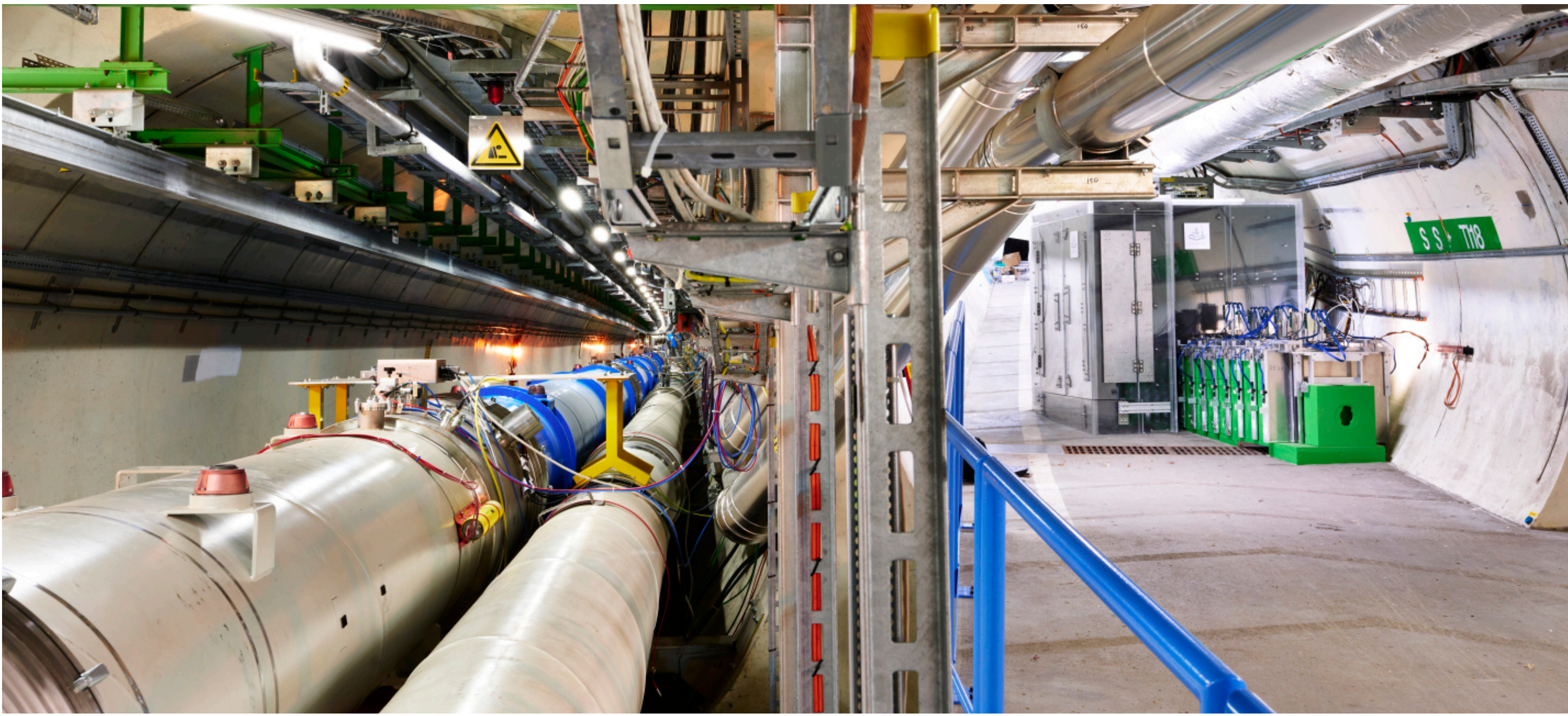
A new Scattering and Neutrino Detector at the LHC

- Status of SND@LHC -



NuINT2022
24–29 Oct 2022
Hoam Faculty House at SNU, Korea

C.S. Yoon (GNU, Korea)
On behalf of SND@LHC Collaboration

Neutrino experiments using Nuclear Emulsion

1978 - 1983 **FNAL E531** ~ 100 kg
charm (lifetime), $\nu_\mu \rightarrow \nu_\tau$ (by-product)

1990 - 2000 **CHORUS (CERN WA95)** ~ 1 ton
$\nu_\mu \rightarrow \nu_\tau$ short baseline (ν as DM)
No ν_τ event, ~2000 charm

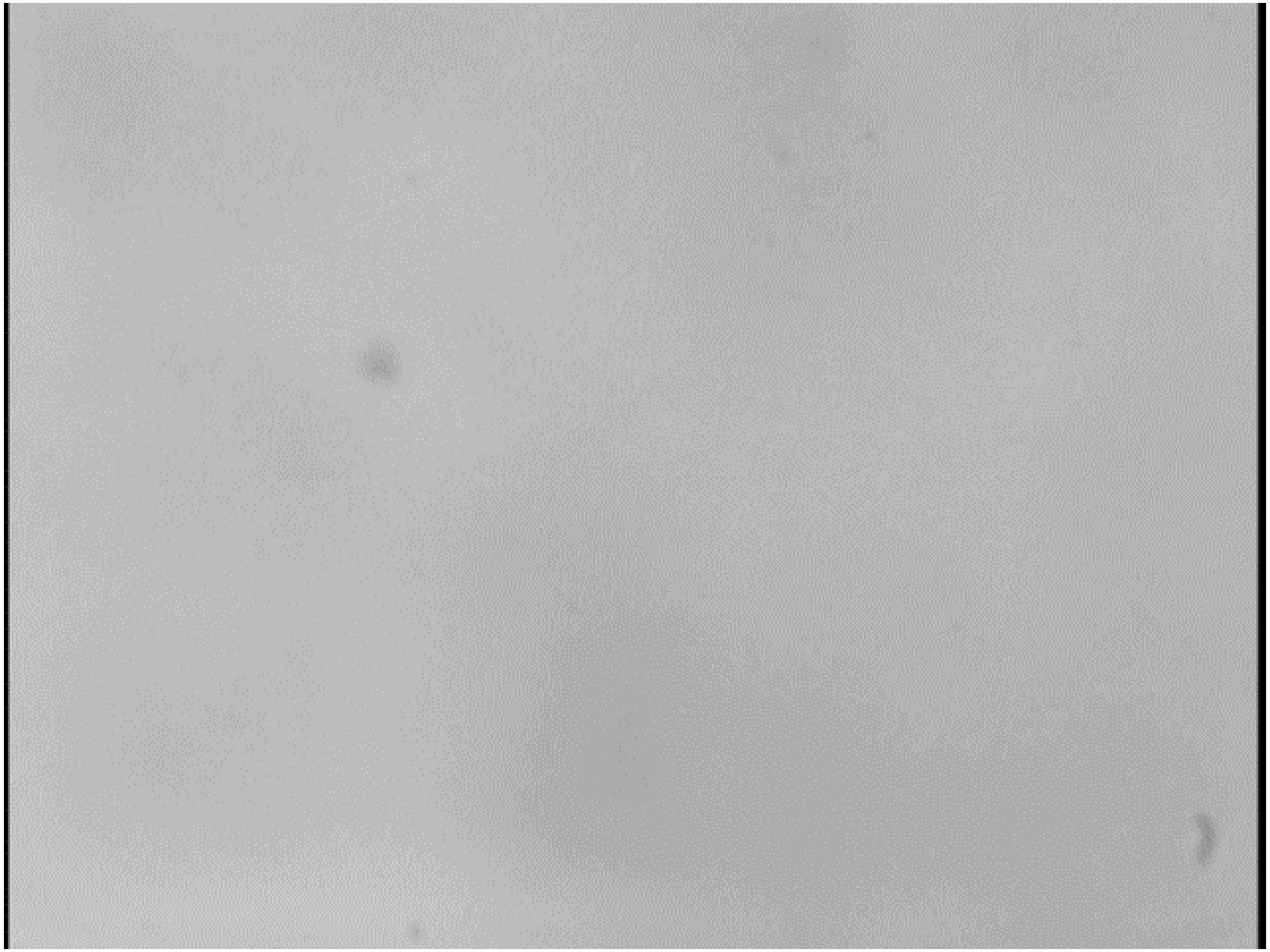
1994 - 2001 **DONuT (FNAL E872)** ~ 1 ton
ν_τ direct observation (9 events)

2000 - **OPERA (CERN CNGS)** ~ 1250 ton
$\nu_\mu \rightarrow \nu_\tau$ long baseline
Appearance mode (10 events)

Recently **SHiP, DsTau (CERN NA65), SND@LHC, FASERν**

The results of CHORUS, DONuT and OPERA are consistent with each other.

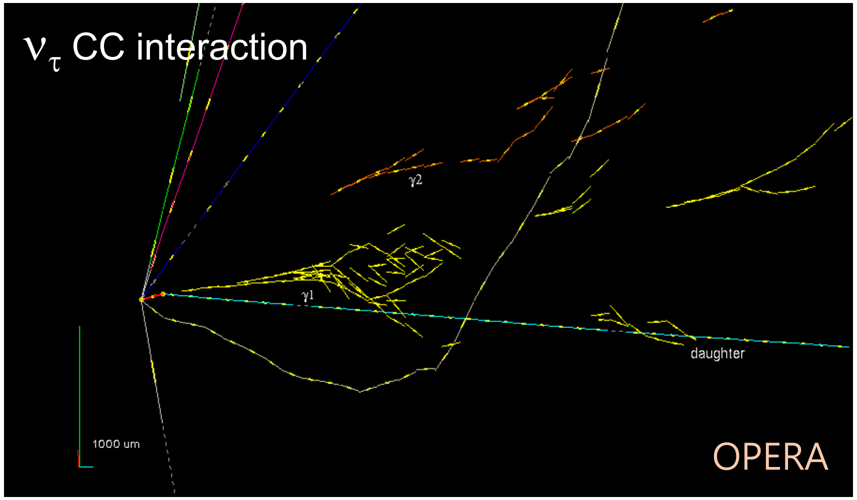
600 GeV π^- interaction in emulsion (FNAL E653)

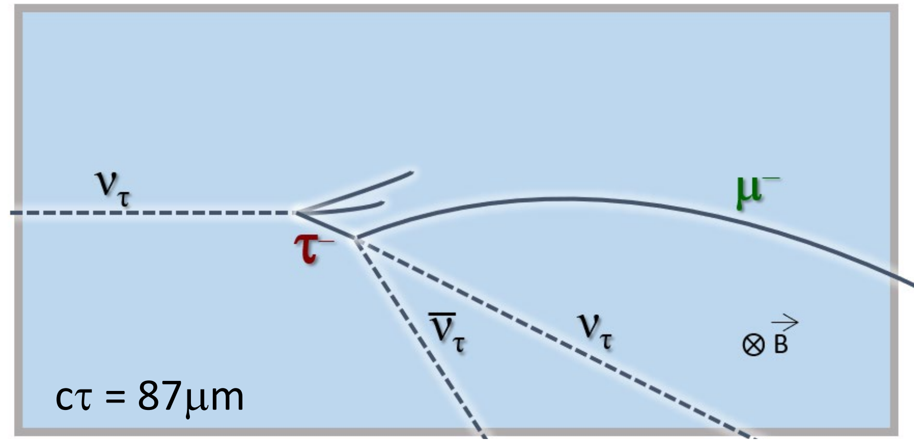


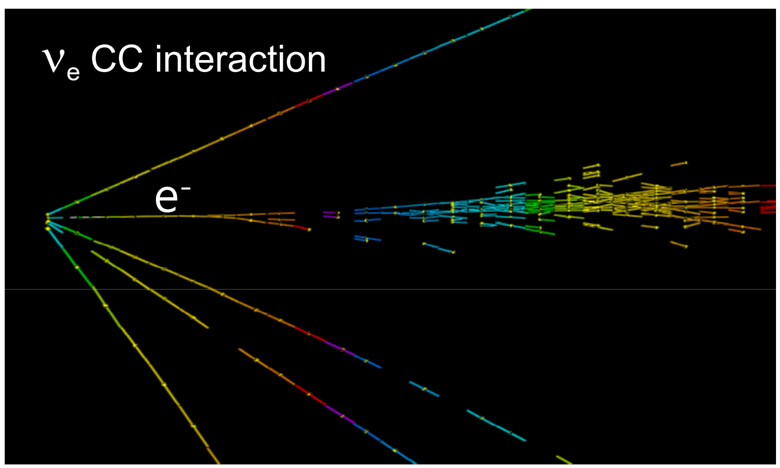
100 μm

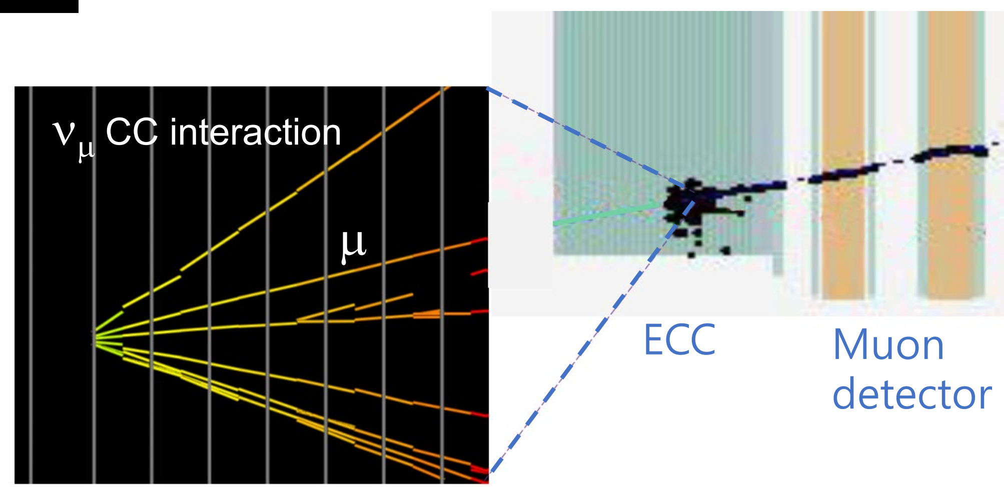
All flavors of Neutrinos can be identified by their scatterings in SND.

