Observation of collider neutrinos with SND@LHC


Credits: Craiyon

Joint Annual Meeting of the SPS and ÖPG

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LHC
Scattering and Neutrino Detector
at the LHC

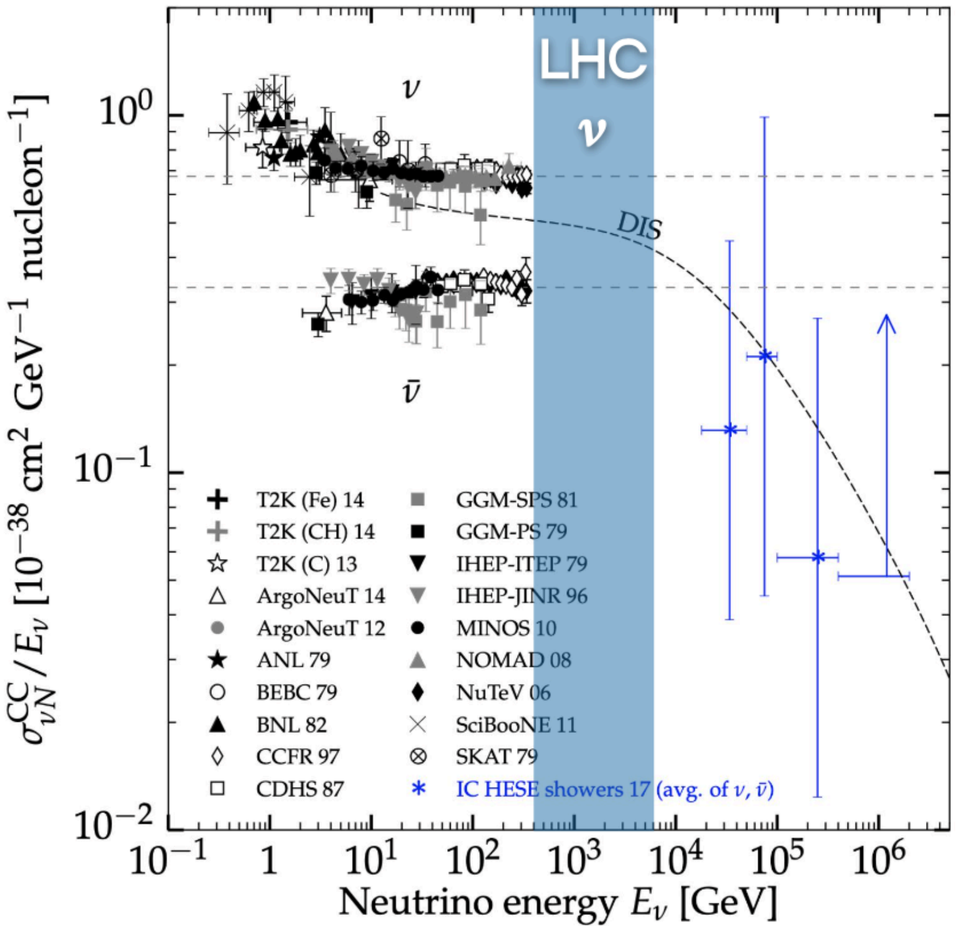
Why Studying neutrinos at the LHC?

Long-standing effort to explore a **neutrino** physics **program** at the Large Hadron Collider (LHC) at **CERN** since the 80's.

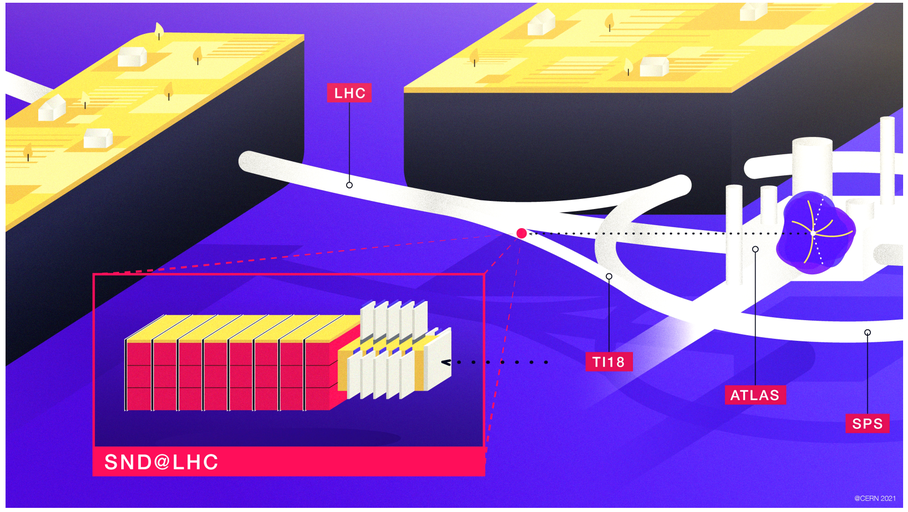
Neutrino Experiments at the LHC?

- Large **neutrino fluxes** produced by *pp* collisions in the **forward** regions
- Very **high neutrino energy** ($E_\nu \in [10^2, 10^3]\,\mathrm{GeV}$), $\sigma_\nu \propto E_\nu$
- Neutrinos of **all flavours can be observed** by a small-scale experiment at the LHC

PRL 122 (2019) 041101

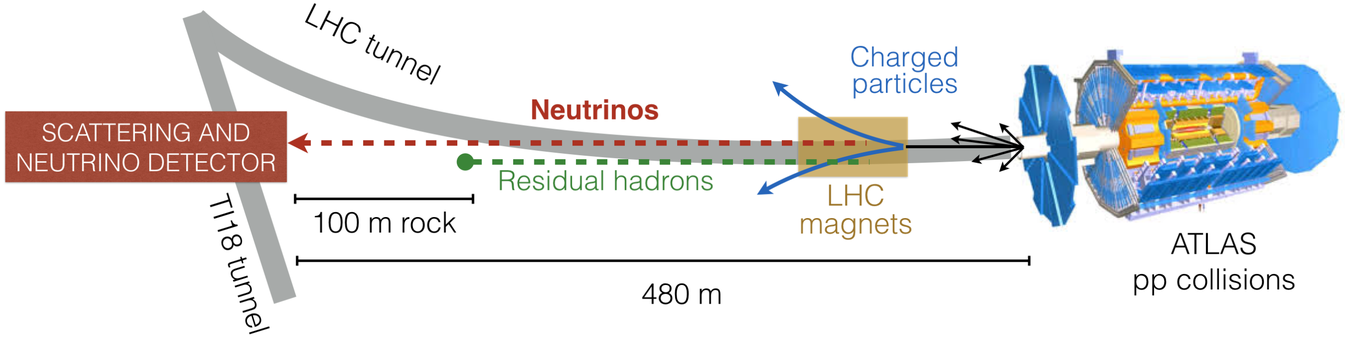


The SND@LHC Experiment



Scattering and Neutrino Detector at the **LHC**:

- **New experiment** at CERN to measure **high energy neutrino** interactions from the LHC at the TeV scale
- Located in **TI18**, a former transfer line from SPS to LEP, **480 m** away from the **ATLAS** interaction point
- Covered **angular acceptance** of $7.2 < \eta < 8.4$ (off axis)
  - Enhanced neutrino production from charm decays
    ⇒ Probing **heavy flavour production** at the LHC

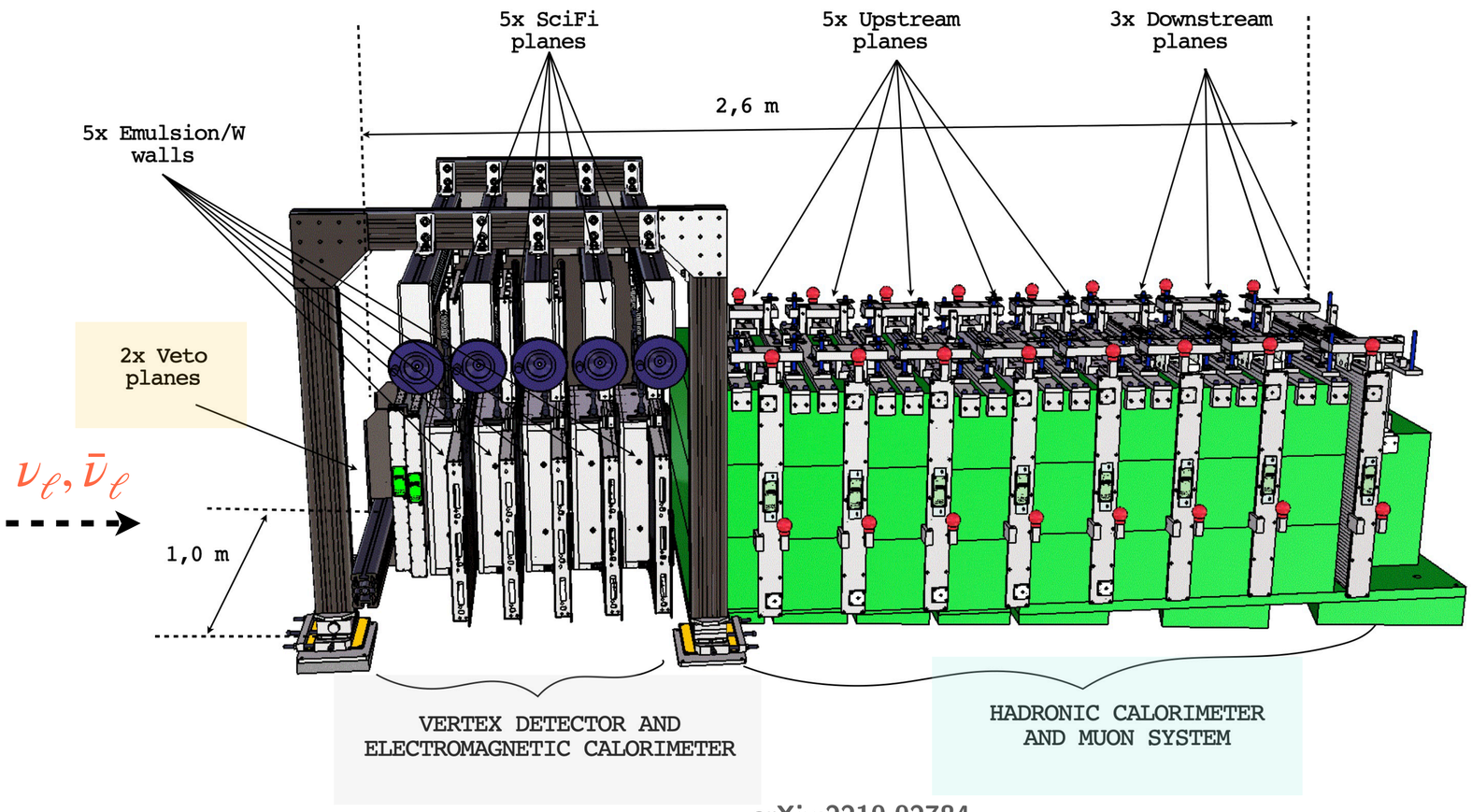


The SND@LHC Detector

Goal: identifying **all** the **neutrino flavours** with high efficiency; searching for **Feebly Interacting Particles** (FIPs)

