### **Astroparticle Physics with the Forward Physics Facility**

**ISVHECRI 2024** Puerto Vallarta, Mexico

### 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!
  - ► <u>z-scale</u>:

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

- z = 0: proton
- $\blacktriangleright$  z = 1: iron
- <u>Large uncertainties</u> in EAS measurements,  $\mathbf{N}$ e.g. composition!



Talk by J. C. Arteaga-Velázquez this afternoon

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





# **Introduction: Atmospheric Neutrinos**

- Atmospheric high-energy neutrino flux:





# **Introduction: Challenges in EAS Physics**

2

- Extensive air showers:
  - Particle production in the far-forward region 10-Low momentum transfer 8 (Typically) non-perturbative regime 6 Complex particle composition 4
  - Energies range over many orders of magnitude
- Modeling of particle interactions in EASs based on phenomenological models

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?









- 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 ( $\eta \gtrsim 7$ )





### 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?



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



### 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

- 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, ...









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

ATLAS





### FAR FORWARD EXPERIMENTS AT LHC RUN 3

FASER: approved March 2019 FASERv: approved December 2019

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



sps ,

UJ12



- 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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line of sight



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





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10-ton-scale noble liquid fine-grained time projection chamber to detect neutrinos and light dark matter







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# **FPF Physics Potential**

### Example:

### FASER $\nu$ pilot detector VS.

- 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
- Costs: ~  $$10^9$
- <u>0 TeV neutrino candidates</u>





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  - First 153 neutrino candidates reported [FASER Collaboration, Phys. Rev. Lett. 131 (2023)]
  - Significance of  $\sim 16\sigma$
  - ~ 10000  $\nu$  candidates expected (~ 10<sup>9</sup> muons\*)

Talk by O. Sato this afternoon

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



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### All previous collider experiments

- Building size, decades of data
- Costs: ~  $\$10^9$
- <u>0 TeV neutrino candidates</u>
- Forward Physics Facility:
  - ~  $10^6 \nu$  candidates expected! (~  $10^{12}$  muons\*)







## The Facility















![](_page_19_Picture_8.jpeg)

# **FPF Physics Program**

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

![](_page_20_Figure_8.jpeg)

![](_page_20_Picture_9.jpeg)

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- <u>Comprehensive physics program:</u>
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  - Quantum Chromodynamics
  - Neutrino physics
  - Astroparticle physics
- <u>Comprehensive description of the FPF:</u>
  - "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/

![](_page_21_Picture_14.jpeg)

### **OPEN ACCESS**

IOP Publishing

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Major Report

### The Forward Physics Facility at the High-Luminosity LHC

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![](_page_21_Picture_22.jpeg)

### FPF Physics Program

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Astroparticle

physics

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## 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

![](_page_23_Picture_6.jpeg)

![](_page_23_Figure_7.jpeg)

# **Light Hadron Production**

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

![](_page_24_Figure_2.jpeg)

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

![](_page_24_Picture_4.jpeg)

![](_page_24_Picture_5.jpeg)

low-energy region relevant!

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# **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</u> <u>testing the forward rapidity region!</u>

![](_page_25_Picture_8.jpeg)

![](_page_25_Picture_9.jpeg)

![](_page_25_Figure_11.jpeg)

![](_page_25_Picture_12.jpeg)

# **Light Hadron Production**

### Example: Neutrino fluxes at FLArE

![](_page_26_Figure_2.jpeg)

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

![](_page_26_Picture_5.jpeg)

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

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## **Prompt Hadron Production**

### • Example: Neutrino fluxes at FASER $\nu 2$

![](_page_27_Figure_2.jpeg)

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

![](_page_27_Picture_4.jpeg)

high-energy region relevant!

15

## **Muon Fluxes at the FPF**

- Muon fluxes at the FPF:
  - Large muon flux at the FPF, e.g.  $\sim 1$  Hz per cm<sup>2</sup> in FASER
  - 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(a)LHC?
  - Dedicated studies of the muon yield at the FPF are ongoing...

![](_page_28_Picture_10.jpeg)

![](_page_28_Picture_11.jpeg)

While we know the origin of neutrinos in the FPF (ATLAS interaction point), studies of muons at the

![](_page_28_Figure_15.jpeg)

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

![](_page_28_Picture_17.jpeg)

Muon fluxes at the FPF:

![](_page_29_Figure_2.jpeg)

Temporary detectors? Simulation studies ongoing...

![](_page_29_Figure_4.jpeg)

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

![](_page_29_Picture_6.jpeg)

![](_page_29_Picture_7.jpeg)

### **BSM Physics & Dark Matter**

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![](_page_30_Picture_6.jpeg)

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BSM physics & dark matter

![](_page_30_Picture_11.jpeg)

![](_page_30_Picture_12.jpeg)

### **Dark Matter Searches**

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

![](_page_31_Picture_2.jpeg)

![](_page_31_Picture_3.jpeg)

![](_page_31_Picture_4.jpeg)

![](_page_31_Picture_6.jpeg)

![](_page_31_Picture_7.jpeg)

![](_page_31_Picture_8.jpeg)

![](_page_31_Picture_9.jpeg)

# 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</u> <u>measurements, i.e. cosmic rays & neutrinos</u>
- Various BSM & dark matter searches
- More information: <u>https://fpf.web.cern.ch/</u>

![](_page_32_Figure_10.jpeg)

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

![](_page_32_Picture_12.jpeg)

![](_page_32_Picture_13.jpeg)

![](_page_33_Picture_1.jpeg)

![](_page_34_Figure_1.jpeg)

### **Experiment Comparison**

![](_page_35_Figure_1.jpeg)

![](_page_35_Picture_2.jpeg)

![](_page_35_Picture_3.jpeg)

### **Neutrino Fluxes at the FPF**

![](_page_36_Figure_1.jpeg)

- Neutrino fluxes ( $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ ) 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)

![](_page_36_Picture_4.jpeg)

![](_page_36_Picture_5.jpeg)

### **Dark Matter Searches**

- Examples:
  - Search for displaced decays of highly-boosted excited DM states produced in pp collisions

![](_page_37_Figure_4.jpeg)

![](_page_37_Picture_5.jpeg)

![](_page_37_Picture_6.jpeg)

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

### Millicharged particle searches as a candidate for a strongly interacting sub-component of DM

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

![](_page_37_Picture_11.jpeg)

# **Neutrino / DM Overview**

![](_page_38_Figure_1.jpeg)

![](_page_38_Picture_2.jpeg)

![](_page_38_Picture_3.jpeg)