SND: Scattering and Neutrino Detector
(**ECC** + SciFi + Muon detector)









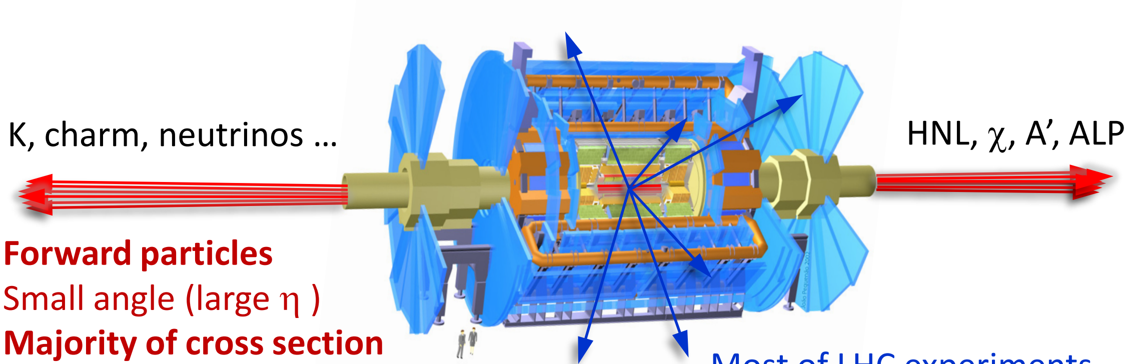
ECC as high precision tracker → ν_τ can be identified by detecting τ track.

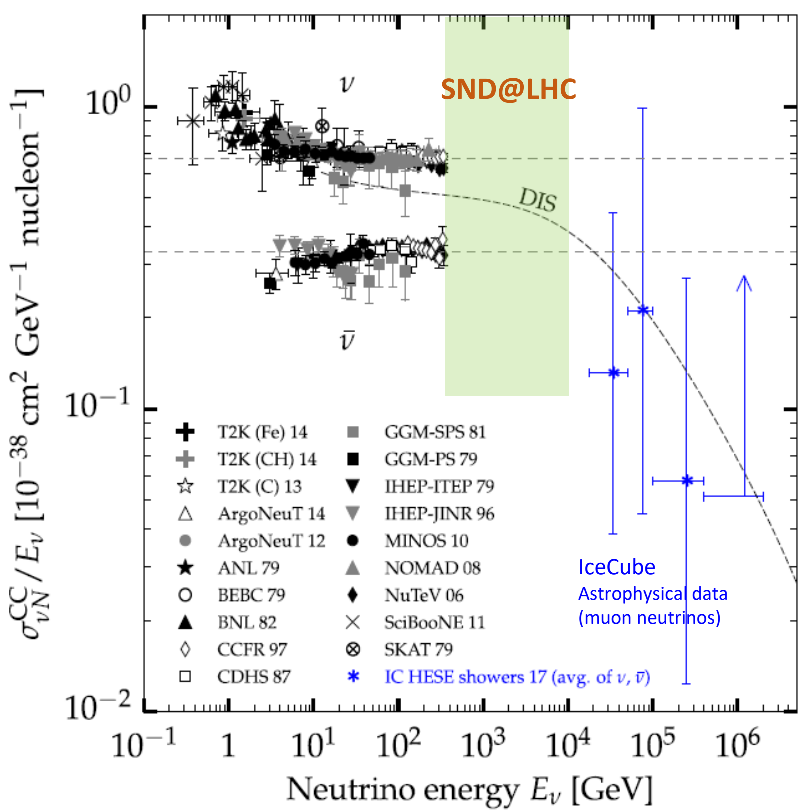
ν_e → by detecting electron track via EM cascade shower

ν_μ → by detecting μ track with help of Muon detector


bottom layer
ν_μ CC event
(OPERA)
170 µm
250 µm

First observation of Collider neutrinos
using LHC forward produced particles



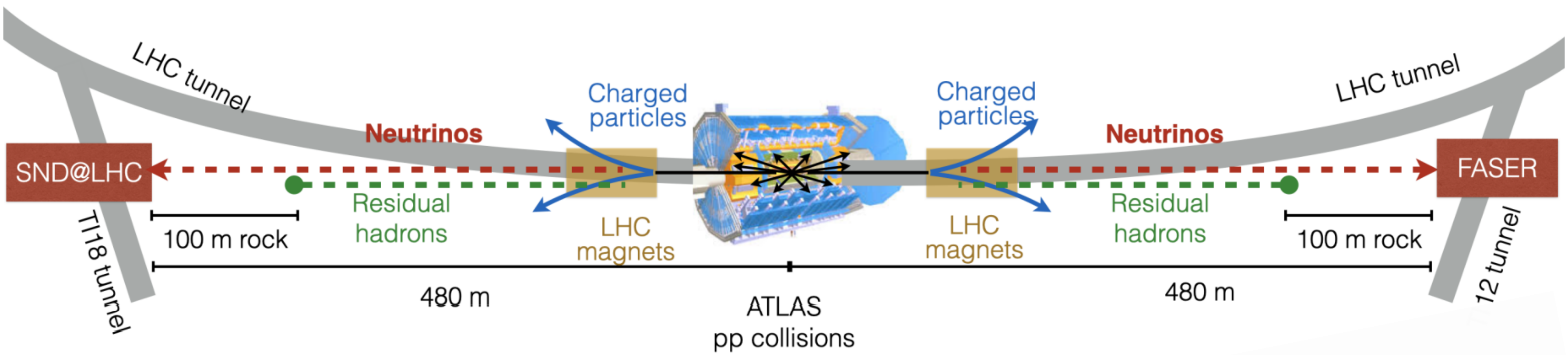


- LHC can create huge numbers of **high-energy neutrinos**. But no neutrinos produced at a particle collider has ever been directly detected.
- LHC is a unique facility for measuring the νN cross sections in the **350 GeV - 10 TeV** range.
- **Early studies for LHC neutrinos**
  Klaus Winter, 1990, Observing tau neutrinos at the LHC
  A. De Rùjula et al., 1993, Neutrino fluxes at LHC
  F. Vannucci, 1993, Neutrino physics at the LHC
  G. De Lellis et al., CMS-XSEN: LHC Neutrinos at CMS
  (ArXiv 1804.04413, 12 Apr 2018)

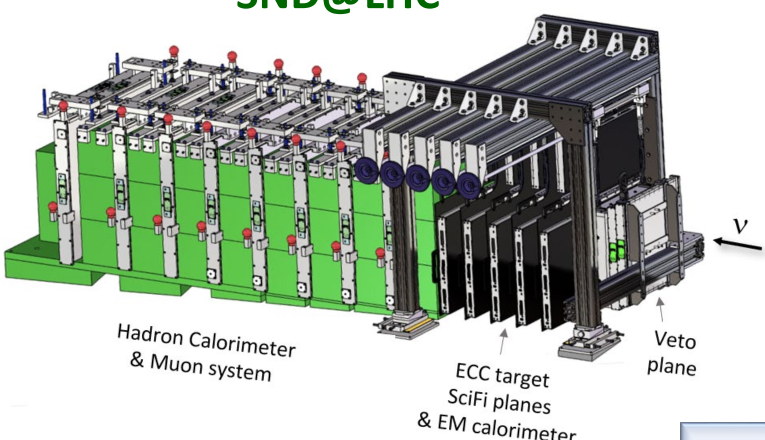
SND@LHC and FASER

Symmetric - 480 m away from ATLAS IP
Complementarity - different η range

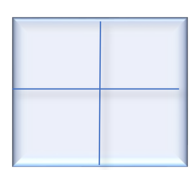
Suitable experimental environment
LHC magnet - deflect charged particles
100 m rock - absorb residual hadrons



