Neutrino studies with SND@LHC

LHCP 2024, Boston USA

LHC

Scattering and Neutrino Detector
at the LHC

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on behalf of the SND@LHC collaboration

KEK

High Energy Accelerator Research Organization

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Motivation

- Measure $pp \rightarrow \nu + X$ cross-section in TeV range
- Studies for potential neutrinos physics at the LHC date back to the 90s
  - Large flux in the forward region
  - Very high neutrino energy ($\sigma_\nu \propto E_\nu$)

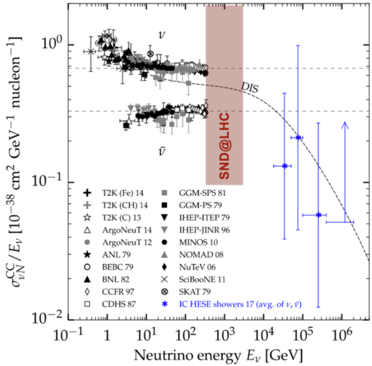
  $\rightarrow$ Can be observed with small-scale LHC experiment
- Two neutrino detectors in operation at LHC's IP1 $\rightarrow$ FASERν and **SND@LHC**

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

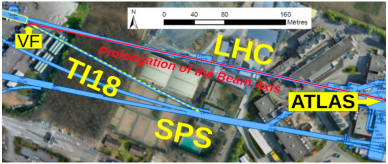
Further studies on the physics potential of an experiment using LHC neutrinos

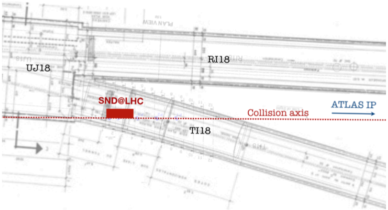


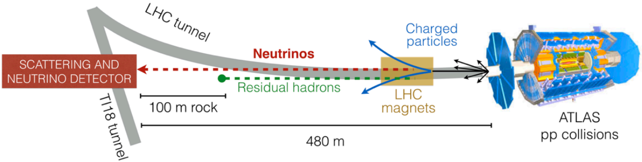
[PRL 122 (2019) 041101]

Detector Location

- Study carried out in 2018 to determine best location for a neutrino experiment
- TI18 determined to be best location for a neutrino detector at the LHC
- 480 m from ATLAS interaction point
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m of rock

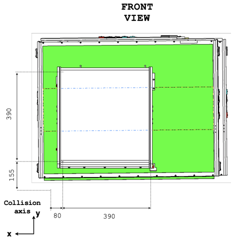


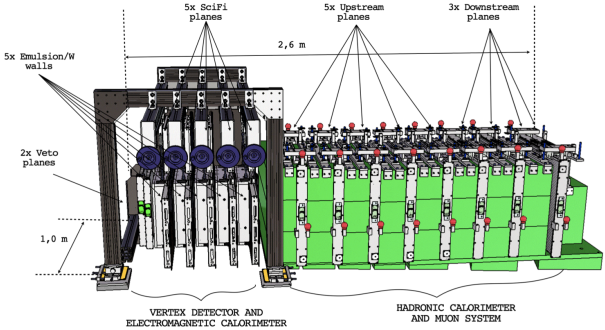




The SND@LHC Detector

- Off-axis location $\rightarrow 7.2 < \eta < 8.4$
- Veto, SciFi Tracker and Muon system
  - select neutrino interactions
  - Identify muons
  - Reconstruct of EM/hadron showers and energy
- Emulsion Cloud Chambers
  - Identify ν interaction vertex and secondary vertices
  - Match event with electronic detectors
  - Complement e.m. energy measurement





[SND@LHC collaboration, JINST 19 P05067 (2024)]

SND@LHC main physics goals

Neutrino Interactions

- Measure production of all three ν species in unexplored TeV range
- First observation of $\bar{\nu}_\tau$

