Neutrinos at the Forward Physics Facility at CERN

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U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

arXiv:2109.10905 [hep-ph]

FPF Forward Physics Facility

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

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

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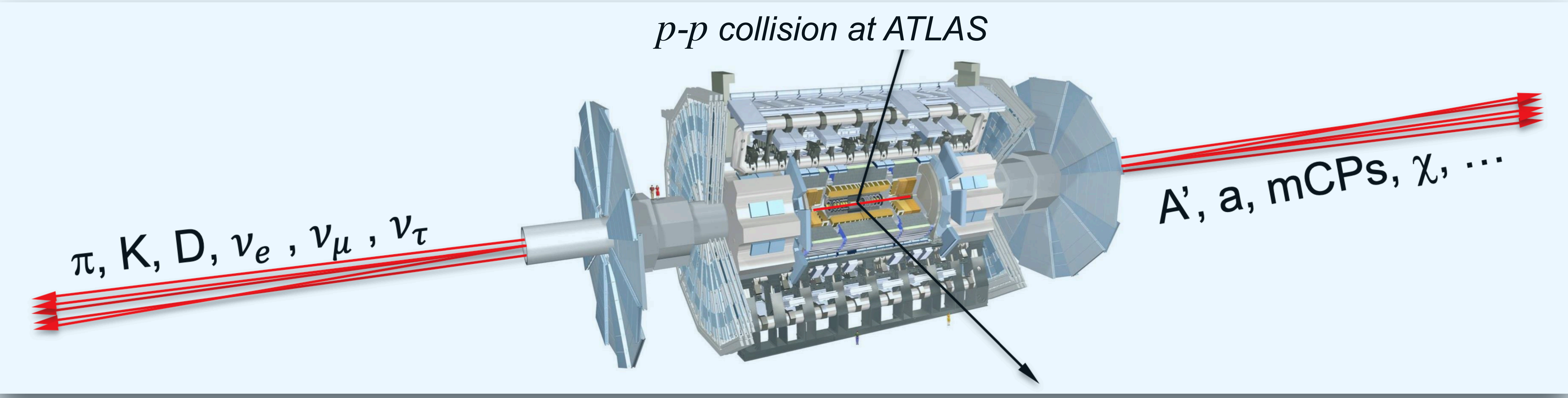
Neutrino-Nucleus Interactions in the SM and Beyond, January 17-21, 2022

Forward Physics at the LHC

- The p-p collisions occurring at the LHC interaction points produce a large number of hadrons along the beam direction. The majority of these particles disappear down the beam pipe and are undetected.

- The decays of these particles (in particular pions, kaons, hyperons, and charmed hadrons) lead to an intense and strongly collimated beam of highly energetic neutrinos of all three flavors in the far-forward region along the beam collision axis.

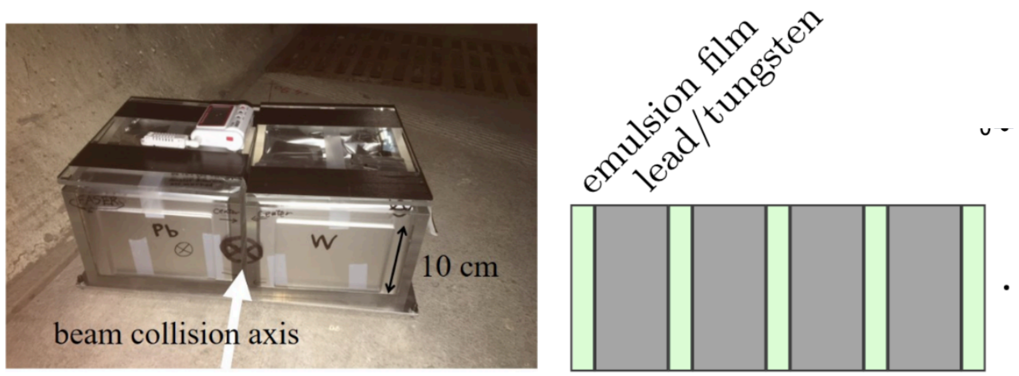
- Far-forward region remain largely unexplored at the LHC.

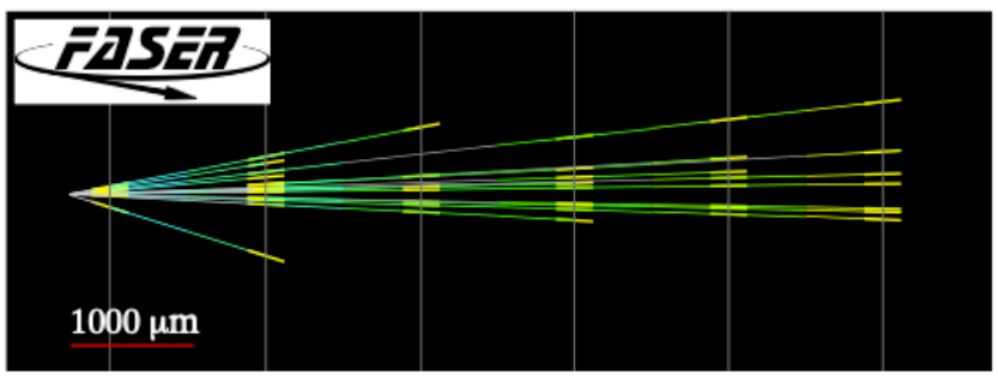


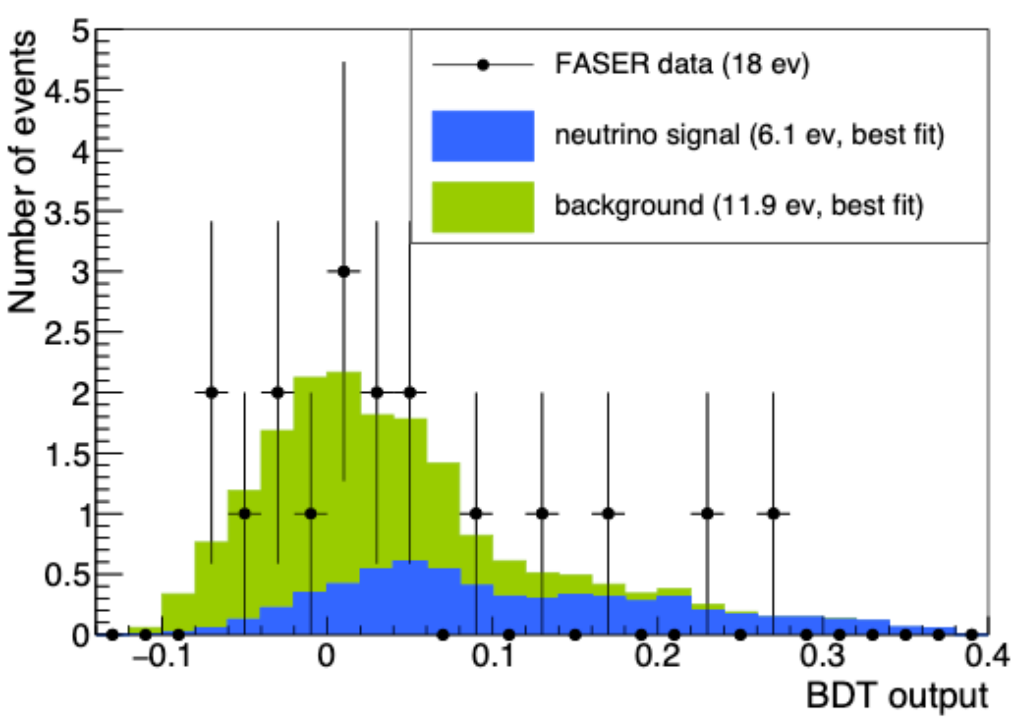
First Neutrino Interaction Candidates at the LHC