SND@LHC

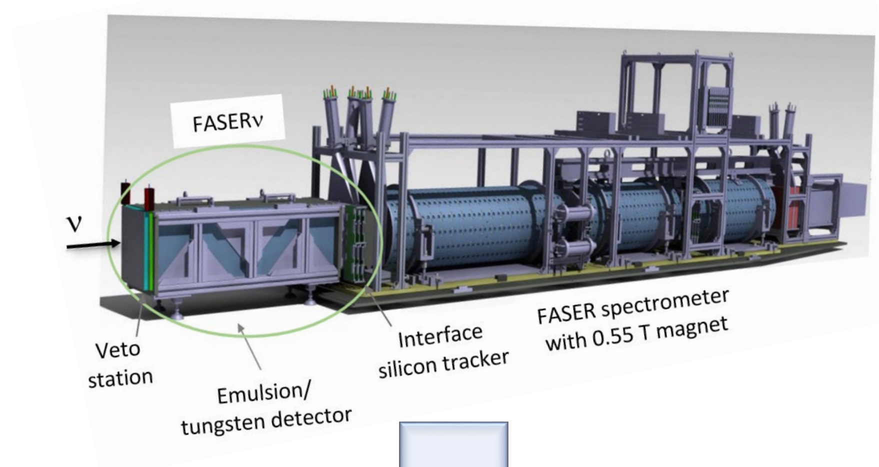


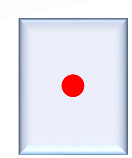
$7.2 < \eta < 8.4$
off-axis



● Beam collision axis

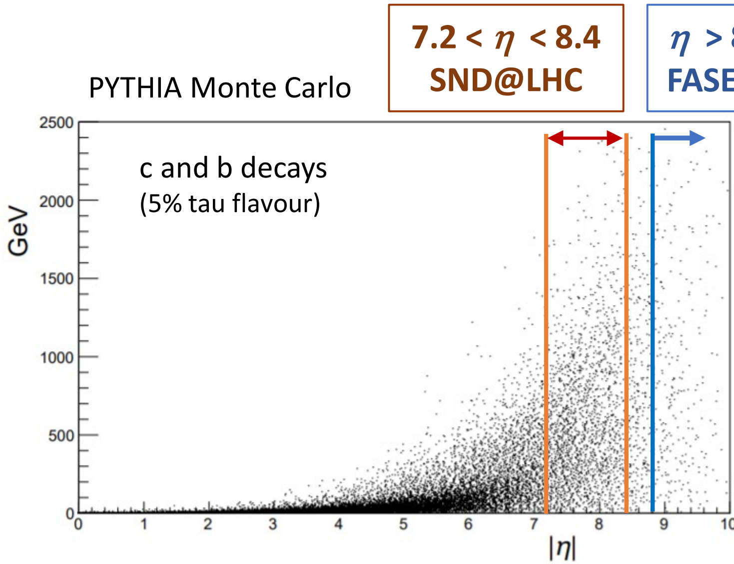
FASER & FASERν

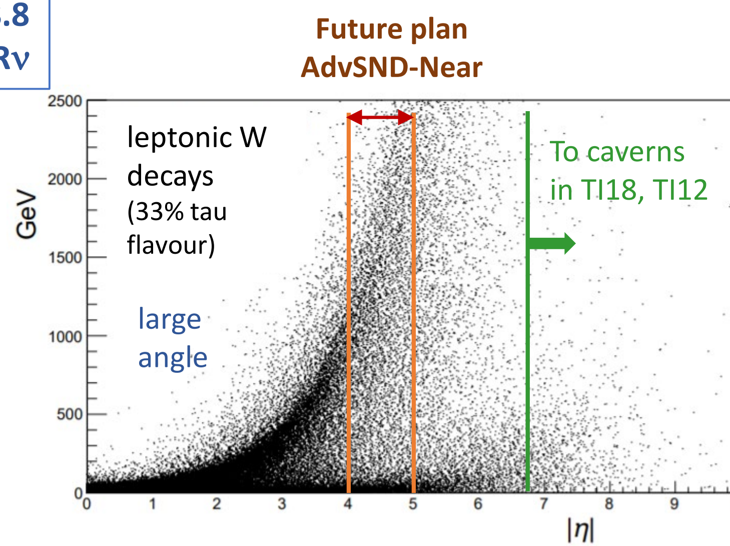




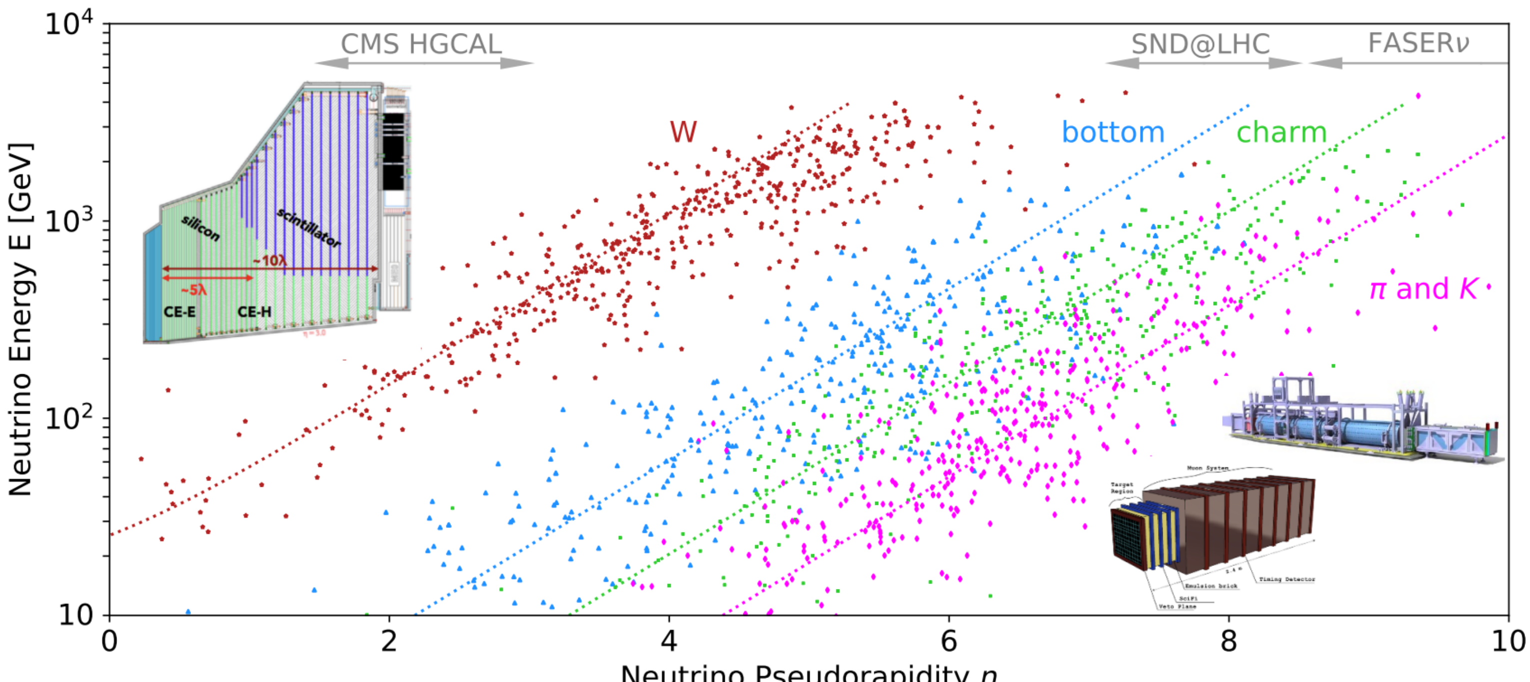
$\eta > 8.8$
on-axis

Energy vs. Pseudo-rapidity of neutrinos from LHC





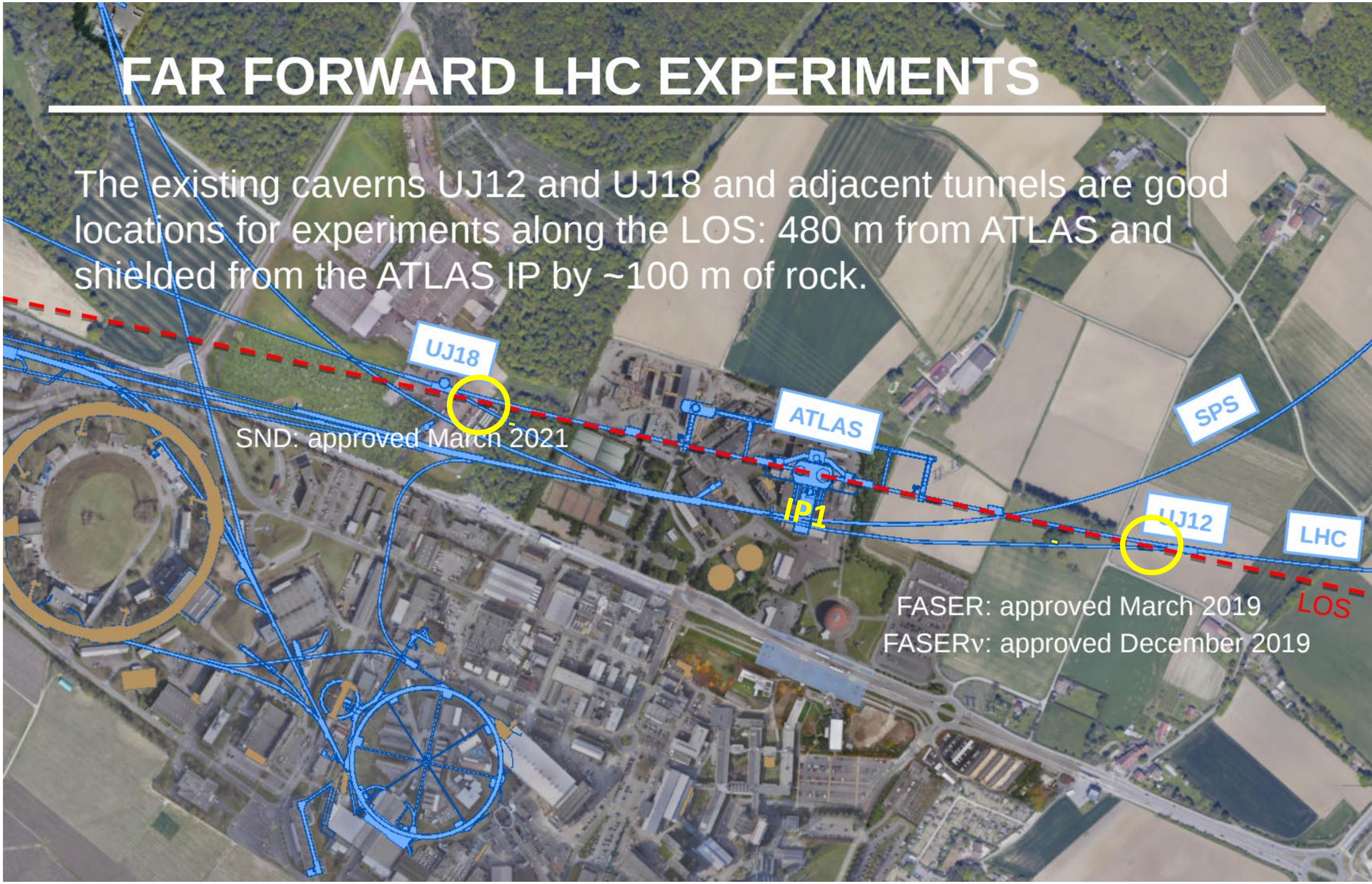
N. Beni, G. De Lellis, A. Di Crescenzo et al., *J. Phys. G* 46 (2019) 115008 [arXiv:1903.06564]



P. Foldenauer, F. Kling and P. Reimitz, [arXiv:2108.05370v1]

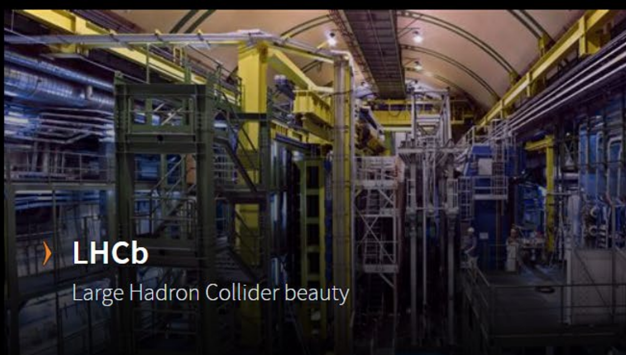
FAR FORWARD LHC EXPERIMENTS

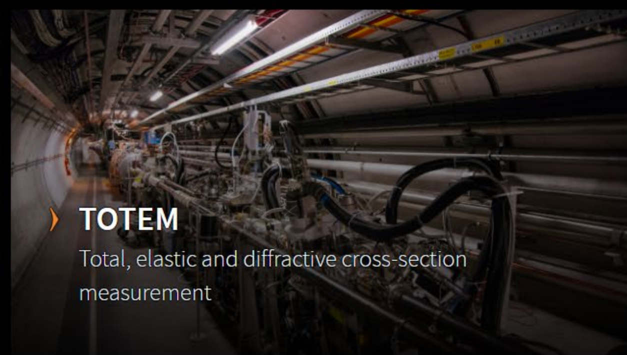
The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.

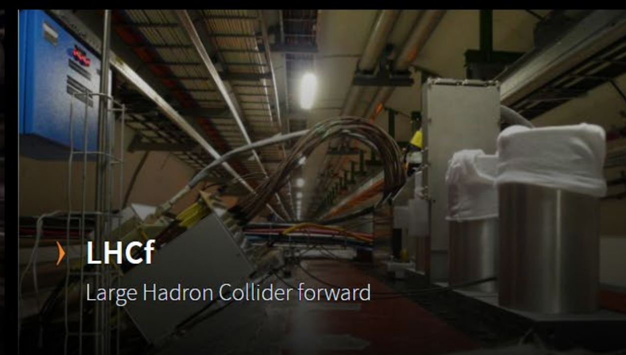


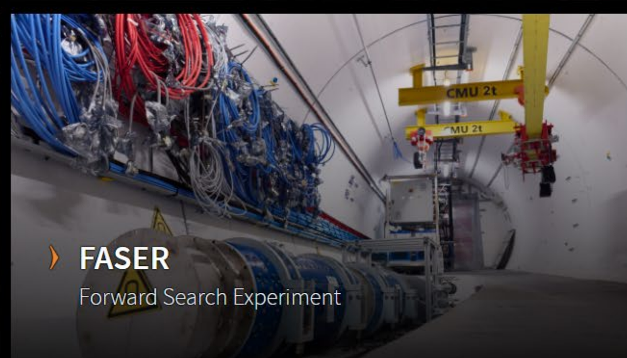
LOS (Line of Sight)
Beam collision axis

LHC experiments









Main physics goal of SND@LHC

- **Study of very high-energy neutrinos** in the unexplored energy range **(350 GeV – 10 TeV)**

  and unexplored pseudo-rapidity region : **$7.2 < \eta < 8.4$** **(off-axis)**

  $\eta > 8.8$ **(on-axis)** → **FASERν**

  → About **2,000 high-energy neutrino interactions** will be able to study.

- **Search for FIMPs** (feebly interacting particles)

  → by detecting **electron recoils or proton recoils** in ECC target

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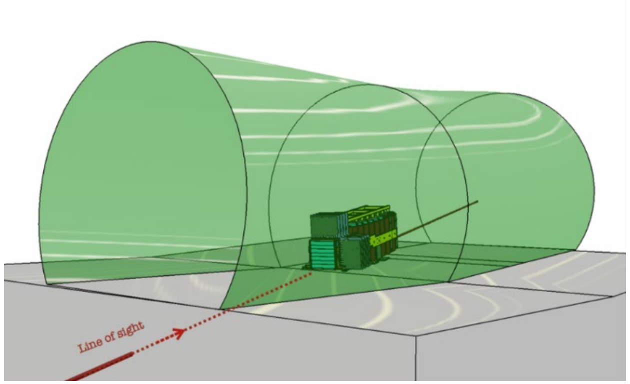
- Data taking is just starting from July 2022

  during **4 years in LHC Run 3 (2022-2025).**

  - total integrated luminosity 290 fb^{-1}

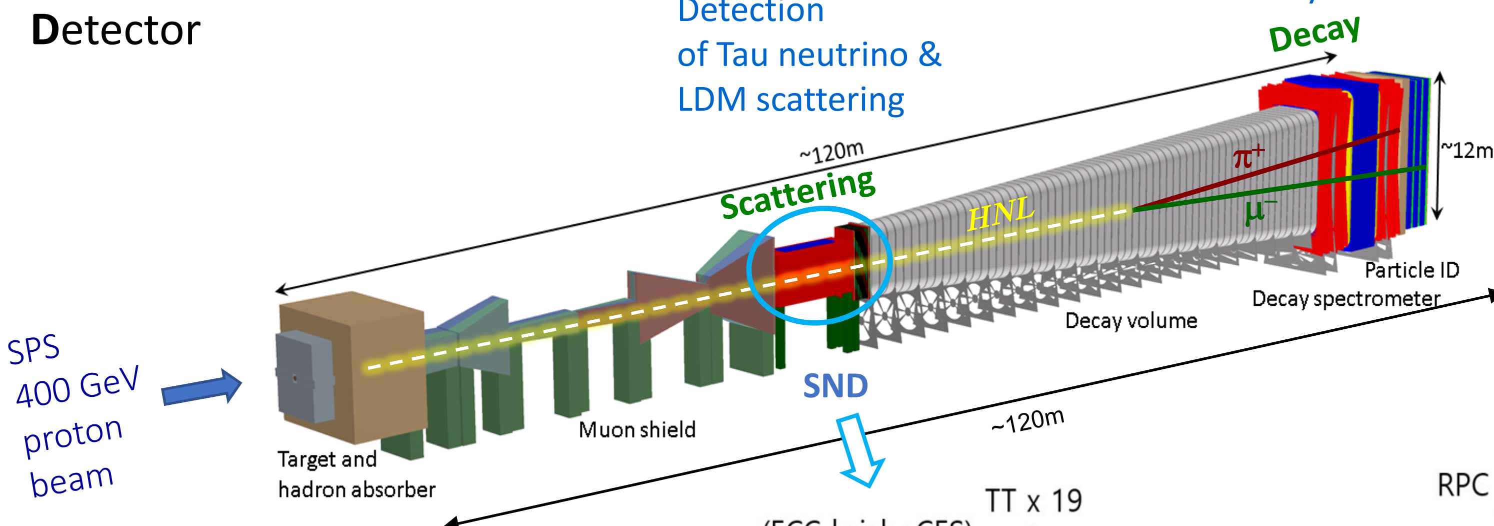


What is SND?

