Neutrino Small Volume Experiment II

Kang Young Lee

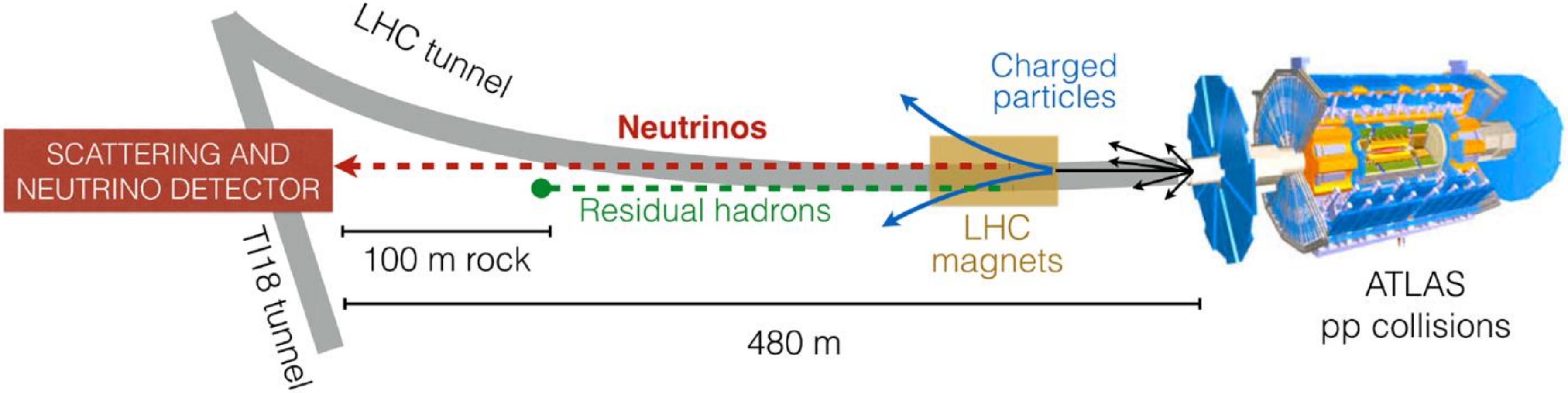
GNU

Thanks to the help of
M. Pac (JSNS2), J. Yoo (COHERENT), and C. S. Yoon (SND@LHC)

@2021 KPS –DPF Meeting 2021.12.18

SND@LHC

Scattering and Neutrino Detector operating at the LHC

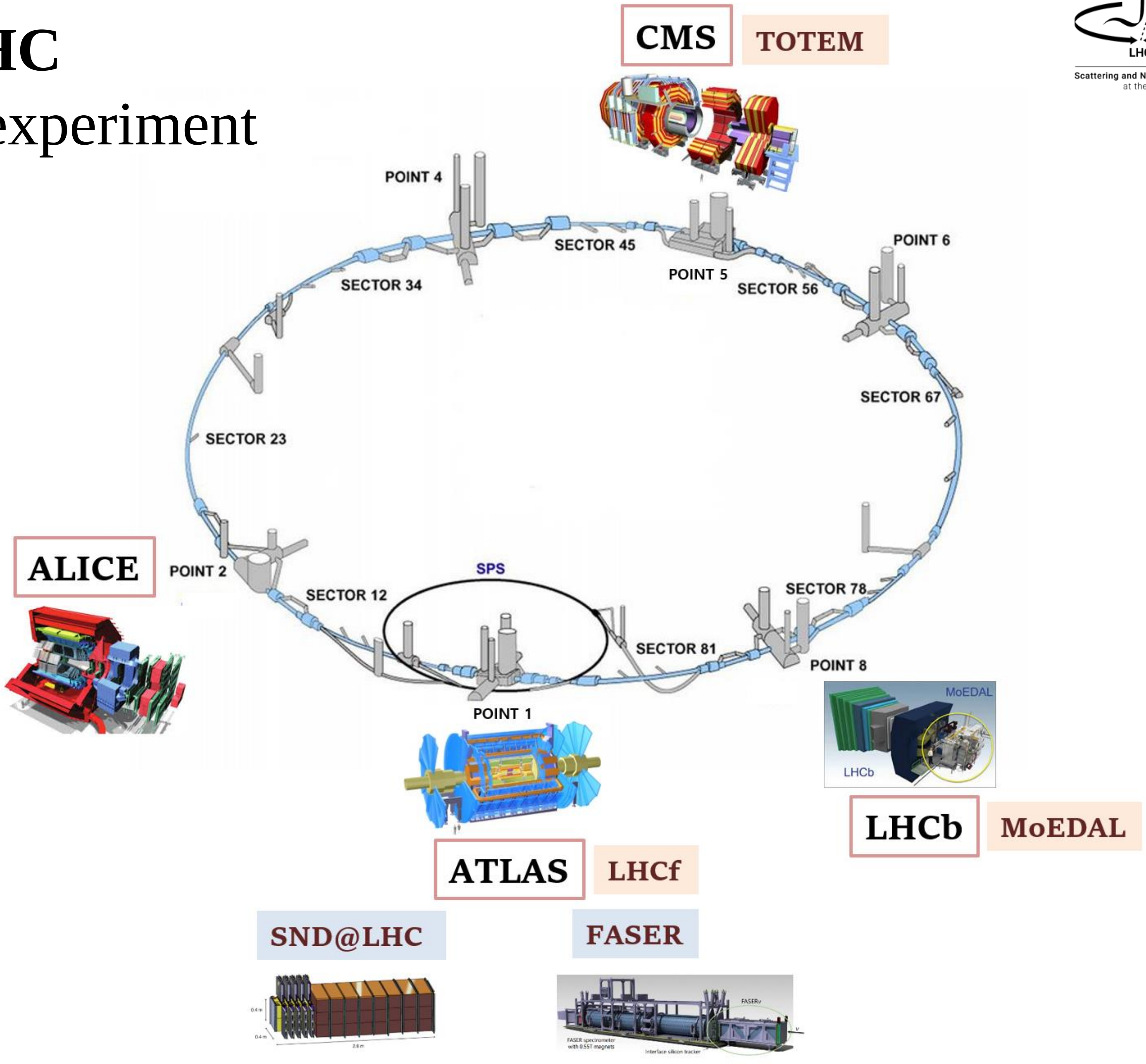


New experiment to study high energy neutrinos and feebly interacting particles produced at the LHC

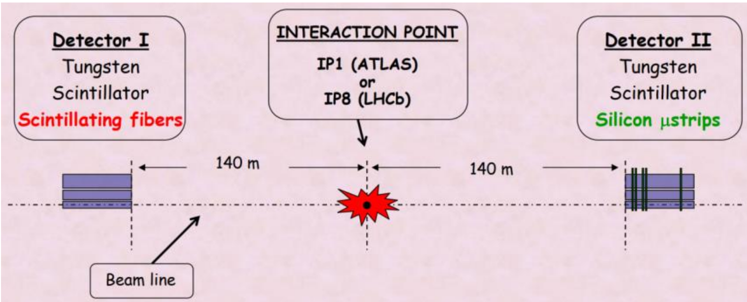
SND@LHC Technical Proposal
https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf

SND@LHC
9th LHC experiment

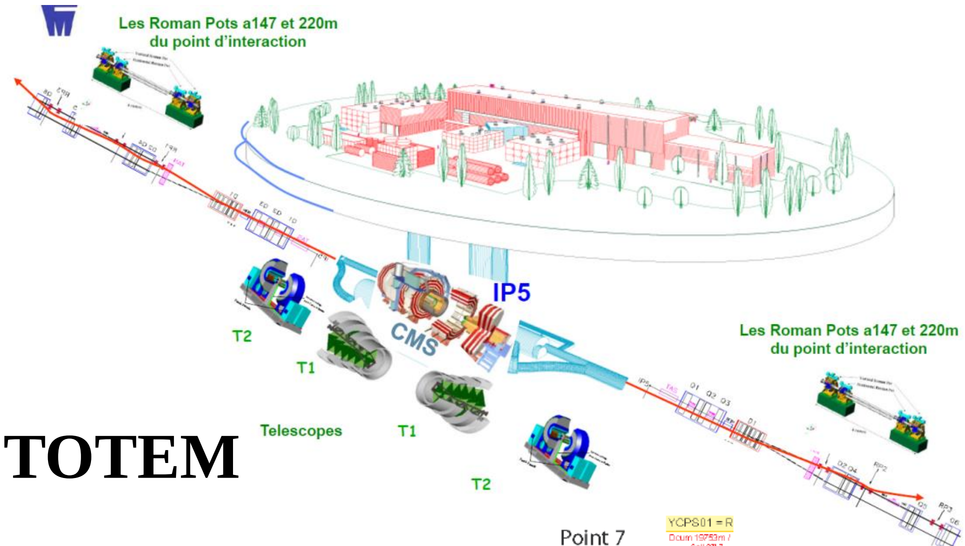
Scattering and Neutrino Detector at the LHC