Solution: **hybrid** detector technology

More in **A. Kauniskangas talk [345]**



arXiv:2210.02784

VETO system

- Two planes of scintillating bars to tag entering charged particles

Target, Vertex Detector and ECAL ($\sim 84\,X_0$, $3\,\lambda_{\text{int}}$)

- 830 kg tungsten target
- Five walls of 60 emulsion films interleaved with tungsten for precise ν vertex reconstruction
- Five Scintillating Fibre planes for calorimetric and timing information

HCAL and Muon System ($\sim 10\,\lambda$)

- Scintillating bars interleaved with 8 iron walls
- Higher granularity in downstream stations for muons tracking and identification

DAQ and Event Reconstruction

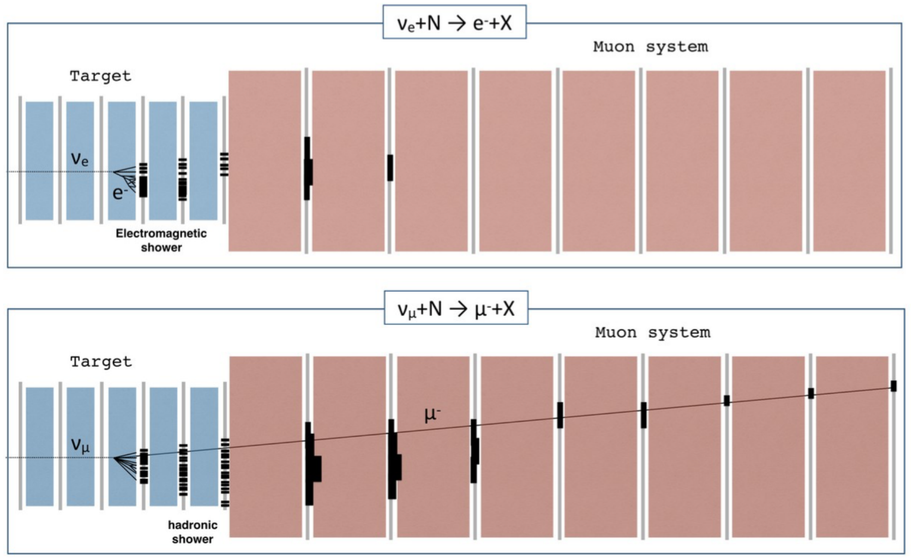
Trigger-less data acquisition and event reconstruction in two steps

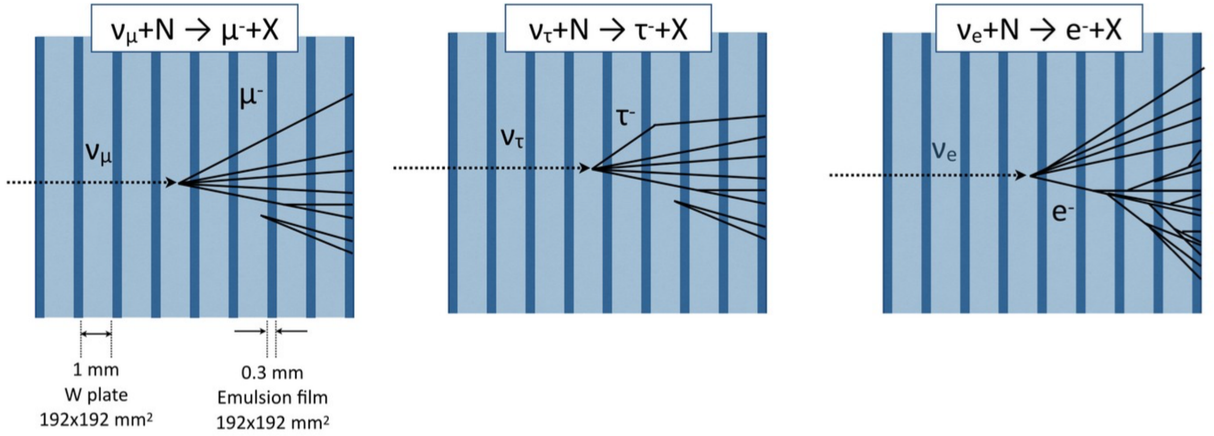
First Phase (Online, Electronic Detectors)

- Identify **signal candidates** (neutrino or FIPs)
- Identify **muons** candidate (SciFi + Muon System)
- **Energy** measurement (SciFi + Muon System)

Second Phase (Offline, Nuclear Emulsions)

- Extract, develop, scan, and analyse the **emulsion data**
- Reconstruct **neutrino** primary and secondary **vertices**
- **Matching** between the emulsion and electronic detectors data (timestamp and Energy measurement)





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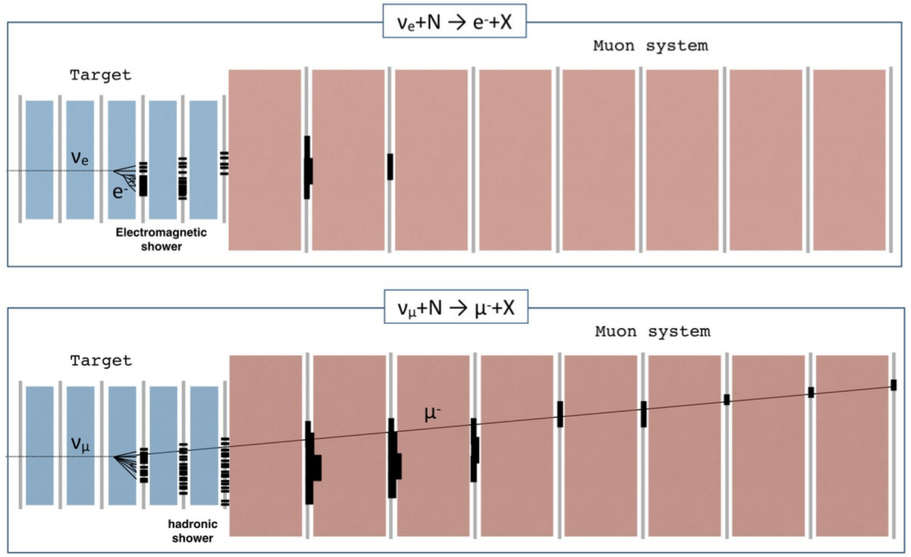
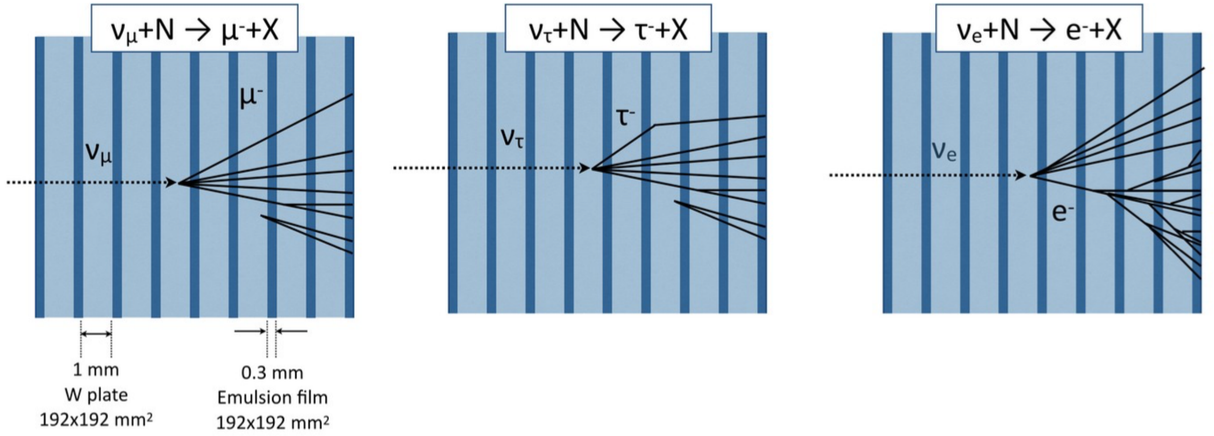




First Results:

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

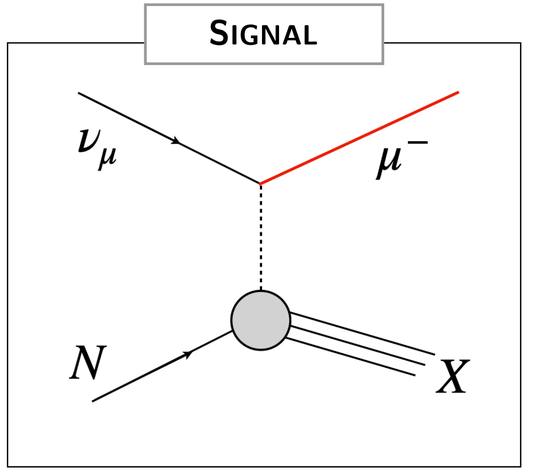
PRL 131, 031802 (2023)

Analysis Strategy: Observation of Muon Neutrinos

PRL 131, 031802 (2023)

Search for **Charged Current** (CC) **Deep Inelastic Scattering** of $\nu_\mu + \bar{\nu}_\mu$ interactions in the SND@LHC **electronic detectors**

- Analysis of **2022 dataset**, corresponding to $36.8\,\mathrm{fb}^{-1}$
  - Expected signal yield ($\nu_\mu + \bar{\nu}_\mu$ interactions) : 157 ± 37
- **Challenge**: background from $\sim 10^9$ **muons**
- **Analysis strategy:**
  - Counting-based approach
  - Use informations from electronic detectors only



Analysis Strategy: Event Selection

PRL 131, 031802 (2023)

