SND@LHC: fantastical neutrinos and where to find them

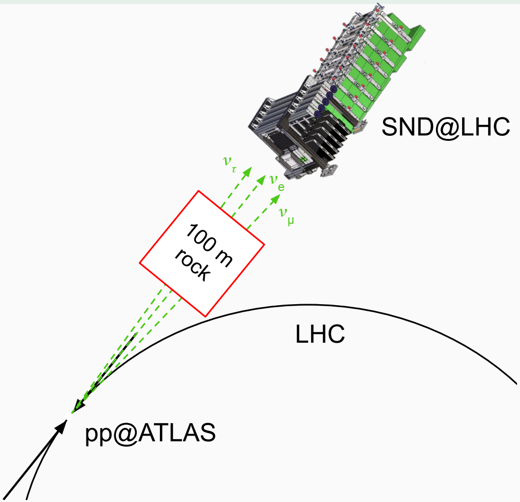
EPPG Seminar

Matei Climescu
Experimental Particle Physics and Gravity (EPPG),
Ghent University

10/02/26

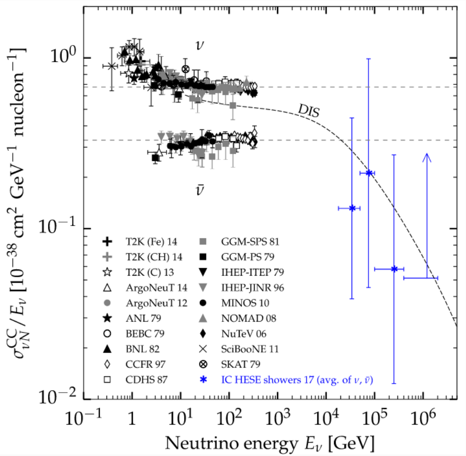
Outline

- Introduction to collider neutrinos and SND@LHC
- Some recent results
- Search for electromagnetic showers in emulsions
- SND@HL-LHC
- Conclusion



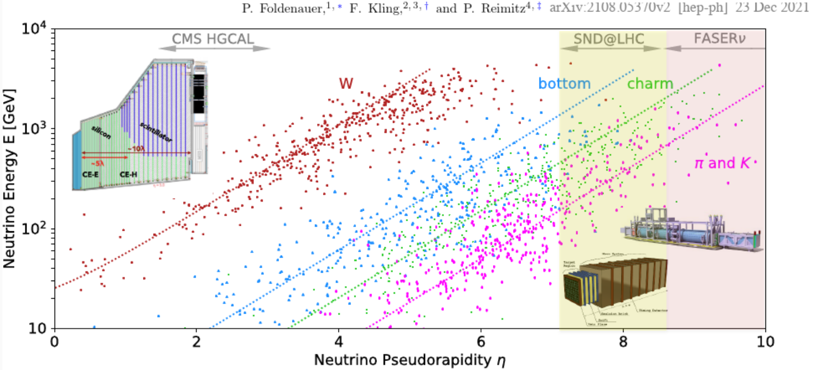
Introduction: why collider neutrinos?

- The observation of collider neutrinos is an old idea Klaus Winter 1990
- It allows for the observation of neutrinos in an underexplored energy range
- Allows to measure the $\mathrm{pp} \to \nu_e + \mathrm{X}$ cross section *via* charm production (expected precision $\mathcal{O}(35\%)$)
- Measure said charm production (expected precision $\sim 5\%_{\text{stat}} \oplus 35\%_{\text{syst}}$)
- Constrain the gluon PDF particularly in the poorly constrained low-x region
- Test lepton flavour universality in the ν sector
- Measure the F_1, F_2 and F_3 structure functions
- FIP searches Boyarski et al. 2021



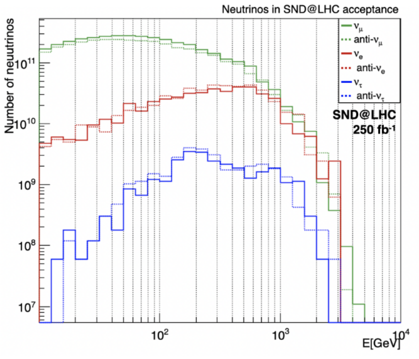
Introduction: how are collider neutrinos produced?

