경상국립대학교
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LHC
Scattering and Neutrino Detector
at the LHC

SND@LHC

Scattering and Neutrino Detector at LHC

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On behalf of SND@LHC Collaboration

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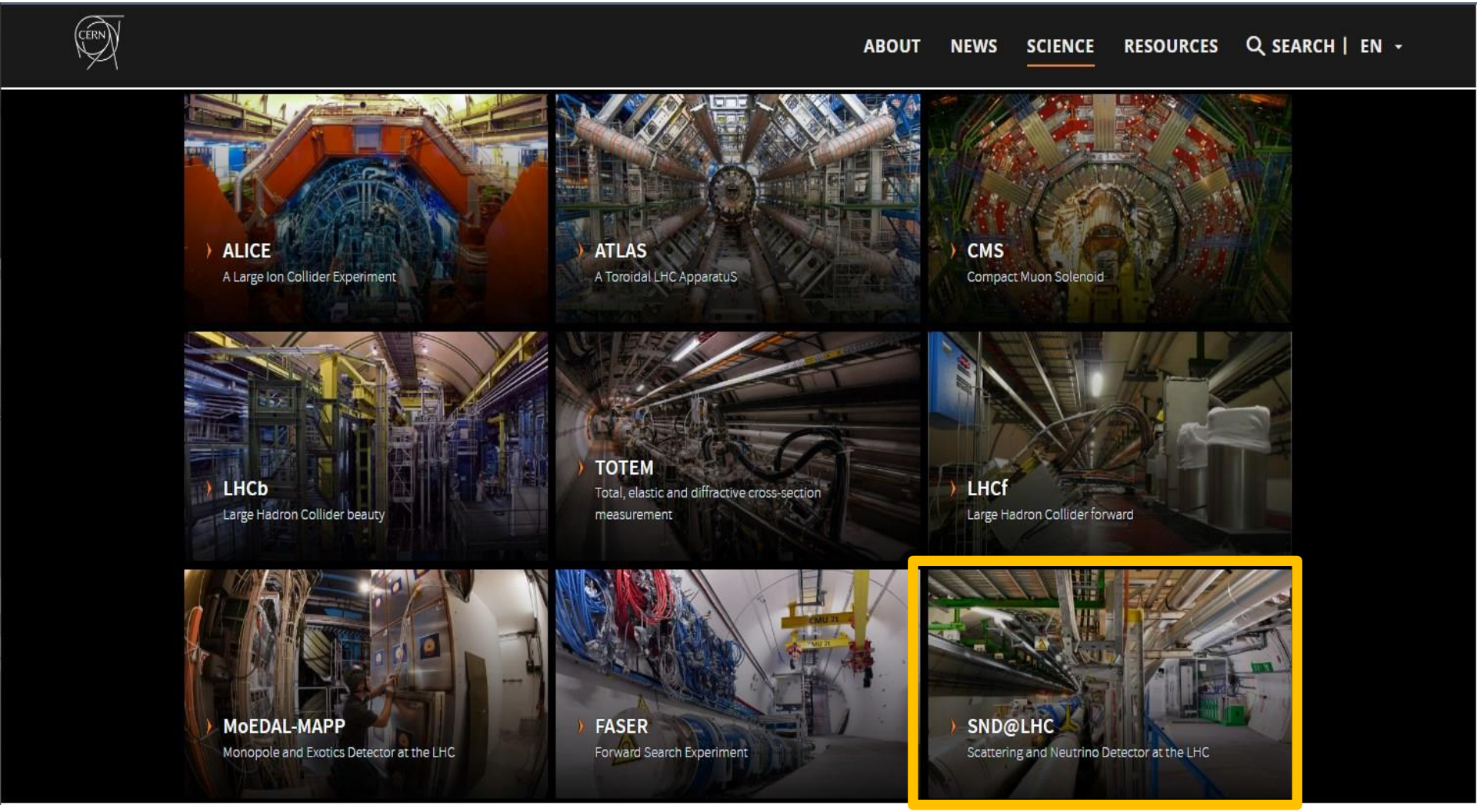
Outline

- Introduction
- SND@LHC
- Analyses & Results
- Conclusion

Introduction

Official LHC Experiments



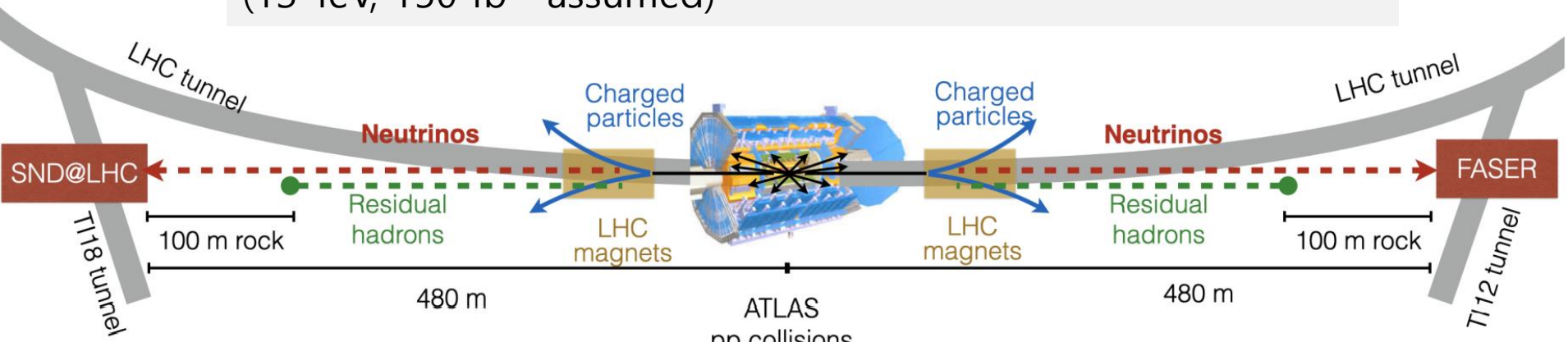
Forward Experiments at the LHC

Physics in the Forward Region

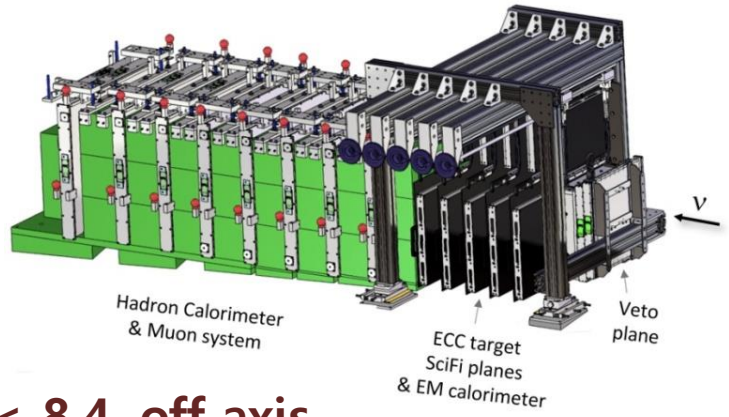
10^{16} inelastic pp scattering events for LHC Run 3

10^{17} π^0, 10^{16} η, 10^{15} D, 10^{13} B, … expected for each hemisphere

(13 TeV, 150 fb^{-1} assumed)

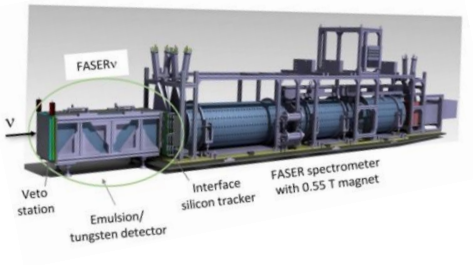


SND@LHC



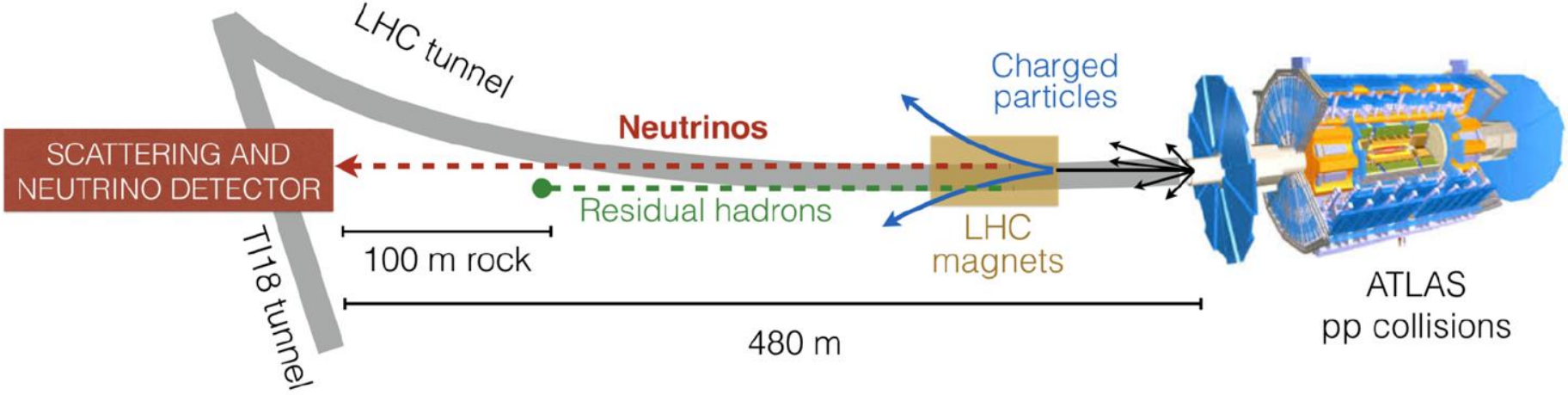
7.2 < η < 8.4, off-axis

FASER & FASERν



η > 8.8
on-axis

The SND@LHC

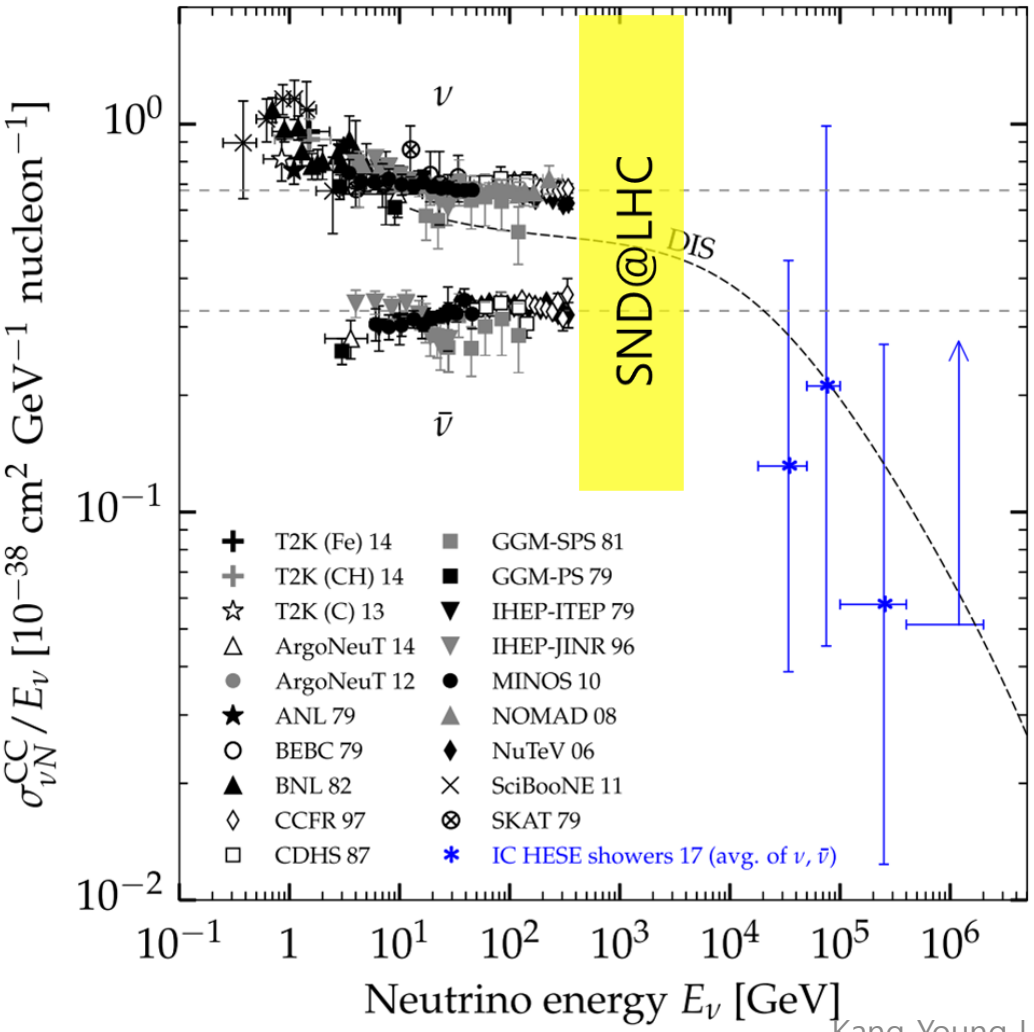


- 480 m away from the ATLAS interaction point (IP1)
- Located in the TI18 tunnel, former positron transfer line to LEP
- Shielded by 100 m rock
- LHC magnet deflects charged particles
- Neutrinos and (if exist) feebly interacting particles (FIPs) arrive at the detector


NUSTORM, ...)
EMPHATIC, EUNUBET,
flux-related
Further long-baseline experiments
Collider "parasitic" experiments or main stream collider searches for RH neutrinos in LHC experiments

Neutrinos at the LHC

PRL 122 (2019) 041101

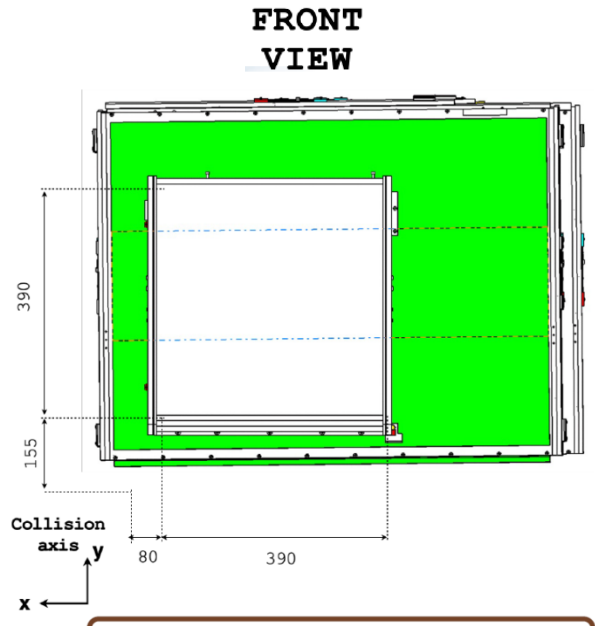


The LHC neutrinos are interesting because…

- First observation of the collider neutrinos
- High energy neutrinos of not explored region,
  300 GeV ~ a few TeV
- Large fluxes in the forward region
- All the 3 flavour neutrinos can be observed.