QCD with neutrinos

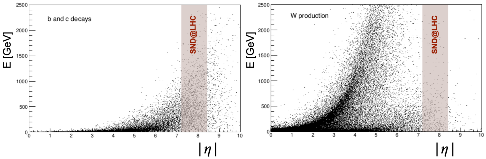
- Decay of charm hadrons contribute significantly to ν flux
  $\rightarrow$ Measure forward charm production
  $\rightarrow$ Constrain gluon PDF at small x

Flavour physics

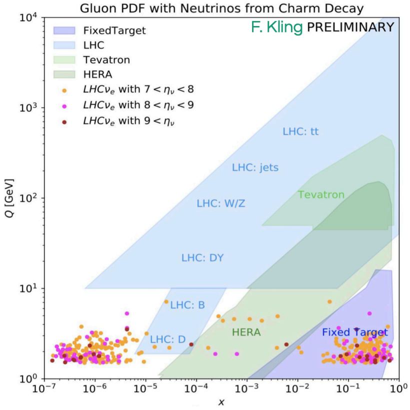
- ν_e/ν_τ, ν_e/ν_μ ratio for LFU test

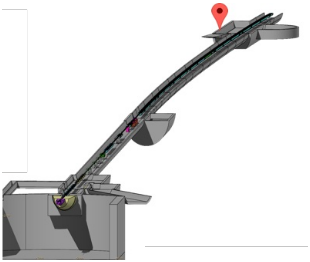
Beyond the Standard Model

- Search for feebly interacting particles



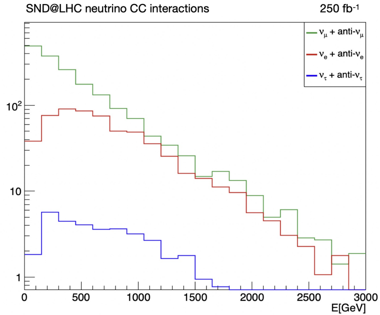
[N Beni et al 2019 J. Phys. G: Nucl. Part. Phys. 46 115008]





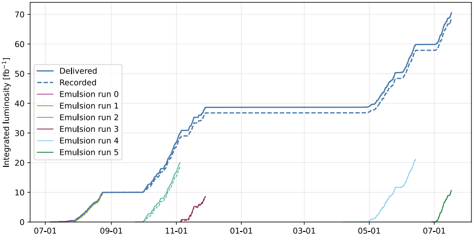
- Model neutrino production in pp collisions with **DPMJET**
- Propagation to SND@LHC with **FLUKA** model of the LHC
- **GENIE** neutrino interaction model
- Neutrino interactions in SND@LHC / 250 fb^{-1}
  - $\nu_\mu + \bar{\nu}_\mu$ charged current: 1270
  - $\nu_e + \bar{\nu}_e$ charged current: 390
  - $\nu_\tau + \bar{\nu}_\tau$ charged current: 30

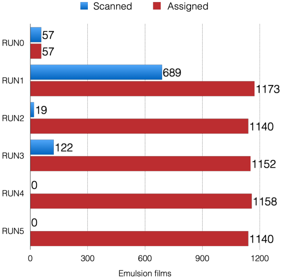
Flavour	Neutrinos in acceptance		CC neutrino interactions		NC neutrino interactions	
	⟨E⟩ [GeV]	Yield	⟨E⟩ [GeV]	Yield	⟨E⟩ [GeV]	Yield
ν_μ	130	3.0×10^{12}	452	910	480	270
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360	480	140
ν_e	339	3.4×10^{11}	760	250	720	80
$\bar{\nu}_e$	363	3.8×10^{11}	680	140	720	50
ν_τ	415	2.4×10^{10}	740	20	740	10
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10	740	5
TOT		4.0×10^{12}		1690		555

