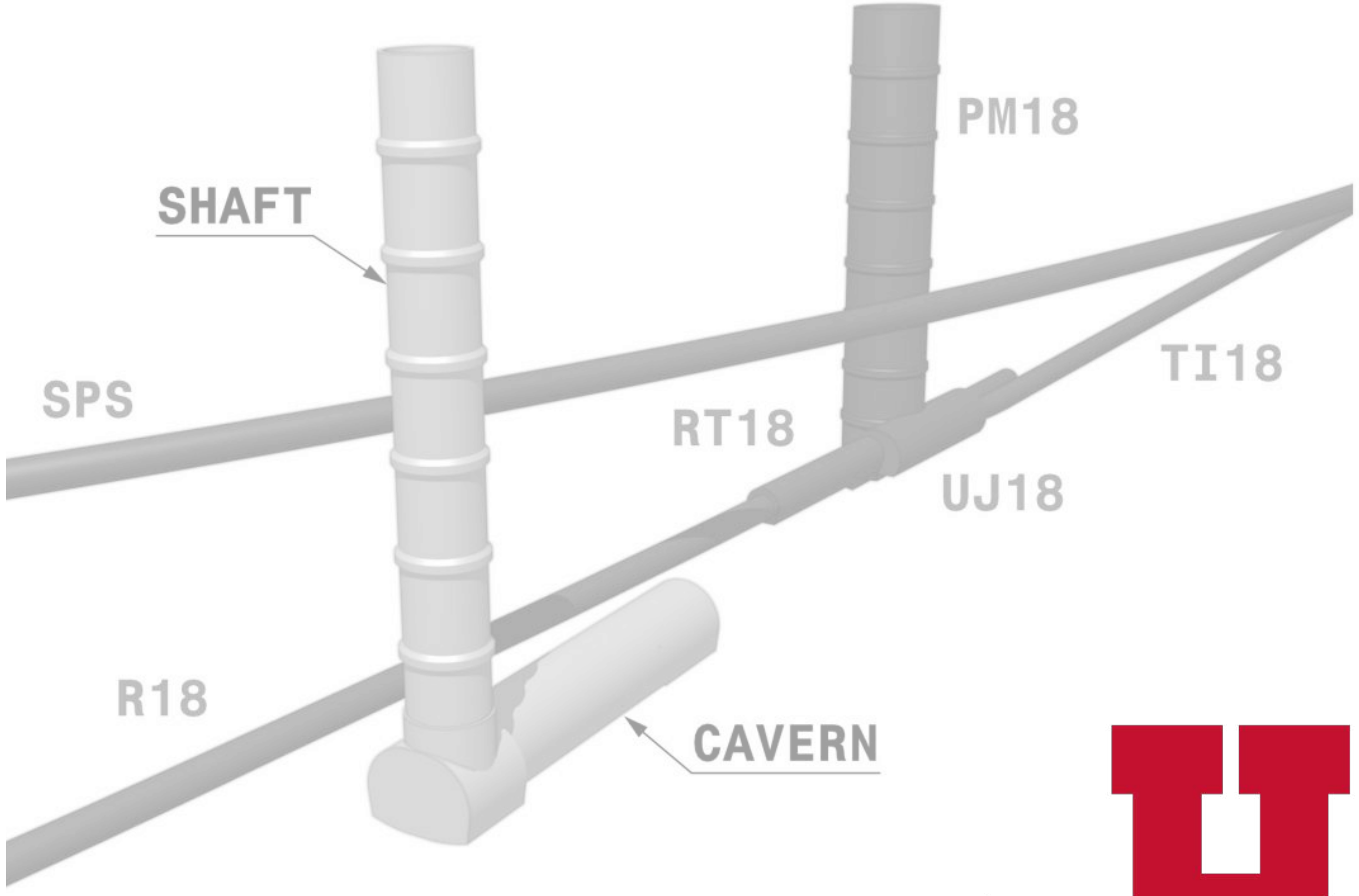
Astroparticle Physics with the Forward Physics Facility

ISVHECRI 2024
Puerto Vallarta, Mexico



Dennis Soldin
University of Utah

Introduction: The Muon Puzzle

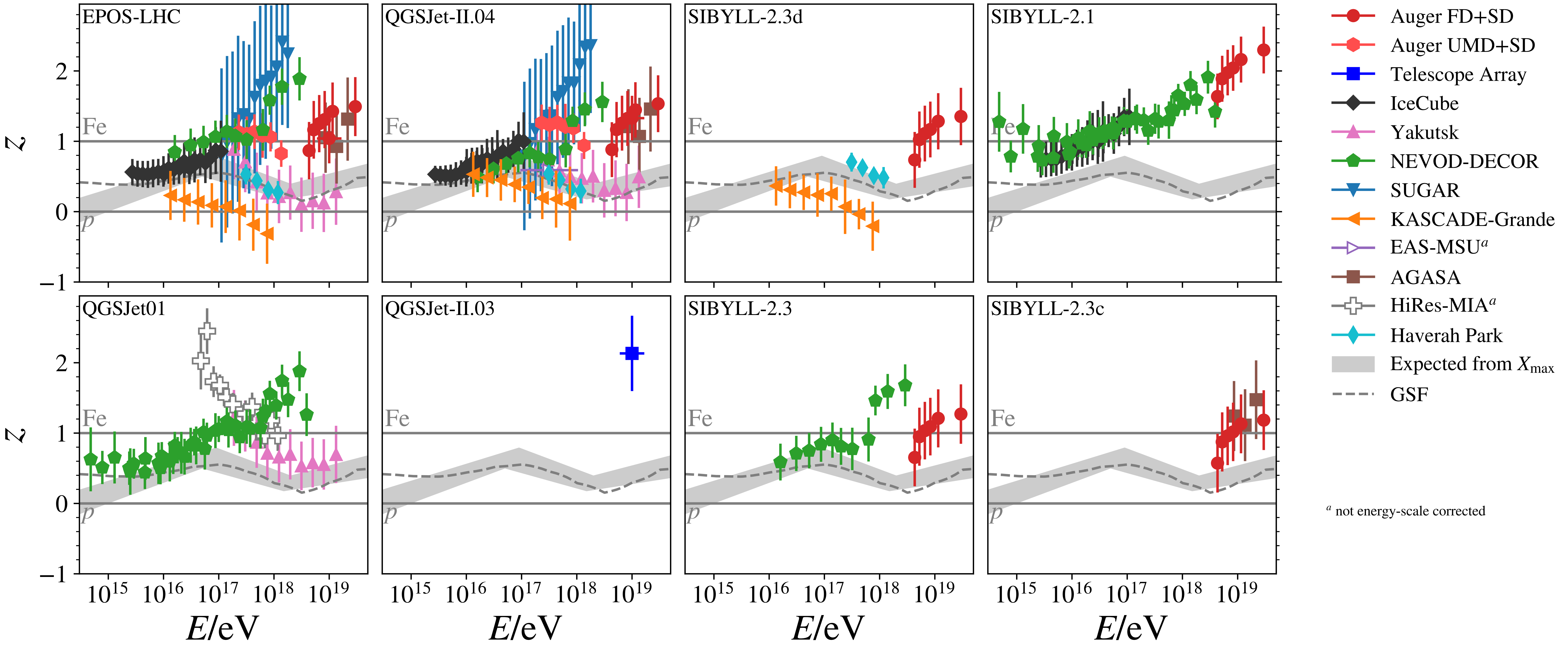
Talk by J. C. Arteaga-Velázquez
this afternoon

- 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:

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

  - $z = 0$: proton
  - $z = 1$: iron

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

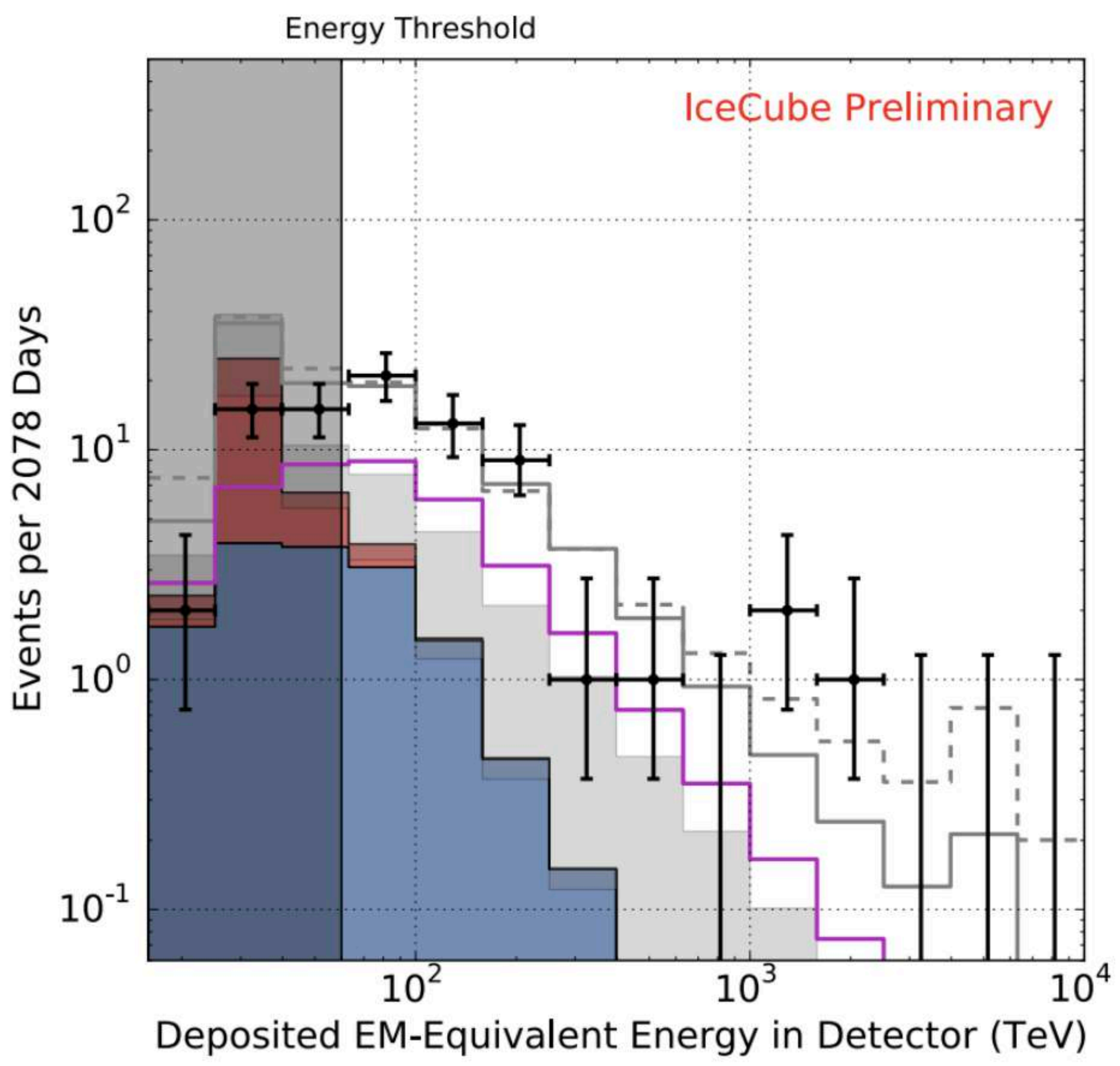


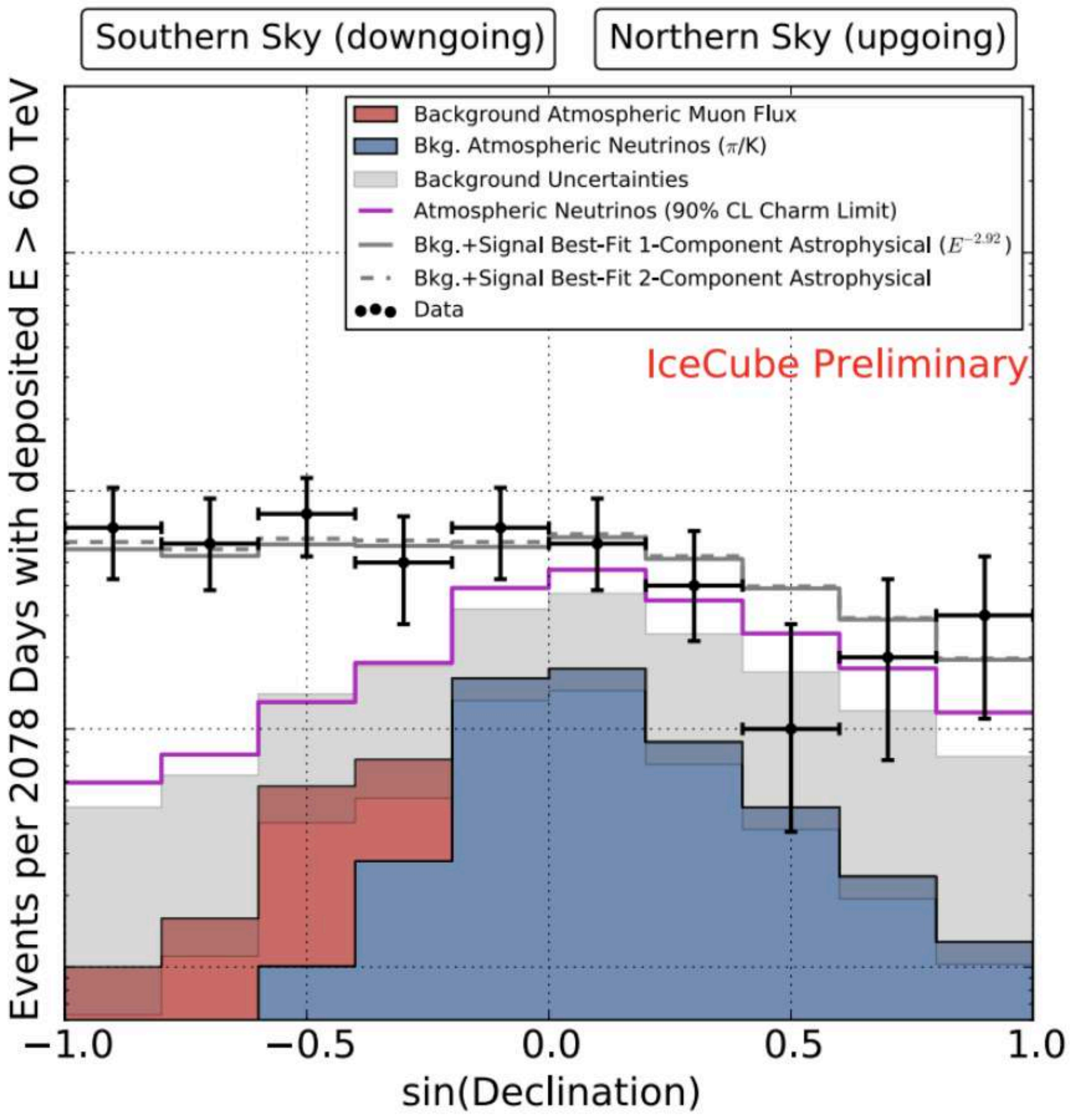
[J. C. Arteaga-Velázquez (WHISP), PoS ICRC2023 (2023) 466]

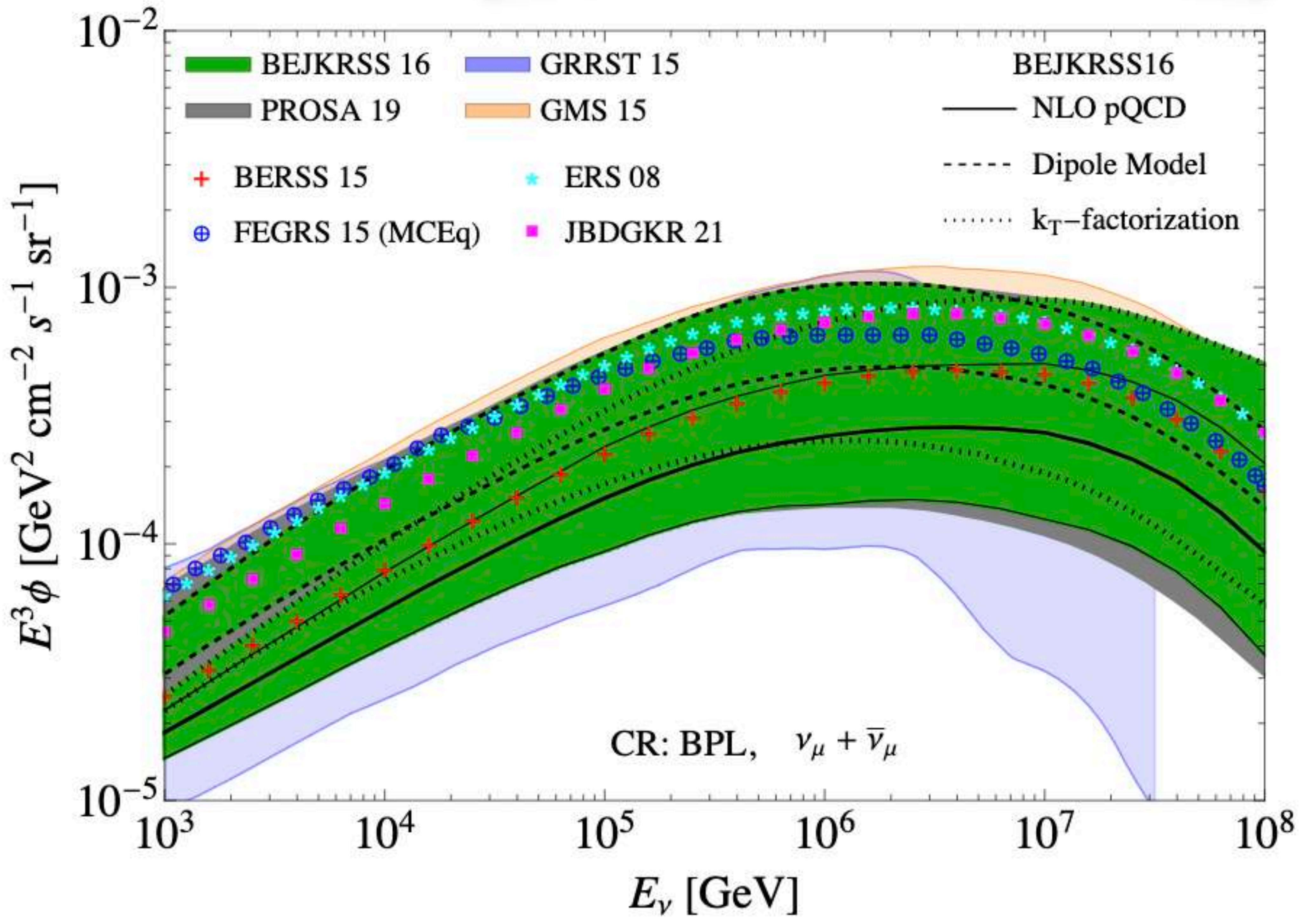
Introduction: Atmospheric Neutrinos

- 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!