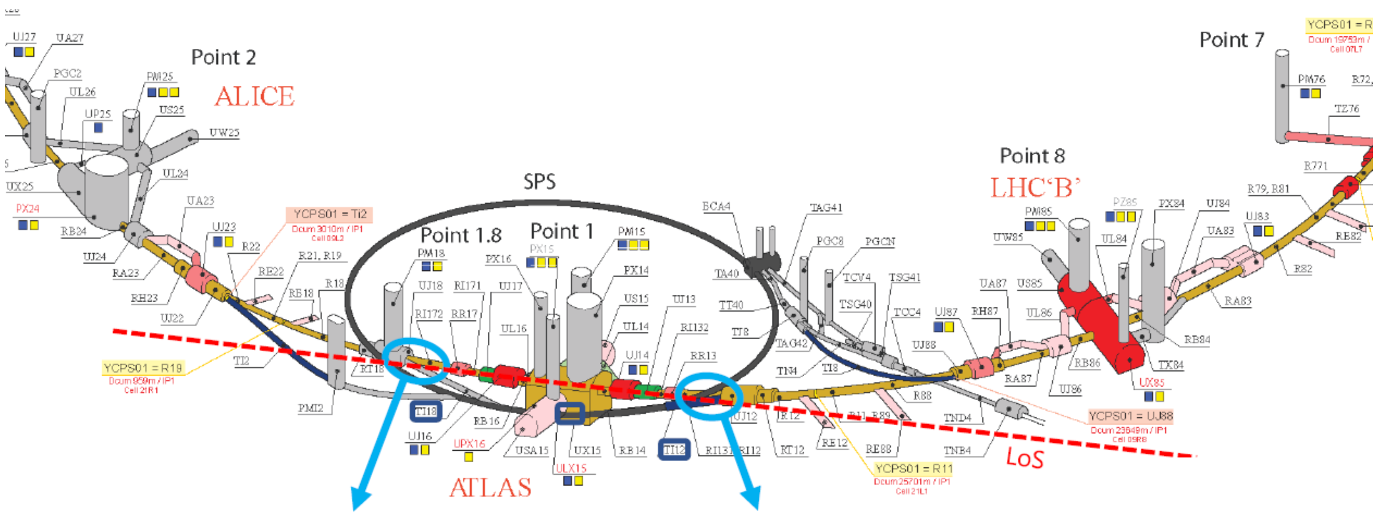
Forward Experiment of LHC



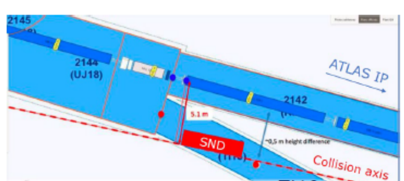
LHCf

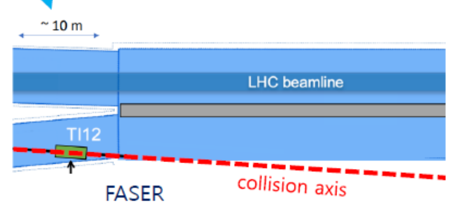


TOTEM



SND@LHC

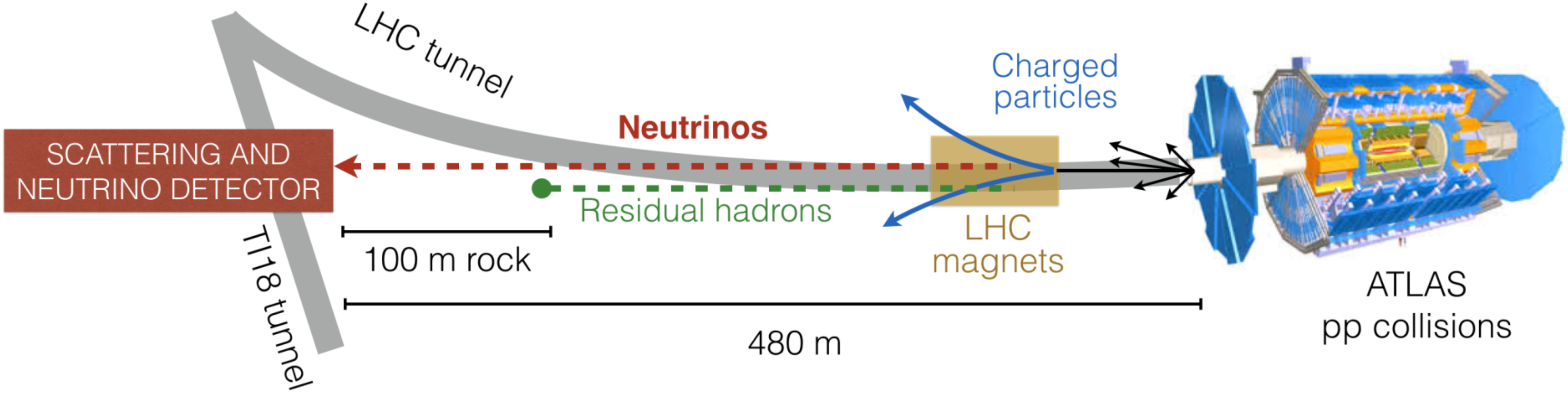




FASER

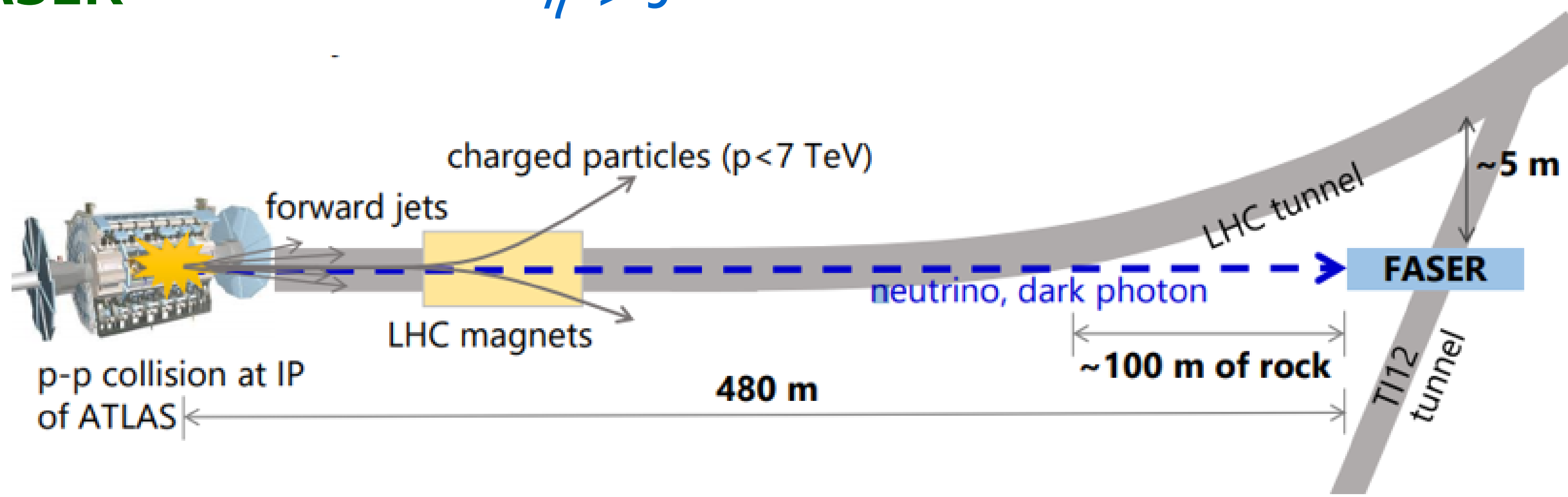
SND@LHC

$7.2 < \eta < 8.6$



FASER

$\eta > 9$

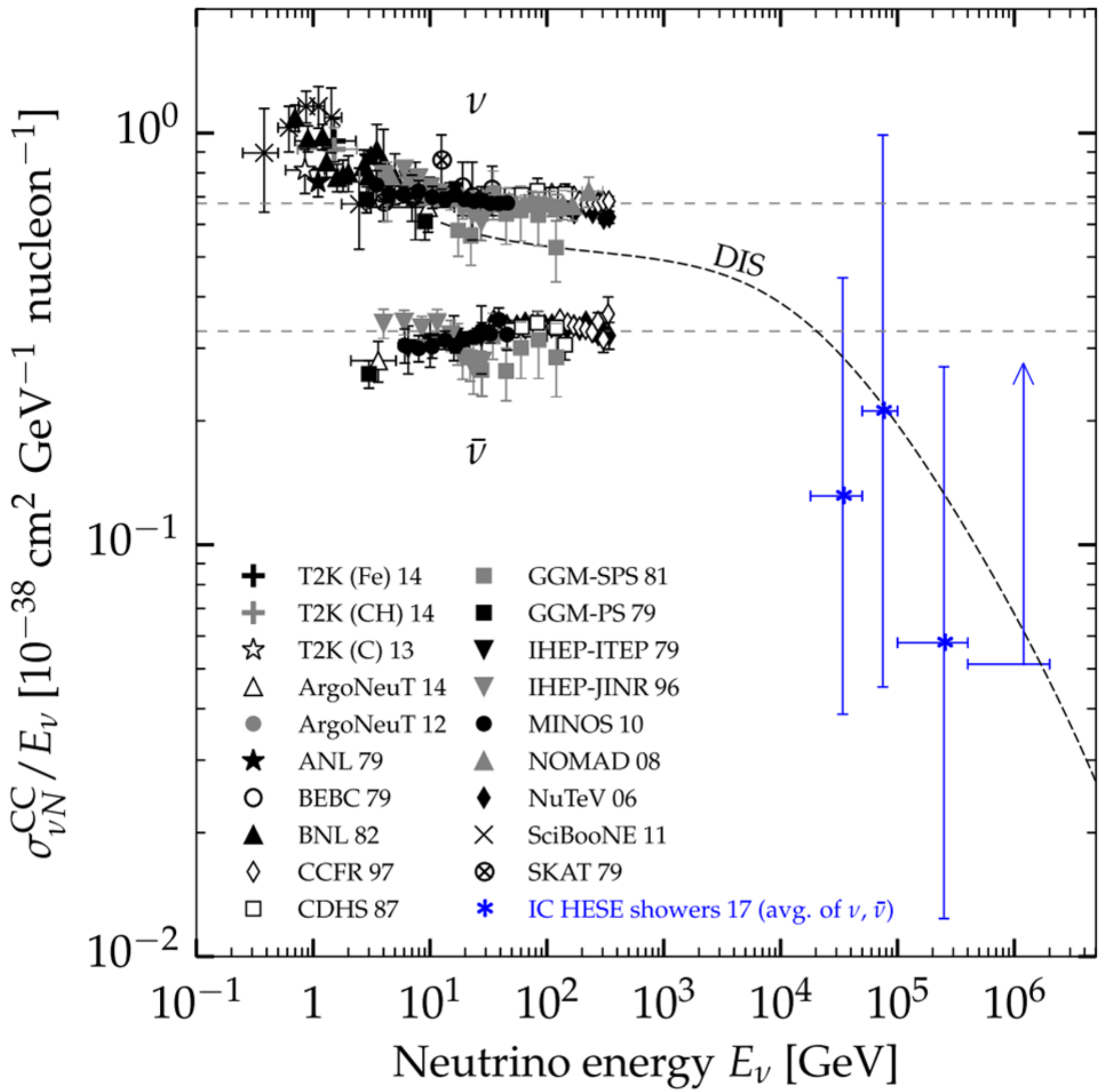


LHC
Scattering and Neutrino Detector at the LHC

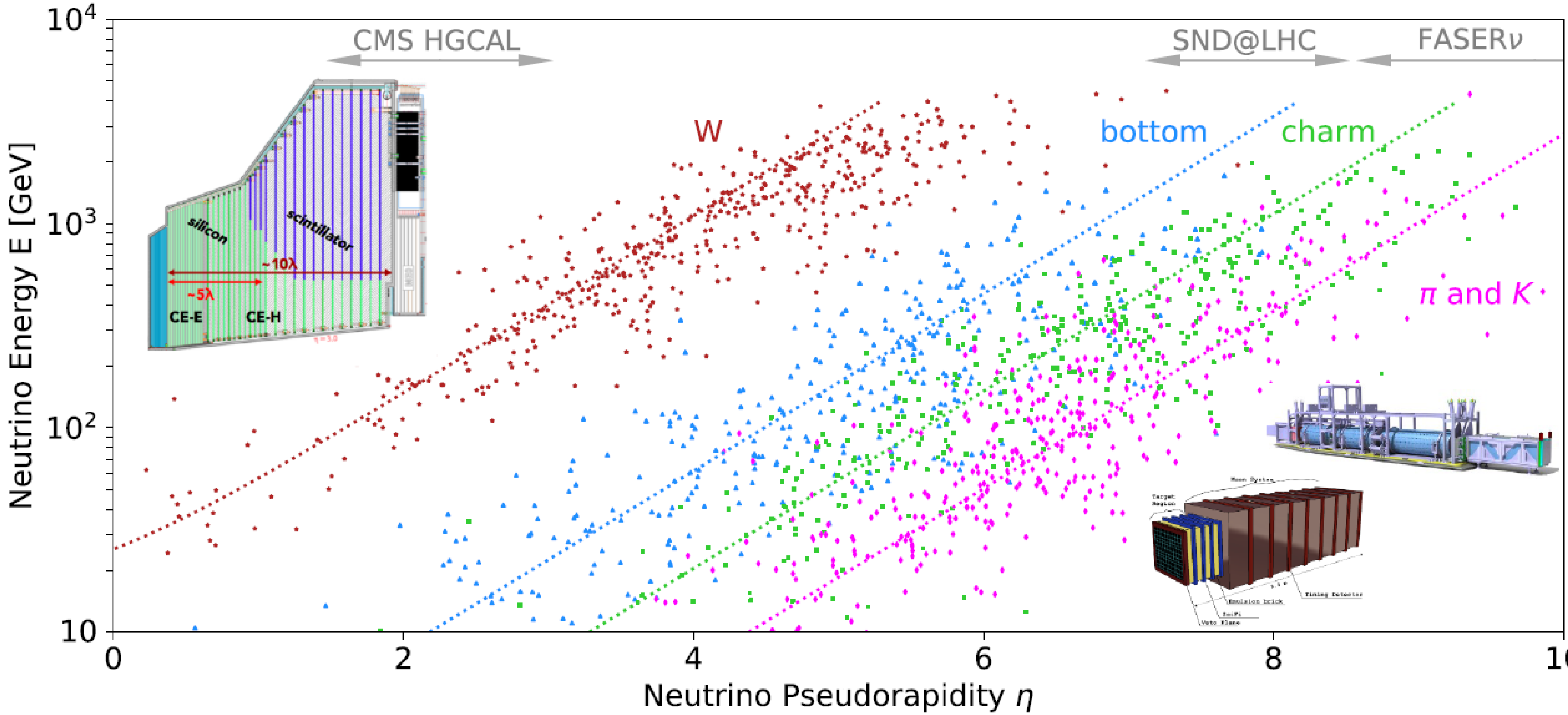
Physics Goals

- **High energy neutrinos** $pp \rightarrow \nu X$ at the LHC studied for the first time
- Expected neutrino energy **350 GeV – TeV**
- Measuring all of **three flavour** neutrinos
- Pseudorapidity region $\mathbf{7.2 < \eta < 8.6}$ (Note that FASERν $\eta > 9$)
- First phase : operation in Run3 to collect **$150 fb^{-1}$**

First direct observation of LHC neutrinos!



- The first study of the high energy neutrinos in 350 GeV-10 TeV range.
- LHC is the unique place to study the high energy.



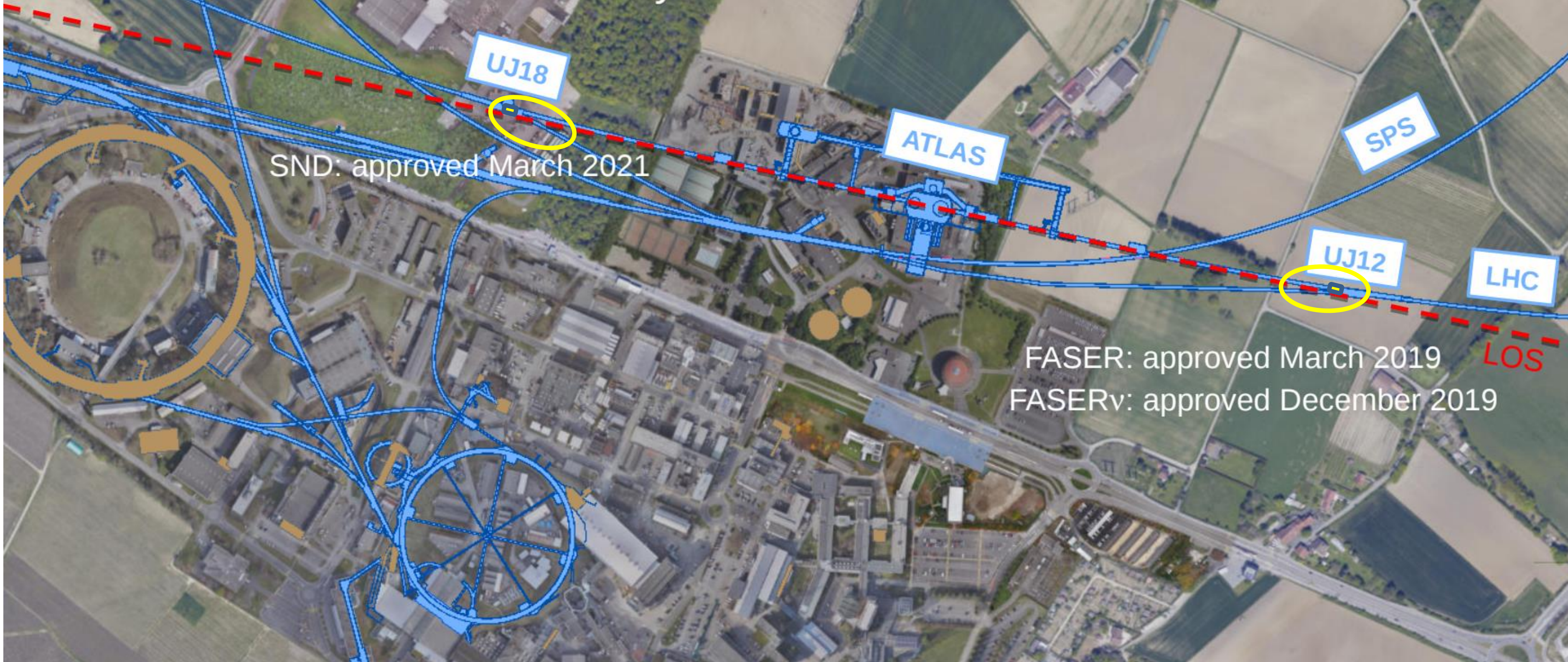
Energy and Pseudorapidity distribution of LHC neutrinos

arXiv: 2108.05370 [hep-ph]

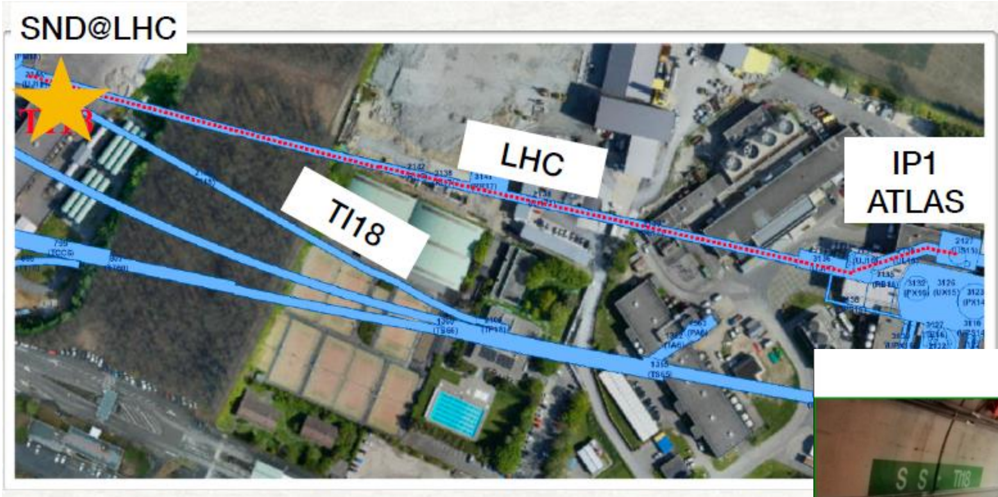
SND@LHC
Scattering and Neutrino Detector at the LHC

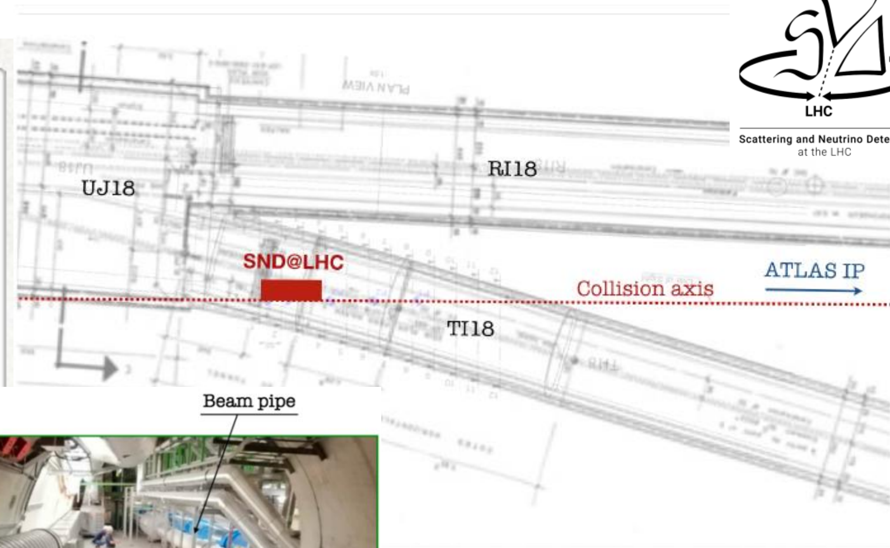
FAR FORWARD LHC EXPERIMENTS

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.

