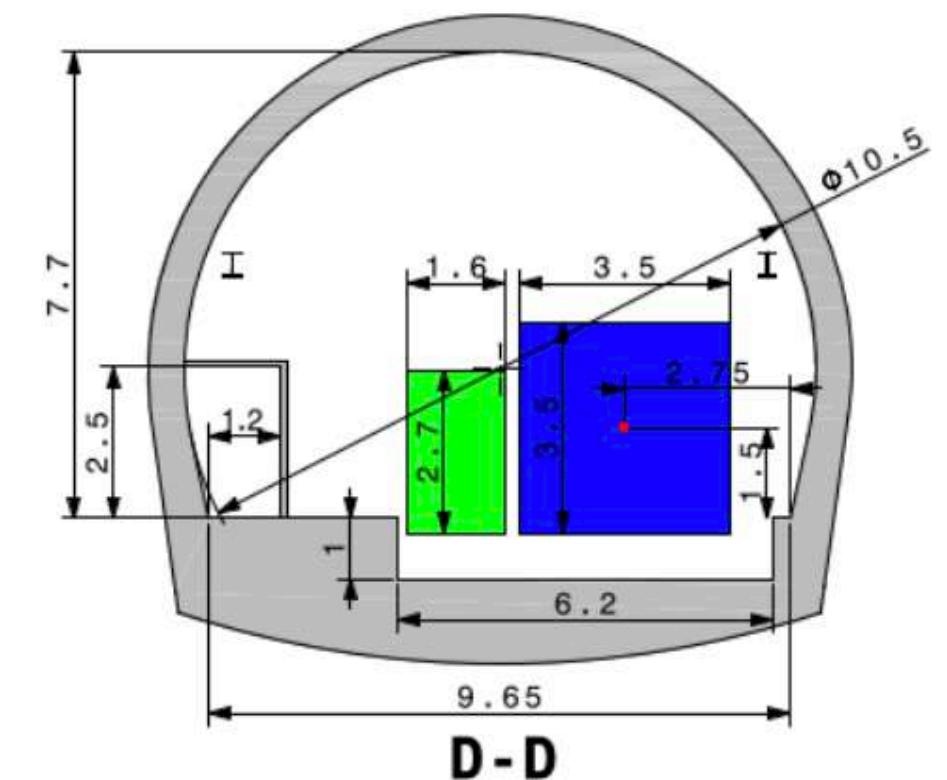
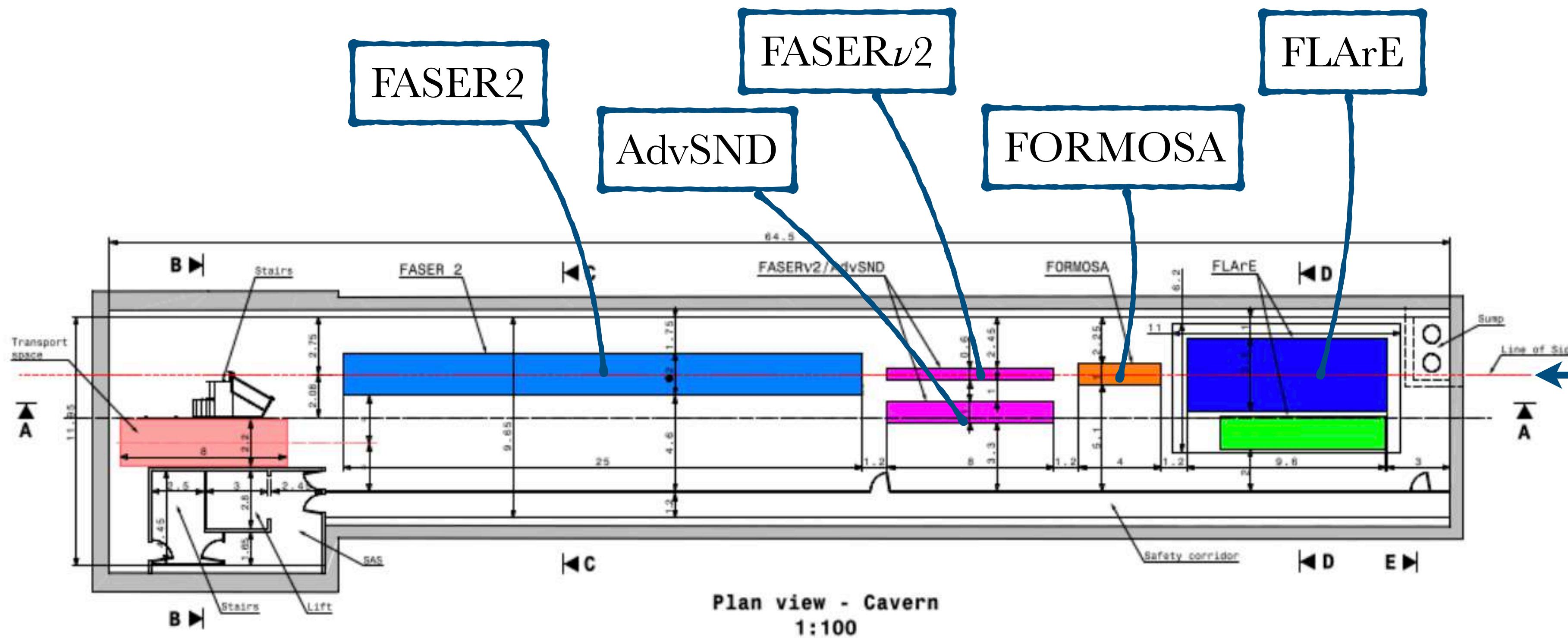
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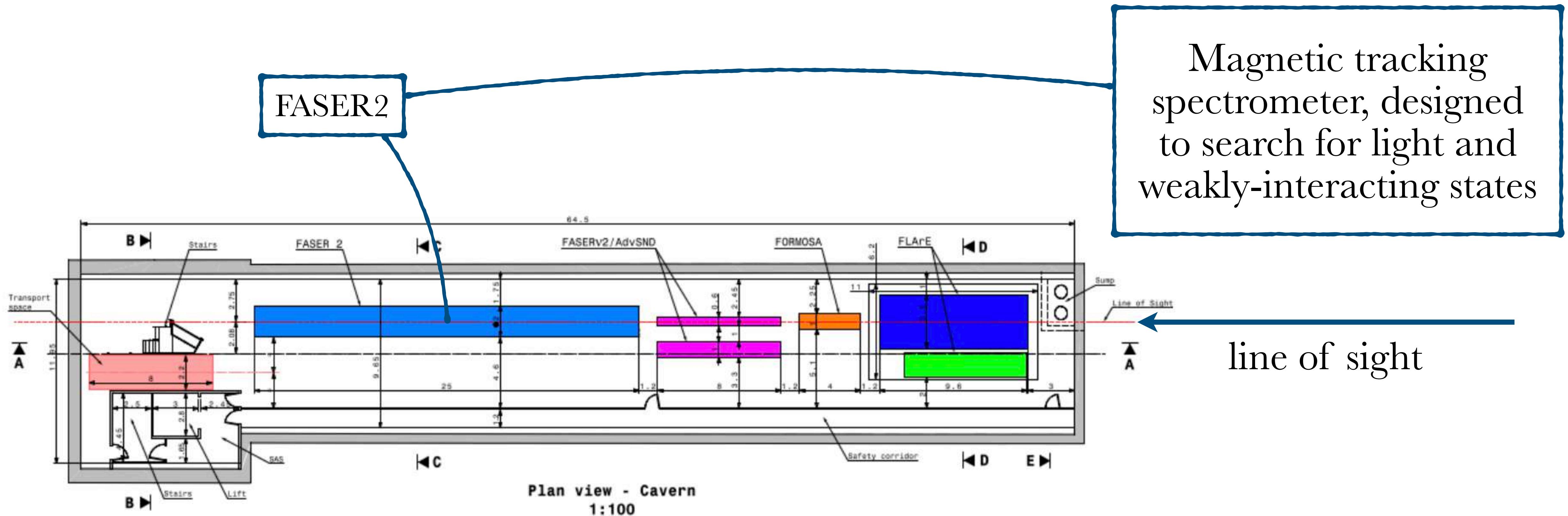


line of sight

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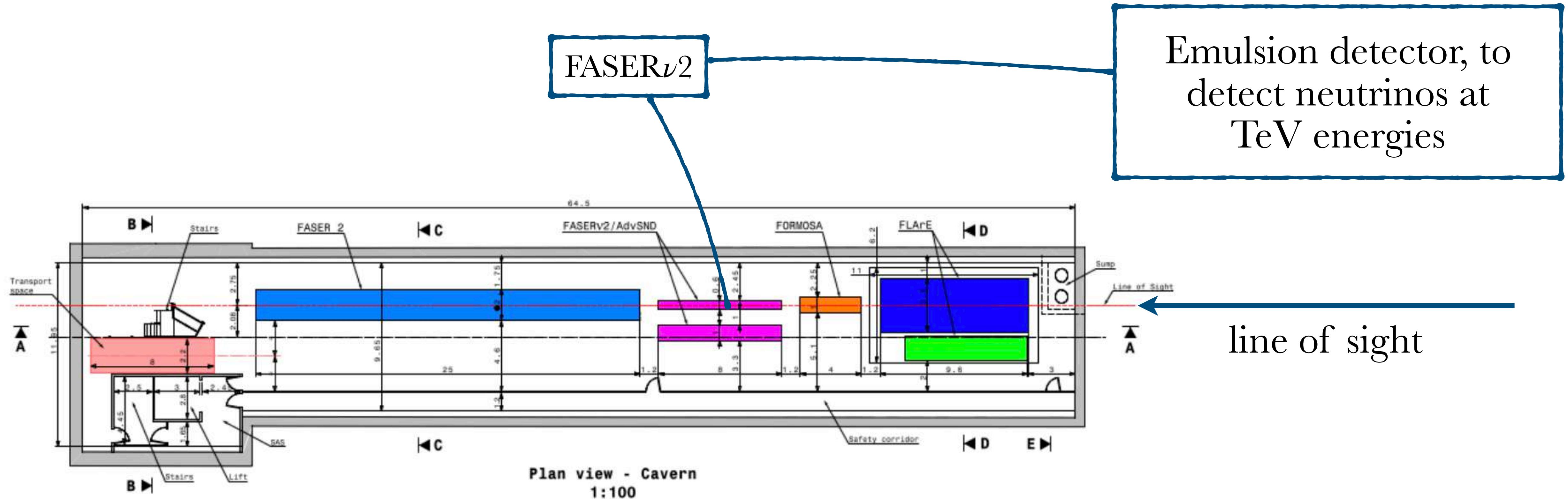


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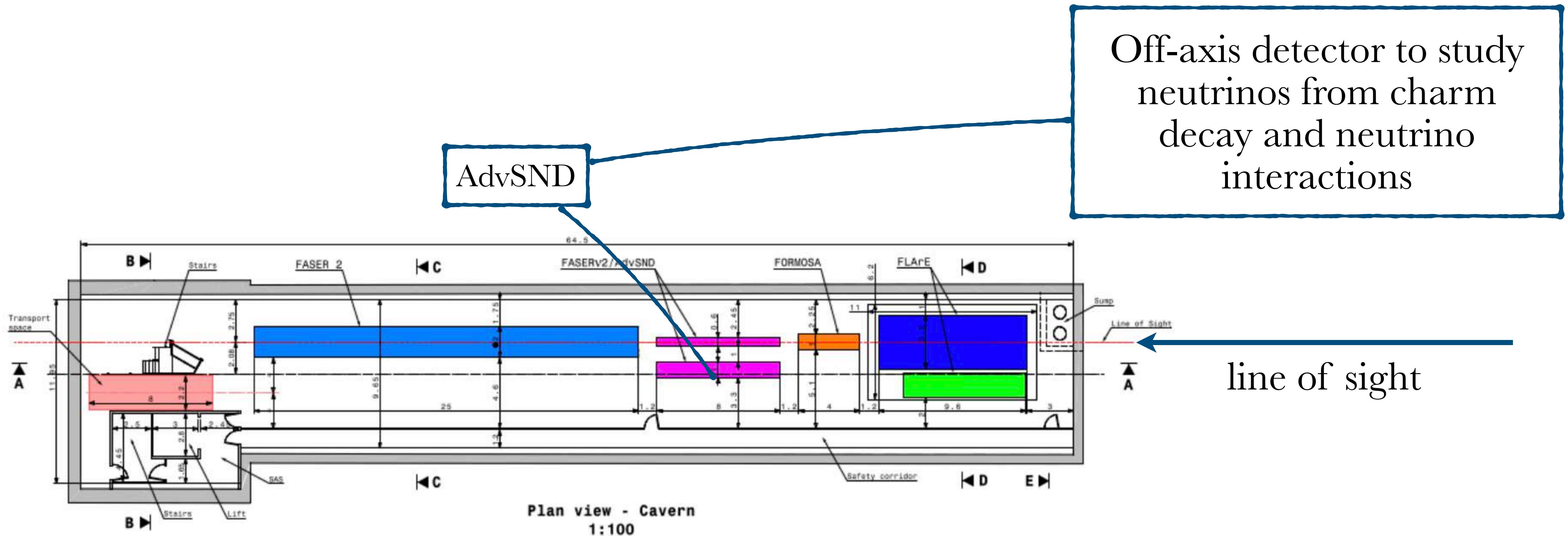


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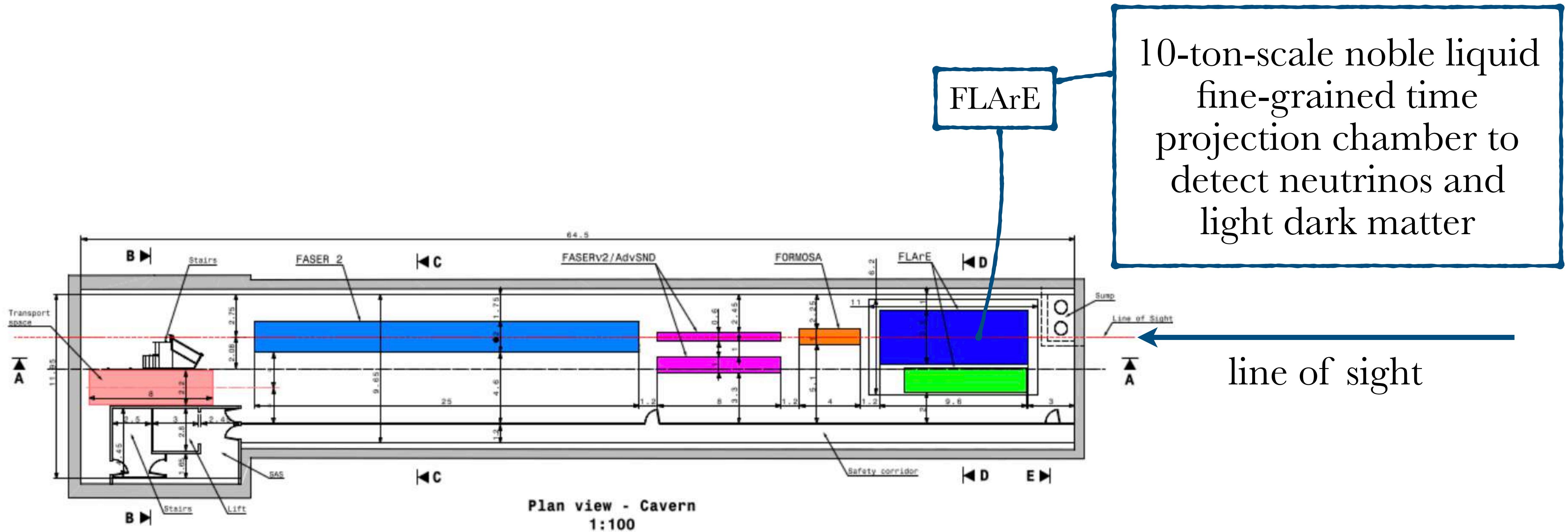


