Scattering and Neutrino Detector at the LHC

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on behalf of the SND@LHC collaboration

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LHC
Scattering and Neutrino Detector at the LHC

HUMBOLDT-UNIVERSITÄT ZU BERLIN

DFG Deutsche Forschungsgemeinschaft

Neutrinos at the LHC

LHC neutrino experiments discussed since 80s/90s

Large neutrino flux in the forward region

Unexplored region of neutrino energy: [10^2 GeV, 10^3 GeV]

$\sigma_\nu \propto E_\nu$

SND@LHC designed to observe neutrinos of all flavour

OPEN ACCESS

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **46** (2019) 115008 (19pp) https://doi.org/10.1088/1361-6471/ab3f7c

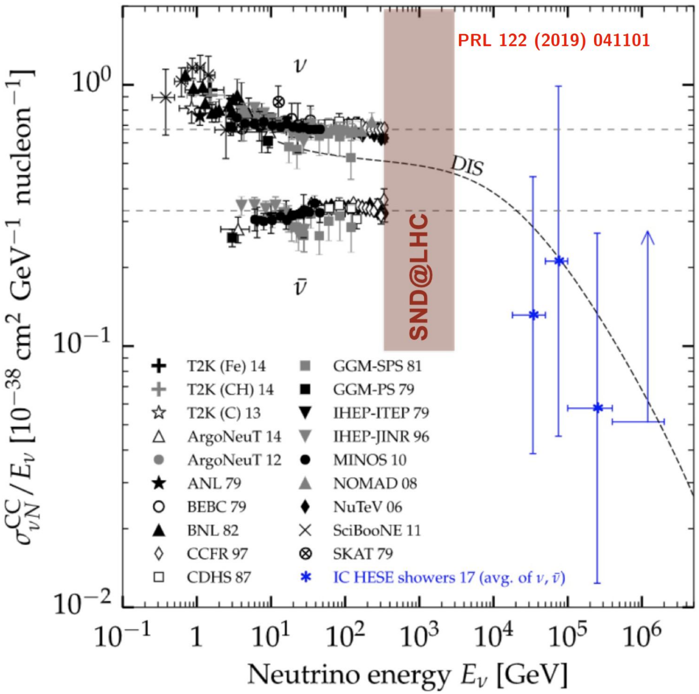
Physics potential of an experiment using LHC neutrinos

OPEN ACCESS

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **47** (2020) 125004 (18pp) https://doi.org/10.1088/1361-6471/aba7ad

Further studies on the physics potential of an experiment using LHC neutrinos



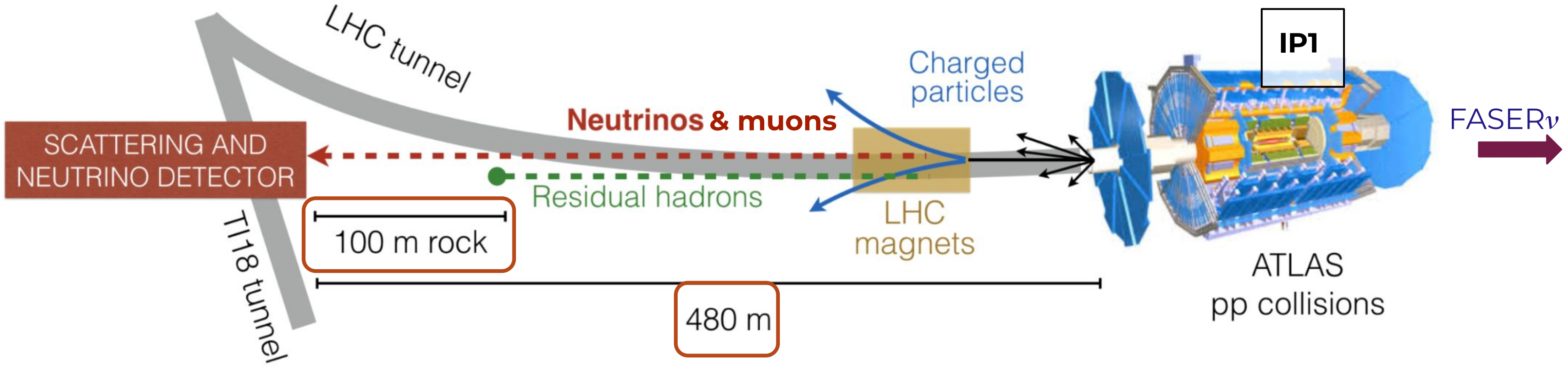
SND@LHC experiment

Experiment location

- Rapidity range 7.2 < η < 8.4 complementary to FASERν experiment
- Re-using LEP transfer tunnel, TI18
- 480m from ATLAS interaction point, IP1

Experimental aims

1. Measure neutrinos of all three flavours
2. Probe charm production using ν_e measurements (next slide)
3. Searching for feebly interacting particles (FIPs)

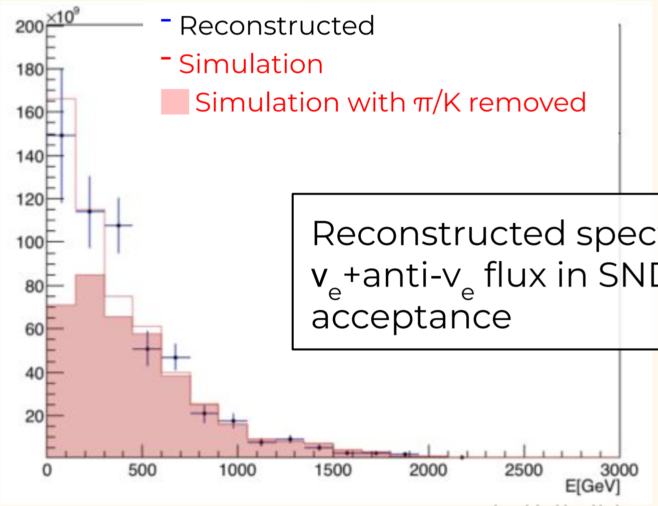


LHC run 3 physics programme: **heavy flavour**

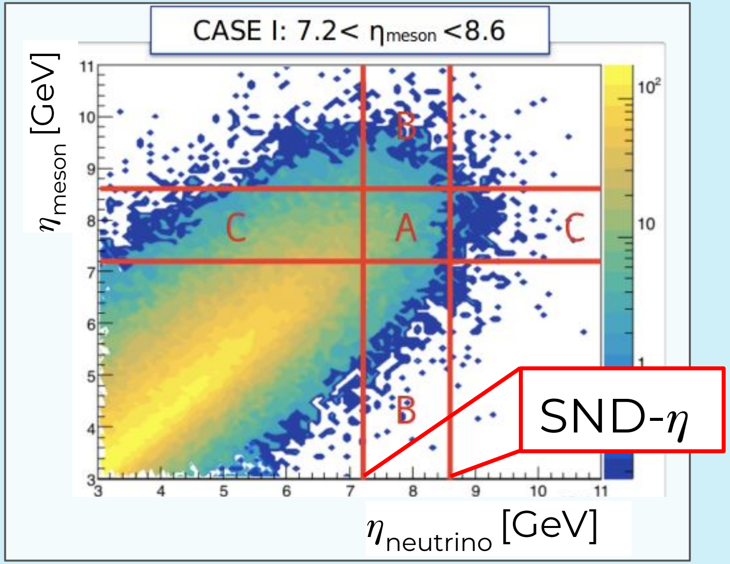
90% (ν_e + anti-ν_e) at SND@LHC come from charmed hadron decays:

1. Measure pp → ν_eX cross section
2. Use as a forward charm production probe
3. Constrain gluon PDFs at low Bjorken-x (< 10^{-6}) (back-up). Inform high energy collider design, neutrino astrophysics

LHCC-P-016



Reconstructed spectrum of ν_e+anti-ν_e flux in SND@LHC acceptance

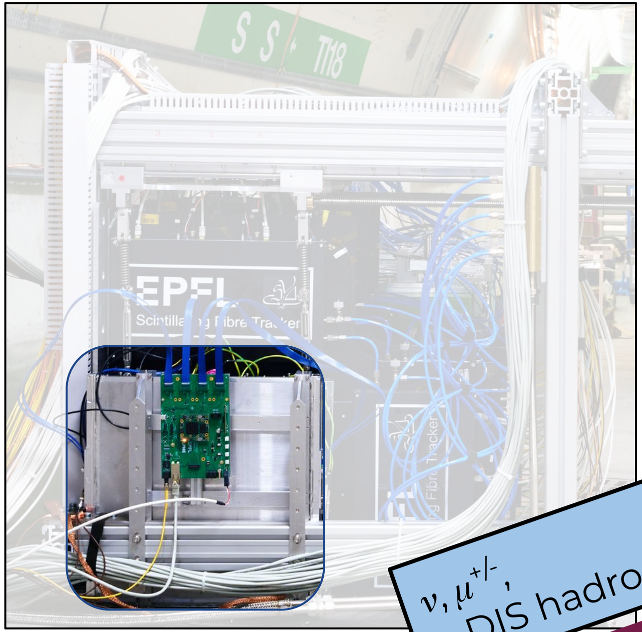


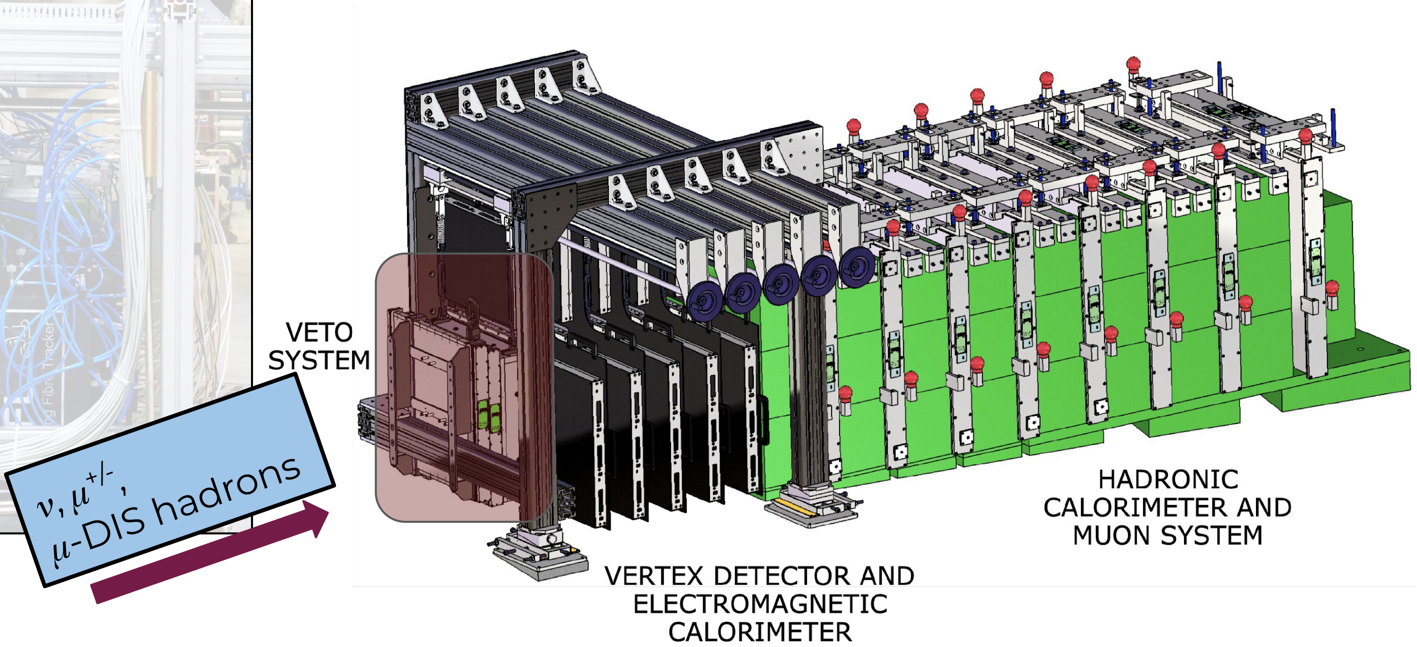
Correlation between pseudo-rapidity of the (ν_e+anti-ν_e) and the parent charmed hadron

Veto system

Goal: veto incident charged particles

2 planes of stacked plastic scintillators read out by silicon photomultipliers (SiPMs)





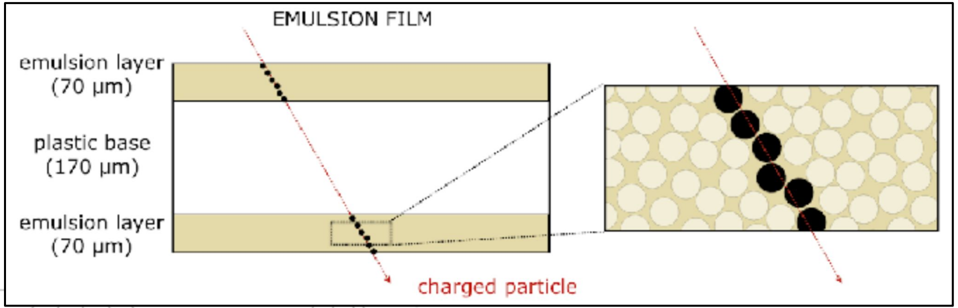
Neutrino target and vertex detector

Goal: measure neutrino interaction points

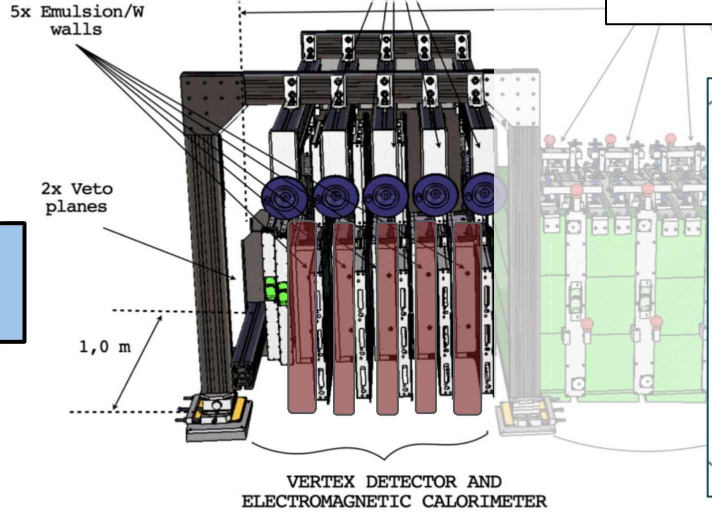
5 emulsion walls. Each wall interleaves nuclear emulsion and Tungsten