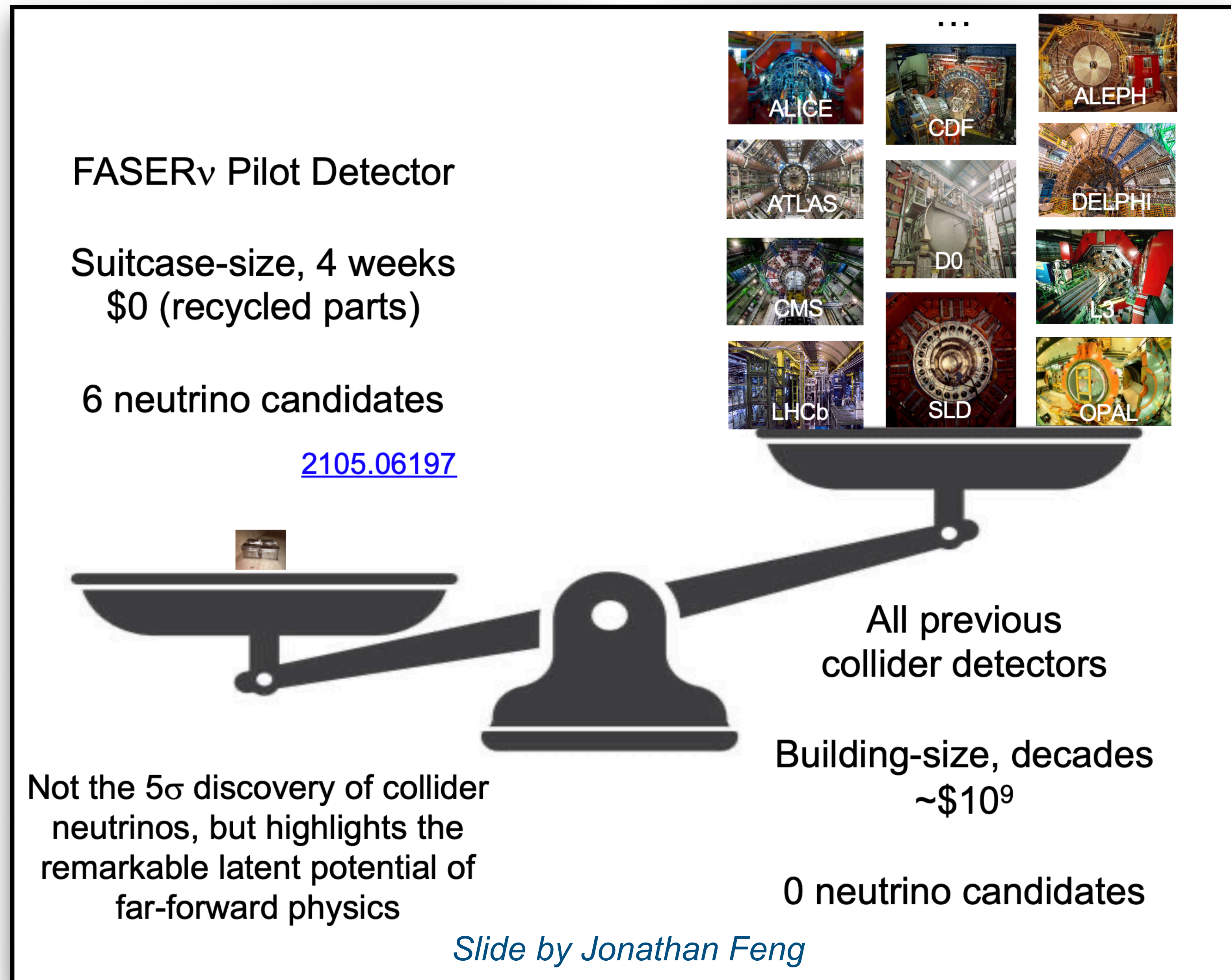
- In 2018, the FASERν collaboration placed a ~30 kg pilot emulsion detector in TI18 for a few weeks. They observed first ever neutrino interaction candidate events at the LHC. Marking the beginning of a new era of neutrino measurements at the LHC forward region.

FASER collaboration: [arXiv:2105.06197 [hep-ex]]