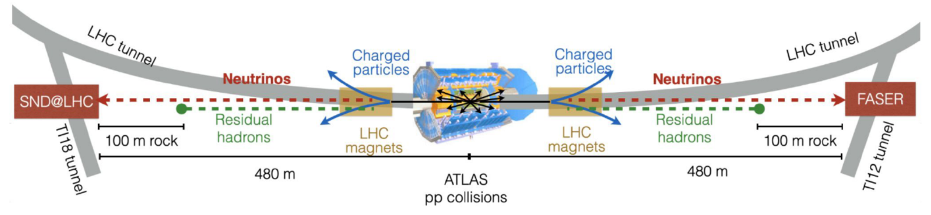
- Collider neutrinos are primarily produced in (semi-)leptonic W, Z^0, b, c, $\mathrm{K}^\pm$ and $\pi^\pm$ decays
- This production is highly η-dependent
    - For $4 < \eta < 5$ the bulk of neutrinos are produced in W decays $\rightarrow$ even flavour distribution
    - For $6.5 < \eta < 9.5$ neutrinos are produced in c and b decays



The tools of the trade: the Scattering Neutrino Detector at LHC (SND@LHC)

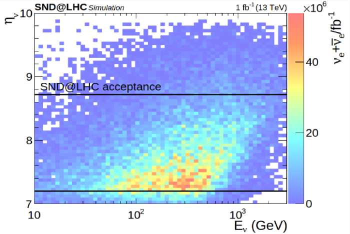
- Detector is placed in the region off-axis in the $7.2 < \eta < 8.4$ range from ATLAS → enhance charm origin of neutrinos
  - $\sim 90\%$ of incoming ν_e are produced in charm decays
  - $\sim 100\%$ of incoming ν_τ from charm decays
  - ν_μ have a more diverse parentage
- Experiment made of a *veto detector*, an *electromagnetic calorimeter and vertex detector* ($800\,\text{kg W}$) and a *hadronic calorimeter*

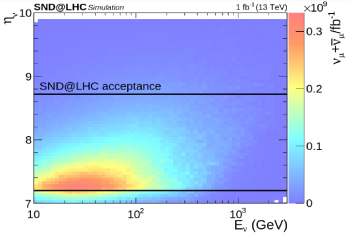


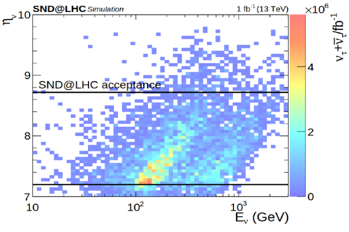


Incoming neutrino flux

- Incoming particle flux is heavily dominated by $\mu^{\pm} \rightarrow$ main background, worsened in 2024 by the change in beam optics
- Neutrino flux is dominated by ν_μ, first observation of collider neutrinos in March 2023, together with FASER
  - Observed through electronic detectors by looking for tracks without a parent muon
- New beam optics in 2025, lower muon flux.
- ν_τ are observed in emulsions, looking at the kink induced in the track
- ν_e may be observed in emulsions and electronic detectors, looking at electromagnetic clusters and distinguishing from muon background