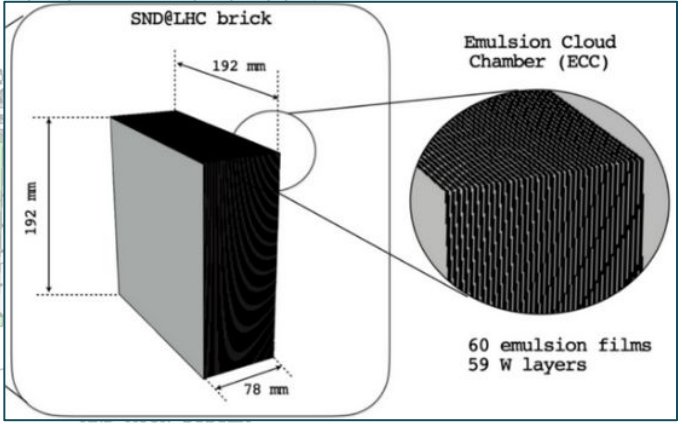
Sub-micron spatial resolution + granularity → τ vertices (kink topology)

Target mass ca. 830 kg, ~40 X_0



ν, $\mu^{+/-}$,
μ-DIS hadrons

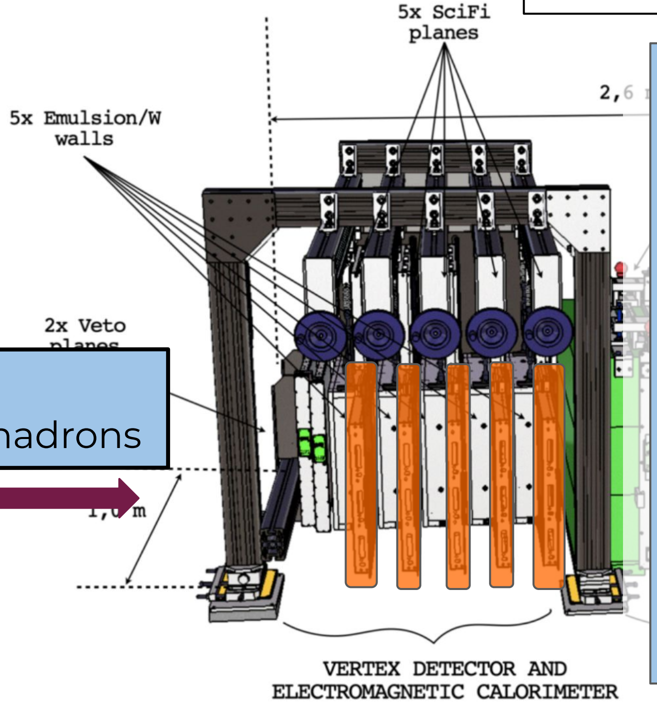




Target tracker and electromagnetic calorimeter (ECAL)

Goals: timestamp emulsion events, EM energy and shower profile reconstruction

5 planes of xy sensitive scintillating fibre mats



ν, $\mu^{+/-}$,
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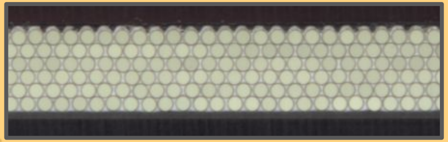
Single Scifi station



6 staggered fibre layers coupled to SiPMs

Hadronic calorimeter and muon system

Planes of stacked plastic scintillators read out by SiPMs.

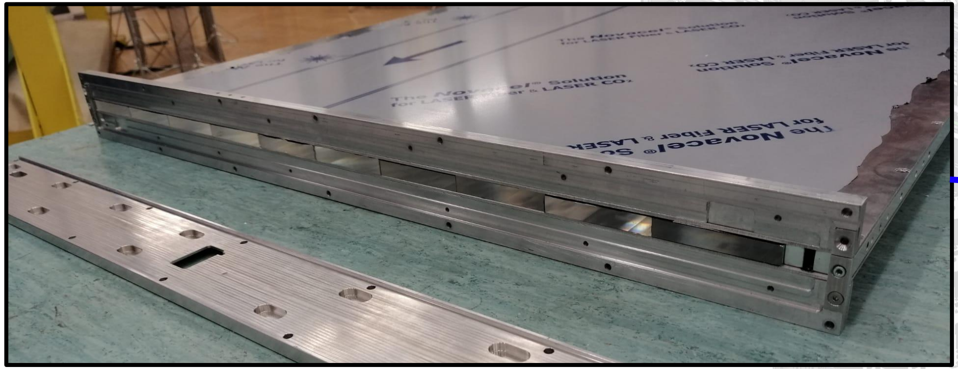
Interleaved with iron walls (green) ~8.5λ

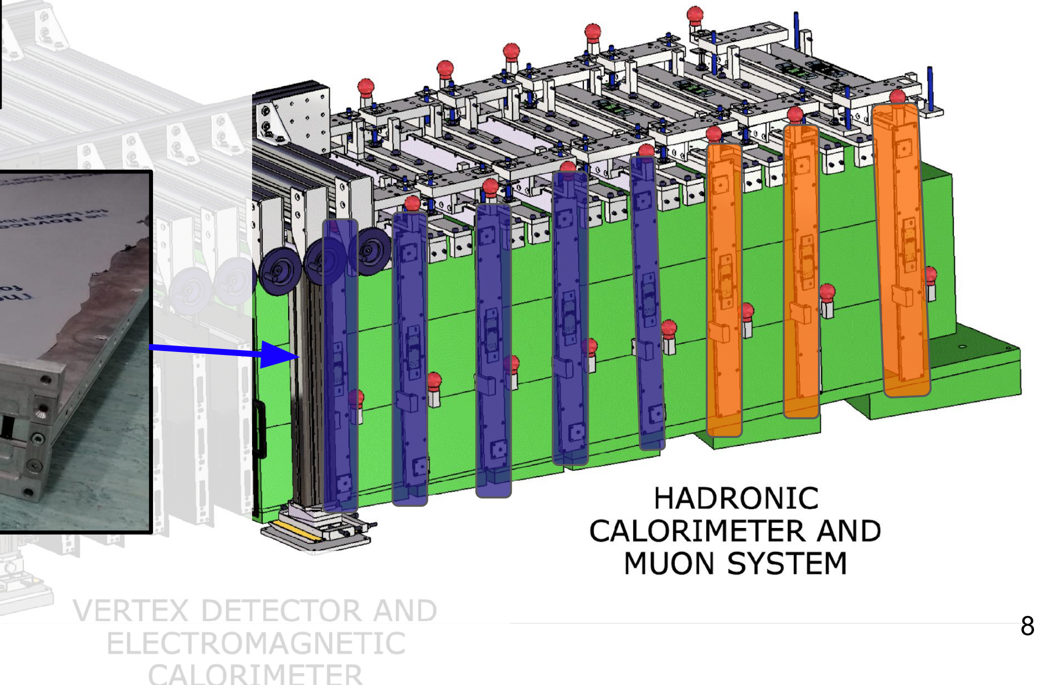
Higher granularity downstream stations used for muon tracking

Goals:

First 5 planes for hadronic energy measurement

Last 4 planes for identifying outgoing muon

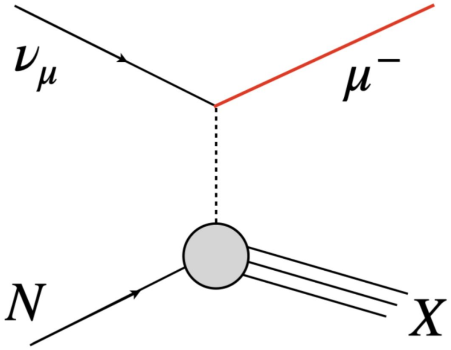


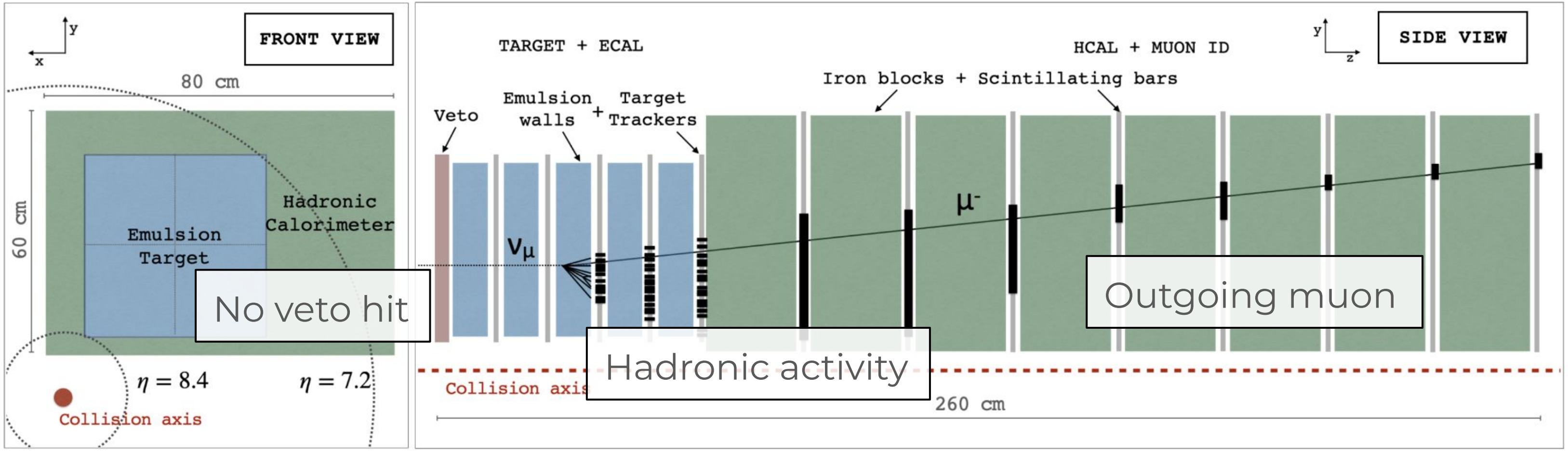


Observation of collider muon neutrinos with the SND@LHC experiment

Using electronic detectors, high purity muon neutrino charged current (CC) deep inelastic scattering (DIS) interaction sample.

36.8 fb^{-1} of 13 TeV LHC data (2022)
Dominant background: neutral hadron production in rock
Estimated 0.086 background events
8 ν_μ candidates observed with a 6.8 σ significance





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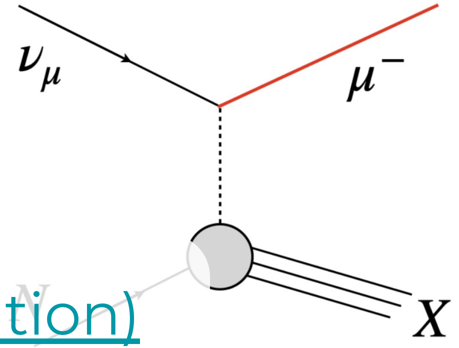

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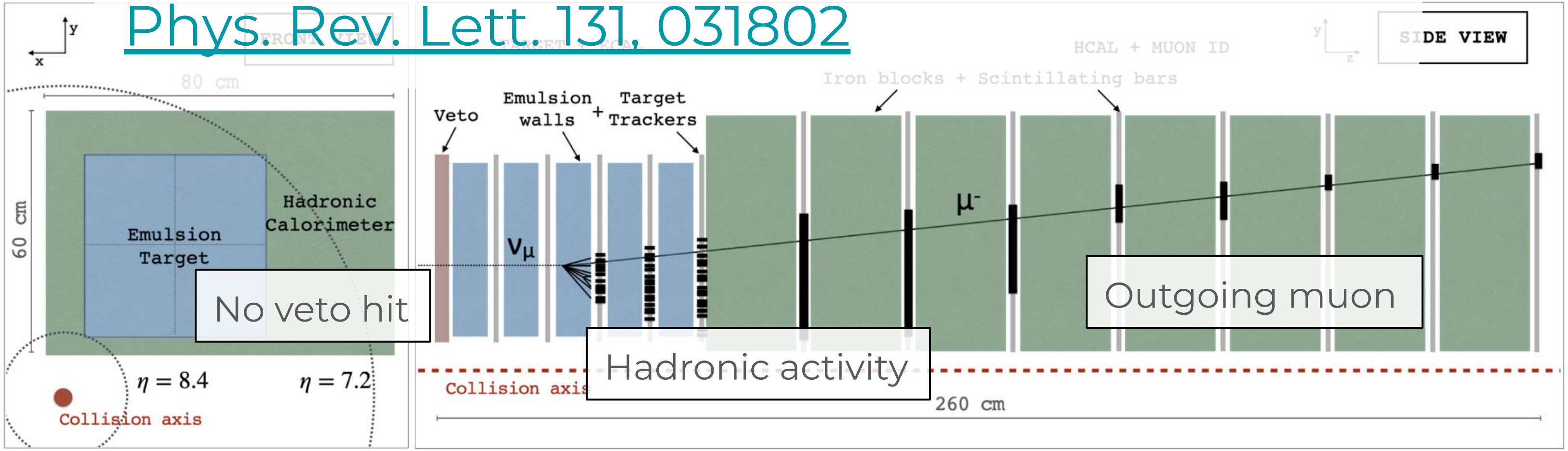
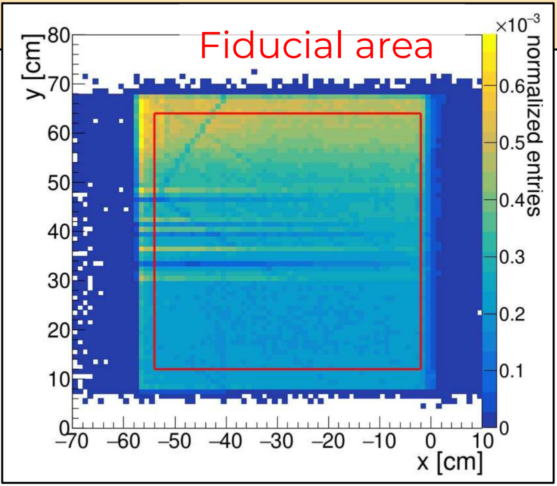
[R. Albanese *et al.* (SND@LHC Collaboration) Phys. Rev. Lett. 131, 031802]