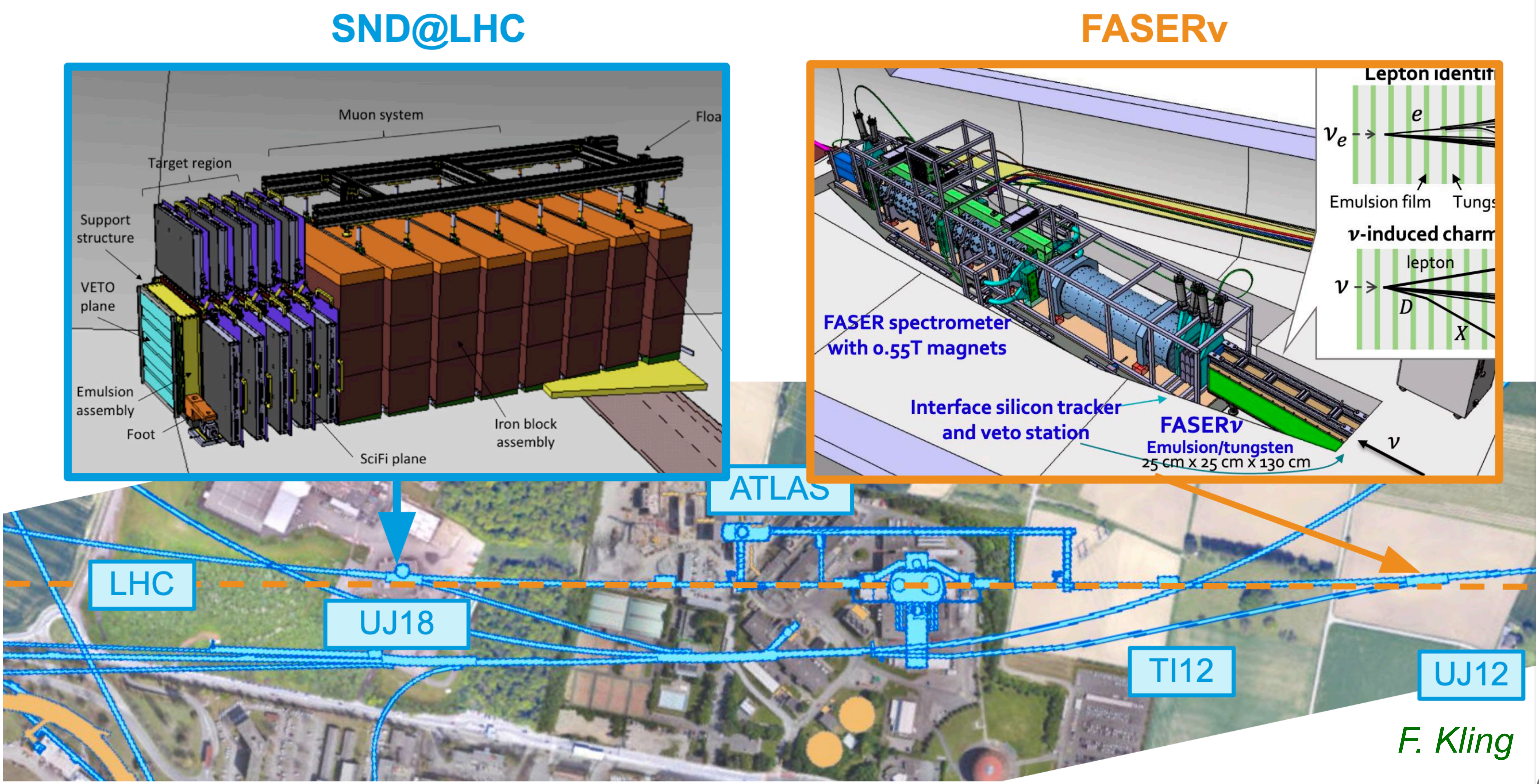






Experiments during LHC Run 3

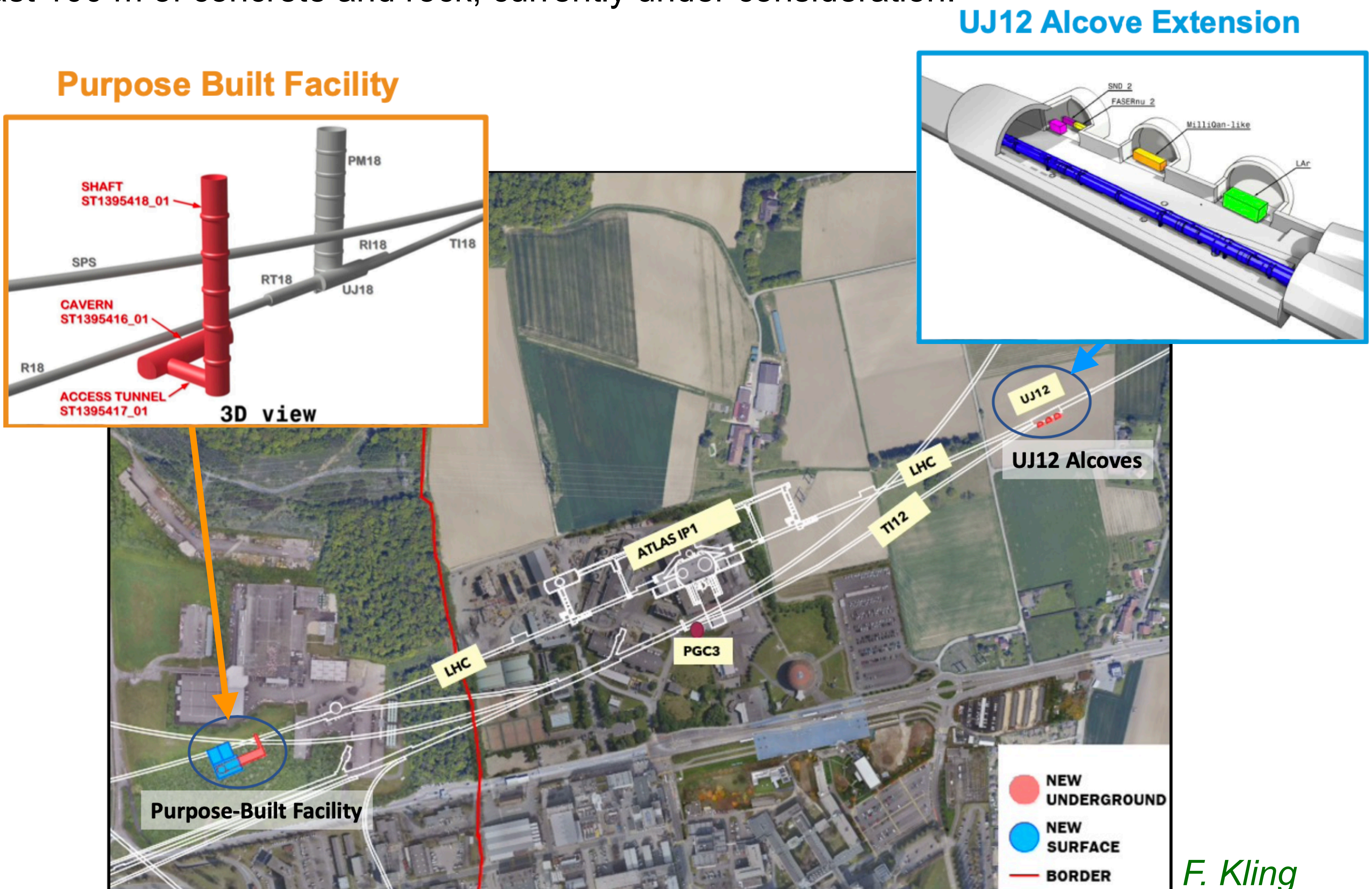
- During the upcoming LHC Run 3, from 2022-24, two detectors will begin operating in the far-forward region of the ATLAS interaction point.
- These detectors are located ~ 500 m from the ATLAS interaction point on the beam collision axis and shielded from by ~100 m of concrete and rock.
- They will detect ~10,000 neutrinos, and will sensitively probe new regions of parameter space in many BSM models that predict new light, weakly-interacting particles.



F. Kling

Forward Physics Facility Proposal

- The FPF is a proposal to extend this program into the High Luminosity LHC (HL-LHC) era, expected from 2027-37. The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.
- Two preferred FPF sites, located along the beam collision axis and shielded from the interaction point by at least 100 m of concrete and rock, currently under consideration.



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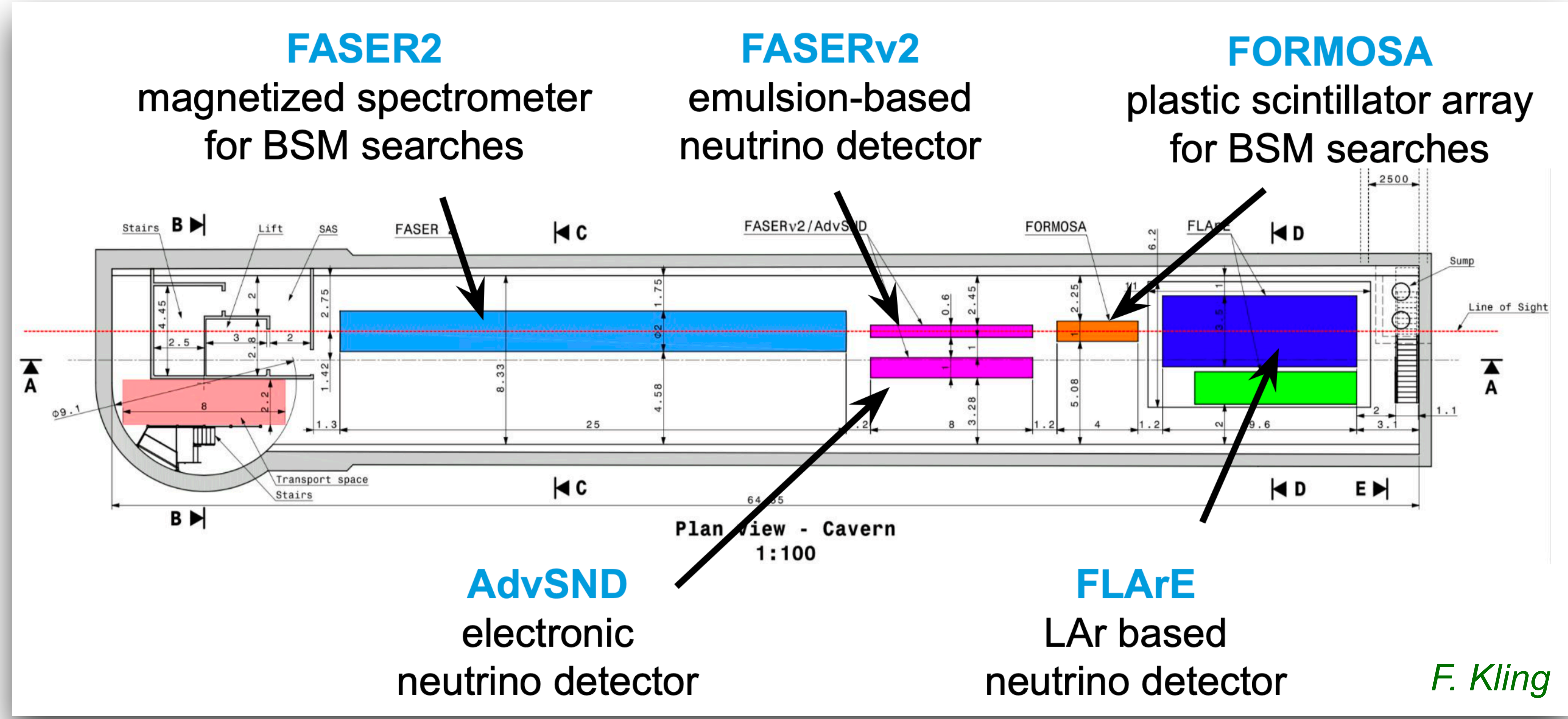
A general layout plan of the purpose-built facility option



FPF Progress and Plans

- Dedicated FPF workshops:

  - FPF Kickoff Meeting, November 2020:
    https://indico.cern.ch/event/955956/
  - FPF2 Meeting, May 2021:
    https://indico.cern.ch/event/1022352/
  - FPF3 Meeting, October 2021:
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  - Upcoming FPF4 workshop
  Jan 31 - Feb 1 2022
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- We have completed a first short paper: **arXiv:2109.10905 [hep-ph]**:
  "The Forward Physics Facility: Sites, Experiments, and Physics Potential"
  A significant effort by ~80 authors distilling key progress on the FPF so far.