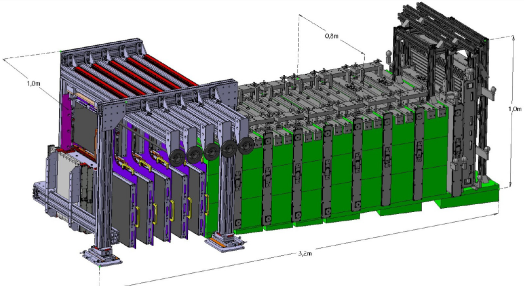


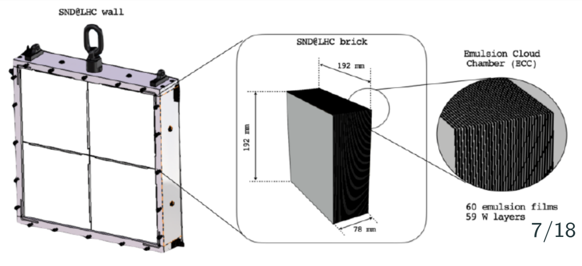




The tools of the trade: SND detector system

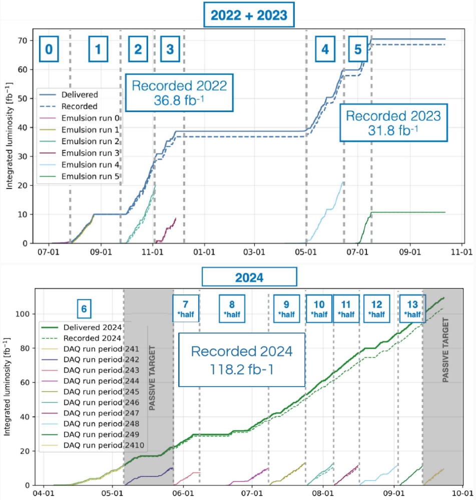
- Nuclear emulsions are known for their their unmatched position resolution (intrinsic point resolution $\sim 50\,\text{nm}$, attained point resolution $< 1\,\mu\text{m}$)
- In SND, the Emulsion Cloud Chamber technique is used:
  - The detector is divided into 5 walls, each made of 4 $19.2 \times 19.2\,\text{cm}^2$ bricks, each brick containing 59 emulsion films interleaved with $1\,\text{mm}$ tungten plates
  - Particles leave *track segments* which are observed after developing, swelling and scanning of the emulsion film, they are then fitted into tracks using a Hough transform and a Kalman filter
- Complementing the emulsion detector are SciFi detectors which offer good tracking $\sim 90\,\mu\text{m}$, excellent timing resolution $\sim 100\,\text{ps}$ and allow to timestamp emulsion data





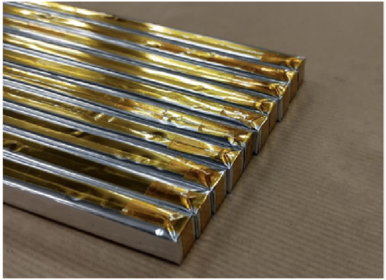
The tools of the trade: the data

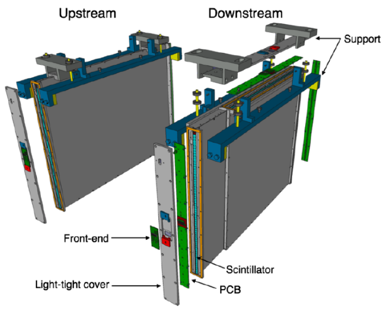
- $68.6\,\mathrm{fb}^{-1}$ of pp collisions recorded in electronic detectors in 2022-2023
  - 97% detector uptime
  - 5 emulsion target replacements
    - Track density $< 4 \times 10^5$ tracks cm^{-2}
    - Limit the exposure to $20\,\mathrm{fb}^{-1}$
- $118.2\,\mathrm{fb}^{-1}$ of pp recorded in electronic detectors in 2024
  - Larger than expected muon flux
  - Modified emulsion replacement strategy
    - Only lower half of the target is instrumented
    - $12\,\mathrm{fb}^{-1}$ exposure
    - 65% of events kept
- Back to previous performance in 2025: $\sim 120\,\mathrm{fb}^{-1}$ recorded



The tools of the trade: SND hadronic calorimeter

- The SND hadronic calorimeter is based on scintillating bars readout by SiPMs and an iron bulk
- It is divided into two sections: an 5 layer UpStream (US) and a 3 layer DownStream (DS) section $\rightarrow$ everything is run triggerless
- The US is made of $82.5 \times 6 \times 1\,\text{cm}$ scintillator bars covered in aluminised mylar and dual-side readout by 16 Hamamatsu S14160-6050HS and 2 S14160-3010PS SiPMs in order to deal with saturation
- The DS is made of $82.5 \times 1 \times 1\,\text{cm}^3$ and $63.5 \times 1 \times 1\,\text{cm}^3$ scintillator bars readout by the same large SiPMs as the US.