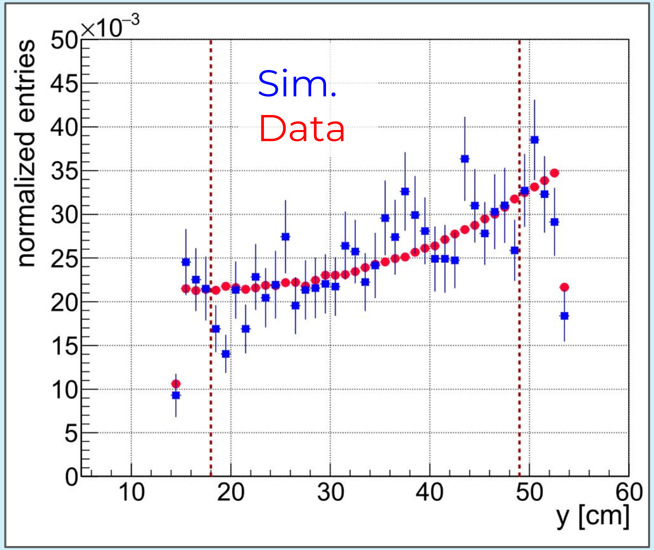
Muon flux measurement

- IP1 muons: dominant event source and background in ν-searches:
  a. No veto → generate showers via bremsstrahlung / muon DIS
  b. Neutral hadrons production in material around SND
- Muon flux evaluated with Scifi tracker, muon system and an emulsion brick
  a. First analysis of SND emulsion: agreement with Scifi



Albanese, R. *et al.* (SND@LHC collaboration) Measurement of the muon flux at the SND@LHC experiment. *Eur. Phys. J. C* 84, 90 (2024)

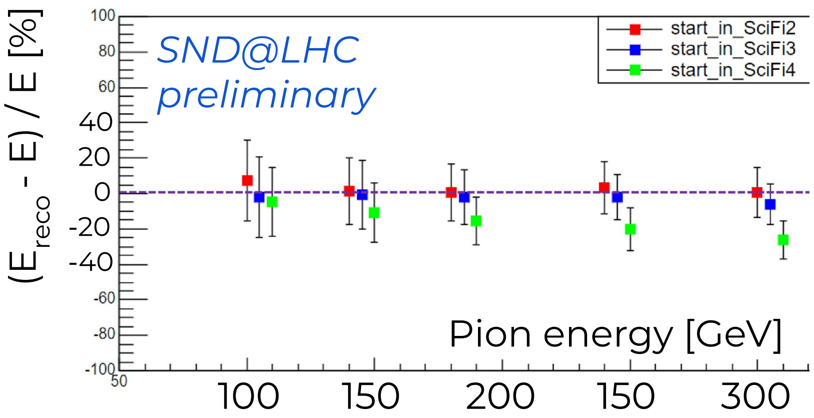
Normalised muon flux in Scifi tracker as a function of height.
Gradient in height reproduced in data

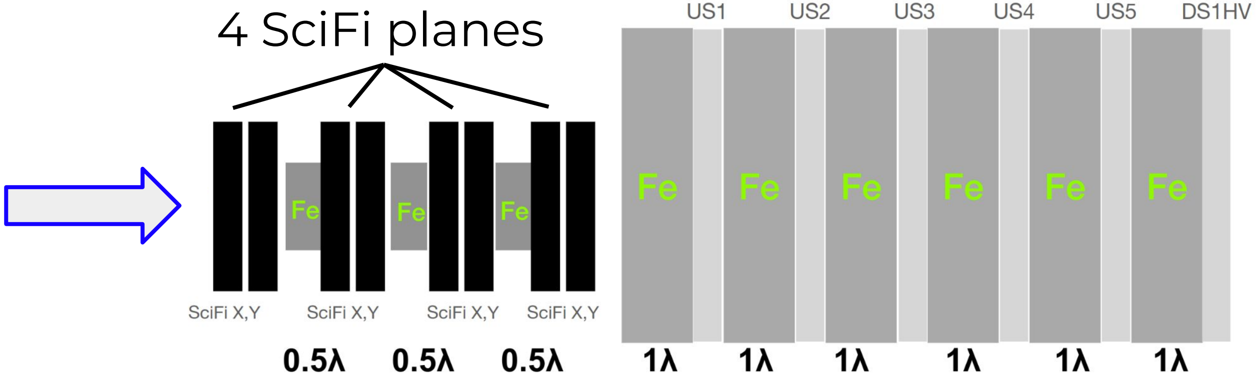


Hadronic energy reconstruction

2023 CERN SPS testbeam, **100 - 300 GeV $\pi^{+/-}$**

1. **Tag shower origin** of the π interaction using SciFi planes
2. Use SiPMs of target tracker planes + HCAL to **reconstruct deposited energy**
3. Perform calibration **to be applied to TI18 detector**