- We are now preparing a Snowmass FPF White Paper, a ~200 page document to be submitted to Snowmass in February-March 2022.

- Get in touch:
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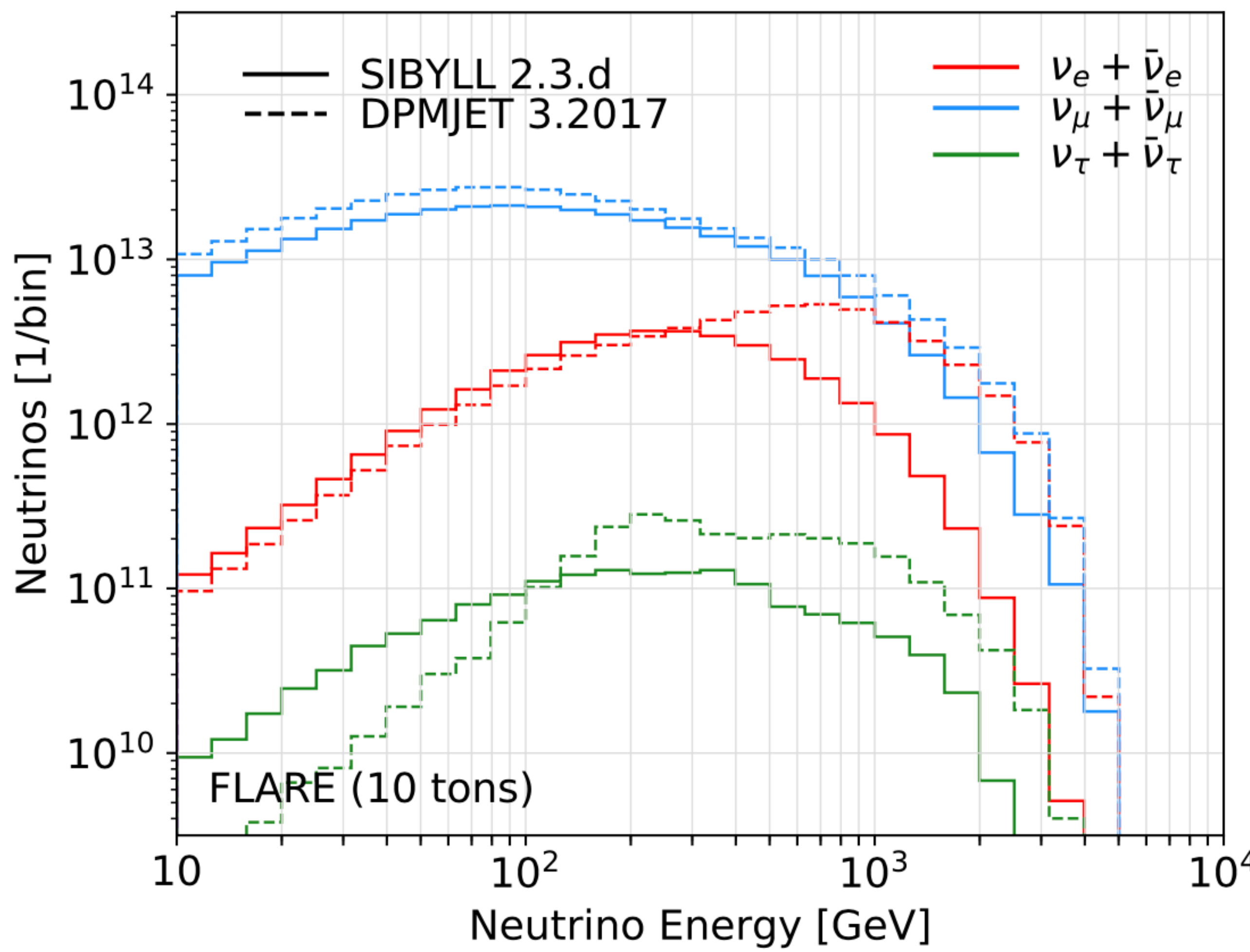
Neutrino Fluxes

- The neutrinos at the FPF originate from weak decay of forward-going hadrons, in particular pions, kaons, hyperons, and charmed hadrons.
- Energy spectrum of neutrinos passing through a 1 m x 1 m cross-sectional area, correspond to the FLArE detector, evaluated using two different event generators.
- There are sizable uncertainties associated with the predictions of the neutrino fluxes.
- Neutrinos energy distributions peaks between 100 GeV - few TeV energies.



Neutrino Interaction Cross Section

- Large statistics of neutrino events, of all neutrino flavors, off different nuclear targets (e.g. tungsten, argon) expected during HL-LHC era.

- The numbers of CC and NC DIS neutrino interactions in the detectors estimated using the fluxes from Sibyll 2.3d and DPMJET 3.2017.

- Large differences between the predictions for the event rate of these two event generators are mainly related to the modeling of the charm component.

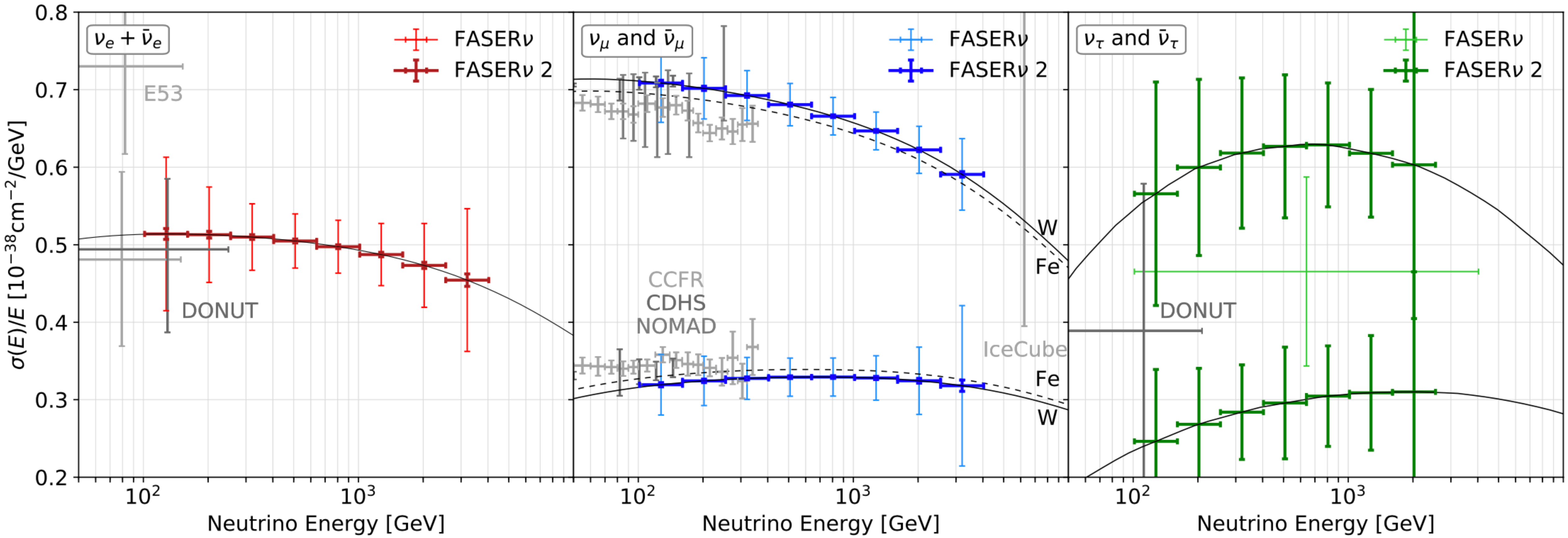
Detector			Interactions at FPF			
Name	Mass	Coverage	CC $\nu_e+\bar{\nu}_e$	CC $\nu_\mu+\bar{\nu}_\mu$	CC $\nu_\tau+\bar{\nu}_\tau$	NC
FASERν2	20 tonnes	$\eta \gtrsim 8.5$	178k / 668k	943k / 1.4M	2.3k / 20k	408k / 857k
FLArE	10 tonnes	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k	89k / 157k
AdvSND1	2 tonnes	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754	17k / 29k
AdvSND2	2 tonnes	$\eta \sim 5$	29 / 14	48 / 29	2.6 / 0.9	32 / 17