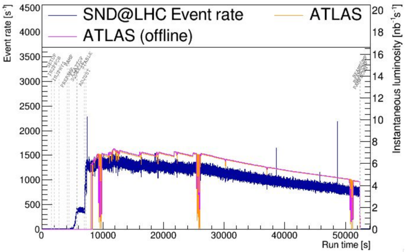


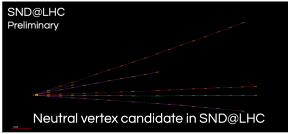
Data taking and integrated luminosity

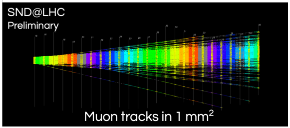
Integrated lumi: Recorded 97.3% of 70.5 fb^{-1} delivered (2022 95%, 2023 99.7%)







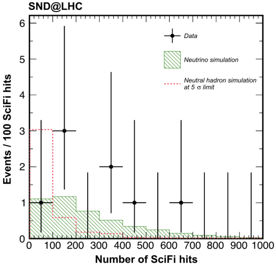




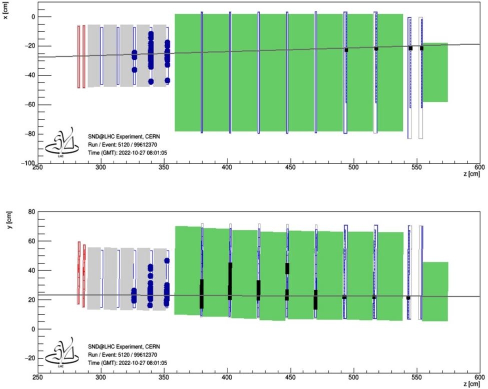
PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment



Oct 27$^{\text{th}}$ 2022

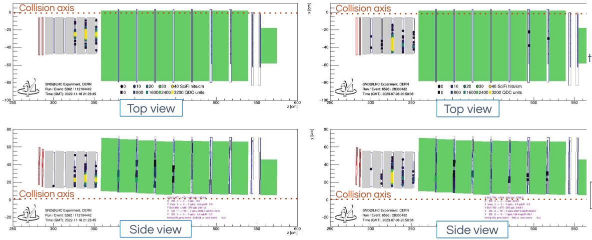


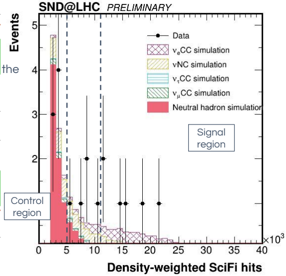
- ν_μ with electronic detectors only
- 2022 data
- 8 events observed events
- 8.6×10^{-2} background
  $\rightarrow 6.8\ \sigma$ significance

$\rightarrow$improved analysis + 2023: 32 events (0.25 bkg) 12 σ significance

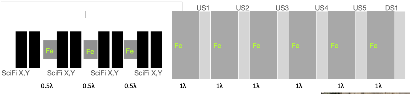
0μ neutrino events

- ν_e CC and ν_τ CC (0μ) + Neutral Current events
- 6 events (0.13 bkg) $\rightarrow$ 5.8 σ significance