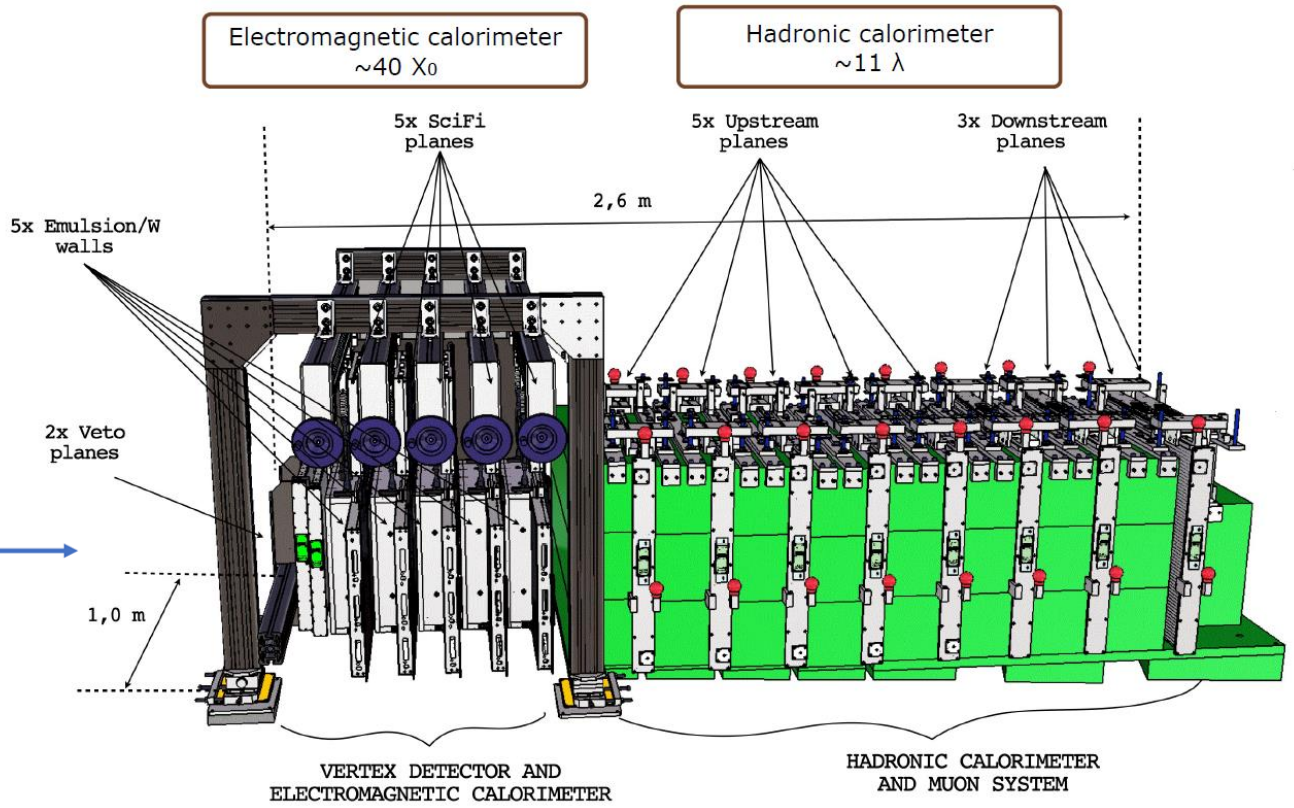
SND@LHC

The SND@LHC Detector



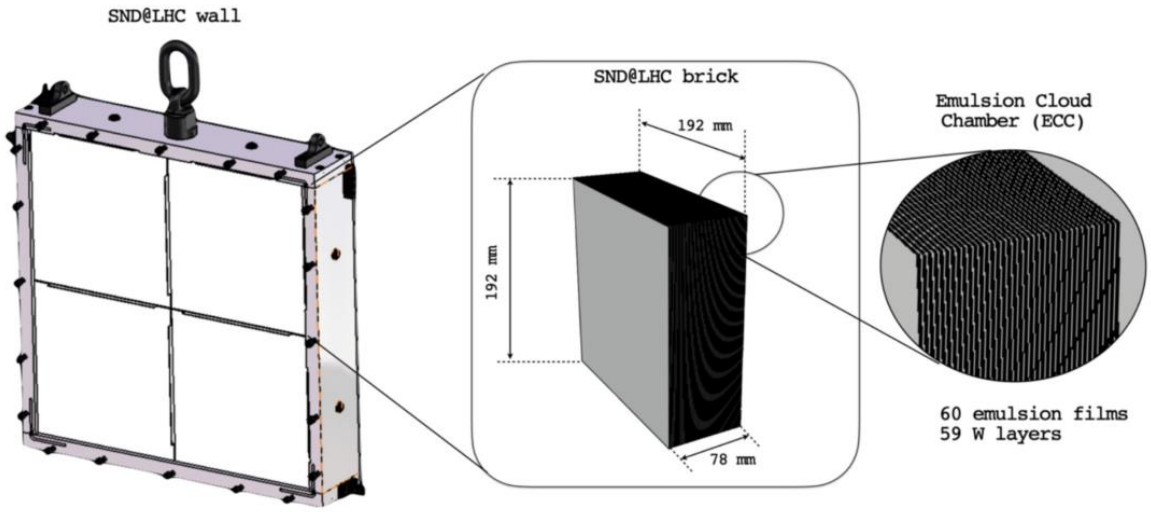
Off axis location

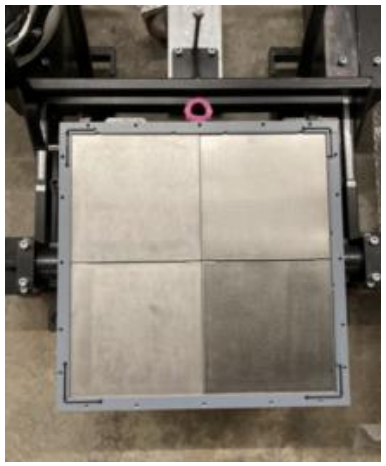
Hybrid detector optimised for the identification of all three neutrino flavours and the FIPs

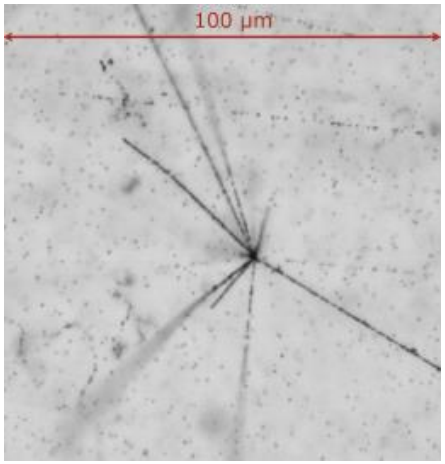


Detector paper : arXiv 2210.02784 to appear on JINST

Emulsion Cloud Chamber



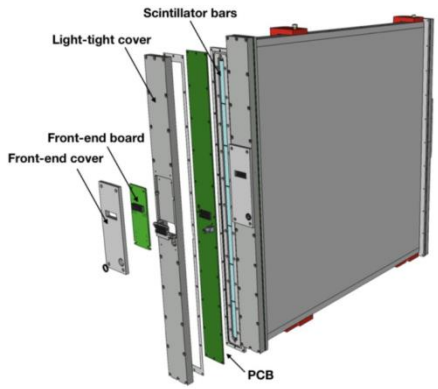




Emulsion target

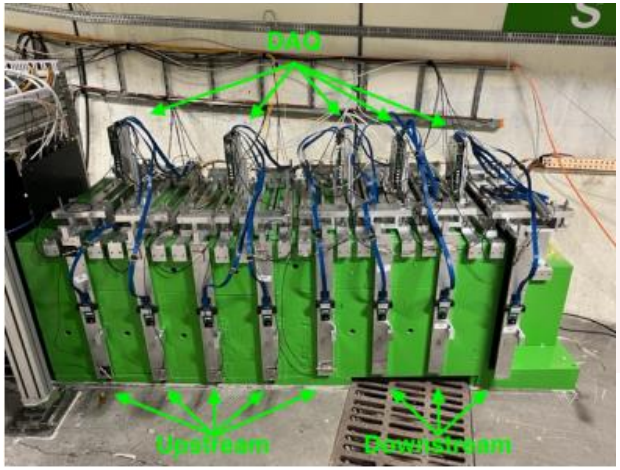
- Emulsion cloud chamber (ECC) brick consists of 60 emulsion films interleaved with 59 tungsten plates
- Total tungsten mass 830 kg
- 5 walls x 4 bricks x 60 emulsion films
- Replaced every 20 fb^{-1}

Other Detector Components



Veto system
- Tags incoming charged particles and consists of 2 planes with 7 Sci bars

SciFi detector
- Scintillating Fiber detectors interface emulsion with electronic detectors for position prediction and timing of outgoing particles.
- Electromagnetic calorimetry



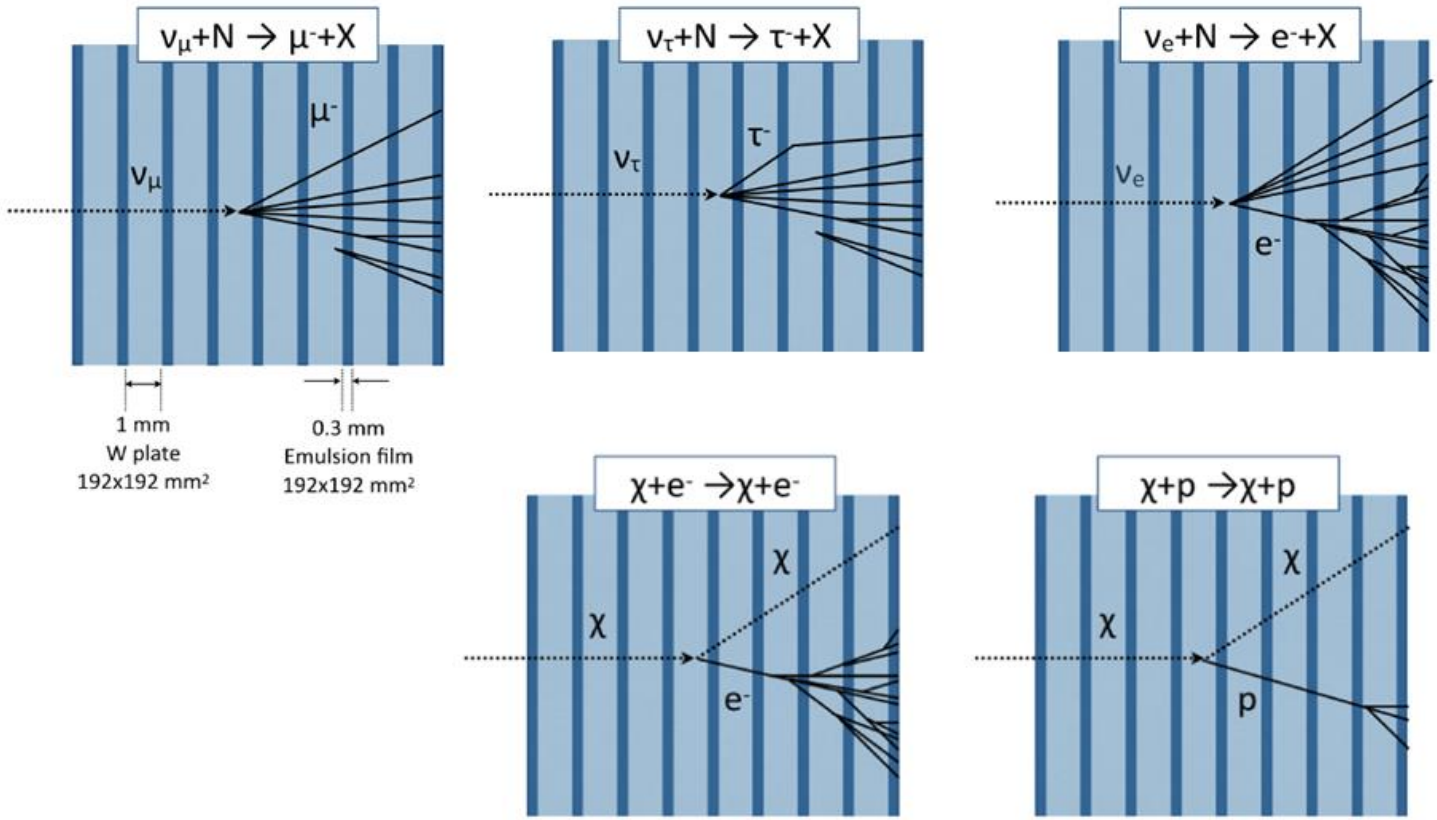
Hadronic calorimeter and muon system
- Upstream : 5 stations of Fe blocks with 10 Sci bars for hadronic calorimetry
- Downstream : 3 stations with 60 horizontal and 60 vertical Sci bars for muon tagging