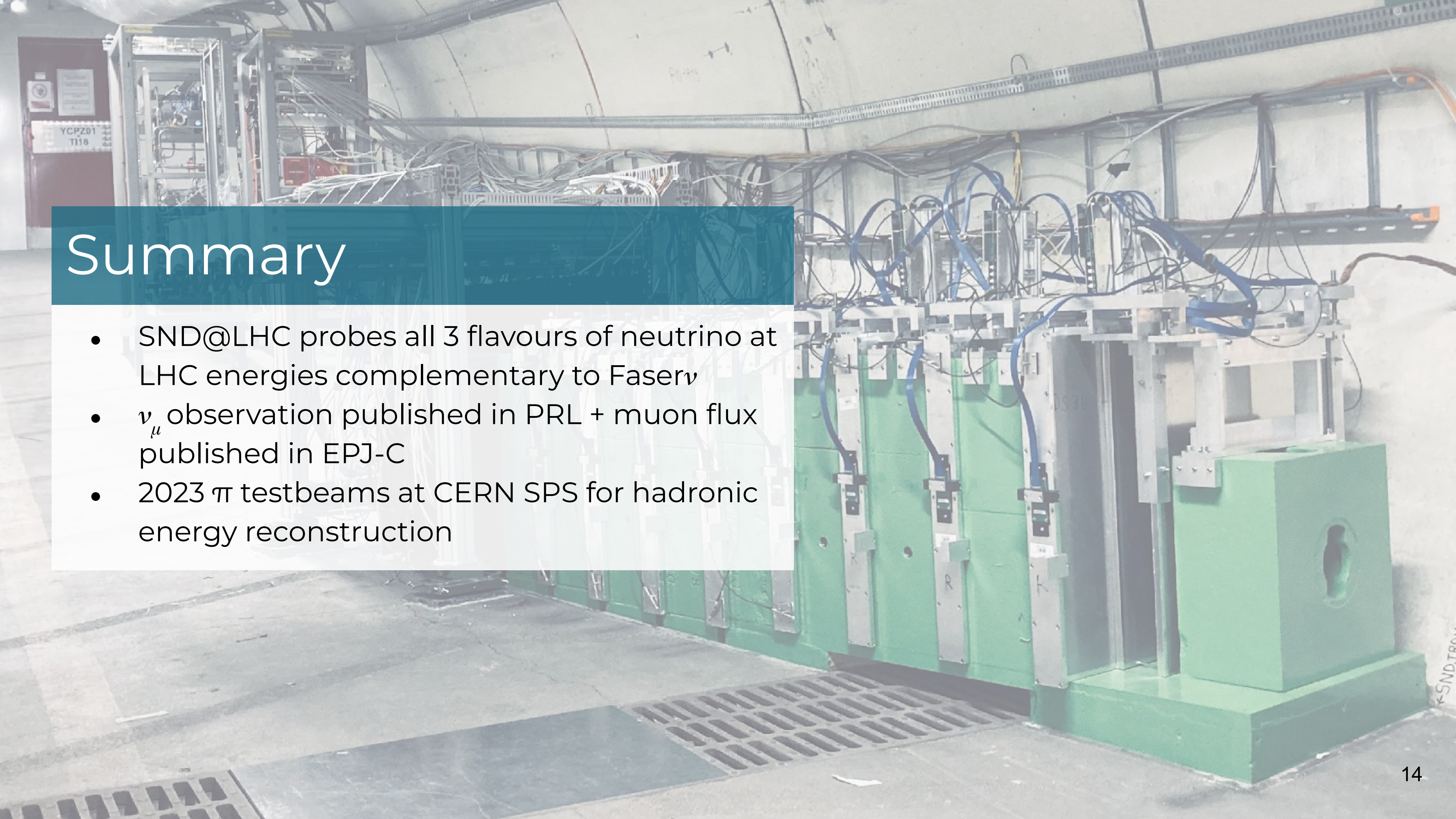




2024 plans

- Additional plane for veto system installed:

  reduced veto inefficiency → stronger neutrino signal observation significance
- Observation of charged current ν_e - DIS interactions
- ν_e / neutral hadron separation with ML methods
- Emulsion track matching to target tracker - timestamp emulsion data
- SND@LHC HL-LHC upgrade R&D (see backup for AdvSND outline)



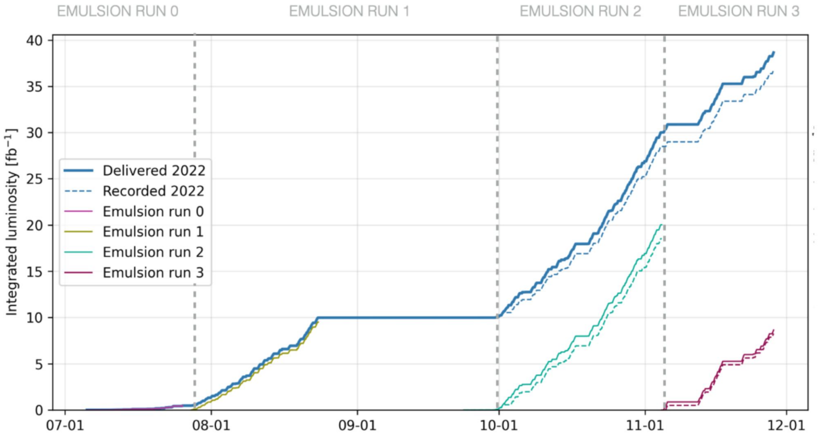
Summary

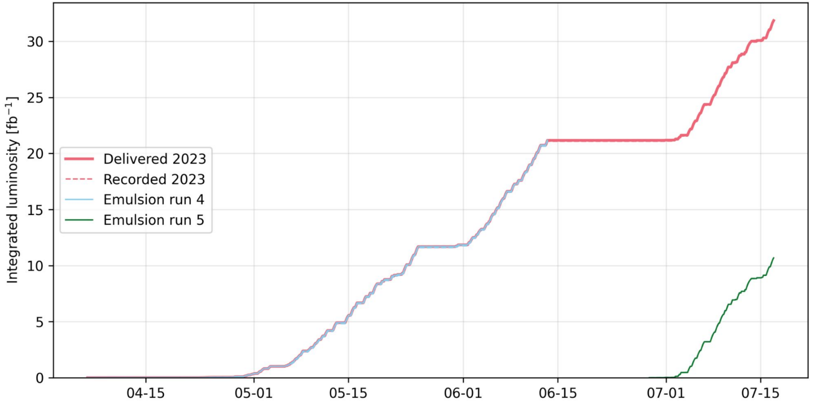
- SND@LHC probes all 3 flavours of neutrino at LHC energies complementary to Faserν
- ν_μ observation published in PRL + muon flux published in EPJ-C
- 2023 π testbeams at CERN SPS for hadronic energy reconstruction

Back up

pp collision data in 2022 and 2023

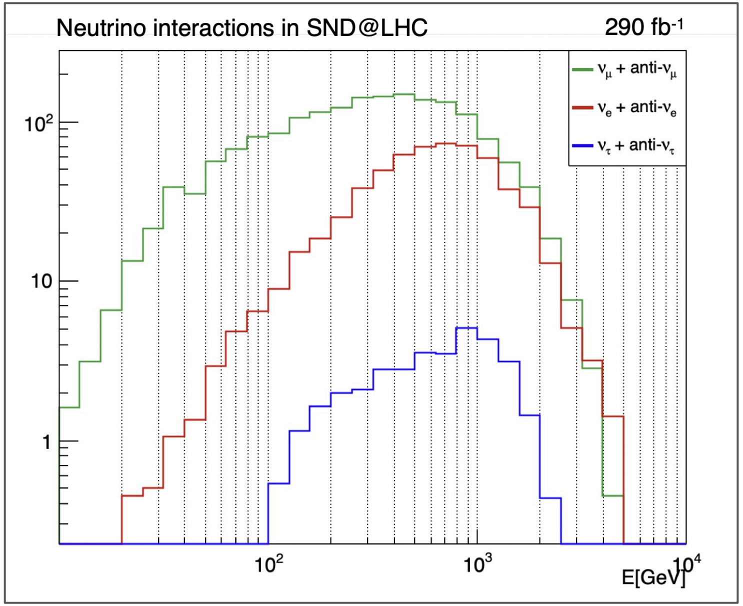
- ~95% detector uptime in 2022
- 36.8 fb^{-1} collected in 2022
- ~30 fb^{-1} collected in 2023





Neutrino expectations in LHC run 3

- Simulations for 290 fb^{-1}
- Upward/downward crossing angle: 0.43/0.57
- Neutrino production in LHC pp collisions performed with **DPMJET3** embedded in FLUKA
- Particle propagation towards the detector through **FLUKA** model of LHC accelerator



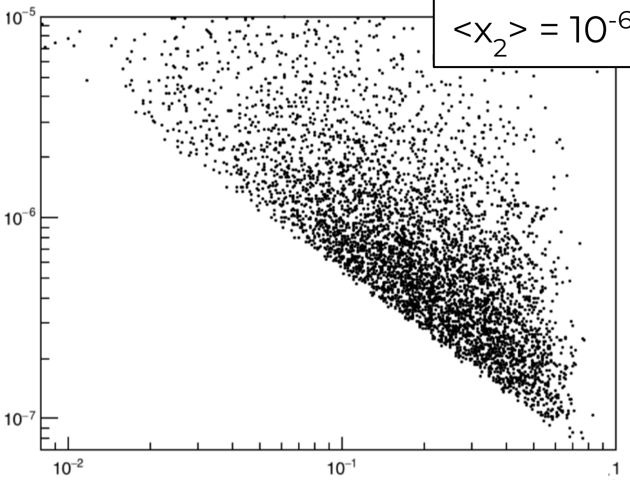
Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Yield	CC neutrino interactions ⟨E⟩ [GeV]	Yield	NC neutrino interactions ⟨E⟩ [GeV]	Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157
ν_e	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58
ν_τ	400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

