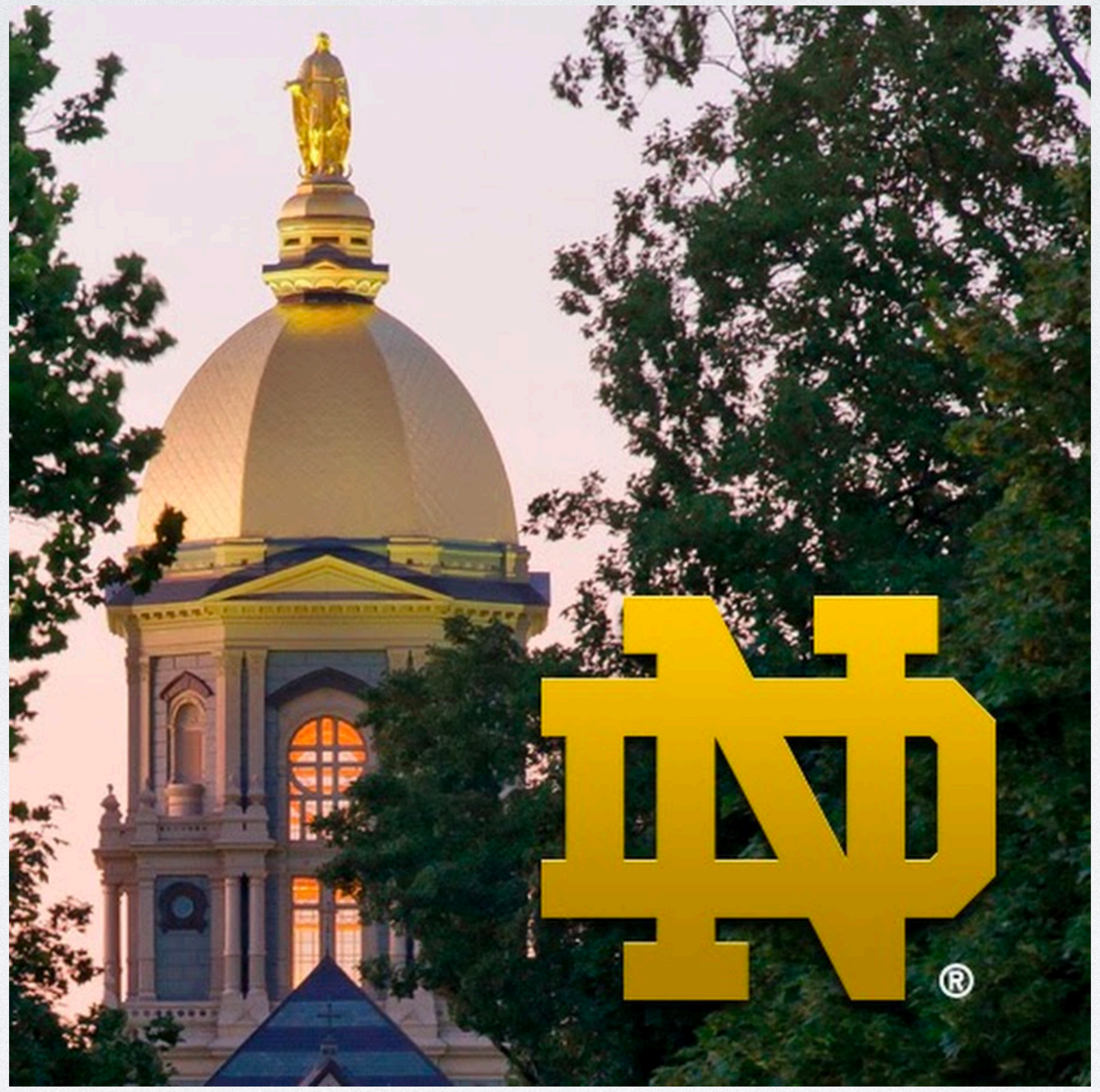
EXPERIMENTAL OVERVIEW: ARTIFICIAL SOURCES

Laura Fields, University of Notre Dame
NuTau 2021 — 28 September 2021

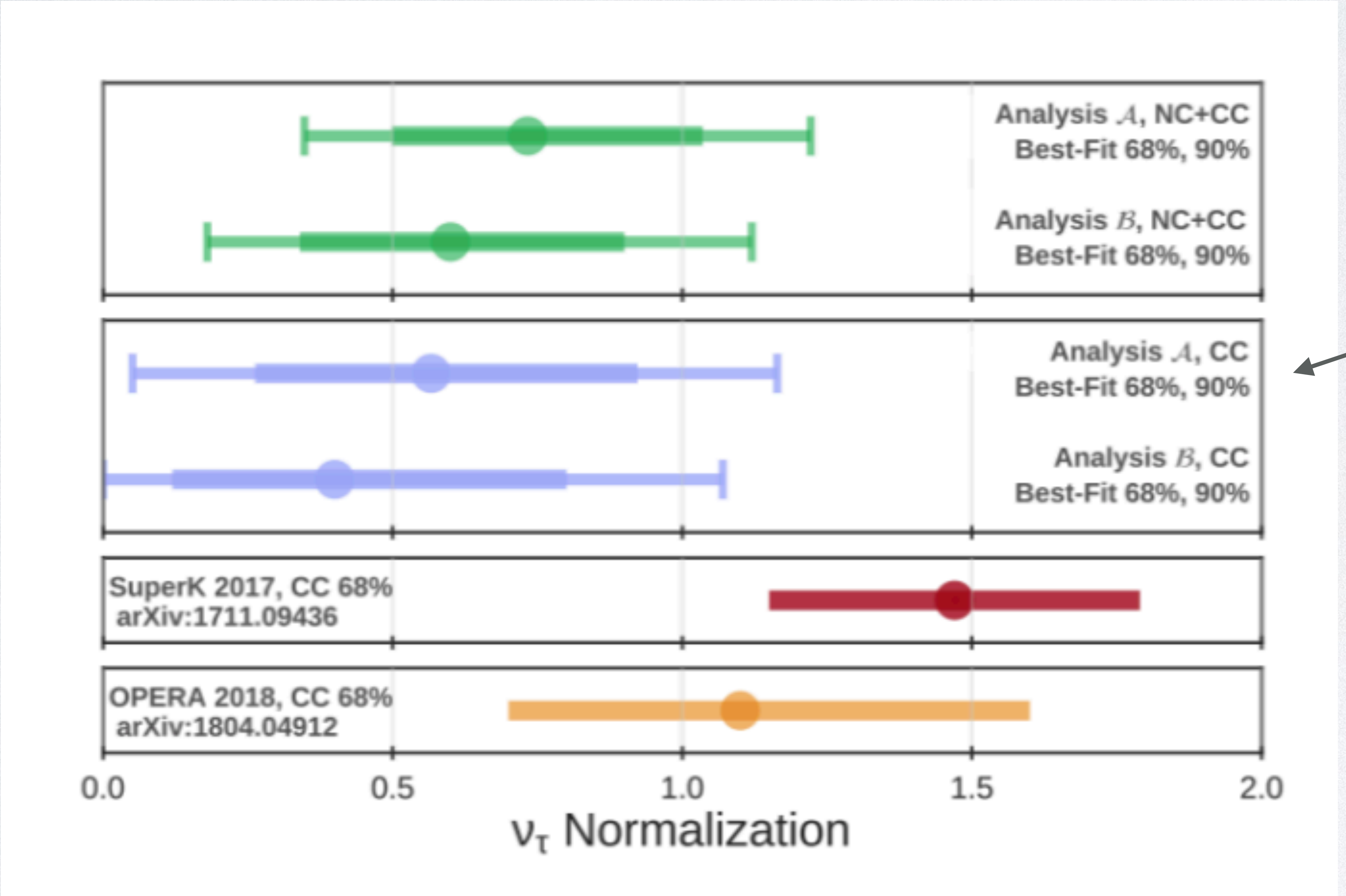
WHO IS TALKING TO ME?



- I am a new associate professor at the University of Notre Dame
- Also a collaborator on MINERvA, EMPHATIC and NA61/SHINE, and DUNE (where I am a leader of the beam group)
- And a convener of the Snowmass Neutrino Frontier Artificial Neutrino Sources group

WHY ARTIFICIAL SOURCES

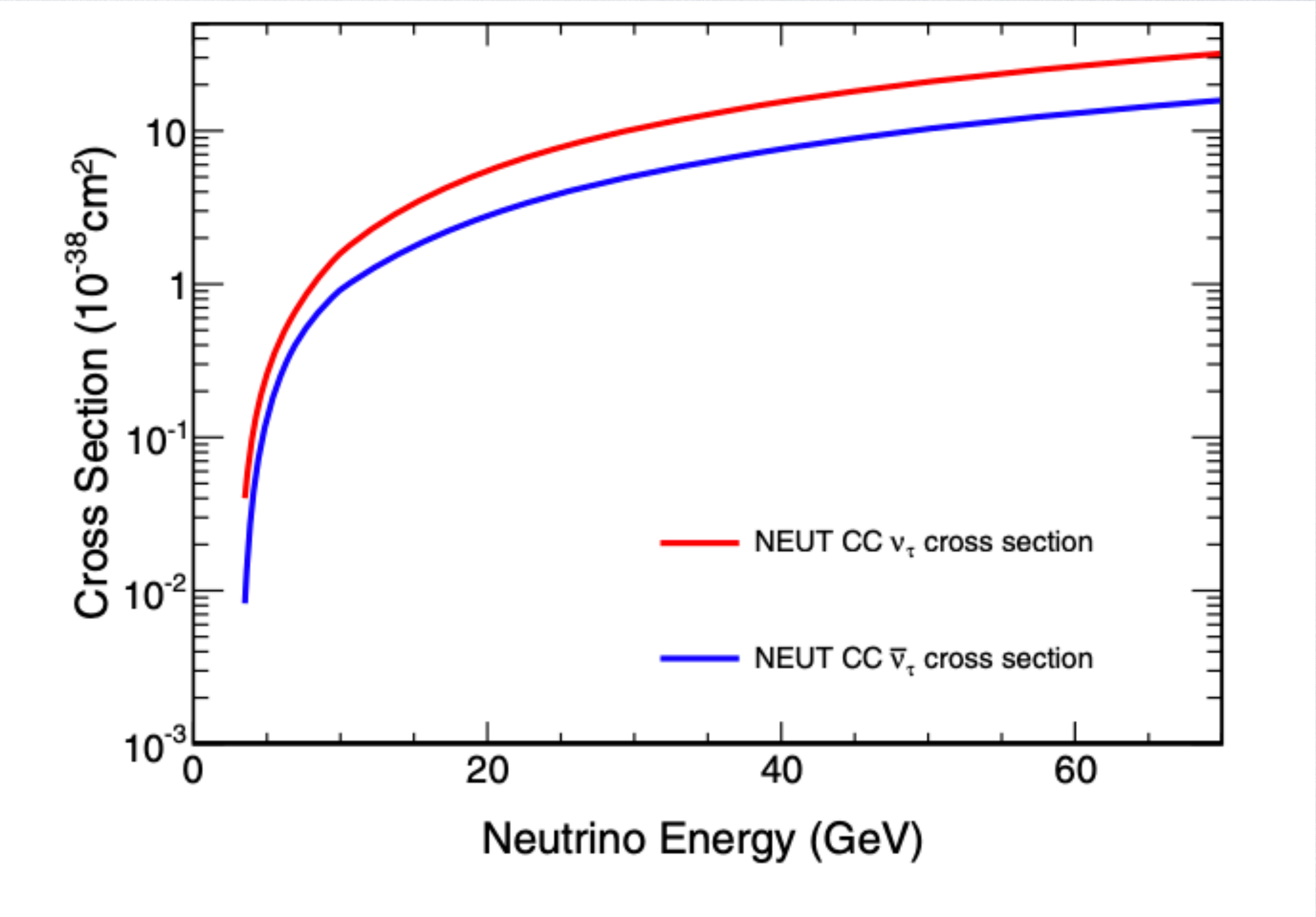
IceCube / Phys. Rev. D99 (2019) 032007



- **Thank you** for holding this workshop and inviting me to speak!
- Past measurements of tau neutrinos are **fairly limited**
- I am excited to see how much we can improve on current measurements, with **both natural and artificial sources**
- What artificial sources bring to the table:
  - Sources that are (in principle) **controllable**
  - Knowledge of the incoming **neutrino angle**
    - A significant advantage in missing energy reconstruction (relevant here since nu tau interactions will always have a neutrino in the final state)

WHAT ARTIFICIAL SOURCES

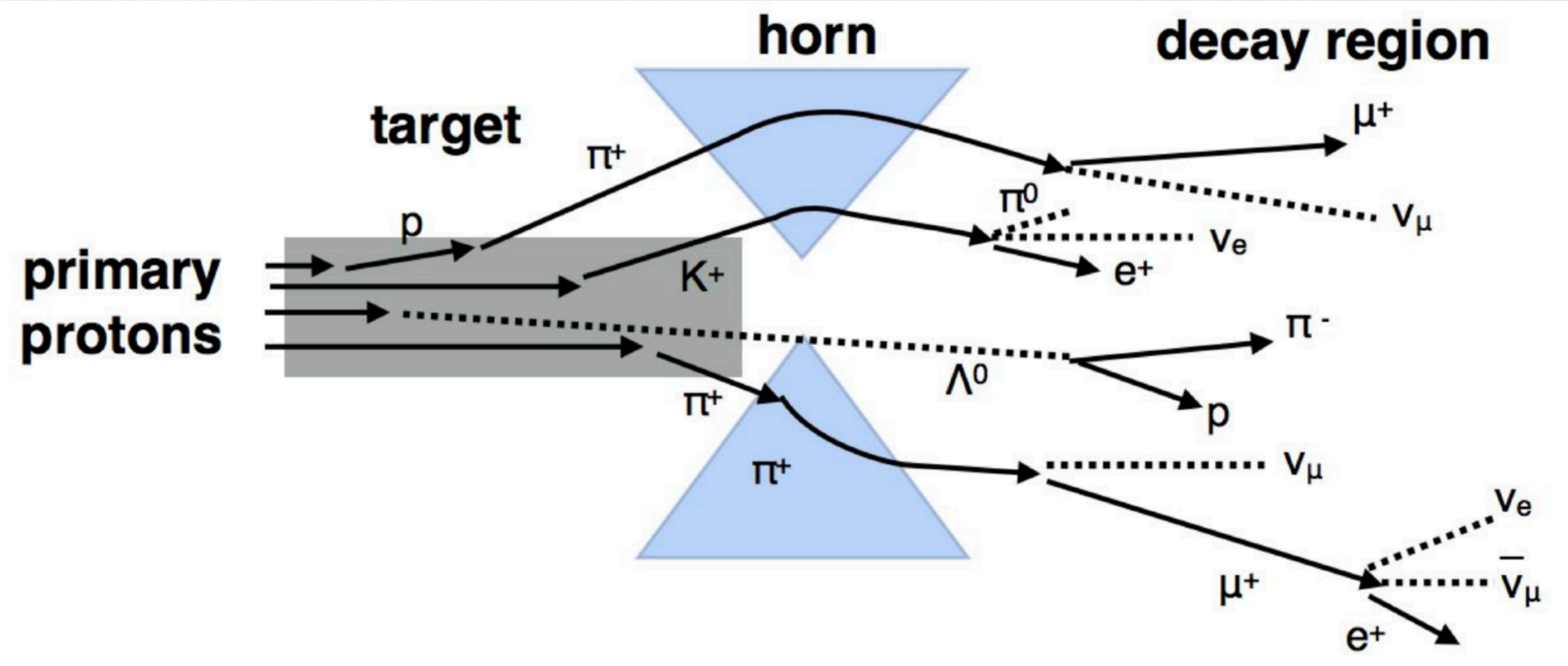
- Generally, when we talk about measuring tau neutrinos, I think we are talking about **charged current interactions**, in which we can measure the flavor of the final state
- Neutral current measurements do have the potential to tell us about new physics that couples to tau neutrinos (see e.g. P. Coloma et. al. J. High Energ. Phys. **2018,** 79 (2018))
- But for this talk, I'm going to **focus on measuring charged current interactions** of tau neutrinos
- The threshold for tau neutrino charged current interactions is **3.5 GeV** (and cross section is very small there)
- This means for artificial neutrino sources, we are talking about **accelerator-based neutrino sources**

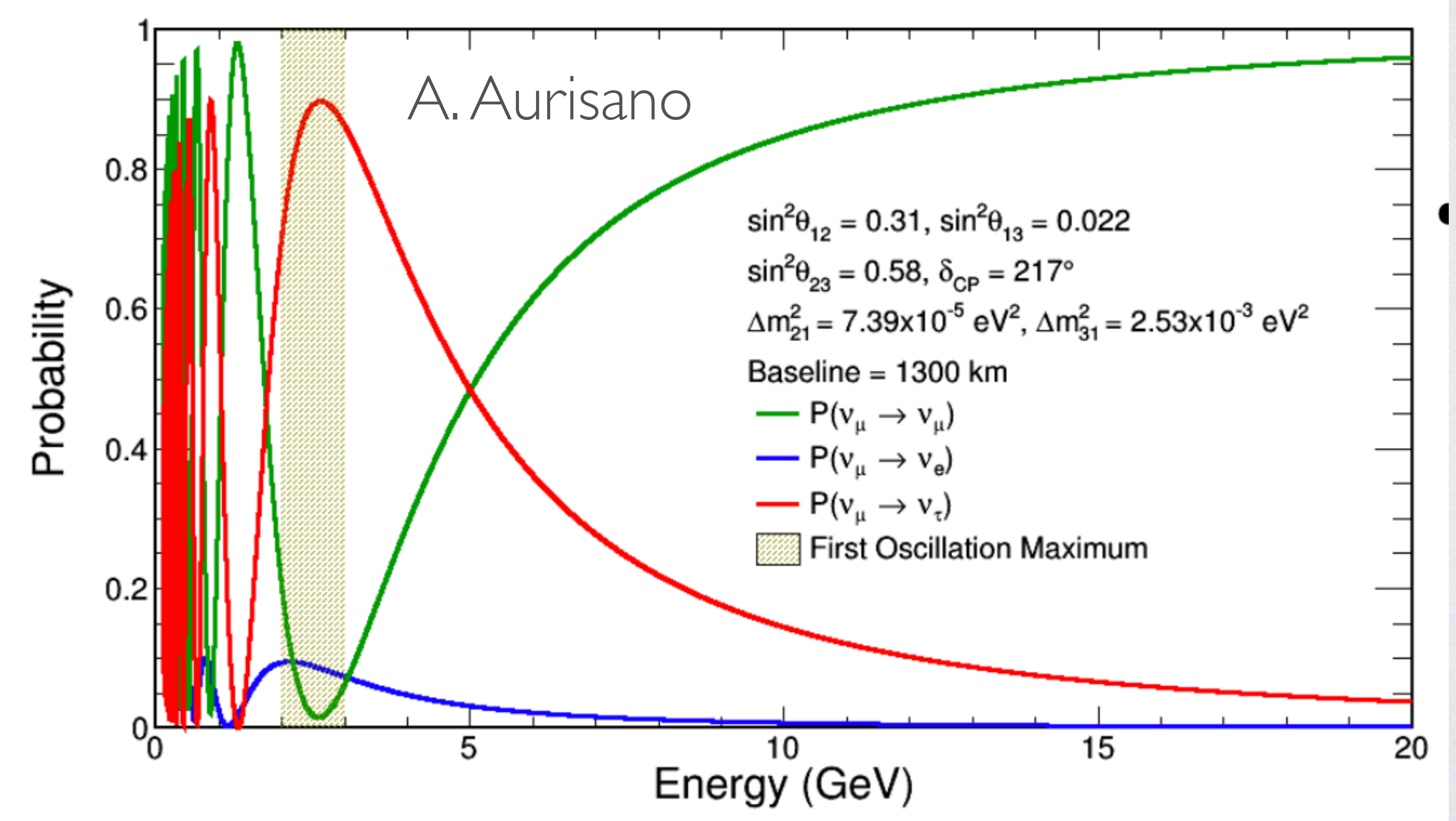


Phys. Rev. D 98, 052006 (2018), arXiv: 1711.09436

WHAT ARTIFICIAL SOURCES

- Three general categories:
  1. **Conventional Neutrino Beams**
     - Past: **Opera**
     - Future: **DUNE** (but probably not Hyperkamiokande)
     - Primary source of ν_τ is **focused pions and kaons decaying to ν_μ, which oscillate** to ν_τ
     - ν_τ are also **present in the beam before oscillation**, but are swamped by ν_μ and ν_e.
     - Excellent opportunity to **measure ν_τ oscillations**, but need ν_τ cross sections as input