Detector View in 2022 and 2023

Physics Cases

- Measurement of the ν **production cross section**
- Measurement of the **forward charm production**
- Neutrino induced **charm production**
- **Lepton flavor universality test** in neutrino interactions
- Measurement of the **NC/CC** ratio
- Direct search for **FIP** through their scattering

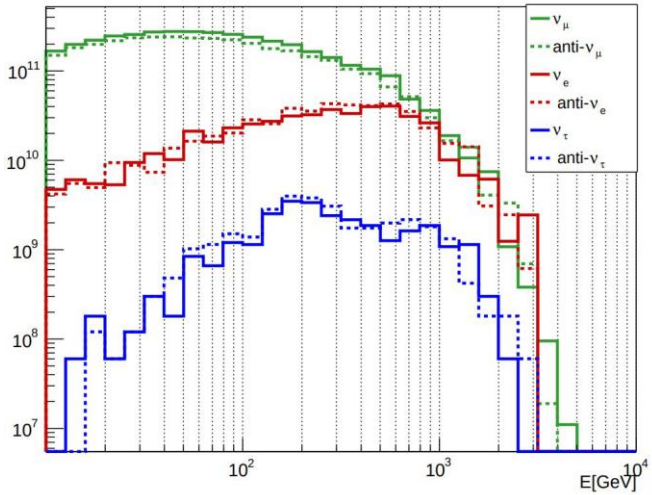
Physics Cases – Event Topology



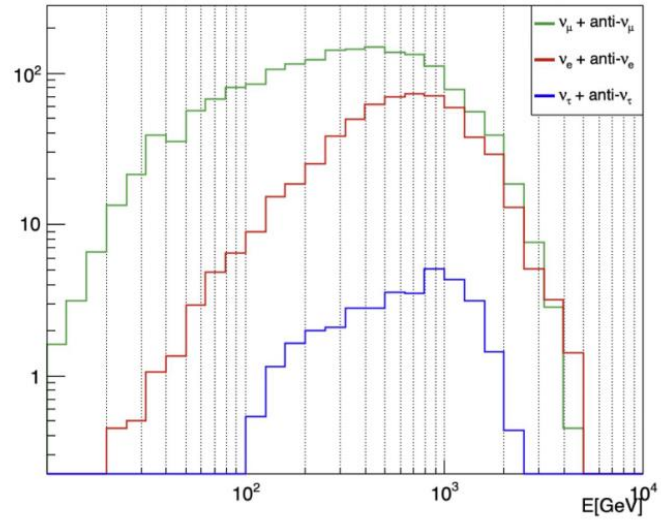
Identification of all three neutrino flavours and FIPs by event topologies in the ECC brick

Physics Cases – Neutrino Production

Incoming Neutrinos to SND



Neutrino interactions in SND



Measurement of $\sigma(pp \rightarrow \nu X)$

- $\nu_\mu + \bar{\nu}_\mu$ charged-current: 1447
- $\nu_e + \bar{\nu}_e$ charged-current: 450
- $\nu_\tau + \bar{\nu}_\tau$ charged-current: 34

Estimated from
290 fb^{-1} in LHC Run 3
Angular acceptance $7.2 < \eta < 8.4$

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

Timeline

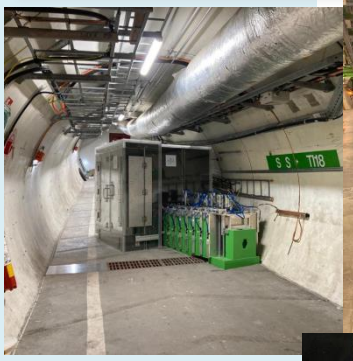
Scattering and Neutrino Detector at the LHC

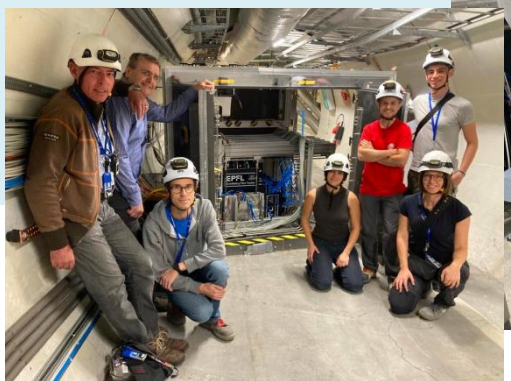
Letter of Intent

TECHNICAL PROPOSAL

SND@LHC

Aug. 27th, 2020	Letter of Intent
Jan. 22nd, 2021	Technical Proposal
March, 2021	Approval by CERN RB
August, 2021	Infrastructure
Oct.13th, 2021	Detector construction completion
December, 2021	Detector installation in TI18
Apr. 7th, 2022	Installation of the first emulsion films
July, 5th, 2022	First 13.6 TeV collisions
July, 26th, 2022	Full target installation

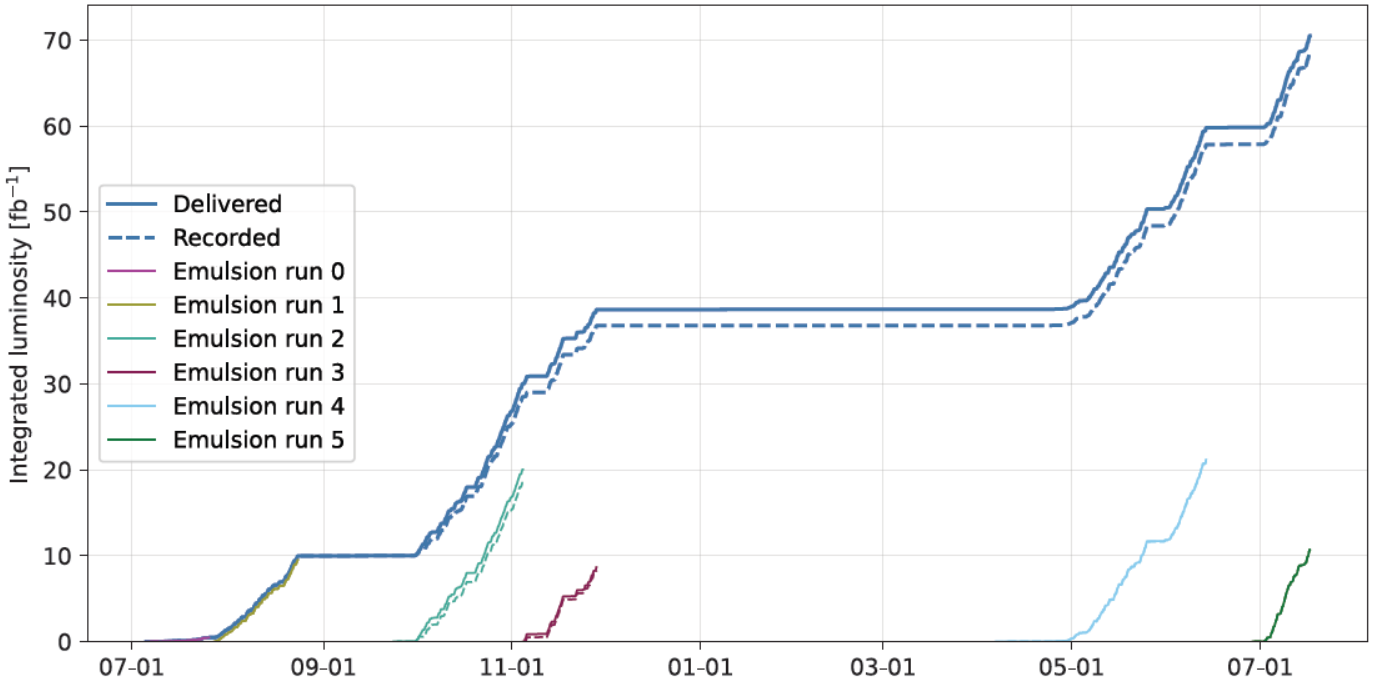




Analyses & Results

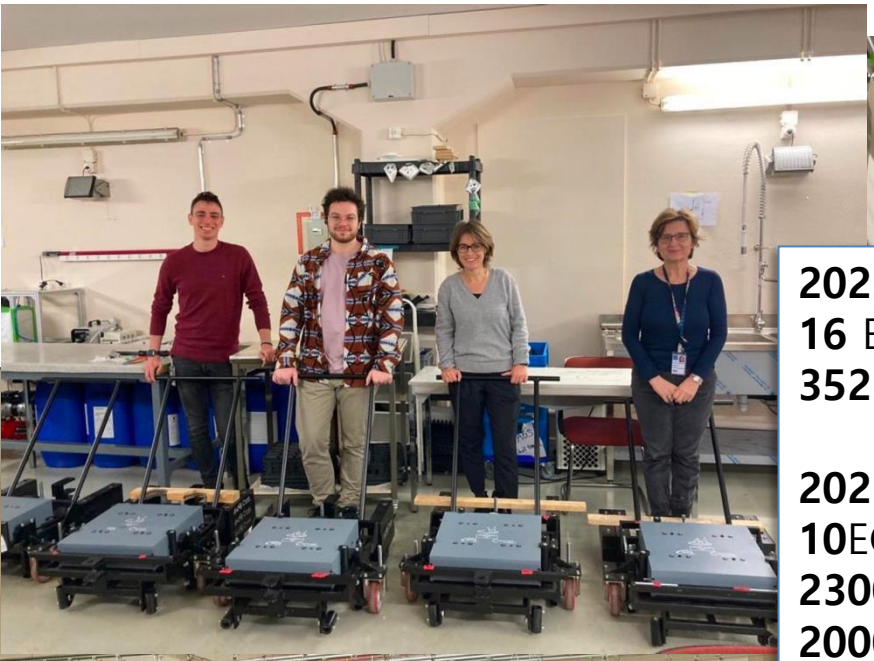
Data taking in 2022 and in 2023

Integrated luminosity



Integrated luminosity: 70.5 fb^{-1}
Recorded efficiency 97.3% (2022 95%, 2023 99.7%)

Emulsion Activities

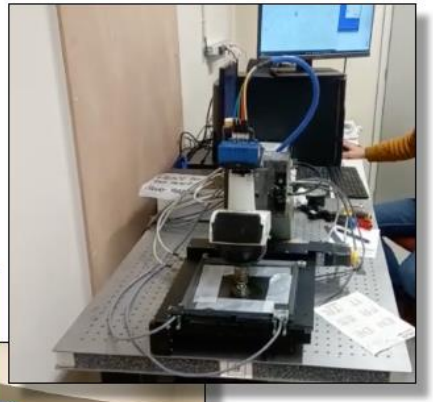


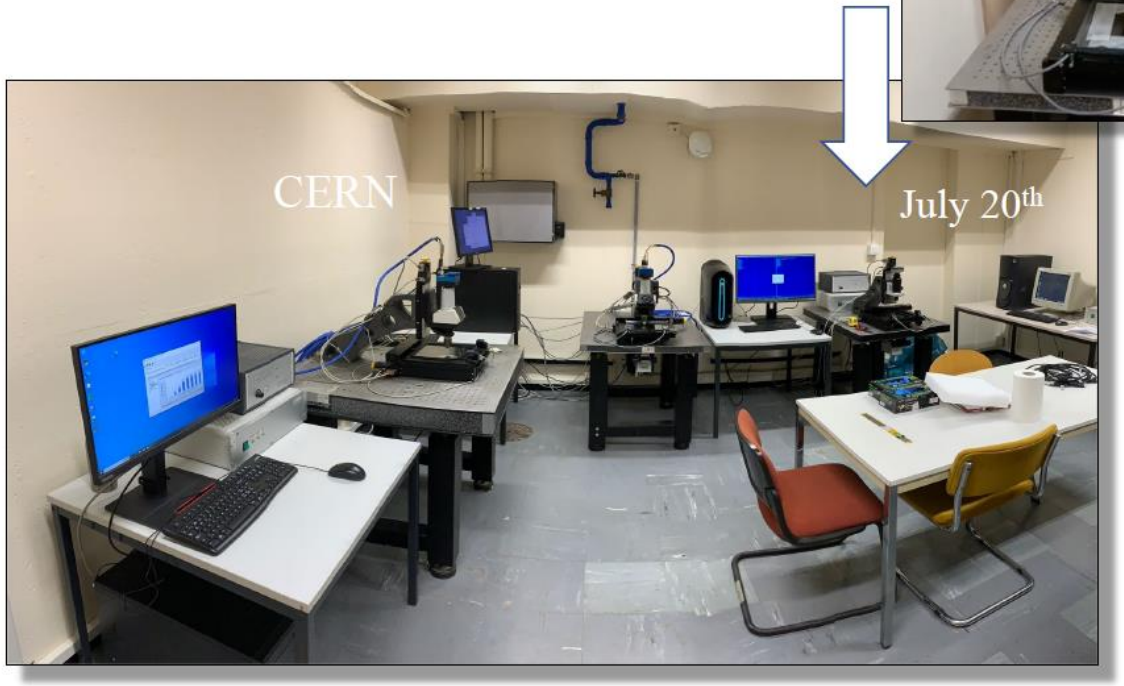
2022
16 ECC Brick walls assembled
3522 emulsion films developed (140 m2)