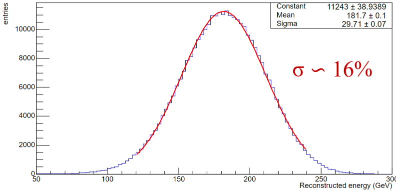


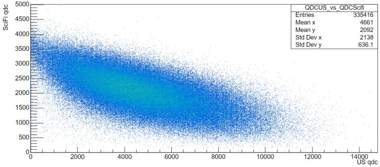


Energy resolution

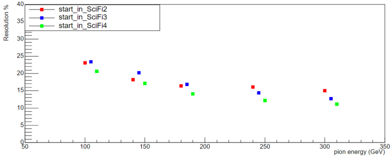


Reconstructed energy for 180 GeV π



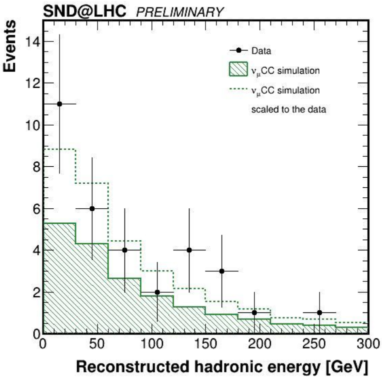


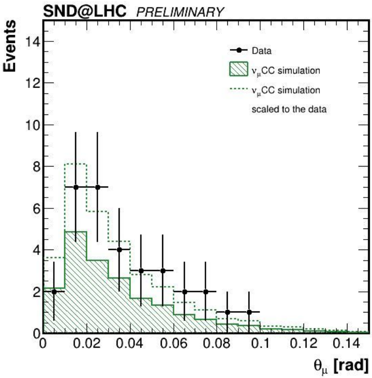
- Energy Calibration at SPS
- pions with 100-300 GeV
- mock target (Fe+Scifi)+ muon (5 US+1 DS)
- Resolution $\sim$ 20%



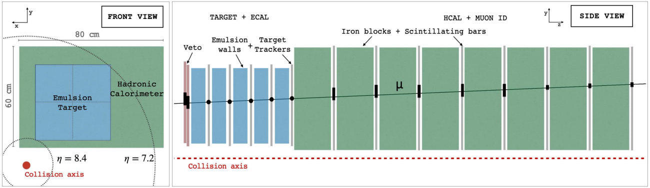
ν_μ energy measurement

- Preliminary reconstruction of the ν_μ energy and μ direction

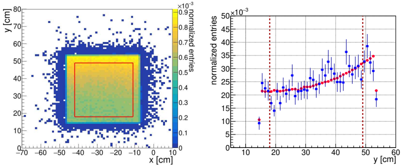




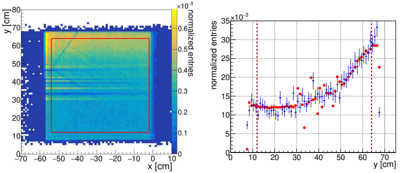
Muon flux in TI18



SciFi



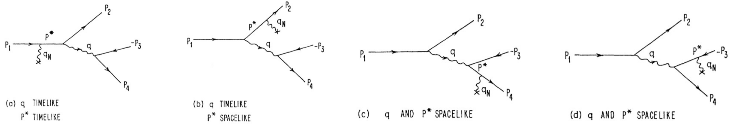
DS Muon



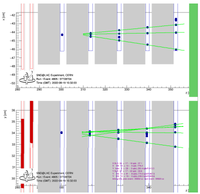
- First measurement of muons at TI18
  - Detector calibration and response
  - MC tuning for muon DIS
- Two independent measurements: SciFi and DS muon system
- Tracking: Hough Transform
- MC generated with FLUKA

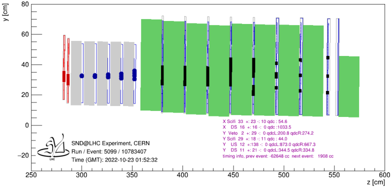
system	muon flux $[10^4\ \text{fb/cm}^2]$ *same fiducial area*
SciFi	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$
DS	$2.02 \pm 0.01(\text{stat.}) \pm 0.08(\text{sys.})$

[R. Albanese et al. (SND@LHC collab.), Eur.Phy.J.C 84,90 (2024)]