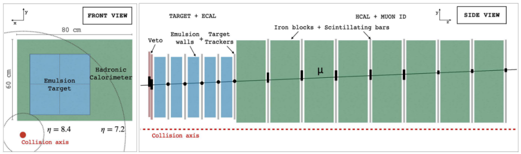


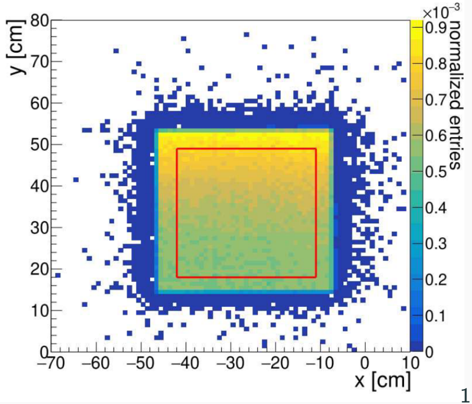


The detector at LHC

Muon flux measurement

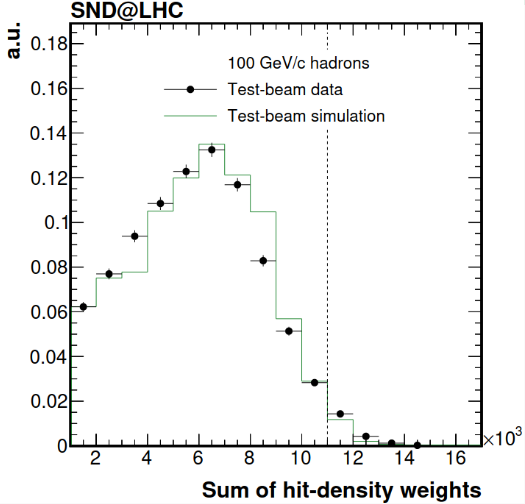
- Crucial for detector operation and physics analysis
  - Main backgrounds are muon induced
  - Measurement was performed for 2022 data https://link.springer.com/article/10.1140/epjc/s10052-023-12380-3
    - Excellent agreement reported in between all subsystems, including emulsions
    - Agreement with MC within 20%
  - Measurement of muon flux in heavy ion collisions
    - Allows for further validation of the background under different physics conditions
    - Cross-check of detector performance





Search for $\nu 0\mu$ events: ν_e CC and NC interactions

- Definition of a fiducial volume
  - No hits in the veto detector
  - No side-entering backgrounds
  - Signal acceptance 12%
- Identification of $\nu 0\mu$
  - SciFi hits weight function $w_i = \sum_{j\neq i}^{N} H(x_j - x_i + 1\,\text{cm}) \times \left[1 - H(x_j x_i - 1\,\text{cm})\right]$
  - No hits in the HCAL back planes $\rightarrow$ no reconstructed muon
  - Large SciFi weighted hits
    - Optimised through MC and validated in test beams
  - Large HCAL clusters
  - Selection efficiency 19%



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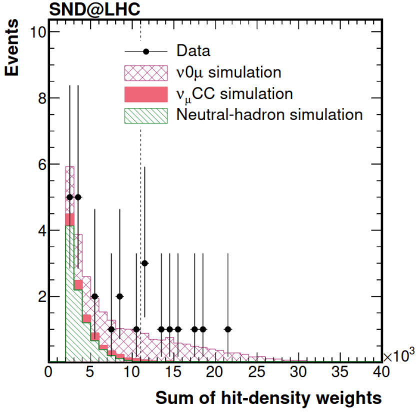
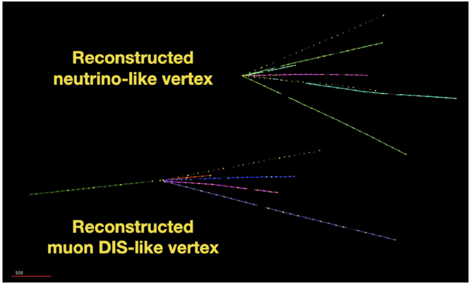
Observation of $\nu 0\mu$ events

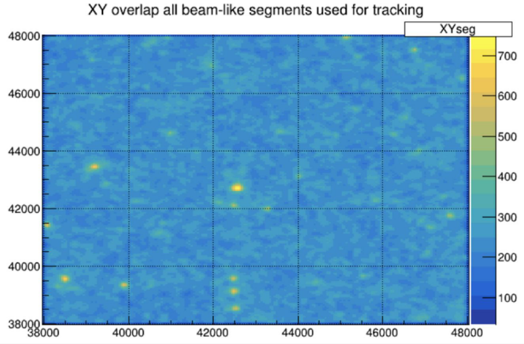
- Neutral hadron background
  - Control and signal region
  - Background scaling based on number of observed events in the control region $\rightarrow$ **0.01** background events in the signal region
- Neutrino background
  - ν_μ CC interactions are the dominant background $\rightarrow$ **0.30** events
  - ν_τ CC1μ interactions: **0.002** events expected
- 0μ obervation
  - Total background 0.32 ± 0.06 events
  - 7.2 signal events expected, $4.9\nu_e$ CC, 2.2 NC, 0.1 ν_τ CC $\rightarrow$ 5.5σ expected
  - 9 events observed $\rightarrow$ 6.4σ