See also yesterday's talk by M. Plum







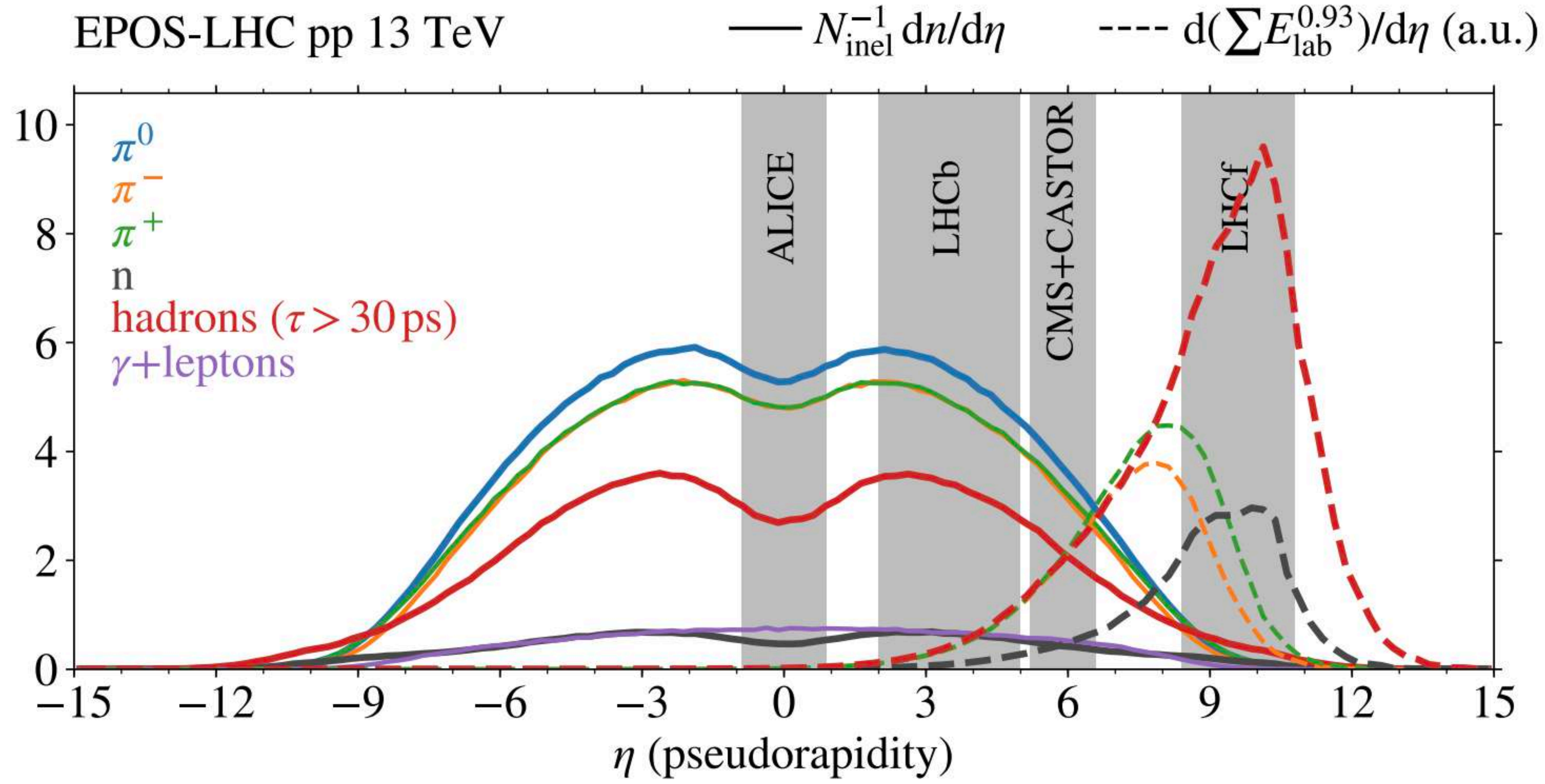
[C. Kopper (IceCube Collaboration), PoS(ICRC2017)981 (2018)]

[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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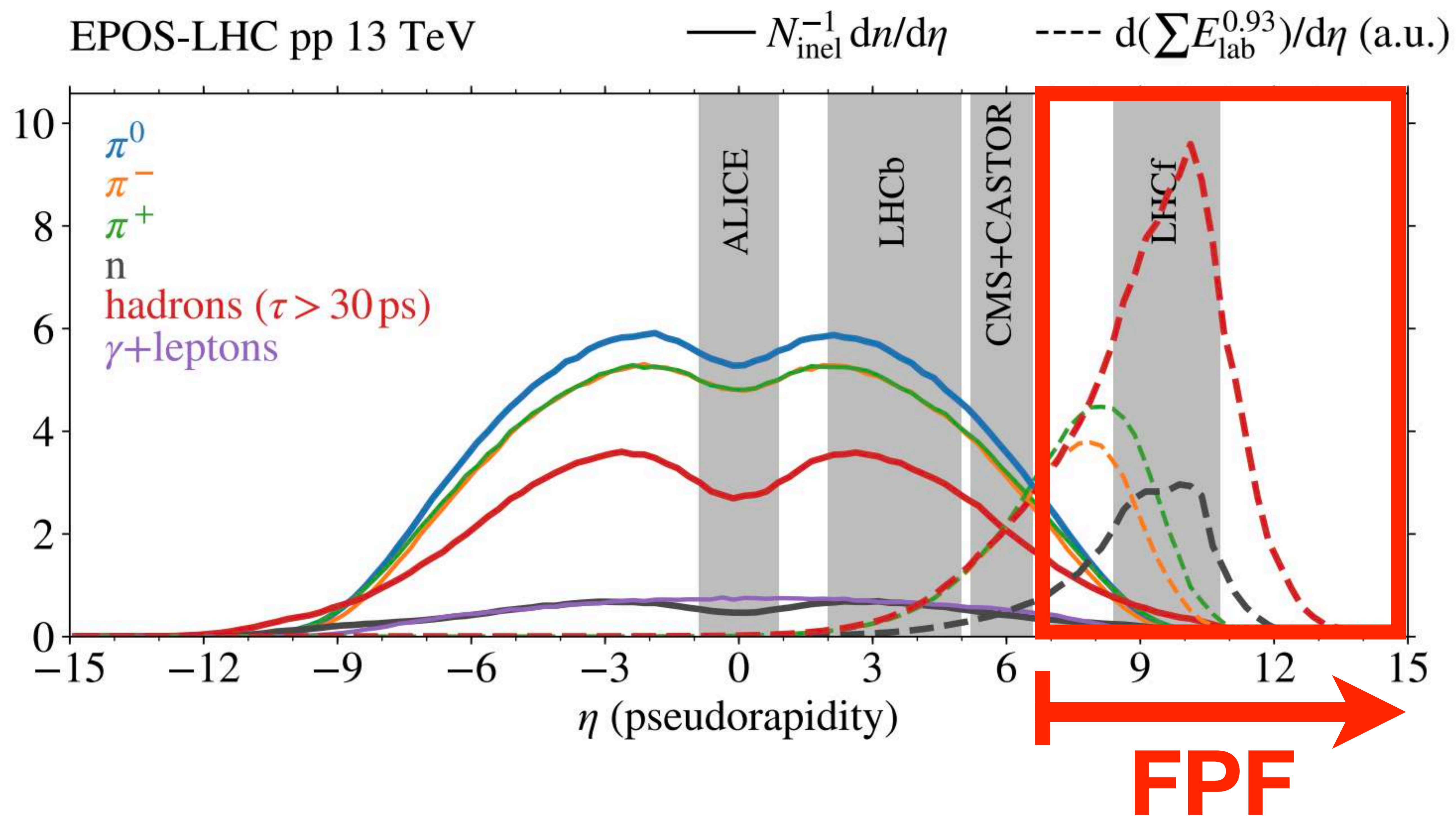
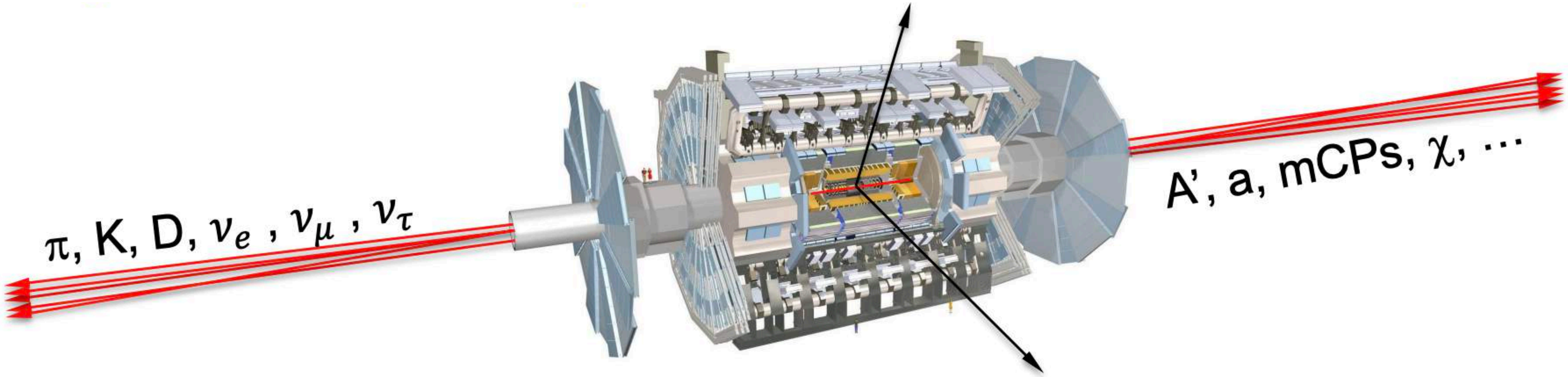


How can we test hadronic interaction models in the far-forward region at accelerators?

The Forward Physics Facility

- <u>What opportunities are we currently missing from a lack of coverage of far-forward physics at the LHC?</u>
- 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, …)
- <u>Proposal:</u> Forward Physics Facility (FPF) at LHC in ATLAS line-of-sight ($\eta \gtrsim 7$)

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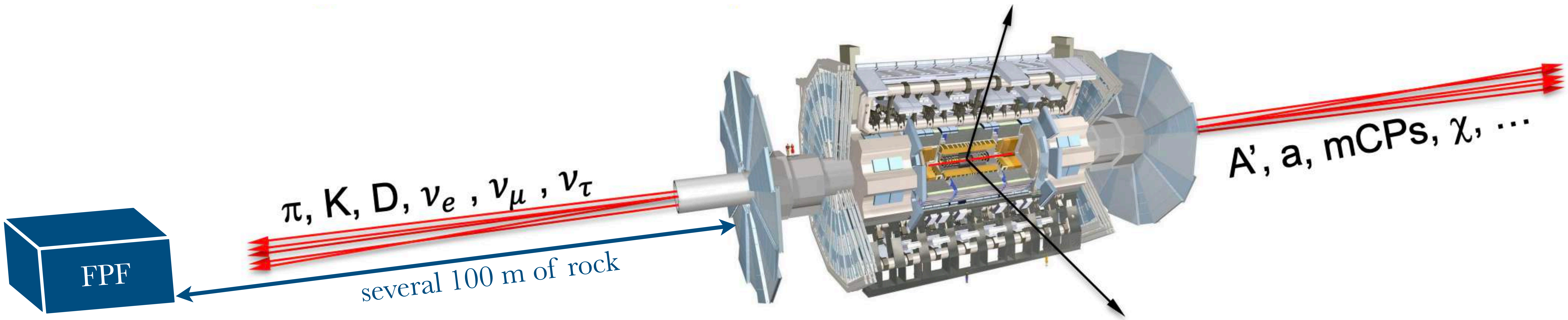

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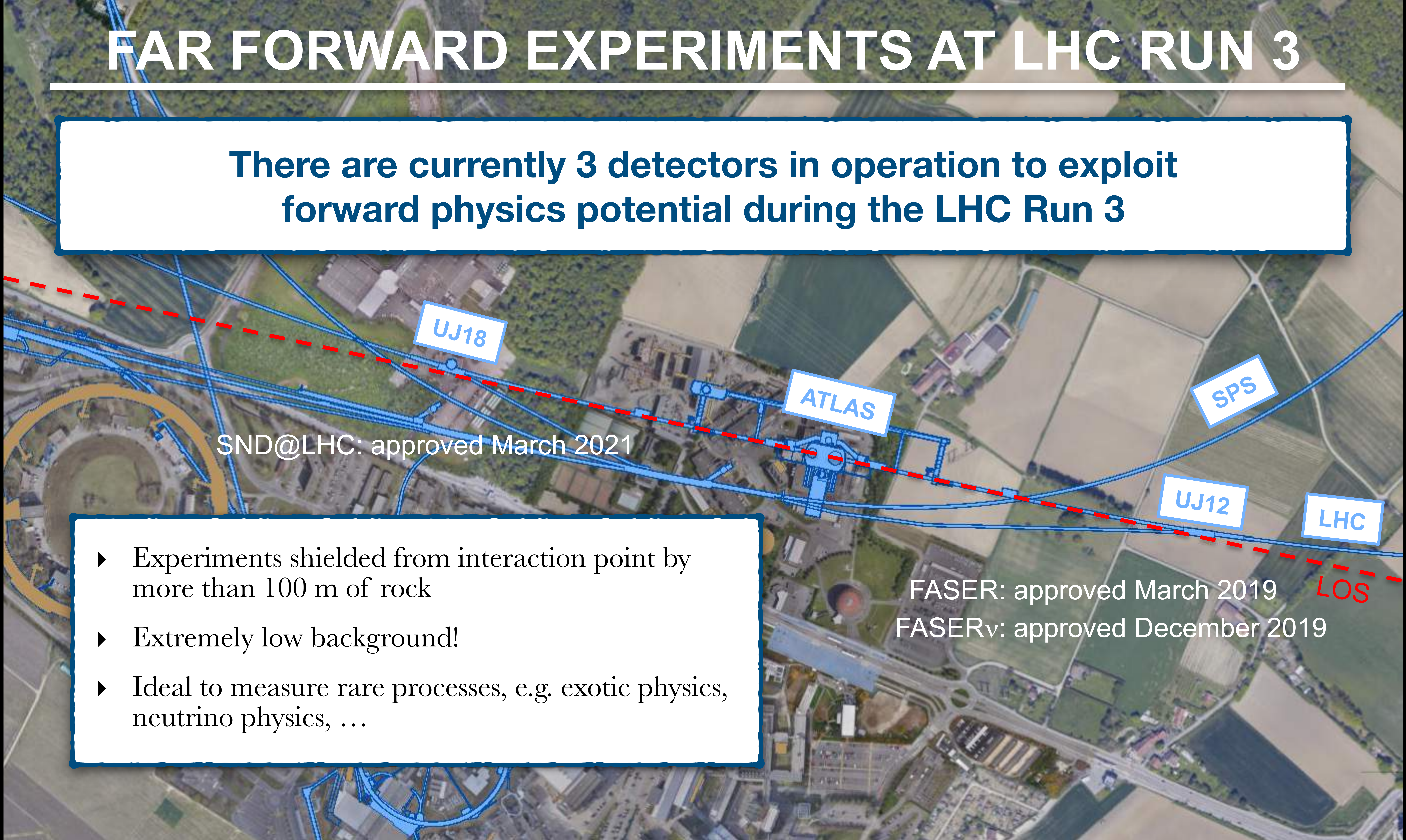
FAR FORWARD EXPERIMENTS AT LHC RUN 3

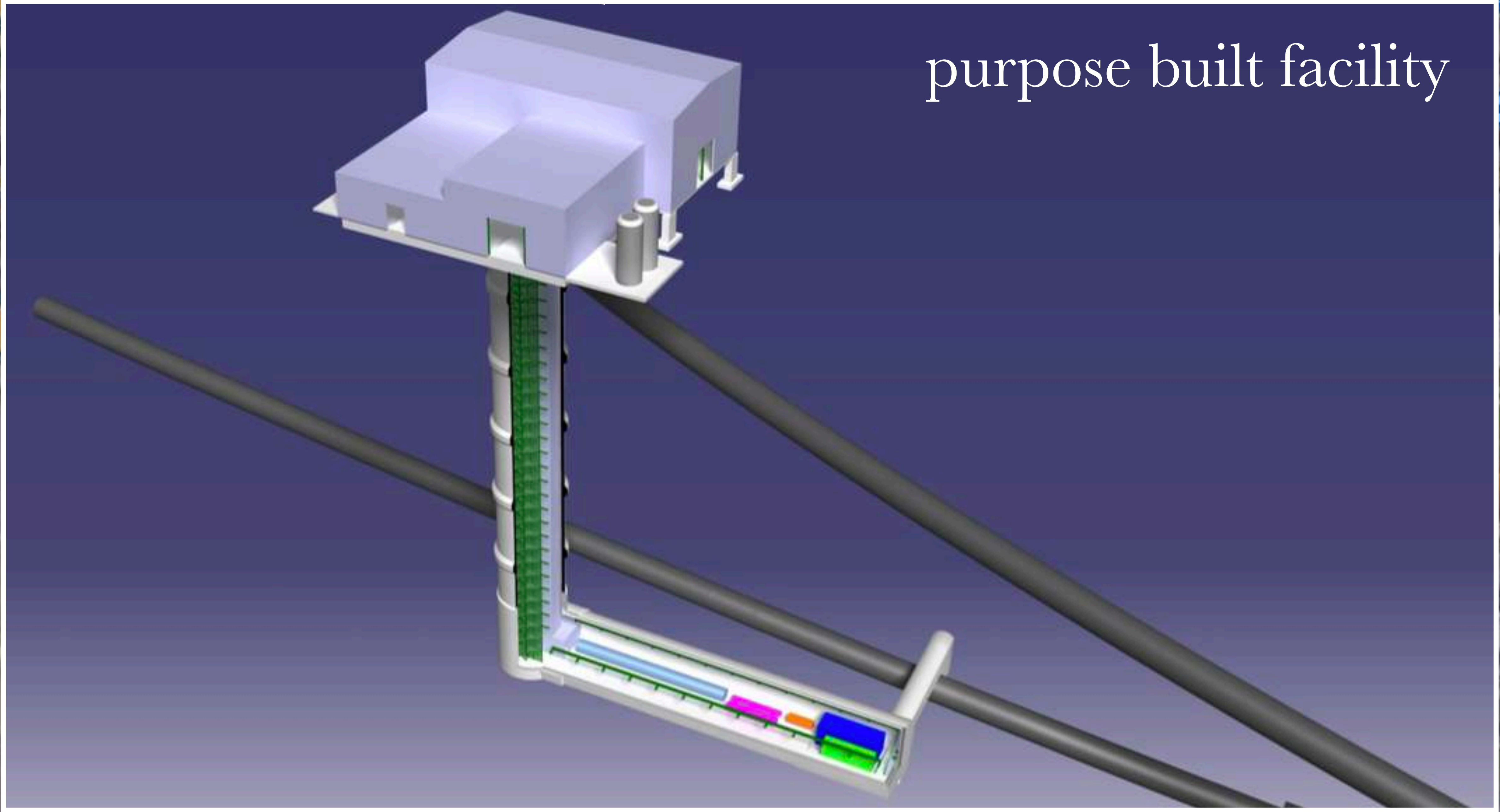
There are currently 3 detectors in operation to exploit forward physics potential during the LHC Run 3



- 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!