TABLE III. The estimated number of neutrino interactions as obtained using two different event generators, `Sibyll 2.3d` and `DPMJET 3.2017`, for FPF experiments located 620 m downstream of the ATLAS IP at the HL-LHC with 14 TeV *pp* collisions and an integrated luminosity of $\mathcal{L} = 3\ \text{ab}^{-1}$.

Neutrino Interaction Cross Section

- **DIS cross section:**
  - The majority of neutrino interaction events can be described by DIS. DIS neutrino interaction cross sections have been measured by beam dump experiments at low energies $E_\nu < 350$ GeV and by IceCube at high energies, $E_\nu > 6.3$ TeV, for muon neutrinos.
  - Large statistics at completely unexplored energy region.

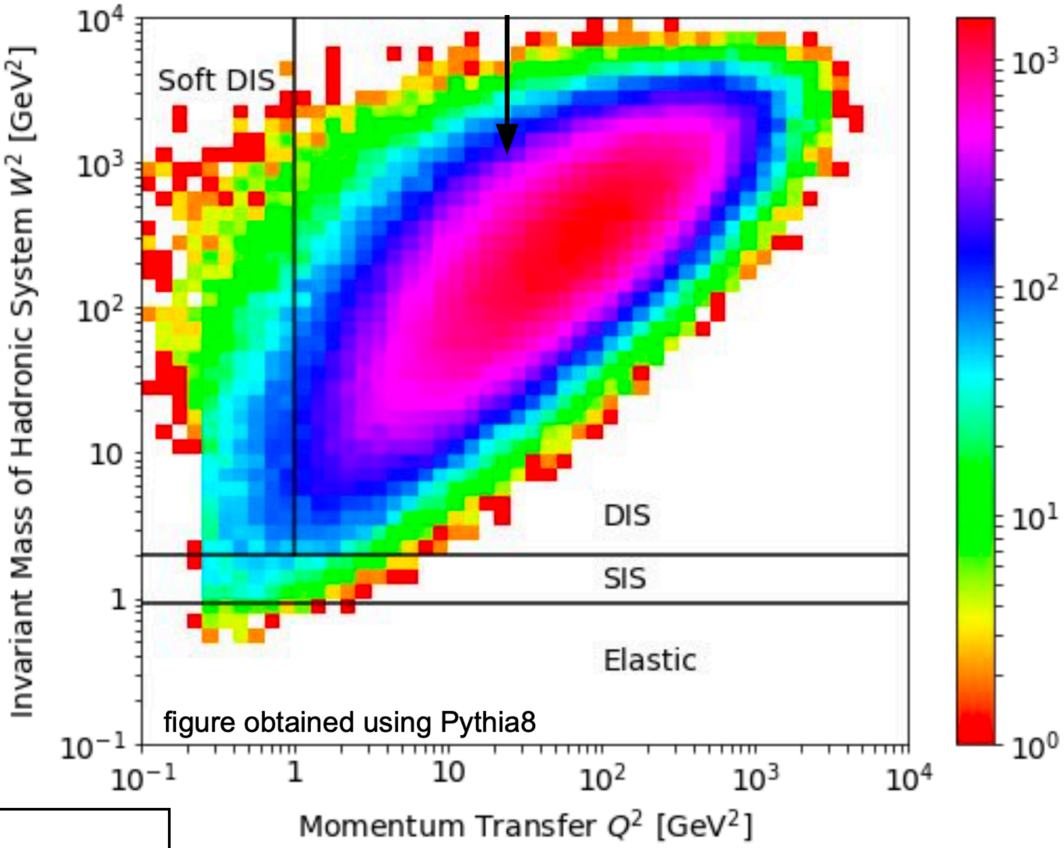
- FASERν at the Run-3 LHC
- FASERν2 at the HL-LHC
- Statistical uncertainty only



  - QCD physics: nuclear parton distributions, higher-order QCD corrections, …

- The first cross section measurements will be performed by the FASERν and SND@LHC detectors during Run 3 of the LHC. These cross section measurements will be further improved by the FPF neutrino detectors FLArE, FASERν2, and AdvSND in the HL-LHC phase with significantly larger event statistics for all three neutrino flavors.

Neutrino Interaction Cross Section



SIS/DIS cross section:

- Expected events for CC scattering in FLArE-10 during HL-LHC exposure.
- Phase space covers 1000s of expected events in the SIS/DIS transition region.

QE/RES cross section:

- Significant expected events in the QE & RES region.

>10^3 expected quasi-elastic and resonant events (estimated with GENIE)

at FLArE	CCQE				CCRES				NCEL	NCRES
	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	all	all
Event Rate	58	590	47	366	167	1673	184	1219	175	1206

S.Trojanowski

Test of lepton universality:

- Intense beam of neutrinos of all three flavors allows unique opportunity to test lepton universality in neutrino scattering.

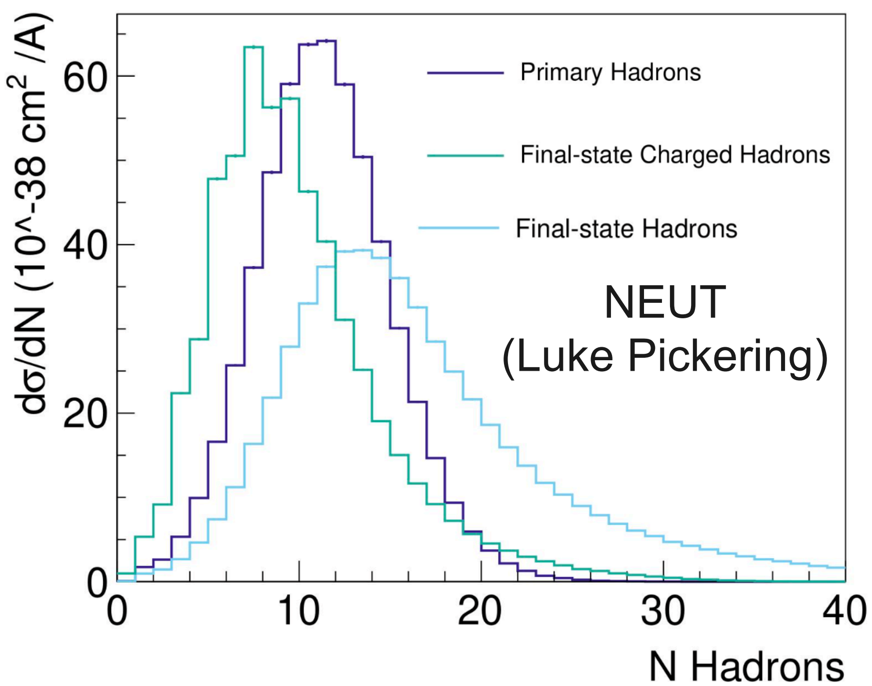
■ The first cross section measurements will be performed by the FASERν and SND@LHC detectors during Run 3 of the LHC. These cross section measurements will be further improved by the FPF neutrino detectors FLArE, FASERν2, and AdvSND in the HL-LHC phase with significantly larger event statistics for all three neutrino flavors.