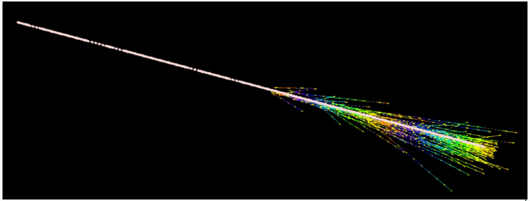


ν_e searches in emulsions

- Neutrino searches in emulsion are done by tagging “hot-spots” in emulsion overlays
- “Hot-spot” properties are then isolated: track angles, energy, topology
- Used to distinguish from background
  → reconstruction and analysis in progress

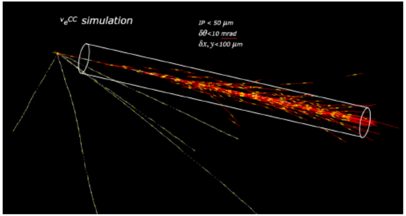


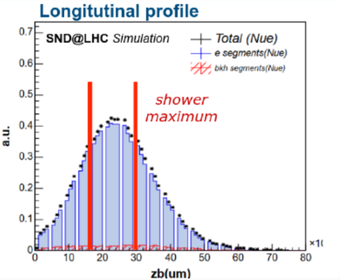


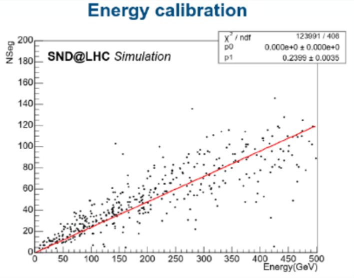


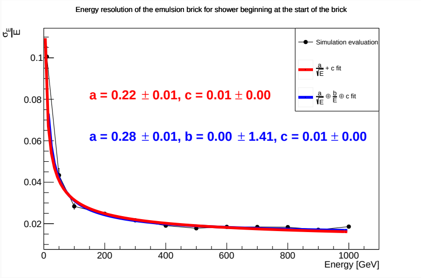
ν_e searches in emulsions: calorimetry

- Reconstruct segments/track within a cylinder
- Estimate the energy given the density
- Primary contributors: systematic efficiency of emulsion in high density-environments



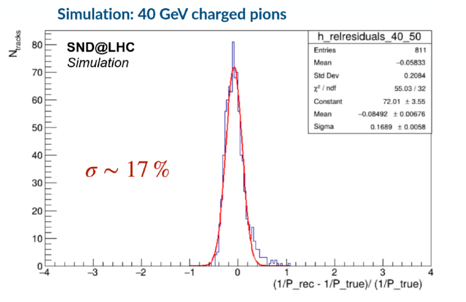


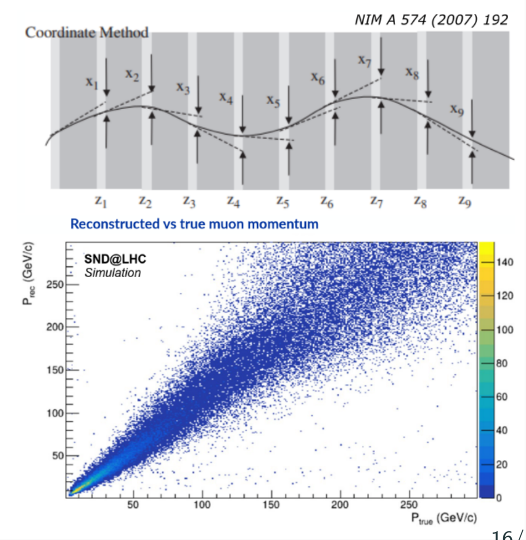




ν searches in emulsions: momentum reconstruction

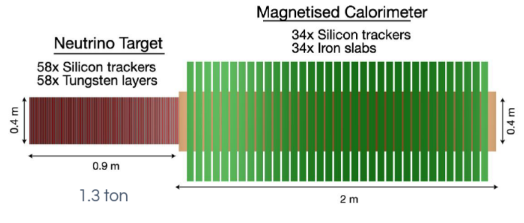
- Measure particle momentum based on Coulomb multiple scattering
- Estimated performance for charged pions $\sim 15 - 25\%$ (simulation)
- Estimated performance for neutral vertices $\sim 20\%$ (simulation)