FASER: approved March 2019

FASERν: approved December 2019

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

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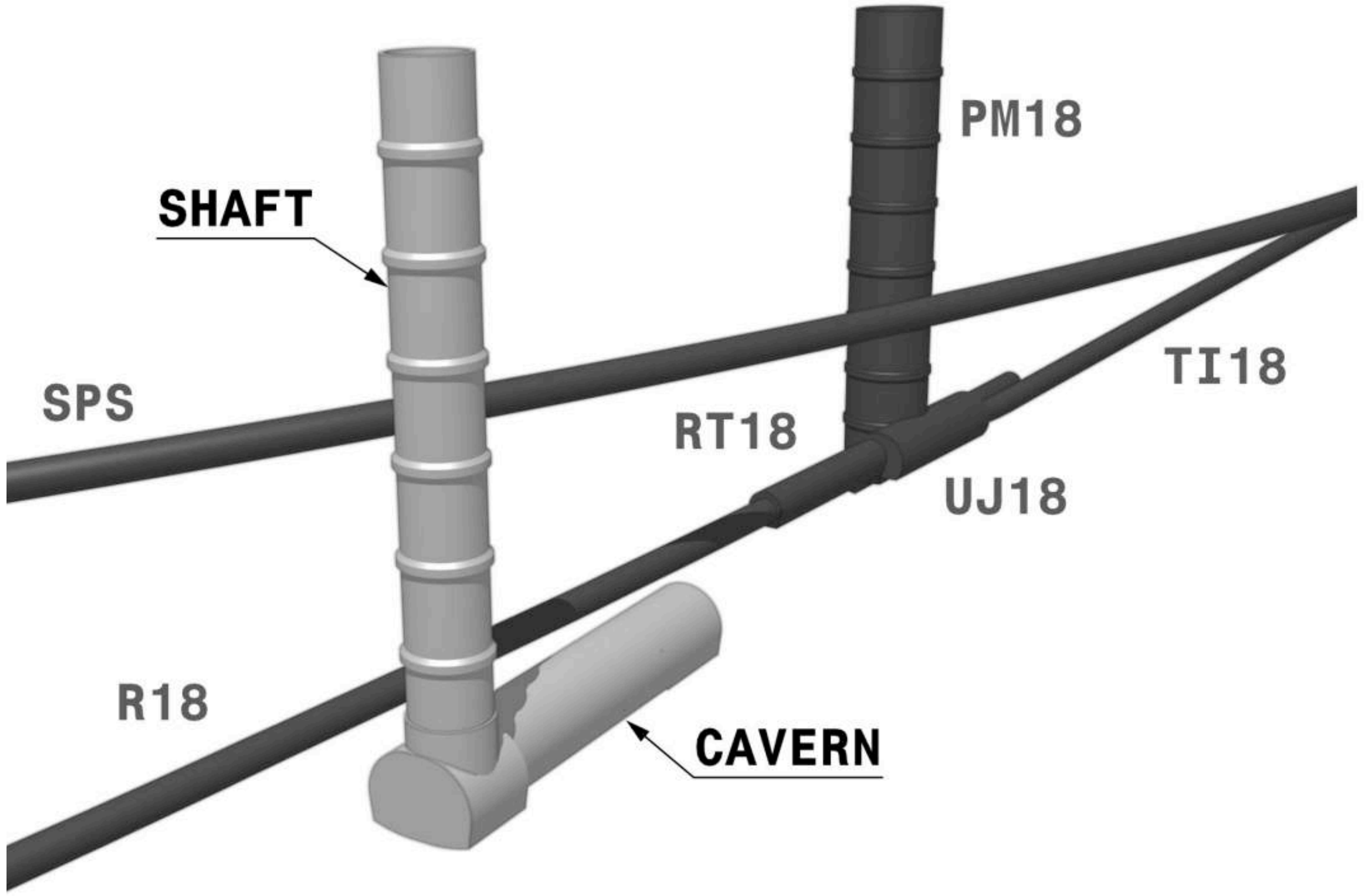
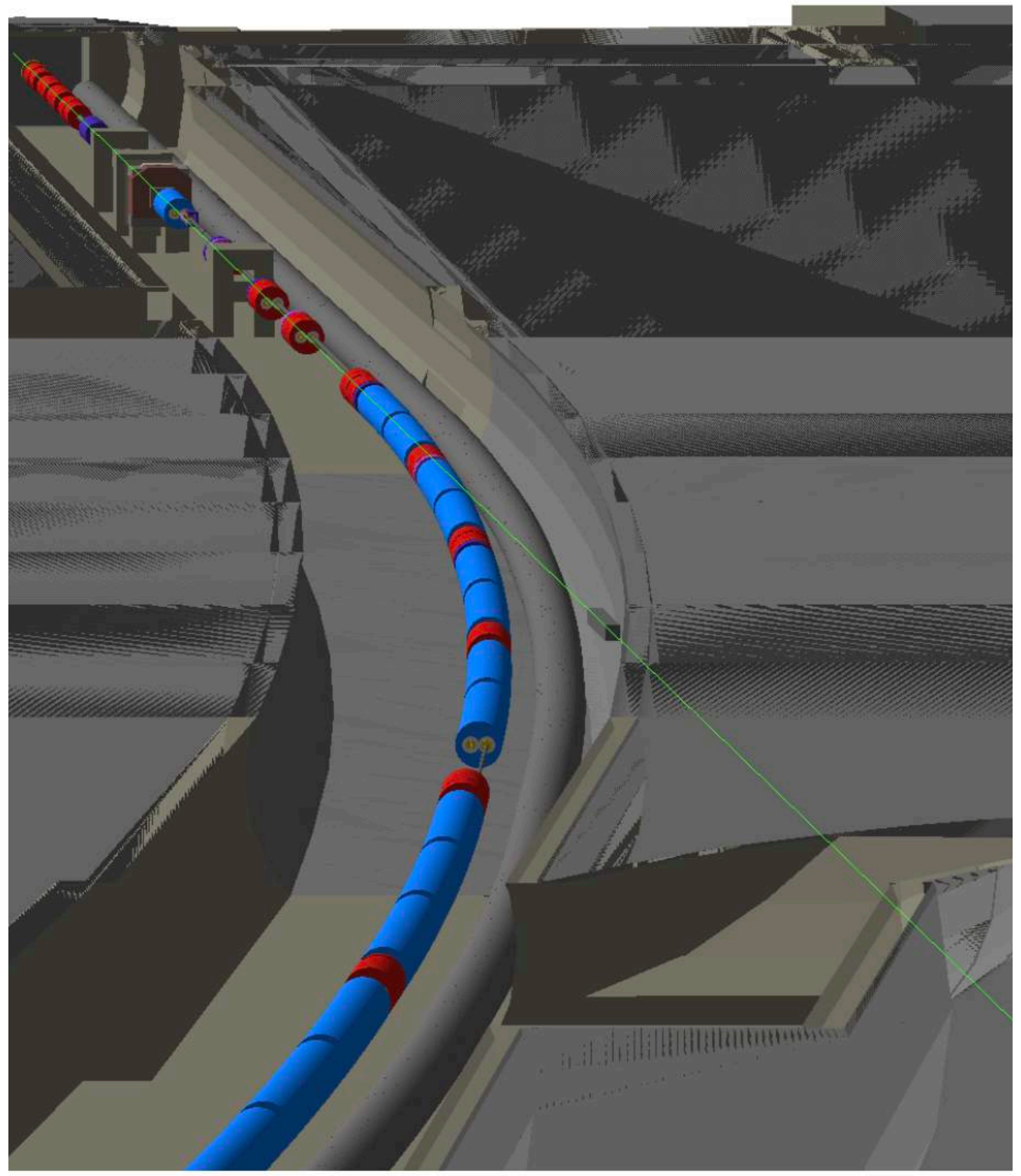
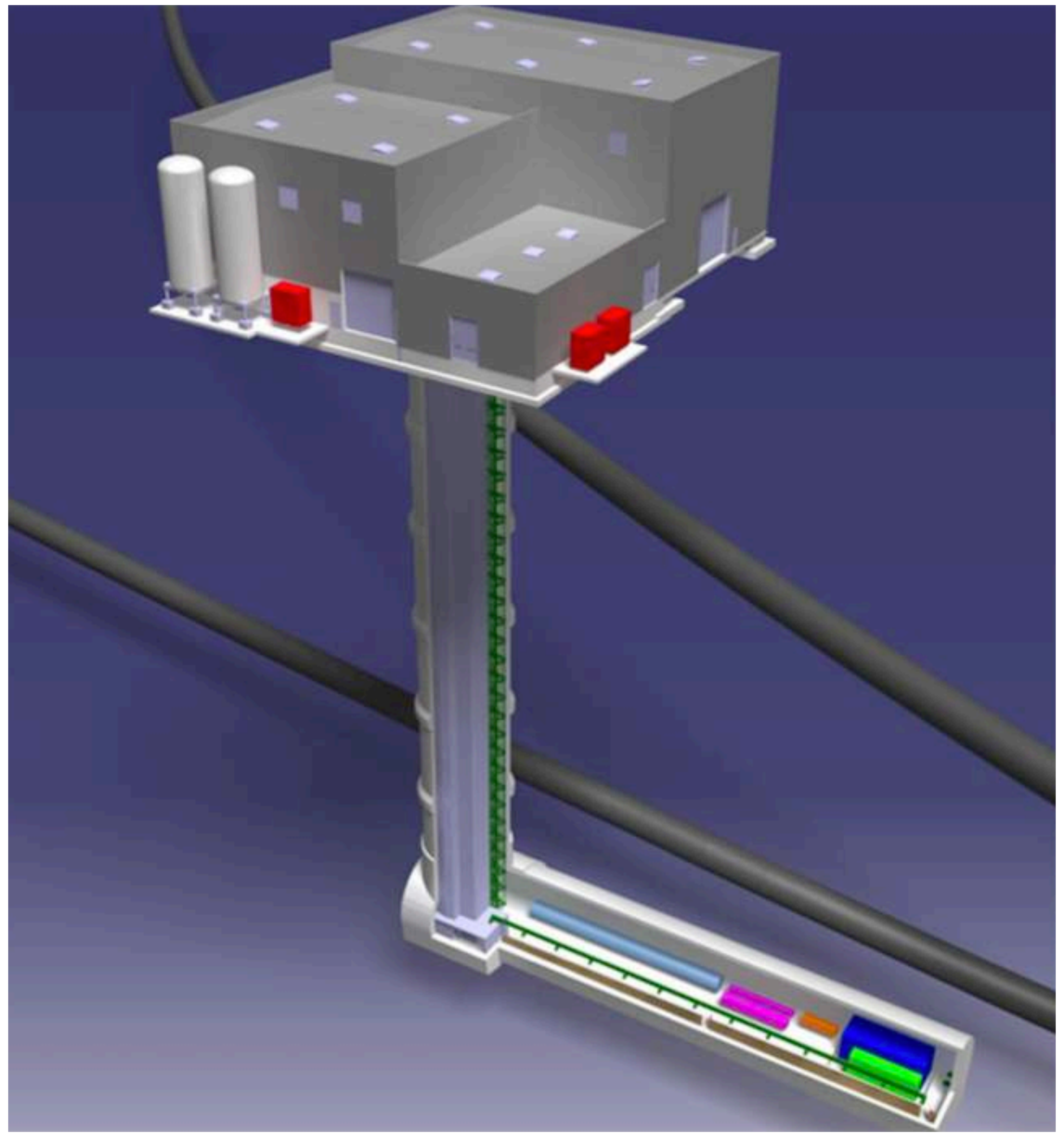
- Purpose built facility to house dedicated experiments in the far-forward region
- In line-of-sight to ATLAS interaction point (separated by several 100 m of rock)
- Currently four proposed experiments*, mainly designed for neutrino detection







* for a complete description of the experiments, please see [J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

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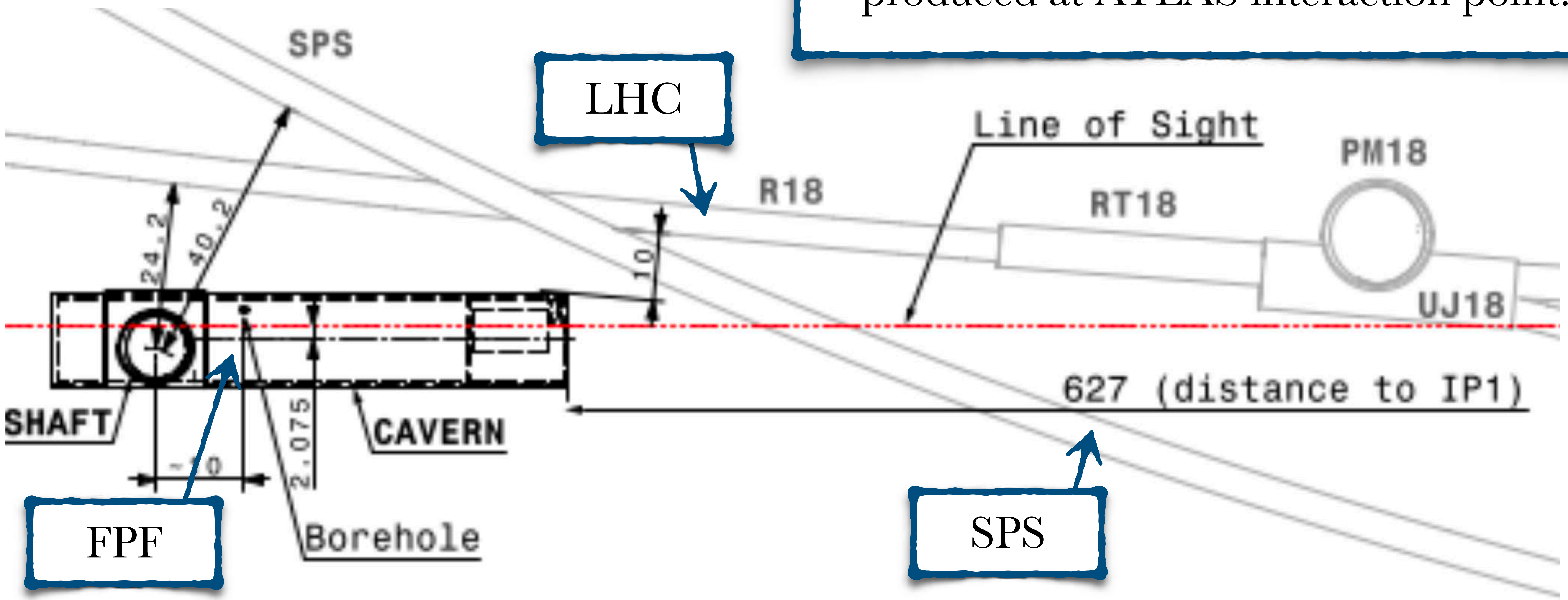

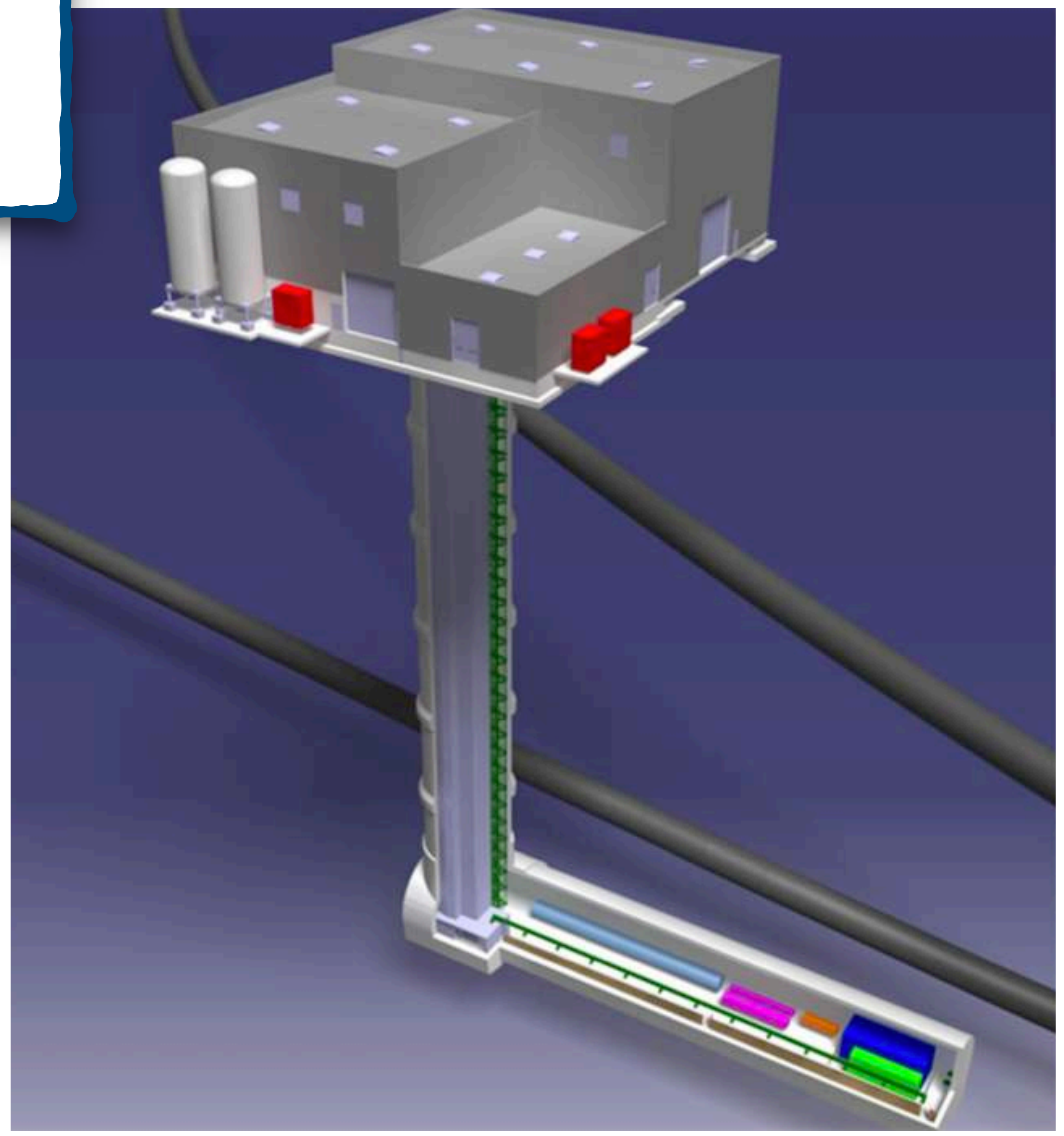

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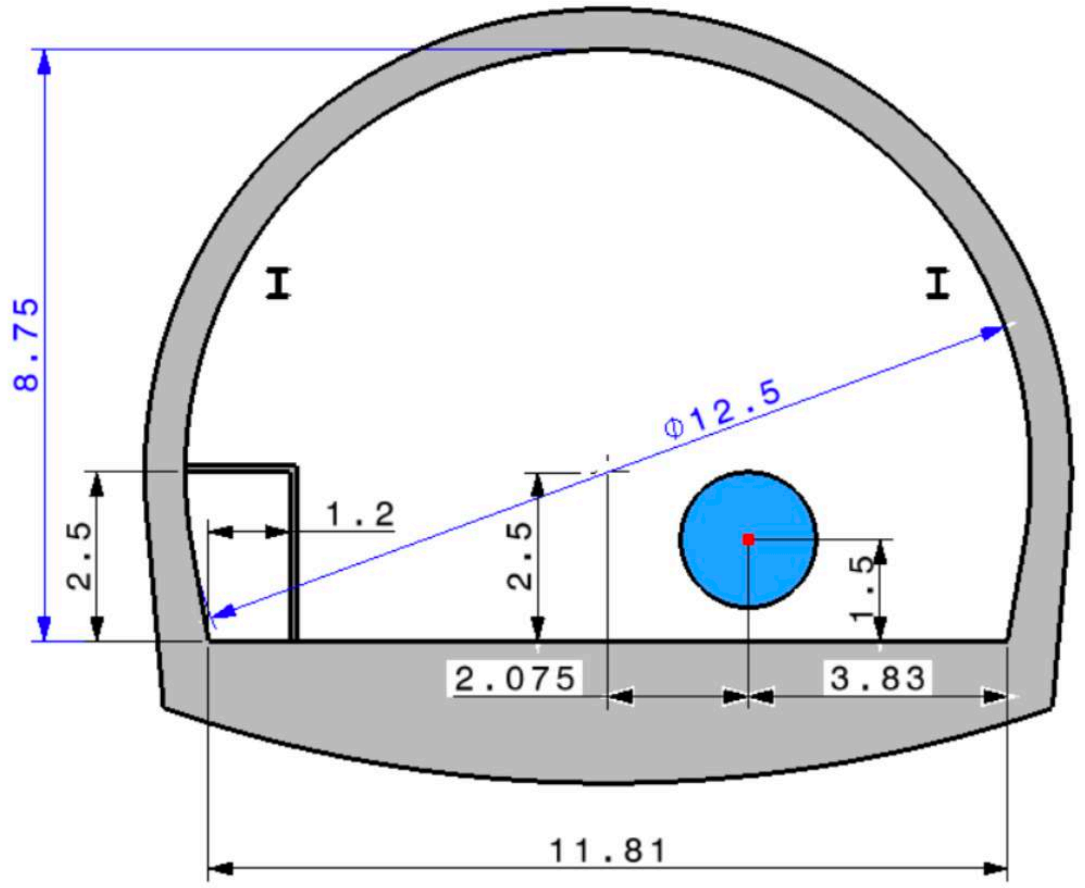

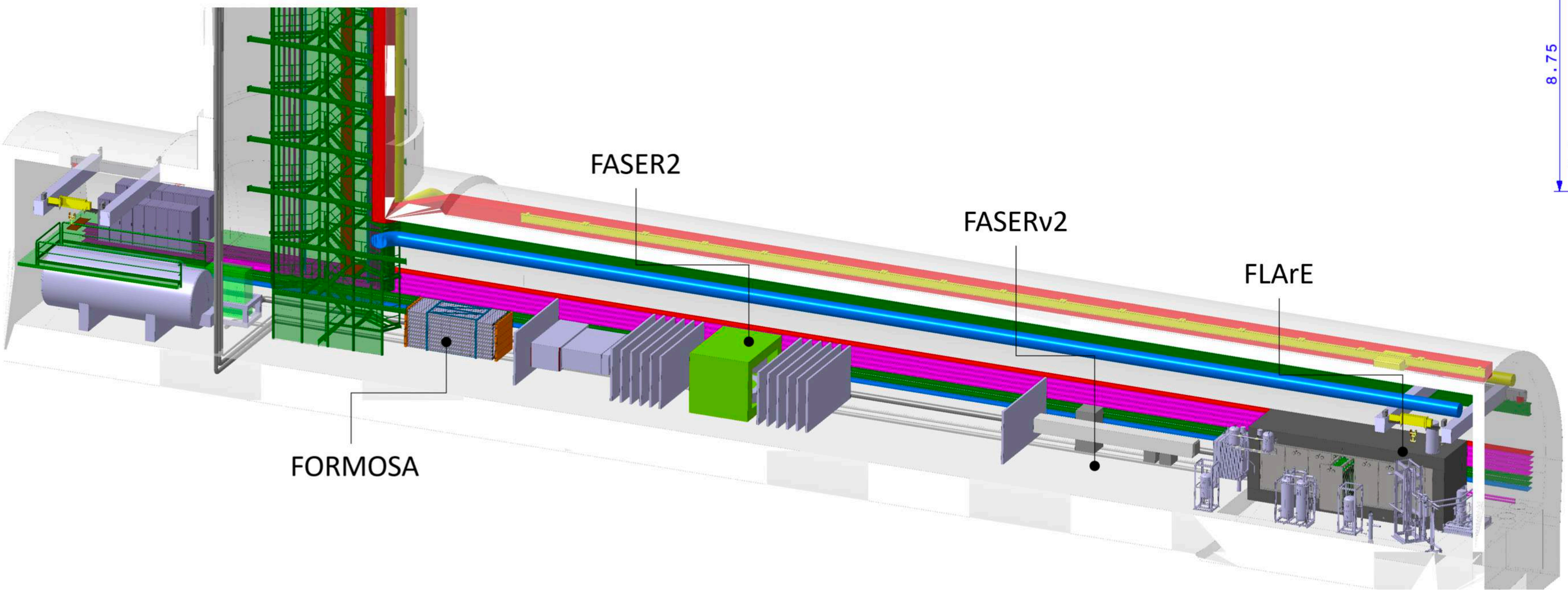

line of sight

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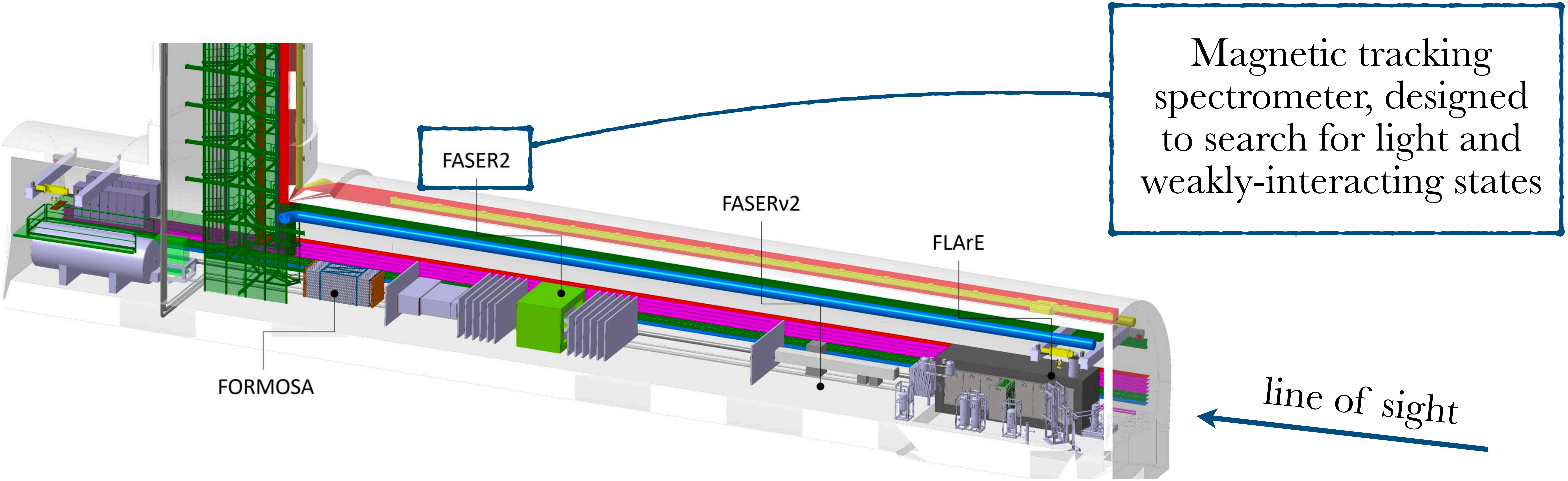

