Scattering and Neutrino Detector at the LHC

SND@LHC upgrades

Ettore Zaffaroni, for the SND@LHC collaboration
LHCP 2024, Boston, USA
05/06/2024

EPFL

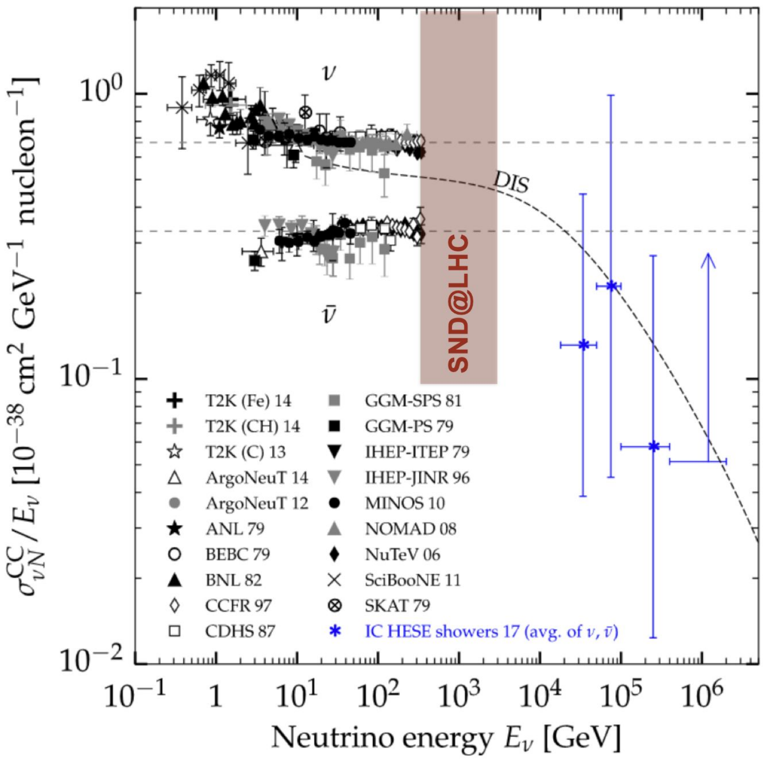
Outline

- The SND@LHC detector in Run 3
- Proposed upgrade for LHC Run 4 and beyond
- Effects on the physics reach

LHC
Scattering and Neutrino Detector
at the LHC

Motivation

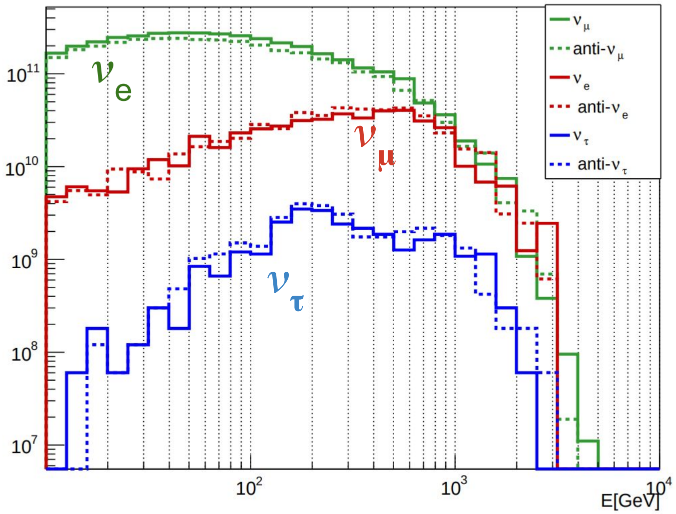
- LHC provides high-energy neutrinos
  - LHC neutrino studies proposed ~30 years ago
- Measure of pp→νX in unexplored domain
  - Energy range from 100s GeV to few TeV
- 2 experiments
  - FASERν, on axis ($\eta > 9$)
  - **SND@LHC**, off axis ($7.2 < \eta < 8.4$), ν mainly produced in charmed hadrons decay



PRL 122 (2019) 041101

Physics programme

- Measurement of charm production at high pseudorapidity ($gg \to c\bar{c}$)
- Probe gluon PDF at low momentum fraction $x \sim 10^{-6}$. Relevant for
  - FCC detectors
  - Extra-galactic neutrino observation (atmospheric neutrino background)
- Test lepton flavour universality with neutrinos
  - Thanks to the ability to distinguish all neutrino flavours
- Direct search of feebly-interacting particles



LHCC-P-016

JINST 19 P05067

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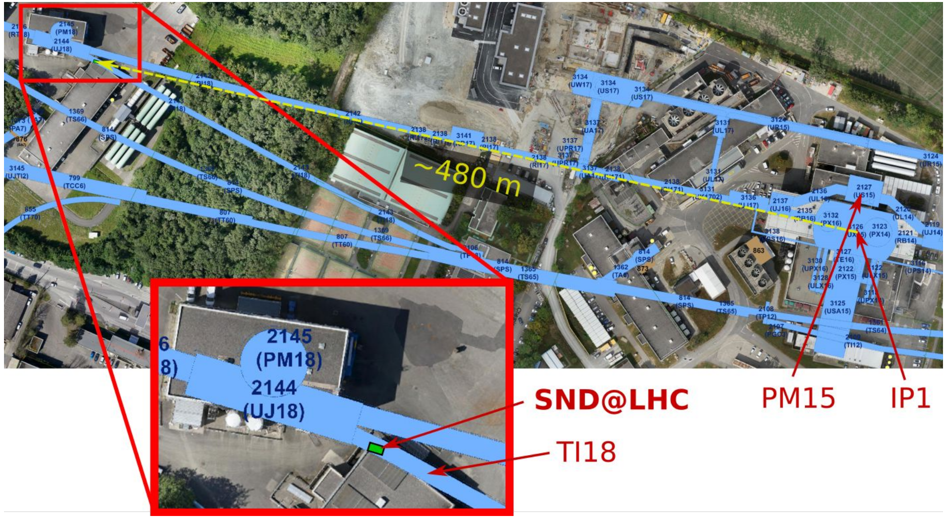
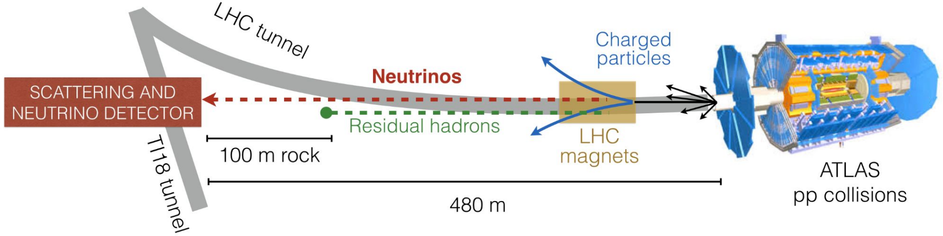
SND@LHC

