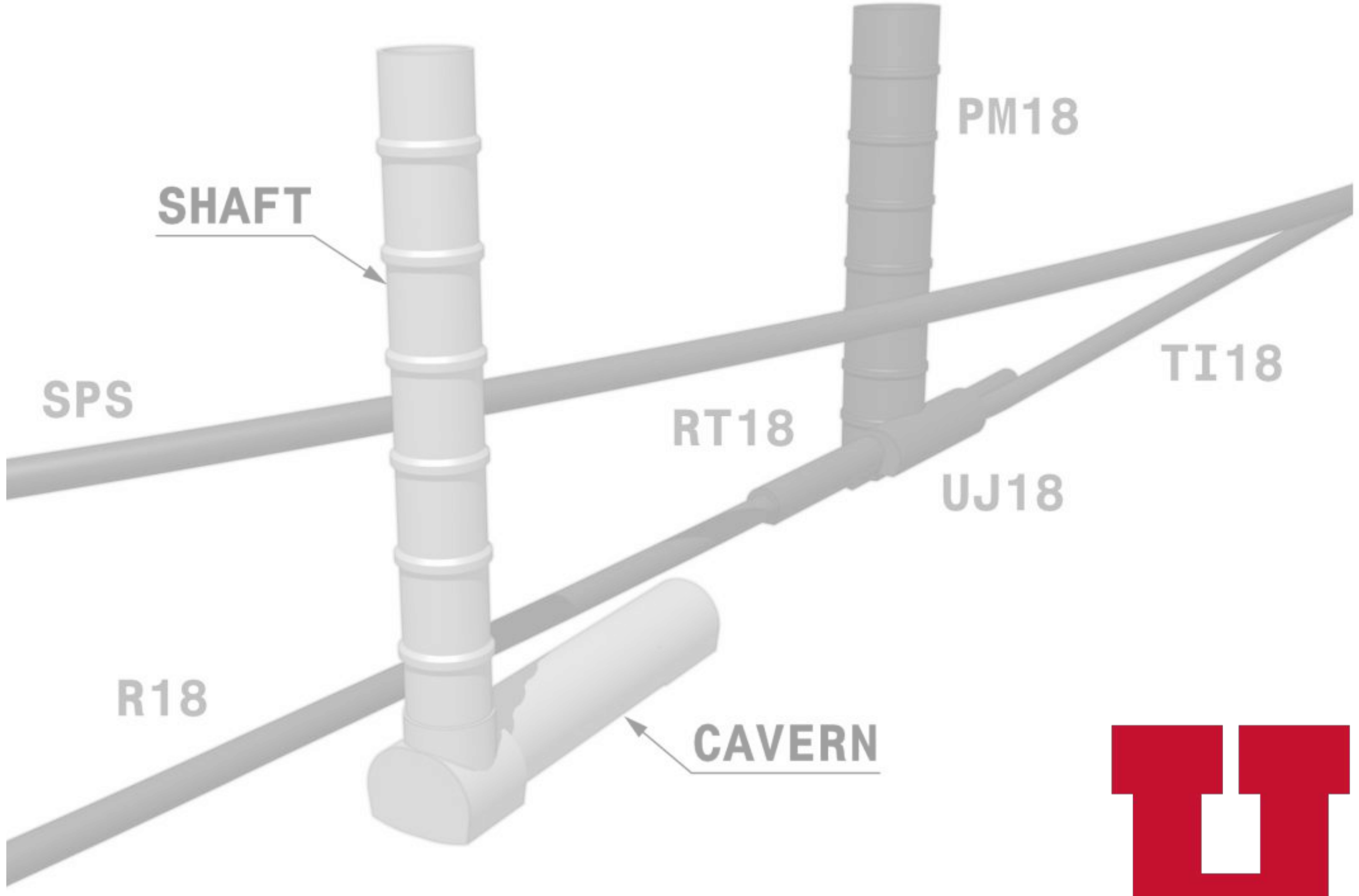
The Forward Physics Facility and its Implications for Astroparticle Physics

Vulcano Workshop 2024
Ischia Island, Italy

Dennis Soldin
University of Utah



Forward Physics Facility

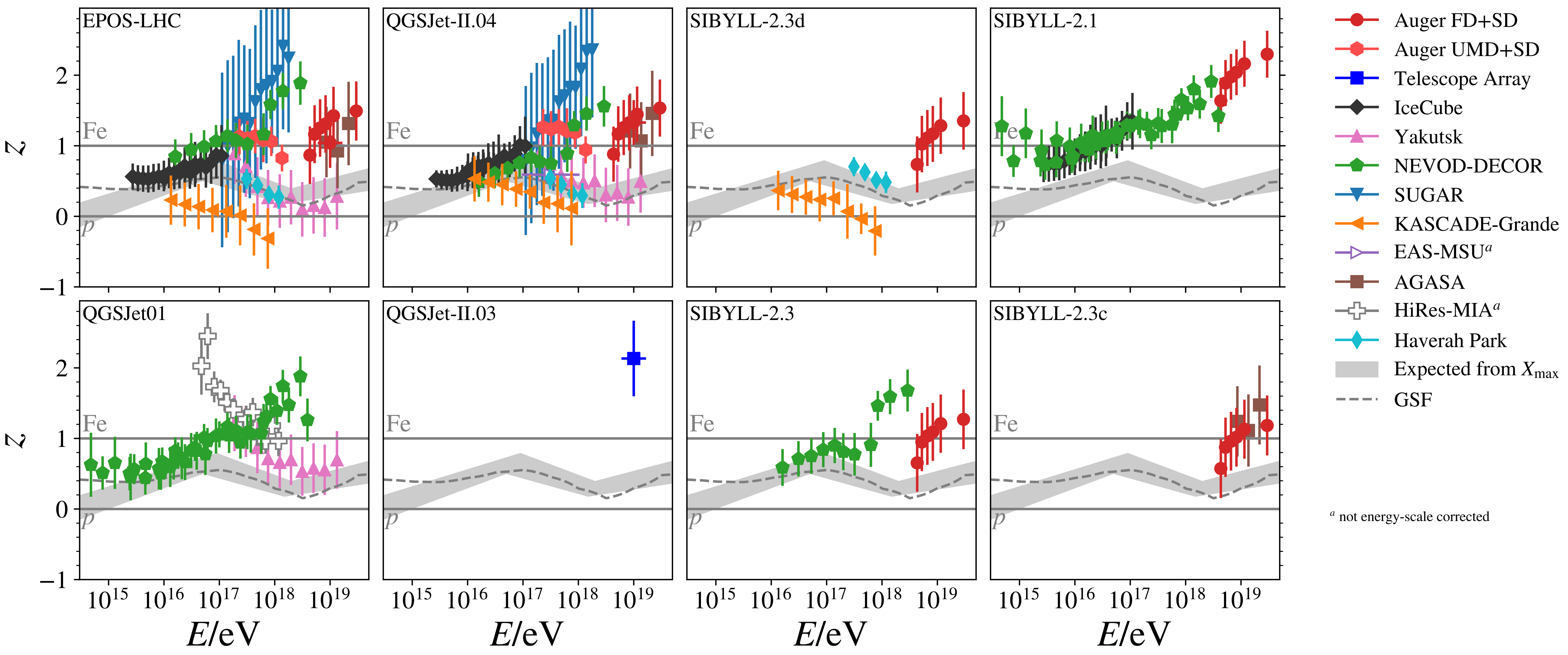
THE UNIVERSITY OF UTAH

Introduction: The Muon Puzzle

- Indirect cosmic ray measurements:
  - Properties of the initial cosmic ray inferred from simulations of extensive air showers (EASs)
  - ~30% more muons observed than expected at the highest energies!
  - z-scale:

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

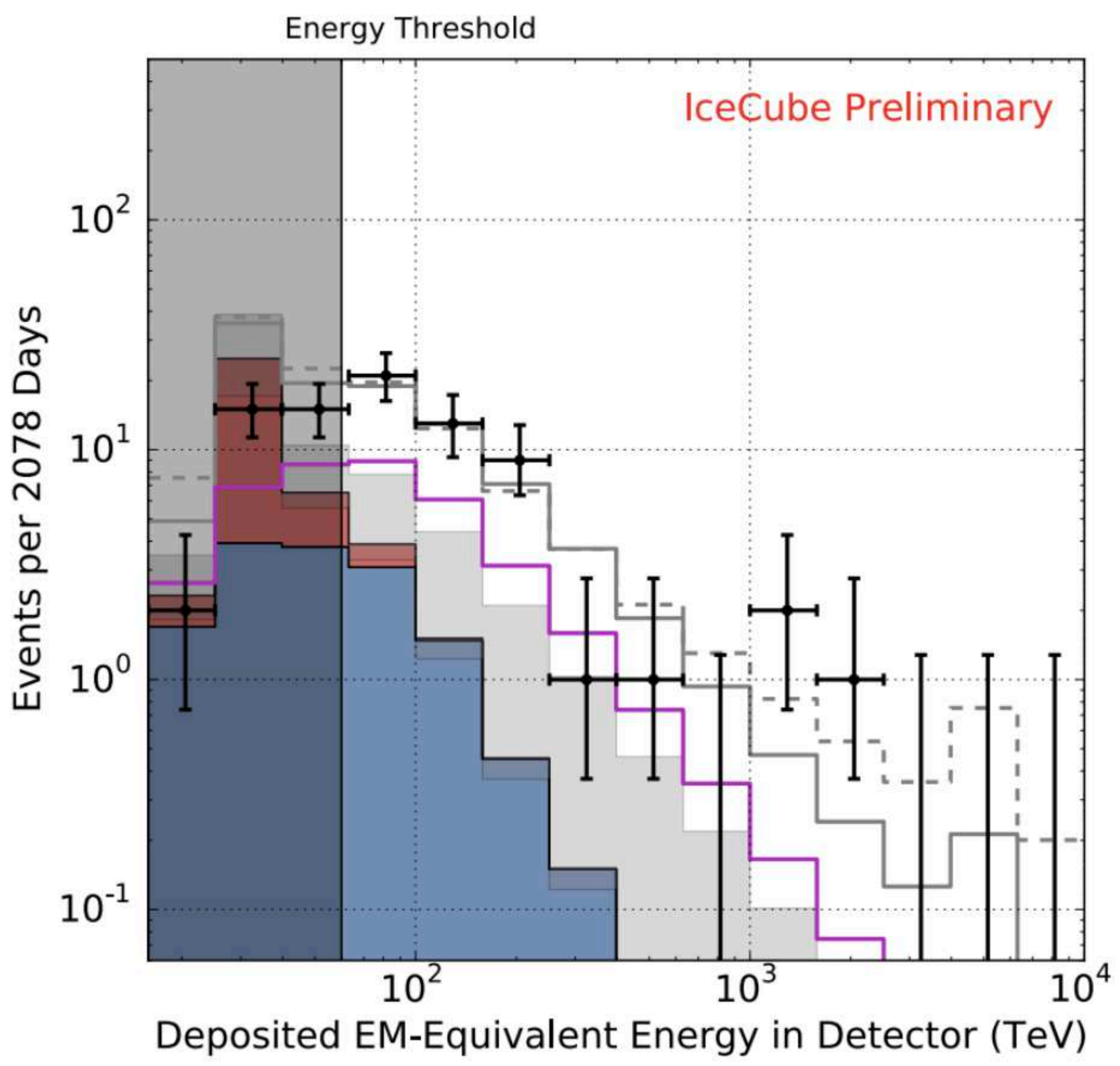
  - $z = 0$: proton
  - $z = 1$: iron
- Large uncertainties in EAS measurements, e.g. composition!

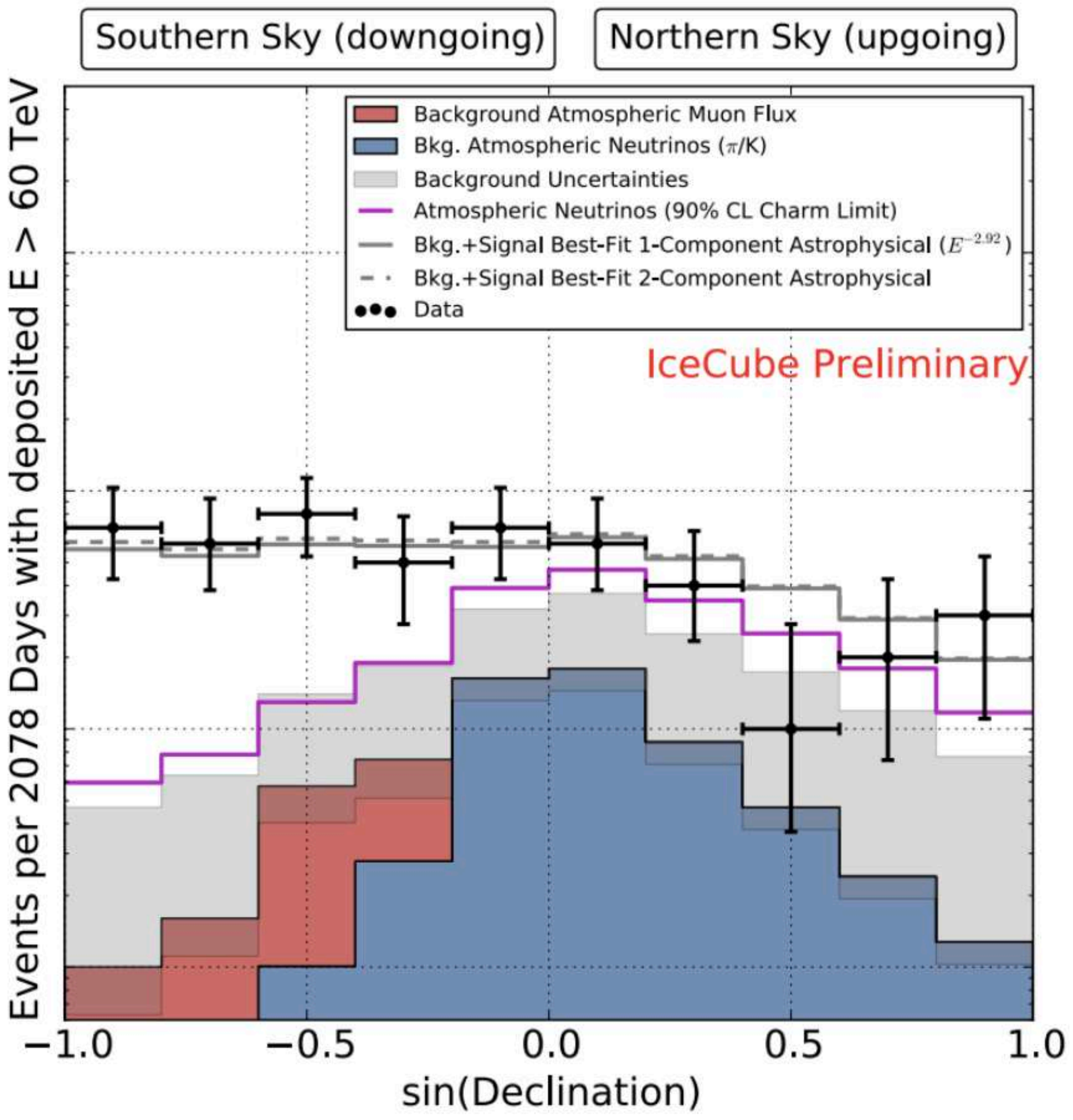


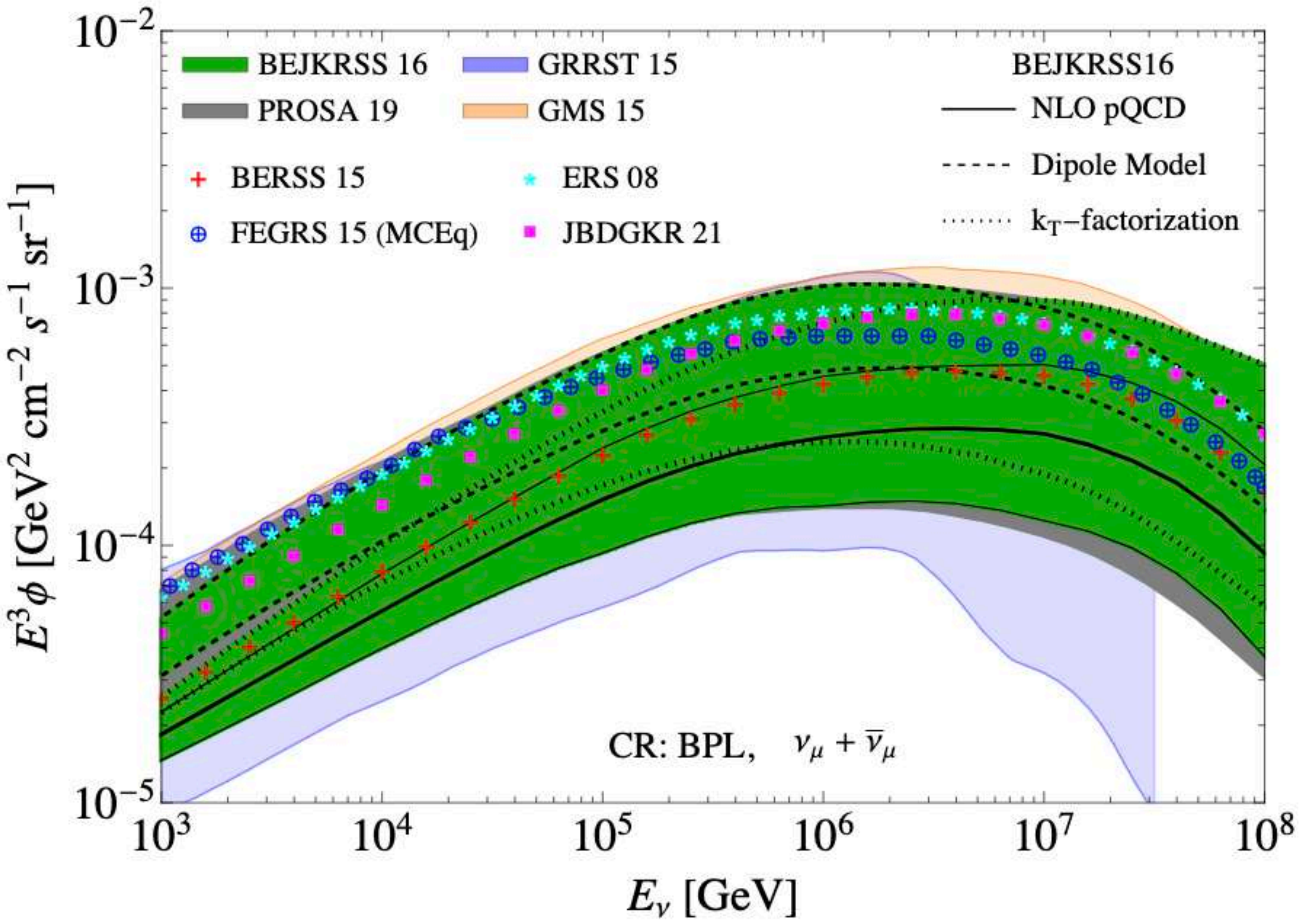
[J. C. Arteaga-Velázquez (WHISP), PoS ICRC2023 (2023) 466]

Introduction: Atmospheric Neutrinos

- <u>Atmospheric high-energy neutrino flux:</u>
  - 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!