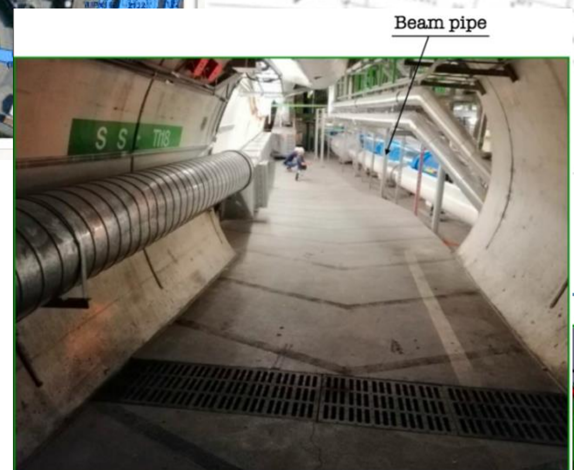


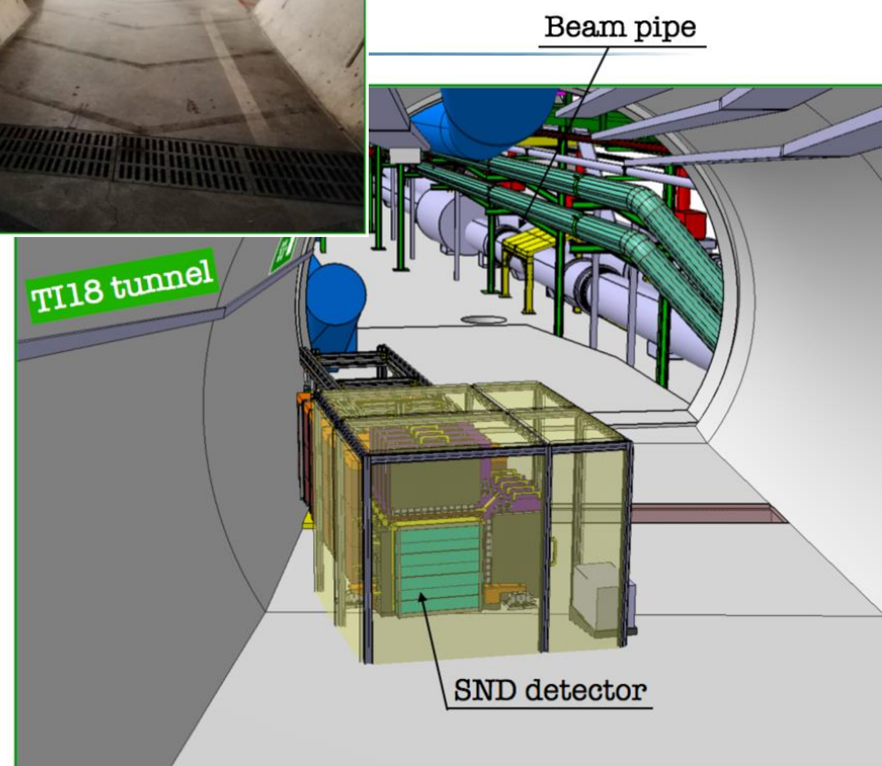
Scattering and Neutrino Detector at the LHC





Location





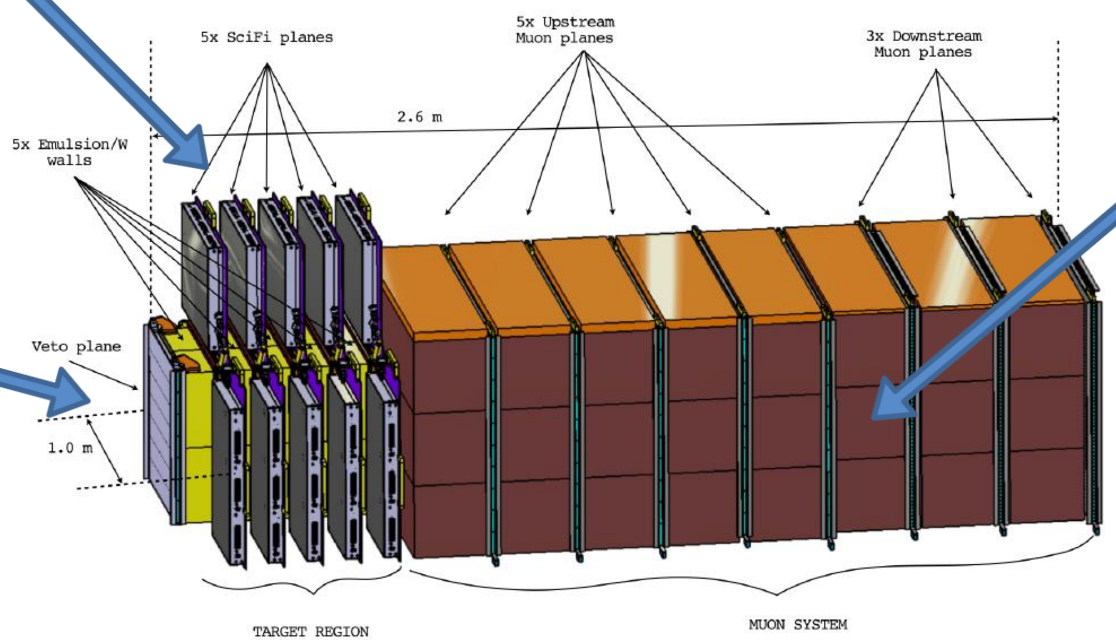
- About 480m away from the ATLAS IP
- TI18 tunnel : former service tunnel connecting SPS to LHC
- Charged particles are deflected by the ATLAS magnet and shielded by 100 m rock

SND@LHC detector

Hybrid detector optimized for the identification of 3 neutrino flavours.

Emulsion Cloud Chambers (ECC) : Emulsion + Tungsten
Scintillating fibers for timing information and energy measurement

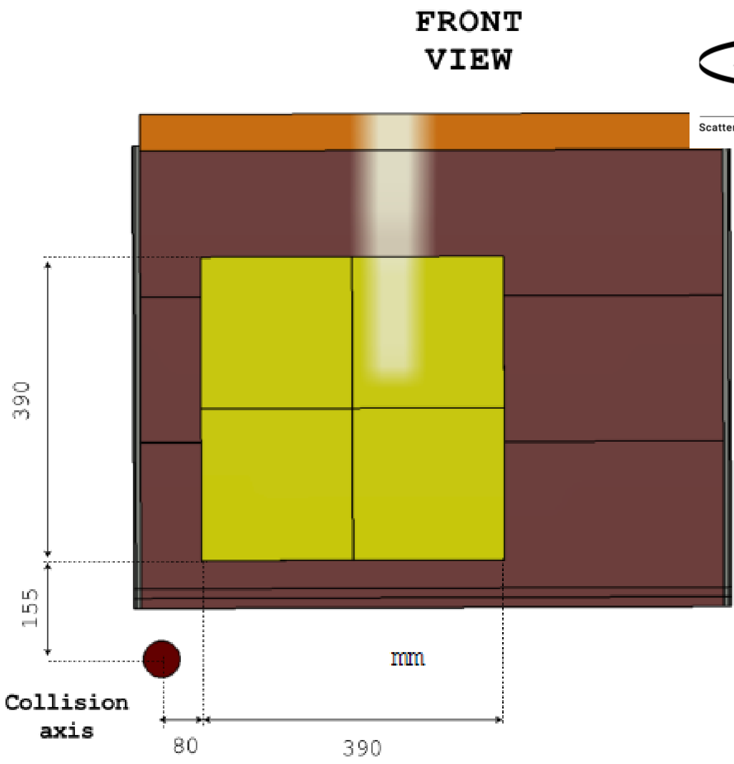
Muon veto plane

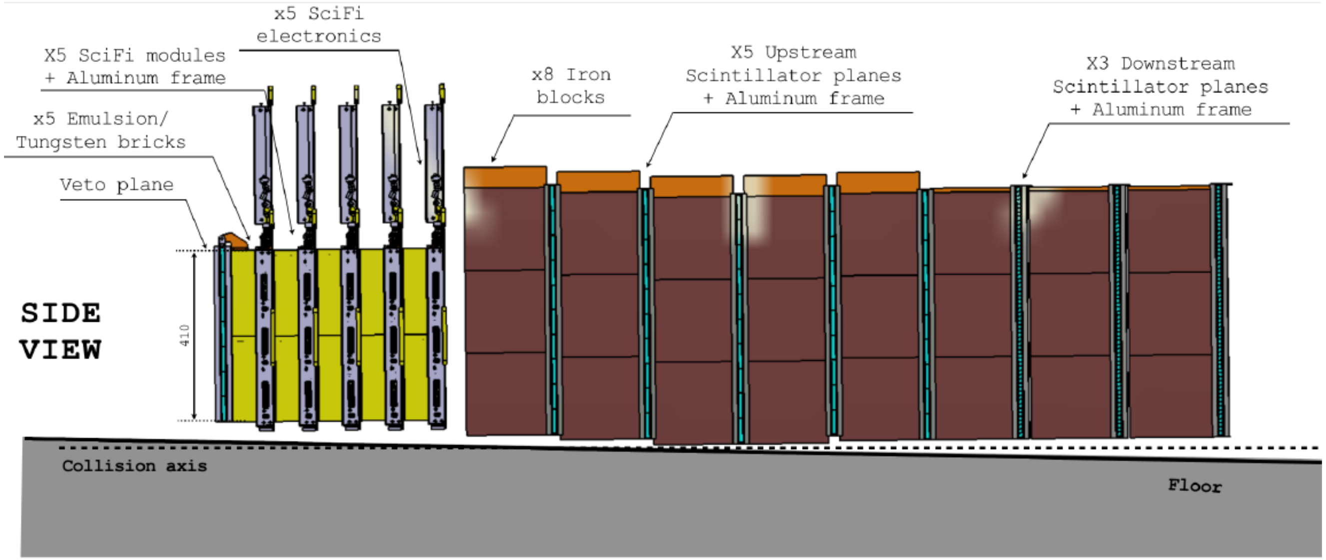


Muon system
Iron walls interleaved with plastic scintillator

The Detector Layout

- Angular acceptance 7.2 < η < 8.6
- Target : Tungsten 830 kg
- Surface : 390x390 mm²



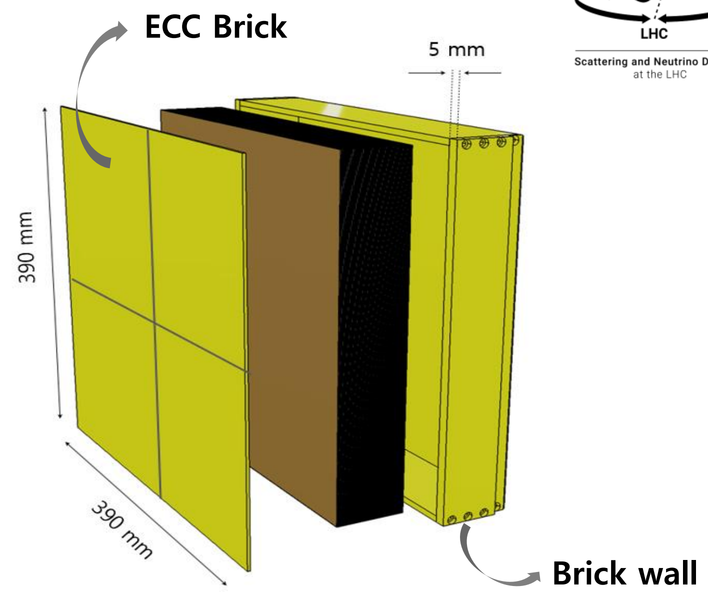


LHC
Scattering and Neutrino Detector
at the LHC

ECC target (& detector)

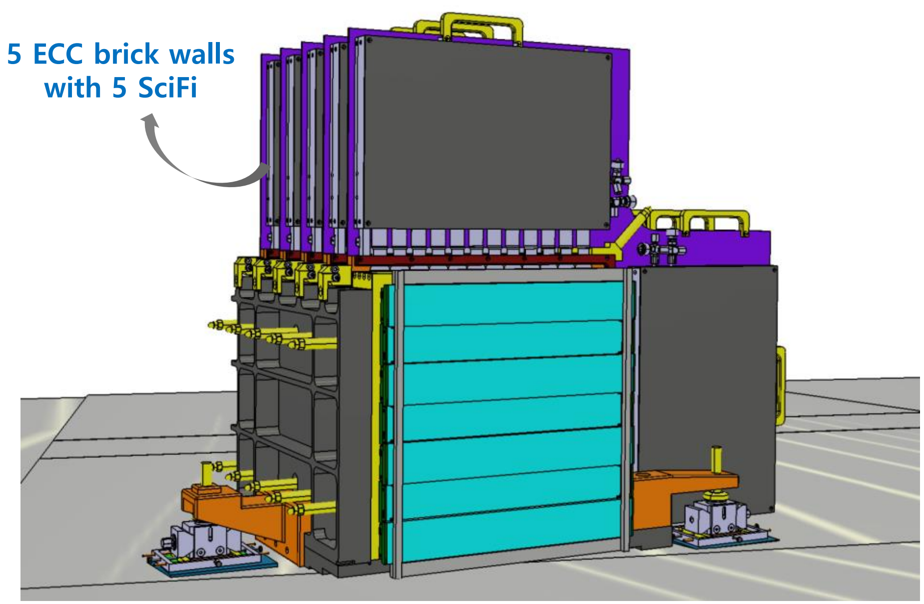
LHC
Scattering and Neutrino Detector at the LHC