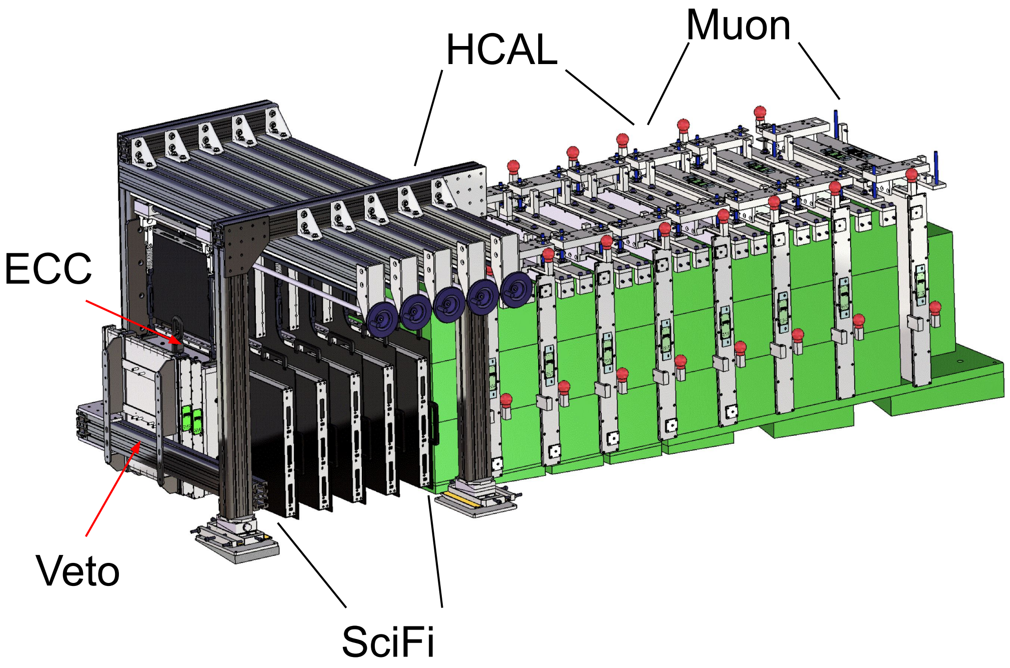
- About 480 m from ATLAS interaction point
- TI18 tunnel
  - Used in the past as transfer line from SPS to LEP
- Shielded by 100 m of rock and LHC magnet deflection
- Angular acceptance: $7.2 < \eta < 8.4$
- First phase: collect 250 fb^{-1} in Run 3





Detector

- Veto
  - Scintillators: tag incoming muons
- Vertex detector and EM calorimeter
  - Emulsion cloud chambers (ECC) w/ tungsten, 5 walls, 830 kg: neutrino interaction detection
  - Scintillating fibres (SciFi) tracker, 5 modules: timestamp, position and energy measurement
- HCAL-Muon system
  - Iron walls (green) and scintillators: energy measurement and muon detection
- Main limitation: has to fit in the TI18 tunnel



Detector paper: JINST 19 P05067

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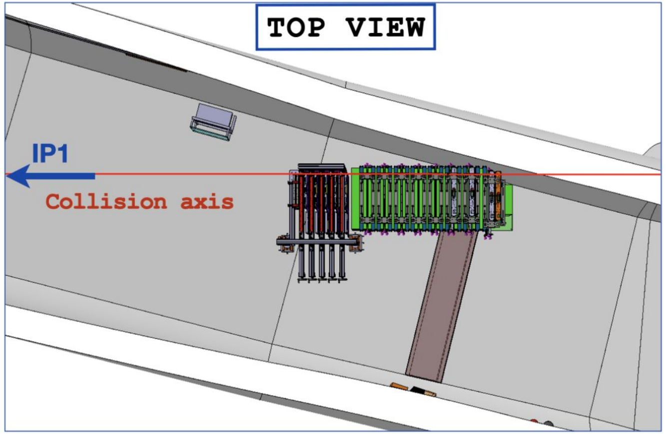
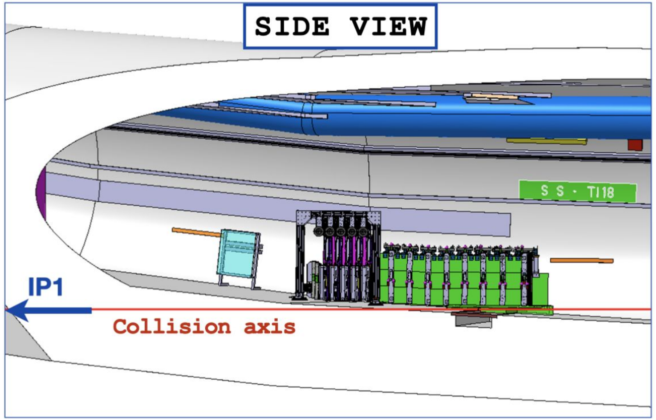
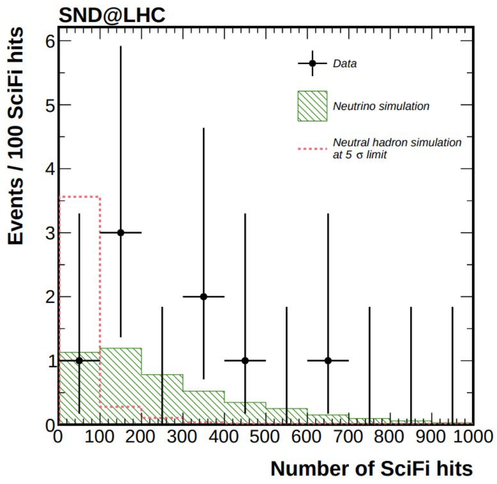


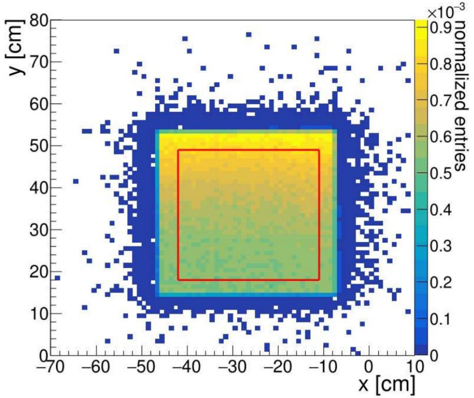


Physics results

- First measurement of muon neutrinos produced at the LHC
  - Using electronic detectors only
    - 32 events observed
  - Emulsion films are currently being scanned
  - See [Chris' presentation]() (Tue)
- Muon flux measurement with electronic detectors and emulsions
  - Remarkable agreement with simulation: ~25 %



