Looking Forward to Tau Neutrinos at CERN -- Experimental Part

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CERN, Geneva, Switzerland

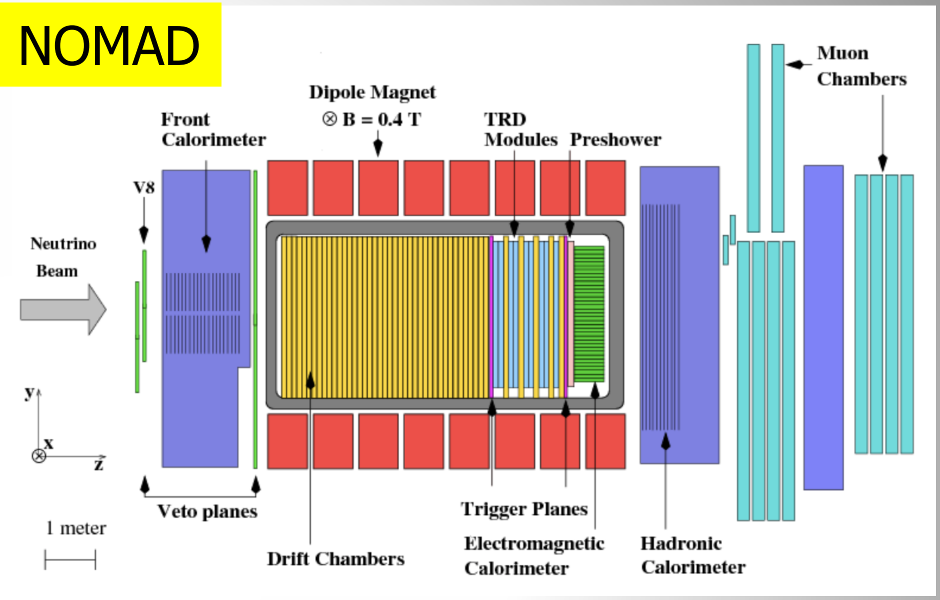
29th September 2021

Neutrinos @ CERN

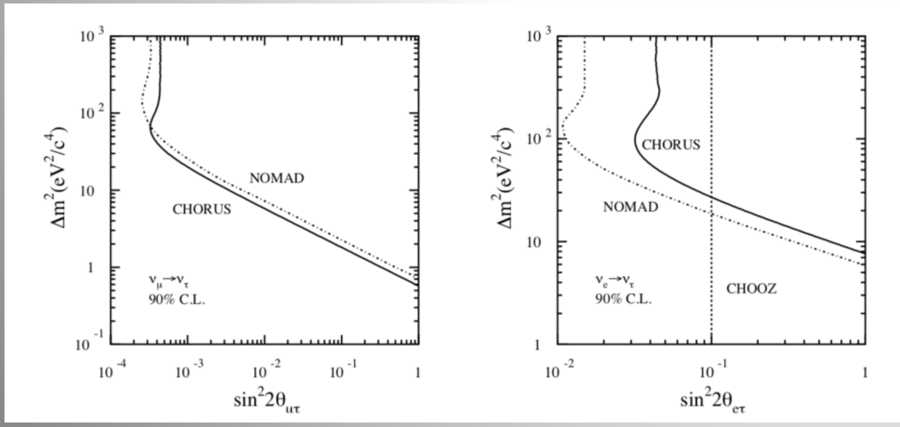
- CERN had a very significant neutrino program starting in 1963 untill about 2000
- Experiments such as Gargamelle, BEBC, CDHS, CHARM-I and II, CHORUS, NOMAD…
- OPERA located in Gran Sasso with CNGS beam from CERN
- Now: revitalized neutrino program @ CERN via
  - The Neutrino Platform and experiments at FNAL/Japan
  - Opportunity for neutrino physics at the LHC
  - Proposed beam dump for experiments e.g. SHiP
  - Dedicated fixed target experiments (NA61, NA65)

Neutrino History @ CERN

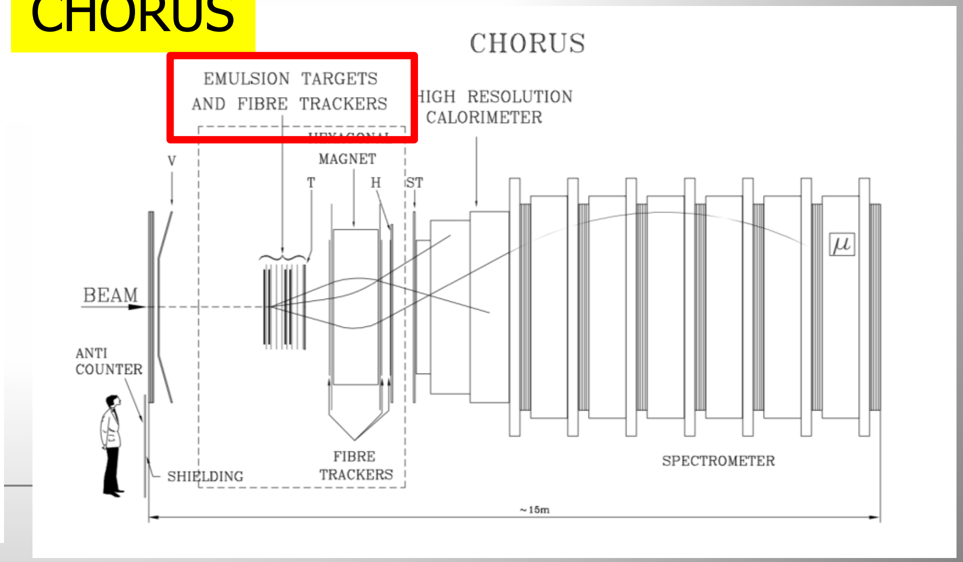
NOMAD



Final results on $\nu_\mu \rightarrow \nu_\tau$ oscillation from the CHORUS experiment arXiv:0710.3361

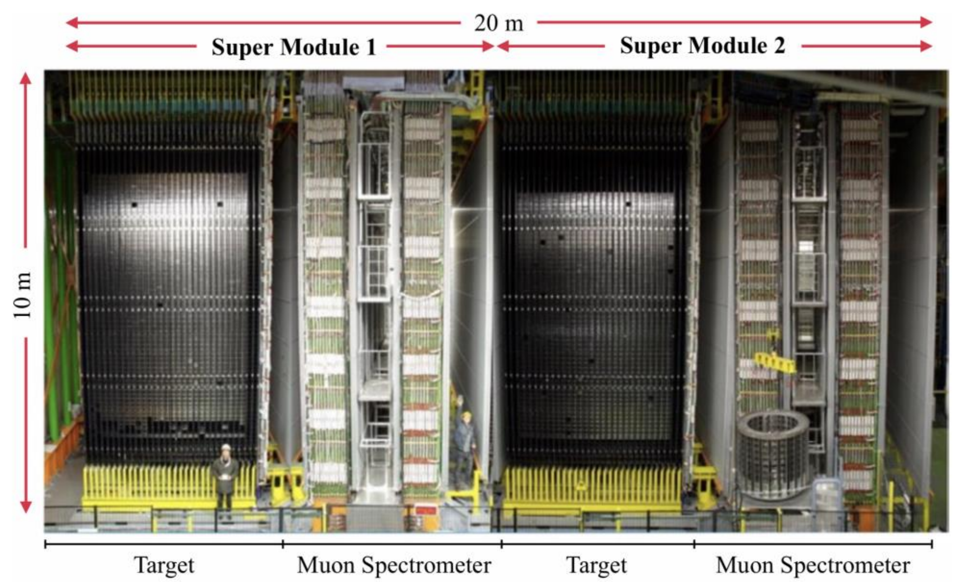


CHORUS



The OPERA Experiment

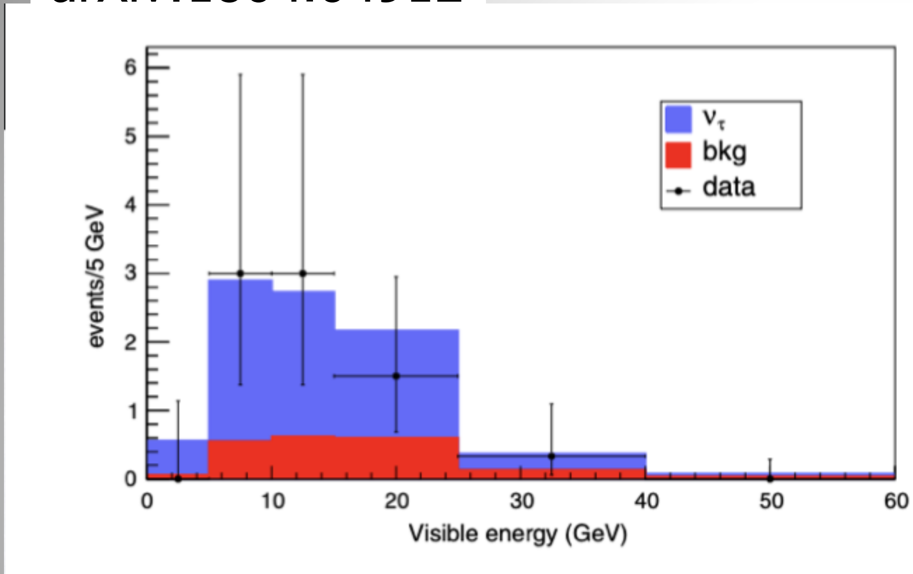
Data taking: 01-01-2008
23-09-2013

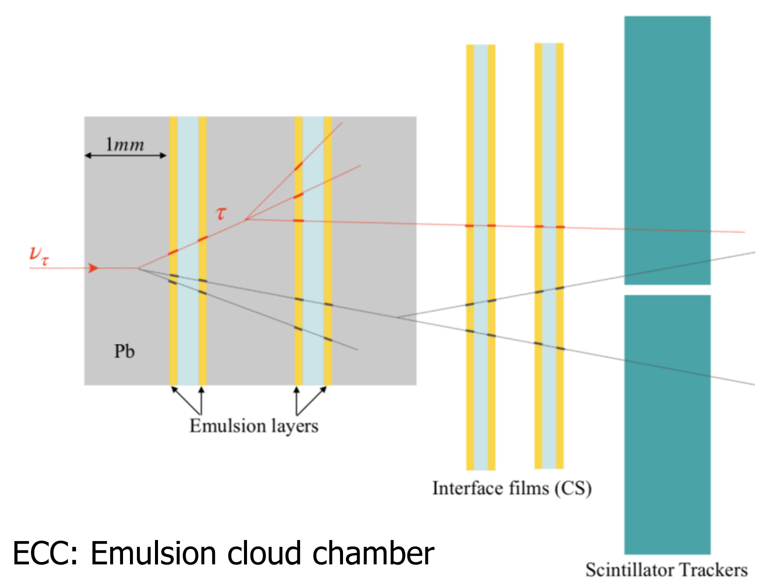


- The OPERA experiment was designed to discover the $\boldsymbol{\nu}_\tau$ appearance in a $\boldsymbol{\nu}_\mu$ beam, from neutrino oscillations.
- Nuclear photographic emulsion/lead target with a mass of about 1.25 kt, with a baseline of 730 km collecting a total of $1.8 \cdot 10^{20}$ protons on target
- The OPERA Collaboration eventually assessed the discovery of $\boldsymbol{\nu}_\mu \rightarrow \boldsymbol{\nu}_\tau$ oscillations with a statistical significance of 6.1σ by observing ten $\boldsymbol{\nu}_\tau$ CC interaction candidates.
- These events have been published on the Open Data Portal at CERN, and in a detailed description of the $\boldsymbol{\nu}_\tau$ data sample to make it usable by the whole community: Scientific Data Vol 8 218 (2021)