Fiducial Volume selection

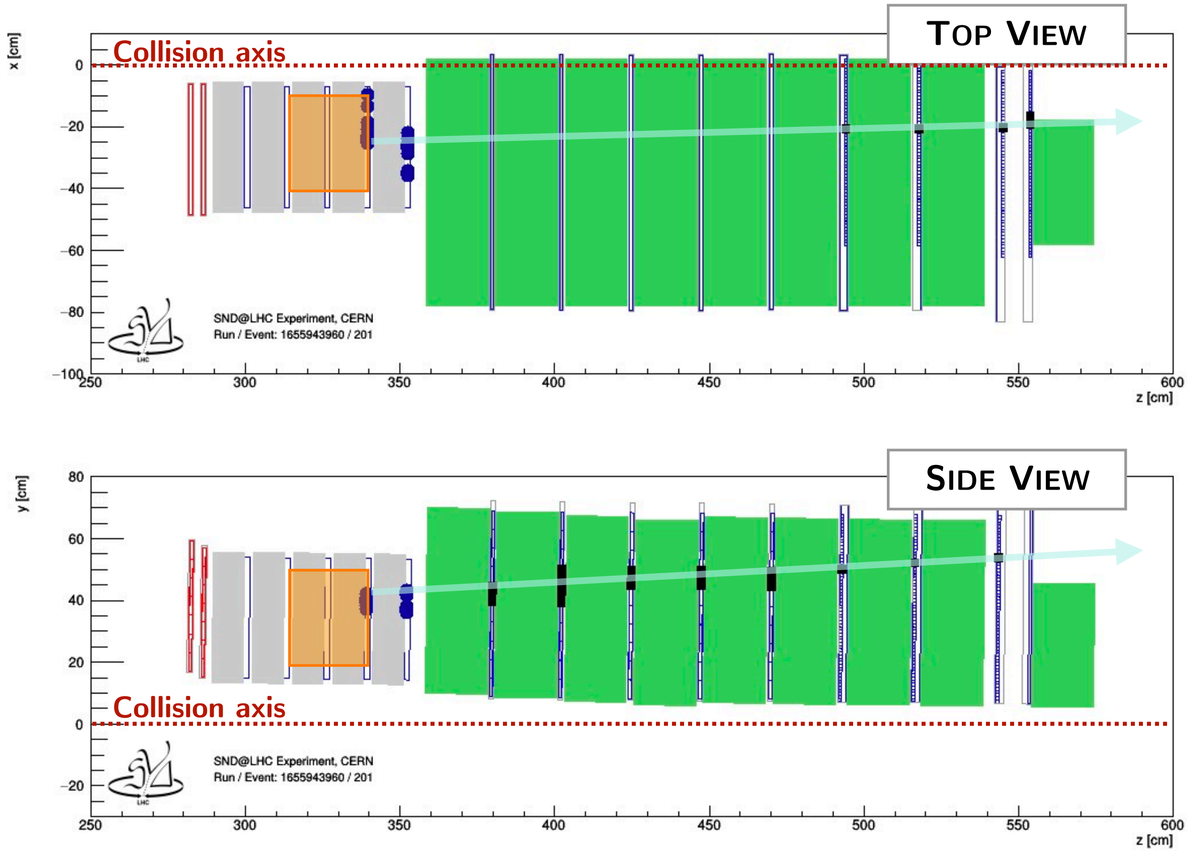
- A Neutral vertex in the 3^{rd} or 4^{th} target walls
- Reject side-entering backgrounds
- Signal acceptance: $7.5\,\%$

Muon neutrino identification selection

- Large hadronic activity in SciFi and HCAL
- A reconstructed and isolated muon track
- Signal selection efficiency: $36\,\%$

Total Number of ν_μ CC Events expected in $36.8\,\text{fb}^{-1}$ after cuts: 4.2

ν_μ CC MC Simulation



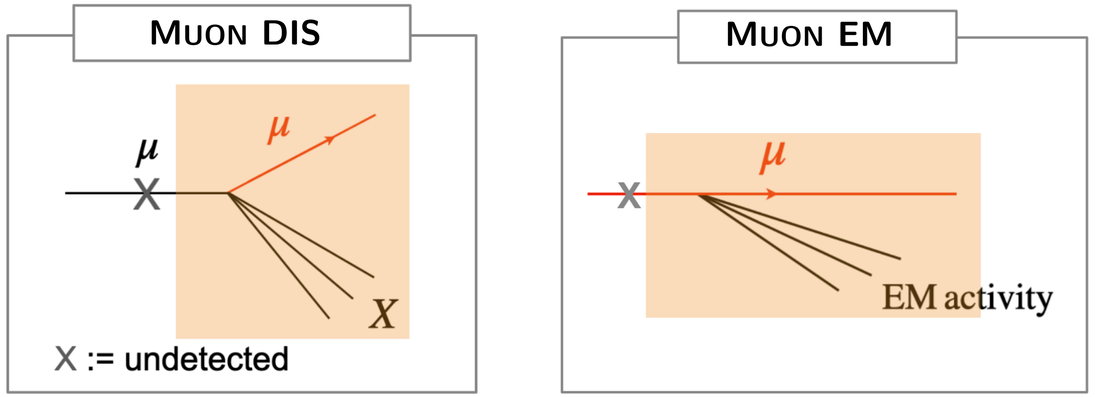
Analysis Strategy: Backgrounds Estimation

PRL 131, 031802 (2023)

Entering muons background

- Incoming muon track possibly missed due to detector inefficiency
- Shower induced by muon DIS interaction or EM activity
- Muons in acceptance: $N_\mu \sim 5 \times 10^8$ SNDLHC-NOTE-2023-001
- Detector inefficiency (two veto and two SciFi planes): 5×10^{-12}

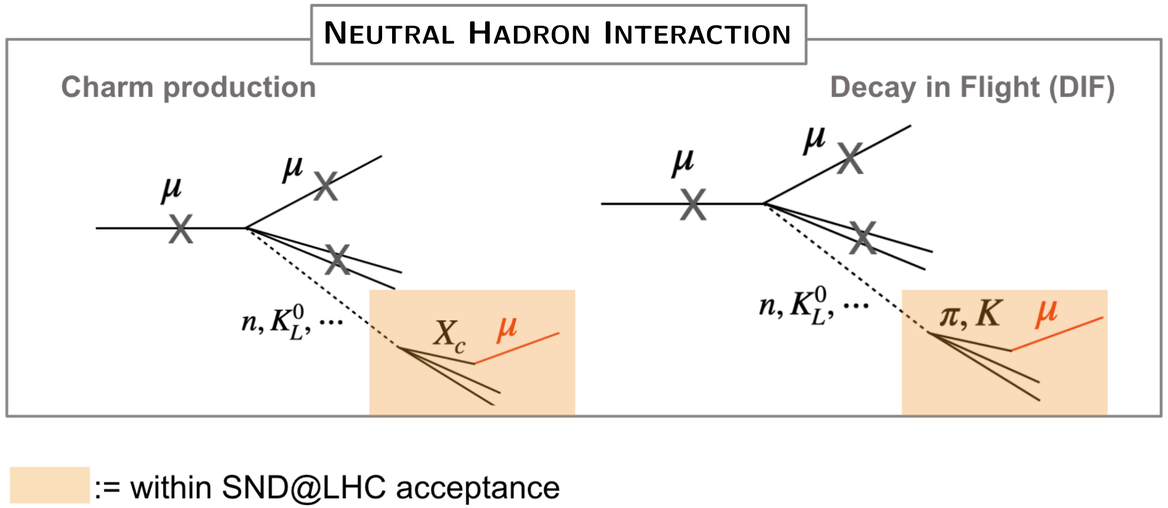
Negligible Background with current selection



Muon induced neutral background

- Neutral hadrons produced by muon DIS upstream of the detector
- Muons originating from charm production or Decay In Flight

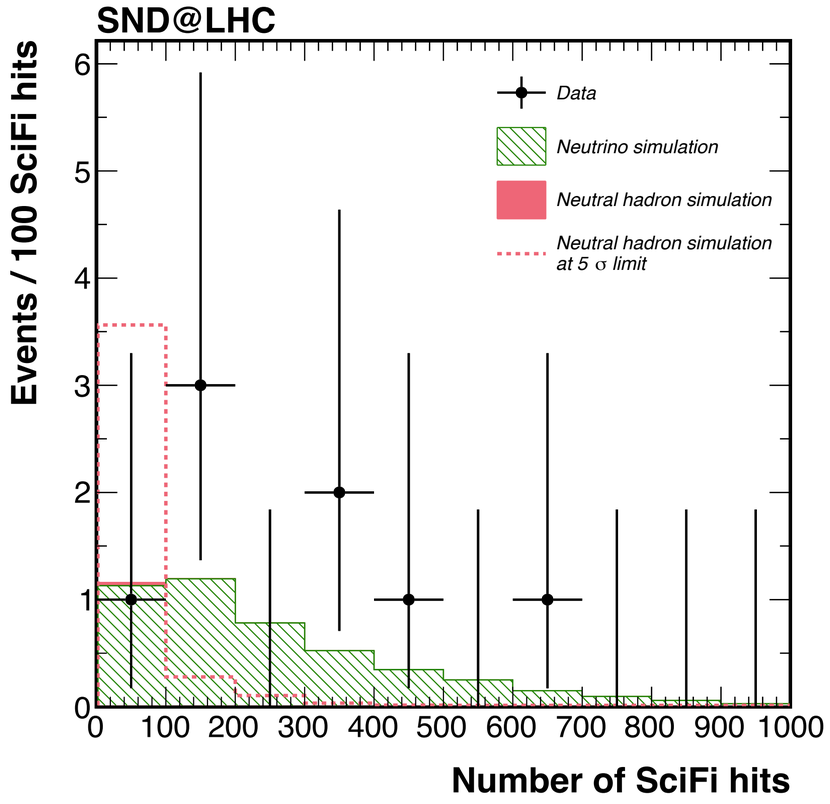
Total number of background events due to neutral hadrons: $(8.6 \pm 3.8) \times 10^{-2}$

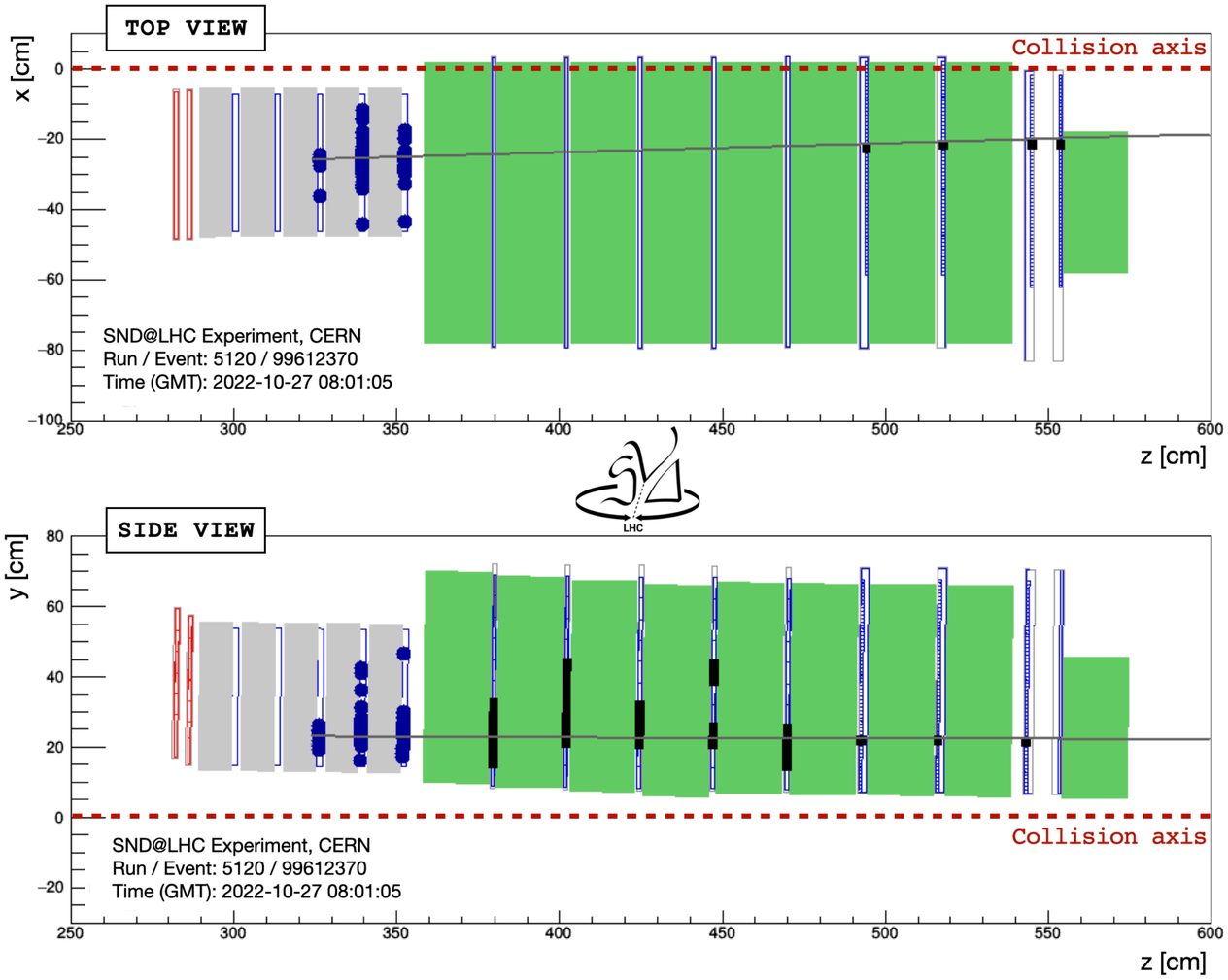


Result: Neutrino Observation

PRL 131, 031802 (2023)