Phys. Rev. Lett. 131, 031802



Eur. Phys. J. C (2024) 84: 90

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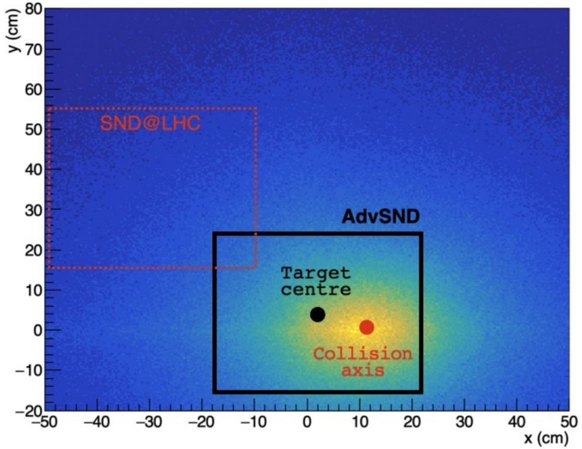
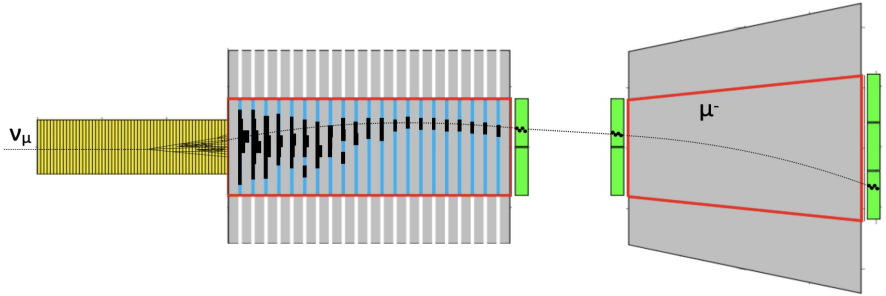
Proposed future upgrades

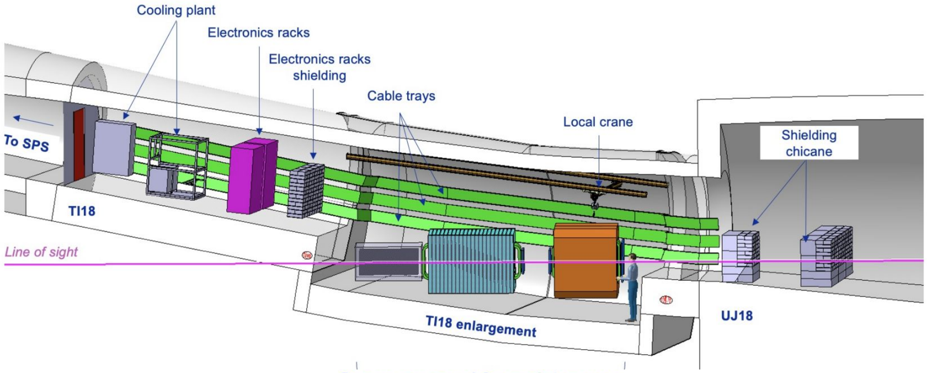
- Civil engineering modifications to the tunnel are feasible in LS3 (2026-2029)
- **LOI recently submitted ([CERN-LHCC-2024-007])**
- **Two upgrade paths**
  - **With dedicated spectrometer**
  - **With magnetized HCAL only**
- Under discussion, addition of a NEAR detector
  - reduce systematics
  - cross section measurements

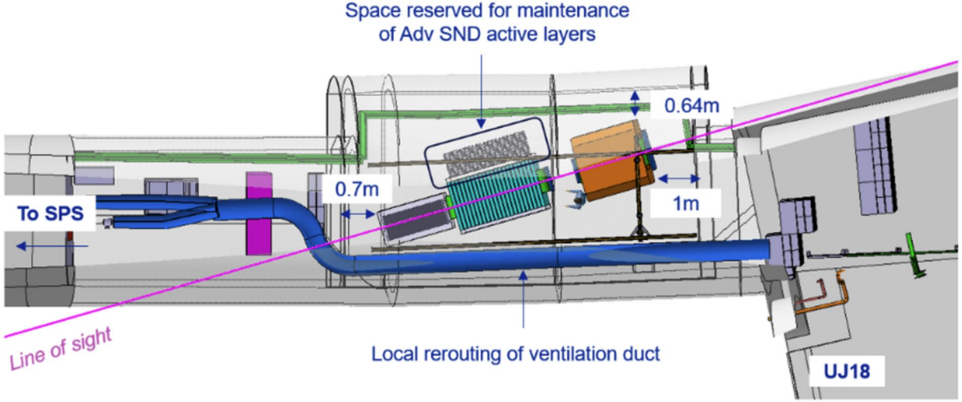




The two upgrade paths

- Feasibility study is currently underway
    - 2 options are considered
    - both minimise impact on HL-LHC upgrades
- **With magnetic spectrometer**
    - **Requires excavation of the tunnel wall and the floor**
- Only magnetized HCAL
    - Floor excavation only
- "Prototype" for SHiP
    - See Oliver's talk (Fri)





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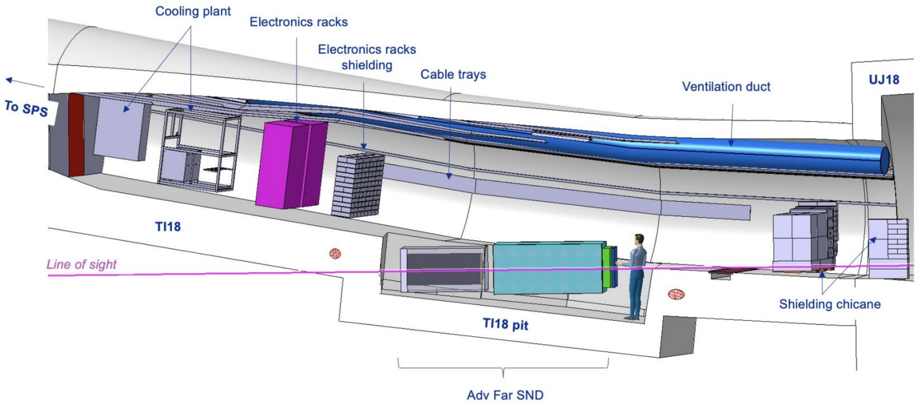