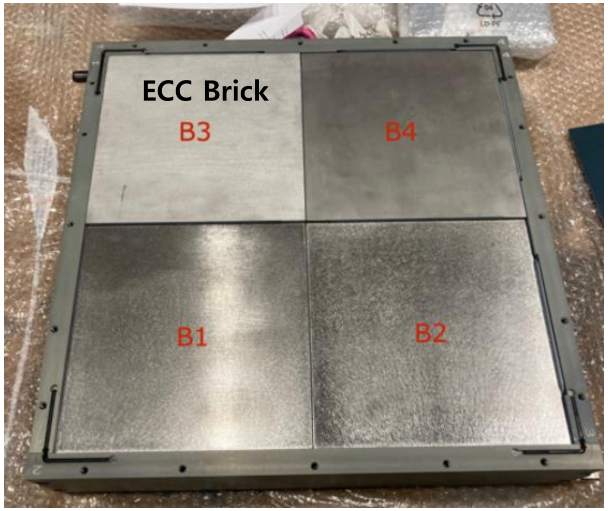
- Number of ECC Brick walls: **5**
- 1 Brick wall → 4 ECC Bricks
- **1 ECC Brick** → Sandwich structure of Emulsion films & Tungsten plates
  - **60** Emulsion films (0.3 mm-thick each)
  - 59 Tungsten plates (1 mm-thick each)



150 fb^{-1} in 3 years → ECC Brick will be replaced about 6 times (every 25 fb^{-1})

- **Total 120 Bricks** : 4 Bricks x 5 walls x 6 times
- Number of films: **7200**
- Total surface: **274 m²**
- Total mass: **830 kg**

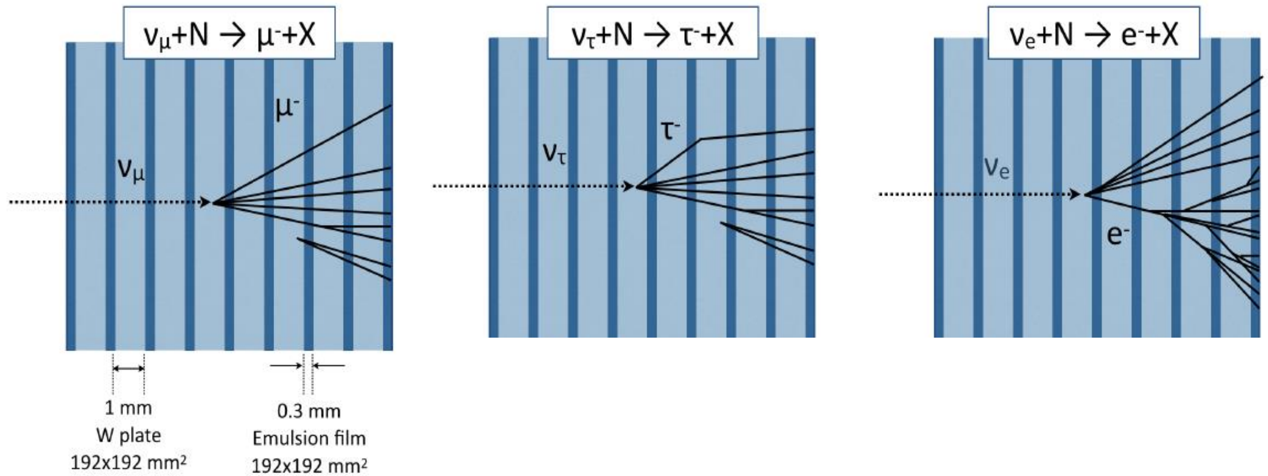




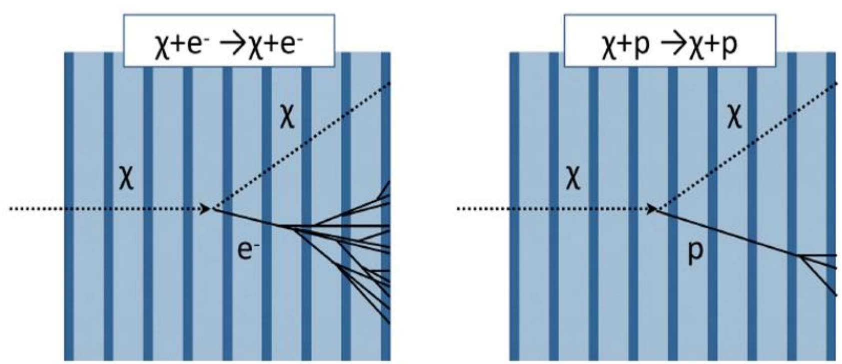
4 ECC Bricks in a Brick wall

Signals reconstructed in the ECC Brick

Neutrino scattering



LDM & FIP scattering



Neutrino expectation

150 fb^{-1} in LHC run 3

LHC
Scattering and Neutrino Detector at the LHC

We can expect about **2,000** high energy neutrino interactions in the ECC target.

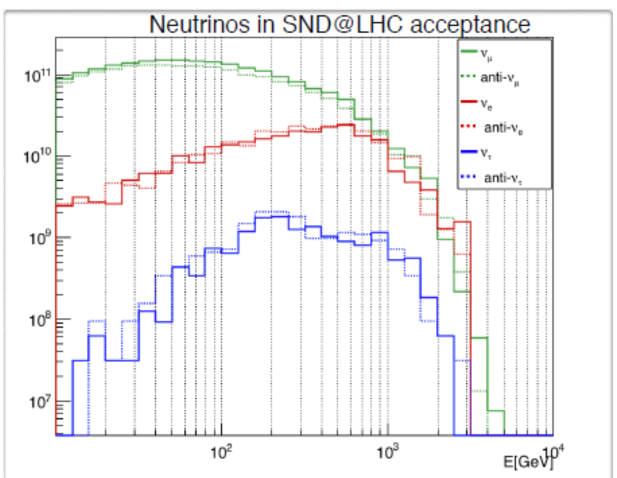
ν production with DPMJET3, **propagation** with FLUKA, **interaction** with GENIE:

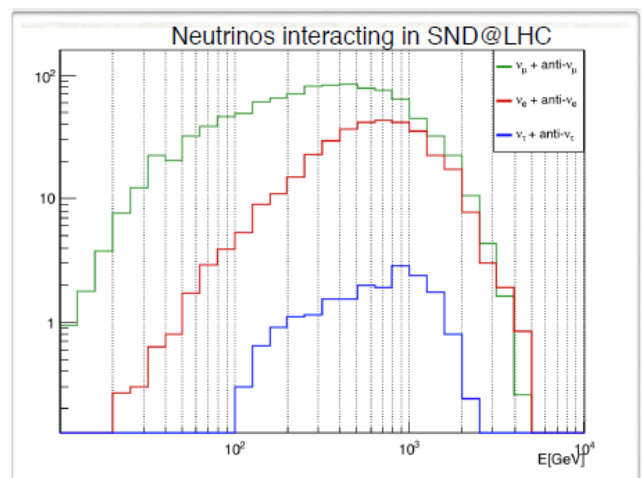
Number of ν's in SND@LHC acceptance

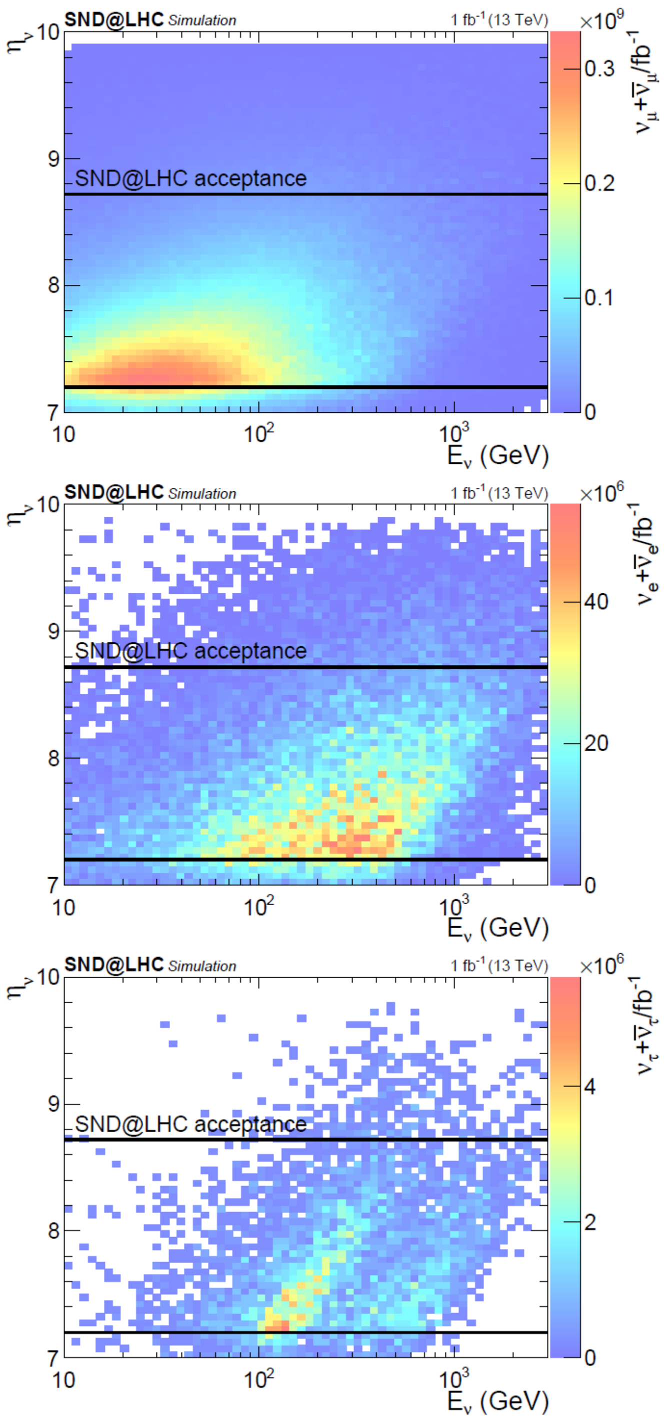
Flavour	Neutrinos in acceptance $\langle E \rangle$ (GeV)	Yield
ν_μ	145	2.1×10^{12}
$\bar{\nu}_\mu$	145	1.8×10^{12}
ν_e	395	2.6×10^{11}
$\bar{\nu}_e$	405	2.8×10^{11}
ν_τ	415	1.5×10^{10}
$\bar{\nu}_\tau$	380	1.7×10^{10}
TOT		4.5×10^{12}

ν's interacting in SND@LHC ECC target

Flavour	CC neutrino interactions $\langle E \rangle$ (GeV)	Yield	NC neutrino interactions $\langle E \rangle$ (GeV)	Yield	
ν_μ	450	730	480	220	330
$\bar{\nu}_\mu$	485	290	480	110	
ν_e	760	235	720	70	114
$\bar{\nu}_e$	680	120	720	44	
ν_τ	740	14	740	4	6
$\bar{\nu}_\tau$	740	6	740	2	
TOT		1395		450	







Neutrino and anti-neutrino flux as a function of neutrino energy and pseudo-rapidity.

Muon-electron-tau neutrinos from top to bottom.

Physics Cases

- Measurement of the **cross section** ($pp \rightarrow \nu X$) in $7.2 < \eta < 8.6$ range
- ν as a probe of **heavy flavour production**
- **Lepton flavor universality test** in neutrino interactions: ν_τ / ν_e and ν_μ / ν_e
- Measurement of the **NC/CC** ratio
- Direct search for **feebly interacting particles** through their scattering

Expectations

Scattering and Neutrino Detector at the LHC

- Measurement of the $pp \rightarrow \nu X$ **cross section**. (~5% ~15%)
- **Heavy flavour production** from ν in pp collision (~5% ~35%)
- **Lepton flavour universality** in neutrino interaction

$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \rightarrow \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \rightarrow \nu_\tau)}, \quad (\sim 30\% \ \sim 20\%)$$

$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}. \quad (\sim 10\% \ \sim 10\%)$$

- Measurement of the CC/NC ratio. (~5% ~10%)

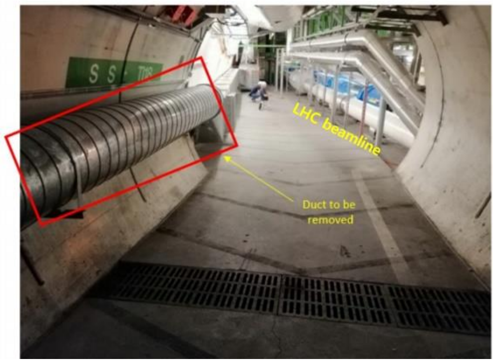
$$P = \frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}}$$

Installation Status

LHC
Scattering and Neutrino Detector at the LHC

SND@LHC

TI18 tunnel (480 m left from ATLAS IP)



2021. 11

FASER

TI12 tunnel (480 m right from ATLAS IP)

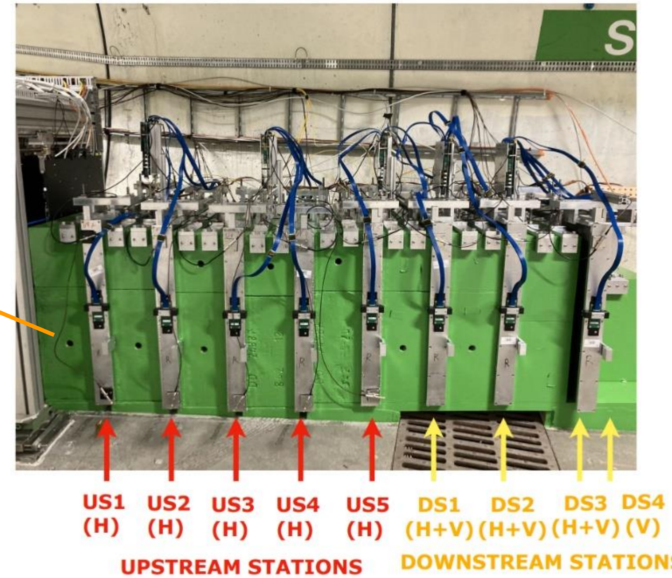
LHC

Scattering and Neutrino Detector
at the LHC

2021. 12

Scattering and Neutrino Detector at the LHC

Muon ID system

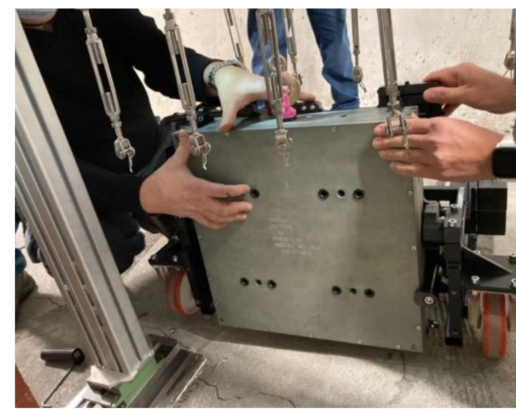


SciFi readout electronics

ECC Brick

Front view

Trolley carrying ECC Brick



ECC Brick installation

2021. 12

SND-LHC is currently a collaboration with 180 members from 24 institutes in 13 countries and CERN..