Observed 8 ν_μ CC candidates with a Statistical Significance of 6.8σ





Run3 Physics Programme: Heavy flavour

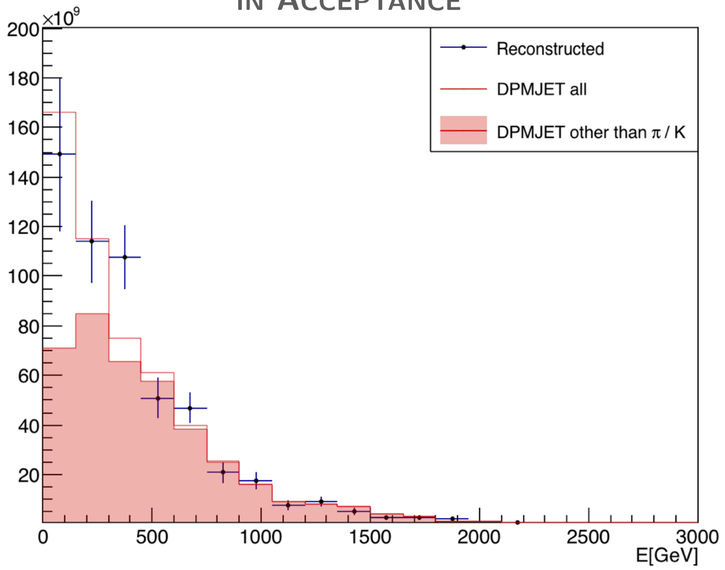
Measurement of the $pp \to \nu_e X$ Cross Section | **Charmed Hadron Production** | **Extraction of Gluon-PDF at *Low* x ($\leq 10^{-6}$)**

- 90% of $\nu_e, \bar{\nu}_e$ produced in SND@LHC from **charmed hadrons** decays

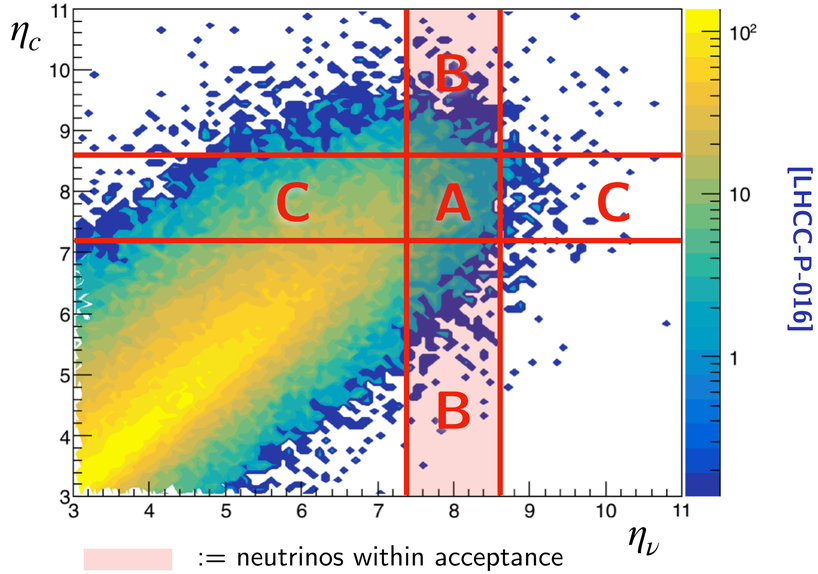
  $\Rightarrow \nu_e(\bar{\nu}_e)$ as a proxy of the **charm production** and **gluon pdf** at very low x
- Impact for **future high energy hadron colliders** and **atmospheric neutrinos**

Measurement	Uncertainty Stat.	Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%

Reconstructed $\nu_e + \bar{\nu}_e$ Spectrum in Acceptance



Correlation between η_ν and η_c



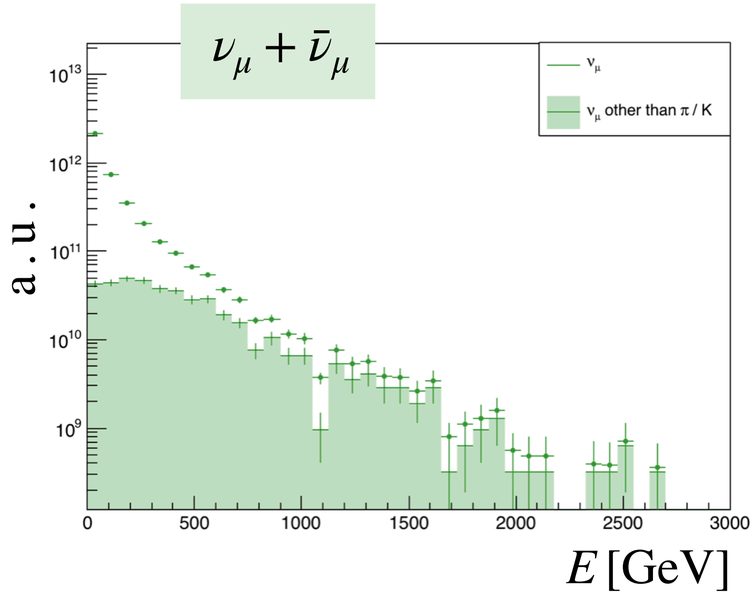
Run3 Physics Programme: Lepton Flavour Universality

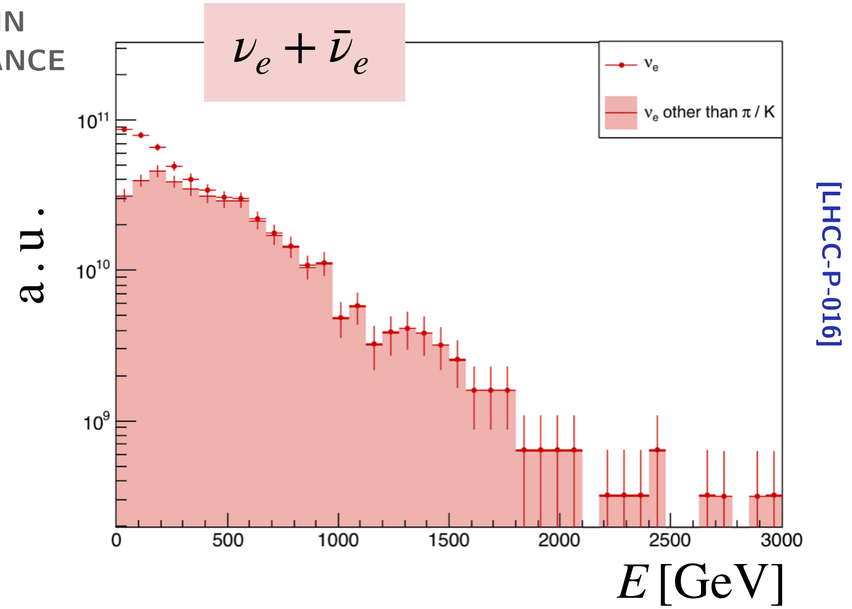
Test Lepton Flavour Universality via **identification** of the 3 **neutrino flavours**

Measurement	Uncertainty Stat.	Sys.
ν_e/ν_τ ratio for LFU test	30%	22%
ν_e/ν_μ ratio for LFU test	10%	10%

- SND@LHC detector can distinguish the three neutrino species
- Use the ratio of events ν_e/ν_μ and ν_e/ν_τ

Neutrinos within Detector Acceptance





[LHCC-P-016]

ν_e/ν_μ

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

$\omega_{\pi/K}$ **contamination fraction** constant above 600 GeV

ν_e/ν_τ

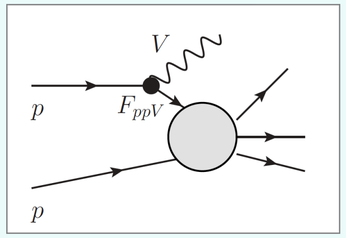
$$R_{13} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\tau+\bar{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i}\,\mathrm{BR}(c_i \to \nu_e)}{\tilde{f}_{D_s}\,\mathrm{BR}(D_s \to \nu_\tau)}$$

ν_τ exclusively from D_s ⇒ R depends on **charm hadronisation fractions** f

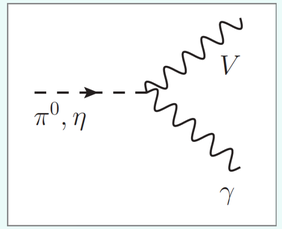
Run3 Physics Programme: BSM Scattering/Decay searches

The SND@LHC detector can explore various **Hidden Sector** models and discover **FIPs**

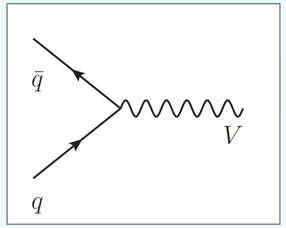
- FIPs production mechanisms (*e.g. Leptophobic* mediator)



Proton Bremsstrahlung



Meson Decay



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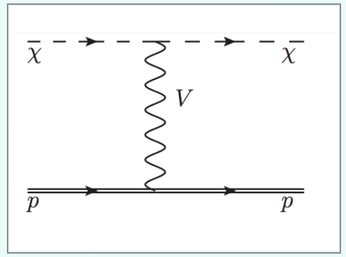
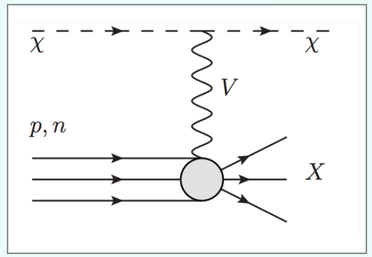
- FIPs **scattering** (*e.g. Light Dark Matter*)