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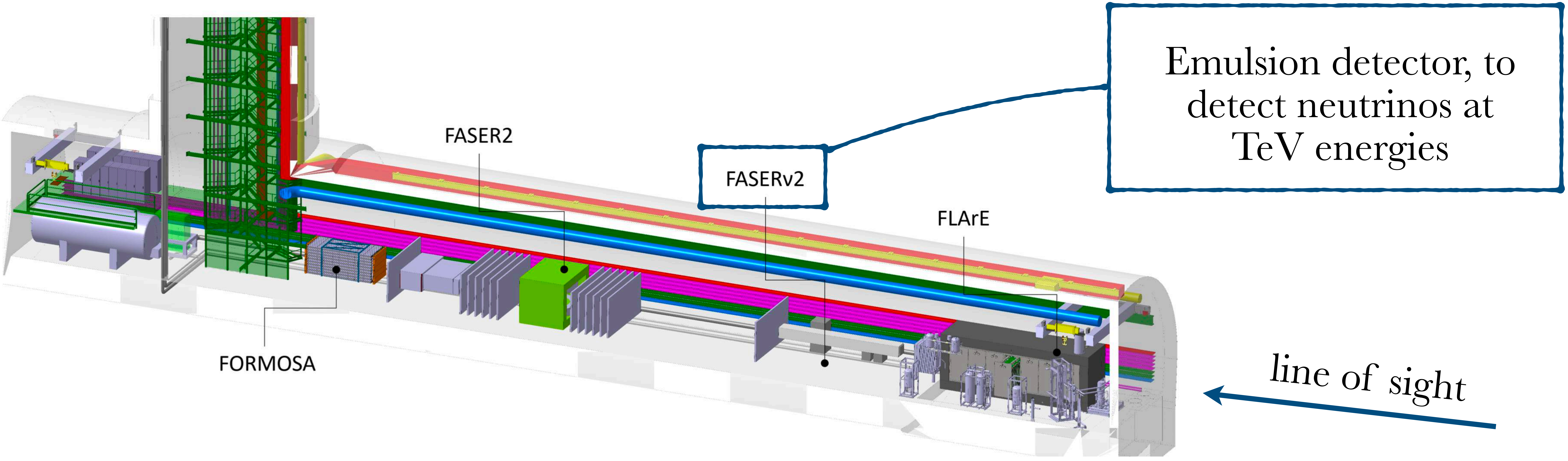

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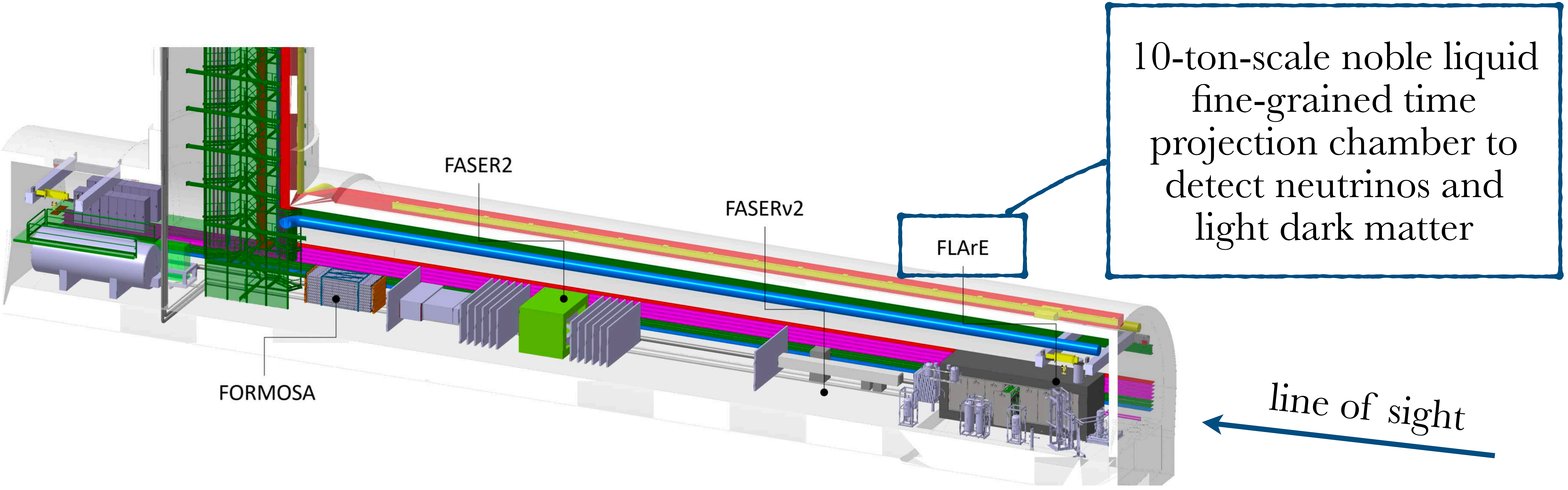

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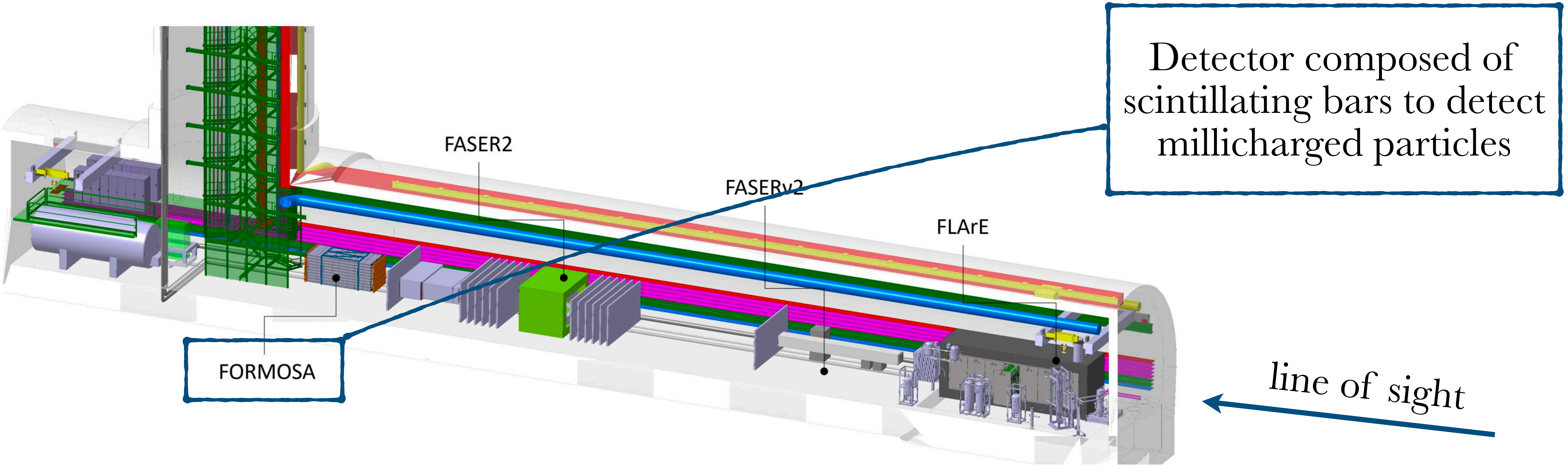

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FPF Physics Potential

- Example:

FASERν pilot detector vs. All previous collider experiments

FASERν pilot detector
- Suitcase size, 4 weeks of data
- Costs: \$0 (recycled parts)
- 6 TeV neutrino candidates
[FASER Collaboration, Phys. Rev. D 104 (2021)]

All previous collider experiments
- Building size, decades of data
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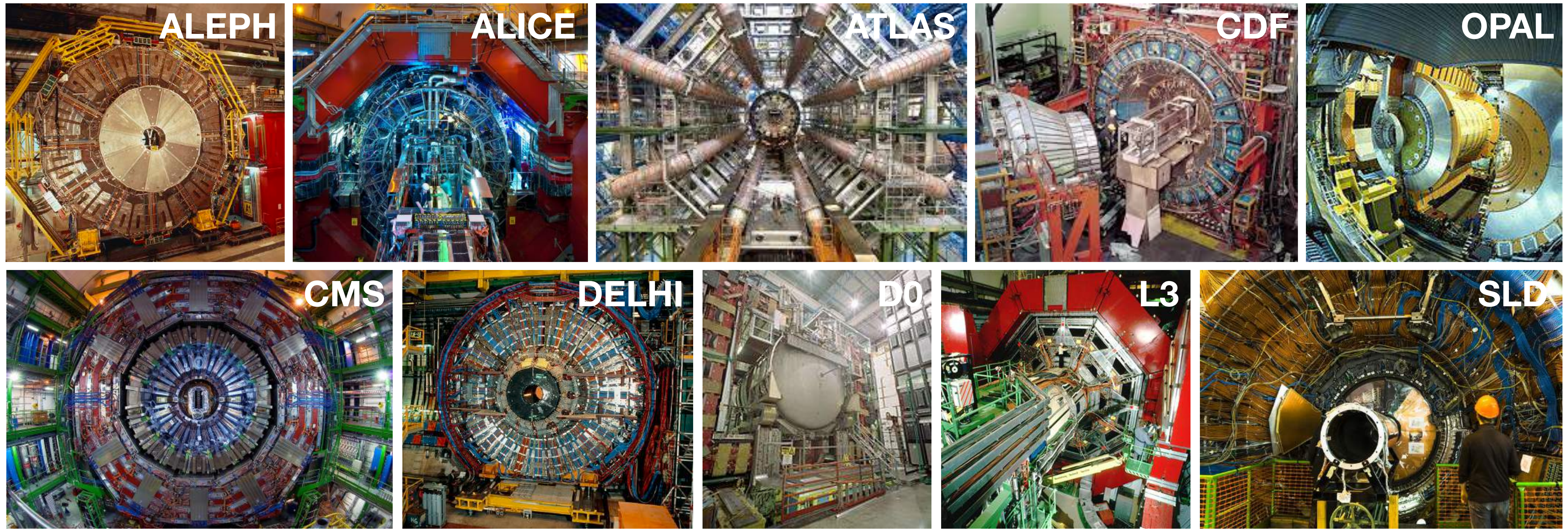

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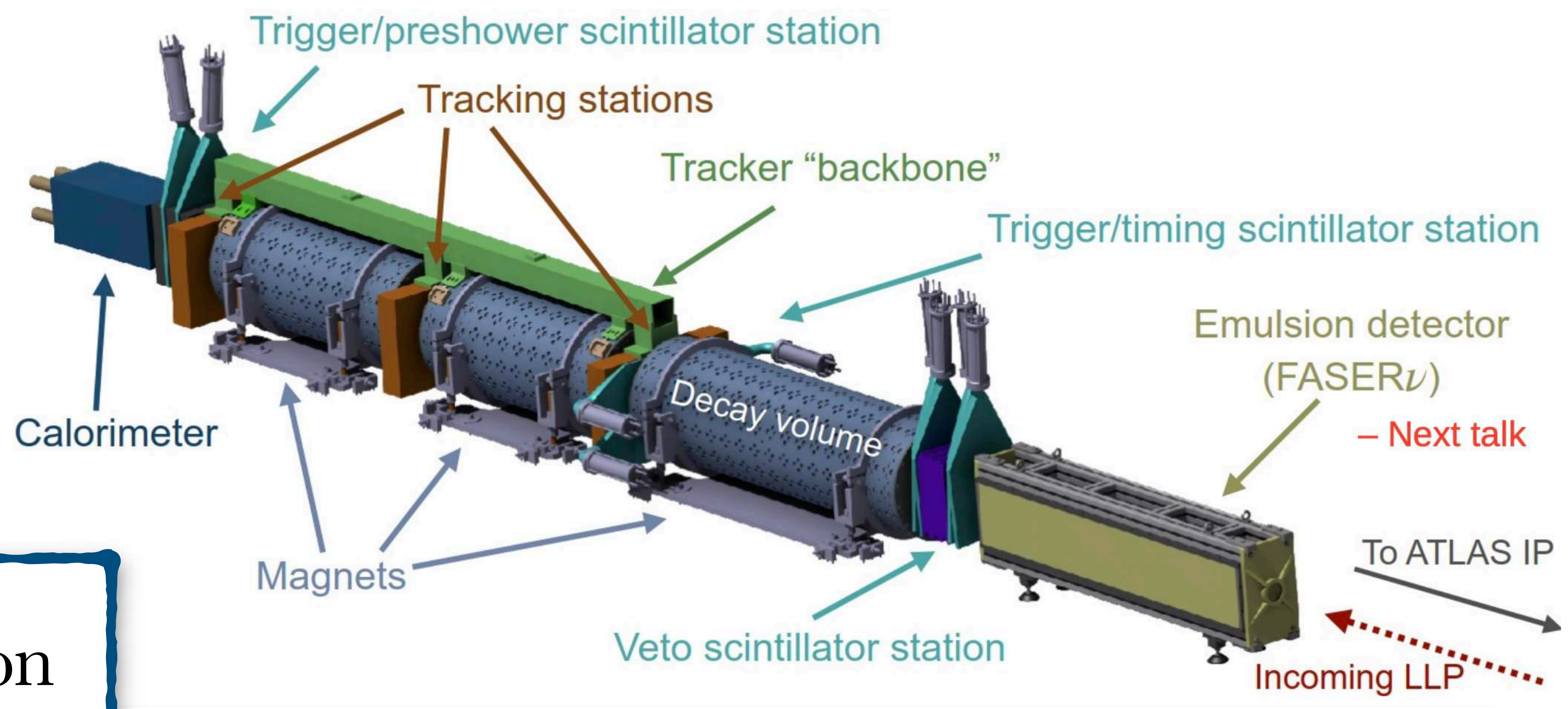
- FASERν years 2022-2024:
  - First 153 neutrino candidates reported
    [FASER Collaboration, Phys. Rev. Lett. 131 (2023)]
  - Significance of $\sim 16\sigma$
  - ~ 10000 ν candidates expected ($\sim 10^9$ muons*)

Talk by O. Sato this afternoon



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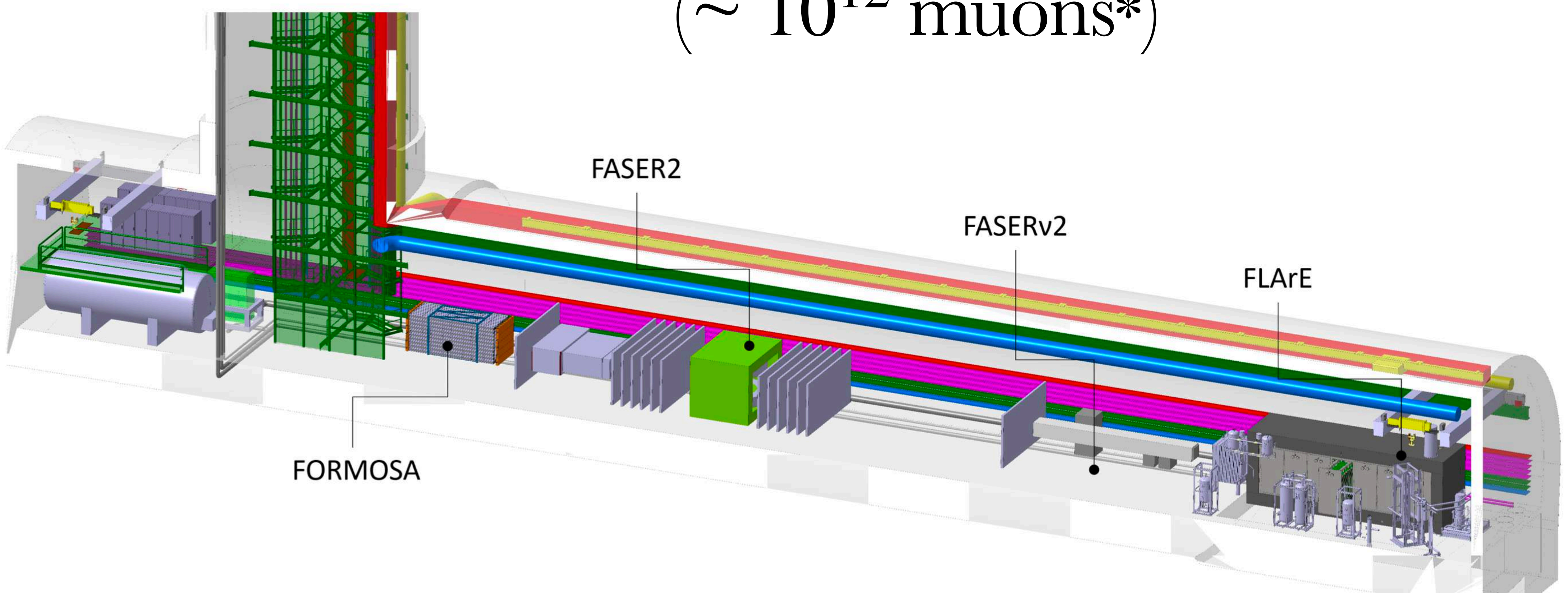
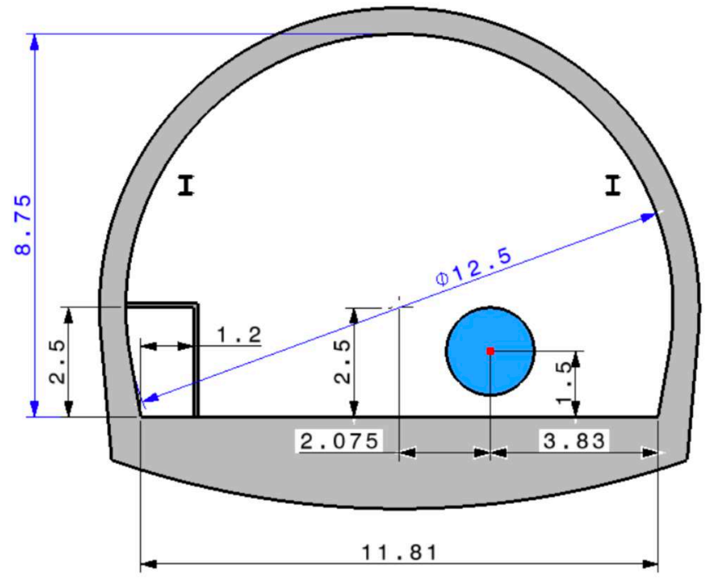
- Forward Physics Facility:
  - $\sim 10^6$ ν candidates expected! ($\sim 10^{12}$ muons*)