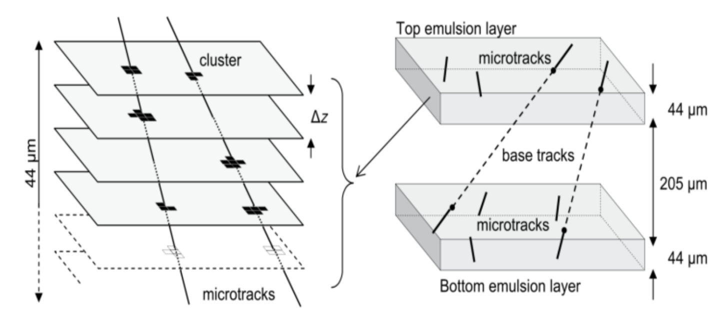
The OPERA Experiment

arXiv:1804.04912

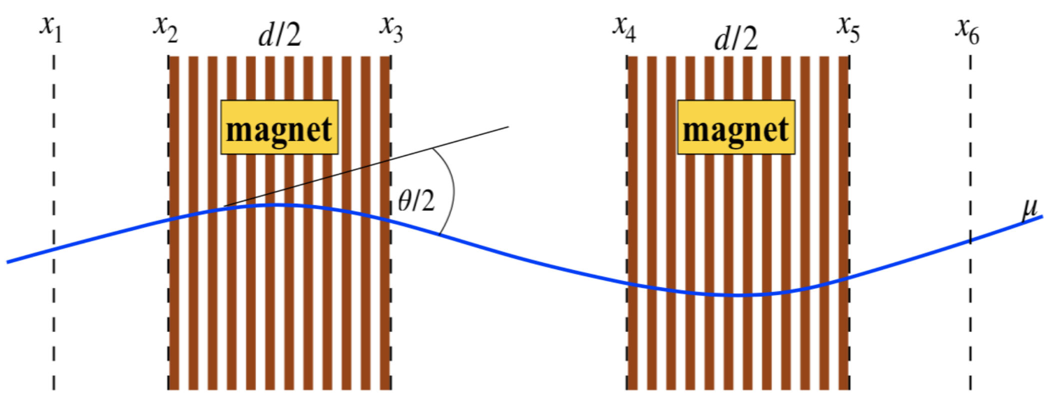




ECC: Emulsion cloud chamber



micro-track reconstruction.



The muon spectrometer

NA65: DsTau Experiment

Measure differentally Ds->tau production to improve tau-neutrino flux precision

Osamu Satu/FPF meeting

DsTau Roadmap

Pilot run 2018 Aug. @H2
Accumulated ~**1.8 · 10^7** interactions

Test beam 2016
- Test of the detector structure

Test beam 2017
- Improved detector structure
- Refine exposure scheme

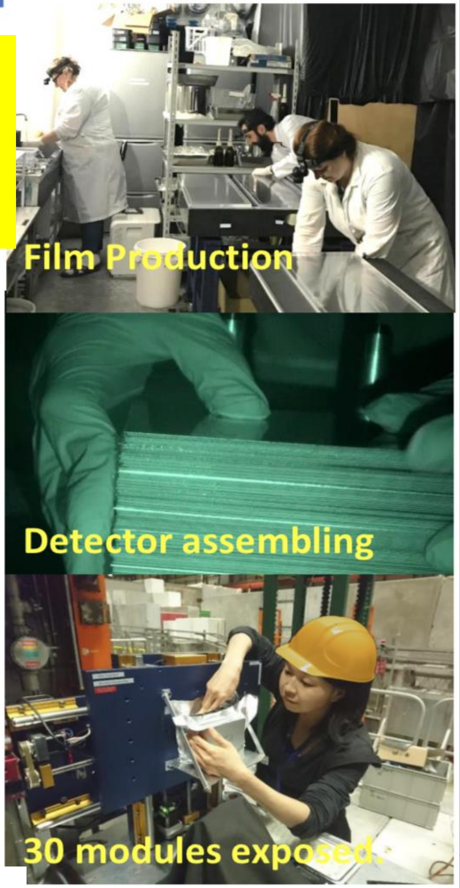
Pilot run 2018
- **1/10** of the full-scale experiment with tungsten target .
- ν_τ flux ~30% uncertainty
- Revise the DONUT result
- Charm physics

Now

Physics run 2021-2022
- **Full scale** experiment with tungsten and molybdenum targets
- Aiming detect **1000** $D_s \rightarrow \tau \rightarrow X$ events
- ν_τ flux~10%

CERN fixed target exp. at the SPS

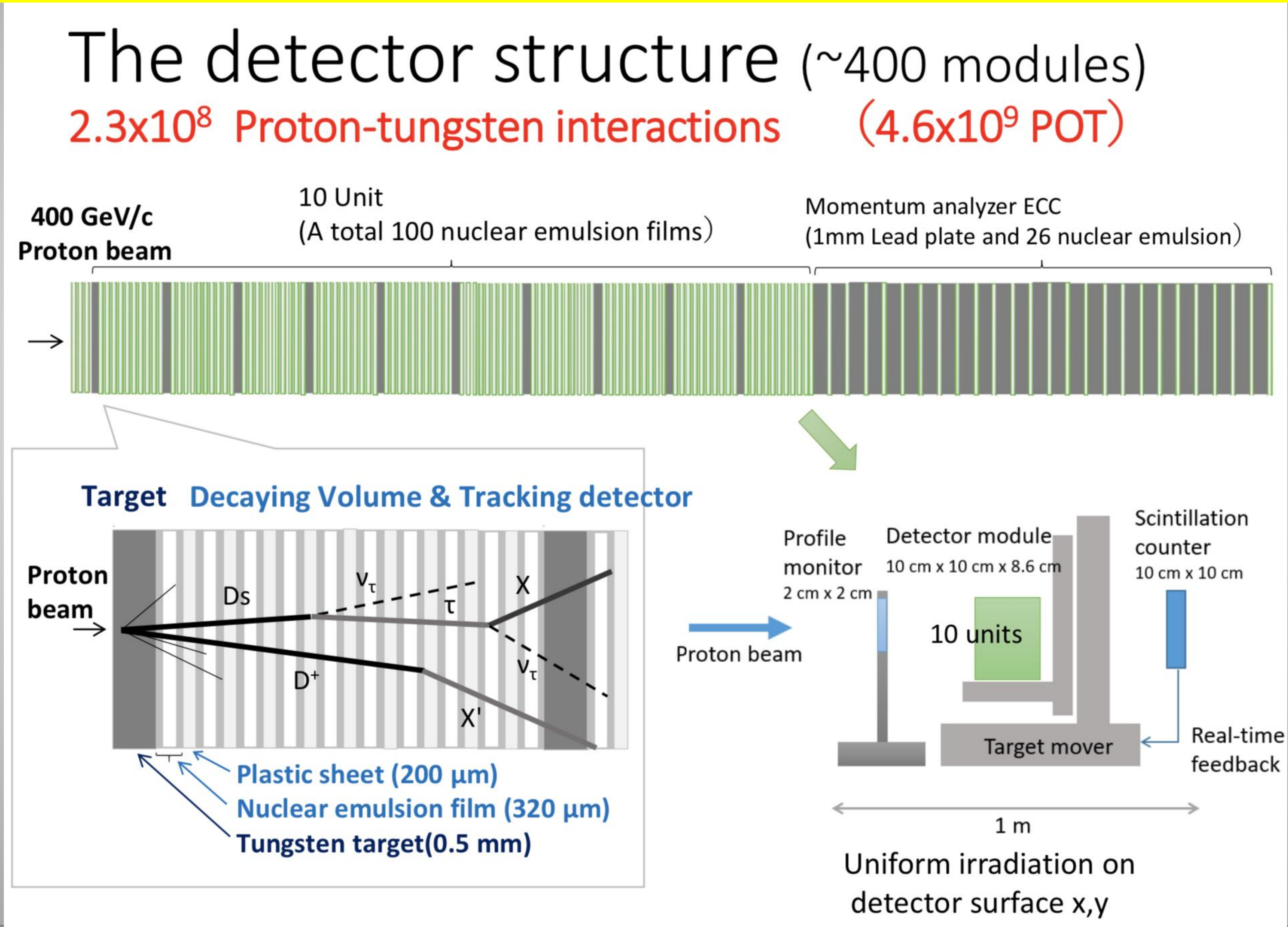
Approved as NA65



Run taking place now!

NA65: DsTau Experiment

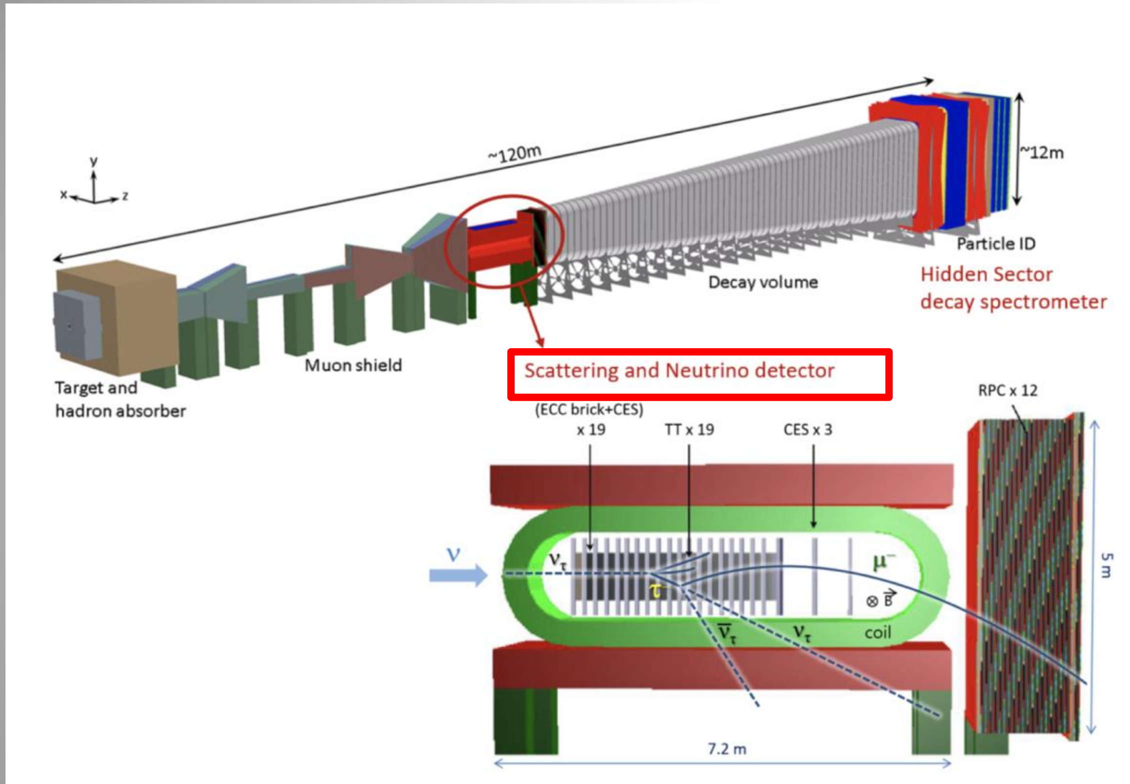
Measure differentally Ds->tau production to improve tau-neutrino flux precision