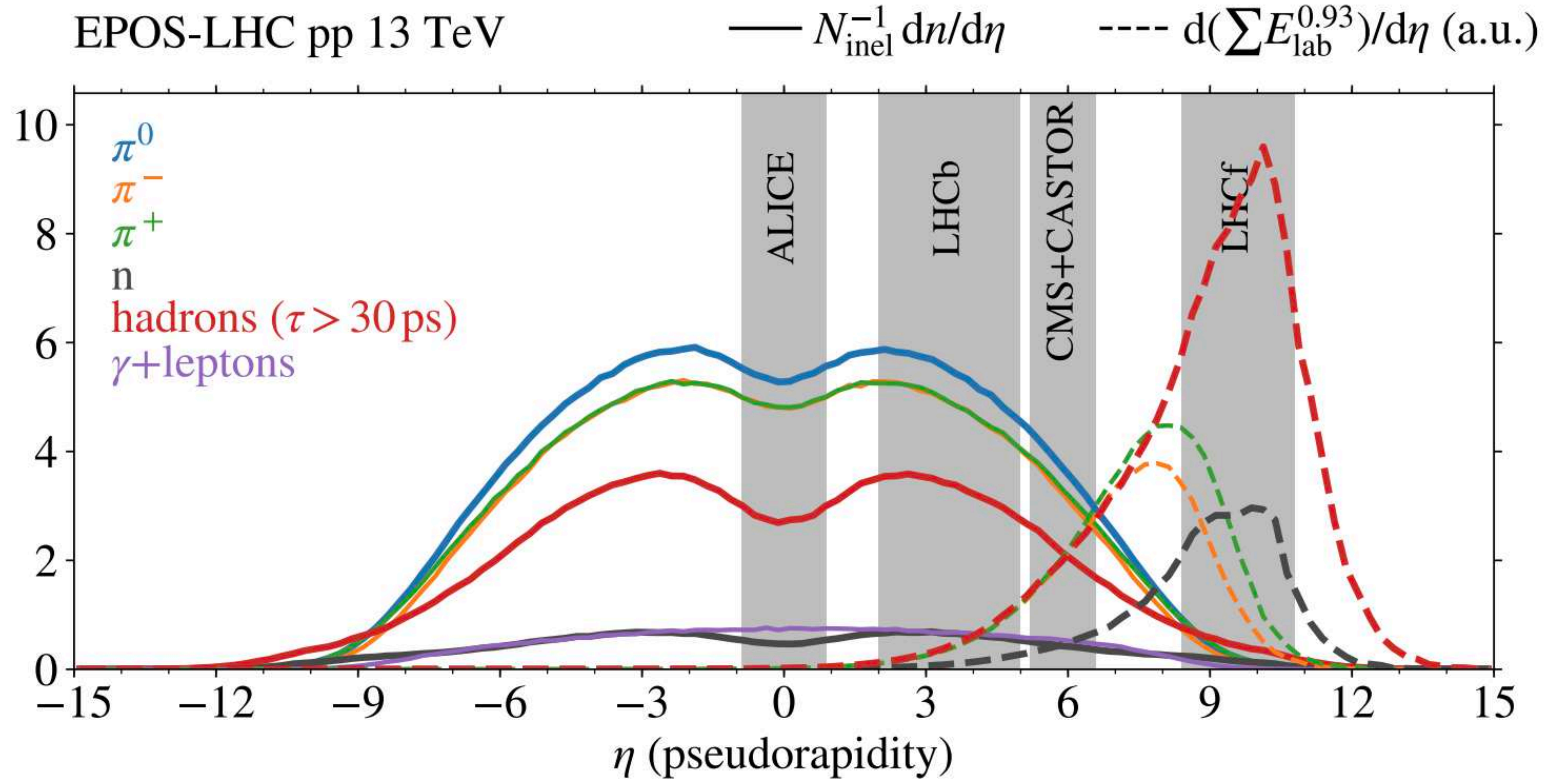
[C. Kopper (IceCube Collaboration), PoS(ICRC2017)981 (2018)]

[PROSA Collaboration, JHEP 04 (2020)]

Introduction: Challenges in EAS Physics

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

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



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

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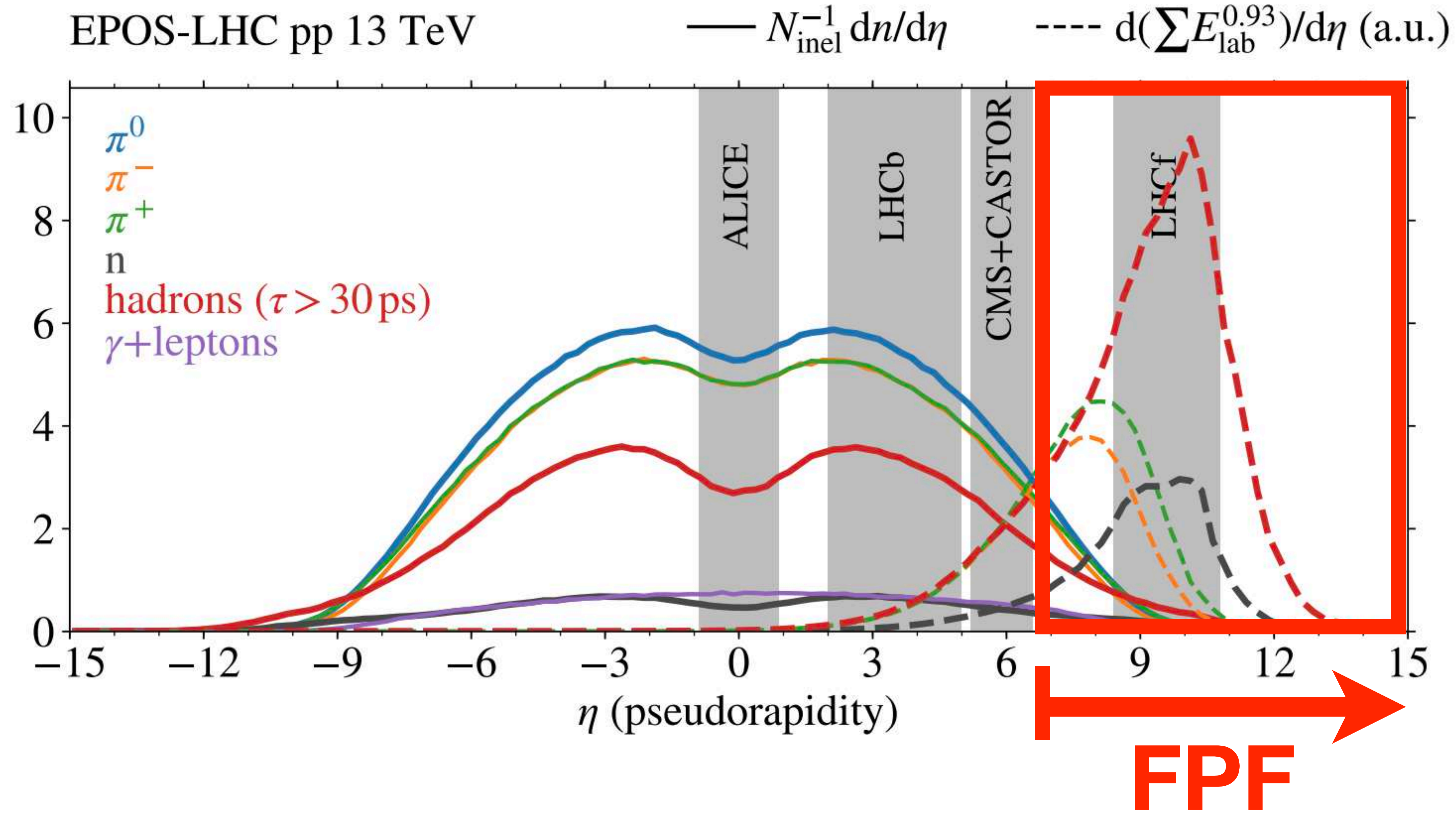
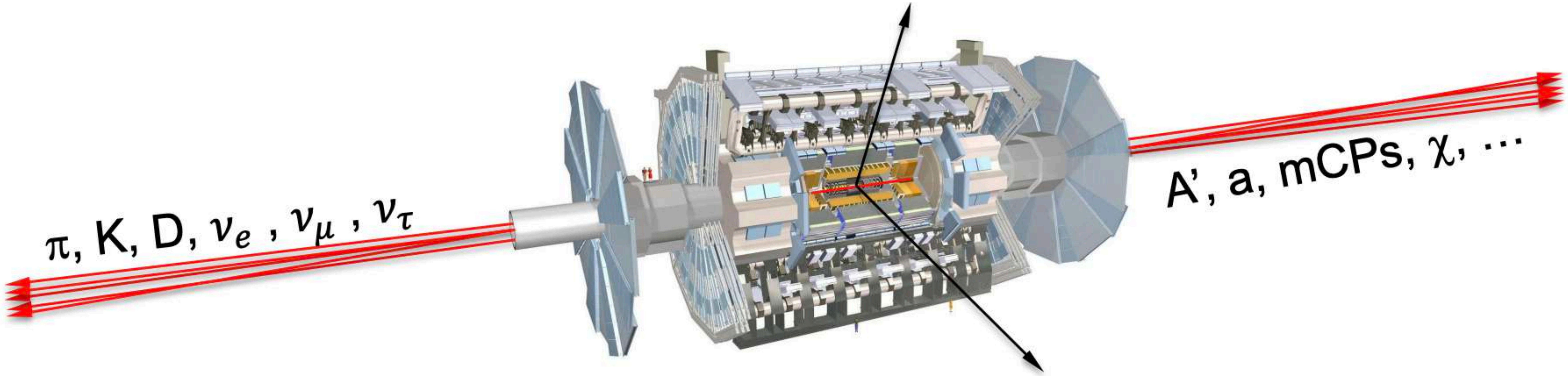


How can we test hadronic interaction models in the far-forward region at accelerators?

The Forward Physics Facility

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



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

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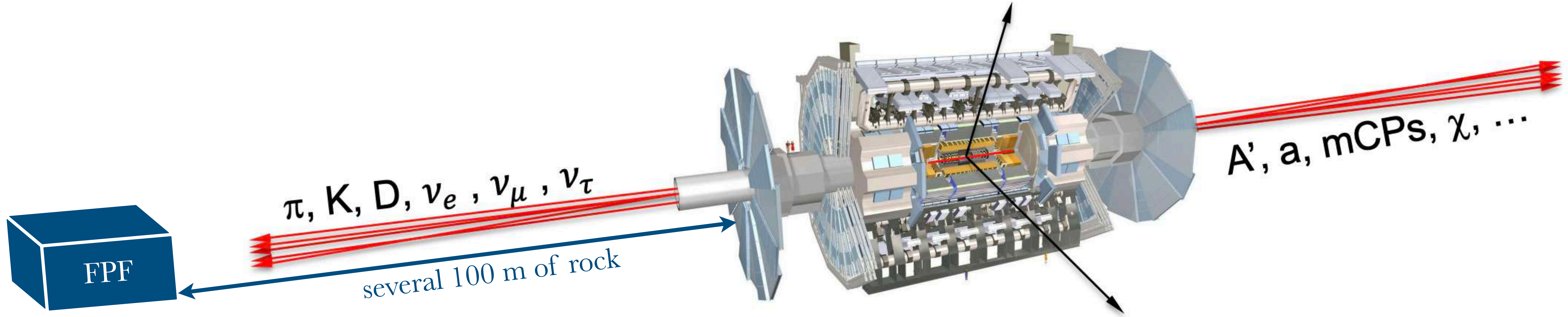

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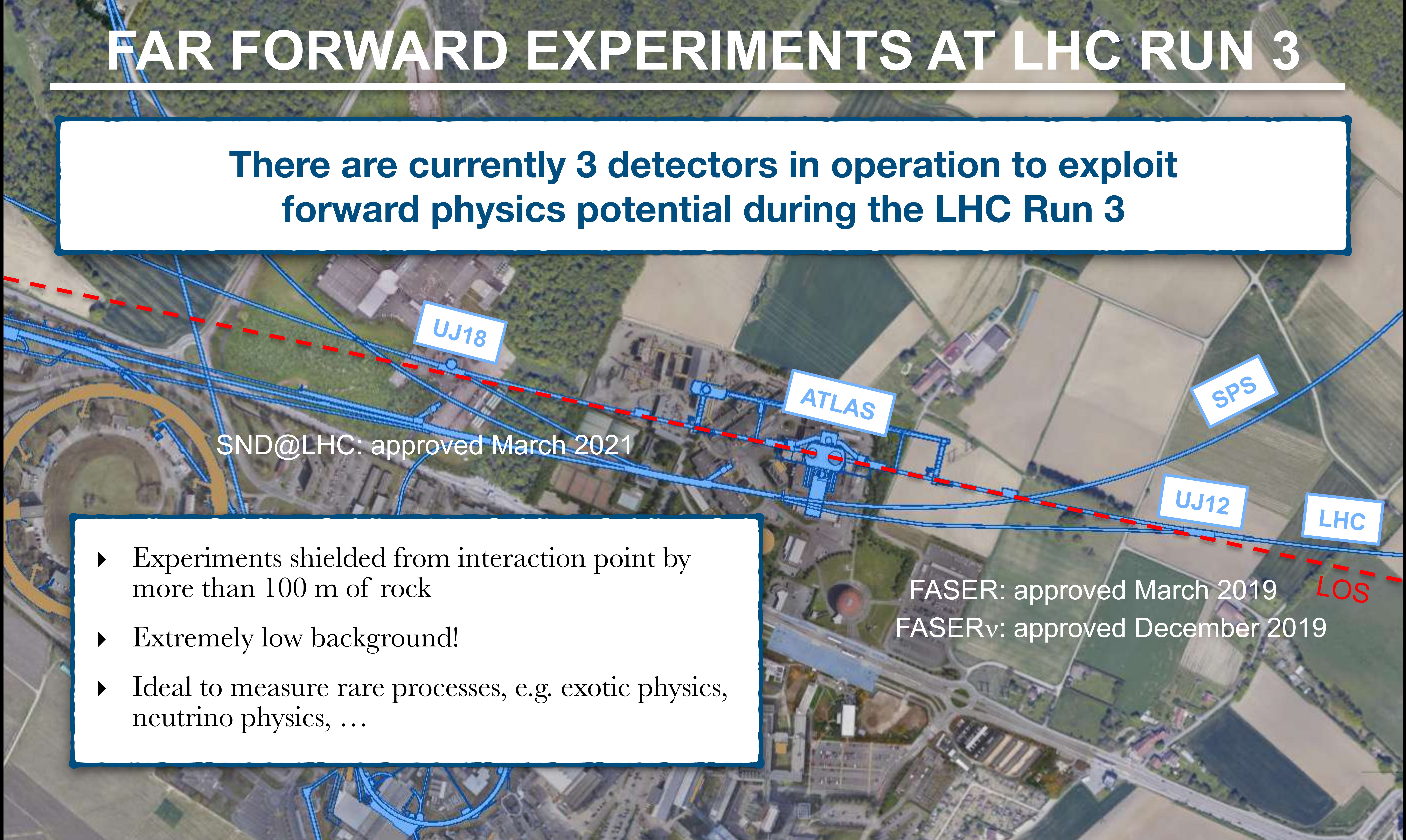
FAR FORWARD EXPERIMENTS AT LHC RUN 3