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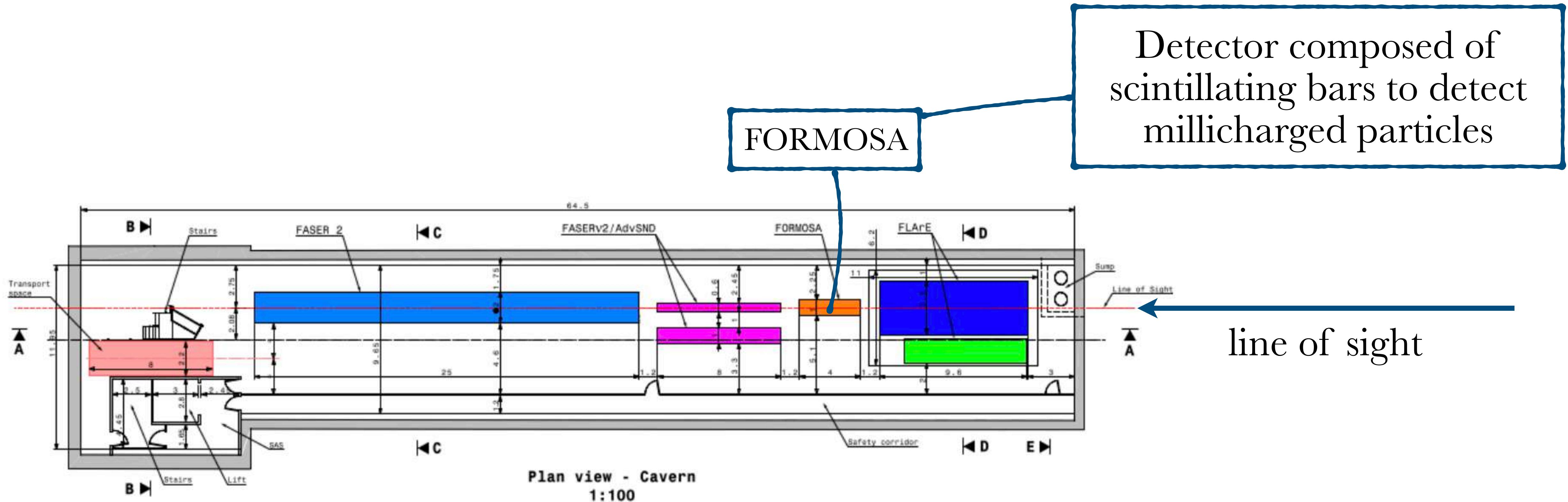


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FPF Physics Potential



► Example:

FASER ν pilot detector

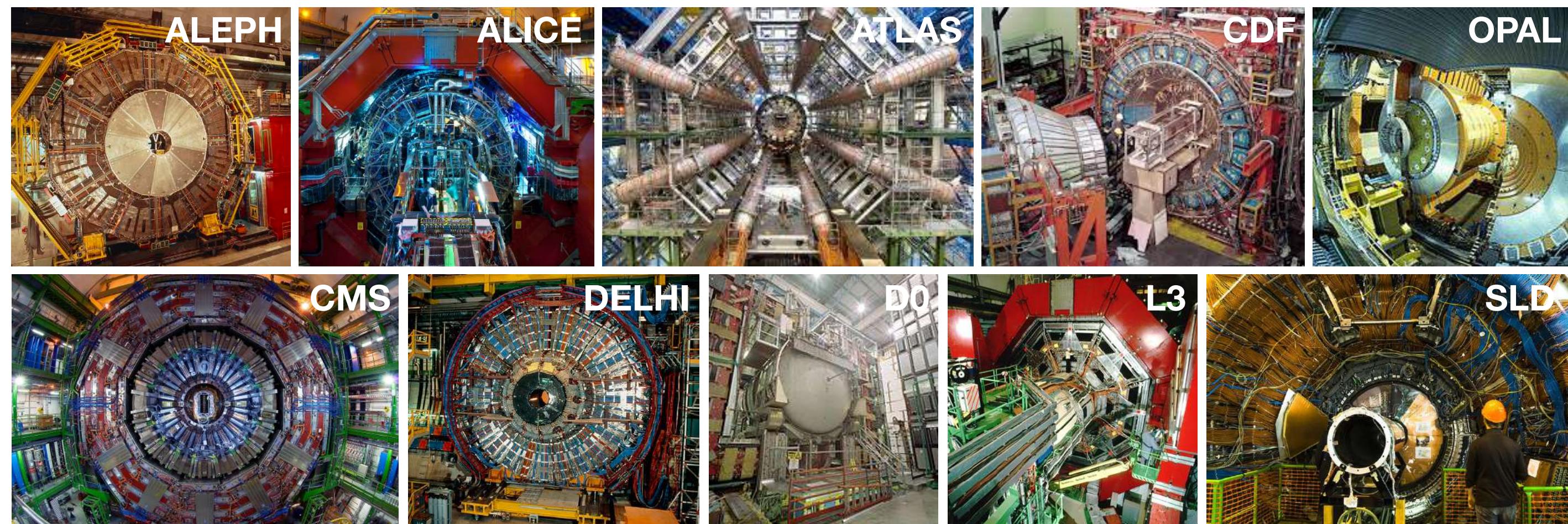
vs.

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



FPF Physics Potential



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FASER ν pilot detector

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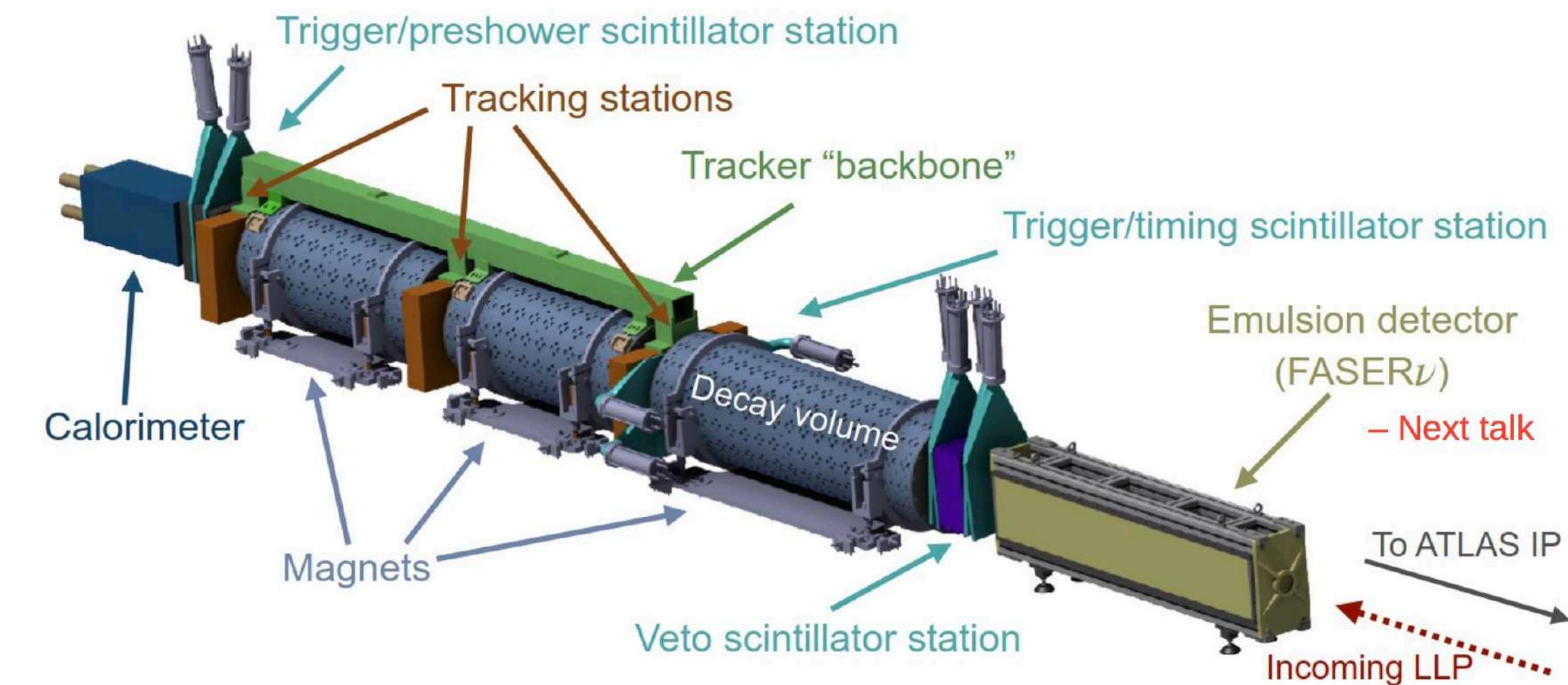
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► FASER ν years 2022-2024:

- First 153 neutrino candidates reported
[FASER Collaboration, Phys. Rev. Lett. 131 (2023)]
- Significance of $\sim 16\sigma$
- $\sim 10000 \nu$ candidates expected
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*origin not well understood, further studies needed (see later slides)

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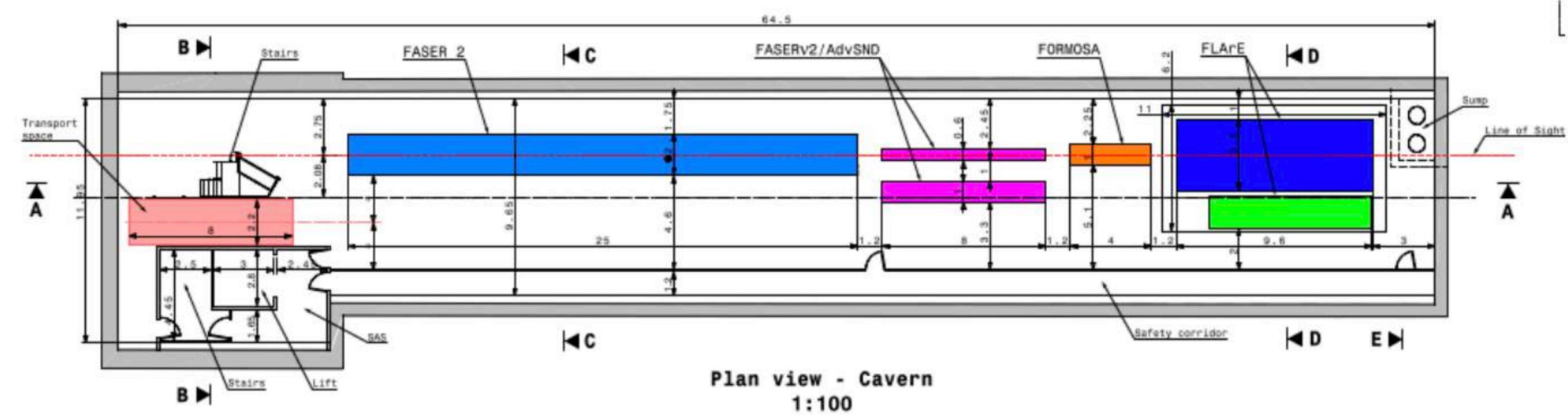
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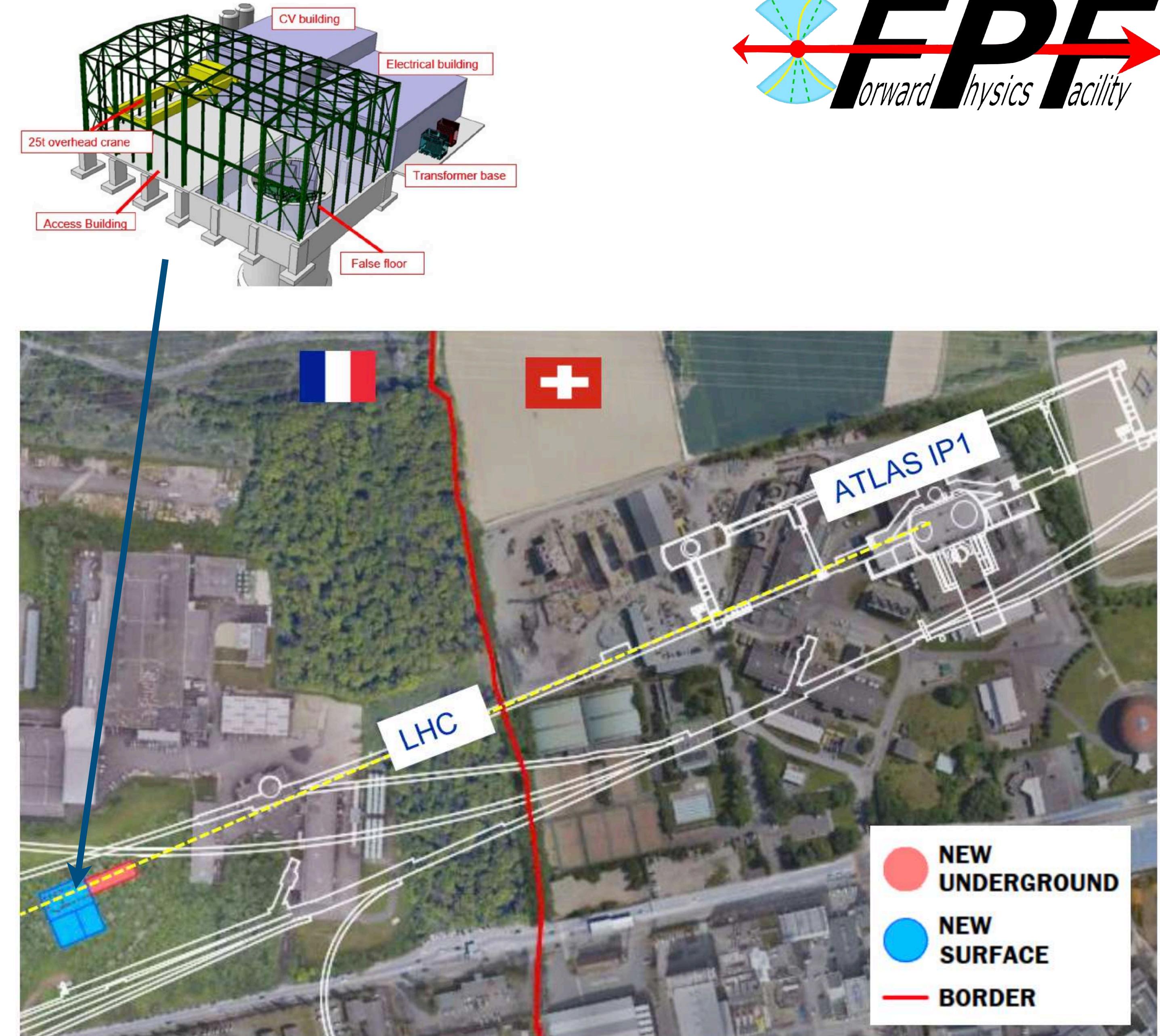
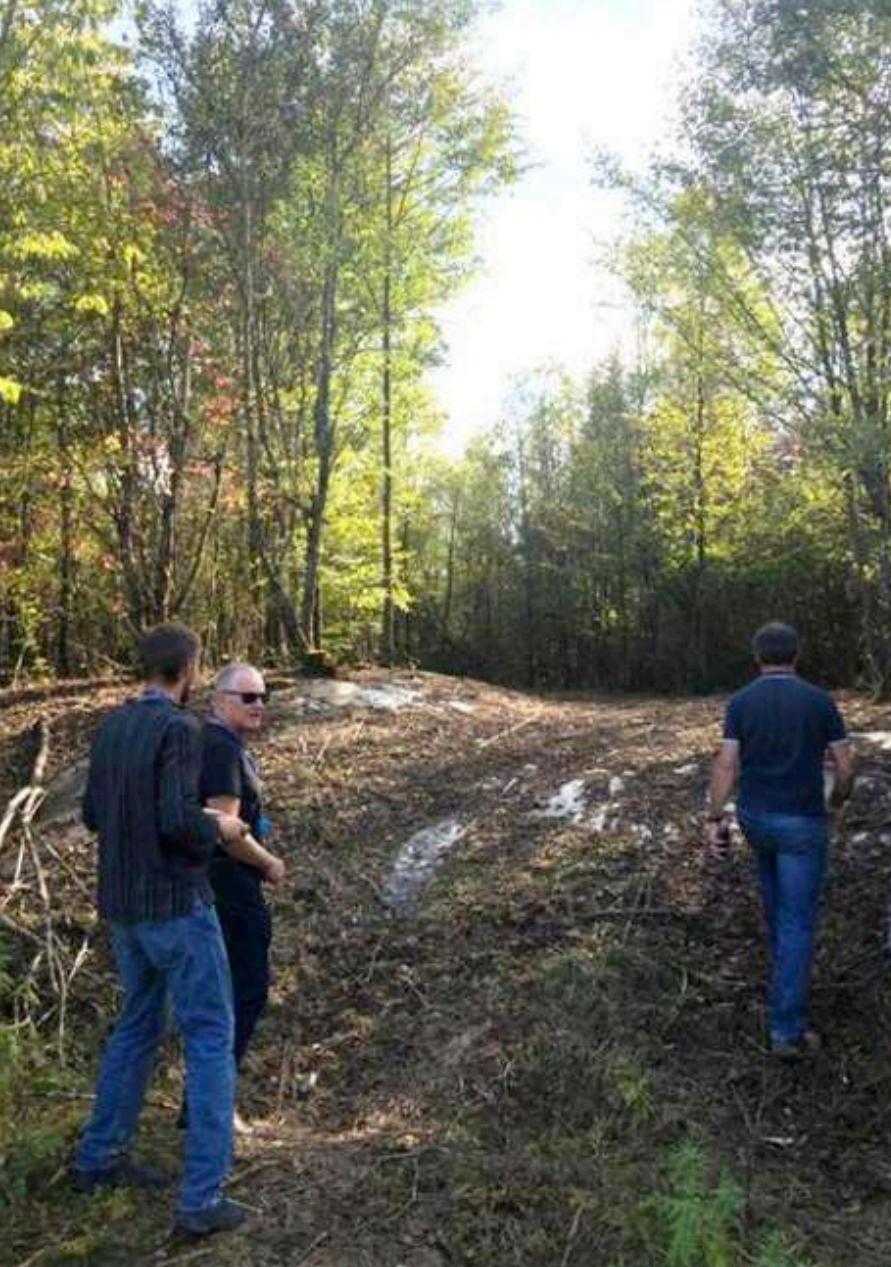
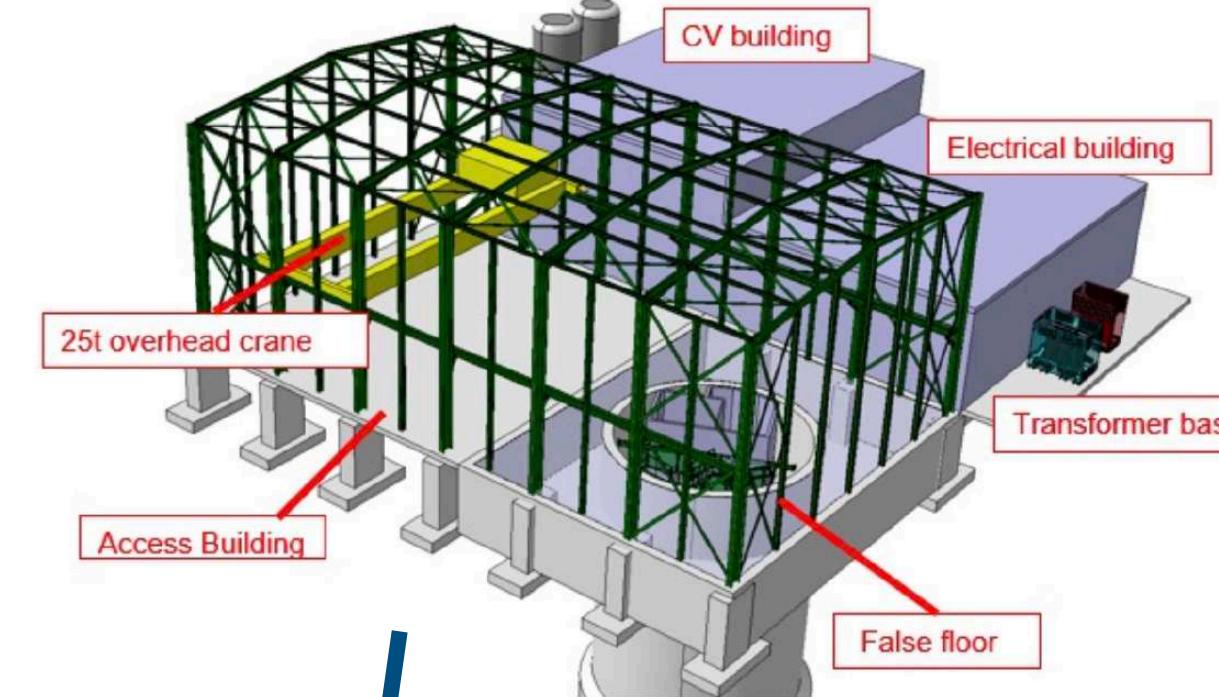
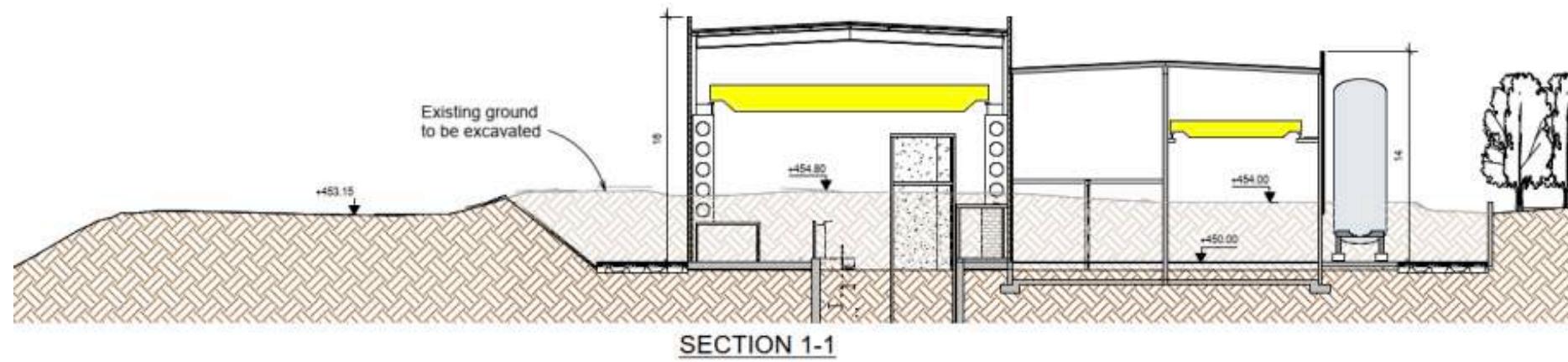
► Forward Physics Facility:

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



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

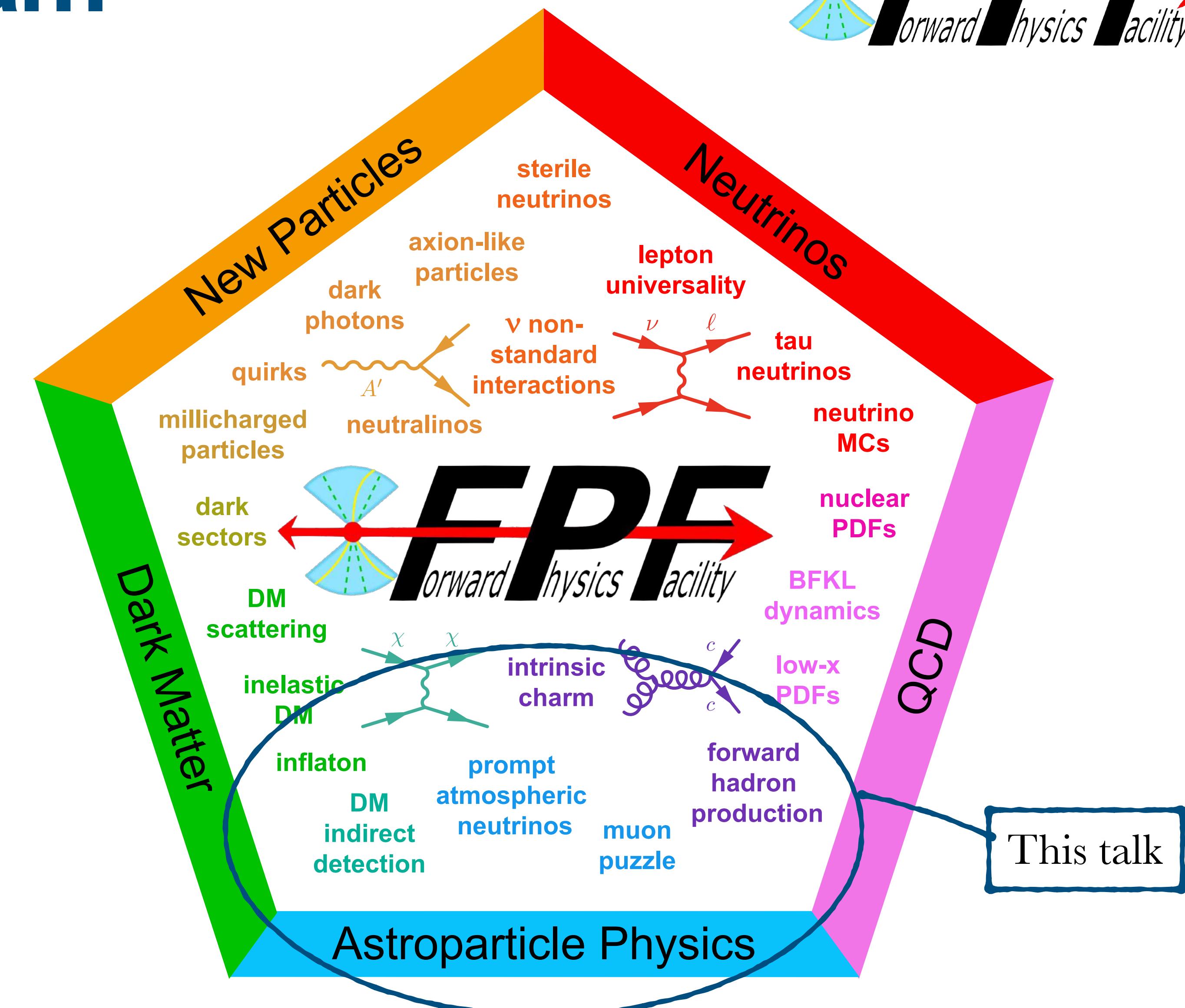
The Facility



FPF Physics Program



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



FPF Physics Program



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 - ▶ 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/>

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Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **50** (2023) 030501 (410pp)
<https://doi.org/10.1088/1361-6471/ac865e>

Major Report

The Forward Physics Facility at the High-Luminosity LHC

Jonathan L Feng^{1,*}, Felix Kling², Mary Hall Reno³, Juan Rojo^{4,5}, Dennis Soldin⁶, Luis A Anchordoqui⁷, Jamie Boyd⁸, Ahmed Ismail⁹, Lucian Harland-Lang^{10,11}, Kevin J Kelly¹², Vishvas Pandey^{13,14}, Sebastian Trojanowski^{15,16}, Yu-Dai Tsai¹, Jean-Marco Alameddine¹⁷, Takeshi Araki¹⁸, Akitaka Ariga^{19,20}, Tomoko Ariga²¹, Kento Asai^{22,23}, Alessandro Bacchetta^{24,25}, Kincso Balazs⁸, Alan J Barr¹⁰, Michele Battistin⁸, Jianming Bian¹, Caterina Bertone⁸, Weidong Bai²⁶, Pouya Bakhti²⁷, A Baha Balantekin²⁸, Basabendu Barman²⁹, Brian Batell³⁰, Martin Bauer³¹, Brian Bauer³⁰, Mathias Becker³², Asher Berlin¹⁴, Enrico Bertuzzo³³, Atri Bhattacharya³⁴, Marco Bonvini³⁵, Stewart T Boogert³⁶, Alexey Boyarsky³⁷, Joseph Bramante^{38,39}, Vedran Brdar^{40,41}, Adrian Carmona⁴², David W Casper¹, Francesco Giovanni Celiberto^{43,44,45}, Francesco Cerutti⁸, Grigoris Chachamis⁴⁶, Garv Chauhan⁴⁷, Matthew Citron⁴⁸, Emanuele Copello³², Jean-Pierre Corso⁸, Luc Darmé⁴⁹, Raffaele Tito D'Agnolo⁵⁰, Neda Darvishi⁵¹, Arindam Das^{52,53}, Giovanni De Lellis^{54,55}, Albert De Roeck⁸, Jordy de Vries^{5,56}, Hans P Dembinski⁵⁷, Sergey Demidov⁵⁸, Patrick deNiverville⁵⁸, Peter B Denton⁵⁹, Frank F Deppisch⁶⁰, P S Bhupal Dev⁶¹, Antonia Di Crescenzo^{8,54,55}, Keith R Dienes^{62,63}, Milind V Diwan⁶⁴, Herbi K Dreiner^{65,66}, Yong Du⁶⁷, Bhaskar Dutta⁶⁸, Pit Duwentäster⁶⁹, Lucie Elie⁸, Sebastian A R Ellis⁷⁰, Rikard Enberg⁷¹, Yasaman Farzan⁷², Max Fleg¹, Ana Luisa Foguel³³, Patrick Foldenauer³¹, Saeid Foroughi-Abari⁷³, Jean-François Fortin⁷⁴, Alexander Friedland⁷⁵, Elina Fuchs^{12,76,77}, Michael Fucilla^{78,79}, Kai Gallmeister⁸⁰, Alfonso Garcia^{81,82},