2023
10ECC Brick walls assembled
2300emulsion films developed (92 m2)
2000Ldisposed chemical solutions

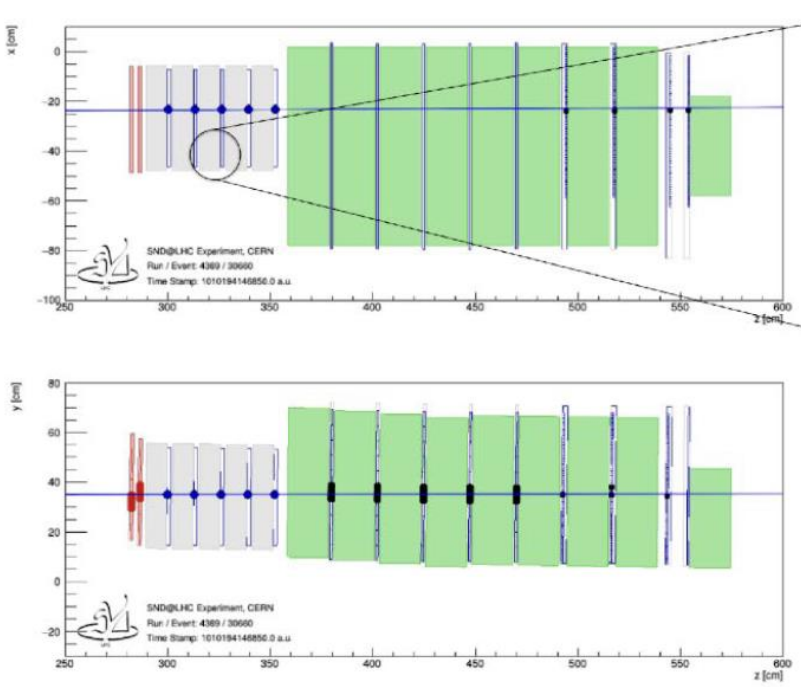
Scanning Room at CERN

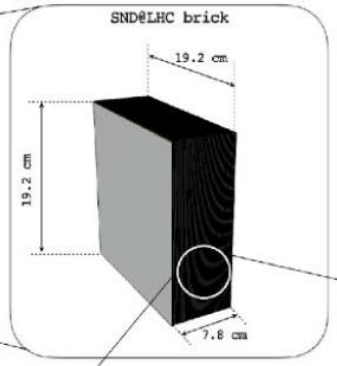
- Room 162/S-024 assigned to SND@LHC to host the scanning station
- Full renovation of the room, installation of electrical and IT sockets
- Hosting 4 microscopes
- - two regularly working since July
  - two upgrades funded by CERN EP
  - Equipment just delivered
  - Will start operation in December



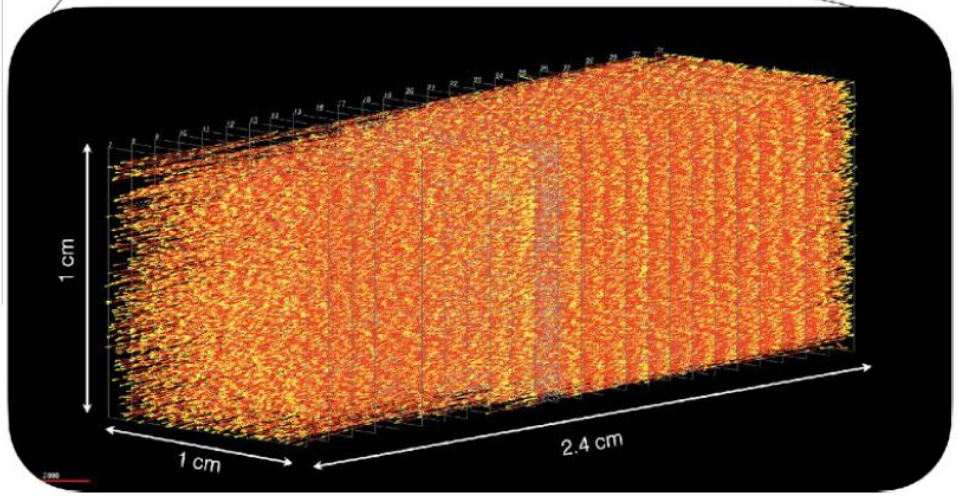


Muon Track Reconstruction



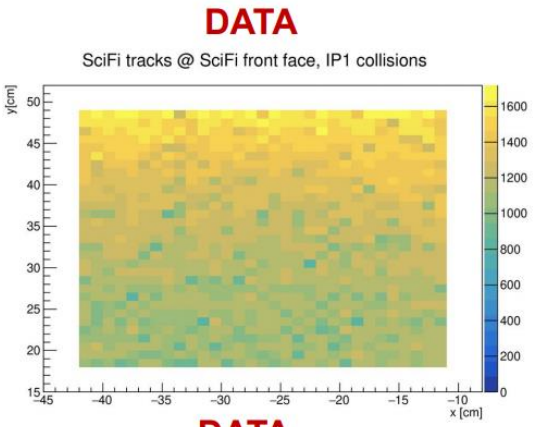


Emulsion Reconstruction
Muon tracks in 1x1cm²
Integrated in Run 0 of
0.51 fb^{-1} (07/04-26/07)



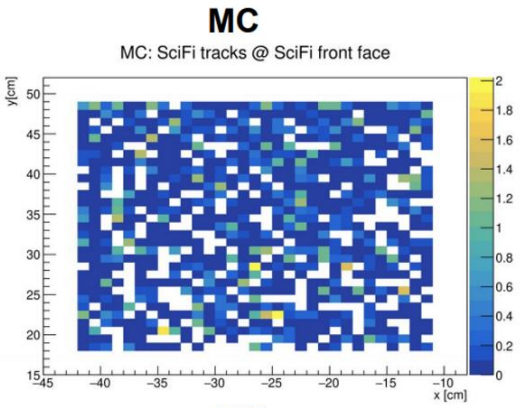
Electronic Detector Reconstruction
Muon track from pp collisions
at 13.6 TeV (06/07/2022)

Data/MC Comparison



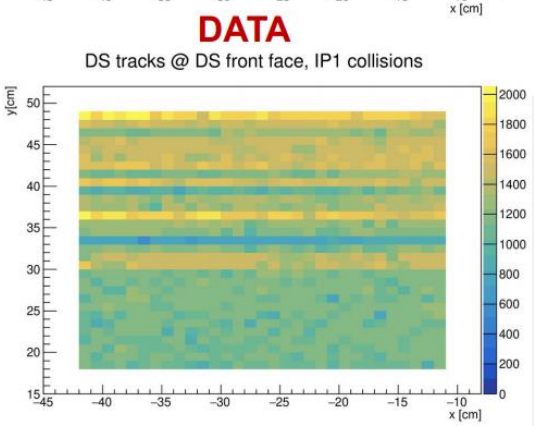
Measured muon track rate in SciFi (31x31 cm^2):

$(1.60 \pm 0.01_{stat}) \times 10^4$ fb/cm^2



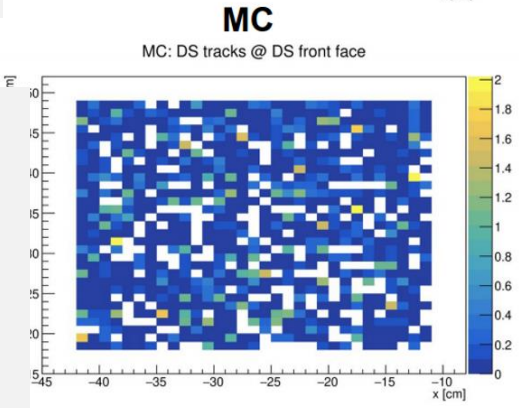
Expected muon track rate in SciFi (31x31 cm^2):

$(1.57 \pm 0.10_{stat}) \times 10^4$ fb/cm^2



Measured muon track rate in Muon system (31x31 cm^2):

$(1.67 \pm 0.01_{stat}) \times 10^4$ fb/cm^2



Expected muon track rate in Muon system (31x31 cm^2):

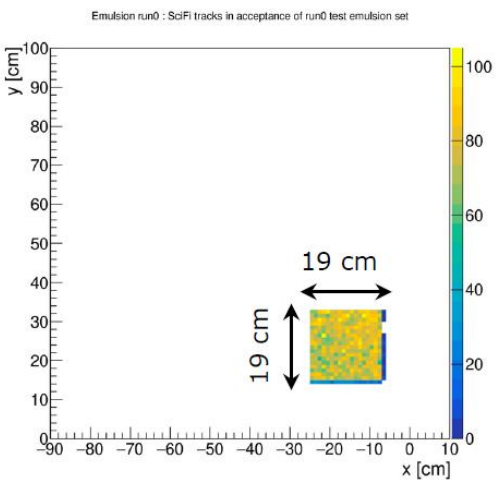
$(1.59 \pm 0.10_{stat}) \times 10^4$ fb/cm^2

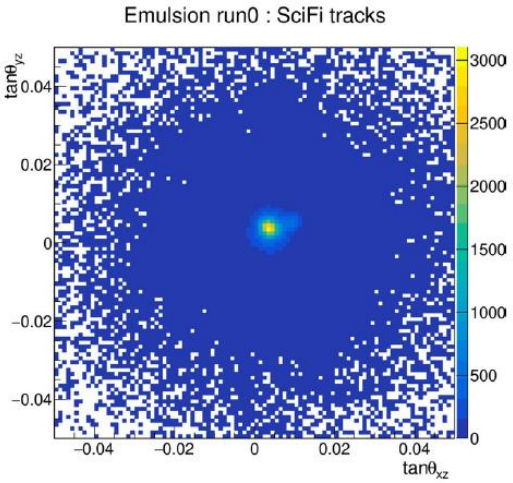
Muon flux from FLUKA
F. Cerutti, M.S. Gilarte
CERN-SY/STI

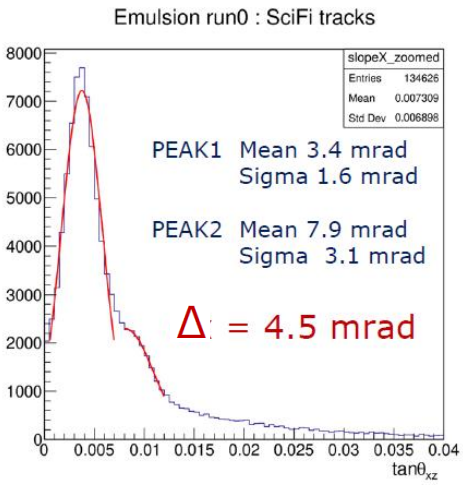
SciFi/Emulsion Comparison

SciFi

Measured rates on BRICK1 surface
1.6x10^4 fb/cm^2

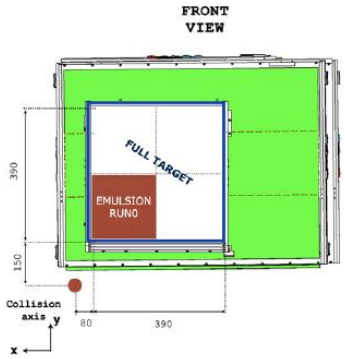


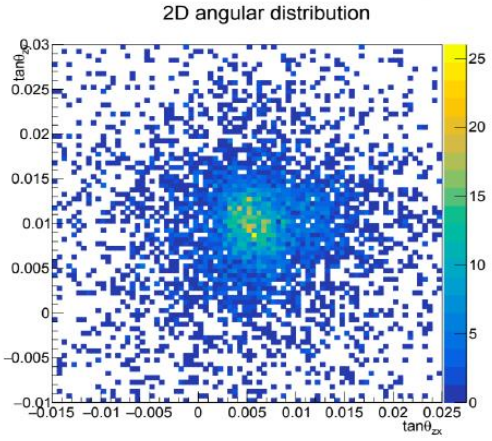


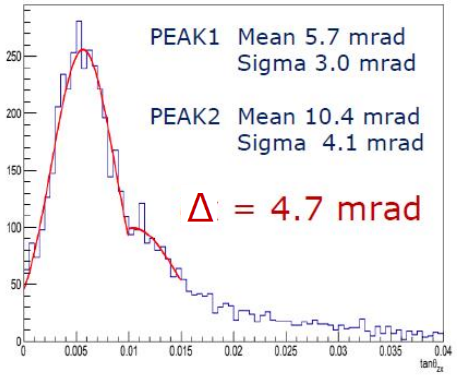


EMULSIONS

Measured rates in BRICK1
1.5x10^4 fb/cm^2







LHC
Scattering and Neutrino Detector at the LHC

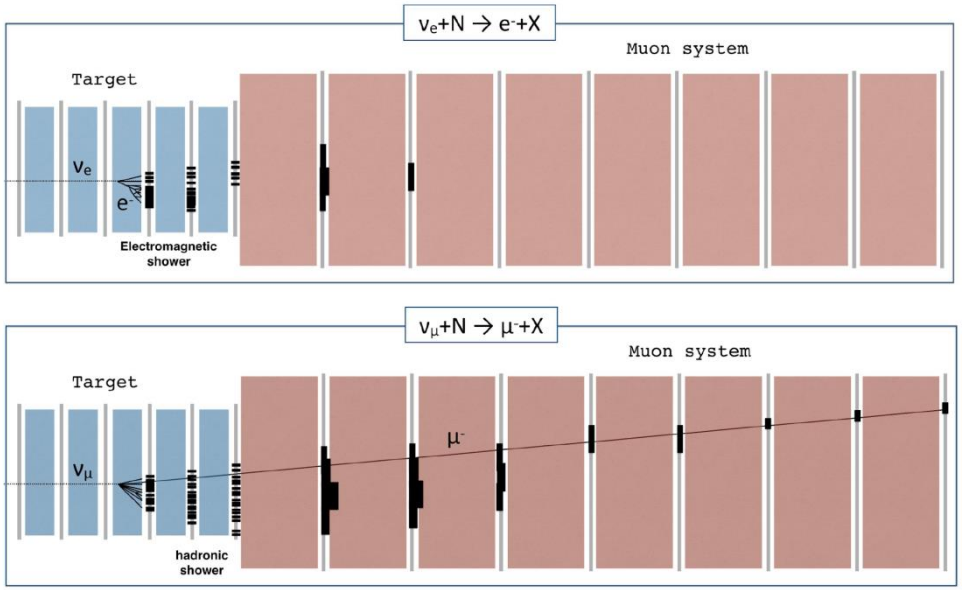
Neutrino Identification Strategy

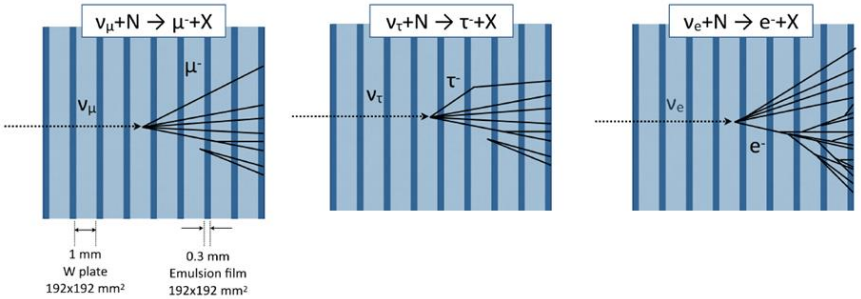
First Stage

- Identify the neutrino candidates in electronic detector data
- Tag muons in the muon system
- Measure electronic and hadronic energies in calorimeters