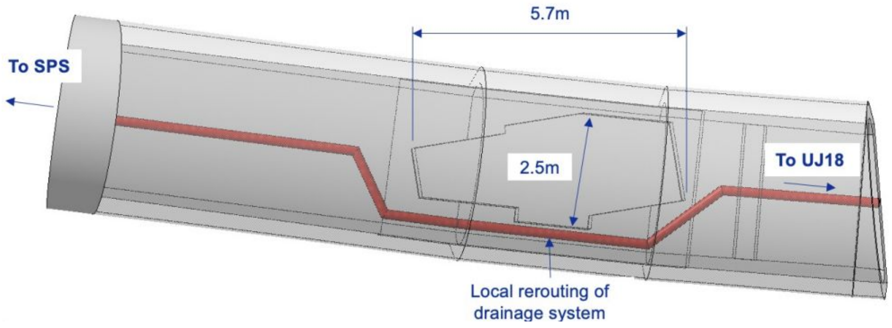

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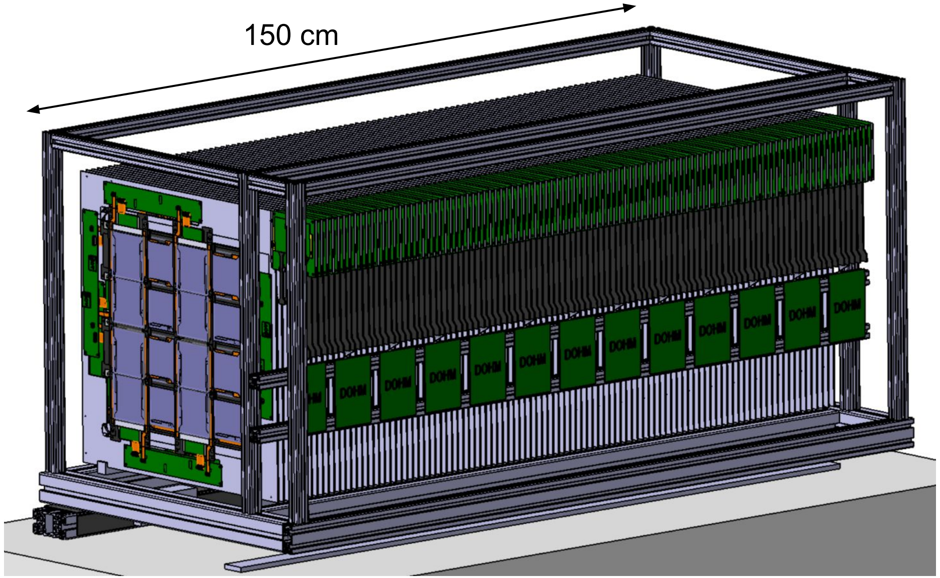
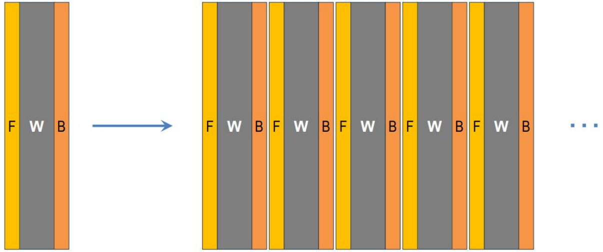
Target and vertex detector

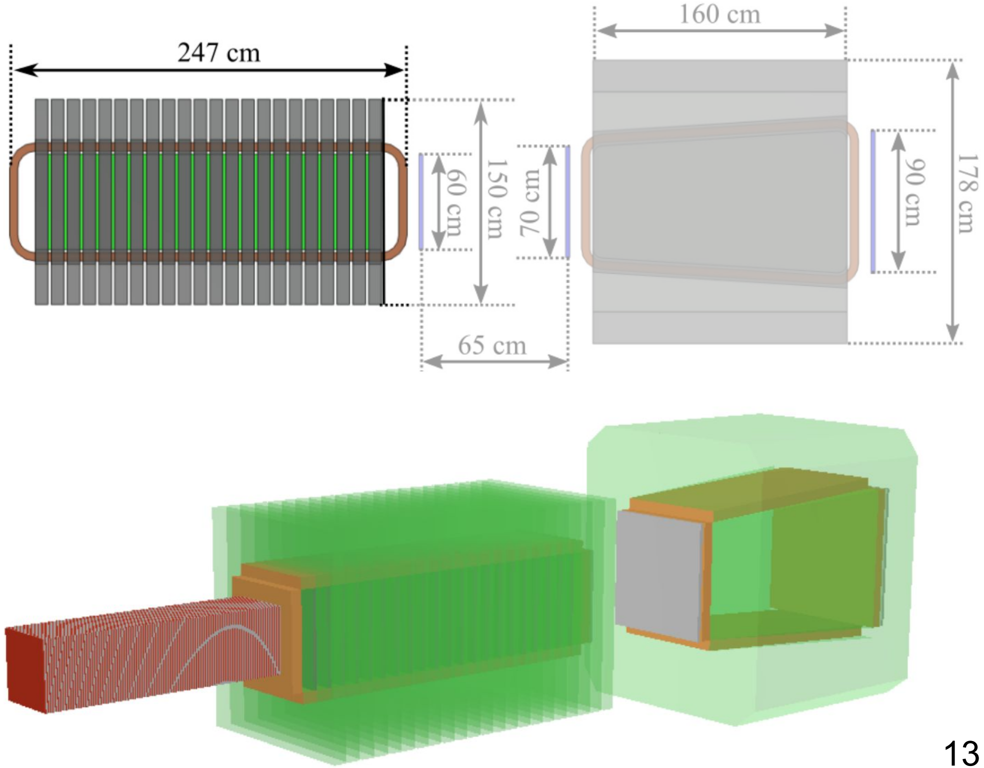
- The current vertex detector exploits the emulsion cloud chamber technology
- This cannot be used in the HL-LHC environment
  - High muon flux
- New silicon vertex detector based on CMS Tracker Outer Barrel strips modules
- Interleaved with 7 mm tungsten plates
  - Instrumented mass: 1.75 t





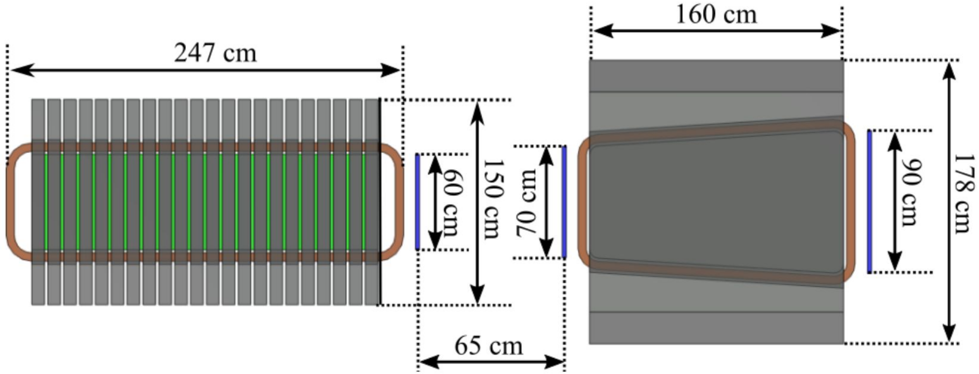
Magnetized hadronic calorimeter

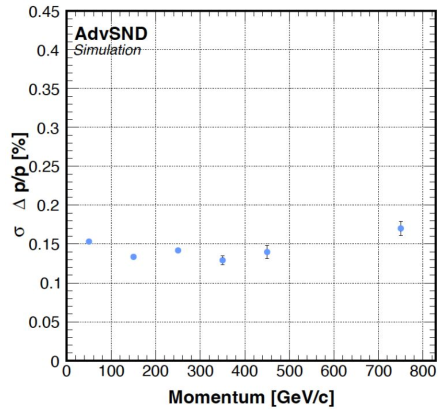
- Similar technology to current one (iron and plastic scintillator)
- Increased segmentation, addition of vertical and tile layers
  - Scintillator every 0.5 λ_{int}
  - addition of Si tracker modules in magnetized HCAL only path
- Addition of a coil around the detector planes
  - Magnetized iron, increases sensitivity to the muon charge
  - 1.75 T field