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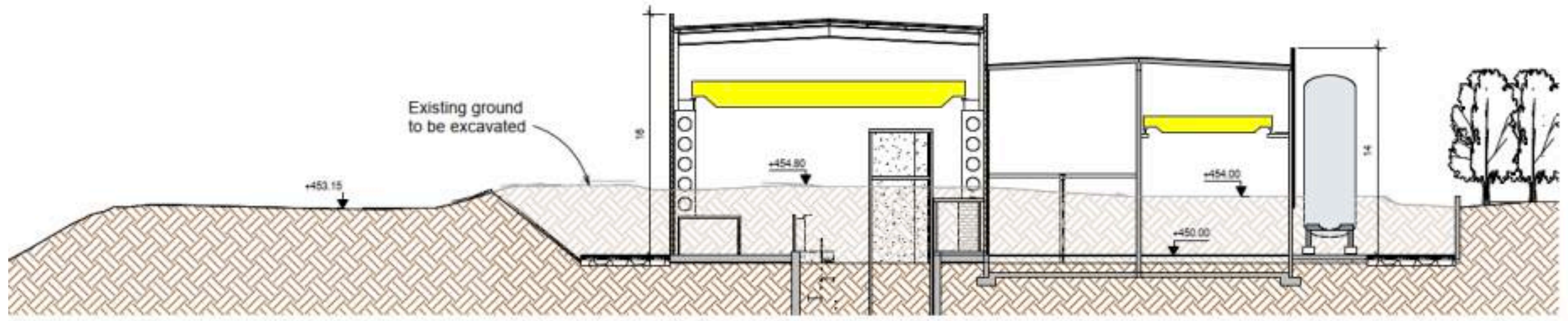
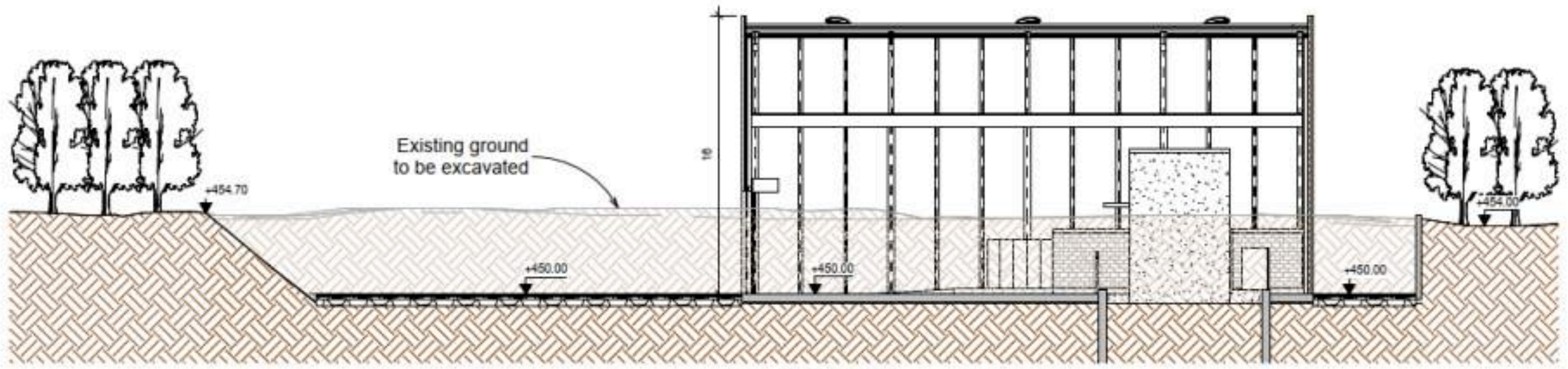
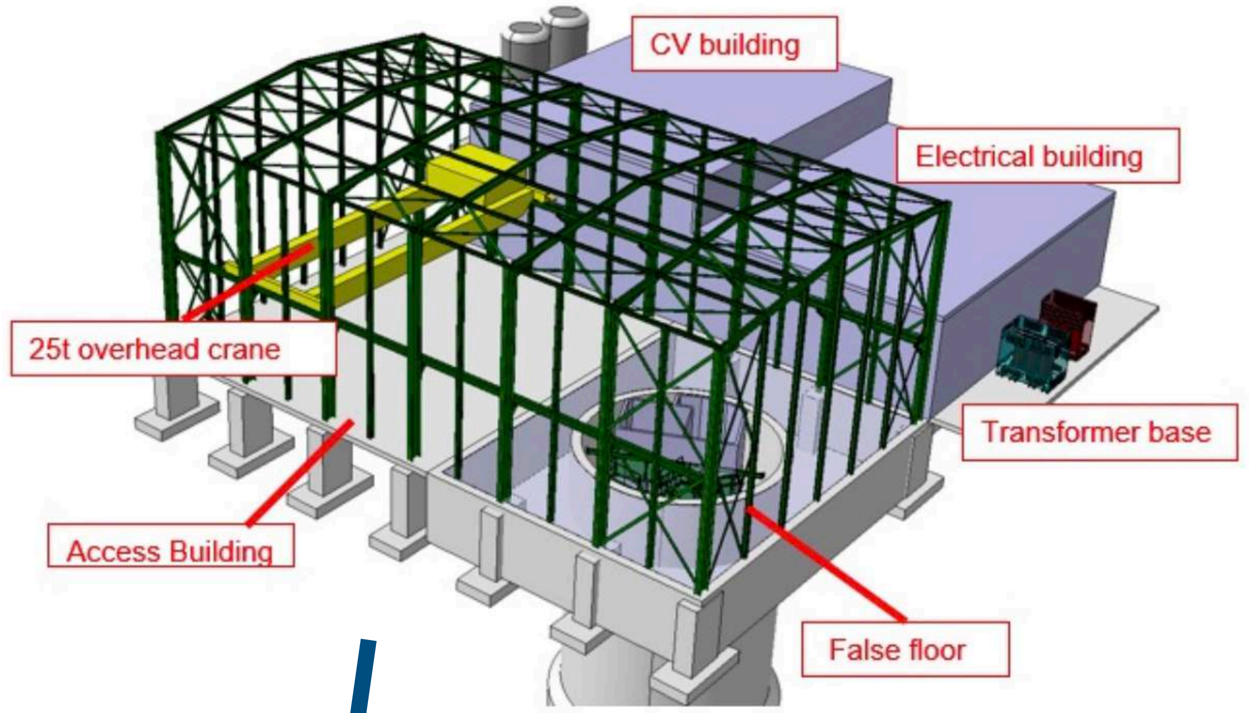
The Facility

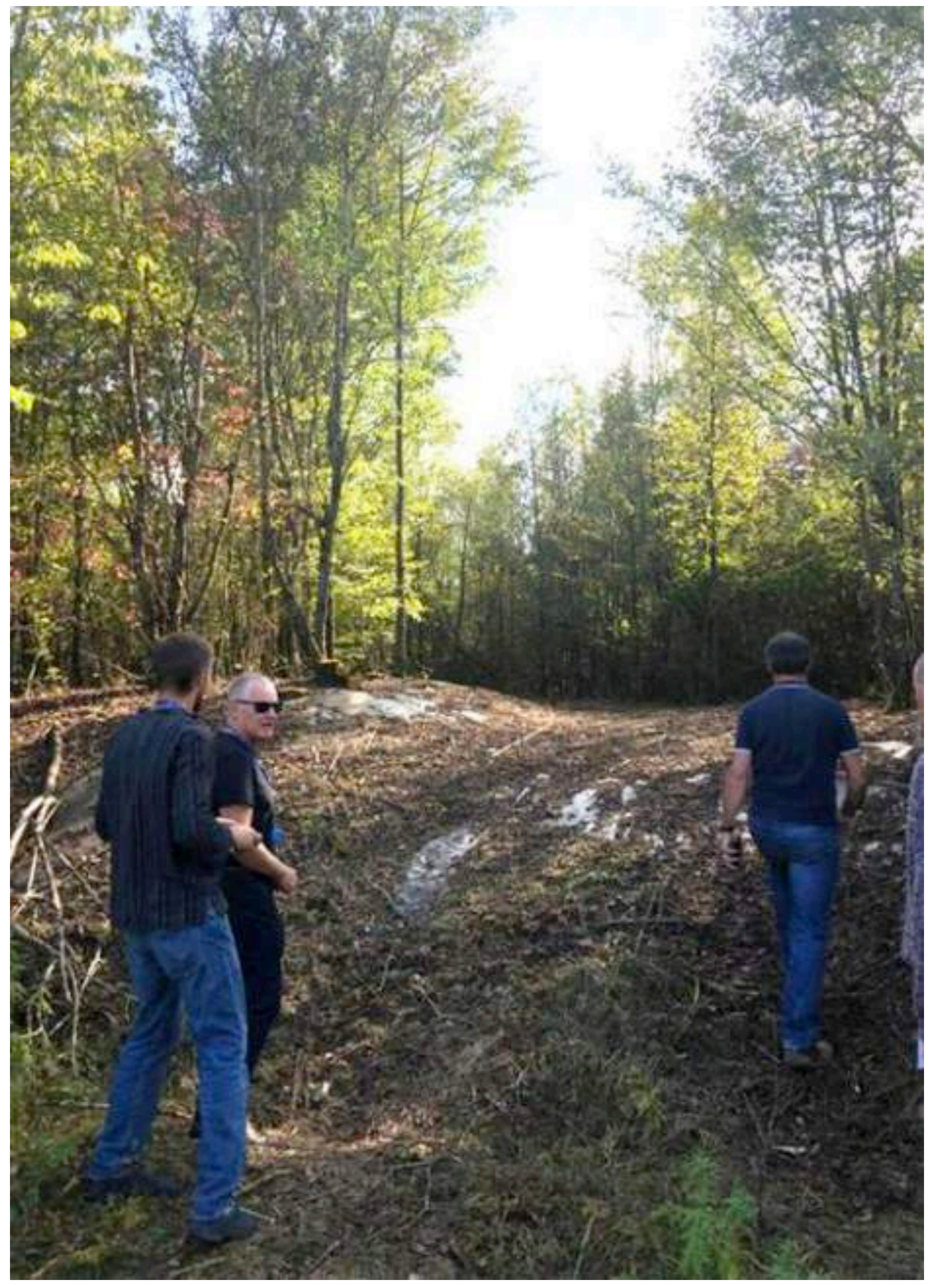


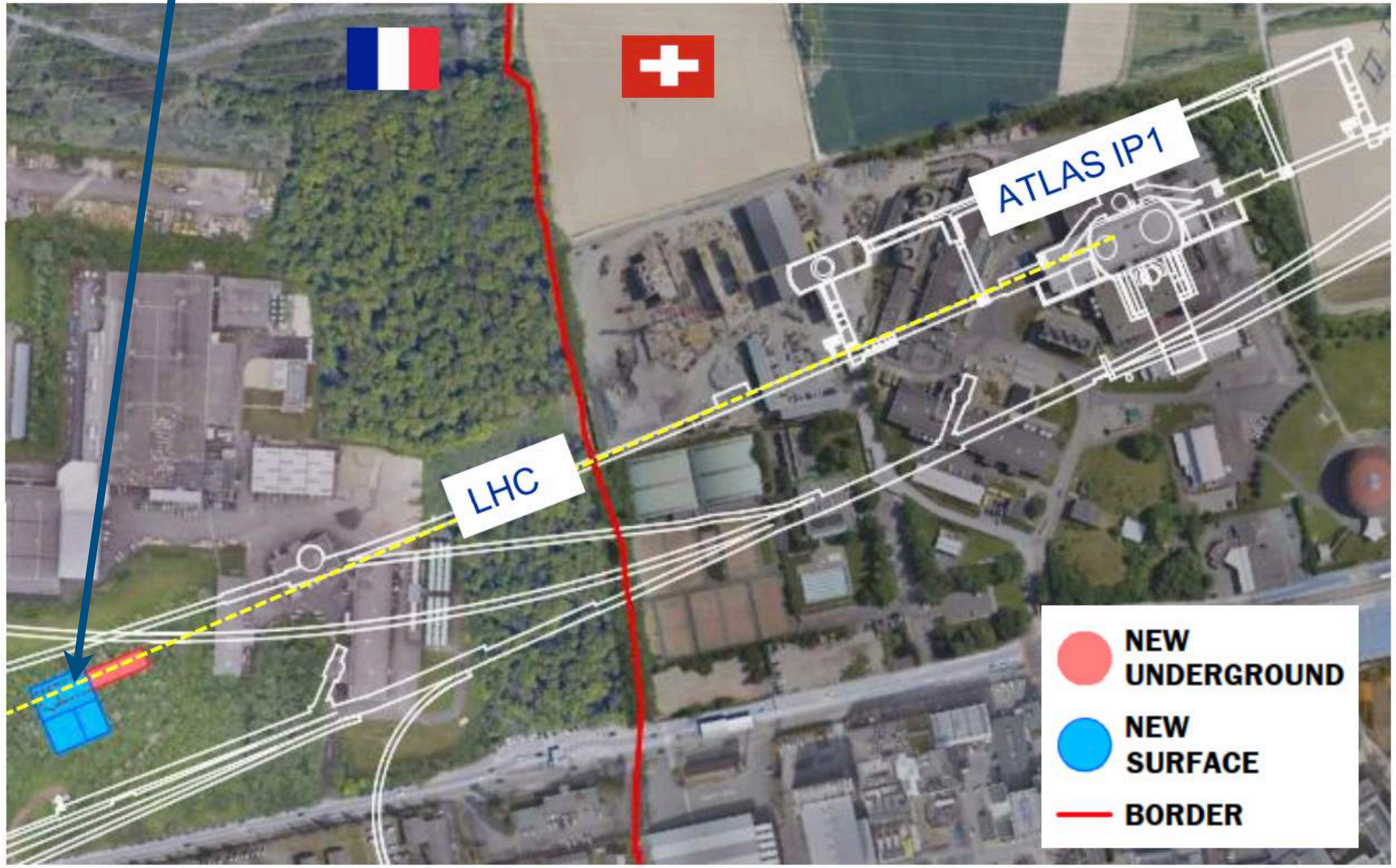
SECTION 1-1



SECTION 2-2

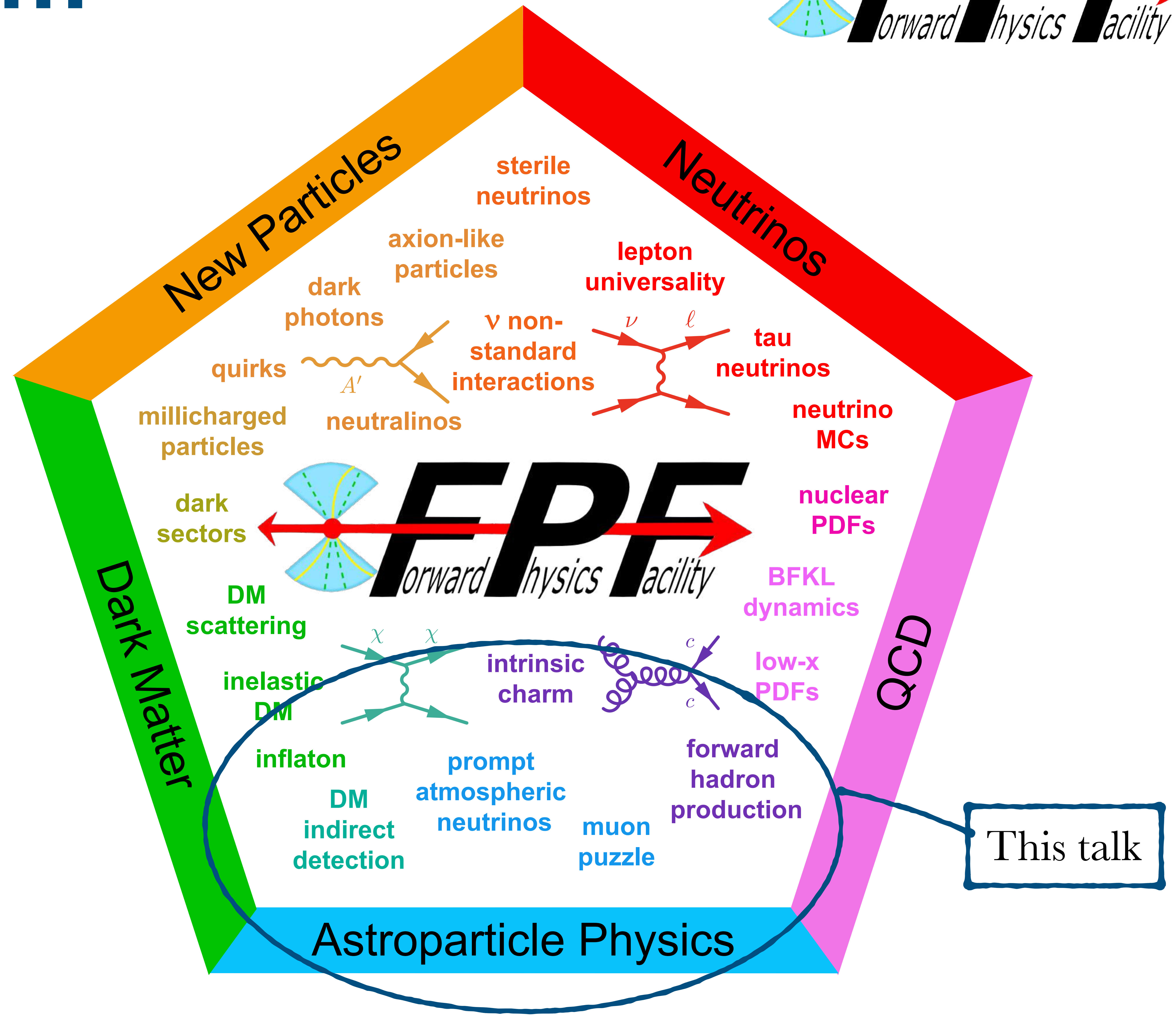






FPF Physics Program

- 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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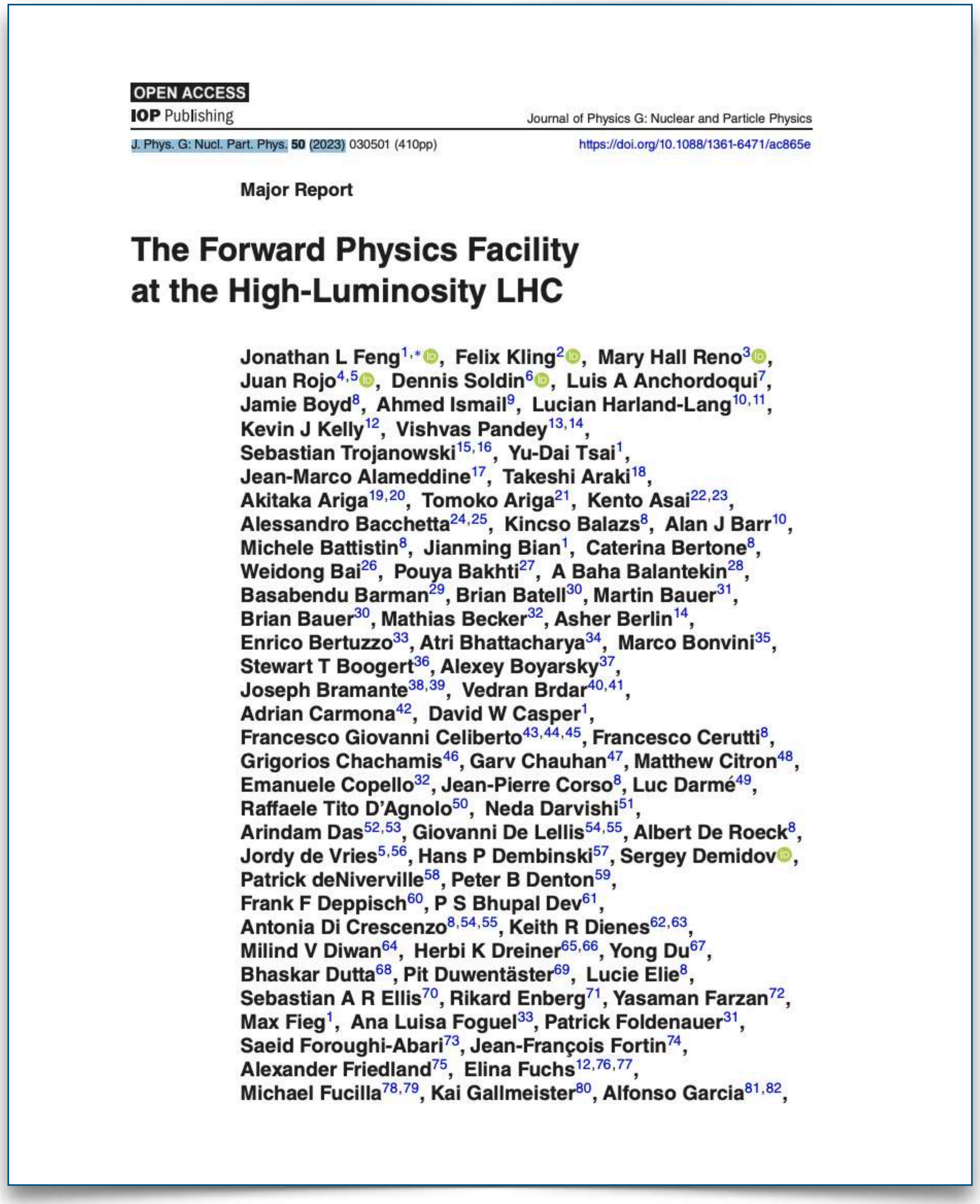
  - Astroparticle physics
- Comprehensive description of the FPF:
  - "Short paper" (77 pages):
    - Phys. Rep. 968 (2022)
  - Snowmass White Paper (~430 pages):
    - J. Phys. G: Nucl. Part. Phys. 50 (2023)
- See also https://fpf.web.cern.ch/



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Major Report

The Forward Physics Facility at the High-Luminosity LHC

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FPF Physics Program

Forward Physics Facility

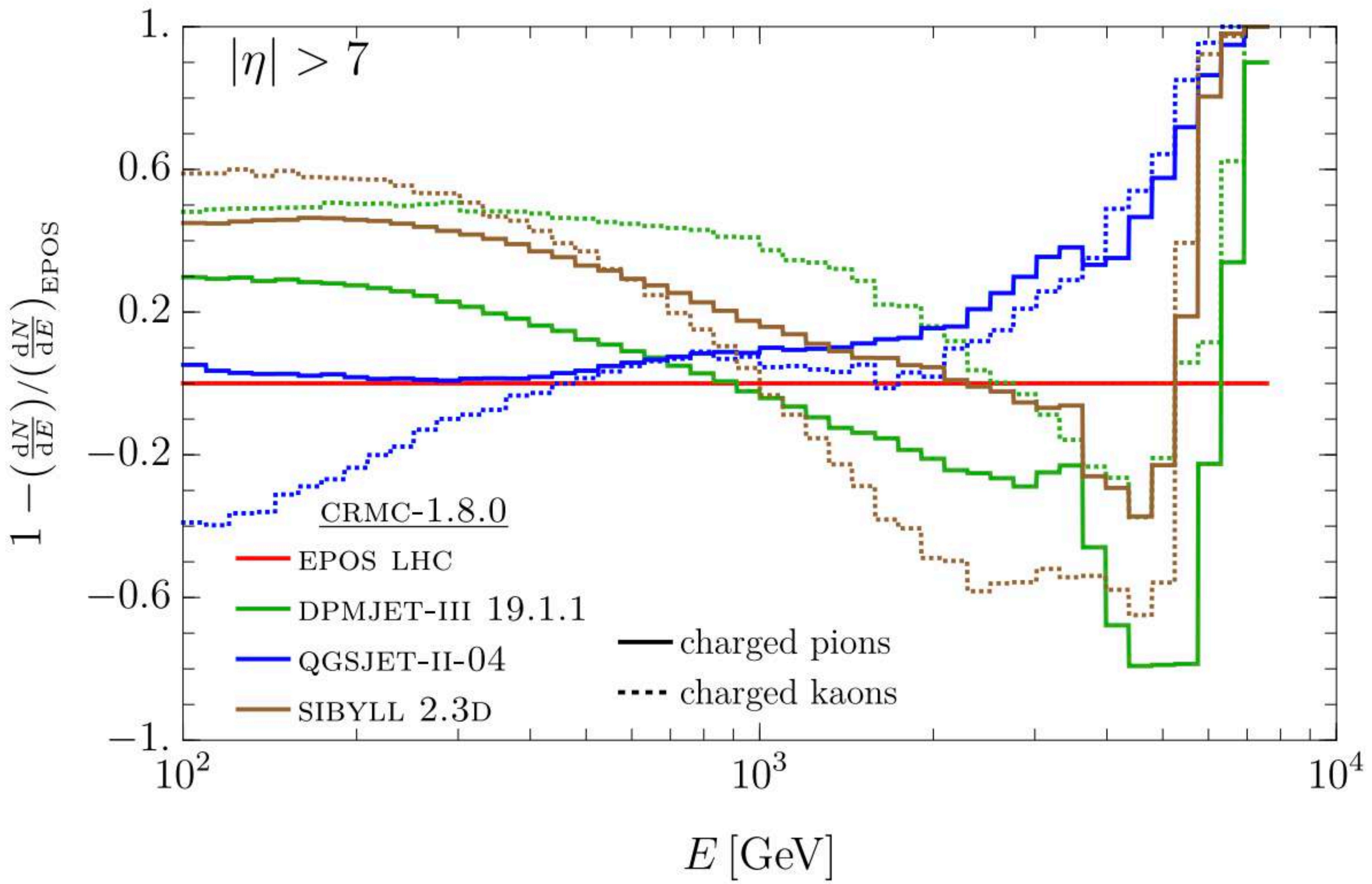
Contents

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
- Measurements of neutrino flues as tests of hadronic interaction models and prompt neutrino production models