Korean group have joined the collaboration with 8 members from 4 institutes below:

K-SND group

Gyeongsang National University
S. H. Kim, K. Y. Lee, B. D. Park, J. Y. Sohn, C. S. Yoon

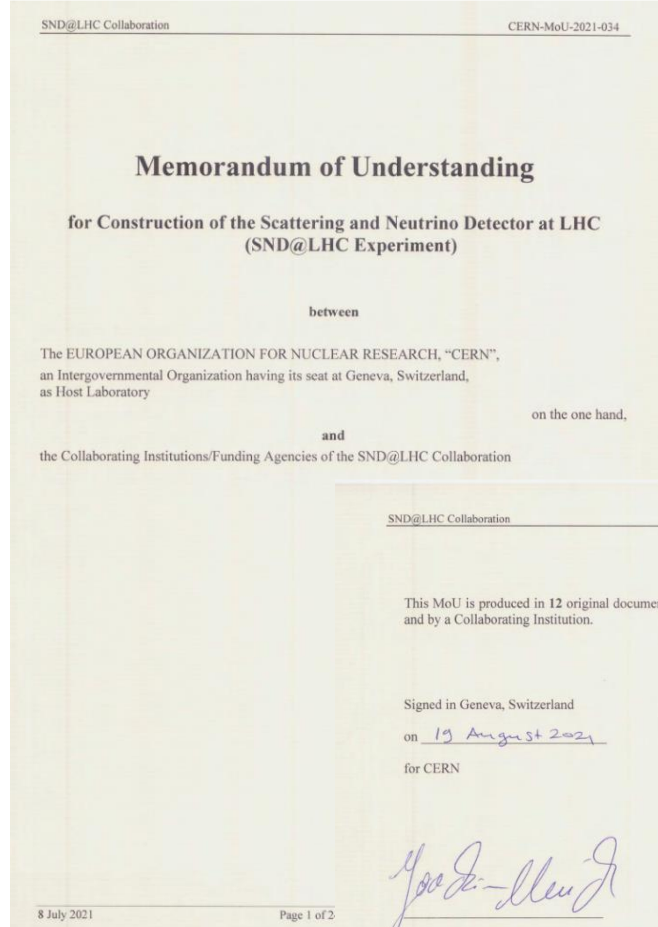
Korea University
K. S. Lee

Gwangju National University of Education
Y. G. Kim

Sungkyunkwan University
K.-Y. Choi

Our Contributions

- Emulsion data analysis
- Emulsion facility construction
- Chemicals for development & Gel production
- FIP search etc.



SND@LHC Collaboration CERN-MoU-2021-034

Memorandum of Understanding

for Construction of the Scattering and Neutrino Detector at LHC (SND@LHC Experiment)

between

The EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH, "CERN",
an Intergovernmental Organization having its seat at Geneva, Switzerland,
as Host Laboratory

on the one hand,

and

the Collaborating Institutions/Funding Agencies of the SND@LHC Collaboration

8 July 2021 Page 1 of 2

SND@LHC Collaboration CERN-MoU-2021-034

This MoU is produced in **12** original documents, each pair signed by CERN as Host Laboratory and by a Collaborating Institution.

Signed in Geneva, Switzerland	Signed in Jinju , Korea
on 19 August 2021	on 02 September 2021
for CERN	for Gyeongsang National University (GNU)
Joachim Mnich Director for Research and Computing	Kang Young Lee

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH CERN

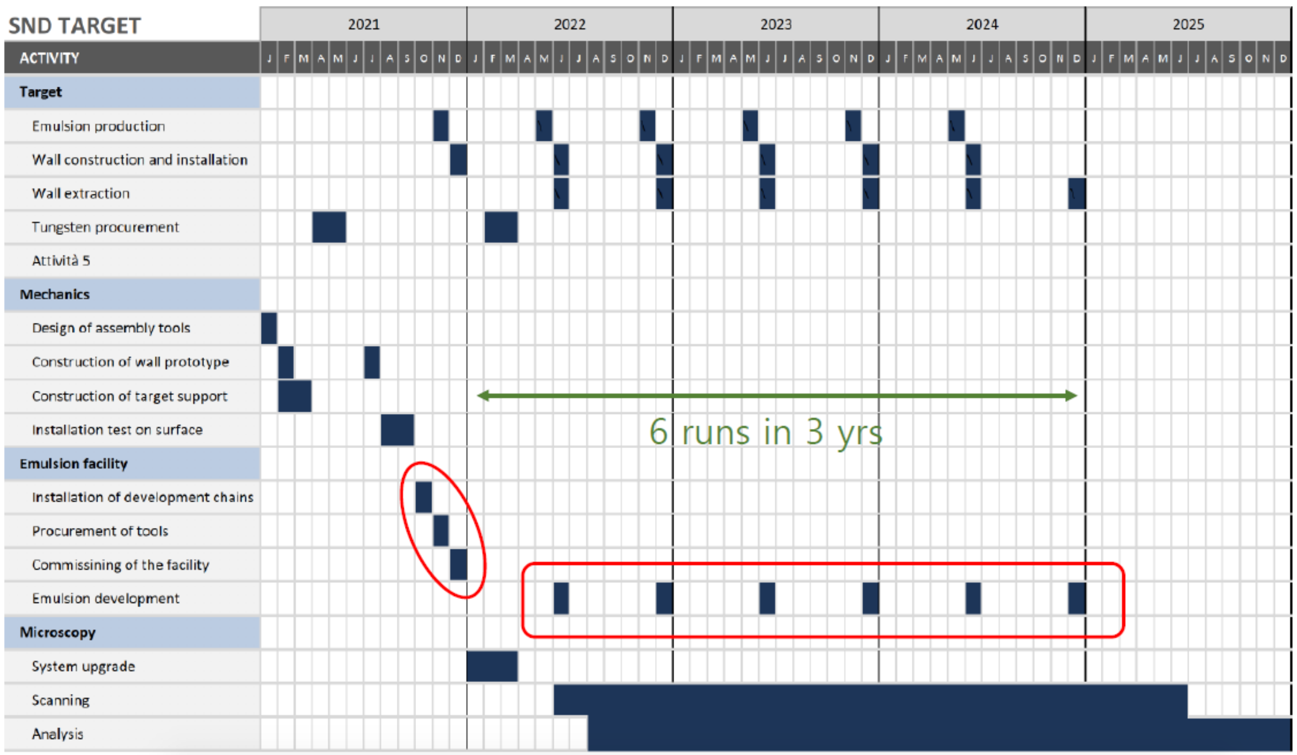
8 July 2021 Page 7 of 24 SND@LHC MoU

MoU 2021. 9

LHC
Scattering and Neutrino Detector at the LHC

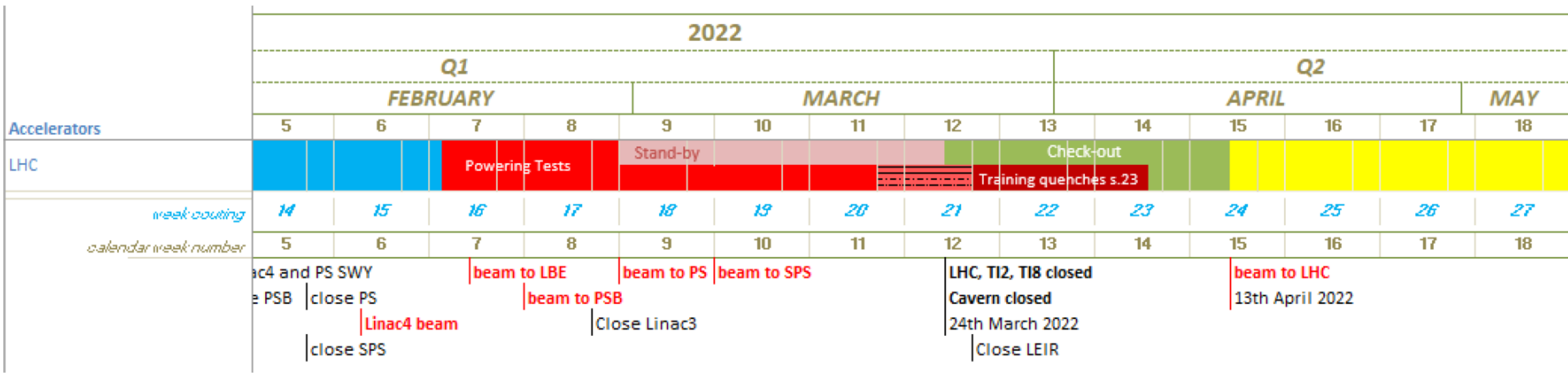
LHC
Scattering and Neutrino Detector
at the LHC

Timeline of the construction, installation and operation of the SND target



YETS 21-22 Master schedule

M. Bernardini



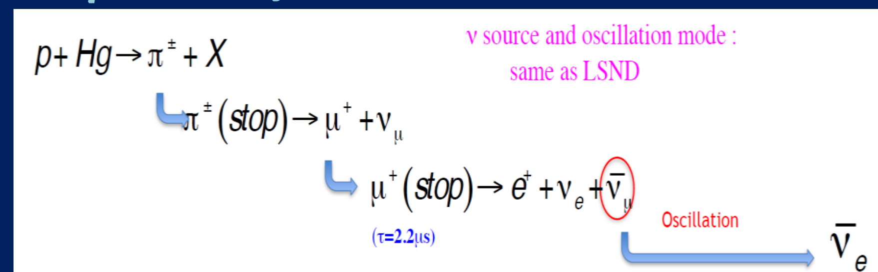
2022 April : LHC turned on.

JSNS^2

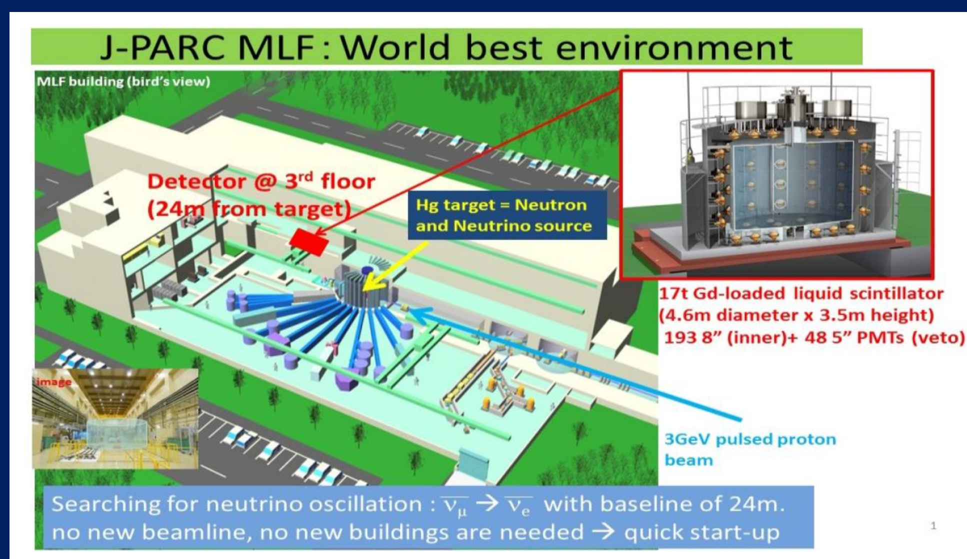
J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source

JSNS2 Experiment

- sensitive to the higher region of $\Delta m_{14}{}^2$ favored by the global fits
- 3 GeV pulsed proton beam from RCS, and a spallation neutron target at J-PARC MLF
- Neutrinos come predominantly from μ^+ decay :



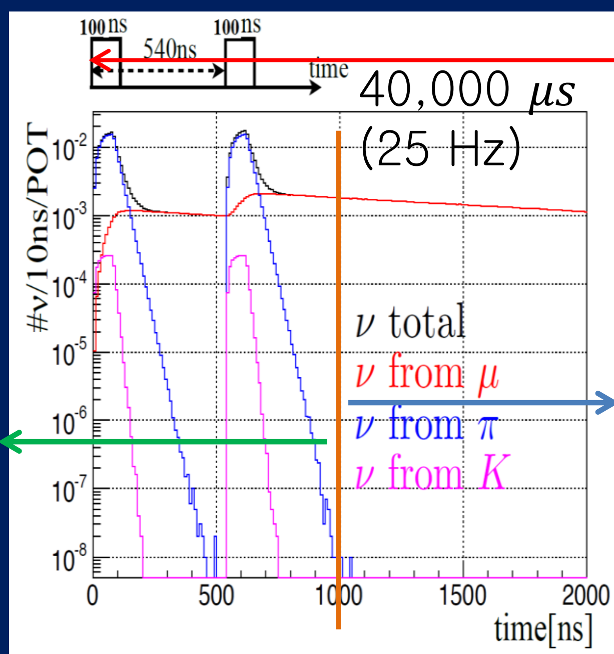
- Oscillations ($\overline{\nu_\mu} \to \overline{\nu_e}$) are detected via inverse beta decay (IBD).

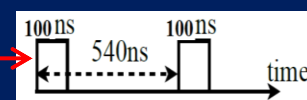


Physics Goals

- Search for $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillation as a direct and an ultimate test for LSND
- Measurement of Neutrino-Induced Nuclear Reaction Cross Sections
  - ⇒ Cross section measurements with neutrinos having a few 10 MeV from muon decay at rest and monochromatic 236MeV from kaon decay at rest
  - ⇒ important for
    - Super Nova explosion
      - core-cooling by neutrino emission
      - neutrino heating on shock wave
      - nucleosynthesis
    - Nuclear reaction cross section

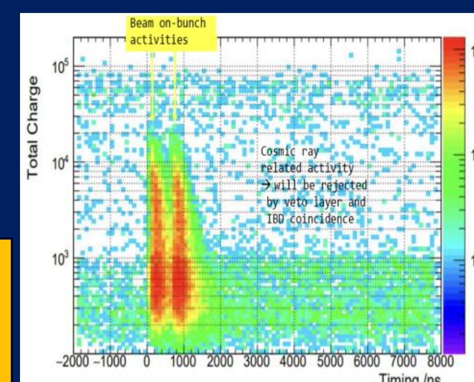
ν from π and K decay : monochromatic





- ν from μ decay
- a timing gate from 1μs to 10μs
- to reduce the cosmic ray background by factor of 9/40,000

First 30 min data (46,5 24 stills)



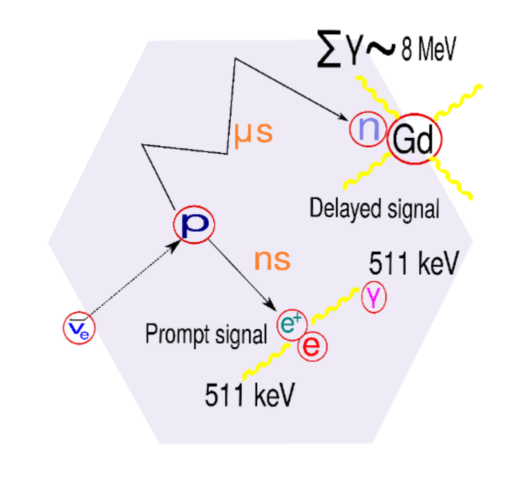
Detection Principle

- Target : 17 tons of Gd loaded Liquid Scintillator (GdLS)
  - ✓ 192 PMTs (TDR)
- Detection method : inverse beta decay