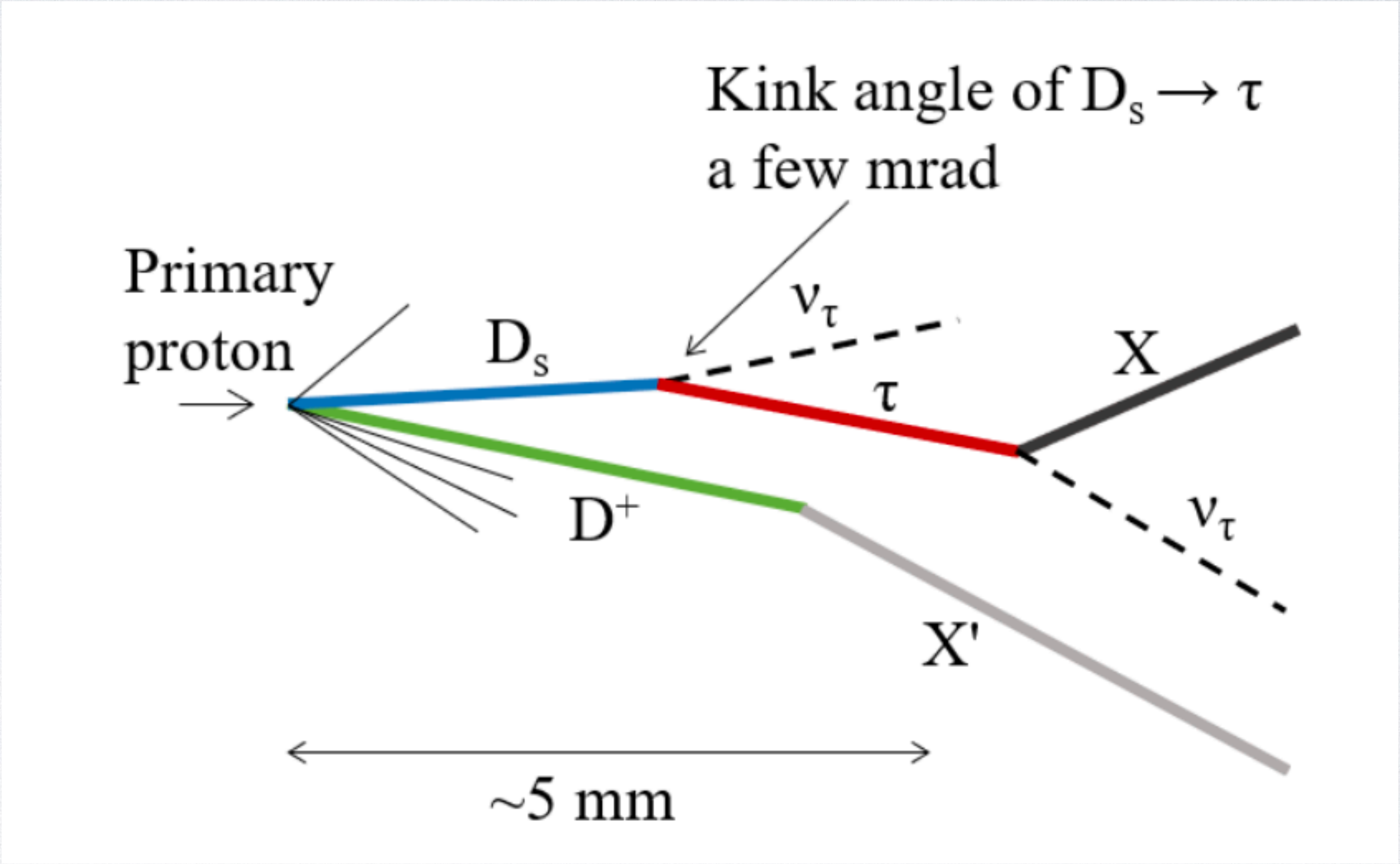


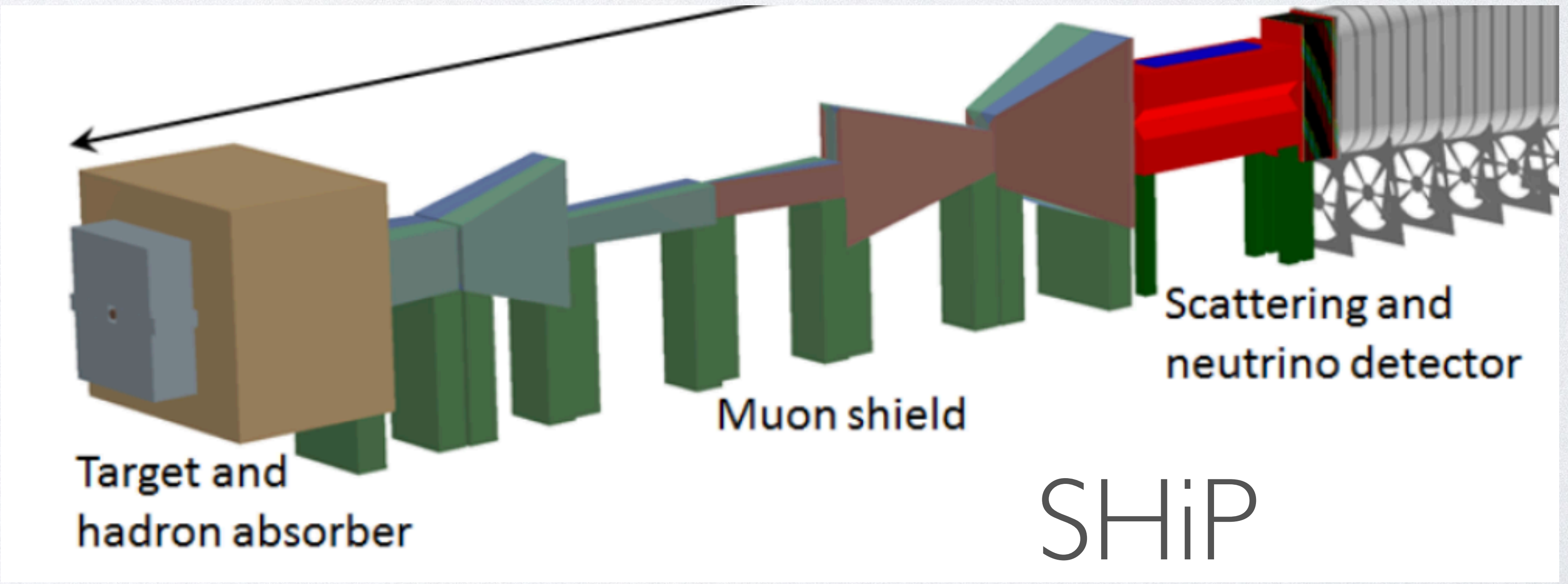
DUNE oscillation probabilities

WHAT ARTIFICIAL SOURCES

- Three general categories:
  2. **Beam dump sources**
     - Past: **DONUT**
     - Future: **SHiP**
     - Source of ν_τ is **primarily decays of Ds** mesons decays (but also a few from D and B) produced in beam dump
     - Lack of focusing/decay volume reduces ν_μ and ν_e
     - An option for **measuring ν_τ cross sections**

J. High Energ. Phys. **2020,** 33 (2020)   *Particles* 3, no. 1: 164-168





Pastore, Alessandra
https://cds.cern.ch/record/2762117

WHAT ARTIFICIAL SOURCES

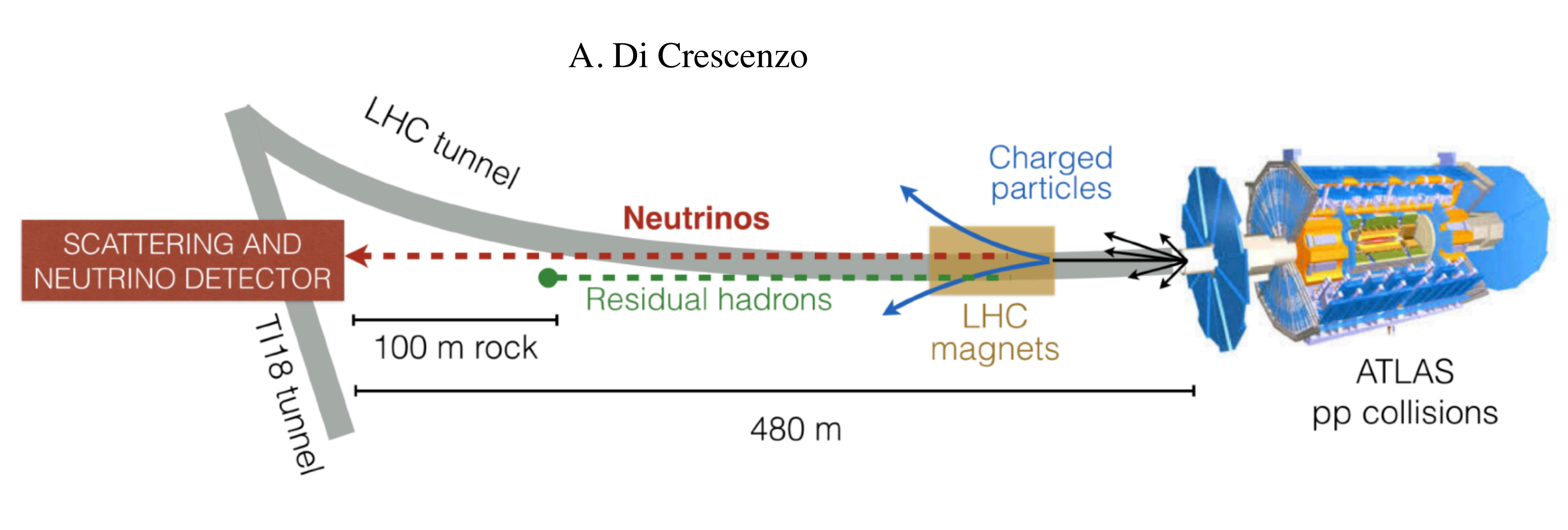
- Three general categories:
  3. New! **Collider sources**
     - Future: **FaserNu, SND@LHC**
     - Farther future: **Forward Physics Facility**
     - At LHC, dominant **source is Ds decays**
     - Very far future: **Muon collider?**

Letter of Interest: Tau-neutrino Production at a multi-TeV Lepton Collider

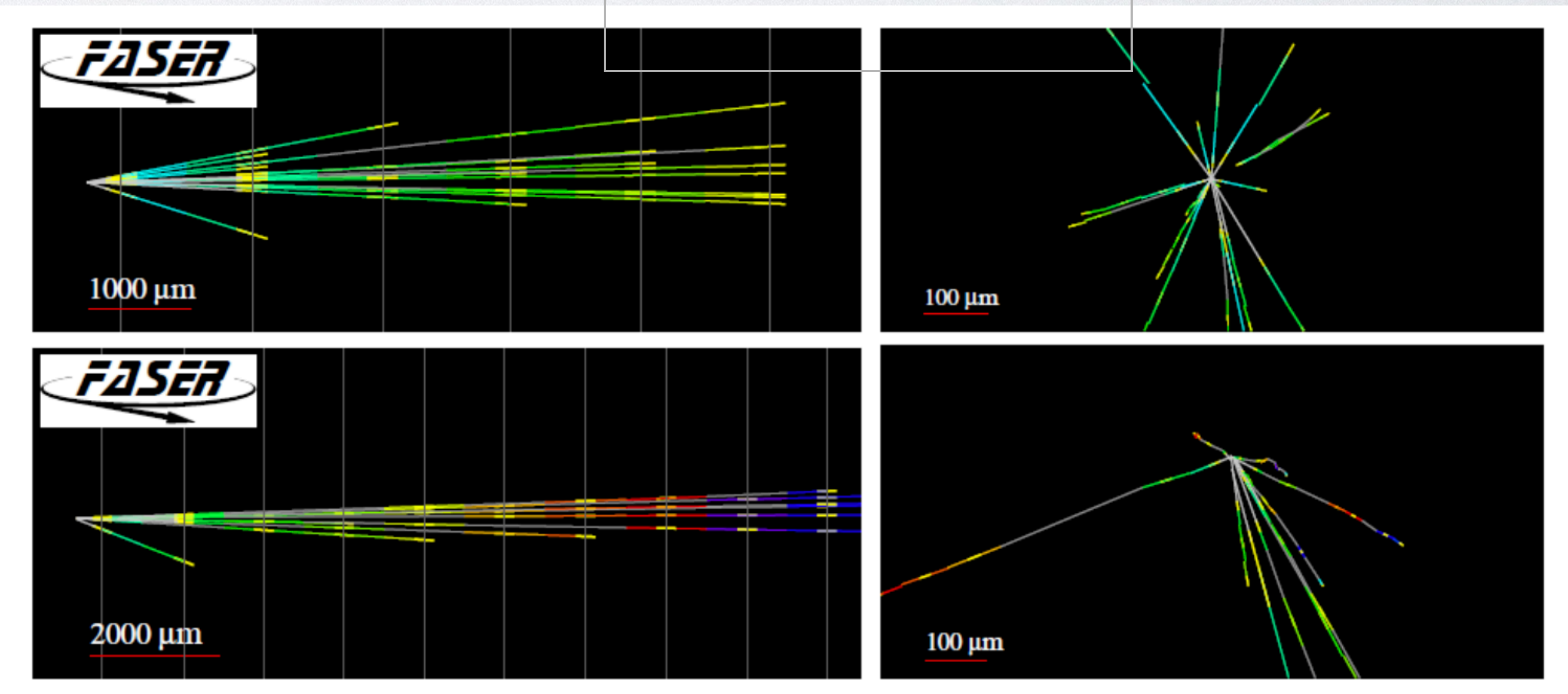
GaetanoMarco Dallavalle, Fabio Maltoni, Silvia Pascoli, Antonio Sidoti

to be submitted to

the Accelerator Frontier (AF04), Energy Frontier (EF03), and Neutrino Frontier (NF06)



arXiv:2105.06197

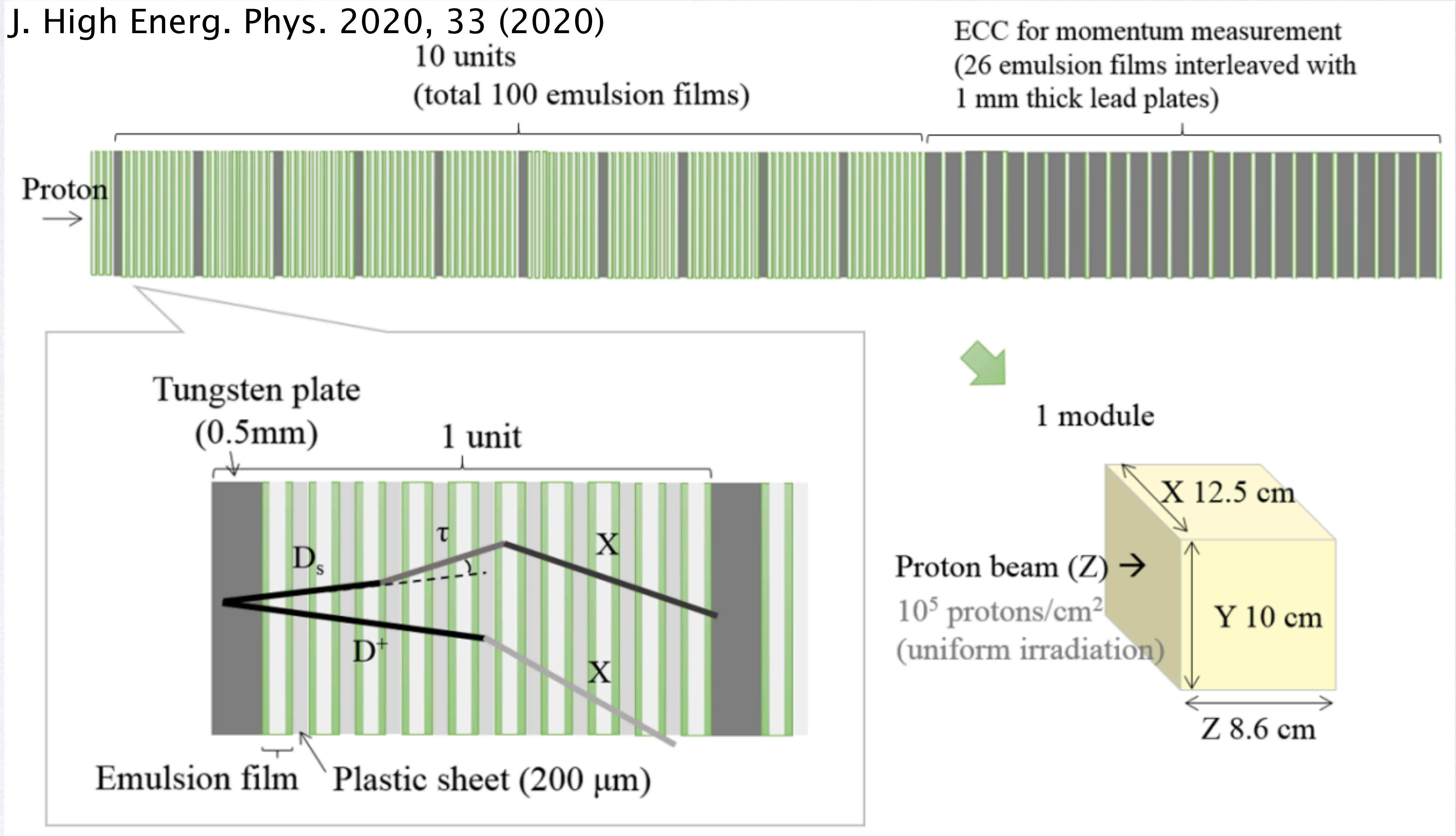


First neutrinos observed @ LHC

TAU FLUX UNCERTAINTIES

- Where we are with **quantifying ν_τ fluxes**:
  1. **Conventional Neutrino Beams**
     - ν_τ come from **oscillated ν_μ flux**; ~15% for Opera, but will be much lower for DUNE (thanks to EMPHATIC, NA61 data and near detectors)
  2. **Beam Dump Sources**
     - Ds production will be constrained to ~10% by **DsTau experiment**
  3. **Colliders**
     - Will use charm production data from LHCb, but **current/ultimate flux uncertainties unclear** (to me)

Ds Tau experiment

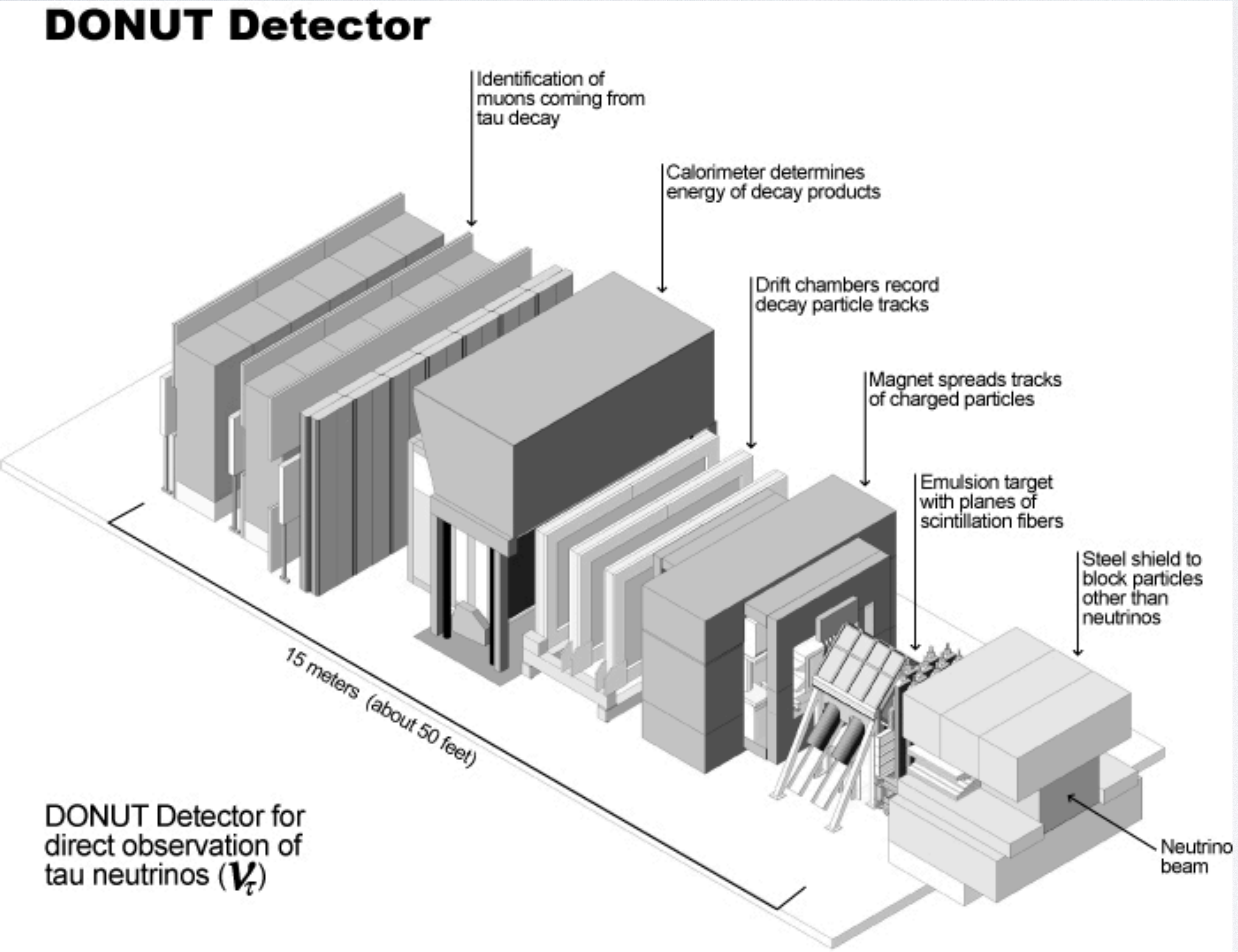


Aims to constrain Ds production to ~10%

See Maria Garzelli's talk on Wednesday for more on fluxes

PAST MEASUREMENTS: DONUT

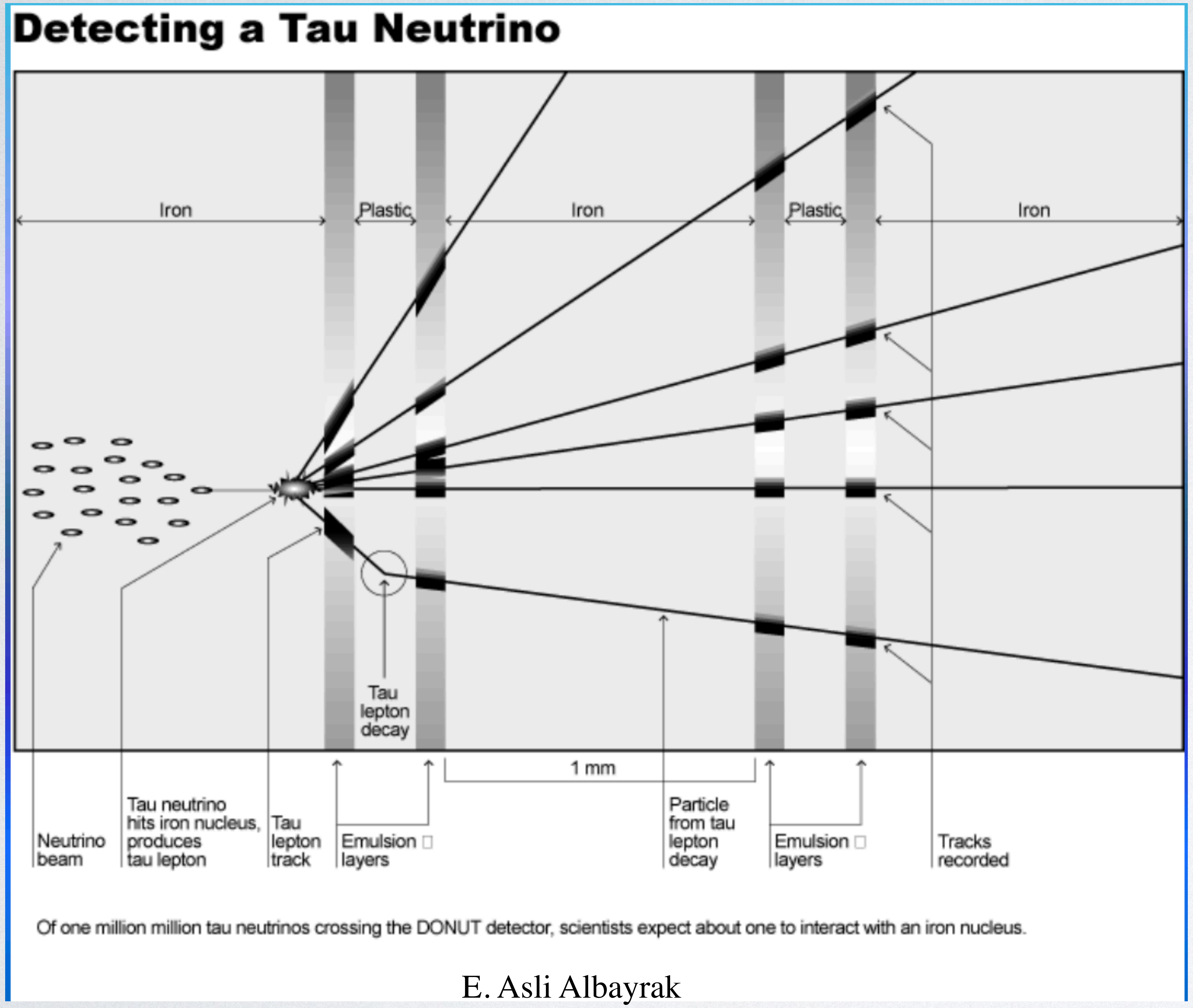
- Humans have seen tau neutrinos from artificial sources twice: first from **DONUT**



- **Beam dump** at Fermilab
- **800 GeV** protons (3.6e17 POT)
- **Emulsion target** + downstream spectrometer

A perfectly preserved snapshot of turn-of-the-century websites!