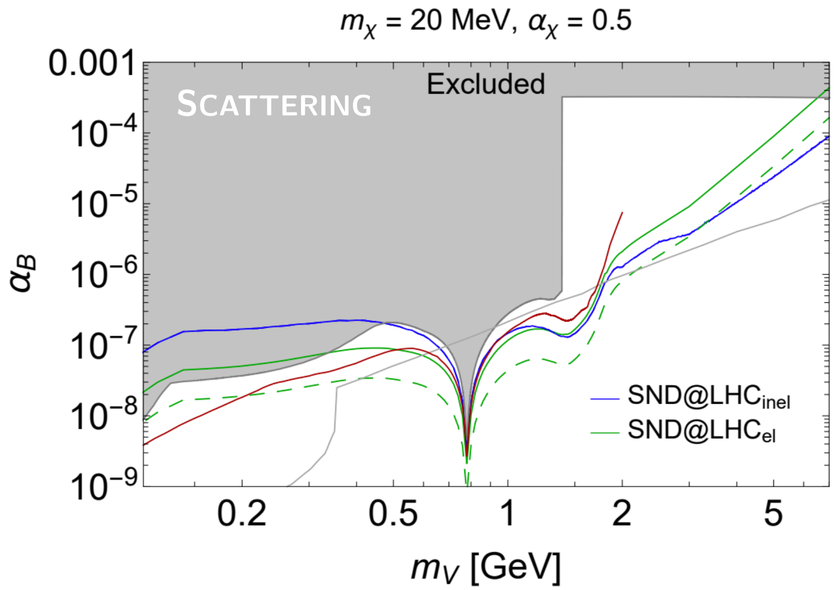


Elastic Scattering



Inelastic Scattering

- FIPs **decay**
  - **HNL**, **Dark Scalar**, **Dark Photon** decaying into a pair of charged tracks, pointing back to the IP



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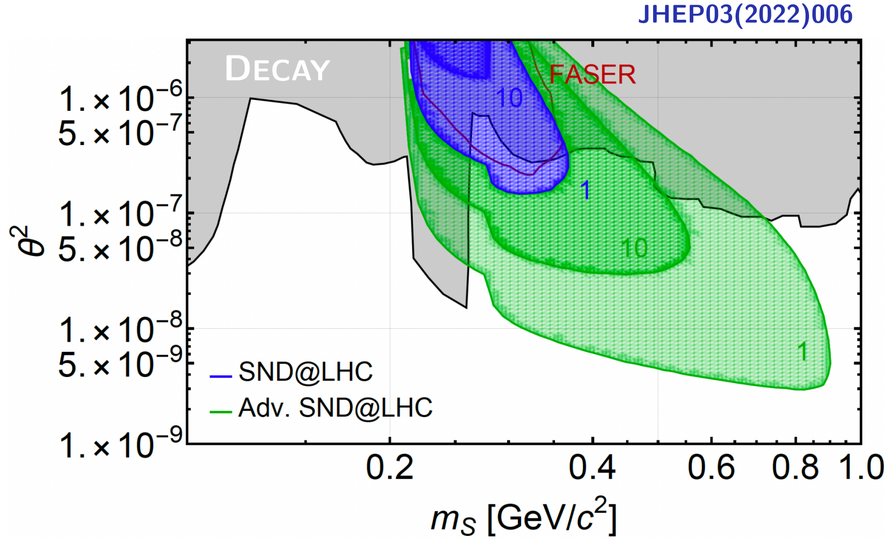


Conclusions

The **SND@LHC** experiment is **exploring uncharted territory** by measuring **neutrinos** produced in the LHC high energy collisions

- Successful detector operations in 2022, with $36.8\,\mathrm{fb}^{-1}$ recorded luminosity
- **First physics result**: **observation of muon neutrinos** from proton-proton LHC collisions with high statistical significance
- A **new era** of measurements at the LHC, with a wide **physics programme**:
  - (high energy) Neutrino physics measurements
  - Heavy Flavour production, QCD, Lepton Flavour Universality with neutrinos
  - Feebly Interacting Particles searches

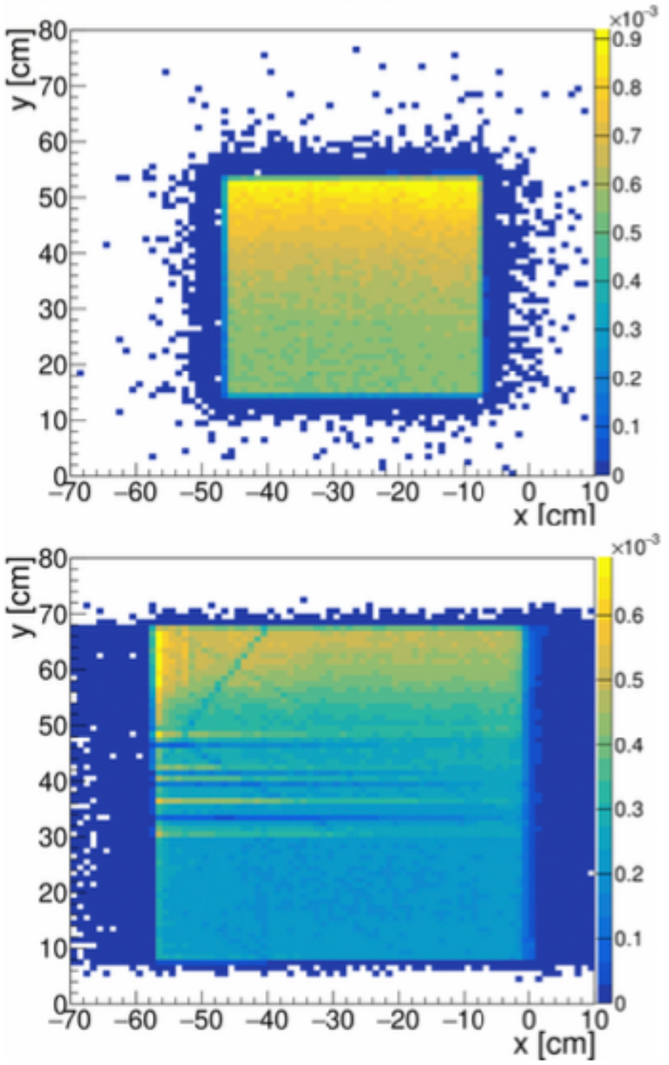
Spare Slides

Muon Flux Measurement

SNDLHC-NOTE-2023-001

- Muon flux measured using electronic detectors
  - **SciFi**: $2.06 \times 10^4\,\mathrm{cm}^{-2}/\mathrm{fb}^{-1}$ (sys. uncert. $3\,\%$)
  - **Downstream Stations**: $2.35 \times 10^4\,\mathrm{cm}^{-2}/\mathrm{fb}^{-1}$ (sys. uncert. $5\,\%$)
  - Agreement between SciFi/DS: $2\,\%$

- Agreement between data and MC at the level of $20 - 25\,\%$
  - **SciFi**: $1.60 \times 10^4\,\mathrm{cm}^{-2}/\mathrm{fb}^{-1}$
  - **Downstream Stations**: $1.79 \times 10^4\,\mathrm{cm}^{-2}/\mathrm{fb}^{-1}$



SciFi

DS

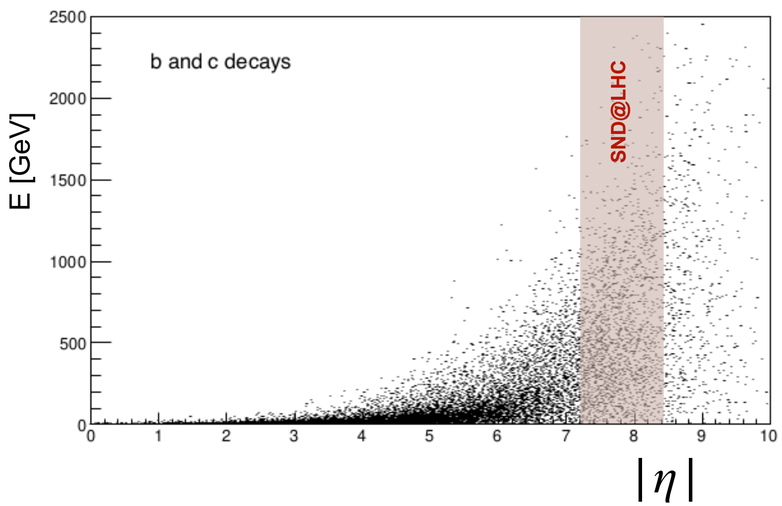
Motivation

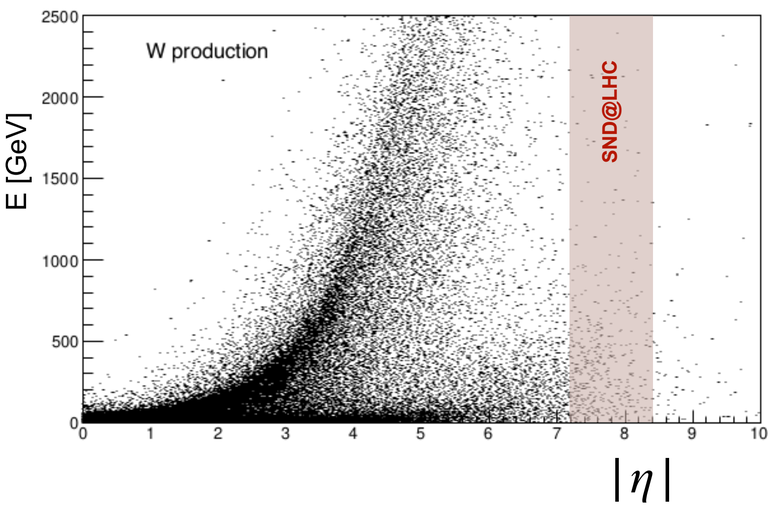
Neutrino Physics Proposals

- XSEN proposal: **LHC neutrinos at CMS** [arXiv:1804.04413]
- **Physics potential** of an experiment using **LHC neutrinos** [arXiv:1903.06564]
- **Further studies** on the physics potential of an experiment using LHC neutrinos [arXiv:2004.07828]
- **SND@LHC** Letter of Intent (LoI), 2020

Interacting ν in $250\,\mathrm{fb}^{-1}$ (Run 3)

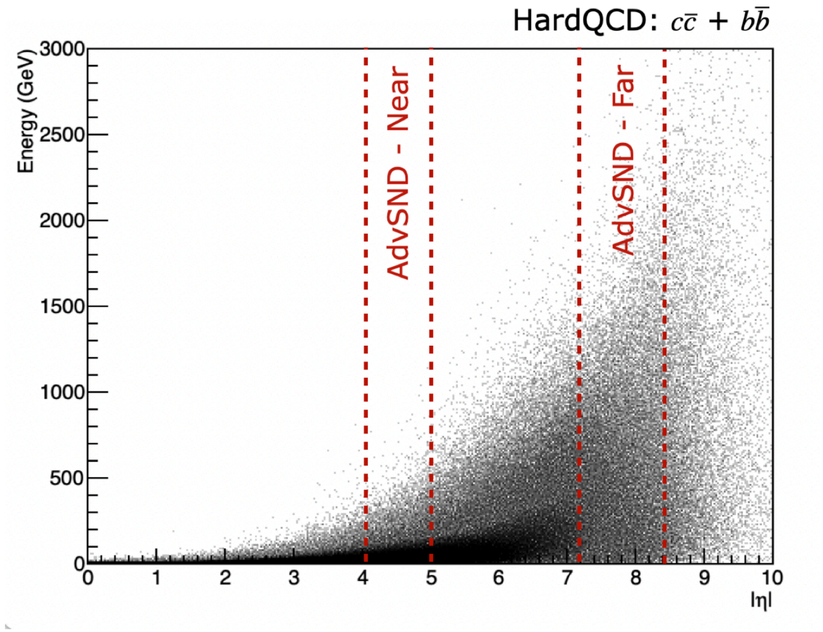
Flavour	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
ν_μ	452	910	480	270
$\bar{\nu}_\mu$	485	360	480	140
ν_e	760	250	720	80
$\bar{\nu}_e$	680	140	720	50
ν_τ	740	20	740	10
$\bar{\nu}_\tau$	740	10	740	5
TOT		1690		555