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

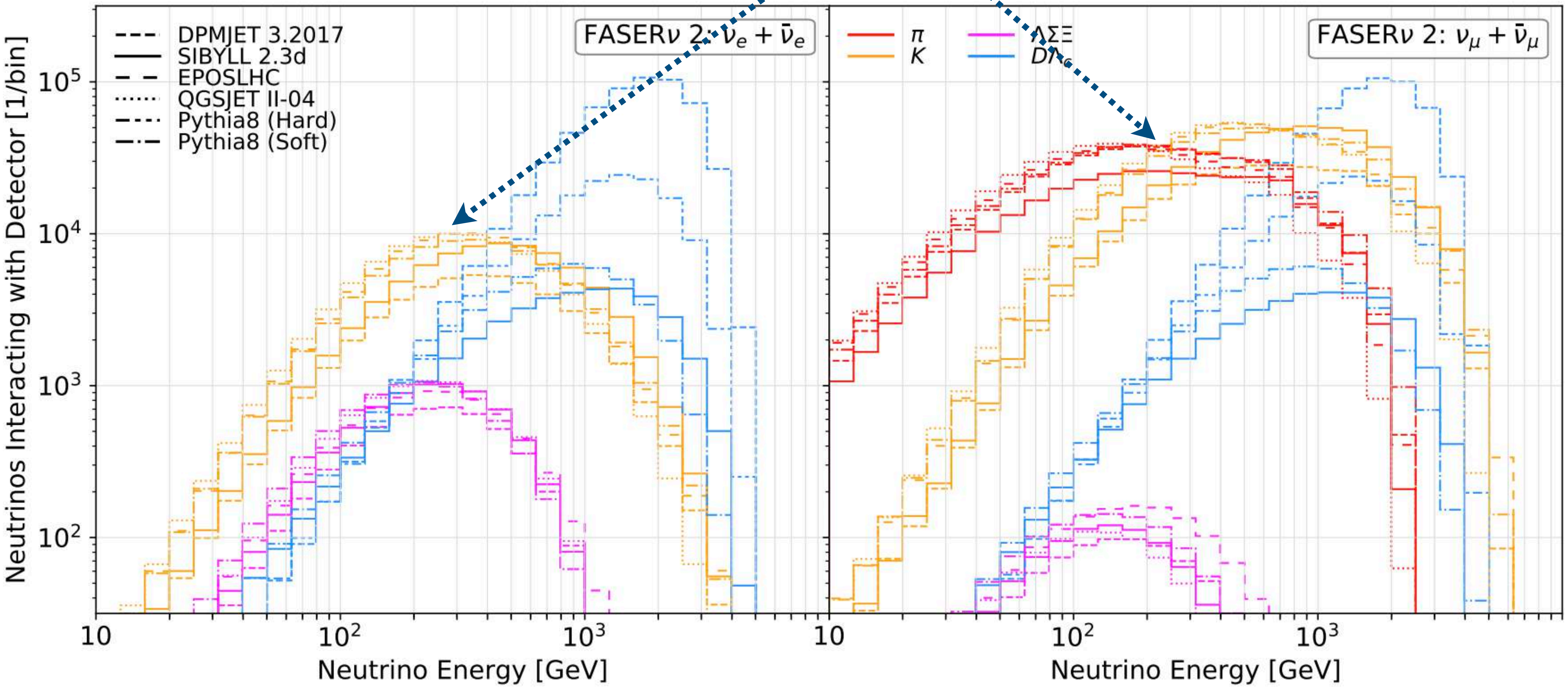


Light Hadron Production

- Example: Neutrino fluxes at FASERν2

low-energy region relevant!

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

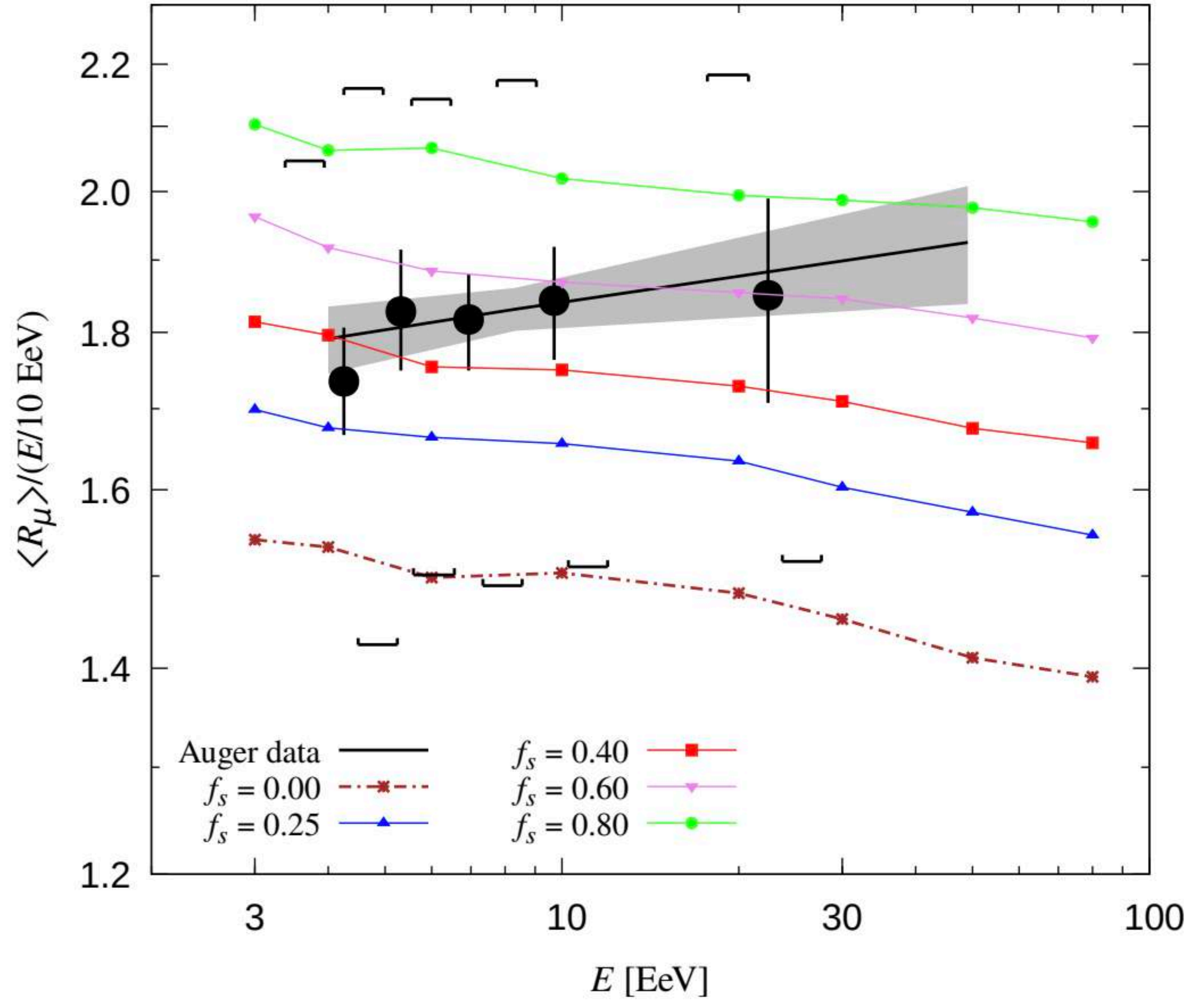


- Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties!

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!
- <u>FPF provides unique opportunities for testing the forward rapidity region!</u>

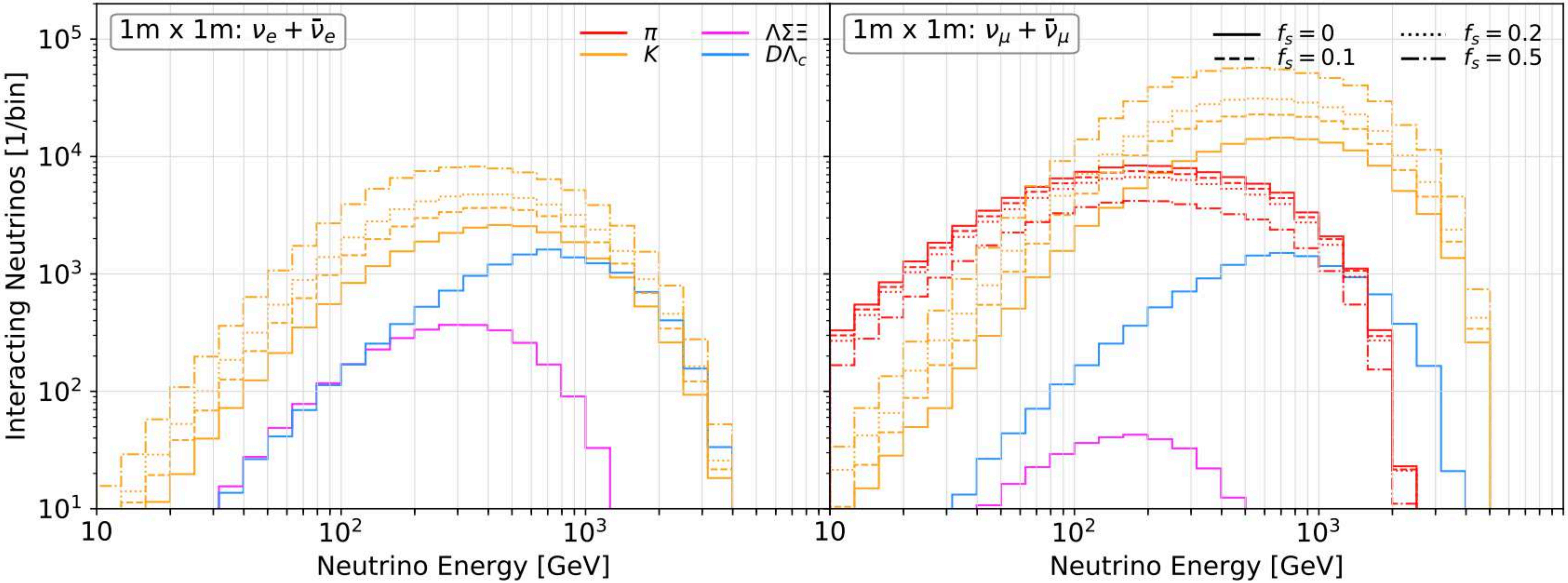
[L. Anchordoqui et al., JHEAp 34 (2022)]



Light Hadron Production

- Example: Neutrino fluxes at FLArE

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



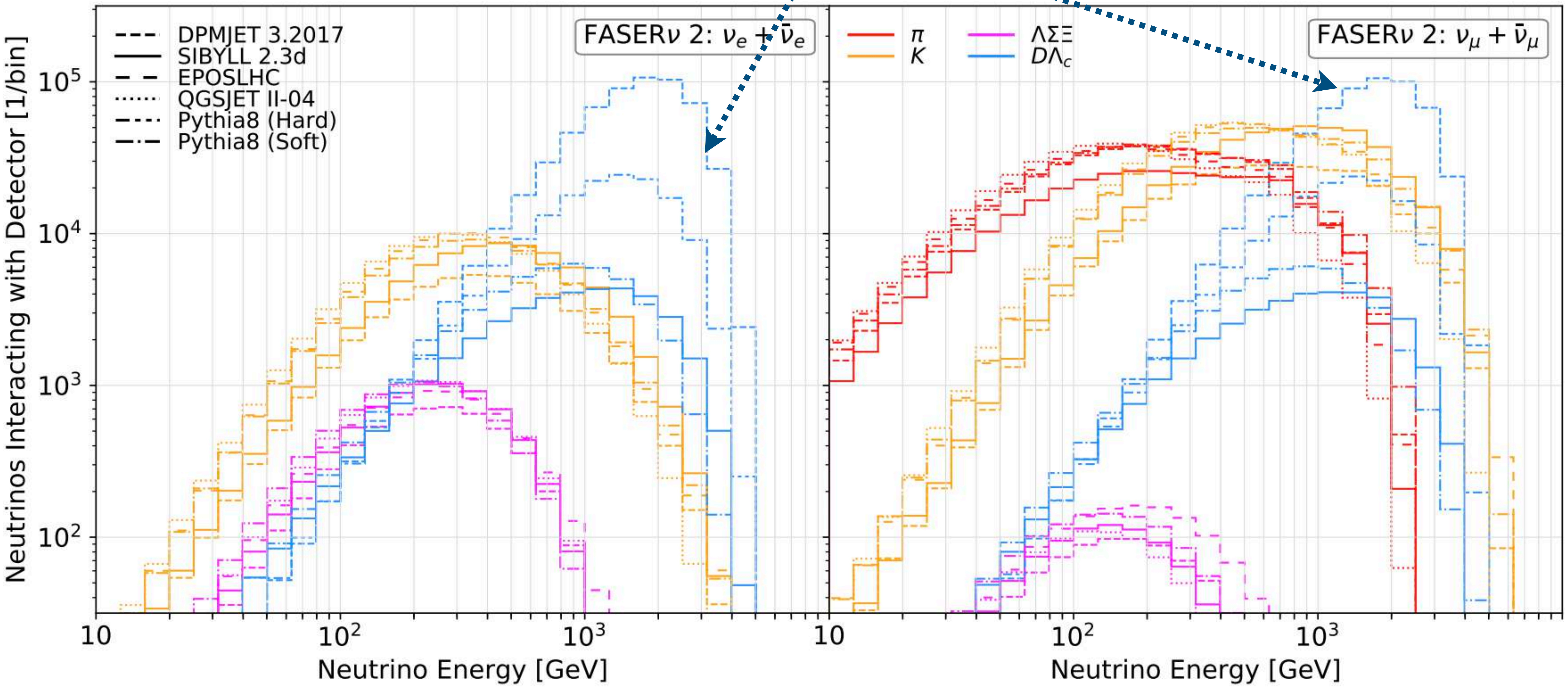
- Model comparison: strangeness enhancement toy model as an example [L. Anchordoqui et al., JHEAp 34 (2022)]

Prompt Hadron Production

- Example: Neutrino fluxes at FASERν2

high-energy region relevant!

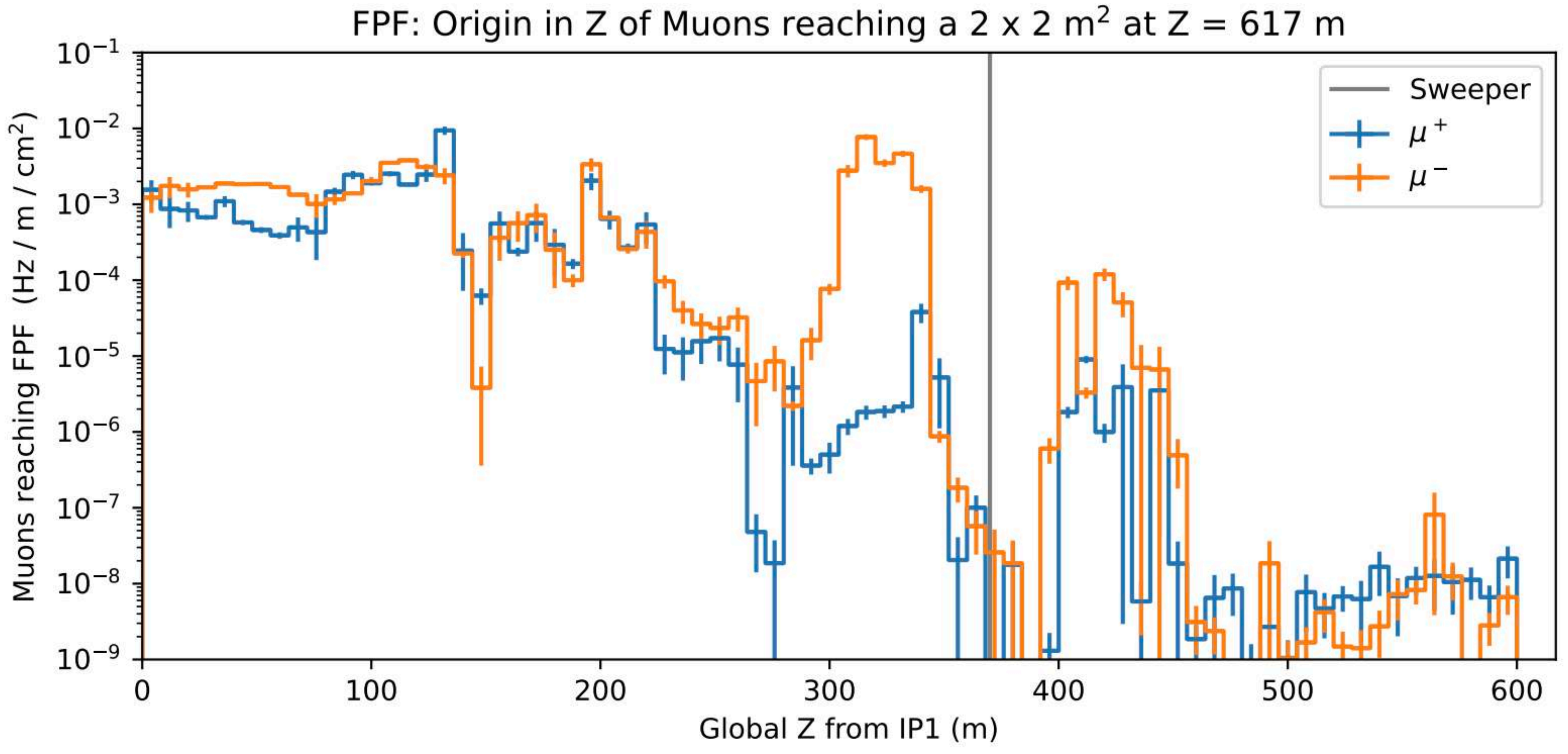
[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]



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

Muon Fluxes at the FPF

- <u>Muon fluxes at the FPF:</u>
  - 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…
  - <u>Open questions:</u>
    - 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…

