TeV Particle Astrophysics
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Kingston, ON

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

Dennis Soldin on behalf of the FPF initiative

Karlsruher Institut für Technologie

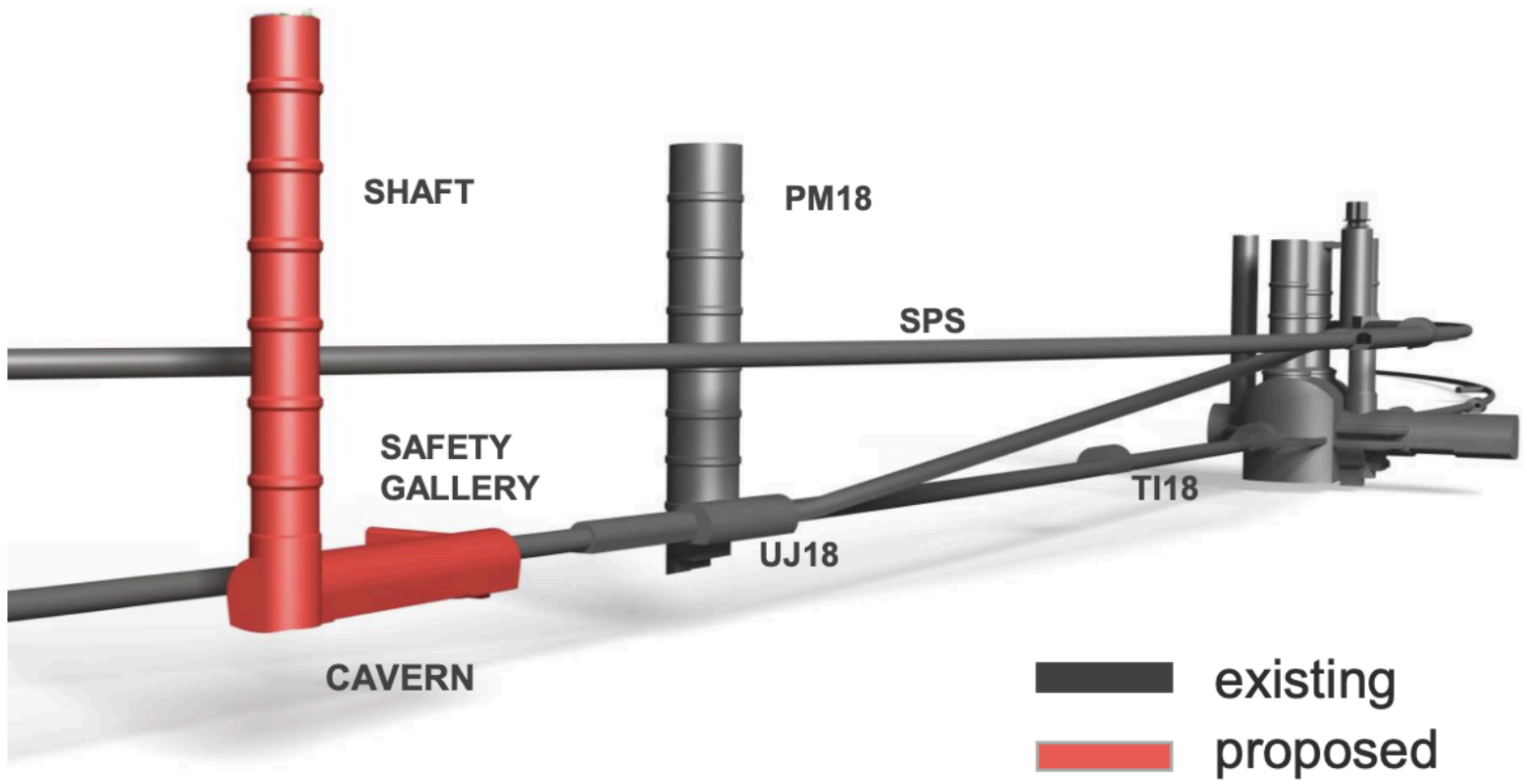
University of Delaware
Bartol Research Institute

Forward Physics Facility

Overview

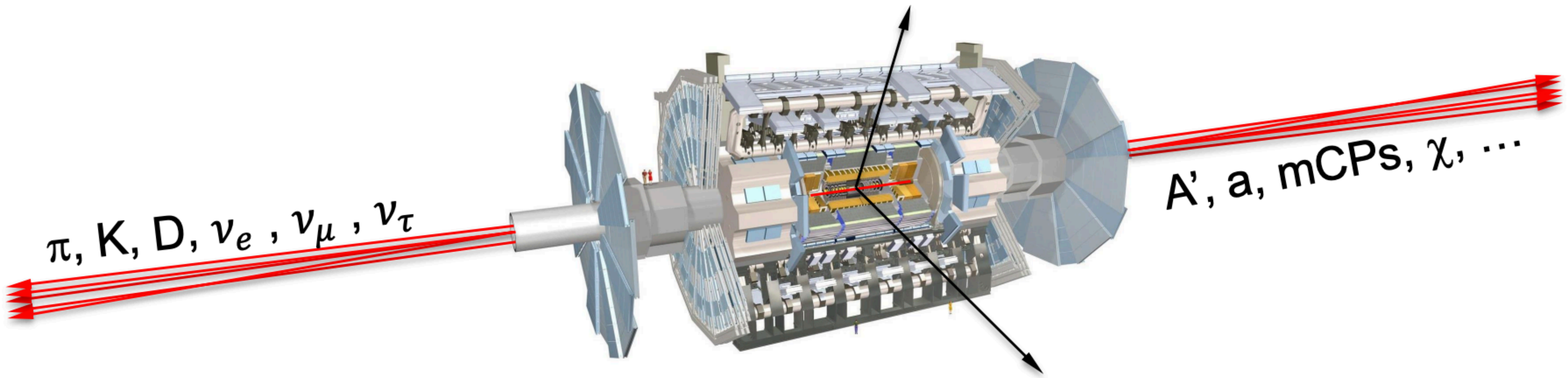
- Introduction
- Facility & Timeline
- Experiments
- Astroparticle Physics with the FPF
- Summary & Conclusions

Forward Physics Facility



Introduction

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



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

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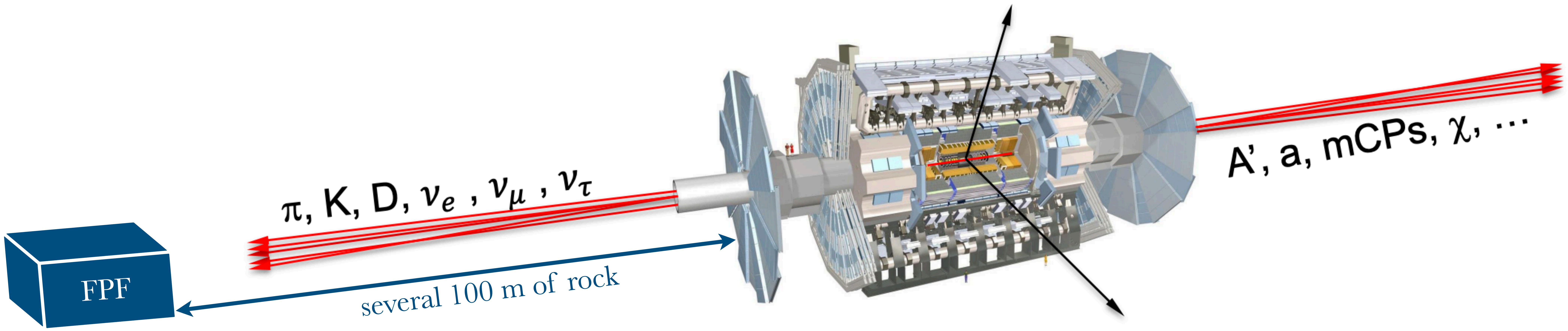

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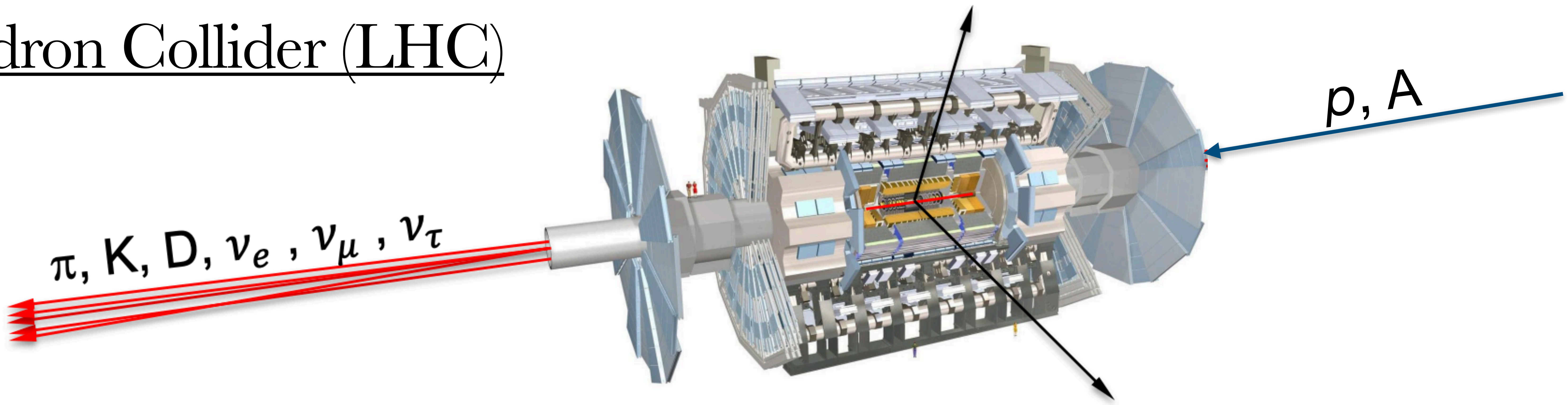
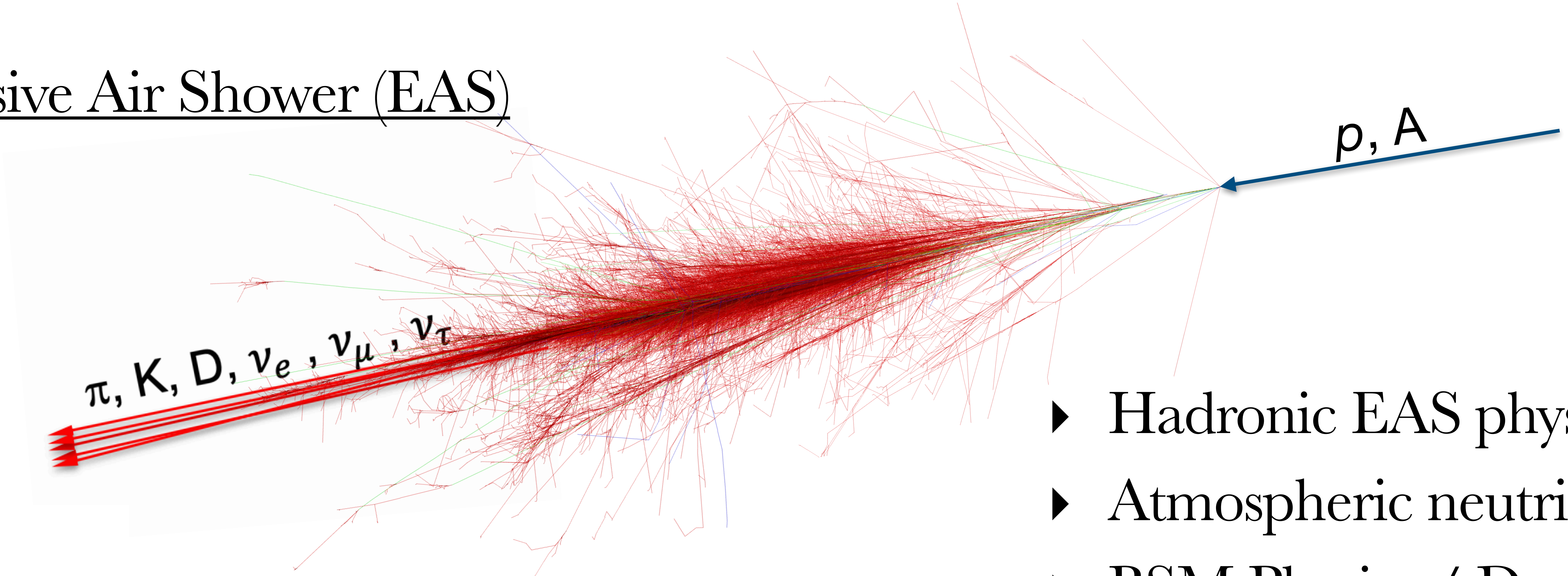
- Large Hadron Collider (LHC)



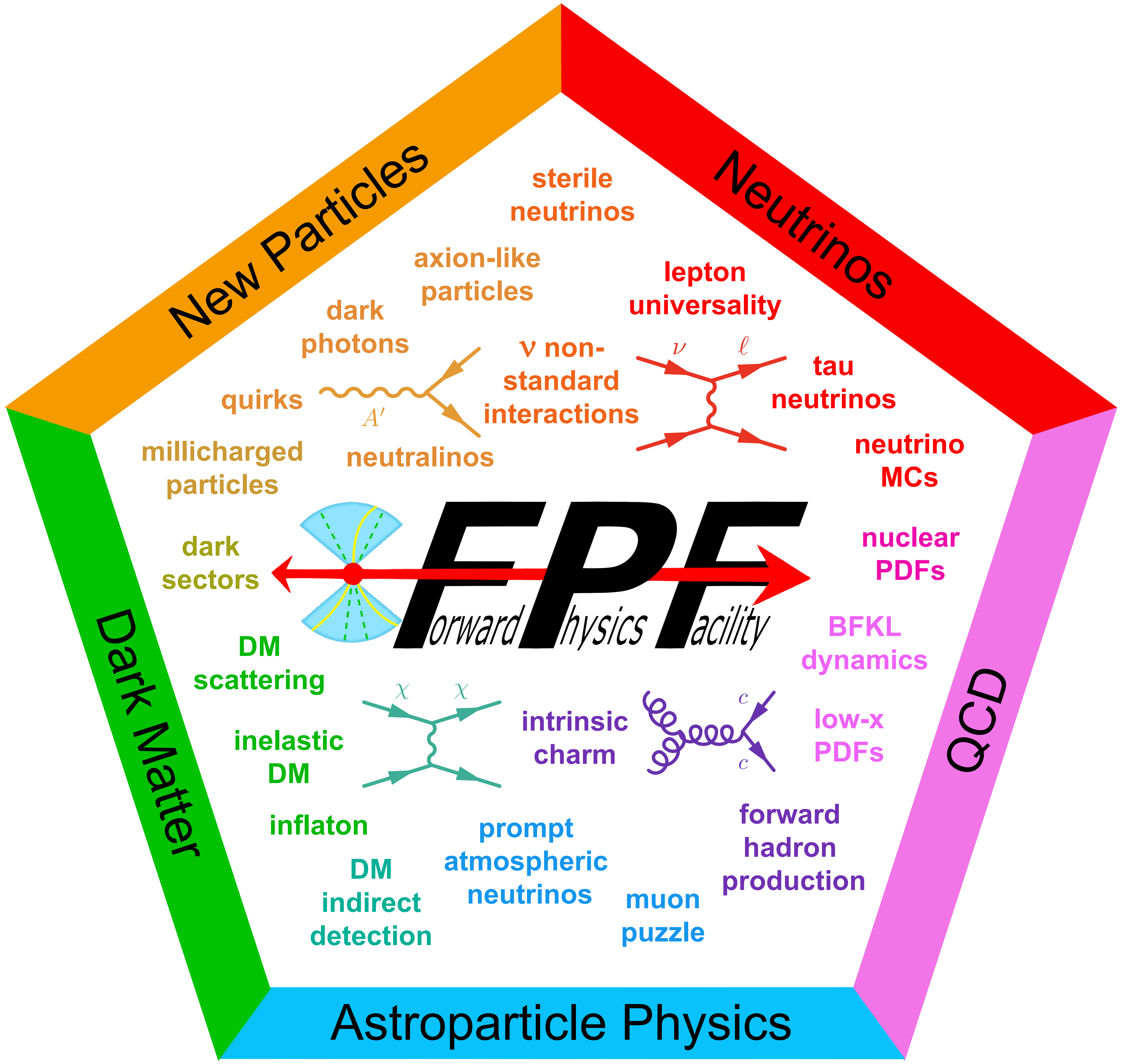
- Extensive Air Shower (EAS)



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

Disclaimer

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



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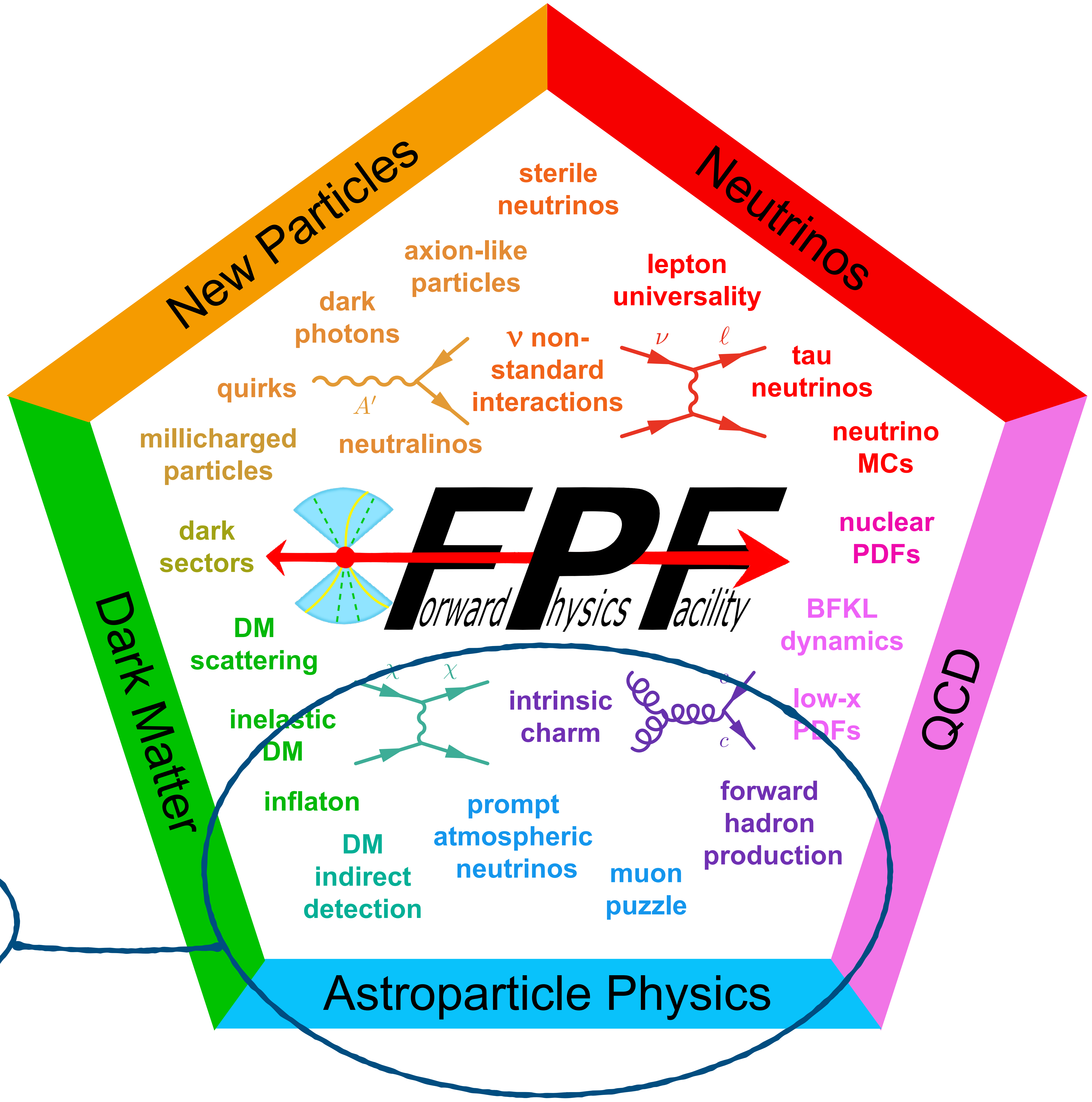
This talk



FPF Short Paper

- Further reading:
  - First "real" paper on FPF
  - About 80 authors
  - About 75 pages
  - Physics Reports 968 (2022) arXiv:2109.10905
  - Collection of ideas
  - Reference for future work
  - Basis for Snowmass White Paper…

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

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

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

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

- <u>Even further reading:</u>
  - Comprehensive 429-page document
  - 236 authors
  - 156 endorsers
  - Accepted by Journal of Physics G
  - Pre-print: arXiv: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

1

Snowmass White Paper

- Comprehensive list of contents:

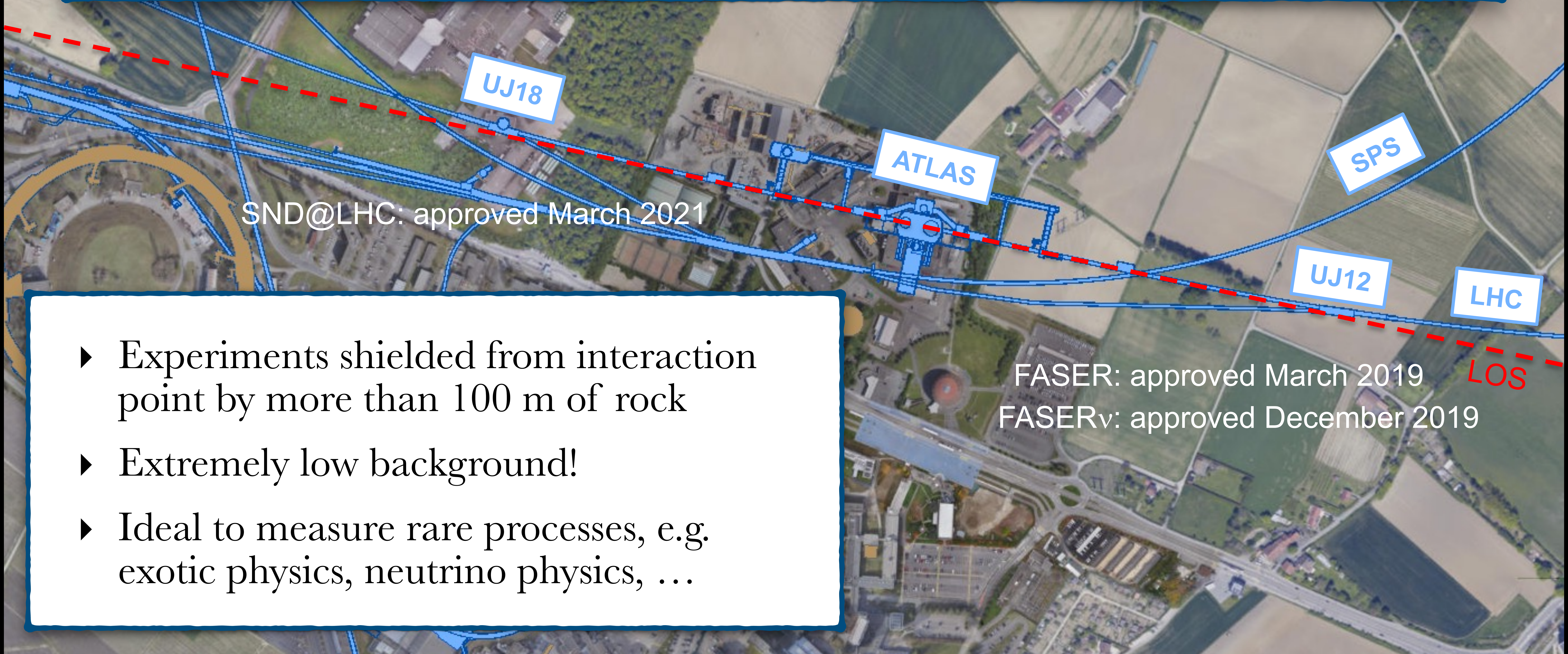
Contents

Focus of this talk

Facility & Timeline

FAR FORWARD EXPERIMENTS AT LHC RUN 3

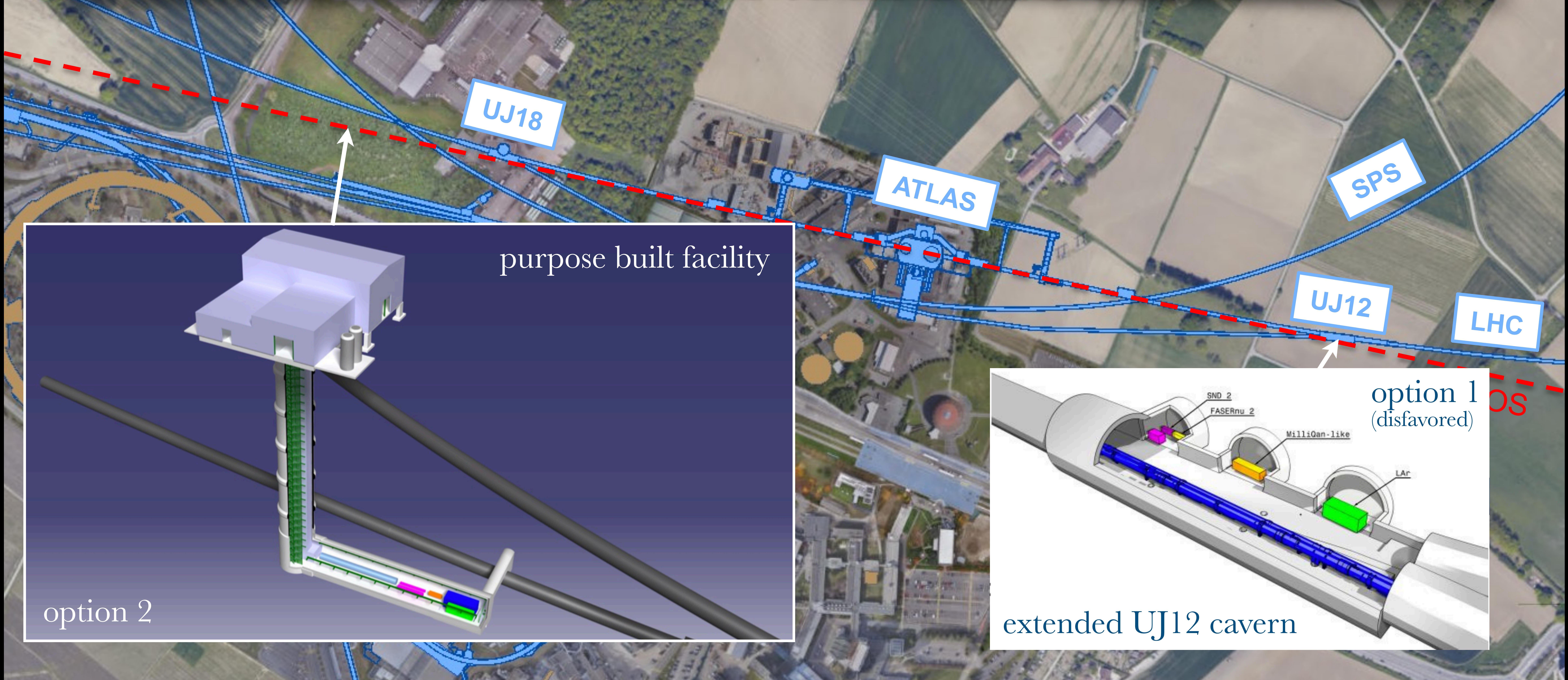
There are currently 3 detectors in operation to exploit forward physics potential during the LHC Run 3



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

FAR FORWARD EXPERIMENTS AT LHC RUN 3

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



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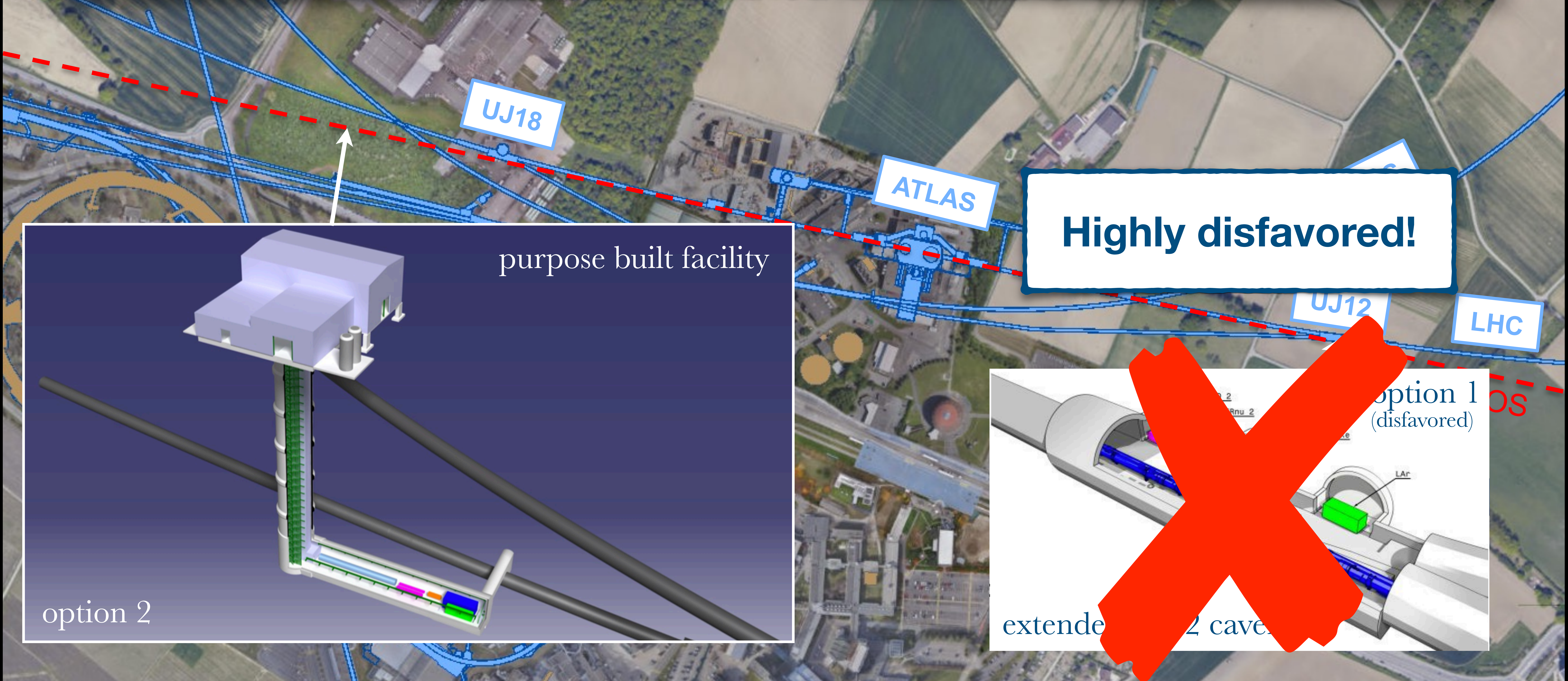
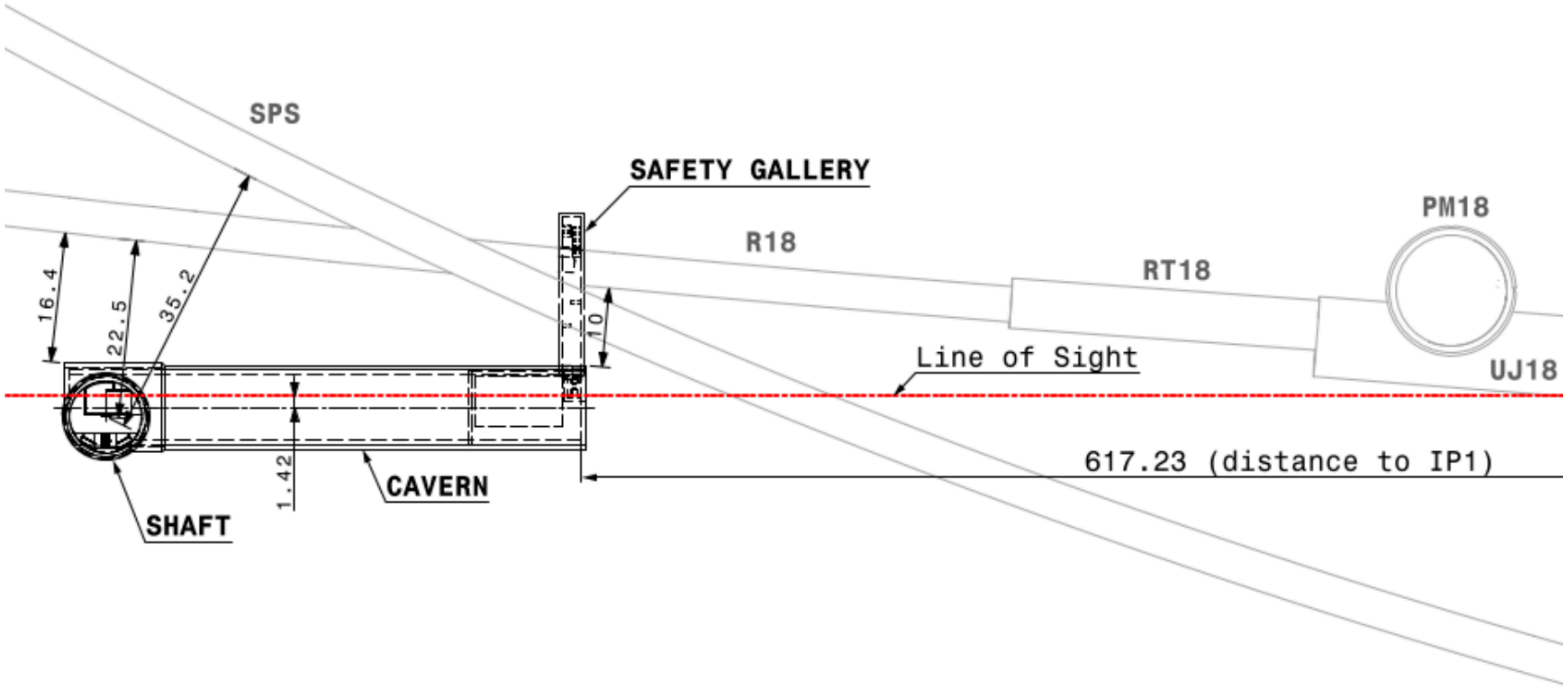
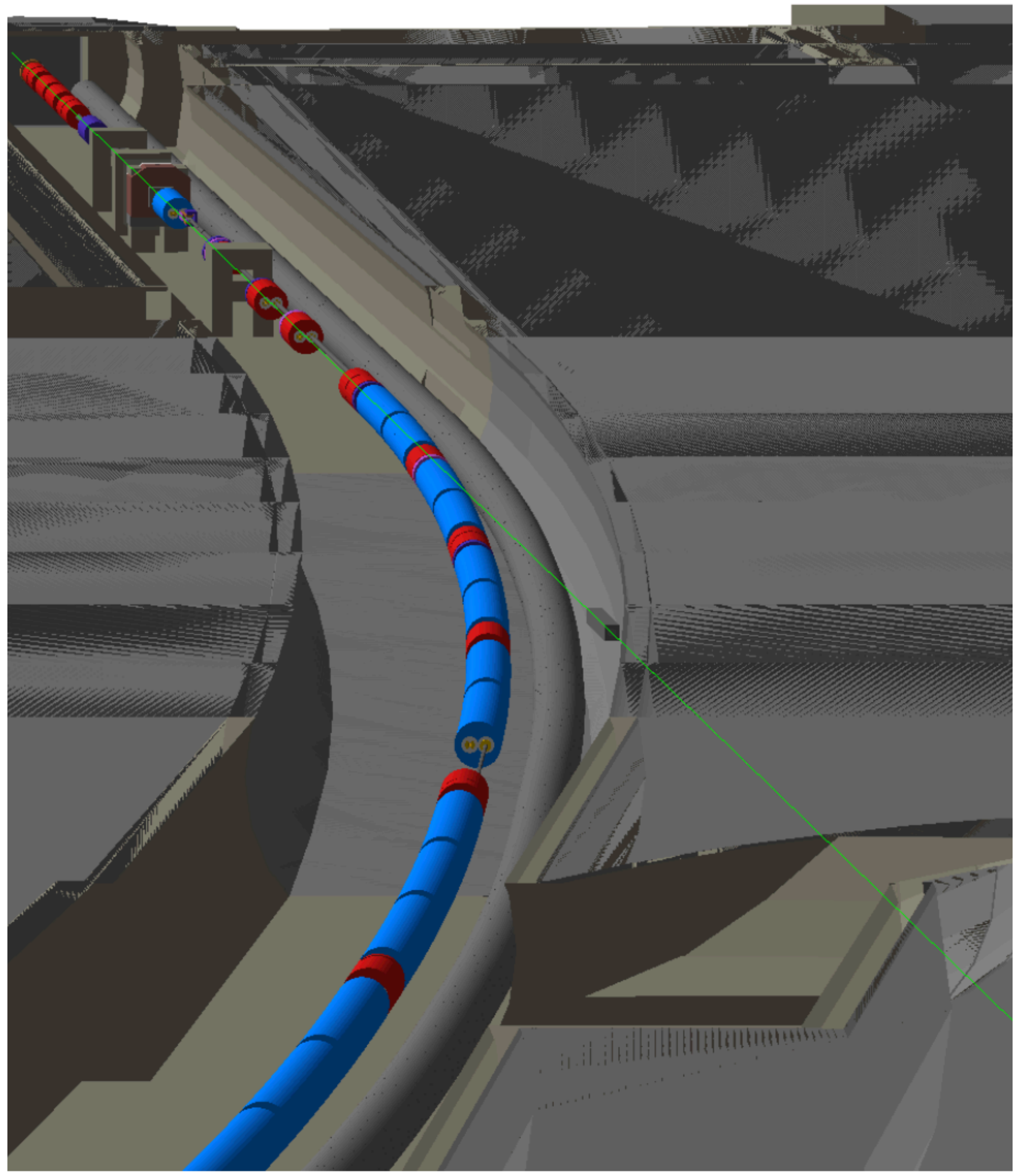


Facility

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





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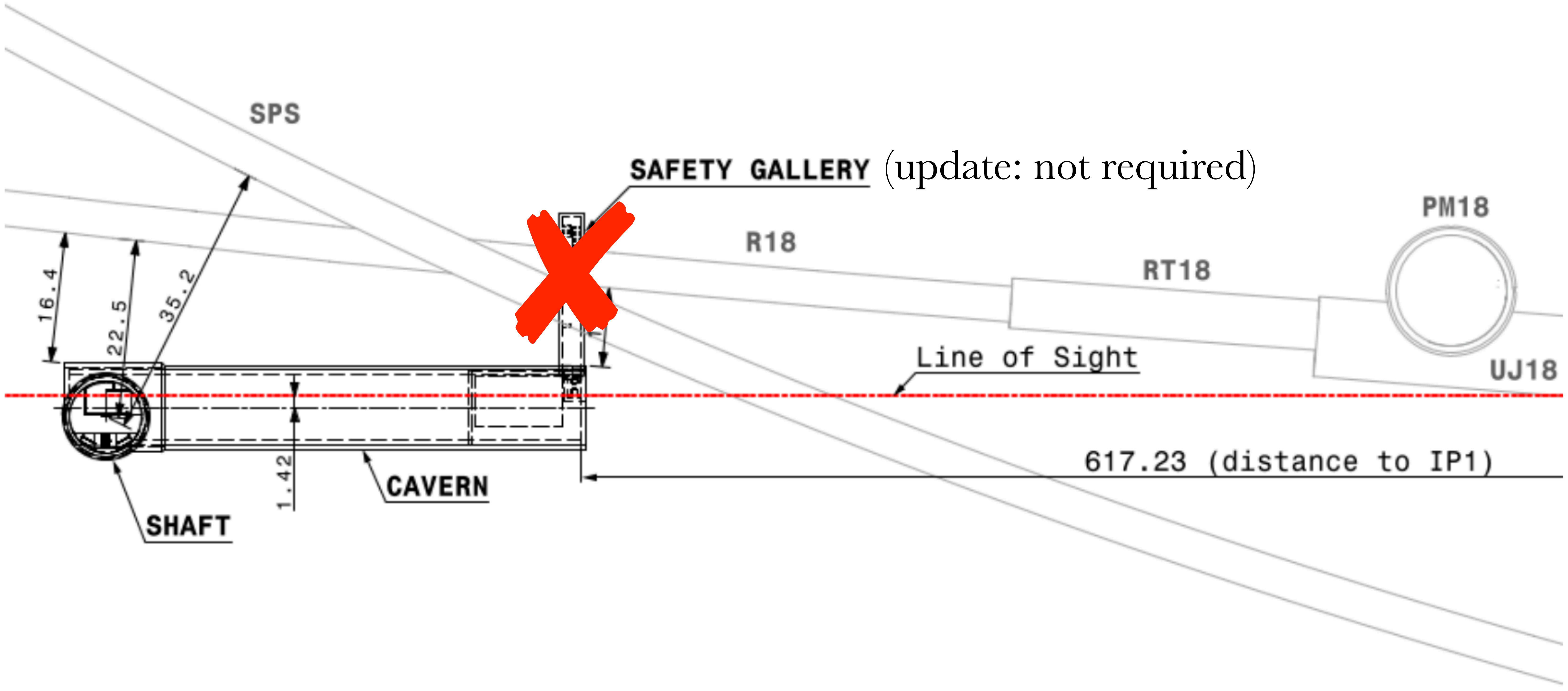

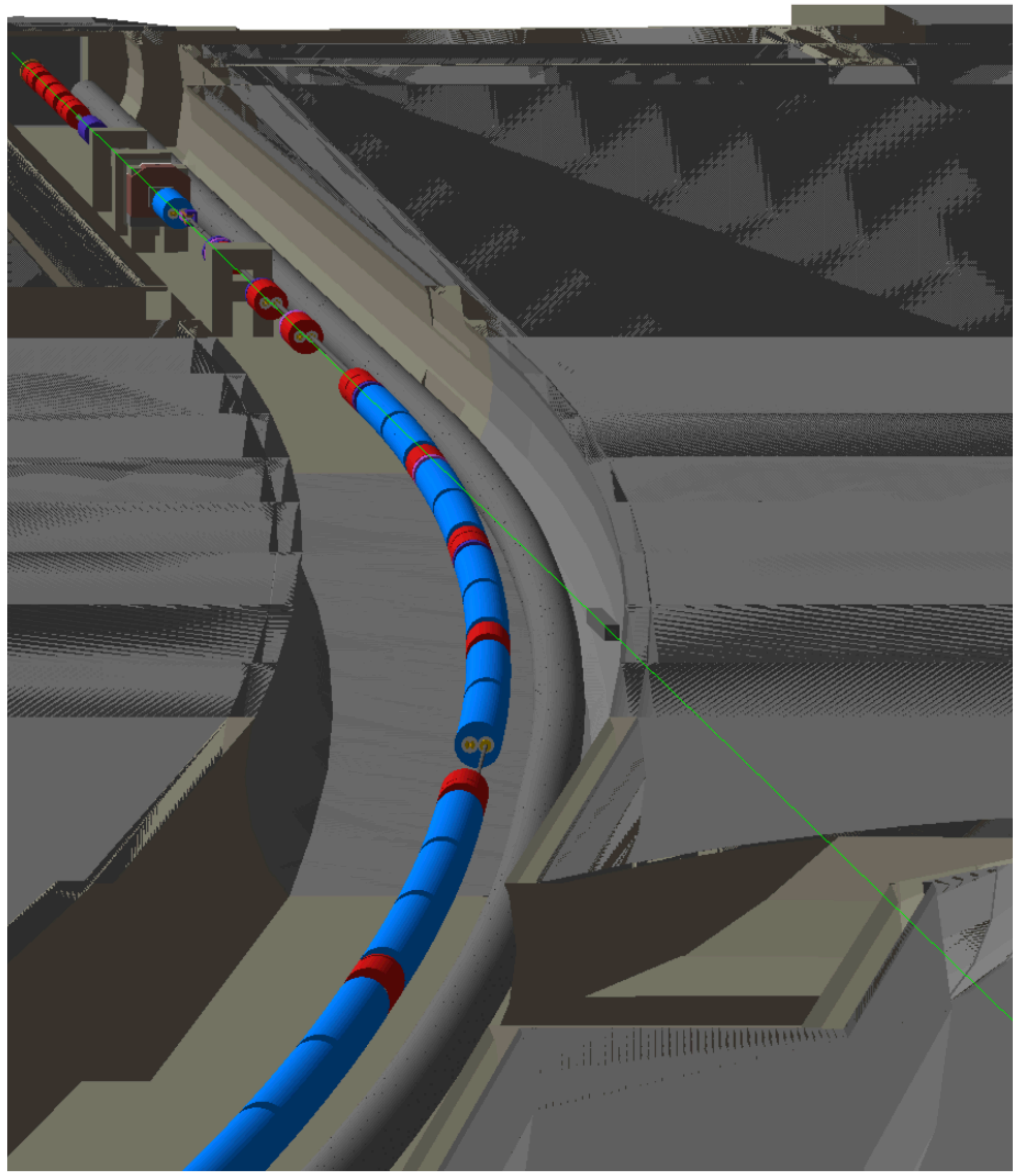

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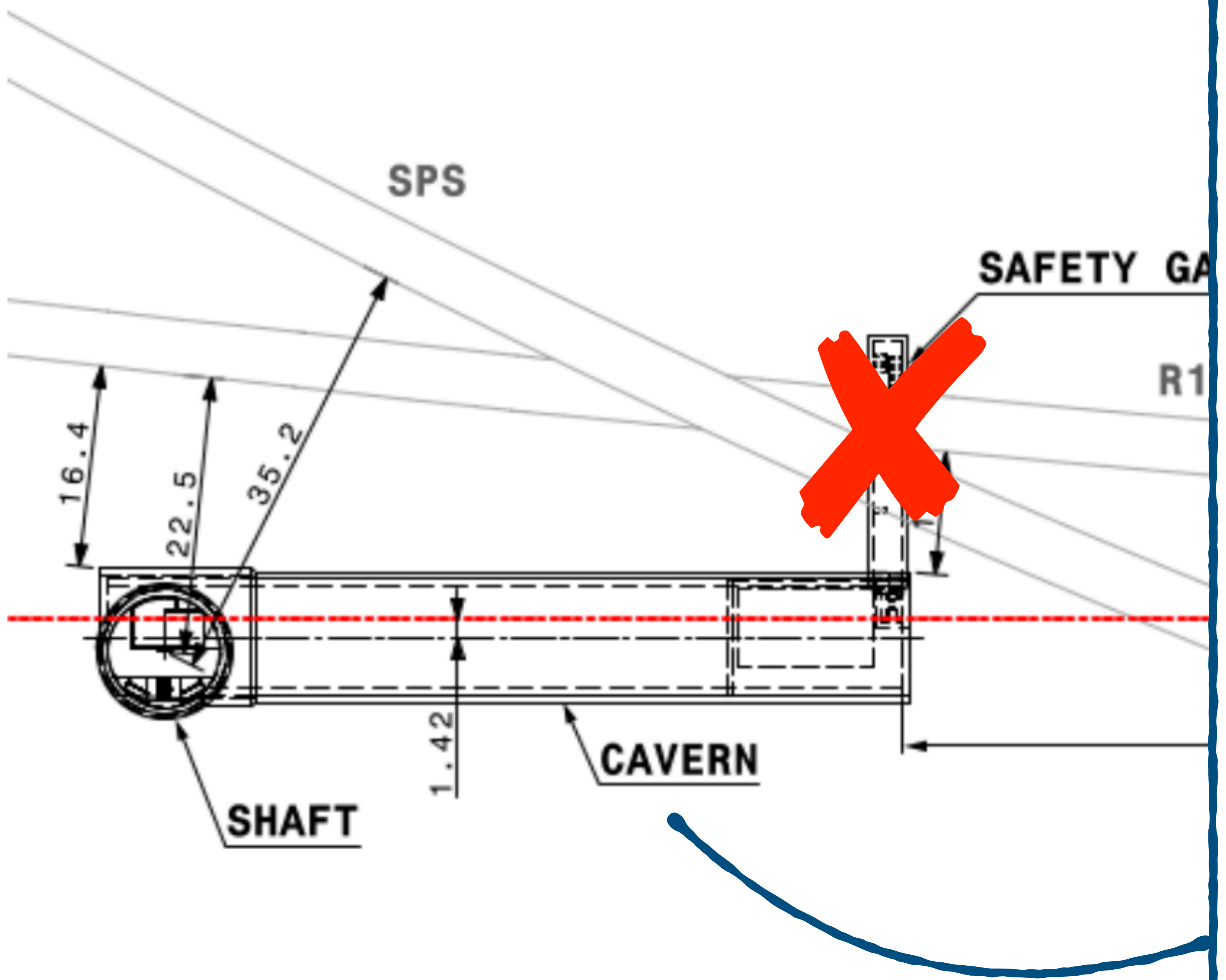

