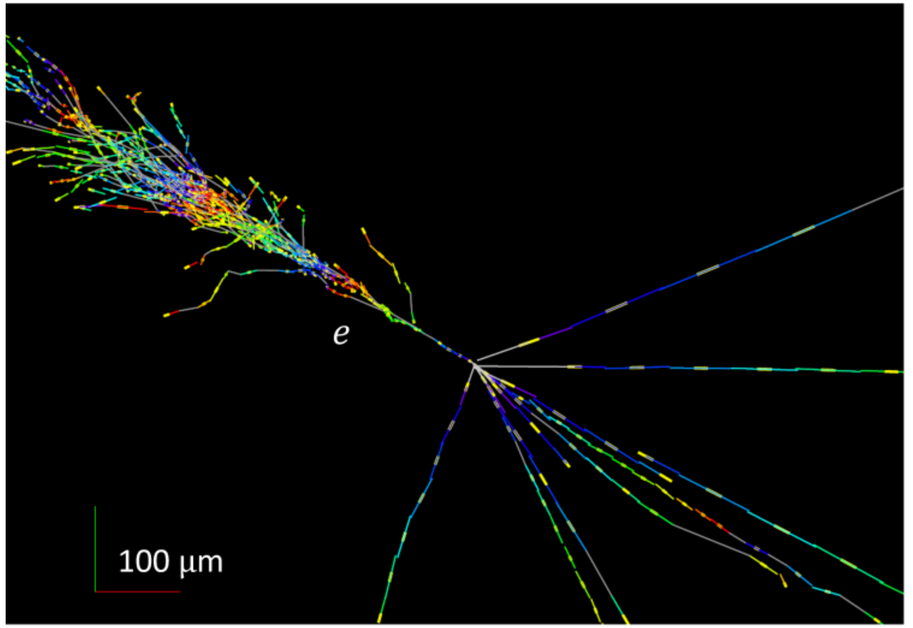
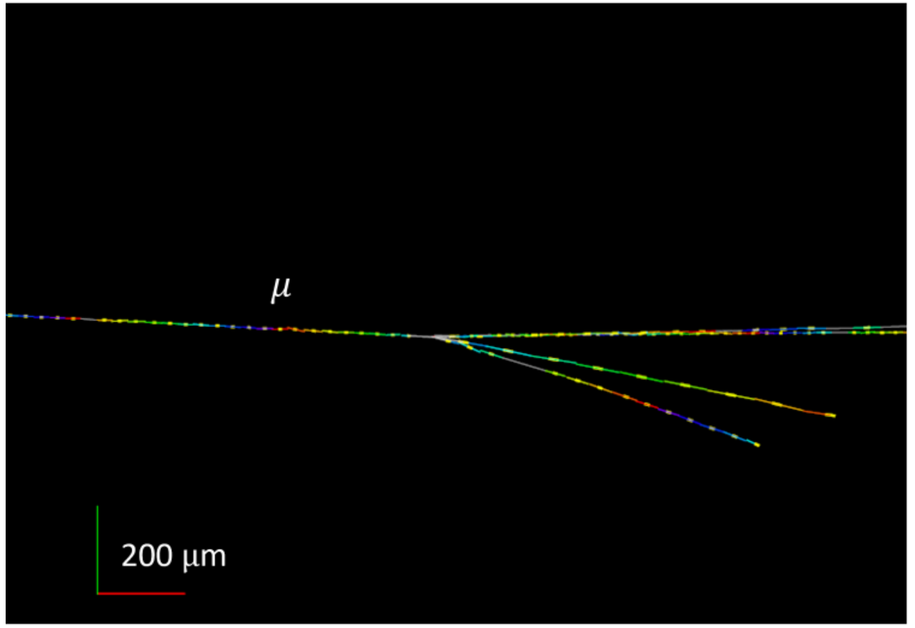
High-Energy Neutrinos at the LHC

IIHE Seminar



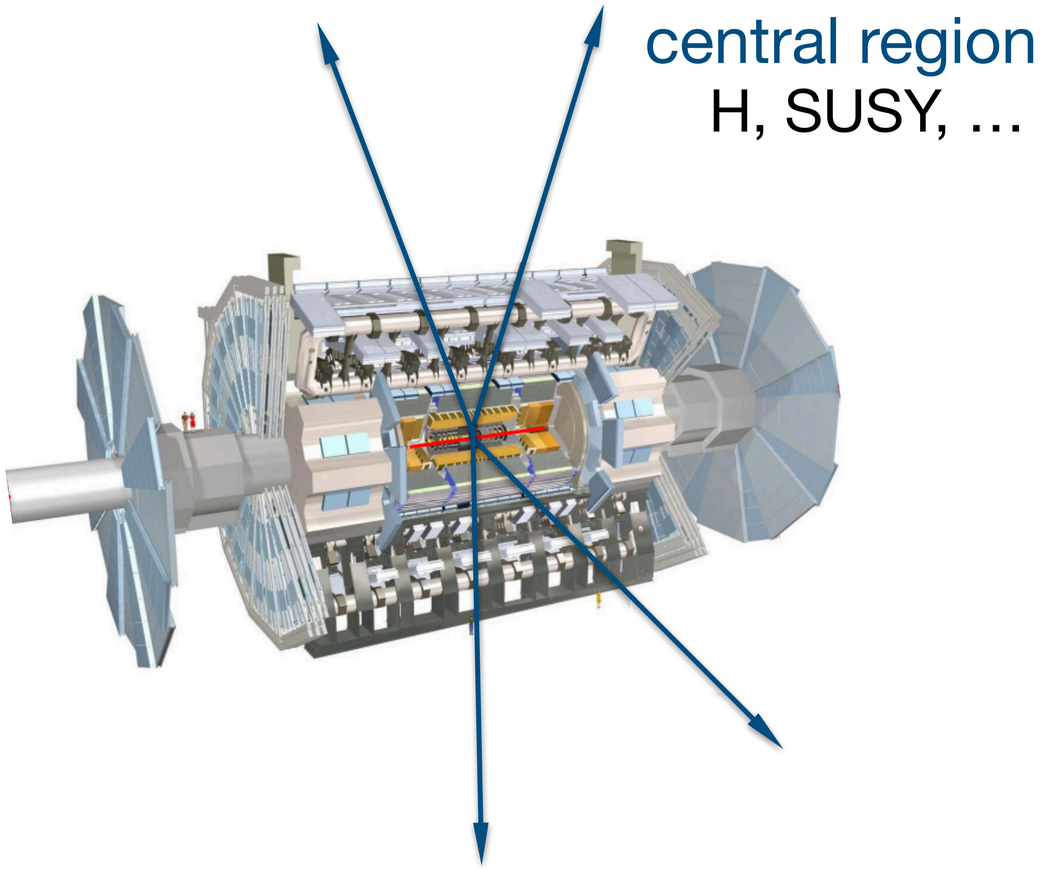


Dennis Soldin
University of Utah

THE UNIVERSITY OF UTAH

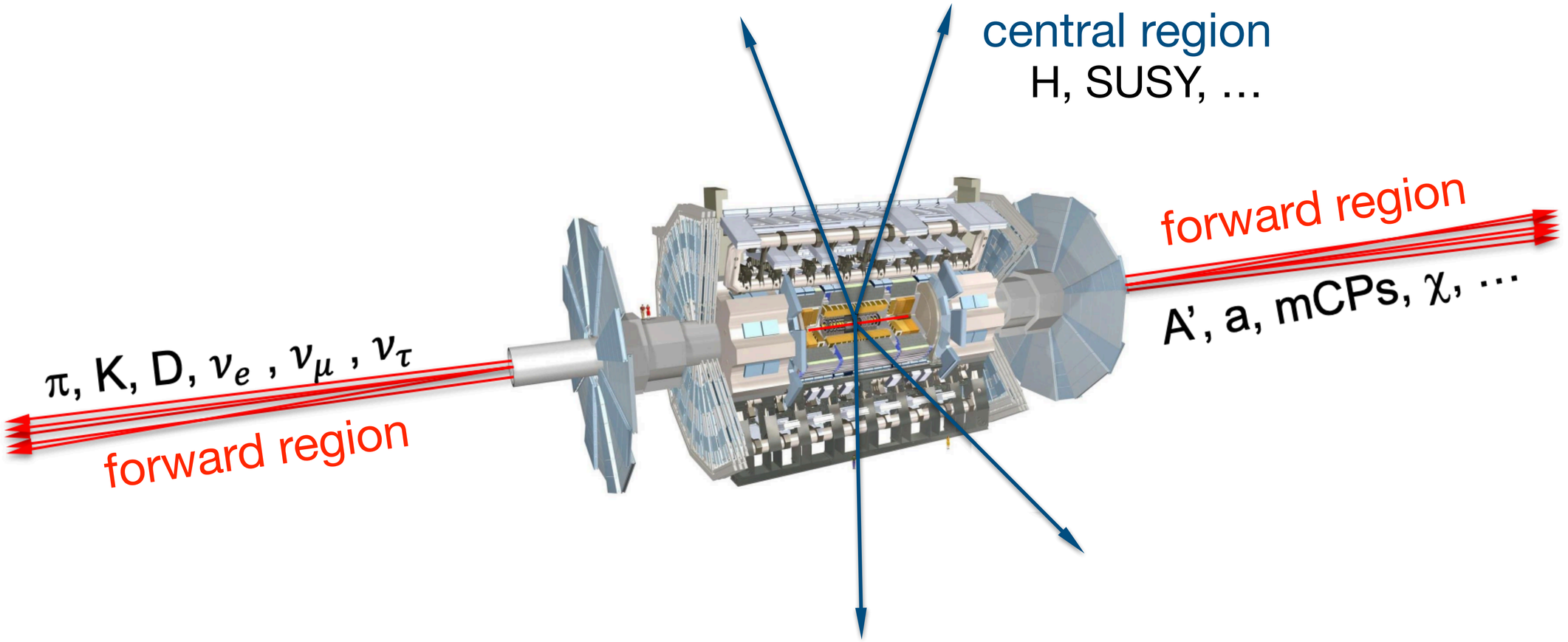
Physics Motivation

- Main focus of LHC are heavy particles: Higgs, SUSY, … .
- Their decay products have high p_T and are distributed almost isotropically
- ATLAS/CMS were constructed to catch them



Physics Motivation

- The LHC produces a huge number of hadrons in the forward direction:
  - $10^{17}\pi^0$, $10^{16}\eta$, $10^{15}D$, …, within 1 mrad of the beam in Run 3 (low p_T but large energy!)
- What opportunities are we currently missing from a lack of coverage of far-forward physics?



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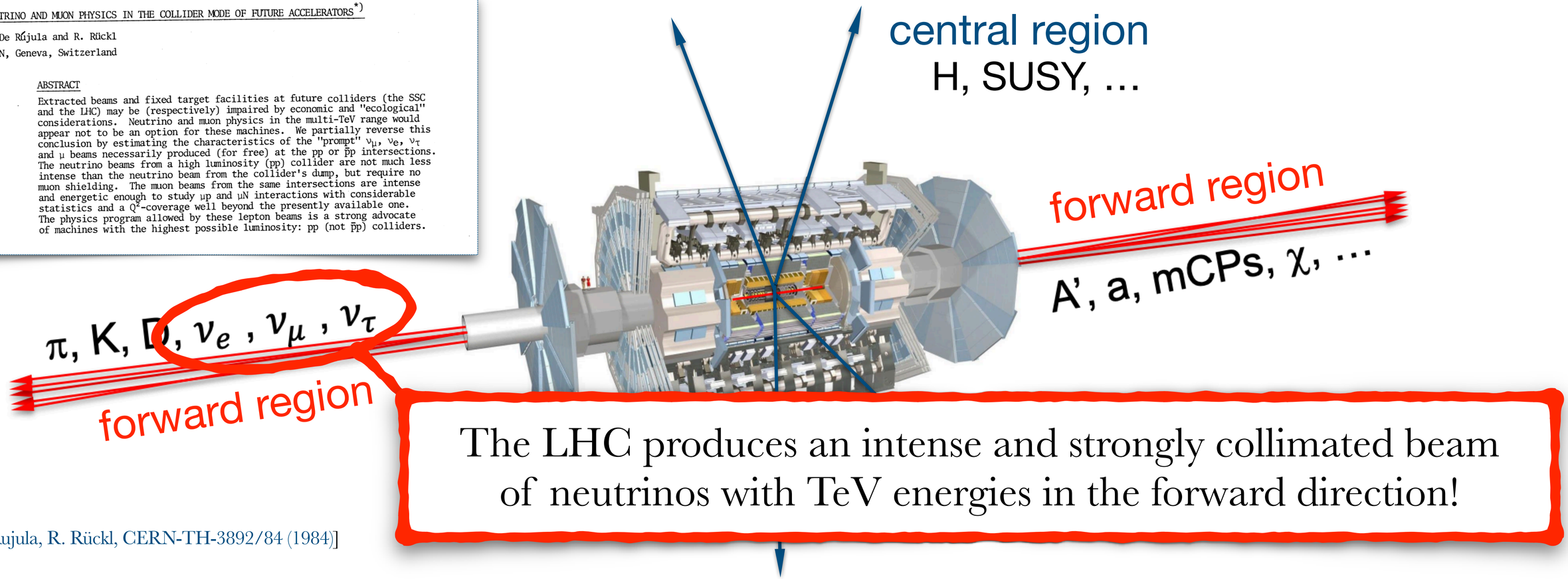
NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl
CERN, Geneva, Switzerland

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.



The LHC produces an intense and strongly collimated beam of neutrinos with TeV energies in the forward direction!

[A. De Rujula, R. Rückl, CERN-TH-3892/84 (1984)]

Physics Motivation

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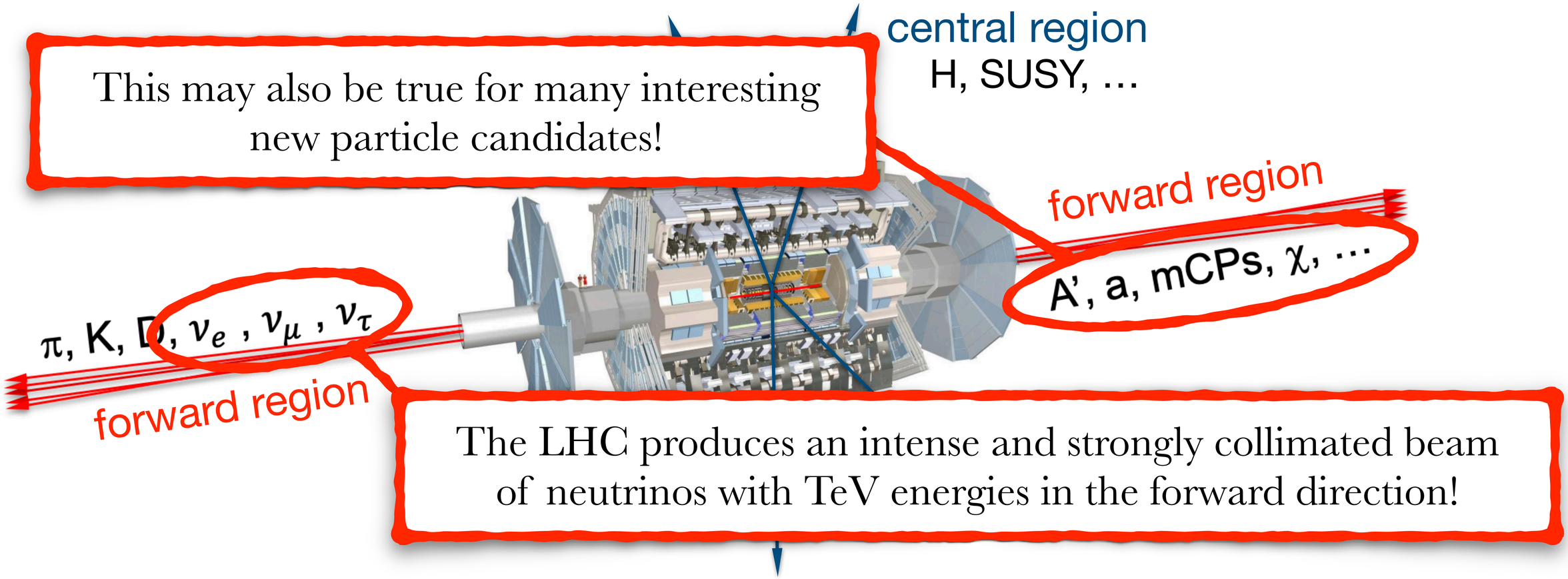
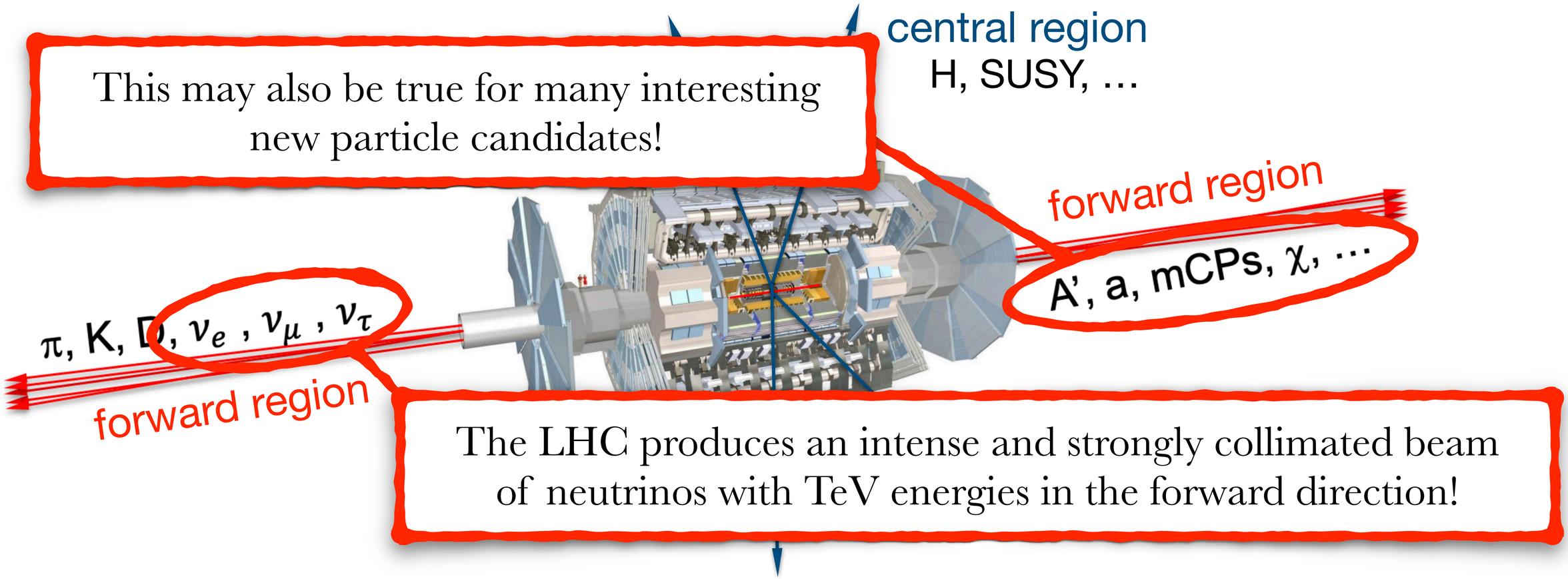


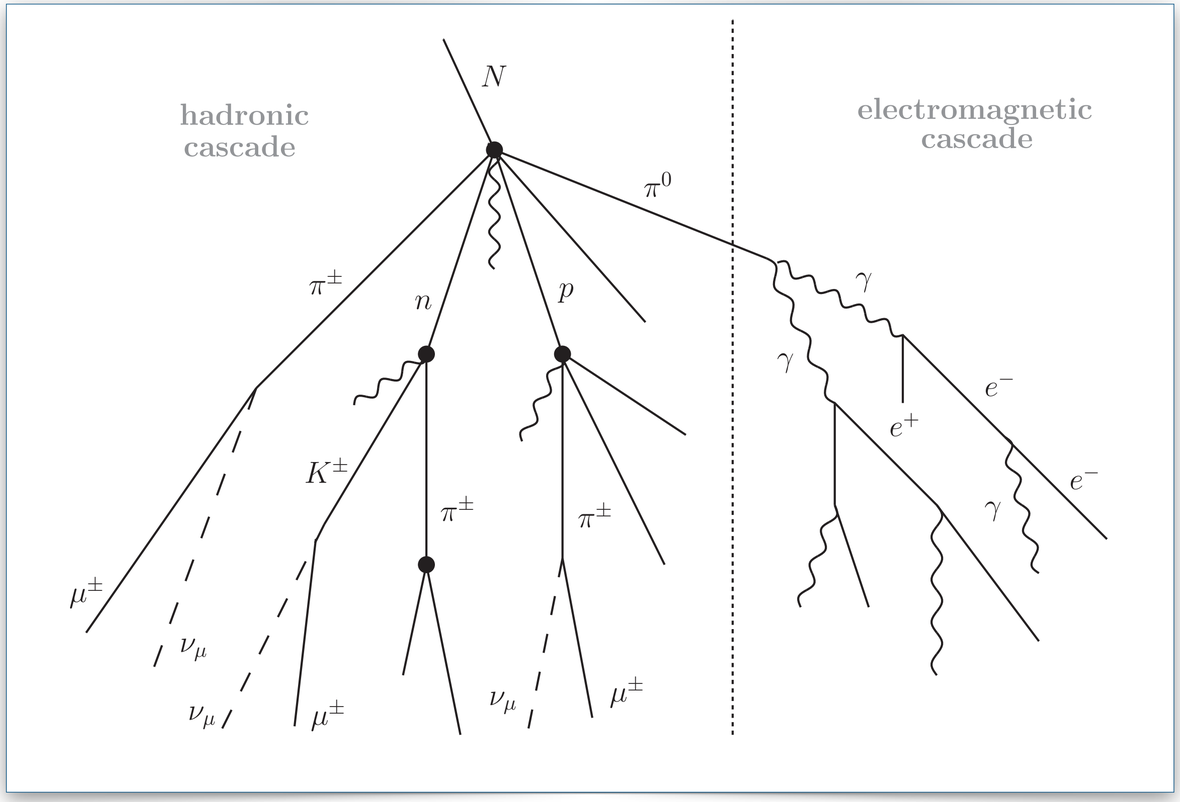
Physics Motivation

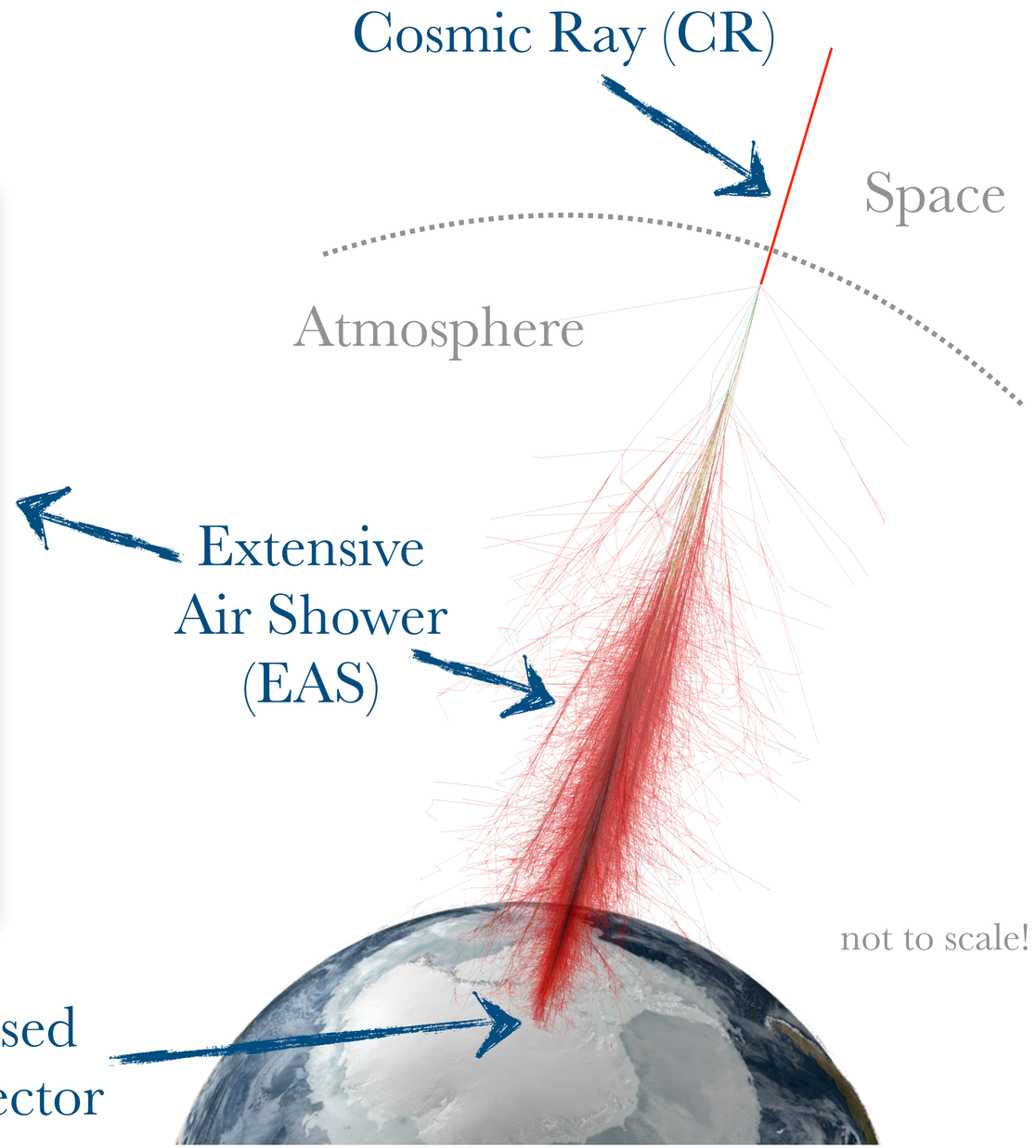
- These particles escape down the beam pipe and remain undetected!
- Indeed, the existing big LHC detectors are perfectly designed NOT to see them…



Physics Motivation

- Strong connection to astroparticle physics!



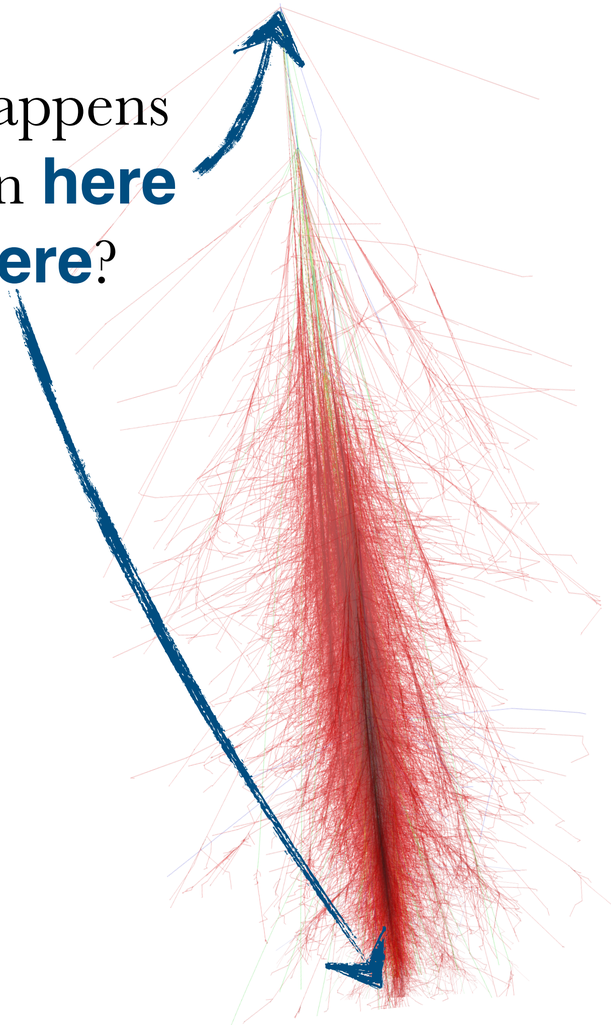


- CR properties inferred from measurements at the ground!

Extensive Air Showers

- CR properties are inferred from the (secondary) particles measured at the ground.

What happens between **here** and **here**?