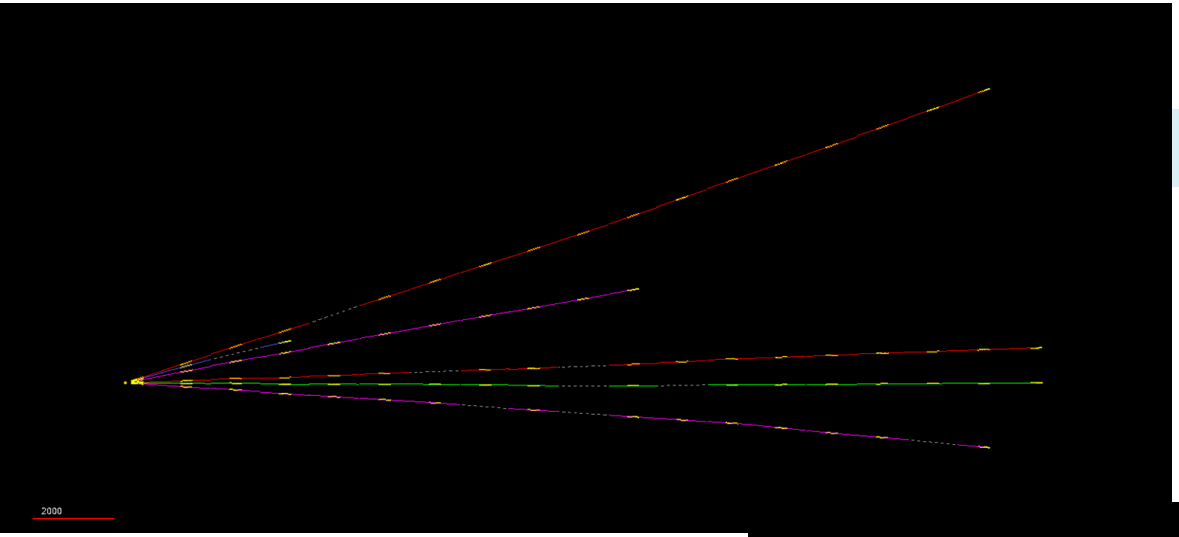
Second Stage

- Identify the neutrino candidates in emulsion data
- Tag electromagnetic showers
- Match events to electronic detector data
- Identify neutrinos of all flavours!

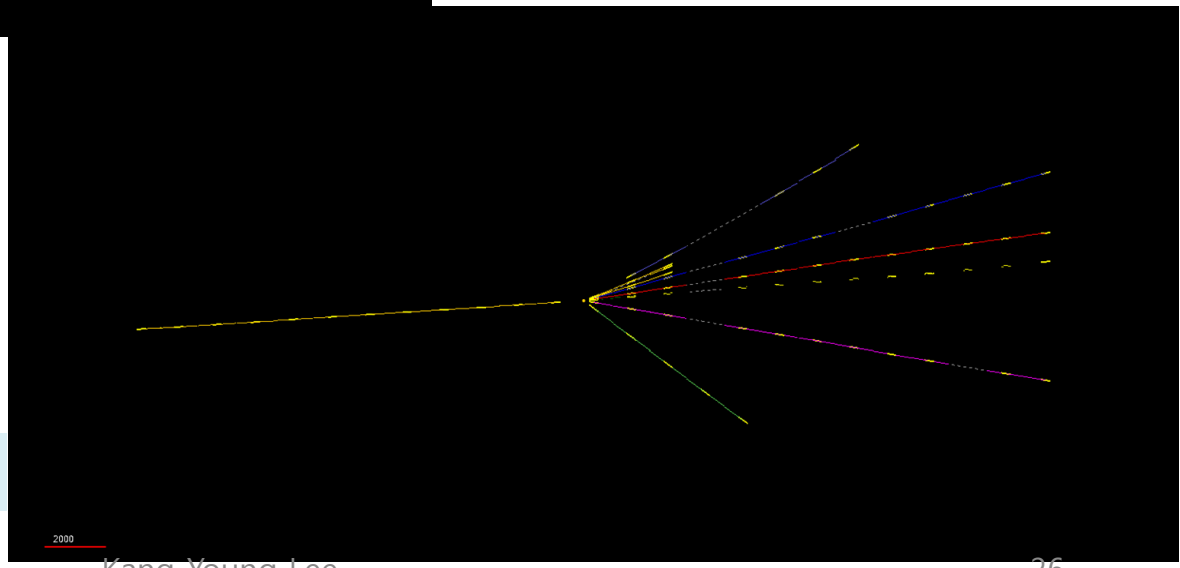




Vertex Reconstruction in Emulsion



Neutral particle interaction



Charged particle interaction

Neutrino Identification with Electronic Detectors

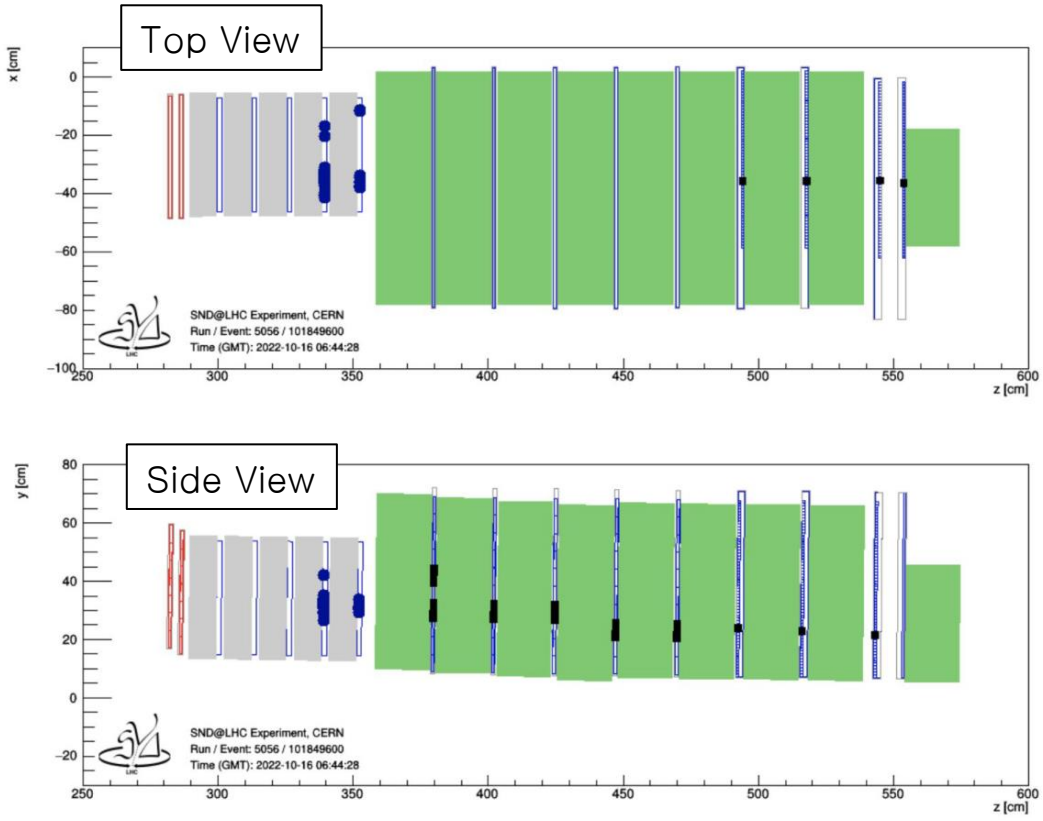
Neutrino selection criteria for electronic detectors

▶ Fiducial volume cuts

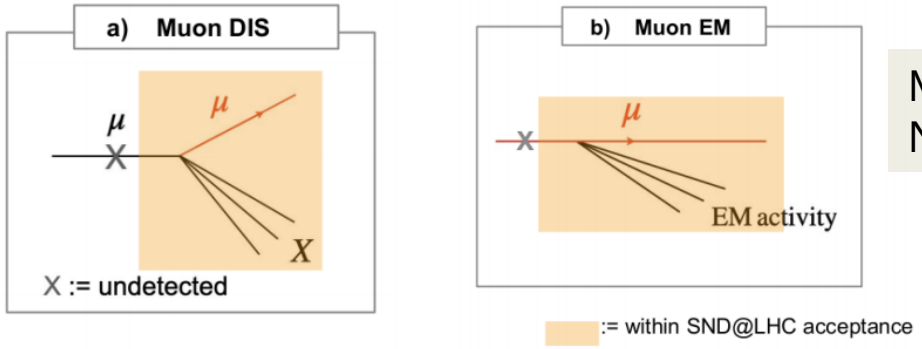
- Require an event from a neutral vertex, located in the 3rd or 4th wall
- Select fiducial cross-sectional area to reject entering backgrounds

▶ Neutrino ID cuts

- Require large EM activity in SciFi and hadronic activity in the HCAL
- Require timing for event produced upstream
- Muon reconstructed and isolated in the muon system



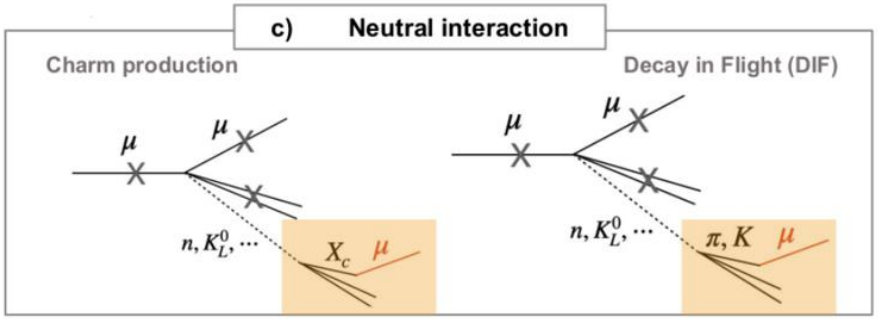
Background Estimation



Muon induced DIS and EM backgrounds
Number of undetected muons entering the target

$$N_{\mu}^{bkg} = N_{\mu} \times (1 - \epsilon_{Veto}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2}) = 5.3 \text{ x } 10^{-12} \; N_{\mu}$$

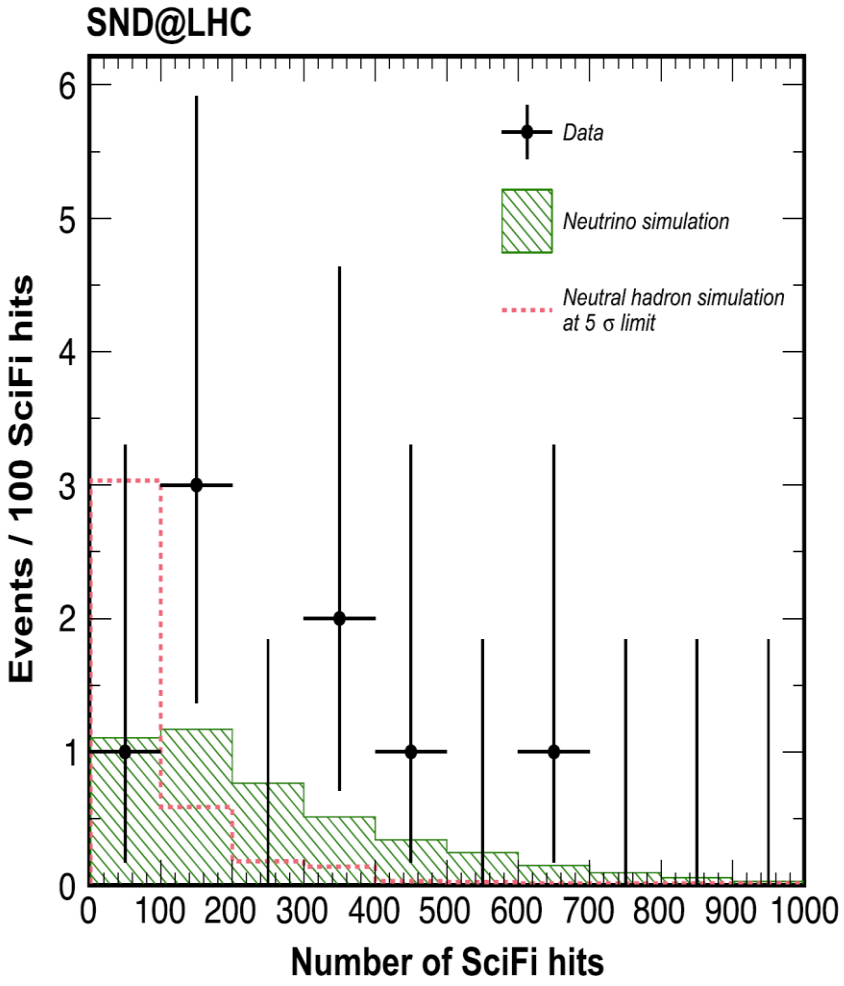
$$N_{\mu} = 1.2 \times 10^{9}$$ *Totally negligible*