Muon system and magnet

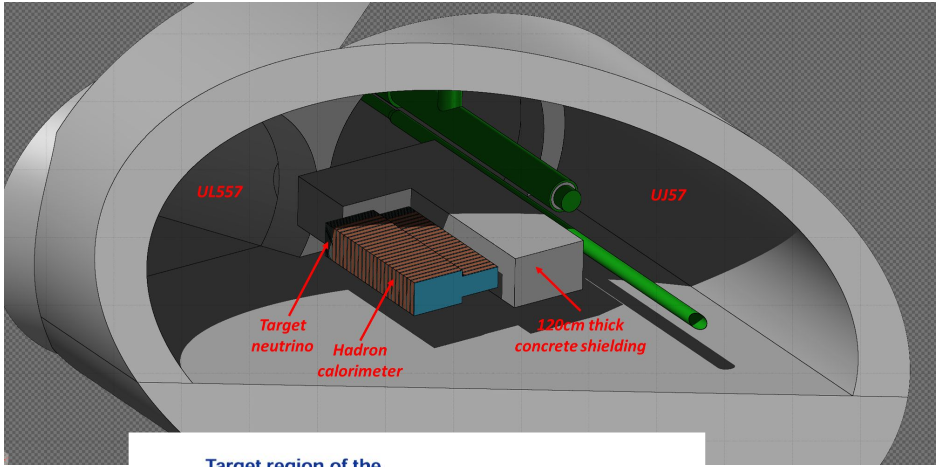
- Muons trajectories measured with drift tubes
  - “MiniDT” technology from CMS
  - 100 µm expected position resolution
- Magnet to further bend the muon trajectories
  - 1.75 T field
- Expected momentum resolution ~16%

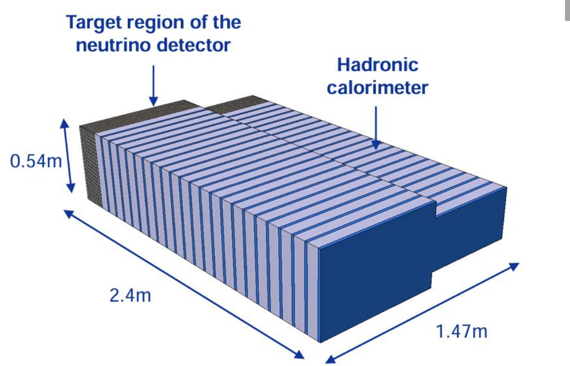




Possible NEAR detector

- Neutrino detector covering 4 < η < 4.5 region
  - Placed close to CMS
  - Precise location is being studied
- Measurement of neutrinos in a region covered by LHCb acceptance
- Drastic reduction of systematics
  - Direct experimental constraints





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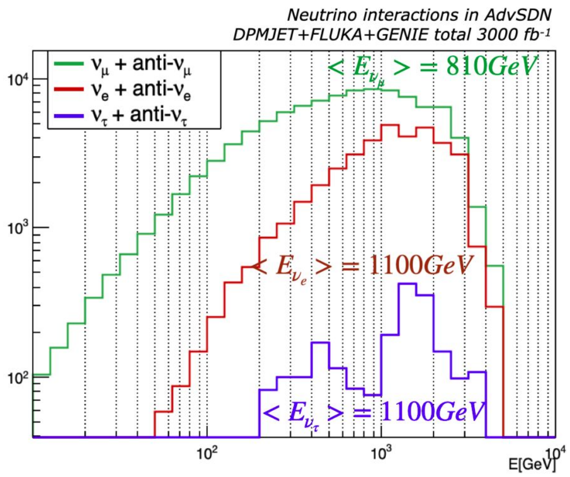
Physics reach

- Significant improvement of statistical and systematics uncertainties
- Possibility to measure neutrinos interaction cross section up to 1 TeV



Flavour	ν in acceptance All	ν in acceptance not from π/K	CC DIS All	CC DIS not from π/K	NC DIS All	NC DIS not from π/K
ν_μ	8.6×10^{13}	8.2×10^{12}	1.2×10^5	3.3×10^4	3.6×10^4	1.0×10^4
$\bar{\nu}_\mu$	7.0×10^{13}	9.6×10^{12}	4.4×10^4	1.8×10^4	1.6×10^4	6.5×10^3
ν_e	1.3×10^{13}	9.1×10^{12}	4.2×10^4	3.6×10^4	1.3×10^4	1.1×10^4
$\bar{\nu}_e$	1.3×10^{13}	9.2×10^{12}	1.9×10^4	1.7×10^4	7.0×10^3	6.1×10^3
ν_τ	7.3×10^{11}	7.3×10^{11}	2.1×10^3	2.1×10^3	6.7×10^2	6.7×10^2
$\bar{\nu}_\tau$	9.4×10^{11}	9.4×10^{11}	1.2×10^3	1.2×10^2	4.6×10^2	4.6×10^2
Tot	1.8×10^{14}	3.8×10^{13}	2.3×10^5	1.1×10^5	7.3×10^4	3.5×10^4

Measurement	Run 3 Uncertainty Stat.	Run 3 Uncertainty Sys.	Run 4+5 Uncertainty Stat.	Run 4+5 Uncertainty Sys.
Charmed hadron yield	5%	35%	1%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	5%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	1%	5%
ν_μ and $\bar{\nu}_\mu$ cross-section	-	-	1%	5%

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Summary

- The SND@LHC detector is successfully taking data since 2022
- The first physics results have been published
  - Many others are on the way
- Two upgrade paths for future upgrades
  - Significant improvements in physics reach


THANK YOU!

Scattering and Neutrino Detector at the LHC

Backup

Neutrino physics in Run 3

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

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
$\bar{\nu}_\mu$	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

Constraints without NEAR detector

- Constraints to PDF
  - Comparing different pseudorapidities (e.g. $\eta > 8$ vs $\eta < 8$), see J. Rojo CERN-TH Colloquium 11/2023
- Cross section / flux
  - Measurements from LHCf (not published yet)