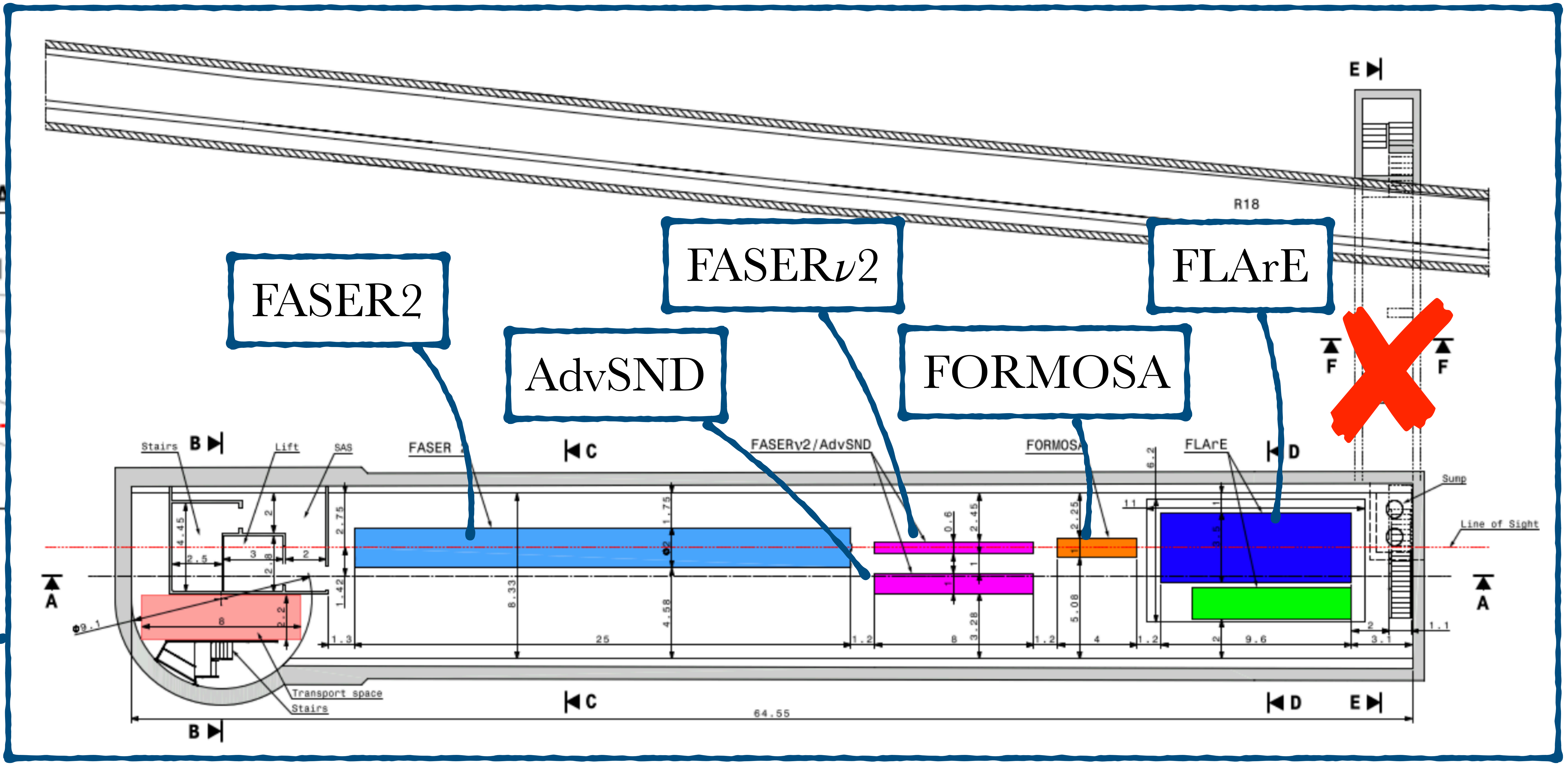

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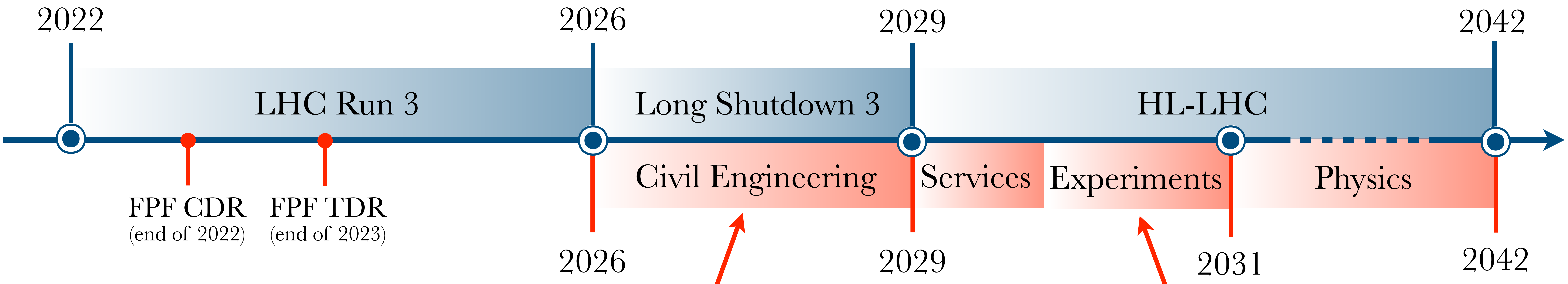