PAST MEASUREMENTS: DONUT



- Tau events identified by **observing the "kink"** created by the decay of a tau lepton
- Operated during the summer of **1997**
- First results announced summer 2000 (four events with a expected background of 0.4)
- Final paper in 2008
  - Emulsion analysis is not quick!
  - **9 events (~ 1 background)**
  - Bkgds:
    - ν_μ and ν_e charm production
    - Hadron reinteractions from NC

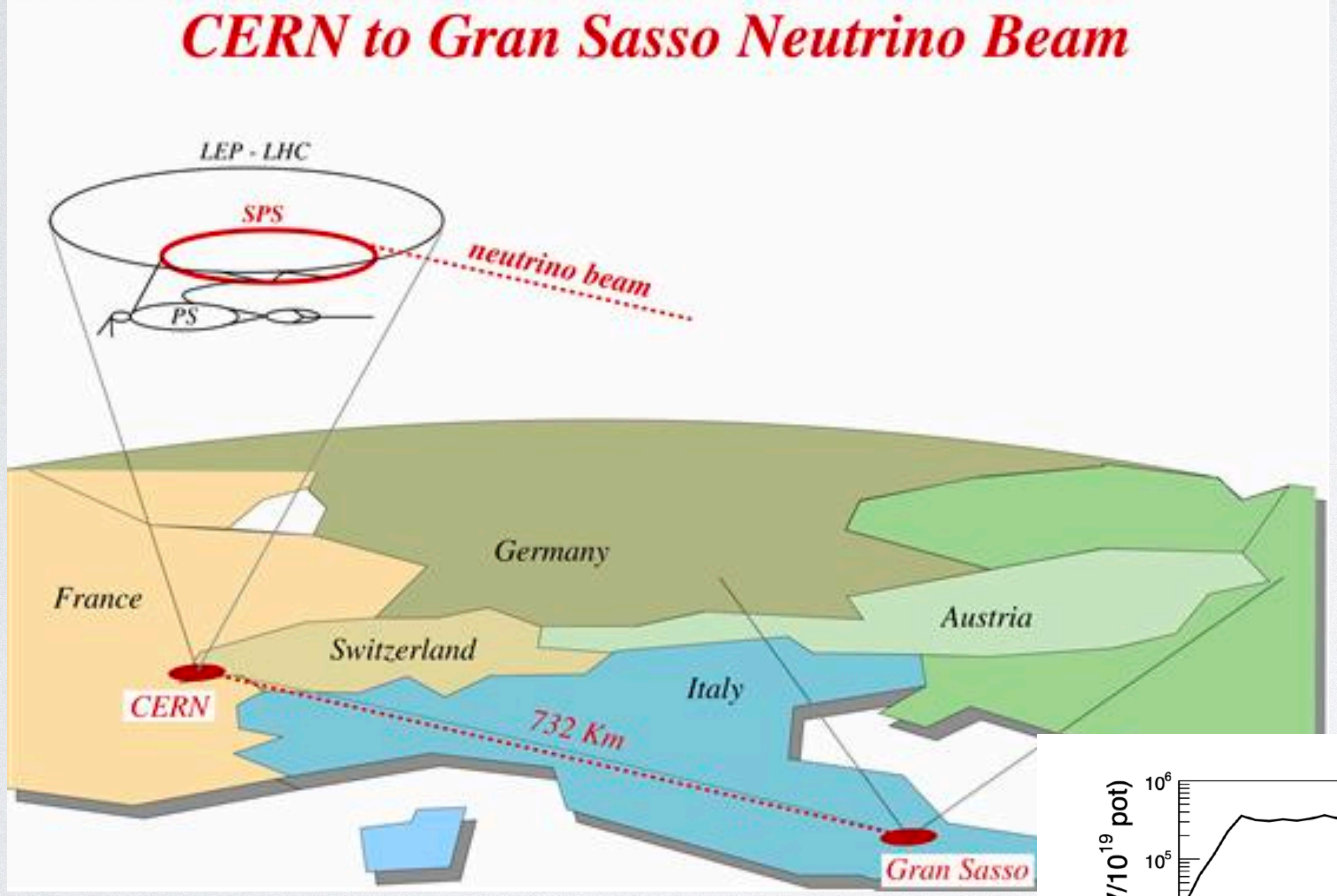
Photo: Fermilab via:
https://www.energy.gov/articles/donut-experiment-today-energy-history

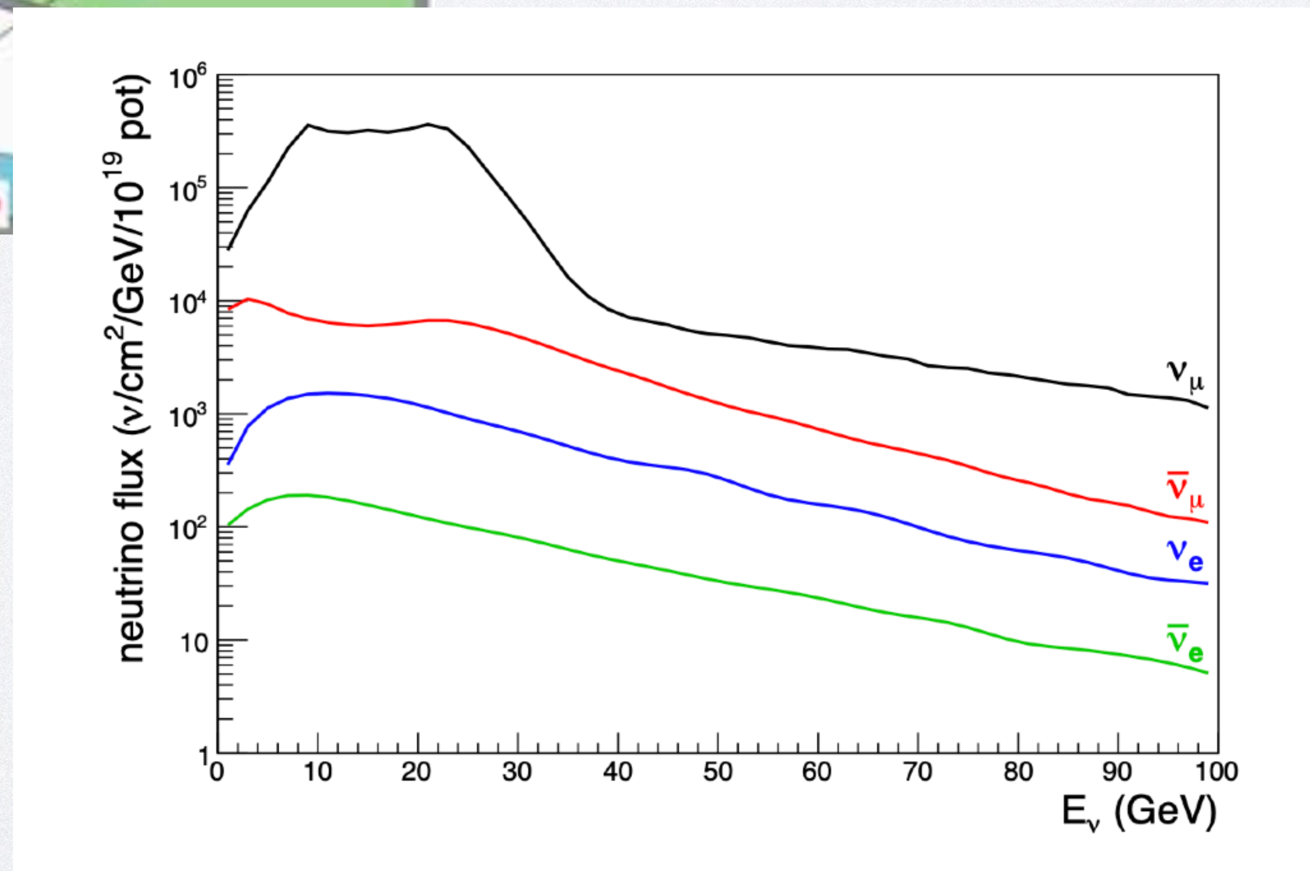
$$\sigma_{\nu_\tau}^{\text{const}} = 0.72 \pm 0.24 \pm 0.36 \times 10^{-38} \quad \text{cm}^2\,\text{GeV}^{-1}$$

Phys.Rev.D78:052002,2008

PAST MEASUREMENTS: OPERA

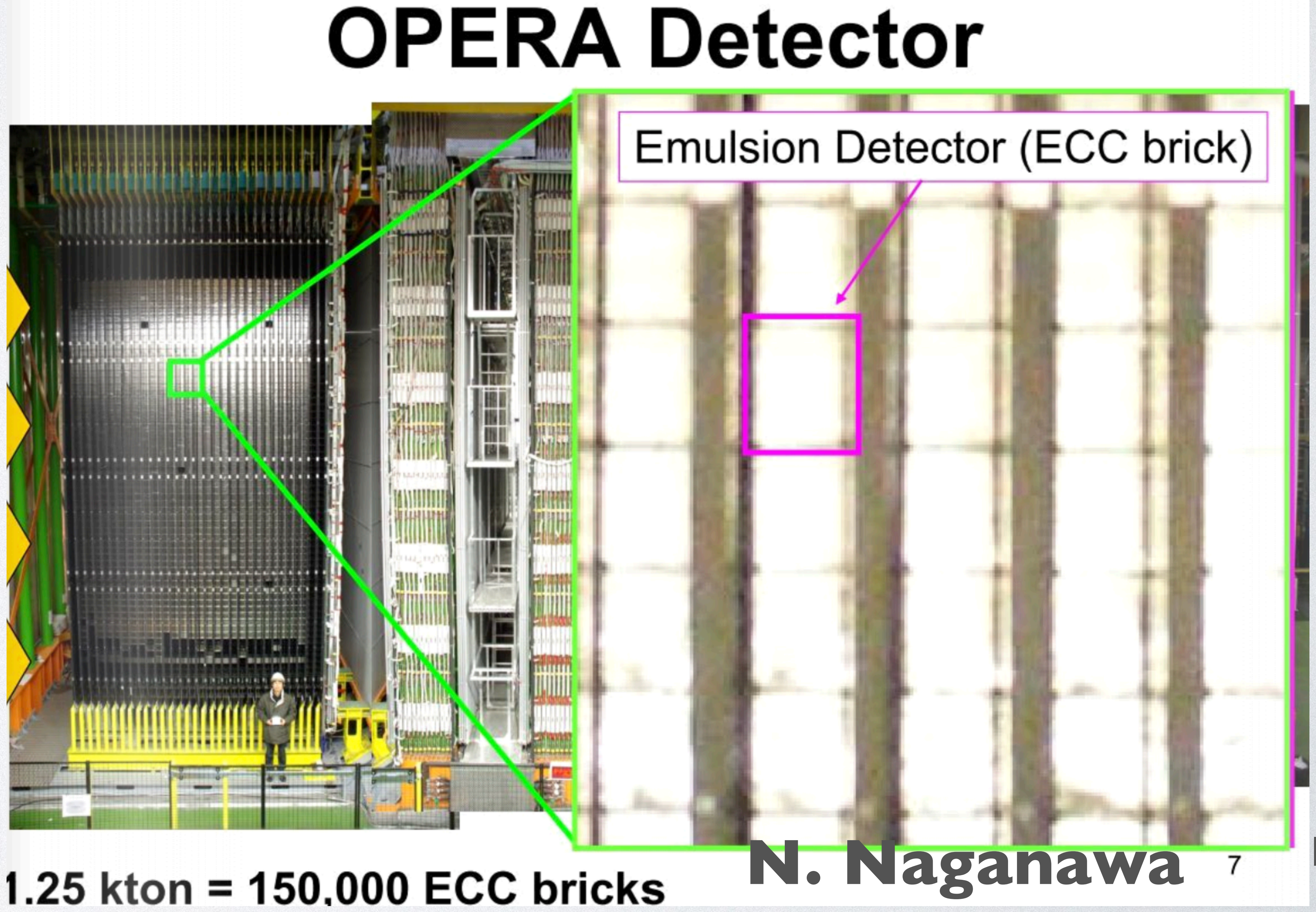
- Humans have seen tau neutrinos from artificial sources twice: and then from **OPERA**



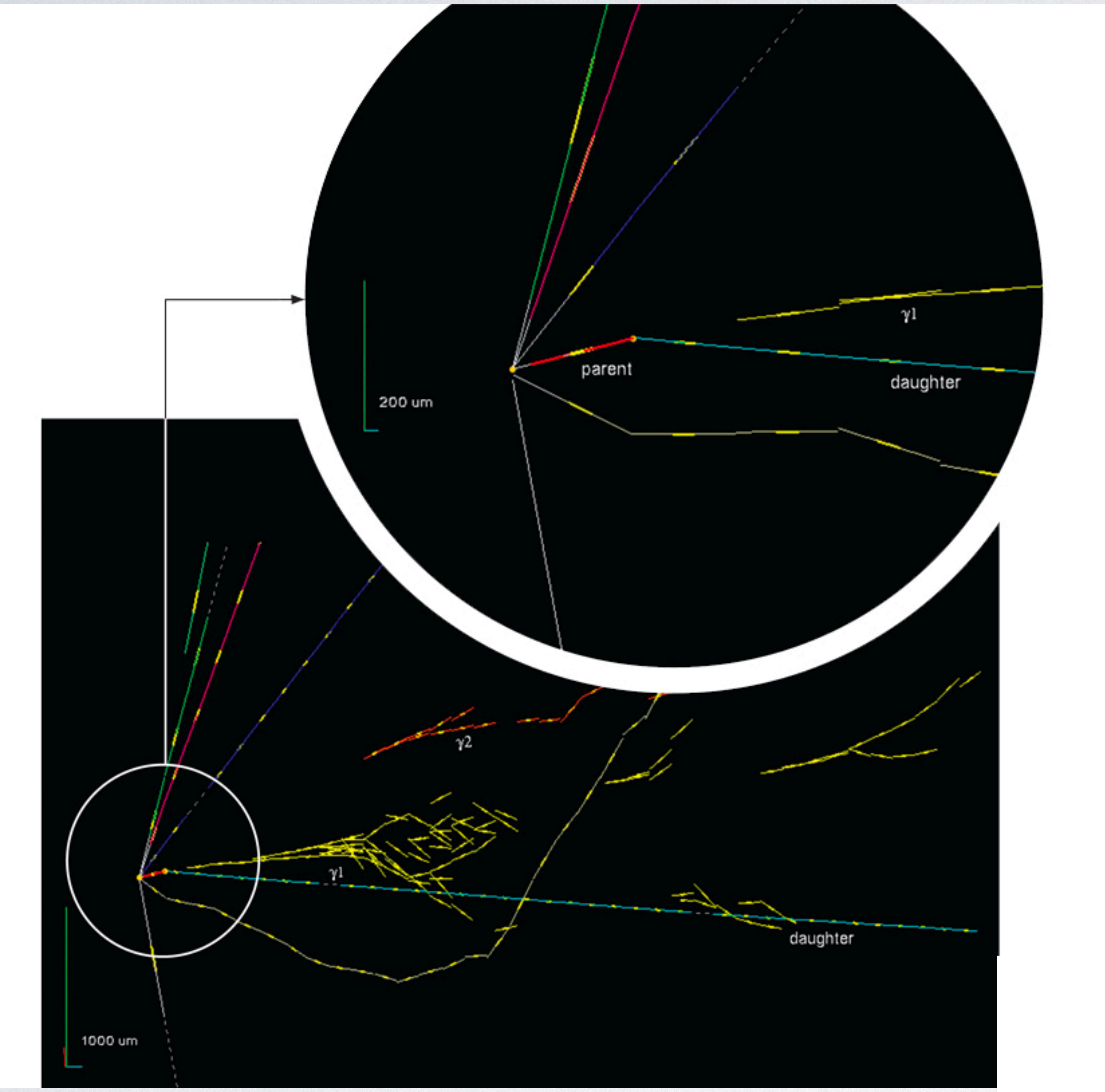


- Used **CNGS beam at CERN** + OPERA detector 732 km away in Gran Sasso

- Used **Emulsion Cloud Chambers** (emulsion sandwiched with lead) interleaved with plastic scintillator



PAST MEASUREMENTS: OPERA



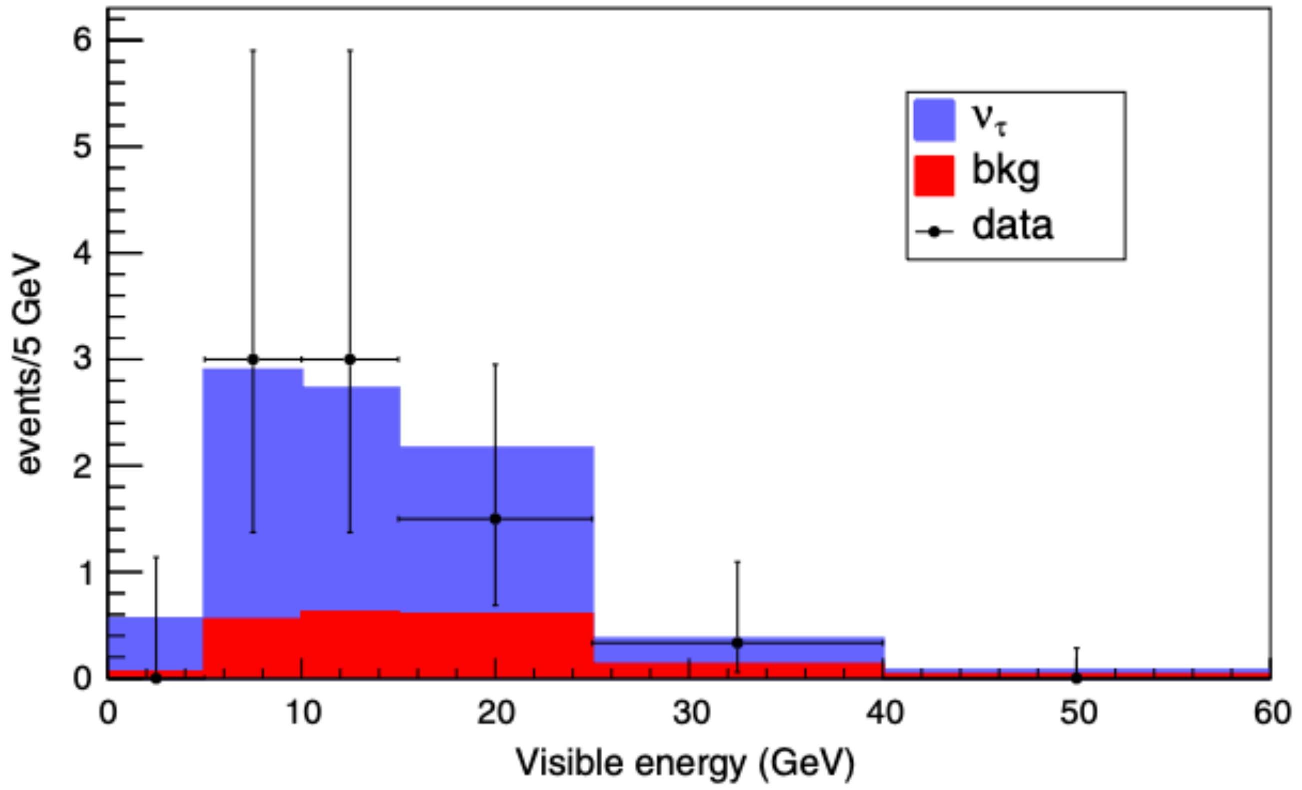
https://www.symmetrymagazine.org/article/february-2011/operas-first-tau-neutrino