Experiment timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

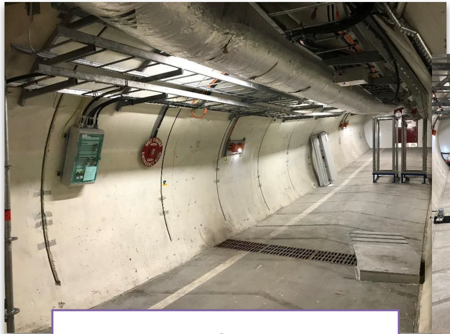
SND@LHC

January 2021

CERN approves new LHC experiment

SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

March 2021

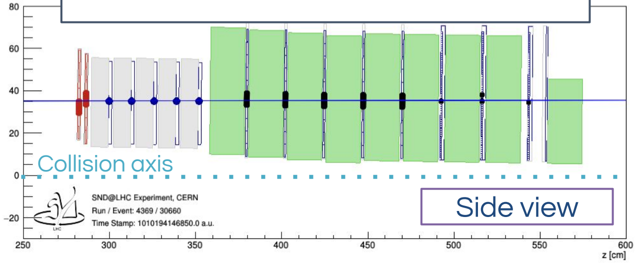


September 2021

December 2021

March 2022

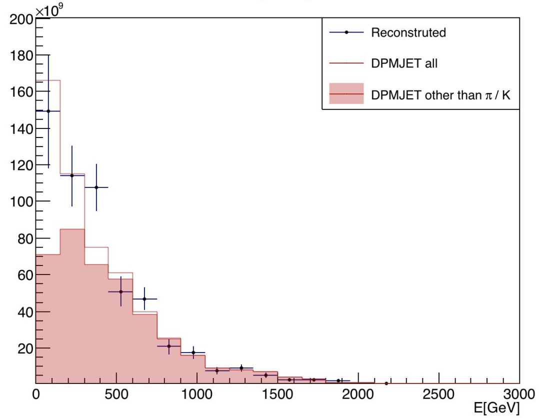
Muon from 13.6 TeV pp collision

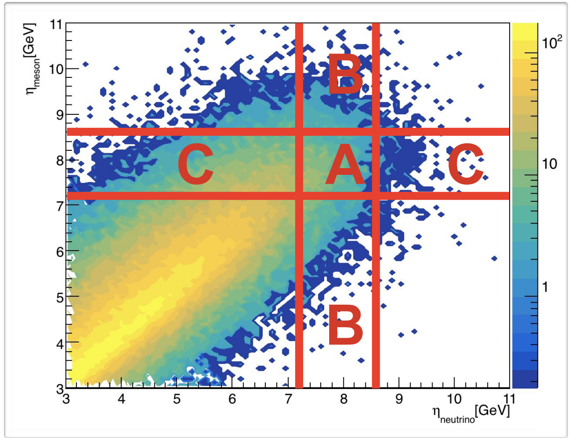


July 2022

Neutrino physics – charm production

- 90% of ν_e events produced in charm decays
  - Measurement of heavy quark production at high η
- Measure $\sigma(pp \rightarrow \nu_e X)$
  - Unfold detector response and find energy spectrum
  - Use SM σ_ν for CC interactions
- Derive charmed hadrons yield
  - Remove contribution from K decays
  - Exploit angular correlation between neutrino and parent hadron





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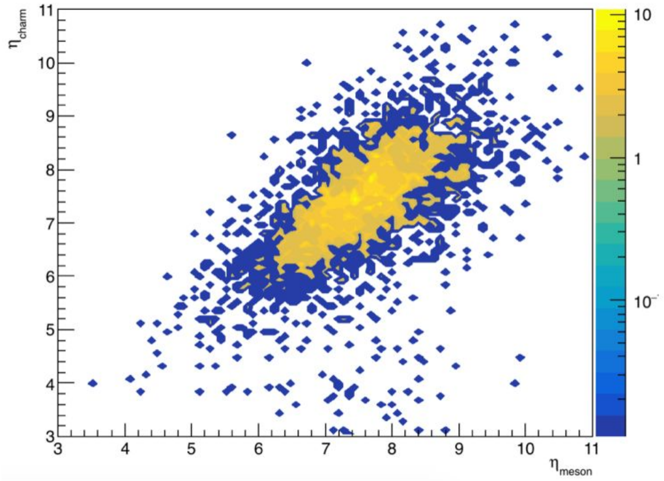
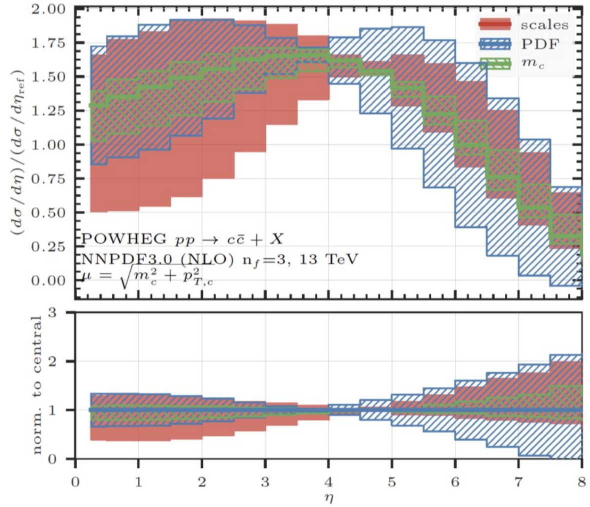
Neutrino physics – QCD

Scattering and Neutrino Detector at the LHC

- Angular correlation between charmed hadron and parent quark
- Dominant cc production process is gg scattering in this η range
  - SND@LHC probes lowest momentum fraction $x \sim 10^{-6}$, gluon PDF unknown
  - Relevant for future circular colliders and atmospheric neutrinos





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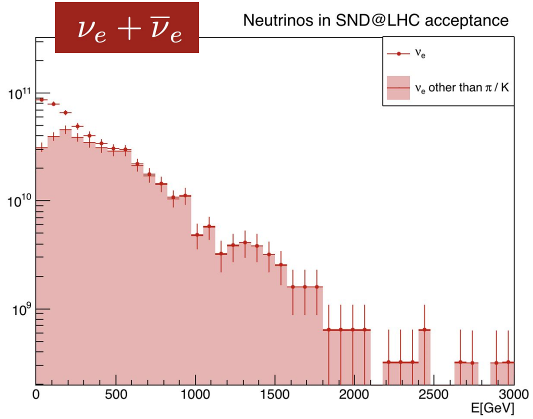
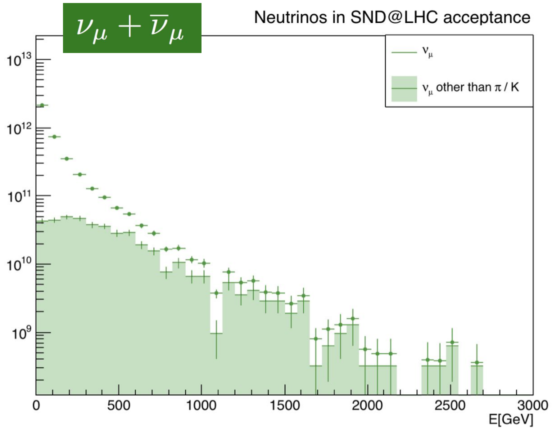
Neutrino physics – LFU

- ν_e and ν_τ mostly come from charm decays
  - R_{13} independent on charm production systematics
  - Depends on decay BR and charm fractions
- Similar for ν_e and ν_μ, R_{12} with contamination by π/K
  - Contamination flat ~35% above 600 GeV
  - No systematics from BR and charm fractions