Muon induced neutral interaction backgrounds

$$N_{\text{neutrals}}^{\text{bkg}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}} = (8.6 \pm 3.8) \text{ x } 10^{-2}$$

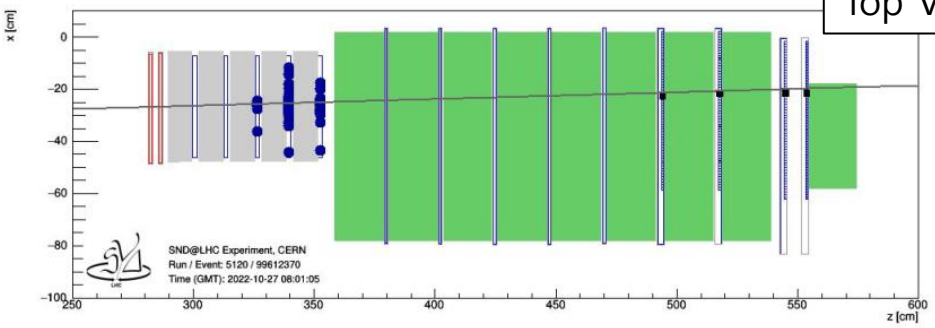
Observed Neutrino Candidates



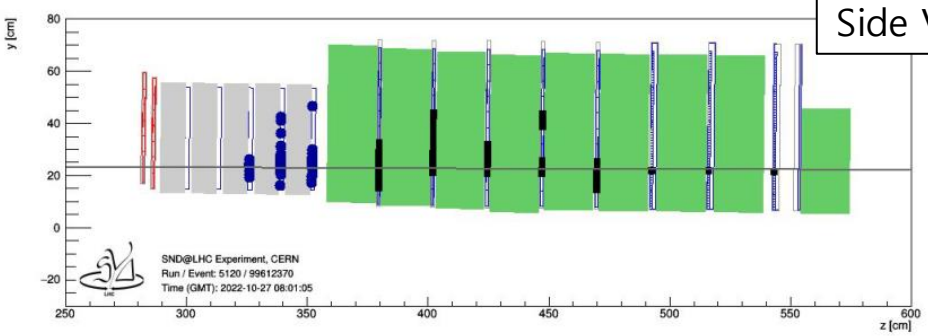
8 observed events and an expected background

$$(8.6 \pm 3.8) \times 10^{-2}$$

Top View



Side View



Electronic detectors only

Oct 27th

Paper Released

PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

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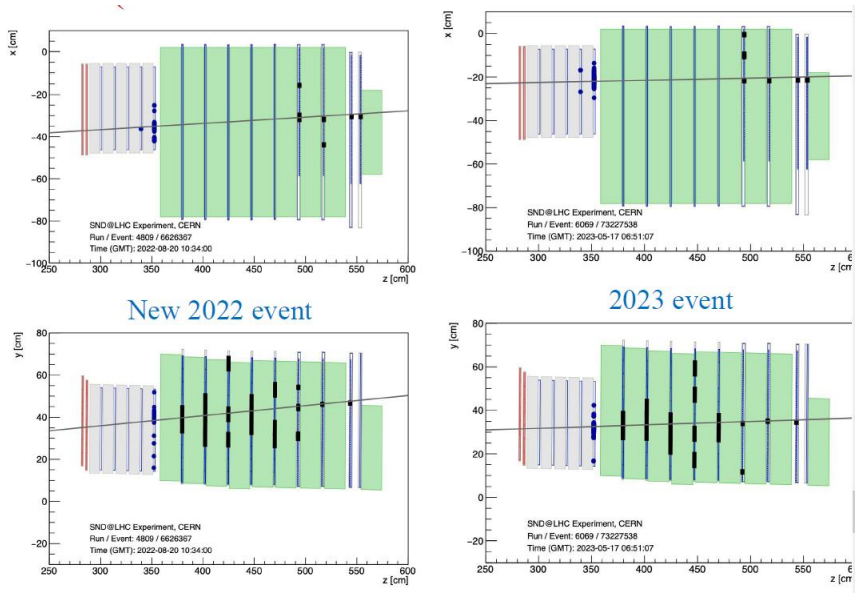
(SND@LHC Collaboration)

LHC
Scattering and Neutrino Detector
at the LHC

Ongoing …

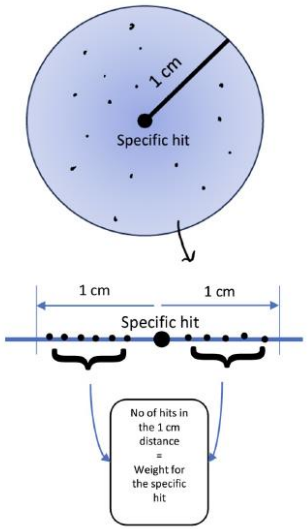
More muon neutrinos

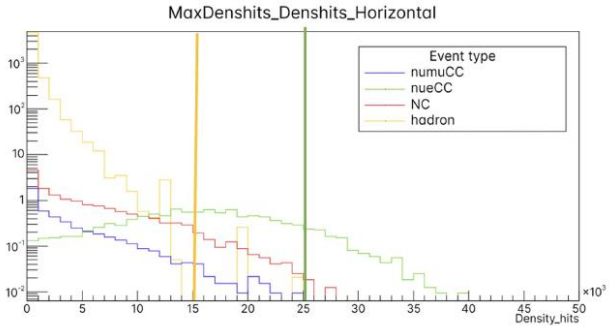


33 events: 16 in 2022 and 17 in 2023

Electron neutrino studies

- Signal selection based on topological and calorimetric information
- Discriminating variable: density of hits in SciFi





- Hit density > 15000
  - negligible neutral hadron background
- Hit density > 25000
  - dominated by ν_e CC events

Events : 10000
Scaled to 70 fb^{-1}

Hit density above 15000:
1.61 NC
0.29 ν_μ CC
7.1 ν_e CC

Scanning emulsion films,
Hardware upgrades,
….

SND@LHC Collaboration

Collaboration: 160 members

24 Institutes in 14 Countries and CERN

2 more Institutes and 1 more Country w.r.t. 2022

Korean Group

Korean group member (SND@LHC & SHiP)

Gyeongsang National University (GNU)

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

Korea University (KU)

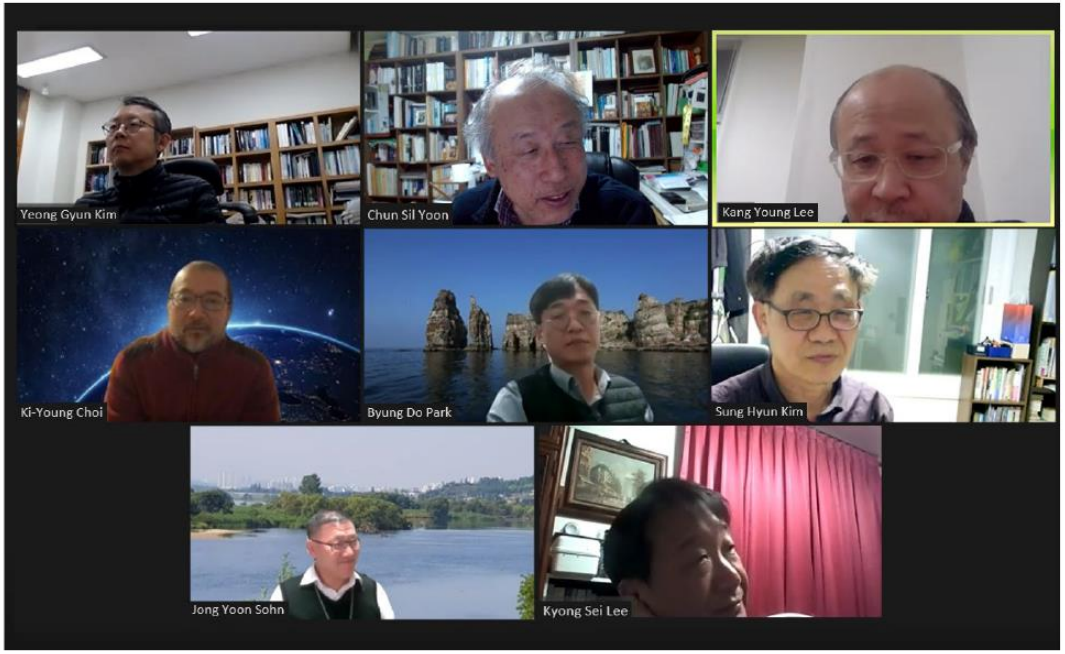
K. S. Lee

Gwangju National University of Education (GNUE)

Y. G. Kim

Sungkyunkwan University (SKKU)

K.-Y. Choi



European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

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Prof. Kang Young Lee
Gyeongsang National University
Department of Physics Education
501 Jinju-daero
52828 Jinju
Republic of Korea

Our reference: DG-DI-RCS-2021-056

Geneva, 23 August 2021

Dear Professor Kang Young Lee,

On behalf of CERN, I have signed the enclosed Memorandum of Understanding for Construction of the Scattering and Neutrino Detector at LHC (SND@LHC Experiment).

May I ask you to sign the two copies of the signature page (page 7), keep the fully signed version for your records and return one signature page to my office:

Office of the Director for Research and Computing
CERN
DG-DI-RCS (C00420)
CH-1211 Geneva 23

Thanking you in advance, I remain

Yours sincerely,

Joachim Mnich

European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

Professor Joachim Mnich
Director for Research and Computing
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Prof. Kang Young Lee
Gyeongsang National University
Department of Physics Education
501 Jinju-daero
52828 Jinju
Republic of Korea

Our reference: DG-DI-RCS-2022-124

Geneva, 7 September 2022

Dear Professor Kang Young Lee,

On behalf of CERN, I have signed the enclosed Memorandum of Understanding for the Maintenance and Operation of the Scattering and Neutrino Detector at LHC (SND@LHC Experiment).

May I ask you to sign the two copies of the signature page (page 7), keep the fully signed version for your records and return one signature page to my office:

Office of the Director for Research and Computing
CERN
DG-DI-RCS (C00420)
CH-1211 Geneva 23