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



SND@LHC: approved March 2021

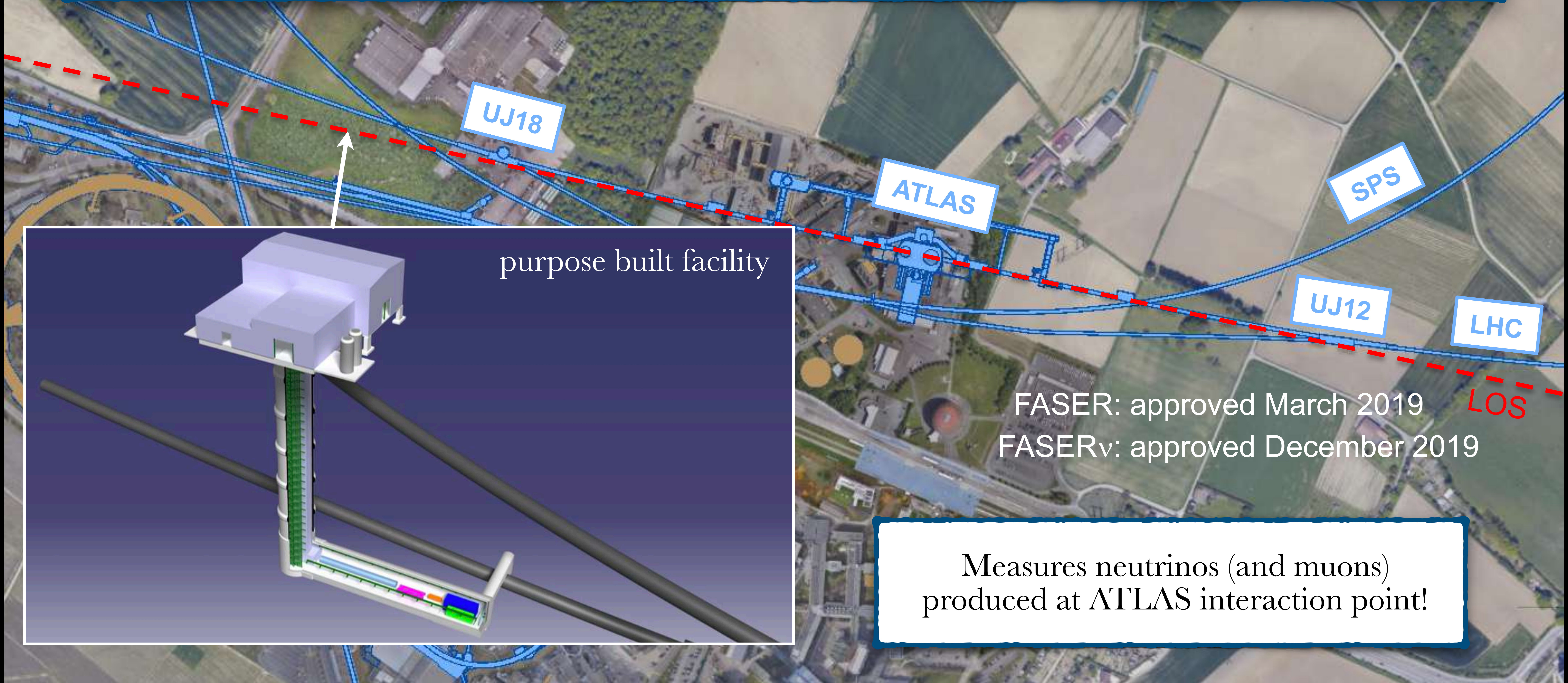
FASER: approved March 2019

FASERν: approved December 2019

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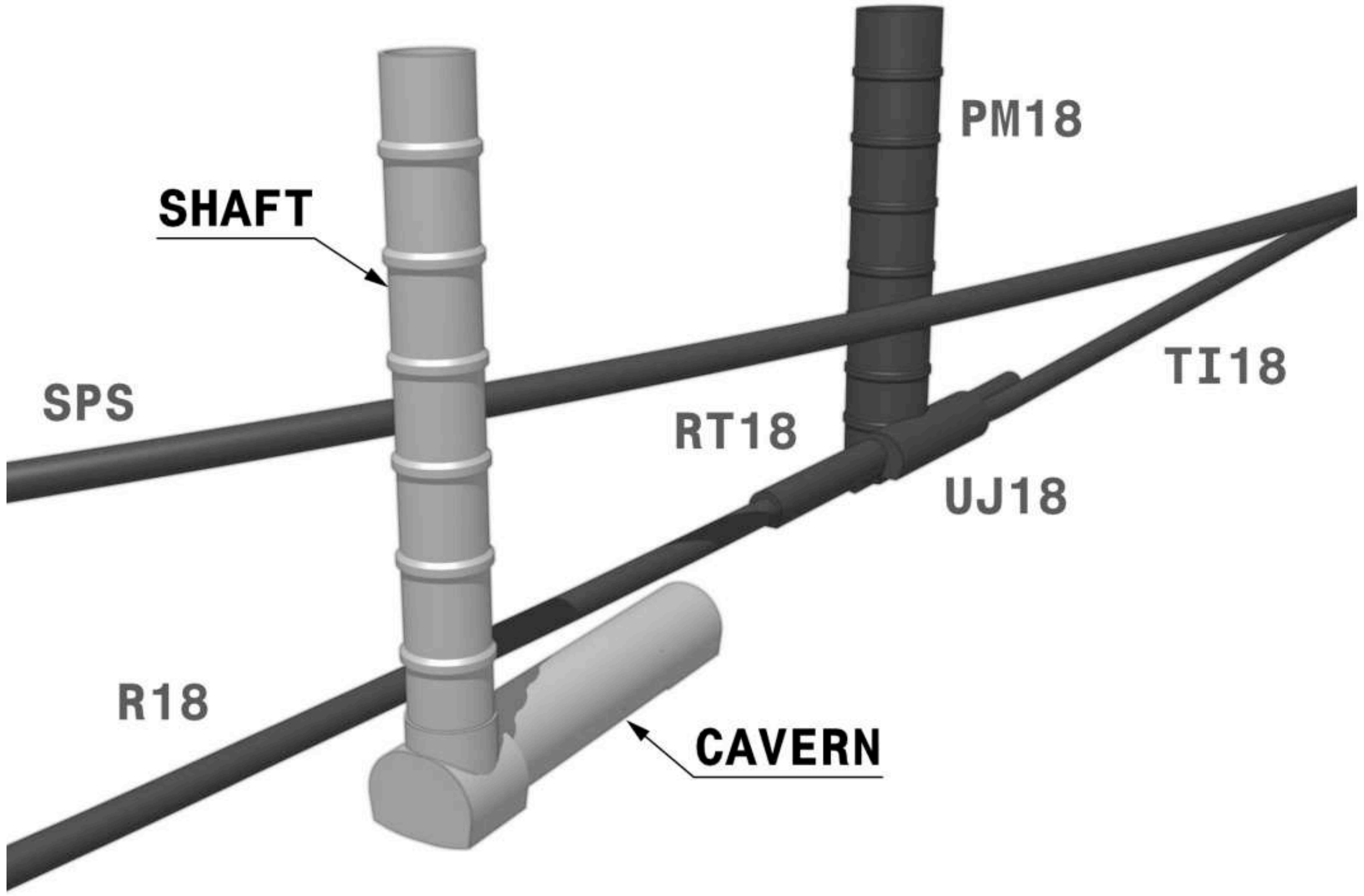
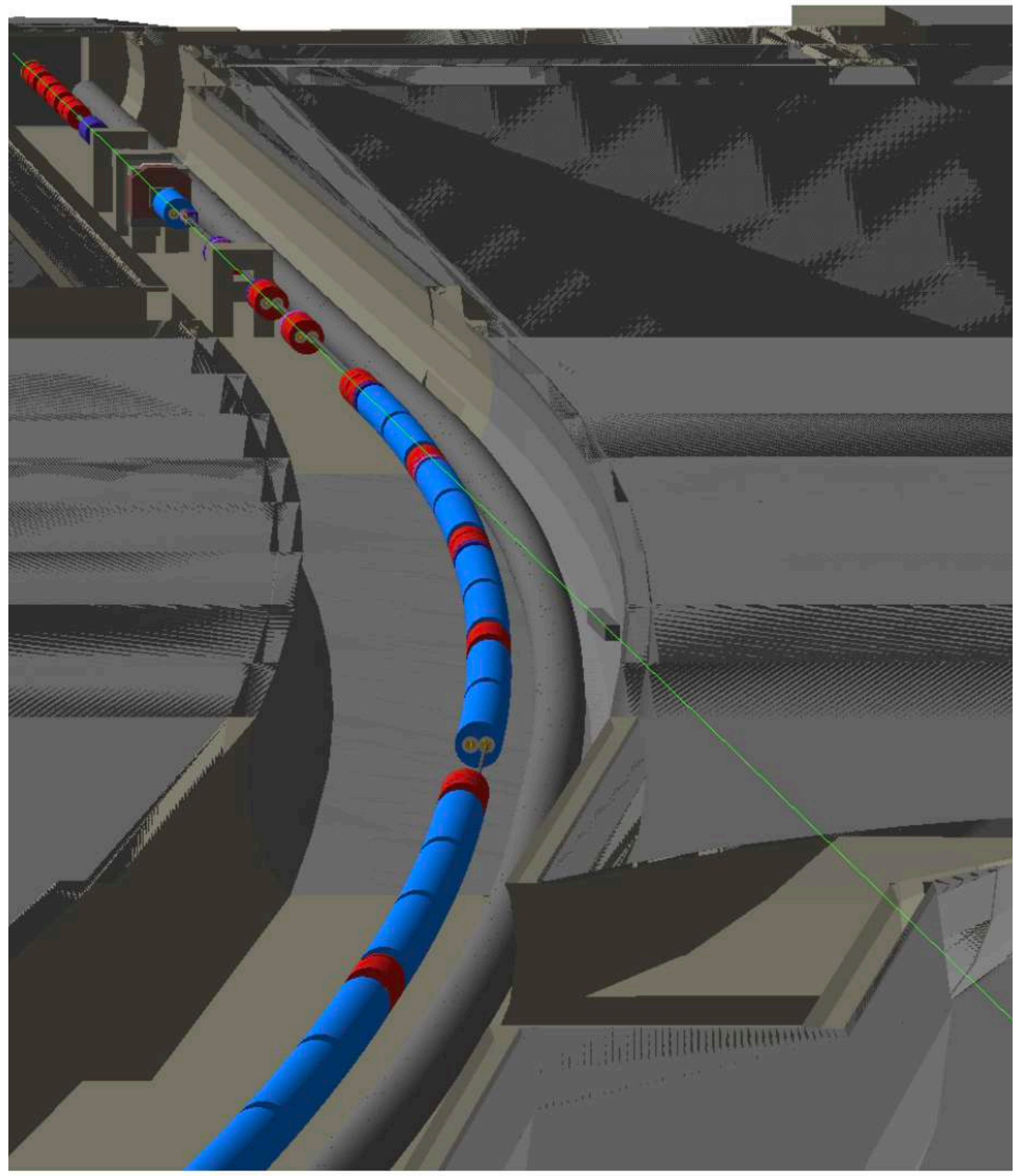
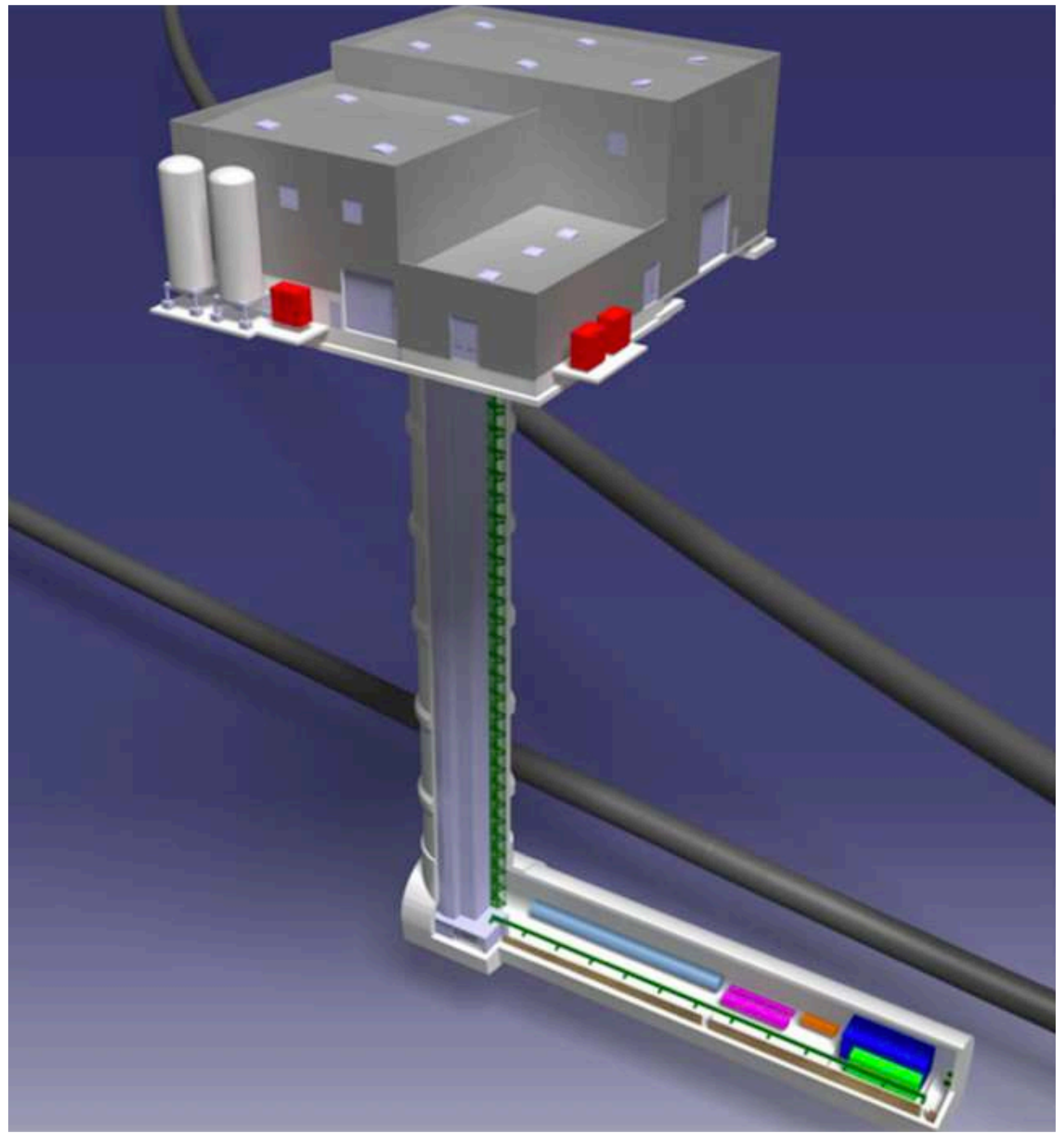
Measures neutrinos (and muons) produced at ATLAS interaction point!

The Forward Physics Facility

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







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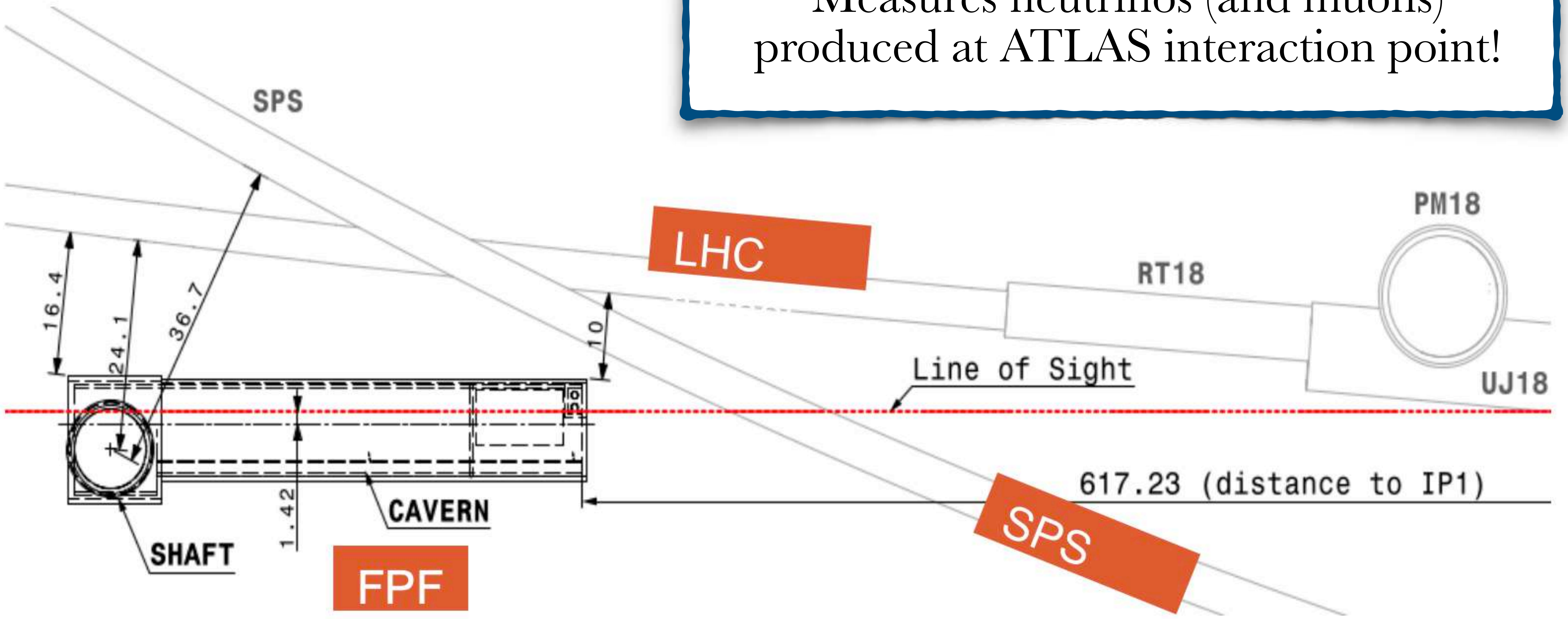

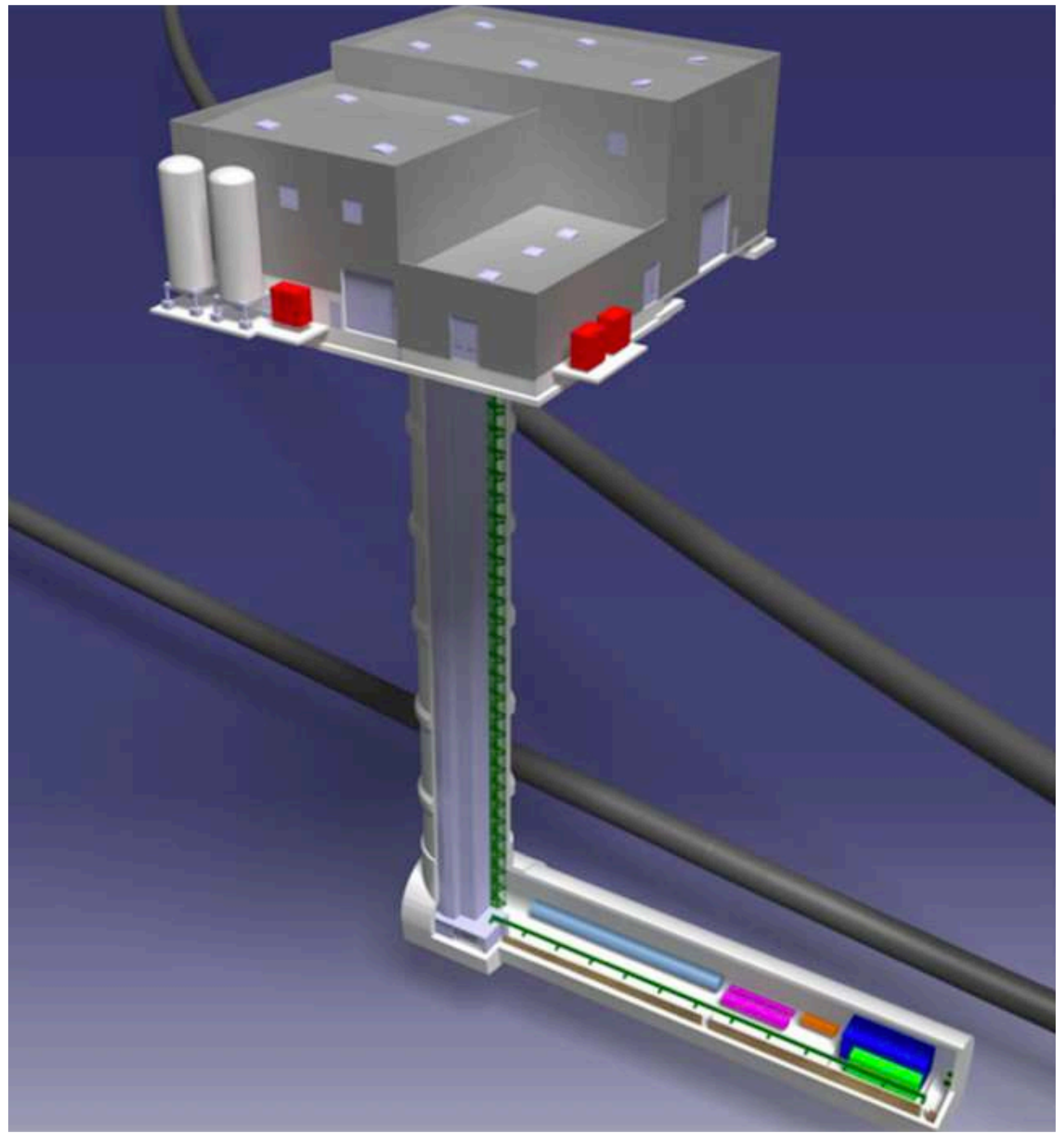

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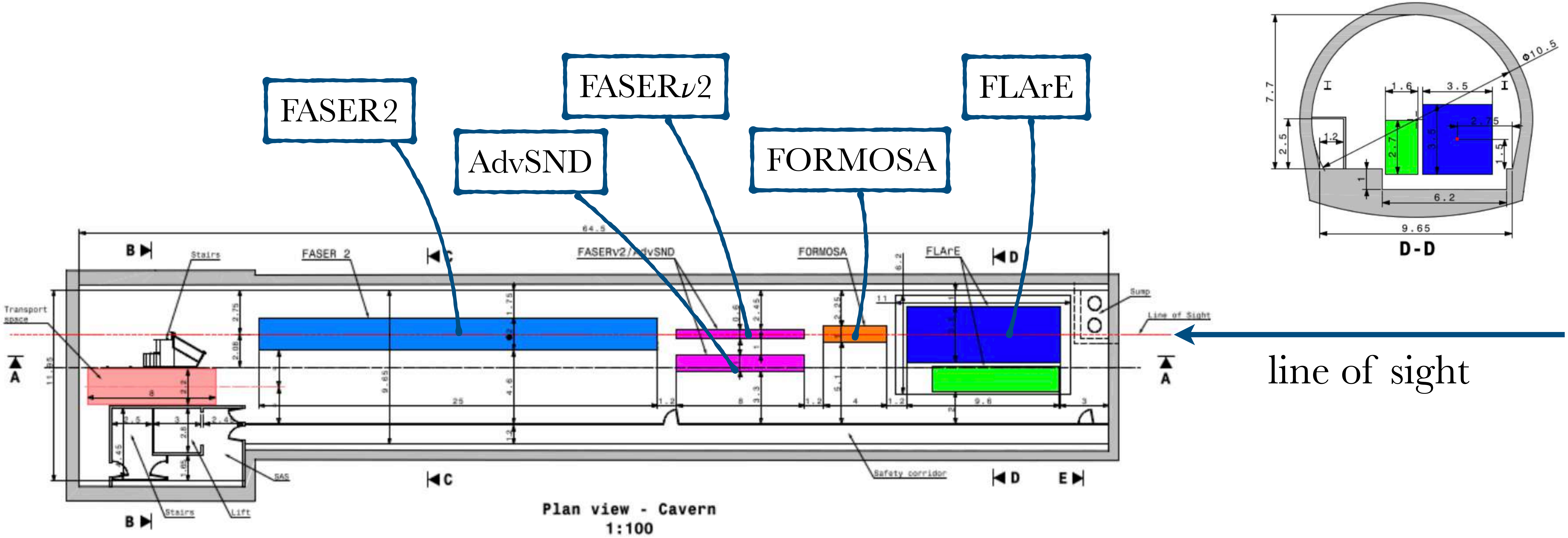