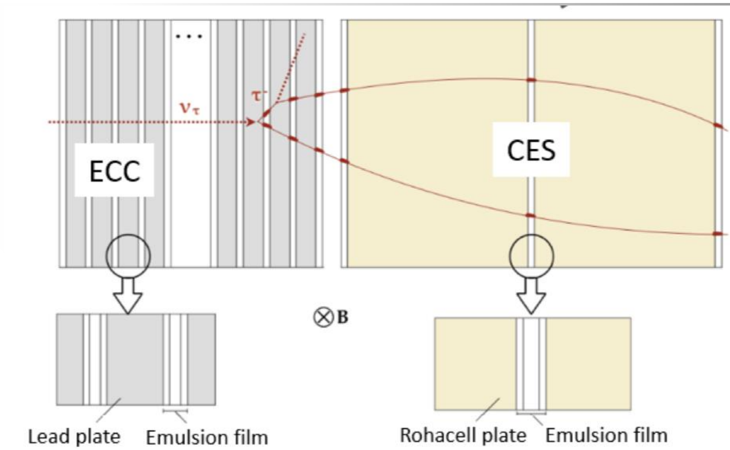
Goal: For beamdump expts: reduce the flux uncertainty 50%->10%

The SHiP Experiment

The Search for Hidden Particles



SHiP has a neutrino program in particular for tau-neutrinos



ECC:Emulsion Cloud Chamber

Beam dump experiment: 400 GeV protons
Total of 2×10^{20} protons in five years

R&D on the BDF/Detectors continuing.
Comprehensive design study by end of 2024

C.S Yoon Nufact19

Detectable interactions/5 year

Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to e$	1000	700
Total	6200	4700

Neutrinos at Colliders

1984: A. De Rujula and R. Ruckl: using colliders as a neutrino source (*)
1990-1993: Further discussion by K. Winter, F. Vanucci, A. De Rujula et al…

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.

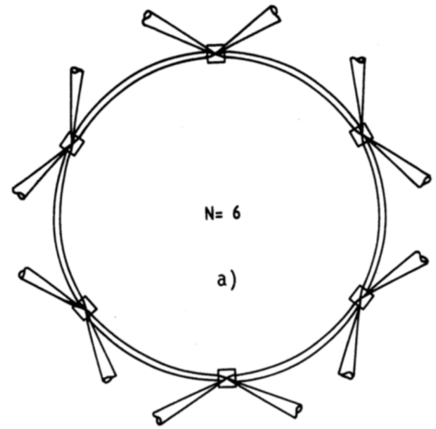
I. INTRODUCTION

The interactions of muons and muon-neutrinos with nucleons have not been experimentally studied with beams of energy in the TeV range. The $\nu_e N$ interactions have been analysed in detail only at energies characteristic of β-decay. Not a single ν_τ has ever been seen to interact in a detector. These are sufficient reasons to justify a ν_e, ν_μ, ν_τ "program" at any future high energy facility, but one can say even more.

$$\Phi_0(\mathrm{LHC}) = \frac{7.25\cdot 10^6}{\mathrm{sec}}\left(\mathcal{L}/10^{33}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\right)$$

$$\Phi_0(\mathrm{SSC}) = \frac{8.65\cdot 10^6}{\mathrm{sec}}\left(\mathcal{L}/10^{33}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\right)$$

(*) CERN-ECFA workshop on hadron Colliders on the LEP tunnel (1984)



Forward production of neutrinos

3

Number of neutrino interactions in a "standard detector" (defined in text) per 10^7 seconds of running with $\mathcal{L} = 10^{33}\ \mathrm{cm^{-2}\,s^{-1}}$

		ν_e from D (= ν_μ from D)	$\bar\nu_e$ from $\bar D$ (= ν_μ from $\bar D$)	ν_e from F^+ (= ν_μ from F^+)	$\bar\nu_e$ from F^- (= $\bar\nu_\mu$ from F^-)	ν_e from Λ_c (= ν_μ from Λ_c)	ν_τ from $F^- \to \tau^- \to \nu_\tau$ plus $F^+ \to \nu_\tau$	$\bar\nu_\tau$ from $F^- \to \tau^+ \to \bar\nu_\tau$ plus $F^- \to \bar\nu_\tau$	Total neutrino interactions
LHC	opt.	8.4×10^4	4.6×10^4	6.3×10^4	3.5×10^4	6.7×10^4	1.1×10^4	3.9×10^3	6.2×10^5
	pess.	8.9×10^4	4.9×10^4	3.3×10^4	1.8×10^4	3.7×10^4	2.9×10^3	1.0×10^3	4.6×10^5
SSC	opt.	2.5×10^5	1.4×10^5	1.9×10^5	1.1×10^5	2.0×10^5	3.3×10^4	1.2×10^4	1.9×10^6
	pess.	2.7×10^5	1.5×10^5	1.0×10^5	5.6×10^4	1.1×10^5	8.8×10^3	3.1×10^3	1.4×10^6

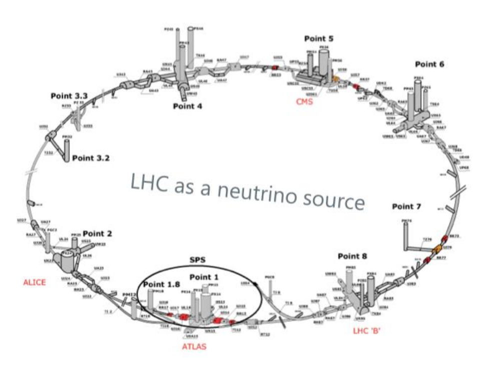
Table 4

Number of charged-current muon-induced interactions in the same conditions as in Table 3

		$\mu^+ \to \bar\nu_\mu$ from D	$\mu^- \to \nu_\mu$ from $\bar D$	$\mu^+ \to \bar\nu_\mu$ from F^+	$\mu^- \to \nu_\mu$ from F^-	$\mu^+ \to \bar\nu_\mu$ from Λ_c	Total CC μ-interactions
LHC	opt.	2.8×10^4	5.2×10^4	2.1×10^4	3.9×10^4	2.2×10^4	1.6×10^5
	pess.	3.2×10^4	5.8×10^4	1.2×10^4	2.2×10^4	1.3×10^4	1.4×10^5
SSC	opt.	8.6×10^4	1.6×10^5	6.5×10^4	1.2×10^5	6.9×10^4	5.0×10^5
	pess.	9.3×10^4	1.7×10^5	3.5×10^4	6.5×10^4	3.8×10^4	4.0×10^5

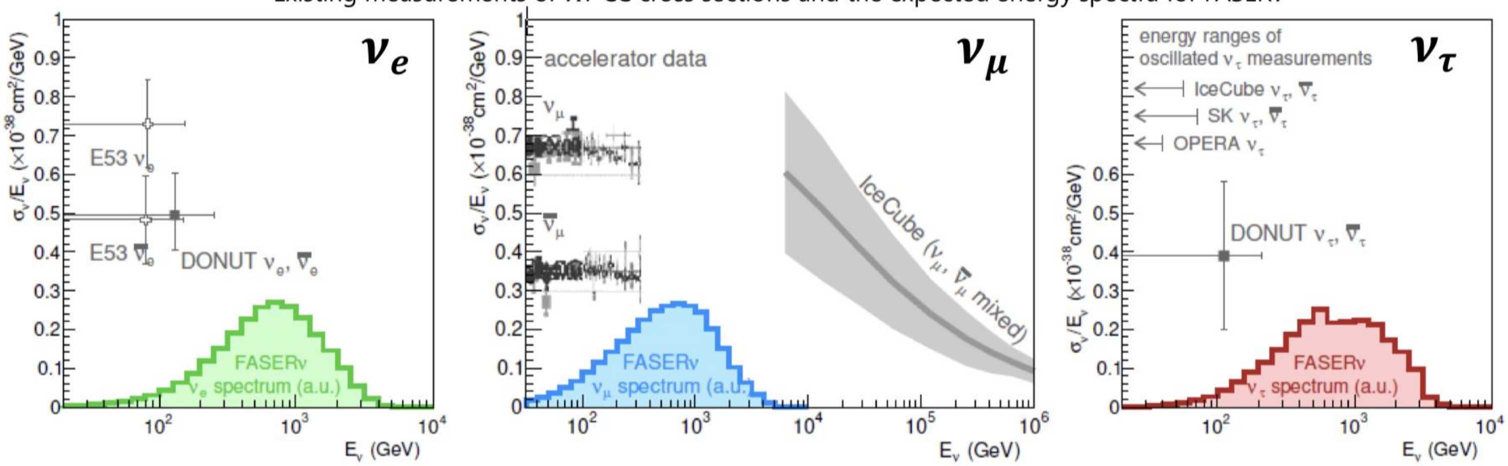
Abundant production of neutrinos at LHC!

2021: Neutrinos at the LHC



- **Studying neutrinos in unexplored energy regime (TeV energies)**
- Neutrinos from the LHC
  - First detection of collider neutrinos
  - High energy frontier of man-made neutrinos
- Cross section measurements of different flavours at high energy
- Probing neutrino-related models of new physics
- The contribution of the **τ** flavour to the neutrino flux is sizeable.

Existing measurements of νN CC cross sections and the expected energy spectra for FASERν



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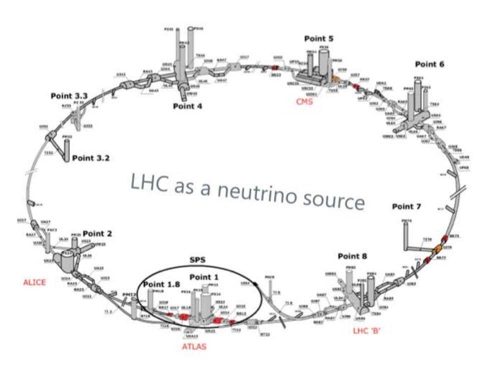