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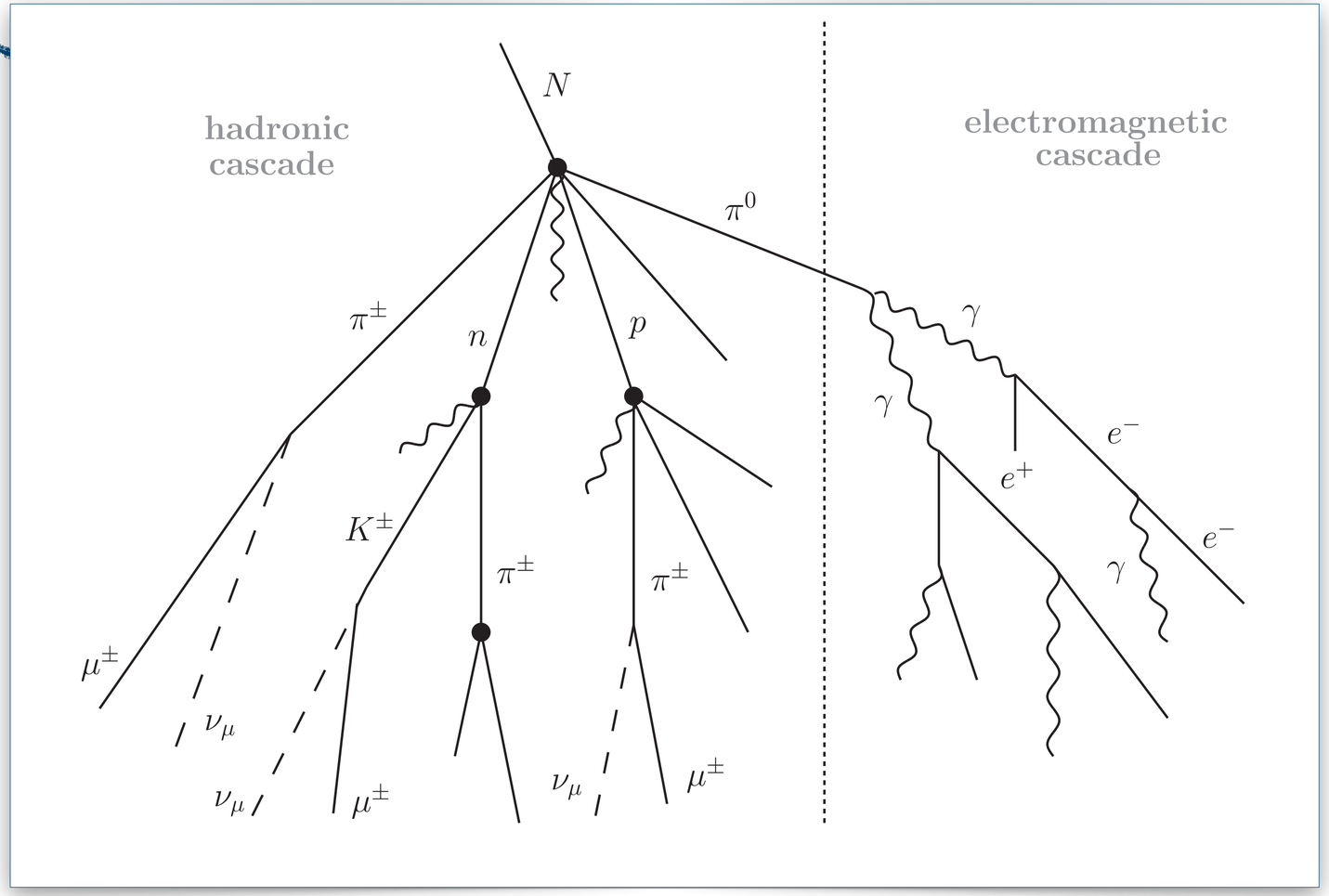

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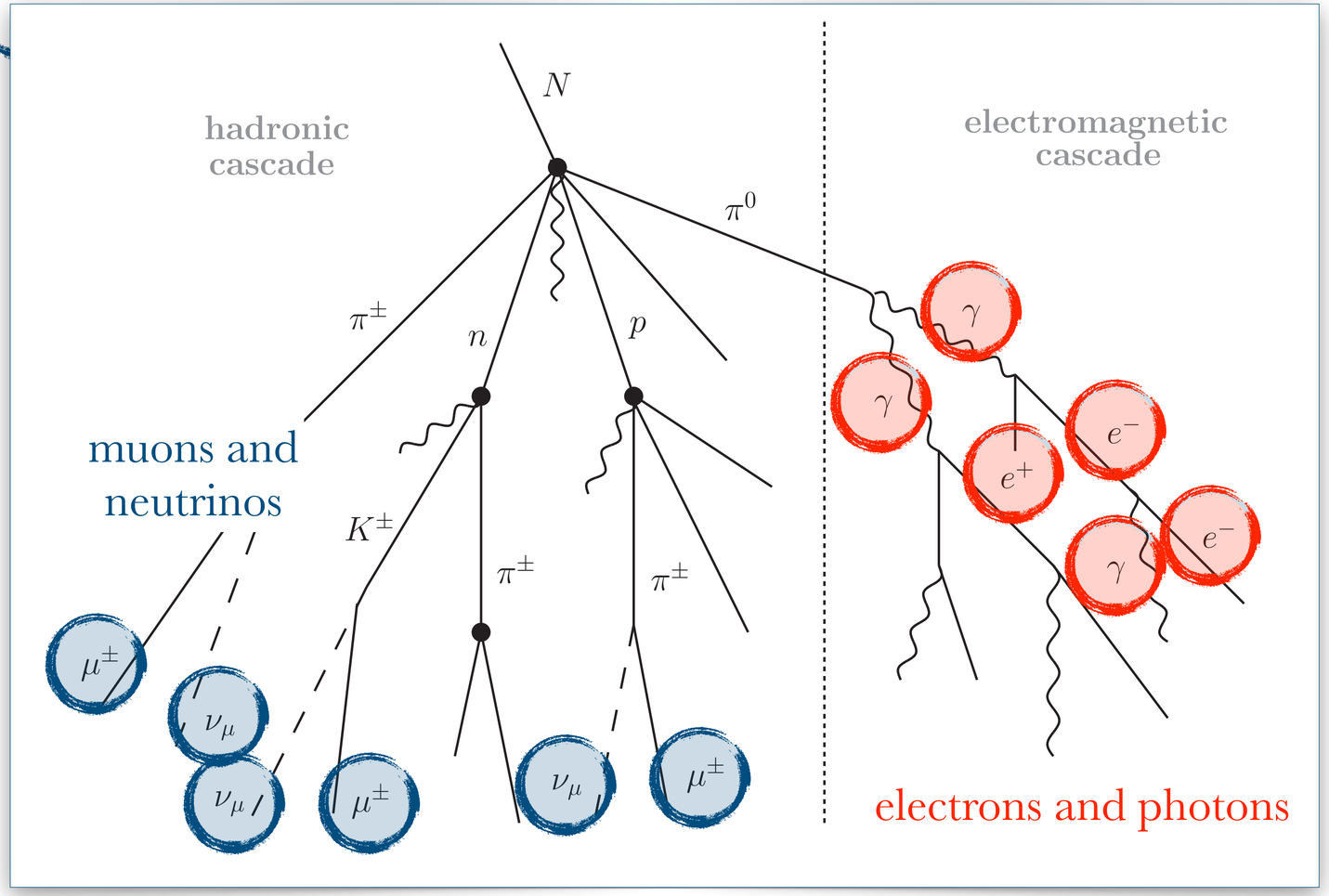
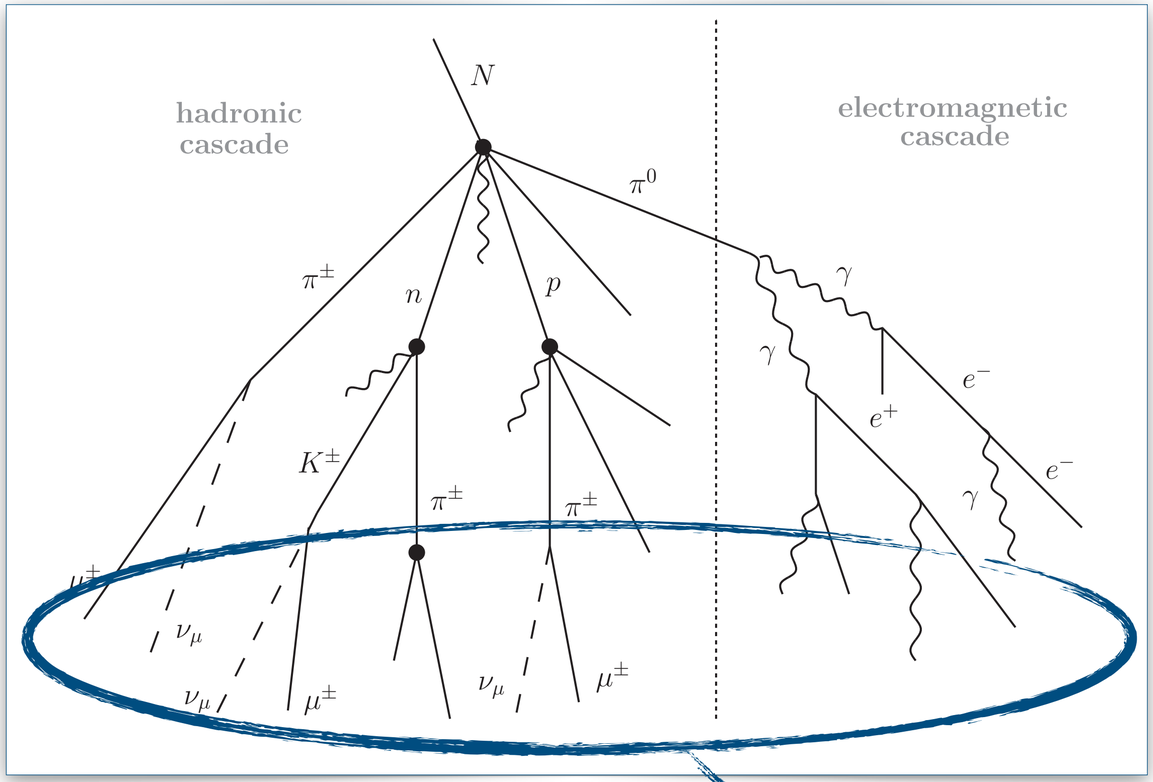
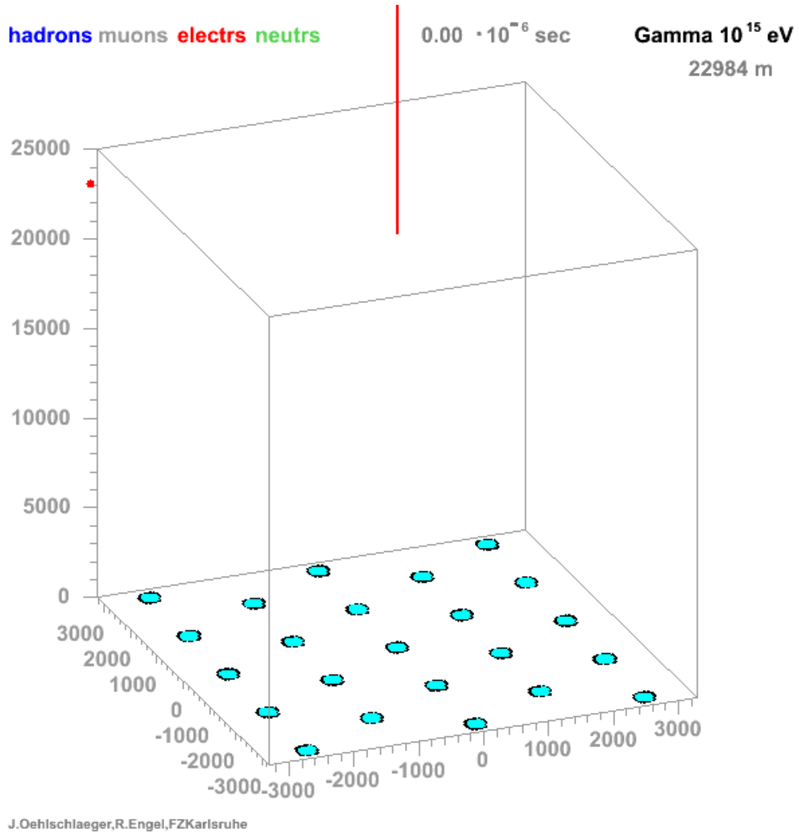


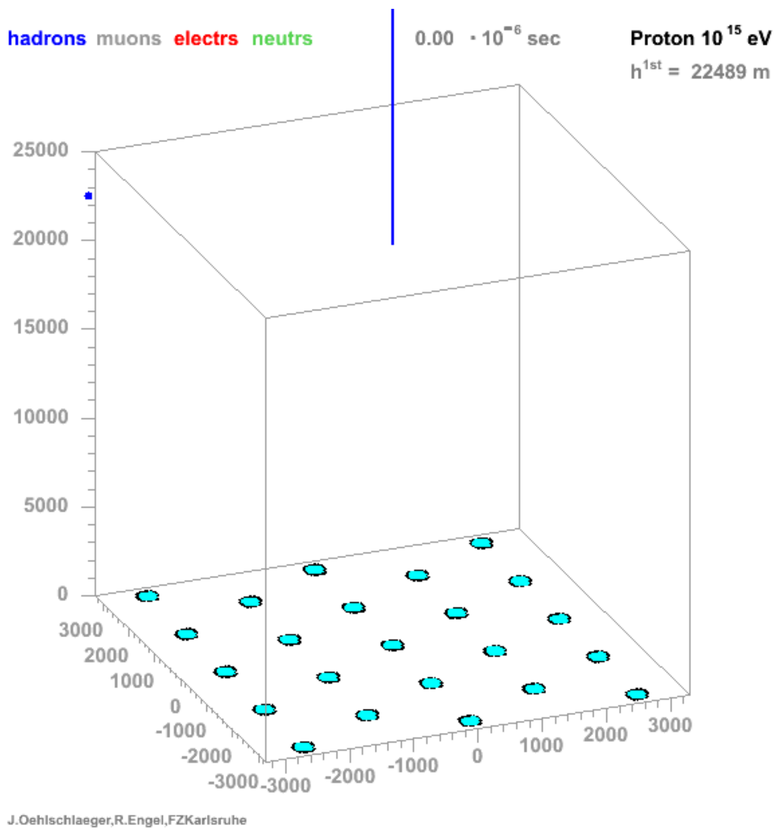
Extensive Air Showers

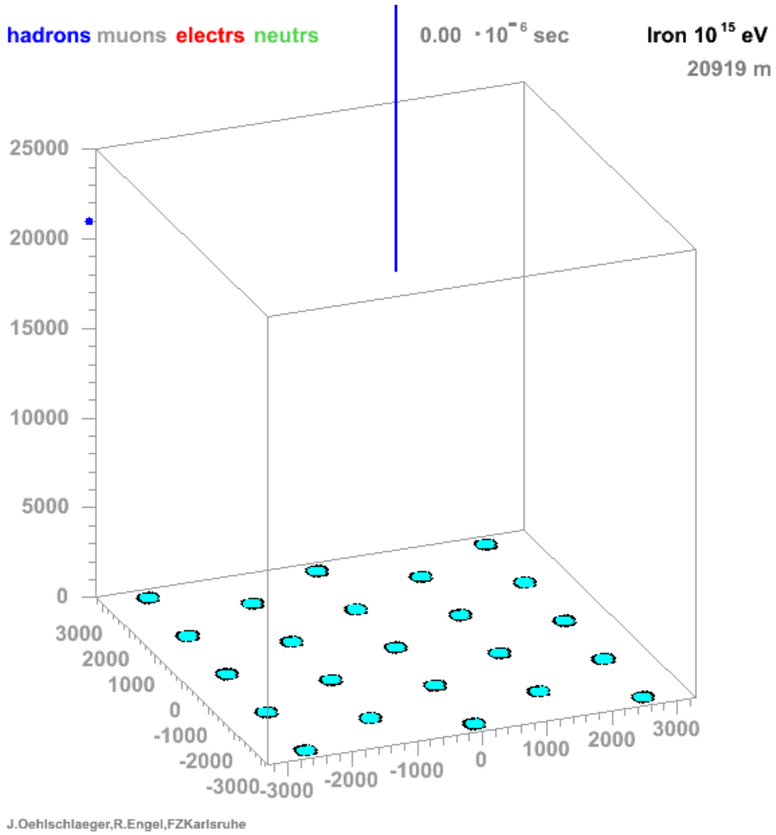


- Observation: We see the complex "mess" after multiple collisions.
- Goal: Find out what initiated the collision.
- Not trivial… actually, pretty hard!

EAS Simulations



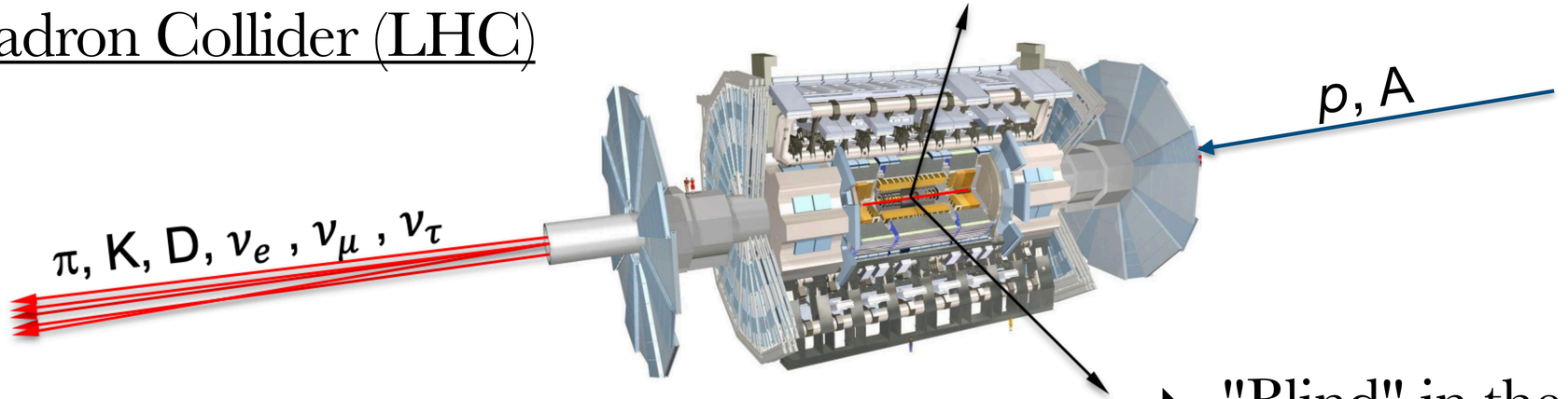




- Simulated gamma, proton, and iron showers at $E_0 = 10^{15}$ eV [https://www.iap.kit.edu/corsika/]
- Challenge: description of particle interactions / particle production in the atmosphere

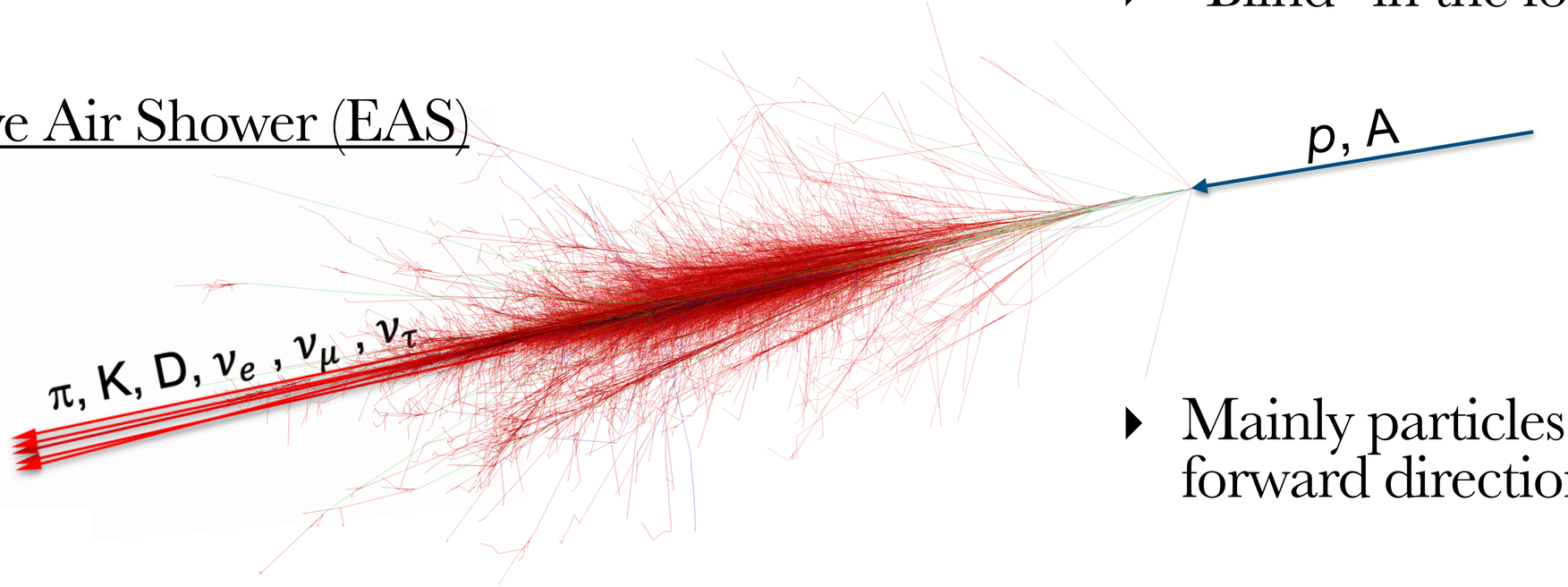
Collider vs. EAS

- Large Hadron Collider (LHC)



- "Blind" in the forward region

- Extensive Air Shower (EAS)



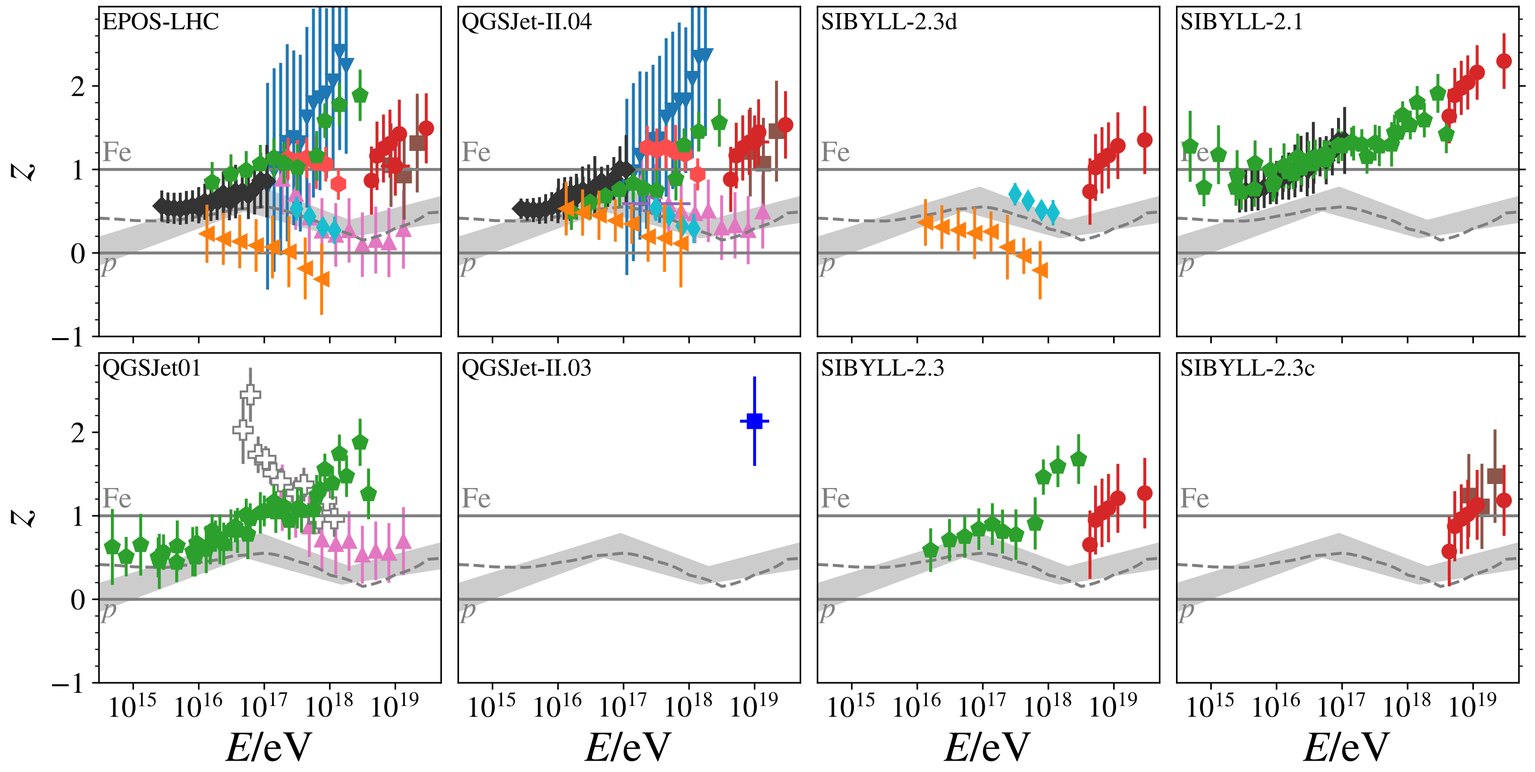
- Mainly particles in the forward direction!

The Muon Puzzle

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

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

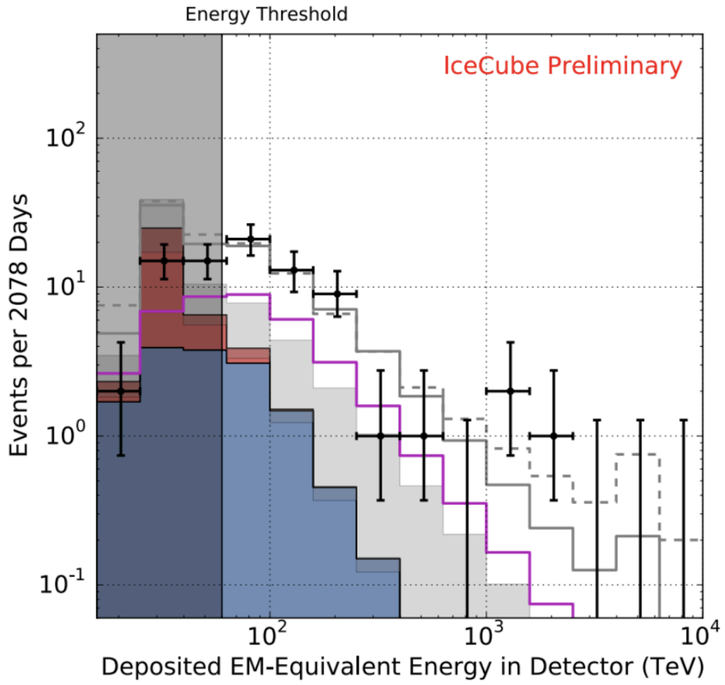
  - $z = 0$: proton
  - $z = 1$: iron
- Large uncertainties in EAS measurements, e.g. composition!

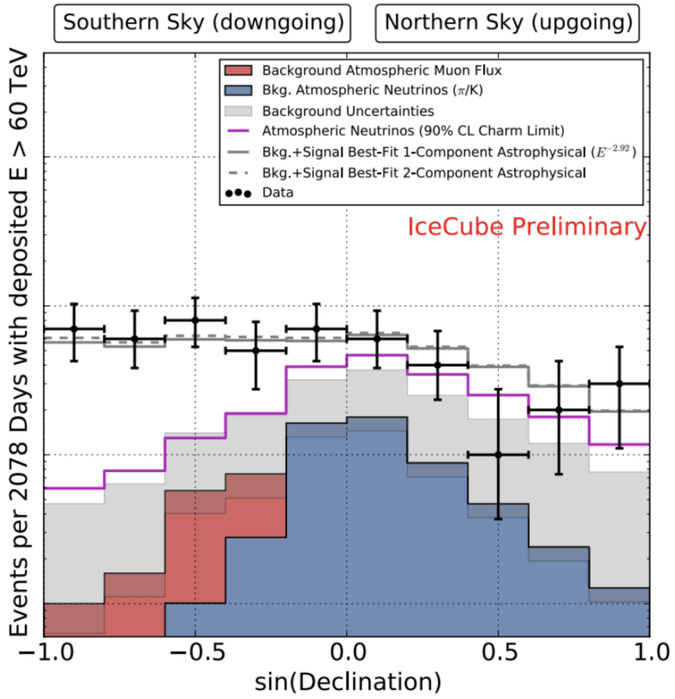


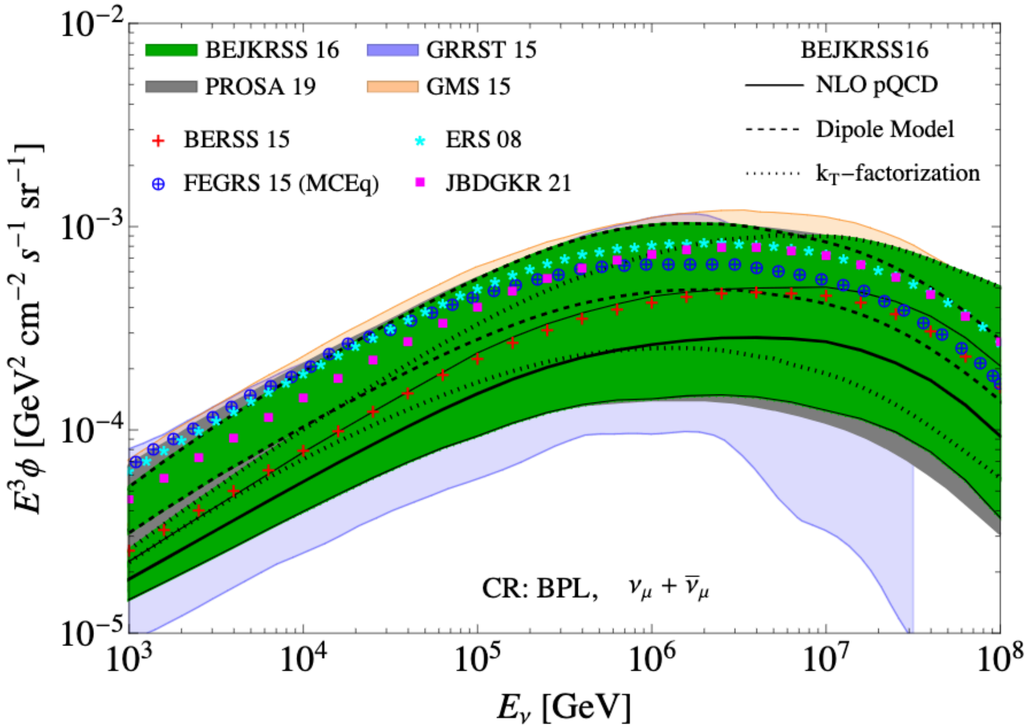
[J. C. Arteaga-Velázquez, D. Soldin (WHISP), PoS ICRC2023 (2023) 466]

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!







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

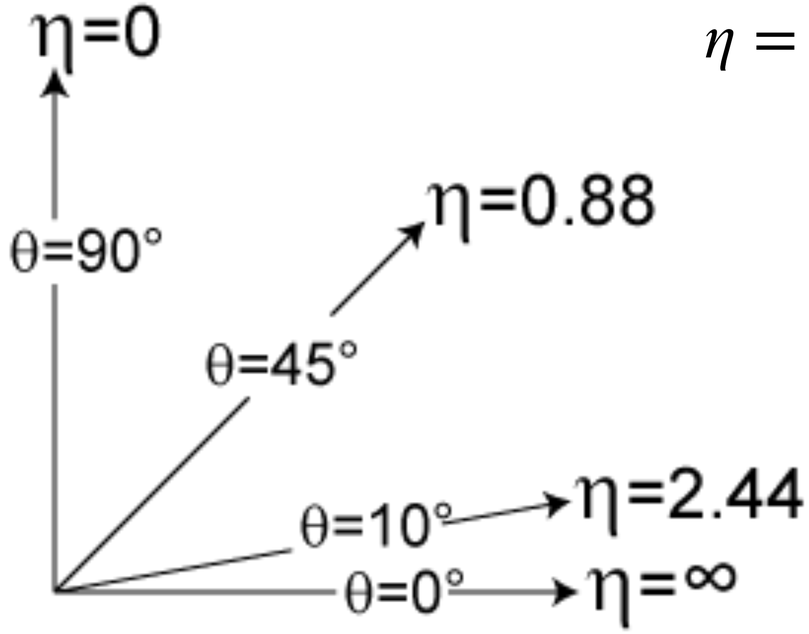
[PROSA Collaboration, JHEP 04 (2020)]

Challenges in EAS Physics

- Extensive air showers:
  - Particle production in the far-forward region
  - Low momentum transfer
  - Non-perturbative regime
  - Complex particle composition
  - Energies range over many orders of magnitude

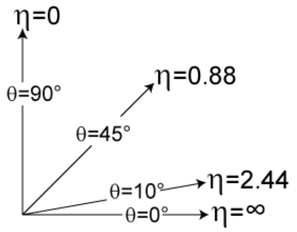
Pseudorapidity:

$$\eta = -\ln\left[\tan(\theta/2)\right]$$



Modeling of particle interactions in EASs based on phenomenological models!