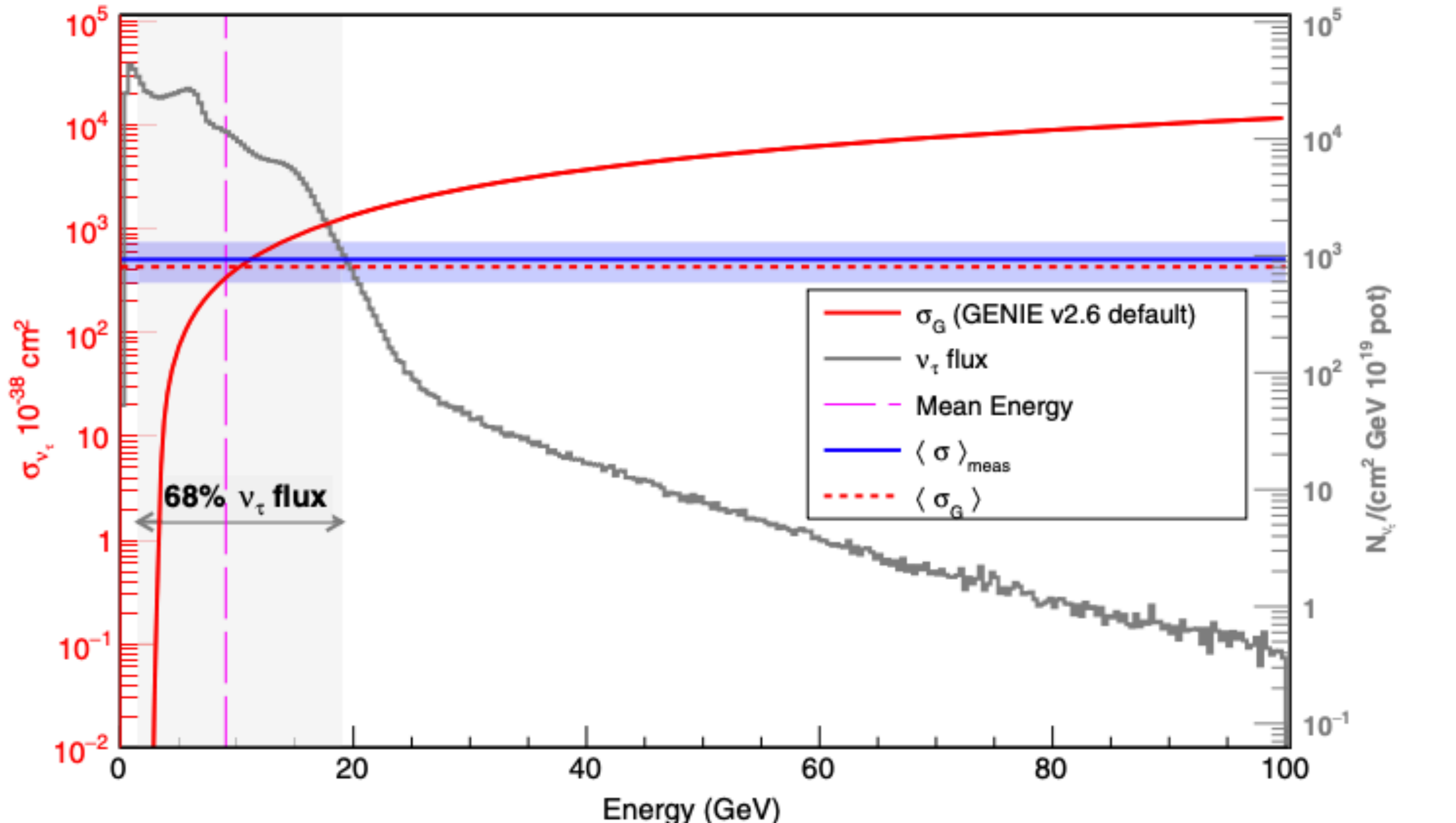
- Similar to Donut, tau neutrinos were **identified by observing the 'kink'** characteristic of tau lepton decay
- Operated 2008-2012 (18e19 POT)
- Final results published 2018 — **10 events with an expected background of 2**
- Bkdgs: ν_μ charm production, hadron reinteractions, Large angle muon scattering

$$|\Delta m^2_{32}| = (2.7^{+0.7}_{-0.6}) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{at 68\% C.L.}$$

Phys. Rev. Lett. **121**, 139901 (2018)

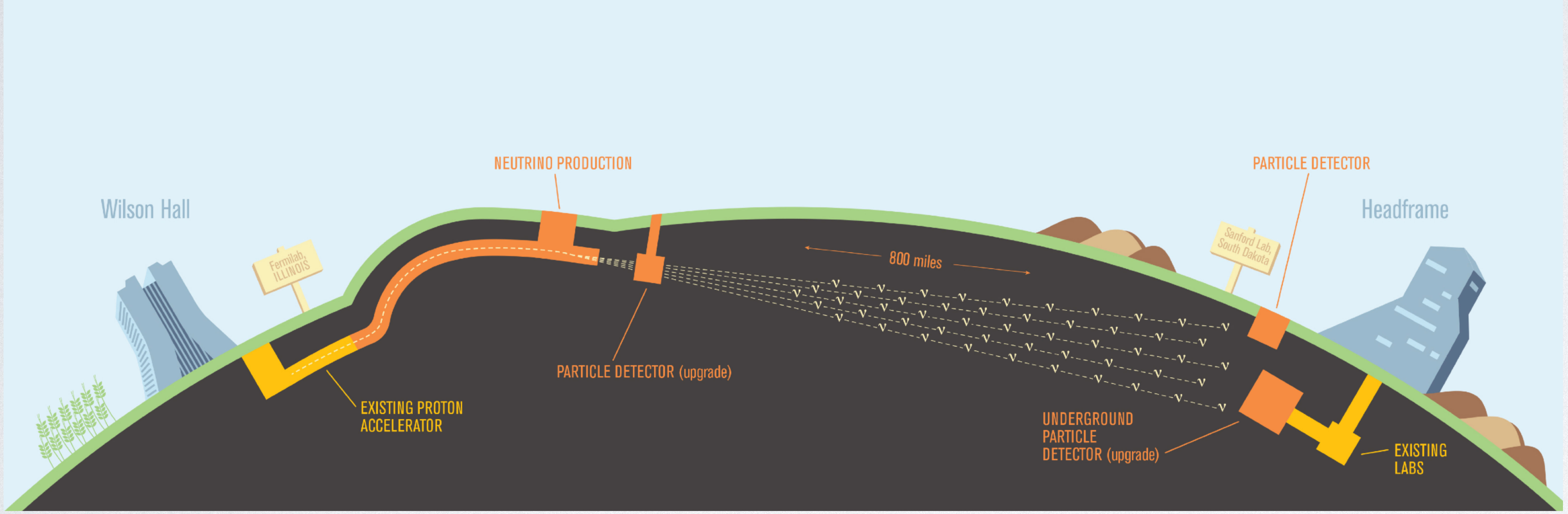
$$\langle\sigma\rangle_{\mathrm{meas}} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ \mathrm{cm}^2,$$ (per lead nucleus)



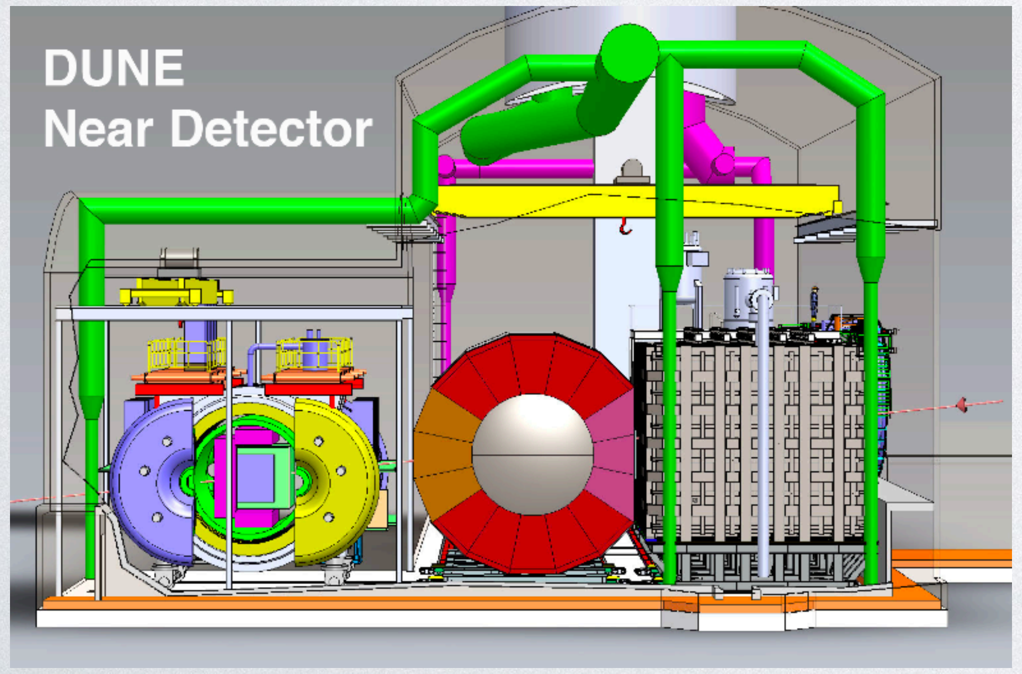


FUTURE: DUNE

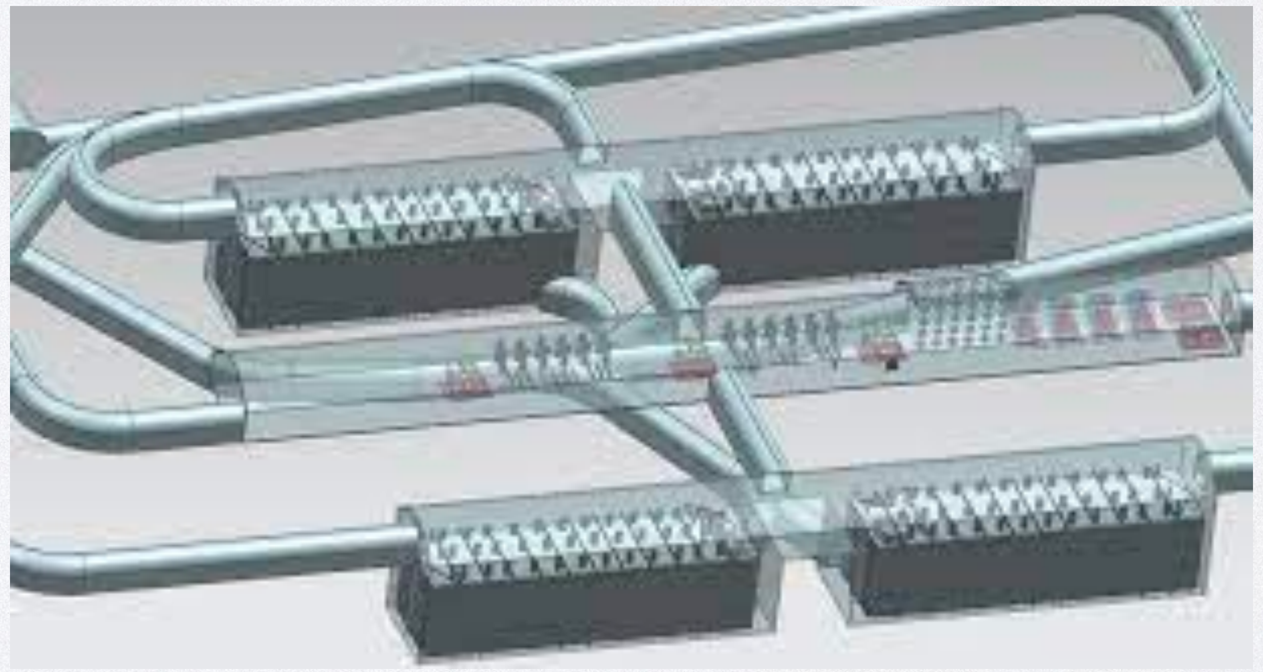
- **DUNE is a long-baseline experiment** that will use neutrinos generated at Fermilab and sent to a large underground detector in South Dakota



Is designed to study $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ channels for mass hierarchy and δ_{cp}, but will **also collect a ν_τ sample**



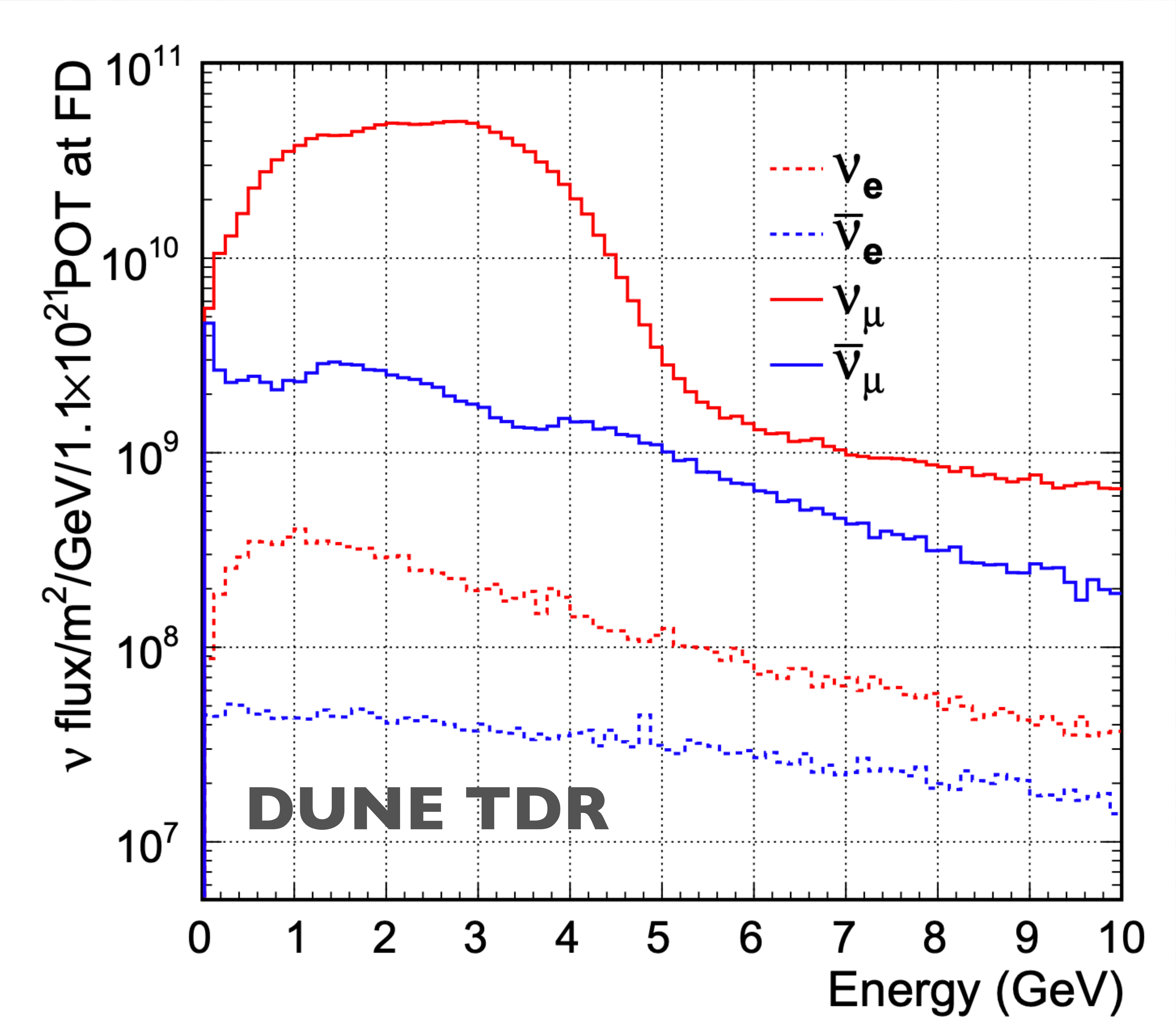
574 m baseline
Several detector components, including 147 ton LAr TPC



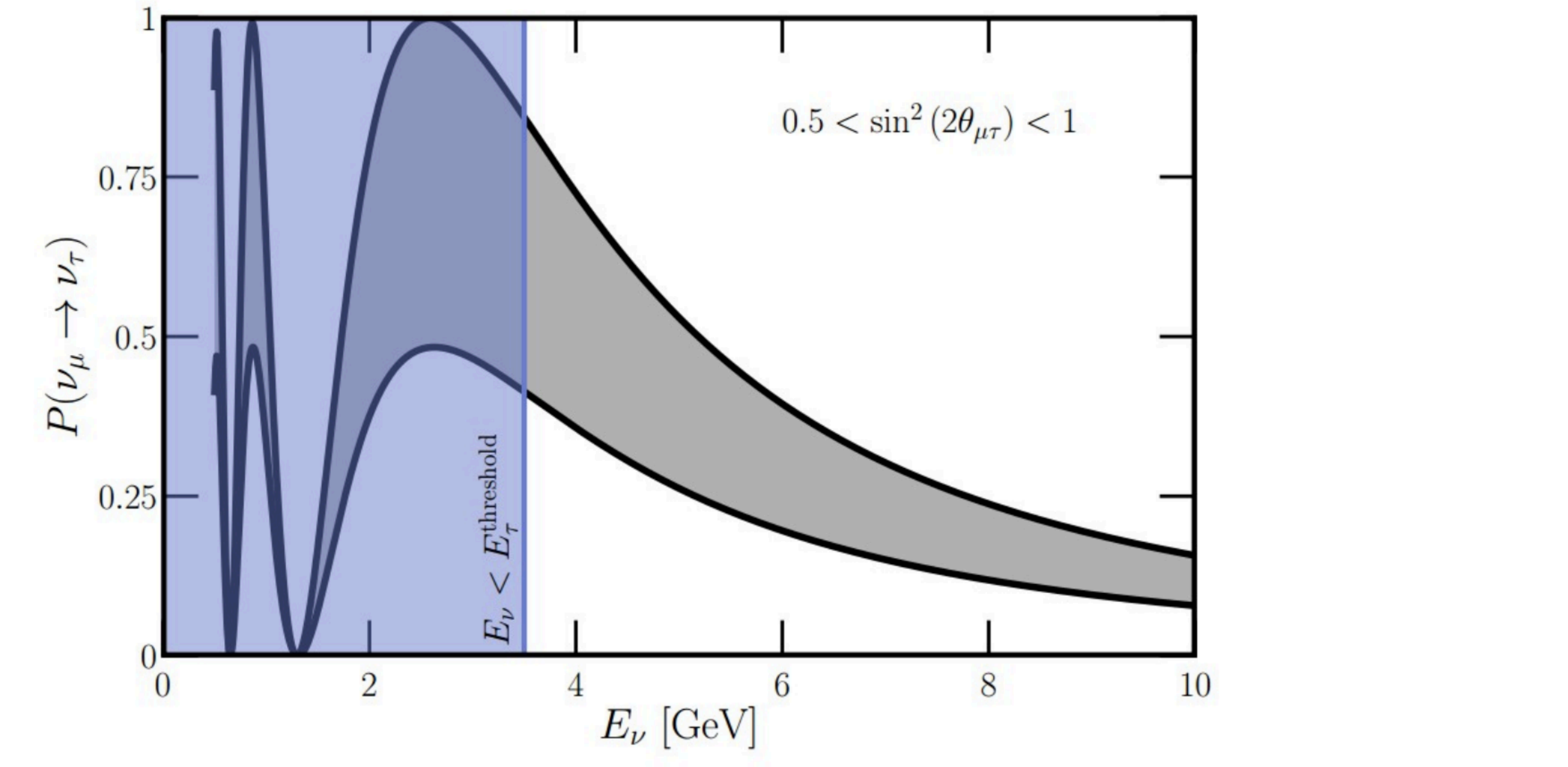
1300 km baseline
4x17 ton LAr TPC

FUTURE: DUNE

- DUNE's flux peaks between **2-3 GeV, and oscillation max is at 2.5 GeV**, which is not ideal for tau neutrinos:

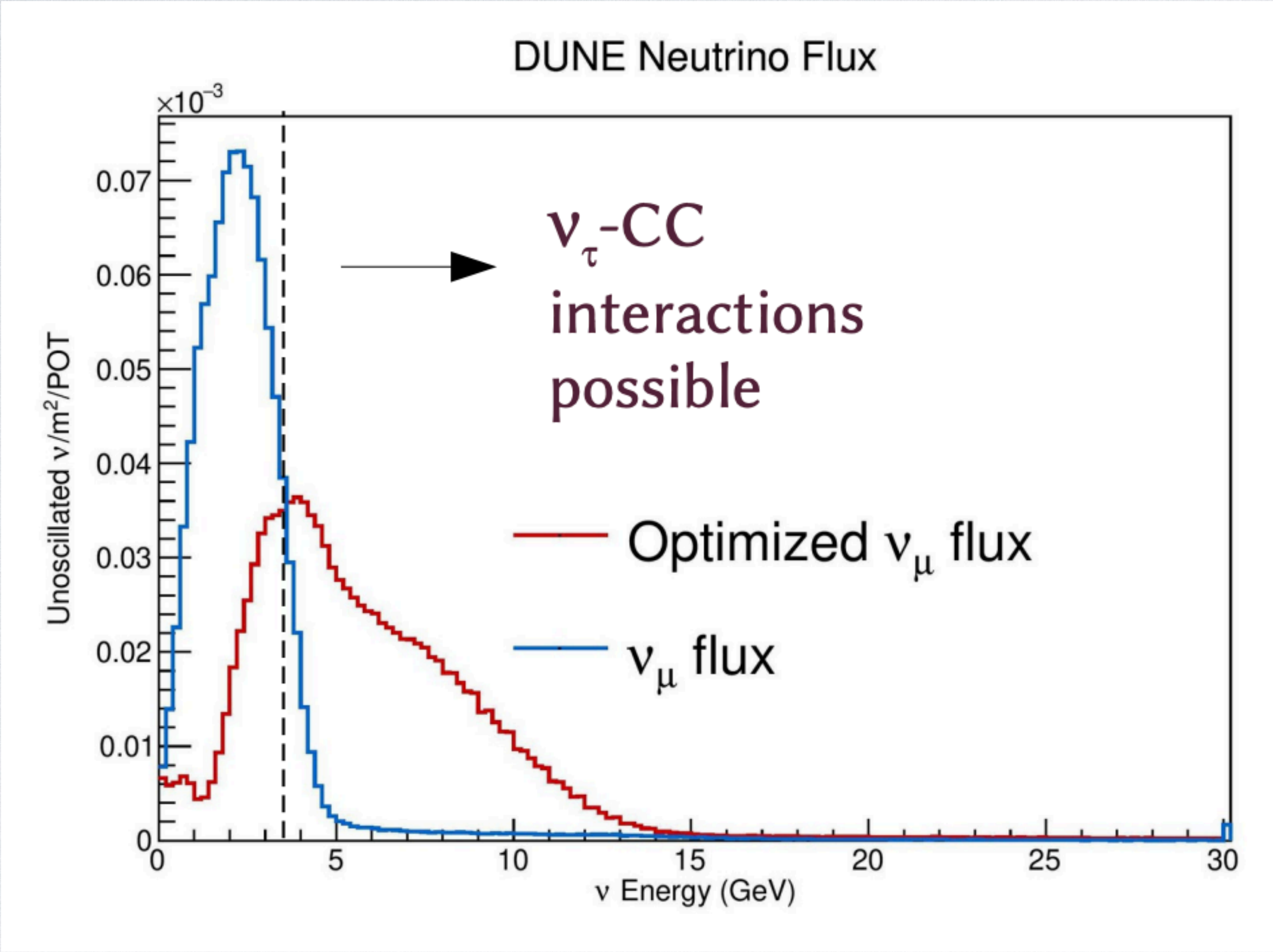


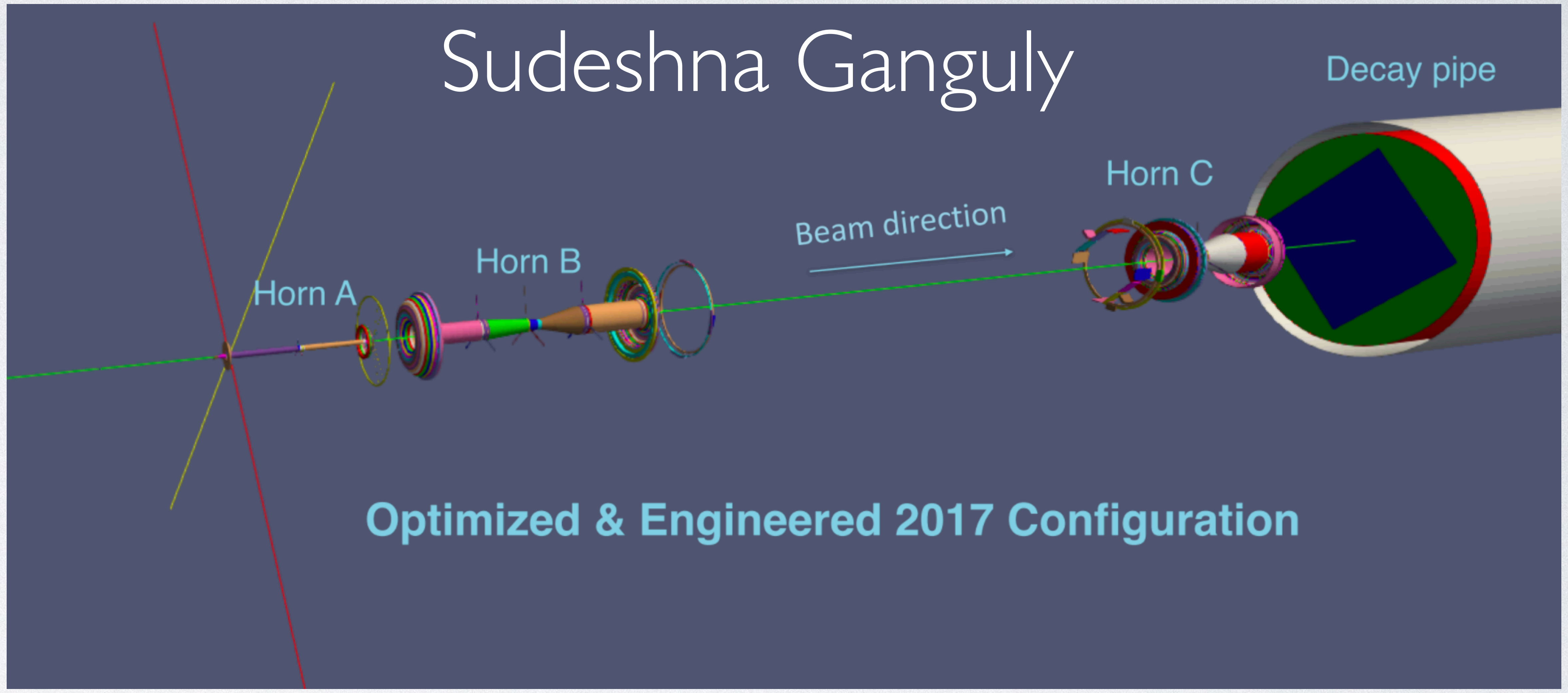
de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)

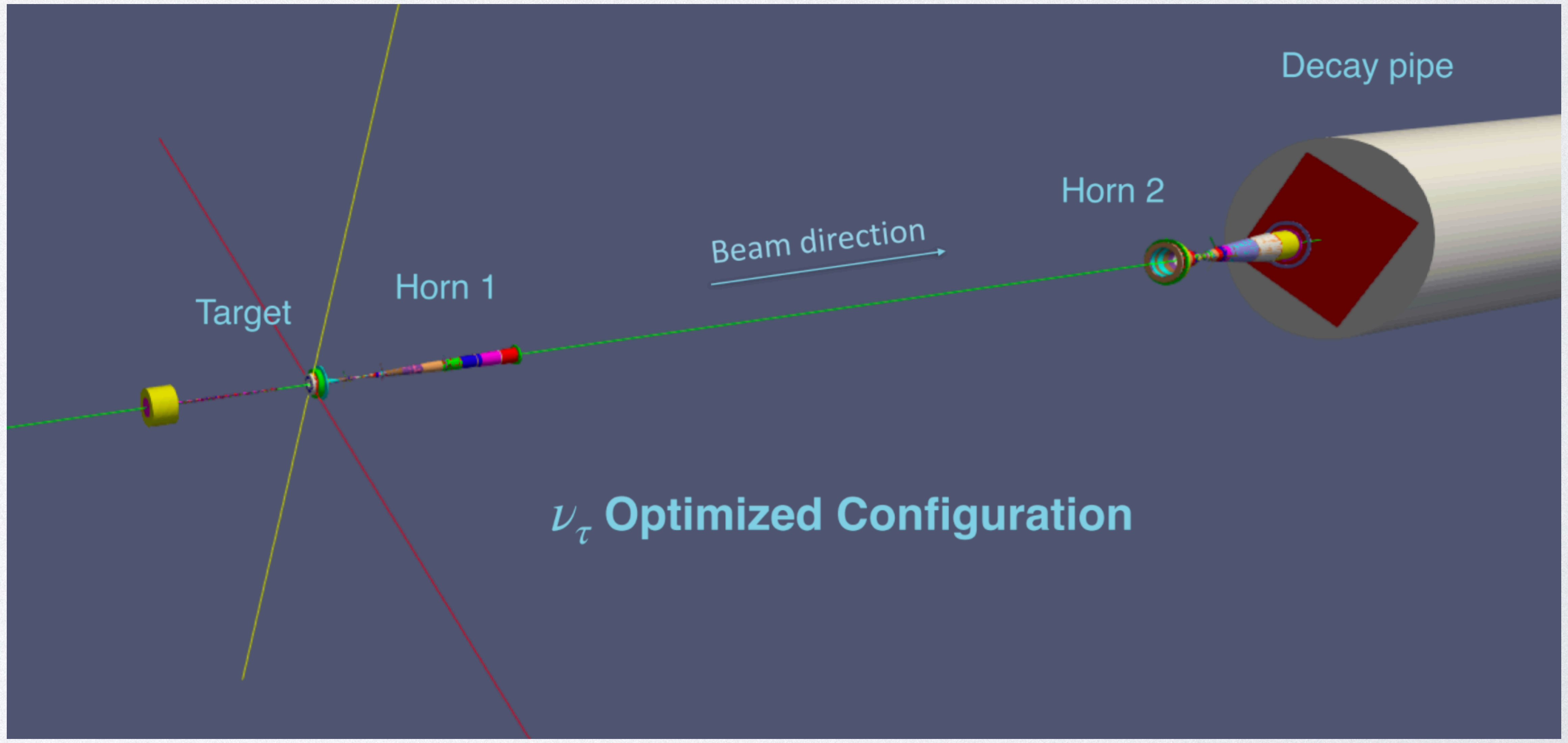


- But will still have quite a few oscillated **tau neutrinos in the high energy tail**
- Where are the **intrinsic tau neutrinos?**
  - LBNF simulation is Geant4-based; Geant4 does not produce charm
  - They are presumably there, but not many of them

FUTURE: DUNE







- Beamline **can be tuned to higher energy** by using two NuMI horns and increasing horn separation
- Fairly **simple optimization**; can probably be improved on, but not dramatically

FUTURE: DUNE

Expected counts/year:

~130 ν_τ in low-energy neutrino mode
~30 $\bar{\nu}_\tau$ in low-energy antineutrino mode
~800 ν_τ in high-energy neutrino mode

τ^- Decay Mode	Branching Ratio
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-2\pi^0\nu_\tau$	9.3%
$2\pi^-\pi^0\nu_\tau$	9.3%
$2\pi^-\pi^+\pi^0\nu_\tau$	4.6%

- Far detector **resolution is not sufficient to see the tau "kink"** as Opera and DONUT did
- DUNE has studied using **kinematic cuts** (first proposed in J. Conrad, et al, PRD 82, 093012 (2010))
  - Select ν_τ with hadronically decaying tau lepton
  - Assume near perfect e/gamma and mu/pi discrimination
  - Simple kinematic cuts on pi± yield good ν_τ CC/NC discrimination
  - Optimistic assumptions **yield ~30% efficiency, 0.5% efficiency** for dominant background (neutral current)
- A **more recent study** (still with some optimistic assumptions) finds:

Mode	beam	charge id	N_{sig}	N_{bg}	$S/\sqrt{B}$
τ_{had}	nominal	✓	79	565	3.3
τ_{had}	nominal	✗	83	731	3.1
τ_{had}	tau-optimized	✓	433	2411	8.8
τ_{had}	tau-optimized	✗	439	3077	7.9
τ_e	tau-optimized	✗	63	33	11.0
τ_e	nominal	✗	13	32	2.3

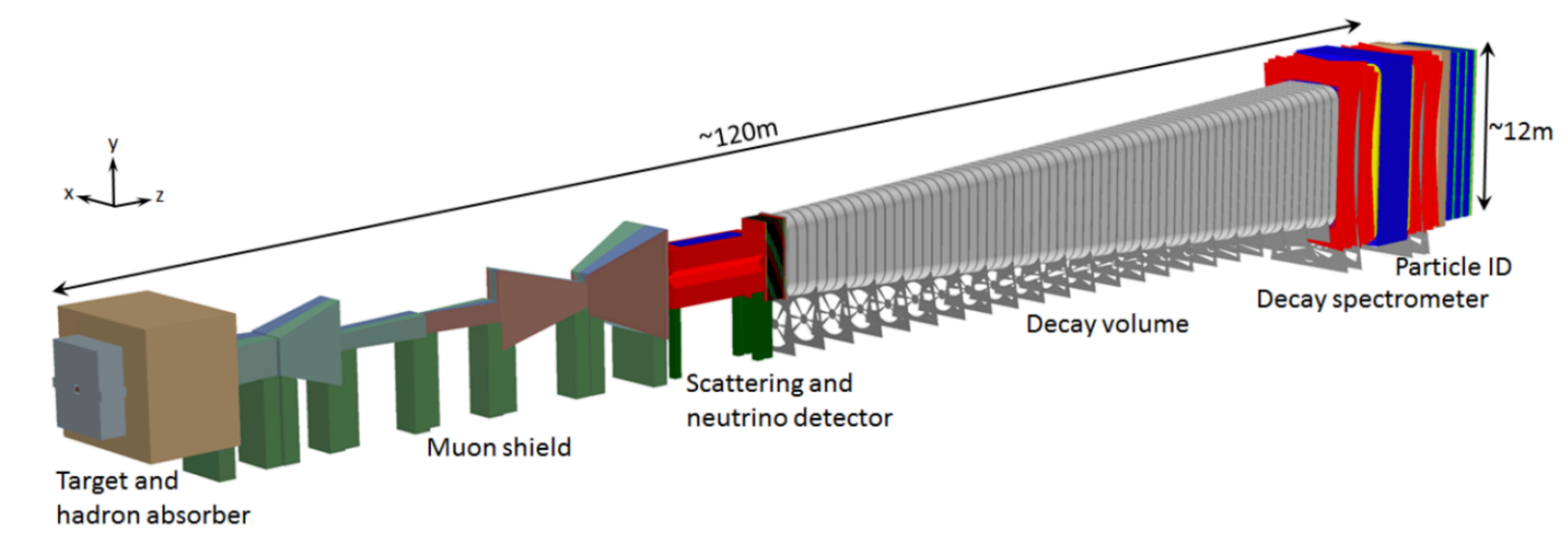
Machado, Schultz, Turner: Phys. Rev. D 102, 053010 (2020)

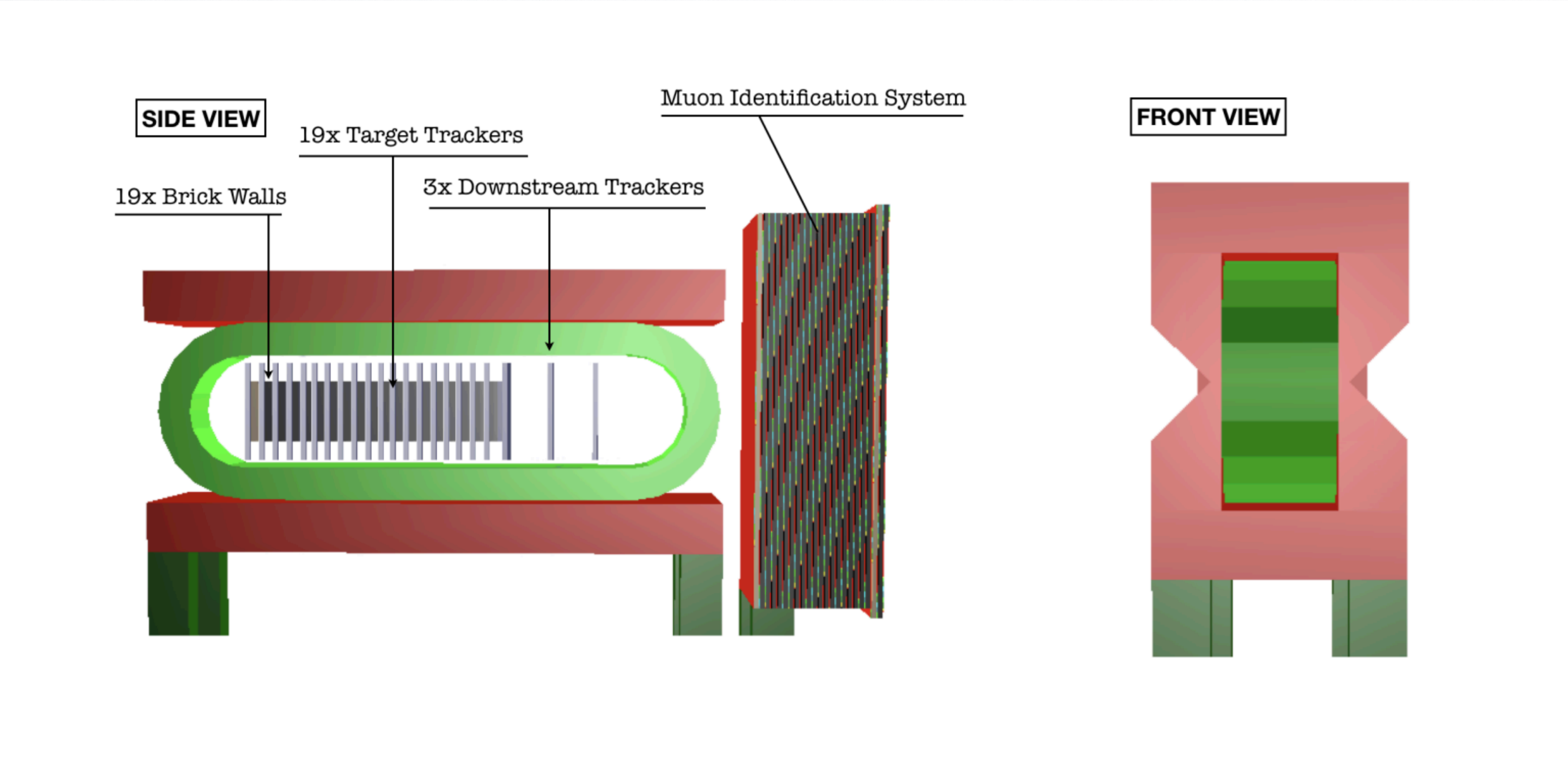
Exactly how well DUNE will be able to measure ν_τ still unclear, but already clear DUNE will substantially improve on current measurements.

FUTURE: SHIP

Pastore, Alessandra

https://cds.cern.ch/record/2762117

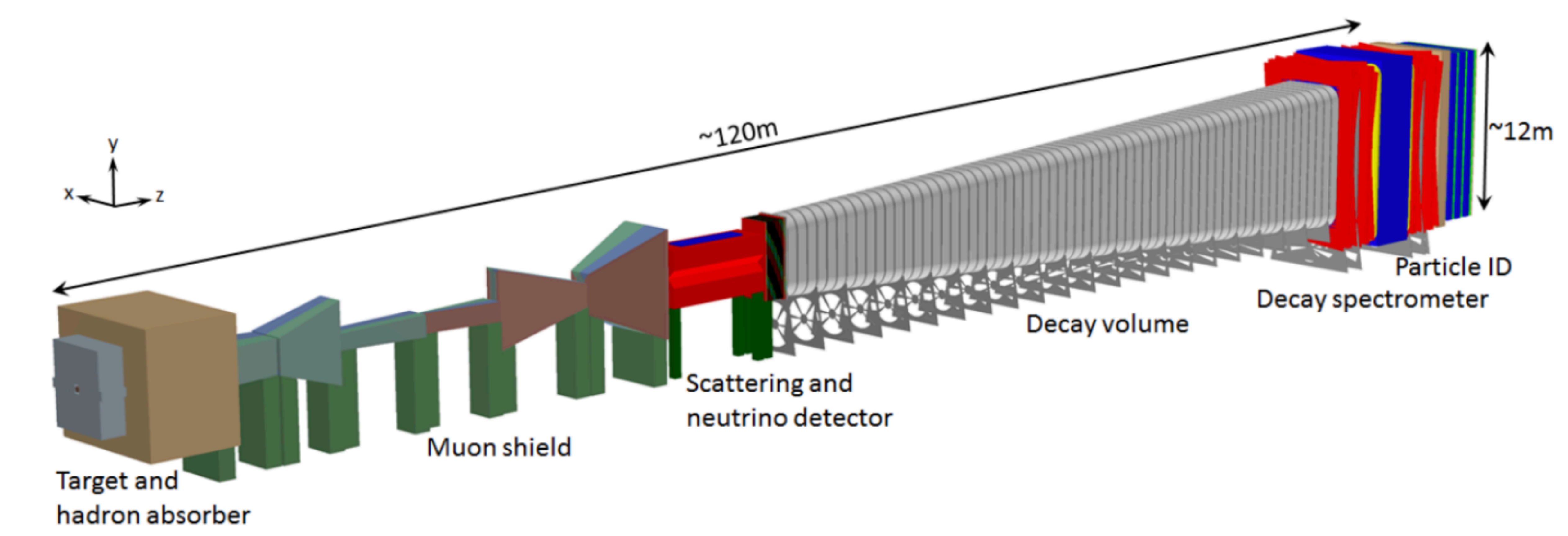




- **SHiP: Beam dump experiment** at the CERN SPS
- **400 GeV** protons, 2e20 POT in 5 years
- Will address three areas of physics:
  - Search for **Hidden Sector** models in the GeV mass range
  - Measurements of **tau neutrinos**
  - **Charm physics**
- Neutrino detector is the **Scattering and Neutrino Detector** ("SND")
  - Uses **Emulsion Cloud Chamber** (ECC) technology used by Opera, combined with additional emusion-based spectrometers, high resolution target trackers (all magnetized), and a downstream muon ID system

FUTURE: SHIP

Pastore, Alessandra
https://cds.cern.ch/record/2762117

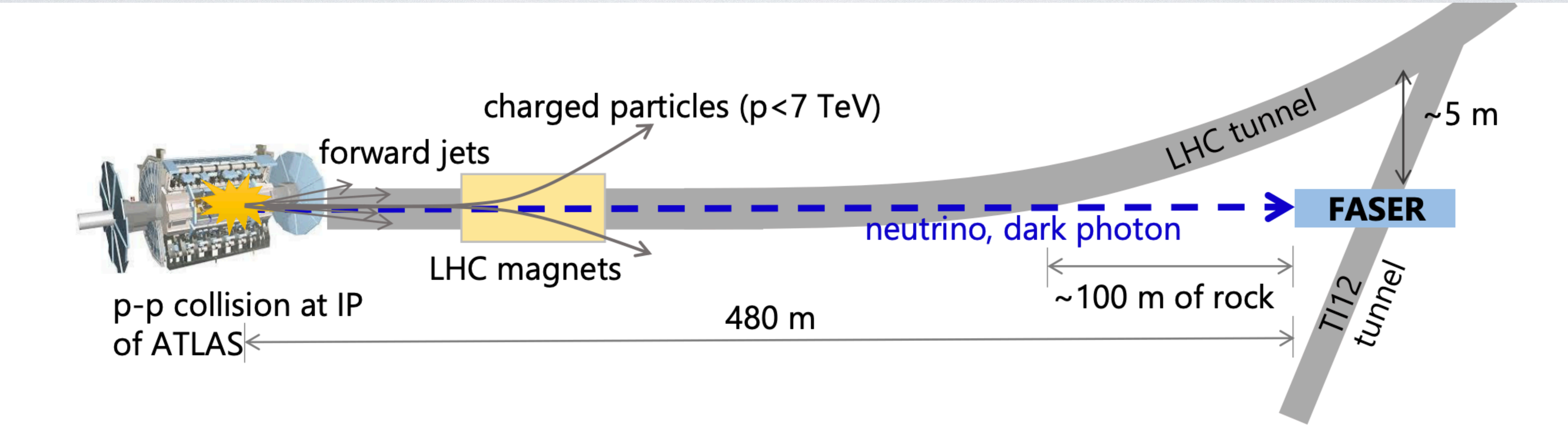


	<E> [GeV]	CC DIS int.
ν_e	59	$1.1 \cdot 10^6$
ν_μ	42	$2.7 \cdot 10^6$
ν_τ	52	$3.2 \cdot 10^4$
$\overline{\nu}_e$	46	$2.6 \cdot 10^5$
$\overline{\nu}_\mu$	36	$6.0 \cdot 10^5$
$\overline{\nu}_\tau$	70	$2.1 \cdot 10^4$