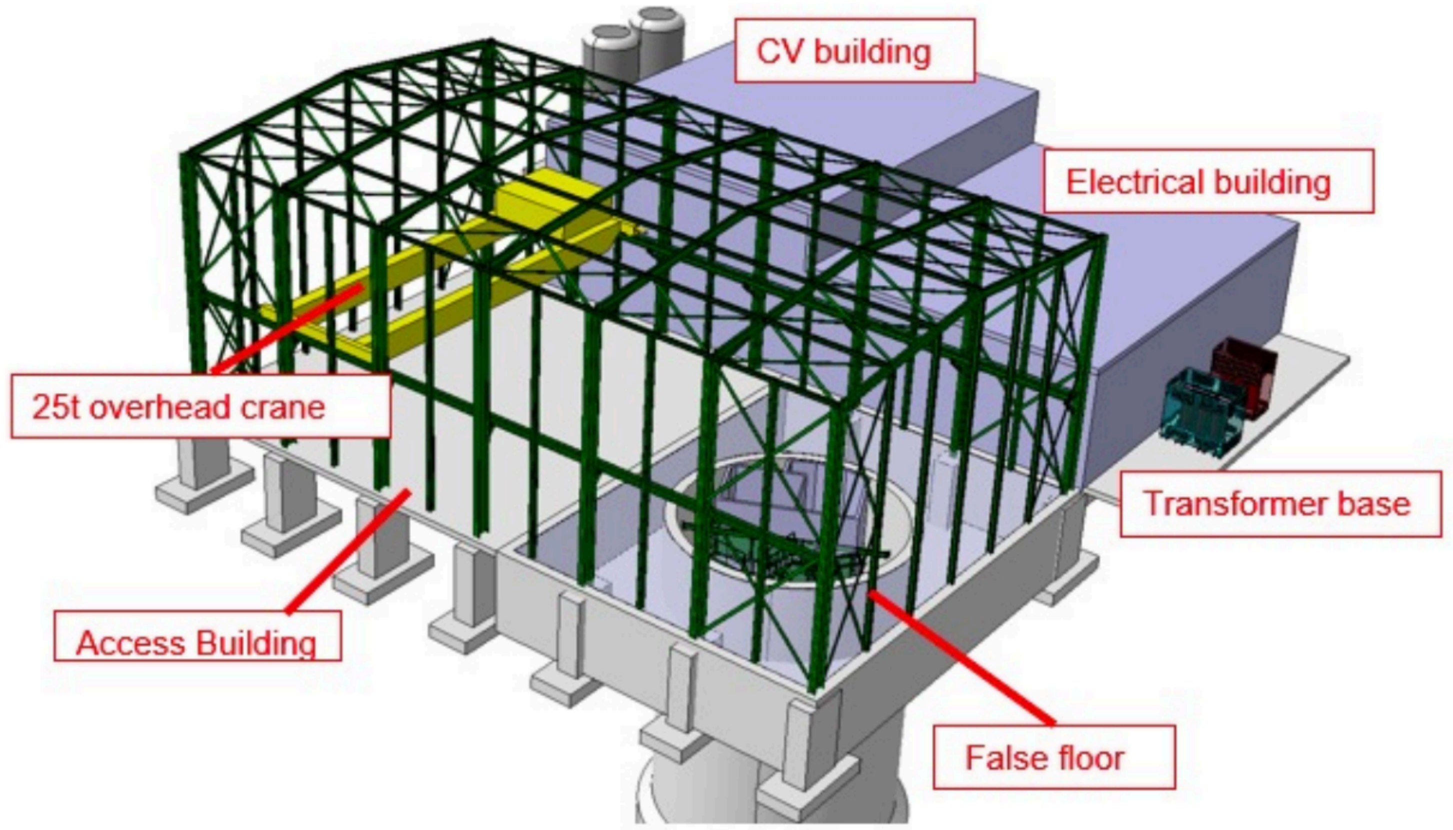

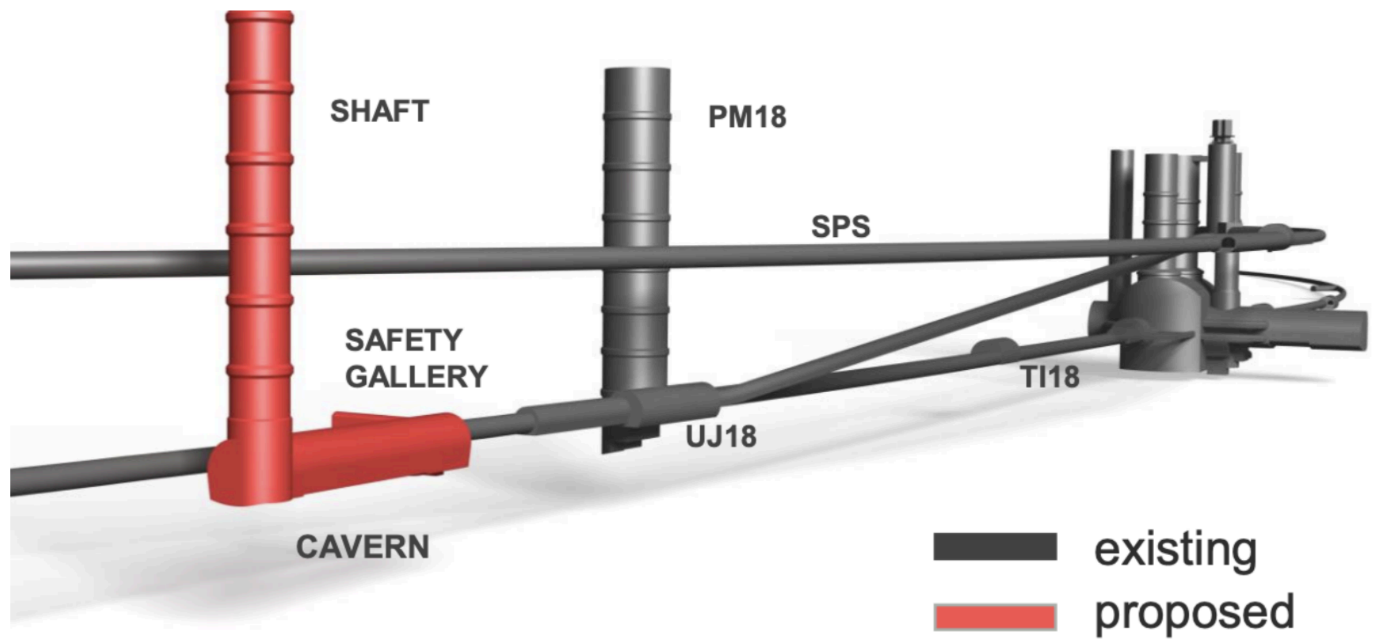

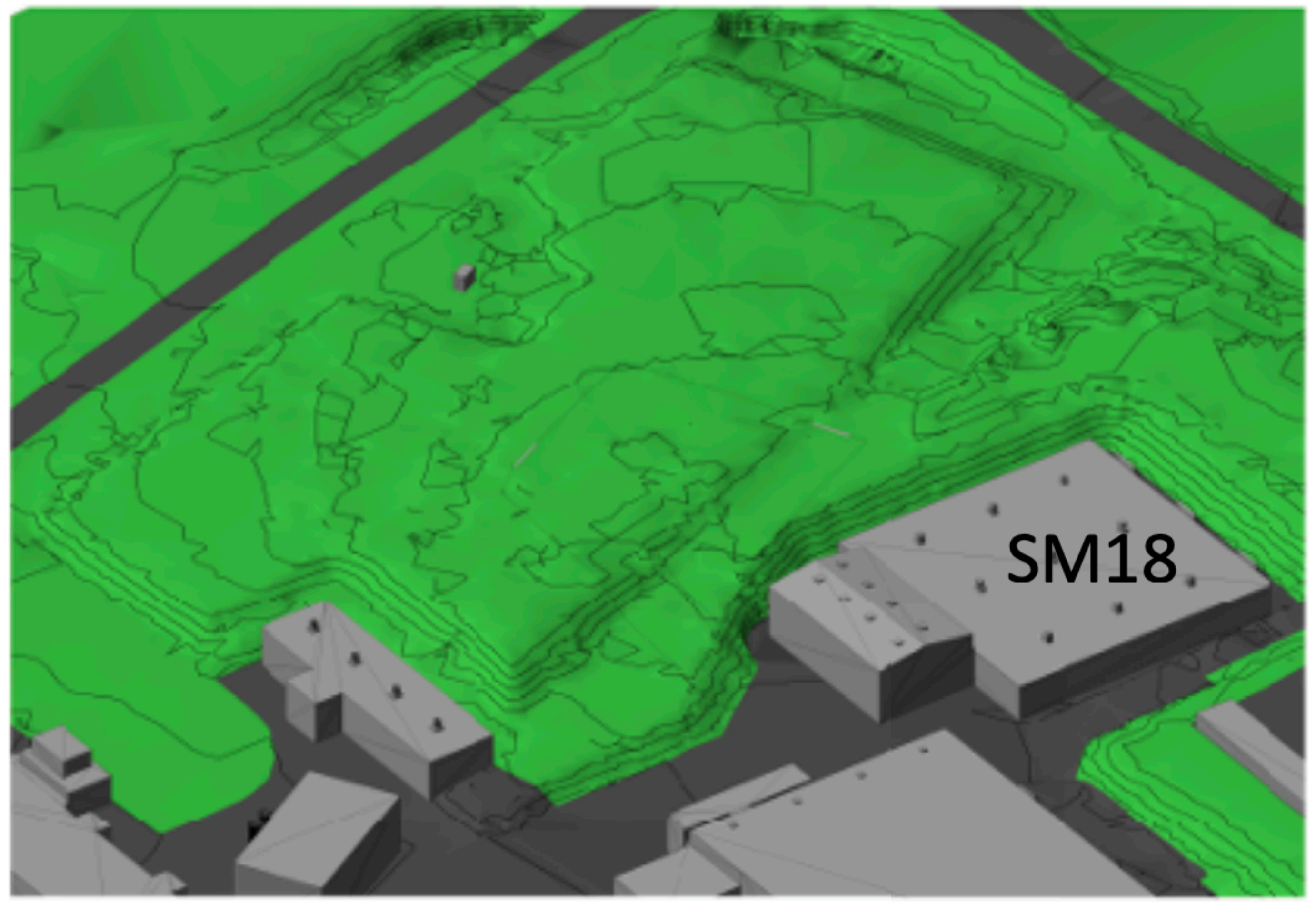

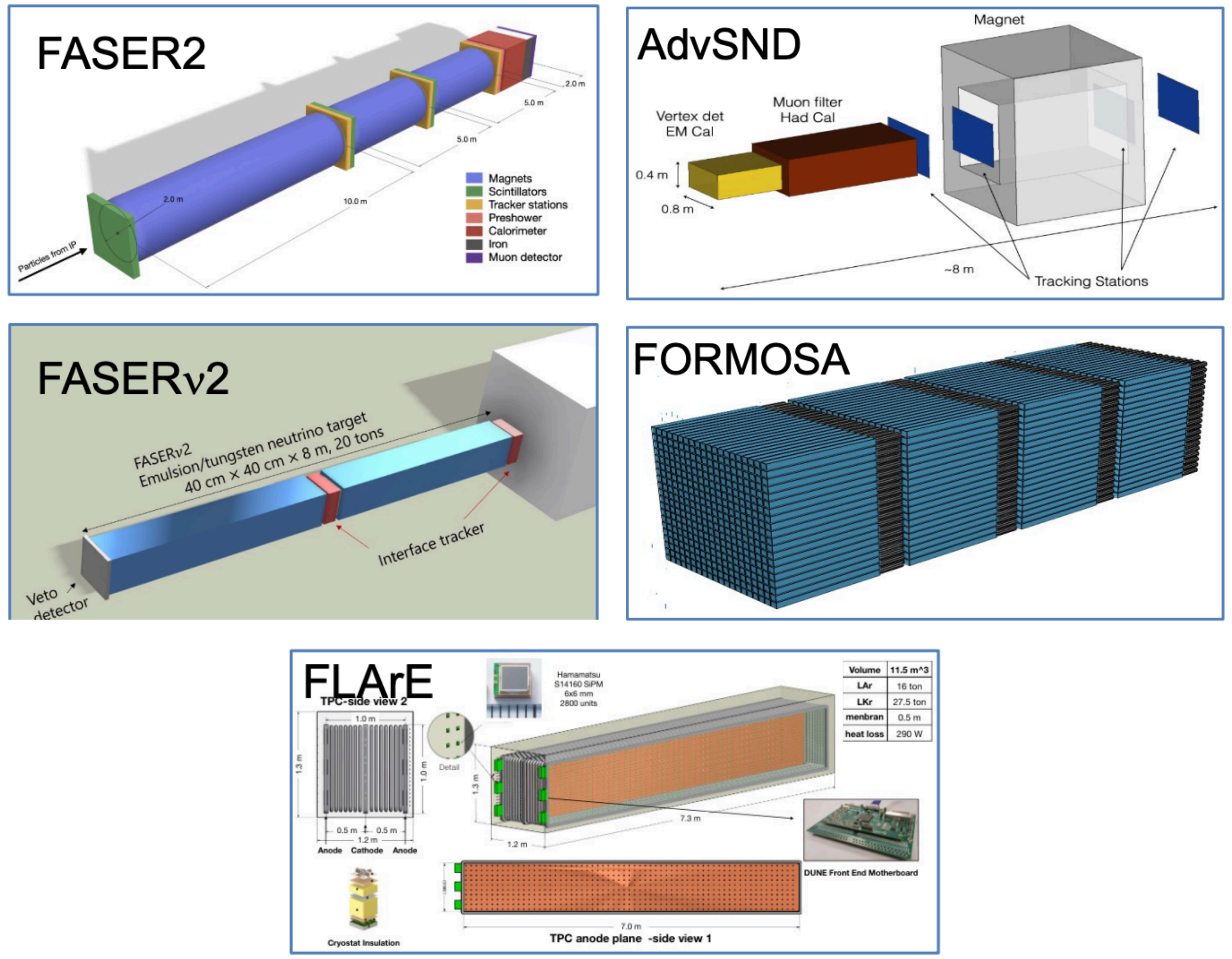

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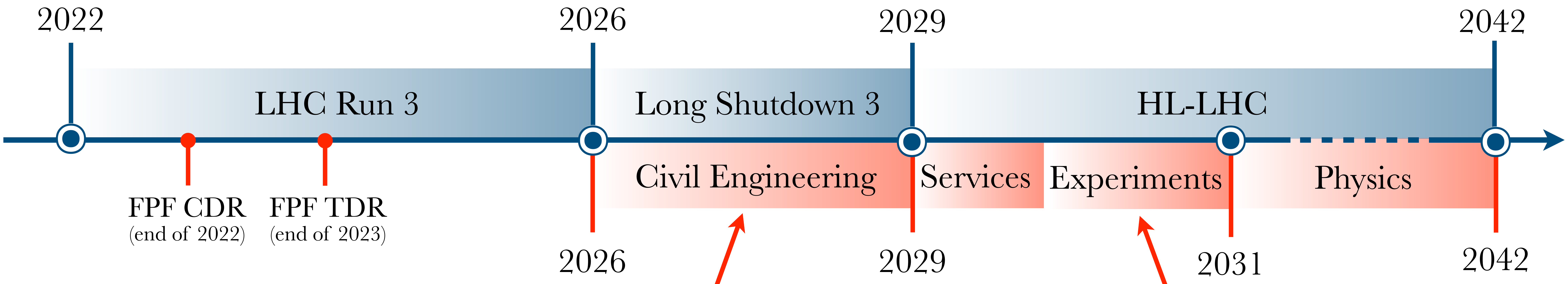
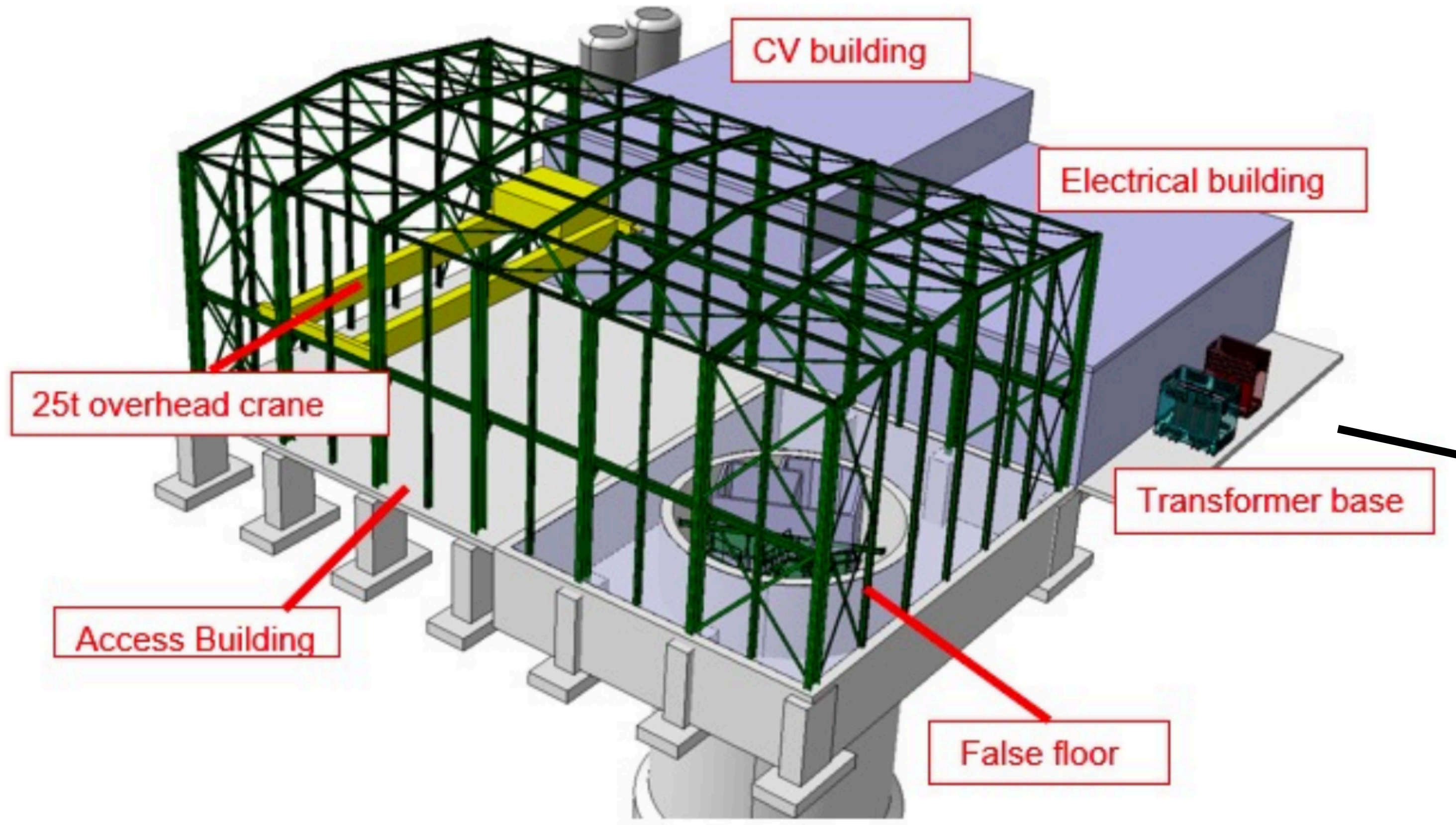
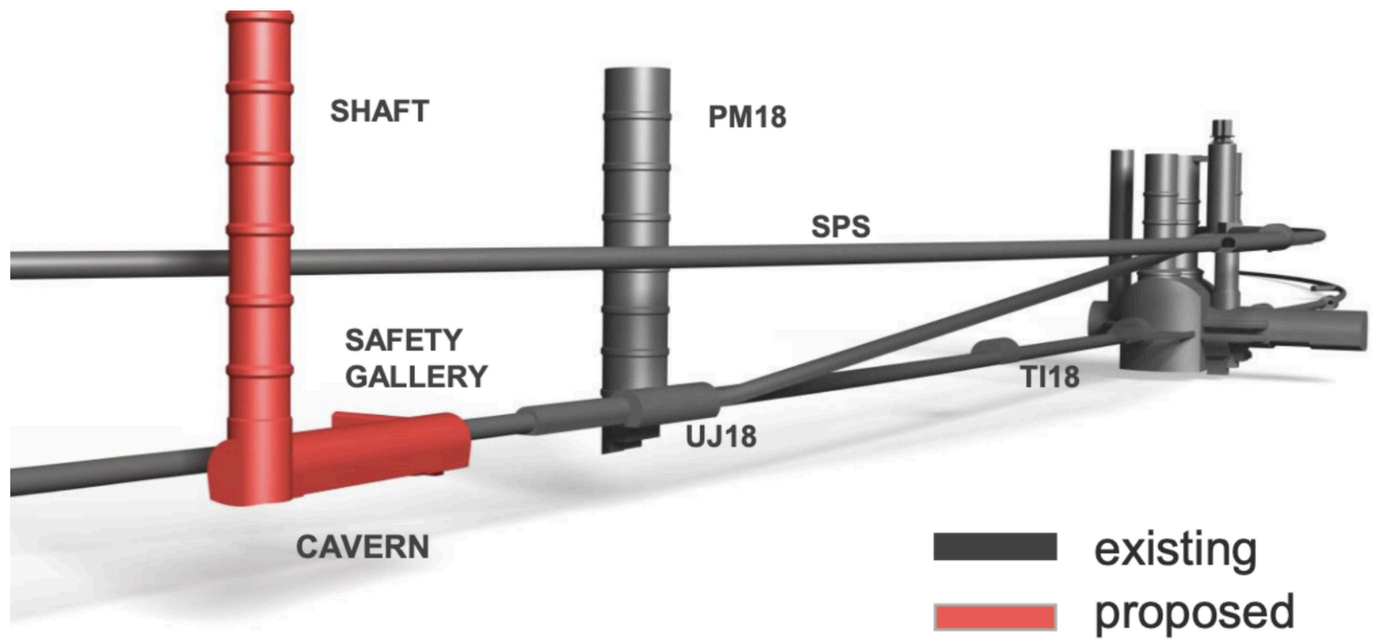
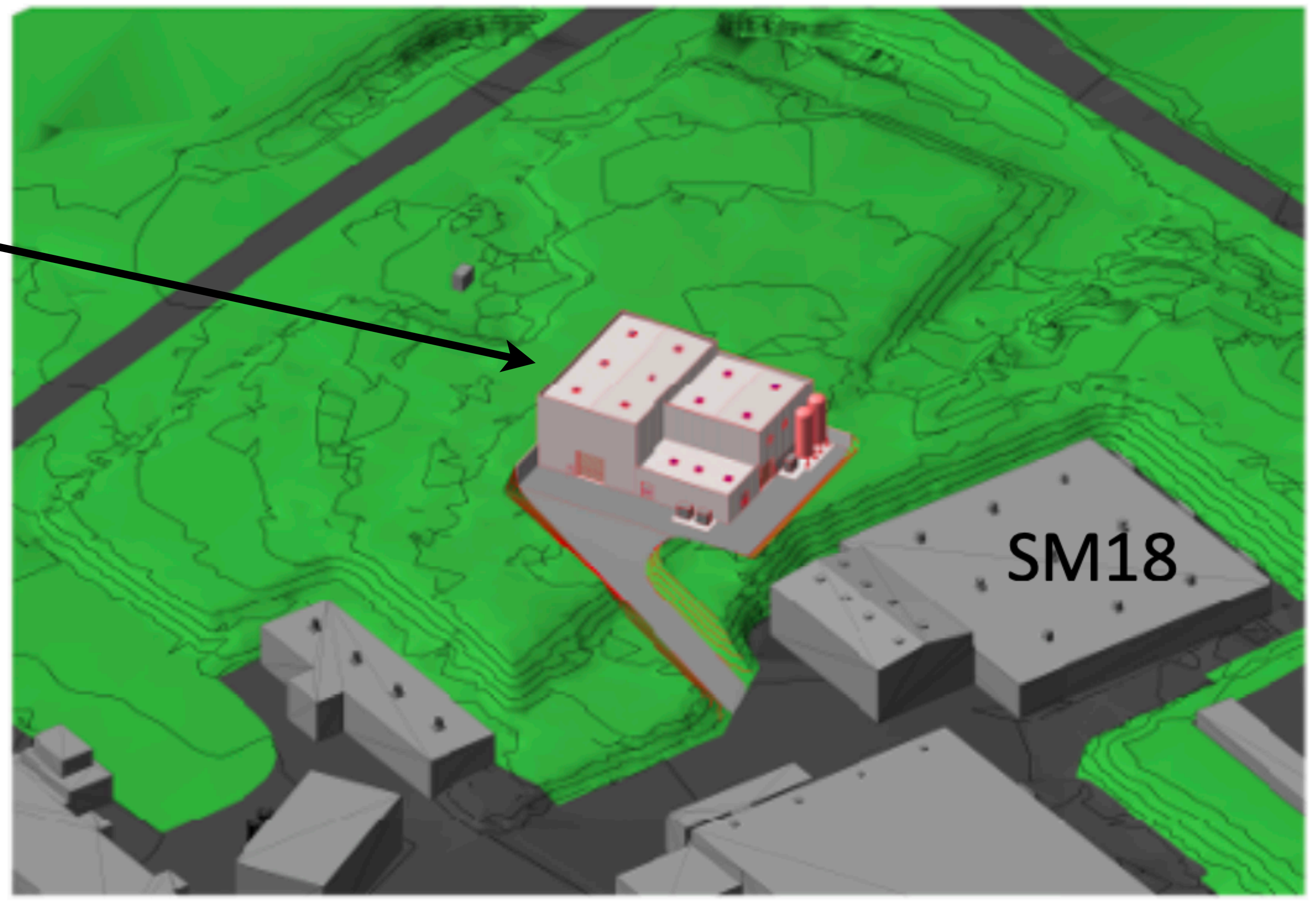
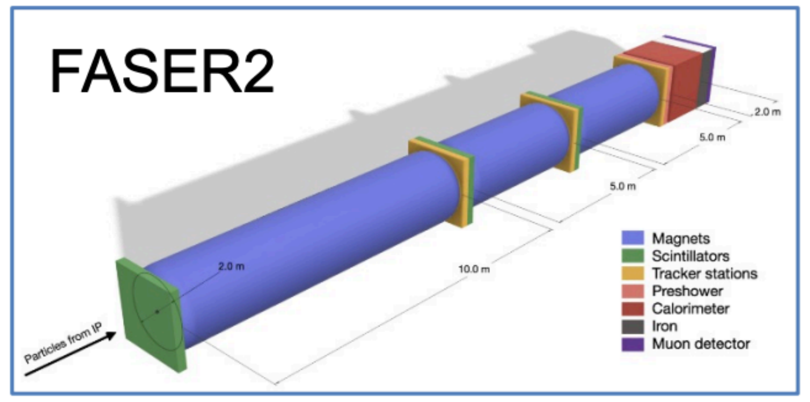
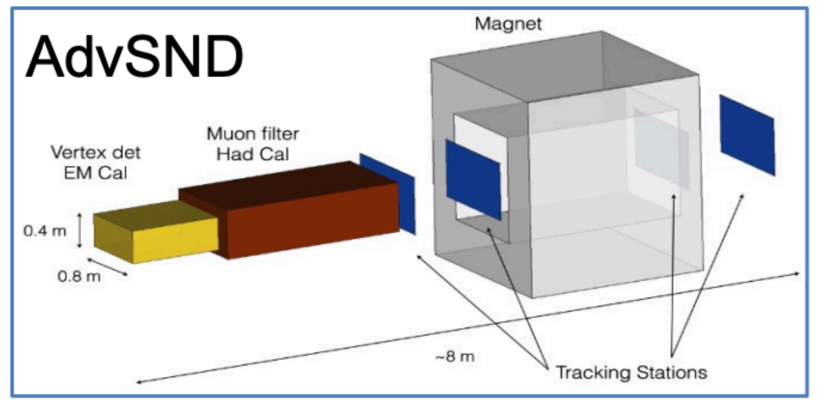


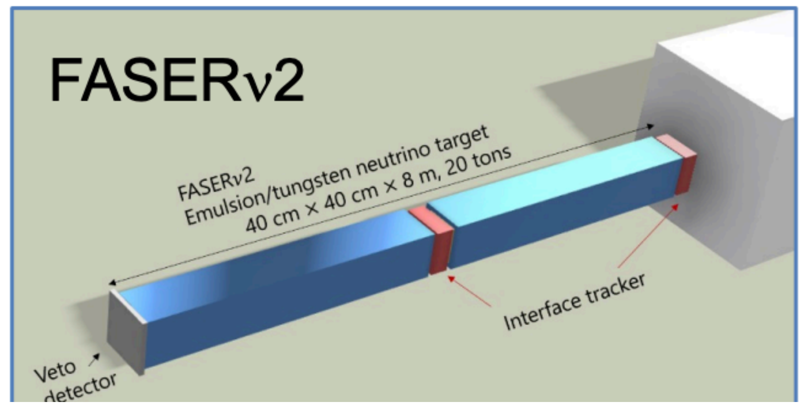


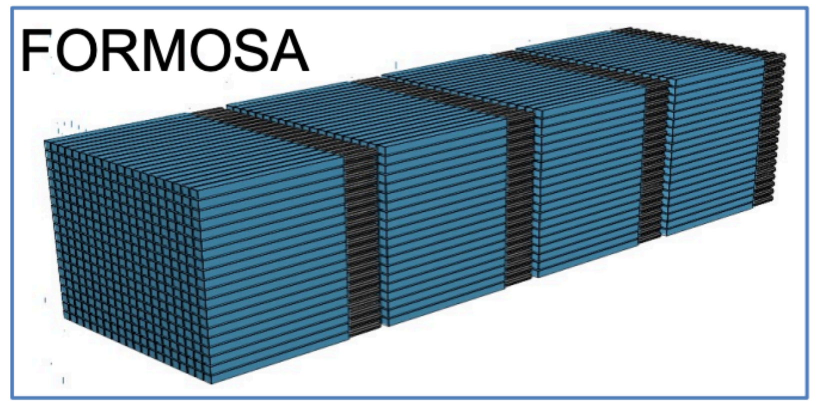


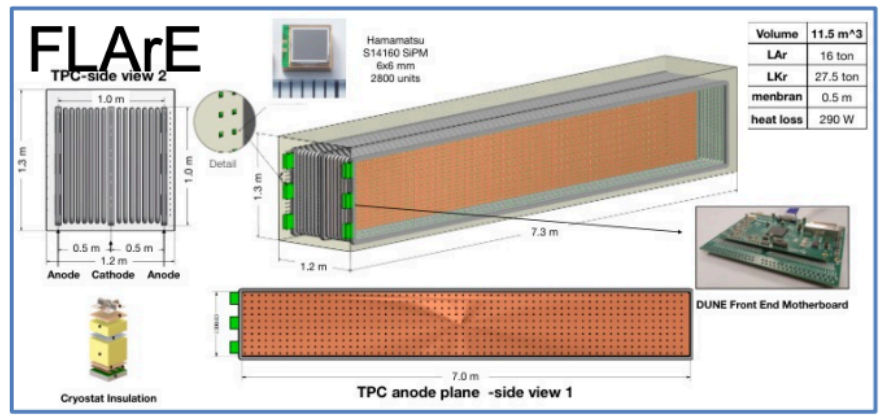












Proposed Experiments

Introduction: FPF Physics Potential

- Example:

FASERν pilot detector vs. All previous collider experiments

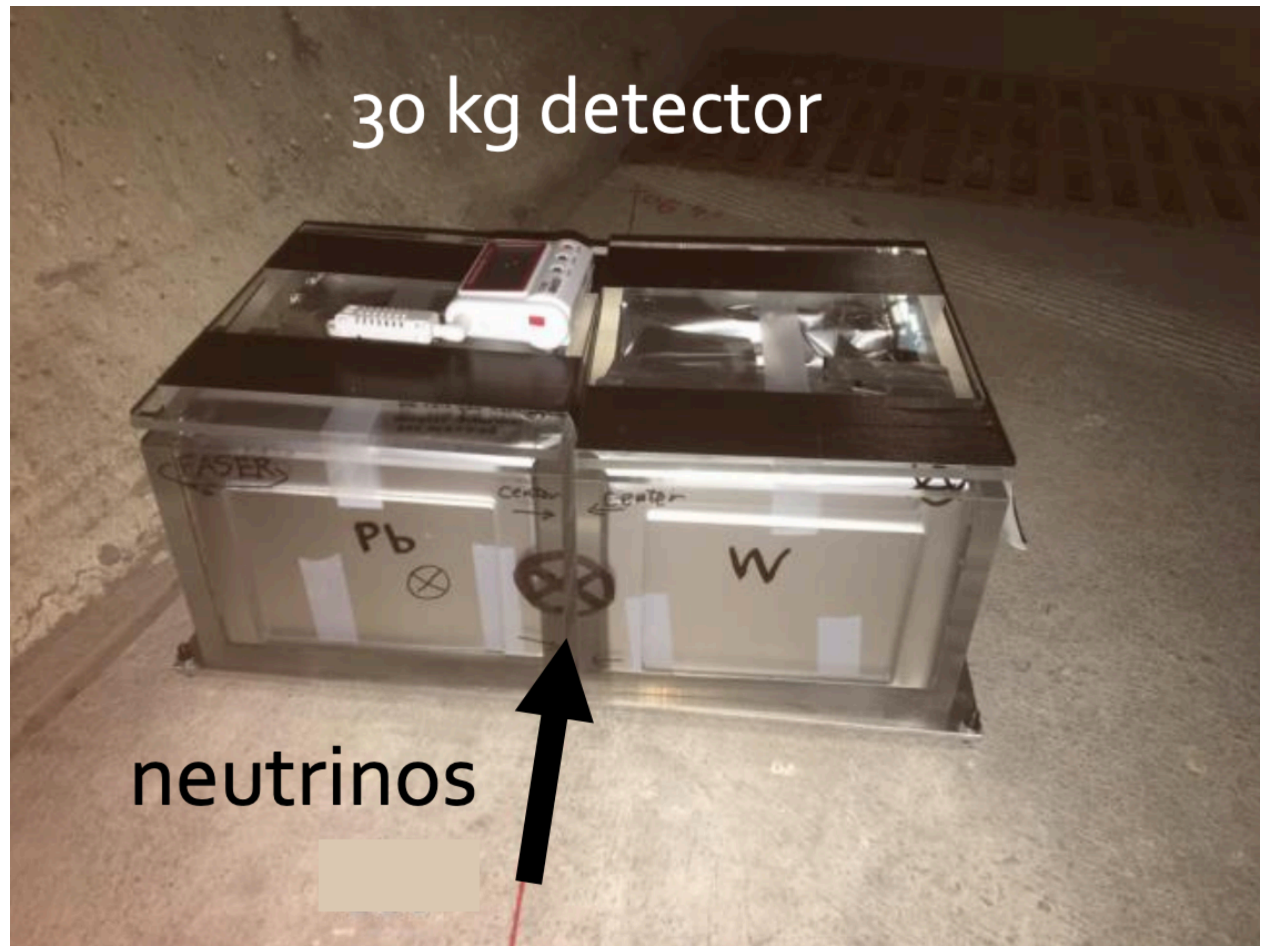
FASERν pilot detector:

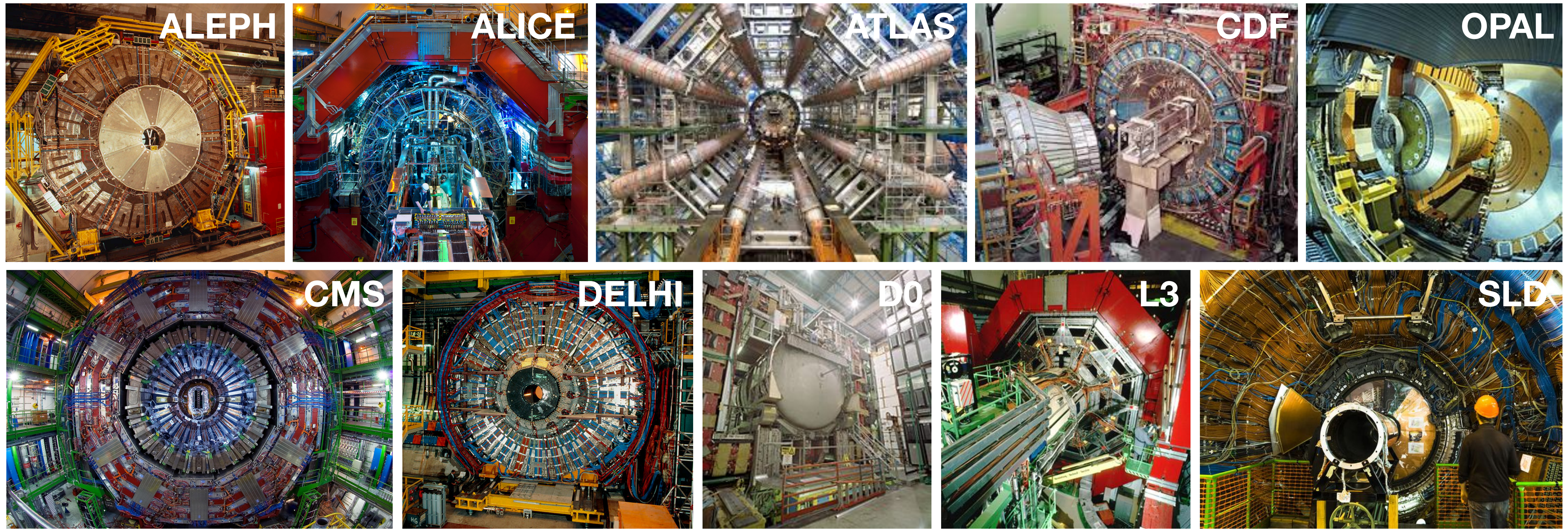
- Suitcase size, 4 weeks of data
- Costs: \$0 (recycled parts)
- 6 neutrino candidates

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

All previous collider experiments:

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





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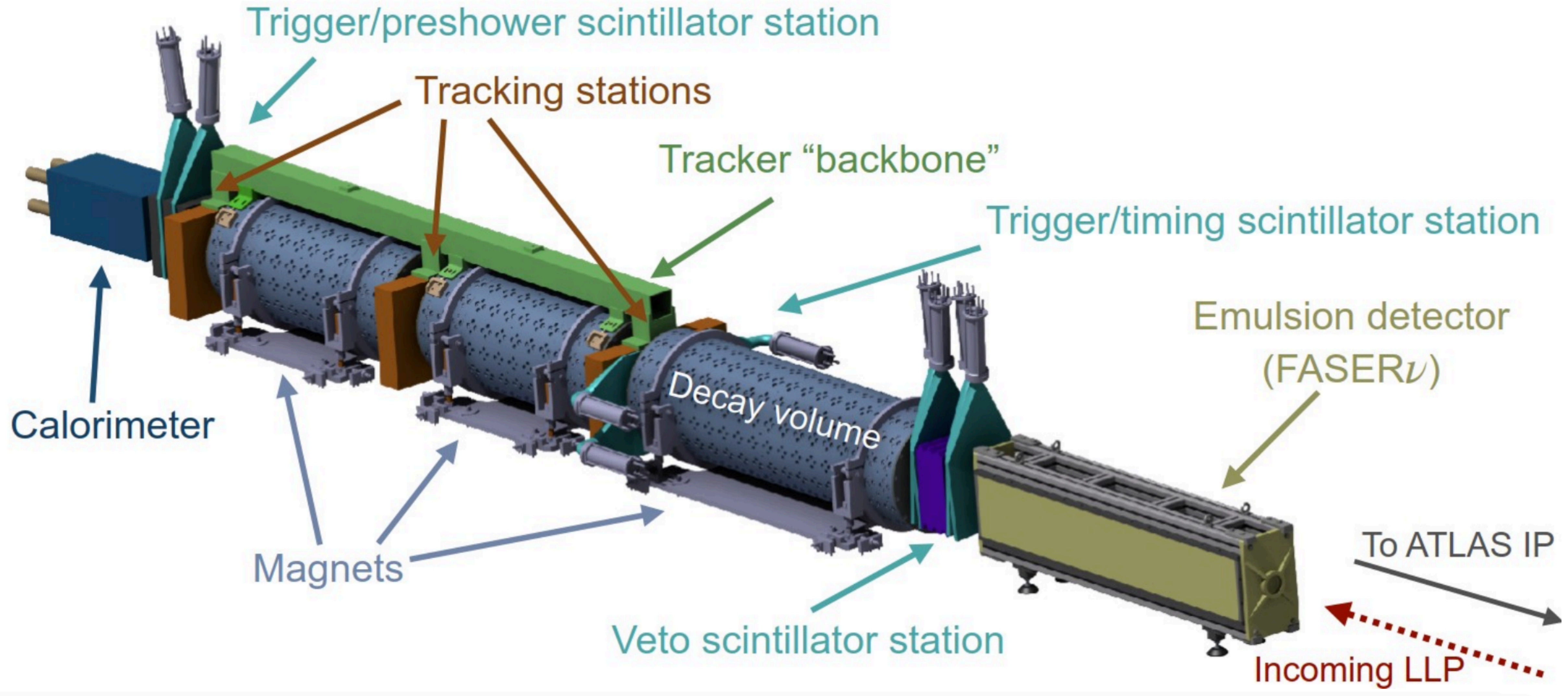
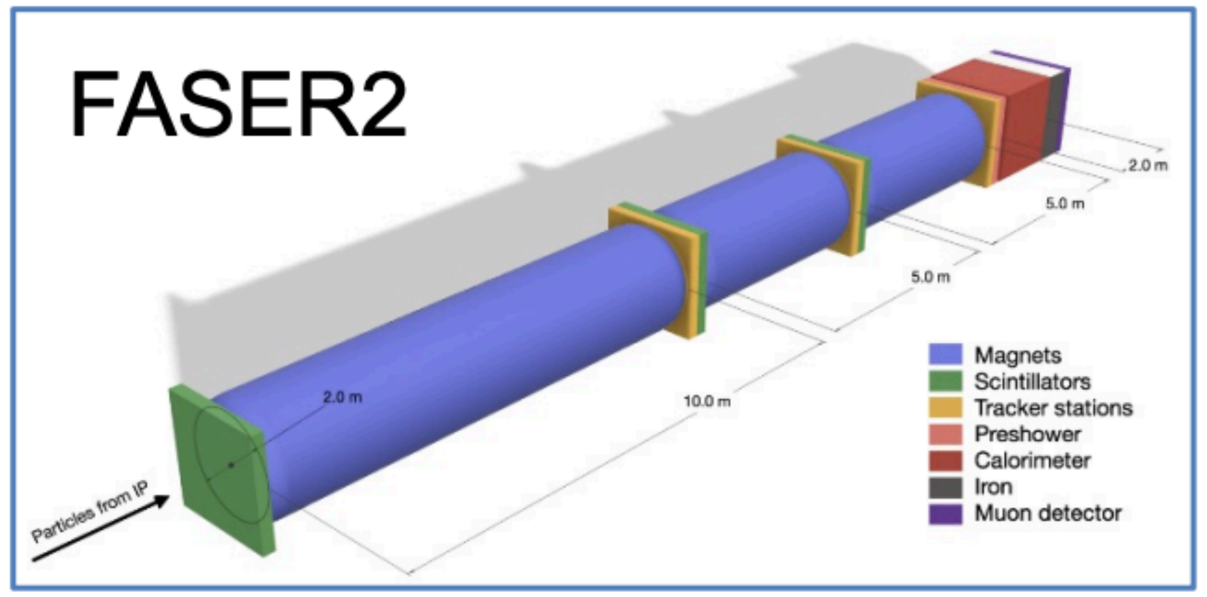
- FASERν years 2022-2024:
  - ~ 10000 ν candidates expected (~ 10^9 muons*)
- Forward Physics Facility:
  - ~ 10^6 ν candidates expected! (~ 10^{12} muons*)