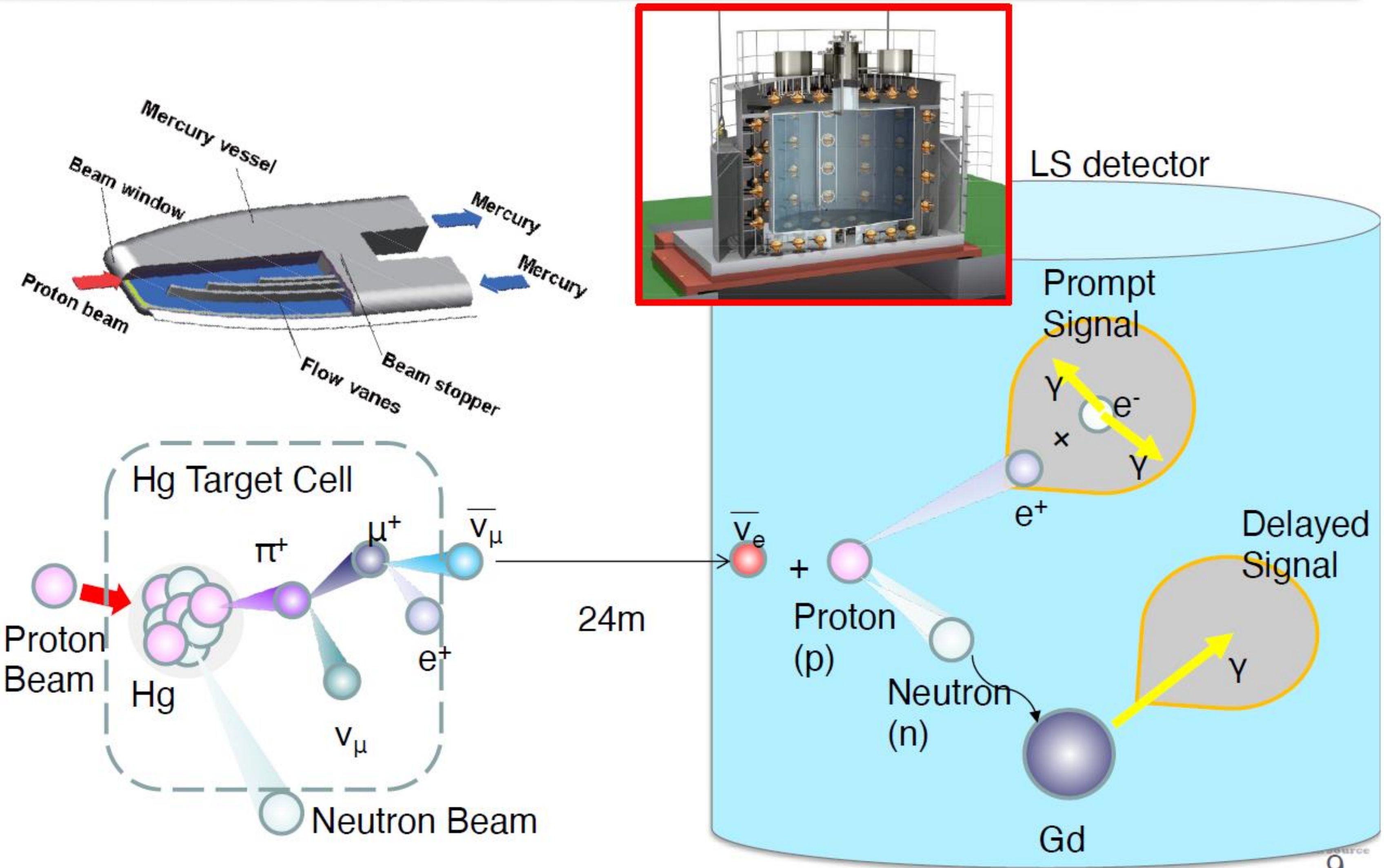
$$\bar{\nu}_\mu \underset{\text{oscillation}}{=>} \bar{\nu}_e + p \rightarrow e^+ + n$$

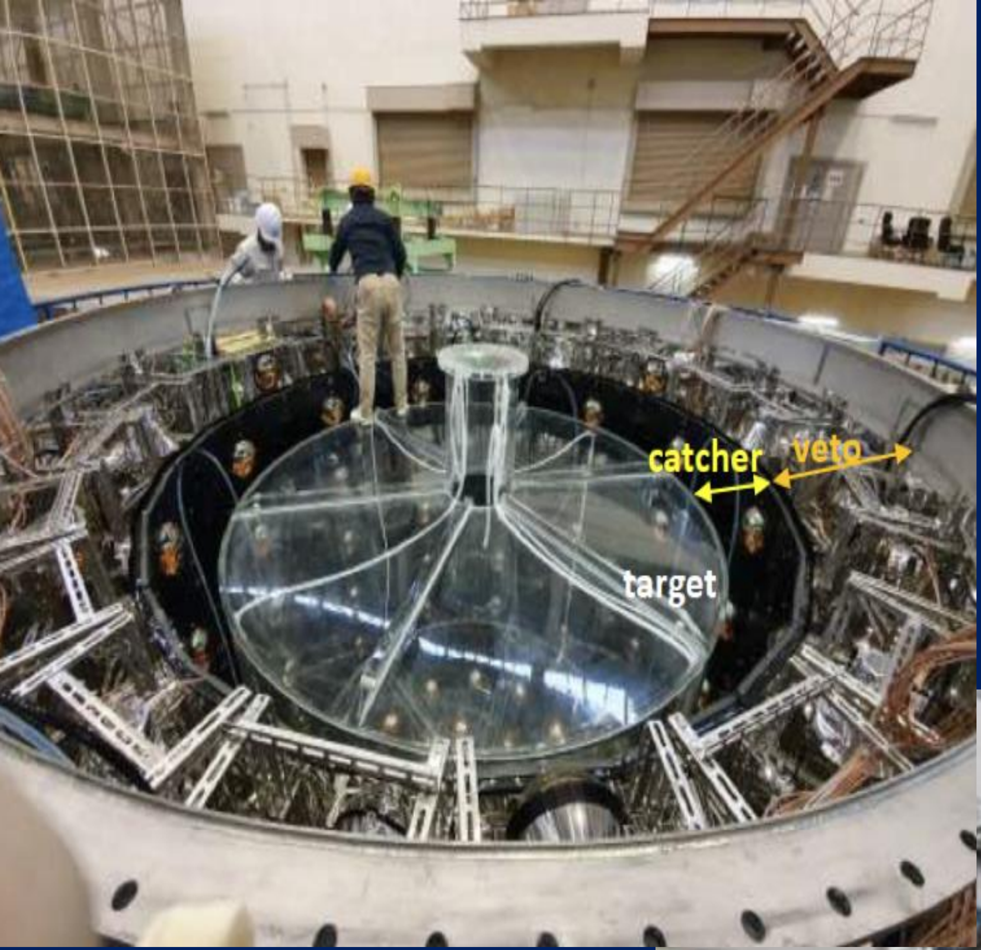
  - ✓ Identify neutrino signal with detecting positron and gammas from neutron capture on Gd
  - ✓ can reduce accidental background
    - ⇒ 8 MeV gammas from Gd, capture time ~30μs
- **Selection criteria for IBD**

	Time from beam	Energy
Prompt signal	$1<T_p<10\mu s$	20<E<60MeV
Delayed signal	$T_p<T_d<100\mu s$	7<E<12MeV



Neutrino; source and detection




catcher
veto
target

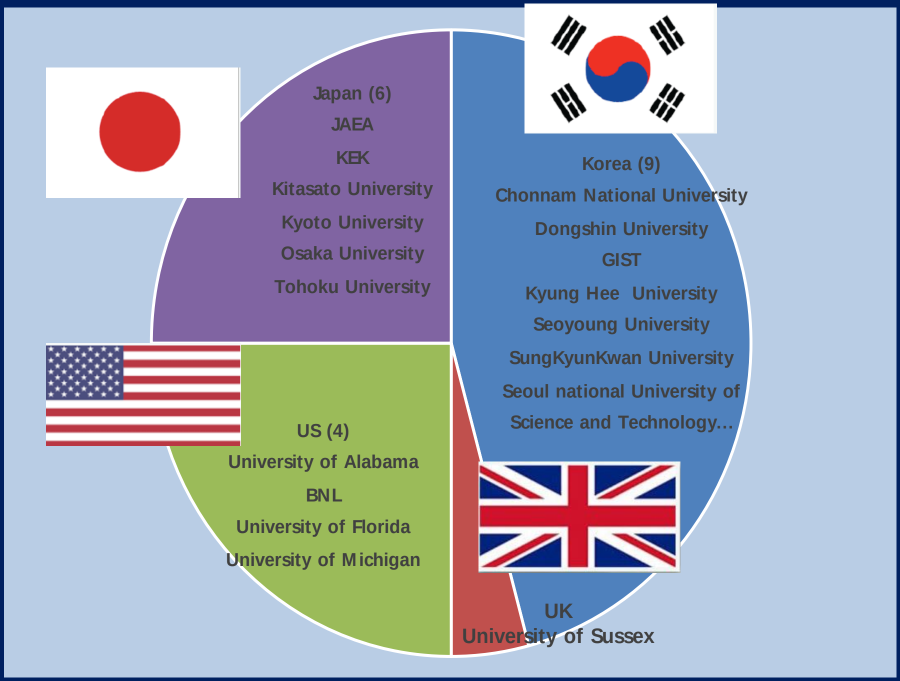
Collaboration

JSNS2 : J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source (E56)

- 6 Japanese Institutions (27 members)
- 10 Korean Institutions (27 members)
- 1 UK Institution (1 member)
- 4 US Institutions (7 members)

Spokesperson : T. Maruyama (KEK)
co-spokesperson : S. B. Kim (SKKU)

Common fund : 5.4M JPY/year
-> from NRF's "해외대형연구시설활용"
-> thanks to NNF



Status

- Detector construction : 2017–2020
- First long-term physics run (Jan–Jun 2021)
- Beam power : 0.6 MW (Jan. 15–Apr. 5), 0.7 MW (Apr. 5–Jun. 22)
- Total accumulated POT $\mathbf{1.45 \times 10^{22}}$ (~13% of TDR)

Korean Group Activities

- Korean Collaborators have published six out of seven papers during 2019–2021 (as a Corresponding author).
- Korean Co-spokesperson : Prof. Soo-Bomg Kim
- Leading role in Physics/DAQ/BKG studies
- Serving as major committee members

Present and Future

- The contribution of the Korean group in JSNS2 has been significant, and we expect that the activities will continue in the future.

COHERENT

The COHERENT Collaboration

COHERENT SNS SPALLATION NEUTRON SOURCE

Multiple Physics Cases: Non-standard neutrino interactions, Weak mixing angle, Accelerator-produced dark matter, Sterile oscillations, Neutrino magnetic moment, Nuclear form factors, Inelastic CC/NC cross sections for SN, Inelastic CC/NC cross sections for weak physics

NSF KICP NNSA CNEC

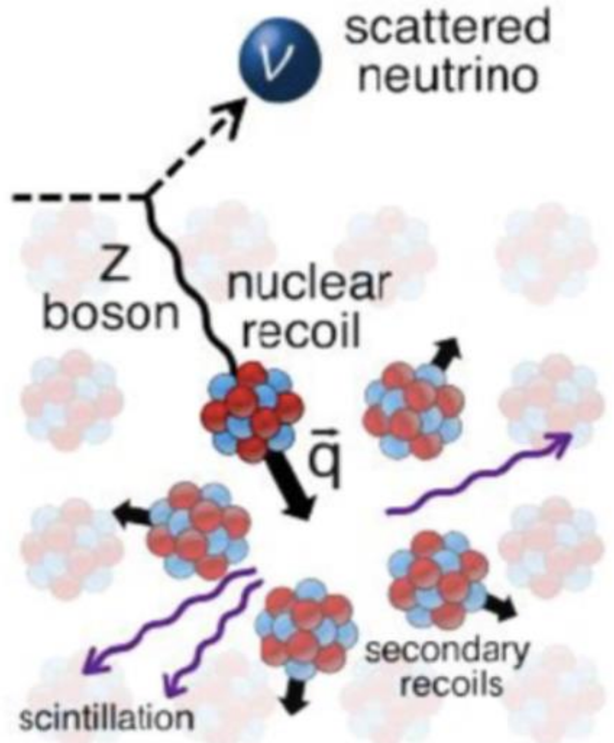
~80 members, ~19 institutions, 4 countries

Oak Ridge National Laboratory
서 울 대 학 교 SEOUL NATIONAL UNIVERSITY
Duke University
UF University of Florida
Los Alamos National Laboratory EST. 1943
Laurentian University Université Laurentienne
Virginia Tech
NC Central University
Sandia National Laboratories
NC State University
Carnegie Mellon University
W University of Washington
University of South Dakota
The University of Tennessee Knoxville
MEPhI
Tufts University
TUNL Triangle Universities Nuclear Laboratory

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Neutral Current

$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu$$



Cross section for zero-momentum transfer limit

$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[Z\omega_p + (A - Z)\omega_n \right]^2$$

$$g(Z_0 u) = \frac{1}{4} - \frac{2}{3}\sin^2\theta_W, \quad g(Z_0 d) = -\frac{1}{4} + \frac{1}{3}\sin^2\theta_W$$