Challenges in EAS Physics



[J. Albrecht et al., Astrophys. Space Sci. 367 (2022)]
[D. Soldin et al., PoS ICRC2025 (2025) 1182]

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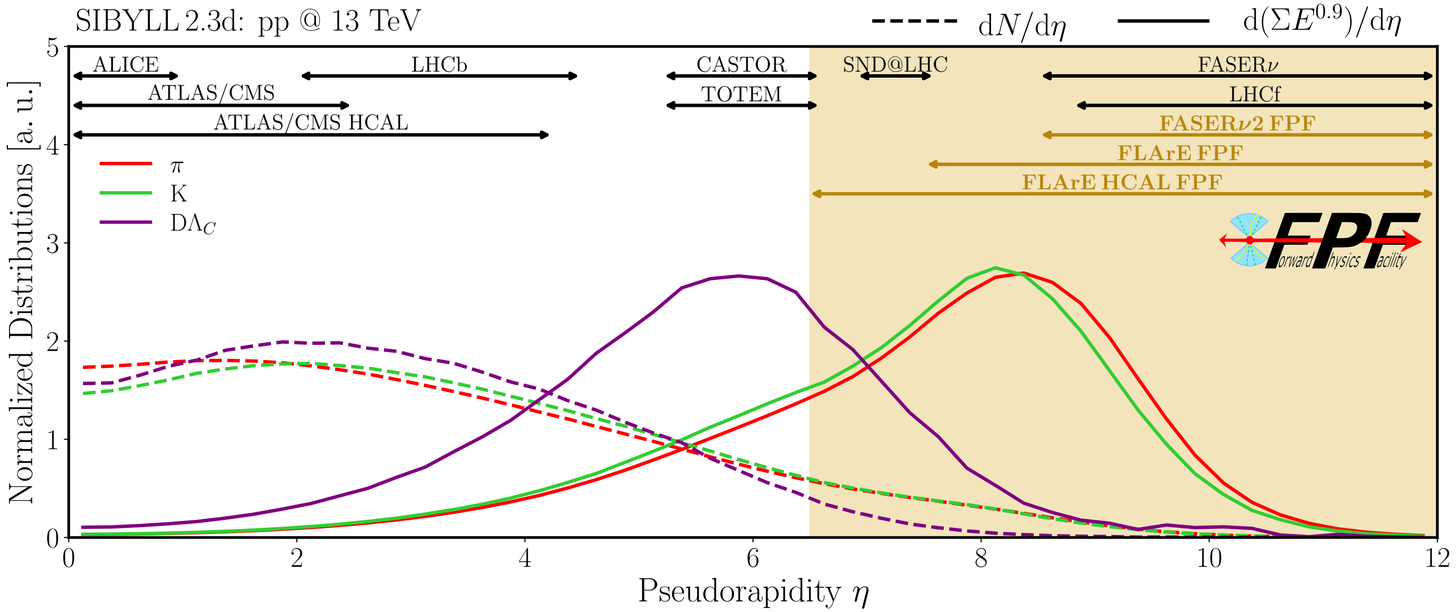

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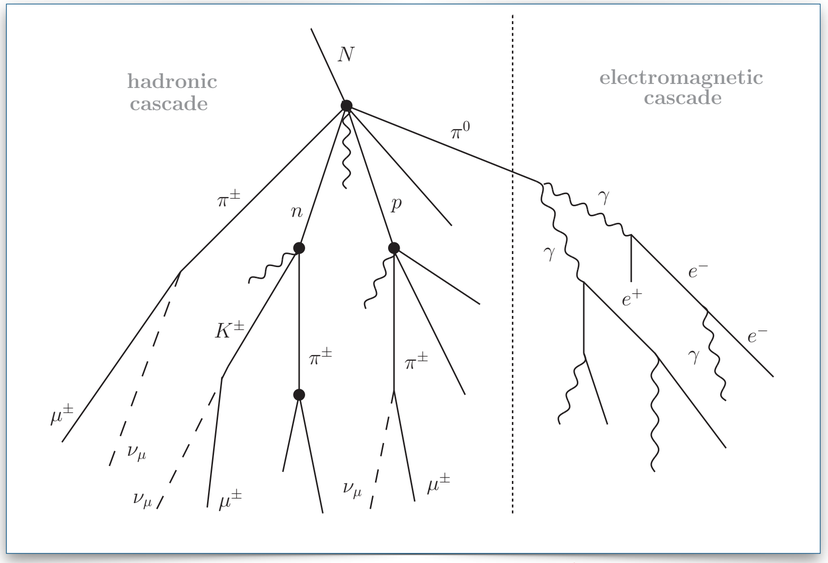
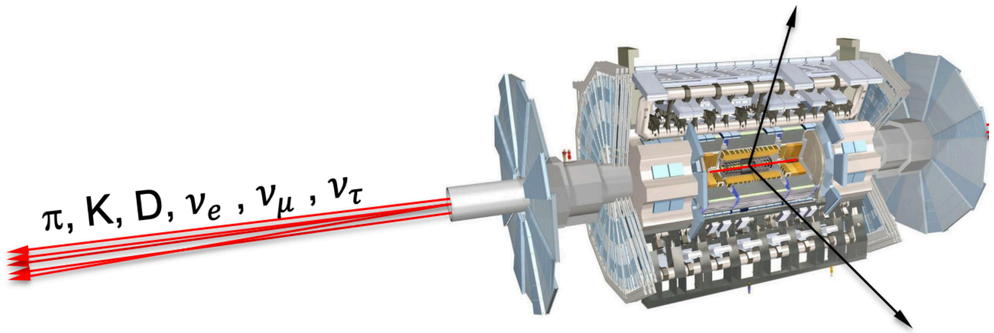
Modeling of particle interactions in EASs based on phenomenological models!

Hadronic Interaction Models

- Hadronic interaction models are based on known particle physics (and beyond)
- Interactions in EAS at LHC energies and beyond
- Various types of hadron interactions in EAS
- Particle production in EAS in the forward region
  - Not accessible by current accelerator experiments
  - Not calculable within perturbative QCD
  - Extrapolations into unknown phase space required!





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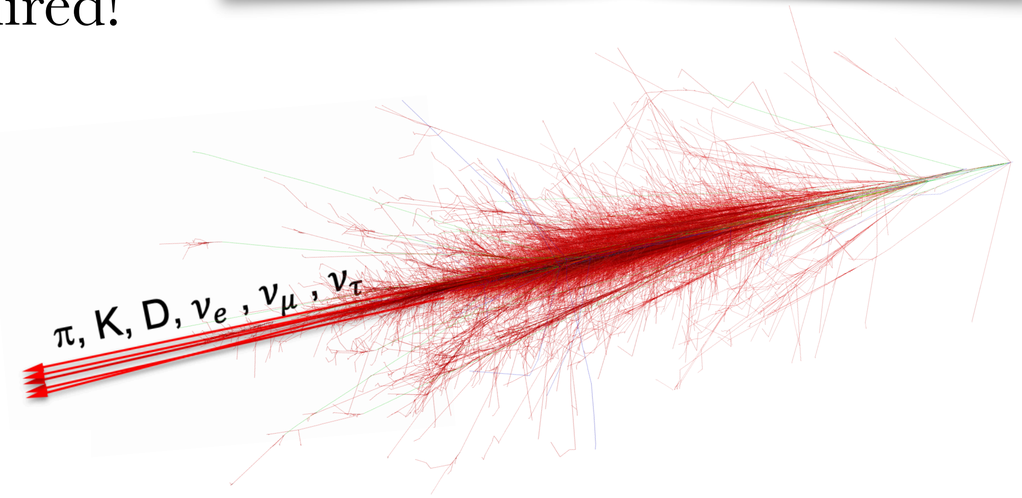

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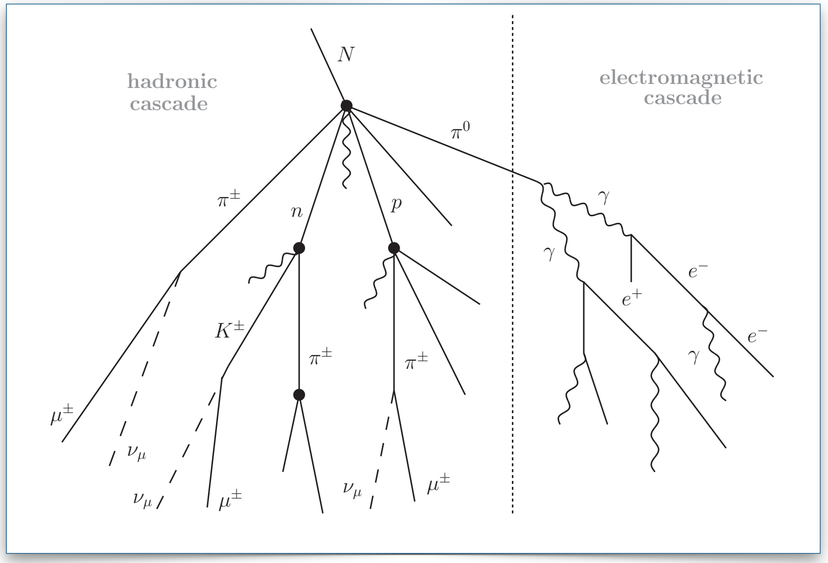
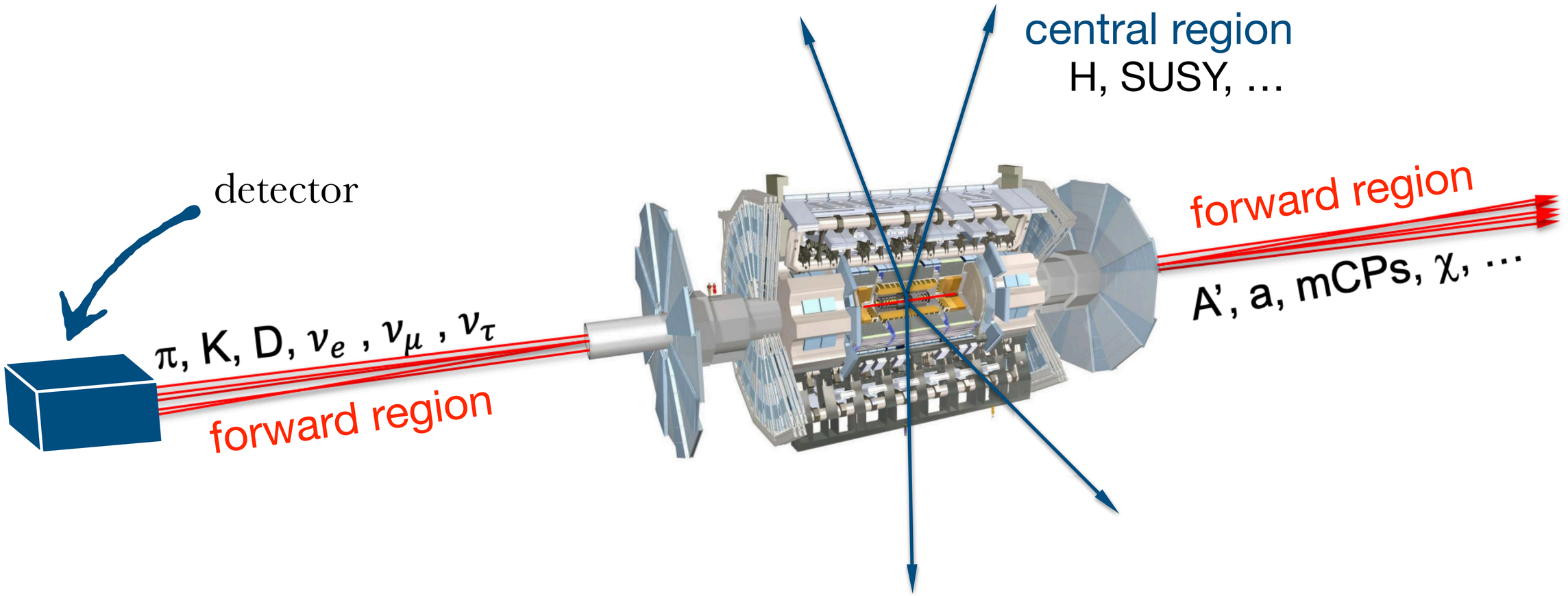


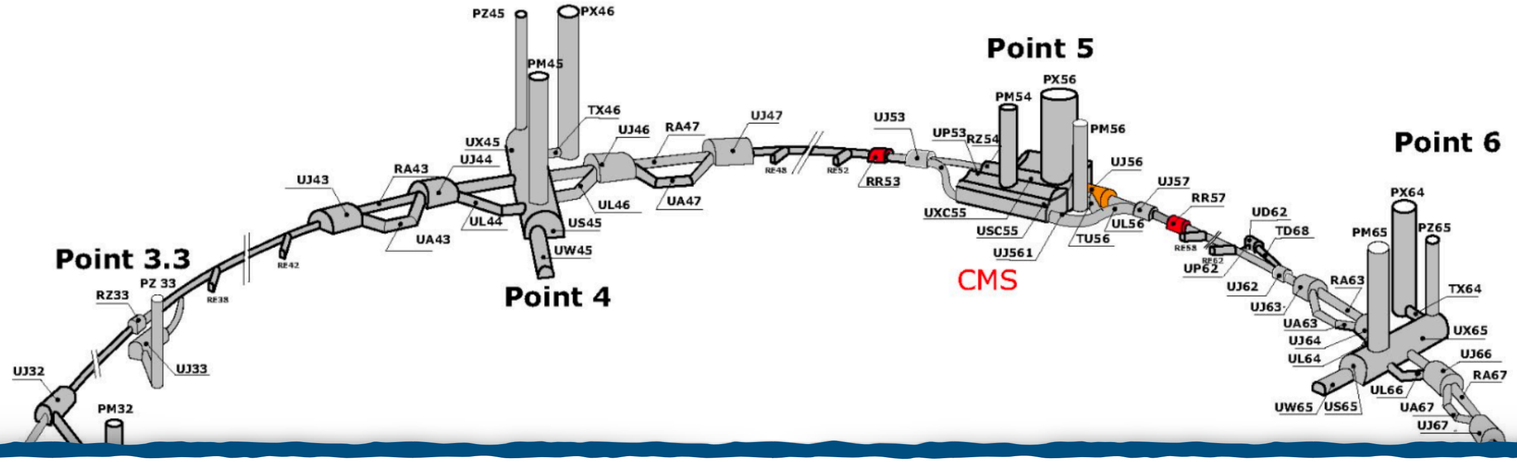
How can we test hadronic interaction models in the far-forward region at accelerators?

Forward Physics at the LHC

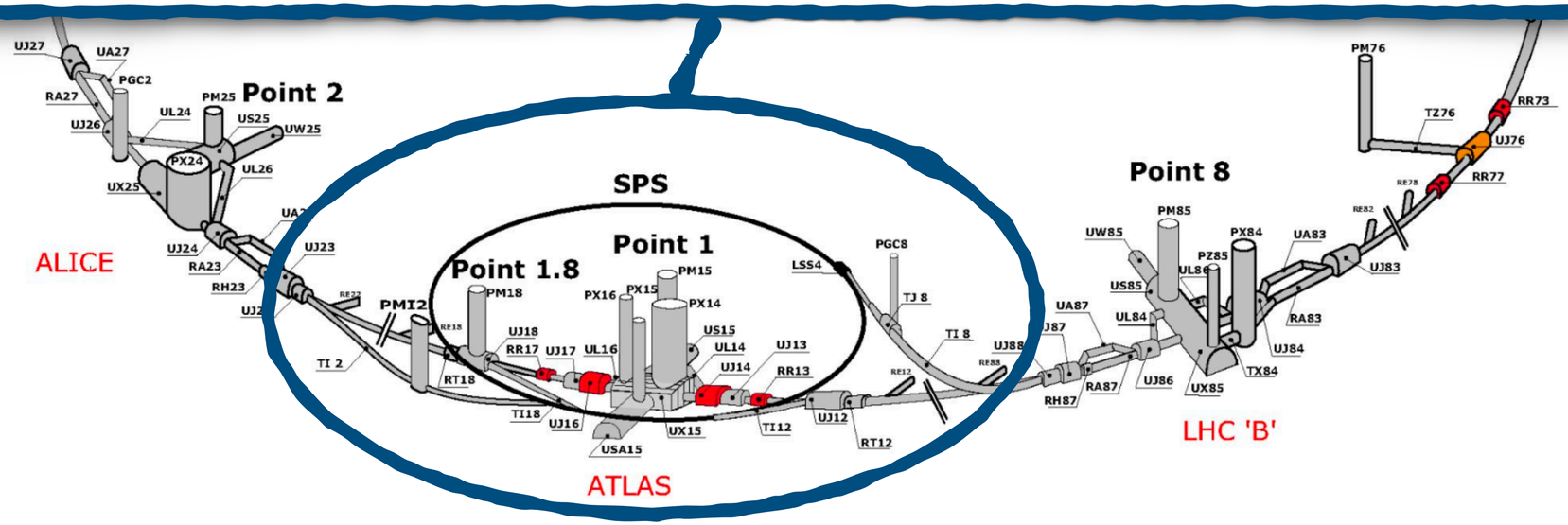
Proposal: Build experiment on the line-of-sight (LOS) of interaction point (IP)!



Possible Location

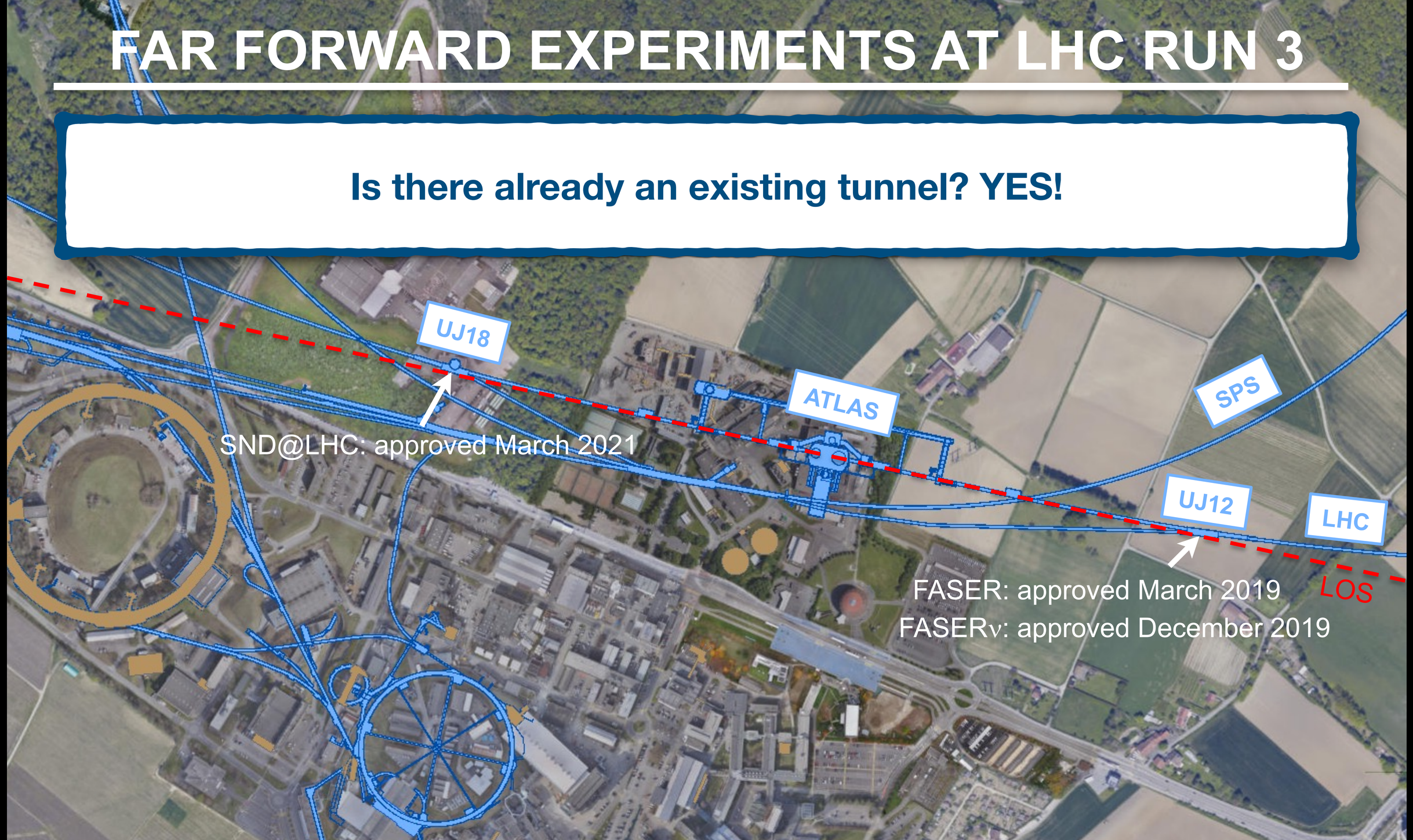


Is there already an existing tunnel?



FAR FORWARD EXPERIMENTS AT LHC RUN 3

Is there already an existing tunnel? YES!



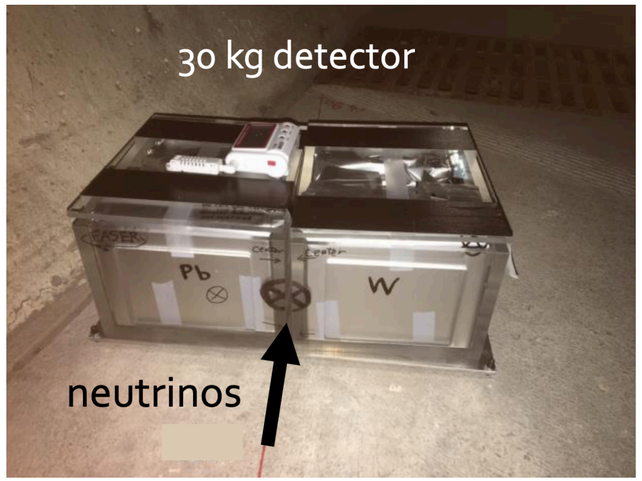
Physics Potential

- In 2018:

  FASERν pilot detector

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

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



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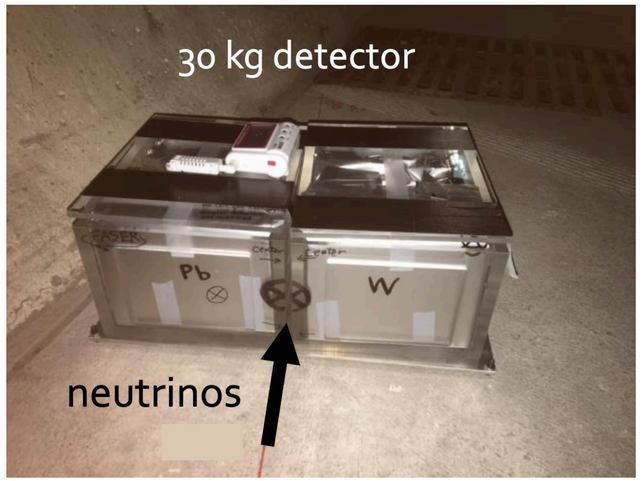
- Suitcase size, 4 weeks of data
- Costs: \$0 (recycled parts)
- 6 TeV neutrino candidates

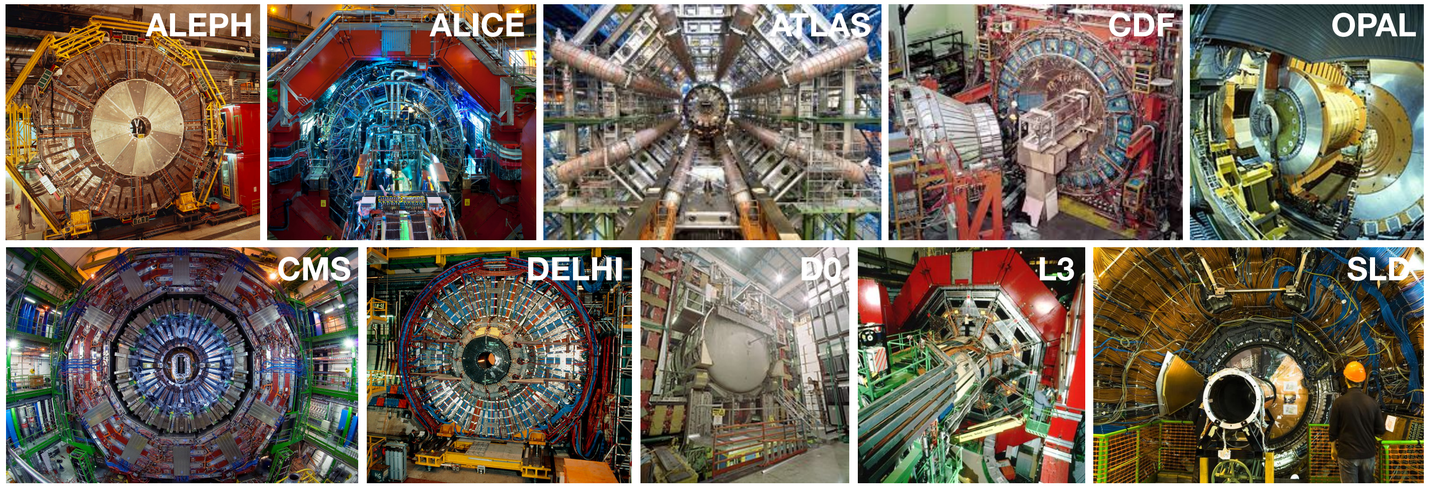
[FASER Collaboration, Phys. Rev. D 104 (2021)]

vs.

All previous collider experiments

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





FAR FORWARD EXPERIMENTS AT LHC RUN 3

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

UJ18

ATLAS

SPS

UJ12

LHC

LOS

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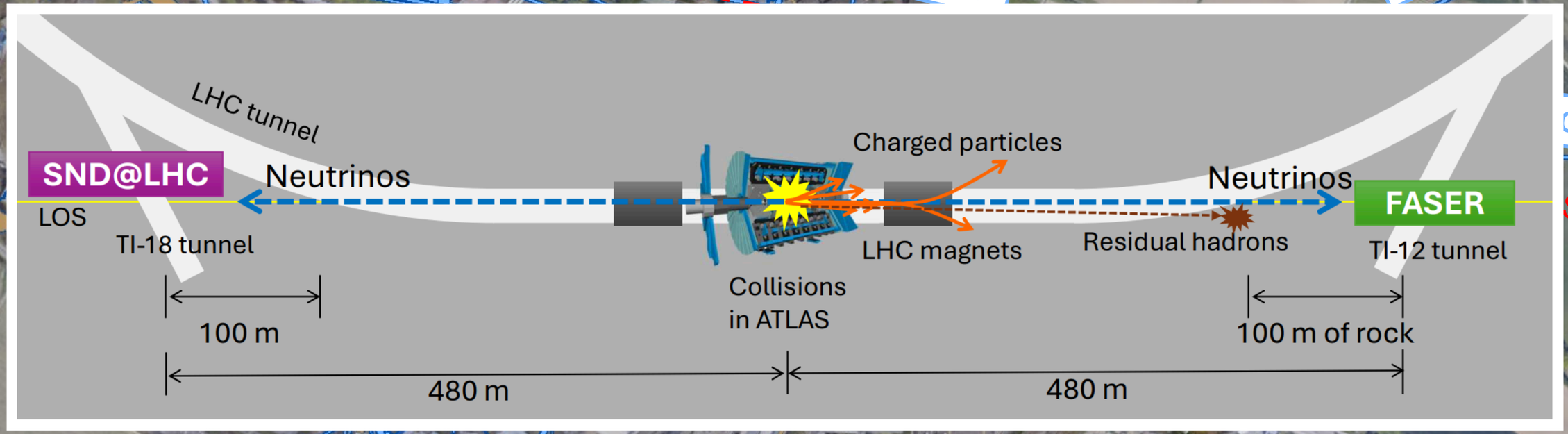

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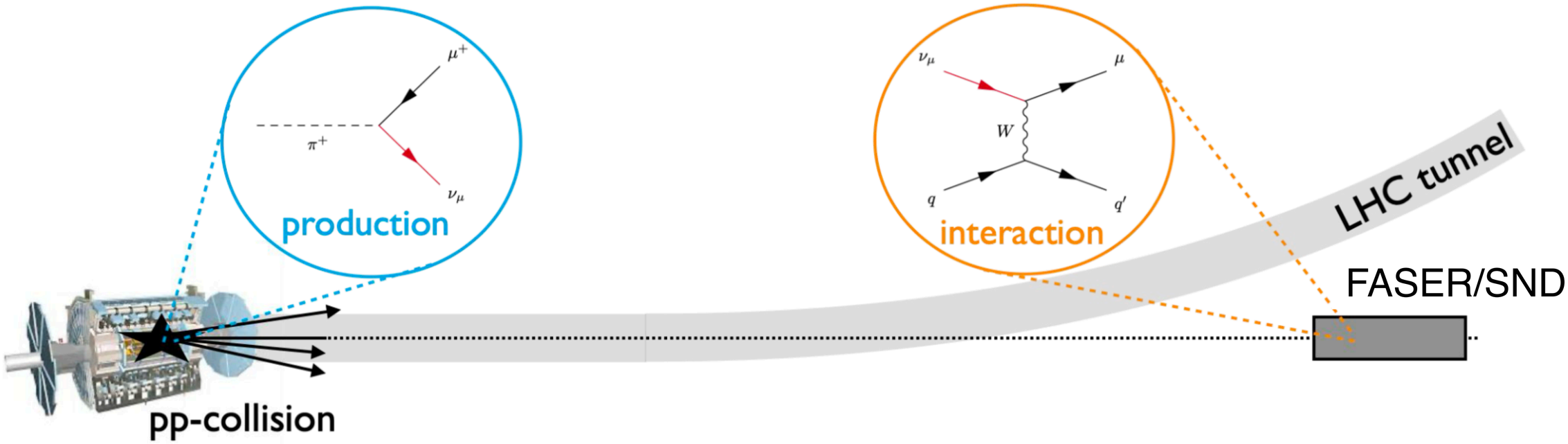

- Complementary probe of forward particle production
- Light and charm hadrons
- Unique laboratory probe of TeV energy neutrino interactions
- Cross sections and nuclear structure