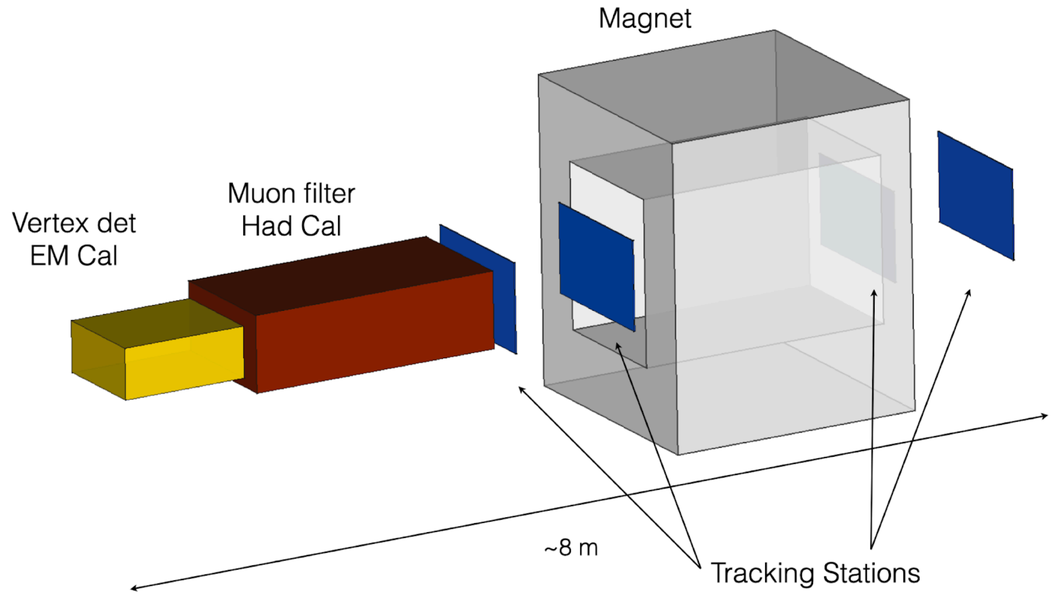




Future Plans: AdvSND

- Propose a near detector in a rapidity range overlapping with LHCb
  - Reduce systematic uncertainty on far detector measurements using LHCb charm production measurements
- Far detector in same rapidity range as current detector
- Detector upgrades
  - Tag muon sign with magnet
  - Replace emulsion vertex detector with electronic technology (HL-LHC emulsion replacement rate is unfeasible)



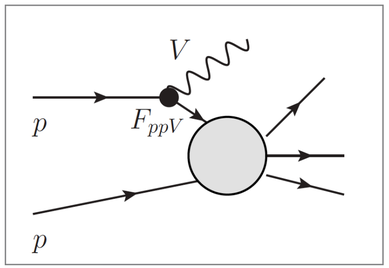


BSM Searches: Scattering

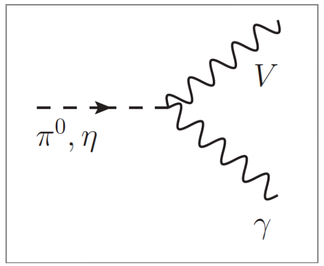
Probe experimental signatures of **FIPs** with SND@LHC to explore various **Hidden Sector** models

- *E.g.* for a *scalar* **Light Dark Matter** candidate χ, coupled to the SM via a Leptophobic Portal:

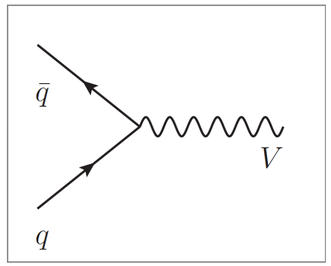
Production Mechanisms



Proton Bremsstrahlung



Meson Decay



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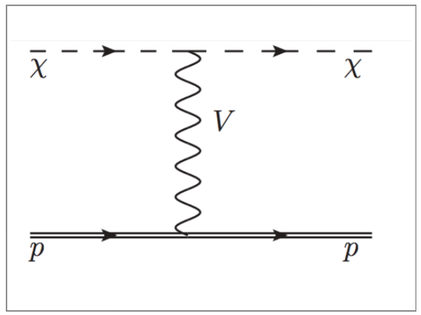
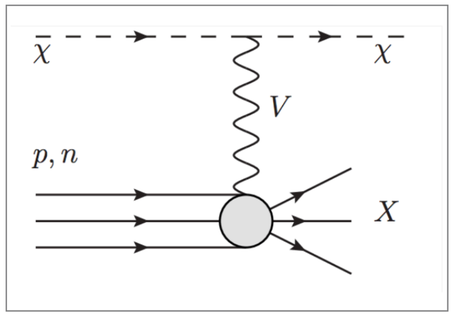
Interaction and Detection



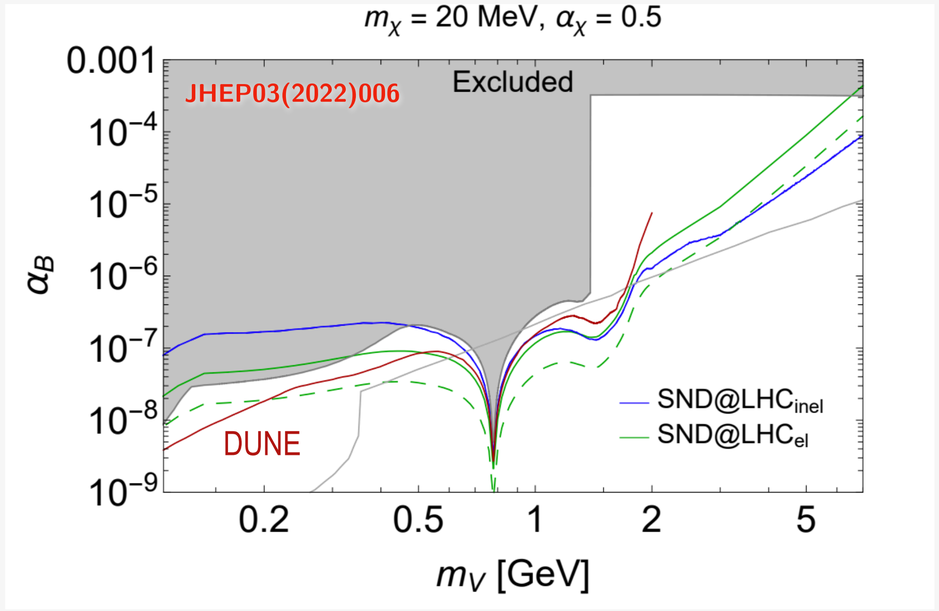
Elastic Scattering



Inelastic Scattering

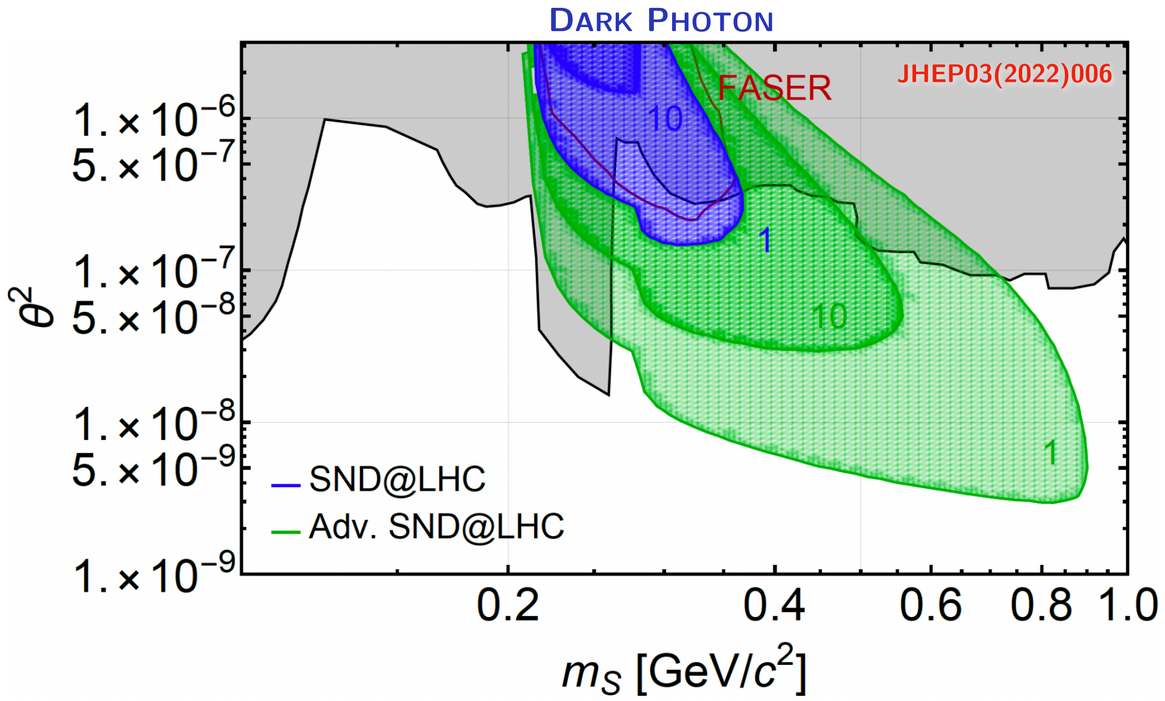
$$\mathscr{L}_{\text{leph}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi)$$

$$\alpha_B = g_B^2/4\pi$$



BSM Searches: Decay

Probe experimental signatures of **FIPs** with SND@LHC to explore various **Hidden Sector** models



Production Mechanisms

- **Dark Scalar:** $B \to H_s S$, proton bremsstrahlung
- **HNL:** mixing with ν_μ or ν_τ
- **Dark Photon:** mesons decay, proton bremsstrahlung

Detection signature: **vertex** of **two charged tracks**, pointing in the direction of the IP