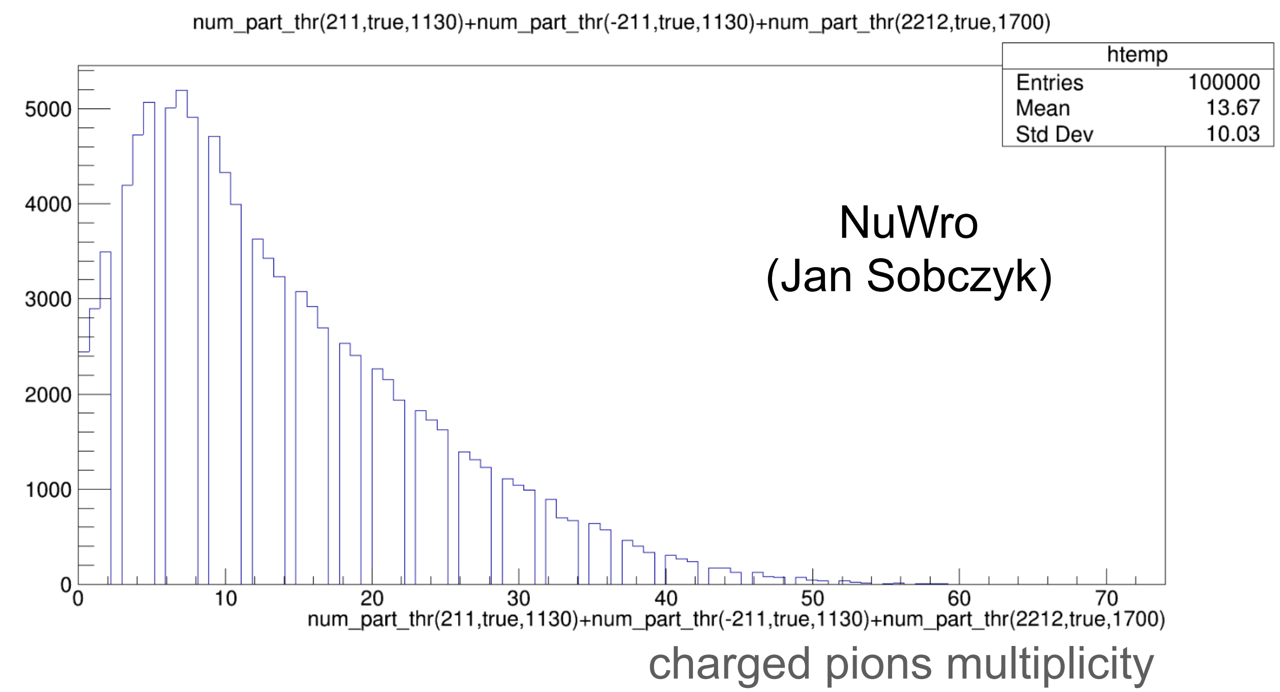
Neutrino Interaction Cross Section: Generators

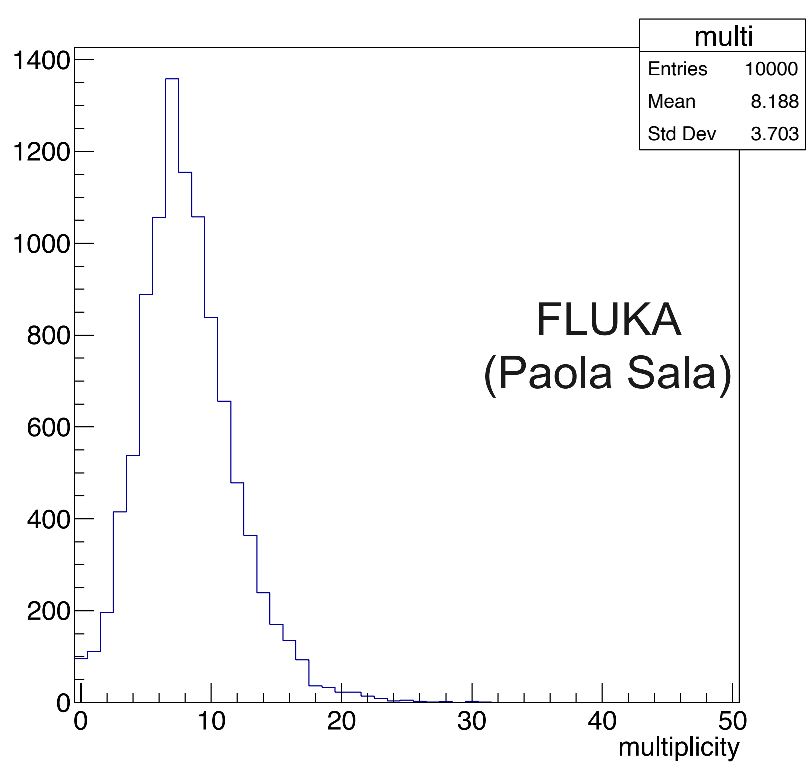
■ Hadron Multiplicity

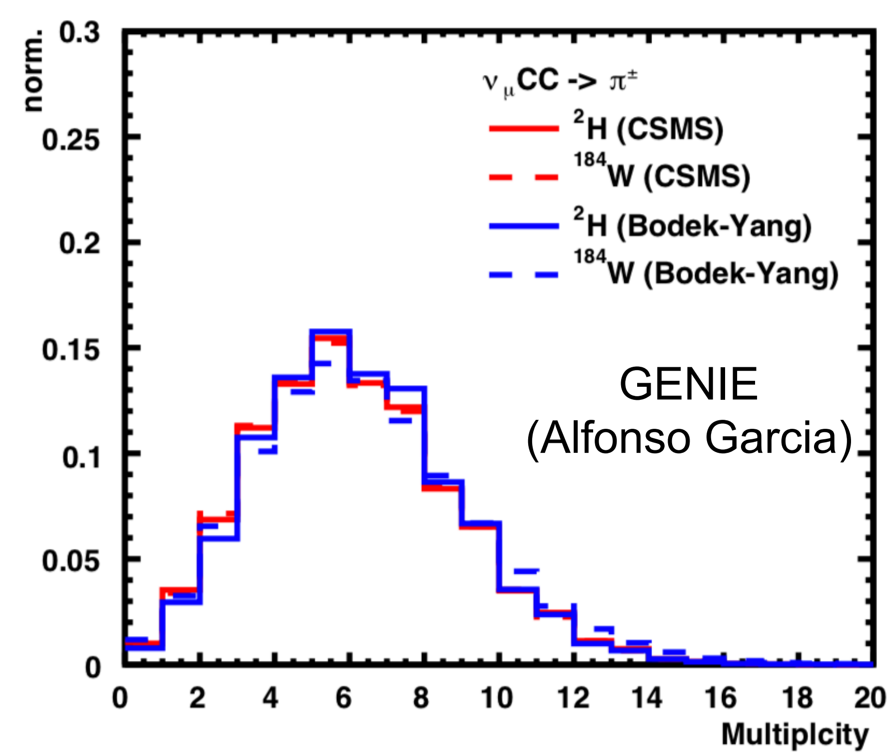
1 TeV ν_μ CC events on W

- Preliminary predictions from different neutrino generators (more detail in the Neutrino Monte-Carlo Generators session at FPF3 Meeting in Oct 2021 https://indico.cern.ch/event/1076733).
A more details comparison is being performed for the FPF white paper.