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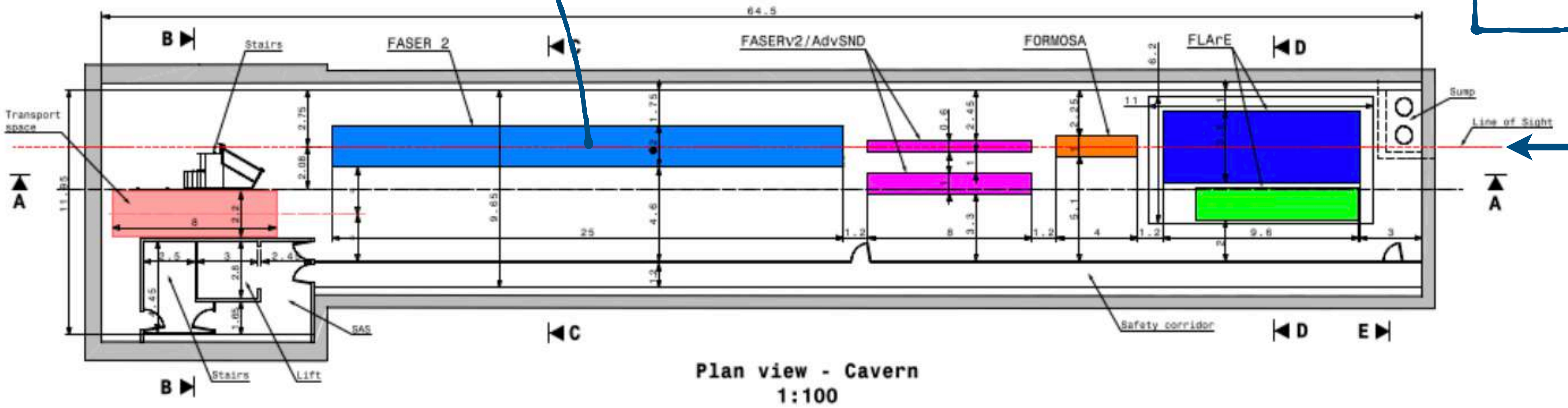
FASER2

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



line of sight

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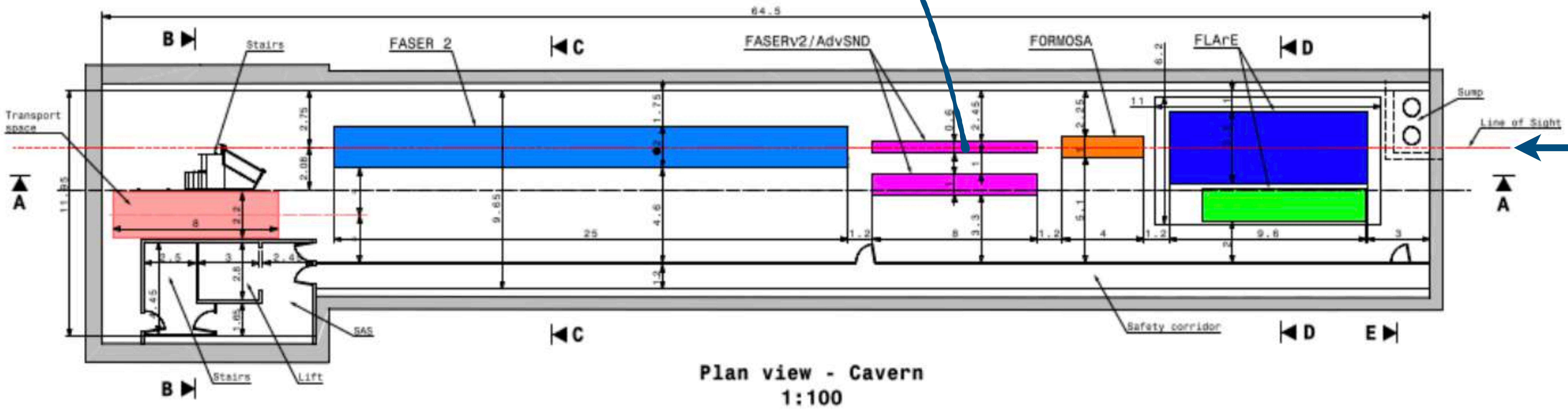
FASERν2

Emulsion detector, to detect neutrinos at TeV energies



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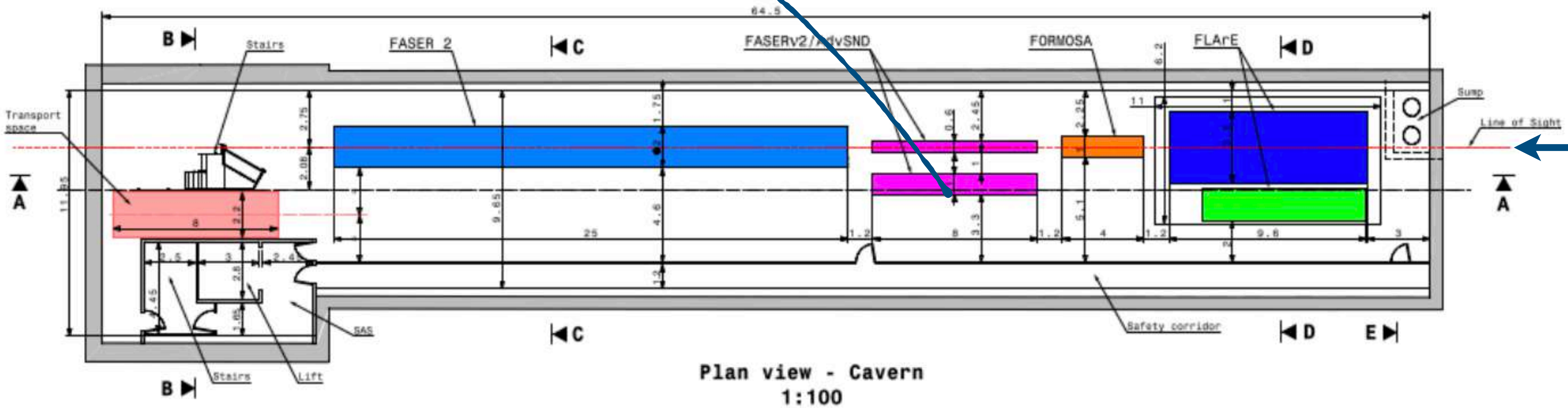
AdvSND

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



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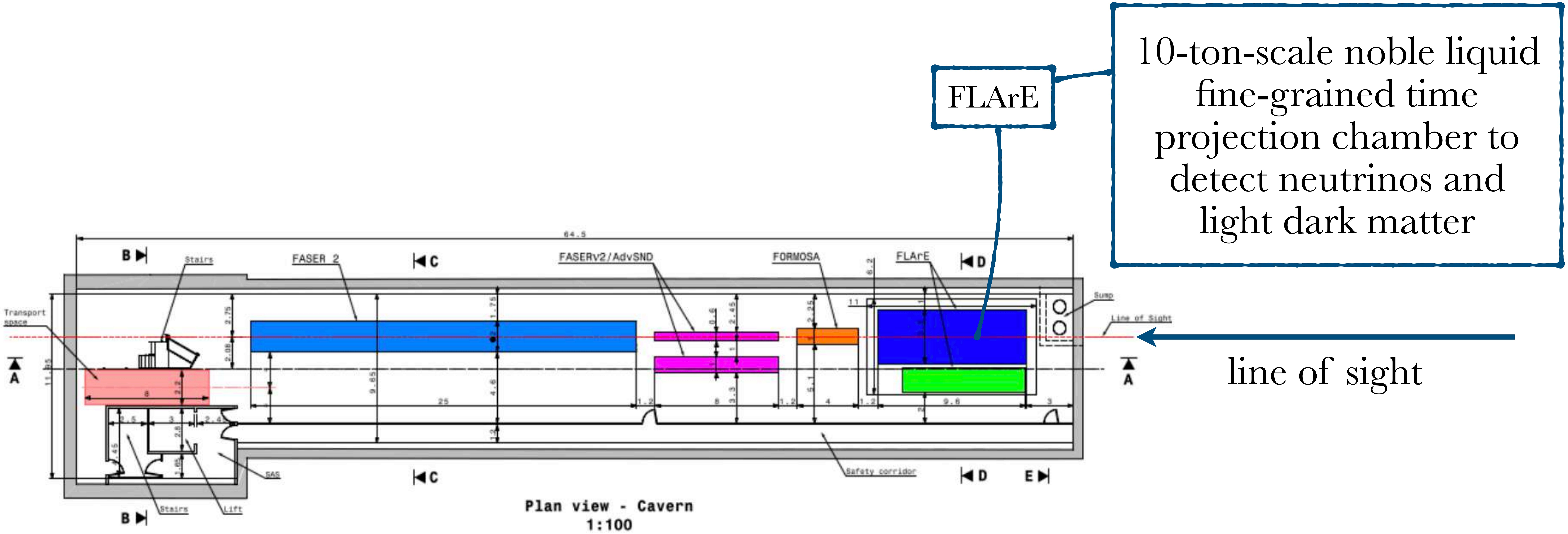

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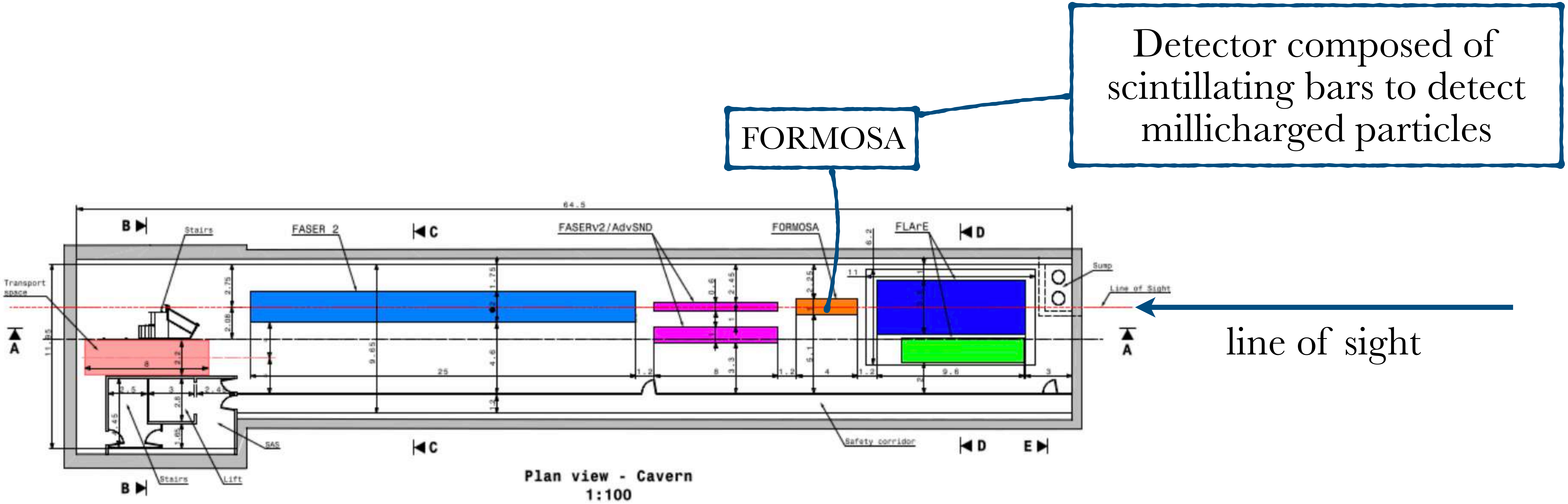

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FPF Physics Potential

- Example:

FASERν 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: ~ $\$10^9$
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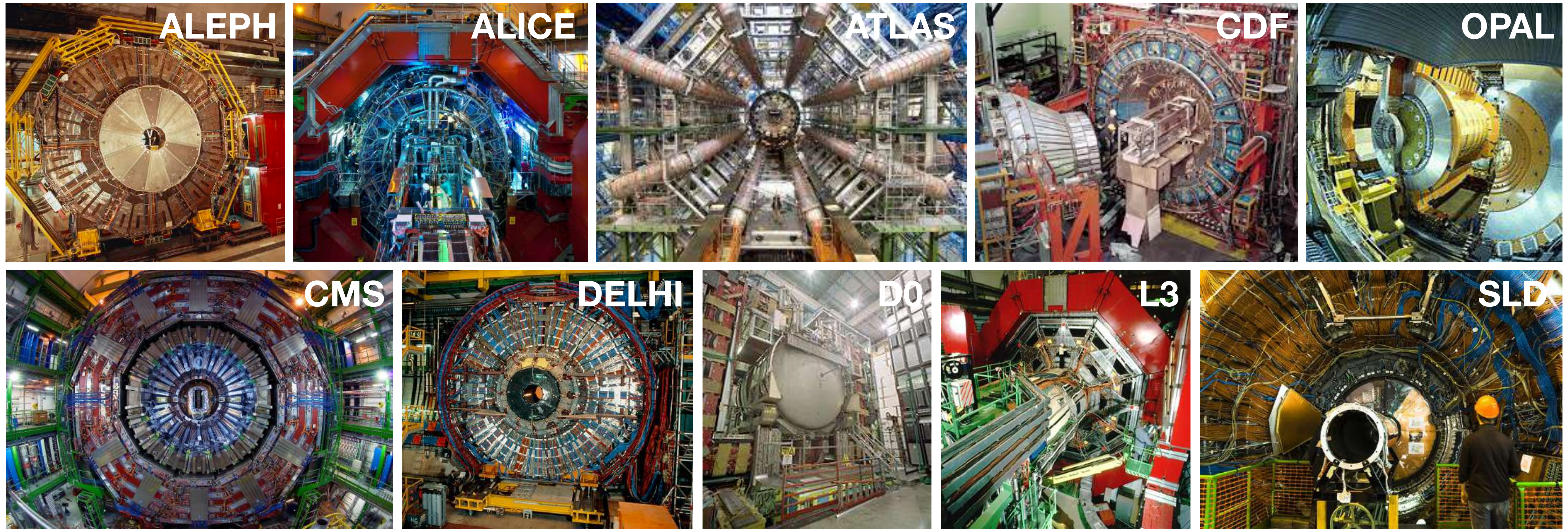

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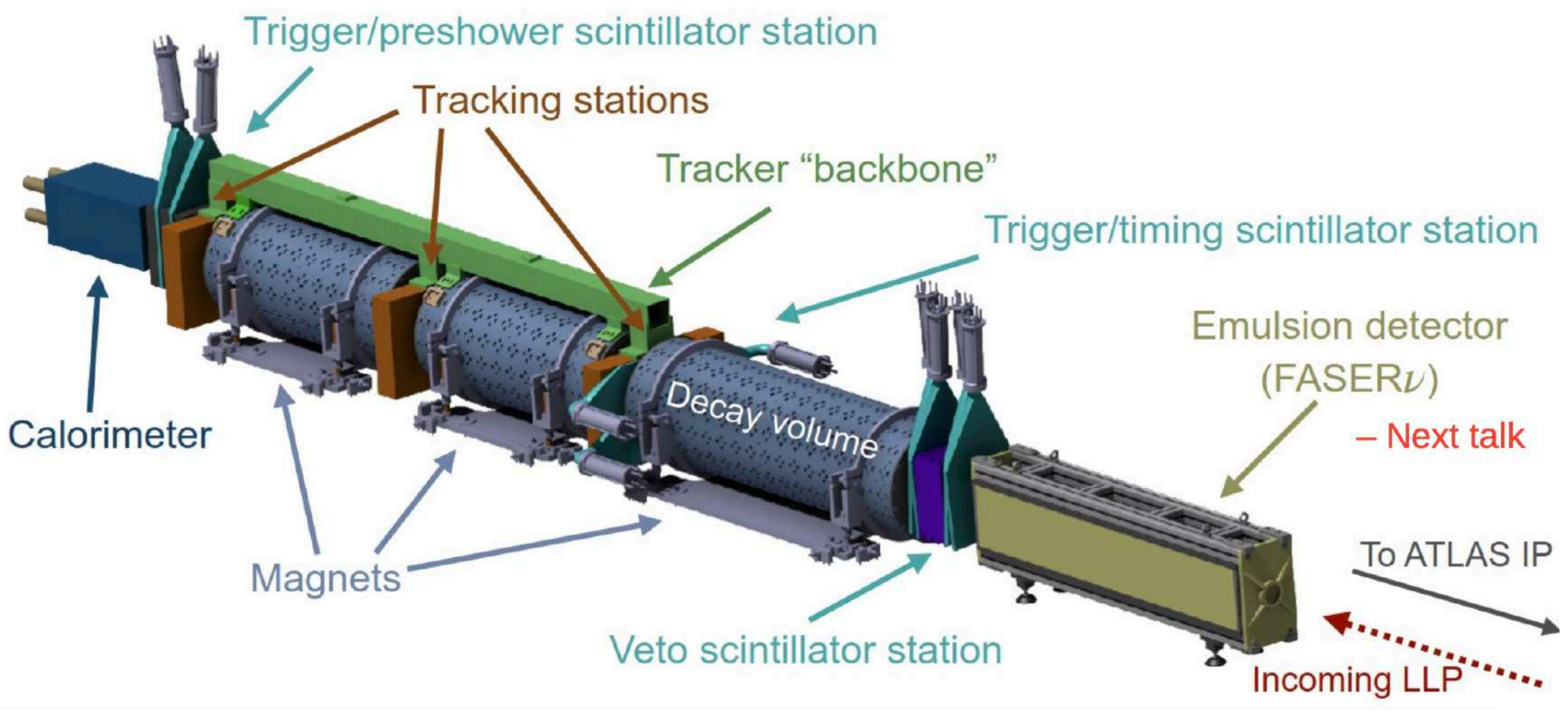
- FASERν years 2022-2024:
  - First 153 neutrino candidates reported
    [FASER Collaboration, Phys. Rev. Lett. 131 (2023)]
  - Significance of $\sim 16\sigma$
  - ~ 10000 ν candidates expected
    ($\sim 10^9$ muons*)



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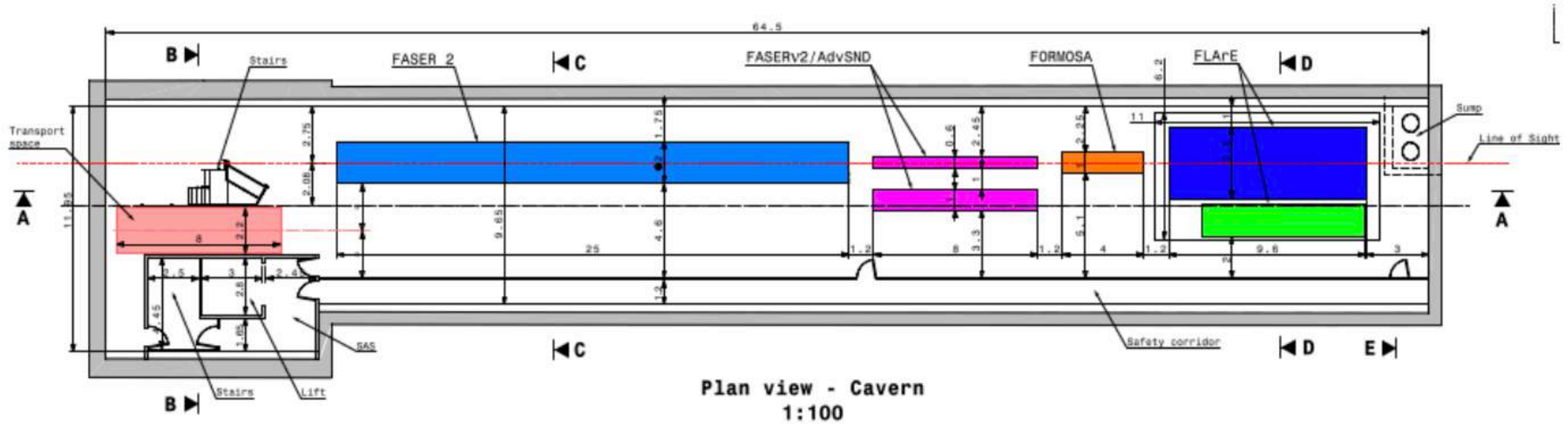
- Forward Physics Facility:
  - $\sim 10^6\ \nu$ candidates expected! ($\sim 10^{12}$ muons*)