Thanking you in advance, I remain

Yours sincerely,

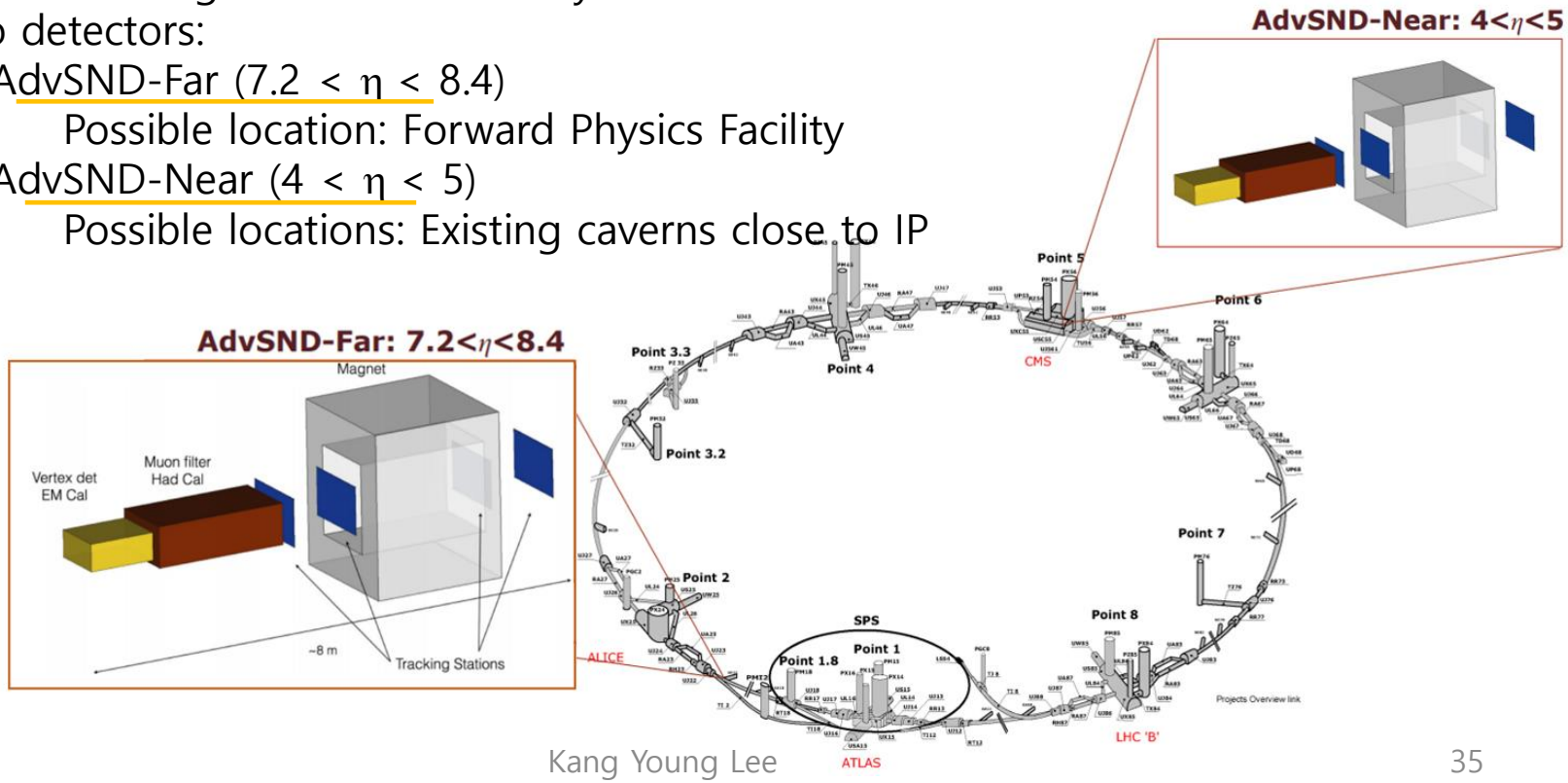
Joachim Mnich

Beyond Run 3

Advanced SND@LHC

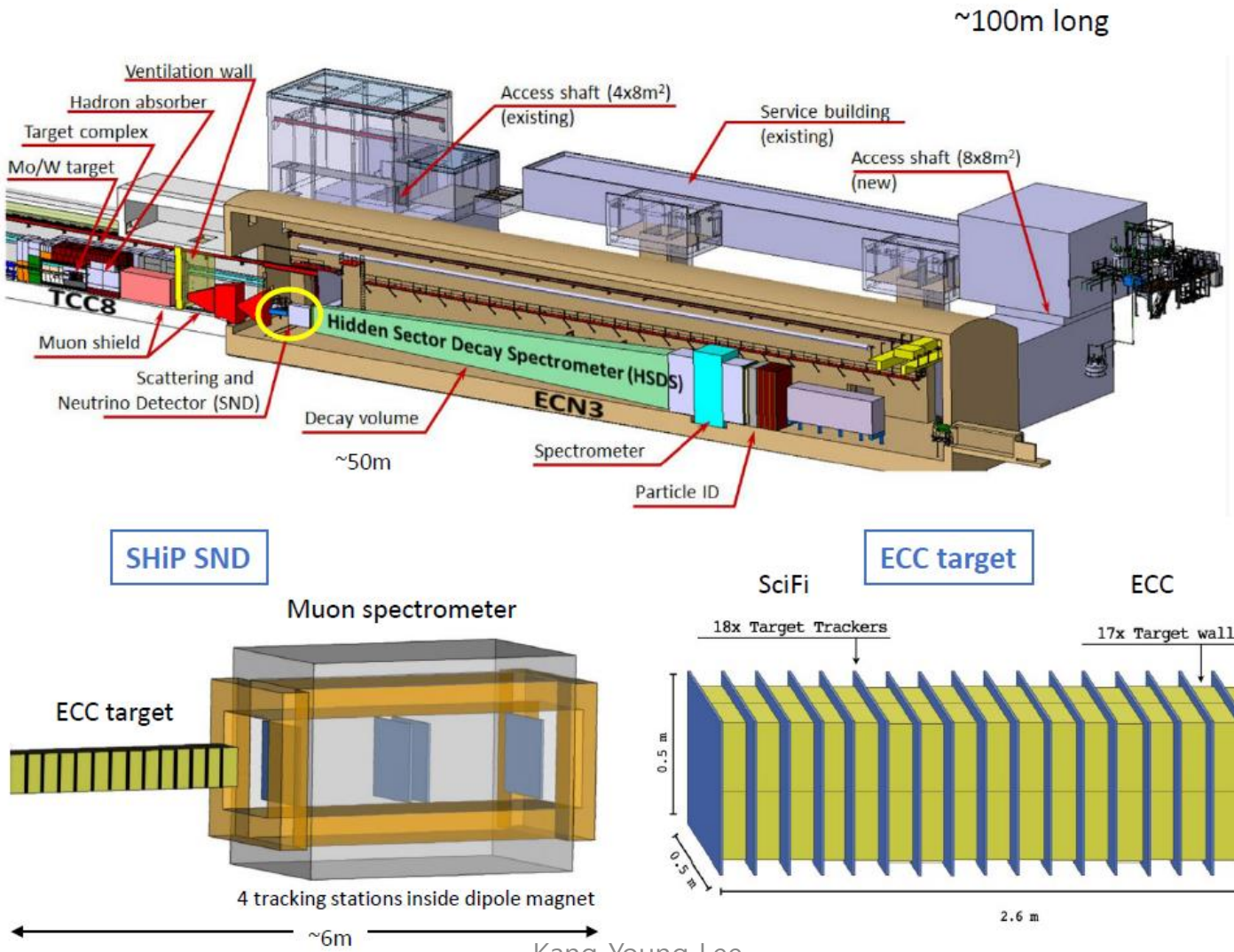
- Future project at HL-LHC era

- Upgrade of SND@LHC during LS 4
- Extension of the physics case
- New technologies and detector layout
- Two detectors:
  - AdvSND-Far (7.2 < η < 8.4)
    - Possible location: Forward Physics Facility
  - AdvSND-Near (4 < η < 5)
    - Possible locations: Existing caverns close to IP

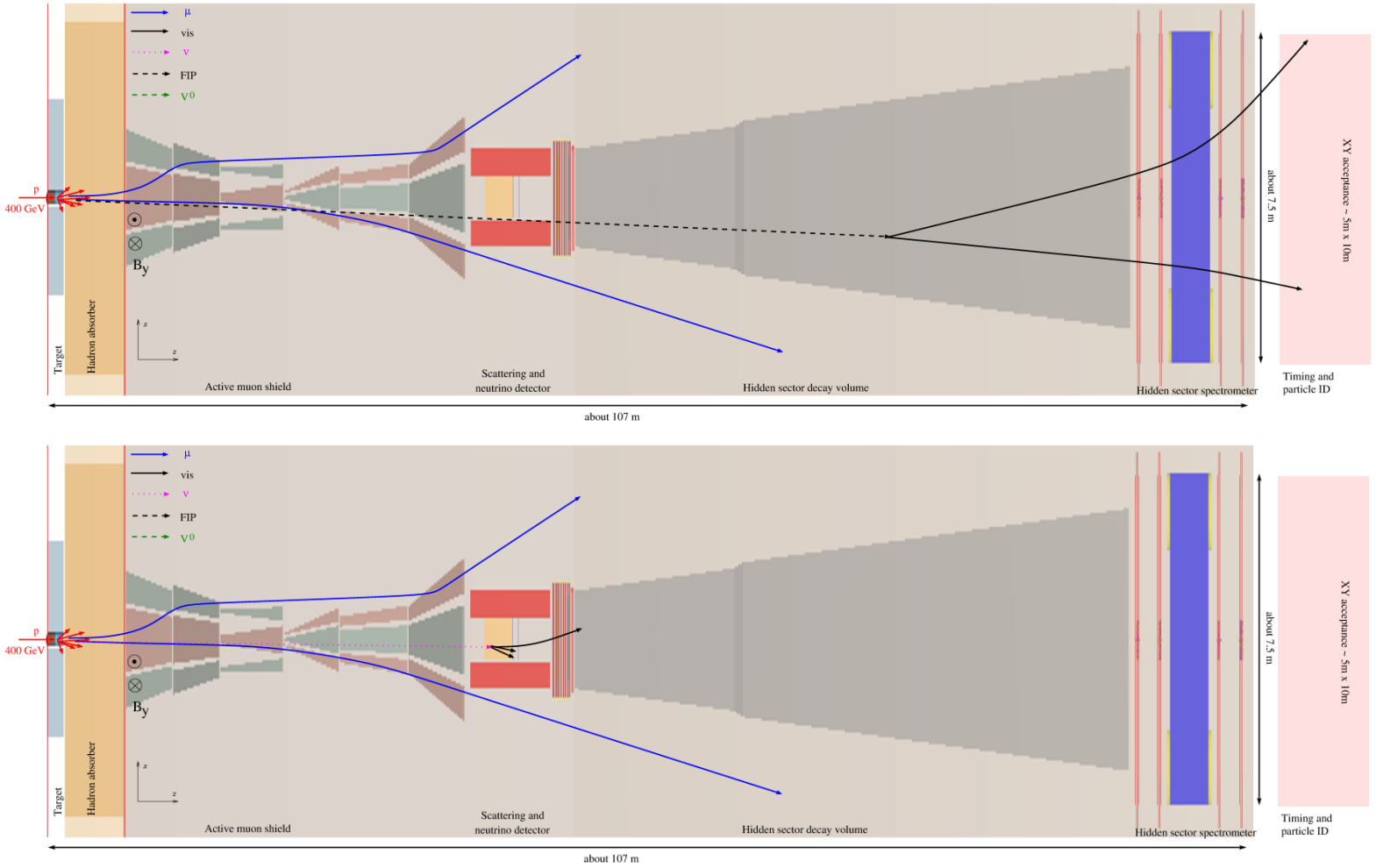


BDF/SHiP at ECN3

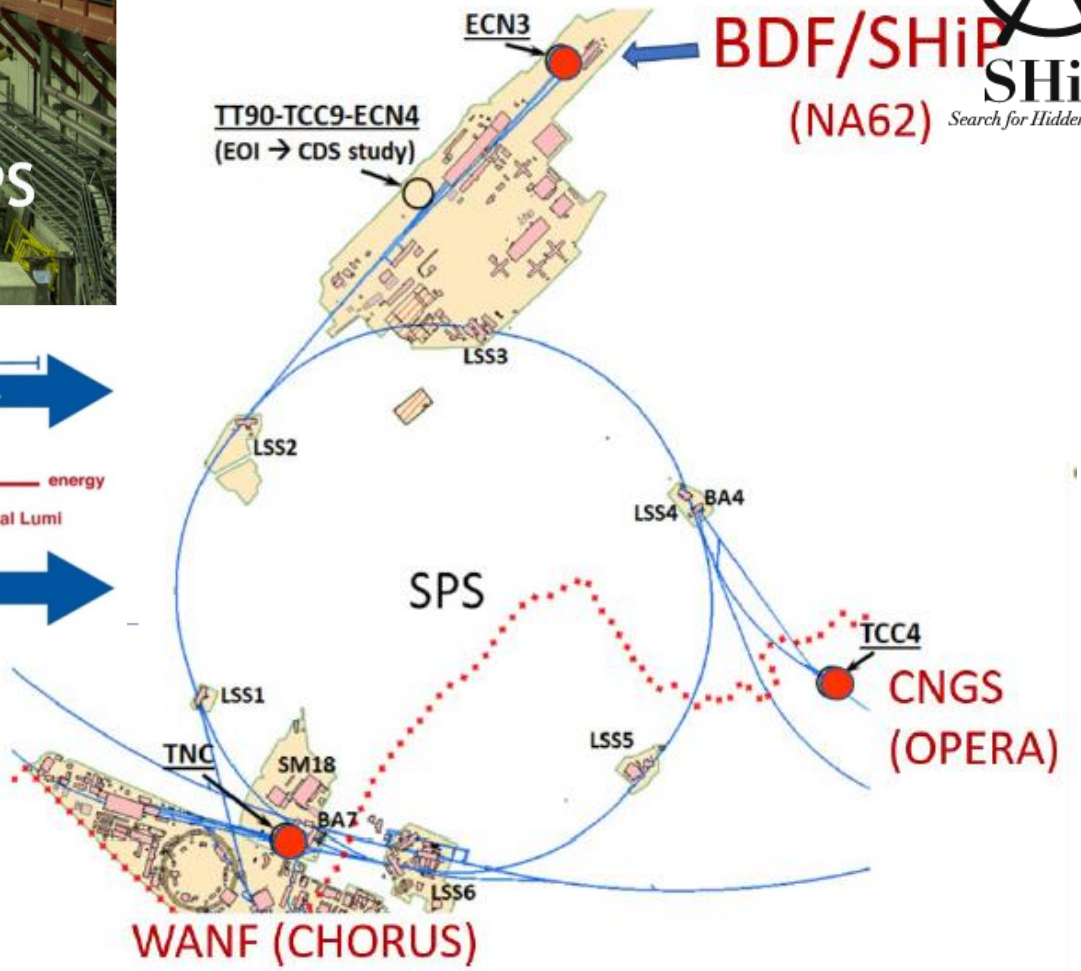
Design of BDF/SHiP detector



BDF/SHiP at ECN3



BDF/SHiP at ECN3



Decision : 6th Dec.

Conclusion

- SND@LHC starts running to perform measurements of ν and search for FIP in the forward region of the LHC.
- SND@LHC collected 39 fb^{-1} data at the LHC Run 3.
- Measurement of muon flux with emulsions and electronic detectors shows good agreements with MC calculation.
- **8 ν_μ CC candidates** are identified with the electronic detectors while the estimated backgrounds are 0.2. Systematic uncertainty is under evaluation to expect significance ~5σ.
- Emulsion scanning & analysis is ongoing. Stay tuned!