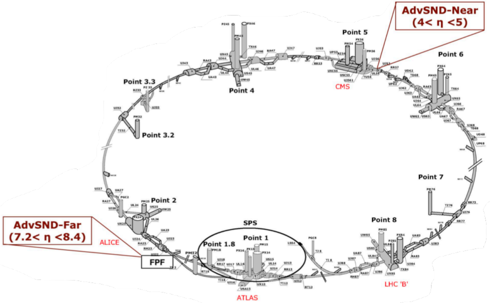


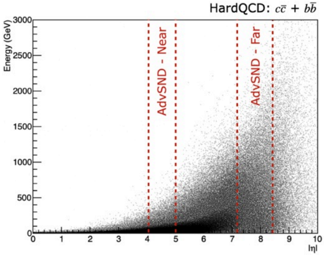
- Trident:
  $\mu^{\pm} + N \to \mu^{+}\mu^{-}\mu^{\pm} + N$
  - Studies in the 60s and 70s
  - Due to identical muons, sensitive to Fermi statistics
- "Background": bremsstrahlung followed by γ-conversion:
  $\mu^{\pm} + N \to \mu^{\pm} + N + \gamma, \gamma + N \to \mu^{-}\mu^{+} + N$
- Both types of events are interesting for SND@LHC
  - For the matching of electronic detectors with emulsion
  - Comparison with GEANT4 predictions (implemented since 2022)
  - Physics measurement, limits for exotic processes producing such a signature

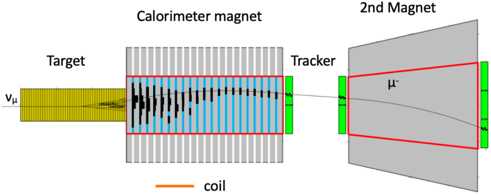




- Plans for SND detector at the HL-LHC
- AdvSND with two off-axis forward detectors
  - Far: $\eta \sim 8$ Reduce systematic uncertainties
  - Near: $\eta \sim 4.5$ link to LHCb measurements & high-energy neutrino physics
- Detector upgrades:
  - Tag muon sign with magnet
  - Replace emulsion vertex detector with electronic technology





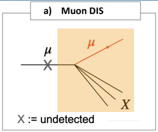


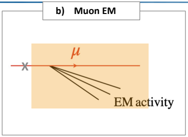
Summary

- The LHC provides a unique possibility to measure neutrino production at the TeV scale
- SND@LHC covers a unique physics program at the LHC to study all 3 neutrino flavors
- Highest energy person-made neutrinos
- Future projects at the HL-LHC are under study

BACKUP

Background evaluation



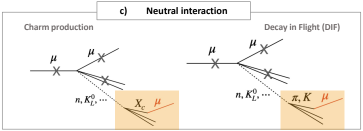


- Muon induced background: undetected muons entering the target (2022 Run3 data)

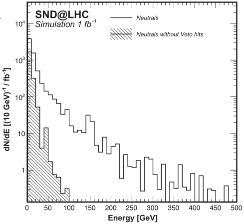
$$N_{bkg} = N_\mu\,(1-\varepsilon_{veto}) \times (1-\varepsilon_{SciFi1}) \times (1-\varepsilon_{SciFi2}) = 5.3\times 10^{-12} N_\mu$$

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

Totally negligible



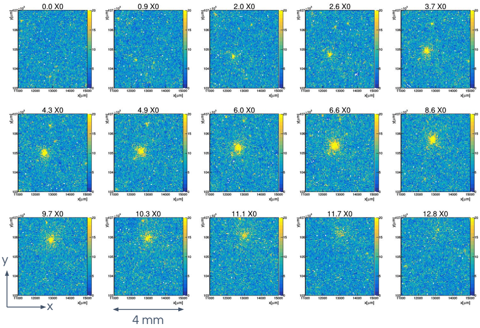
within SND@LHC acceptance



- Muon-induced neutral interactions

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

ν_e CC in emulsion

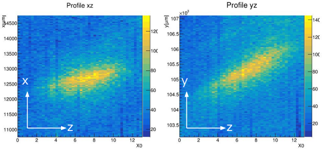


Strategy

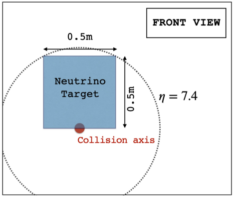
- Identify regions of high track density in the emulsions.
- Consistent with the expectation of electromagnetic shower development.
- Search for neutral vertices associated to identified showers.

Status

- Electromagnetic shower patterns identified.
- Vertex association ongoing.