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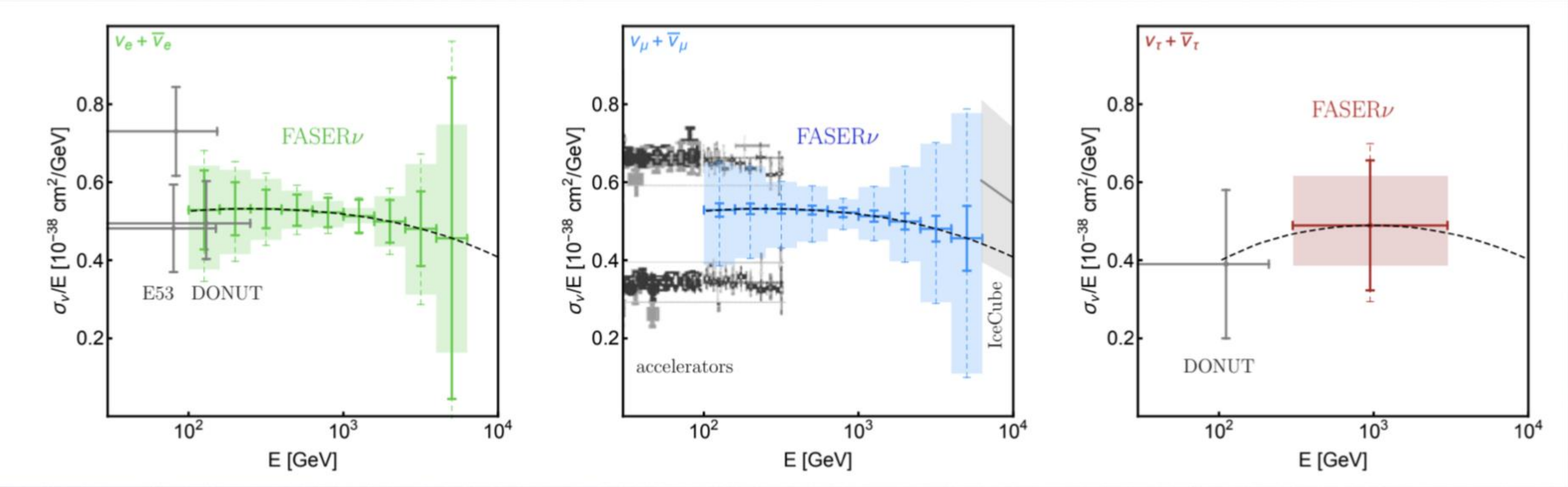
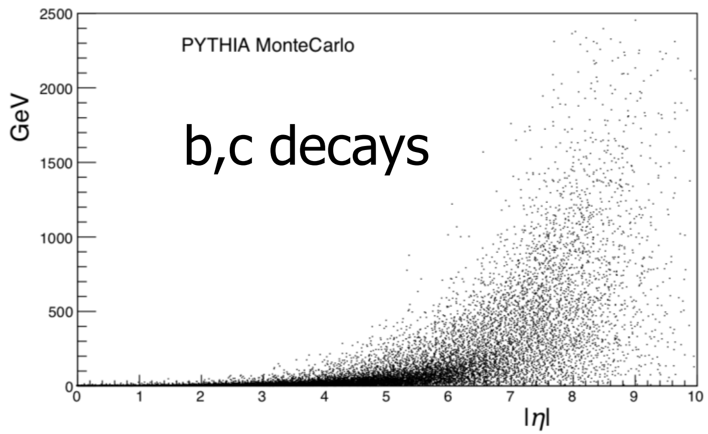


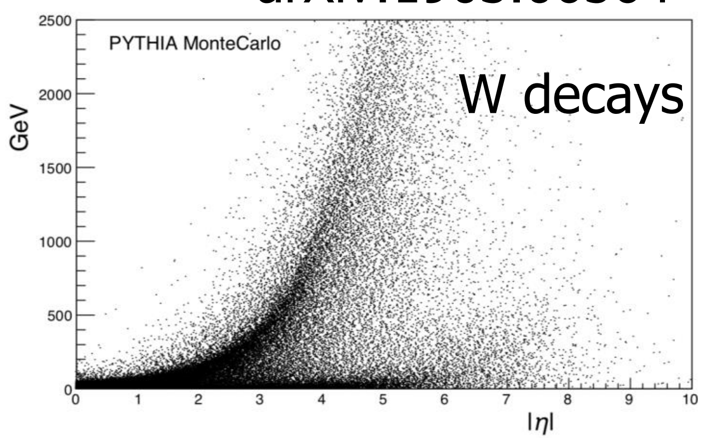
Neutrinos at the LHC

Several proposals were emerging at a similar time in 2018-2020: XSEN, FASER**ν**, SND@LHC, all based on the emulsion technique

- Flavour composition and energy reach of the neutrino flux from proton-proton collisions depend on the pseudorapidity η. At large η, energies can exceed the TeV, with a sizeable contribution of the **τ** flavour.
- A dedicated detector could intercept this intense neutrino flux in the forward direction, and measure the interaction cross section on nucleons in the unexplored energy range from a few hundred GeV to a few TeV. The high energies of neutrinos result in a larger **ν**N interaction cross section, and the detector size can be relatively small.



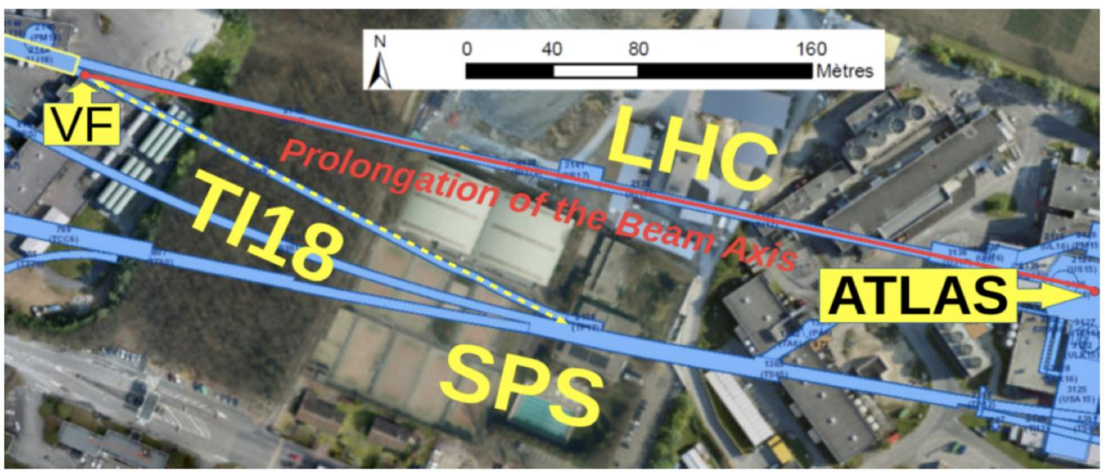
arXiv:1903.06564

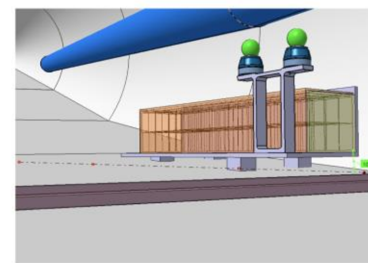


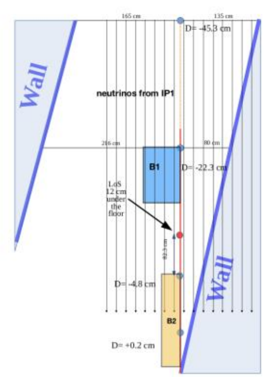
Neutrinos at the LHC: XSEN

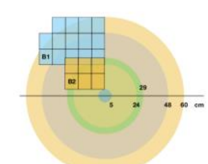
arXiv:1804.04413, arXiv:1903.06564

- Four locations were considered as hosts for a neutrino detector: 25 m. 90-120m and 240m from the CMS IP, and 480 m from ATLAS IP. TI18 emerges as the most favourable location.
- A small detector in TI18 could measure, for the first time, the high-energy **ν**N cross section, and separately for **τ** neutrinos, with good precision.









Neutrino Experiments at LHC

LETTER OF INTENT

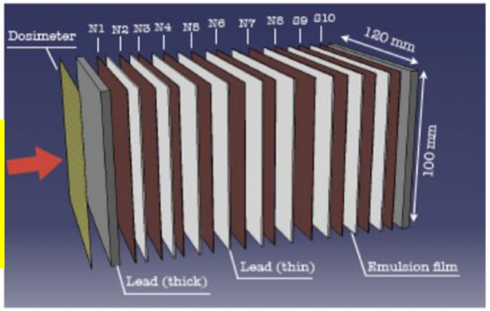
XSEN: a νN Cross Section Measurement using High Energy Neutrinos from pp collisions at the LHC

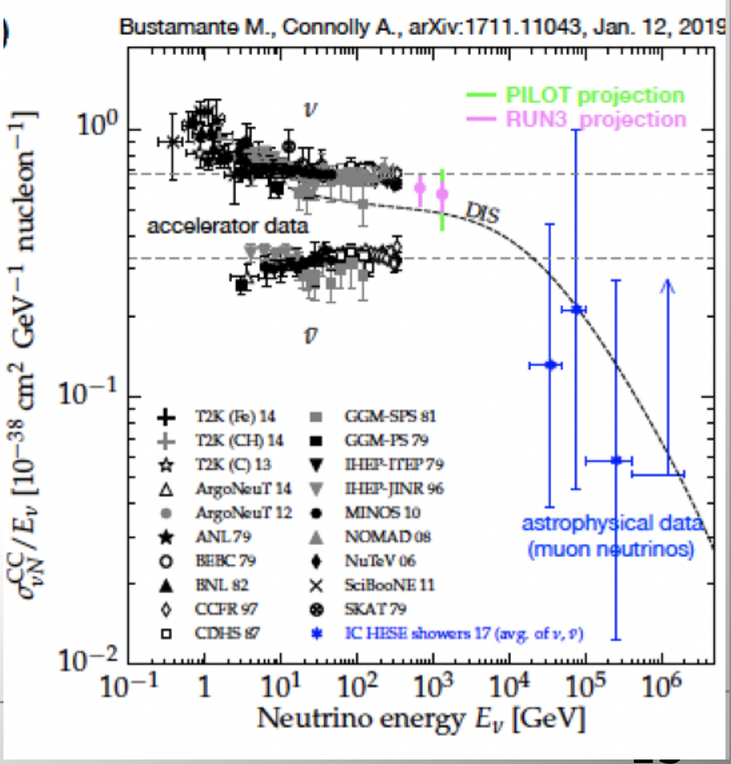
N. Beni[1,2], S. Buontempo[3], T. Camporesi[2], F. Cerutti[2], G.M. Dallavalle[4], G. De Lellis[2,3,5], A. De Roeck[2], A. De Rújula[6], A. Di Crescenzo[3,5], D. Fasanella[4], A. Ioannisyan[2,7], D. Lazic[8], A. Margotti[4], S. Lo Meo[4,9], F.L. Navarria[4], L. Patrizii[4], T. Rovelli[4], M. Sabaté-Gilarte[2], F. Sanchez Galan[2], P. Santos Diaz[2], G. Sirri[4], Z. Szillasi[1,2], C. Wulz [10]

arXiv:1910.11430

The XSEN experiment

- Emulsion only detector
- Stacks are "OPERA" style

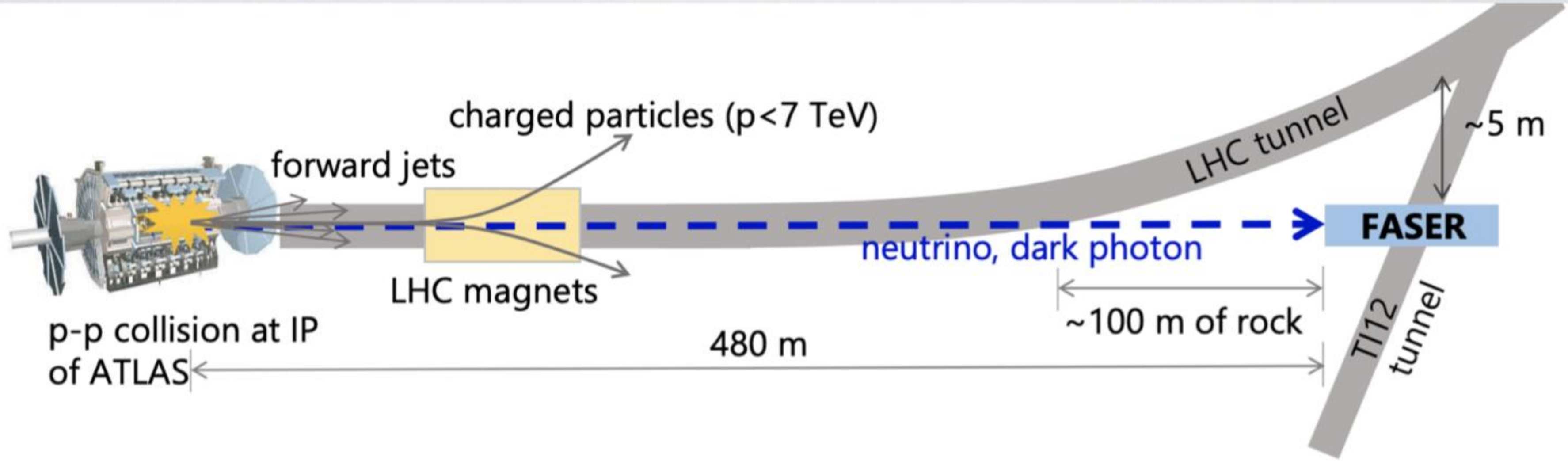




Plan was a 2-staged detector
- Pilot run with 0.5 ton mass first year
- Second run with 150 fb^{-1} with one (or two) detectors with 1.5 ton each
- Slightly off-axis for better b,c acceptance