Scattering and **N**eutrino **D**etector

Detection of Tau neutrino & LDM scattering

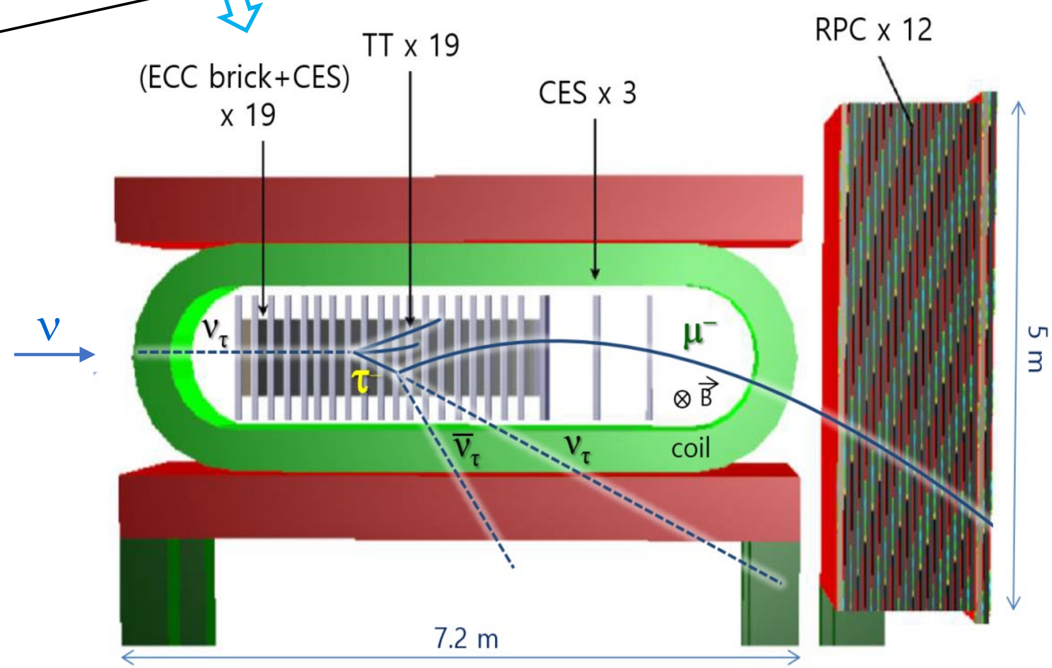
Detection of Hidden particle decay



SHiP SND

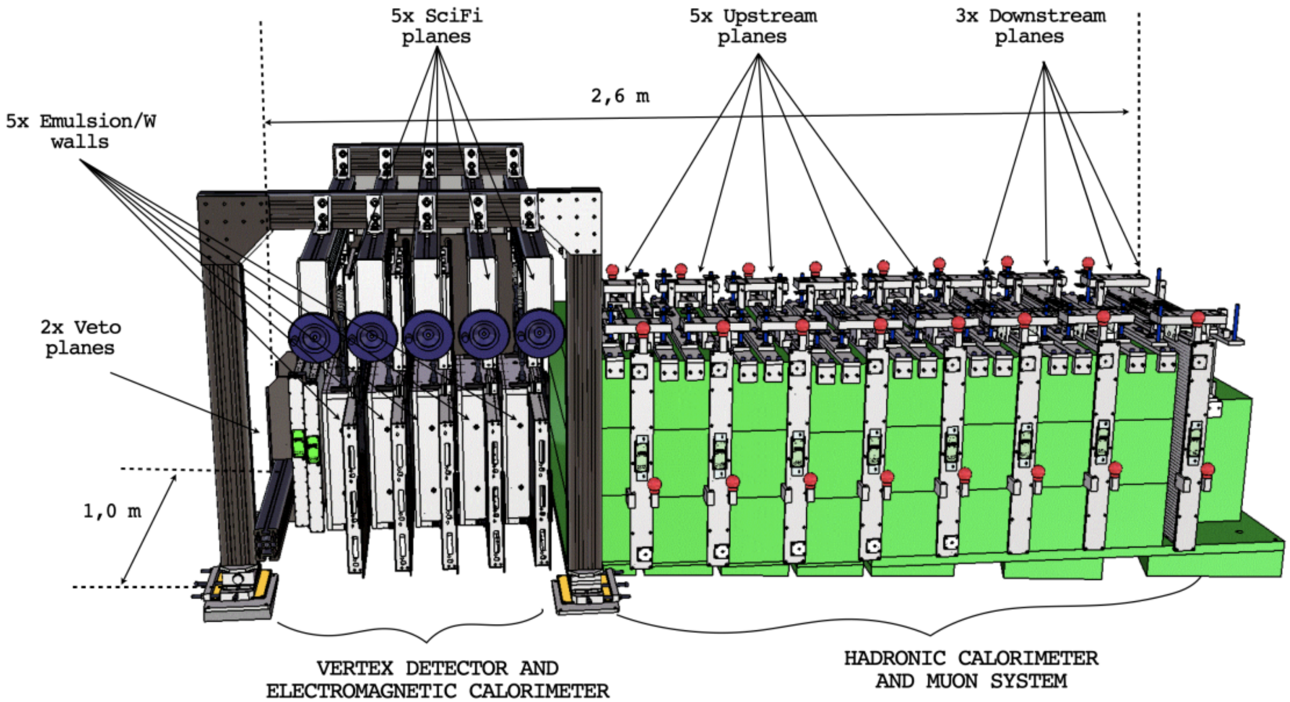
ECC target :
Emulsion Cloud Chamber
2 x 2 bricks x 19 walls
(80 x 80 cm^2 /wall)
~ 8 tons

RPC : Muon ID, charge



SND@LHC detector

- **Emulsion-Counter Hybrid detector** : optimized for the identification of three neutrino flavours and for the detection of feebly interacting particles
- **Veto plane** : tag penetrating muons
- **Vertex detector + ECAL** : **ECC** (Emulsion Cloud Chamber) for detection of **ν interactions** & Scattering and decay of **FIMPs**, and for momentum measurements
  SciFi for position prediction, timing and E measurement of outgoing particles
- **Muon system + HCAL** : iron walls interleaved with plastic scintillator planes for fast time resolution and E measurement



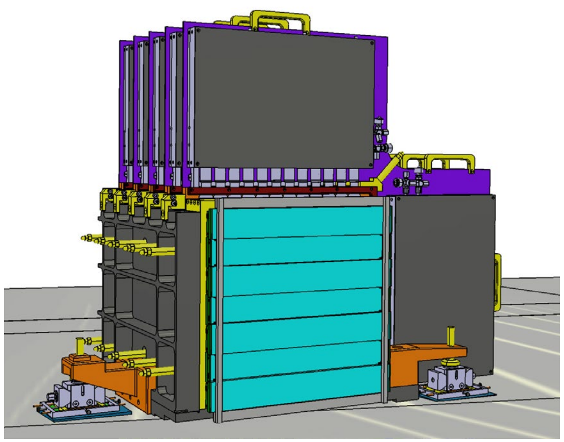
ECC target + SciFi

ECC (Emulsion Cloud Chamber) target & detector

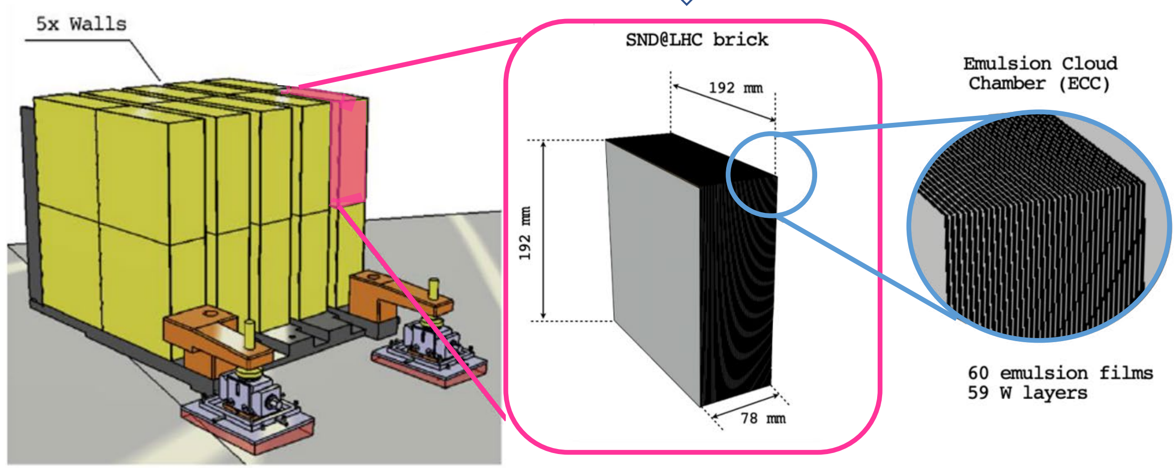
- **5 ECC Brick walls**
  - 2 x 2 bricks x 5 walls
  - weight 830 kg (~40 X_0)
  - surface 44 m²

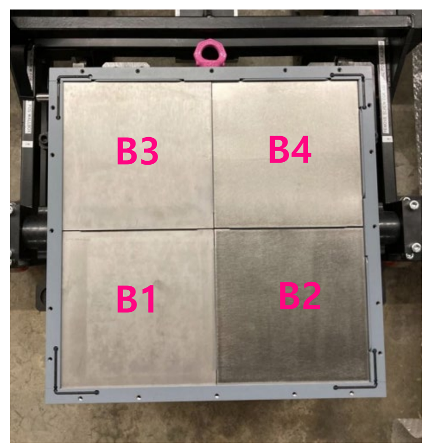
Replace every ~25 fb^{-1}
(total ~290 fb^{-1} in 4 yrs)
~3 times replacements / yr

- **ECC Brick**
  - **56 Tungsten layers** (1 mm-thick each)
    & **57 Emulsion films** (310 μm-thick each)
  - Surface **19.2 x 19.2 cm²**



5 ECC brick walls & 5 SciFi walls





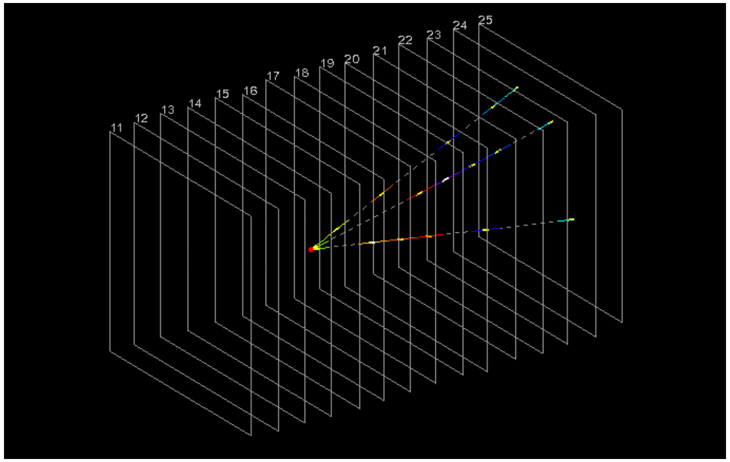
1 wall (4 bricks inside)

41.5 kg

Nuclear emulsion : 3D image detector & Precision tracker

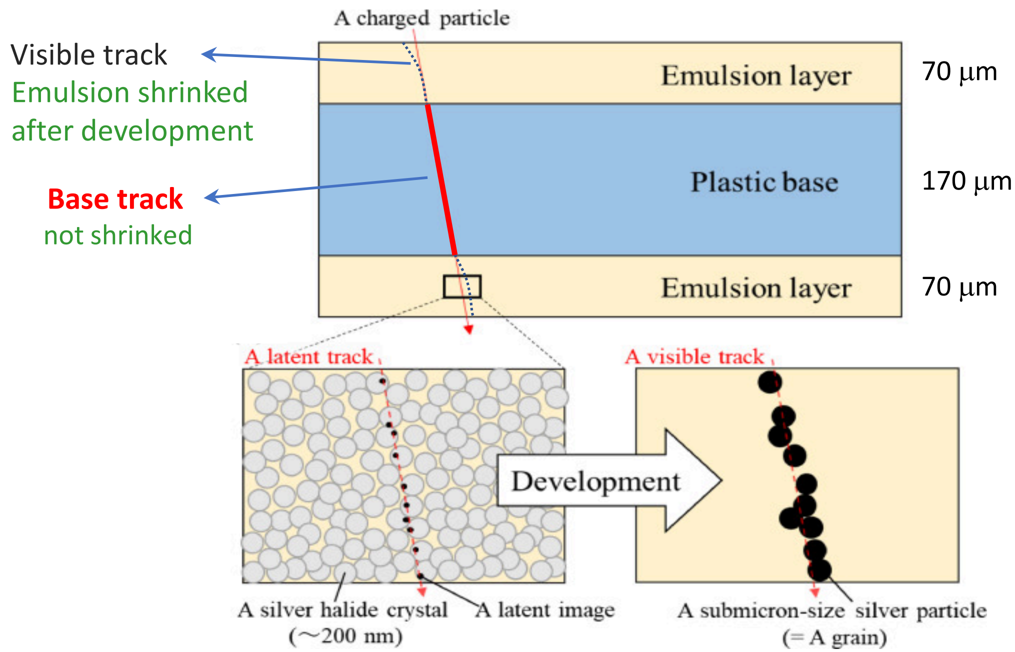
(Spatial resolution < 1 μm)