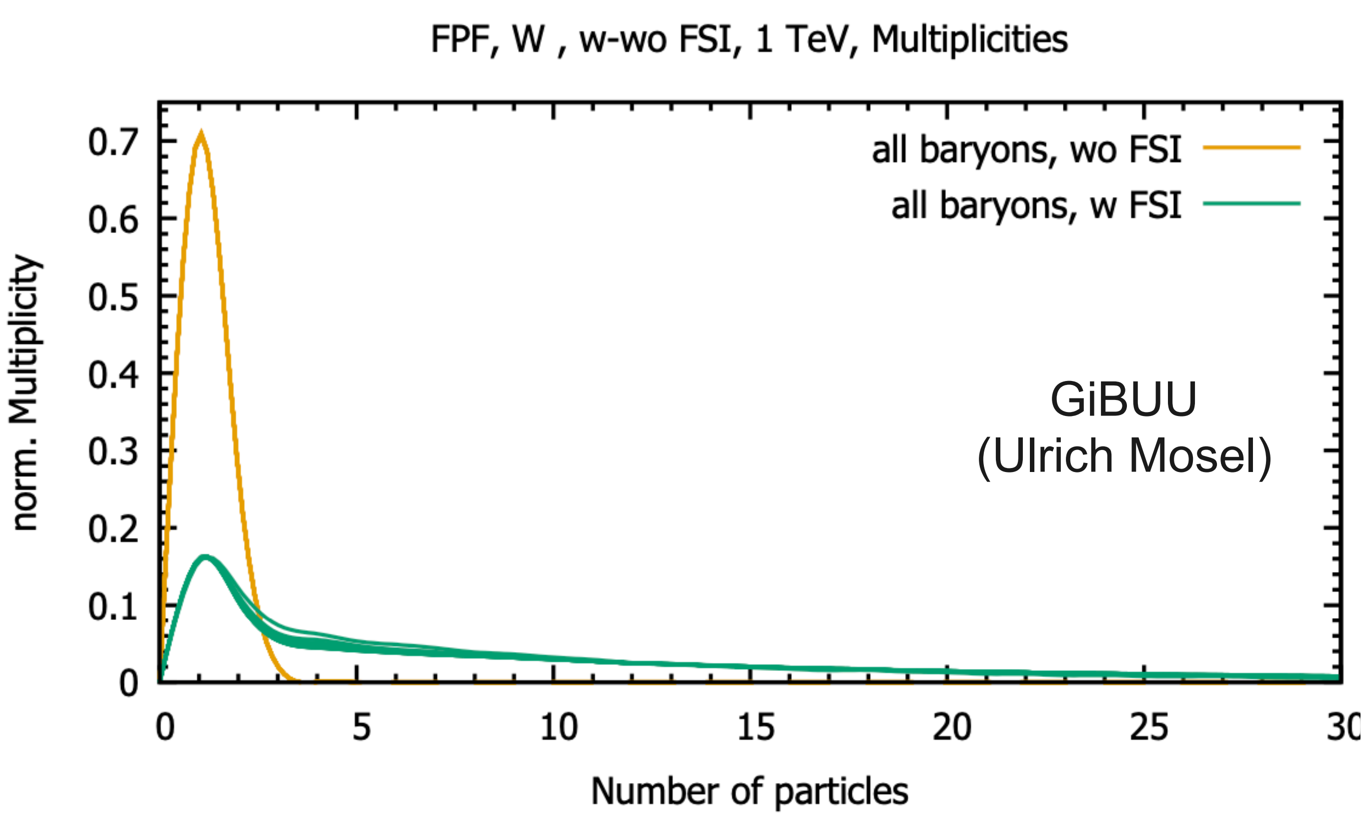
Neutrino Interaction Cross Section: Generators

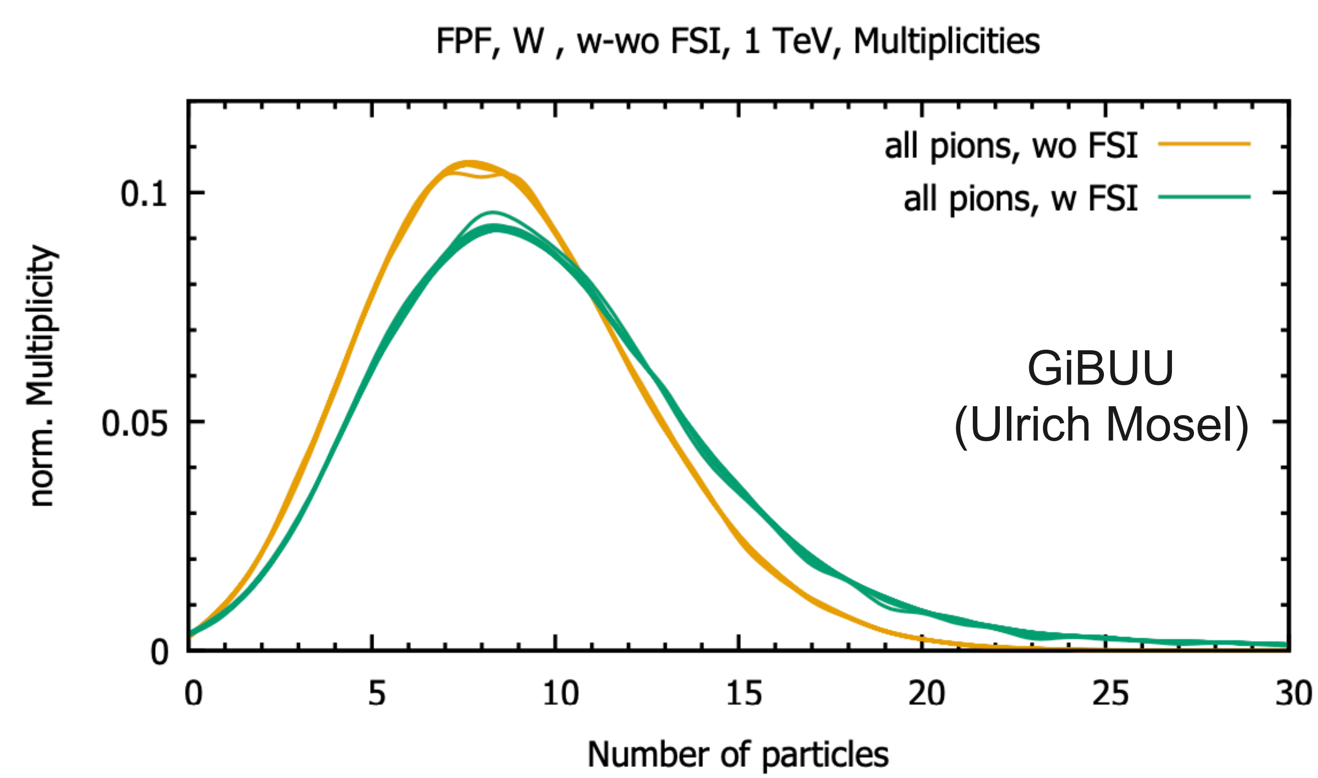
■ Avalanche Effect

- From the GiBUU part of the FPF white paper:

All baryon multiplicity: Without FSI, the distribution peaks at multiplicity = 1 with a tail up to about 3 - 4. With FSI, the multiplicity distribution peak height is decreased by about a factor of 5 and a long tail reaching up to about 25 develops. A consequence of the so-called **'avalanche effect'** in which initial nucleons collide with others on the way out of the target.

Pion multiplicities: Show a much less effect of FSI. The initial pion multiplicity distribution hardly changes.