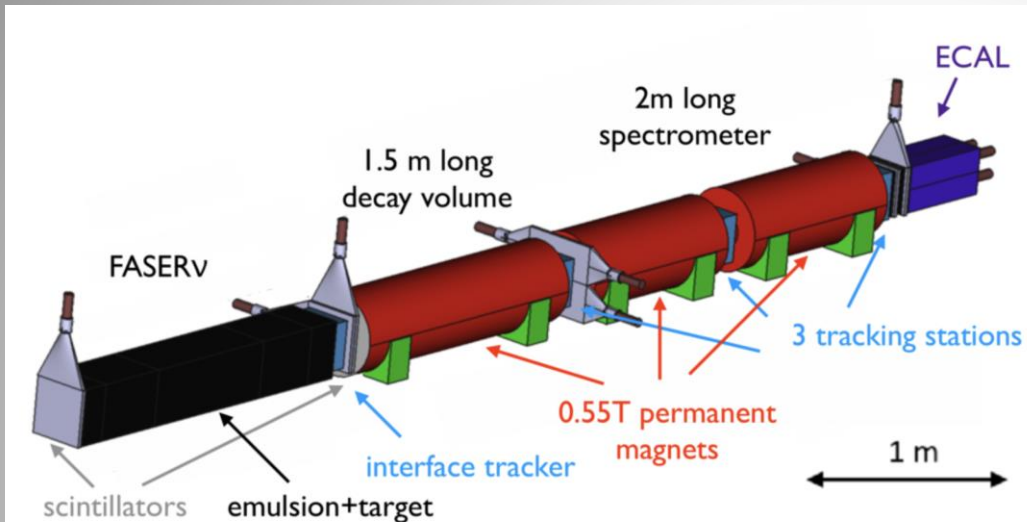
XSEN basically merged with SND@LHC

The FASER Experiment



- **FASER (new particle searches)** approved Mar. 2019.
  - Targeting light, weakly-coupled new particles at low p_T.
- **FASERν (neutrino measurements)** approved Dec. 2019.
  - First measurements of neutrinos from a collider and in unexplored energy regime.
- Detector now mostly installed and will be ready for Run 3 of the LHC starting spring 2022

The FASER Experiment



arXiv:1708.09389, arXiv:1811.10243

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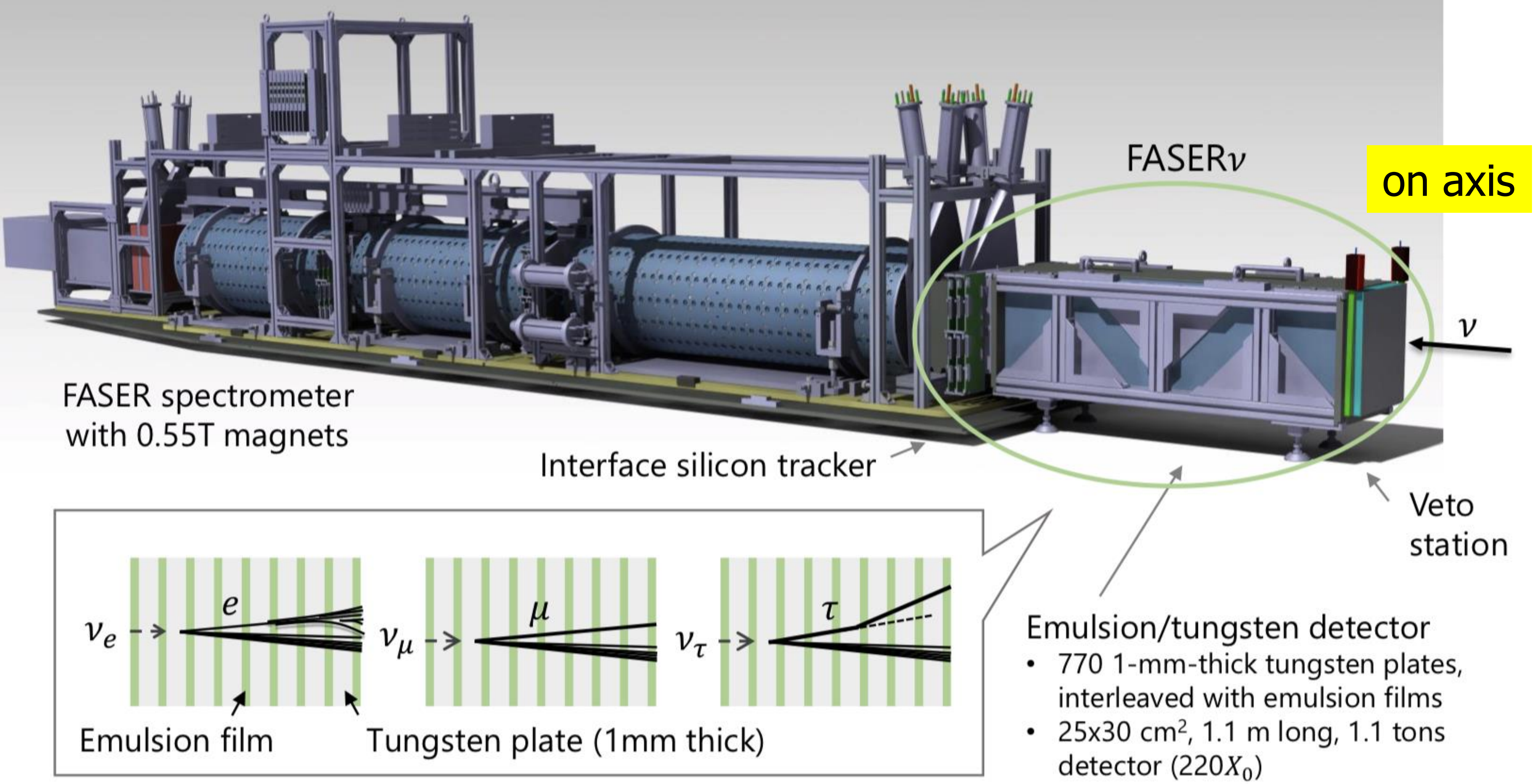
The FASERν Experiment

arXiv:1908.02310

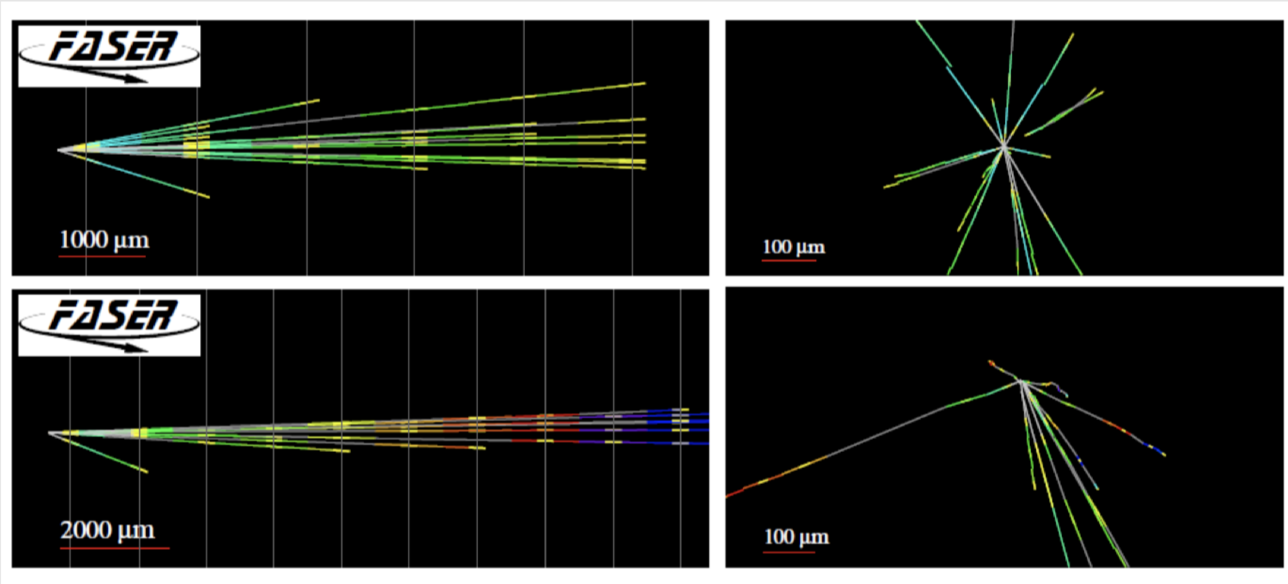


Emulsion/tungsten detector

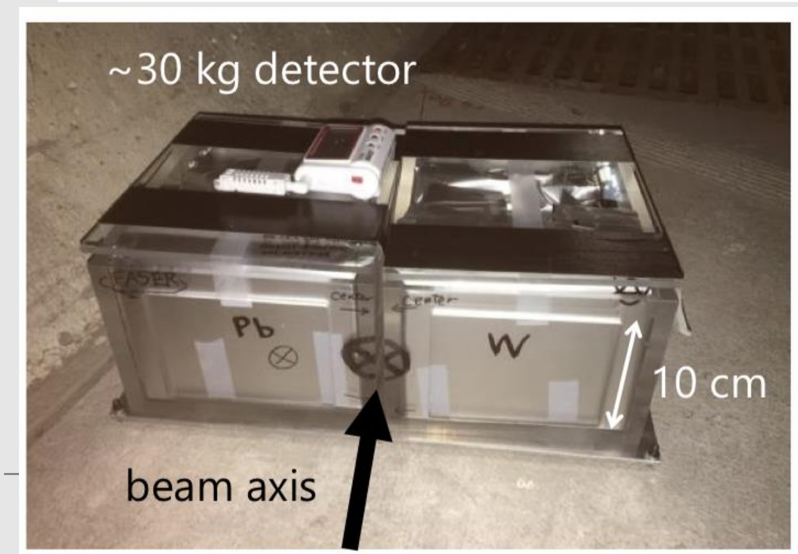
- 770 1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm^2, 1.1 m long, 1.1 tons detector ($220X_0$)