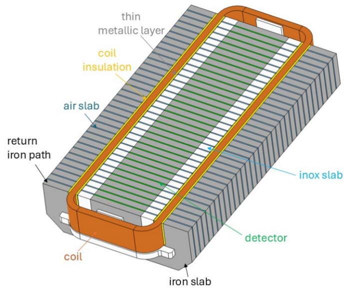




SND@HL-LHC

- Upgrade approved for Run4
  - Deal with higher luminosity and expand physics reach
- Repurpose the CMS Strip Tracker in the new vertex tracker and EM calorimeter $\rightarrow$ high performance silicon-tungsten tracker/high granularity ECAL
- Silicon-iron calorimeter is added to the back of the tungsten target to optimise hadronic shower reconstruction and muon tracking
- Fast timing trigger detector will be added to share trigger with ATLAS
- An iron HCAL with a magnet will be added to allow tracking of μ and distinction of ν and $\bar{\nu}$





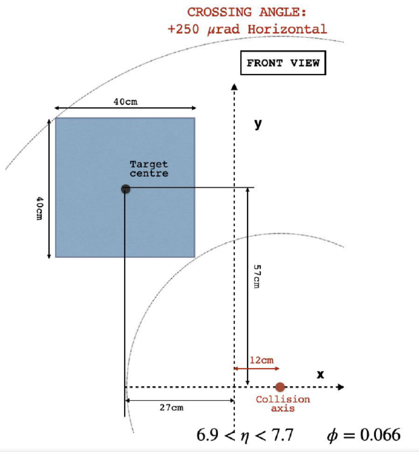
Conclusion

- SND@LHC measures neutrinos in the forward direction of pp collisions
- Rich physics program: forward charm production, lepton flavour universality, neutrino interactions
- $300\,\mathrm{fb}^{-1}$ of data accumulated over 4 years
- Collider neutrinos were reported in 2023
- Neutrinos without a final state muon were reported in 2024
- Muon trident was reported in 2025
- Upgrade is planned for HL-LHC $\rightarrow$ new physics reach, more statistics
- Our collider ν program is just starting!

Backup: SND@HL-LHC, detector location

- Detector will be moved upstream and upwards $\rightarrow$ done to fit in new conditions
- Could excavate a trench on the tunnel floor $\rightarrow \times 7$ statistics CERN-LHCC-2024-014

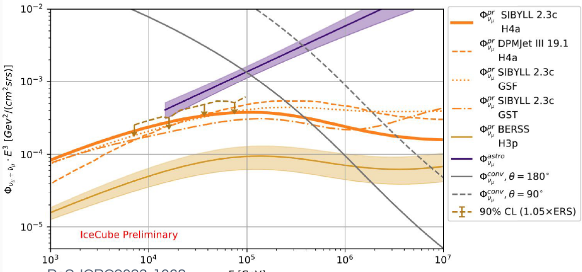
	CC DIS Interactions (3k fb^{-1}, 1.3 ton)	
Flavour	total (DPMJET)	cc-bar (DPMJET)
$\nu_\mu + \bar{\nu}_\mu$	1.5x10^4	2.4x10^3
$\nu_e + \bar{\nu}_e$	3.4x10^3	2.7x10^3
$\nu_\tau + \bar{\nu}_\tau$	2.8x10^2	2.8x10^2
Total	**1.9x10^4**	**5.4x10^3**



Backup: astroparticle physics and SND

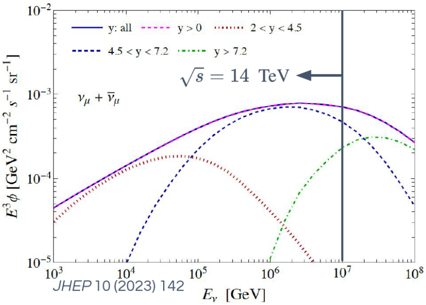
- ν flux from prompt charm decay is not known
  - Significant contribution in the transition region between atmospheric and astrophysical neutrino flux
- LHC neutrinos from charm with $\eta \sim 7$ correspond to atmospheric ν up to $E_\nu \sim 10^7$ GeV in the transition region

Current IceCube limits on the prompt neutrino flux, along with model predictions.



PoS-ICRC2023-1068

Prompt flux of atmospheric neutrinos broken down by charm hadron rapidity in the pp collision frame.