Location: UJ12/TI12

Location: UJ12/TI12

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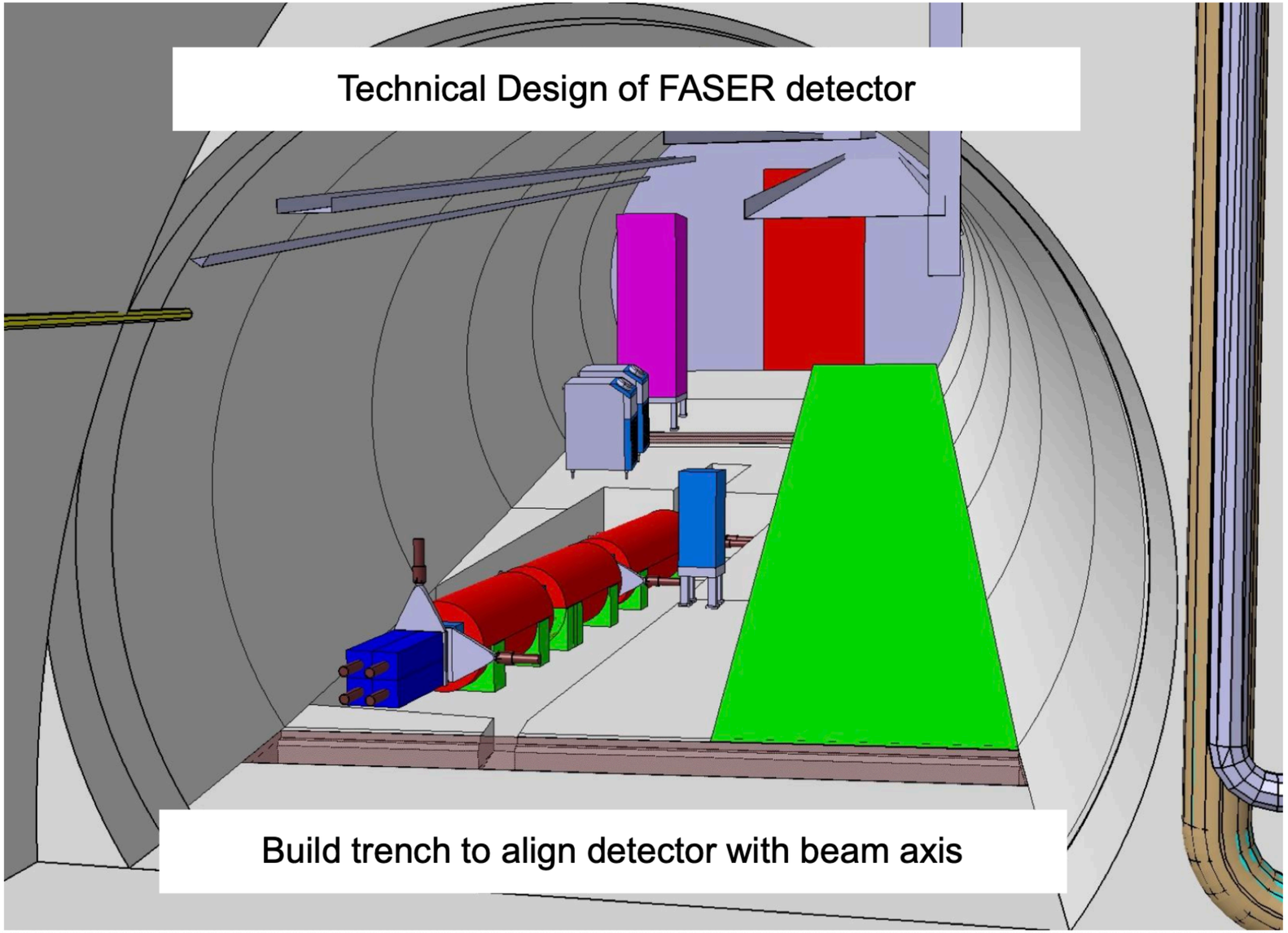
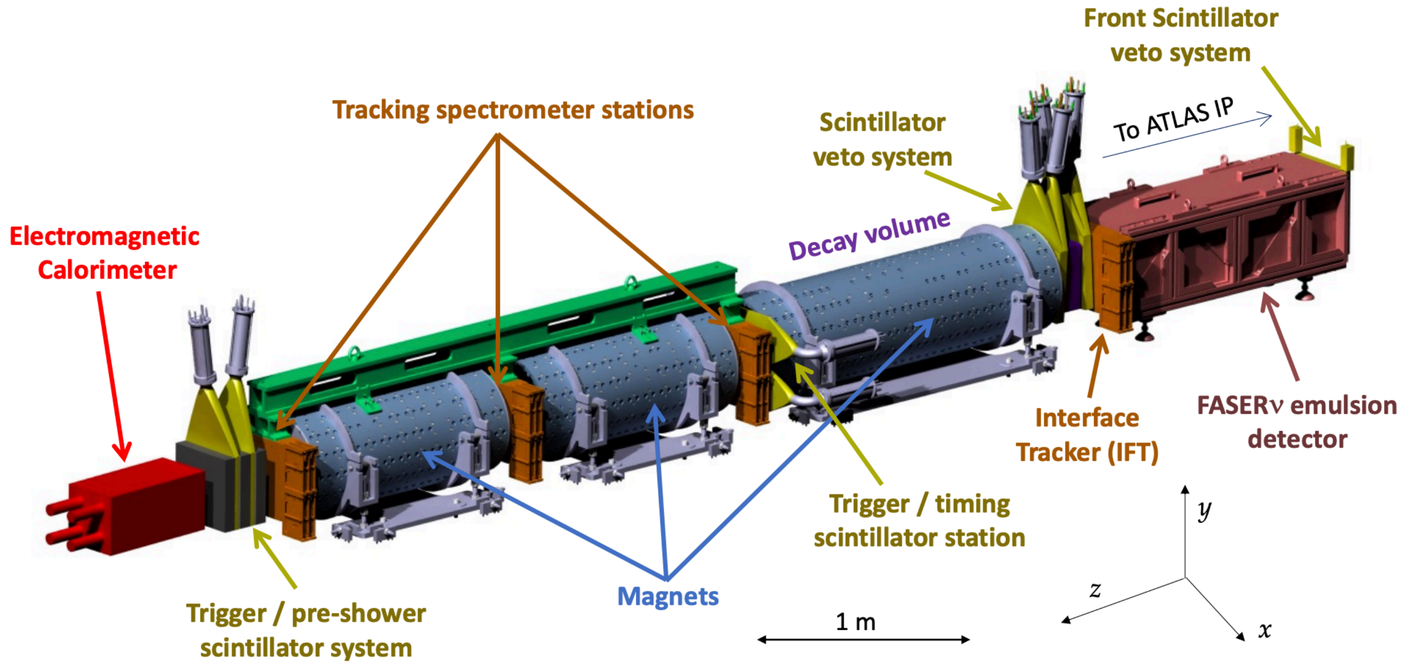


FASER/FASERν

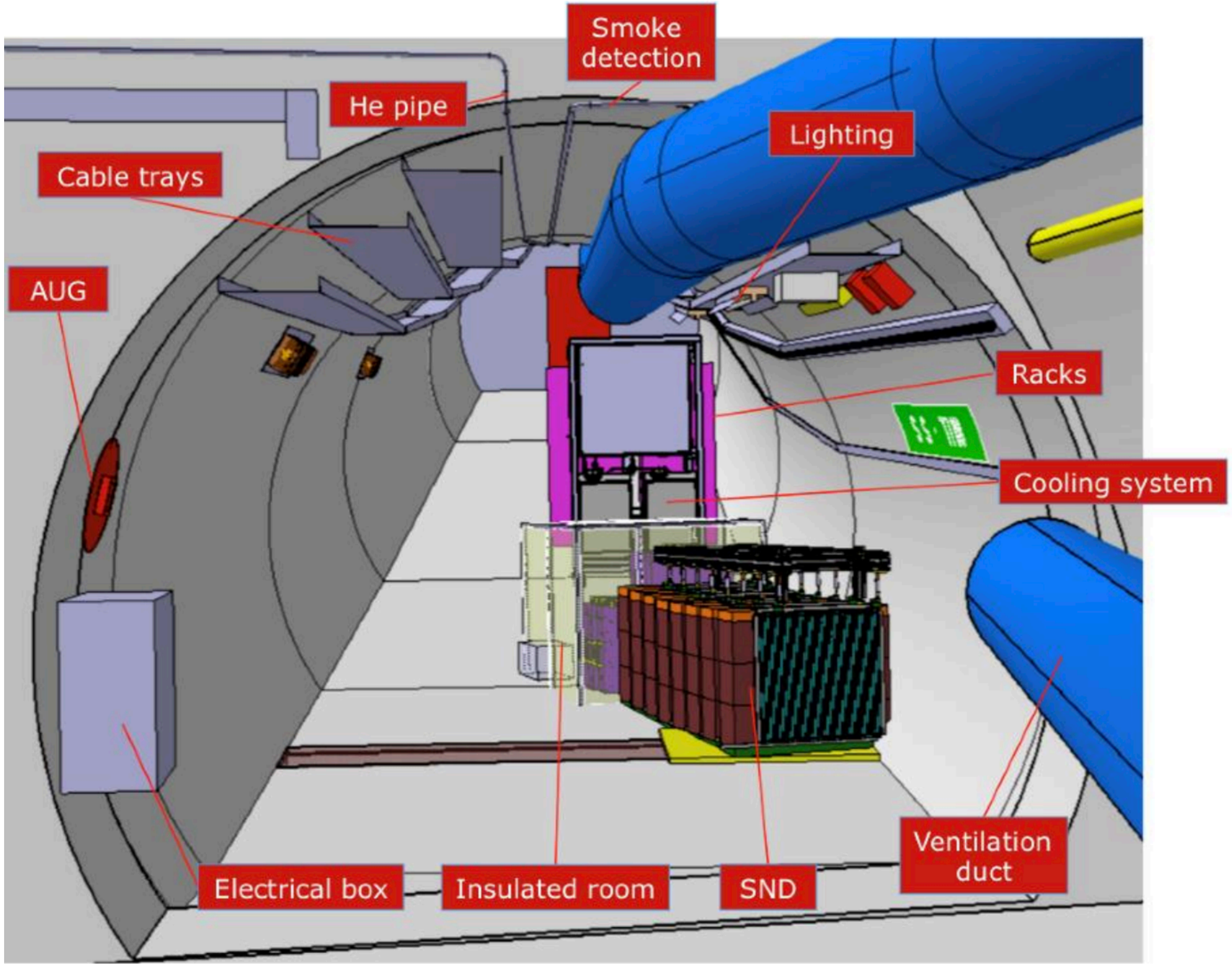
FASER/FASERν

- Pseudorapidities: $\eta > 8.8$
- FASER:
  - Multiple electronic detector components
    - Veto scintillators
    - Tracking spectrometer
      (30μm position resolution)
    - Electromagnetic calorimeter
      (~1% energy resolution)
- FASERν:
  - 730 tungsten plates, interleaved with nuclear-emulsion films
  - 1,100 kg target mass



[FASER Collaboration, JINST 19 (2024)]

Location: UJ18/TI18



SND@LHC

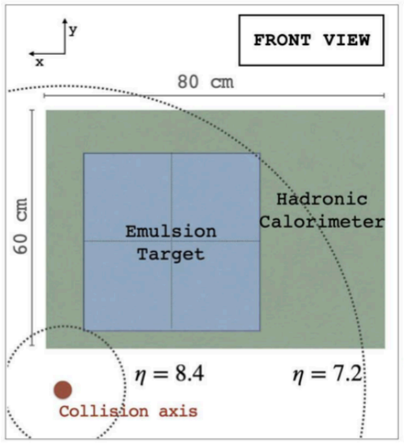
LHC

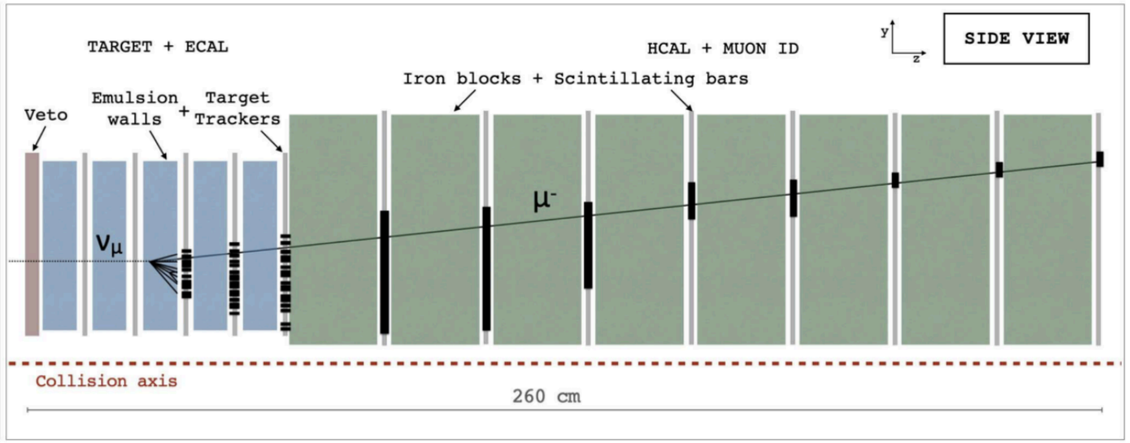
Scattering and Neutrino Detector
at the LHC

SND@LHC

- Pseudorapidities: $7.2 < \eta < 8.4$
- Multiple electronic detector components
  - Veto scintillators
  - Scintillating bars (scintillating fiber, SciFi) station for tracking
    (100μm position resolution)
- Five emulsion cloud chambers, each
  - 60 nuclear emulsion films
  - Interleaved with 59 tungsten plates
  - 800 kg tungsten target

LHC
Scattering and Neutrino Detector
at the LHC

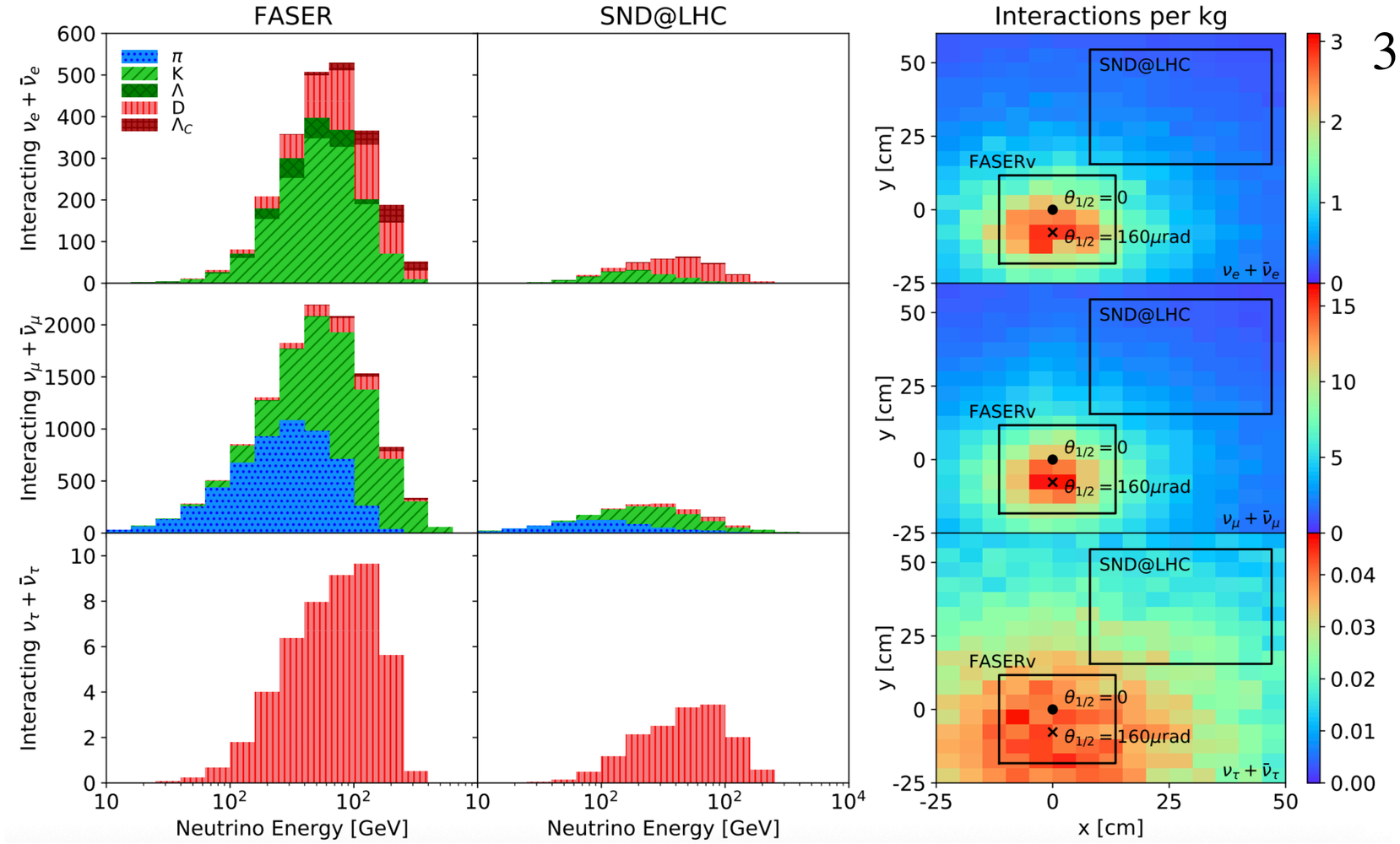




[SND@LHC Collaboration, JINST 19 (2024)]

Expected Fluxes (Run 3)

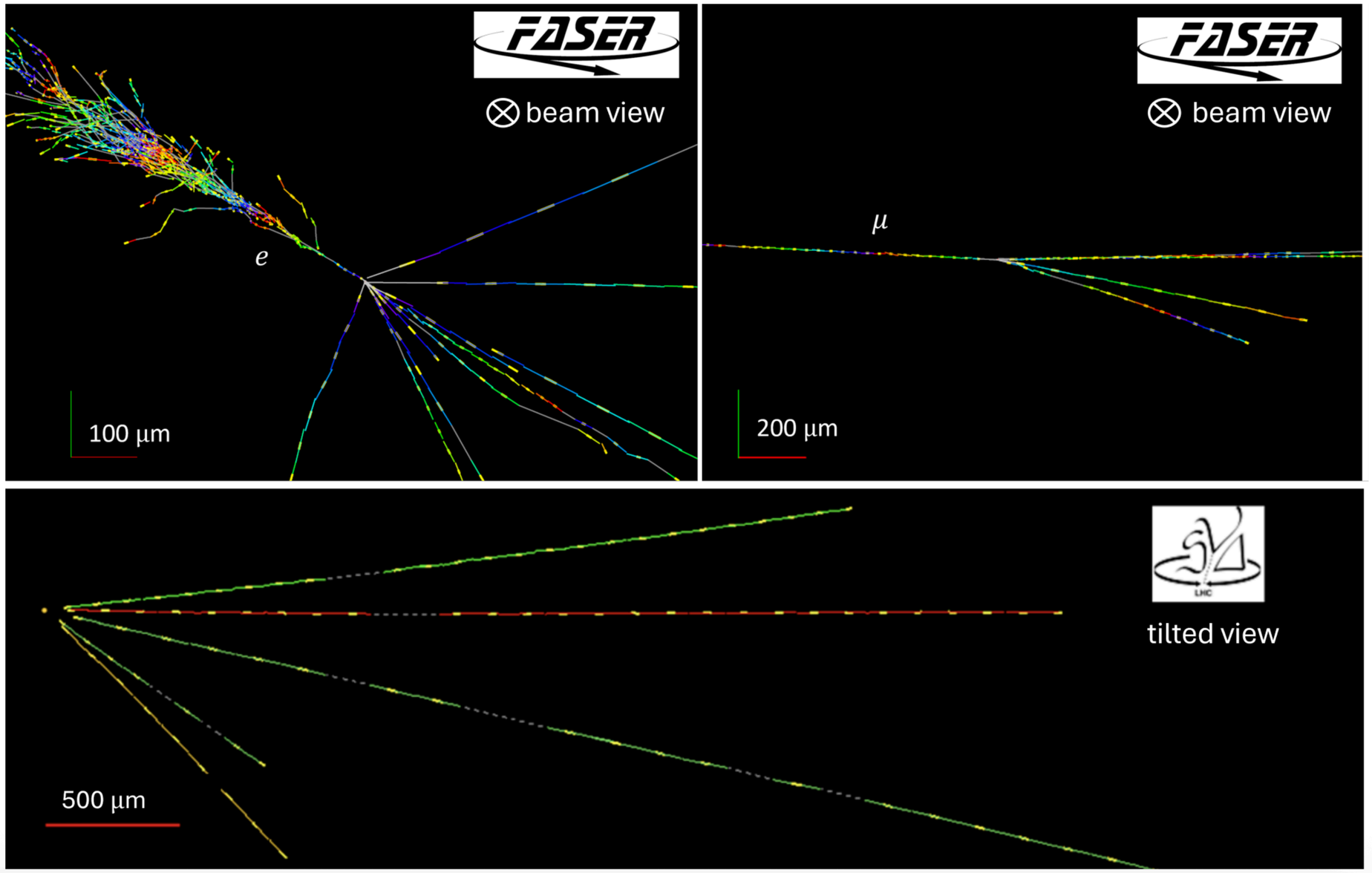
[A. Ariga et al., arXiv:2501.10078]



$350\,\mathrm{fb}^{-1}$

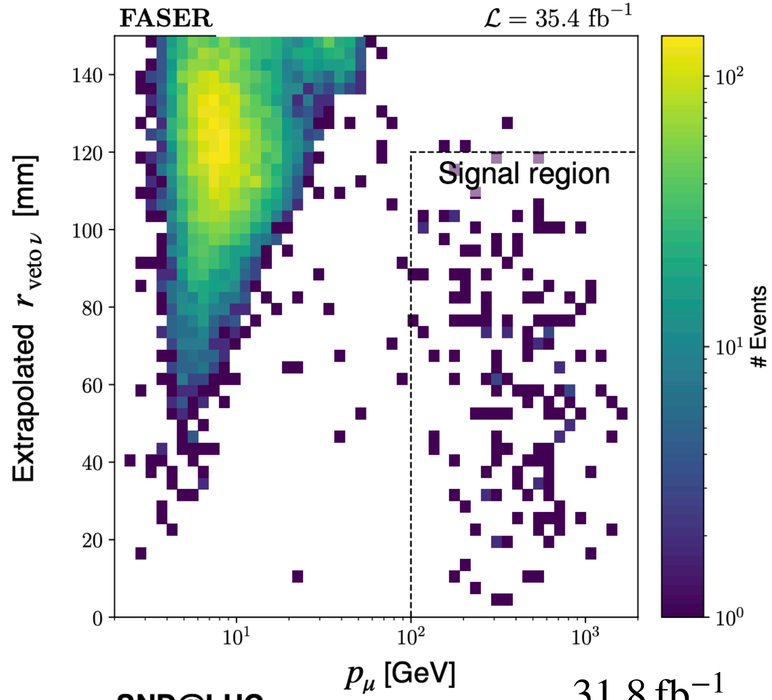
Experiment	Quantity	ν_e	ν_μ	ν_τ
FASER	N_{int}	2331^{+1227}_{-544}	12014^{+1145}_{-1636}	46^{+77}_{-21}
	average energy	785 GeV	716 GeV	849 GeV
SND@LHC	N_{int}	307^{+307}_{-116}	1694^{+297}_{-549}	15^{+26}_{-7}
	average energy	442 GeV	357 GeV	596 GeV

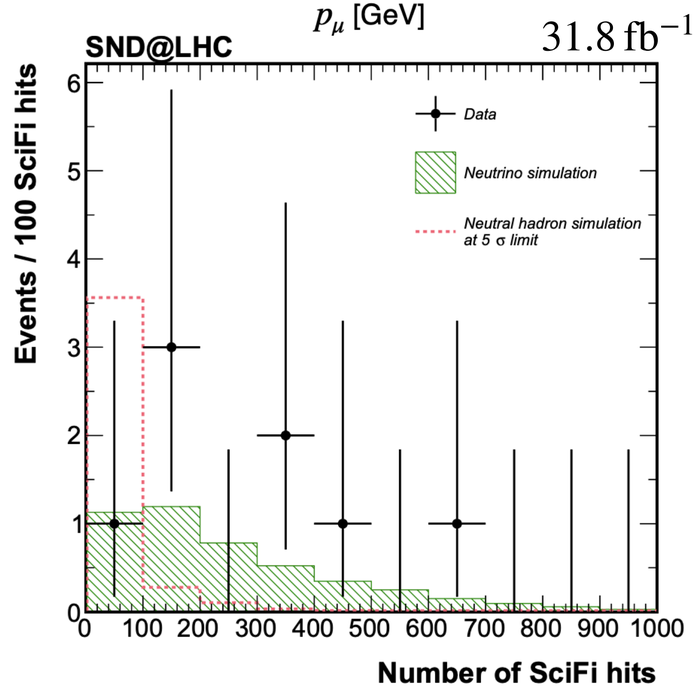
Example Events



First Collider Neutrinos!

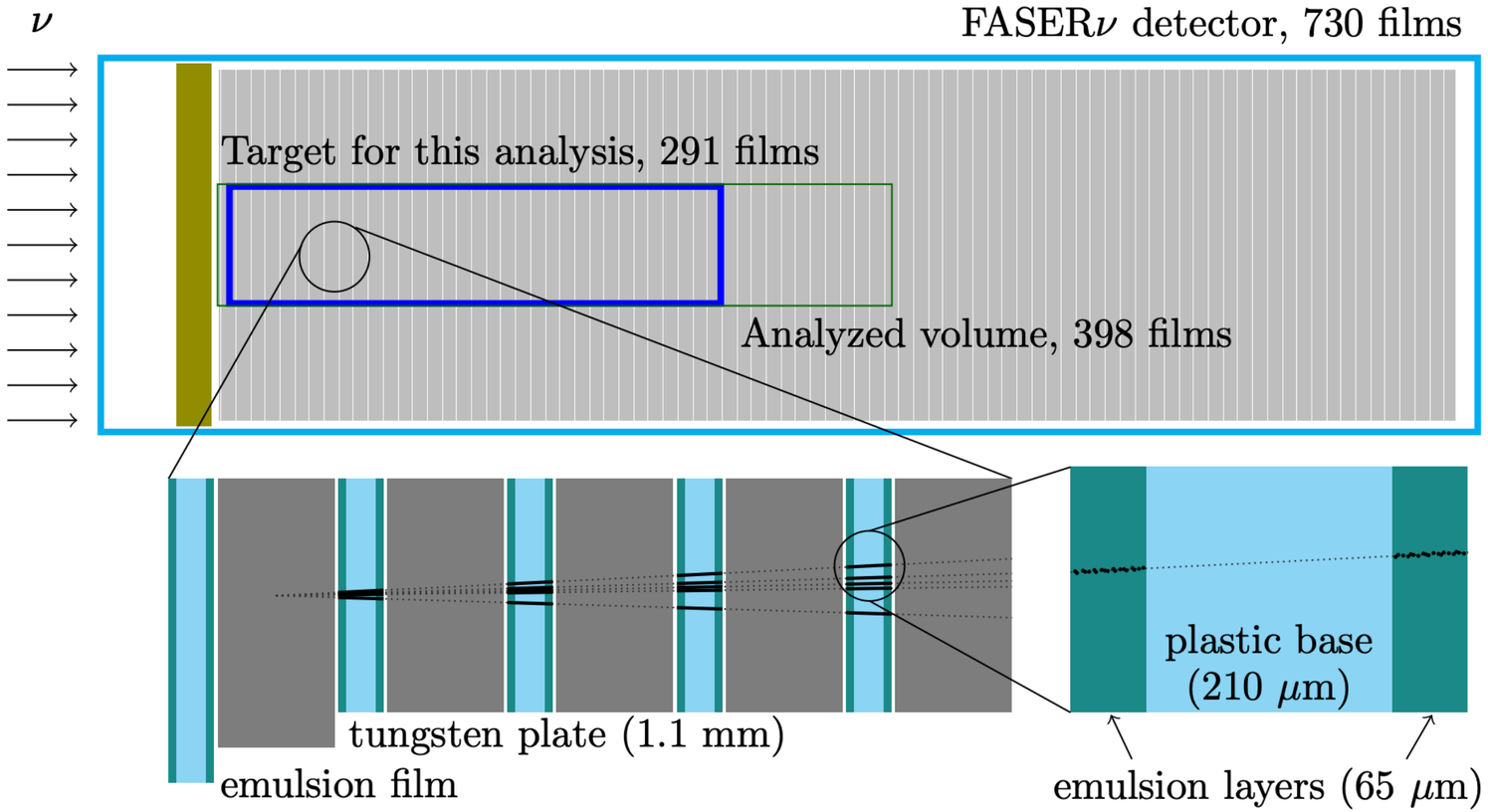
- Search strategy:
  - Charged current ν_μ events through muon appearance
  - Electronic detector only
- FASER:
  [FASER Collaboration, Phys. Rev. Lett. 131 (2023)]
  - Background: $(0.11 \pm 0.06) + (0.08 \pm 1.83)$
  - Result: 153 ν_μ events (16σ)
- SND@LHC:
  [SND@LHC Collaboration, Phys. Rev. Lett. 131 (2023)]
  - Background: (0.076 ± 0.031)
  - Result: 8 ν_μ events (7σ)





First Collider Neutrinos!