FPF Physics Program



Contents

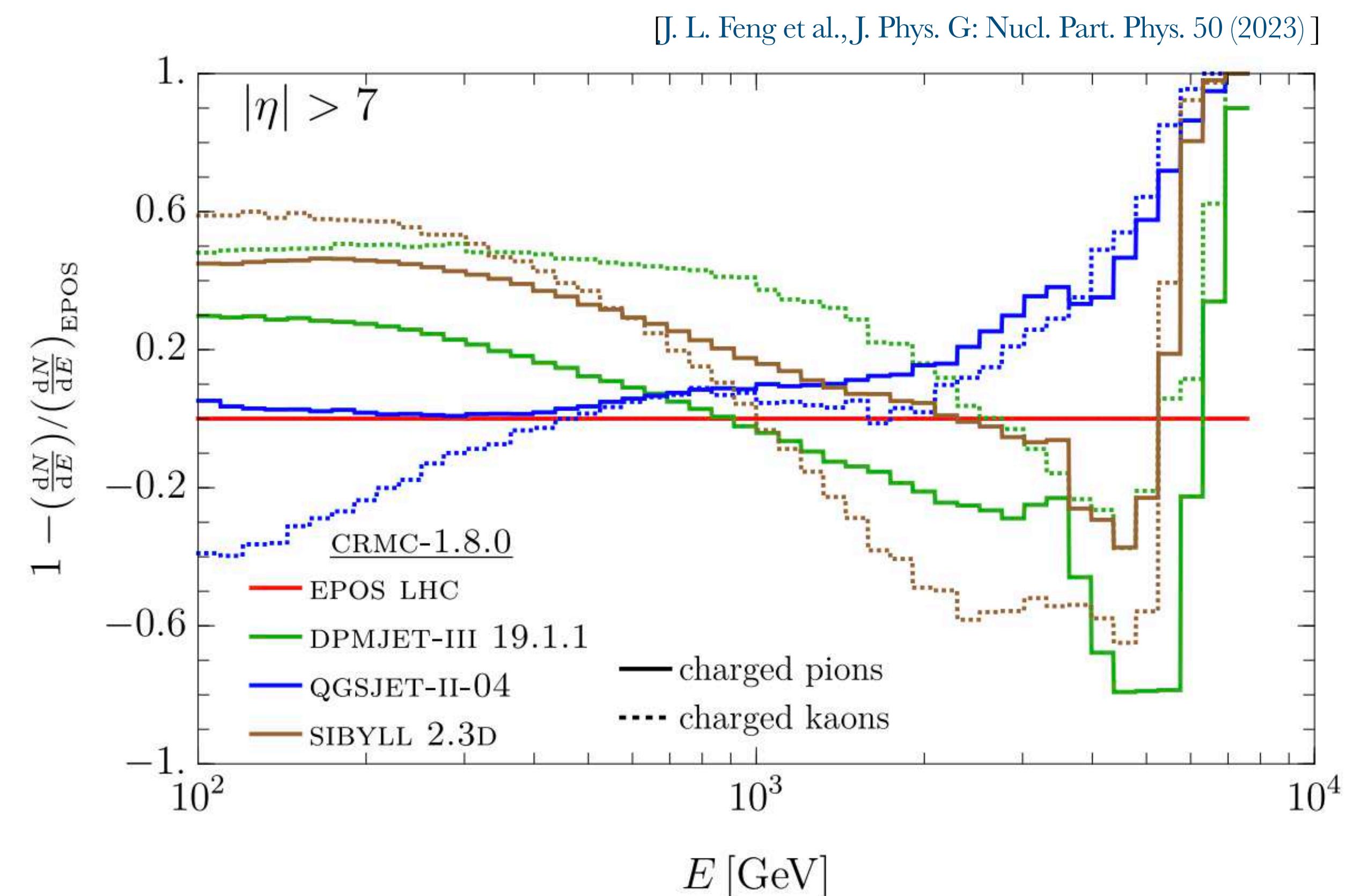
1 Introduction 2 The Facility 2.1 Purpose-Built Facility 2.1.1 Experimental Cavern 2.1.2 Access Shaft 2.1.3 Safety Gallery 2.1.4 Support Buildings and Infrastructure 2.2 Services 2.3 UJ12 Alcoves Option 2.4 Engineering Costs 2.5 Choice of Baseline Facility 2.6 FLUKA Studies of the FPF Environment and Backgrounds 2.6.1 Introduction to FLUKA 2.6.2 The FLUKA Model of the ATLAS Insertion 2.6.3 Radiation Characterization in the Dispersion Suppressor 2.6.4 Validation of FLUKA Estimates 2.7 Radiation Protection Studies 2.7.1 Radiation Protection at CERN 2.7.2 Radiation Protection FLUKA Simulations 2.7.3 Radiation Protection Aspects and Constraints 2.8 BDSIM Studies of the FPF Environment and Backgrounds 2.8.1 Introduction 2.8.2 BDSIM Model of the LHC IP1 2.8.3 Simulation Procedure 2.8.4 Muon and Neutrino Fluxes 2.8.5 Outlook 2.9 The PROPOSAL Framework For Simulating Particles Fluxes 2.10 Sweeper Magnet 2.10.1 Sweeper Magnet Location 2.10.2 Conceptual Magnet Design 3 Experiments 3.1 FASER2 3.1.1 Physics Goals and Design Considerations 3.1.2 Detector Configurations 3.1.3 Magnet and Tracker Requirements 3.2 FASER ν 2 3.2.1 Physics Goals 	Contents 14 3.2.2 Detector Requirements 3.2.3 Emulsion Film Production 3.2.4 Readout and Analysis 3.3 AdvSND 3.3.1 Physics Goals 3.3.2 Detector Layout 3.4 FLArE 3.4.1 Physics Requirements 3.4.2 Detector Design Considerations 3.4.3 Cryogenics and Noble Liquid Circulation System 3.4.4 Research and Development 3.5 FORMOSA 3.5.1 Detector Design 3.5.2 Backgrounds and Sensitivity 4 Long-Lived Particles 4.1 Monte Carlo Tools for BSM: FORESEE 4.2 Long-Lived Vector Particles 4.2.1 Dark Photon 4.2.2 $B - L$ Gauge Boson 4.2.3 $L_i - L_j$ Gauge Bosons 4.2.4 $B - 3L_i$ Gauge Bosons 4.2.5 B Gauge Boson 4.2.6 Production via Proton Bremsstrahlung 4.2.7 Additional Production Modes 4.2.8 Decays of Light Vector Particles 4.3 Long-Lived Scalars 4.3.1 Existing Constraints on the Dark Higgs 4.3.2 Dark Higgs as Relaxion 4.3.3 Dark Higgs as Relaxed Relaxion 4.3.4 Dark Higgs and Neutron Star Mergers 4.3.5 Dark Higgs as Inflaton 4.3.6 Flavor-philic Scalars 4.3.7 Two Higgs Doublet Models 4.3.8 Sgoldstino 4.3.9 Crunching Dilatons 4.4 Long-Lived Fermions 4.4.1 Heavy Sterile Neutrinos 4.4.2 Light Long-lived Sterile Neutrinos in ν SMEFT 4.4.3 Heavy Neutral Leptons with Tau Mixing in Neutrino Mass Models 4.4.4 Tree-level Decays of GeV-Scale Neutralinos from D and B Mesons 4.4.5 Radiative Decays of Sub-GeV Neutralinos from Light Mesons 4.4.6 Fermion Portal Effective Operators 4.5 Long-Lived Axion Like Particles 4.5.1 Overview on Axion Like Particles 4.5.2 Charming ALPs 4.5.3 Bremming Enhanced ALP Productions and FPF Sensivity 4.6 Long-Lived Particles in Non-Minimal Models 4.6.1 Inelastic Dark Matter 4.6.2 Inelastic Dark Matter from Dark Higgs Boson Decays 5 Dark Matter and BSM Scattering Signatures 5.1 Dark Matter Scattering 5.1.1 Dark Photon Mediator Models 5.1.2 Hadrophilic Dark Matter Models 5.1.3 Dark Matter Search in the Advanced SND@LHC Detector 5.1.4 Dark States with Electromagnetic Form Factors 5.2 Millicharged Particles 5.3 Quarks 6 Quantum Chromodynamics 6.1 Forward Particle Production and QCD in Novel Regimes 6.1.1 Introduction 6.1.2 Low- x Resummation at the LHC and Its Impact on the FPF Program 6.1.3 Charm Production in the Forward Region within k_T Factorisation 6.1.4 Forward Charm Production in k_T Factorization and the Role of Intrinsic Charm 6.1.5 Charm Production at Very Forward Rapidities in the Color Dipole Formalism 6.1.6 Charm Production in the Forward Region and Intrinsic Charm in the CT Framework 6.1.7 Probing the Multidimensional Structure of Hadrons at the FPF 6.1.8 Monte Carlo Studies of High-energy QCD Reactions at the FPF 6.1.9 High-energy QCD via a FPF+ATLAS Timing Coincidence 6.1.10 BFKL Phenomenology and Inclusive Forward Processes 6.2 Modelling Forward Physics with Monte Carlo Event Generators 6.2.1 Introduction 6.2.2 Event Generation for Forward Particle Production with Pythia 8 6.2.3 Event Generation for Forward Particle Production with Sherpa 6.2.4 Improved MC Generation of Forward Particle Production 6.2.5 Neutrinos at the FPF from Proton-Lead Collisions 6.3 Neutrino-induced Deep Inelastic Scattering: Constraints on Nucleon Structure 6.3.1 Introduction 6.3.2 Impact of Neutrino-induced DIS within the nCTEQ Framework 6.3.3 Impact of Neutrino-induced DIS within the (n)NNPDF Framework 6.3.4 Neutrino DIS Cross Sections on a Tungsten Target 7 Neutrino Physics 7.1 Overview 7.2 Neutrino Fluxes 7.2.1 Neutrino fluxes from Monte Carlo Generators 8 Astroparticle Physics 8.1 Modelling Cosmic Ray Air Showers 8.1.1 The Muon Puzzle and Beyond 8.1.2 Probing Hadronic Interaction Models at the FPF 8.1.3 Complementary Probes of Strangeness Enhancement: Auger Meets the FPF 8.2 Understanding the Atmospheric Background of Astrophysical Neutrinos 8.2.1 Atmospheric Backgrounds in Large-Scale Neutrino Telescopes 8.2.2 Prompt Atmospheric Neutrino Production 8.3 Dark Matter Searches and Their Impact on Astrophysics and Cosmology 8.3.1 Dark Matter from Freeze-In Semi-Production 8.3.2 Freeze-In Sterile Neutrino Dark Matter 8.3.3 Imprints of Scale Invariance and Freeze-In Dark Matter at the FPF 8.3.4 Rich Dark Sector and Complementarity with Indirect Searches 	Contents 15 4.6.3 Dynamical Dark Matter 4.6.4 Light Dark Scalars through Z' and EFTs 4.6.5 Beyond the Minimal Dark Photon Model: Lepton Flavor Violation 4.6.6 $U(1)_{T3R}$ Gauge Boson 4.6.7 Dark Axion Portal 4.6.8 Heavy Neutrino Production via a $B - L$ Gauge Boson 4.6.9 Search for Sterile Neutrino with Light Gauge Interactions 4.6.10 The ν_R -philic Dark Photon 4.6.11 Secondary Production in BSM and Neutrino Interactions 4.6.12 Light Dark Sector Going Through Chain Decay 4.6.13 Bound State Formation and Long-Lived Particles 7.3 Neutrino Cross Sections 7.3.1 Deep-Inelastic Scattering 7.3.2 Neutral-Current Scattering 7.3.3 Quasi-Elastic and Resonance Regions for FPF Physics 7.3.4 Interface of Shallow- and Deep-Inelastic Scattering 7.3.5 Role of Final State Interactions 7.3.6 Scattering with Electrons 7.4 Monte Carlo Tools for Neutrino Interactions 7.4.1 GENIE 7.4.2 NEUT 7.4.3 NuWro 7.4.4 Generator Comparisons 7.4.5 Giessen Model and GiBUU Generator 7.5 Beyond Standard Model Physics with Neutrinos 7.5.1 Effective Field Theories at the FPF 7.5.2 NSI and Effective Field Theories 7.5.3 Neutral current cross section and non-standard interactions 7.5.4 BSM Interactions in Light of New Mediators 7.5.5 Secret Neutrino Interaction 7.5.6 Probing Light Gauge Bosons via Tau Neutrinos 7.5.7 Neutrino Magnetic Moments 7.5.8 Up-scattering through the Neutrino Dipole Portal 7.5.9 FASER/FPF Sterile Neutrino Oscillations 7.5.10 Neutrinophilic Mediator/Dark Matter Production at the FPF 8.4 Acknowledgements 8.5 References 	Contents 16 7.2.2 Neutrino Fluxes from k_T -Factorization 7.2.3 Tau Neutrino Fluxes from Heavy Flavor: PDF Uncertainties in NLO Perturbative QCD 10
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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

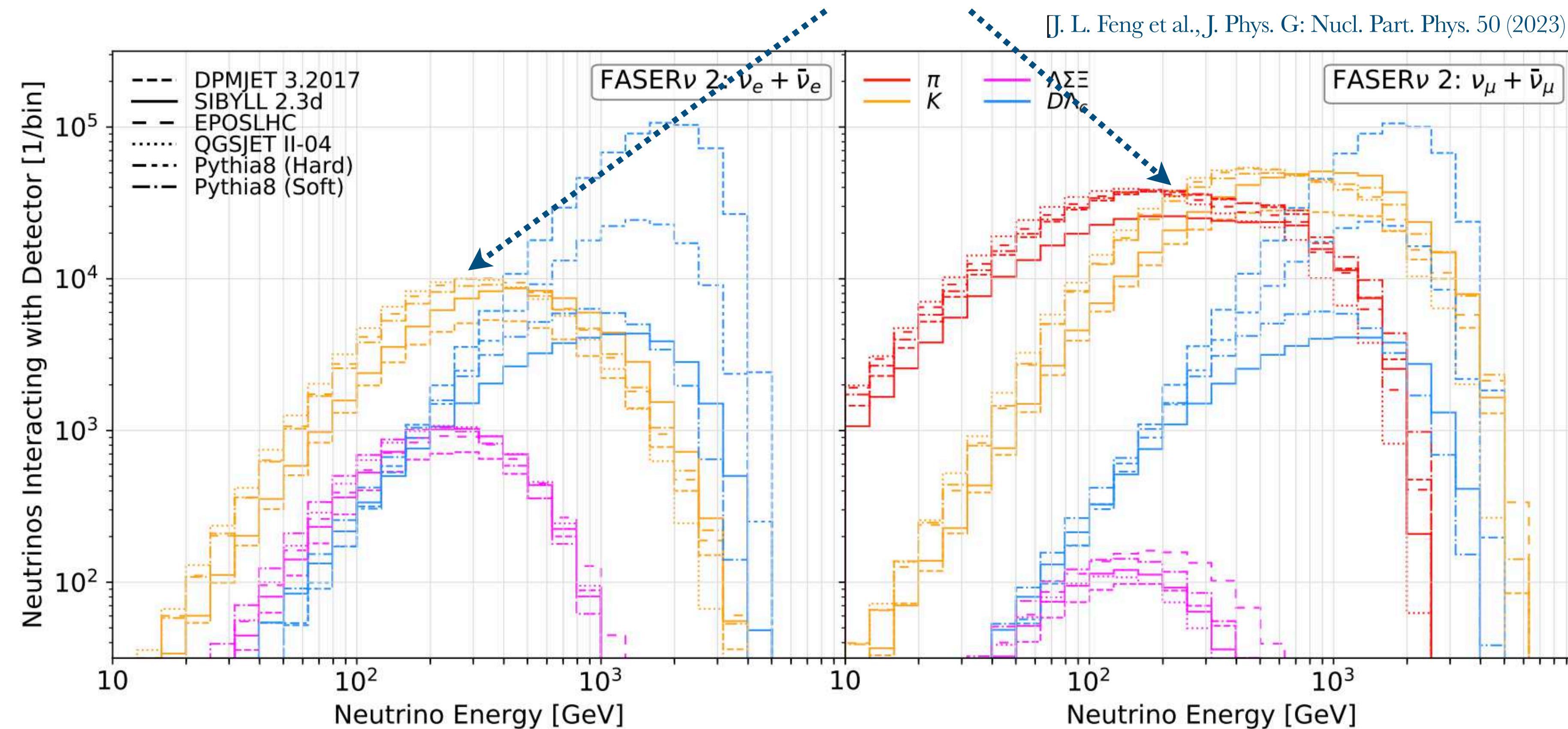


Light Hadron Production



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

low-energy region
relevant!

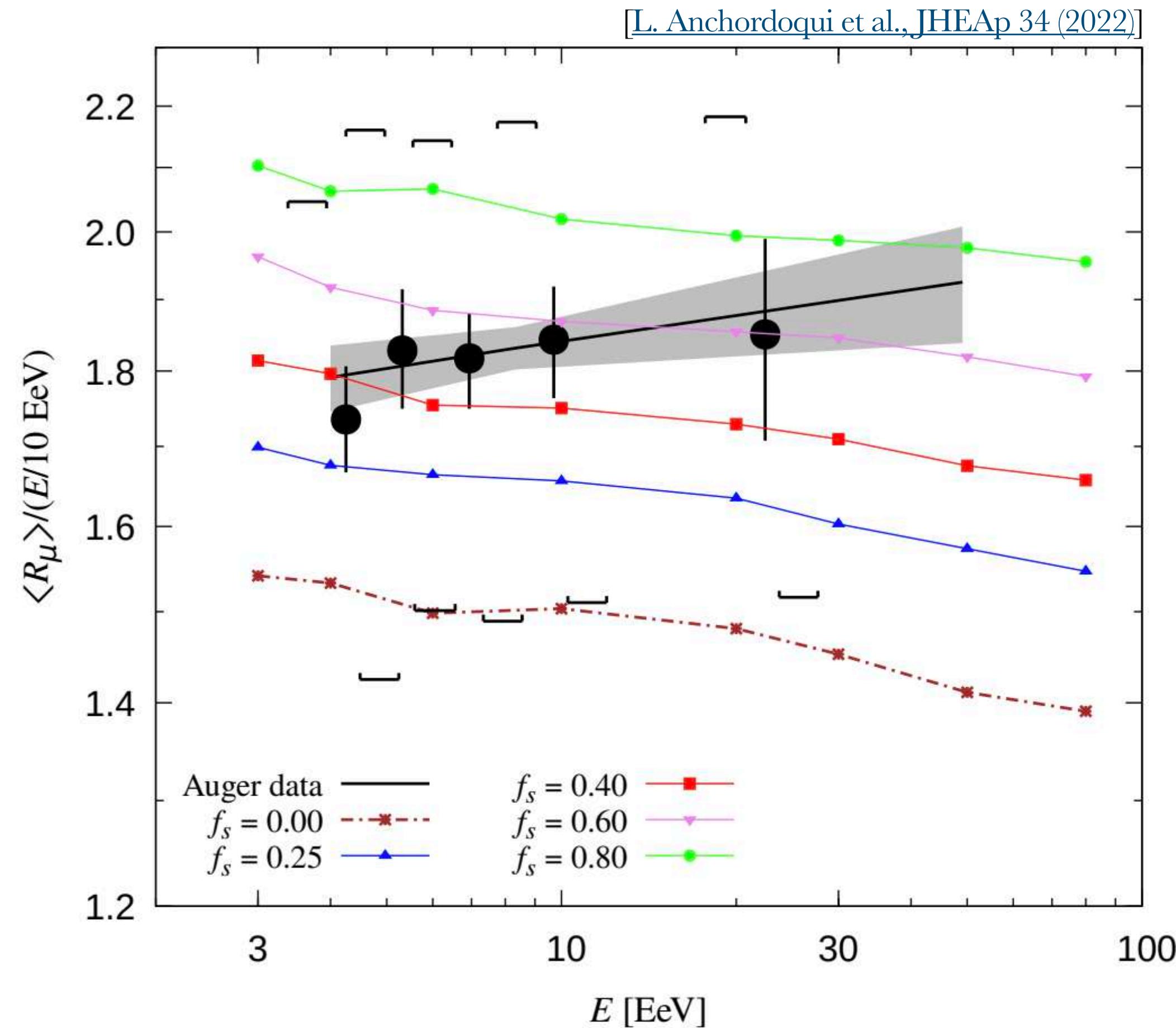


- ▶ Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties!