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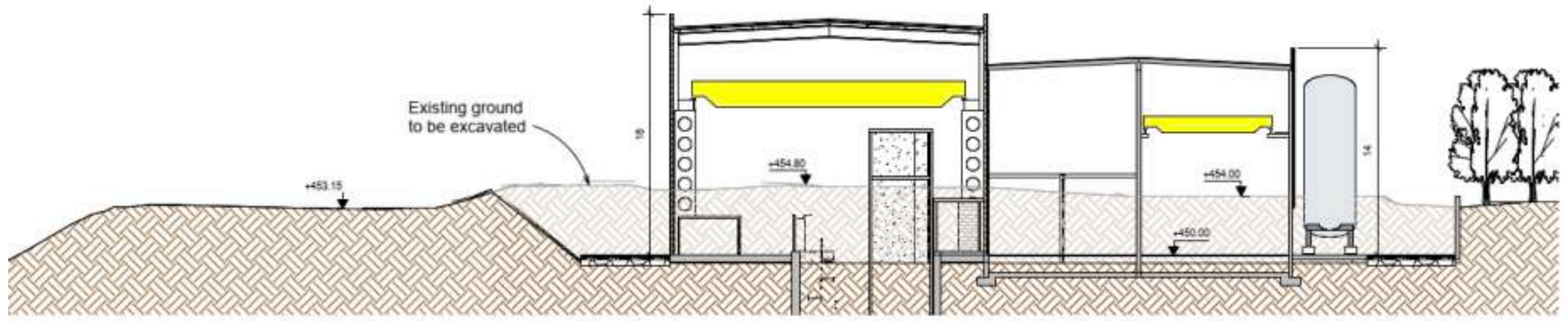
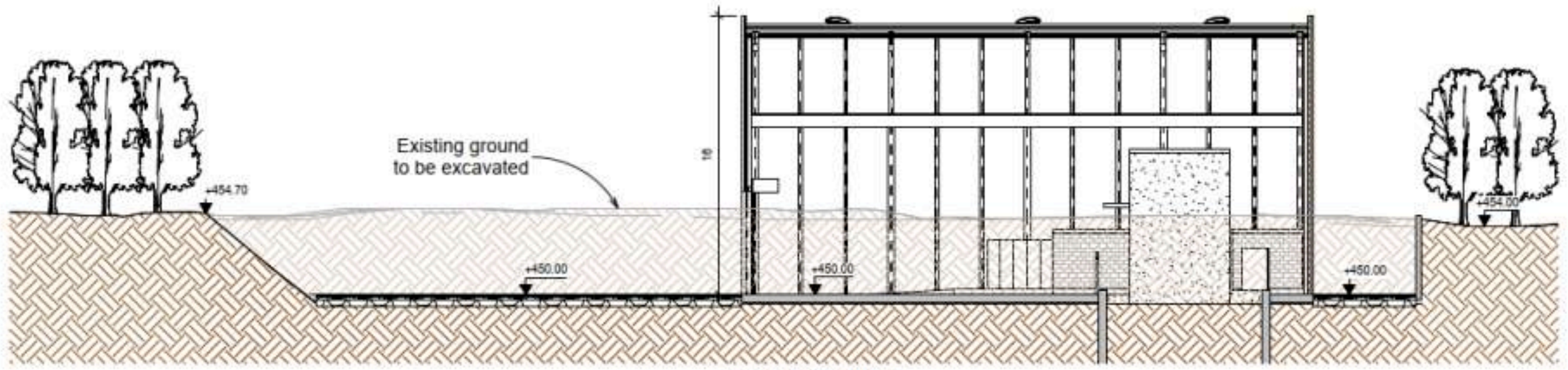
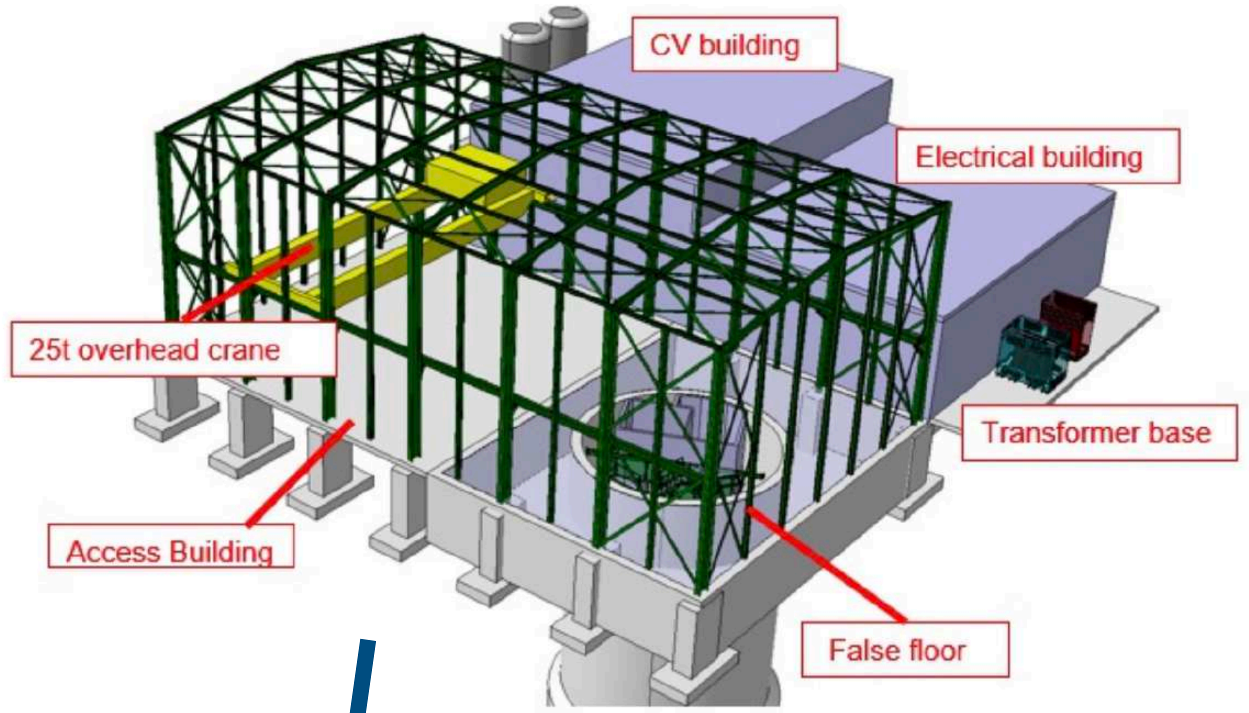
The Facility

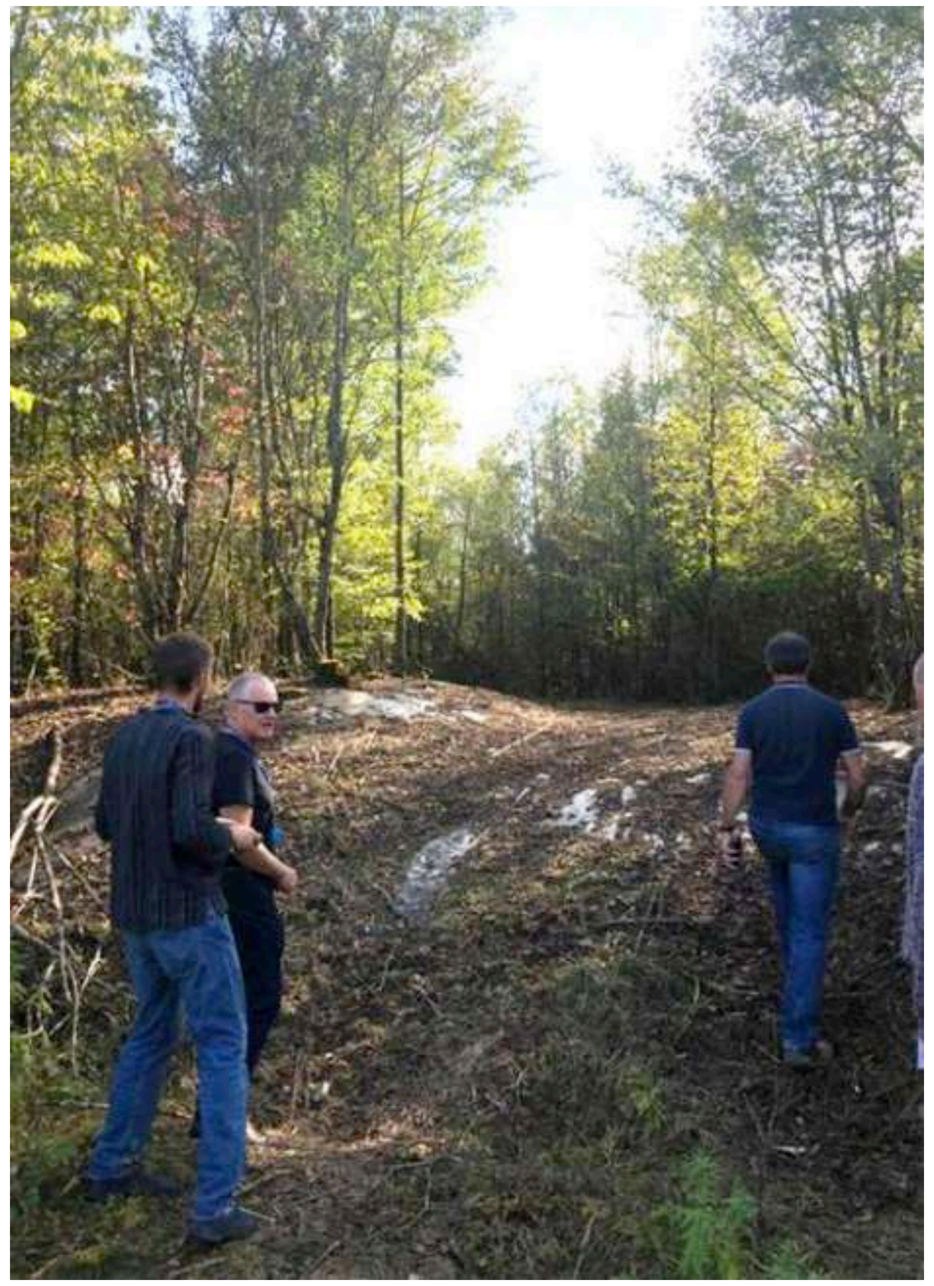


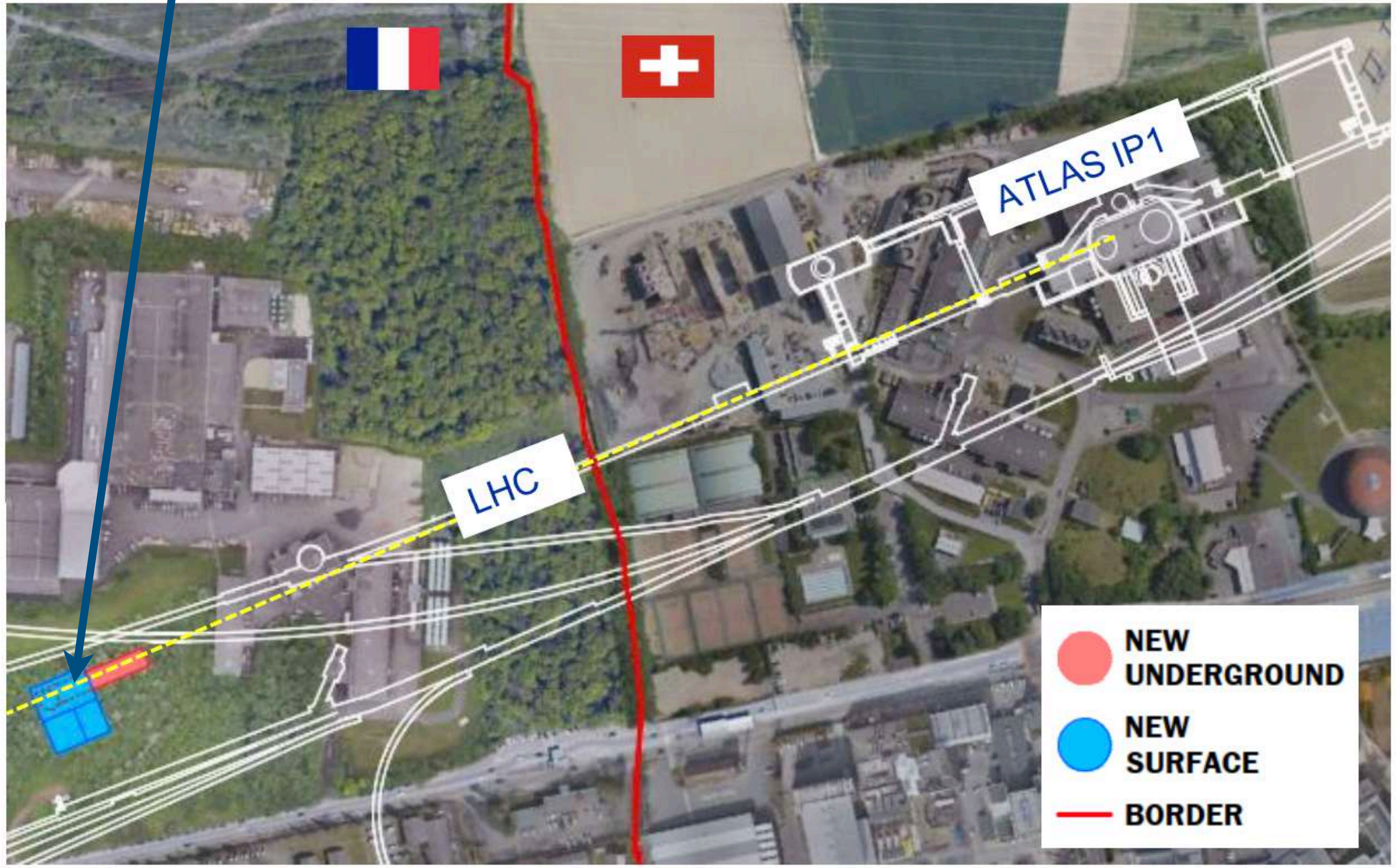
SECTION 1-1



SECTION 2-2

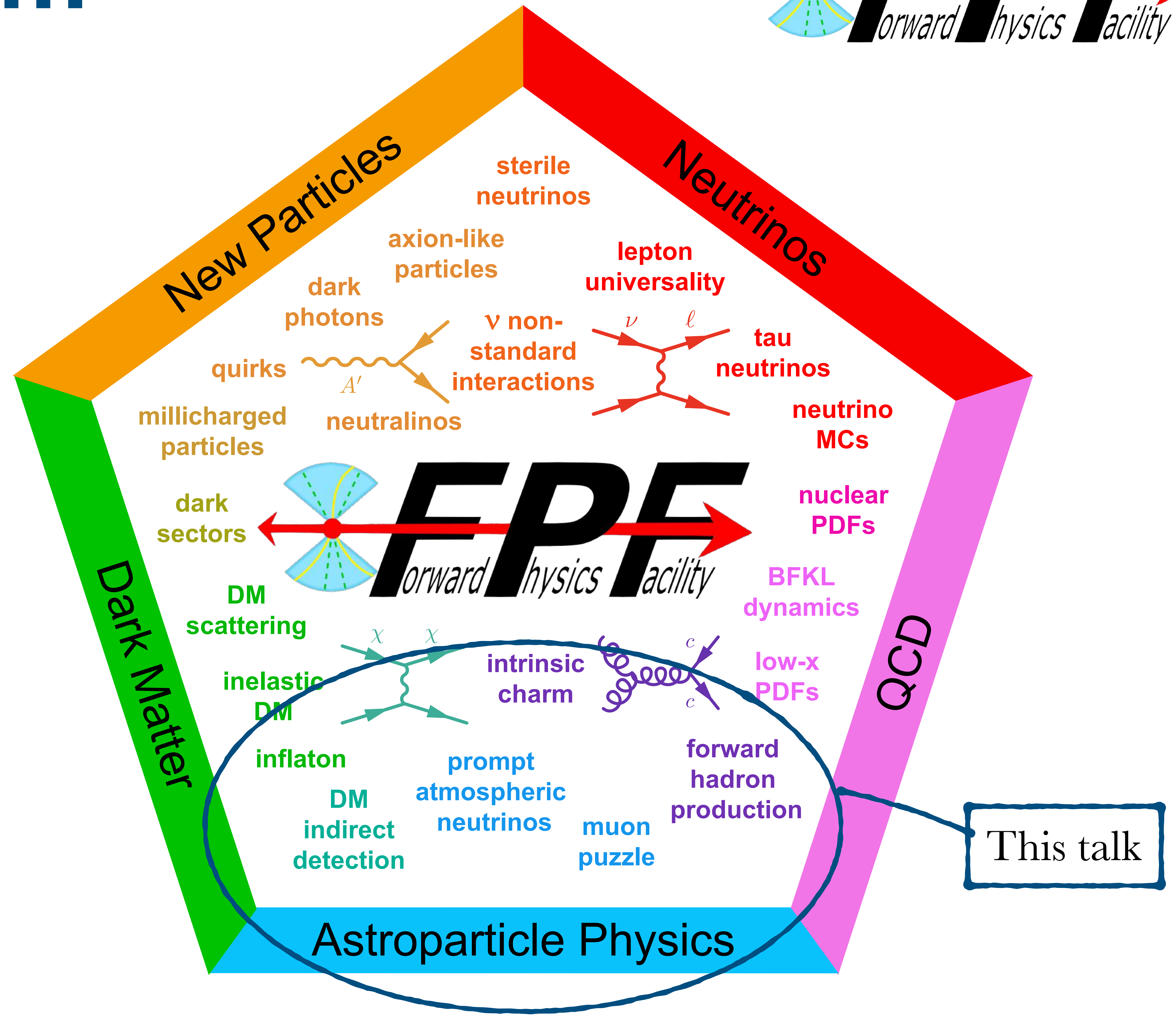






FPF Physics Program

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



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  - 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/

OPEN ACCESS
IOP Publishing
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 Kling[2], Mary Hall Reno[3], Juan Rojo[4,5], Dennis Soldin[6], Luis A Anchordoqui[7], Jamie Boyd[8], Ahmed Ismail[9], Lucian Harland-Lang[10,11], Kevin J Kelly[12], Vishvas Pandey[13,14], Sebastian Trojanowski[15,16], Yu-Dai Tsai[1], Jean-Marco Alameddine[17], Takeshi Araki[18], Akitaka Ariga[19,20], Tomoko Ariga[21], Kento Asai[22,23], Alessandro Bacchetta[24,25], Kincso Balazs[8], Alan J Barr[10], Michele Battistin[8], Jianming Bian[1], Caterina Bertone[8], Weidong Bai[26], Pouya Bakhti[27], A Baha Balantekin[28], Basabendu Barman[29], Brian Batell[30], Martin Bauer[31], Brian Bauer[30], Mathias Becker[32], Asher Berlin[14], Enrico Bertuzzo[33], Atri Bhattacharya[34], Marco Bonvini[35], Stewart T Boogert[36], Alexey Boyarsky[37], Joseph Bramante[38,39], Vedran Brdar[40,41], Adrian Carmona[42], David W Casper[1], Francesco Giovanni Celiberto[43,44,45], Francesco Cerutti[8], Grigorios Chachamis[46], Garv Chauhan[47], Matthew Citron[48], Emanuele Copello[32], Jean-Pierre Corso[8], Luc Darmé[49], Raffaele Tito D'Agnolo[50], Neda Darvishi[51], Arindam Das[52,53], Giovanni De Lellis[54,55], Albert De Roeck[8], Jordy de Vries[5,56], Hans P Dembinski[57], Sergey Demidov, Patrick deNiverville[58], Peter B Denton[59], Frank F Deppisch[60], P S Bhupal Dev[61], Antonia Di Crescenzo[8,54,55], Keith R Dienes[62,63], Milind V Diwan[64], Herbi K Dreiner[65,66], Yong Du[67], Bhaskar Dutta[68], Pit Duwentäster[69], Lucie Elie[8], Sebastian A R Ellis[70], Rikard Enberg[71], Yasaman Farzan[72], Max Fieg[1], Ana Luisa Foguel[33], Patrick Foldenauer[31], Saeid Foroughi-Abari[73], Jean-François Fortin[74], Alexander Friedland[75], Elina Fuchs[12,76,77], Michael Fucilla[78,79], Kai Gallmeister[80], Alfonso Garcia[81,82],