Emulsion as Precision Tracker

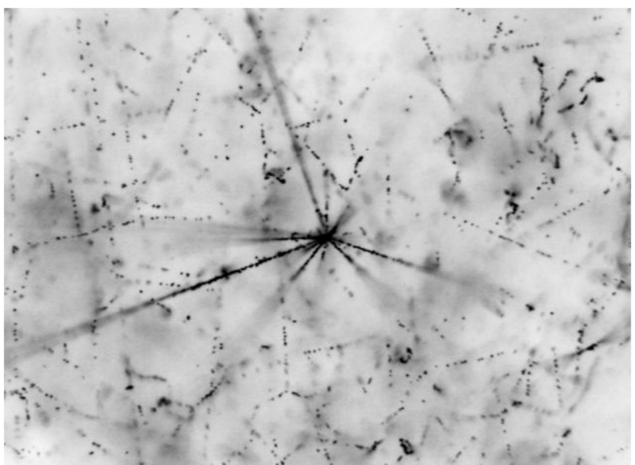


Reconstruction of events using **Base tracks**

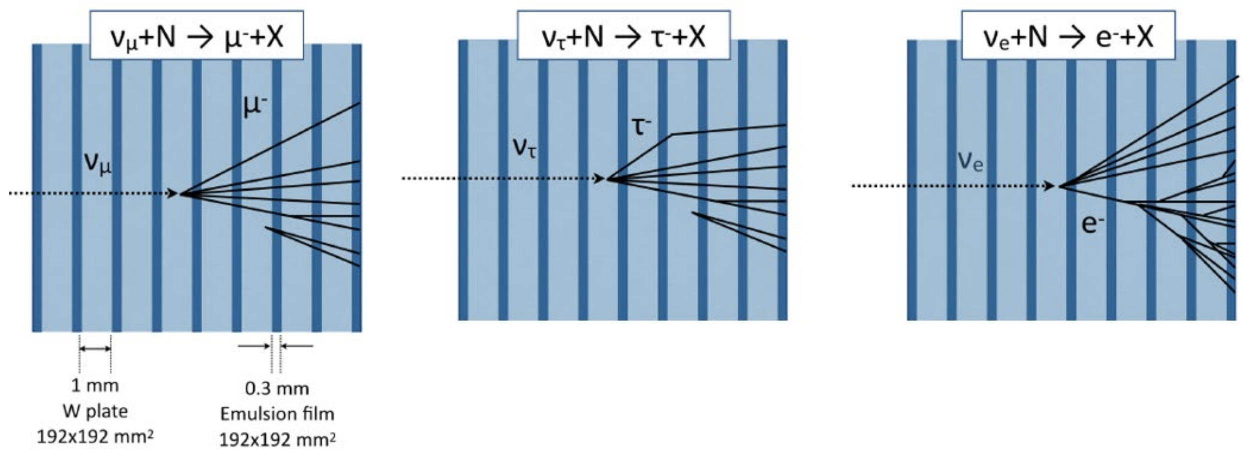
Cross-sectional view of emulsion plate



3D image detector



Neutrino event in emulsion



Physics program in LHC Run 3 (2022-2025)

- Measurement of the **cross section** **(pp → ν X)** in $7.2 < \eta < 8.4$ range
- **Lepton flavor universality test** in neutrino interactions:
  by measuring ν_τ/ν_e and ν_μ/ν_e (all 3 neutrino flavors can be identified)

$$R_{13} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\tau+\bar{\nu}_\tau}} = \frac{\Sigma_i f_{c_i} Br(c_i \to \nu_e X)}{f_{D_s} Br(D_s \to \tau \nu_\tau)}, \quad R_{12} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\mu+\bar{\nu}_\mu}} = \frac{1}{1+\omega_{\pi,K}}$$

Contamination from π / K (E > 600 GeV)

- Measurement of the **NC/CC ratio**

$$P = \frac{\Sigma_i \sigma^{\nu_i}_{NC} + \sigma^{\bar{\nu}_i}_{NC}}{\Sigma_i \sigma^{\nu_i}_{CC} + \sigma^{\bar{\nu}_i}_{CC}}$$

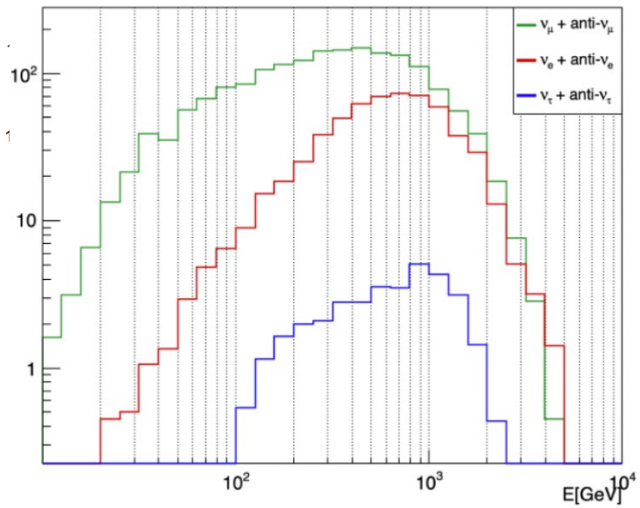
- Direct search for **feebly interacting particles** through their scattering and decay
- Unique opportunity to prove physics of **heavy flavor production at LHC** in the region not accessible to ATLAS, CMS and LHCb
- ν_e as a probe of charm quark production (~ 90% ν_e from charm)

Neutrino expectations in Run 3

Integrated luminosity in Run 3 : **290 fb^{-1}**

$\sqrt{s}$ = 13 TeV

ν interactions in SND@LHC 290 fb^{-1}



CC NC

Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Yield	CC neutrino interactions ⟨E⟩ [GeV]	Yield	NC neutrino interactions ⟨E⟩ [GeV]	Yield	
ν_μ	120	3.4×10^{12}	450	1028	480	310	1914
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157	
ν_e	300	4.0×10^{11}	760	292	720	88	596
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58	
ν_τ	400	2.8×10^{10}	740	23	740	8	47
$\bar{\nu}_\tau$	380	3.1×10^{10}	740	11	740	5	
TOT		7.3×10^{12}		1930		625	

~2500 high energy neutrino events

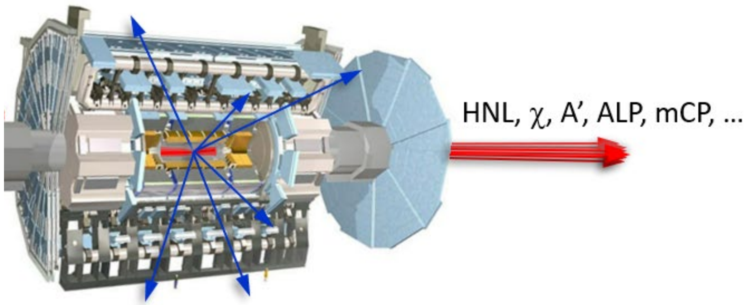
The energy spectrum of **incoming neutrinos and anti-neutrinos** in the pseudo-rapidity range covered by the SND@LHC detector, $7.2 < \eta < 8.4$, normalised to 290 fb^{-1} .

About **1930 CC and 630 NC Neutrino interactions** are expected **in the target volume** mainly from ν_μ (73%) and ν_e (25%).

ν production with DPMJET3, **propagation** with FLUKA, **interaction** with GENIE.

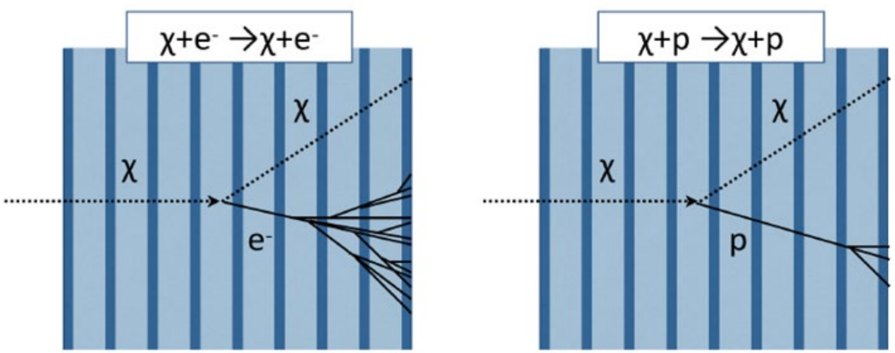
Feebly Interacting Particles

- Search for LDM & Hidden sector



Most of LHC experiments
large angle (small η)
Small cross section

LDM scattering



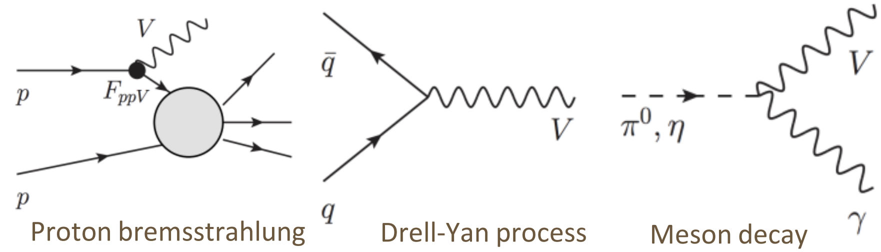
A' (V) → χ χ   LDM pair

χ e → χ e   e-recoil
χ p → χ p   p-recoil

A' (V) → ℓℓ   lepton pair

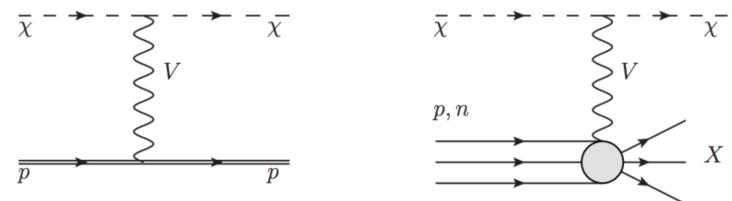
One example: a scalar particle **V** coupled to the Standard Model via **a leptophobic portal**.

Production:

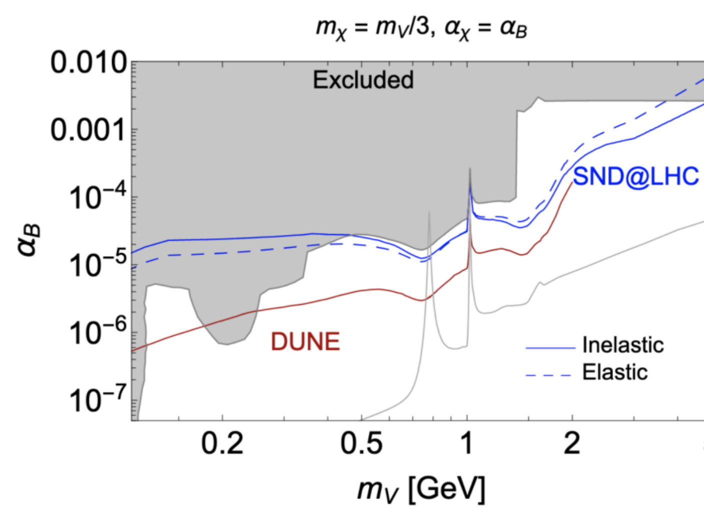


Proton bremsstrahlung   Drell-Yan process   Meson decay

Detection: χ elastic/inelastic scattering off **nucleons** of the target



Elastic scattering   Inelastic scattering



Sensitivity to the leptophobic portal

arXiv:2104.09688

Detector installation in TI18 underground tunnel

2021. 9

2021. 11

2021. 12

2022. 3

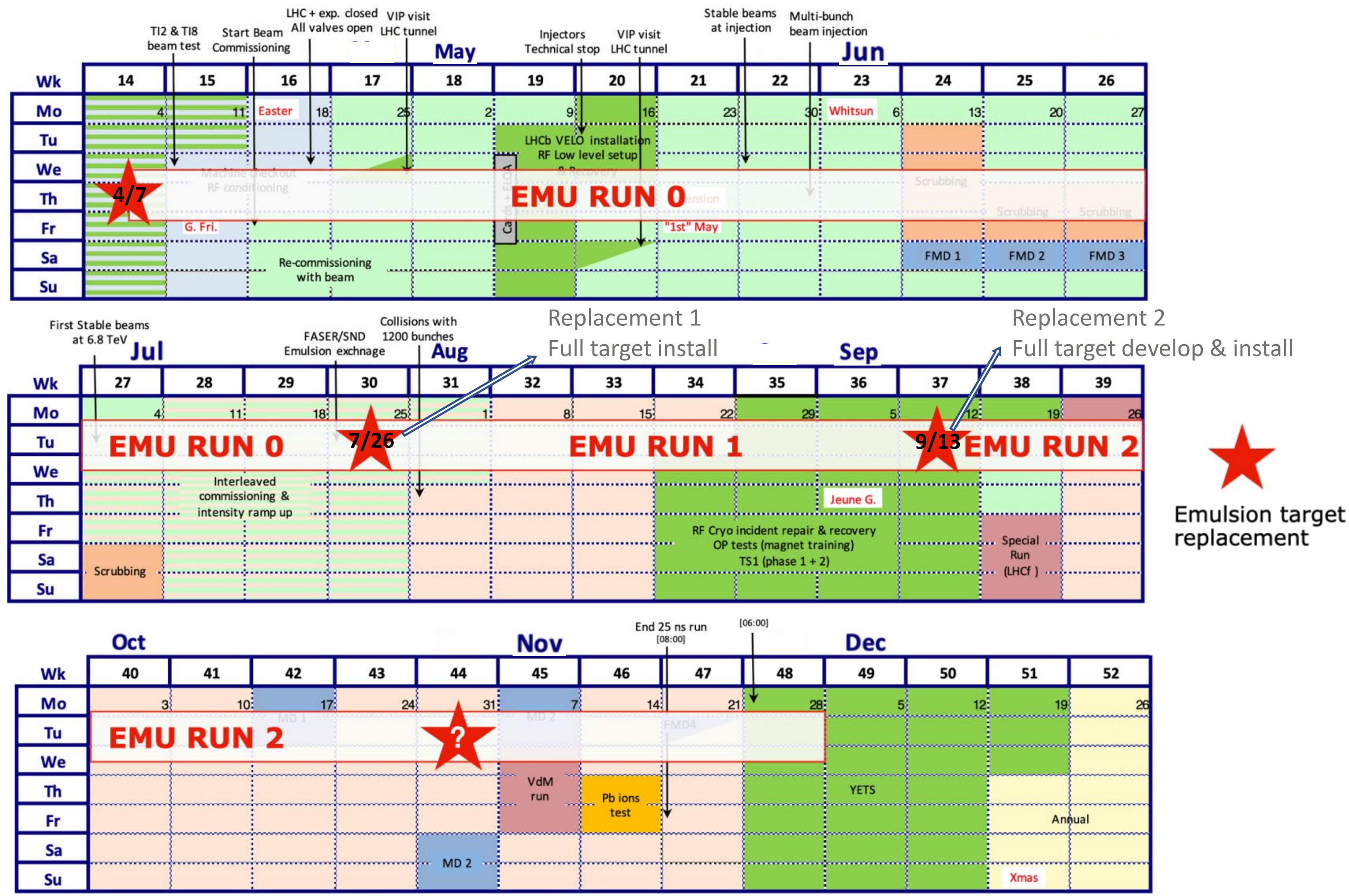
Current view of TI18 tunnel

LHC ring SND@LHC detector

Emulsion facility at CERN

Emulsion target replacements in 2022

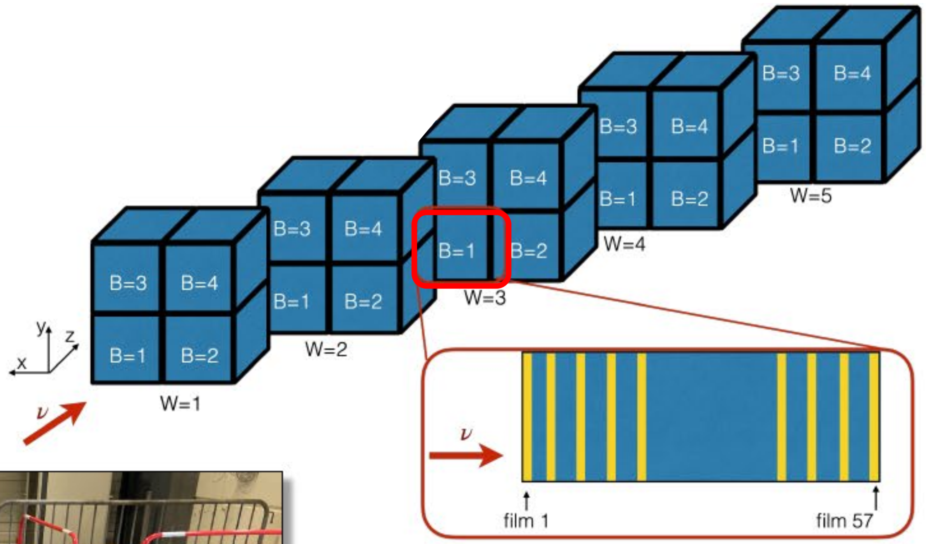
- **RUN #0** Integrated luminosity: 0.52 fb^{-1} **Emulsion films: 57** target mass: 41 kg
- **RUN #1** Integrated luminosity: 10.5 fb^{-1} **Emulsion films: 1173** target mass: 830 kg
- **RUN #2** Taking data **Emulsion films: 1140** target mass: 830 kg



Emulsion Target #0

¼ of **Wall 3** equipped with emulsions
Number of emulsion films: **57** (Nagoya)

Installation in the target: 7 Apr 2022
Extraction from the target: 26 July 2022



One brick

7 Apr – Wall 3 in TI18

26 July – Walls of Emulsion Target#0 extracted

ECC Brick wall replacement (Target #1, 26 July 2022)

Emulsion Target #2

13 Sept 2022

Trolleys ready to be transported

Target replacement

Emulsion Target #1: Development

13 – 23 Sept 2022

- Number of emulsion films: 1173
- First use of development facility and tools with full emulsion load
- Three parallel chains > 10h/day to complete development in 10 days

	day 1	2	3	4	5	6	7	8	9	10
Chemical bath preparation	■									
Extraction from the wall		■								
Chemical treatment Nagoya films			■	■						
Chemical treatment Slavich films						■	■			
Drying				■	■	■	■	■		
Surface cleaning Nagoya films					■	■	■	■		
Thickening							■	■	■	
Drying								■	■	■
Packaging									■	■

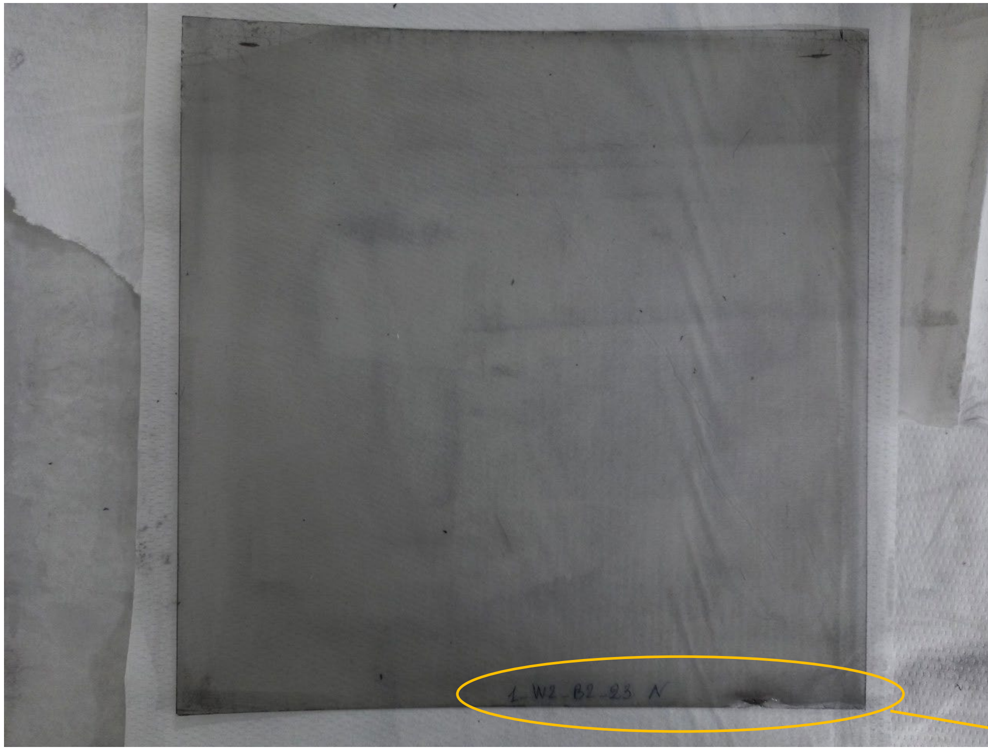
ECC target assembly → Installation → Extraction →

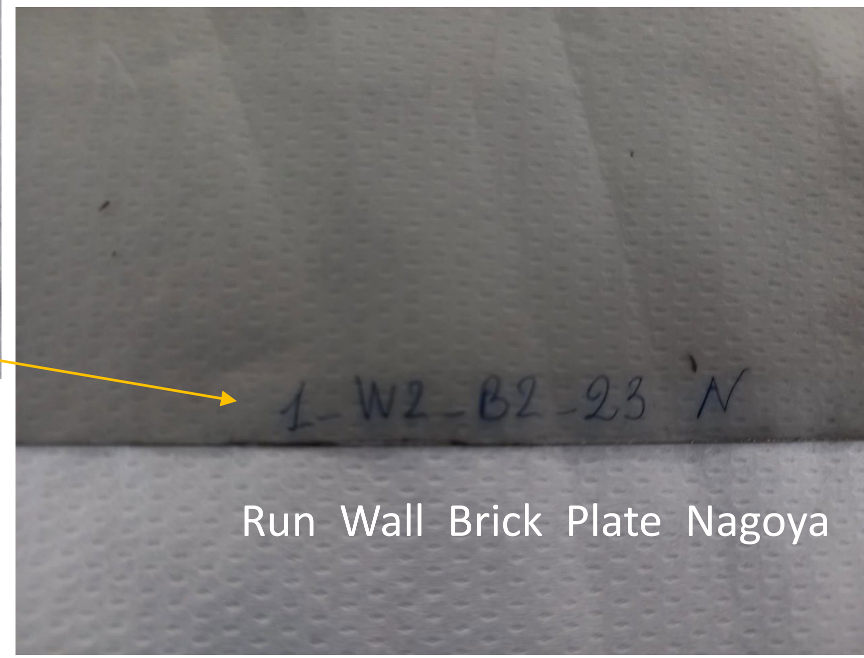
Emulsion development → Scanning → Event analysis

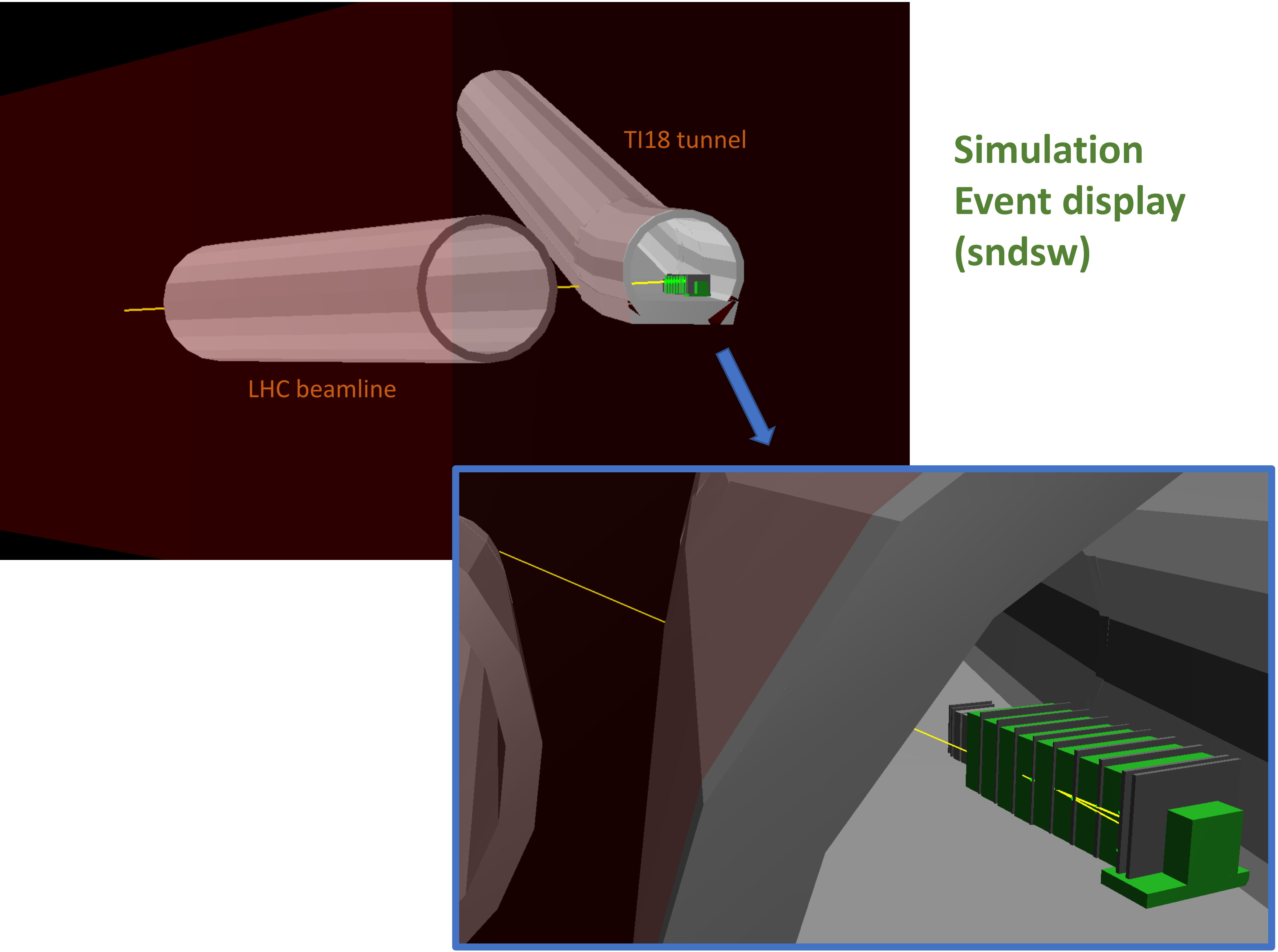
Emulsion drying after development

Sept 2022

Developed Emulsion film
19.2 cm x 19.2 cm







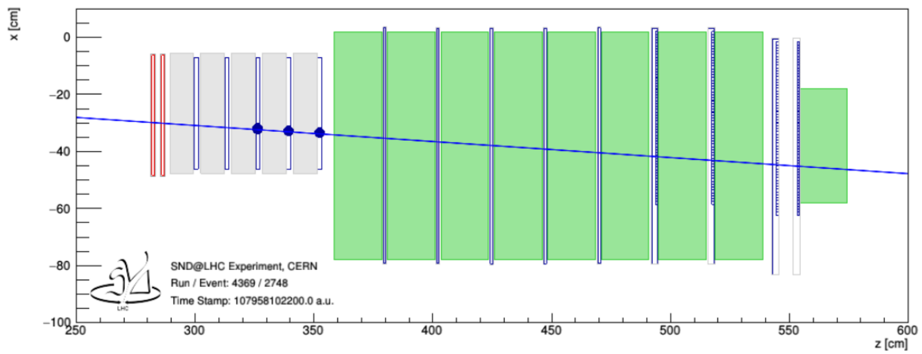
Simulation
Event display
(sndsw)