- First search for charged current ν_e and ν_μ events in emulsion detector (FASERν)
- 128.8 kg subset of volume analyzed (9.5 fb^{-1})



[FASER Collaboration, Phys. Rev. Lett. 133 (2024)]

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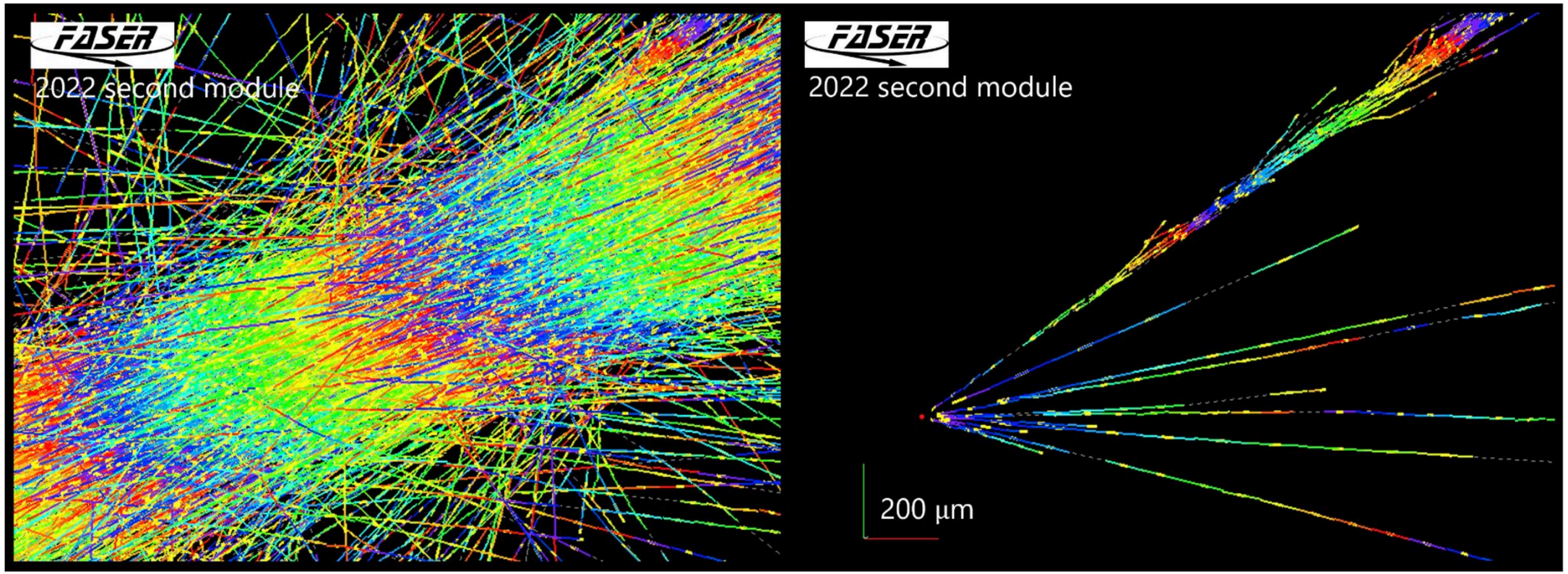
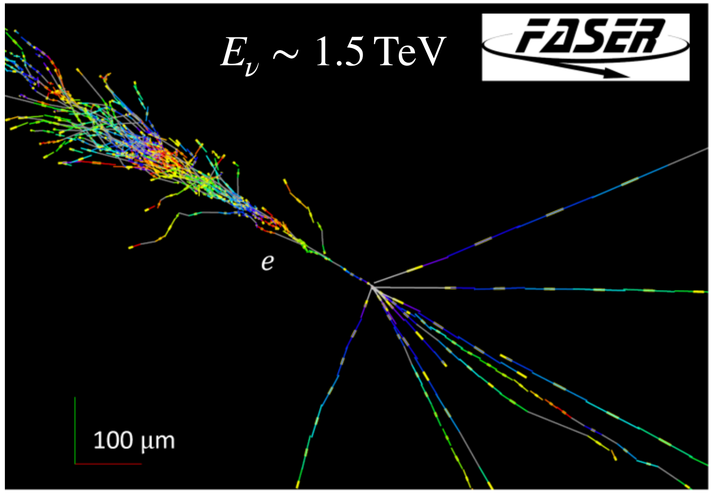
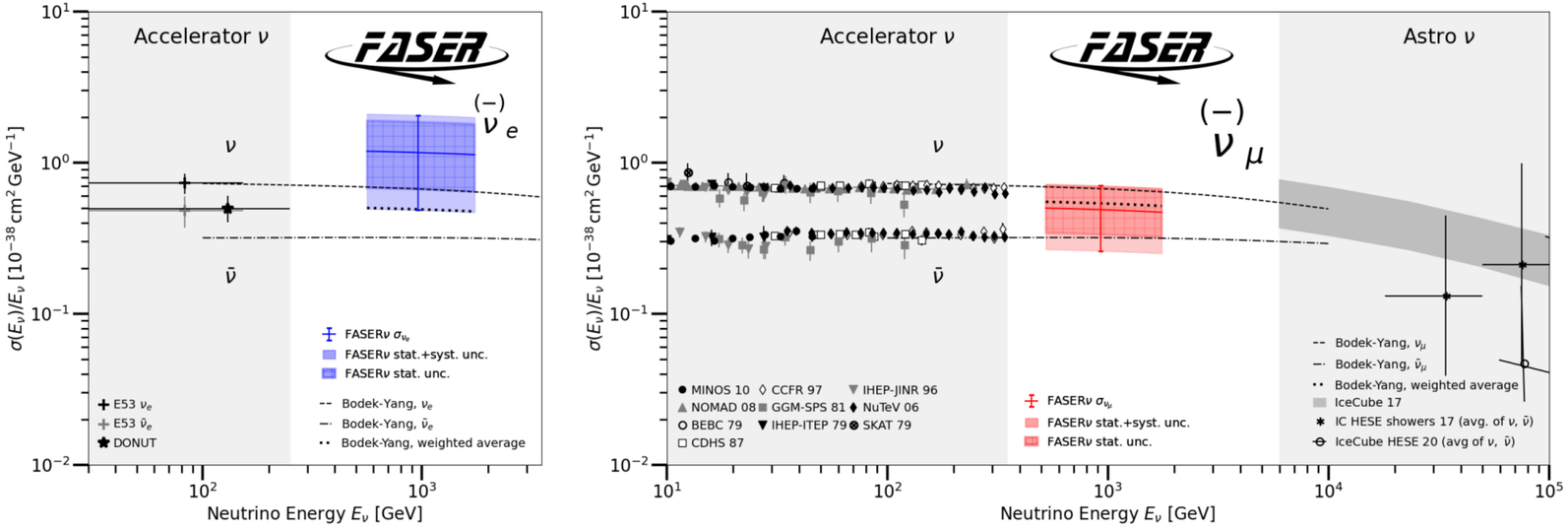


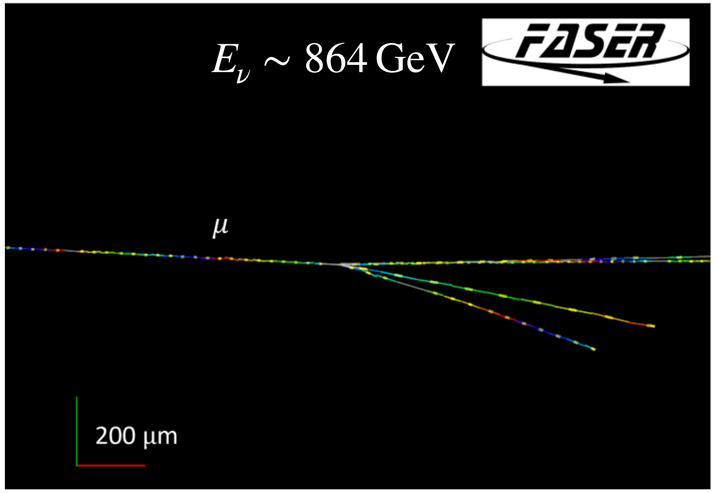
[FASER Collaboration, Phys. Rev. Lett. 133 (2024)]

First Collider Neutrinos!

- First search for charged current ν_e and ν_μ events in emulsion detector (FASERν)
- 128.8 kg subset of volume analyzed (9.5 fb^{-1})
- Result:
  - 4 ν_e candidates (5.2σ)
  - 8 ν_μ candidates (5.7σ)

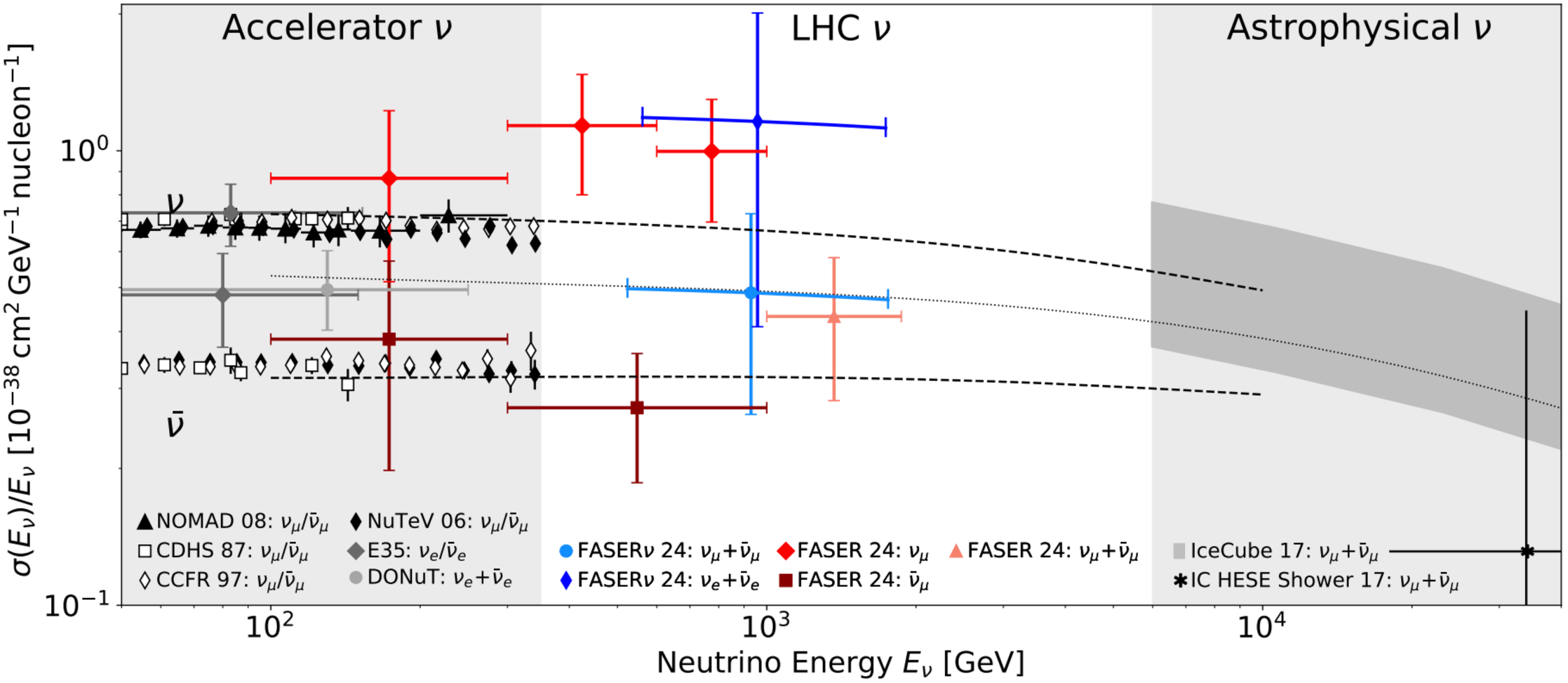






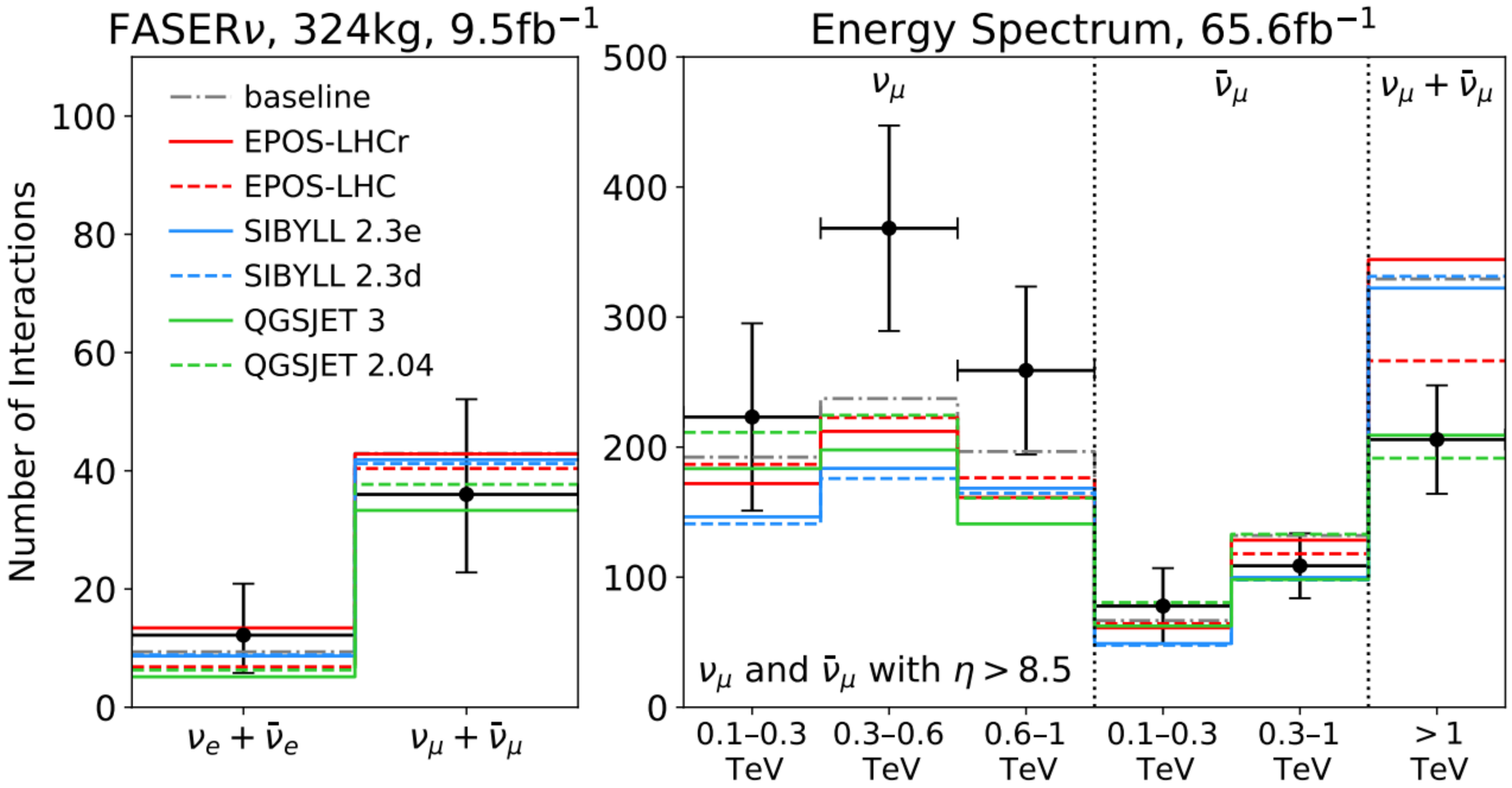
[FASER Collaboration, Phys. Rev. Lett. 133 (2024)]

Neutrino Cross Sections



[FASER Collaboration, Phys. Rev. Lett. 133 (2024)]
[FASER Collaboration, Phys. Rev. Lett. 134 (2024)]

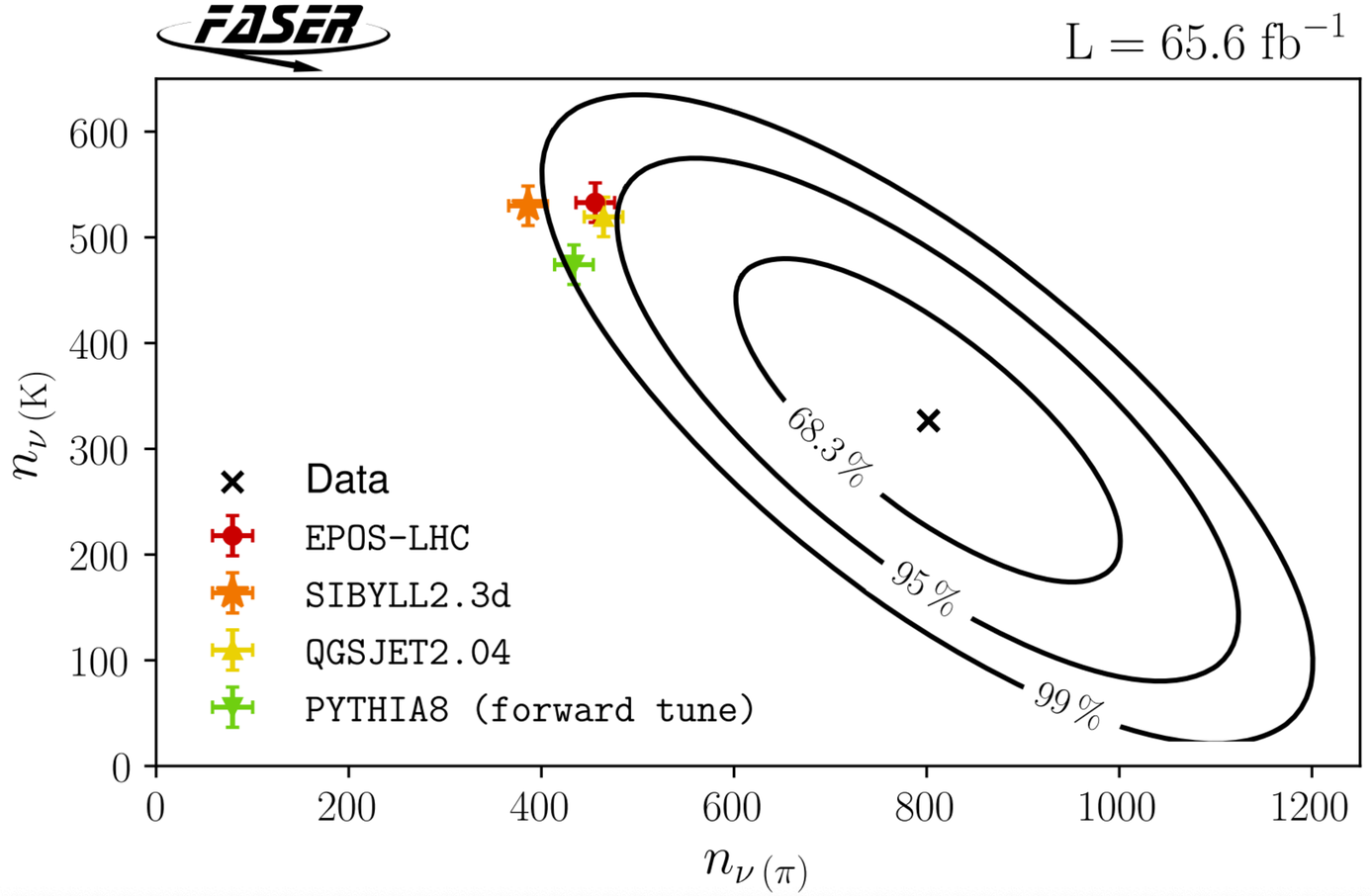
Neutrino Forward Fluxes



[FASER Collaboration, PoS ICRC2025 (2025) 349]

Neutrino Forward Fluxes

- Number of neutrino interactions from pion and kaon decays
- In strong tension with all MC generators tested!



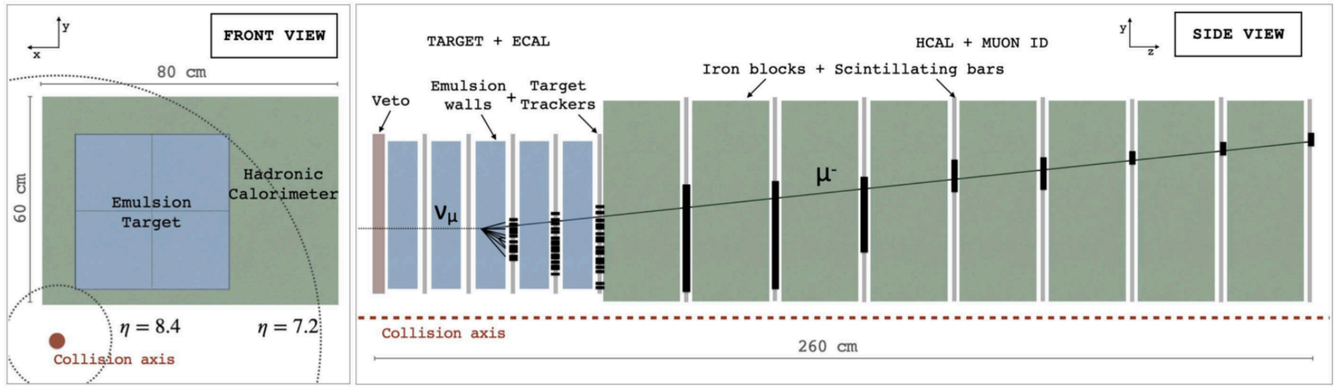
[FASER Collaboration, Phys. Rev. Lett. 134 (2024)]

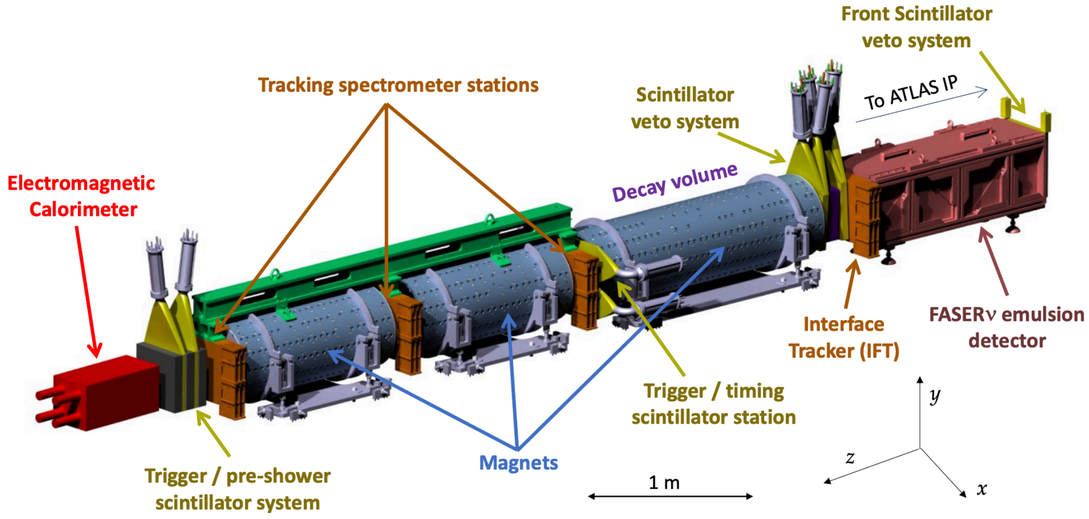
Run 4 Detector Upgrades

[A. Ariga et al., arXiv:2501.10078]

- HL-LHC luminosities make it challenging to use emulsion detector efficiently
- Several detector upgrades under investigation…

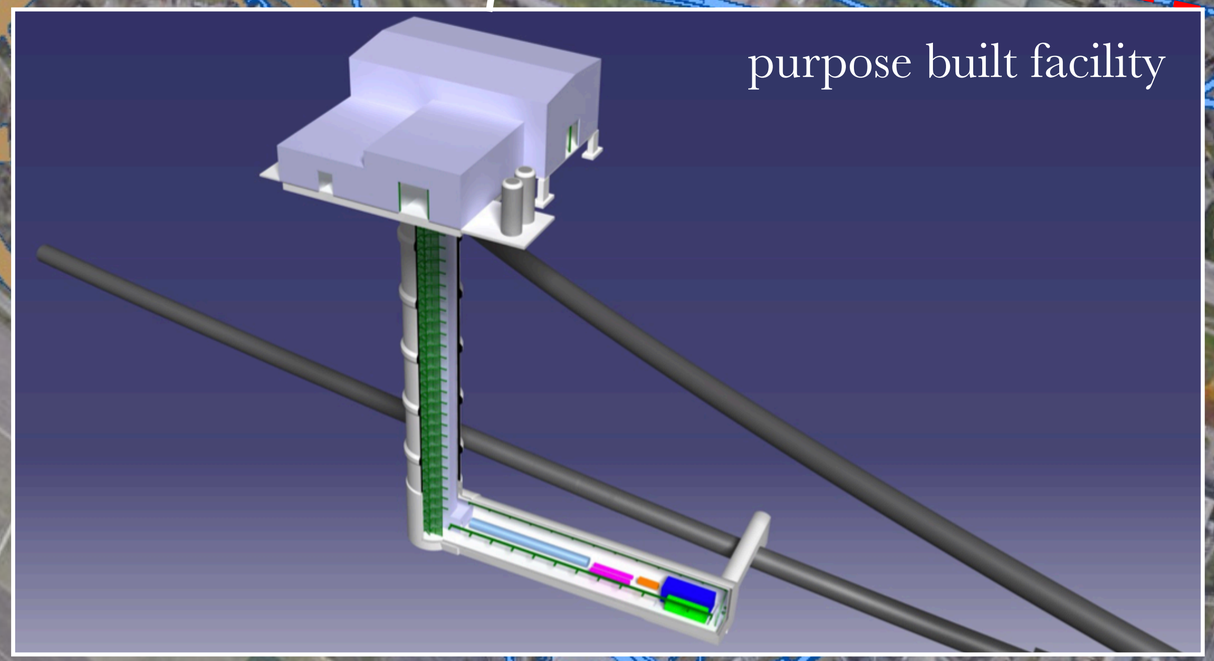
How to further extend this program into the HL-LHC era?





FAR FORWARD EXPERIMENTS AT LHC RUN 3

How to further extend this program into the HL-LHC era?



UJ18

ATLAS

SPS

UJ12

LHC

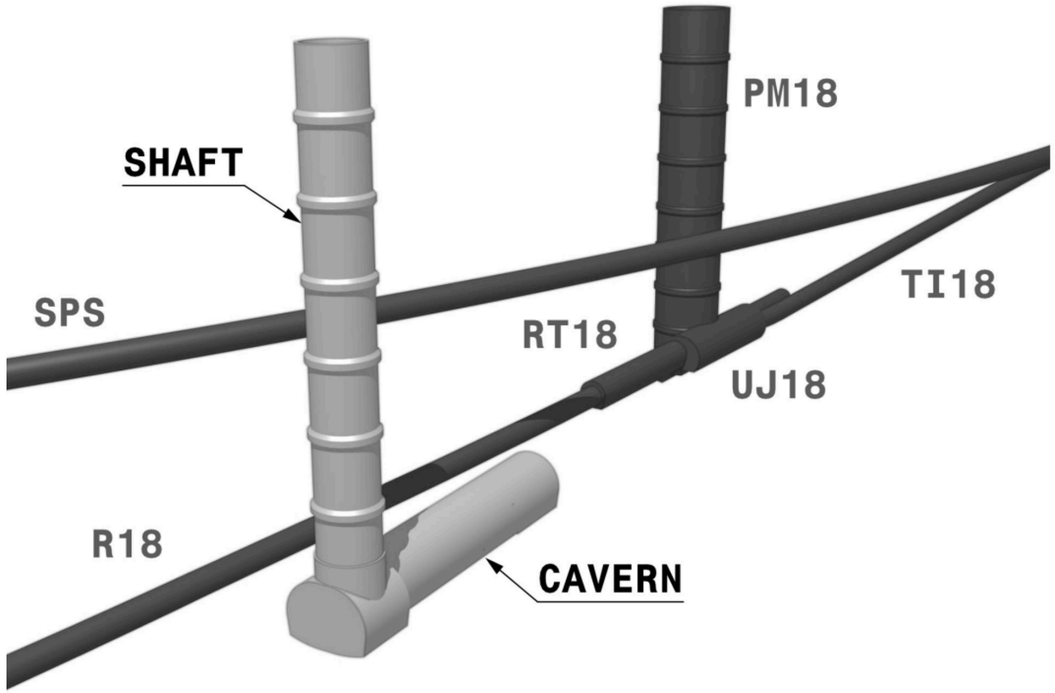
LOS

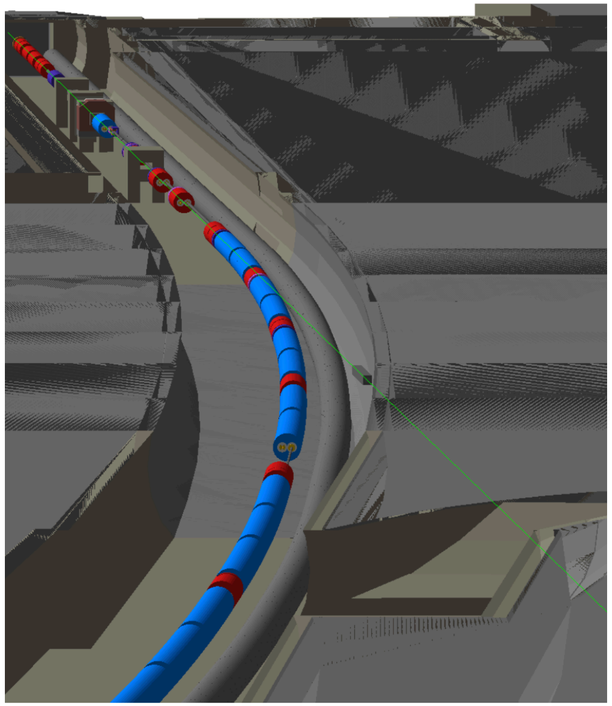
FASER: approved March 2019

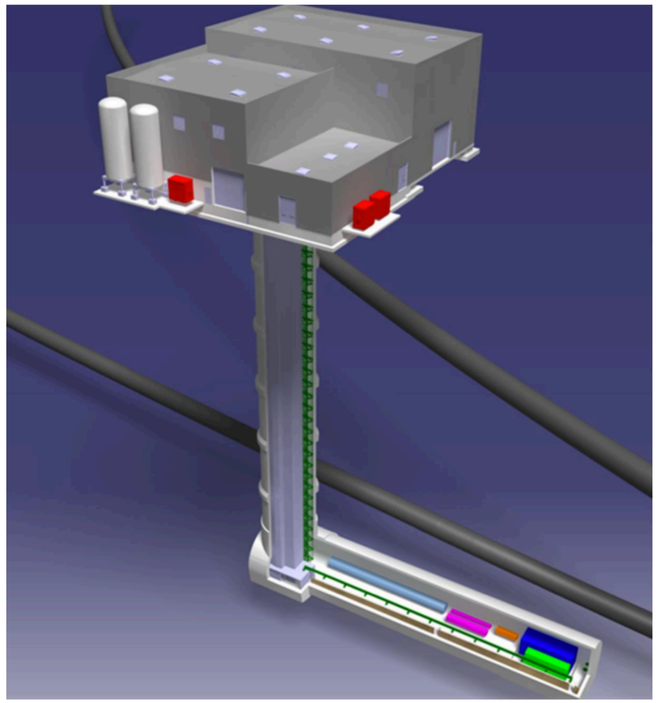
FASERν: approved December 2019

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 four proposed experiments







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

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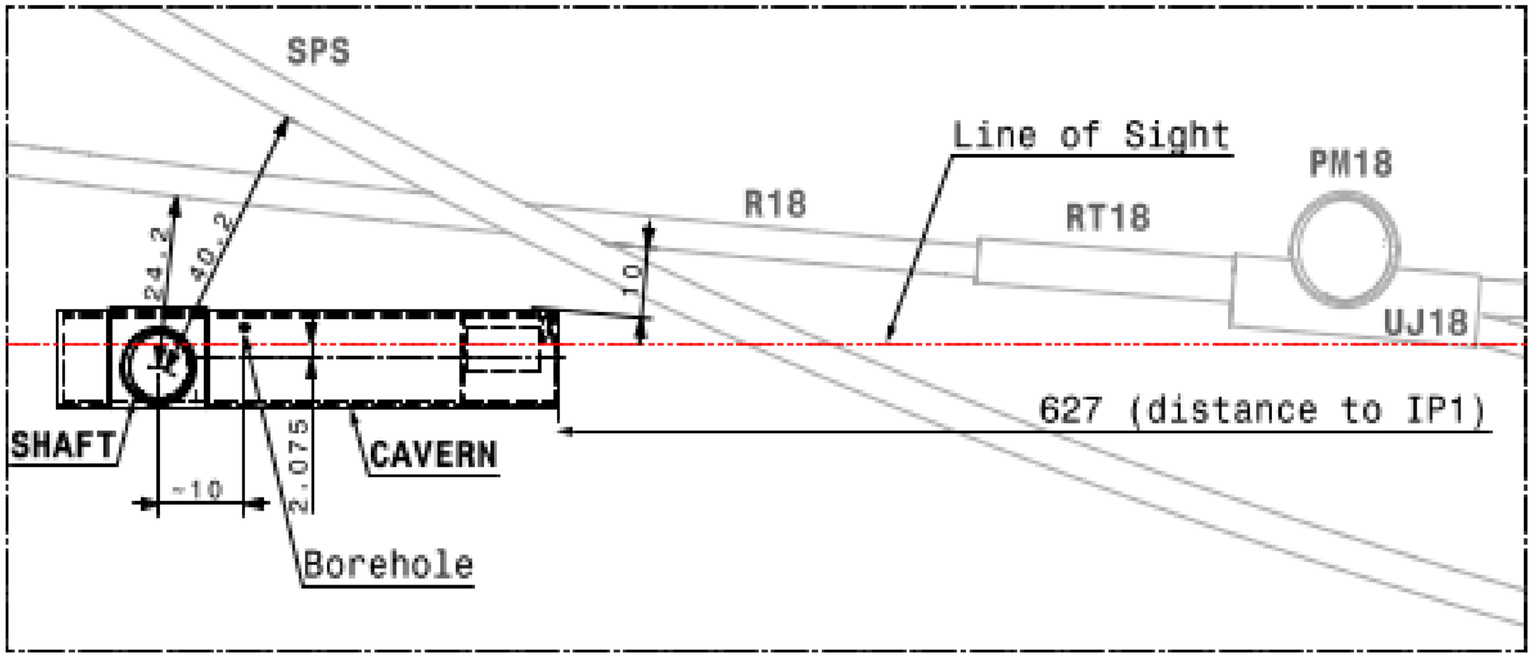
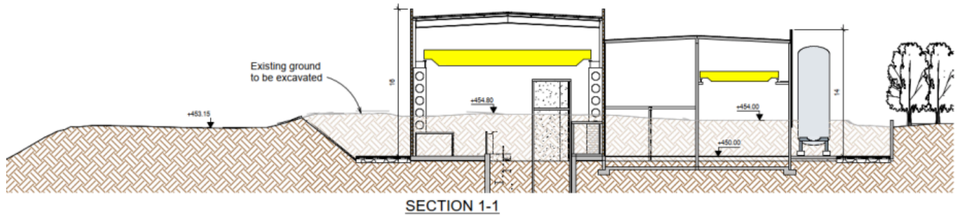
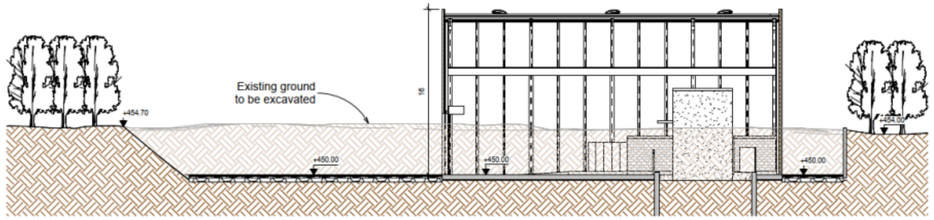