- **32,000 tau neutrinos** expected in 5-year run
- Also expect **21,000 tau *antineutrinos***, which have never been observed
- Will make precise measurements of tau **interaction cross sections**
  - Particularly sensitive to **unmeasured F4 and F5 structure functions**
  - Primary background: charm production from ν_e/ν_μ CC
- Collaboration is concluding the **Comprehensive Design phase**, moving forward to produce TDRs by 2021-2022

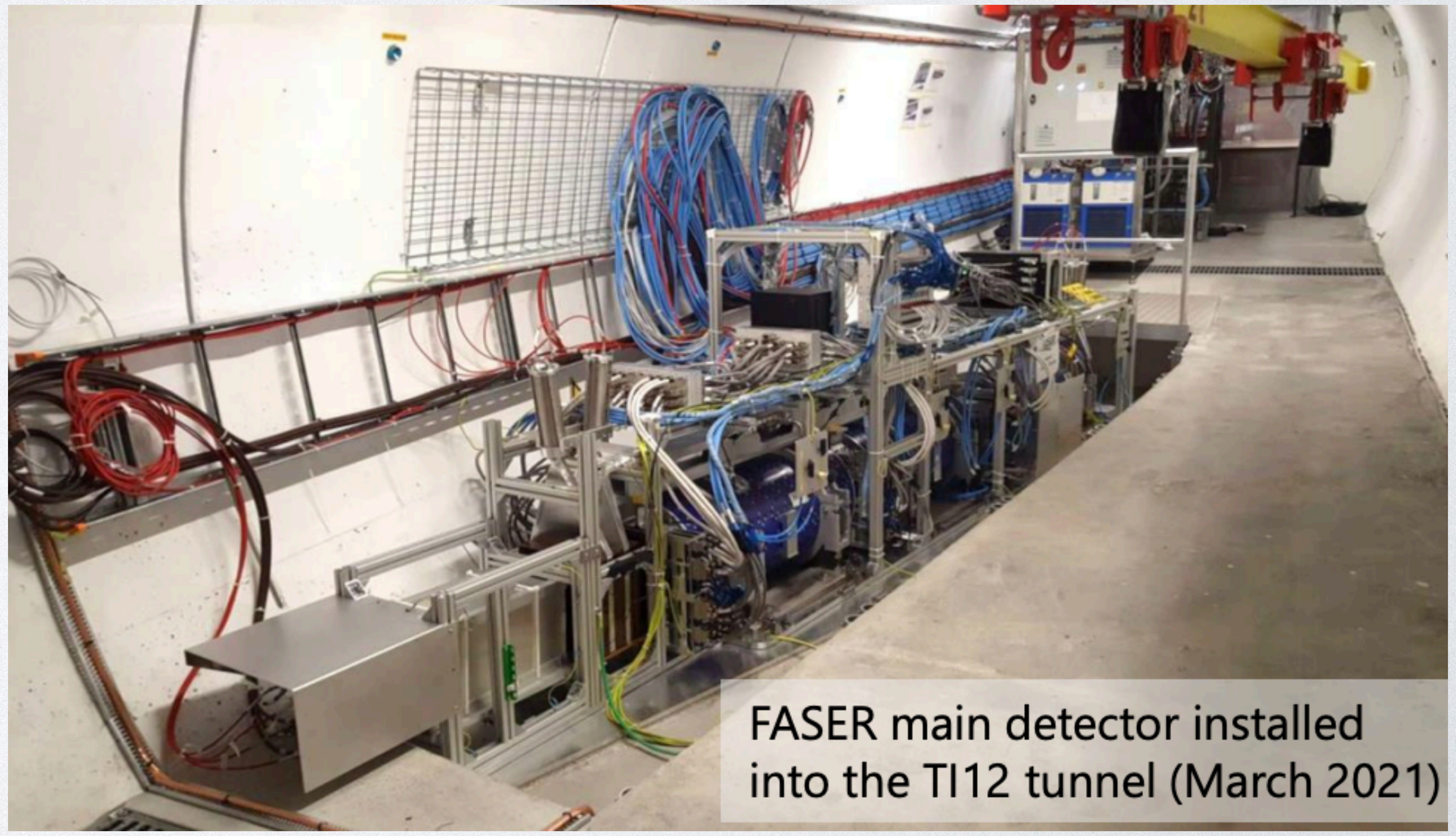
SHiP
Search for Hidden Particles

FUTURE: FASERν

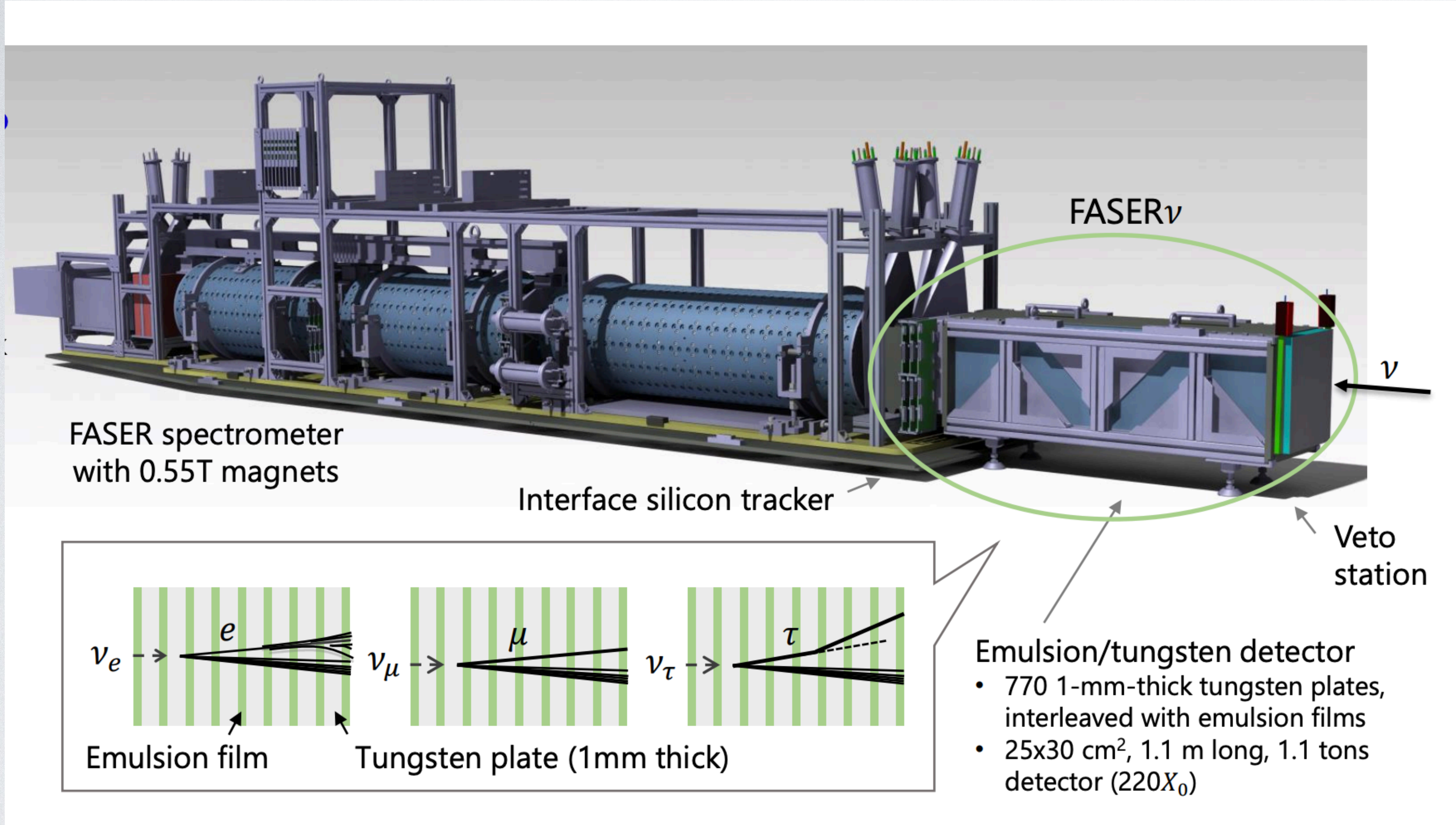


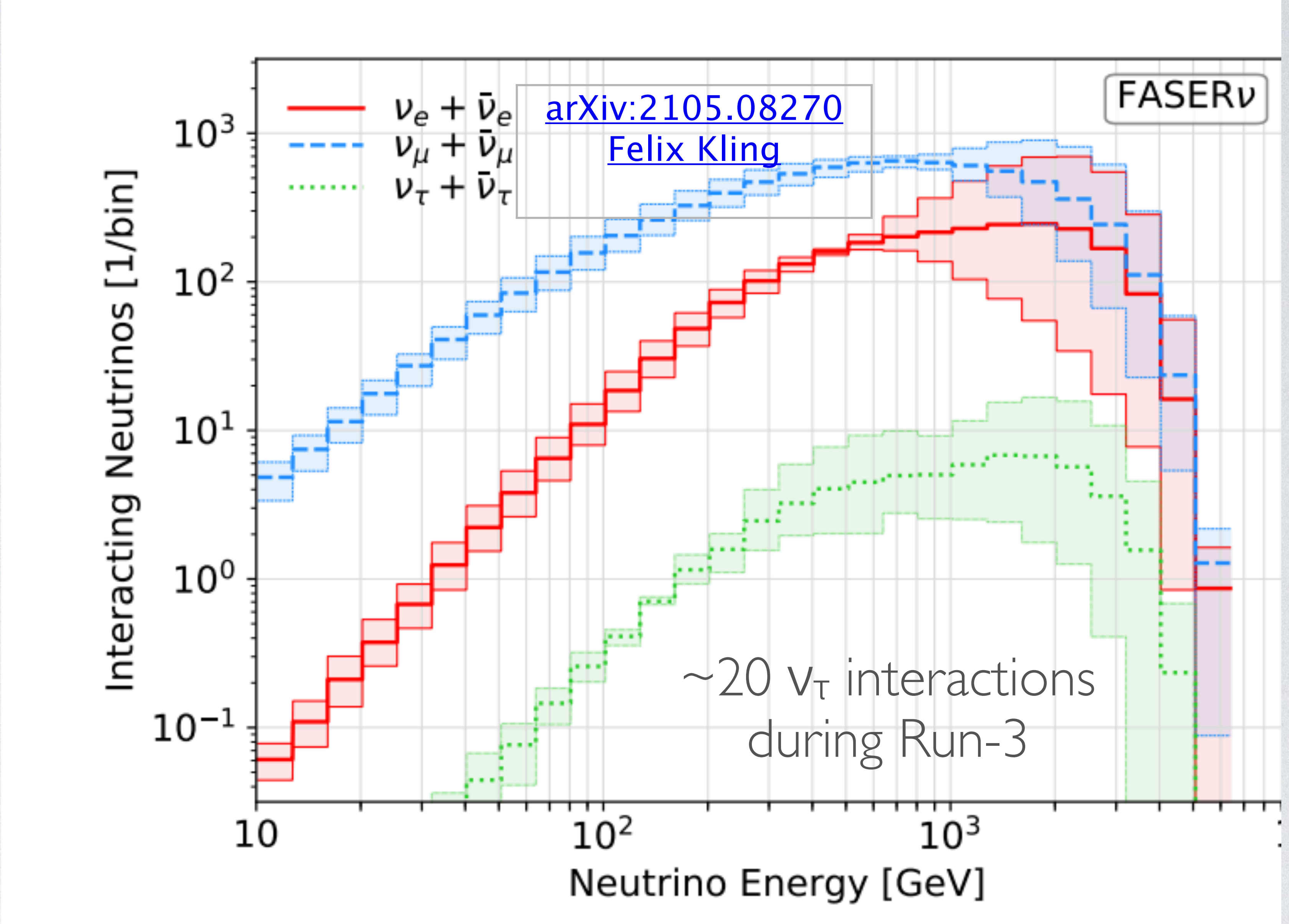
Tomoko Ariga

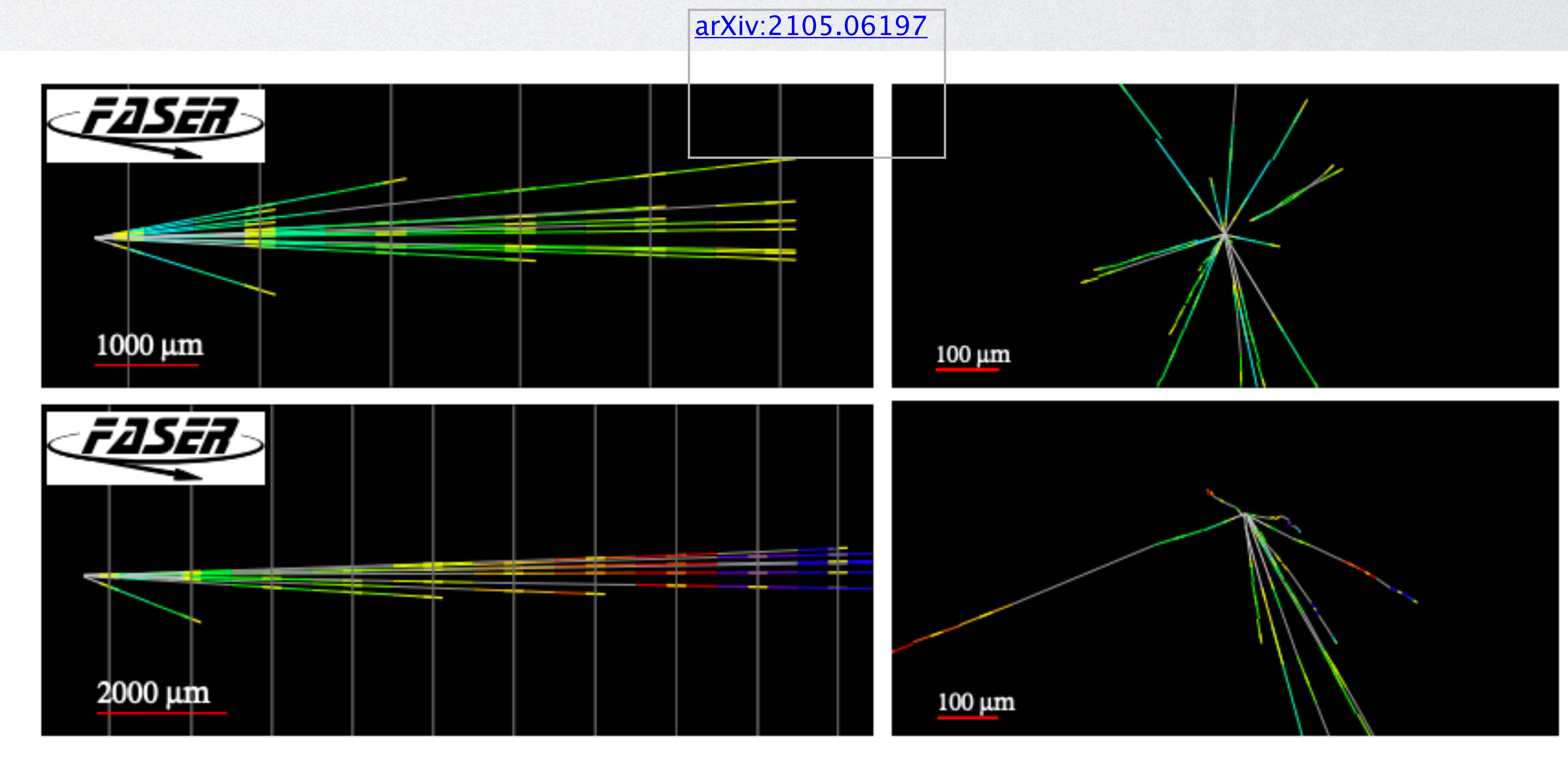
- **FASER**: a new experiment studying forward particles from ATLAS collisions with two components:
  - FASER: search for new light, weakly coupled particles at low P_T
  - FASERν: measurements of neutrinos from a collider
- **Pilot run in 2018** during LHC Run-2
- Both were approved in 2019 and **will take data during LHC Run-3** (2022-2024)



FUTURE: FASERν



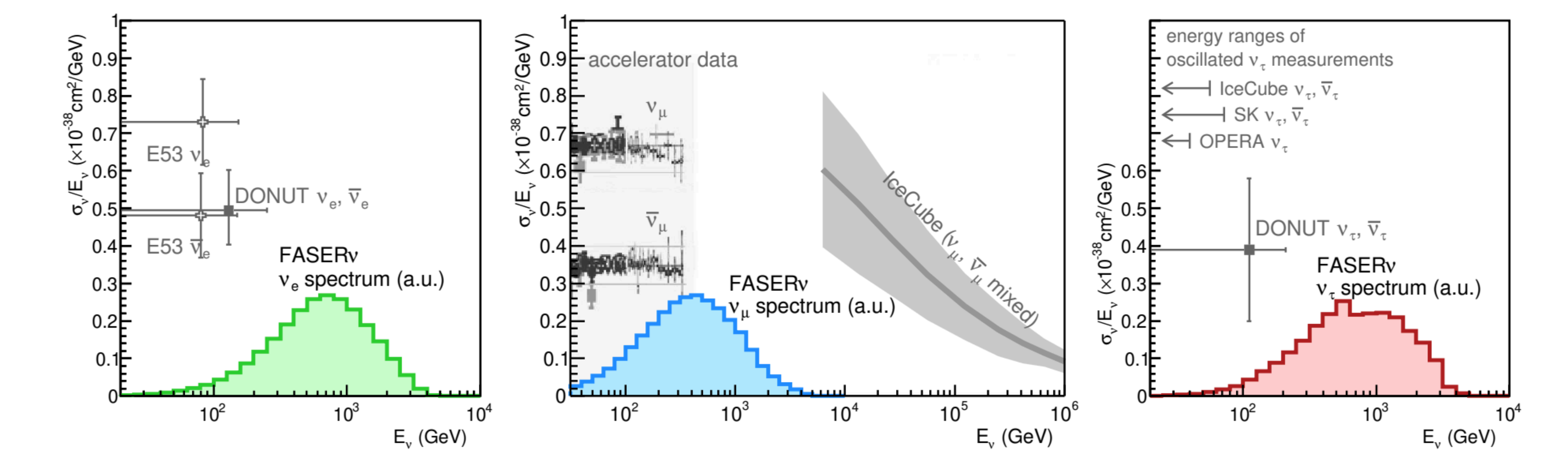


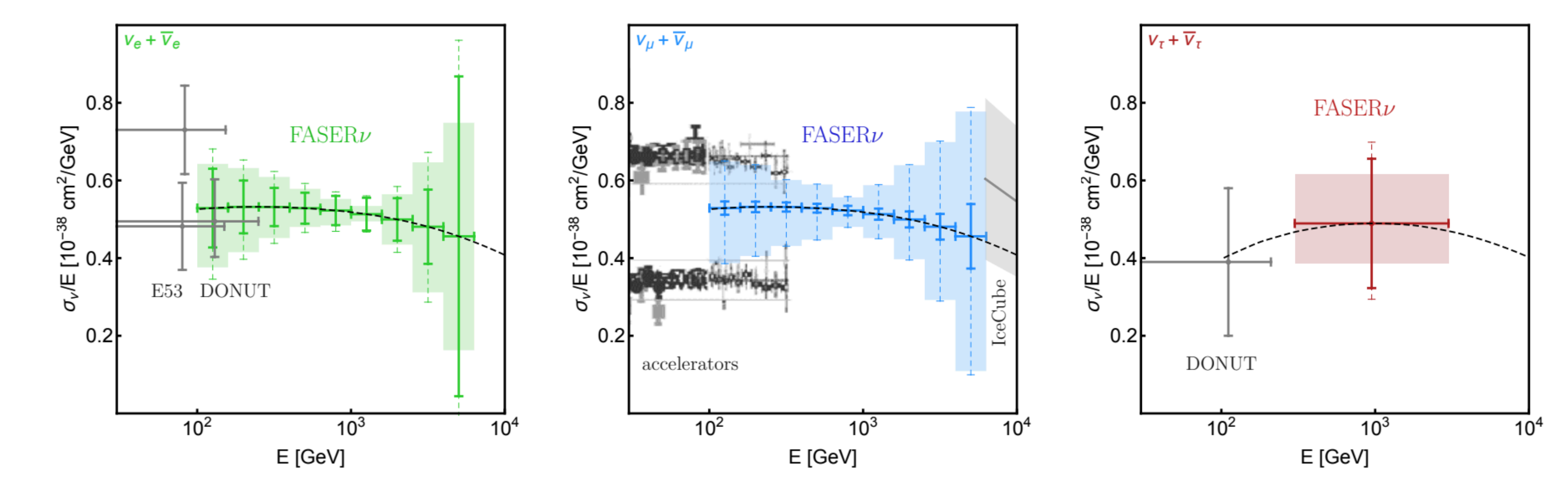


- FASERν is upstream of the main FASER detector and a silicon detector that is an interface between FASER and FASERν
- Can **distinguish all three neutrino flavors**
- **First neutrinos from the LHC** announced this year