Real data in TI18

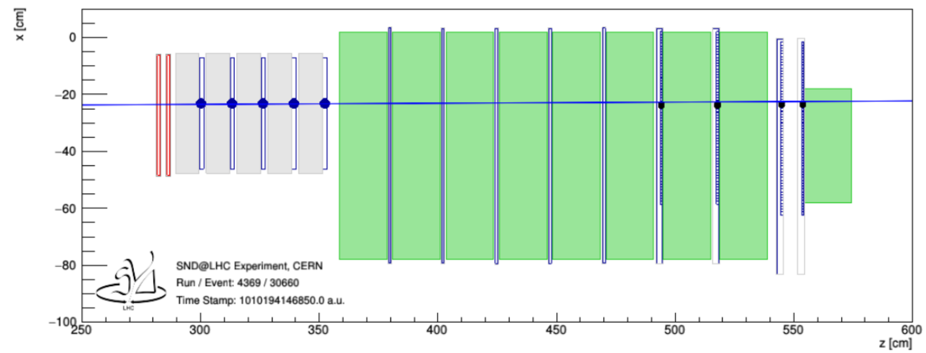
Cosmic ray
(5 Mar 2022)

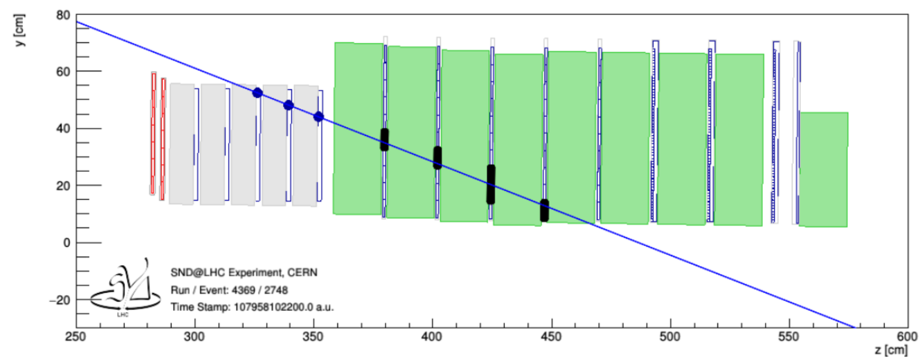
LHC beam
Muon from pp collision @13.6 TeV
(6 July 2022)

Top view

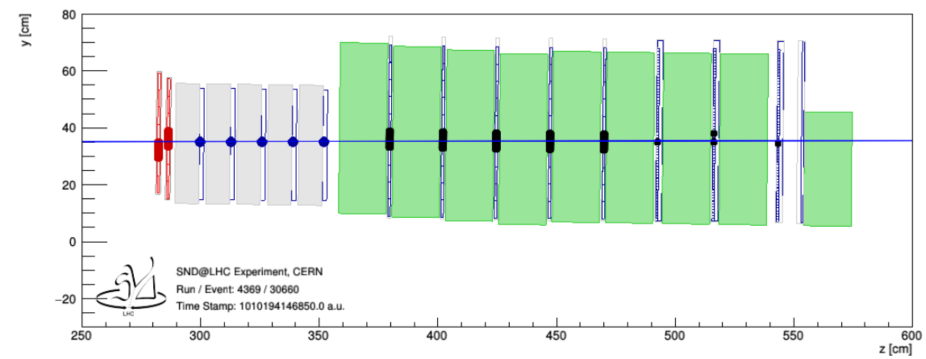


Top view





Side view

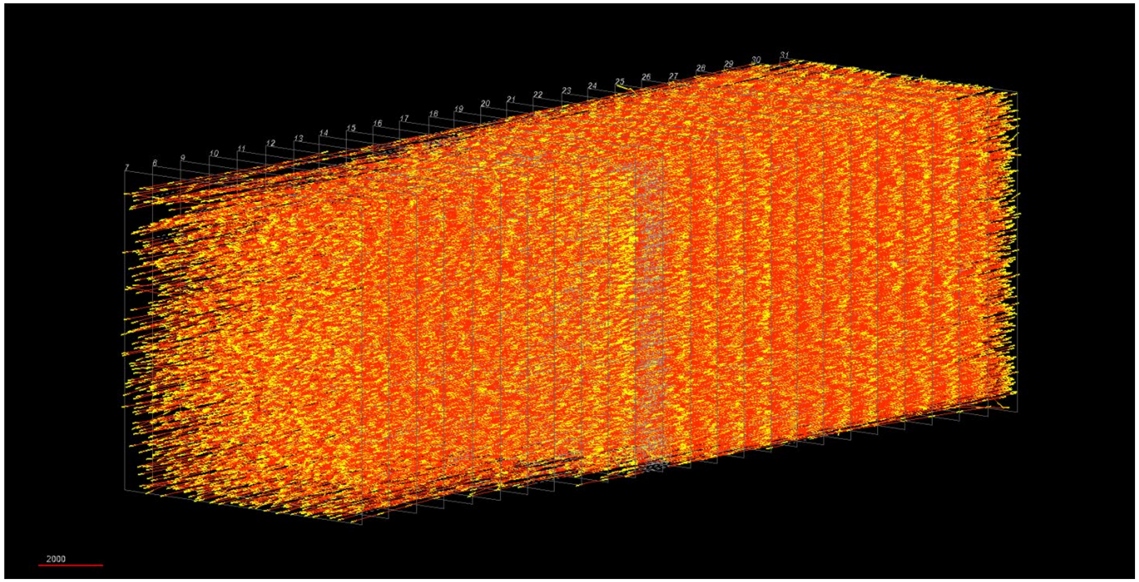


Side view

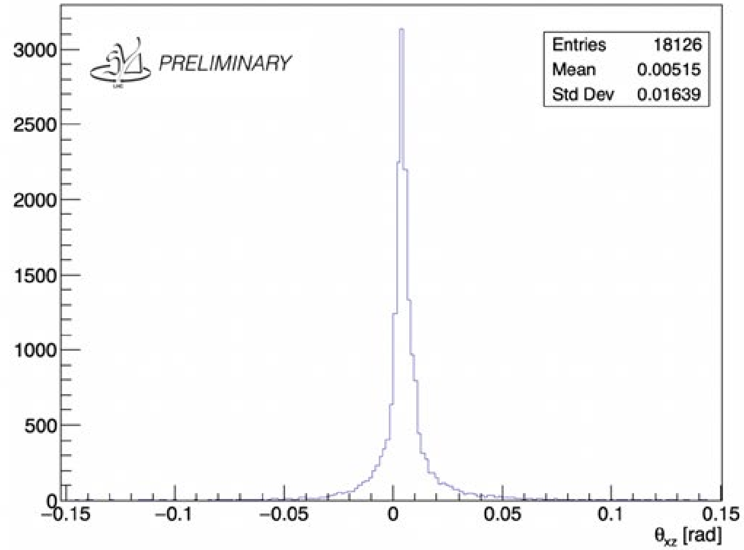
Emulsion data

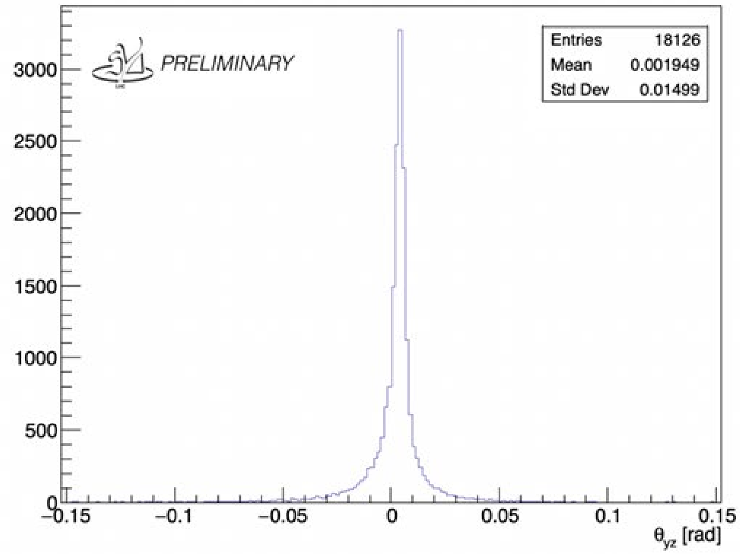
Reconstructed tracks

Run #0 (April - July 2022)
L = 0.52 fb^{-1}
Area = 1 cm^2



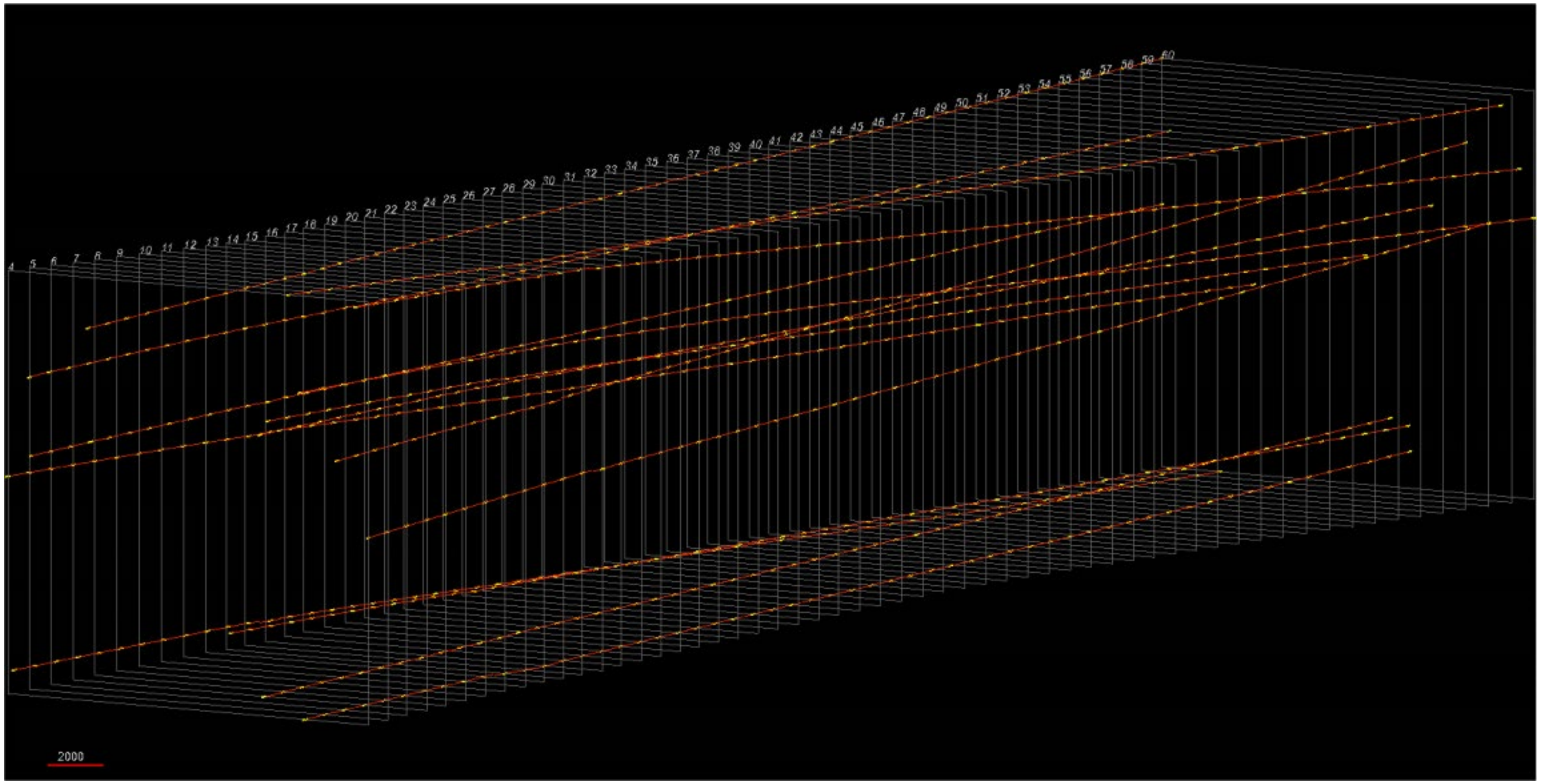
Reconstructed tracks in the first run @13.6 TeV. Their directions are compatible with those coming from p-p collisions at IP1, after alignments for plate by plate connections.