[J. L. Feng, ..., D. Soldin et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

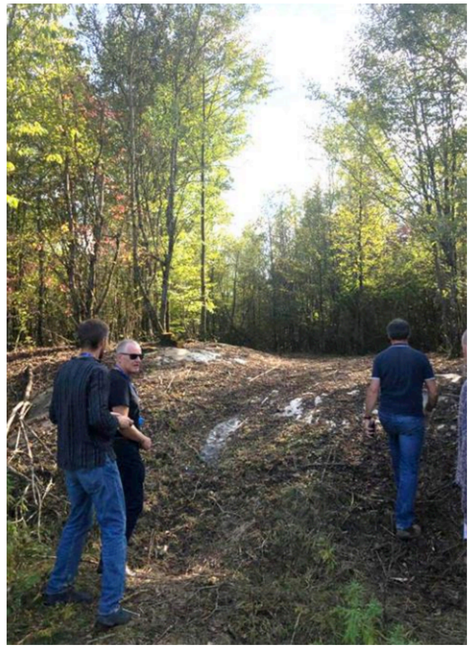
The Facility

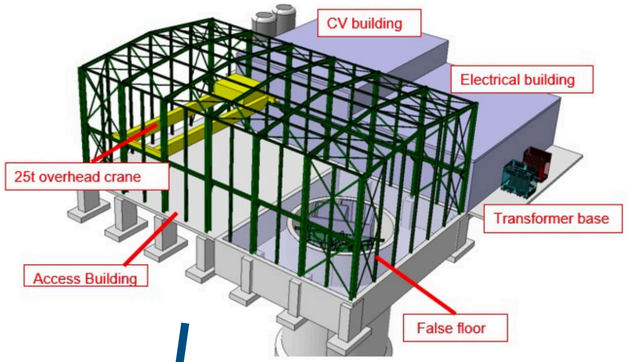


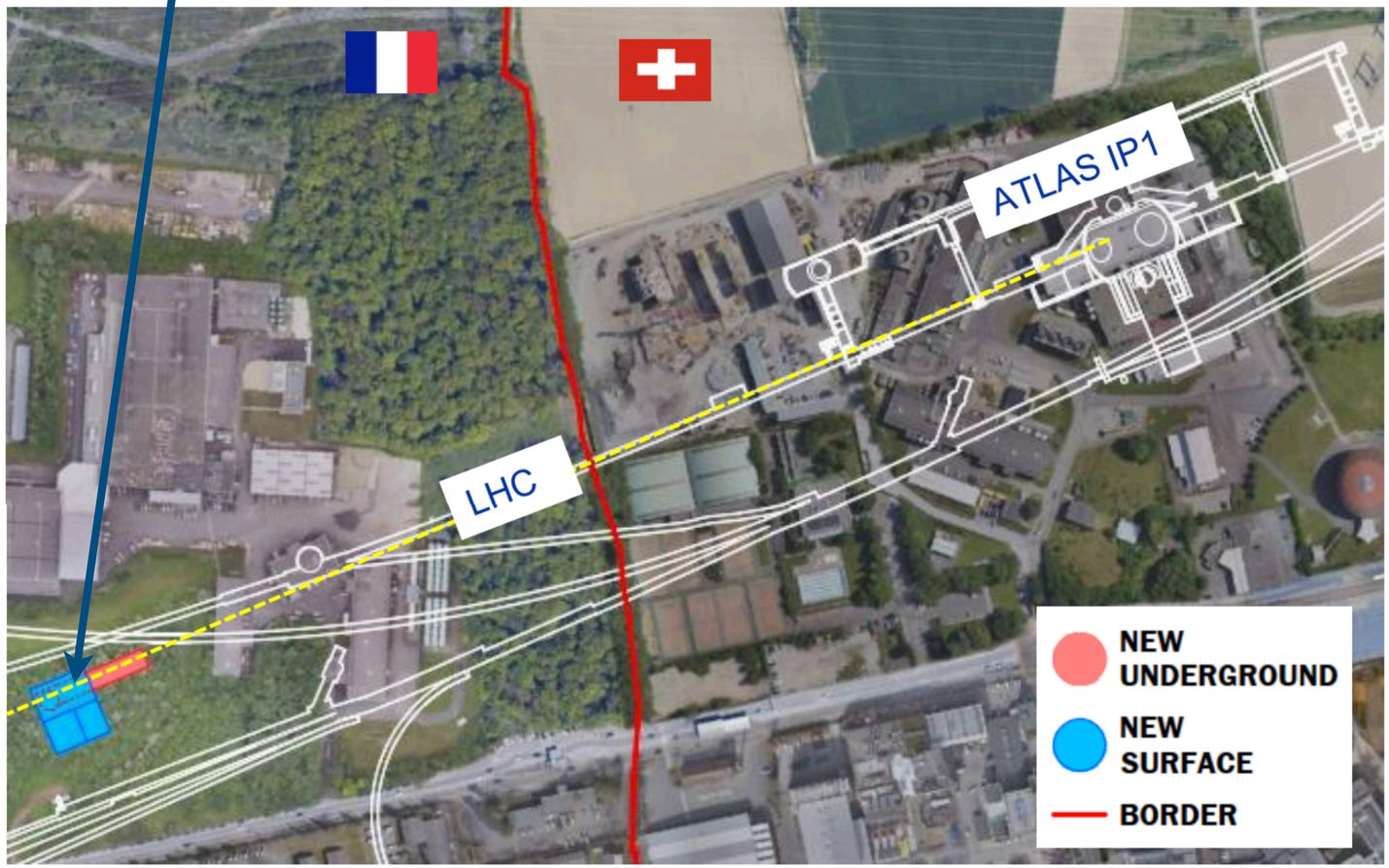
SECTION 1-1



SECTION 2-2

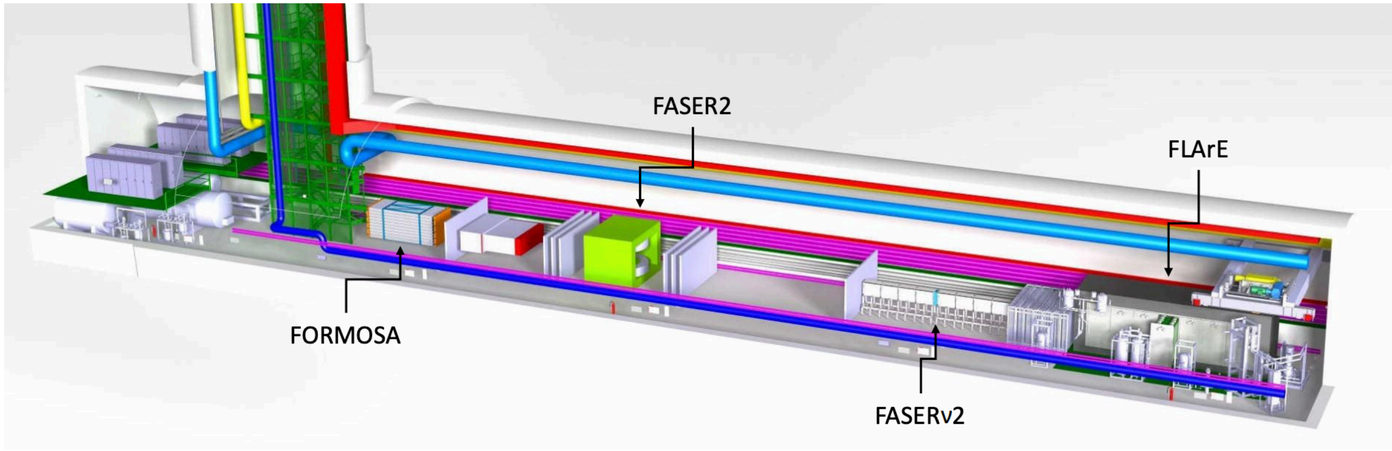


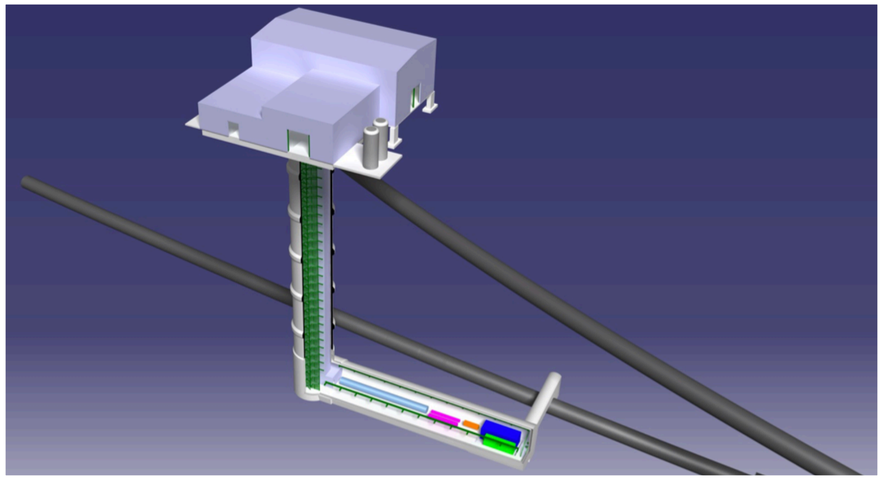




Forward Physics Facility

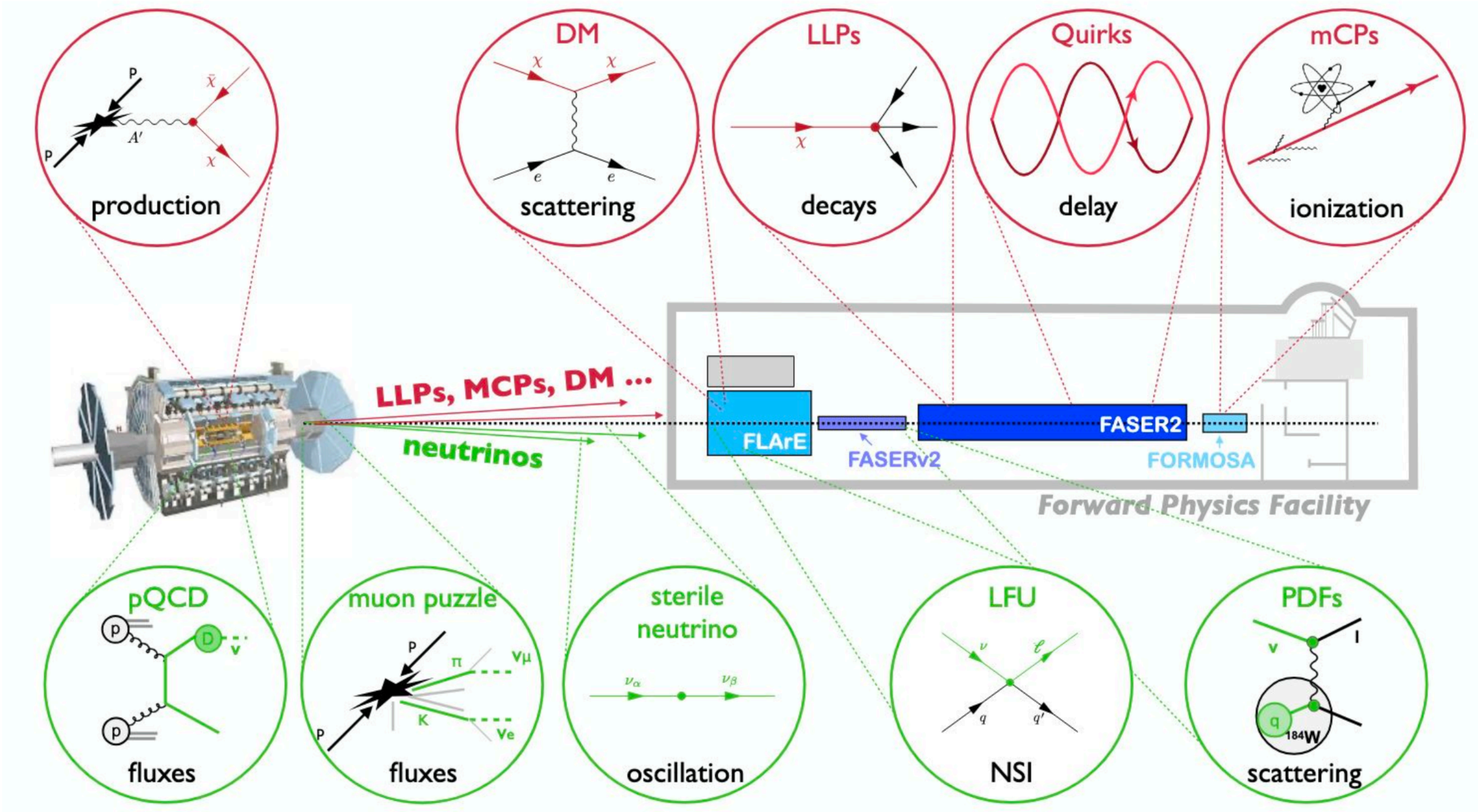
- Pseudorapidities: $\eta \gtrsim 7.5$
- Four proposed experiments:
  - FASER2
    - Magnetic tracking spectrometer
      (search for light and weakly-interacting states)
  - FASERν2
    - Emulsion detector
      (detection of TeV neutrinos)
  - FLArE
    - 10-ton noble liquid fine-grained TPC
      (detection of neutrinos and light dark matter)
  - FORMOSA
    - Scintillating bars (detection of millicharged particles)





[J. Adhikary, ..., D. Soldin et al., Eur. Phys. J. C 85 (2025)]
[J. L. Feng, ..., D. Soldin et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

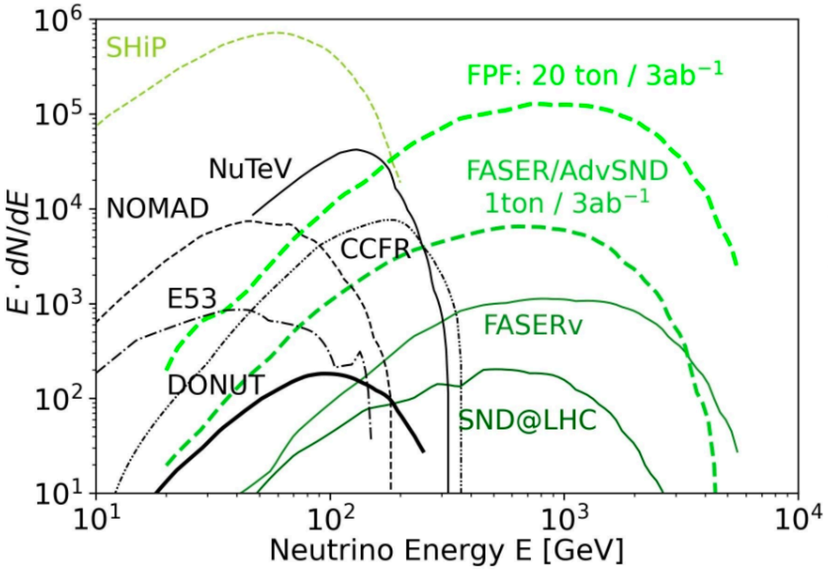
Physics Opportunities

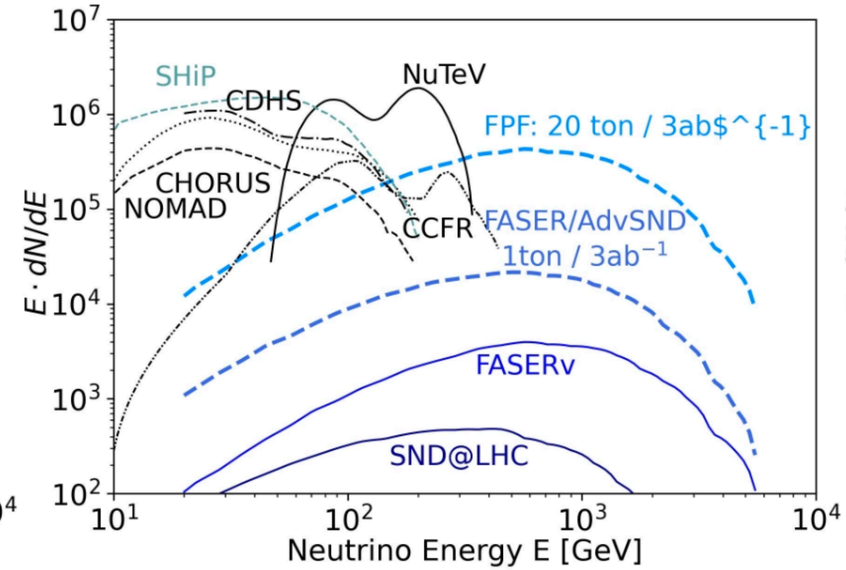


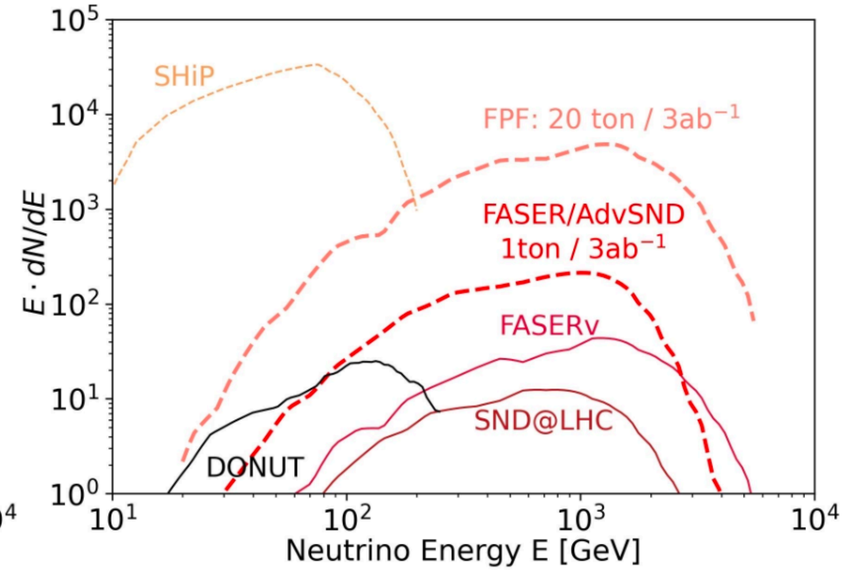
[J. L. Feng, ..., D. Soldin et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Physics Opportunities

- LHC neutrinos uniquely cover unexplored TeV energy range
- Thousands of neutrino interactions in current detectors
- Millions of neutrino interactions expected at FPF detectors
  - Including several thousands of tau neutrinos!



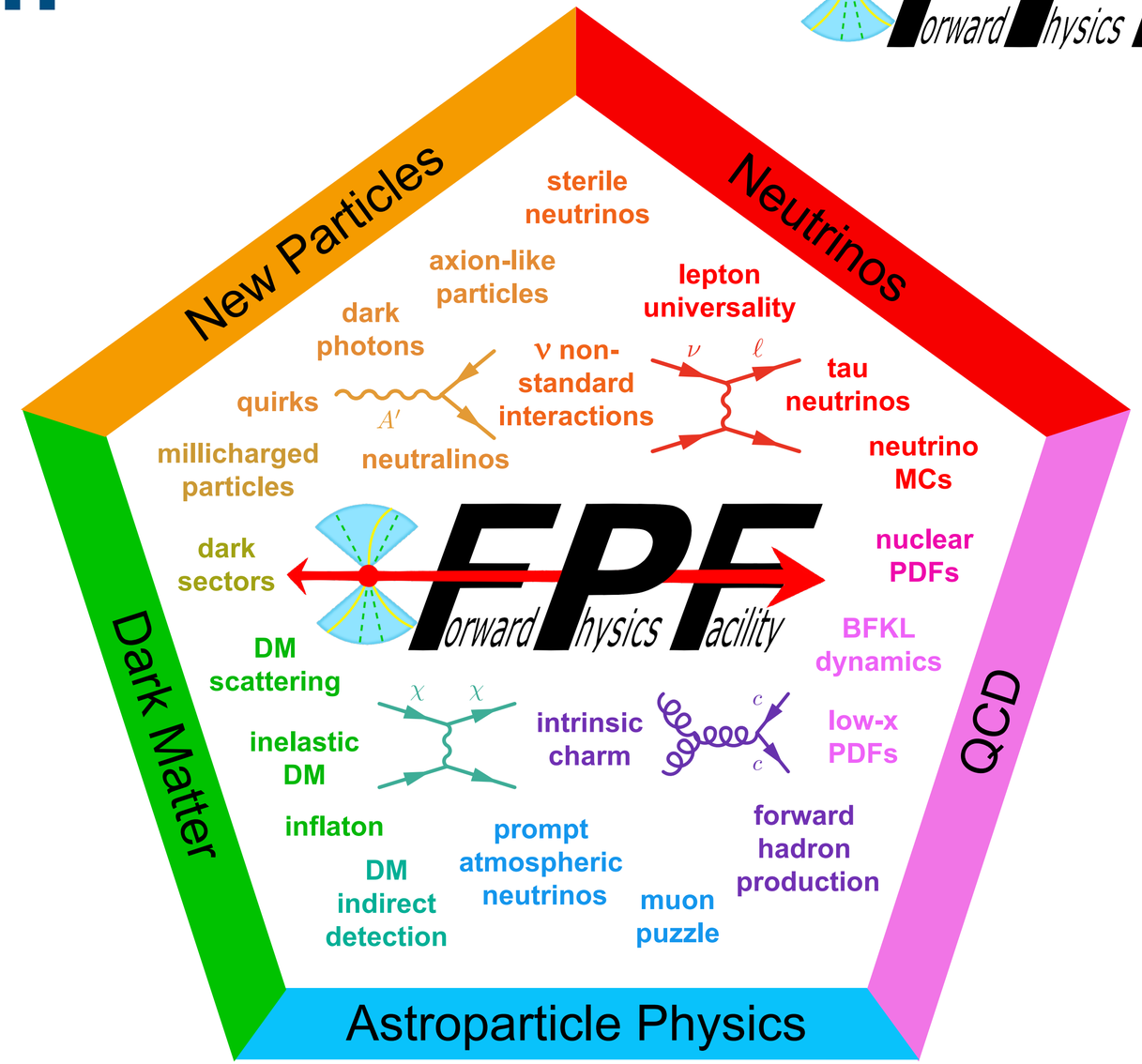




[J. L. Feng, ..., D. Soldin et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

FPF Physics Program

- Large (multi-)community effort!
- Comprehensive physics program:
  - Long-lived particles
  - Dark Matter and BSM scattering
  - Quantum Chromodynamics
  - Neutrino physics
  - Astroparticle physics
- More information:
  - https://fpf.web.cern.ch



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

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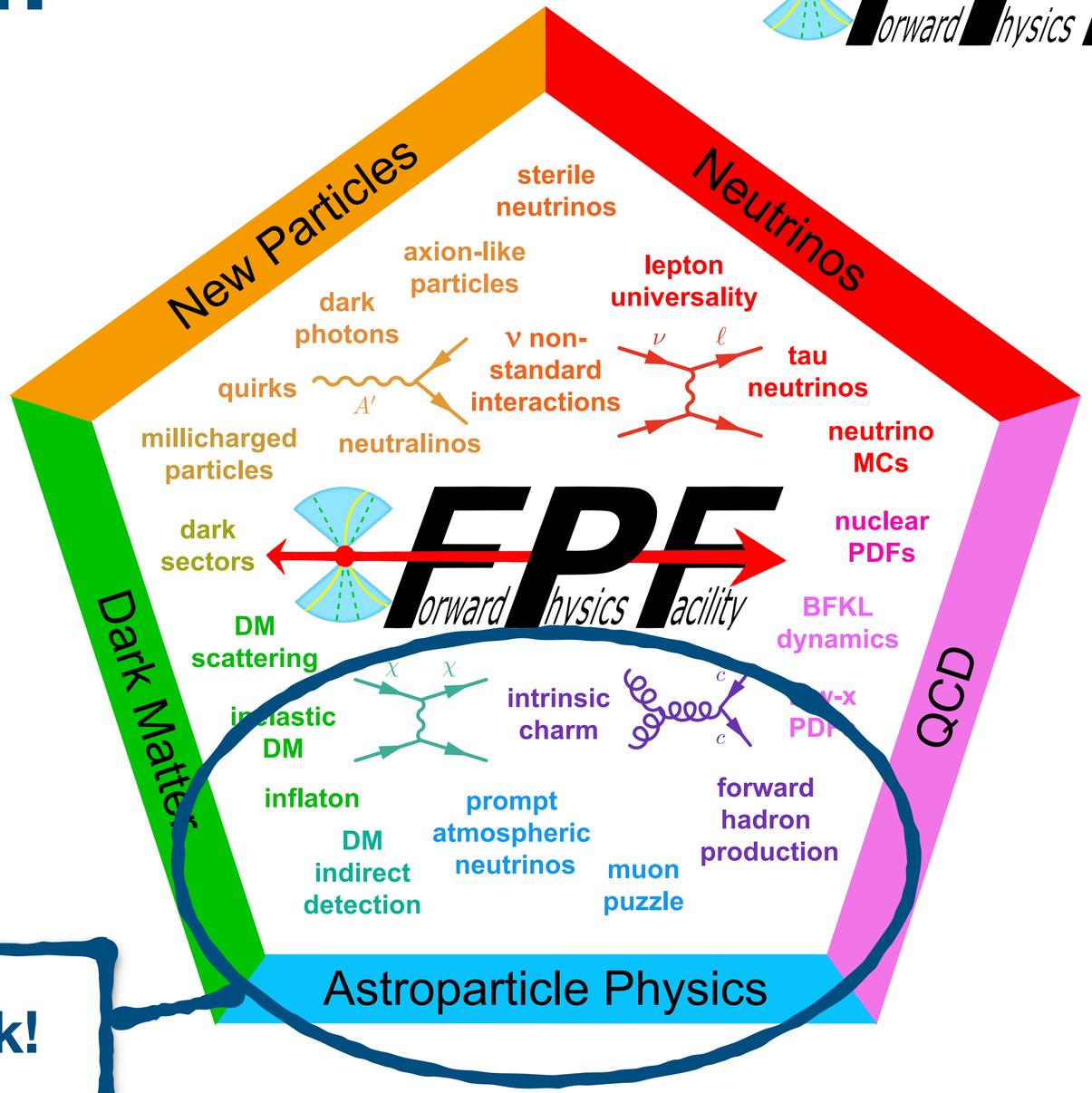
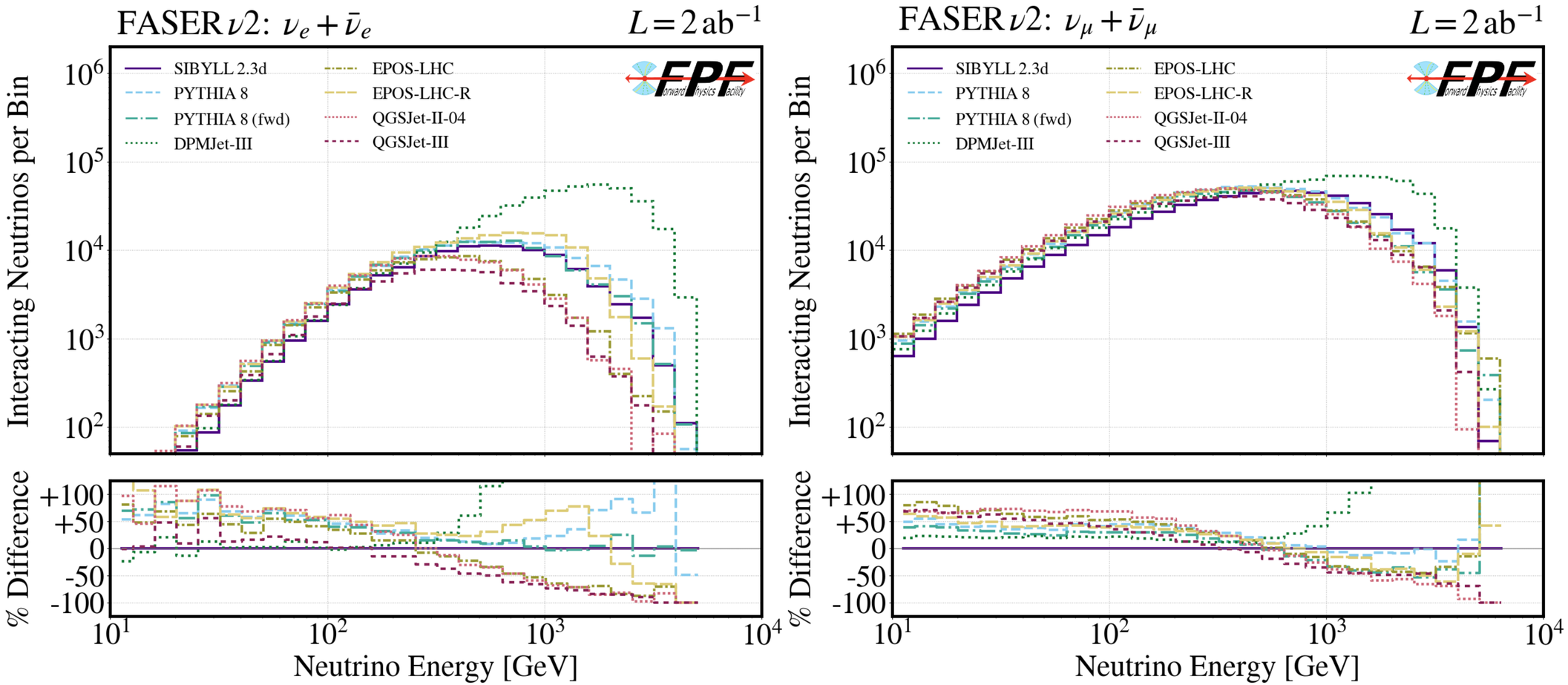