FPF Physics Program

Forward Physics Facility

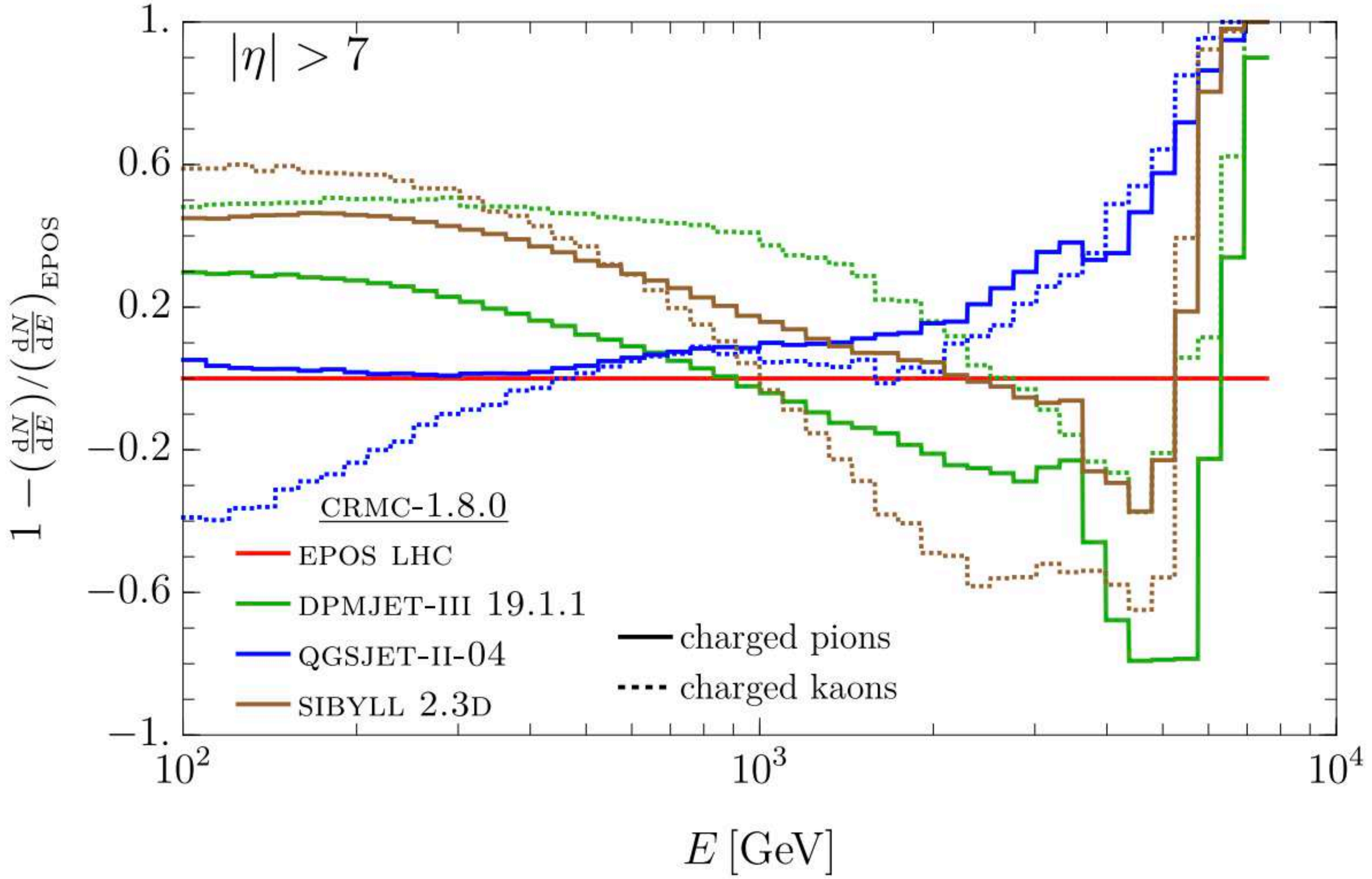
Contents

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
- <u>Measurements of neutrino flues as tests of hadronic interaction models and prompt neutrino production models</u>

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

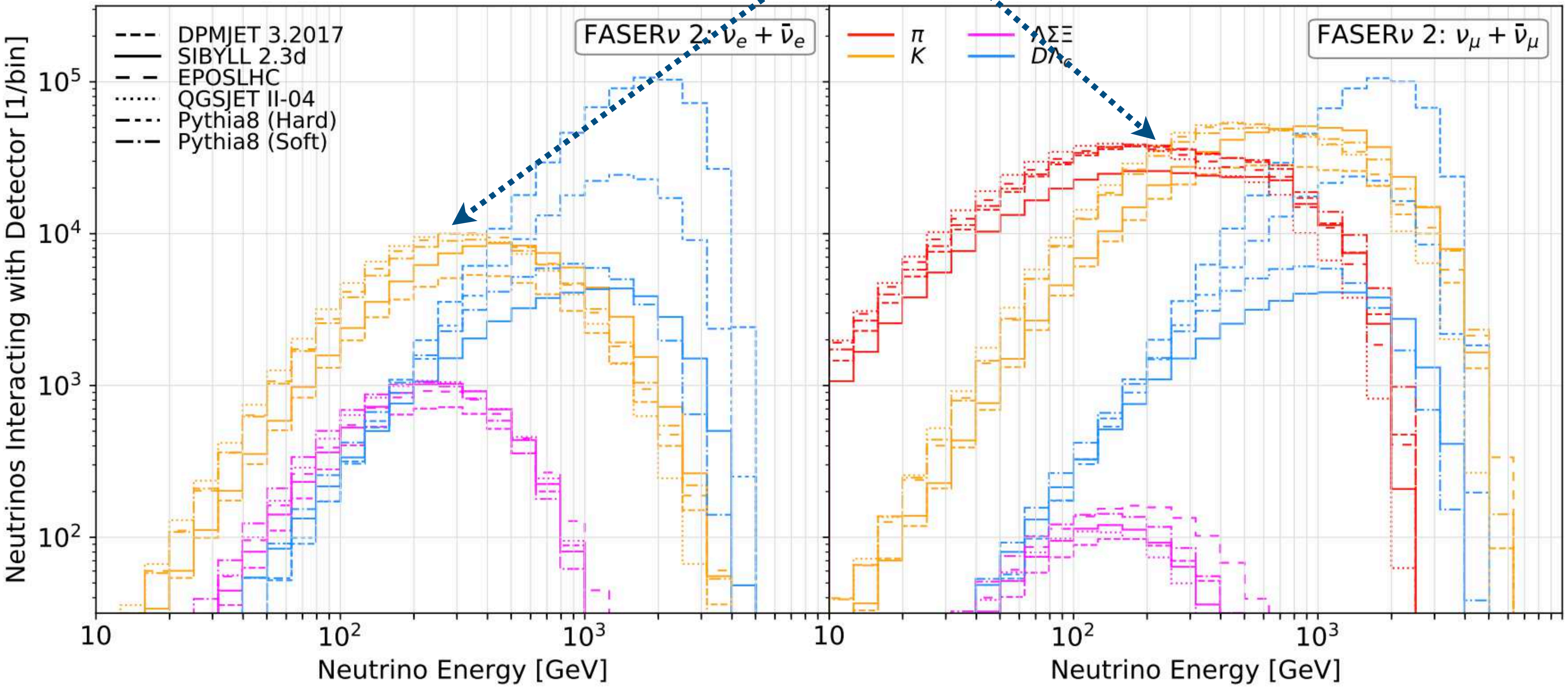


Light Hadron Production

- Example: Neutrino fluxes at FASERν2

low-energy region relevant!

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

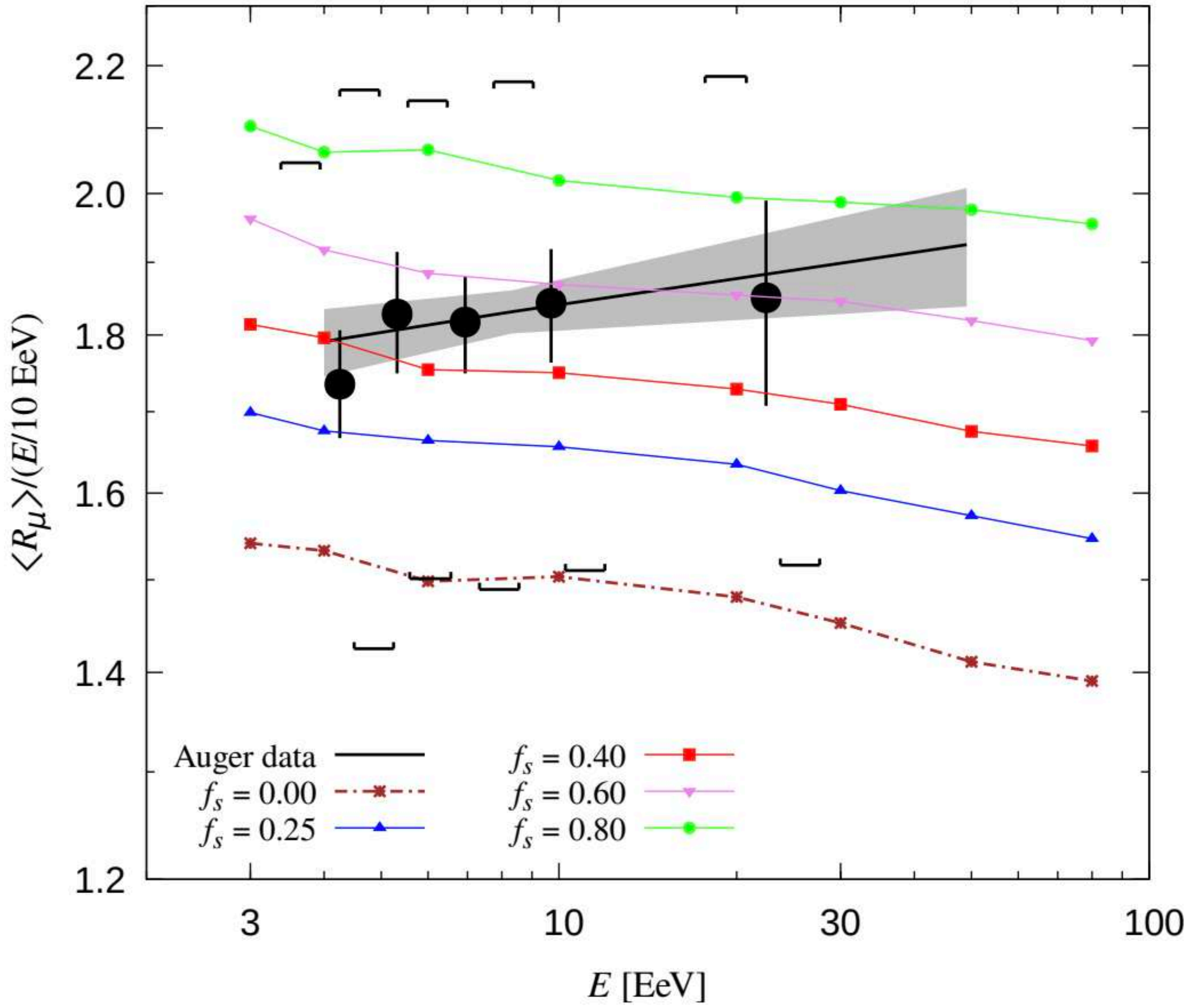


- Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties!

Light Hadron Production

- Indications for strangeness enhancement in the mid rapidity region reported by ALICE
  [J. Adam et al. (ALICE), Nature Phys. 13, 535 (2017)]
- Can this effect also be seen in hadrons produced at forward rapidities?
- Simple toy model:
  [L. Anchordoqui et al., JHEAp 34 (2022)]
  - Strangeness enhancement realized by $\pi \leftrightarrow K$ swapping
  - Swapping fraction f_s
- Possible explanation for the Muon Puzzle in EAS!
- FPF provides unique opportunities for testing the forward rapidity region!

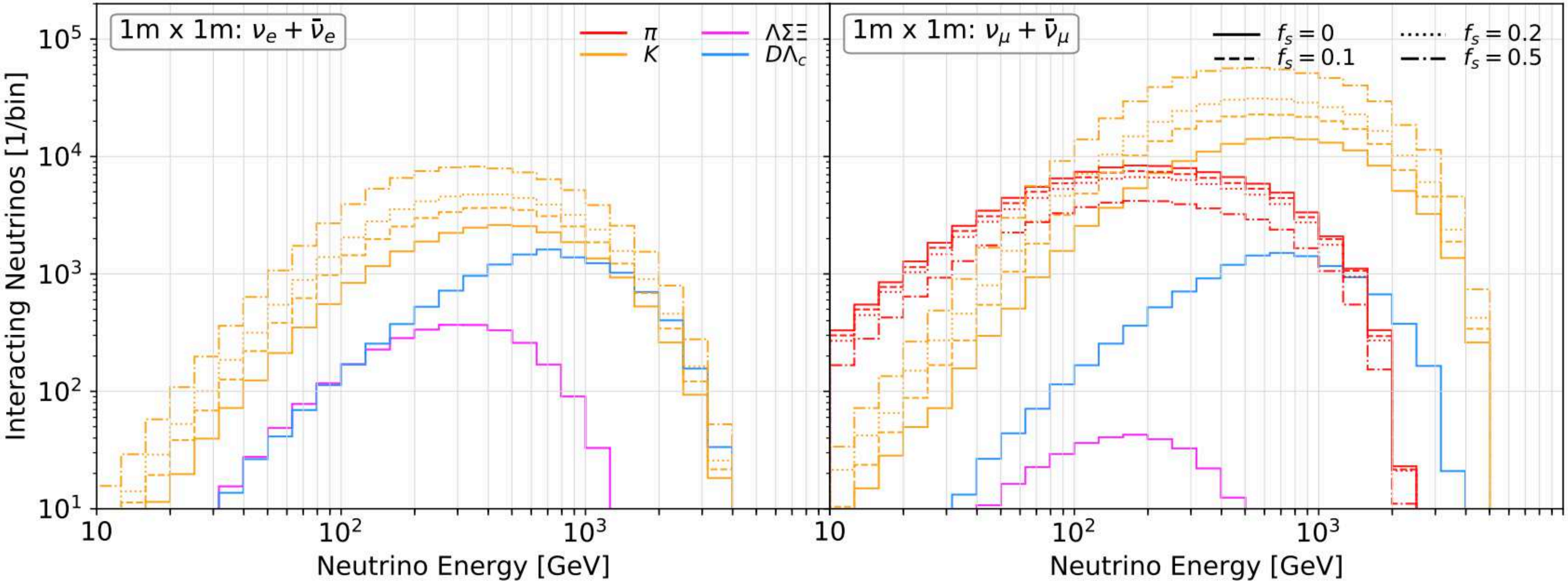
[L. Anchordoqui et al., JHEAp 34 (2022)]



Light Hadron Production

- Example: Neutrino fluxes at FLArE

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



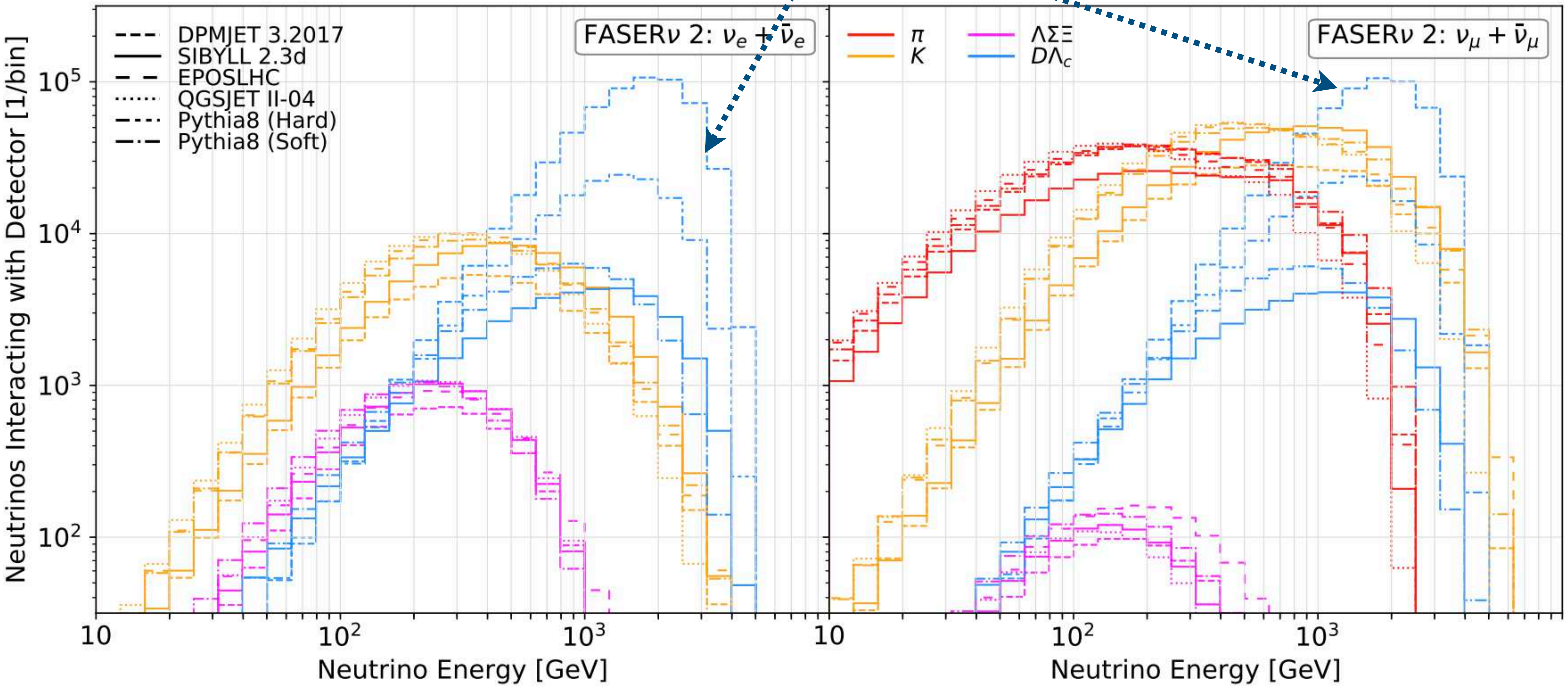
- Model comparison: strangeness enhancement toy model as an example [L. Anchordoqui et al., JHEAp 34 (2022)]

Prompt Hadron Production

- Example: Neutrino fluxes at FASERν2

high-energy region relevant!