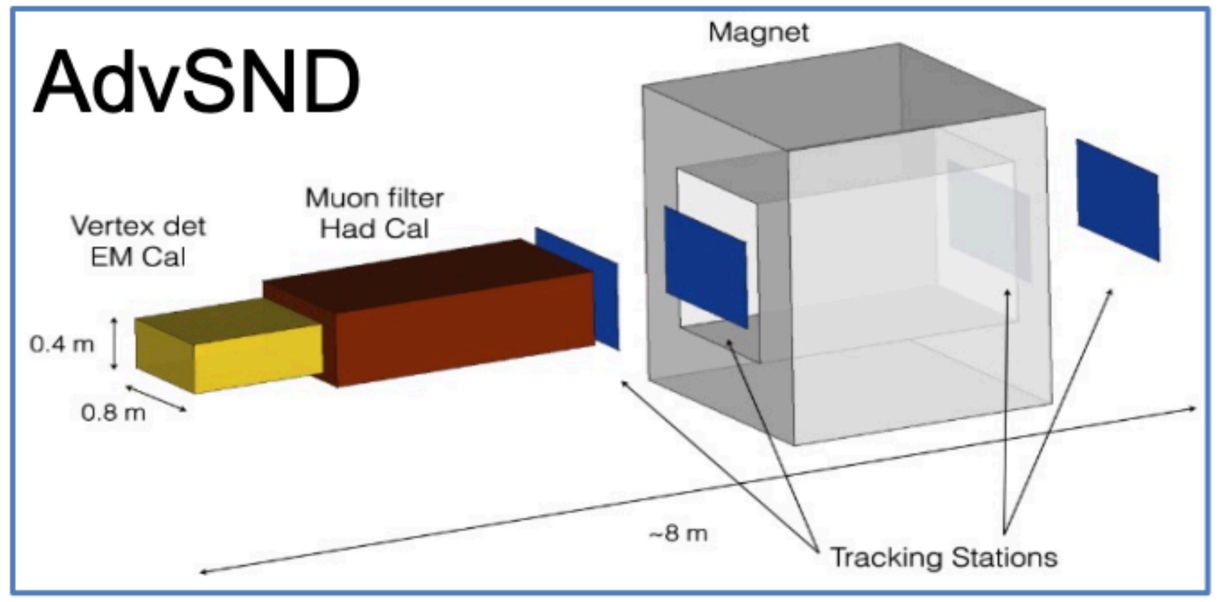


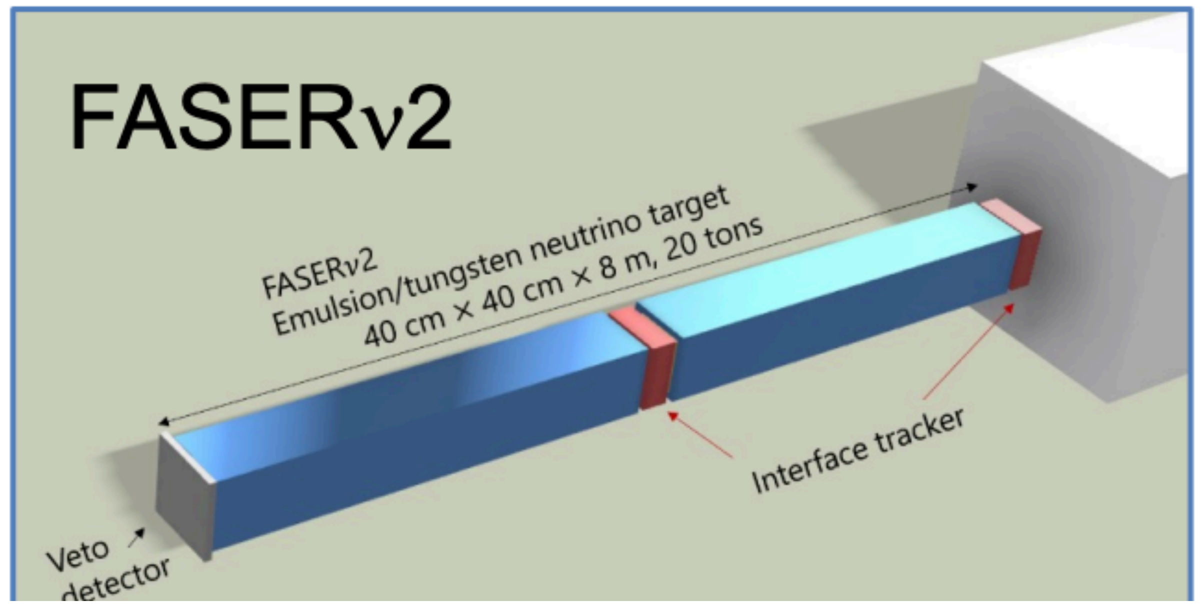
*origin not well understood, further studies needed

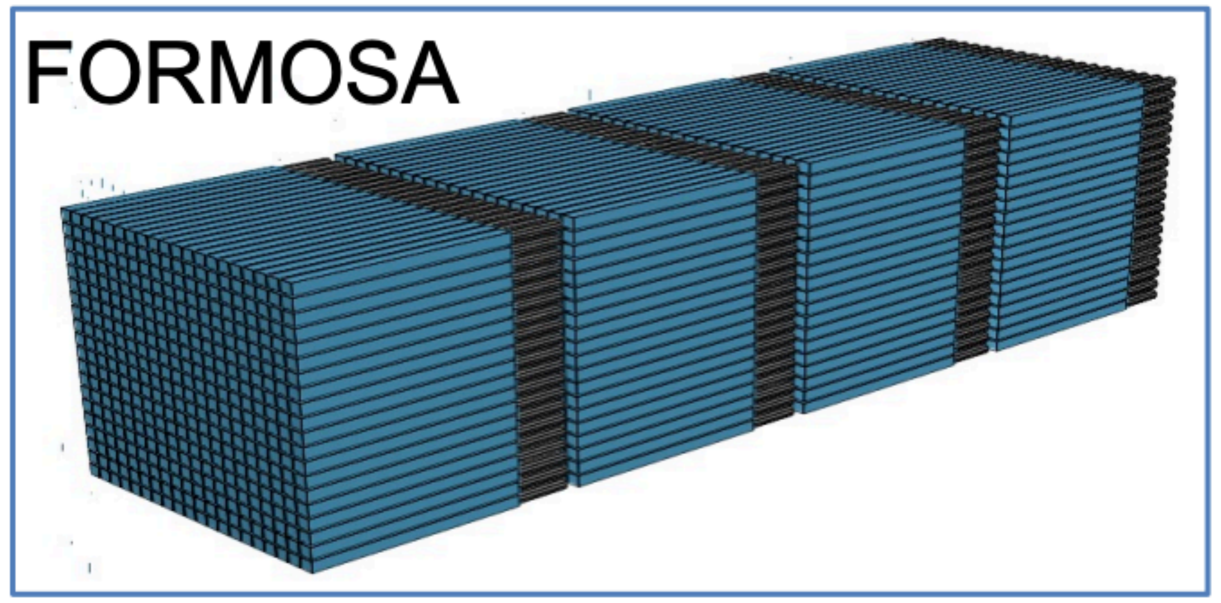
Proposed FPF Experiments

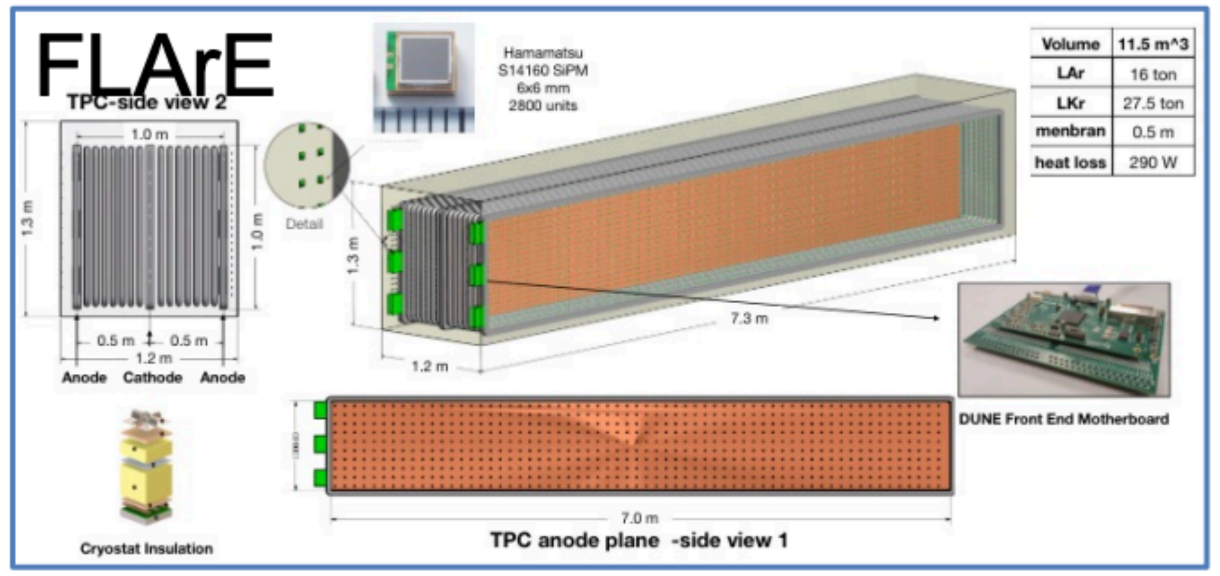
- <u>Currently 5 proposed experiments* with different (main) physics goals:</u>
  - FASER2
    - Long-lived particles (LLPs)
  - FASERν2
    - TeV neutrinos
  - AdvSND
    - TeV neutrinos
  - FORMOSA
    - BSM physics: millicharged particles
  - FLArE
    - TeV neutrinos & light dark matter









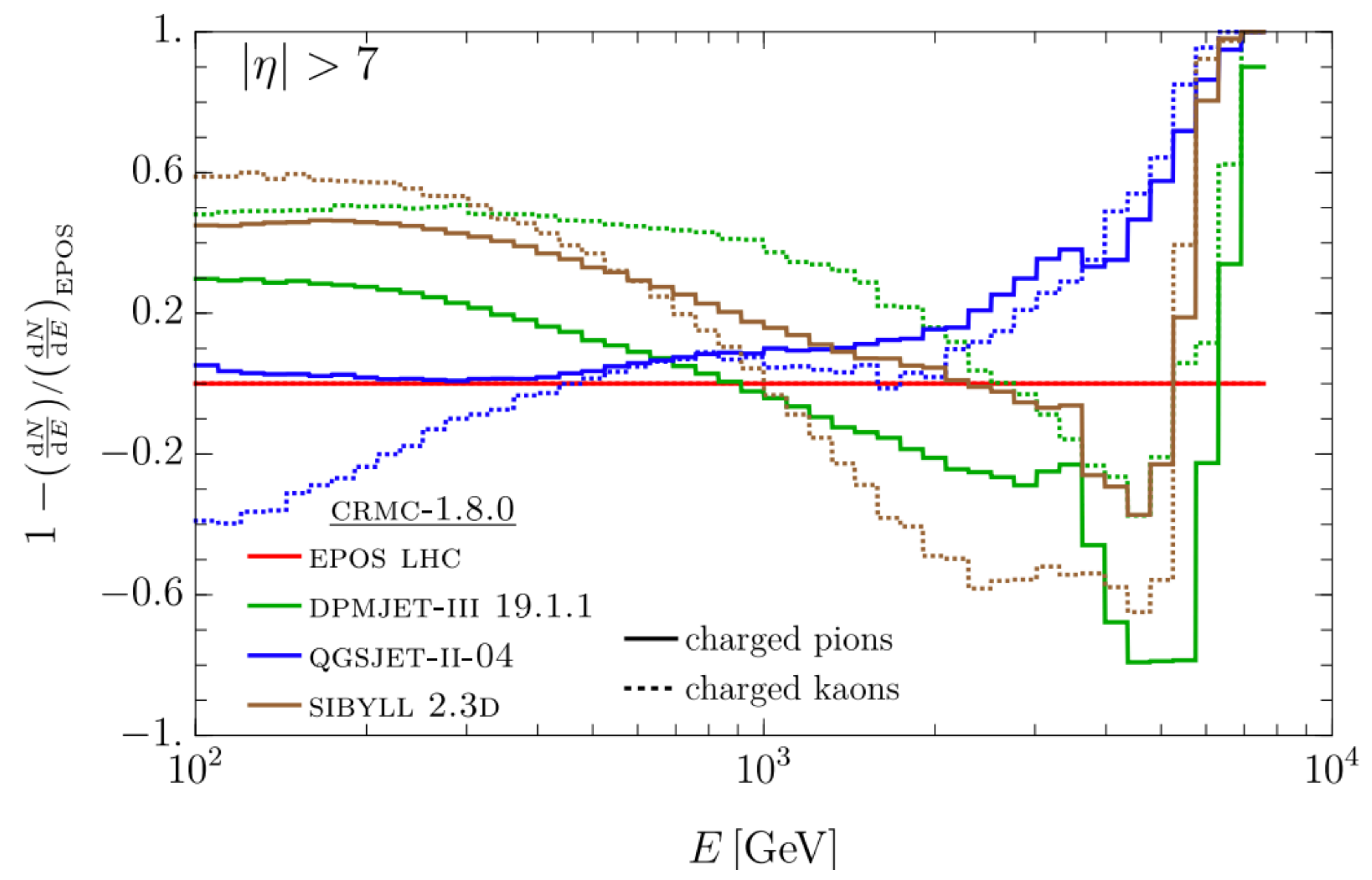


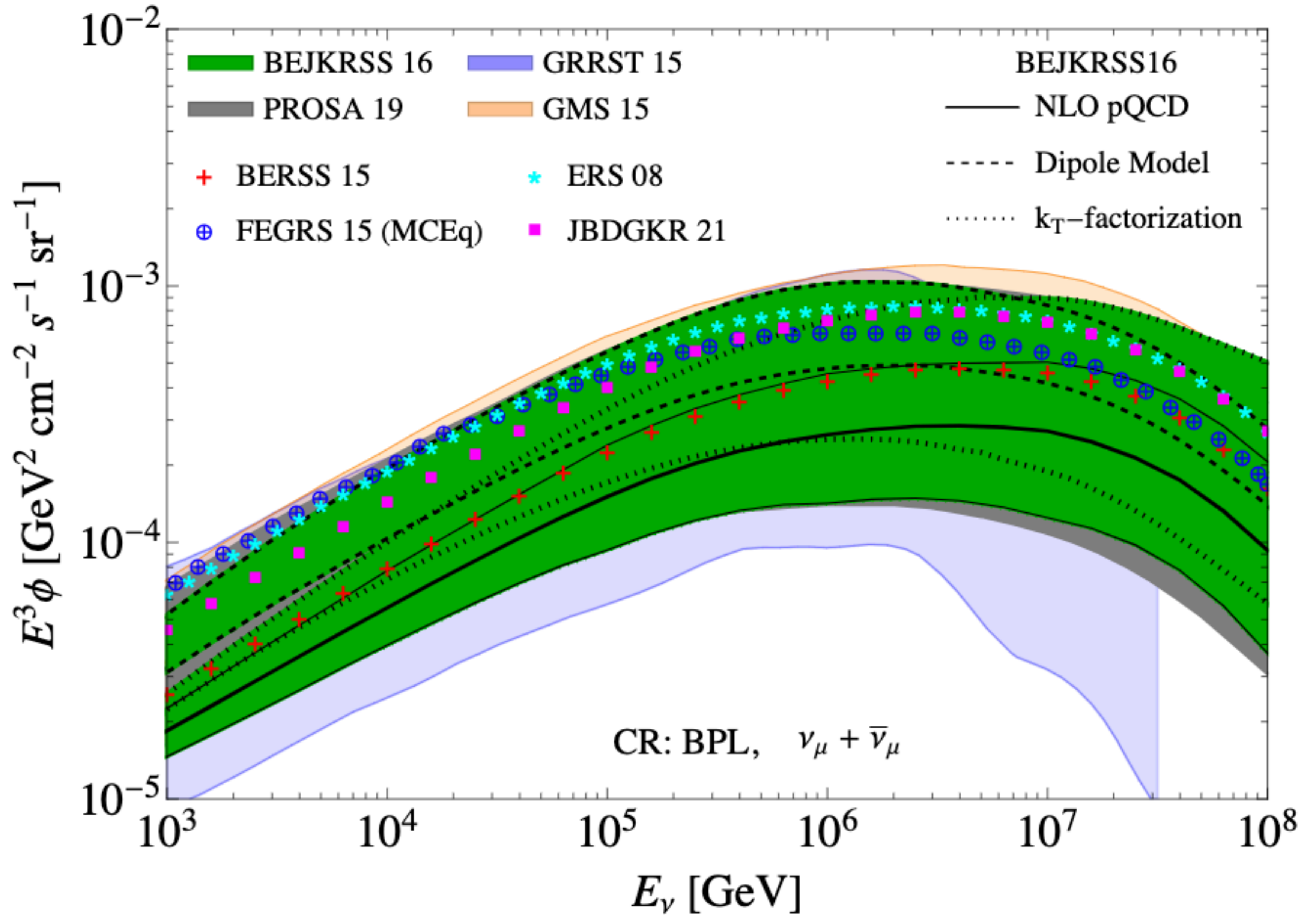
* for a complete description of the experiments, please see FPF white paper