Light Hadron Production



- ▶ 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?
[[L. Anchordoqui et al., JHEAp 34 \(2022\)](#)]
- ▶ 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!

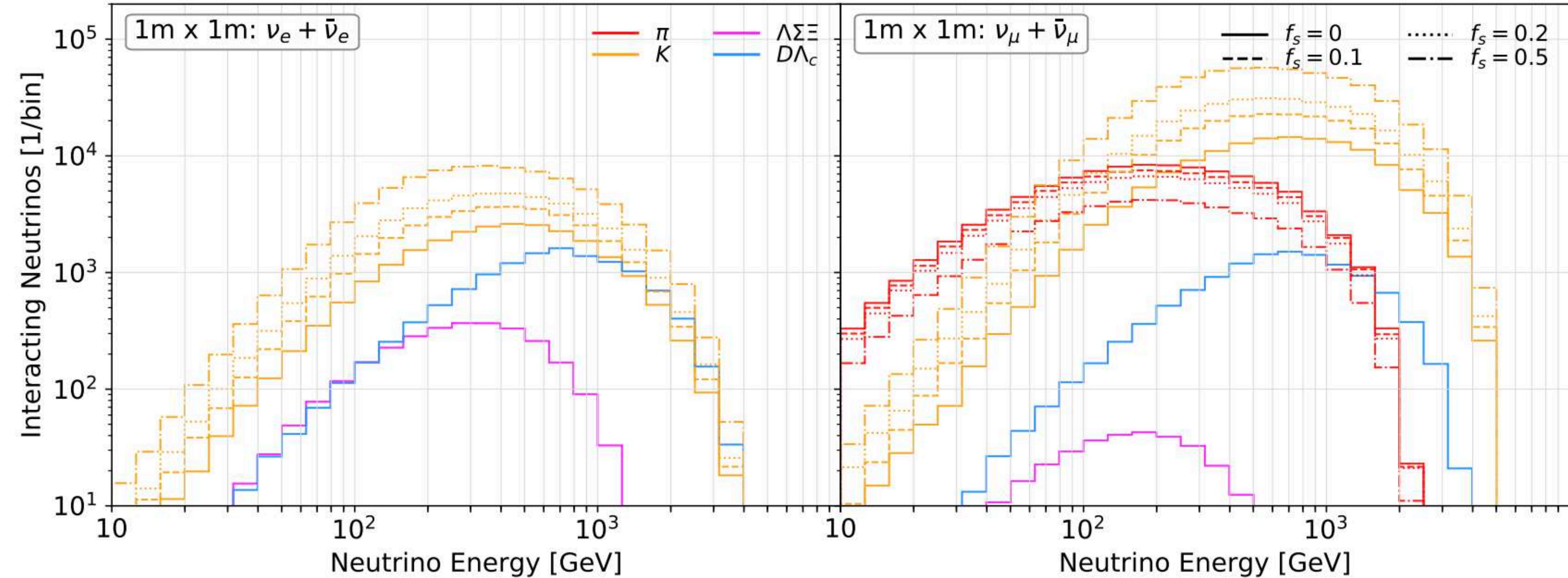


Light Hadron Production



- ▶ Example: Neutrino fluxes at FLArE

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



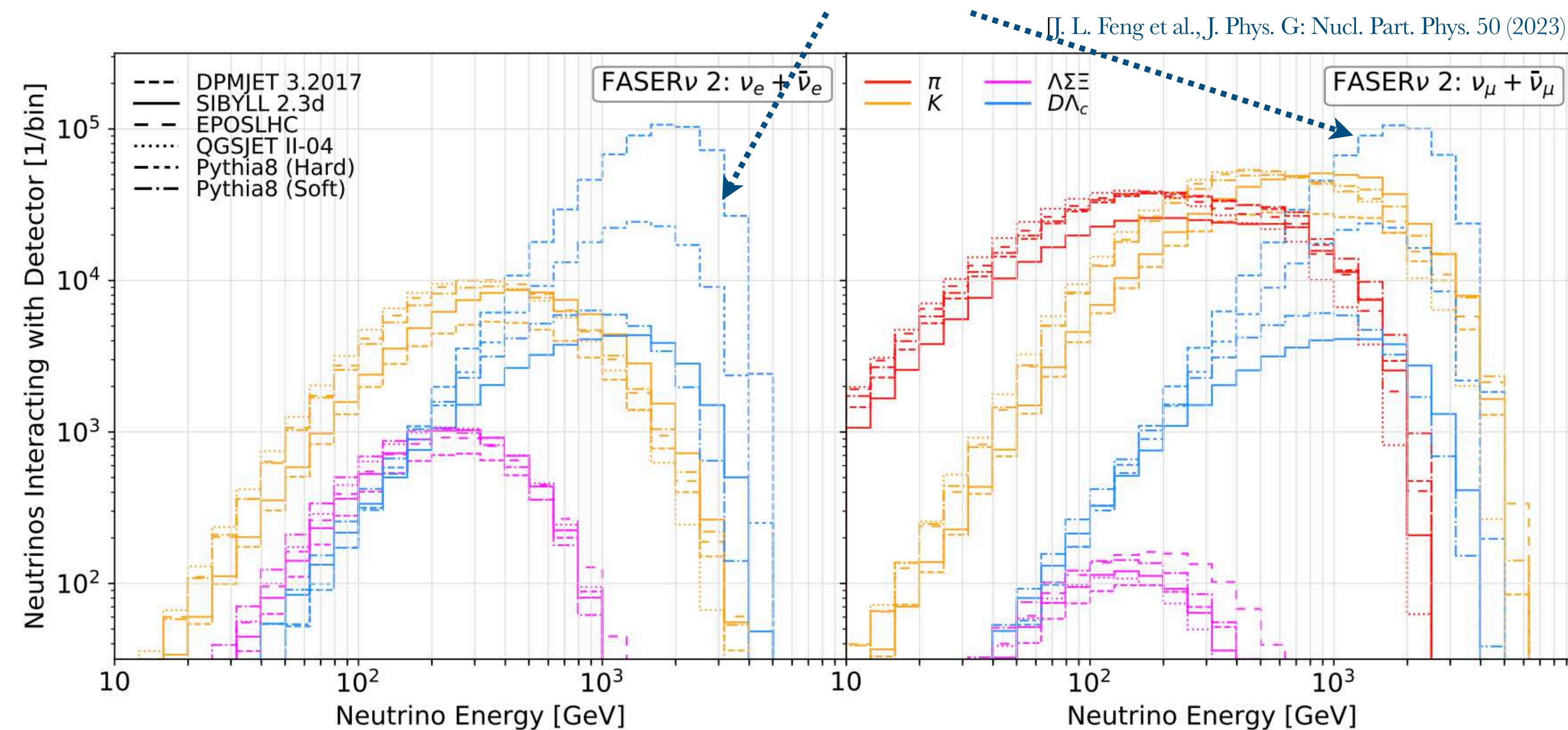
- ▶ Model comparison: strangeness enhancement toy model as an example [L. Anchordoqui et al., JHEAp 34 (2022)]

Prompt Hadron Production



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

high-energy region
relevant!

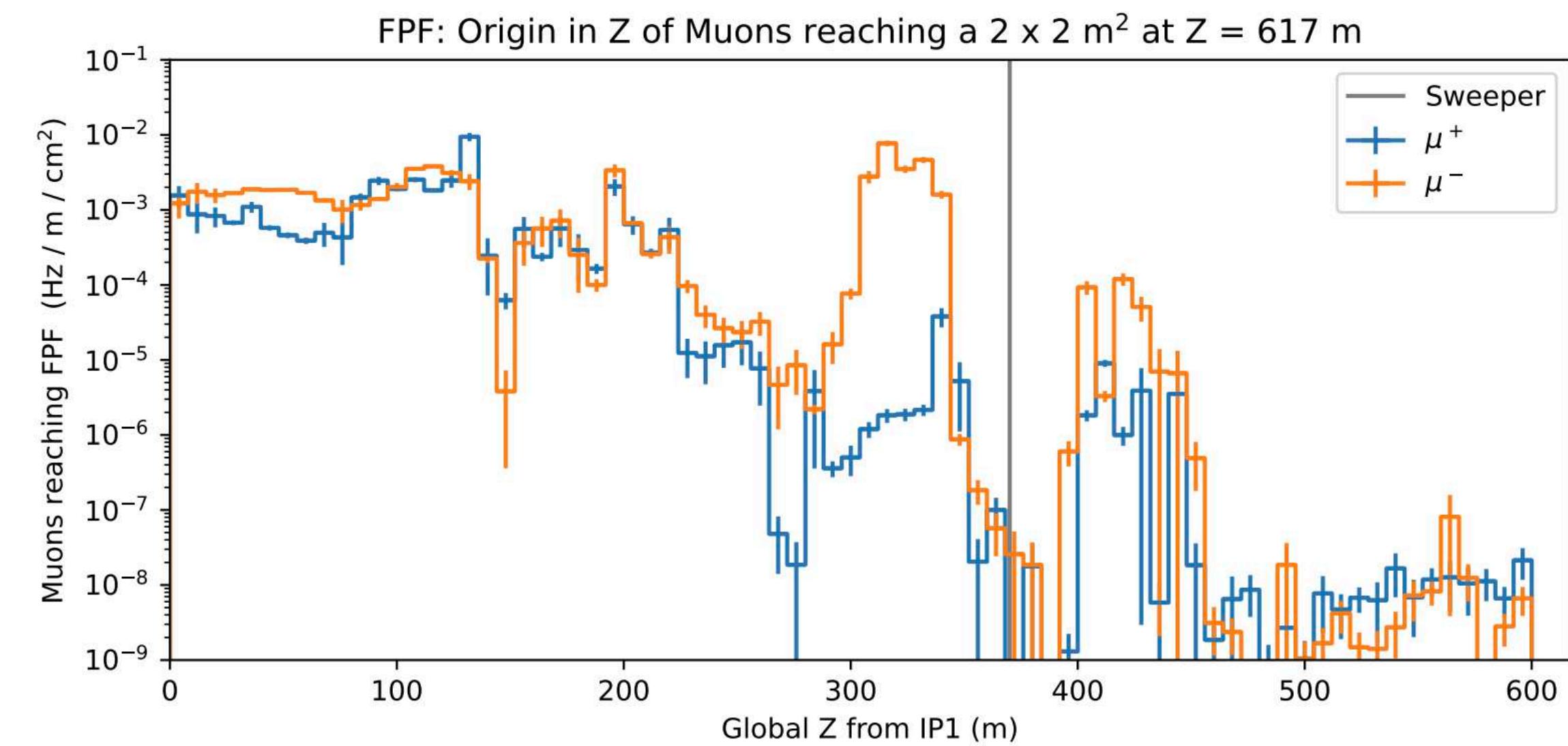


- ▶ Measurements of charm production will reduce uncertainties in atmospheric prompt flux

Muon Fluxes at the FPF



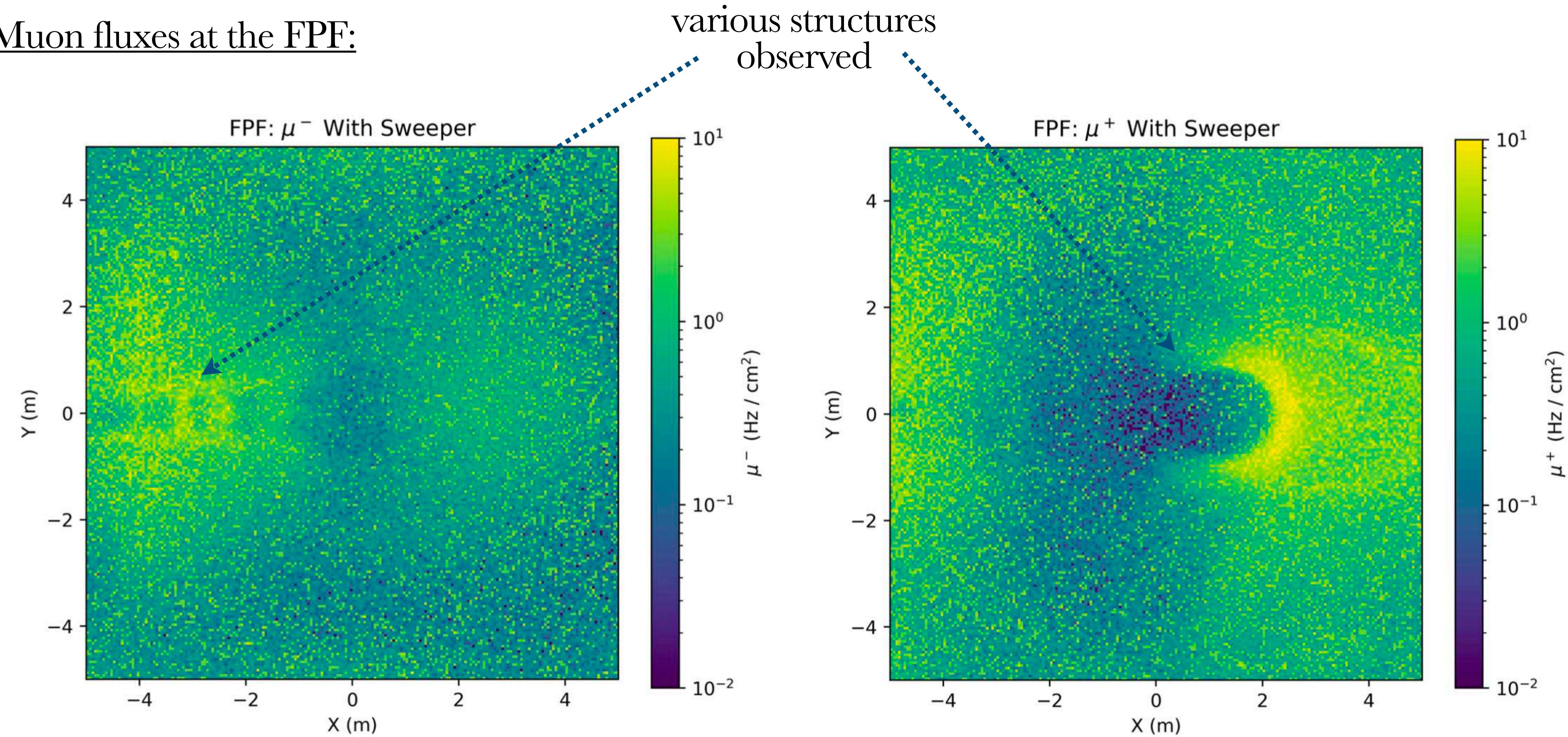
- ▶ Muon fluxes at the FPF:
 - ▶ Large muon flux at the FPF, e.g. ~ 1 Hz per cm^2 in FASER
 - ▶ While we know the origin of neutrinos in the FPF (ATLAS interaction point), studies of muons at the FPF are challenging as the origin of production is uncertain...
- ▶ Open questions:
 - ▶ Can we use muons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