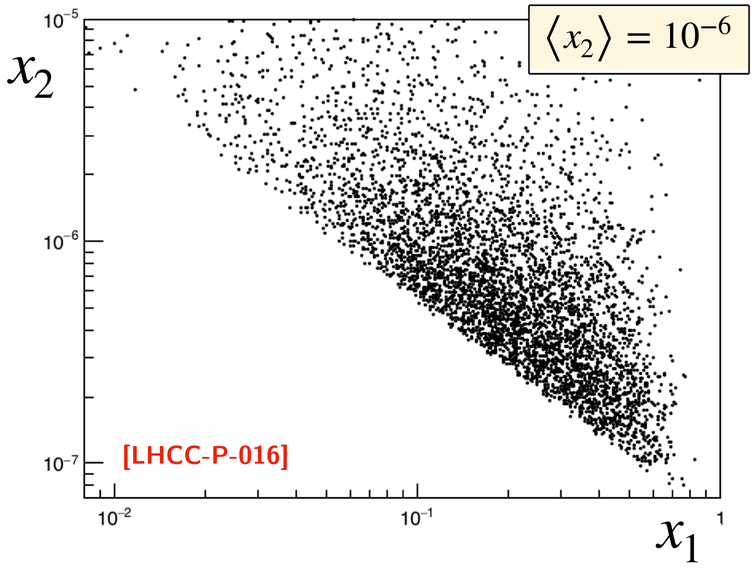
- Di-lepton pair $\ell\ell'$, lepton and meson pair, pair of mesons
- Probe smaller couplings ⇒ larger decay length
- Dedicated background study is needed

Neutrino Physics: QCD Measurements

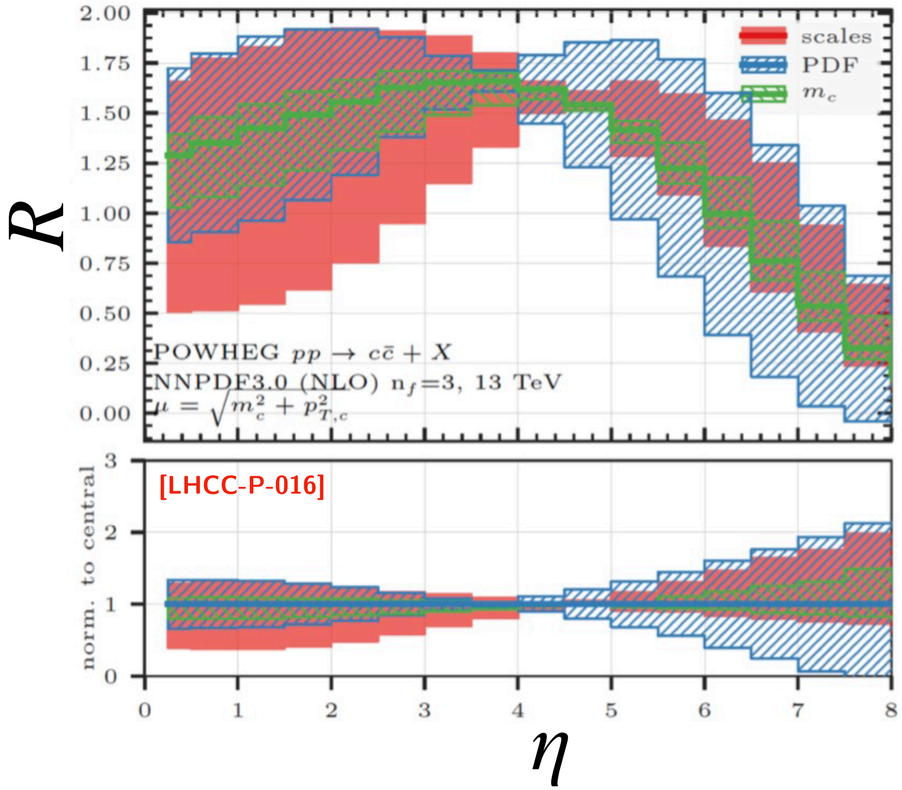
Extraction of Gluon-PDF at Uncharted *Low* x values ($\leq 10^{-6}$)

- LHC dominant partonic process is *gluon-gluon* scattering for the **associated charm production** ($c\bar{c}$)
- Gluon PDFs at low x relevant for **Future Circular Colliders** and **atmospheric neutrinos**

Correlation btw x_1 and x_2 for events within Detector Acceptance



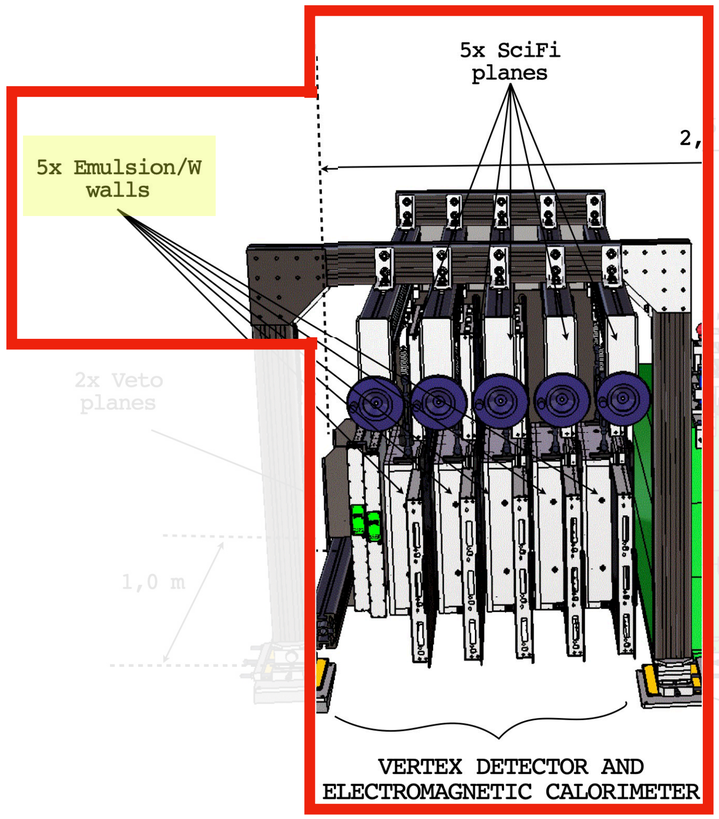
Ratio Btw Xsec Measurements at different Energies and η Values

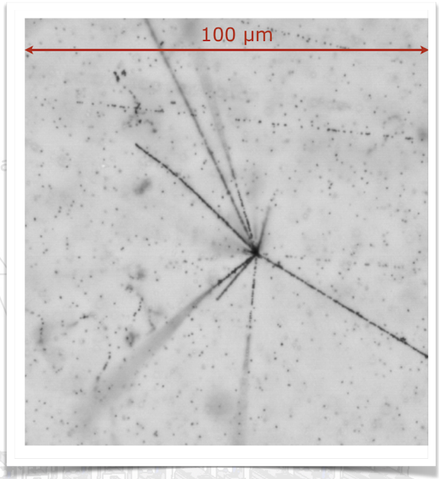


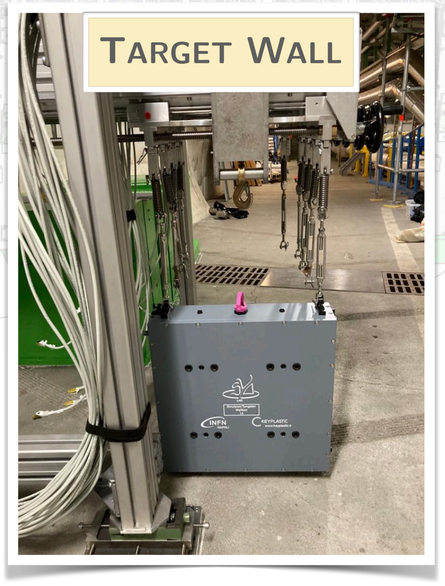
$$R = \frac{d\sigma/d\eta\,(13\,\text{TeV})}{d\sigma/d\eta\,(7\,\text{TeV})}$$