FUTURE: FASER ν

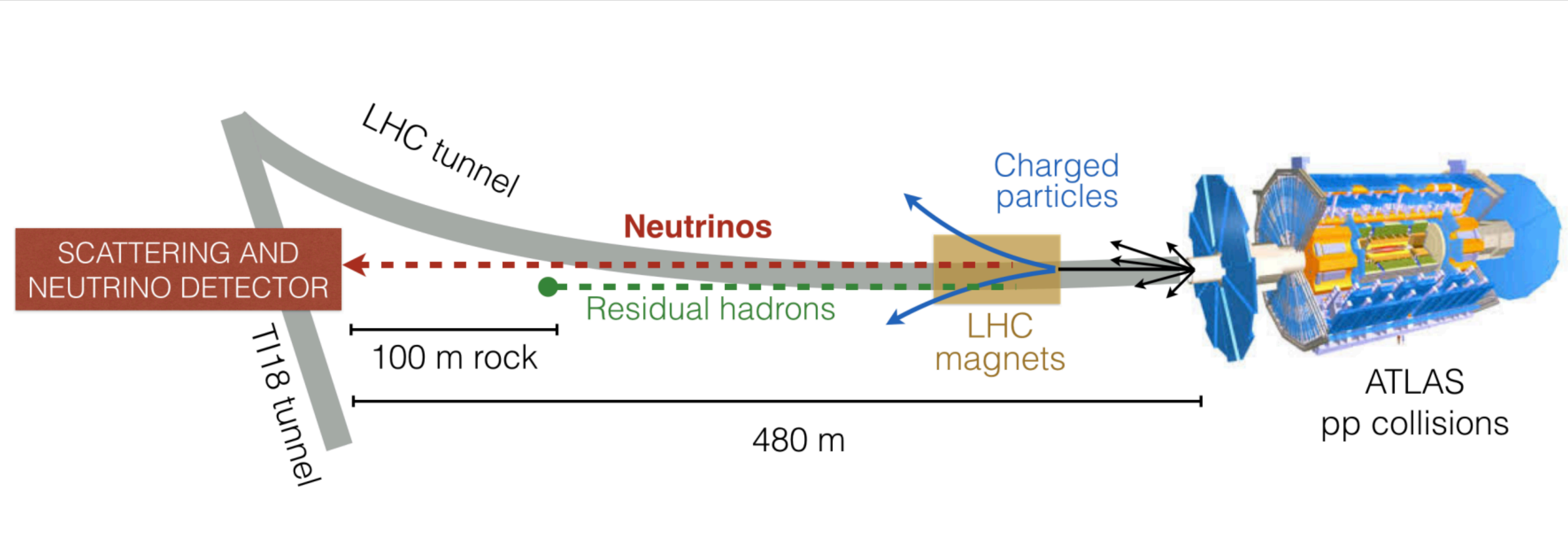
- Physics Goals
  - Measure **neutrino cross-sections** in unmeasured energy regions; comparisons across three flavors = **test of lepton universality**





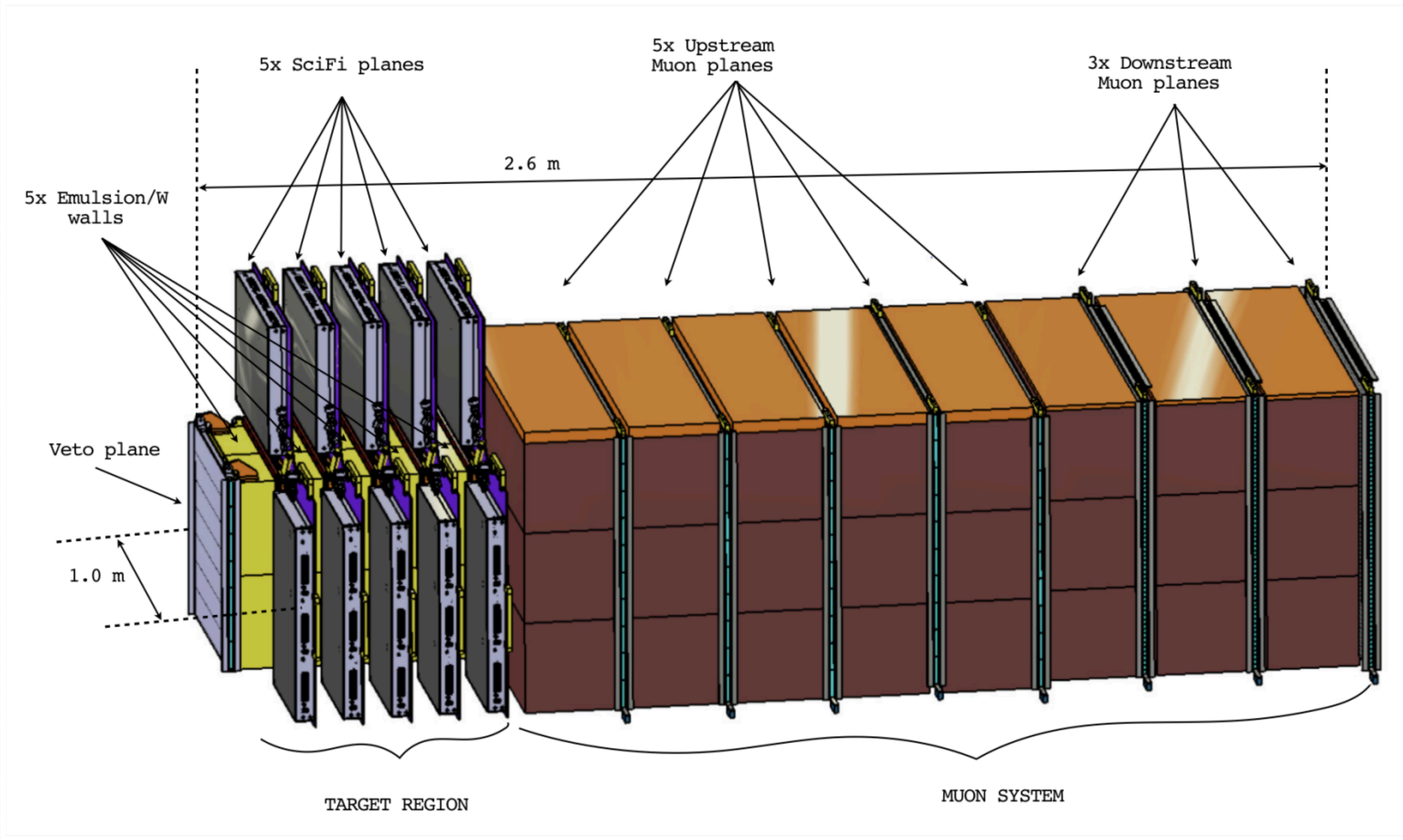
- Other physics goals:
  - Searches for **BSM**
    - light weakly coupled gauge bosons (could decay to ν_τ and enhance ν_τ flux)
    - NSI
    - Sterile Neutrinos
    - DM Candidates
  - Flux measurements provide **novel constraint to LHC event generators**

FUTURE: SND@LHC

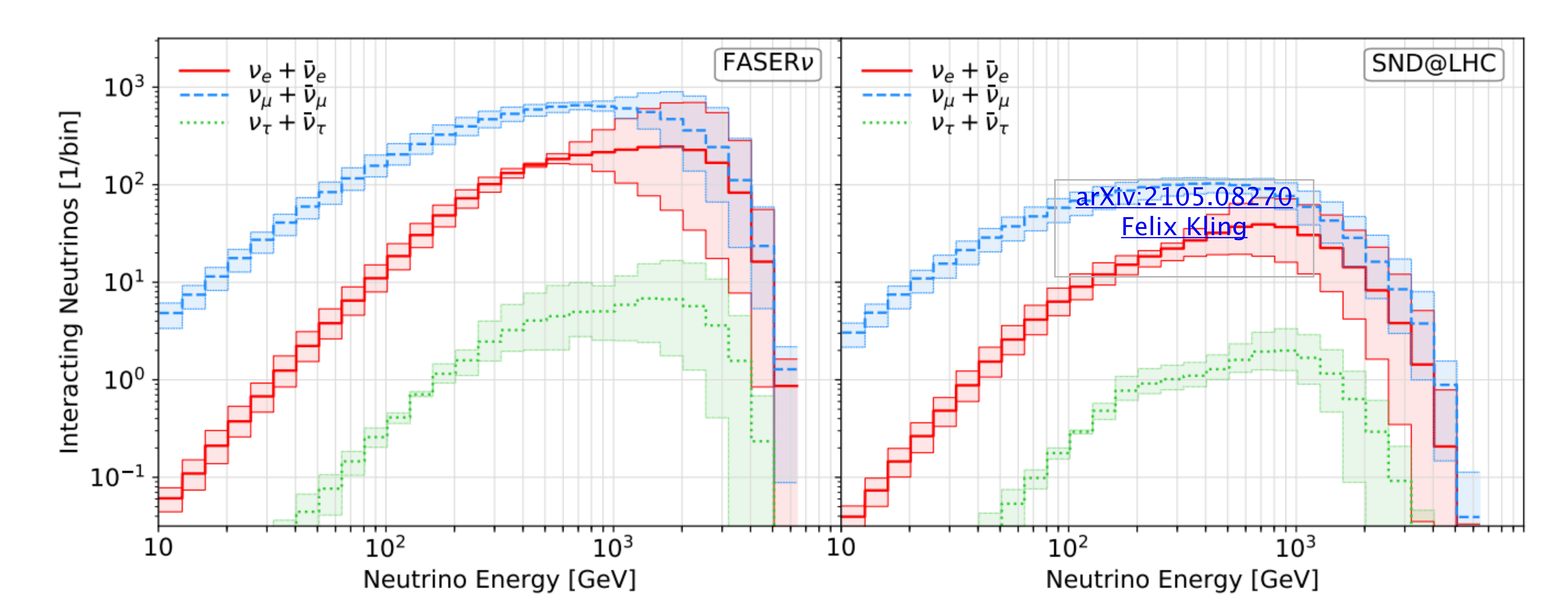


- **SND@LHC**
  - Located in TI18 Tunnel, same distance (480 m) from ATLAS interaction point, but on opposite side, displaced from beam axis

- Detector is a **small-scale prototype of the SND detector** that is planned for SHiP
  - Veto Plane
  - Target: Tungsten interleaved with emulsion + scintillating fiber (SciFi) tracker
  - Muon system: Iron + scintillator



FUTURE: SND@LHC



Flavour	CC neutrino interactions ⟨E⟩ (GeV)	Yield
ν_μ	450	730
$\bar{\nu}_\mu$	485	290
ν_e	760	235
$\bar{\nu}_e$	680	120
ν_τ	740	14
$\bar{\nu}_\tau$	740	6
TOT		1395

A. Di Crescenzo

- **Fluxes at off-axis position are reduced** compared to on-axis location, but expect 14 ν_τ ν during LHC Run-3.
- Biggest background is from **ν_μ charm production**, expected to be ~3 in Run-3, and can be further reduced
-

SND@LHC Physics Goals:

Measurement	Uncertainty Stat.	Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	20%
ν_e/ν_μ ratio for LFU test	10%	10%
Measurement of NC/CC ratio	5%	10%

FUTURE: FORWARD PHYSICS FACILITY

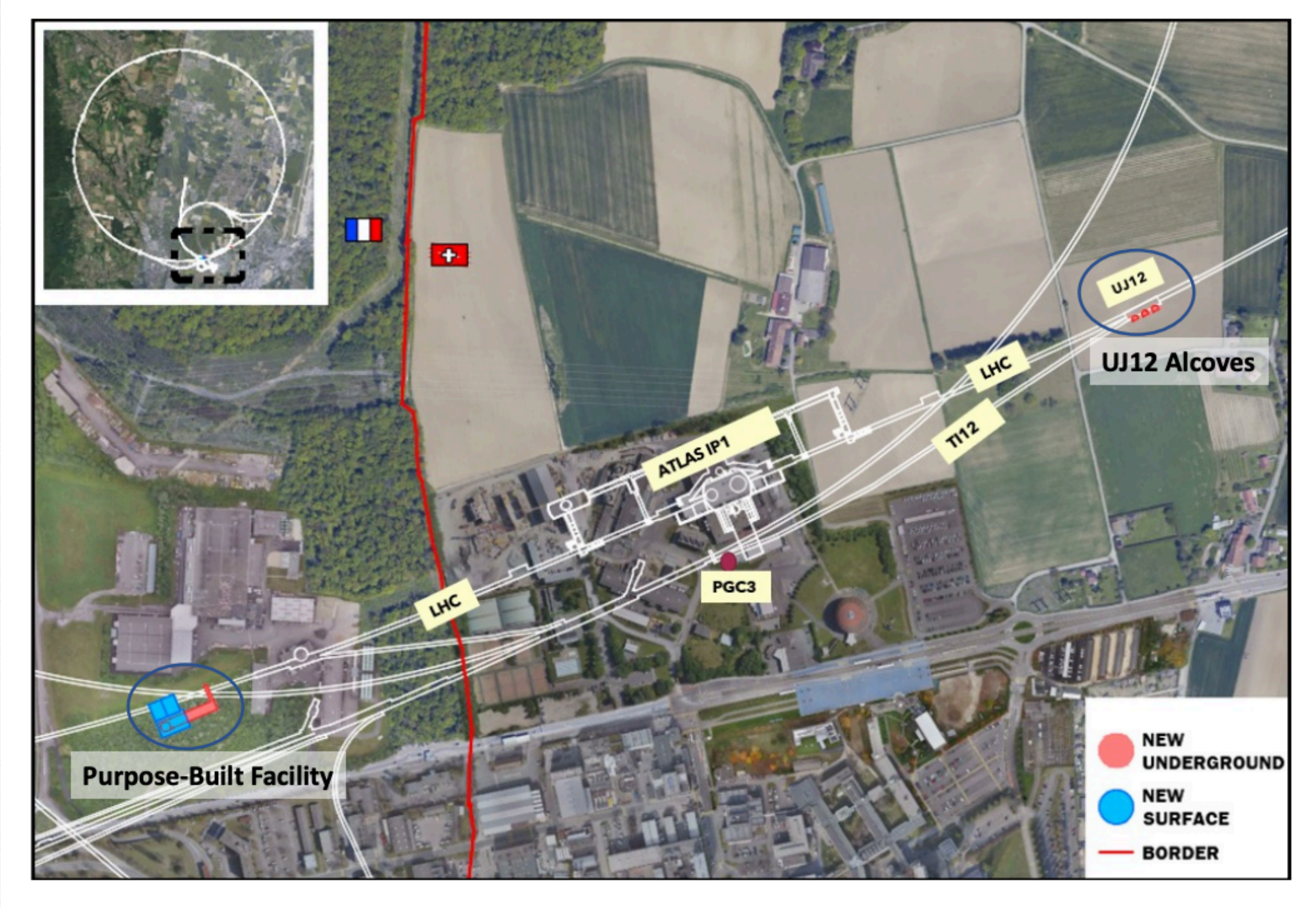
arXiv:2109.10905

BNL-222142-2021-FORE, CERN-PBC-Notes-2021-025, DESY-21-142, FERMILAB-CONF-21-452-AE-E-ND-PPD-T
KYUSHU-RCAPP-2021-01, LU TP 21-36, PITT-PACC-2118, SMU-HEP-21-10, UCI-TR-2021-22

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

Forward Physics Facility: a proposal for a new cavern for forward physics in the HL-LHC era, including three neutrino experiments

III. Proposed Experiments
- A. FASER2
- B. FASERν2
- C. Advanced SND@LHC
- D. FLArE: Forward Liquid Argon Experiment
- E. FORMOSA: FORward MicrOcharge SeArch



FUTURE: FORWARD PHYSICS FACILITY

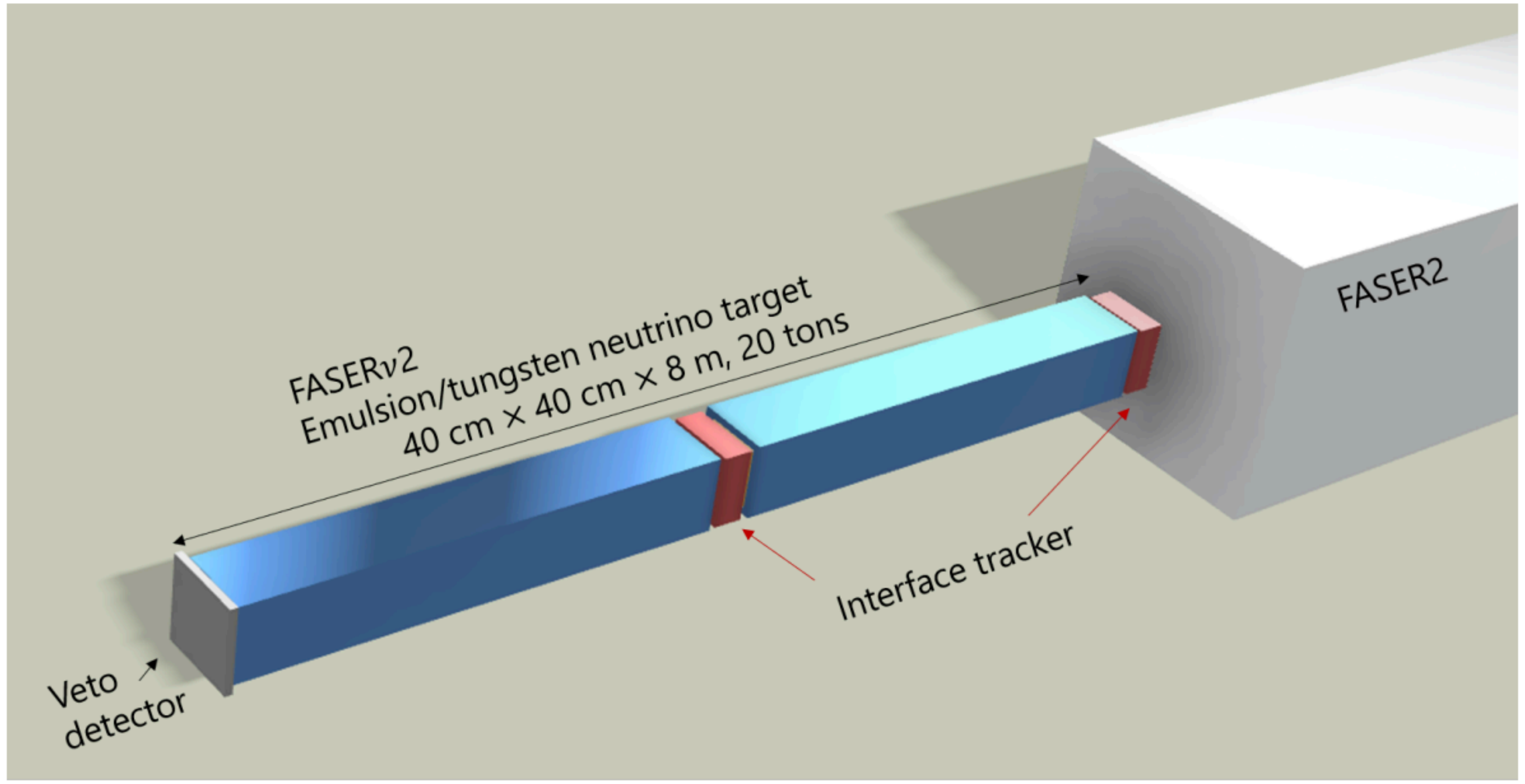
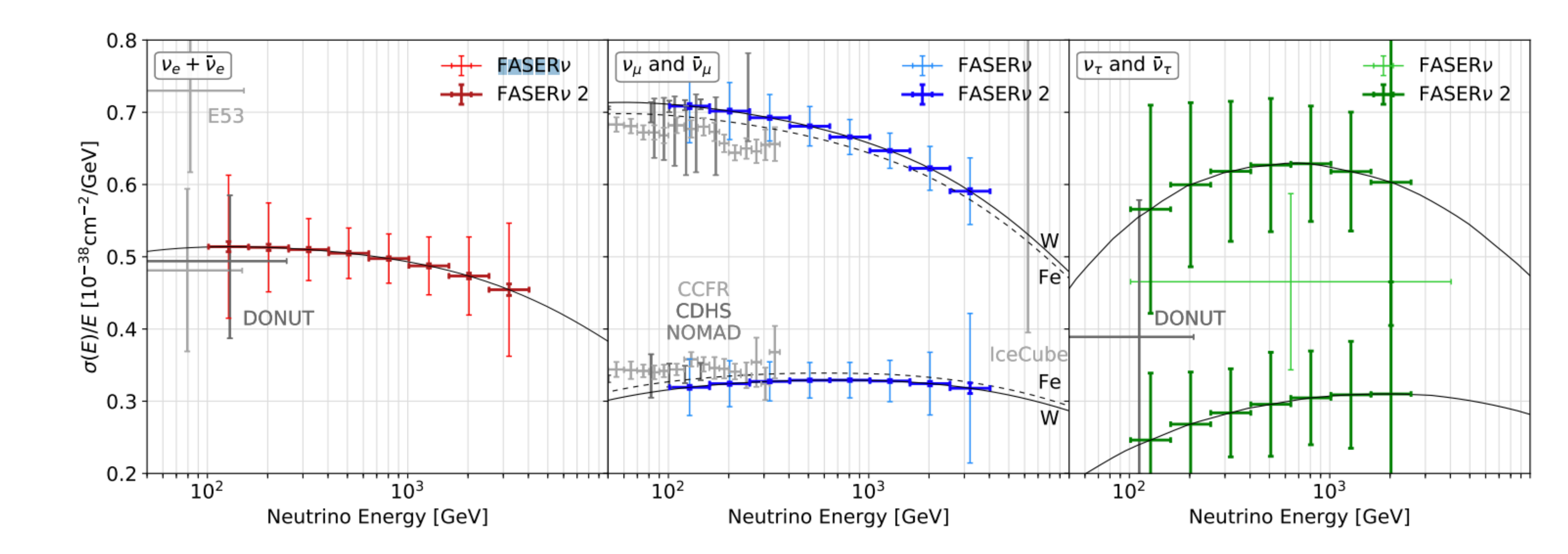
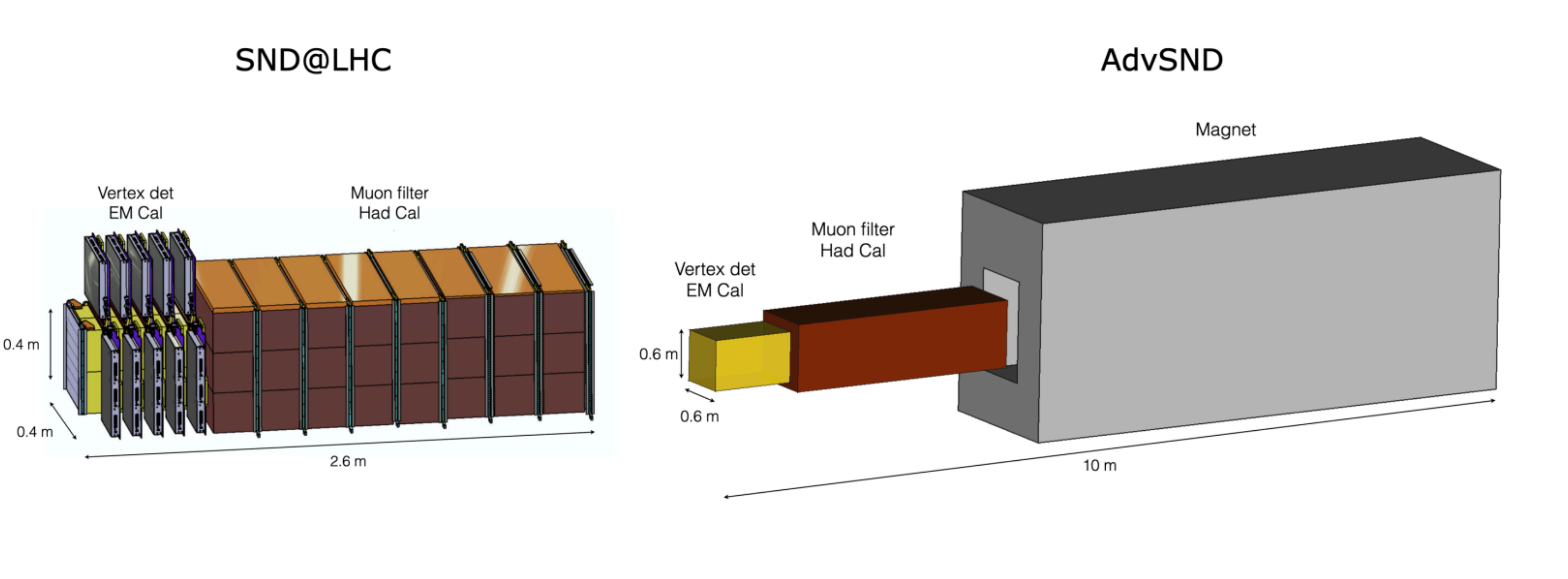


FIG. 11. Conceptual design of the FASERν2 detector.