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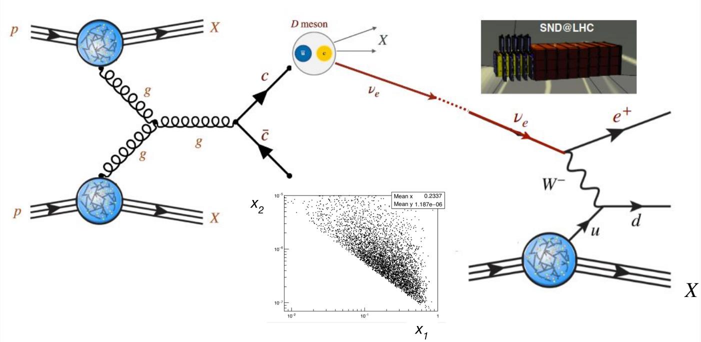
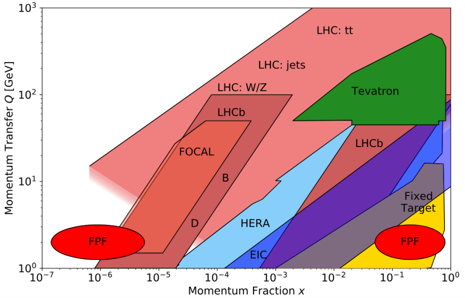
Backup: QCD@SND





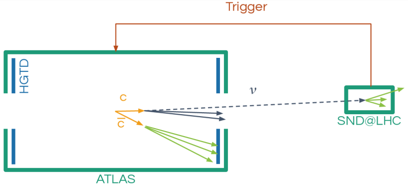
Adapted from Juan Rojo's CERN TH-Colloquium and the SND Technical Proposal

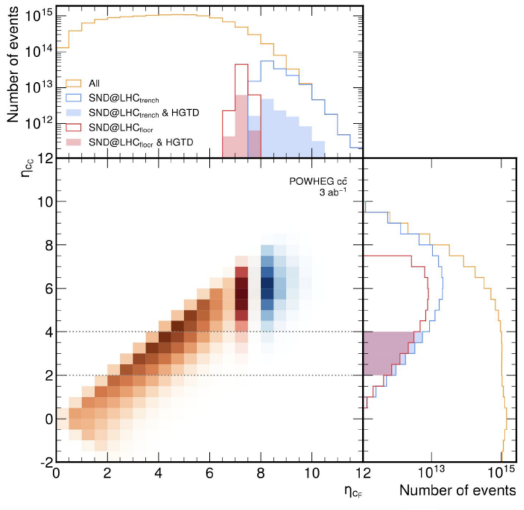
10.1088/1361-6471/ac865e

→ Charm decays significantly contribute to ν flux, forward charm production allows constraining gluon PDF at very small x

Backup: SND@HL-LHC, synergies with ATLAS and HGTD

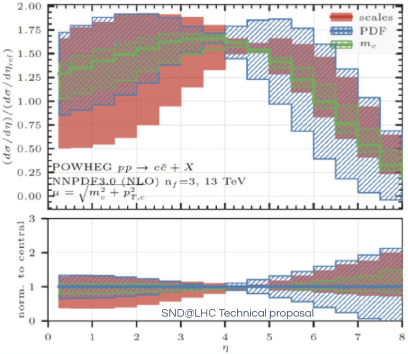
- About 10% of di-charm, $\mathcal{O}(500)$ events, would be emitted within the HGTD acceptance
- Could be used for a clean flavour ratio measurement
  $\rightarrow$ fast detectors to resolve pile-up + send a trigger signal to ATLAS

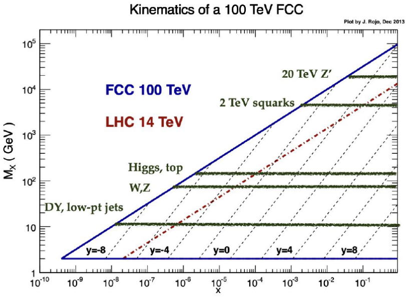


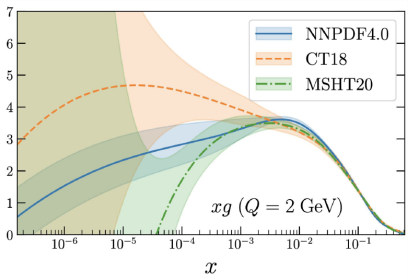


Backup: FCC-hh physics and SND

- Physics potential at FCC-hh is in large part located in very low x
  - EW, Higgs...
- Low x pdf are poorly constrained
  $\rightarrow$ SND@LHC!