$$\eta_{\text{ref}} \in [4, 4.5]$$

The SND@LHC Detector

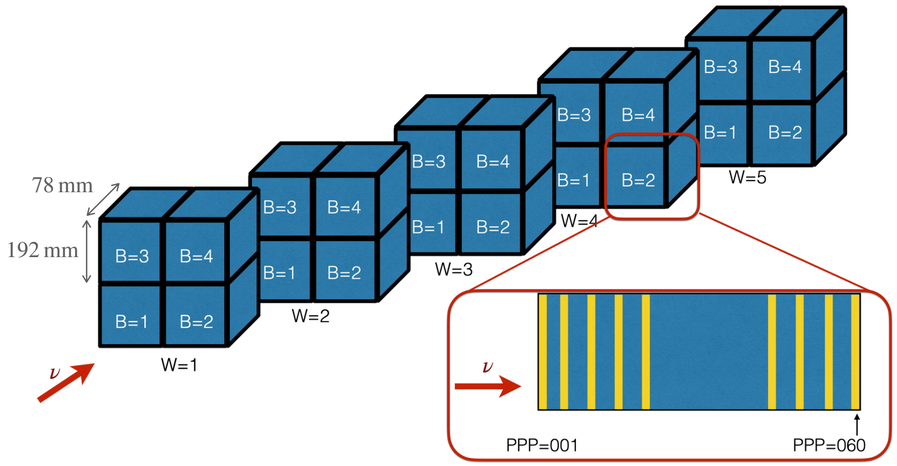




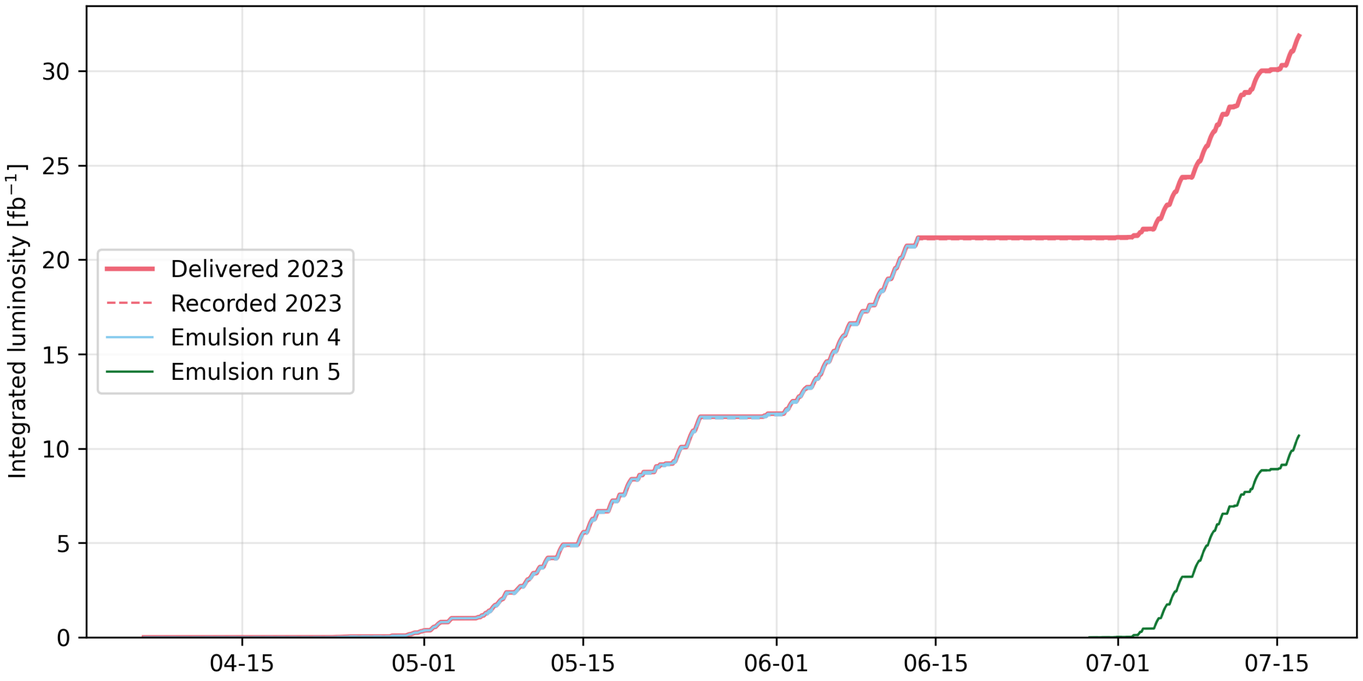


Neutrino Target and Vertex detector

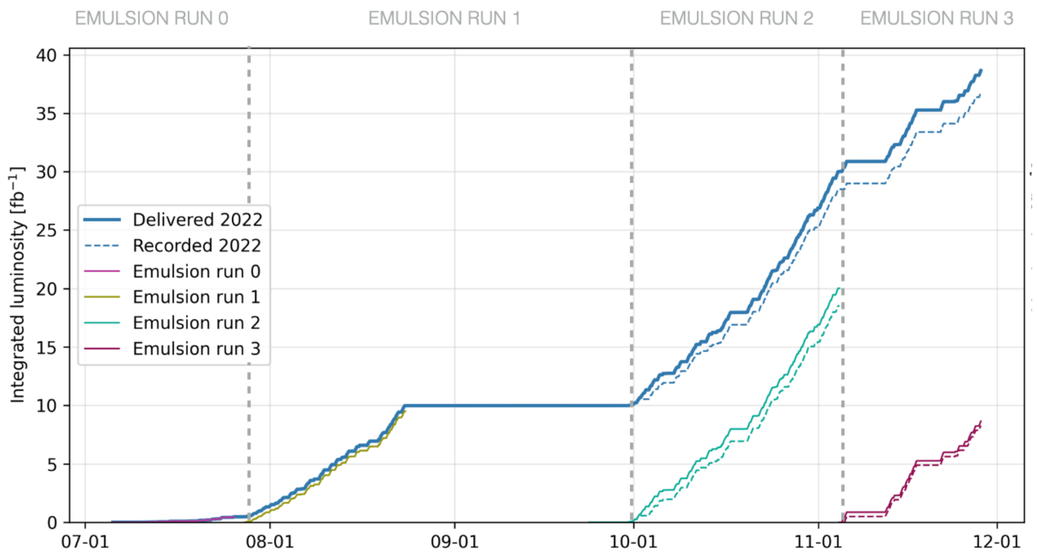
- **Goal:** detecting **neutrino** interactions
- 5 walls of 4 x unitary cells (***bricks***)
- **Emulsion Cloud Chamber**: 60 layers of **emulsion** ($300\,\mu$m-thick) interleaved with **tungsten** plates (1 mm-thick)
- **Sub-micrometric** position resolution
- Fiducial mass ca. $830\,$kg



pp Collision Data in 2023



pp Collision Data in 2022



Successful data-taking since the beginning of Run 3

- **Detector** operation **uptime** $\sim 95\,\%$
- **Total recorded luminosity**: $36.8\,\mathrm{fb}^{-1}$
- Three **emulsion** detector **replacements** in 2022
- Additional $\sim 30\,\mathrm{fb}^{-1}$ collected in 2023

Start beam commissioning *First stable beams @6.8TeV* *End of run*

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN0													39 kg	0.46 fb^{-1}
EMULSION RUN1													807 kg	9.5 fb^{-1}
EMULSION RUN2													784 kg	20.0 fb^{-1}
EMULSION RUN3													792 kg	8.6 fb^{-1}

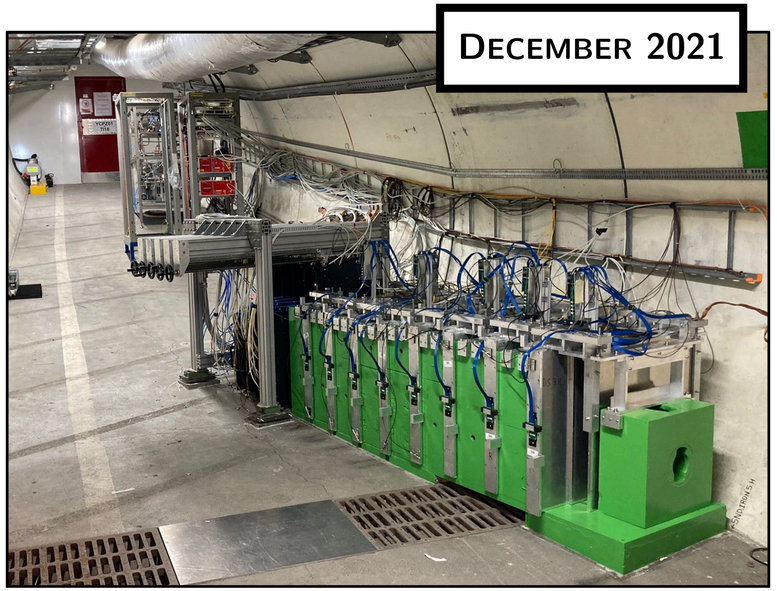
The Experiment Timeline

Letter of Intent
August 2020

March 2021
Approval by CERN Research Board

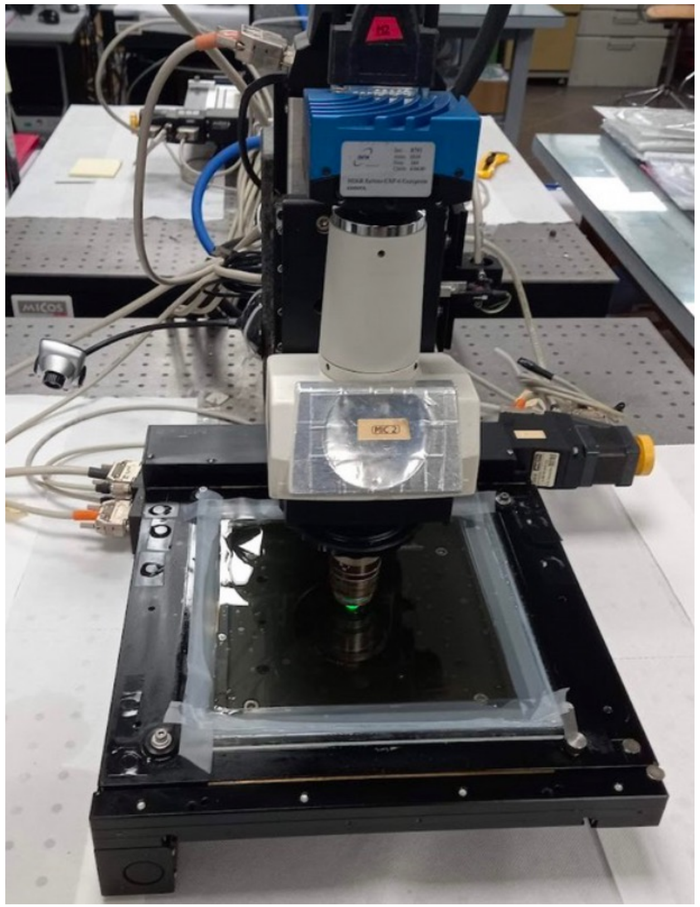
Completion of Detector Installation
December 2021

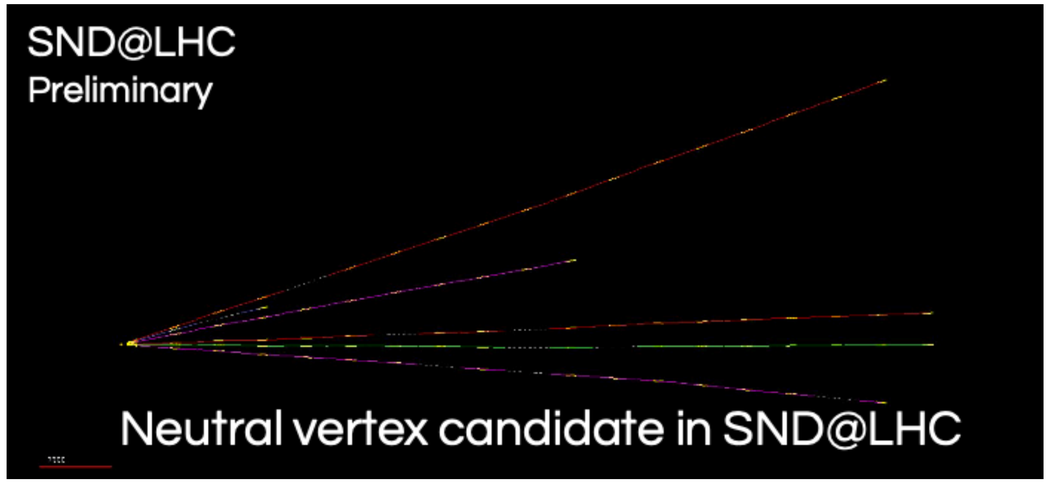
April 2022
Collection of First Run3 Data

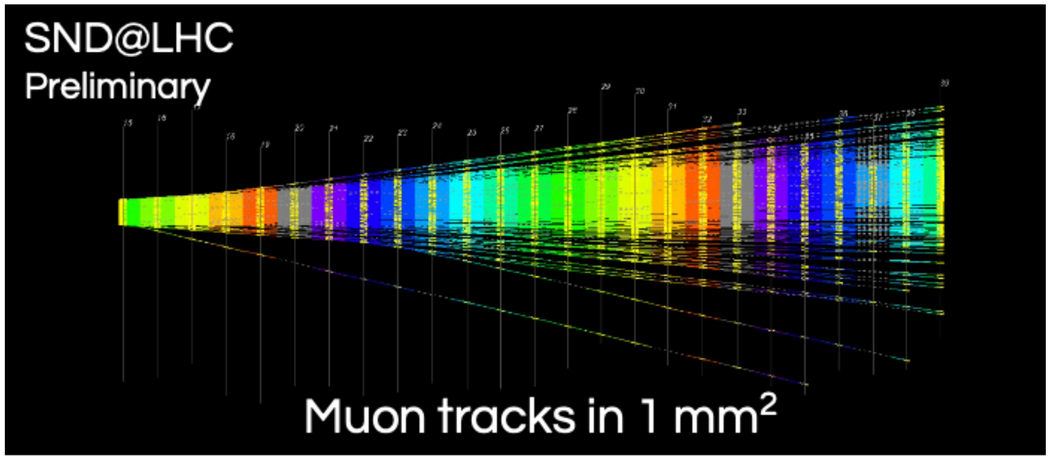


Nuclear Emulsions Analysis

The **analysis** of the emulsions data is currently ongoing







Measured **track density** per $10\,\mathrm{fb}^{-1}$: $10^5\,\mathrm{cm}^{-2}$