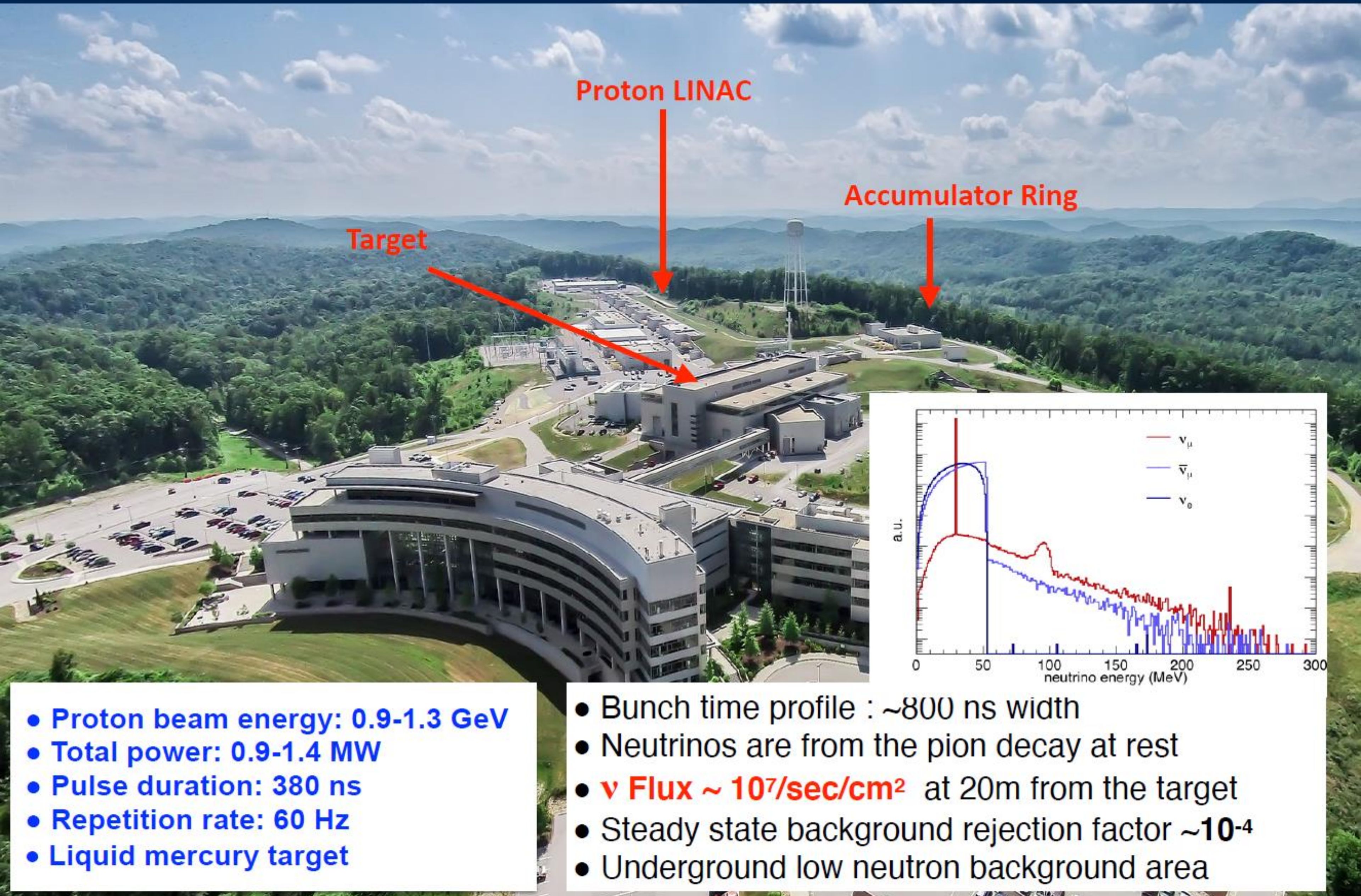
$$\omega_p = \frac{G_F}{4}(4\sin^2\theta_W - 1), \quad \omega_n = \frac{G_F}{4}$$

$\sin^2\theta_W = 0.231$ → proton coupling is not significant

Differential cross section for finite momentum transfer

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1 - 4\sin^2\theta_w)Z - (A - Z)\right]^2 M \left(1 - \frac{ME}{2E_\nu^2}\right) F(Q^2)^2$$

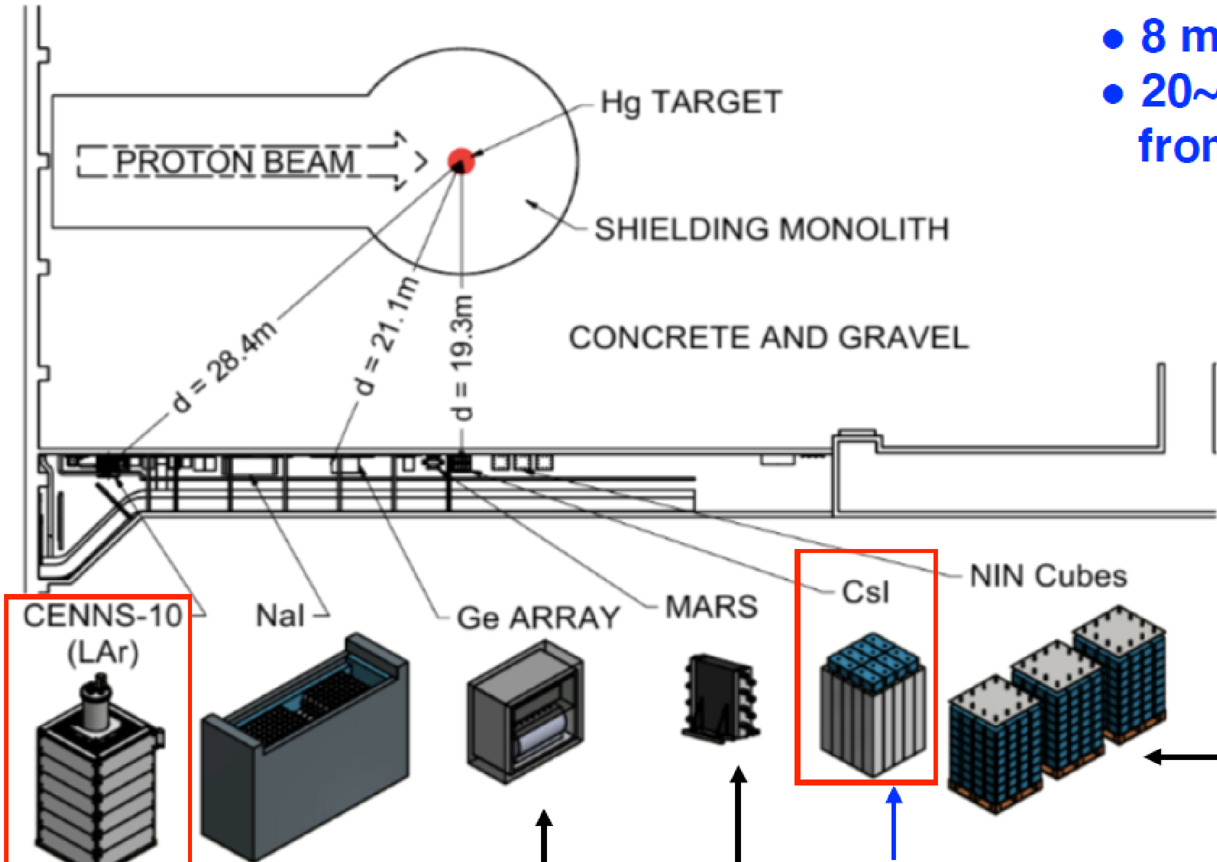
Spallation Neutron Source: Oak Ridge National Laboratory



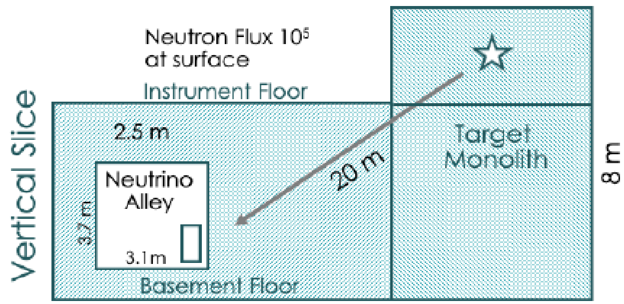
- **Proton beam energy: 0.9-1.3 GeV**
- **Total power: 0.9-1.4 MW**
- **Pulse duration: 380 ns**
- **Repetition rate: 60 Hz**
- **Liquid mercury target**

- Bunch time profile : ~800 ns width
- Neutrinos are from the pion decay at rest
- **ν Flux ~ 10^7/sec/cm^2** at 20m from the target
- Steady state background rejection factor **~10^{-4}**
- Underground low neutron background area

Neutrino Alley at SNS



- 8 m.w.e vertical overburden
- 20~30 m of gravel and concrete from target to the alley



Nubes: 4 LS cells/cube
(2*2L+2*1.3L, EJ-301 –PSD capability)
surrounded by lead / iron / copper

CsI[Na]: decommissioned:
14.5 kg crystal, single PMT, LY of 13.4 PE/keV, ~8 keVnr threshold

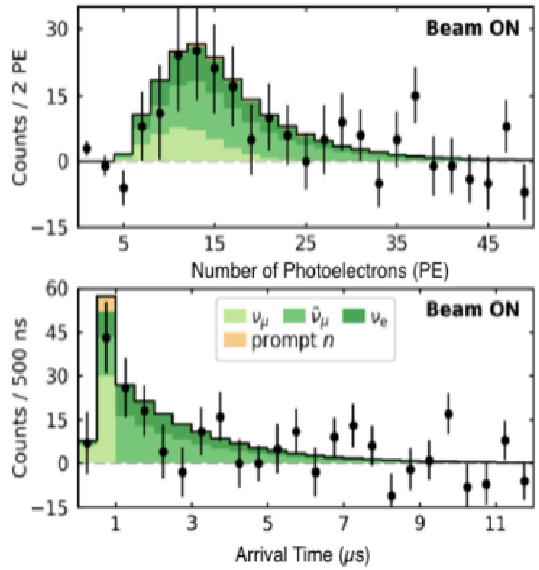
MARS, deployed: plastic scintillator interleaved with Gd coated Mylar sheets

HPGe PPC: 5 kg (cryostat ready) → 16 kg, ~1keVnr threshold

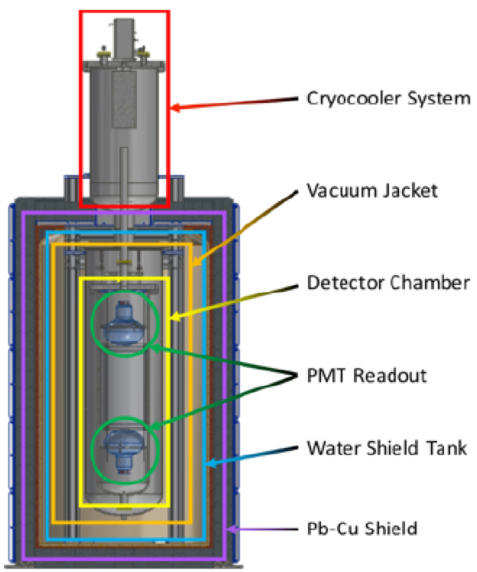
NaI[Tl]: segmented 185 kg deployed, ~13 keVnr threshold

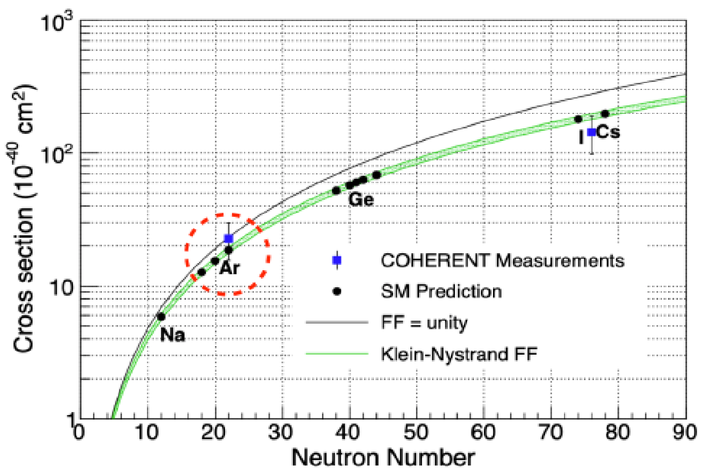
CENNS-10: 22 kg liquid argon detector, 2 PMTs readout, LY of 4.5 PE/keV, ~20 keVnr threshold

CEvNS Measurement 2017 and 2021



- **2017 CsI measurement**
  - Science 357, 6356 (2017)
  - 173 signal events ➔ 6.7σ
- **2021 CsI results (new)**
  - 333 signal events ➔ 12.5σ
  - $\sigma_{\nu\text{-CsI}} = (1.7 \pm 0.3) \times 10^{-38}$ cm^2





Conclusive measurement of CEvNS (N^2) using multiple targets!

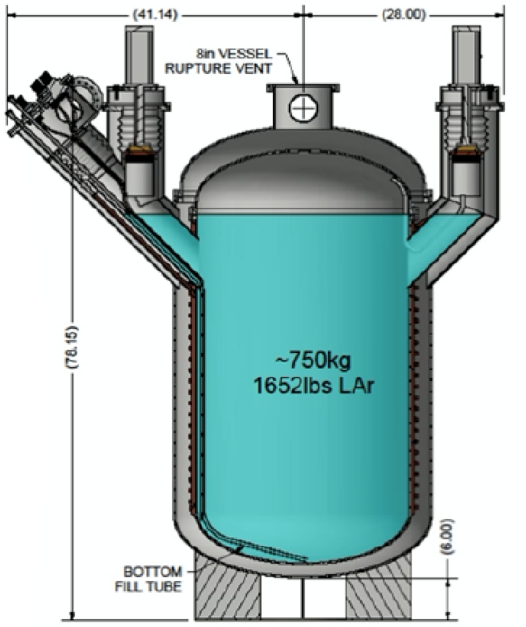
- **2021 Ar measurement**
  - PRL 126 012002 (2021)
  - CEvNS measurement by 3.5σ
  - σ_{ν}-Ar = $(2.2 \pm 0.7) \times 10^{-39}$ cm^2
  - Best Non-Standard Interaction constraint
- Factor 2 more data (analyzing)

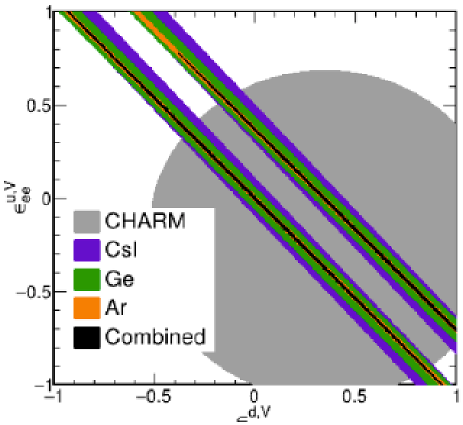
Future of COHERENT

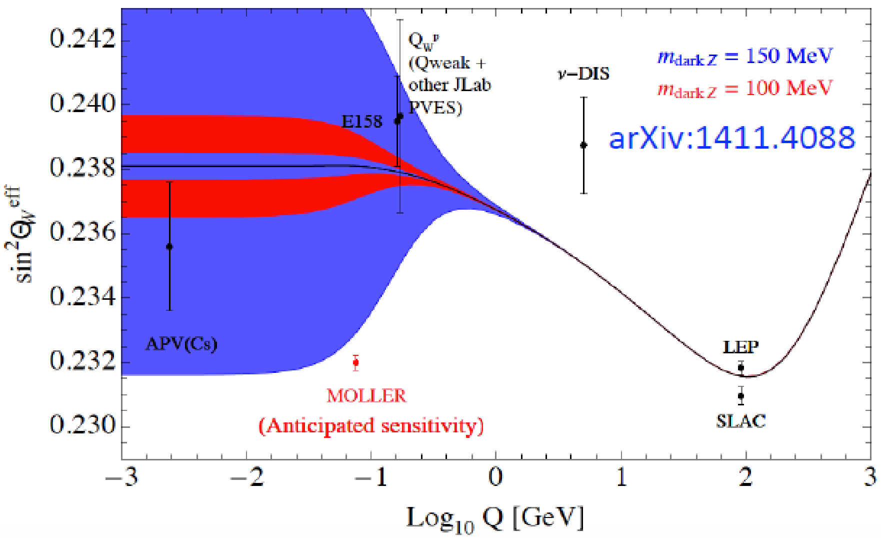
- **COHERENT has a robust suite of future experiments,** including Ge, NaI, MARS, NIN, and **a ton-scale LAr detector**