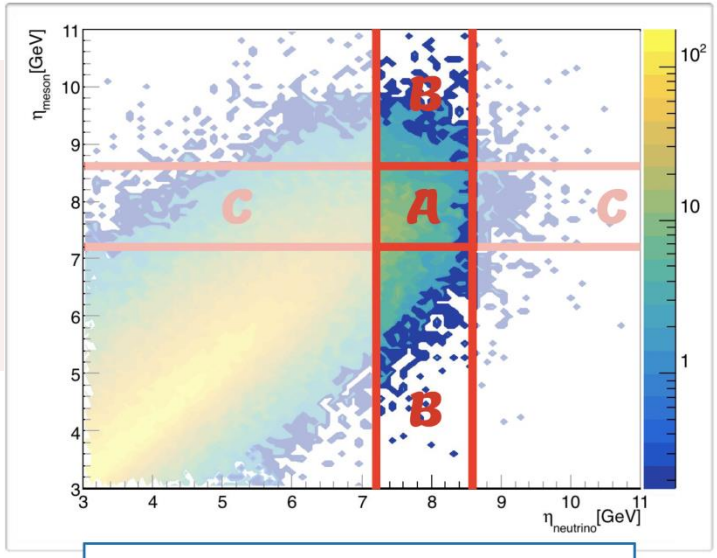
Thank you!

Backup Slides

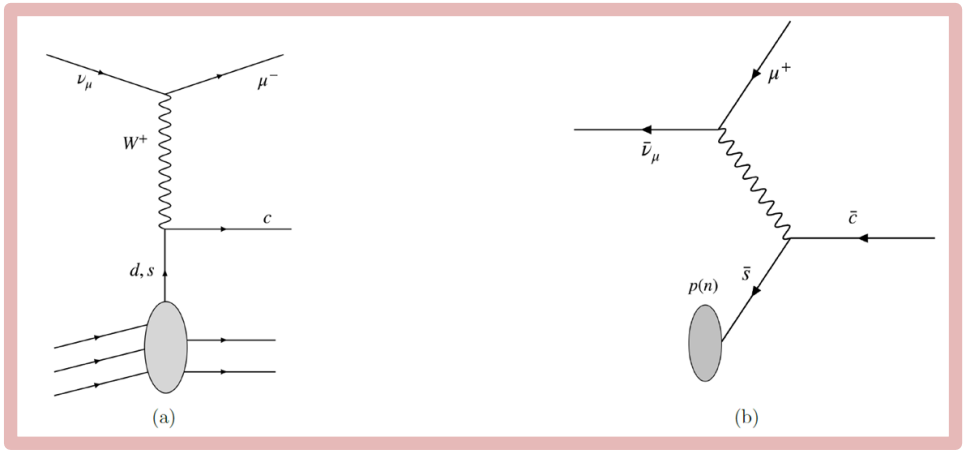
Physics Cases – Charm Physics

Neutrino production from charm decays

90% of ν_e production is expected to be charm decays.
→ as a probe of charm production
→ impact on the gluon PDF at very small x



Correlation between η_ν and η_c



Charm production in neutrino CC interactions

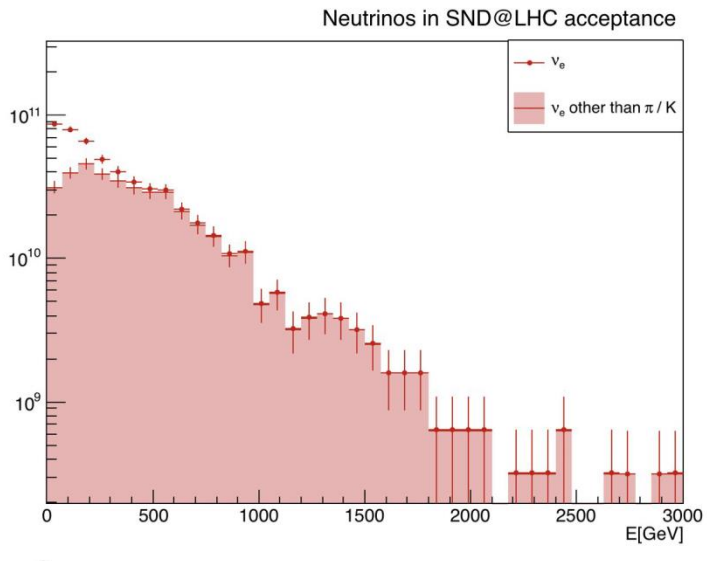
High energy neutrino can produce charm quark via DIS

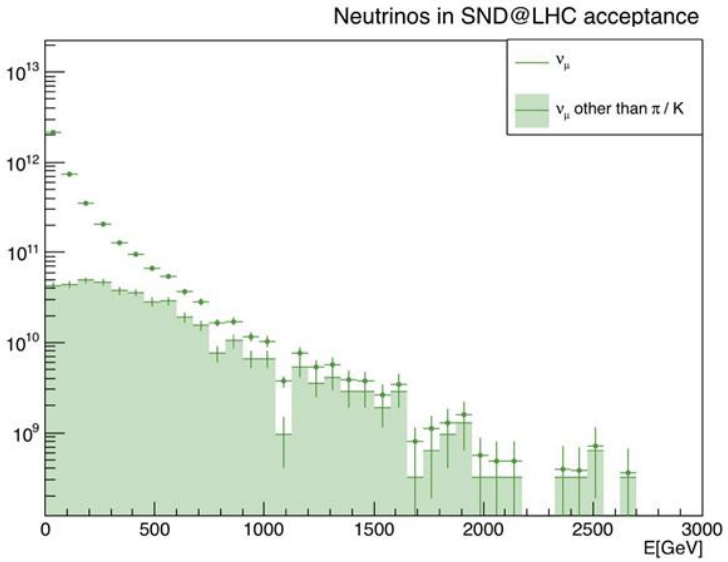
Physics Cases – Lepton Universality Test

- All 3 flavors of neutrinos can be identified.
- Unique opportunity to test lepton flavour universality with neutrinos
- ν_e/ν_τ and ν_e/ν_μ ratios

Expected uncertainties

- ν_e/ν_τ
  - Statistical: 30%
  - Systematic: 20%
- ν_e/ν_μ
  - Statistical: 10%
  - Systematic: 10%





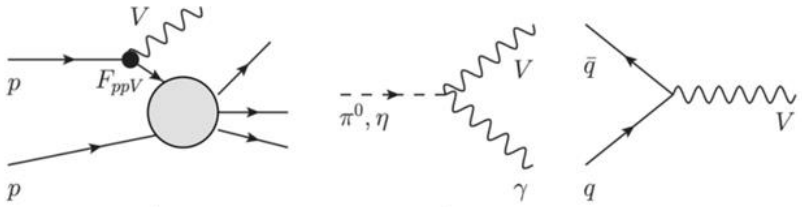
$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i}\tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s}\tilde{Br}(D_s \to \nu_\tau)},$$

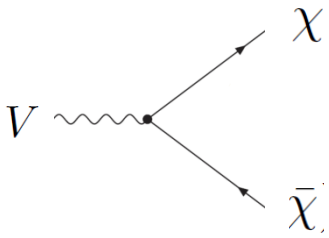
$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

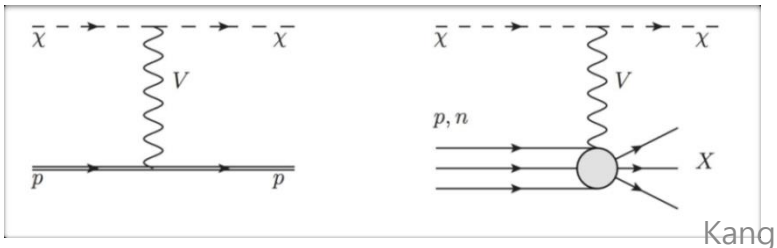
Physics Cases – FIP search

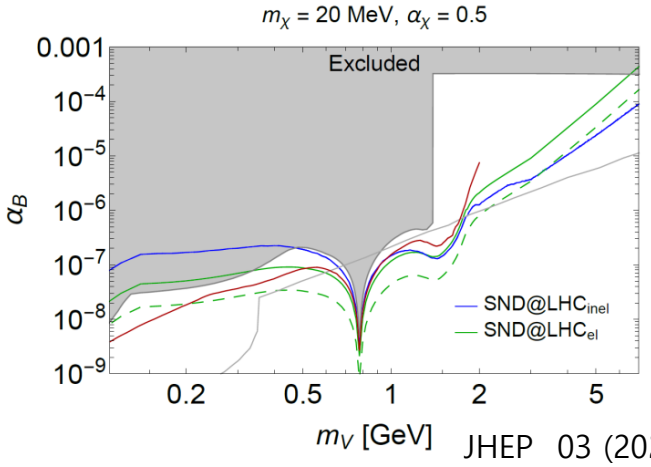
Direct search for FIP through scattering in the detector

e.g. leptophobic dark photon and light DM









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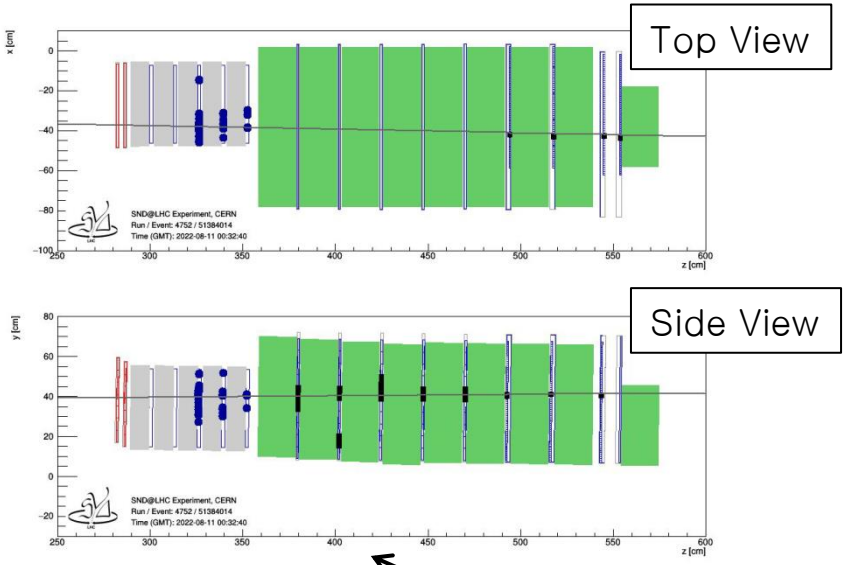
Dark photon can be produced at IP1 through p bremsstrahlung, meson decays, Drell-Yann process etc..

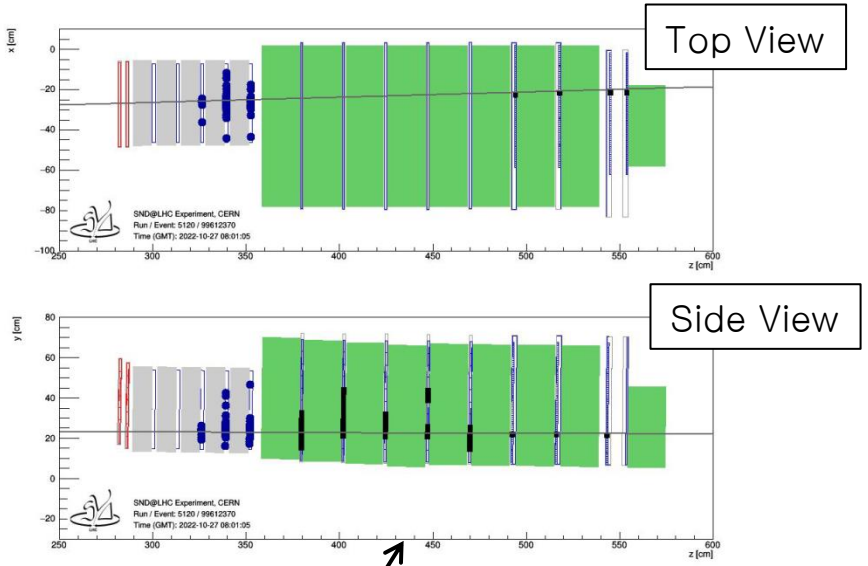
Dark photon decays into LDM.

LDM scatterings in the detector
LDM decays in the detector

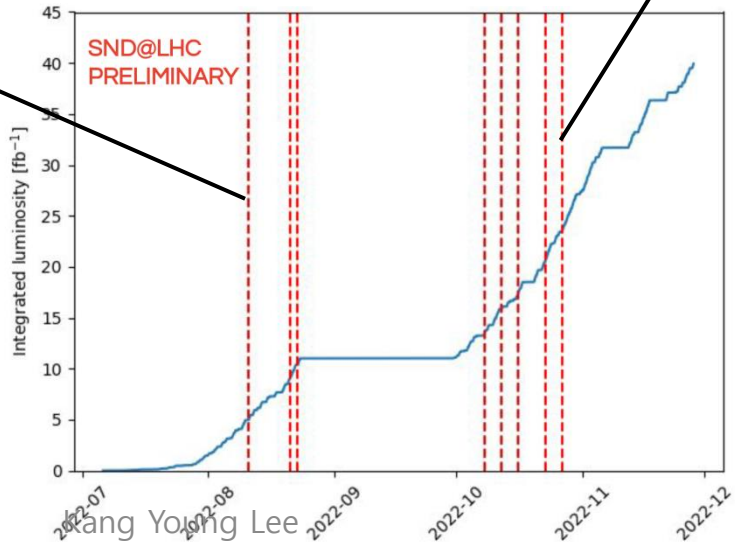
Observed Neutrino Candidates



Aug 11th



Oct 27th



8 ν_μ CC candidates observed
(5 expected)
0.2 background yields estimated