The FASERν Experiment

First Neutrino interaction candidates at the LHC



arXiv:2105.06197

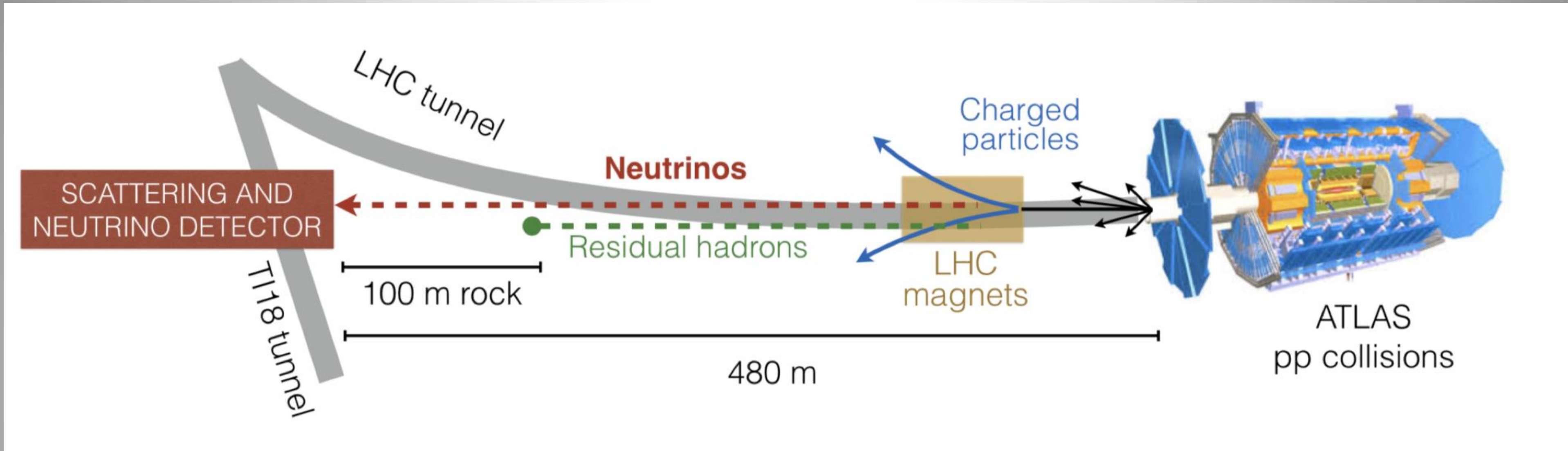


A 30 kg emulsion detector was installed in TI18 and 12.2 fb^{-1} data collected in 2018

Analyzed target mass 11 kg

In a BDT analysis, an excess of neutrino signal is observed with a statistical significance 2.7σ from null hypothesis

The SND@LHC Experiment

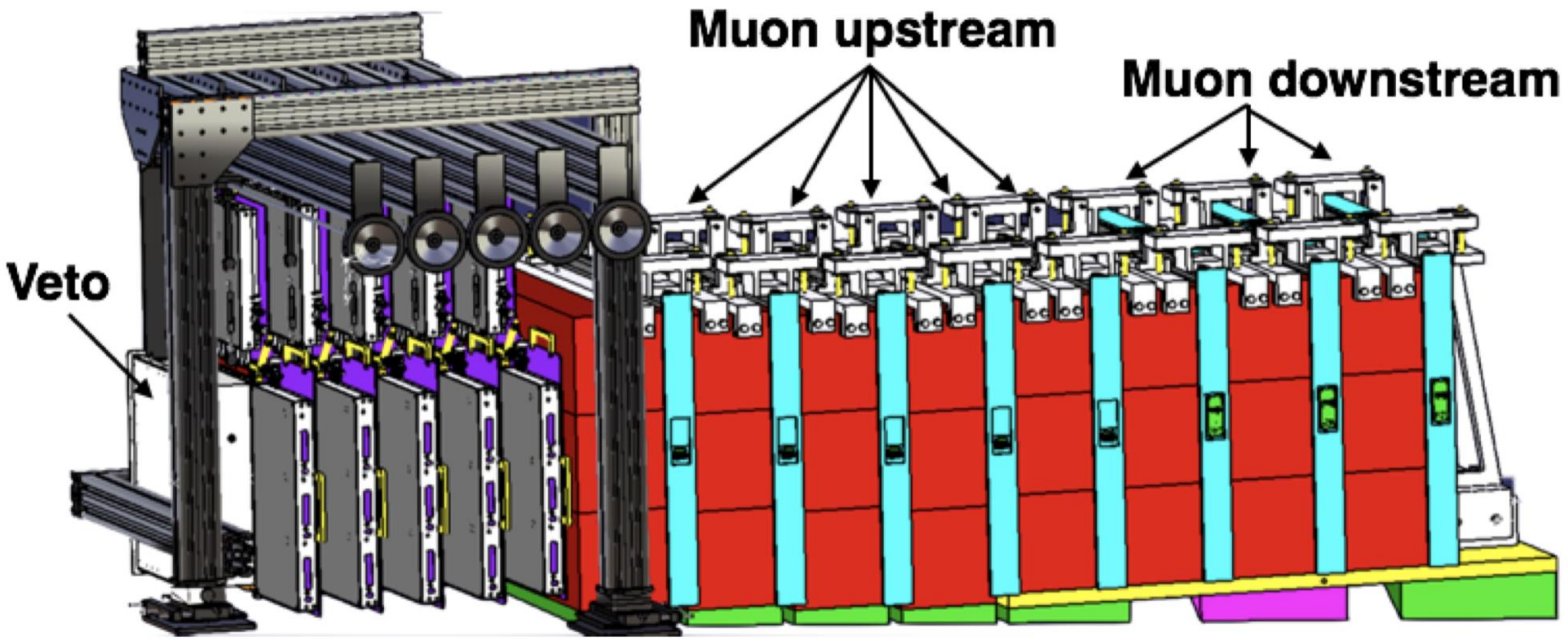


- Stand-alone experiment 480m downstream of IP1 in TI18 for neutrino measurements and searches for FIPs in the pseudorapidity region $7.2 < \eta < 8.7$ (off axis)
- Approved by the CERN Research Board on 17 March 2021 https://snd-lhc.web.cern.ch/
- Installation in the tunnel TI18 starting November 2021
- Aim to be ready for day 1 or Run 3 Spring 2022

The SND@LHC Experiment

A detector for neutrino interactions and searches for FIPs

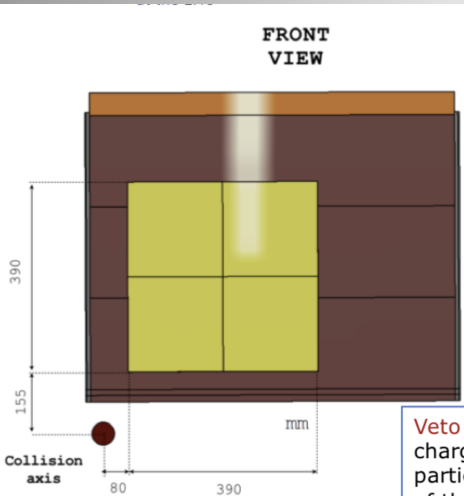
- Target is nuclear emulsion (ECC) plus scintilating fibre tracking
- Muon identification (scintillating bars), also for calorimetry (iron)



SND@LHC is a small-scale prototype of the scattering and neutrino detector of the SHiP experiment

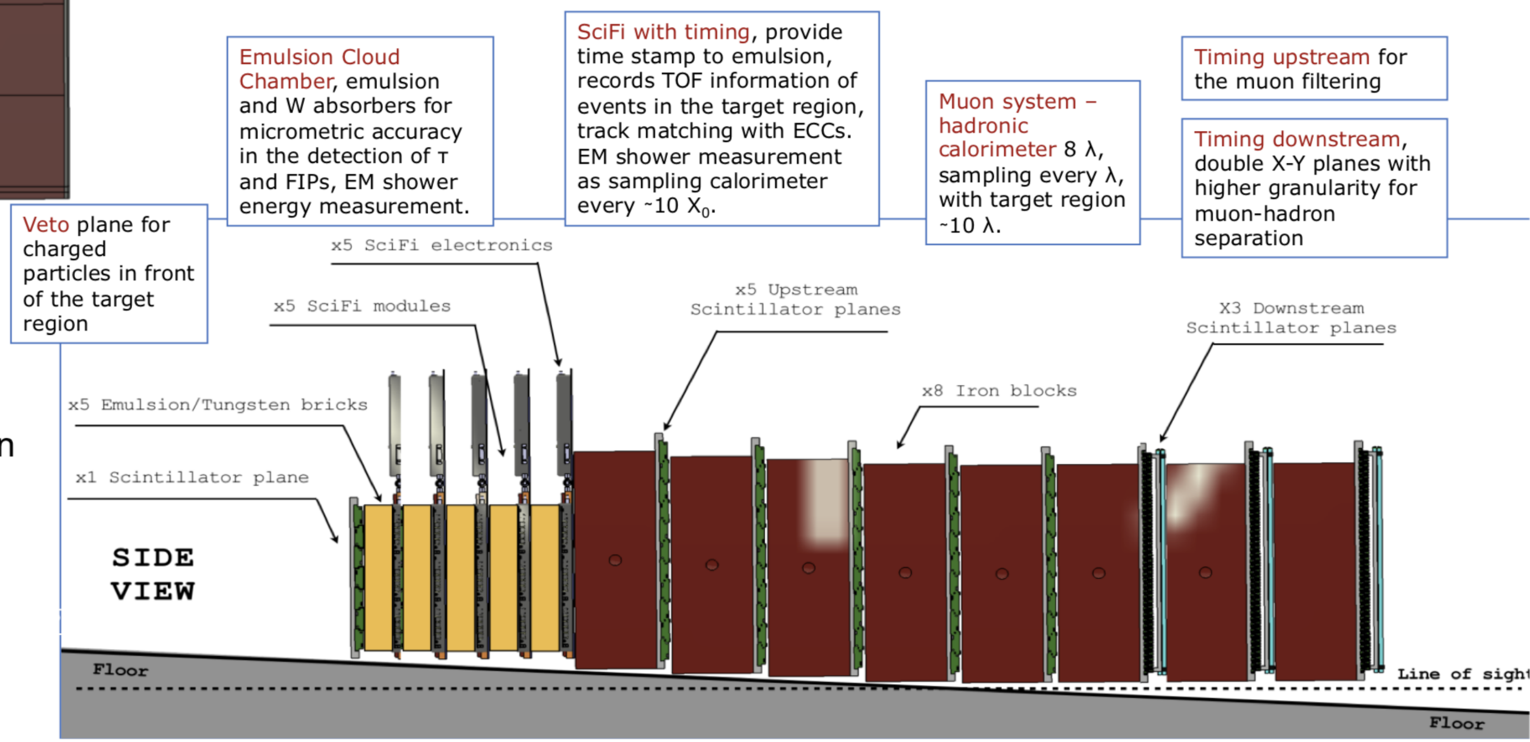
The SND@LHC Experiment

Detailed detector layout



Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ



Off axis location
Angular acceptance:
$7.2 < \eta < 8.7$
Target material: Tungsten
Target mass: 830 kg
Surface: 390 x 390 mm^2