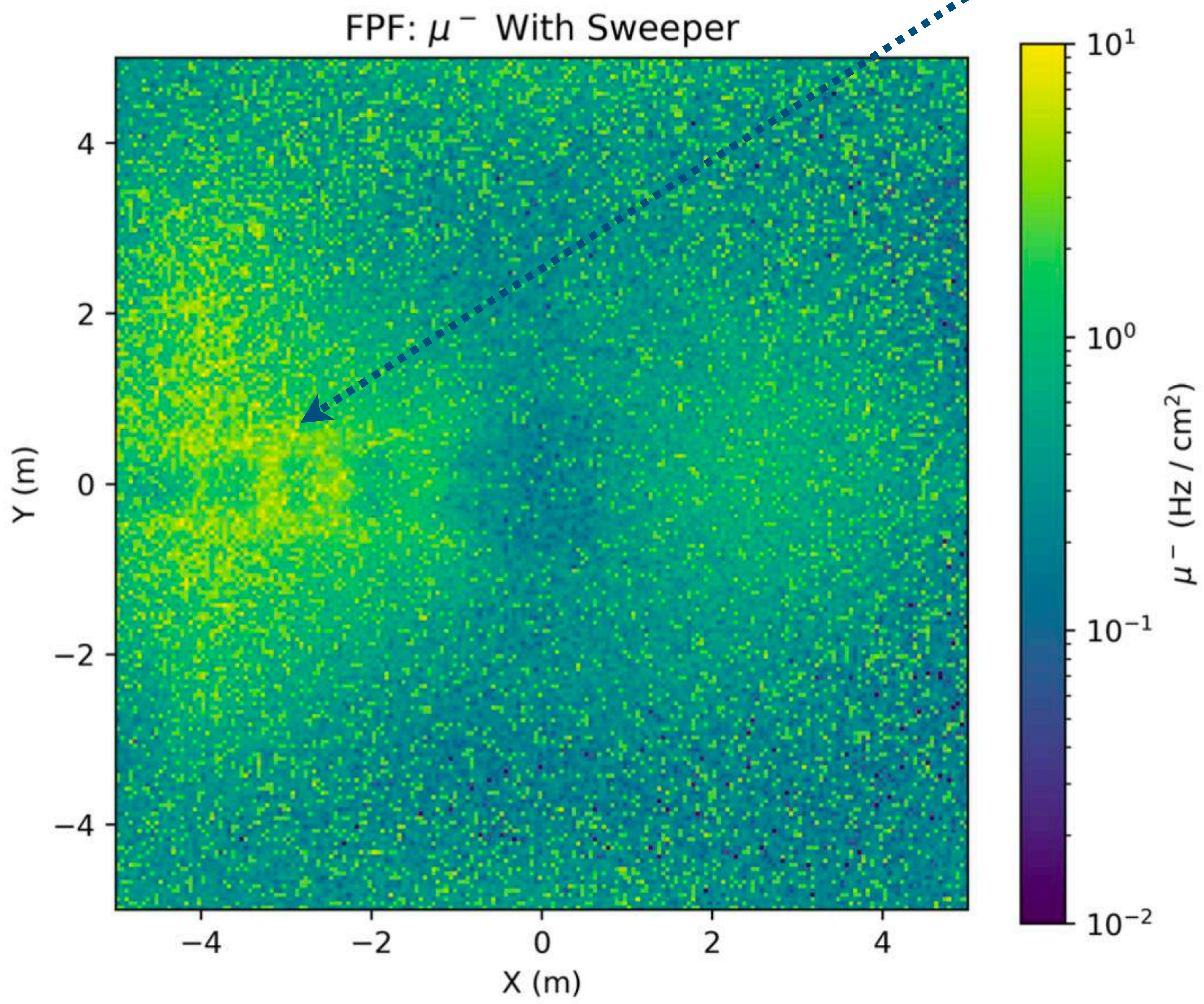


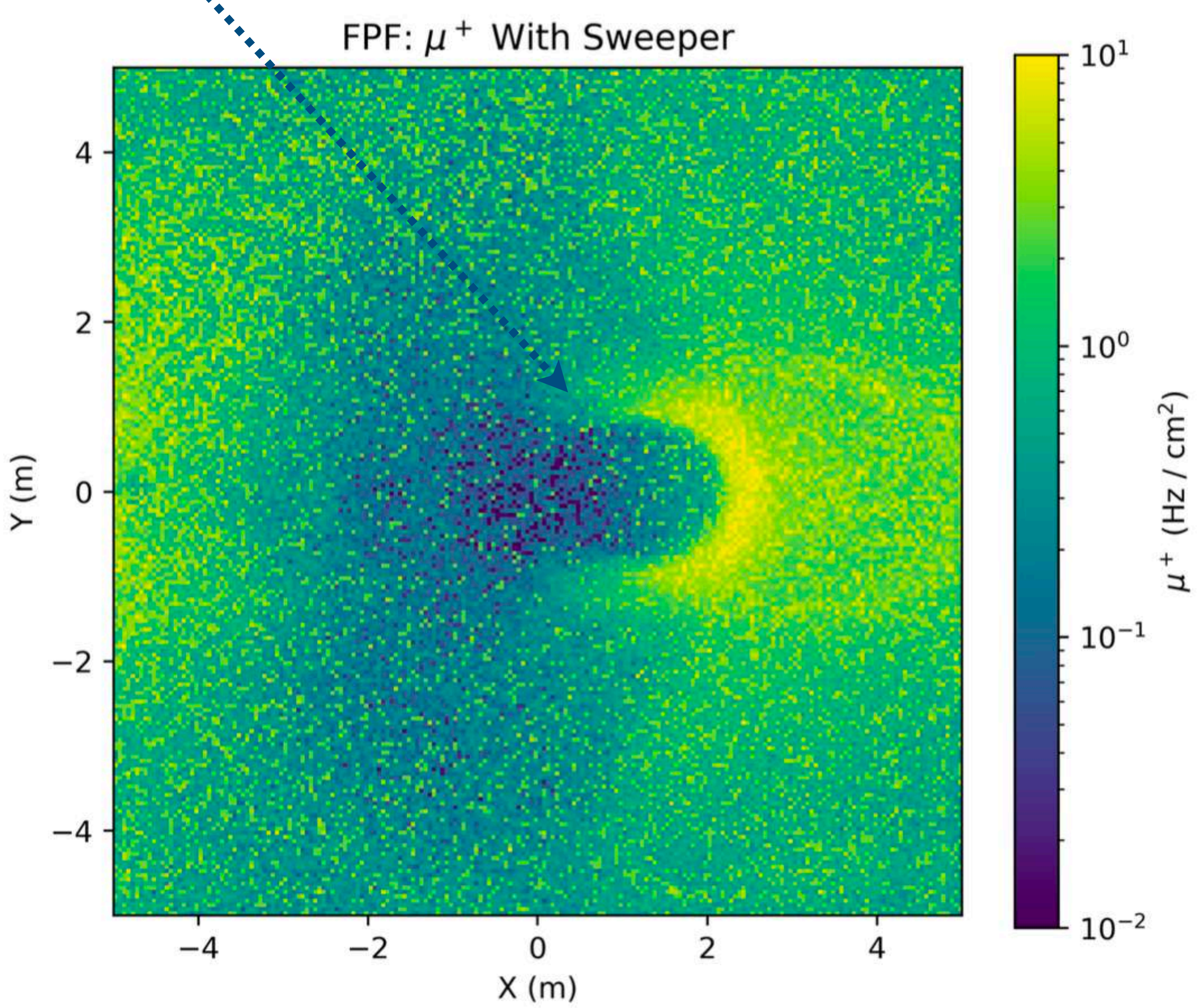
[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Muon Fluxes at the FPF

- Muon fluxes at the FPF:

various structures observed





- Temporary detectors? Simulation studies ongoing…

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

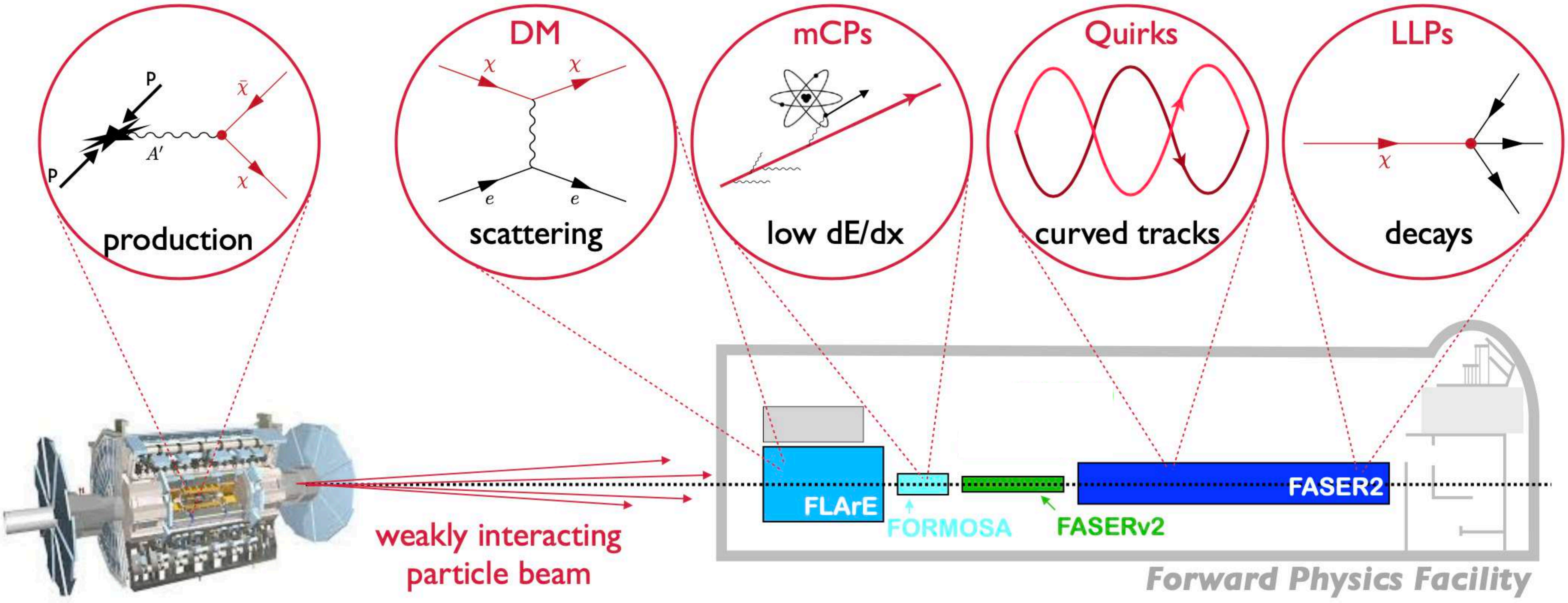
BSM Physics & Dark Matter

Contents

BSM physics & dark matter

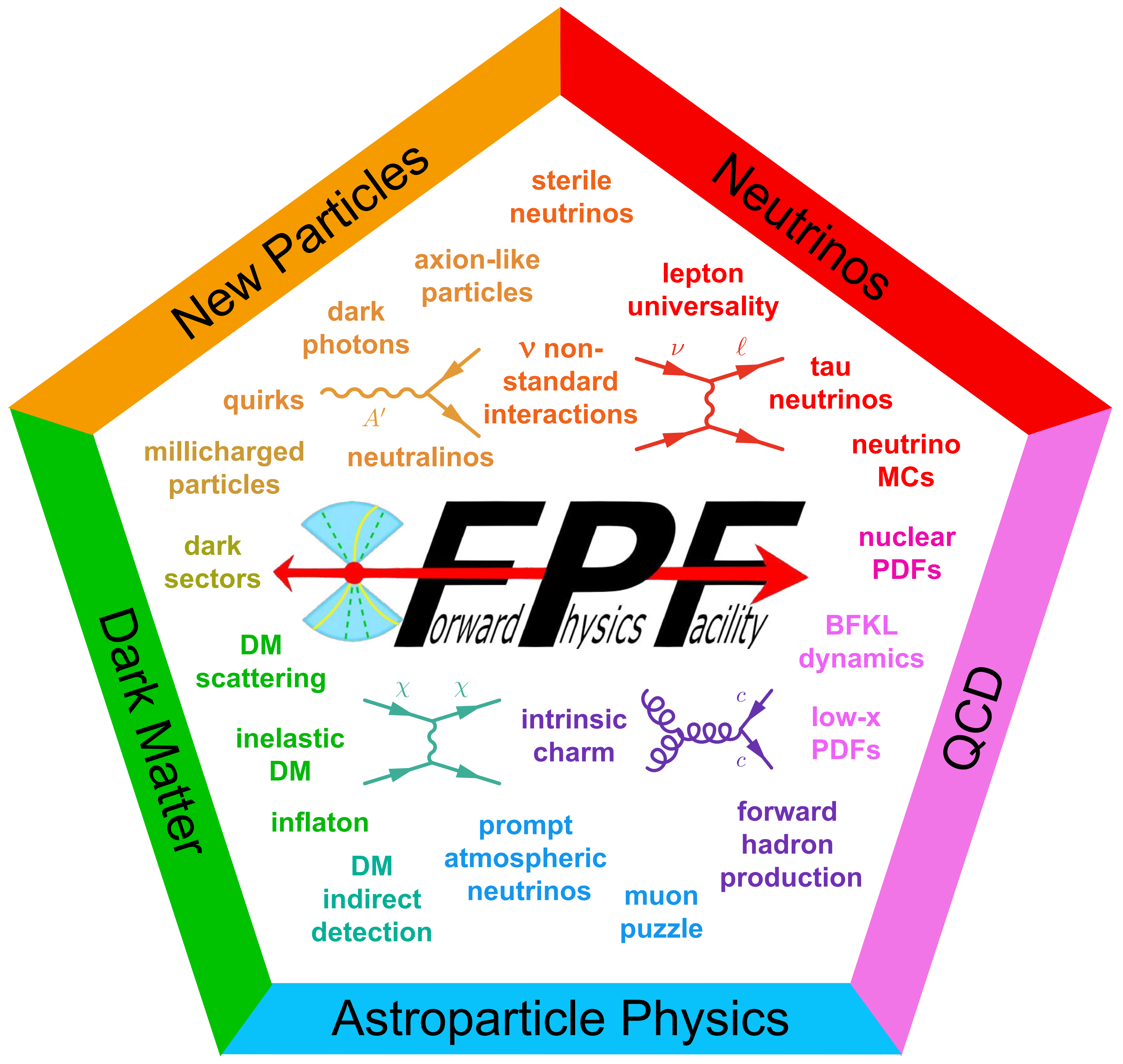
Dark Matter Searches

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



Summary

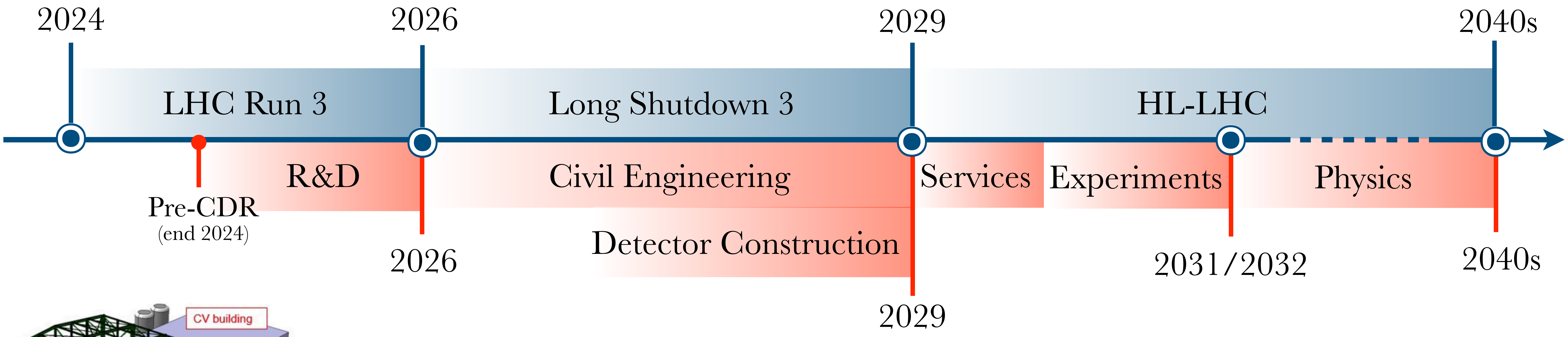
- Cosmic ray measurements highly rely on interpretation based on MC simulations of EASs
  - Large discrepancies observed in the muon content of EAS
- High-energy neutrinos from EASs are background for astrophysical neutrino searches
  - Prompt neutrino flux not well understood
- The FPF is a proposal to measure particle production at the HL-LHC in the ATLAS line-of-sight ($\eta \gtrsim 7$)
- Comprehensive and diverse physics program
- <u>Reduced uncertainties for astroparticle physics measurements, i.e. cosmic rays & neutrinos</u>
- <u>Various BSM & dark matter searches</u>
- More information: https://fpf.web.cern.ch/

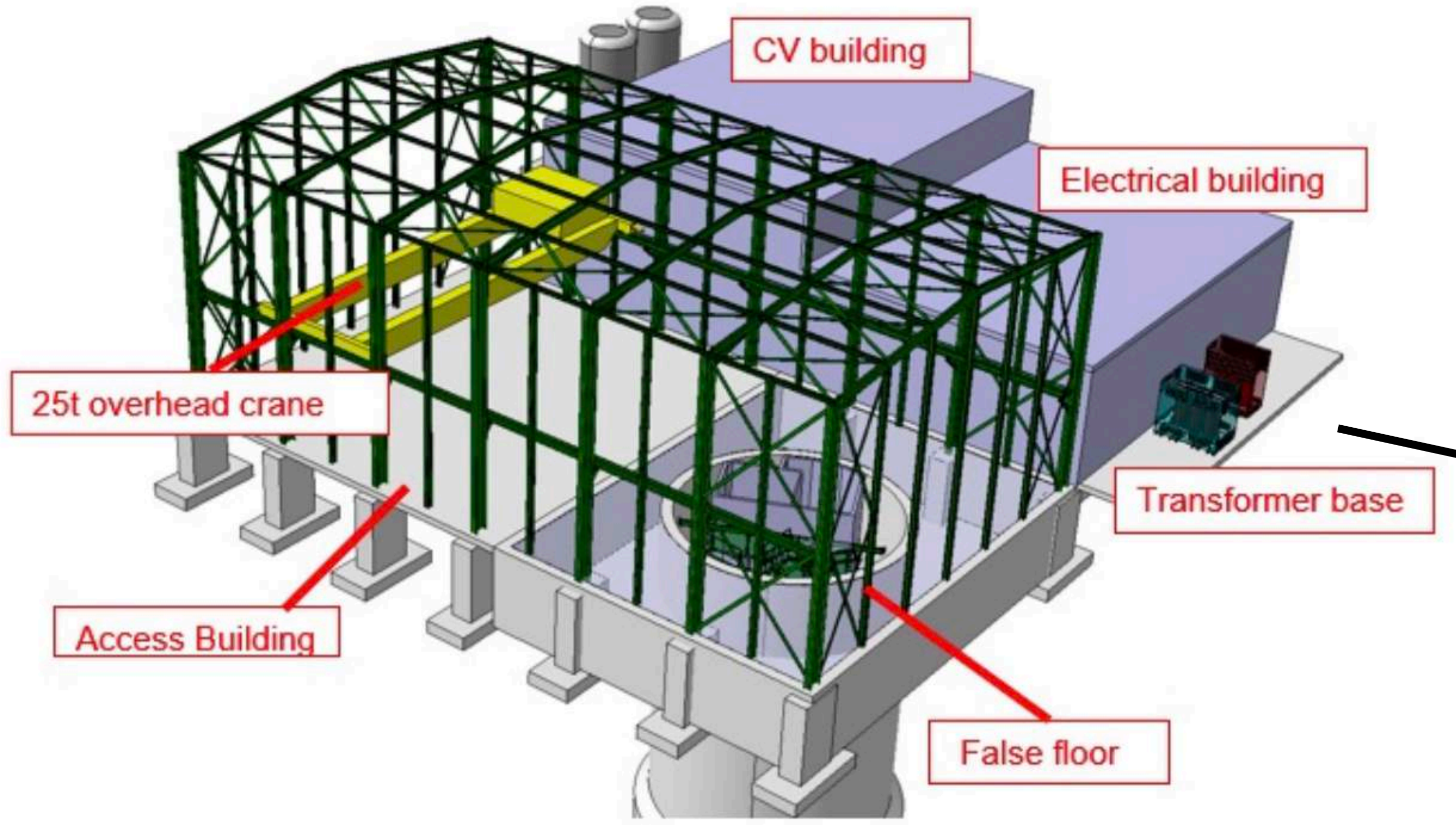


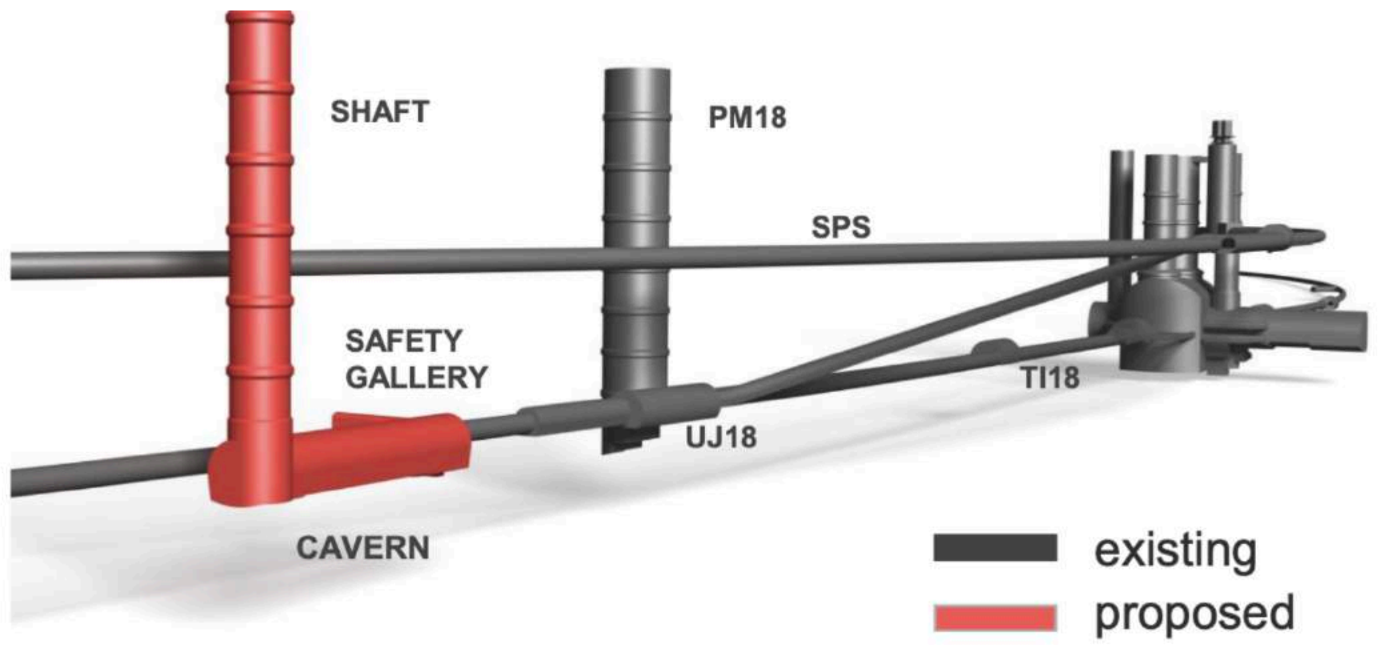
Please don't hesitate to contact us if you want to contribute!