[J. L. Feng, ..., D. Soldin et al., J. Phys. G: Nucl. Part. Phys. 50 (2023)]

Astroparticle Physics

- Example: Neutrino fluxes at FASERν2



[D. Soldin et al., PoS ICRC2025 (2025) 1182]

[J. Adhikary, ..., D. Soldin et al., Eur. Phys. J. C 85 (2025)]

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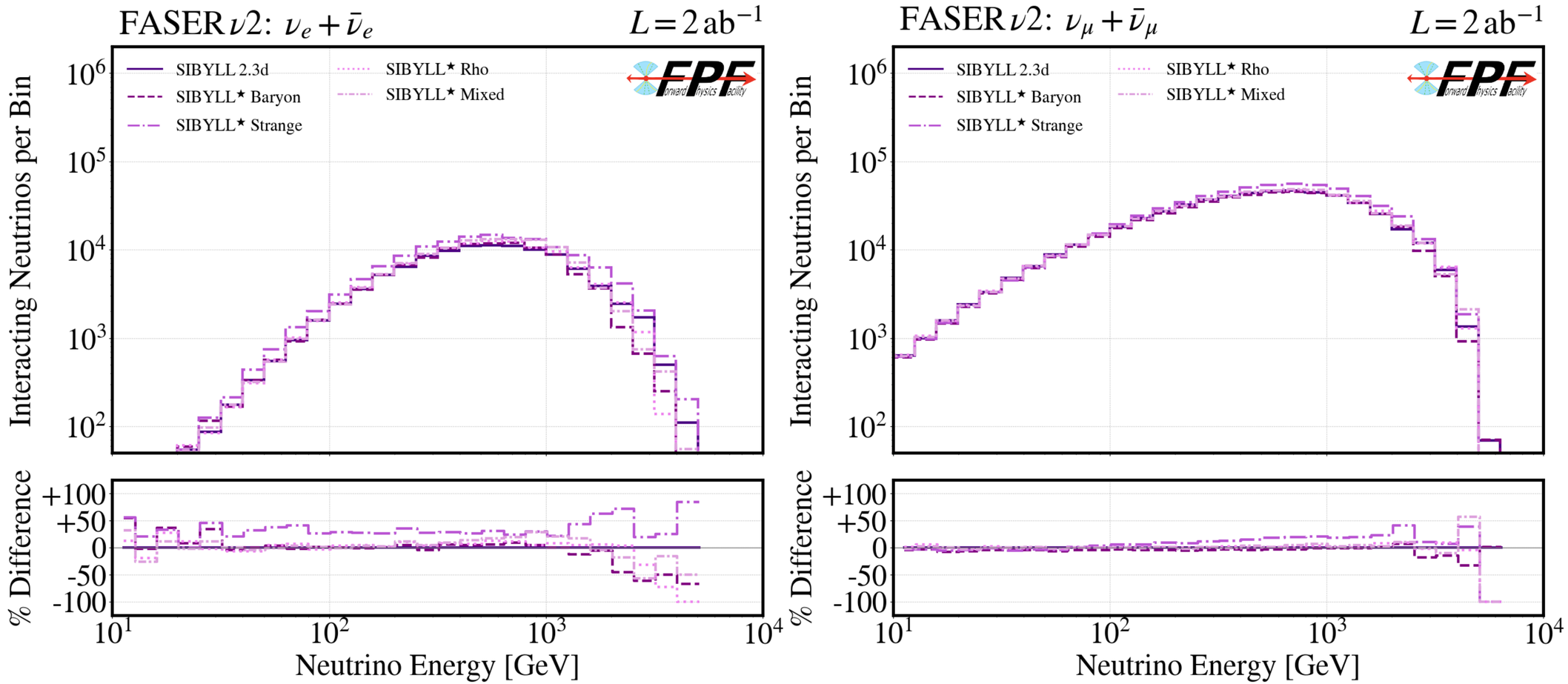

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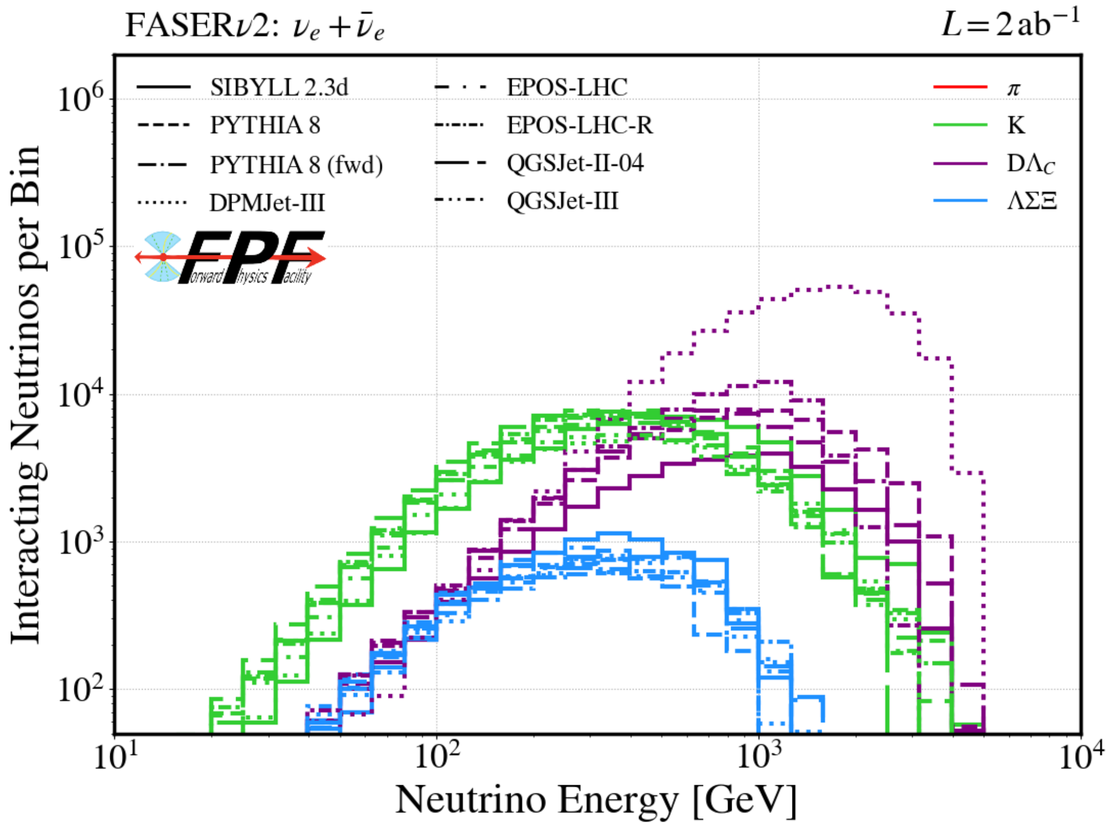
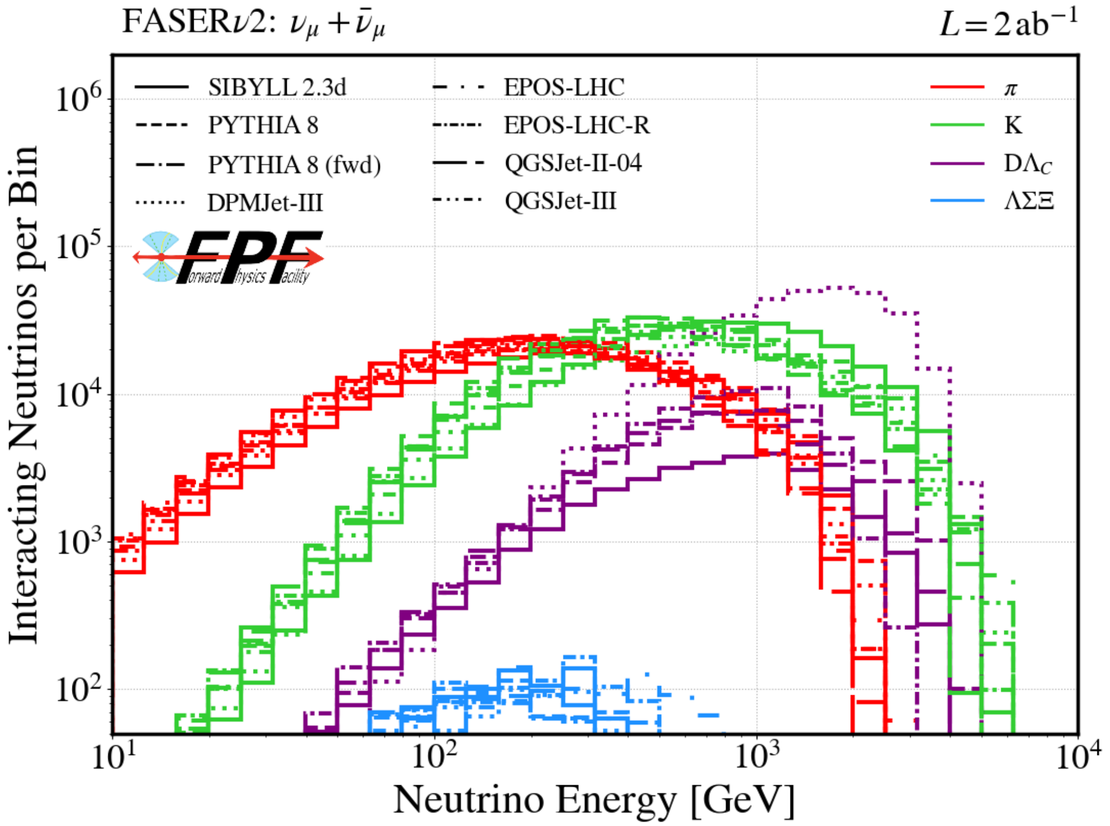


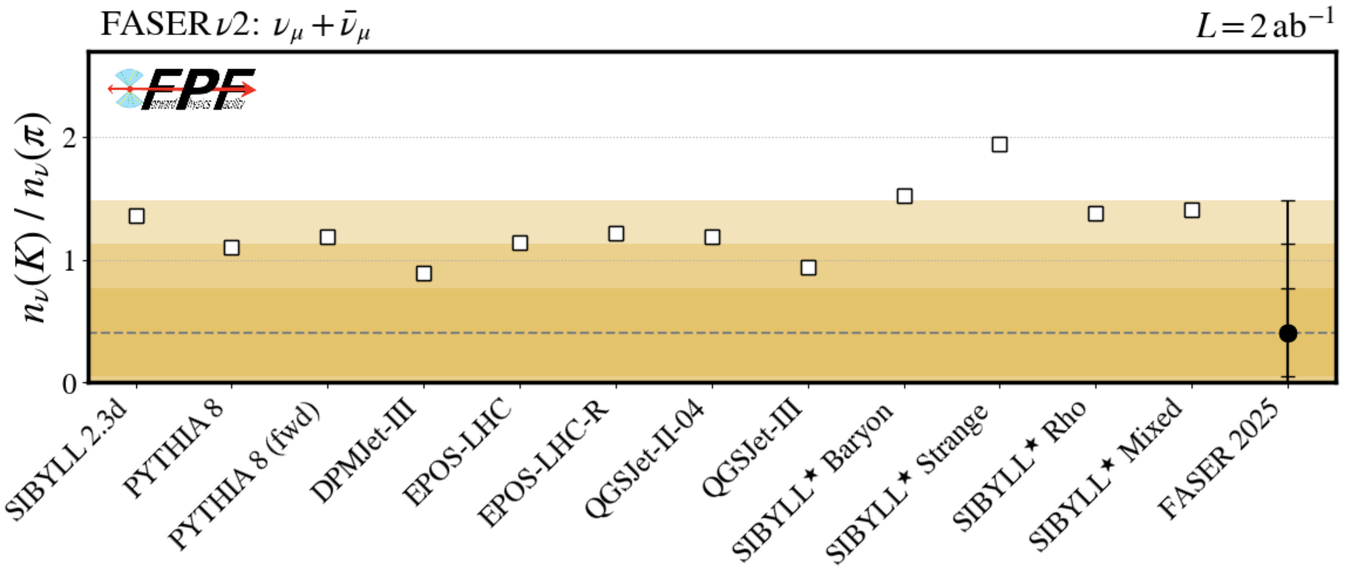


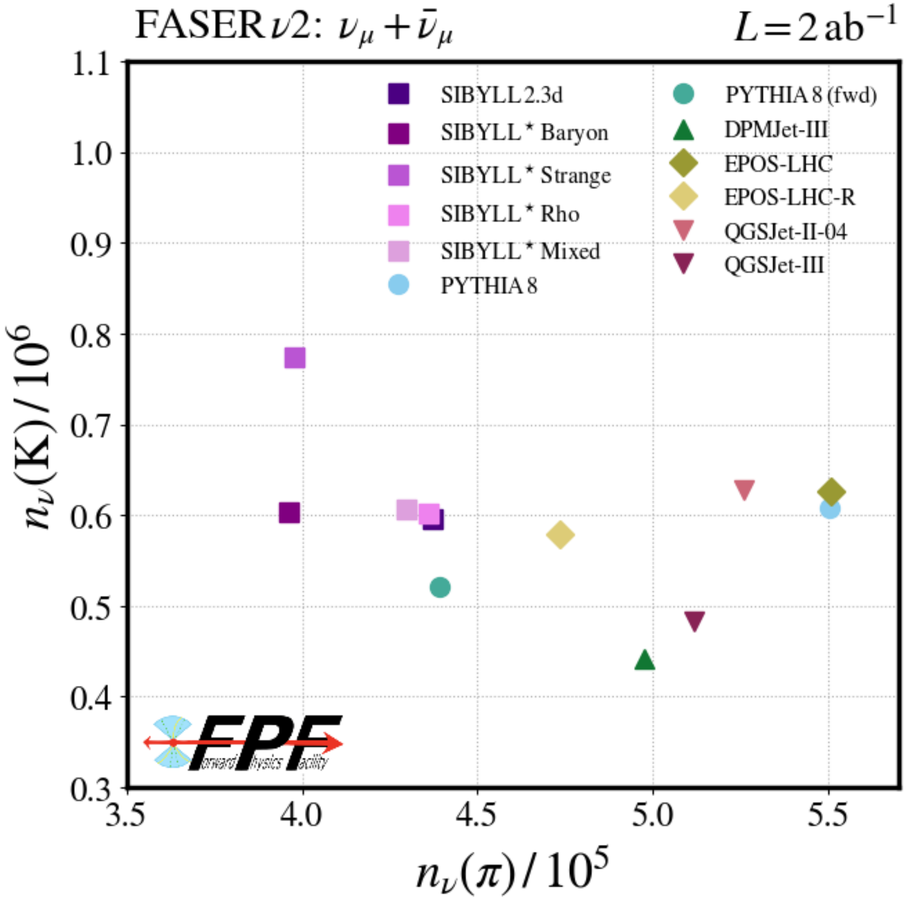
[D. Soldin et al., PoS ICRC2025 (2025) 1182]

[J. Adhikary, ..., D. Soldin et al., Eur. Phys. J. C 85 (2025)]

Astroparticle Physics

- FASER measurement: [FASER Collaboration, Phys. Rev. Lett. 134 (2024)]
  - Number of neutrino interactions from pion and kaon decays
- FPF data and improved methods will put strong constraints on the kaon/pion ratio!
  - Constraints for hadronic interaction models!



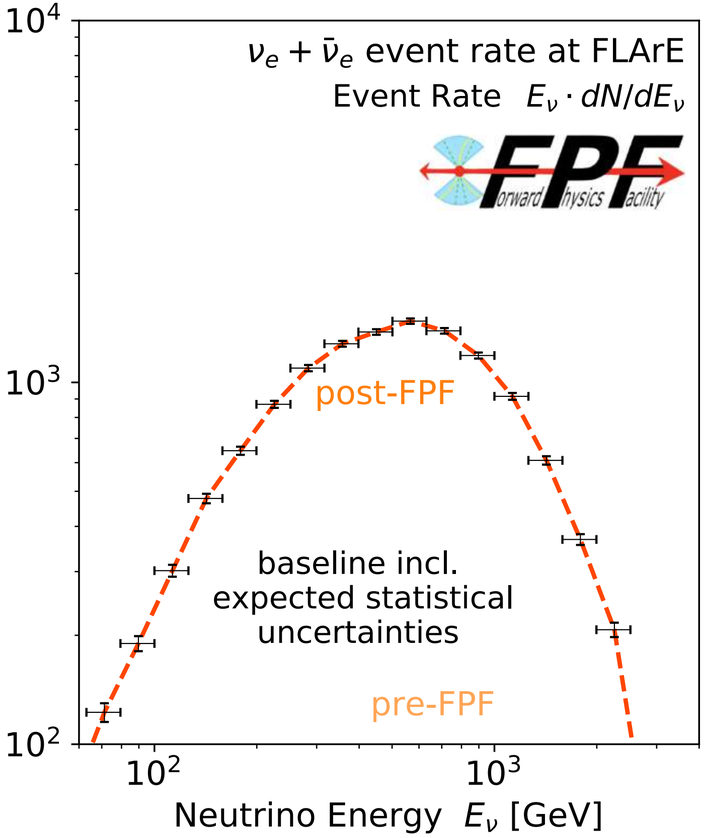


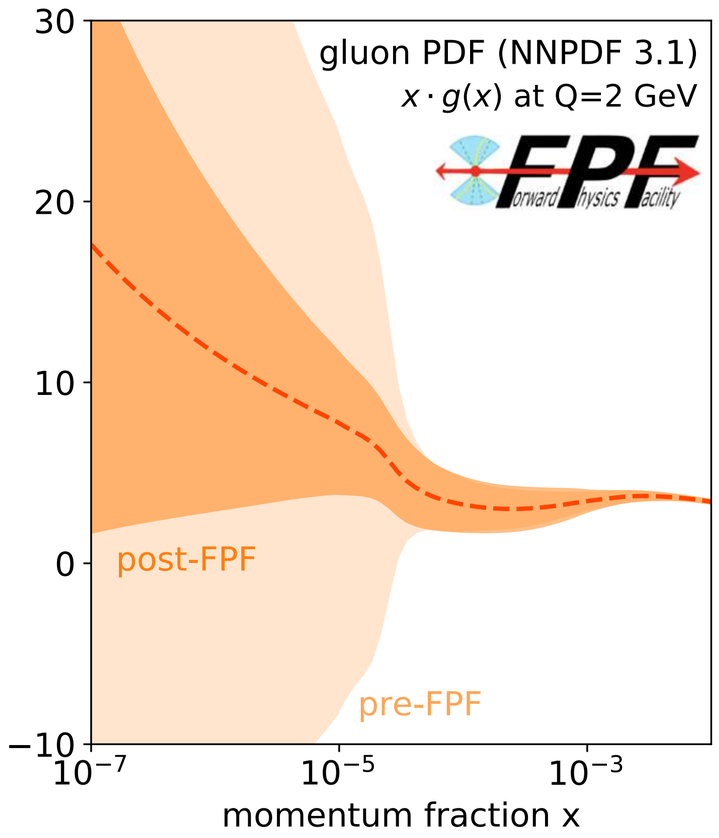
[D. Soldin et al., PoS ICRC2025 (2025) 1182]

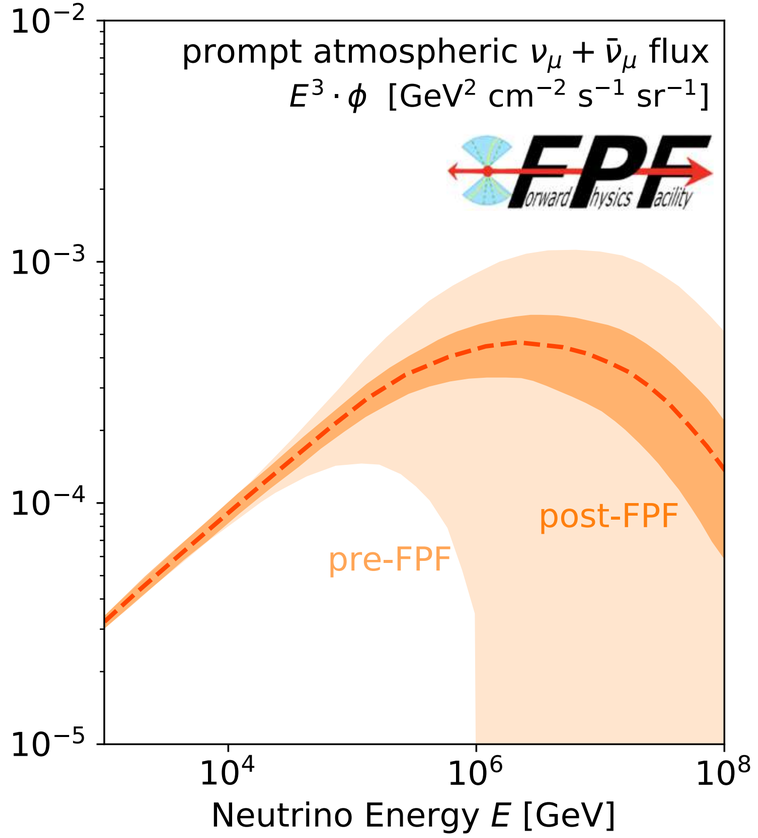
[J. Adhikary, ..., D. Soldin et al., Eur. Phys. J. C 85 (2025)]

Prompt Neutrinos

- FLArE measurement:
  - Small-x gluon PDFs



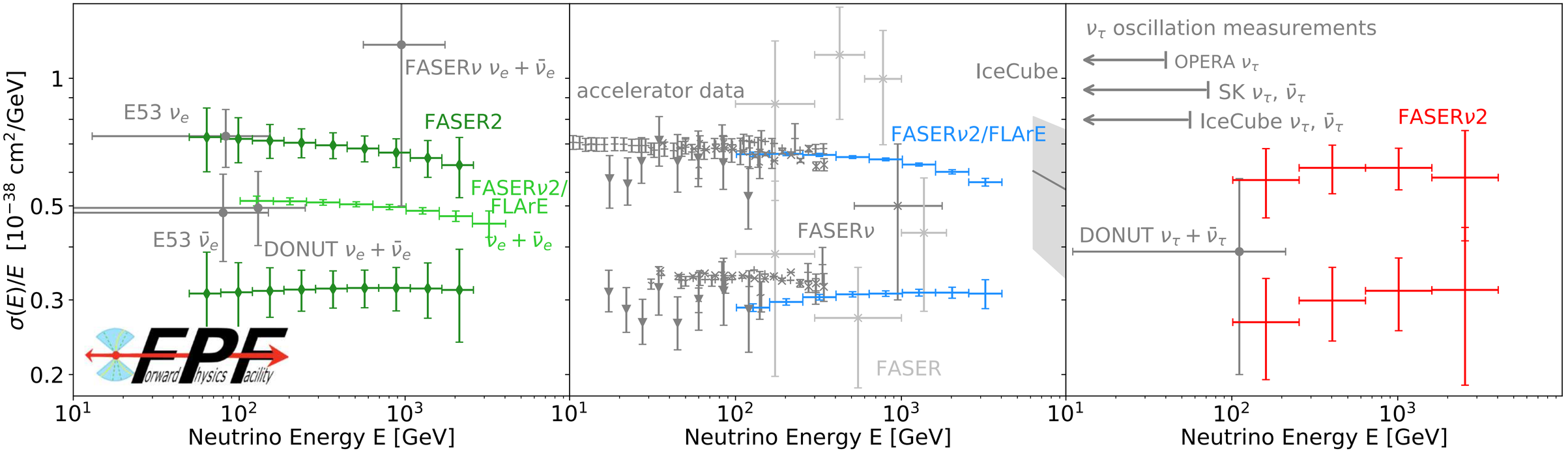




[J. Adhikary, ..., D. Soldin et al., Eur. Phys. J. C 85 (2025)]

Neutrino Cross Sections

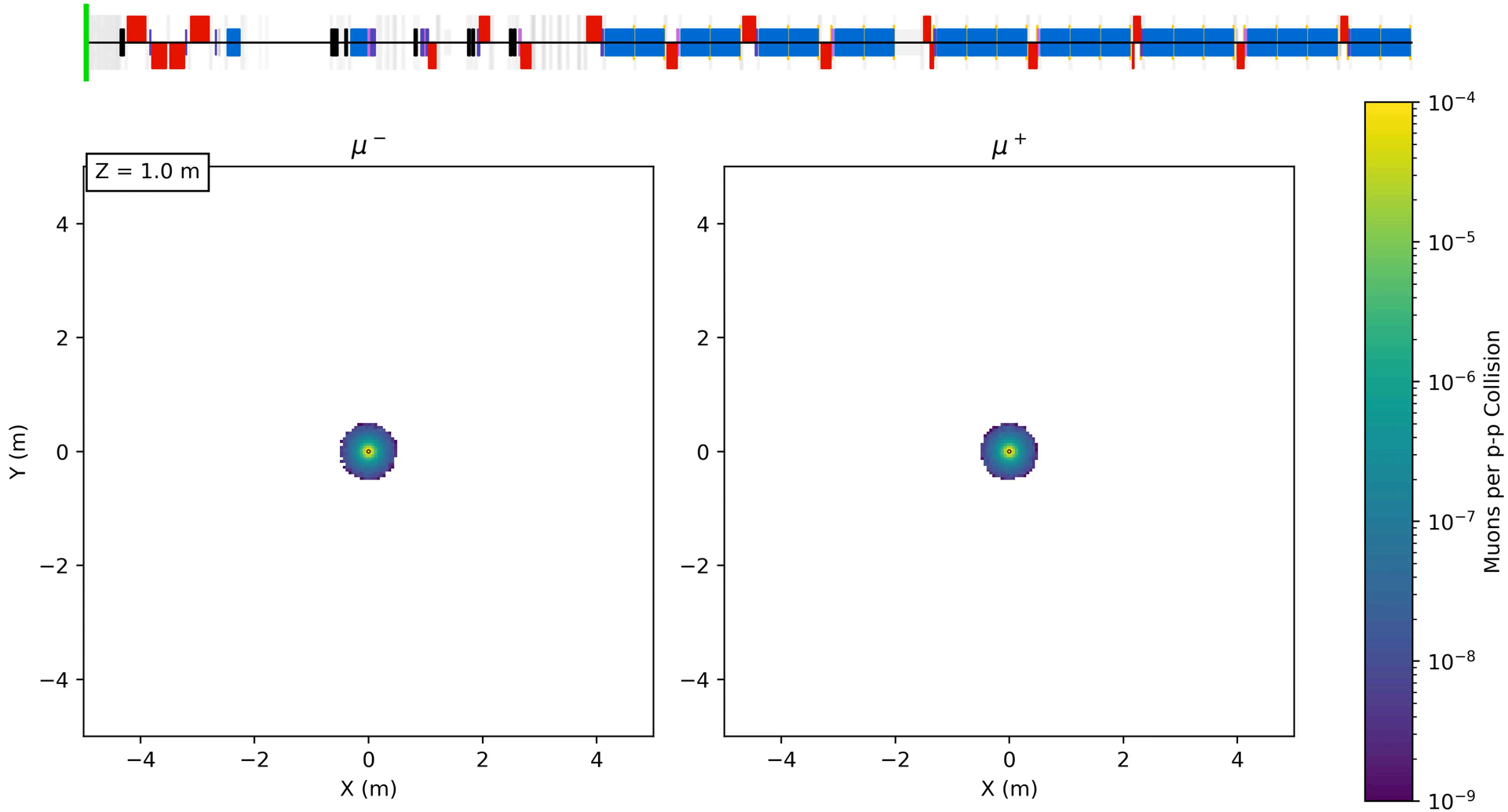
- Neutrino cross section measurements:



[J. Adhikary, ..., D. Soldin et al., Eur. Phys. J. C 85 (2025)]

Muon Fluxes

- Muon fluxes at the FPF:



Muon Fluxes

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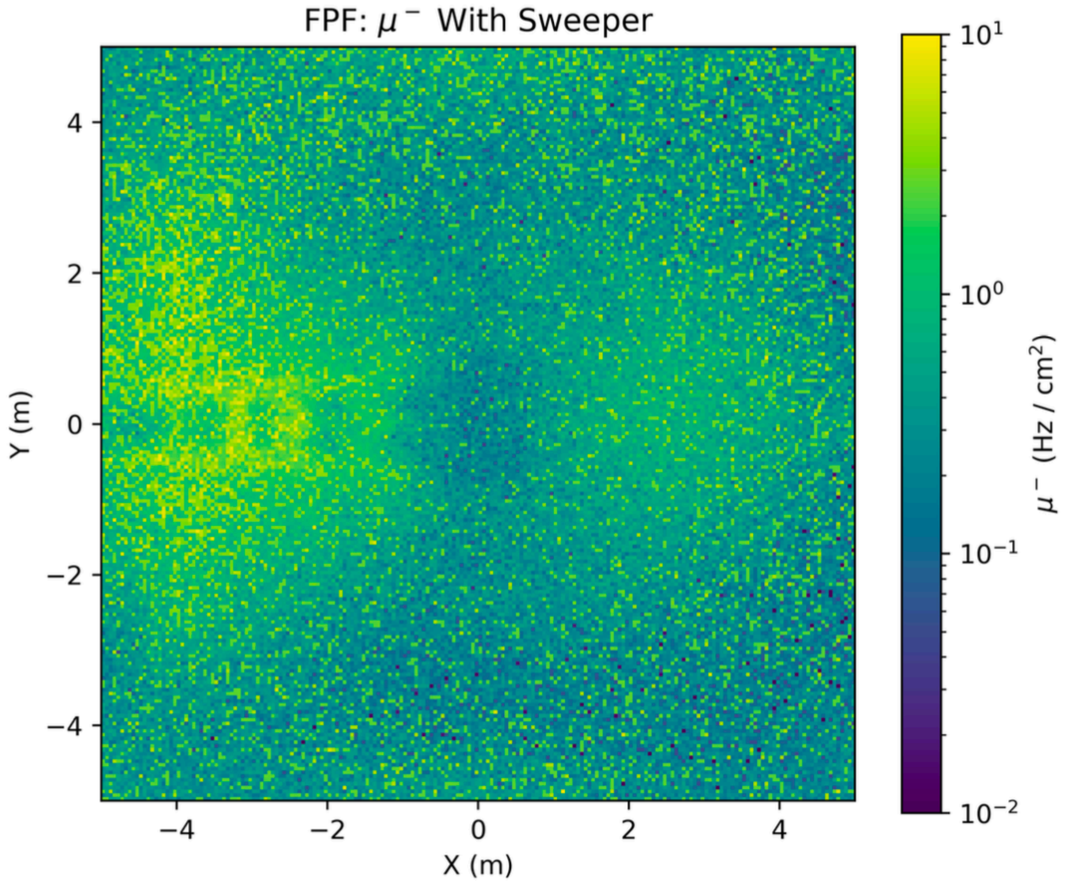