The SND@LHC Experiment

- Muon Detector (partially) being assembled in the H8 beamline at CERN – Iron + Scintillator
- Subjected to pion test beam (180 GeV, 100 GeV)

- Installation in TI18 in November

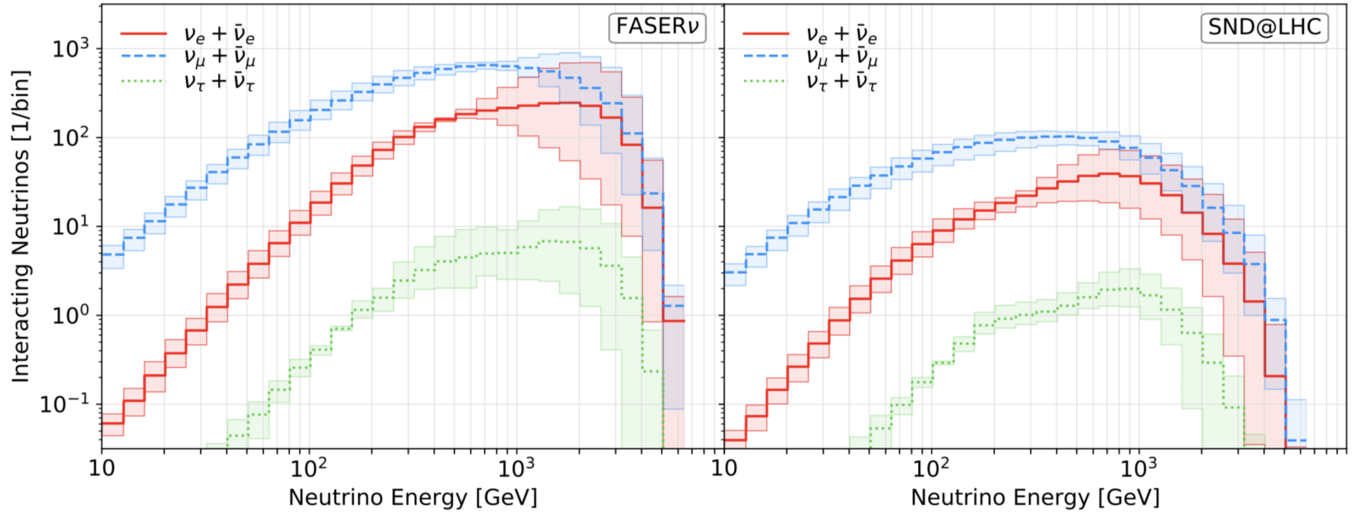
FASERν / SND@LHC

Differences between the two experiments:

- FASERν on axis and SND@LHC slightly of axis (enhance fraction of decays from charm)
- FASERν has a permanent magnet
- FASERν kinematics using multiple Coulomb scattering technique
- SND@LHC has a hadronic calorimeter, timing detectors and an active target

-> Complementary experimental set-ups

arXiv:2105.08270
Felix Kling

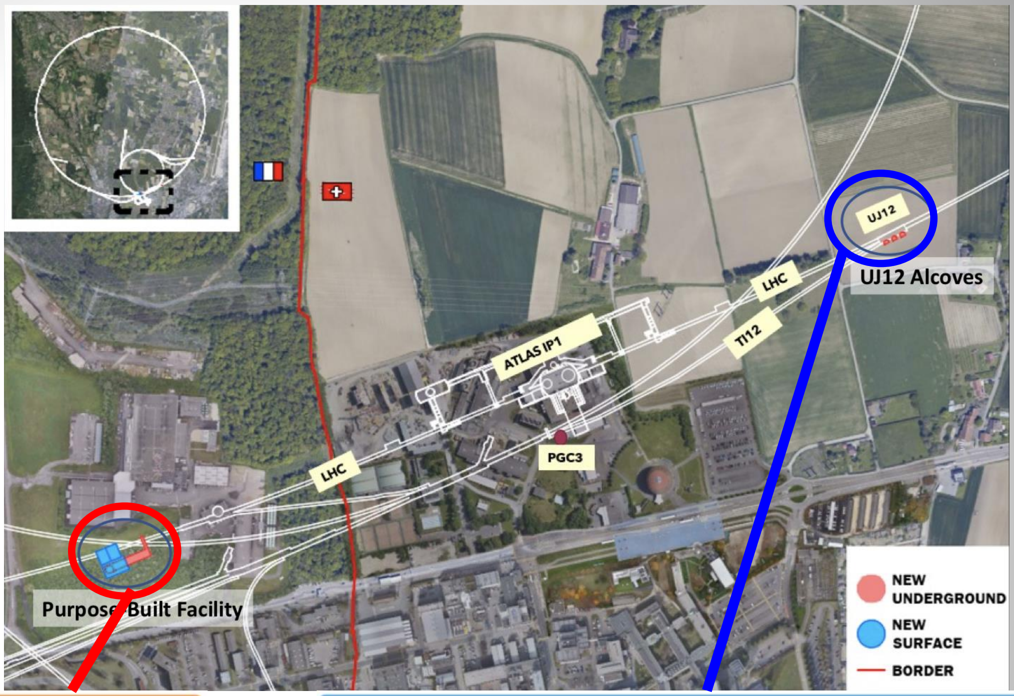


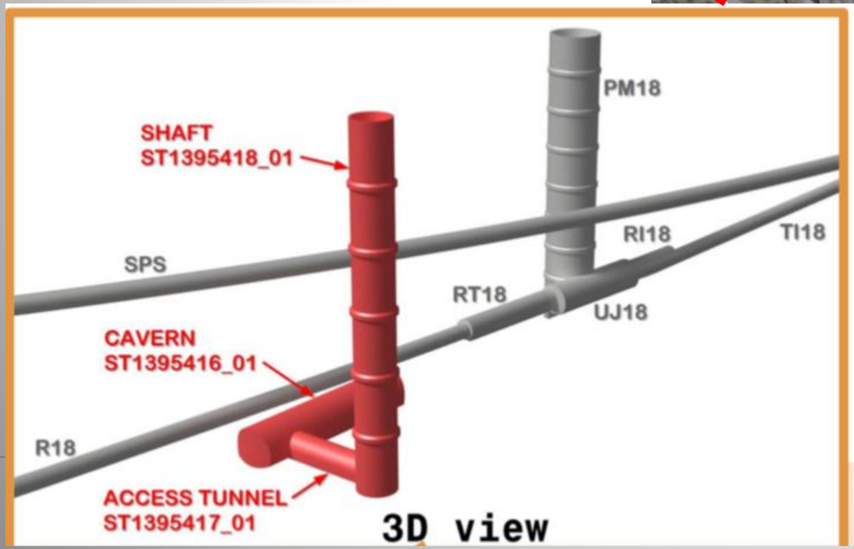
The Forward Physics Facility

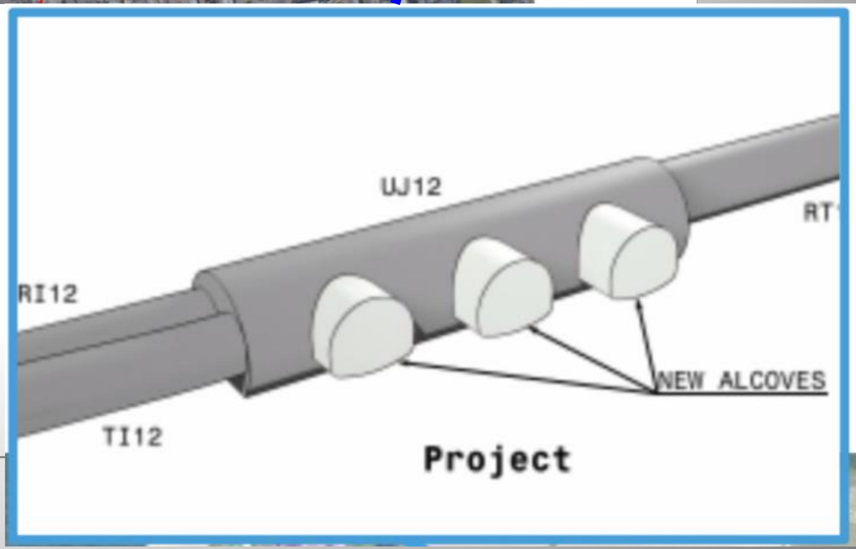
arXiv:2109.10905

A new facility proposed for the LHC phase 2 operation i.e. HL-LHC (2028-2037)

Two options ->



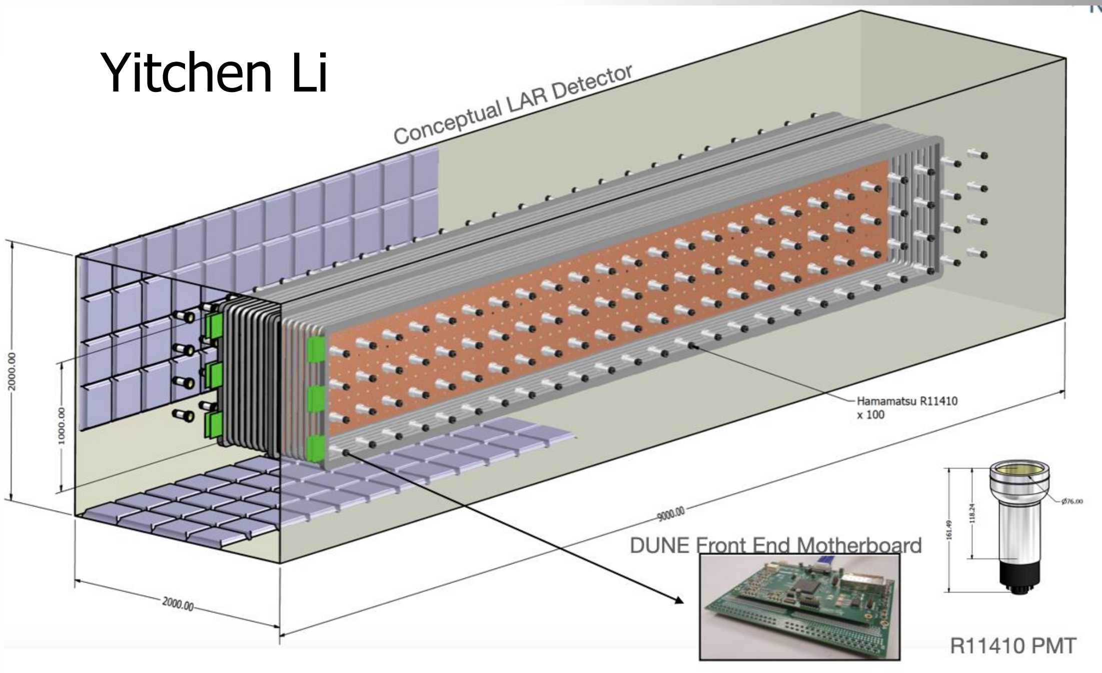




The Forward Physics Facility

Proposal: A liquid argon TPC - FLArE
Excellent technology or neutrino detection, but also for FIPS coming from pp collisions such as light Dark Matter

	Value
Detector length	7 m
TPC drift length	0.75 to 1.00 m
TPC height	1.5 m
Total LAr mass	$\sim$ 50 tonnes
Fiducial mass	10 – 20 tonnes
Background muon rate	$\sim 1/\mathrm{cm}^2/\mathrm{s}$
Neutrino event rate	$\sim 50/\mathrm{tonne}/\mathrm{fb}^{-1}$
Stopping power (MIP)	2.1 MeV/cm
Radiation length	14 cm
Interaction length	85 cm
Molière radius	9 cm
Light yield	50 ph/keV
Scintillation time	singlet 7 ns, triplet 1.6 μs
Rayleigh scattering length	90 cm
Ionization charge yield	10 fC/cm
Electron drift velocity	1.6 mm/μs
Electron diffusion coefficient	7.2 cm^2/s
Achievable drifting electron lifetime	> 10 ms
Demonstrated drift length	3.6 m



Large detector & total integrated luminosity increases by a factor 20 w.r.t. Run 3!