Contents

1	Introduction	17
2	The Facility	21
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
3	Experiments	57
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 ν 2	62
3.2.1	Physics Goals	62

13

	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
4	Long-Lived Particles	85
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 ν 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	Bremming Enhanced ALP Productions and FPF Sensisivity	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 ν_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
5	Dark Matter and BSM Scattering Signatures	205
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	Quarks	223
6	Quantum Chromodynamics	229
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 Pythia 8	254
6.2.3	Event Generation for Forward Particle Production with Sherpa	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)INPDF Framework	268
6.3.4	Neutrino DIS Cross Sections on a Tungsten Target	271
7	Neutrino Physics	273
7.1	Overview	273
7.2	Neutrino Fluxes	274
7.2.1	Neutrino Fluxes from Monte Carlo Generators	274

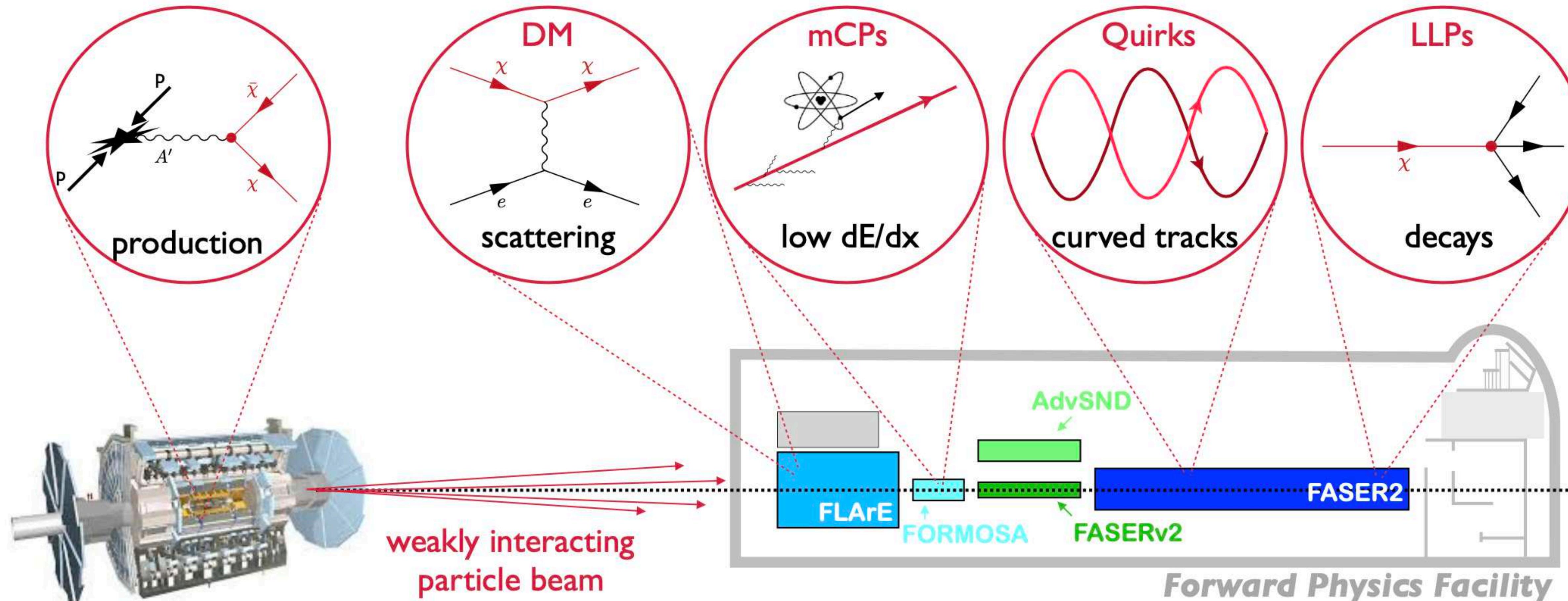
	Contents	16
7.2.2	Neutrino Fluxes from k_T -Factorization	281
7.2.3	Tau Neutrino Fluxes from Heavy Flavor: PDF Uncertainties in NLO Perturbative QCD	281
7.3	Neutrino Cross Sections	287
7.3.1	Deep-Inelastic Scattering	288
7.3.2	Neutral-Current Scattering	291
7.3.3	Quasi-Elastic and Resonance Regions for 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	Ciessen Model and GRILLI 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
8	Astroparticle Physics	327
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	Probing Atmospheric Neutrino Fluxes	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
	Acknowledgements	353
	References	357

BSM physics &
dark matter

Dark Matter Searches



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



Dark Matter Searches

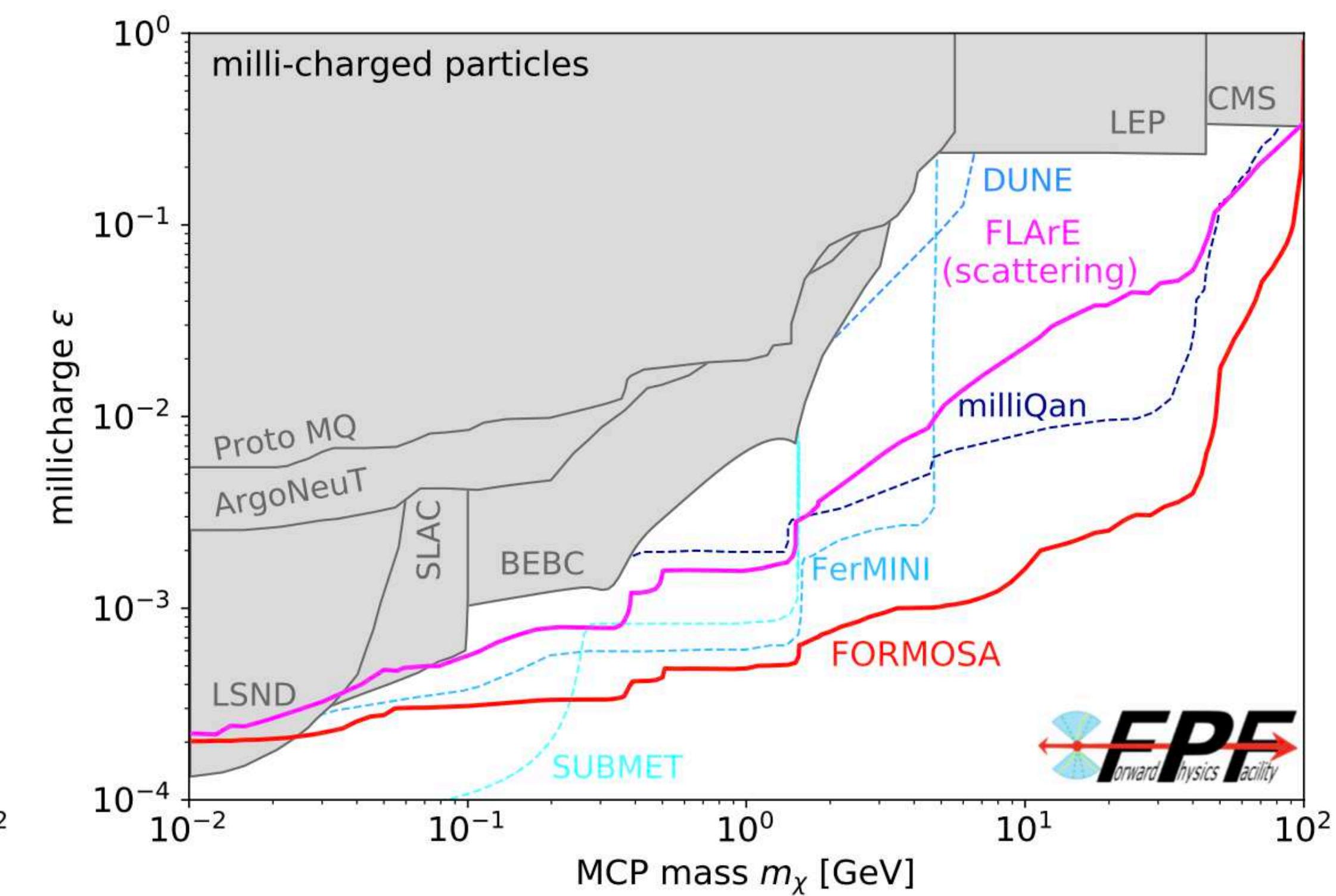
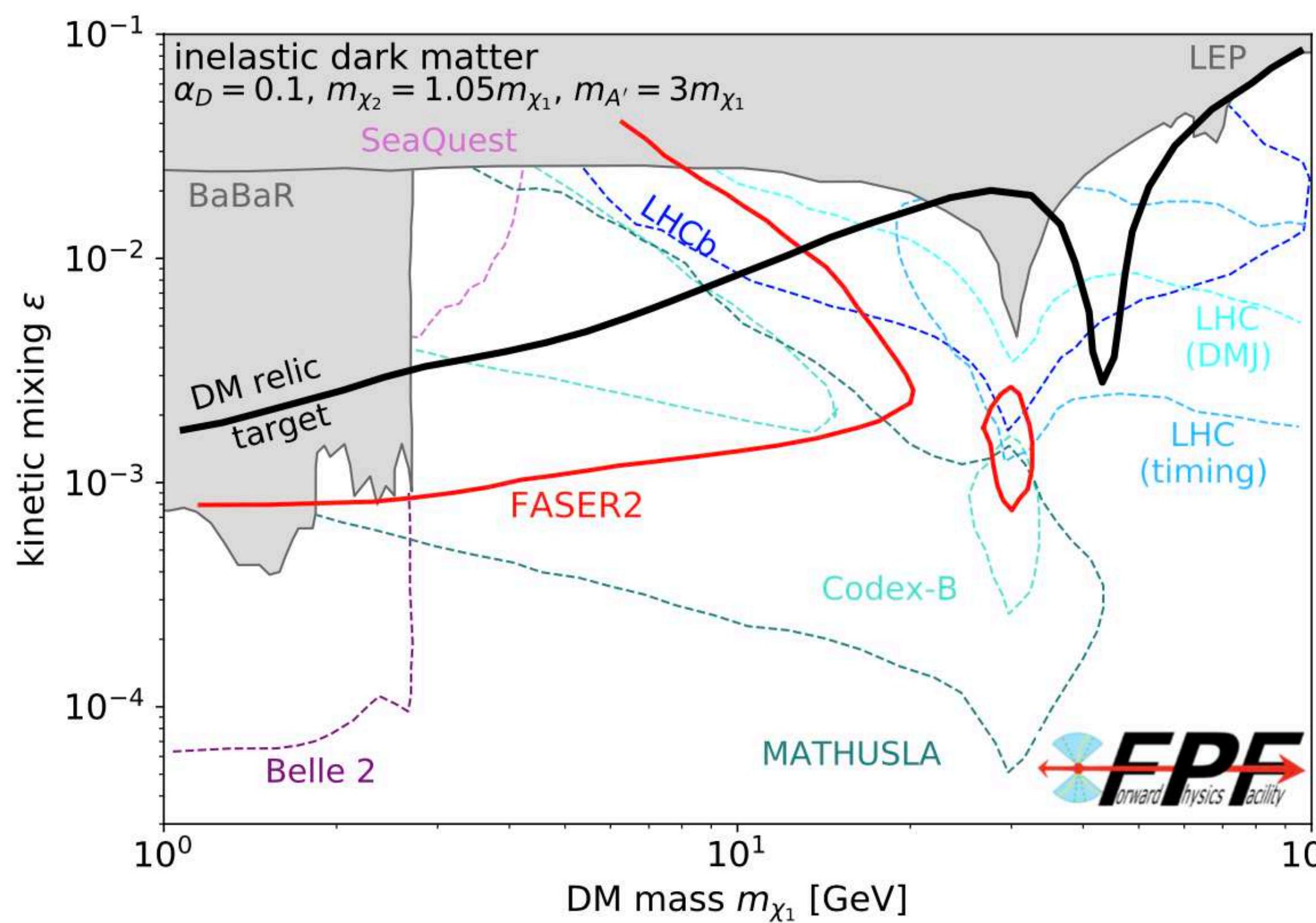


- ▶ Examples:

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

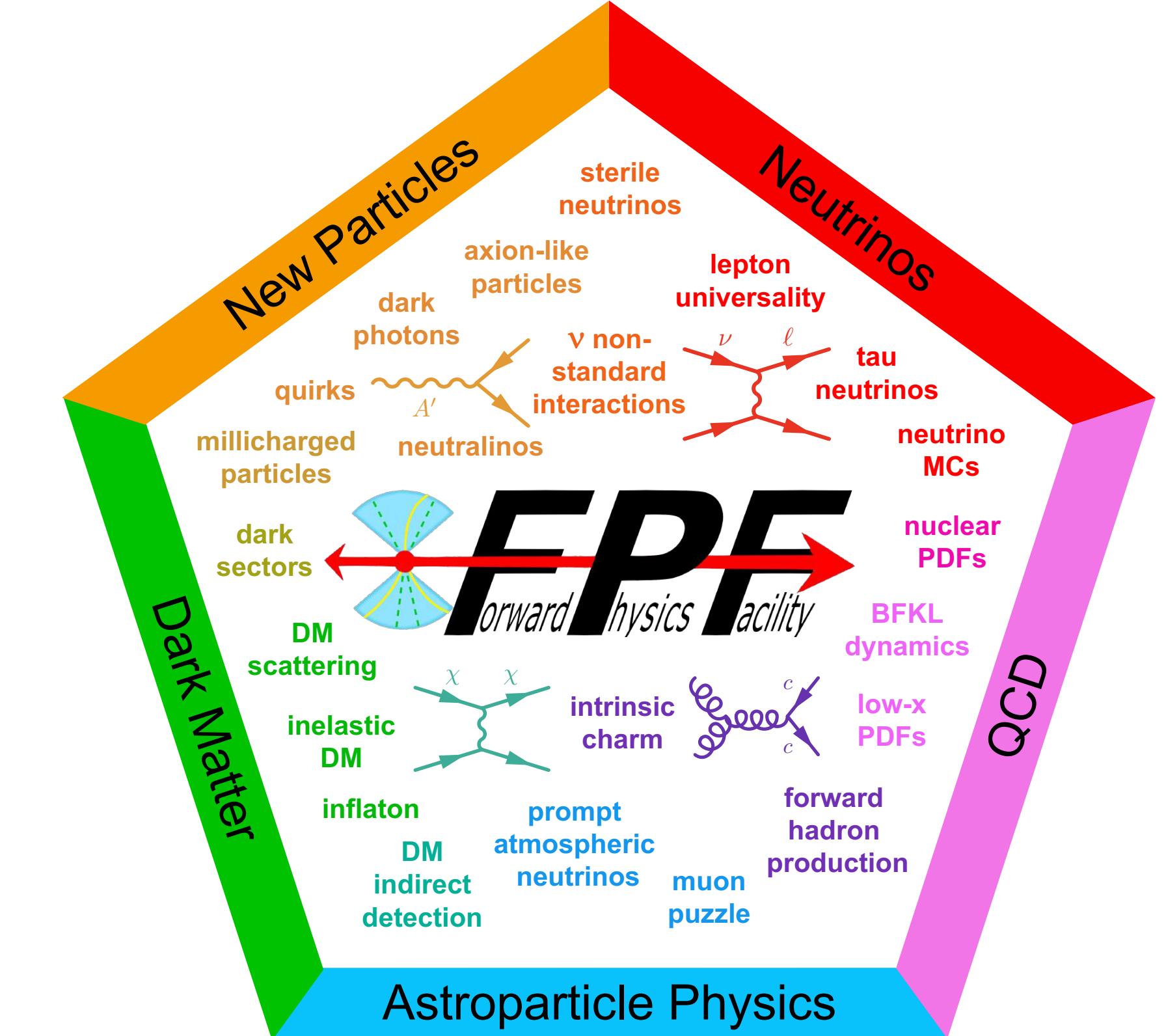
- ▶ Search for displaced decays of highly-boosted excited DM states produced in pp collisions
- ▶ Millicharged particle searches as a candidate for a strongly interacting sub-component of DM