Astroparticle Physics with the FPF

Overview: Astroparticle Physics at the FPF

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

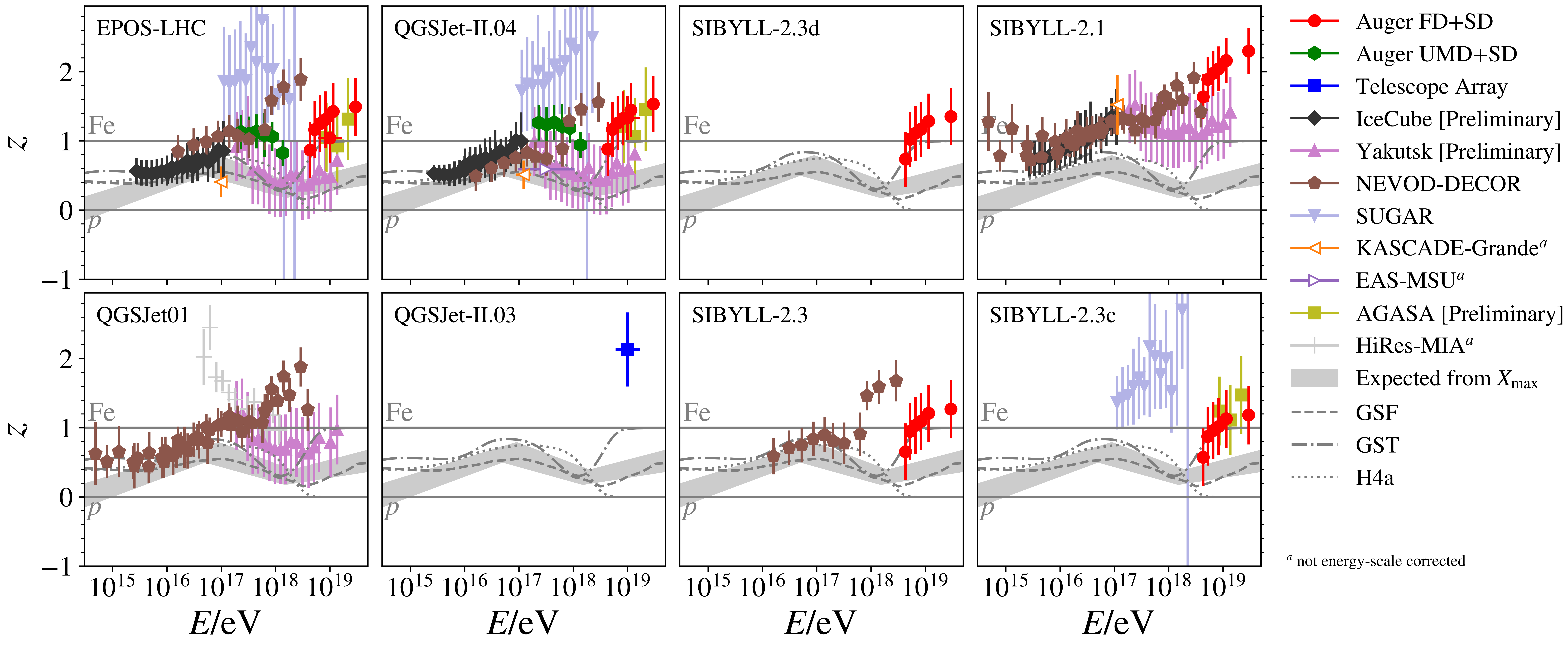




The Muon Puzzle in EAS

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

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



DS et al. (WHISP), PoS(ICRC2021)349 (2021), arXiv:2108.08341

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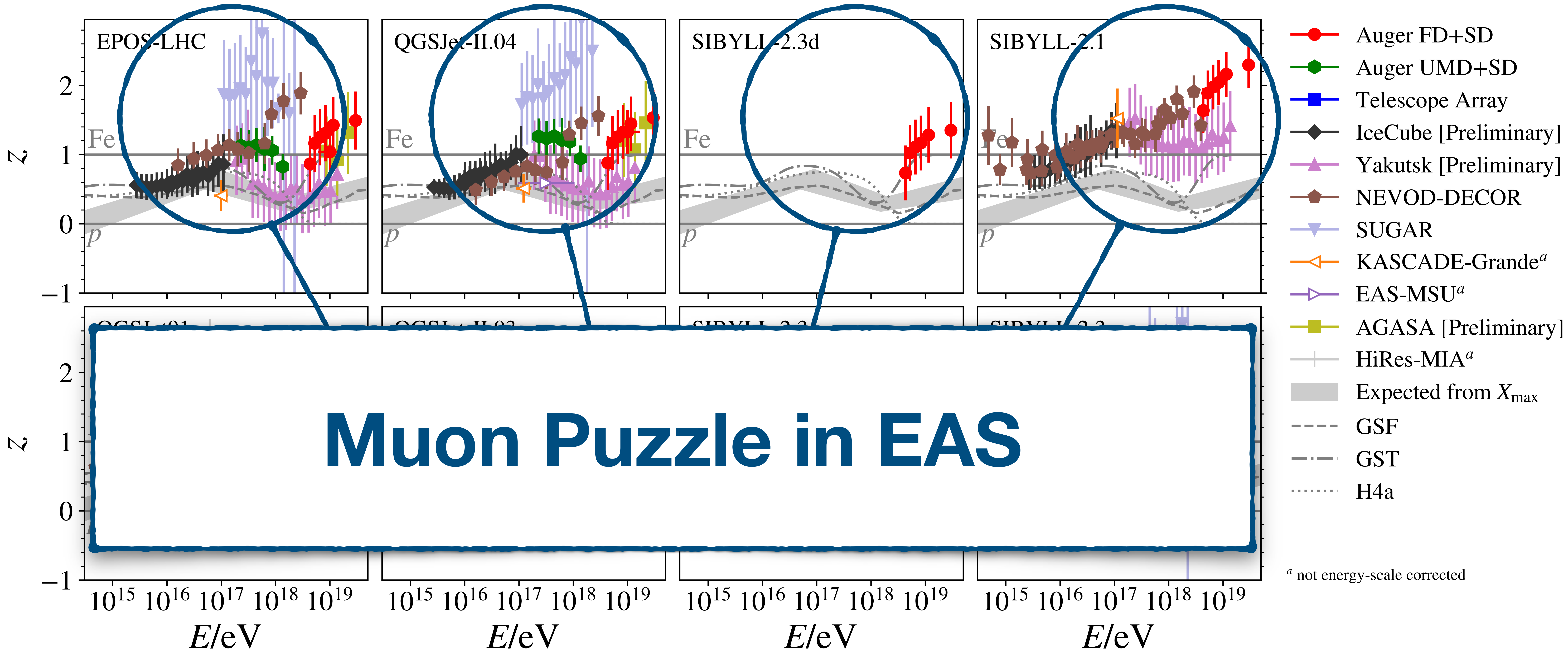
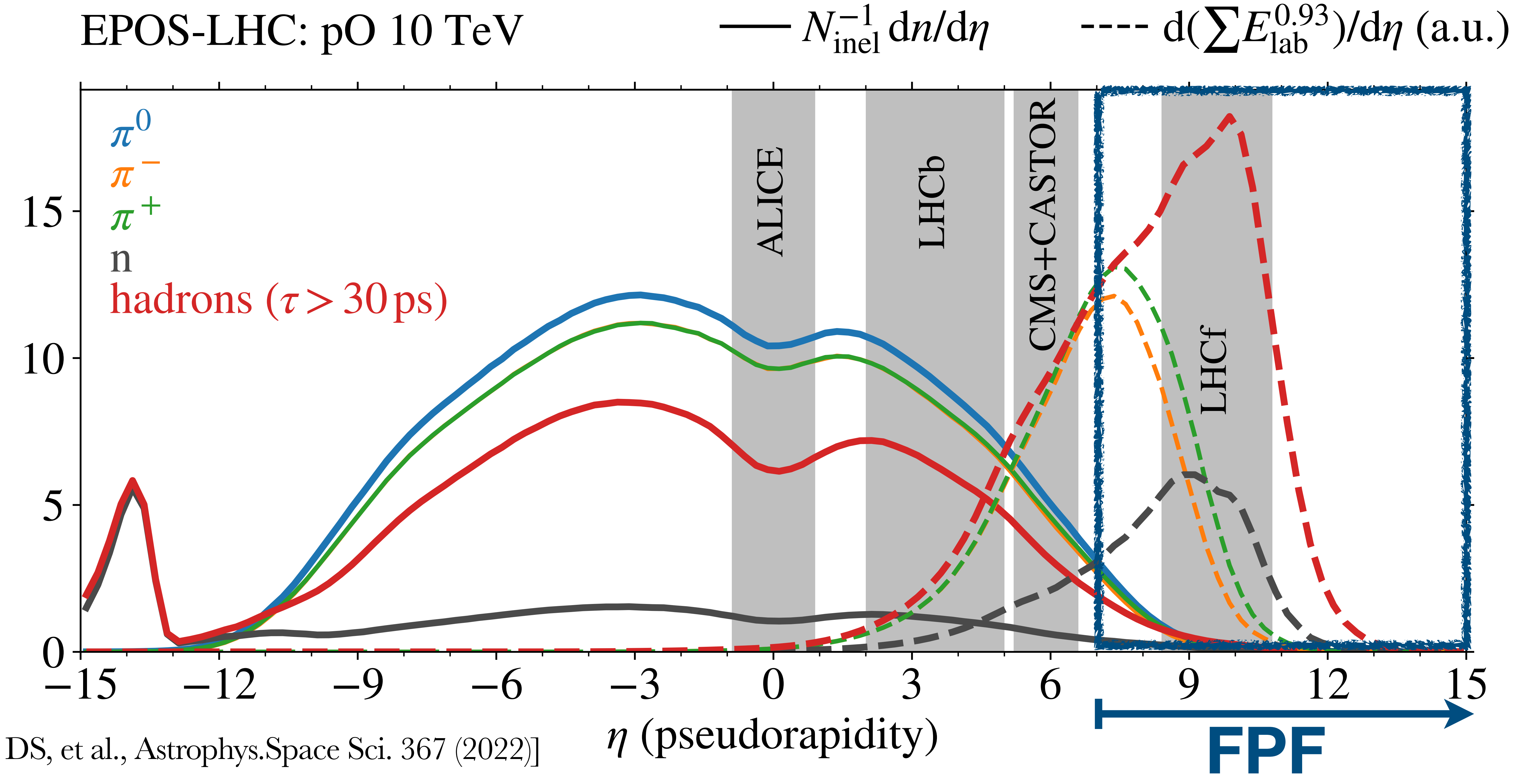


DS et al. (WHISP), PoS(ICRC2021)349 (2021), arXiv:2108.08341

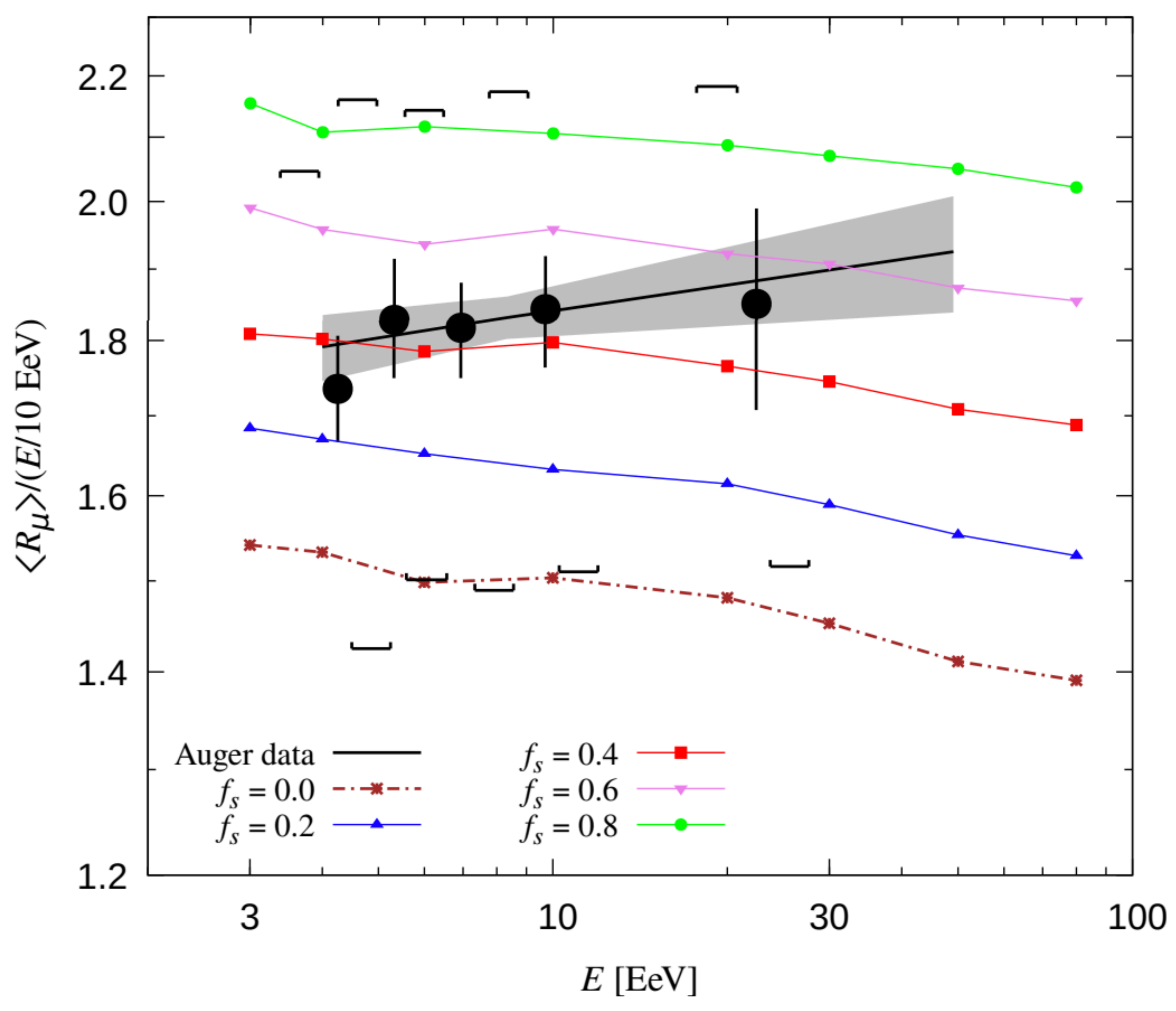
Modeling Cosmic Ray Air Showers

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



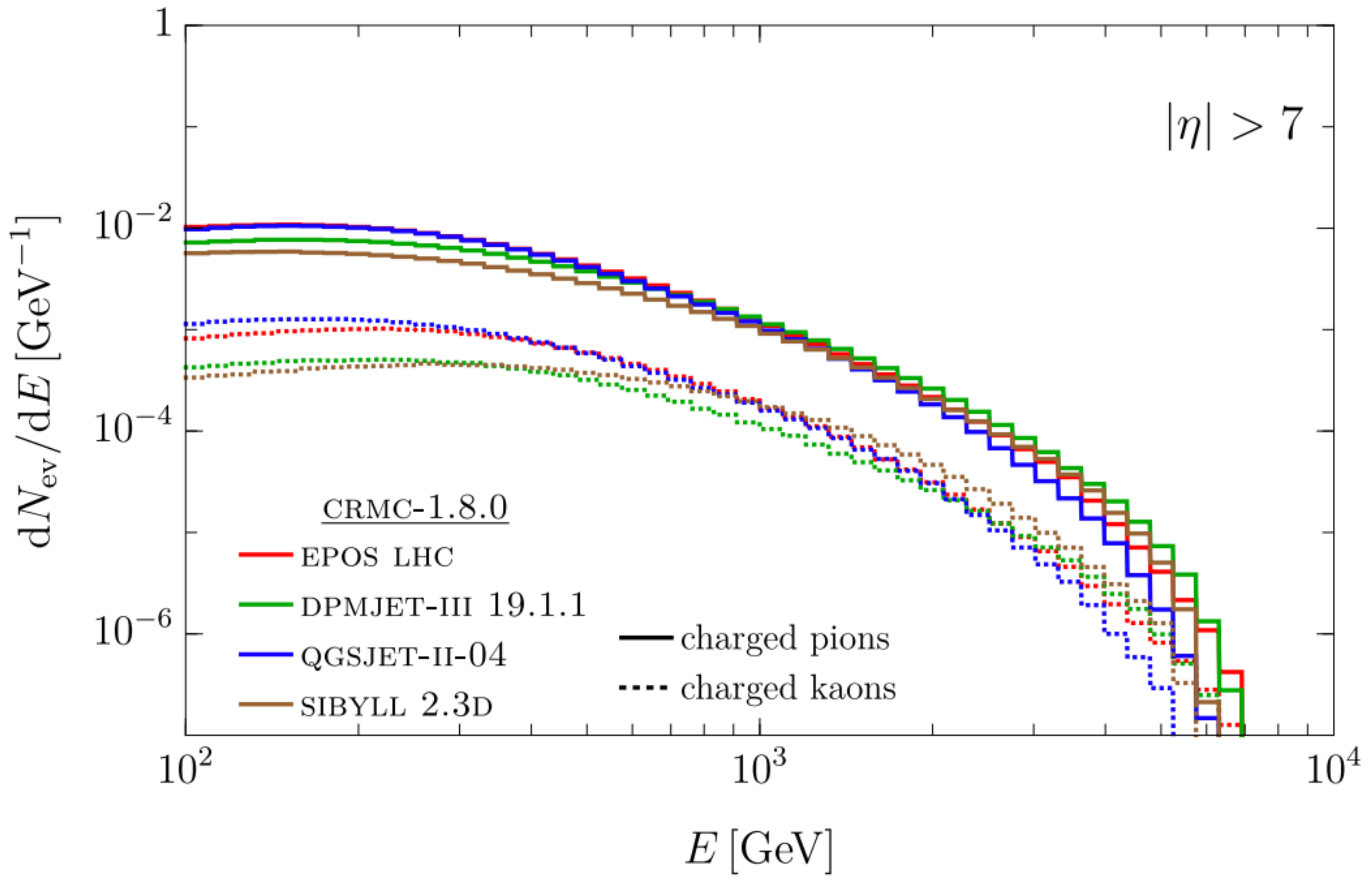
[J. Albrecht, DS, et al., Astrophys.Space Sci. 367 (2022)]

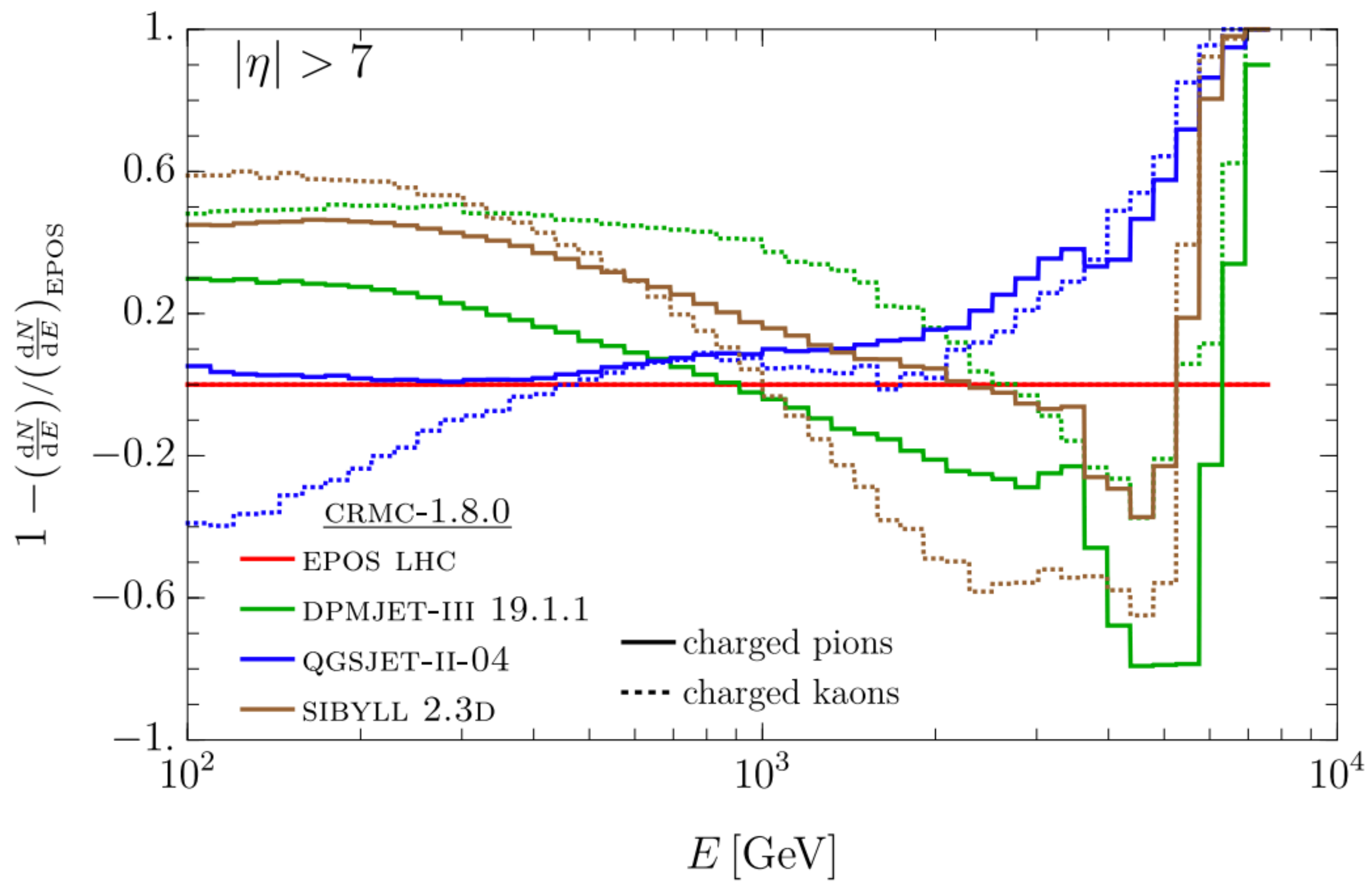
[L. A. Anchordoqui et al., arXiv:2202.03095 (2021)]



Modeling Cosmic Ray Air Showers

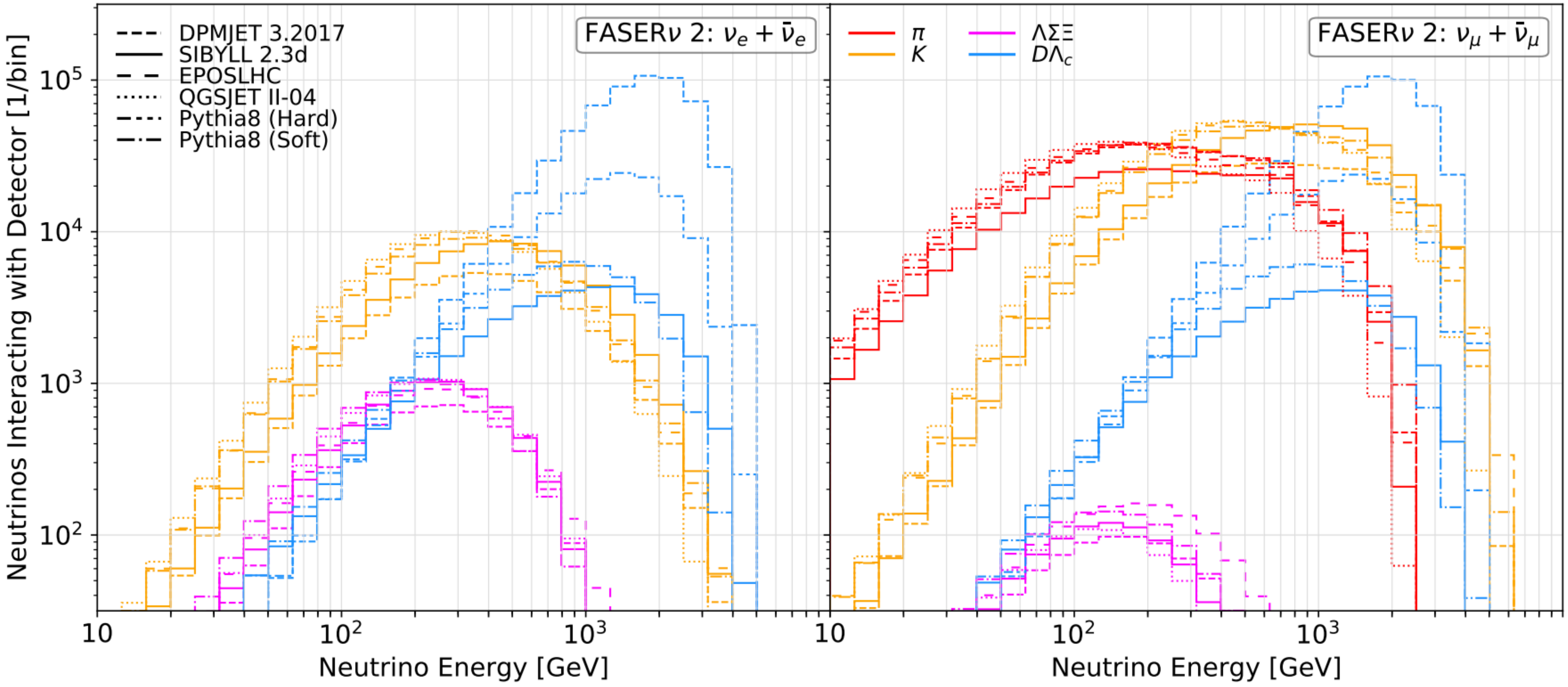
- Electron/muon neutrinos at the FPF are proxies for pion/kaon distributions
- Muons can also possibly constrain pion/kaon production (challenging due to secondary scattering, deployment of sweeper magnets under investigation)
- Test of EAS models → reduced uncertainties in EAS/neutrino measurements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





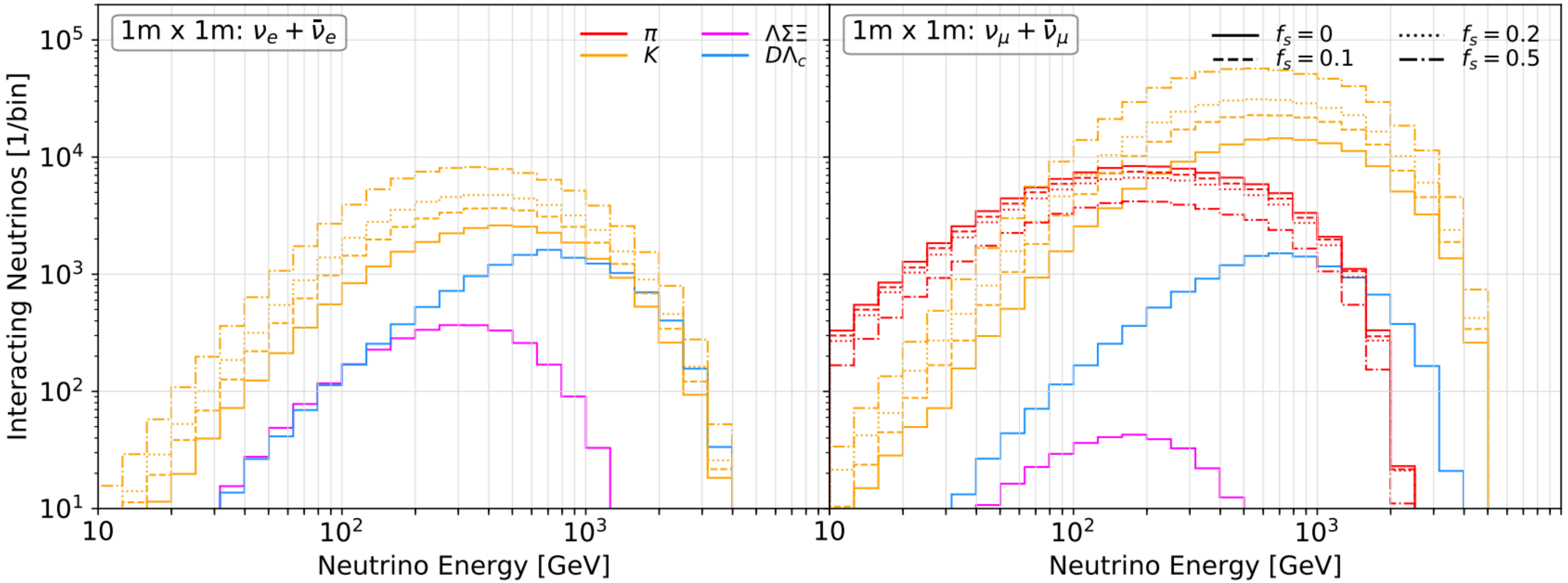
Modeling Cosmic Ray Air Showers

- Expected neutrino fluxes in FASERν2:



Modeling Cosmic Ray Air Showers

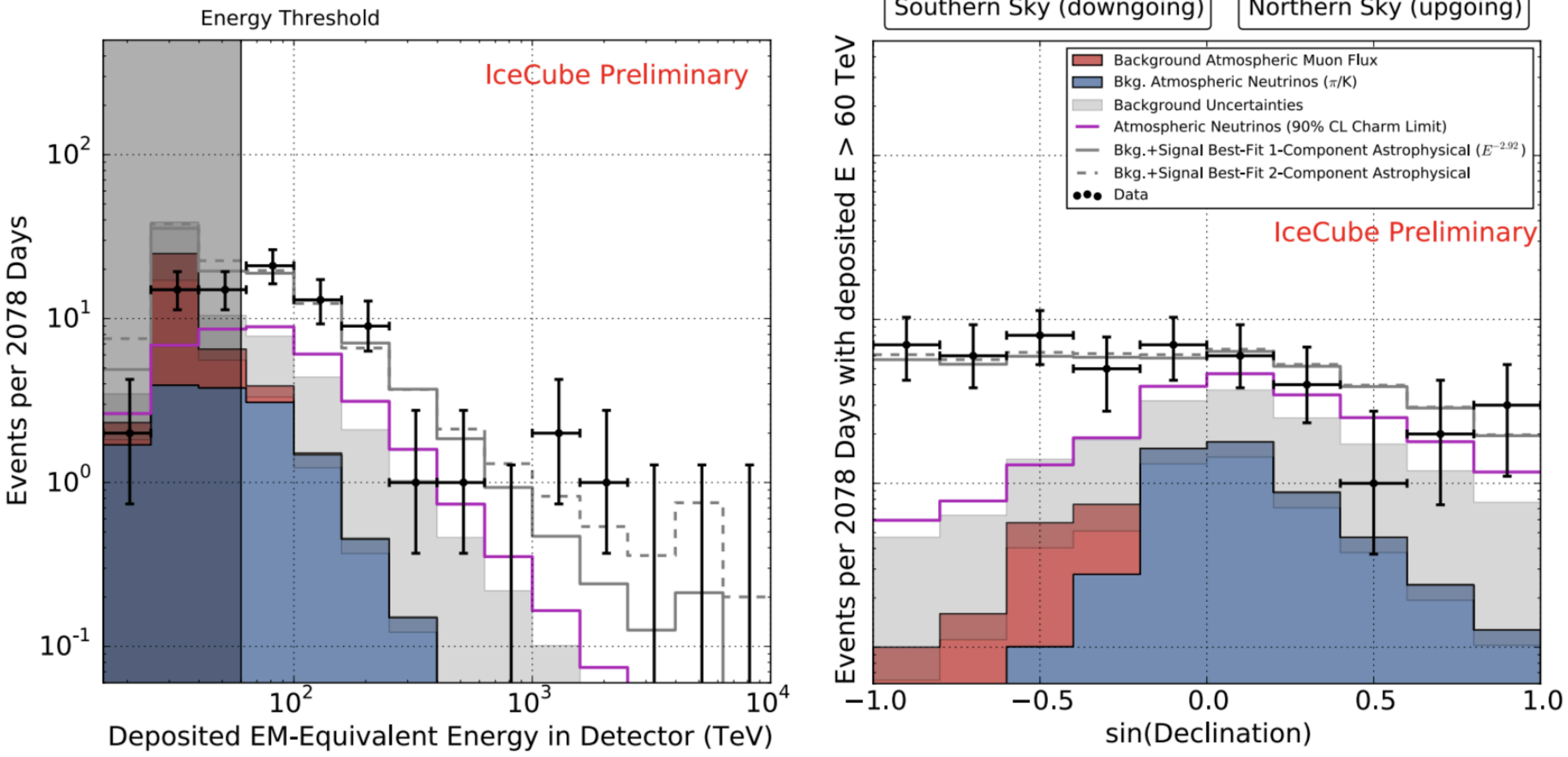
- Expected neutrino fluxes in FLArE (incl. strangeness enhancement toy model):



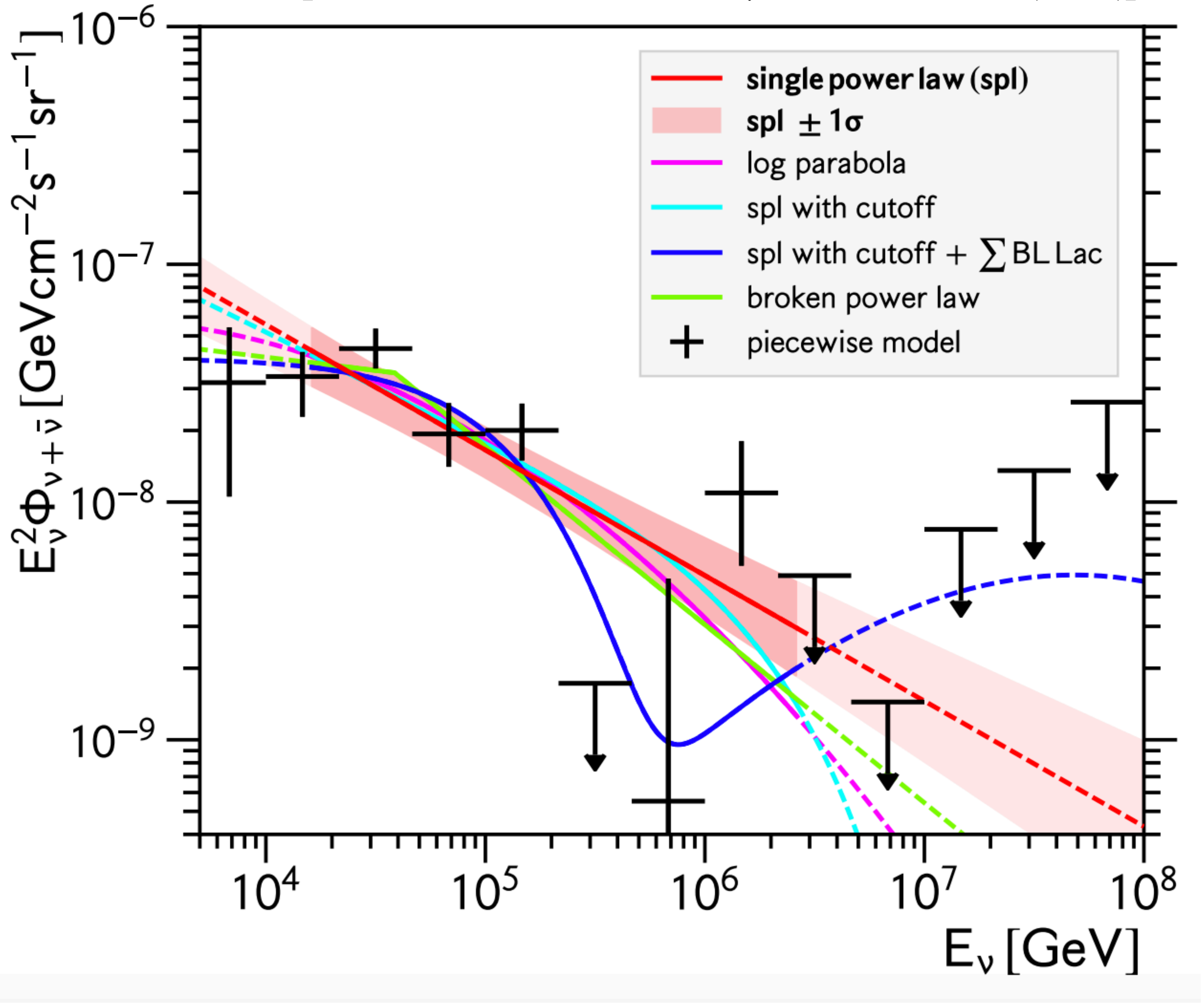
Understanding Atmospheric Neutrinos

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

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

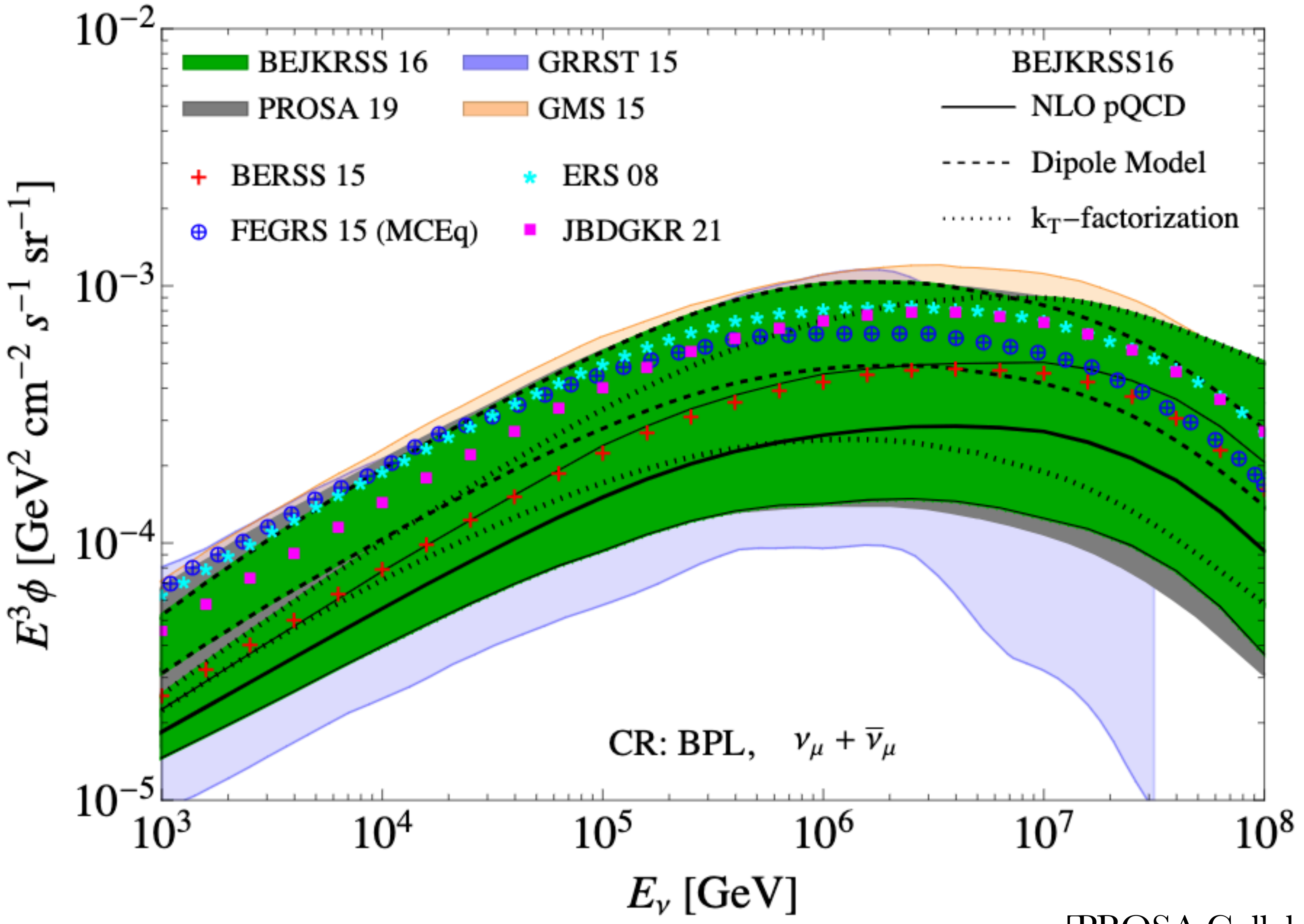


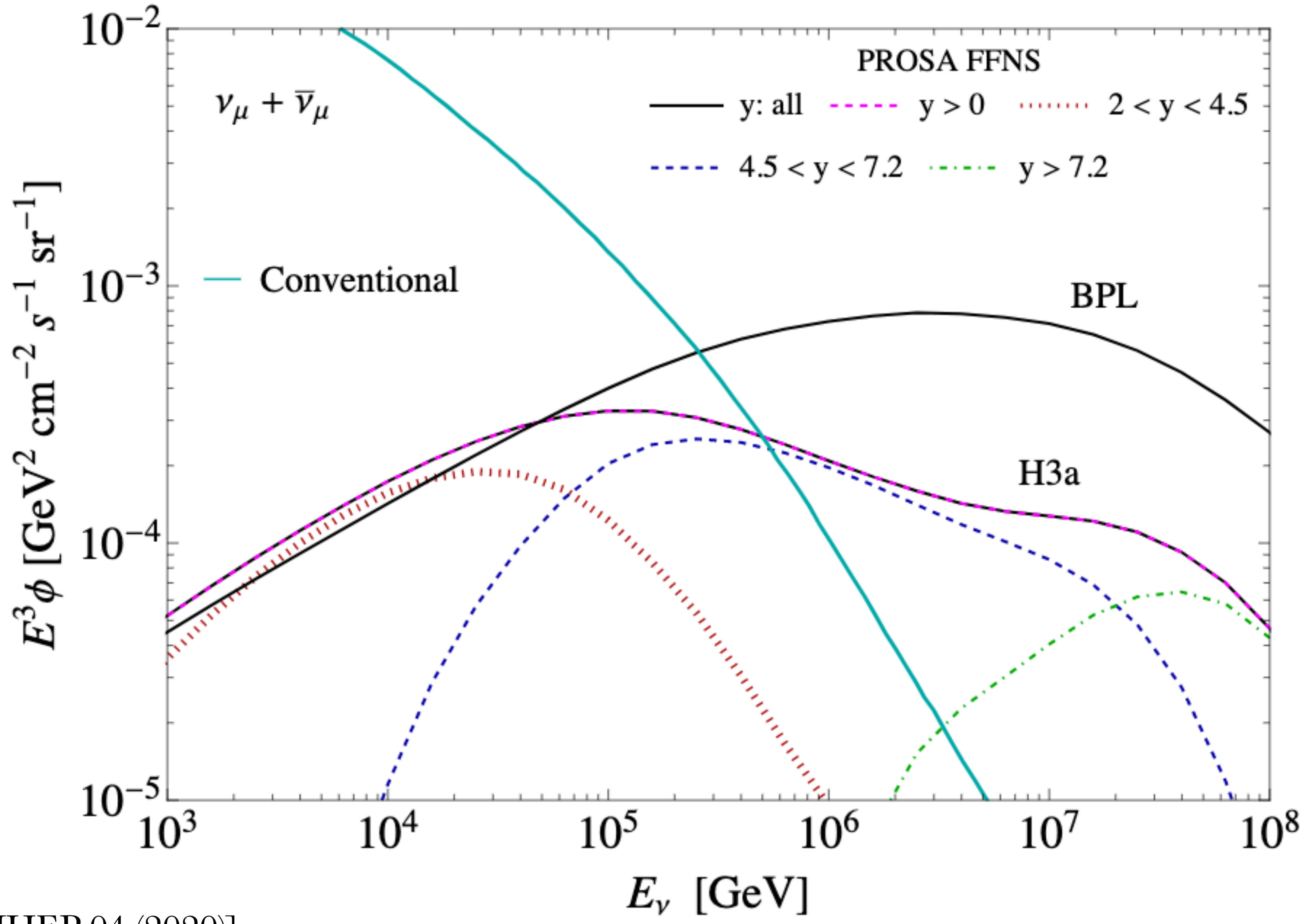
[IceCube Collaboration, Phys. Rev. Lett. 125 (2020)]



Understanding Atmospheric Neutrinos

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





[PROSA Collaboration, JHEP 04 (2020)]

Dark Matter Searches

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

Dark Matter Searches

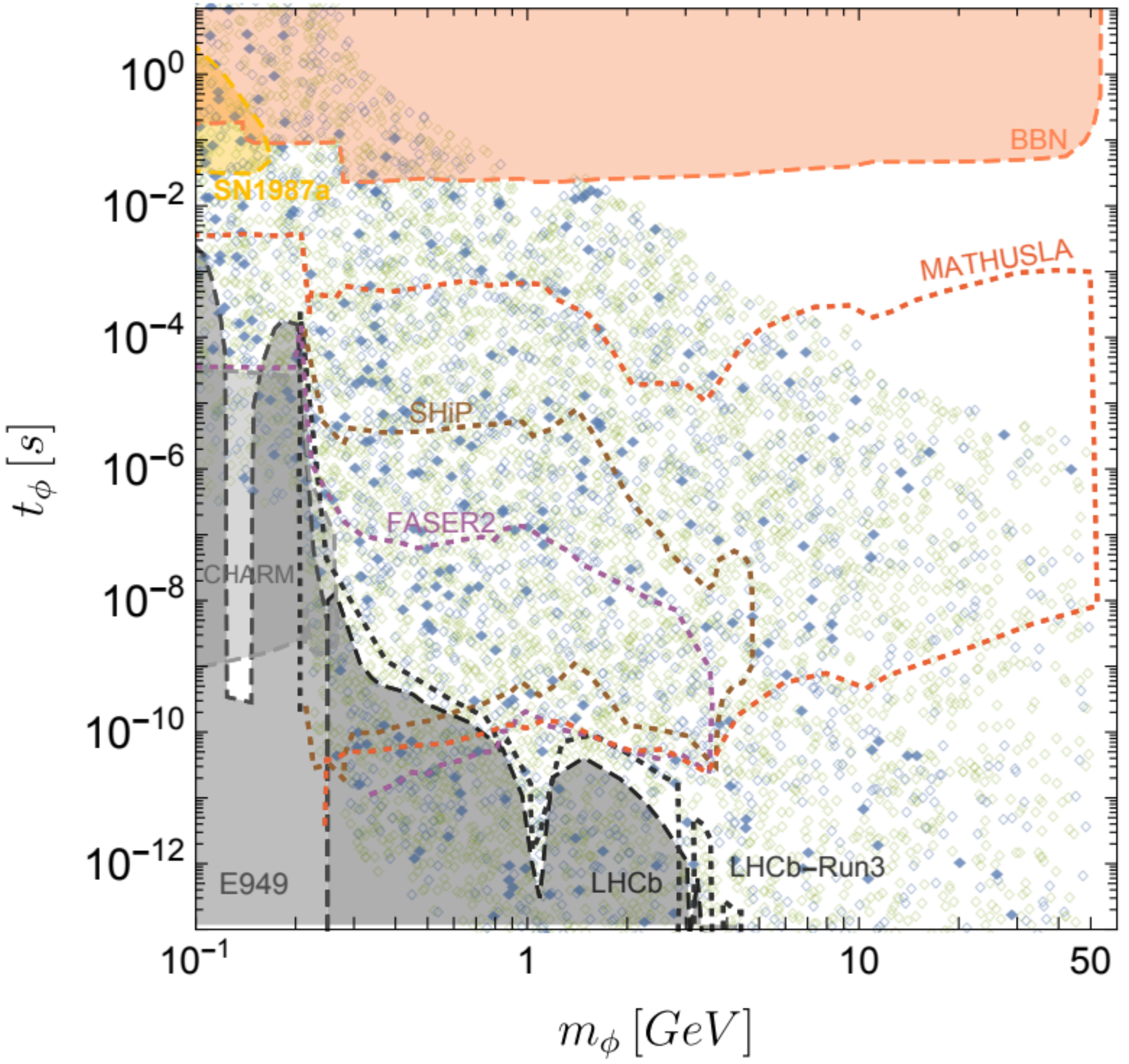
Example: Dark Matter from Freeze-In Semi-Production

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

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

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

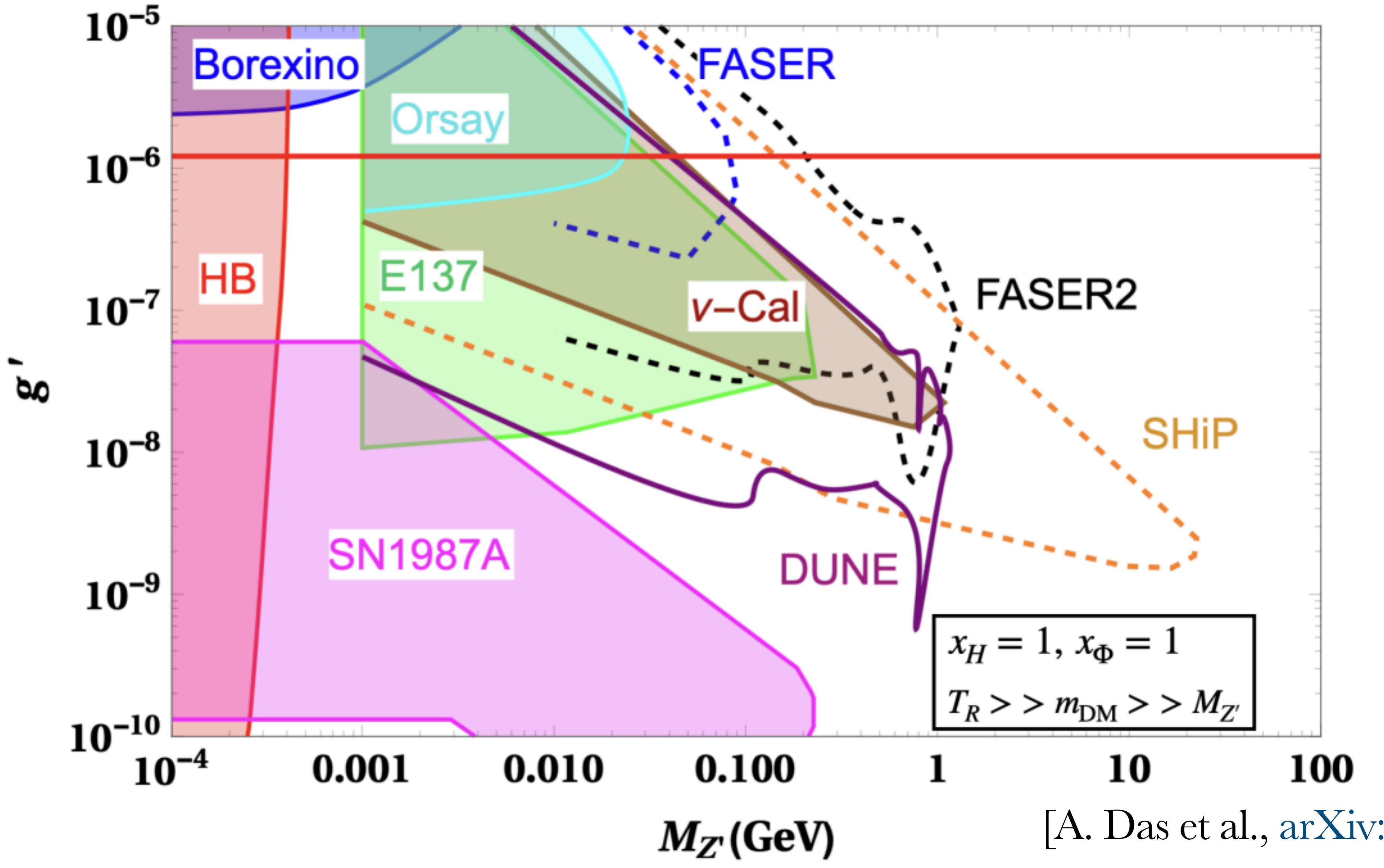
[A. Hryczuk, M. Laletin, JHEP 06 (2021)]