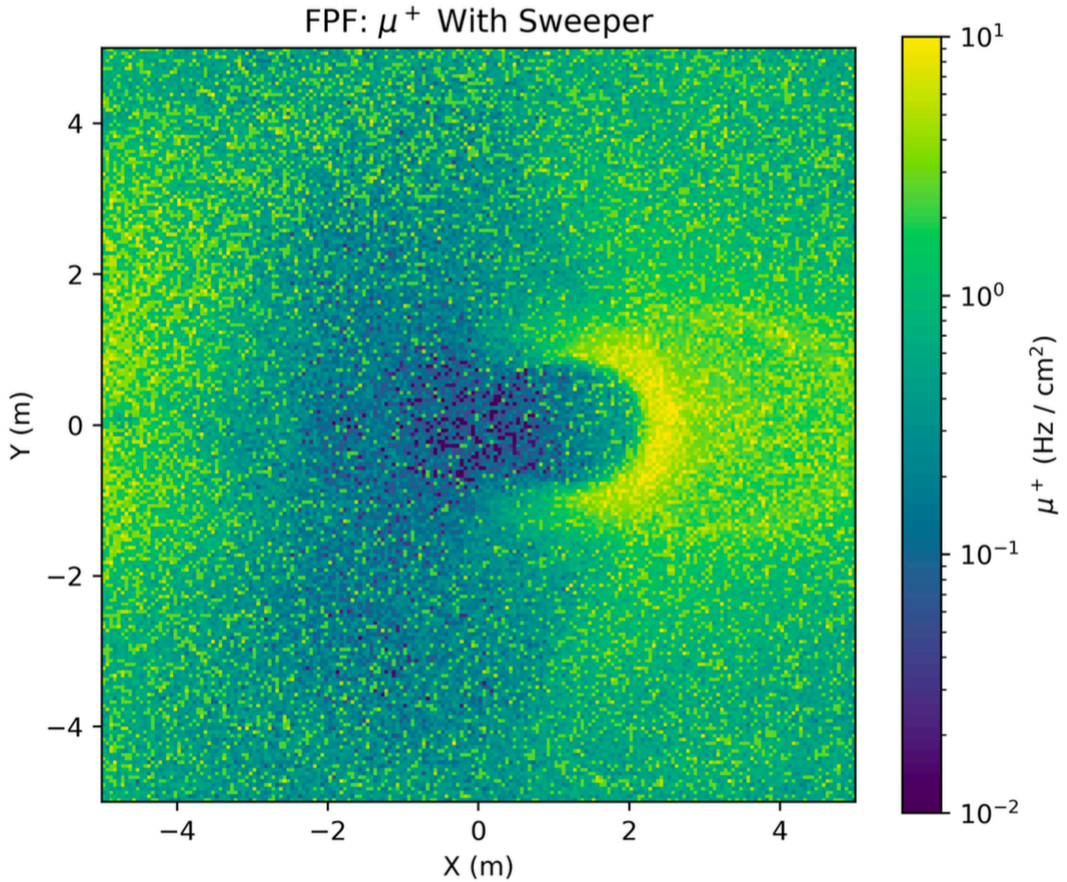

- Temporary detectors? Simulation studies ongoing…

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

FPF Documentation

- FPF "Short Paper" (77 pages, ~80 authors)
  - Phys. Rep. 968 (2022)
- Snowmass White Paper (~430 pages, ~250 authors)
  - J. Phys. G: Nucl. Part. Phys. 50 (2023)
  - Recent update
- EPPSU Scientific Program (25 pages, 26 authors)
  - Eur. Phys. J. C 85 (2025)
- Technical documents
  - Facility technical study
  - Muon flux study
  - Vibration study
  - Geotechnical report
- Many more
  - https://fpf.web.cern.ch

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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 Campa… Grigorios Cha…

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],

Eur. Phys. J. C (2025) 85:430

https://doi.org/10.1140/epjc/s10052-025-14048-6

THE EUROPEAN PHYSICAL JOURNAL C

Review

Scientific program for the Forward Physics Facility

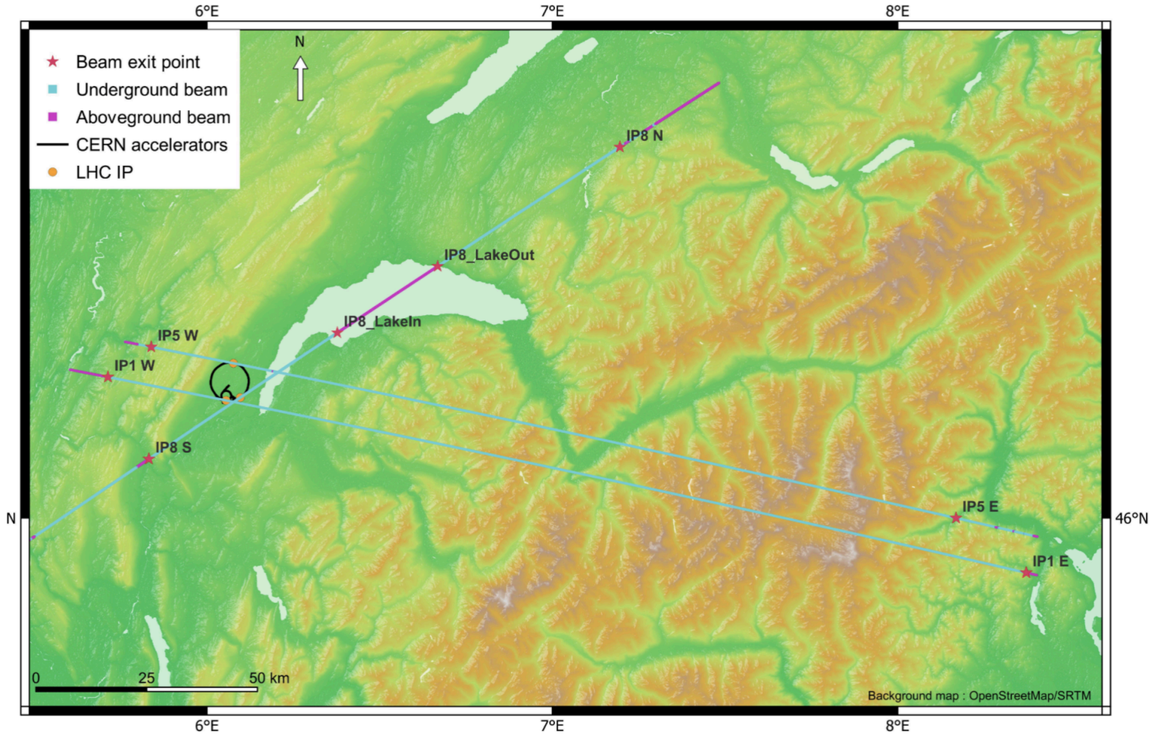
Jyotismita Adhikary[1], Luis A. Anchordoqui[2], Akitaka Ariga[3,4], Tomoko Ariga[5], Alan J. Barr[6], Brian Batell[7], Jianming Bian[8], Jamie Boyd[9], Matthew Citron[10], Albert De Roeck[9], Milind V. Diwan[11], Jonathan L. Feng[8], Christopher S. Hill[12], Yu Seon Jeong[13], Felix Kling[14,a], Steven Linden[11], Toni Mäkelä[8], Kostas Mavrokoridis[15], Josh McFayden[16], Hidetoshi Otono[5], Juan Rojo[17,18], Dennis Soldin[19], Anna Stasto[20], Sebastian Trojanowski[1], Matteo Vicenzi[11], Wenjie Wu[8]

More…

- Proposal for medium-baseline detectors
- Forward LHC Observatory Underwater for Neutrinos and the Dark sEctoR (FLOUNDER)
  - Water Cherenkov detector in lake Geneva
- Lake Emulsion Detector (LED)
  - Water emulsion detector in lake Geneva
- Electronic detector in Jura Mountains

Detecting LHC Neutrinos at Surface Level

Akitaka Ariga,[1,2] Steven Barwick,[3] Jamie Boyd,[4] Max Fieg,[3] Felix Kling,[5] Toni Mäkelä,[3,*] Camille Vendeuvre,[4] and Benjamin Weyer[4]



IP/Side	luminosity	distance	relative flux	comment
IP1W	3000 fb^{-1}	26.9 km	0.1	in Jura mountains
IP1E	3000 fb^{-1}	183 km	0.0025	very far
IP5W	3000 fb^{-1}	18.7 km	0.25	in Jura mountains
IP5L	3000 fb^{-1}	9 km	1	in lake Geneva
IP5E	3000 fb^{-1}	166 km	0.0029	very far
IP8L	300–600 fb^{-1}	26 km	0.0125–0.025	in lake Geneva
IP8S	300–600 fb^{-1}	24.6 km	0.0133–0.0266	in Jura mountains
FASER/SND	3000 fb^{-1}	480 m	351	TI12/TI18
FPF	3000 fb^{-1}	620 m	210	purpose-built cavern

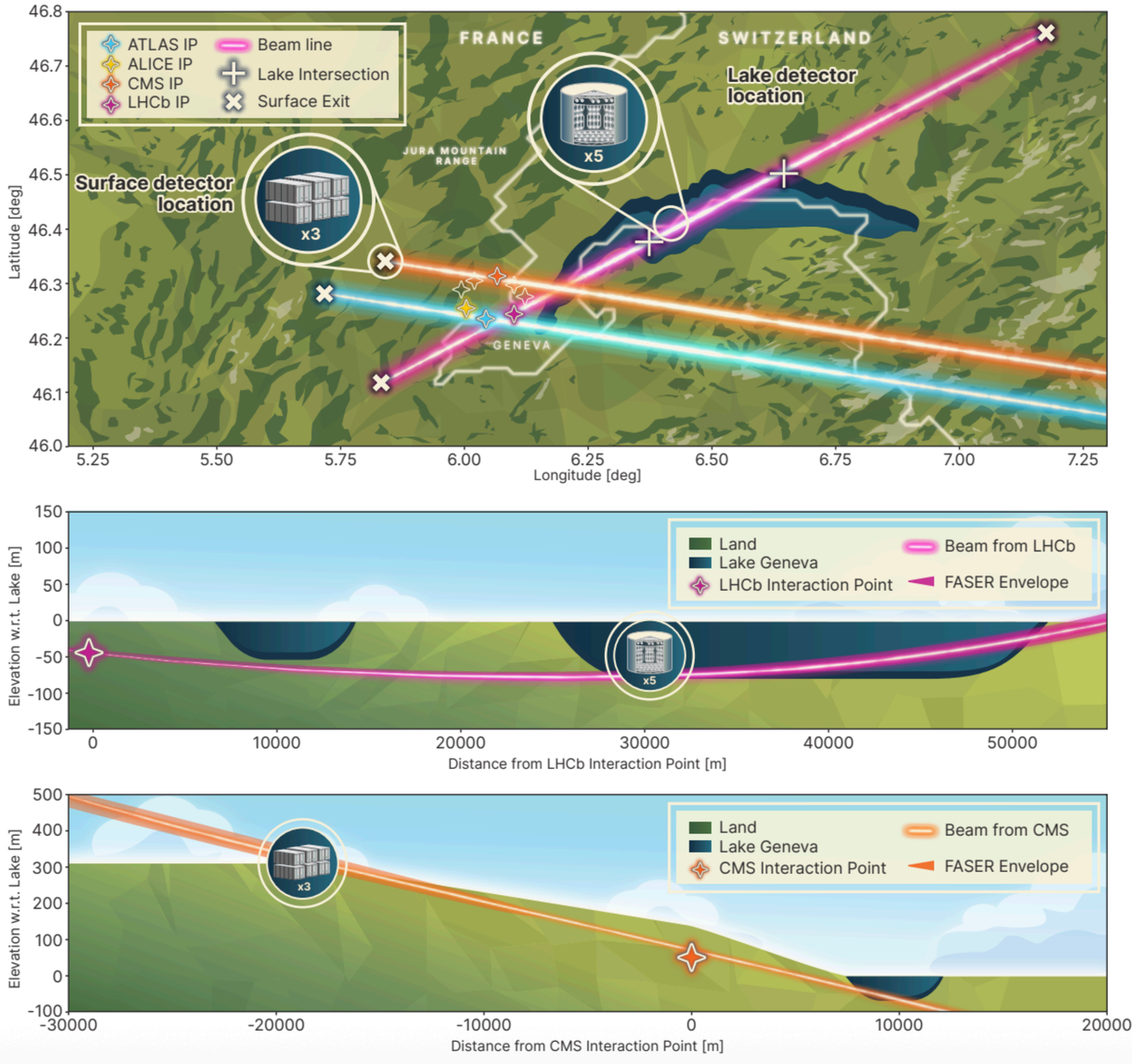
[A. Ariga et al., arXiv:2501.06142 (2025)]

SINE / UNDINE

- Proposal for medium-baseline detectors
- Surface-based Integrated Neutrino Experiment (SINE)
  - ~18 km from CMS IP
  - Surface-based scintillator panel detector (ν_μ detection)
- UNDerwater Integrated Neutrino Experiment (UNDINE)
  - ~30 km from LHCb IP (lake Geneva)
  - Water Cherenkov detector (all flavors)

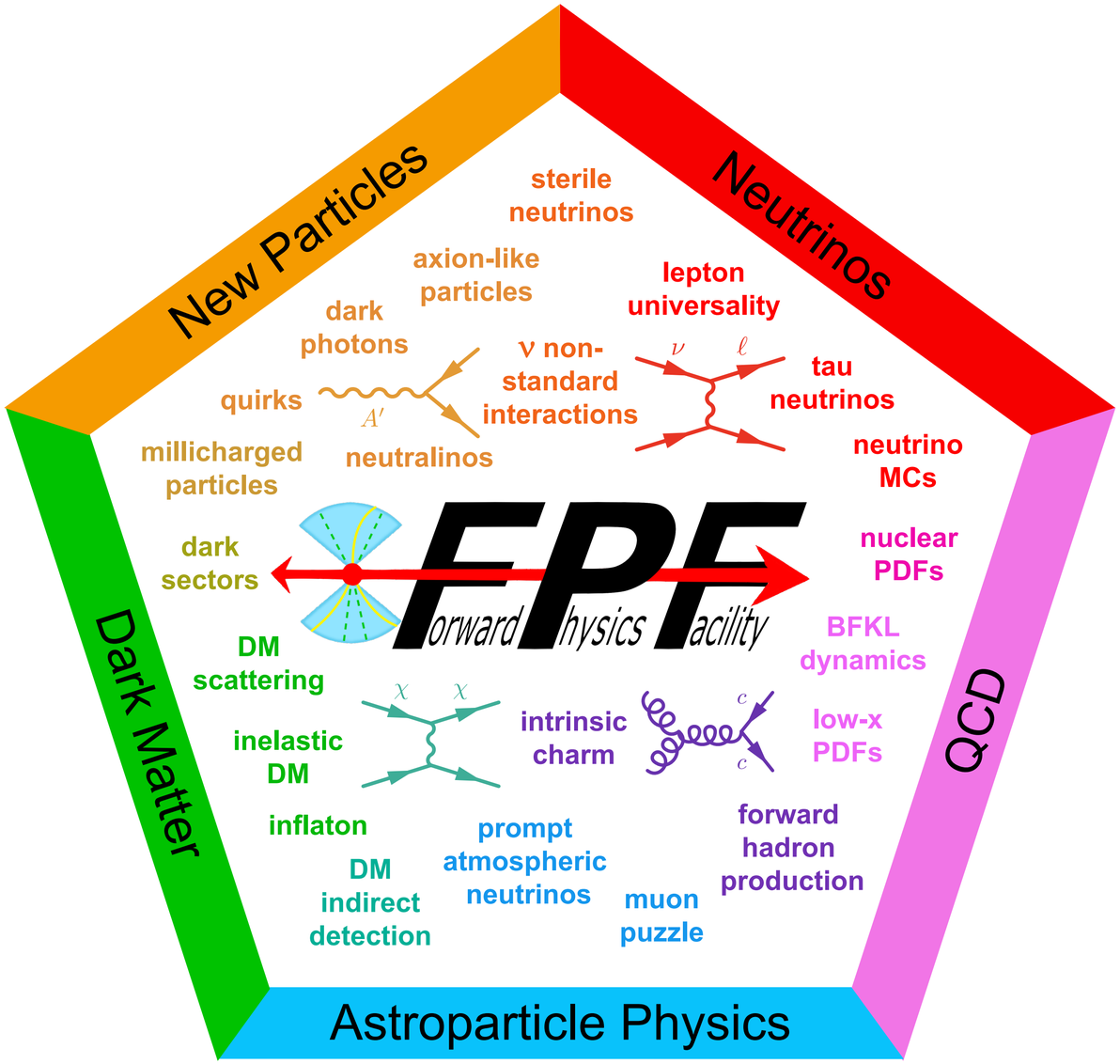
Lake- and Surface-Based Detectors for Forward Neutrino Physics

Nicholas W. Kamp,[1,*] Carlos A. Argüelles,[1,†] Albrecht Karle,[2,‡] Jennifer Thomas,[2,3,§] and Tianlu Yuan[2,¶]



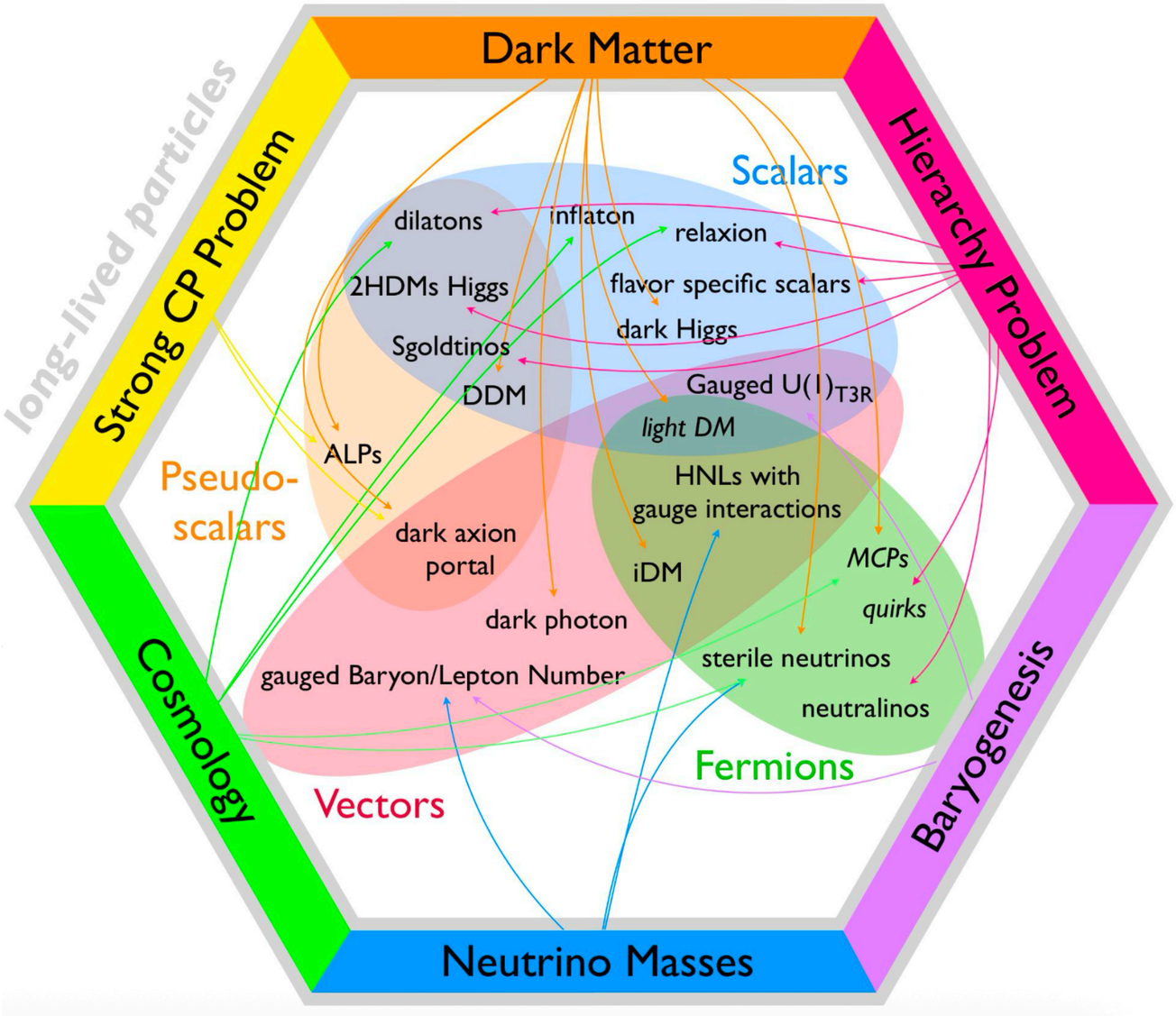
[N. W. Kamp et al., arXiv:2501.08278 (2025)]

Exciting Forward Physics Opportunities with Collider Neutrinos!



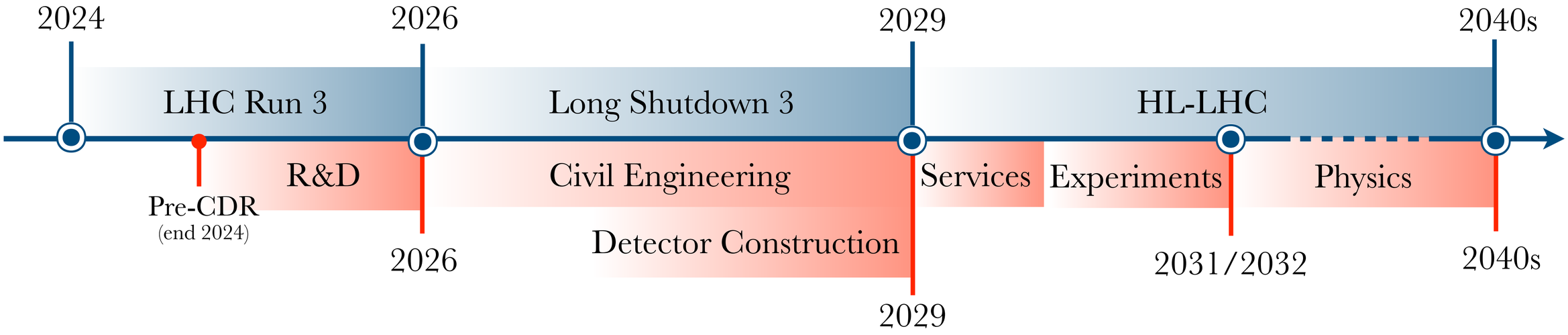
BACKUP

FPF Physics Program



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

FPF Timeline



[J. Adhikary, ..., D. Soldin et al., arXiv:2411.04175 (2024)]

FPF Cost

Ref.	Work Package	Cost [CHF]	Percentage of the CE Works
1.	Underground Works	12,392,344.00	35%
1.1	Preliminary activities	1,845,000.00	5.2%
1.2	Access shaft	4,424,143.00	12.5%
1.3	Experimental Cavern	6,123,201.00	17.3%
2.	Surface Works	6,727,231.00	19%
2.1	General items	720,776.00	2.0%
2.2	Topsoil and earthworks	702,227.00	2.0%
2.3	Roads and network	796,122.00	2.3%
2.4	Buildings	4,508,106.00	12.8%
2.4.1	Access building	2,224,786.00	6.3%
2.4.2	Cooling and ventilation building	1,497,350.00	4.2%
2.4.3	Electrical Building	563,689.00	1.6%
2.4.5	External platforms	222,281.00	0.6%
3.	General items	11,815,899.00	33.4%
4.	Miscellaneous	4,397,504.00	12.4%
	TOTAL CE WORKS	**35,332,978.00**	**100.0%**

~$43 million

[J. Adhikary, ..., D. Soldin et al., arXiv:2411.04175 (2024)]

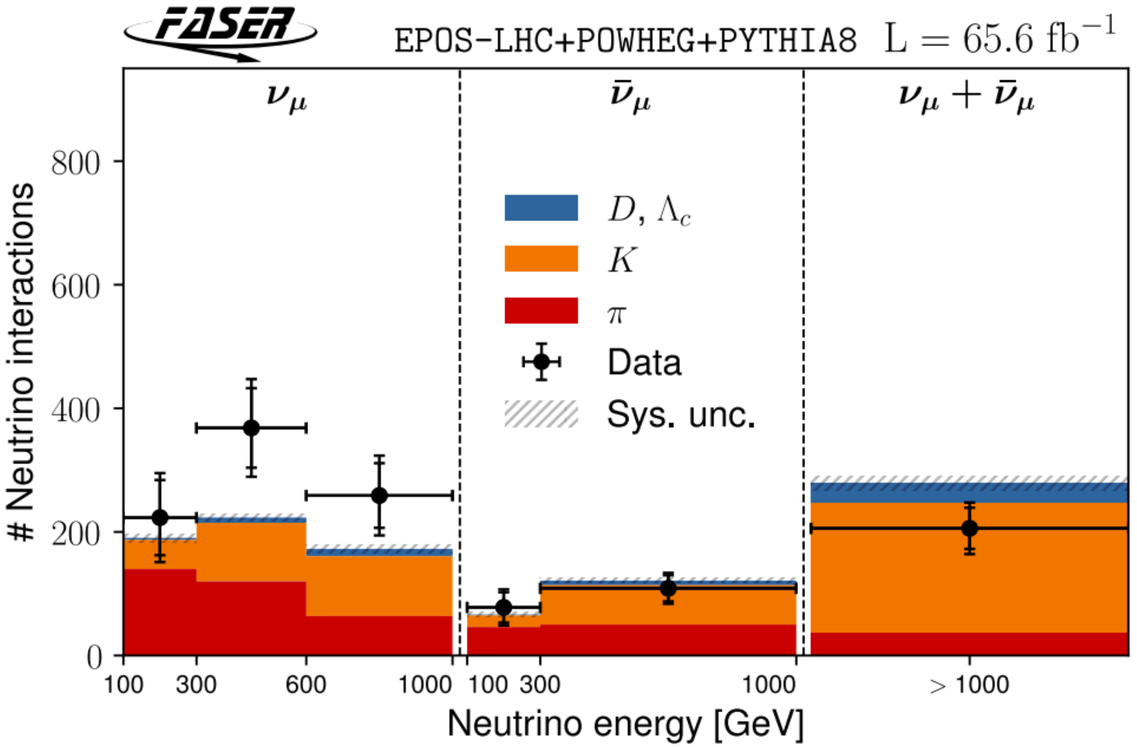
FPF Cost

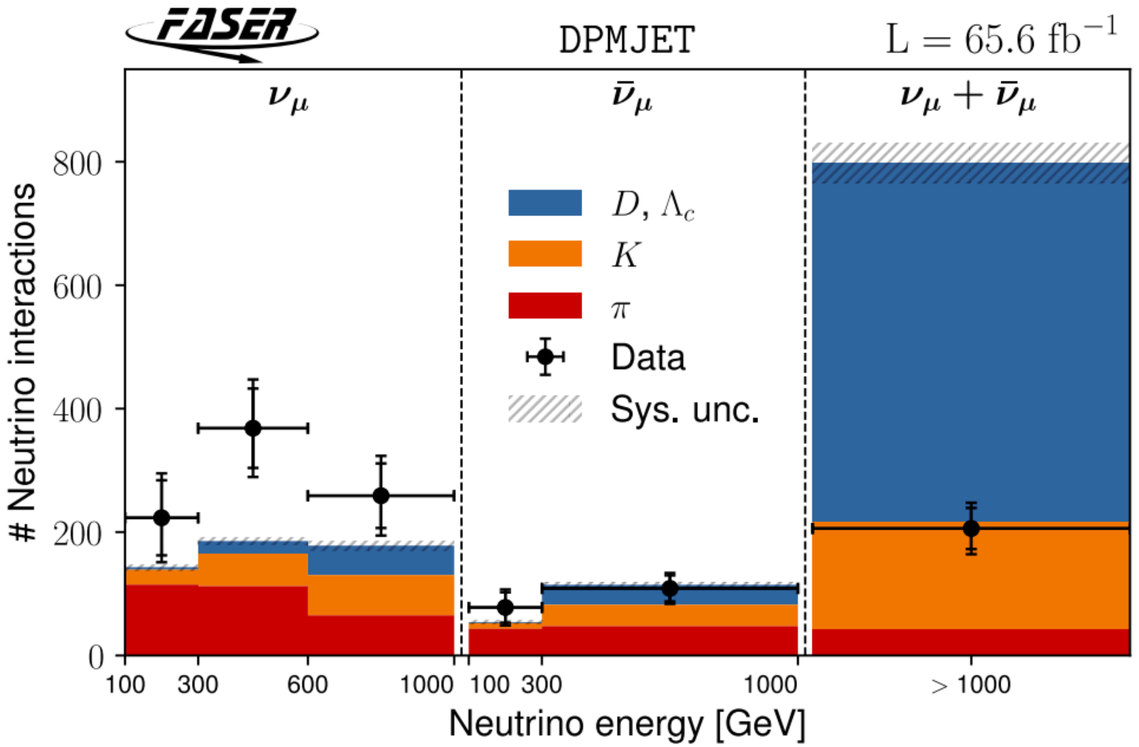
Experiment Costs		Core costs only
FASER2	11.6 MCHF	3+3 tracker layers, SAMURAI-style magnet, dual-readout calorimeter
FASERν2	15.9 MCHF	Tungsten target, scanning system, emulsion films (10 replacements), interface detector
FLArE	10.8 MCHF	Cryostat, proximity cryogenics, detectors
FORMOSA	2.3 MCHF	Plastic scintillator, PMTs, readout
Total	**40.6 MCHF**	Core cost experimental program

~$50 million

[J. Adhikary, ..., D. Soldin et al., arXiv:2411.04175 (2024)]

Neutrino Forward Fluxes





- Mild excess over prediction
- Model inconsistent with data

[FASER Collaboration, Phys. Rev. Lett. 134 (2024)]