Emulsion data

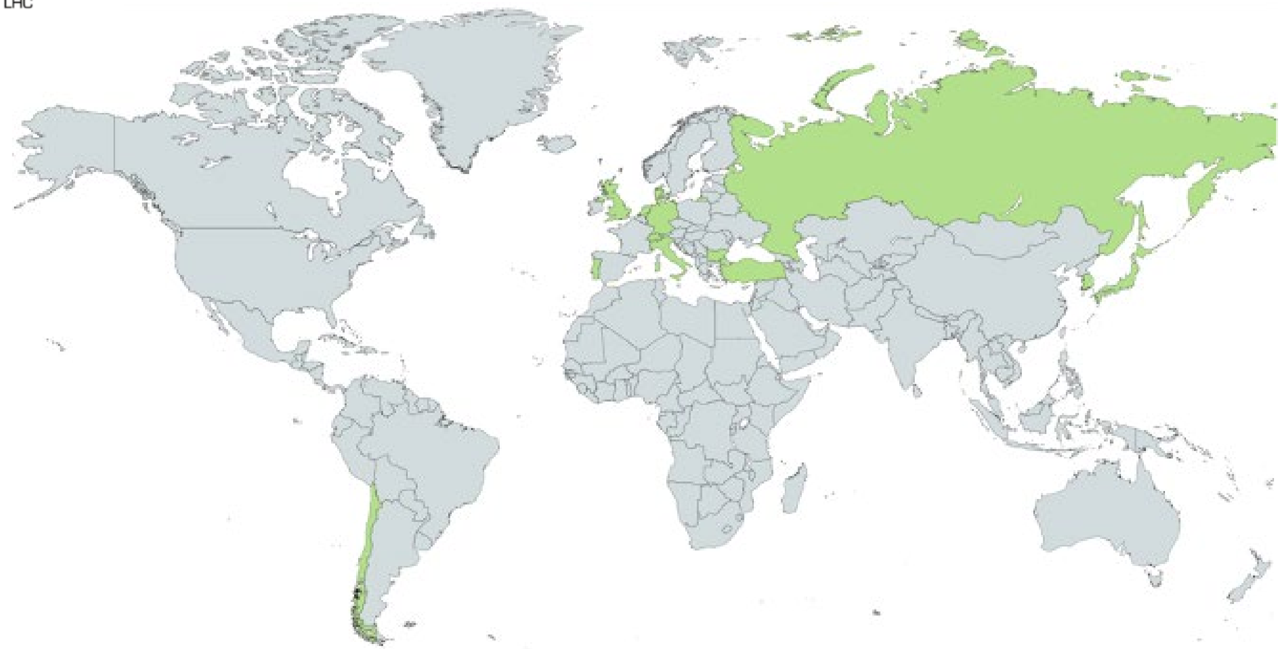
Muon tracks reconstructed in the emulsion target.
No neutrino event yet.



15 tracks selected randomly in 1 x 1 cm^2 → **57 emulsion films (1 brick)**

RUN#0 emulsion target: **7 April - 26 July 2022**

SND@LHC Collaboration



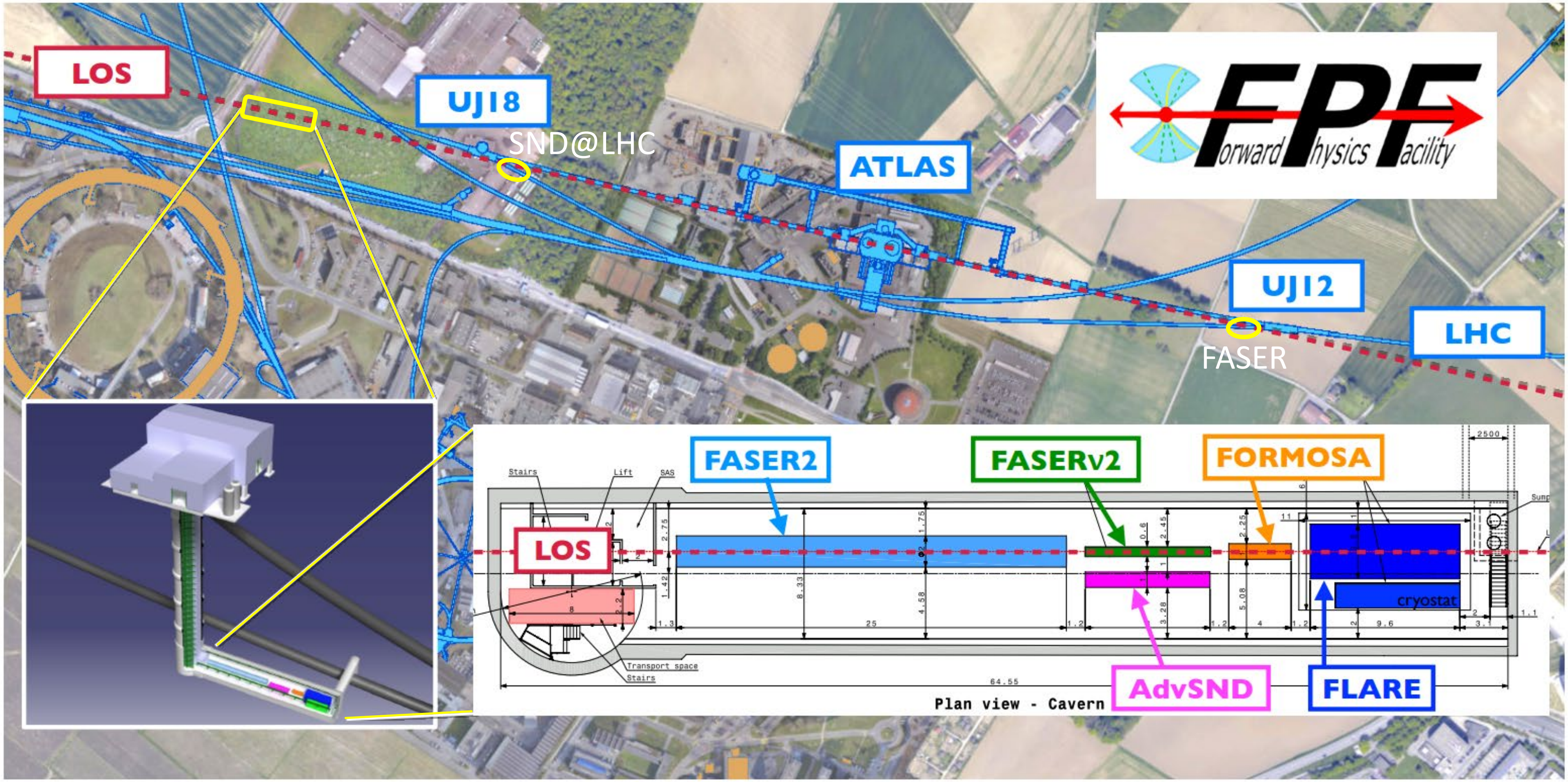
Bulgaria
Denmark
Germany
Italy
Japan
Korea
Russia
Switzerland
Turkey
United Kingdom
Portugal
Chile
Brazil
CERN

180 members, 24 institutes
13 countries & CERN

FPF (Forward Physics Facility)

Future project at HL-LHC era

Phys. Rept. 968 (2022) 1-50



- Baseline option: 630 m from ATLAS IP
- The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments:

  AdvSND (Far) **FORMOSA:** Searching for millicharged particles

  FASER2 & FASERν2 **FLArE:** Dark sector search

Our future plan (idea) – Advanced SND@LHC

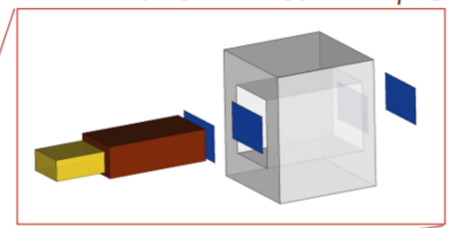
A. Di Crescenzo

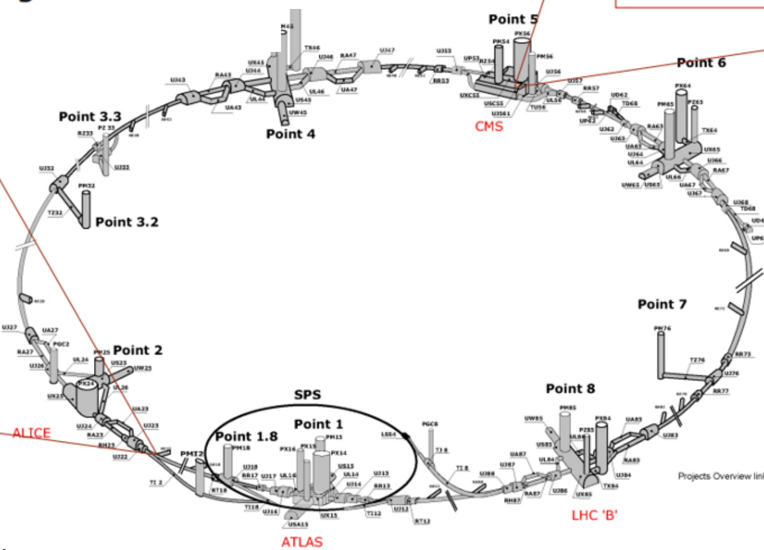
- Upgrade of SND@LHC in view of an extended run during Run 4:
  - Extension of the physics case
  - New technologies and detector layout
  - Two detectors
    - AdvSND-Far ($7.2<\eta<8.4$)

      Possible locations: TI18, Future Forward Facility
    - AdvSND-Near ($4<\eta<5$)

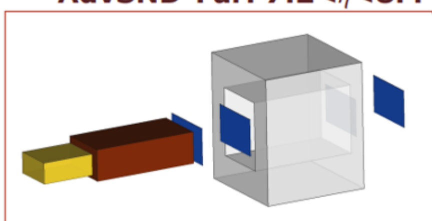
      Possible locations: existing caverns close to IP

AdvSND-Near: $4<\eta<5$





AdvSND-Far: $7.2<\eta<8.4$



Neutrino interactions in ECC target (Expectation 3000 fb^{-1})

AdvSND-Far

Flavour	ν in acceptance		CC DIS	
	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	6.3×10^{12}	1.5×10^{11}	1.2×10^{4}	200
$\nu_e + \bar{\nu}_e$	6.7×10^{12}	1.7×10^{11}	1.2×10^{4}	220
$\nu_\tau + \bar{\nu}_\tau$	7.1×10^{11}	4.7×10^{10}	880	40
Tot	1.4×10^{13}		2.5×10^{4}	

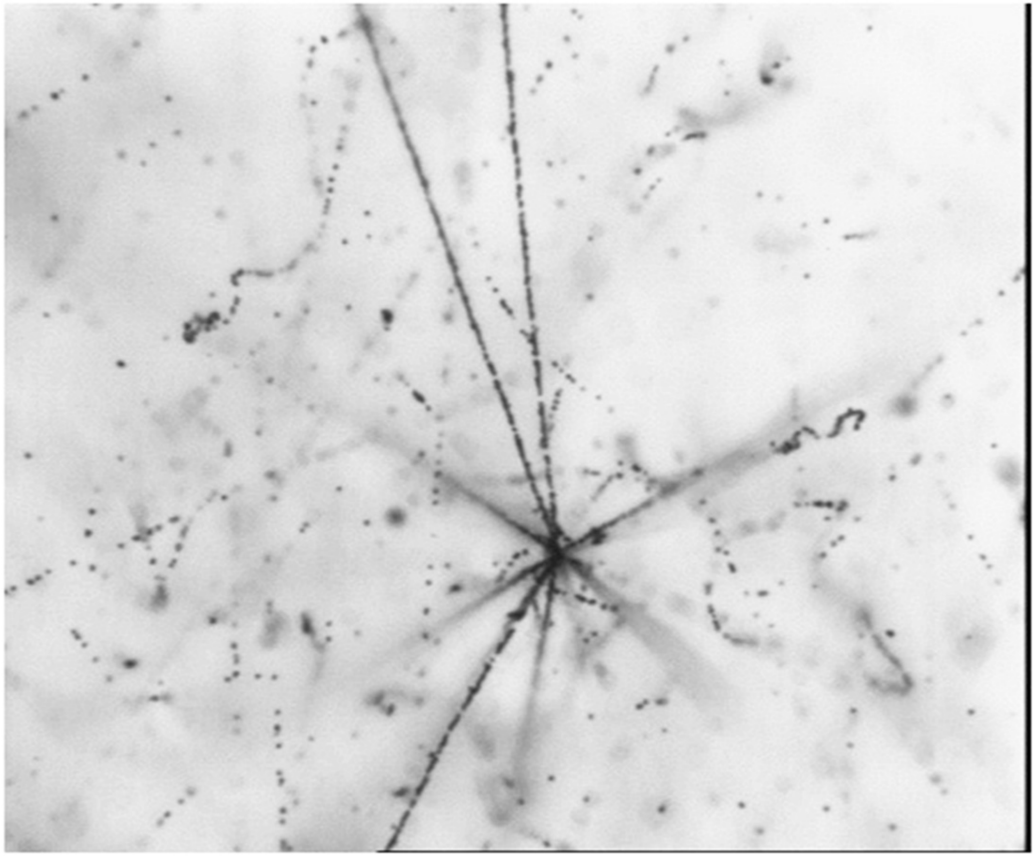
AdvSND-Near

Flavour	ν in acceptance		CC DIS	
	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	2.1×10^{12}	3.3×10^{11}	980	200
$\nu_e + \bar{\nu}_e$	2.2×10^{12}	3.3×10^{11}	1000	200
$\nu_\tau + \bar{\nu}_\tau$	2.7×10^{11}	1.4×10^{11}	80	50
Tot	5.4×10^{12}		2.5×10^{3}	

Summary

- Forward produced particles from LHC Run 3 beam started to come to the SND@LHC Emulsion target (from July 2022).
- So far, two replacements of full Emulsion targets have been done (July and Sept 2022).
- Emulsion film development performed in the new Emulsion Facility (~1200 films in 10 days).
- Scanning is just starting (after plate alignments).

→ waiting for the first Collider neutrino event with identified flavor!



Thank you for your attention !