- FASERν2:
  - **10 x mass and 20 x luminosity** of FASERν
  - Of order of 10^5 ν_e, 10^6 ν_μ, and 10^3 ν_τ
  - **High rate of muons** from LHC might be a limiting factor
    - Studies underway on adding an upstream magnet to reduce background
  - Magnetized detector components would facilitate **separation of ν_τ and anti-ν_τ**

FUTURE: FORWARD PHYSICS FACILITY

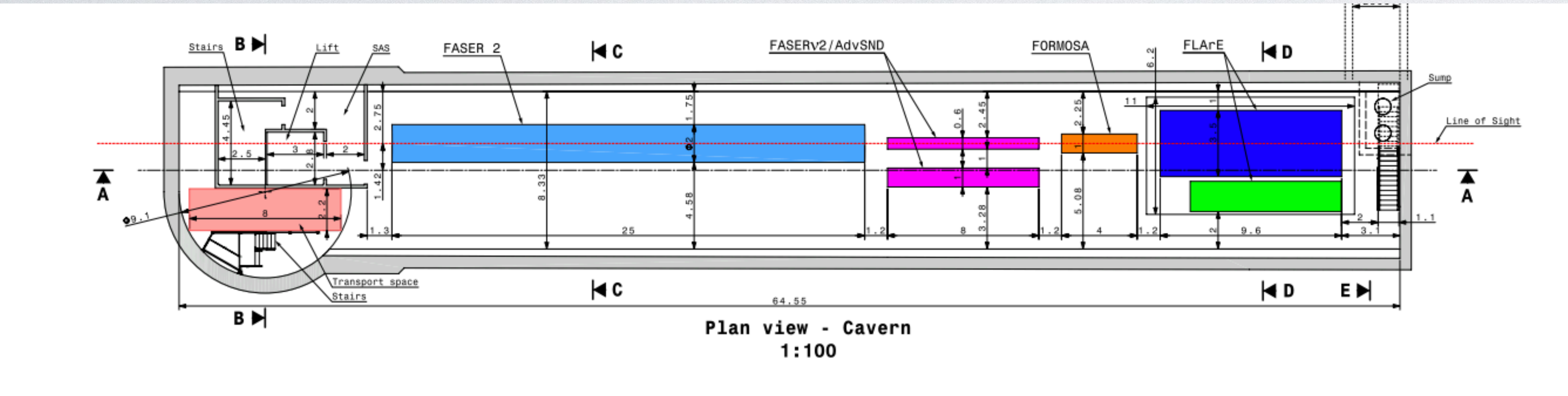


- **SND@LHC is envisioning two upgraded detectors** at different off axis angles
  - One inside the FPF with angular coverage **similar to SND@LHC**
  - One in a separate location w/ **overlaps with LHCb rapidity** to reduce systematics

- Also studying addition of an **upstream sweeper magnet**
- Also considering alternative(?) to emulsion "use of **compact electronic trackers with high spatial resolution** fulfilling both tasks of vertex reconstruction with micrometer accuracy and electromagnetic energy measurement"

FUTURE: FLARE

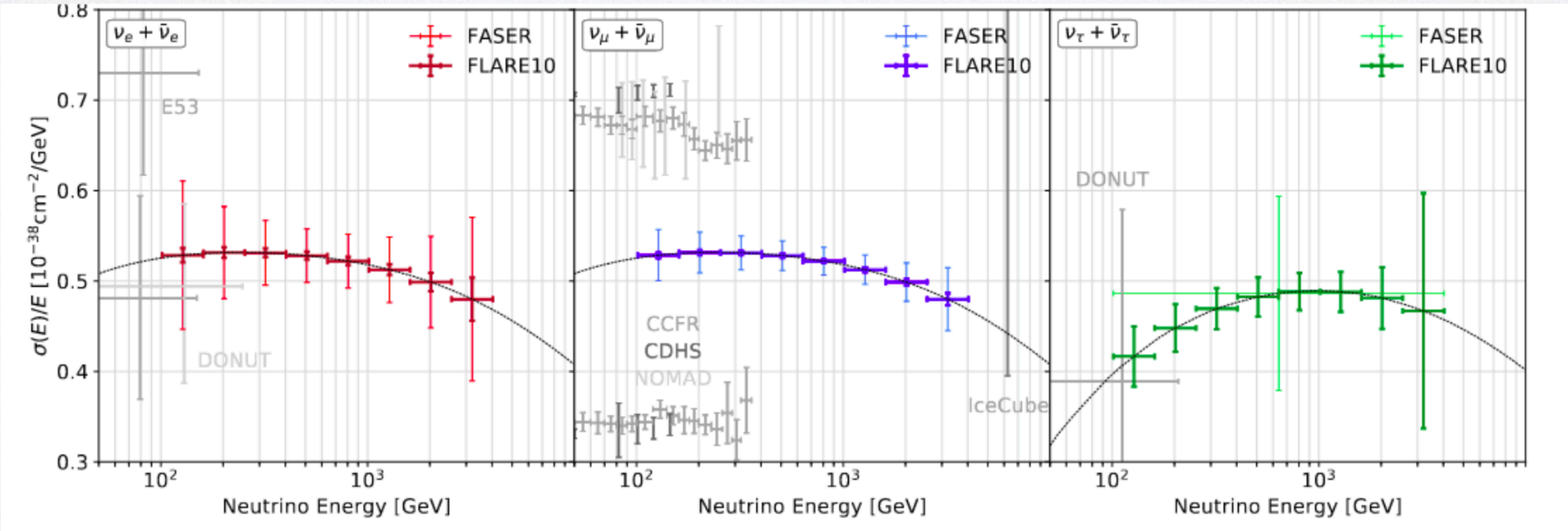
One possible configuration of FPF



- FPF is also considering a **liquid Argon TPC**
- **FLaRE**: a 10-ton LArTPC + scintillation light detection
- Build on CERN's experience with ProtoDUNE
- Would collect **thousands of ν_τ**

- Precise capability to reconstruct tau and reject background **needs further study**
- Would also be key element of FPF searches for **light dark matter**

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



FUTURE: DUAL PHASE READOUT LARTPC

- Although not currently planned for a detector, the **possibility of sub-millimeter pitch LArTPCs** for studying NuTaus is also being considered:

Snowmass2021 - Letter of Interest

Dual-Readout Time Projection Chamber: exploring sub-millimeter pitch for directional dark matter and tau identification in ν_τCC interactions.

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Abstract
We propose the development of Dual-Readout Time Projection Chambers (TPC) capable of submillimeter tracking resolution via the readout of positive ions at the cathode. Detection at micron-scale pitches in massive detectors implies major technological challenges. However, there are several emerging technologies that may make micron-scale tracking of ions a reality during the next Snowmass period, enabling such a detector to be realized at scale. If it can be demonstrated, such a technology has the potential to push DM detection under the neutrino floor sensitivity and unlock a full exploration of nu tau interactions, two of the most burning questions in contemporary and foreseeable future particle physics.

CONCLUSION

- So far, we have seen **19 tau neutrino candidates** from artificial sources
- We will see a few more from **SND@LHC and FASERν** during LHC run-3
- In the longer term, we will see a lot more from **SHiP, DUNE**, and the experiments at the **Forward Physics Facility**
- Most of these **rely heavily on emulsion** for ν_τ identification, but DUNE (and others?) will attempt it with a **Liquid Argon TPC**
- ν_τ reconstruction is **a challenge, but a rewarding one**
- You can look forward to more details on all of these experiments at this workshop

Thanks for Listening!

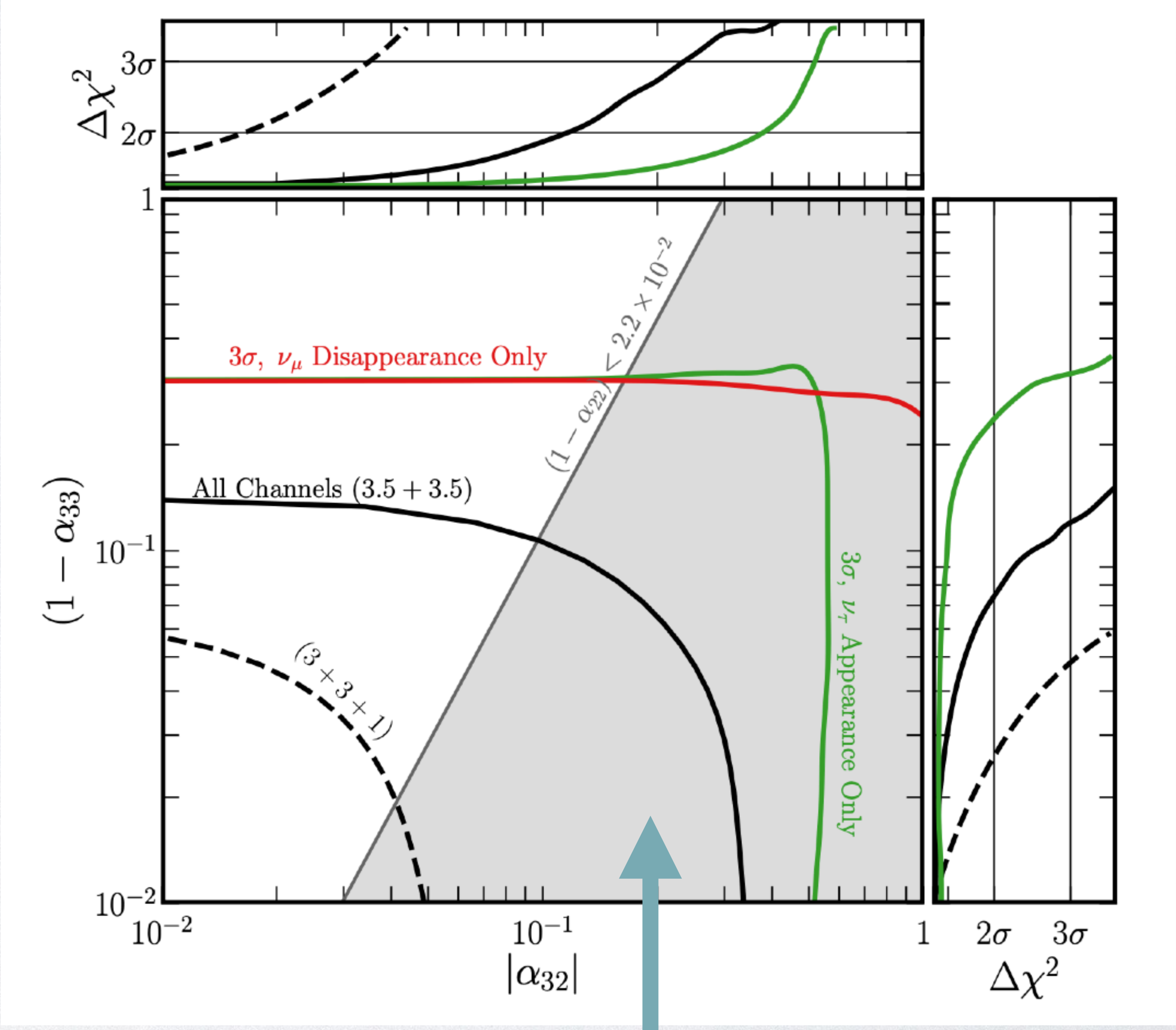
Also: Thanks to the people who helped me locate material for this talk, including Felix Kling, Albert De Roeck, and Adam Aurisano

BACKUP

FUTURE: DUNE

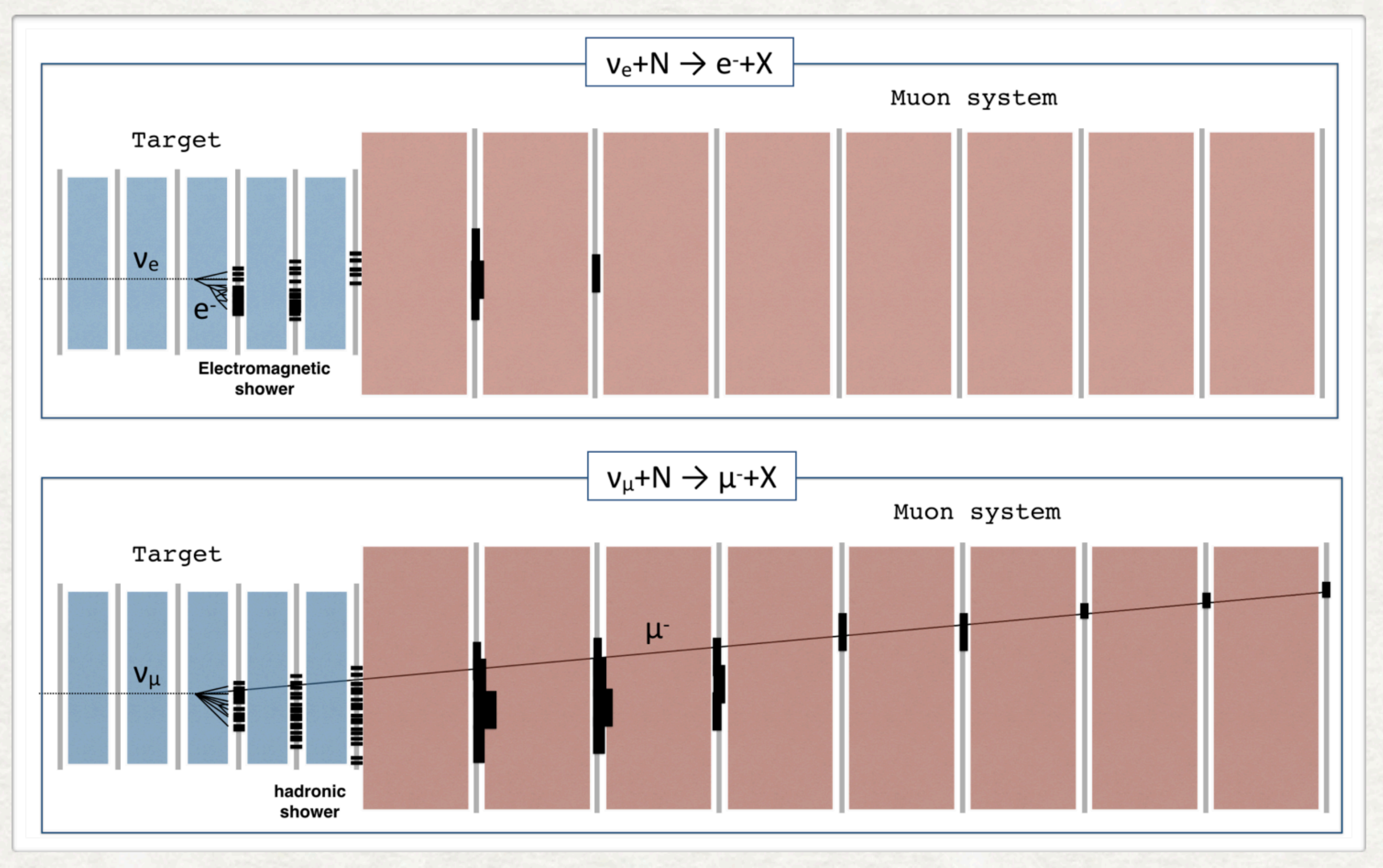
Shamelessly stolen from:
Phys. Rev. D 100, 016004 (2019) de Gouvêa, Kelly, Stenico, Pasquini

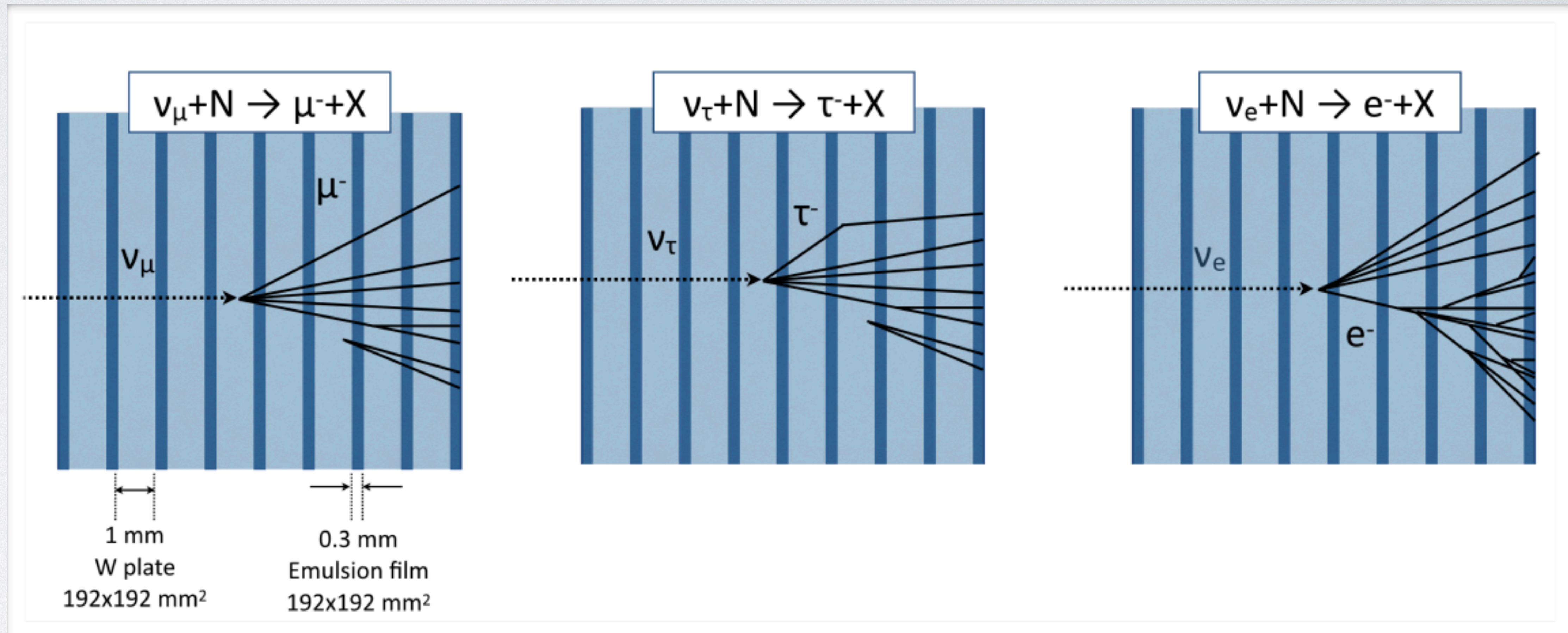
- **What will we learn** from ν_τ at DUNE?
  - Assuming 3-flavor unitarity, can **ν_τ charged-current cross section** on argon (with sensitivity to F_4 and F_5 structure functions)
  - Assuming cross section prediction, can measure **3-flavor oscillation parameters**
    - Generally not competitive with measurements using ν_e appearance and ν_μ disappearance, but an **important test of PMNS unitarity**
    - Estimates indicate that DUNE can **constrain the unitarity of the 3rd column to ~5%**
  - Searches for **new physics**: light and heavy steriles, NSI



DUNE Sensitivity to parameters of one non-unitarity scenario — adding ντ improves sensitivity, as does 1 year of running in a tau optimized beam.

FUTURE: SND@LHC





A. Di Crescenzo

- Reconstruction proceeds in **two stages**, first with electronic detectors, then adding fine-detail from emulsion
  - Emulsion allows **identification of ν_τ via kink**