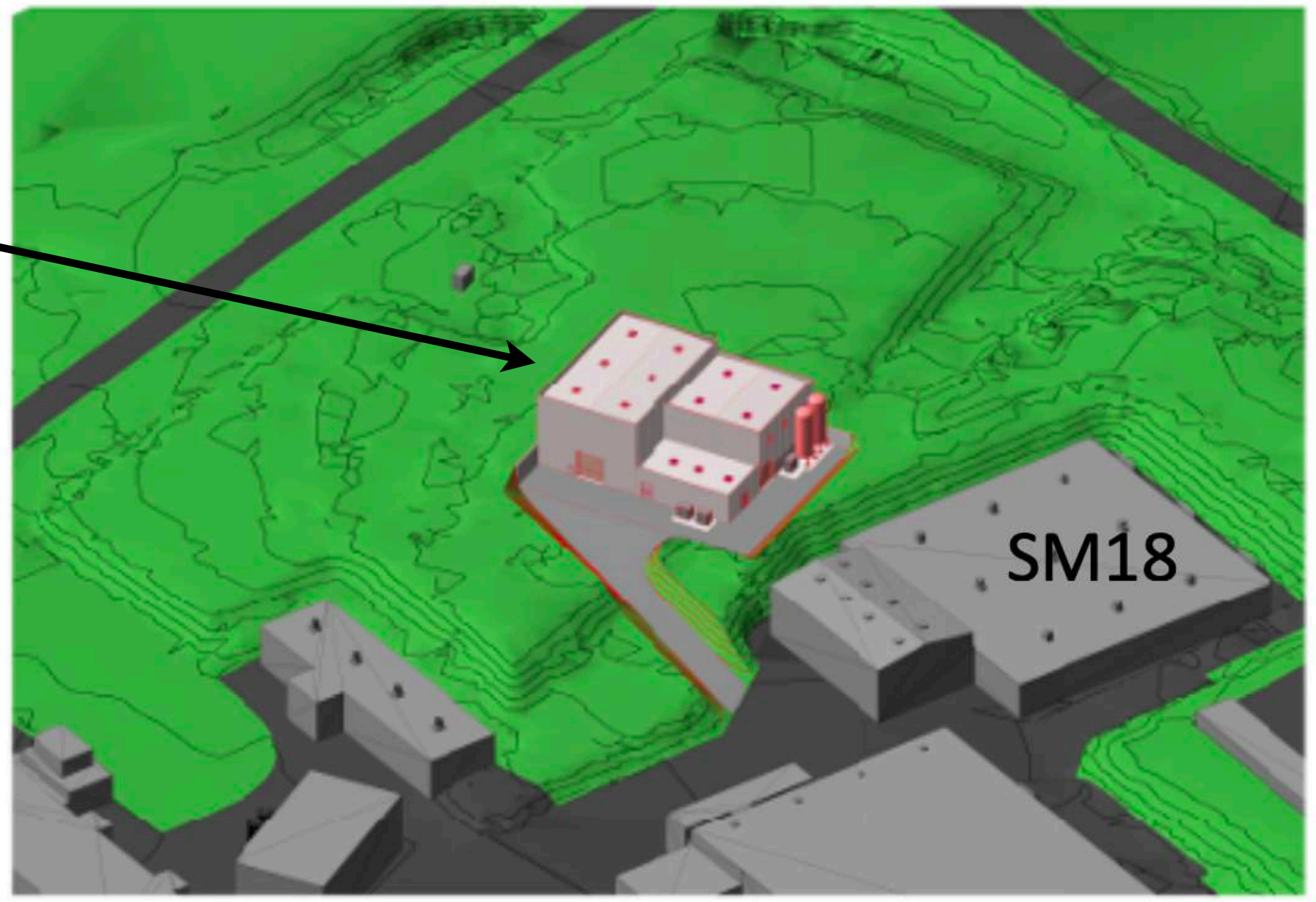
Backup

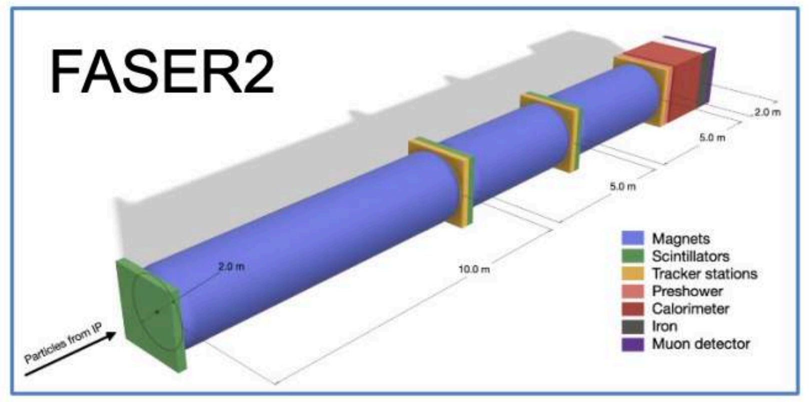
FPF Timeline

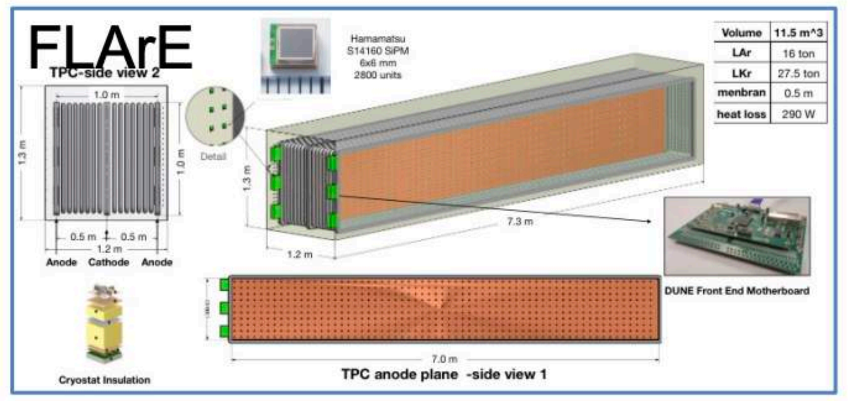


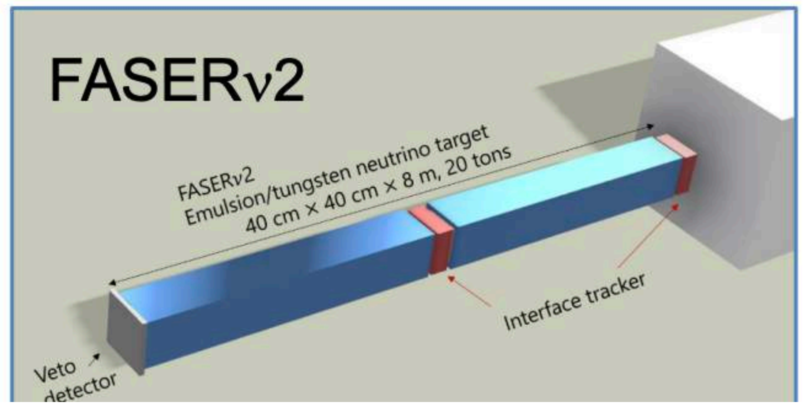


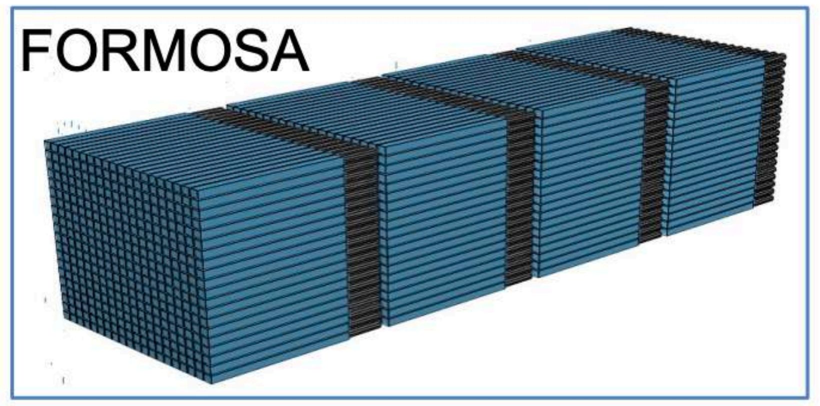






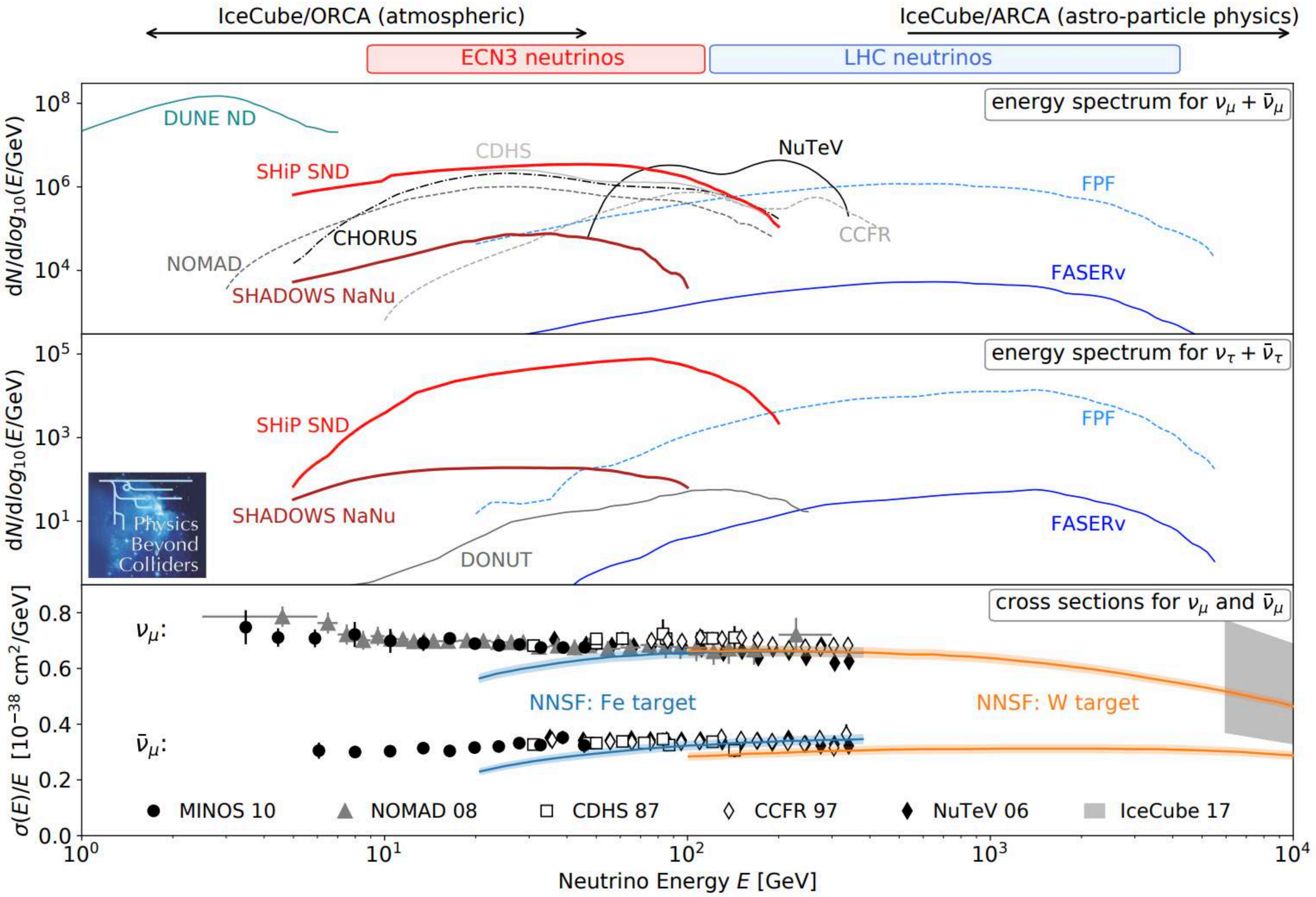




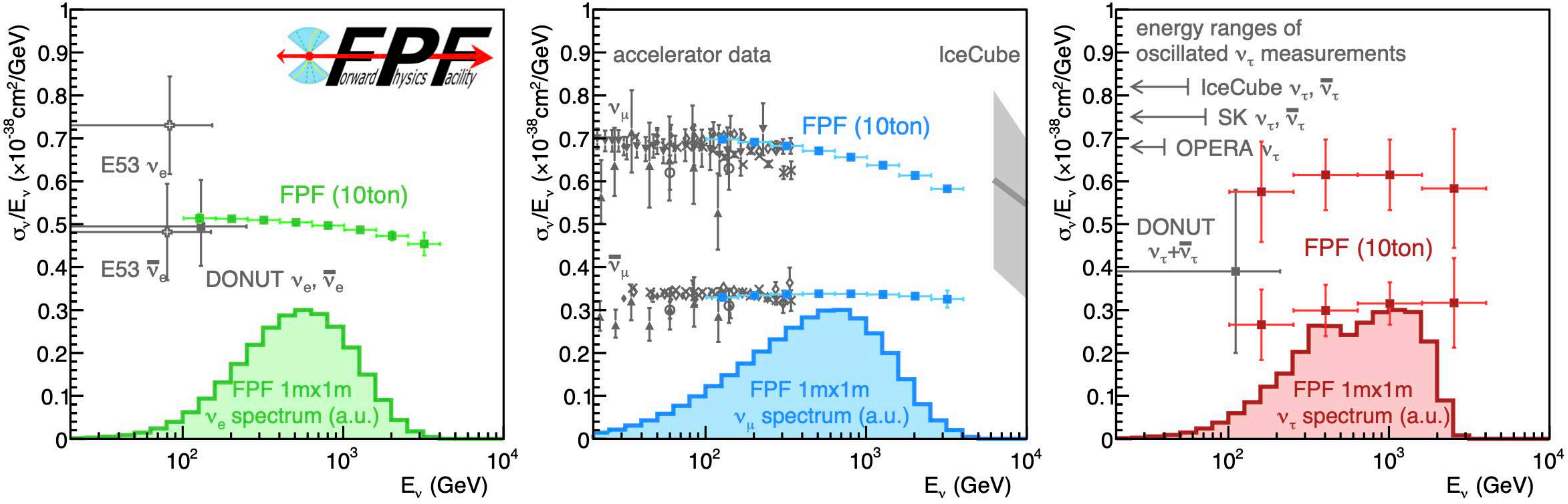


[J. L. Feng et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Experiment Comparison



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)

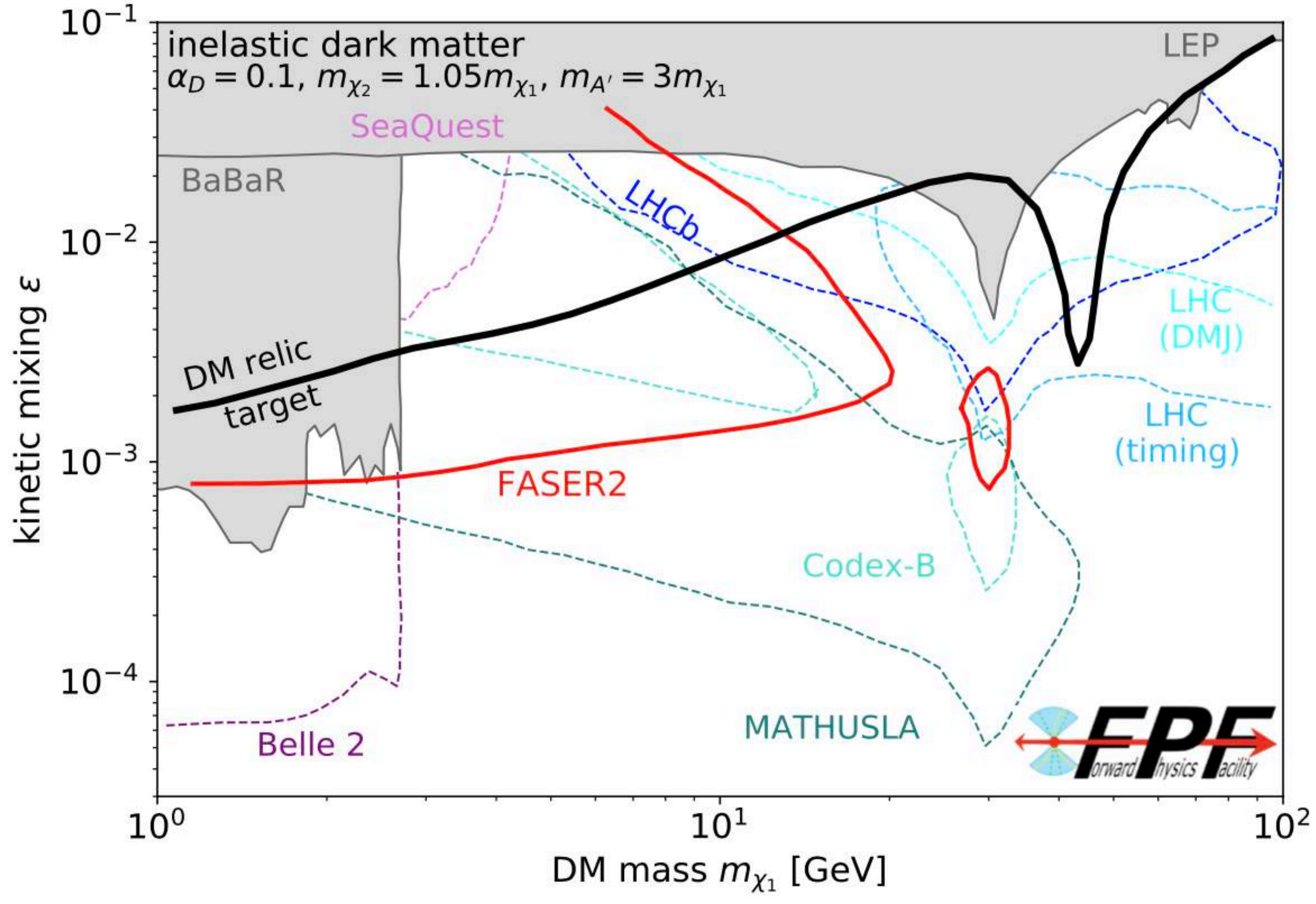
Dark Matter Searches

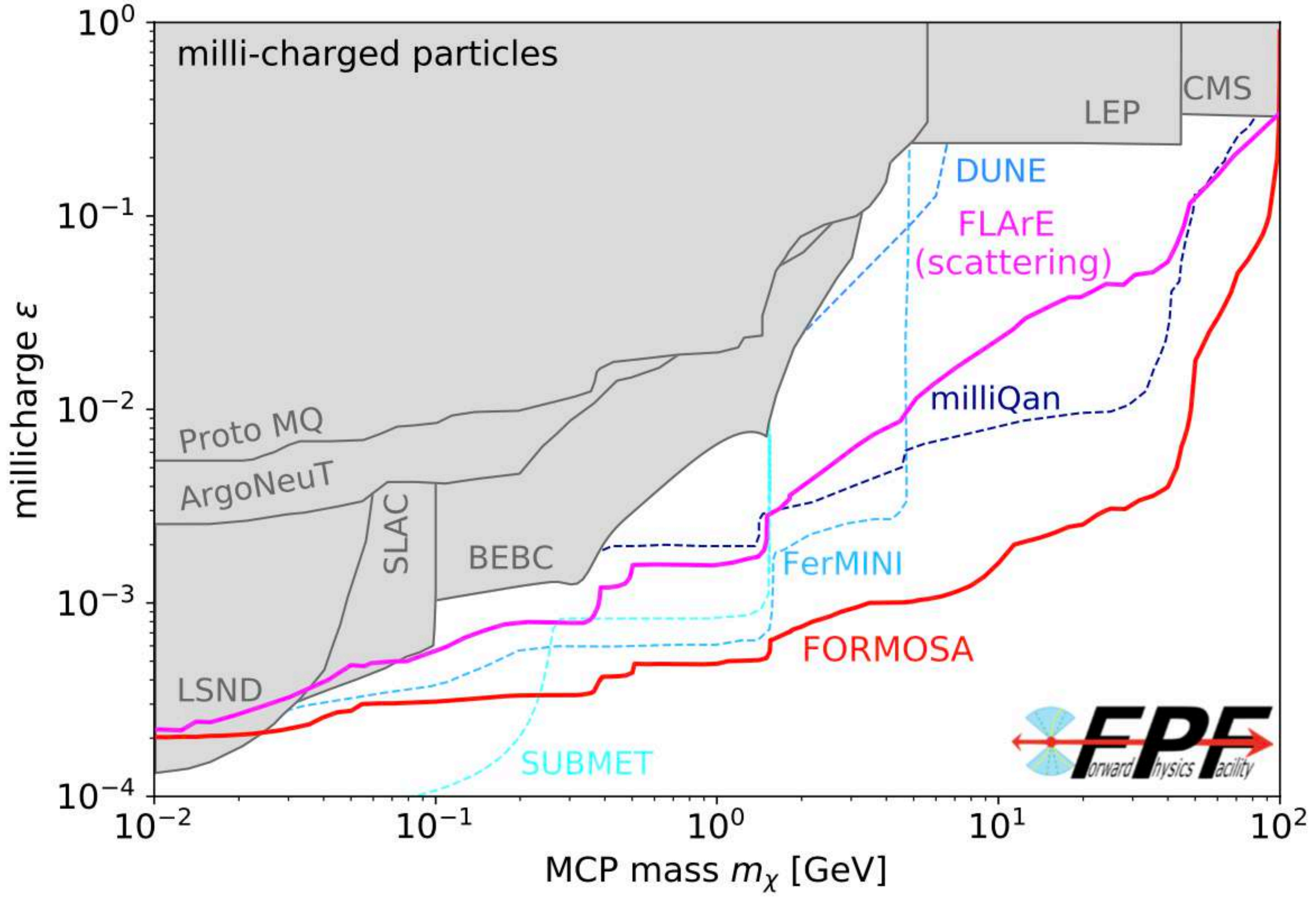
- Examples:

[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)]





Neutrino / DM Overview