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

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





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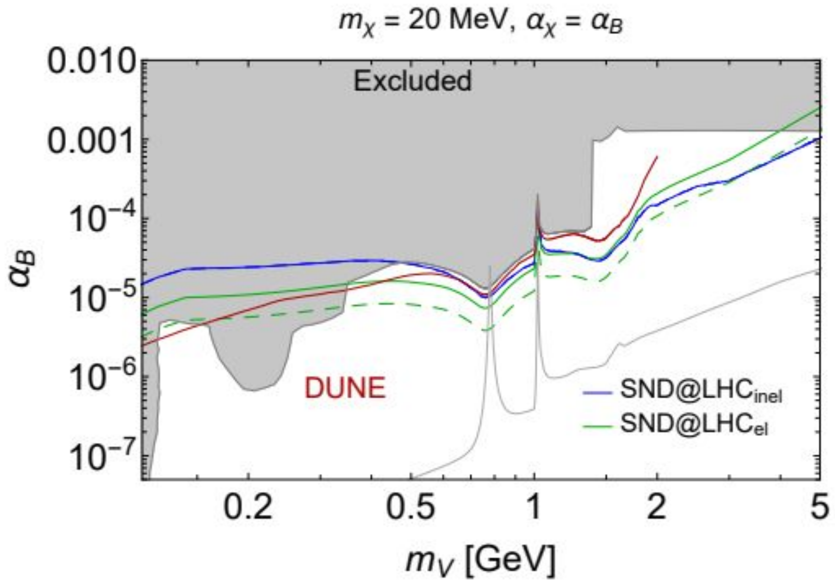
BSM physics - scattering

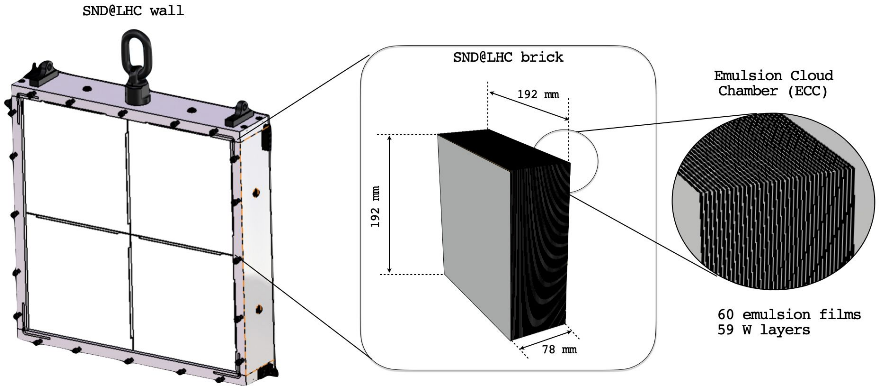
- Dense target also suited to search for feebly interacting particles
- E.g. search for light dark matter (< 1 GeV)
  - Other direct detection experiments sensitive lo large masses
  - Complementary to missing energy technique
- Several models and signatures
  - Elastic or inelastic scattering off nucleons
  - Elastic scattering off electrons
  - Time-of-flight techniques (sensitive to larger masses)

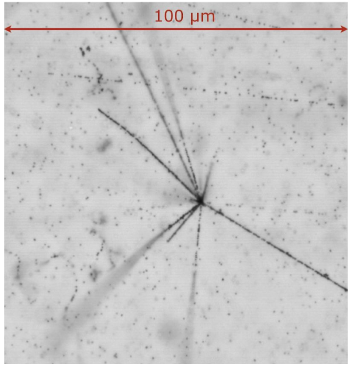


JHEP03(2022)006

Emulsion cloud chambers

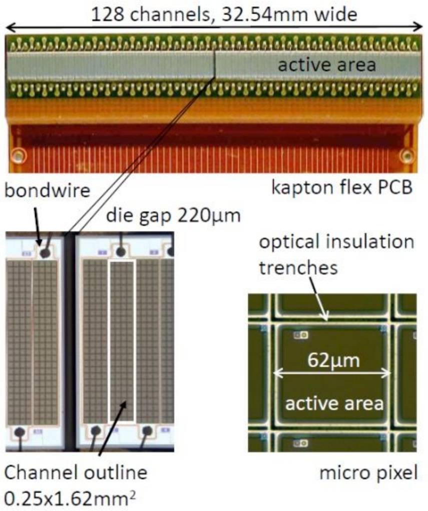
- 5 walls interleaved with SciFi modules
  - 1 wall: 60 alternating layers of tungsten sheets (1 mm) and emulsion films (0.3 mm)
- Micrometric spatial resolution but no timestamp
- Vertex detector, ecal (40 X_0 per wall)
  - Allow to identify tau neutrinos
- Exposed for ~25 fb^{-1}, then developed and scanned

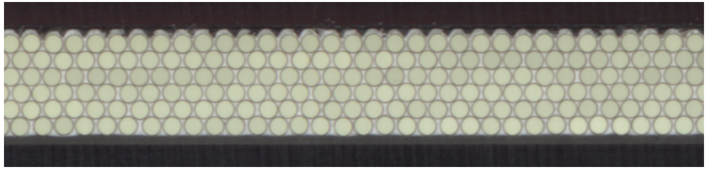




Target tracker

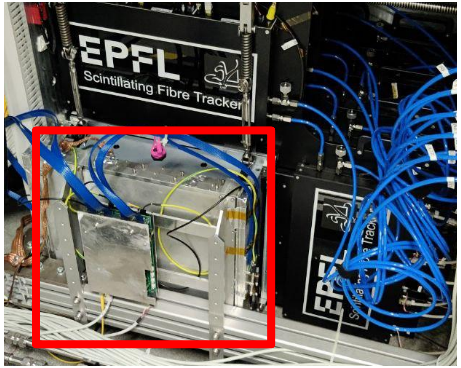
- Based on LHCb SciFi technology
- Scintillating fibre mats read out by SiPMs
  - 39x39 cm^2 active area
- < 100 um spatial resolution
- ~350 ps time resolution
- Locate neutrino interactions in emulsions and assign timestamp
- First energy measurement (refined after emulsions development)