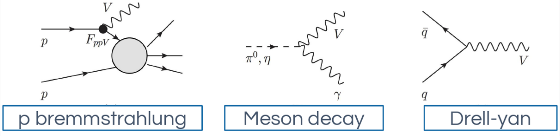




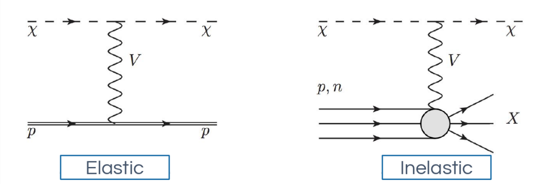
Backup: searches for FIPs and dark sectors at SND@LHC

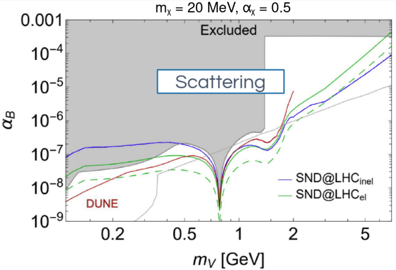
→ SND can detect dark sector particles in 2 main ways:

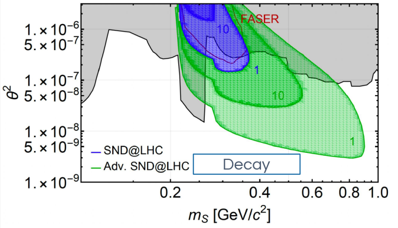
1. Scattering in the detector: e.g. interacting with nucleons through leptophobic portal



2. Decaying in the detector: appearence of charged tracks in the detector (DS, ALPs, HNLs, DP...)





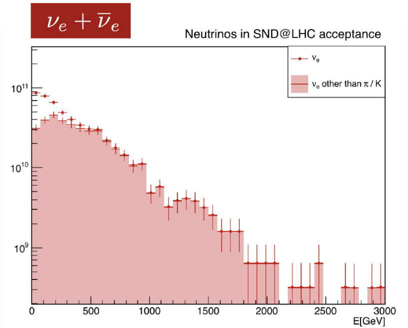


J. High Energ. Phys. **2022**, 6 (2022)

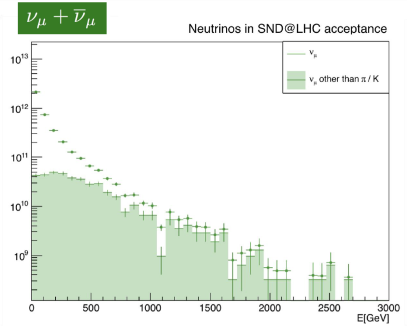
Backup: tests of lepton flavour universality

- Charm decays contribute to all neutrino flavours
- SND has excellent flavour identification capabilities

$\rightarrow$ allows for an independent LFU test in the neutrino sector: $\frac{N_{\nu_e}}{N_{\nu_\tau}}$ & $\frac{N_{\nu_e}}{N_{\nu_\mu}}$



$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \widetilde{f}_{c_i} \widetilde{\text{Br}}(c_i \rightarrow \nu_e)}{\widetilde{f}_{\text{D}_\text{s}} \widetilde{\text{Br}}(\text{D}_\text{s} \rightarrow \nu_\tau)}$$



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

Backup: SND timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

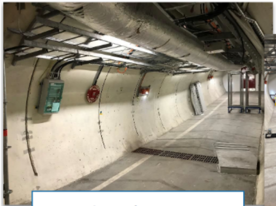
SND@LHC

January 2021

CERN approves new LHC experiment

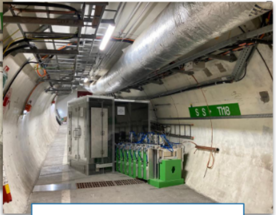
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

March 2021

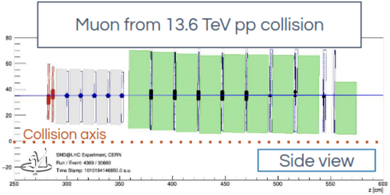


September 2021

December 2021



March 2022



July 2022