BSM Neutrino Physics: Examples

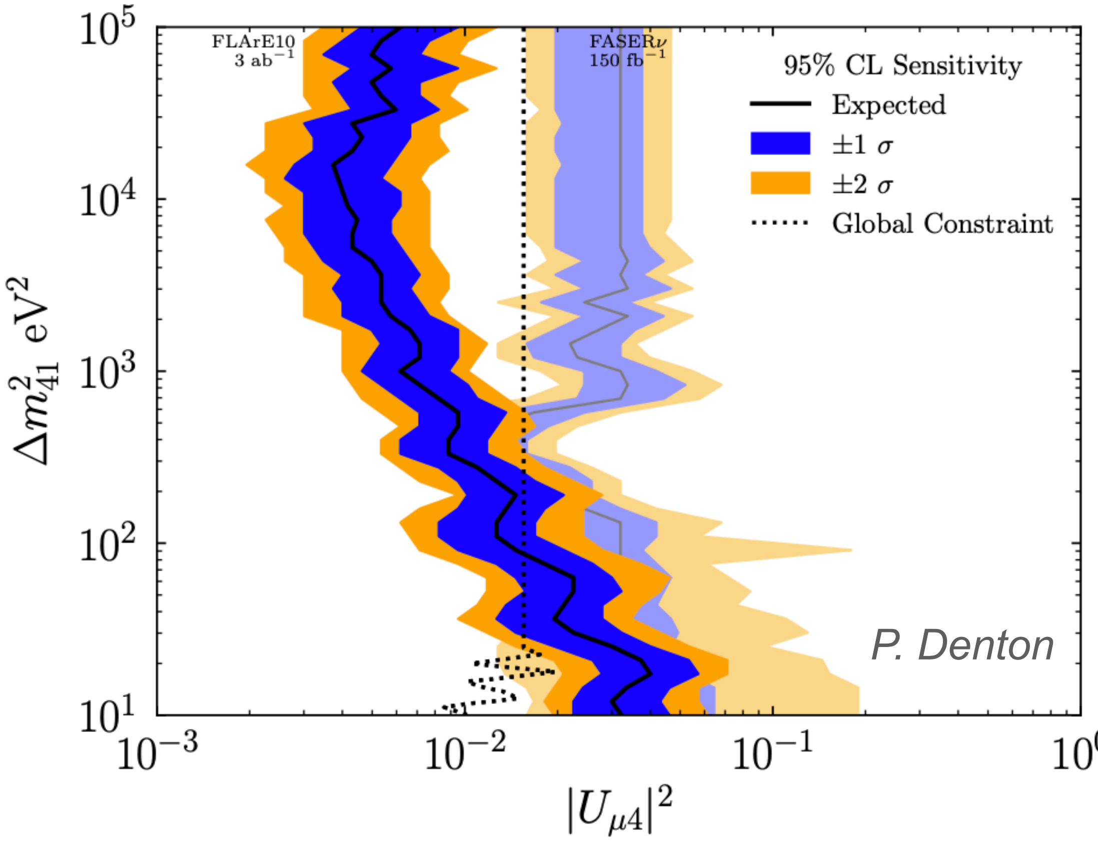
- FPF neutrino measurements will also have the potential to discover or constrain BSM neutrino physics, such as sterile neutrino oscillations, neutrino dipole moments, non-standard interactions, etc.

- Examples from: [arXiv:2109.10905 [hep-ph]]

• **Oscillation to sterile neutrinos:**

- Given that the baseline is L ~ 600 m and the neutrino energies are typically E_ν ~ few 100 GeV, the sterile neutrino masses in the sensitivity range of the FPF will be of the order of tens of eV (Δm^2_{41} ~ 1000 eV^2).

- Constraints on the mixing parameter of a sterile neutrino that can be probed by FASERν at LHC Run 3 and by FLArE-10 at the HL-LHC with at 95% CL.

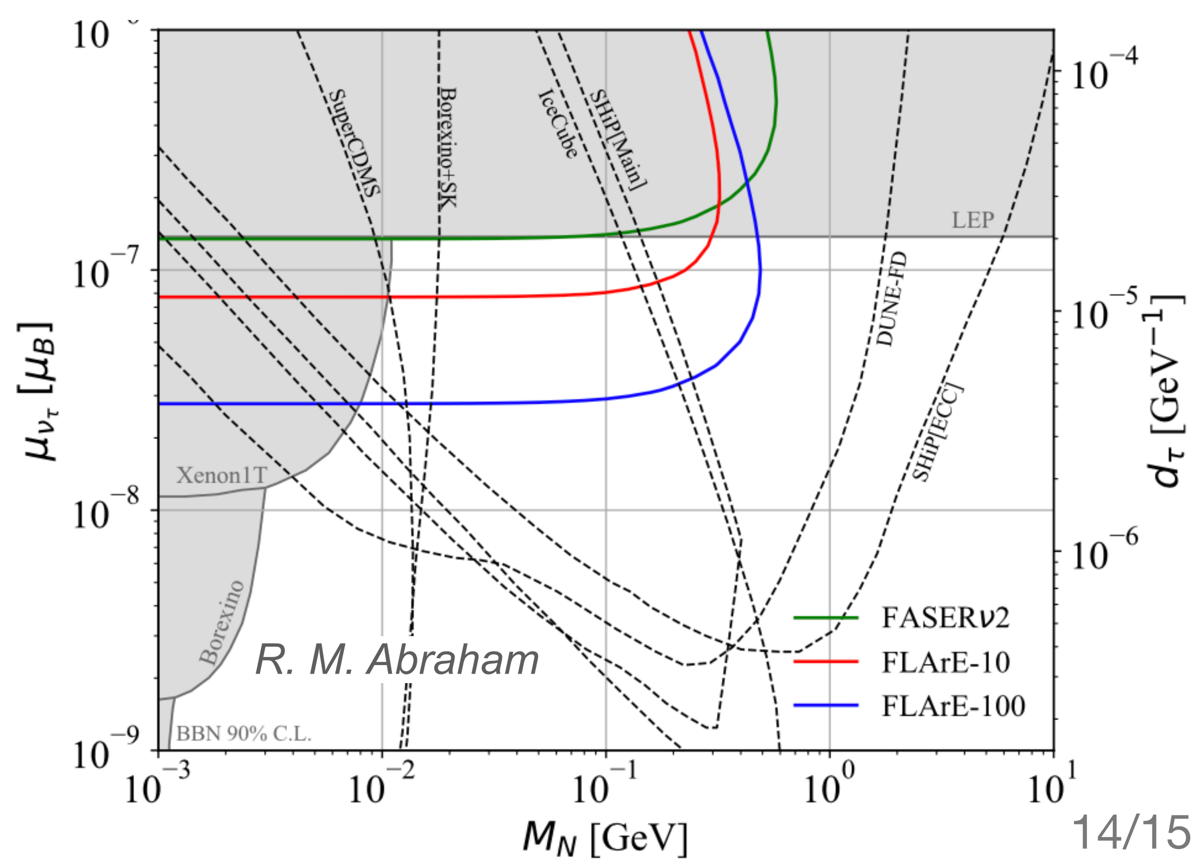


• **Neutrino Magnetic Moments:**

- Constraints on neutrino magnetic moments by looking at nutau-electron scattering.

- The grey shaded regions are current constraints from terrestrial experiments, and the black dashed lines are projected sensitivities.

- Projected exclusion bounds at 90% CL at FASERv2, FLArE-10, and FLArE-100 for the tau neutrino's magnetic moment.



Summary and Outlook

- ✦ The physics potential of the far-forward region at the LHC is being explored now.
- ✦ FASER and SND@LHC will soon start to perform searches for new particles and neutrino measurements in the far-forward region of the LHC during Run 3.
- ✦ We propose a Forward Physics Facility to continue this program with improved detectors during the HL-LHC era.
- ✦ It will open up many new opportunities of BSM physics searches, neutrino physics and QCD, and will significantly extend the LHC's physics program.
- ✦ Ideas and contributions to further strengthen the FPF potential more than welcome!