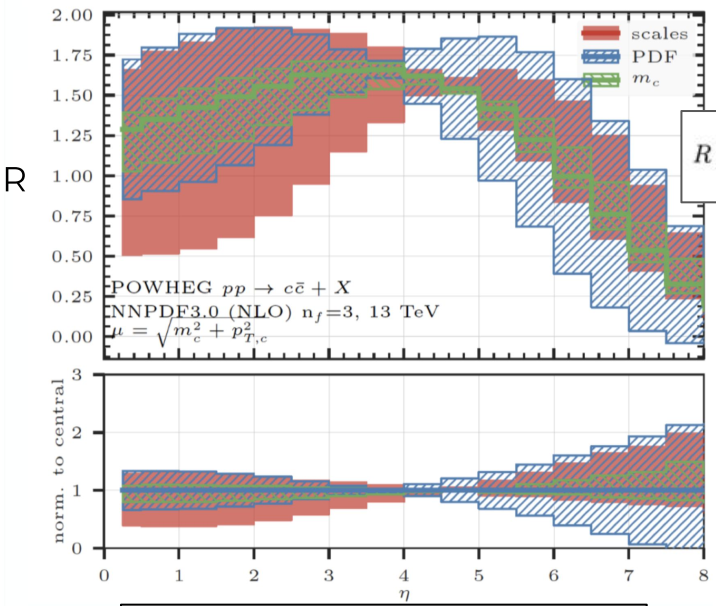
QCD measurements - gluon PDF at low x ($\leq 10^{-6}$)

LHC dominant partonic process for associated charm production at the LHC is gluon-gluon scattering

Extraction of gluon PDF in very small x-region: future circular colliders & neutrino astrophysics

Correlation between x_1 and x_2 for events in the SND@LHC acceptance





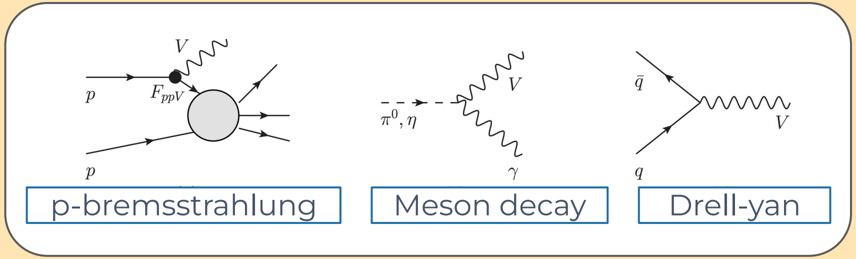
$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

$\eta_{ref} = 4.5$

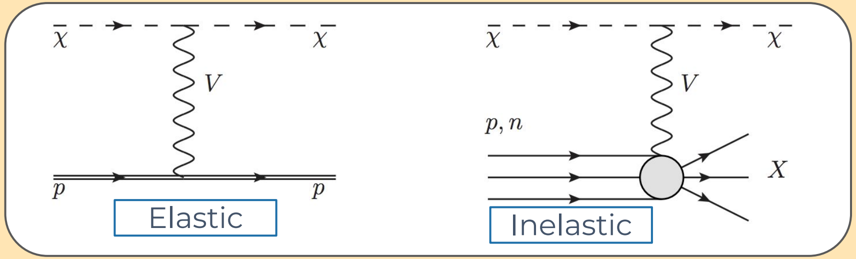
Reduction of scale uncertainties
Constraint the PDF with data

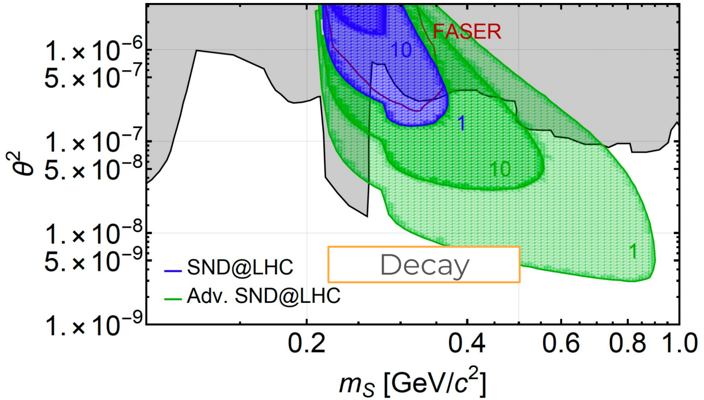
Feebly interacting particles (FIPs)

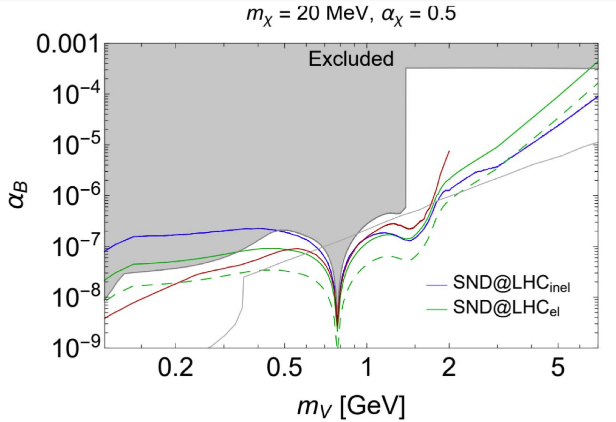
Decaying in the detector : dark scalars, heavy neutral leptons or dark photons decaying into a pair of charged tracks.



Scattering in the detector. E.g., scalars interacting with nucleons via a leptophobic portal.



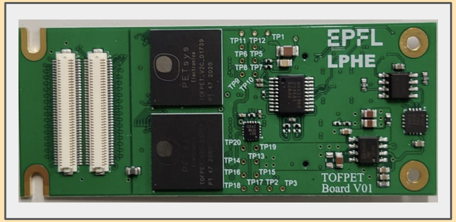


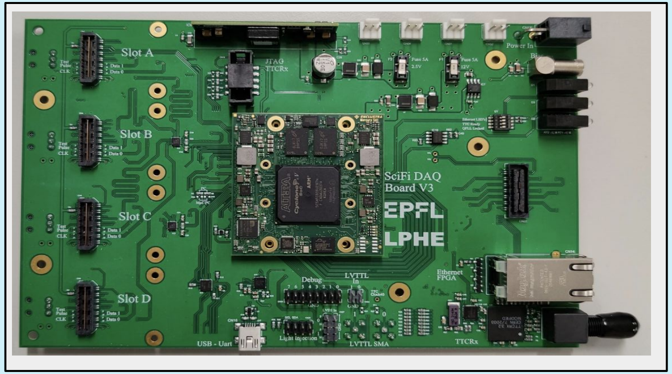


J. High Energ. Phys. 2022, 6 (2022)

Data acquisition

- TOFPET2 ASIC front end board
- Low signal threshold: 0.5 p.e
- Intrinsic time resolution of 40 ps





- DAQ boards using Cyclone V FPGA
- Timing synchronous with LHC clock @ 160 MHz
- LHC timing, trigger and control system (TTC) handled via optical fibre
- Handle input from 4 TOFPET2 ASICs, 512 channels
- All electronic signals above threshold sent to DAQ server

- DAQ server runs timestamp based event builder
- Implements 2-stage noise filter
- Events saved to disk in root format