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



Summary

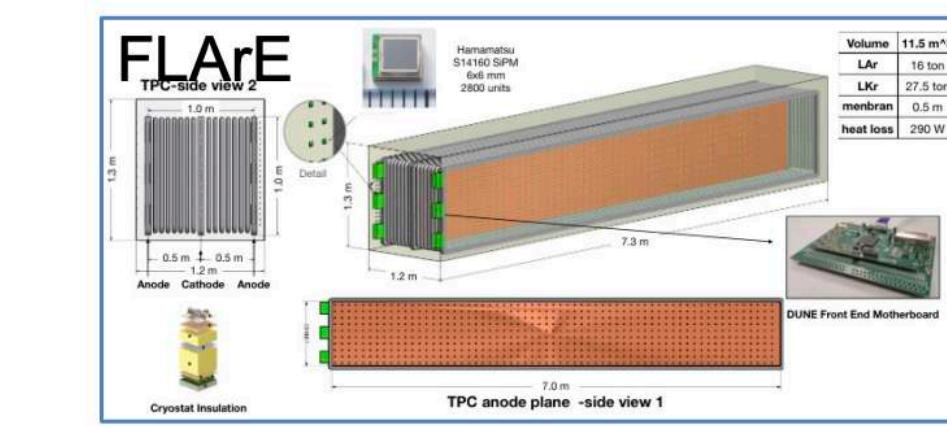
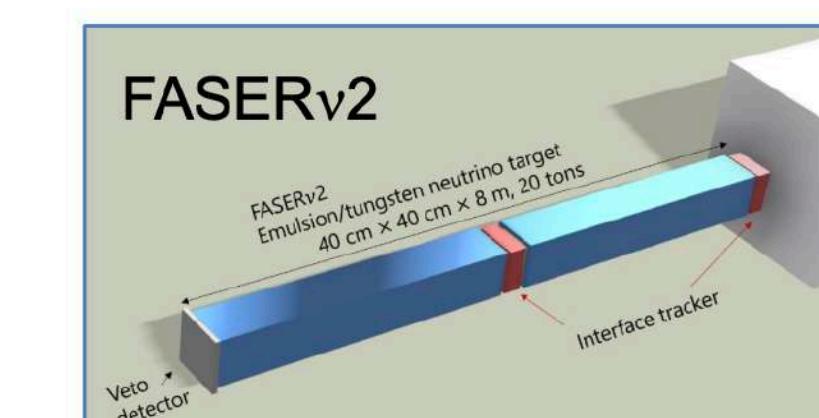
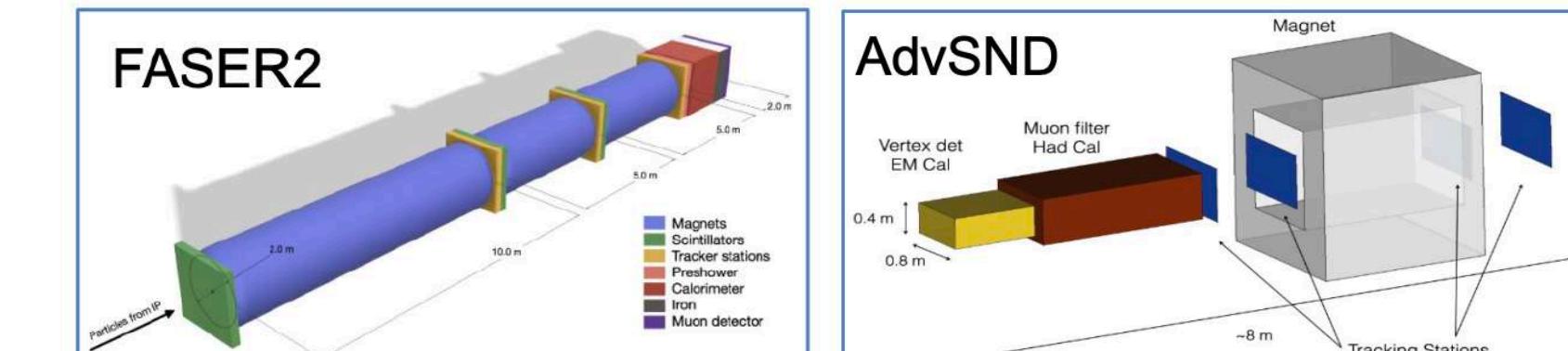
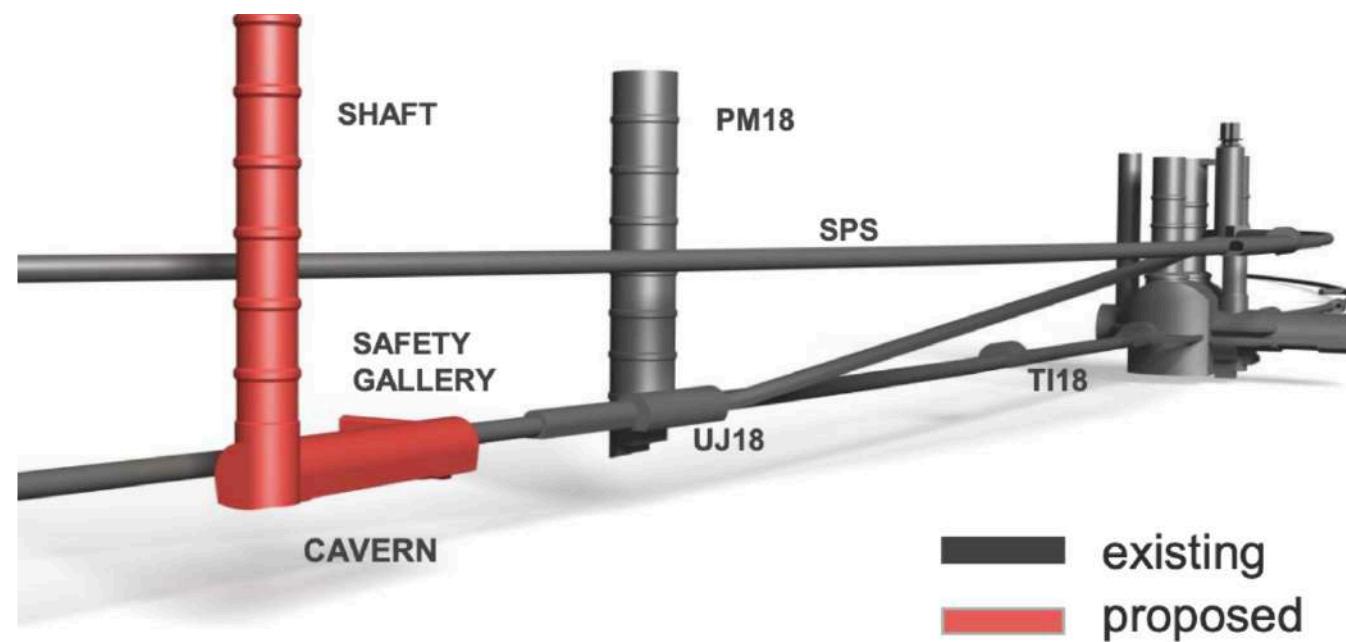
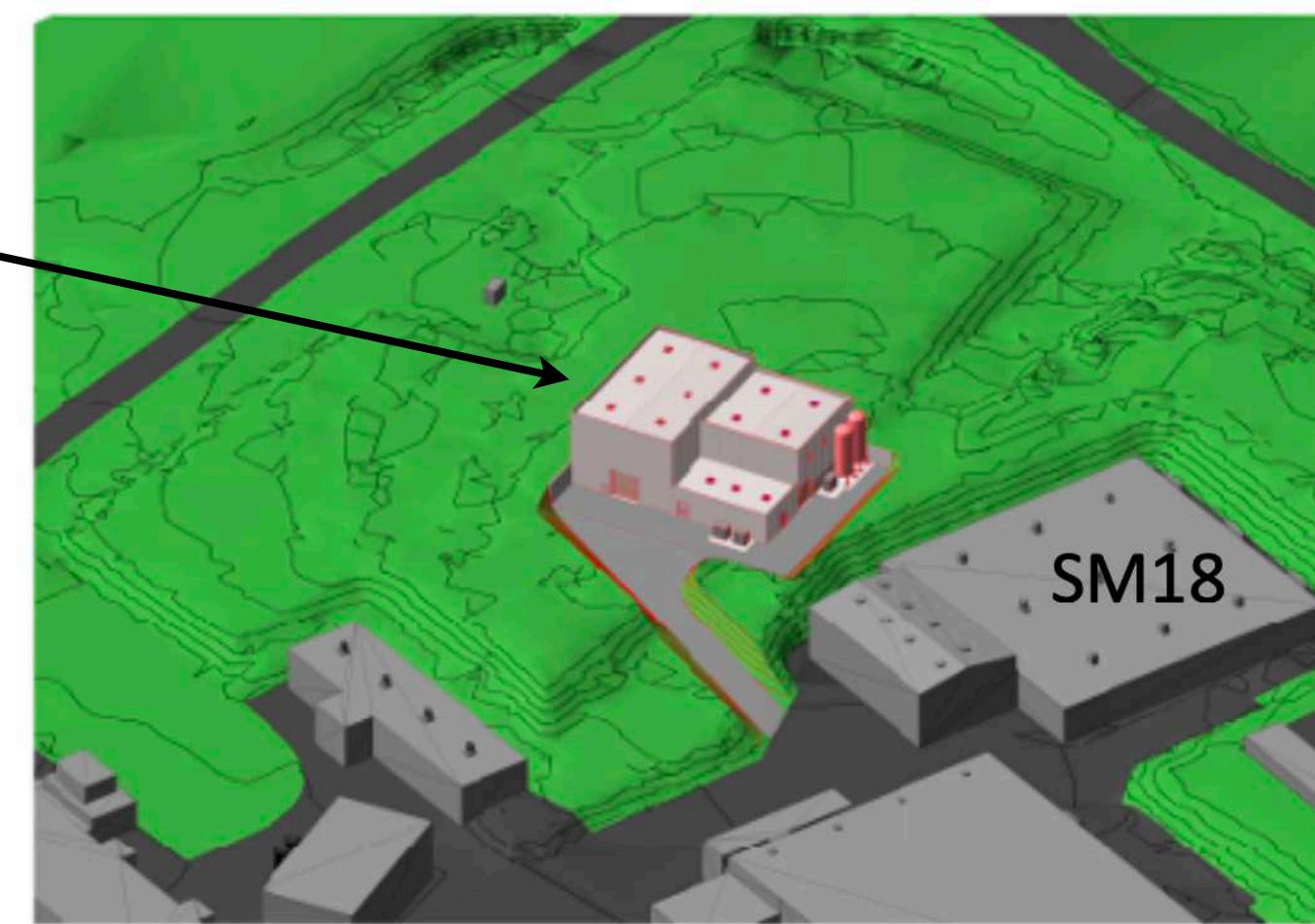
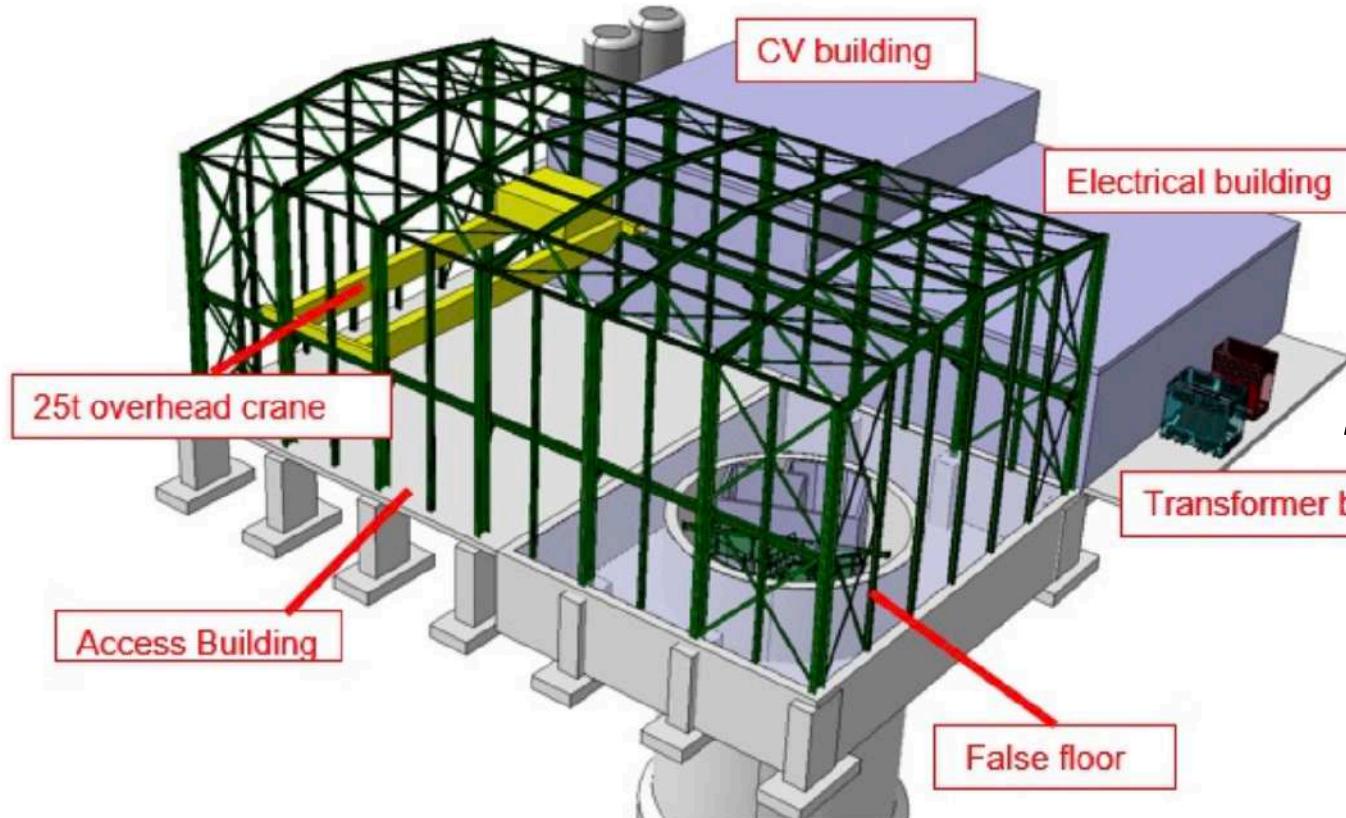
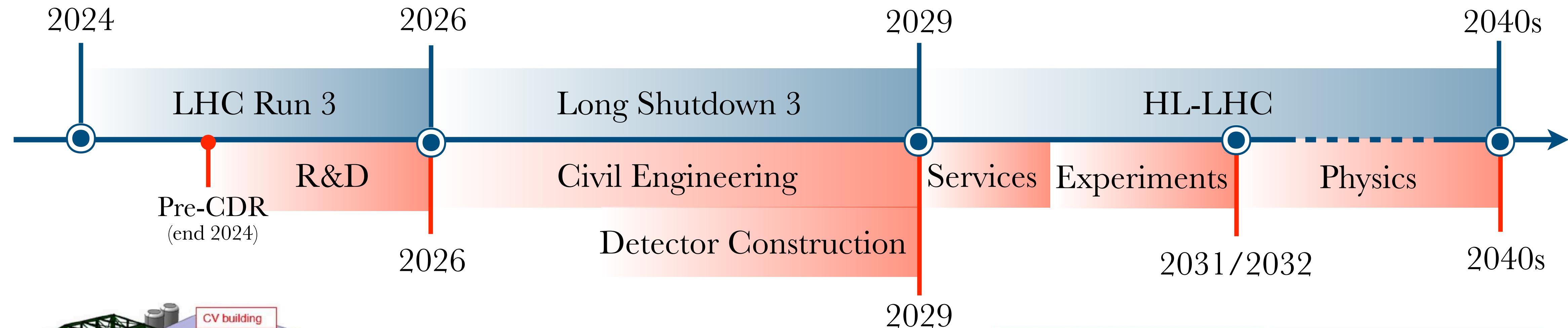
- ▶ Cosmic ray measurements highly rely on interpretation based on MC simulations of EASs
 - ▶ Large discrepancies observed in the muon content of EAS
- ▶ High-energy neutrinos from EASs are background for astrophysical neutrino searches
 - ▶ Prompt neutrino flux not well understood
- ▶ The FPF is a 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/>