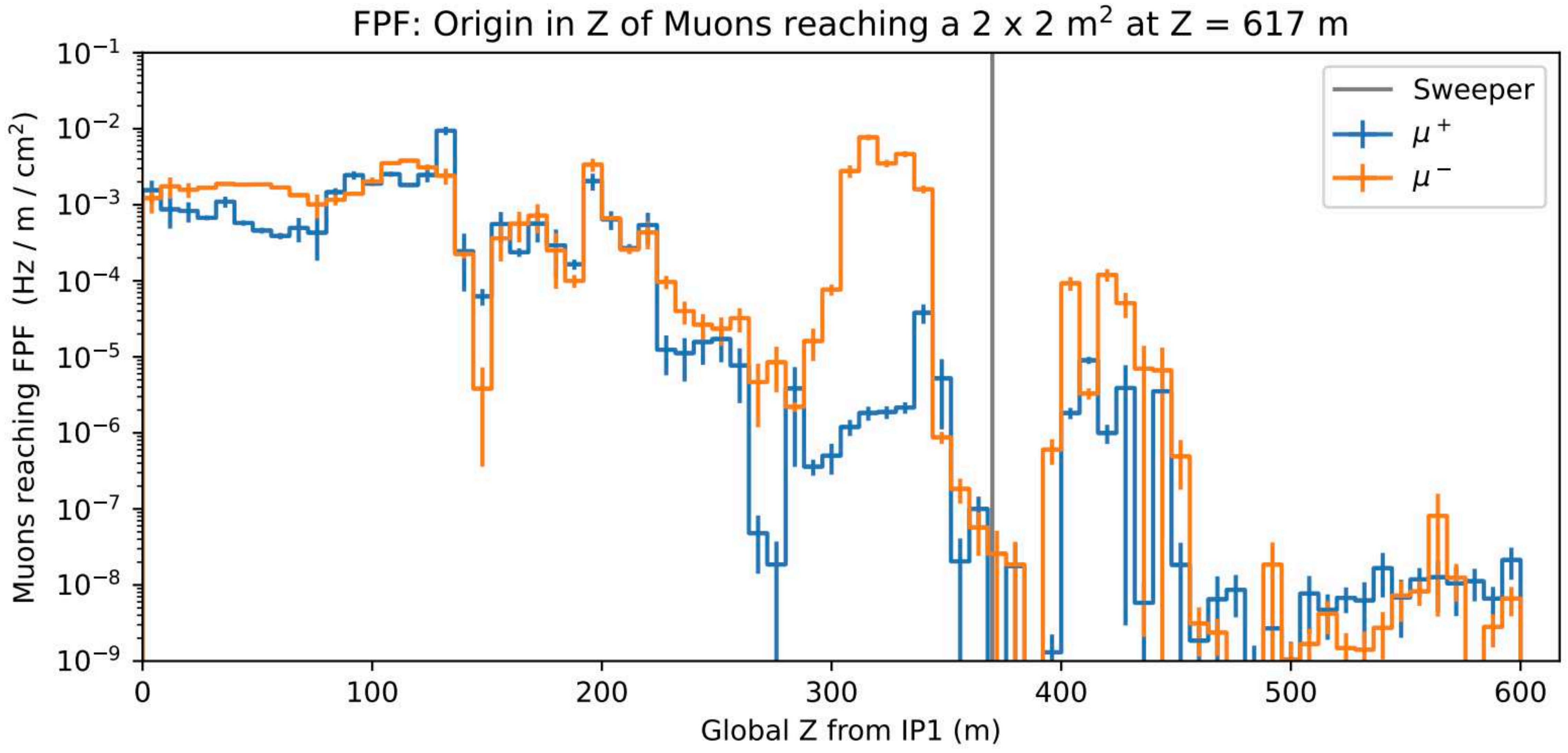
[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]



- 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…

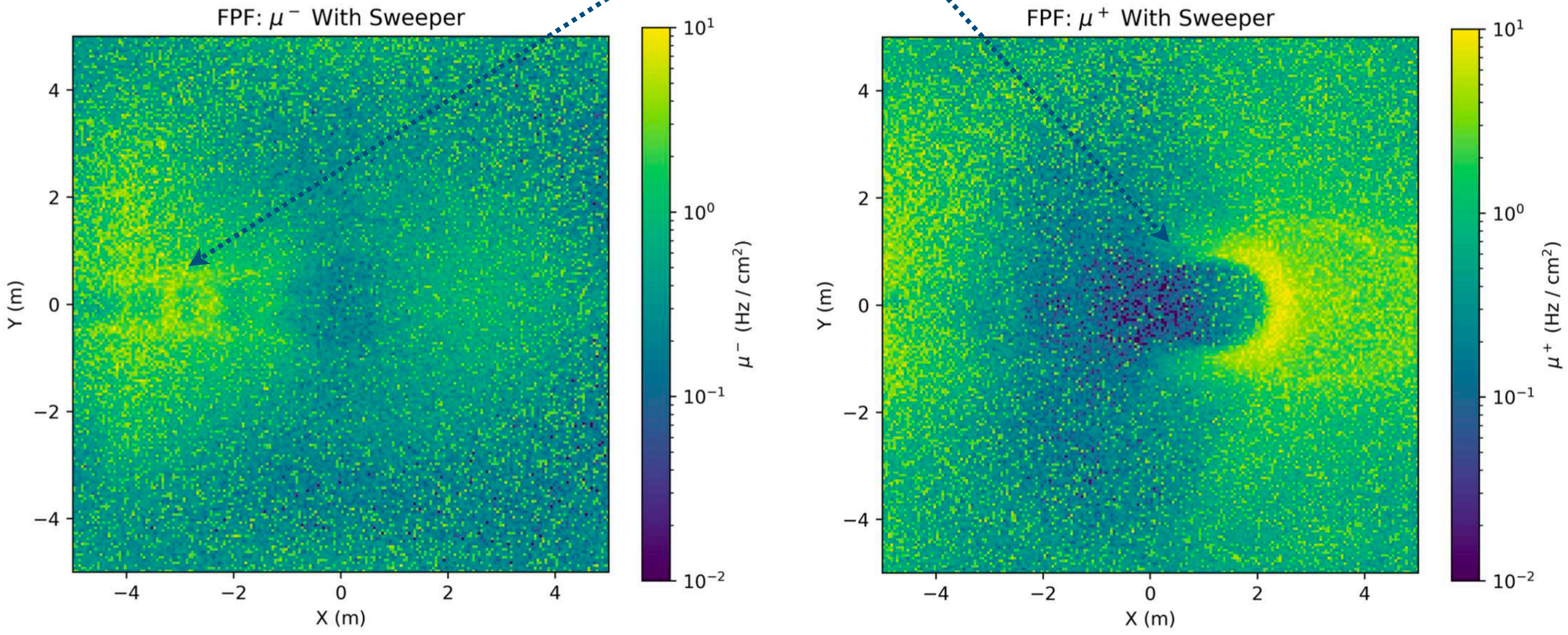


[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Muon Fluxes at the FPF

- <u>Muon fluxes at the FPF:</u>

various structures observed



- Temporary detectors? Simulation studies ongoing…

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

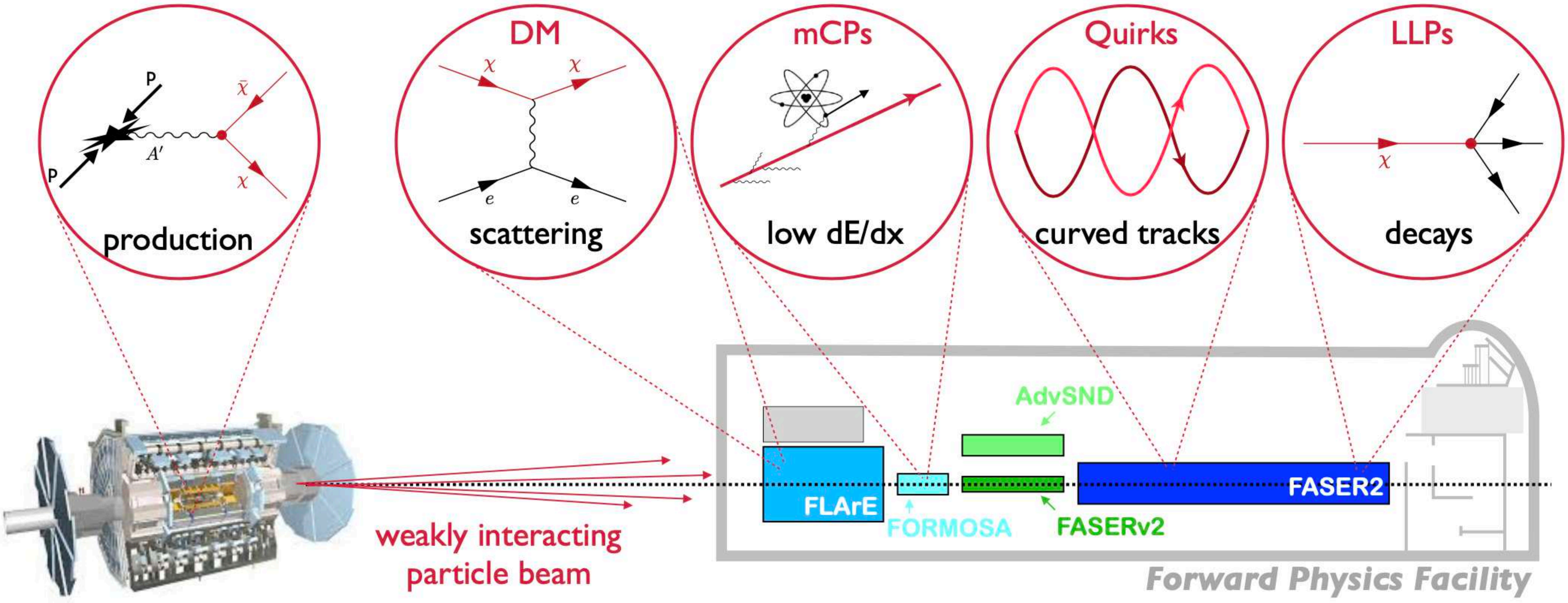
BSM Physics & Dark Matter

Contents

BSM physics & dark matter

Dark Matter Searches

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



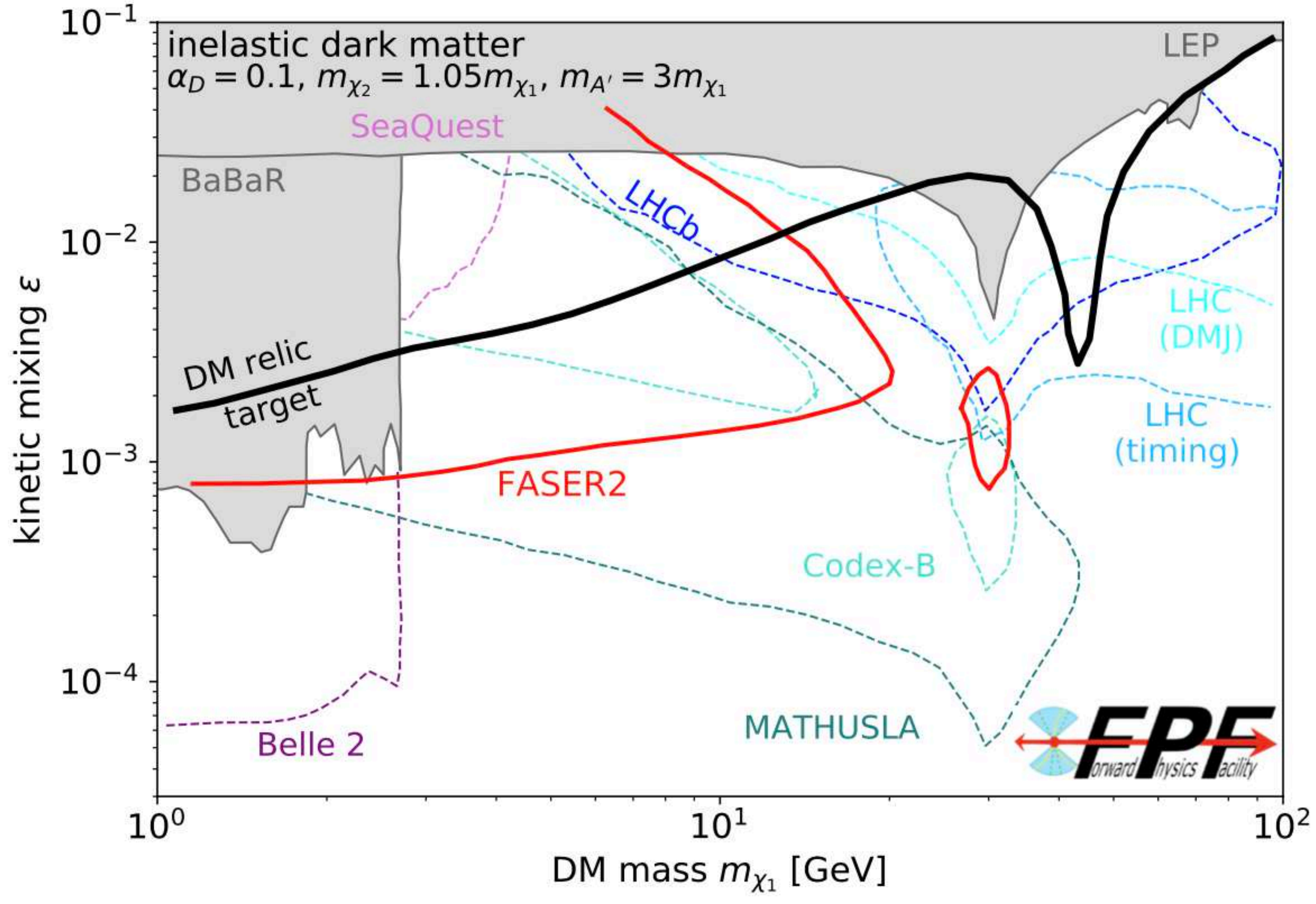
Dark Matter Searches

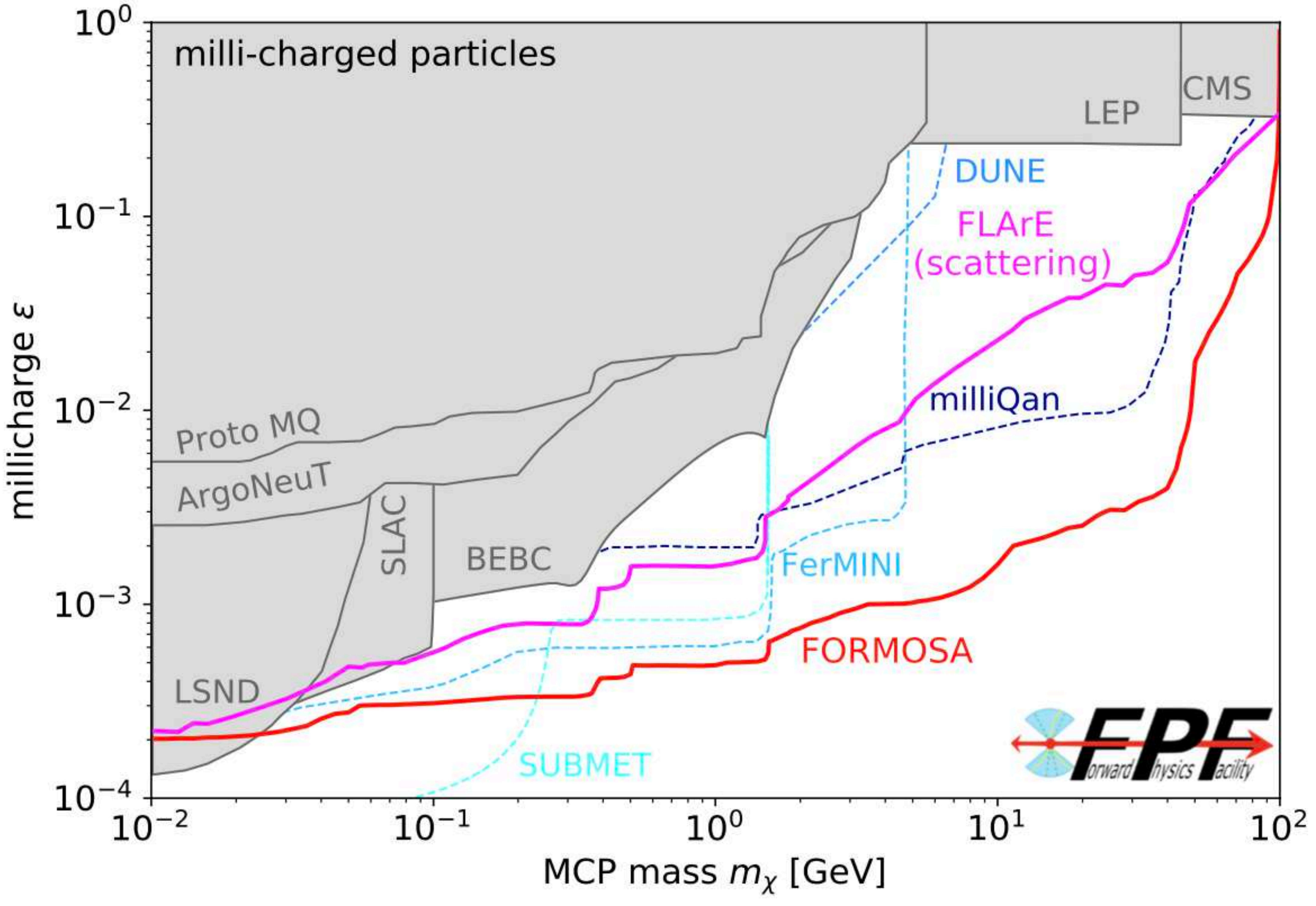
- <u>Examples:</u>

[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

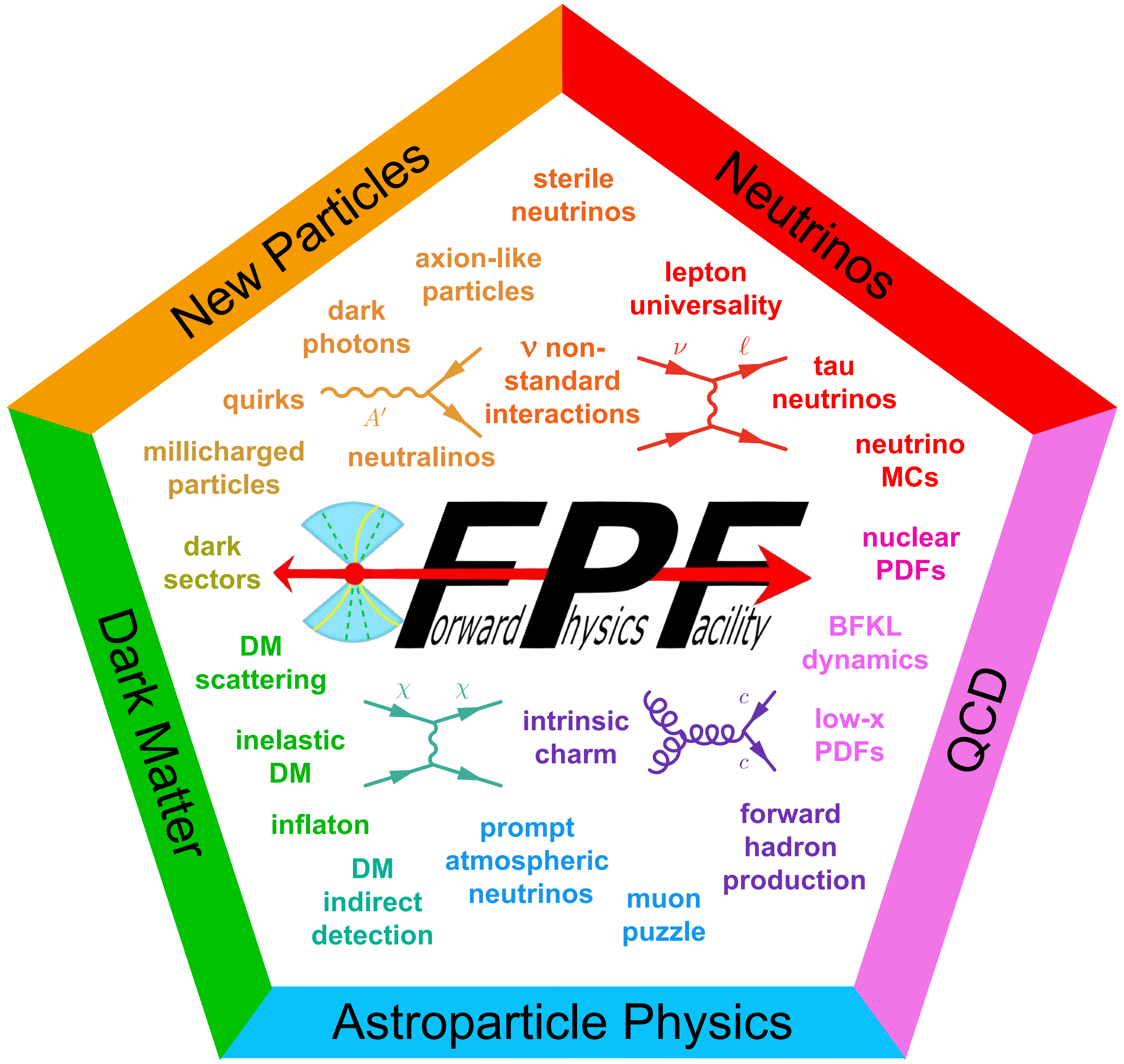
[S. Foroughi-Abari, F. Kling, Phys. Rev. D104 (2021)]