Contact. M. Diwan

Capabilities for tau-neutrino measurements still require detailed studies

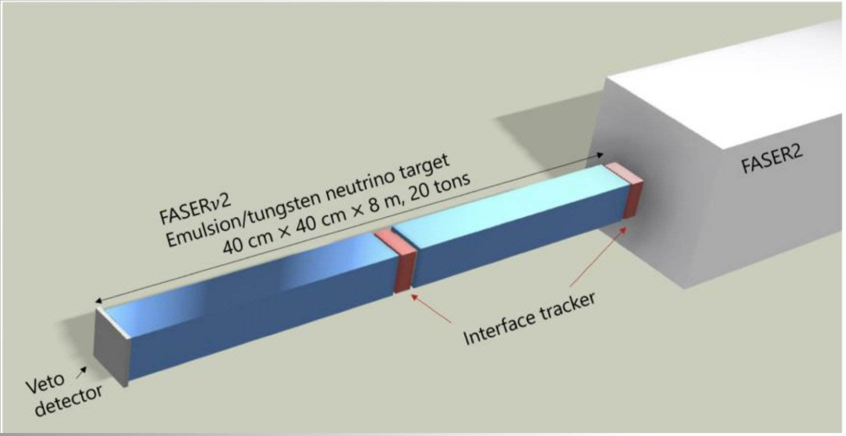
The Forward Physics Facility

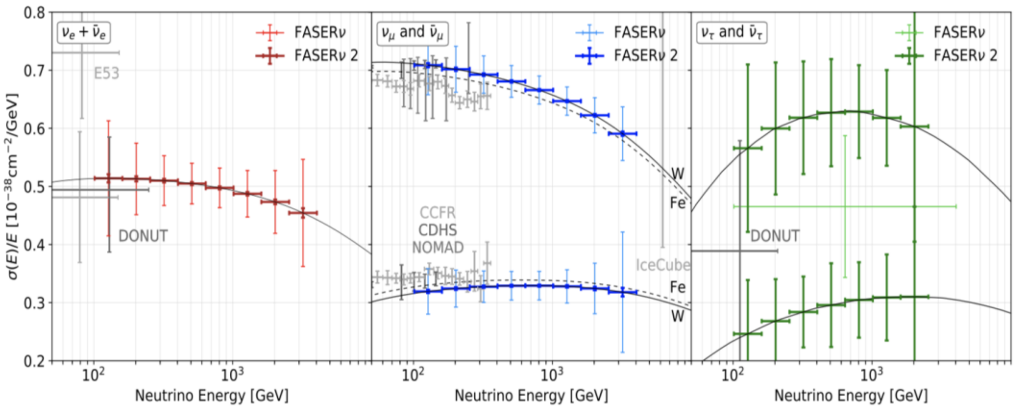
Proposal: A bigger version of FASER -> FASER2 and FASERν2

FASER: Larger acceptance and larger decay volume

FASERnu: 20 tons target mass (increase from 1.1 ton)
3.3k emulsion layers interleaved with 2 mm tungsten
Interface detectors to connect with FASER

arXiv:2109.10905





Run 3: 150 fb^{-1} HL-LHC: 3 ab^{-1}

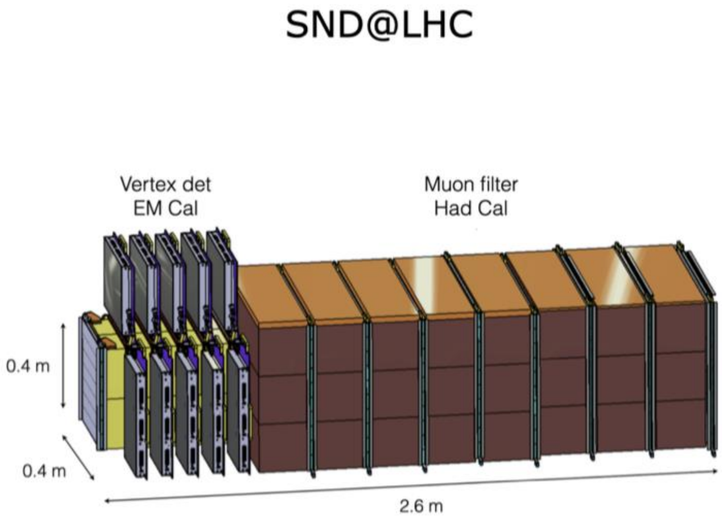
Concern: the expected high muon flux.. Sweeping magnet needed for the plan to exchange the emulsions only once a year

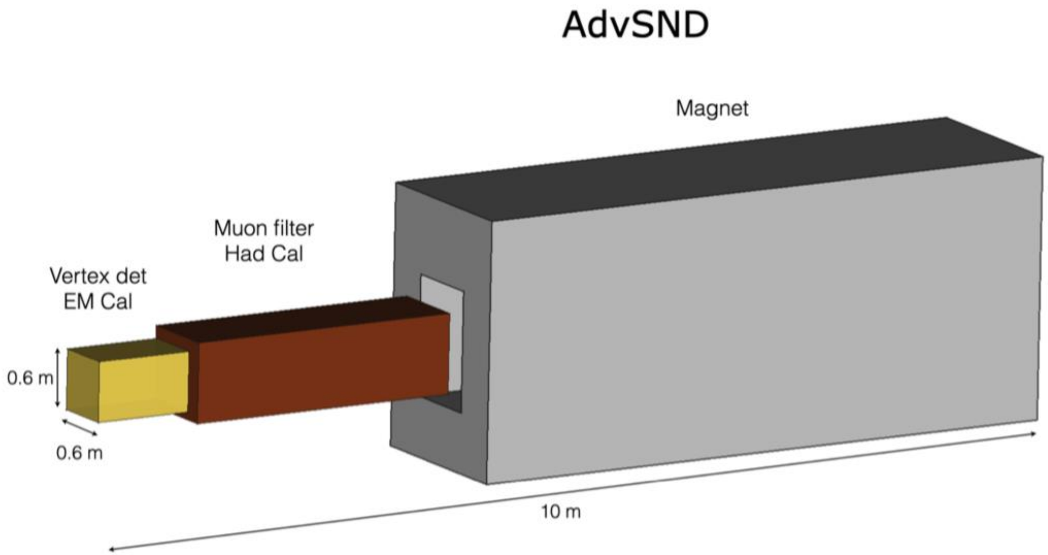
The Forward Physics Facility

Proposal: two detectors, at different η regions (~ 8 and ~ 5)

For the forward detector the changes with SND@LHC are:

- Compact electronic detector for the active target (or emulsion)
- Magnetic spectrometer for muons
- Target mass minimum 2 tons, but up to 10 tons being studied





Concern: the expected high muon flux.. Sweeping magnet needed if emulsions will be used in the target

Neutrino Rates @ LHC

From Felix Kling

Event rates at LHC neutrino experiments:
estimated with two LO MC generators: SIBYLL / DPMJET

	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

O(10) tau neutrinos at FASERv and SND@LHC:
similar to event rate at DONuT and OPERA

FPF detectors will record thousands of tau-neutrino interactions

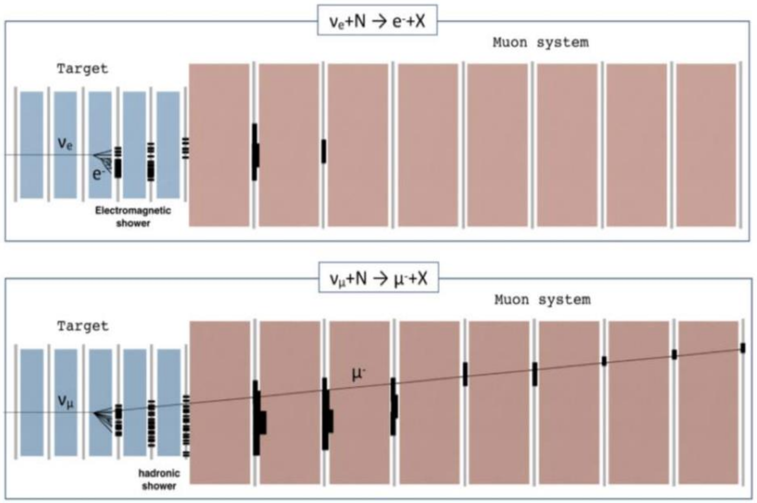
Summary

Experiments relevant for tau–neutrino studies @CERN

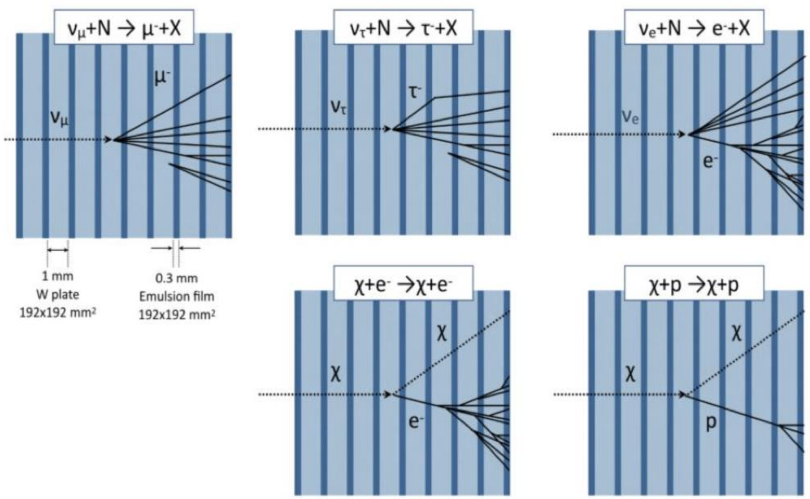
- NA65: taking data now
- SHiP: few thousand neutrino and anti-neutrinos detected in 5 years, however its future is not yet clear
- Neutrino experiments at the LHC are now becoming a reality: FASERν and SND@LHC. These will be give a few tens of tau-neutrinos. Neutrinos detected in these experiments will be in the few 100 GeV – few TeV range
- Large statistics samples can be collected at a future Forward Physics Facility, with several thousand events in three possible detectors
- The FPF is still a study, no CERN commitment yet..

The SND@LHC Experiment

- **First phase: electronic detectors**
  - ν candidates
  - μ's
  - em showers (SciFi)
  - ν energy (SciFi+Muon)
- **Second phase: nuclear emulsion**
  - em showers
  - ν vertex reconstruction
  - match with candidates from electronic detectors



ν_e (top) and ν_μ (bottom) CC interactions



Reconstructible signal topologies in emulsion