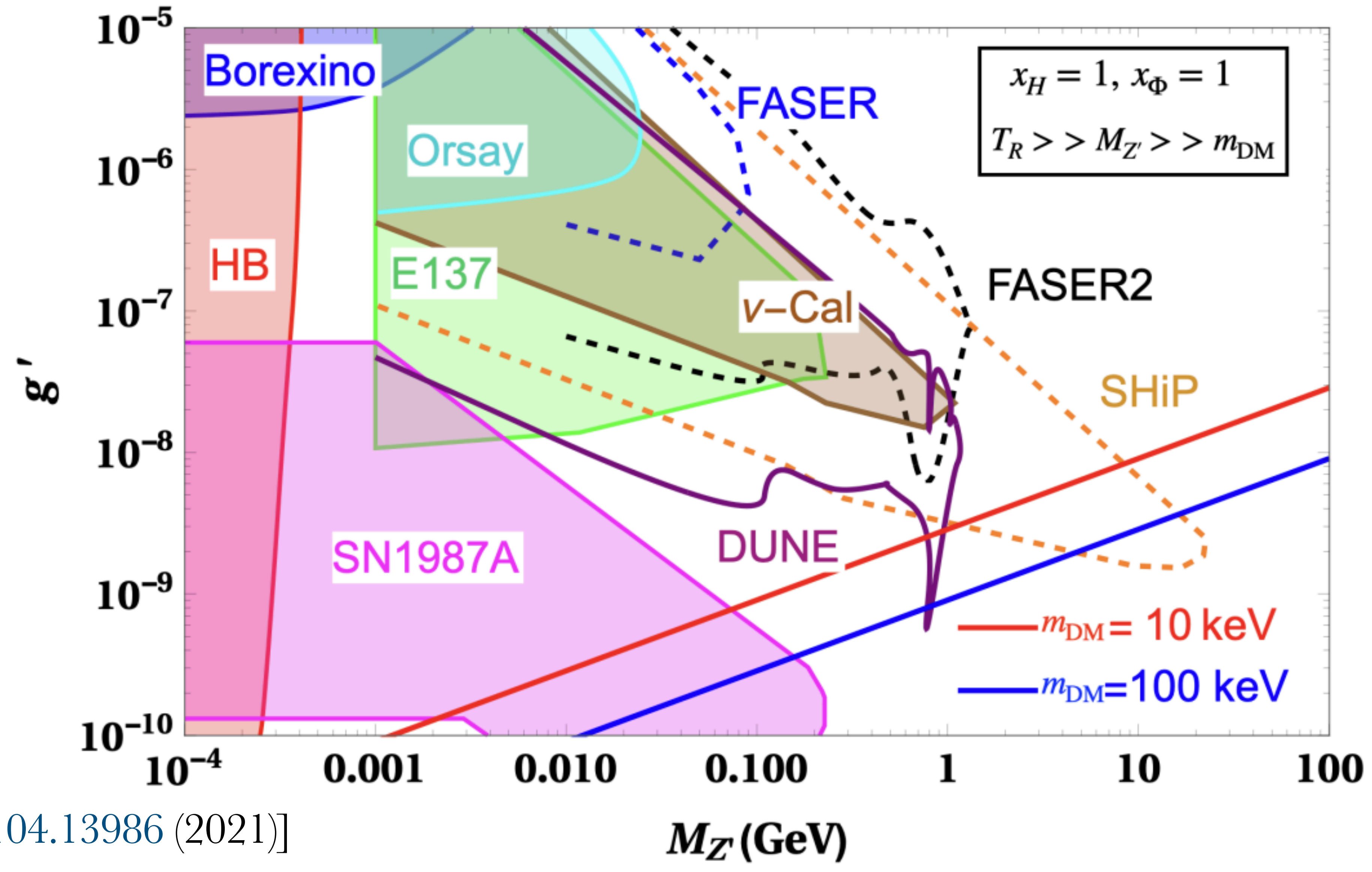


Dark Matter Searches

Example: Freeze-In Sterile Neutrino Dark Matter

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



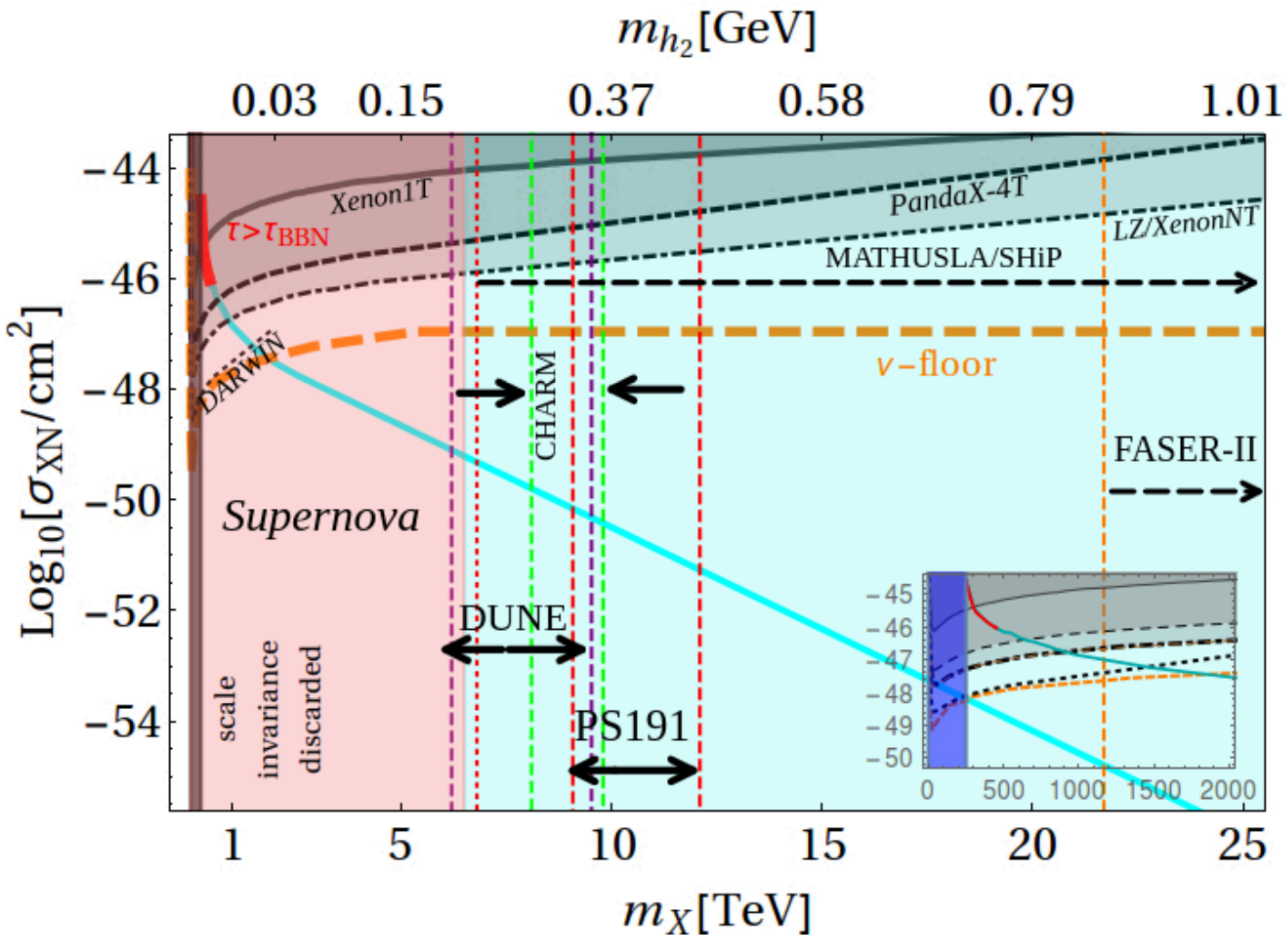


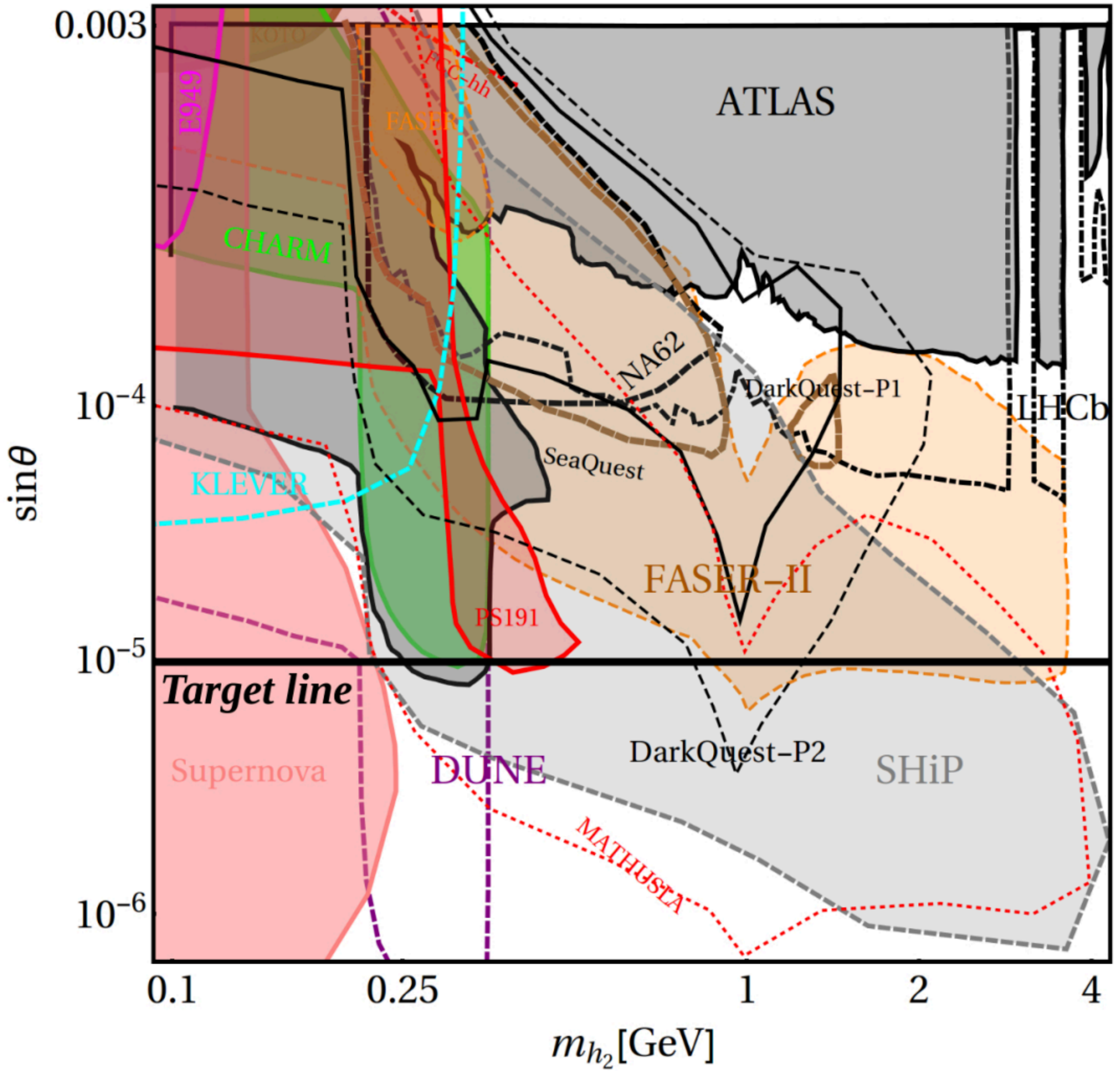
[A. Das et al., arXiv:2104.13986 (2021)]

Dark Matter Searches

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

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





Dark Matter Searches

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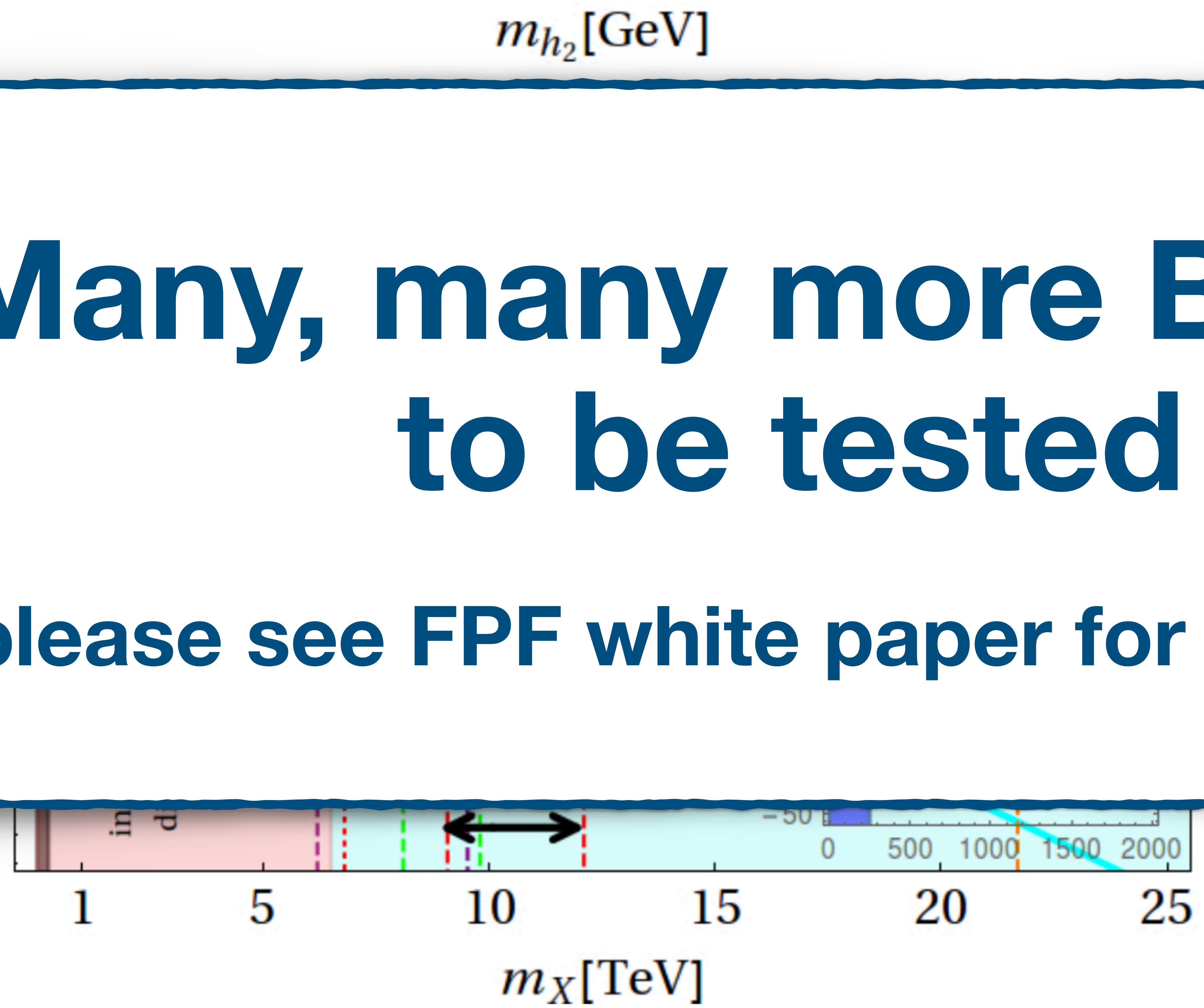
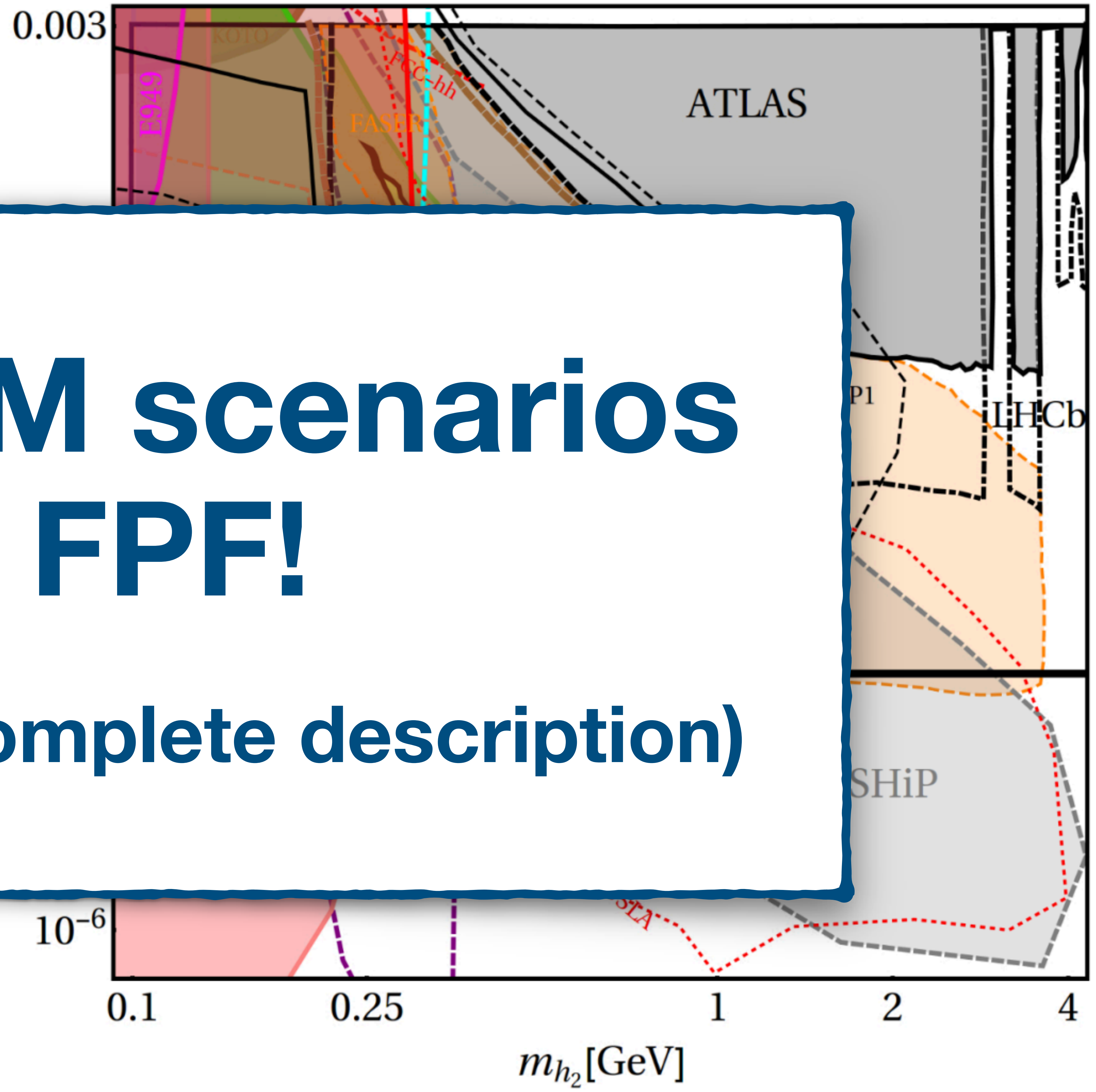


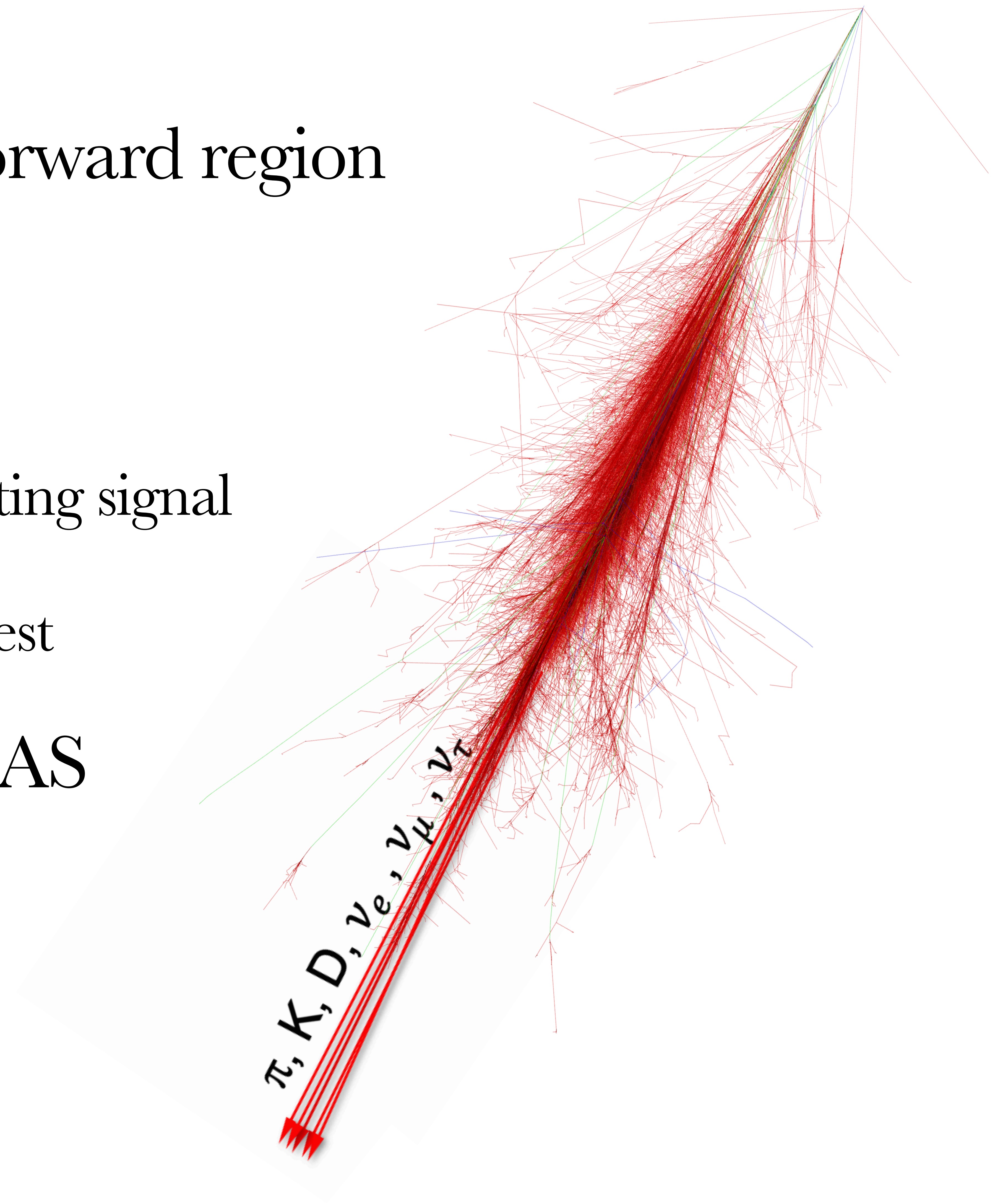


Many, many more BSM scenarios to be tested at FPF!

(please see FPF white paper for a complete description)

Summary & Conclusions

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



Summary & Conclusions

- Further reading:
  - FPF Short Paper: Physics Reports 968 (2022), arXiv:2109.10905
  - FPF White Paper: Accepted by Journal of Physics G, arXiv:2203.05090
- Many thanks to all contributors and conveners!
- If you have any further questions or input, please don't hesitate to contact us:

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Thank You!