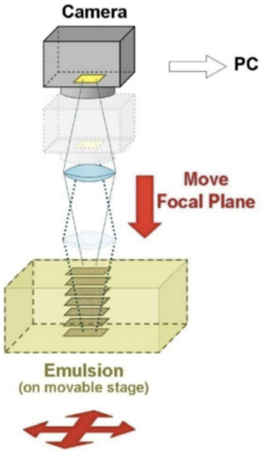
Emulsion logistics and processing

Emulsion replaced every < 20 fb^{-1} keeps occupancy manageable

Replacement possible during LHC short accesses

5 microscopes around Europe and Russia working in parallel

Distributed data processing in progress



(a) (b) (c)

ν_μ observation, simulation

FLUKA Monte Carlo: neutrino production in pp collisions

DPMJET3: pp event generation

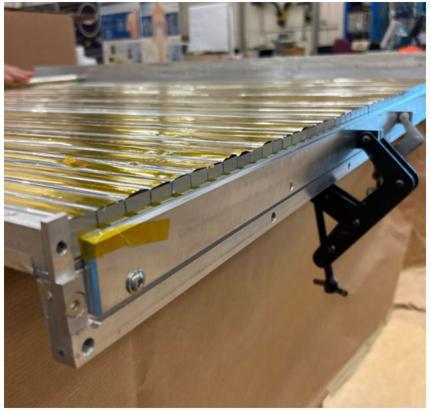
FLUKA propagates the particles towards SND@LHC

157 +/- 37 interactions expected. Uncertainty given by difference between using DPMJET3 and SIBYLL to predict the ν_μ flux at SND@LHC

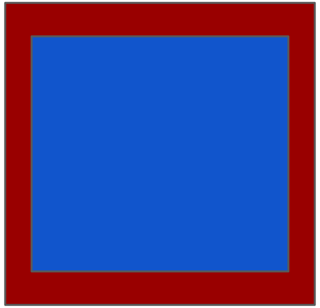
ν_μ observation, selection cuts

Fiducial volume cut: reduce background from side-entering neutral hadrons

First 2 SciFi planes are added as a veto to reduce the impact of muon induced backgrounds



Exposed scintillators of a DS plane



Reduced fiducial area in *xy*

TABLE I. Number of events passing the selection cuts in the data and signal simulation.

	Data	Signal simulation
All	8.4×10^9	157
Fiducial volume	4.9×10^5	11.9
One muonlike track	17	6.1
Large SciFi activity	13	5.1
Large hadronic activity	12	4.7
Low muon system activity	8	4.2

ν_μ observation, background estimation

- Inefficiency of our charged particle veto dominated by deadspace between stacked scintillators.
- 1st + 2nd SciFi included in veto
- Jan 2024: installation of a third veto plane

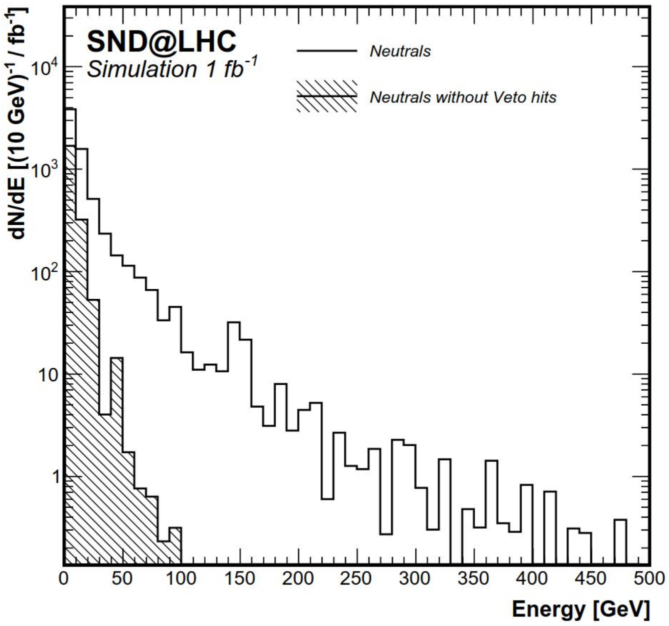
Background yield after all cuts: 8.6 +/- 3.8 x10^{-2}, dominated by K_L^0s. 44% uncertainty from three sources:

1. Difference in the muon flux between the simulated and measured muons, 22%
2. Hadron interaction model differences*, 31%
3. Available statistics in the simulations, 21%

*models are QGSP_BERT_HP_PEN and FTFP_BERT

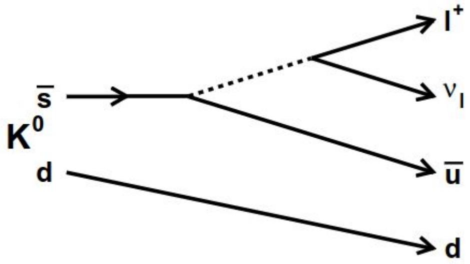
Backgrounds & inefficiencies

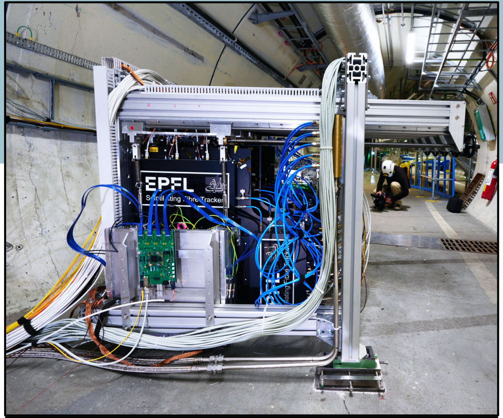
Neutral hadrons from muon-rock interactions



Inefficiency of our charged particle veto dominated by deadspace between stacked scintillators.

Feb 2024: installation of a third veto plane





Veto inefficiency

Muon interaction in rock can produce neutral kaons or neutrons which can mimic a ν_μ interaction.

Left: simulation shows neutral particles without a veto hit are less than 100 GeV.

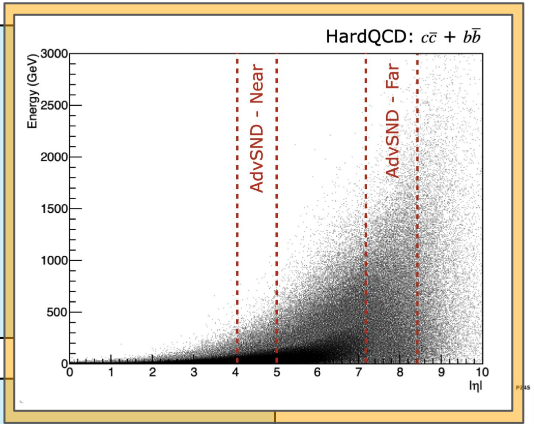
SND@LHC beyond LHC run 3

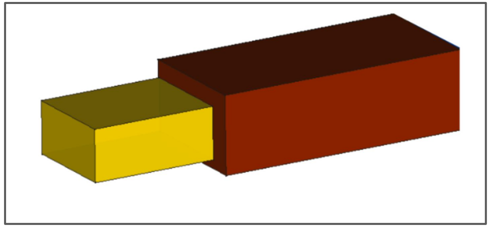
<u>AdvSND-Far (upgrade of existing detector)</u>

Improve statistics

Extend SND@LHC detector principle to HL-LHC

Add B-field for ν / anti-ν distinction





<u>AdvSND-Near (new detector)</u>

Overlap with LHCb η-range where c/b production is measured

Reduce AdvSND-Far systematics