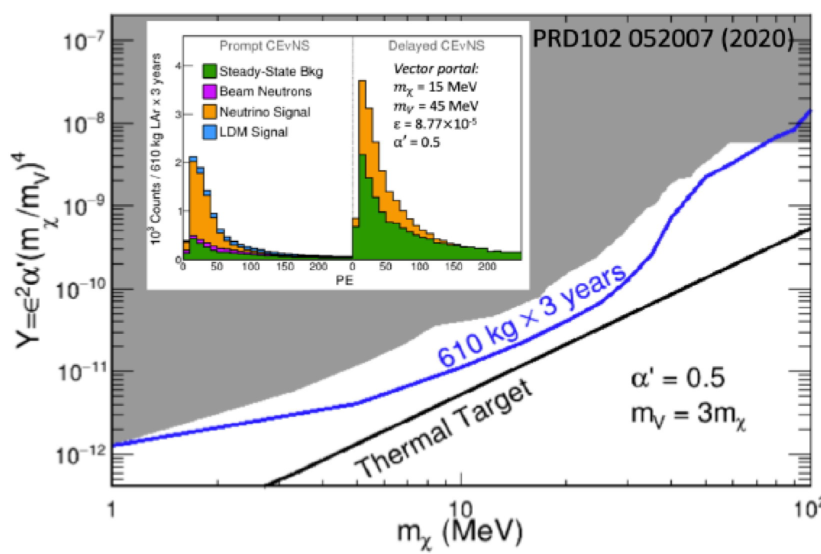
- **New ton-scale LAr detector (Jonghee Yoo, SNU)**
  Expect ~10,000 CEvNS/3year
  - Precision measurement of CEvNS
  - Beam-induced dark matter search
  - Non-standard interactions
  - Neutron radius measurement

  ➔ Full of new physics cases









Future Neutrinos at SNS

FTS 2021	2022	2024	2028 STS Neutrino Hall
1.4 MW	1.7 MW	2.0 MW	FTS: 2.0 MW @ 45 Hz STS: 0.7 MW @ 15 Hz

Calorimetry

COHERENT "First Light" Program
- CEvNS with HPGe, NaI
- Heavy Water Flux Normalization of FTS

Ton-Scale Argon Calorimetry
- CEvNS studies
- Dark Matter searches
- quark-lepton couplings for ν mass ordering
- Low Threshold Detector R&D
- Supernovae neutrino cross sections

Directionality

Heavy Water Ring Imaging Design
- Improved Flux Normalization
- ν_e-oxygen Interactions for Hyper-K

Argon Detector R&D for STS
- Scalable Low threshold Light Collection
- R&D for Position/Direction Reconstruction
- Direction reconstruction for CC-leptons
- Study for coherent inelastic interactions

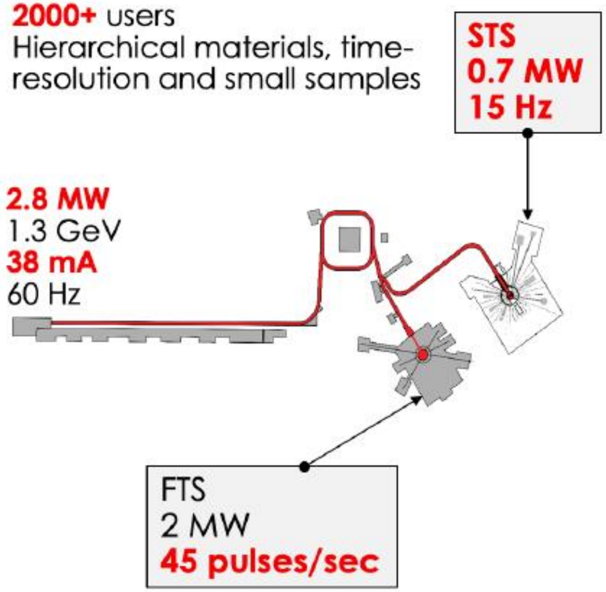
Discovery Scale

Neutrino Program at 2nd Target Station

10-ton Liquid Argon
- Beam induced dark Matter searches
- Precision CEvNS studies
- Precision Ar cross sections measurement
- Weak Mixing Angle
- Neutrino EM properties

Heavy Water Ring Imaging
- Flux Normalization of STS
- Precision ν_e-oxygen for Hyper-K

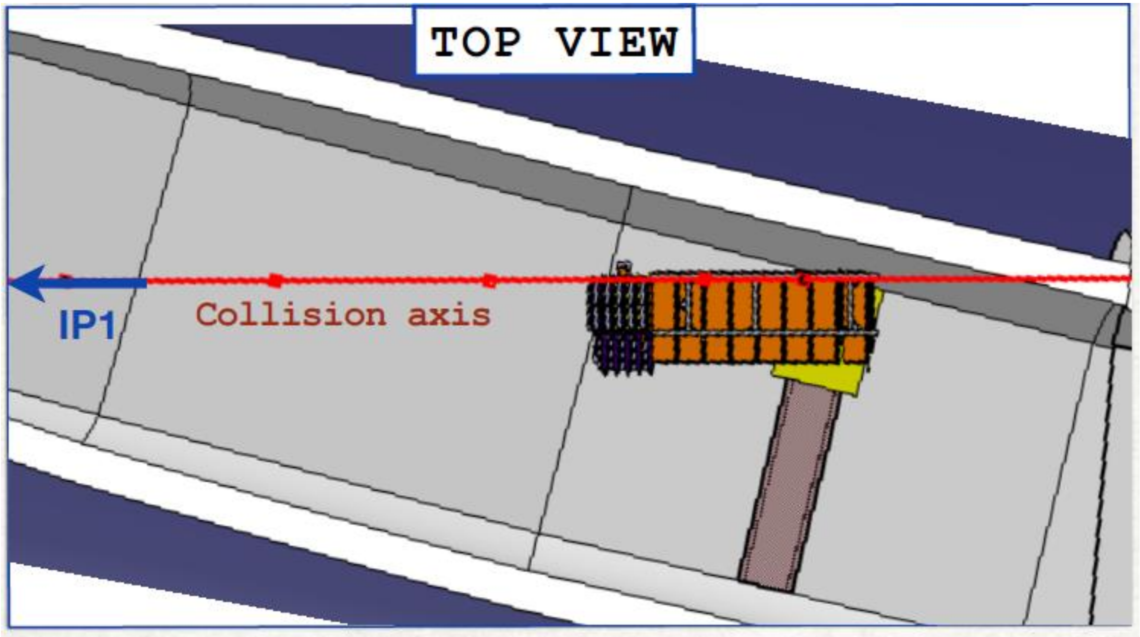
- **2000+** users
- Hierarchical materials, time-resolution and small samples

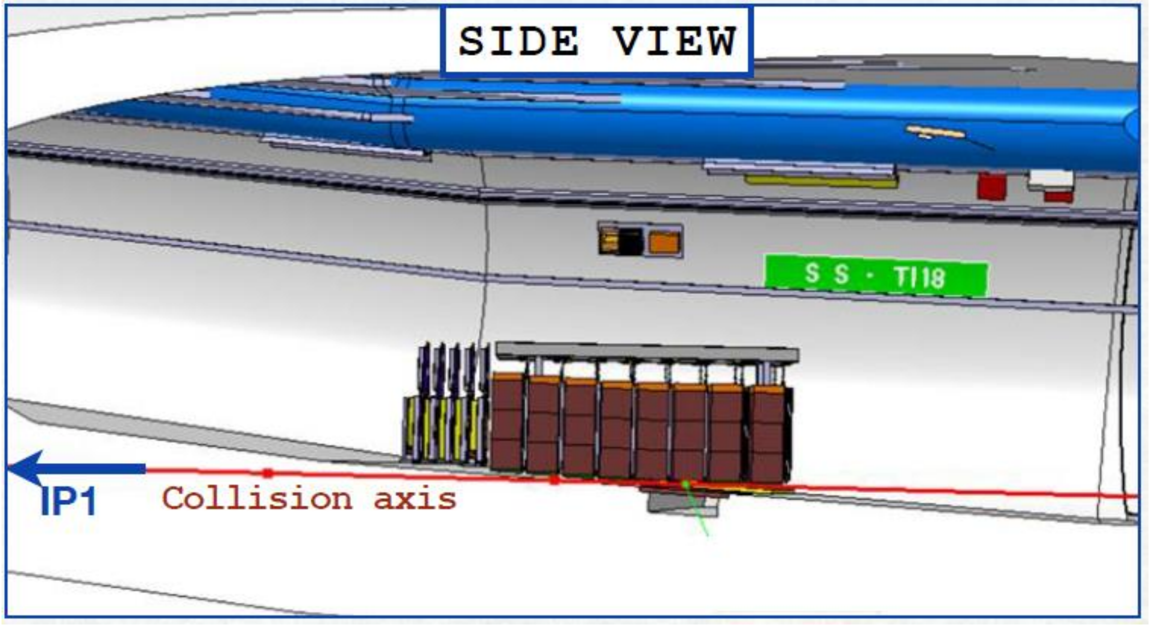


감사합니다.

Backup Slides

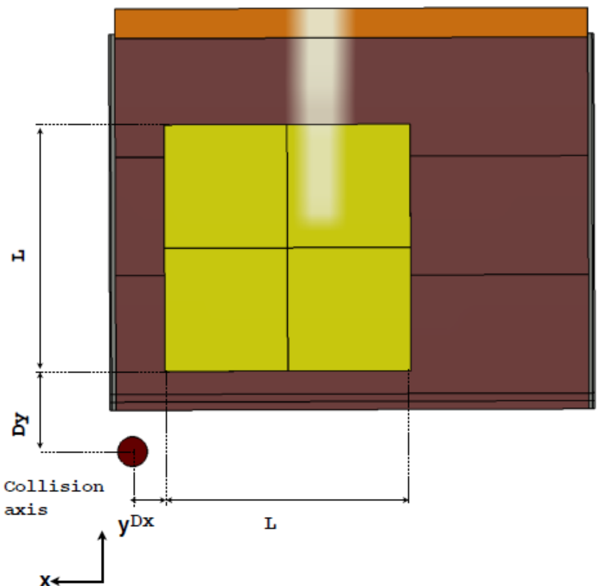
Detector design is constrained from the tunnel and the uphill floor.





PSEUDO-RAPIDITY RANGE

TECHNICAL PROPOSAL



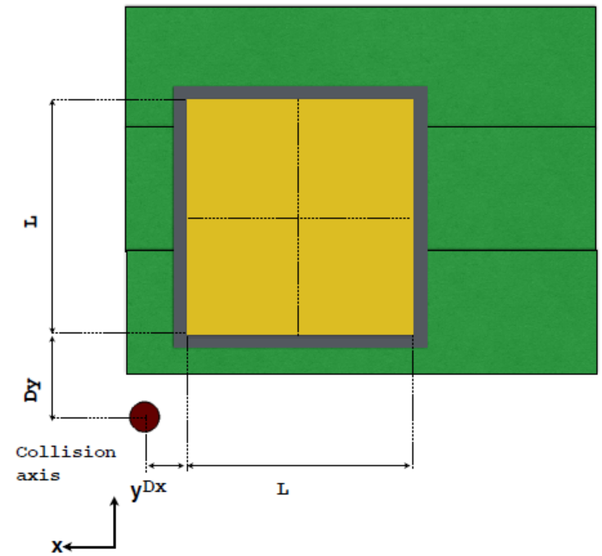
Distances wrt P3 (FASER+2)
Dx = 80 mm
Dy = 155 mm
Dz = 1017 mm

Target dimensions
L = 390 mm

Distance of P3 wrt IP1
Dz0 = 482000 mm

$$\eta = [7.20, 8.62]$$

TI18 INSTALLATION



Distances wrt P1(FASER CENTRE)
Dx = 75.4 mm
Dy = 191.6 mm + 7.0 mm
Dz = 2889 mm

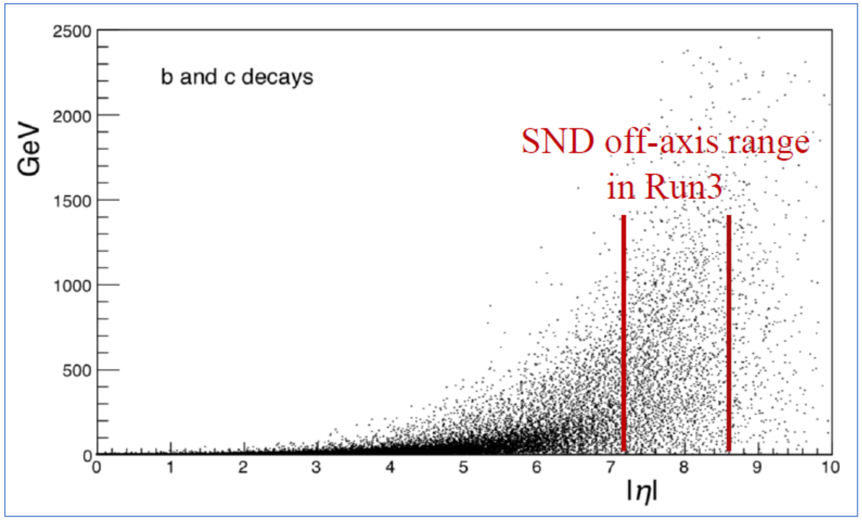
Target dimensions
L = 385 mm

Distance of P3 wrt IP1
Dz0 = 480000 mm

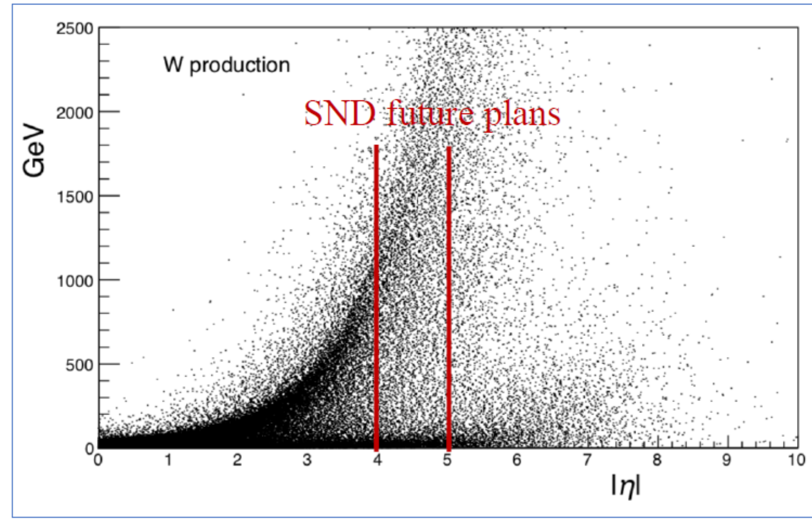
$$\eta = [7.17, 8.42]$$

Neutrinos from b, c and W

ν_τ ~5% for 6.5< η <9



Br (ν_τ) ~ 33%



Mostly for η < 5

- W decays could be tagged at IP detectors → See future plans under Outlook
- Tagging the ν flavour → study lepton flavour violation although with low statistics

CERN is unique in providing energetic **ν** (from LHC) and measure pp → **ν**X in an unexplored domain

- SciFi cooling water circulating.