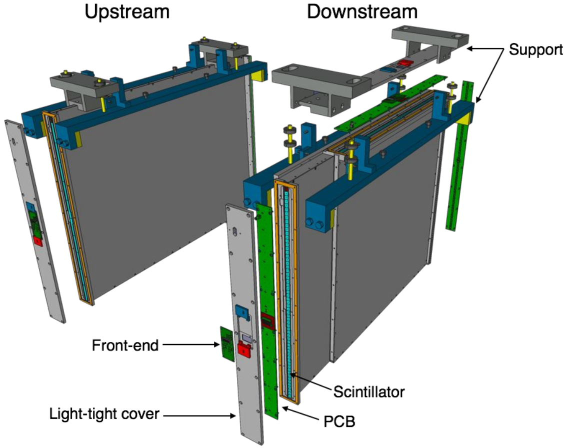




Veto and HCAL-muon system

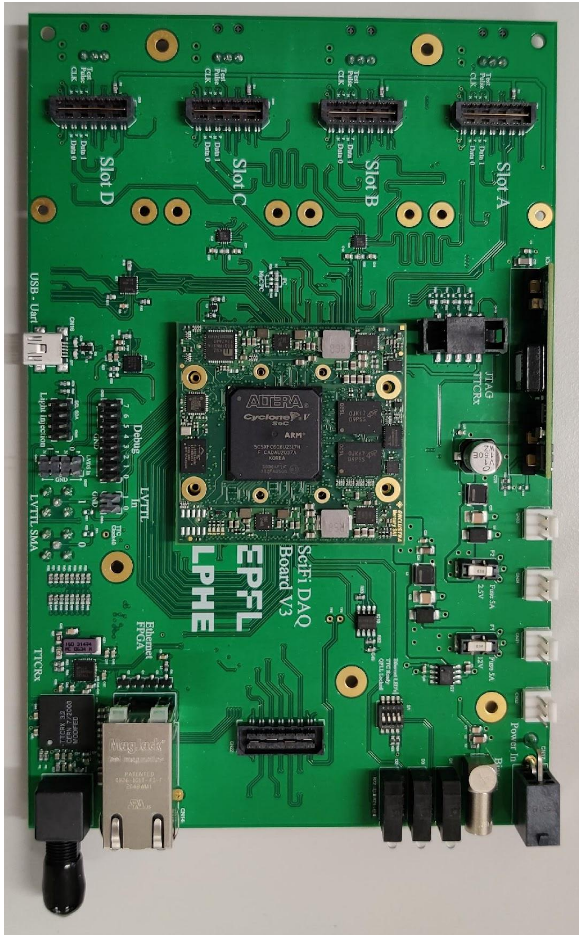
- Scintillator bar of different sizes
- Veto 42x42 cm^2
  - Optimized for particle detection efficiency
- Upstream HCAL 80x60 cm^2
  - Optimized for energy measurement
- Downstream muon 80x60 cm^2
  - Optimized for muon isolation and detection efficiency





The DAQ boards

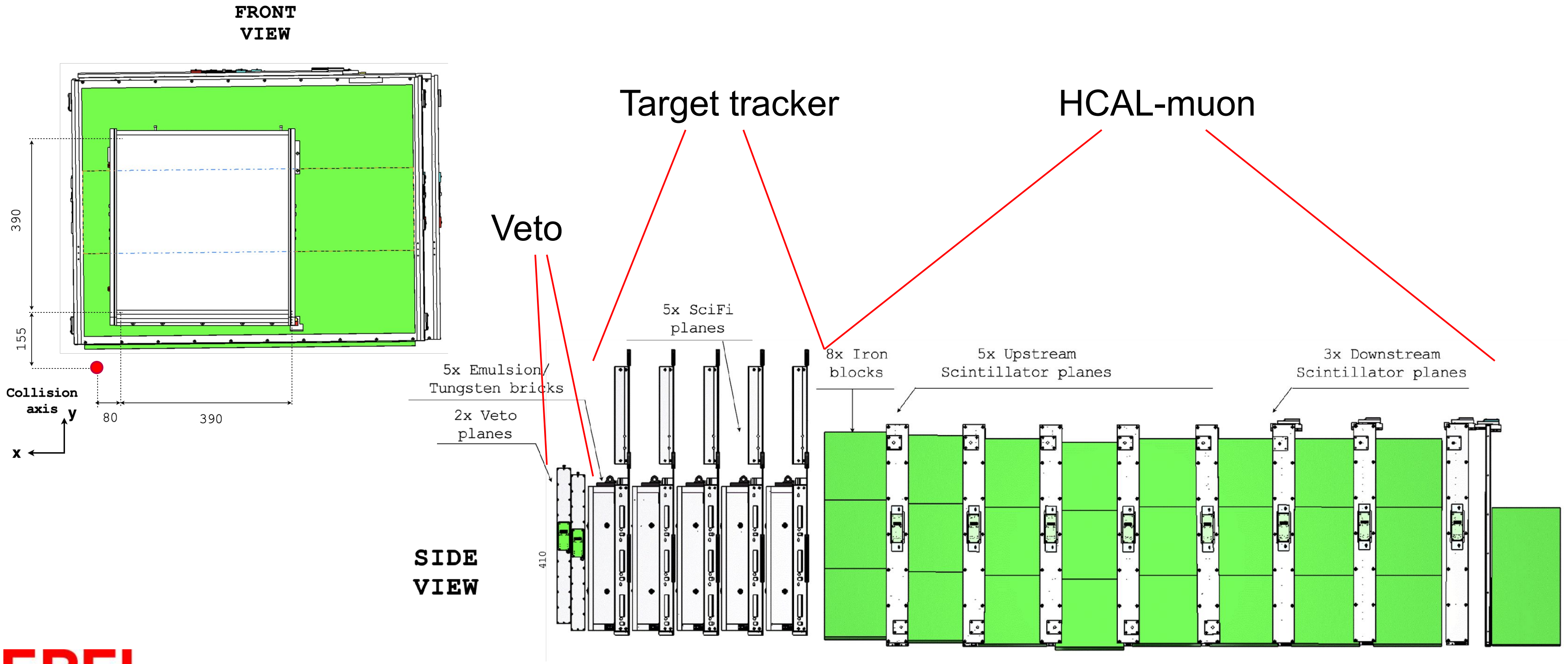
- Same DAQ board for all subsystems
- Developed at EPFL, based on Cyclone V processor+FPGA
  - Clock from TTC system, using TTCrx chip
  - Data transmitted over Ethernet to the server
- 4 front-end board slots
  - 512 channels in total



The front-end boards

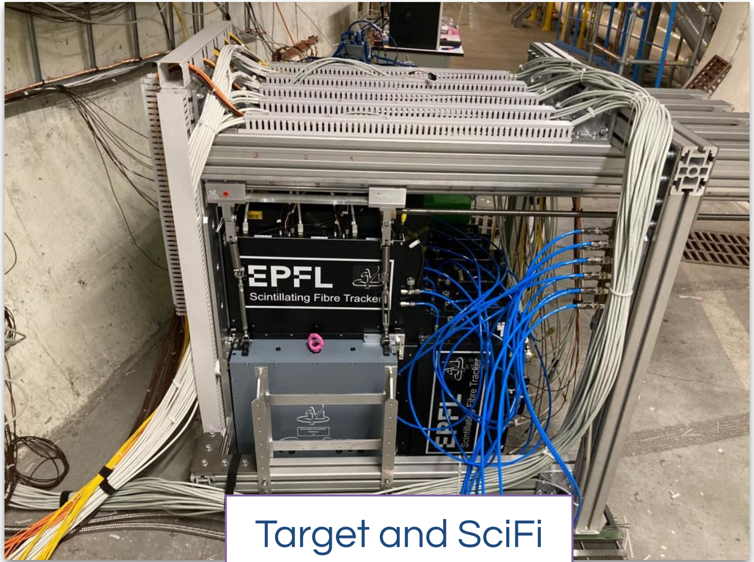
- Each board contains 2 TOFPET2 chips
  - Analogue front-end and ADCs
  - Data fully digitized
  - 128 channels in total
- Allows for low signal thresholds (0.5 pe)
  - 3-threshold system for best time and amplitude resolution and dark noise reduction
- Good timing (40 ps resolution) and amplitude measurement with charge integration or time-over-threshold

Detector


FRONT
VIEW
390
155
Collision
axis
y
x
80
390
Target tracker
HCAL-muon
Veto
5x SciFi
planes
8x Iron
blocks
5x Upstream
Scintillator planes
3x Downstream
Scintillator planes
5x Emulsion/
Tungsten bricks
2x Veto
planes
410
SIDE
VIEW

Detector installation in TI18

Target wall



Target and SciFi

Veto system

Muon system

ν_μ CC-like candidate event in Run 3 data

2022 Aug 11th