Summary

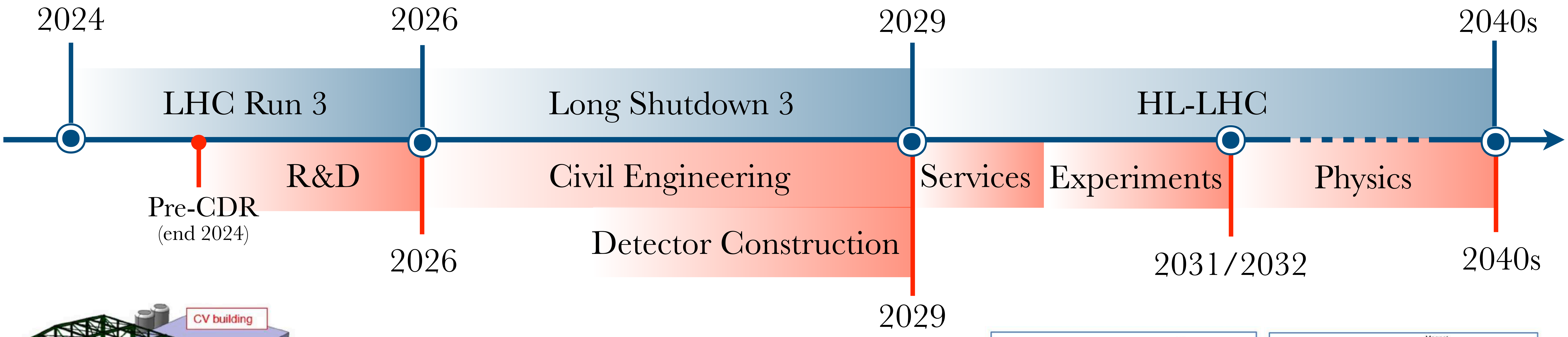
- Cosmic ray measurements highly rely on interpretation based on MC simulations of EASs
  - Large discrepancies observed in the muon content of EAS
- High-energy neutrinos from EASs are background for astrophysical neutrino searches
  - Prompt neutrino flux not well understood
- The FPF is a proposal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

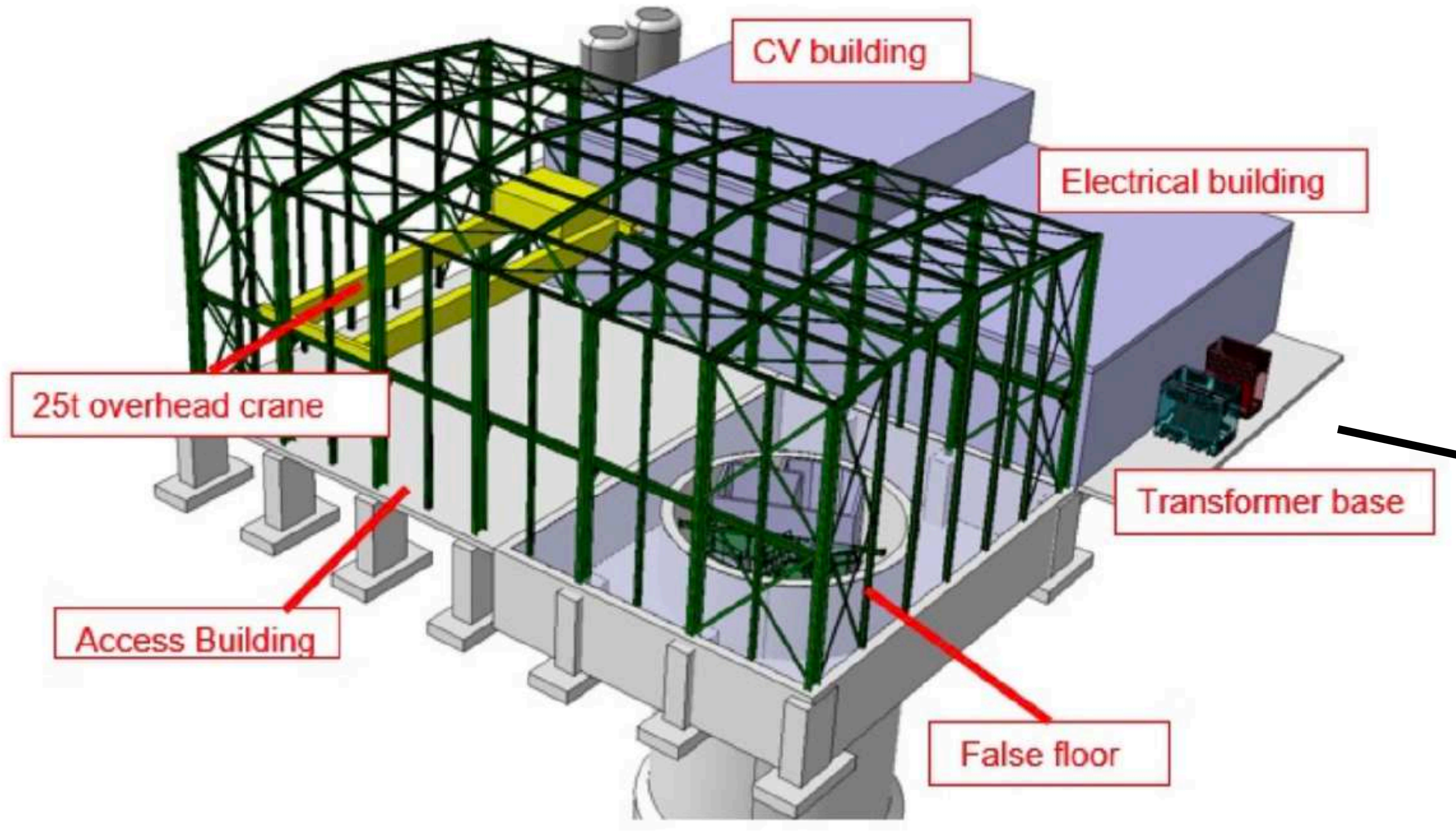


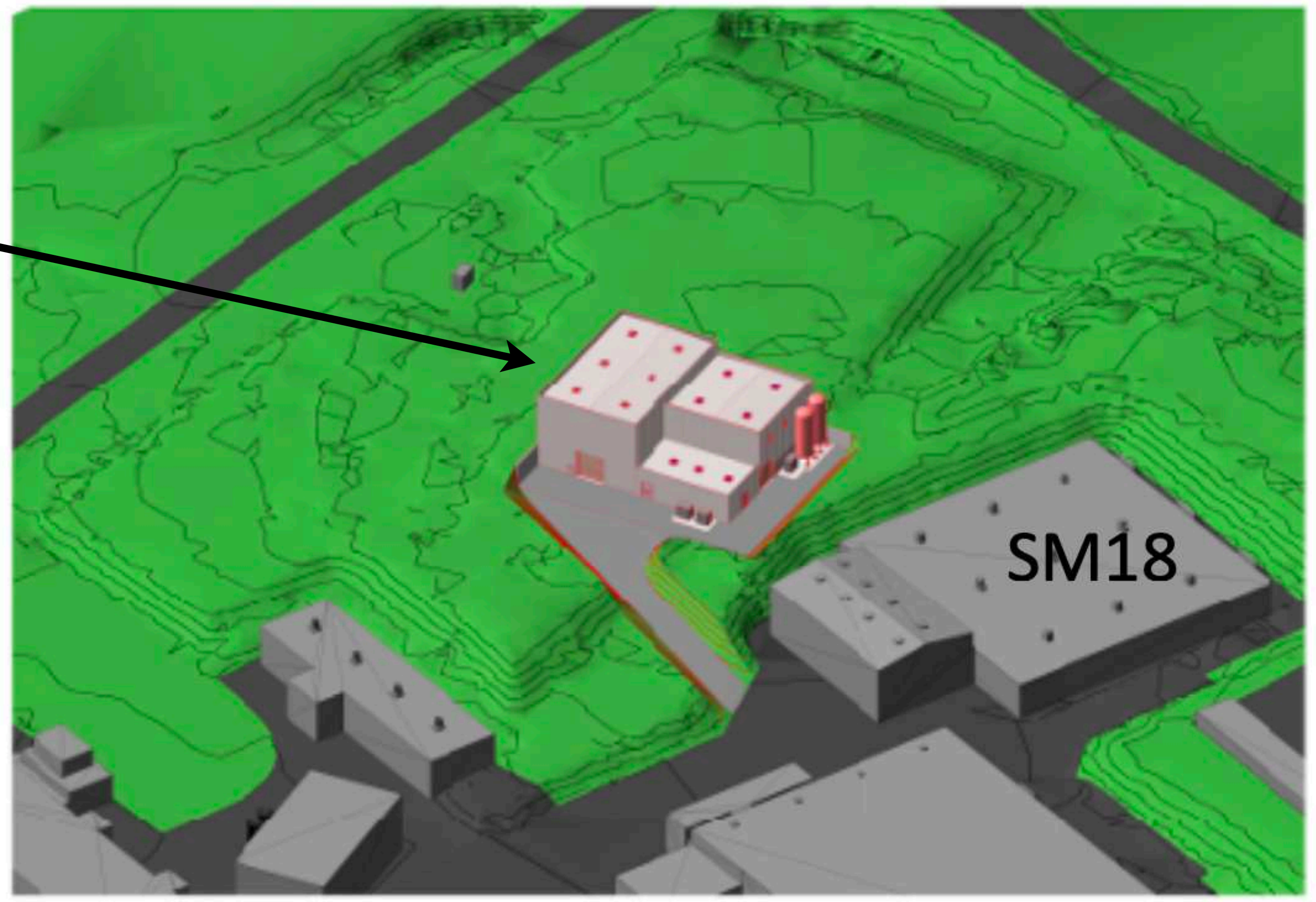
Please don't hesitate to contact us if you want to contribute!

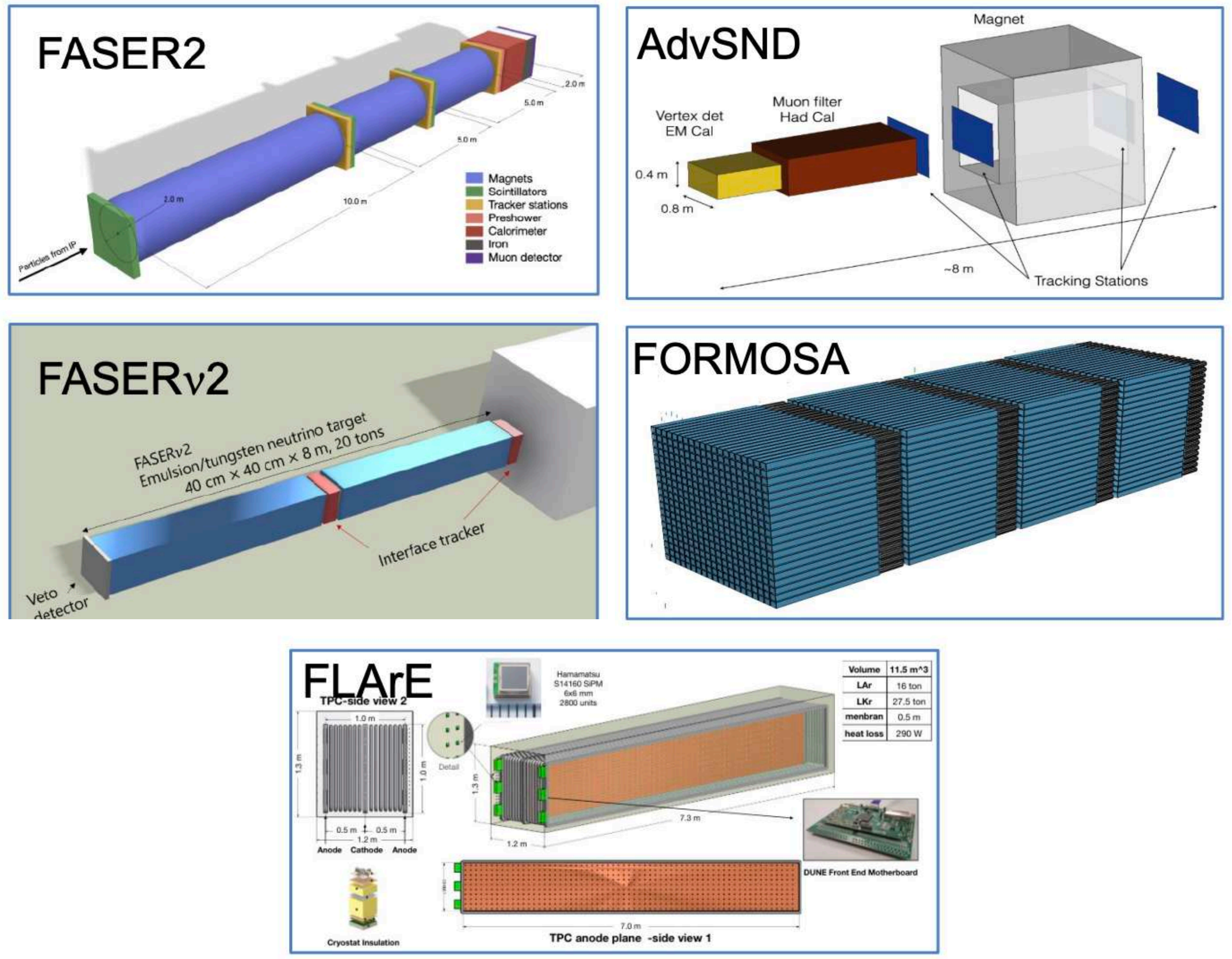
Backup

FPF Timeline



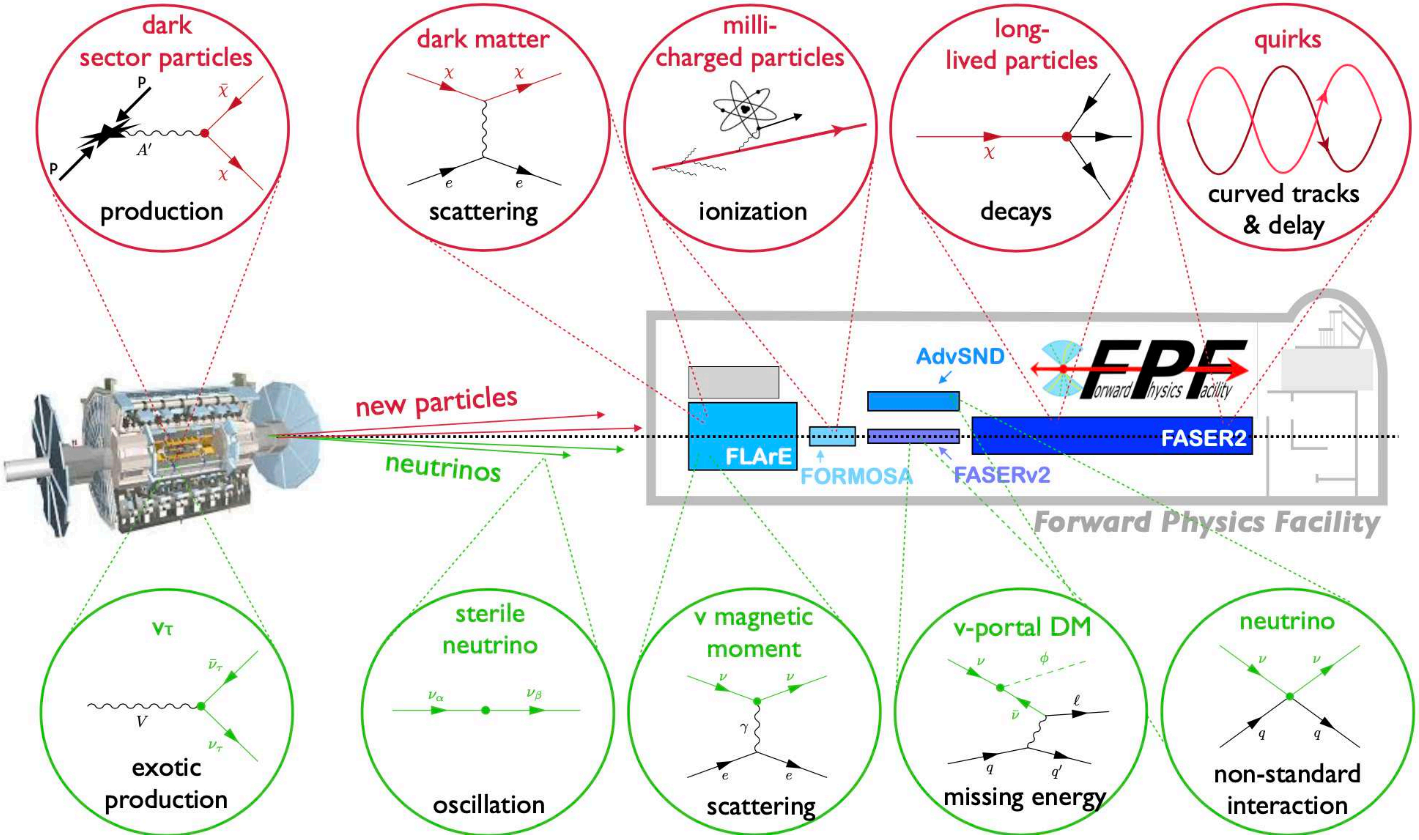




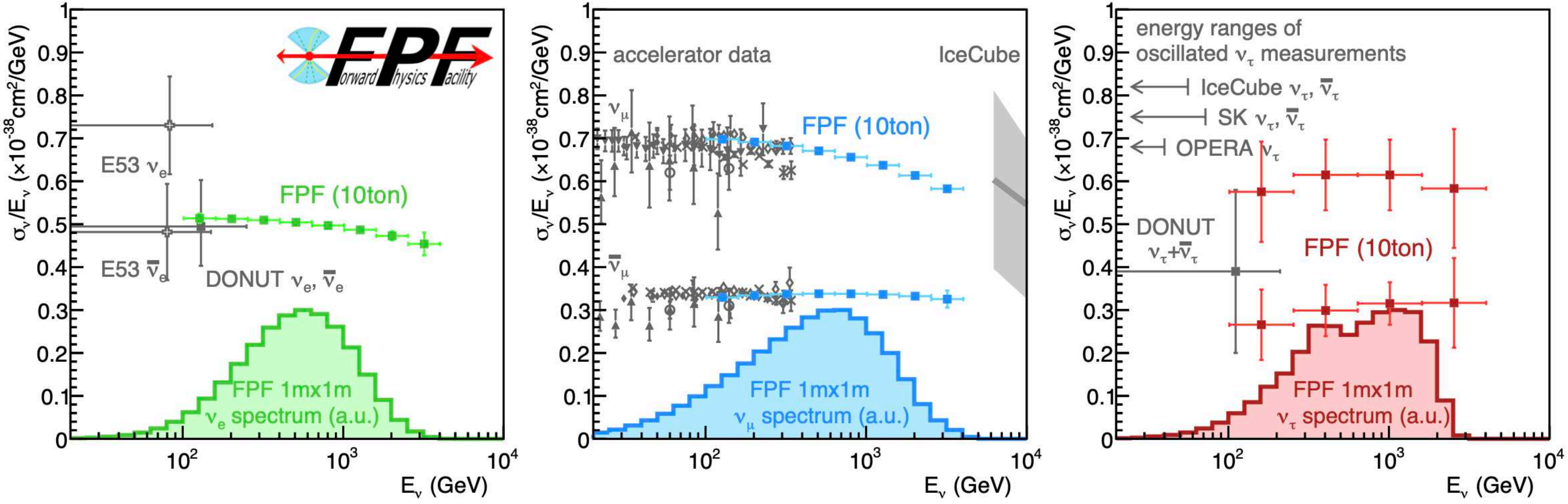


[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Neutrino / DM Overview



Neutrino Fluxes at the FPF



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