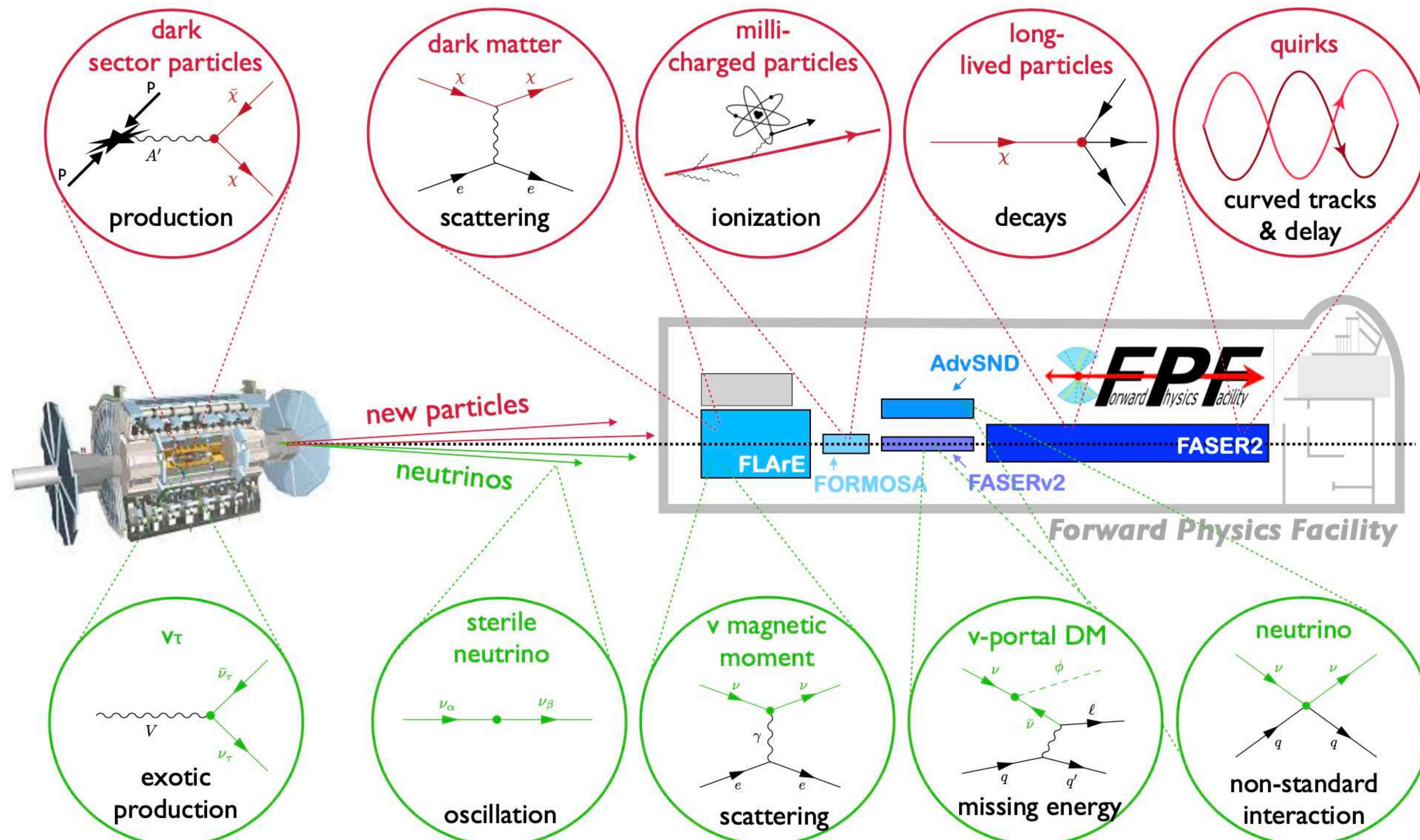
Please don't hesitate to contact us if you want to contribute!

Backup

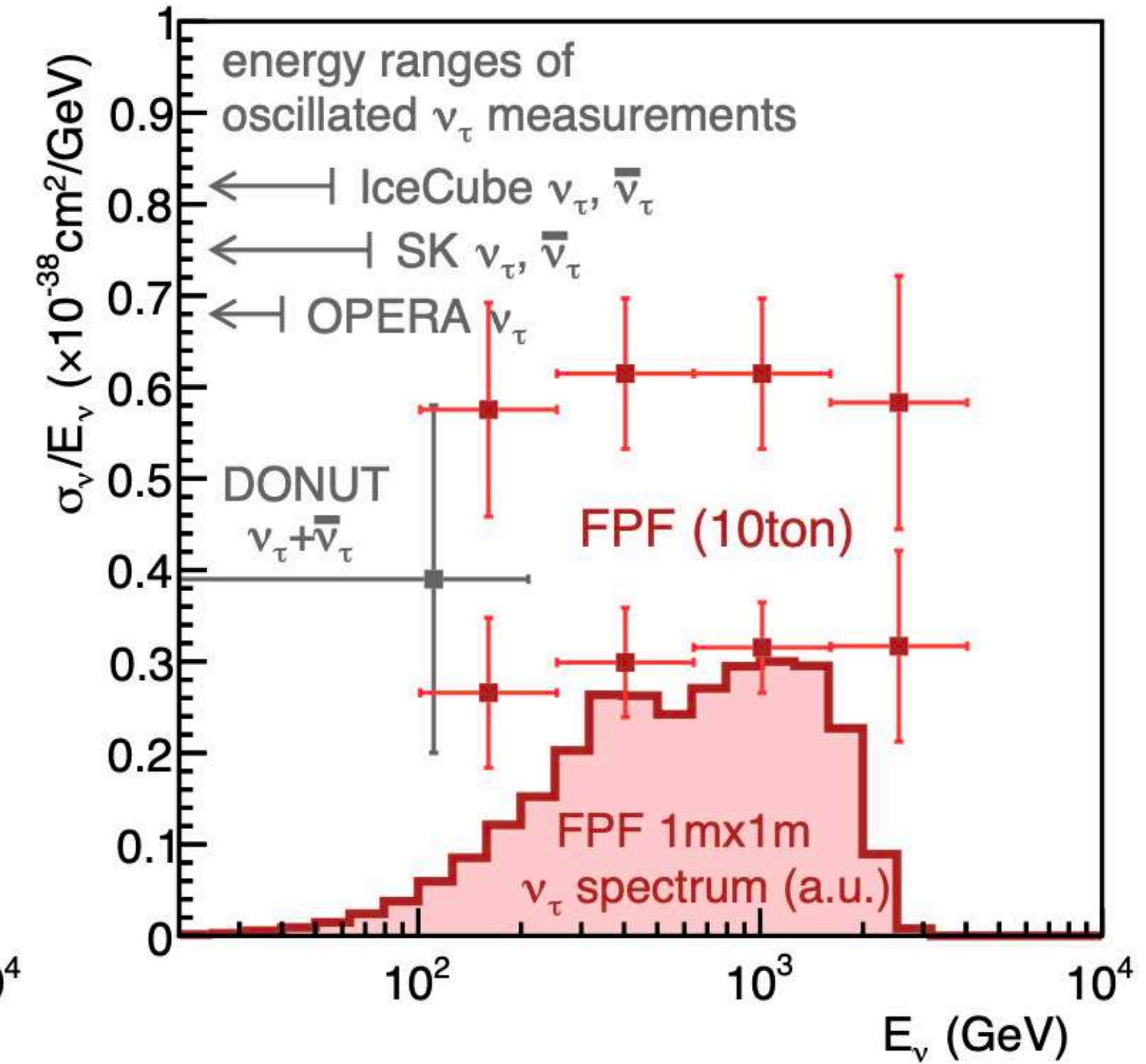
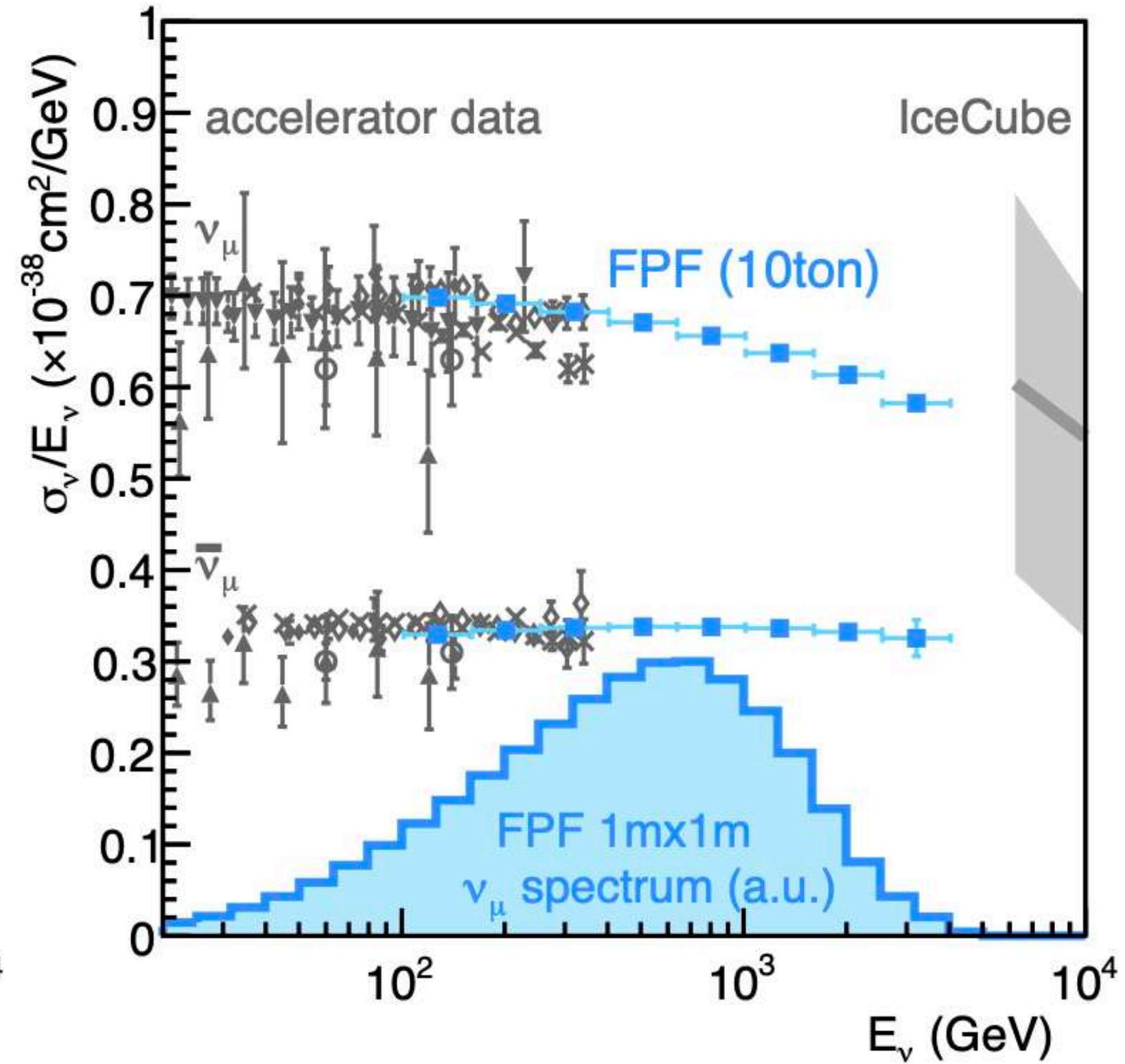
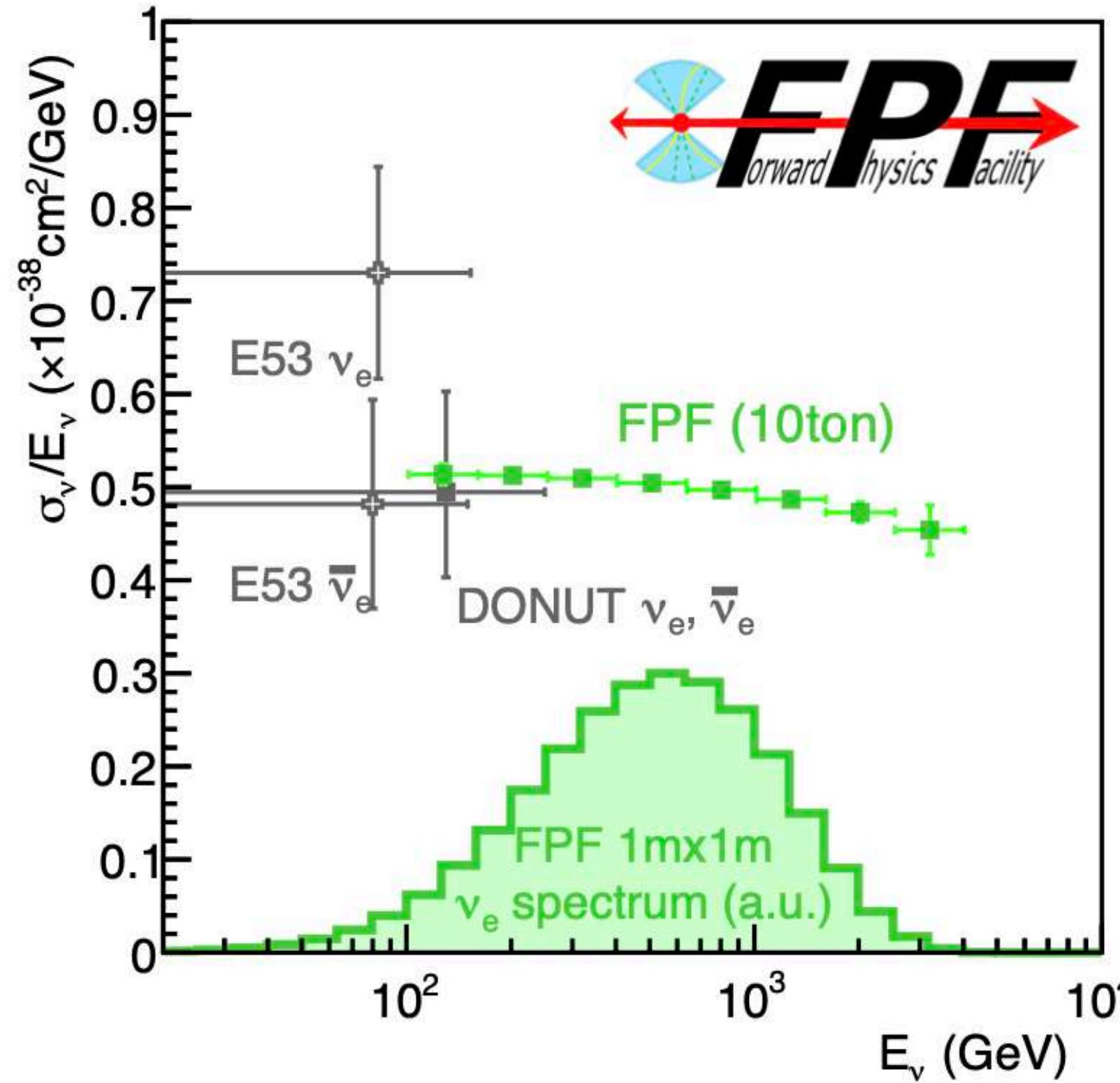
FPF Timeline



Neutrino / DM Overview



Neutrino Fluxes at the FPF



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