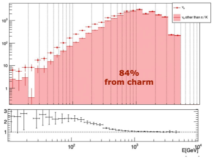


Off-axis configuration

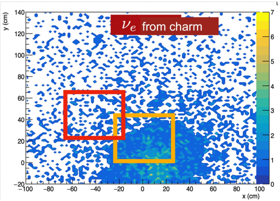


Flavour	CC neutrino interactions Yield	NC neutrino interactions Yield
ν_μ	6.9×10^4	2.0×10^4
$\bar{\nu}_\mu$	2.5×10^4	9.0×10^3
ν_e	2.1×10^4	6.5×10^3
$\bar{\nu}_e$	1.0×10^4	4.0×10^3
ν_τ	950	300
$\bar{\nu}_\tau$	580	240
TOT	1.3×10^5	4.1×10^4

Scattering and Neutrino Detector at the LHC



Active surface: ~50×50 cm^2
Tungsten mass ~ 2 tons



Lowered by ~15 cm
Partial overlap with FASER useful for data comparison/systematics
Gain in statistics × 4 w.r.t. current location for equal luminosity
> 150k ν interactions

Vertex detector: combination of silicon trip and pixel detectors
Ongoing studies on optimal configuration and e/π^0 separation performance

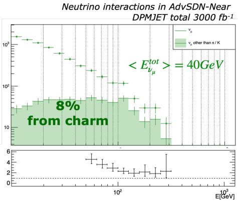
Advanced NEAR: neutrino expectation

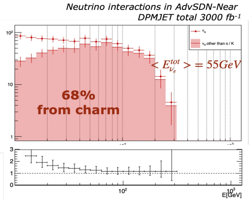
AdvSND-Near

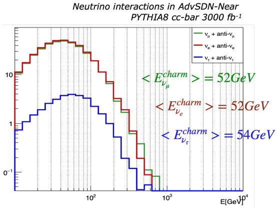
η	[4.0, 4.62]
φ	3.5 %
mass (ton)	5
surface (cm²)	147x53.5
distance (m)	87.2

Expectations in **3000 fb^{-1}**

	CC DIS Interactions			
Flavour	**total (DPMJET)**	**cc-bar (DPMJET)**	**cc-bar (PYTHIA8)**	**bb-bar (PYTHIA8)**
$\nu_\mu + \bar{\nu}_\mu$	17500	1025	950	47
$\nu_e + \bar{\nu}_e$	1800	1100	975	50
$\nu_\tau + \bar{\nu}_\tau$	75	75	75	10
Total	**19375**	**2200**	**2000**	**107**







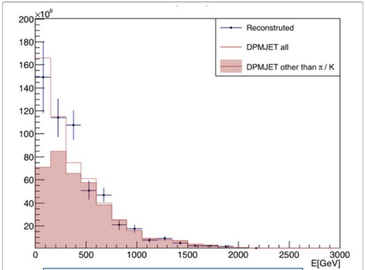
LHCb ~ 180k charmed hadrons https://link.springer.com/article/10.1007/JHEP05(2017)074 in the 4 to 4.5 η range → ~ 18k ν_e

Data acquisition

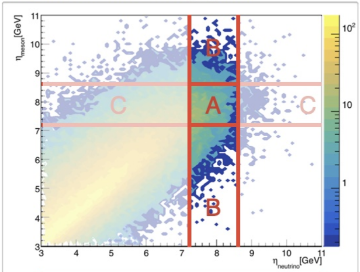
- All electronic detectors are read out by TOFPET2-based front-end boards
  - Low signal threshold: 0.5 p.e.
  - Good timing: 40 ps
  - 128 channels
- DAQ boards based on Cyclone V FPGA
  - Run at 160 MHz, aligned with the LHC clock
  - Collect data from four front-end boards (512 channels)
  - Get clock from LHC time, trigger and control system (TTC) via optical fibre
  - All hits above threshold sent to DAQ server over ethernet
- DAQ server
  - Receives hits from DAQ boards, 17k channels in total
  - Runs timestamp-based event-building code
  - Applies online noise filter conditions based on event topology
  - Saves data to disk in ROOT format

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%	22%
ν_e/ν_μ ratio for LFU test	10%	10%
NC/CC ratio	5%	10%

- Expect 90% of $\nu_e + \nu_e$ to originate from charm decays.
  - SND@LHC $\nu_e + \nu_e$ are a probe of forward charm production.
  - Forward charm production measurement constrains gluon PDFs at very low x (10^{-6}).
- Impact on future higher energy hadron colliders and neutrino astrophysics.

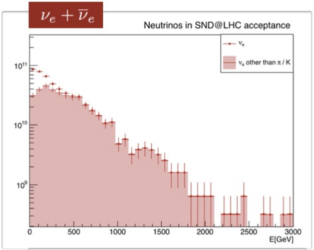


Reconstructed $\nu_e + \overline{\nu}_e$ spectrum at SND@LHC.

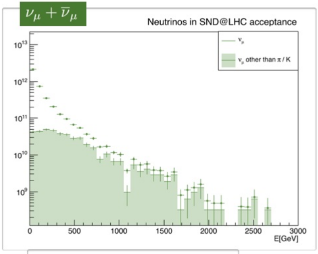


Correlation between η_ν and η_c

- Charm hadron decays contribute to the flux of all three types of neutrinos at SND@LHC.
- The detector has excellent flavour identification capabilities.
- Unique opportunity to test lepton flavour universality with neutrinos.
  - Take ratios of event rates: ν_e/ν_τ and ν_e/ν_μ.

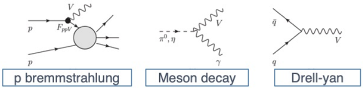


$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

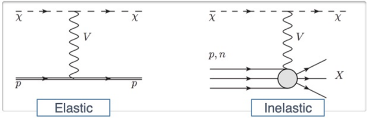


$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\boxed{\omega_{\pi/k}}}.$$

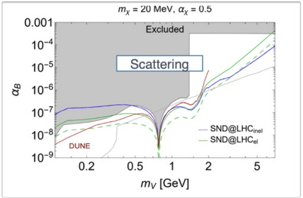
- SND@LHC is sensitive to new **dark sector** particles.

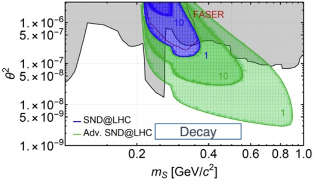


  - **Scattering** in the detector.
    - E.g., scalars interacting with nucleons via a leptophobic portal.



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





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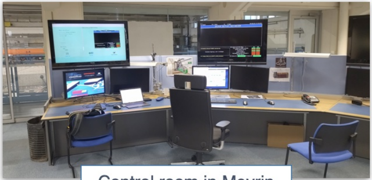
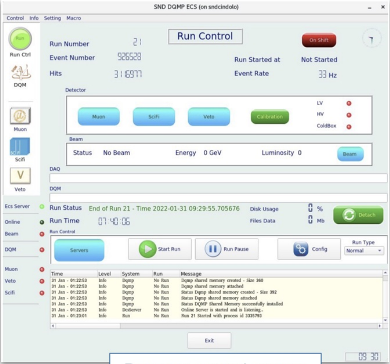
Experiment operation

- Normal detector operation can be performed remotely.
  - Control system automatically recovers from most frequent hiccups.
- 24/7 data taking shifts during physics runs.
  - Shifter must be in CERN area.
  - Physical control room available.
- Emulsion preparation and development shifts.



Control room in Meyrin



Detector control system

Software and analysis tools

- Fluxes at LHC TI-18 tunnel generated with DPMJET + Fluka model of the LHC.
  - Maintained by CERN Sources, Targets and Interactions Group SY/STI.

In `sndsw` FairROOT based software:

- Propagation of particles through the TI-18 tunnel and detector modeled with Geant4.
  - Digitization models.
- Neutrino event generation with GENIE.
- Muon DIS event generation with PYTHIA.
- Analysis tools:
  - Electronic detector track reconstruction.
  - Emulsion reconstruction with FEDRA.
  - Detector alignment tools.
- Online data quality monitoring.