WORKSHOP

Machine Learning for HEP

Physics in SND@LHC

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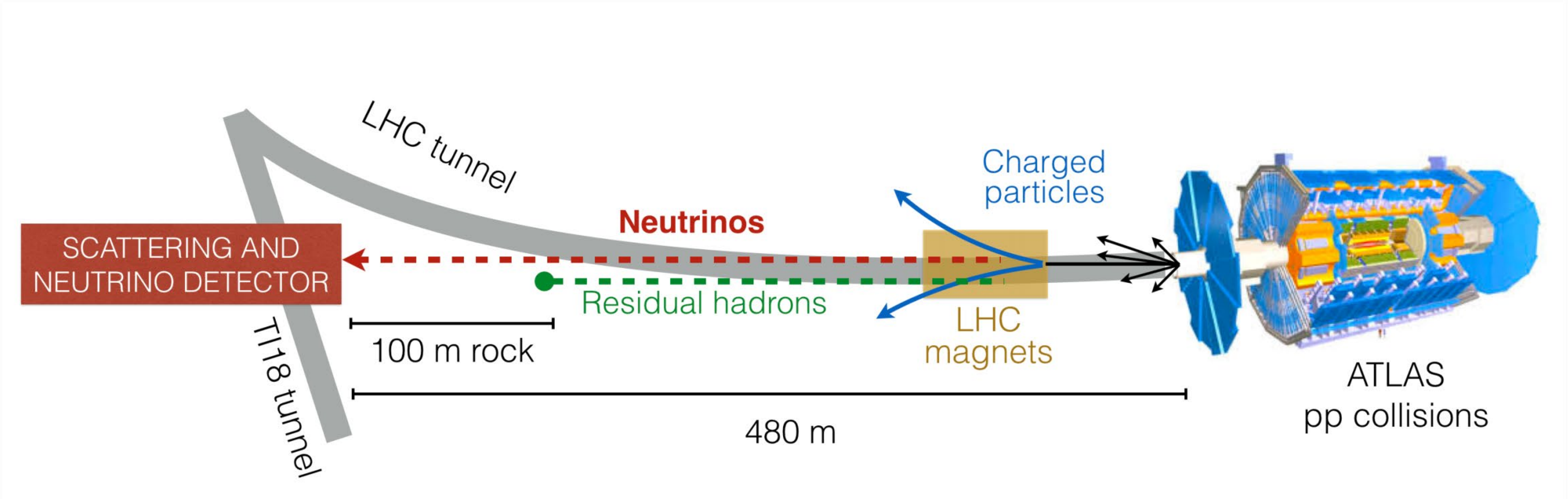
Physics in SND@LHC

Yeong Gyun Kim (GNUE)

SND@LHC

- The Scattering and Neutrino Detector at the LHC



SND@LHC

- Installed in the **TI18 tunnel** at the distance of **480 m from the ATLAS IP** along the beam collision axis.
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by **100 m rock**
- The pseudo-rapidity range covered by the target **$7.2 < \eta < 8.6$**, in which neutrinos are mostly produced in heavy quarks decays
- First Phase: Operation in **Run 3** to collect **290 fb^{-1}**


YCPZ01
TI18
DS 3H
SND.IRON.S.H

SND@LHC

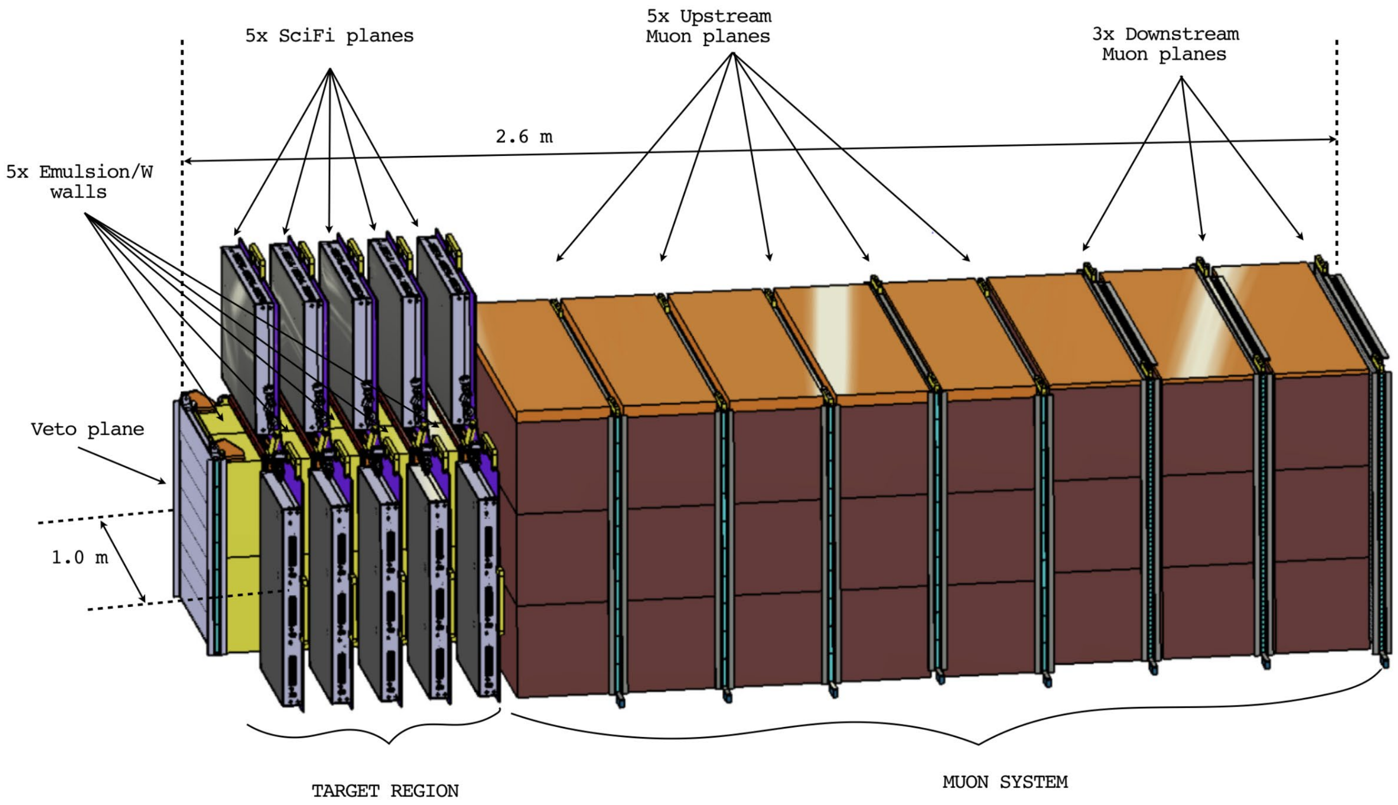


Figure 5: Layout of the proposed SND@LHC detector.

SND@LHC

- **VETO PLANE**:
  two planes of scintillator bars act as a veto for charged particles

- **TARGET REGION**:
  five walls of Emulsion Cloud Chamber (Emulsion+Tungsten), each followed by a Scintillating Fiber plane (timestamp)

- **MUON SYSTEM**:
  eight iron slabs, each followed by one or two planes of scintillating bars

SND@LHC

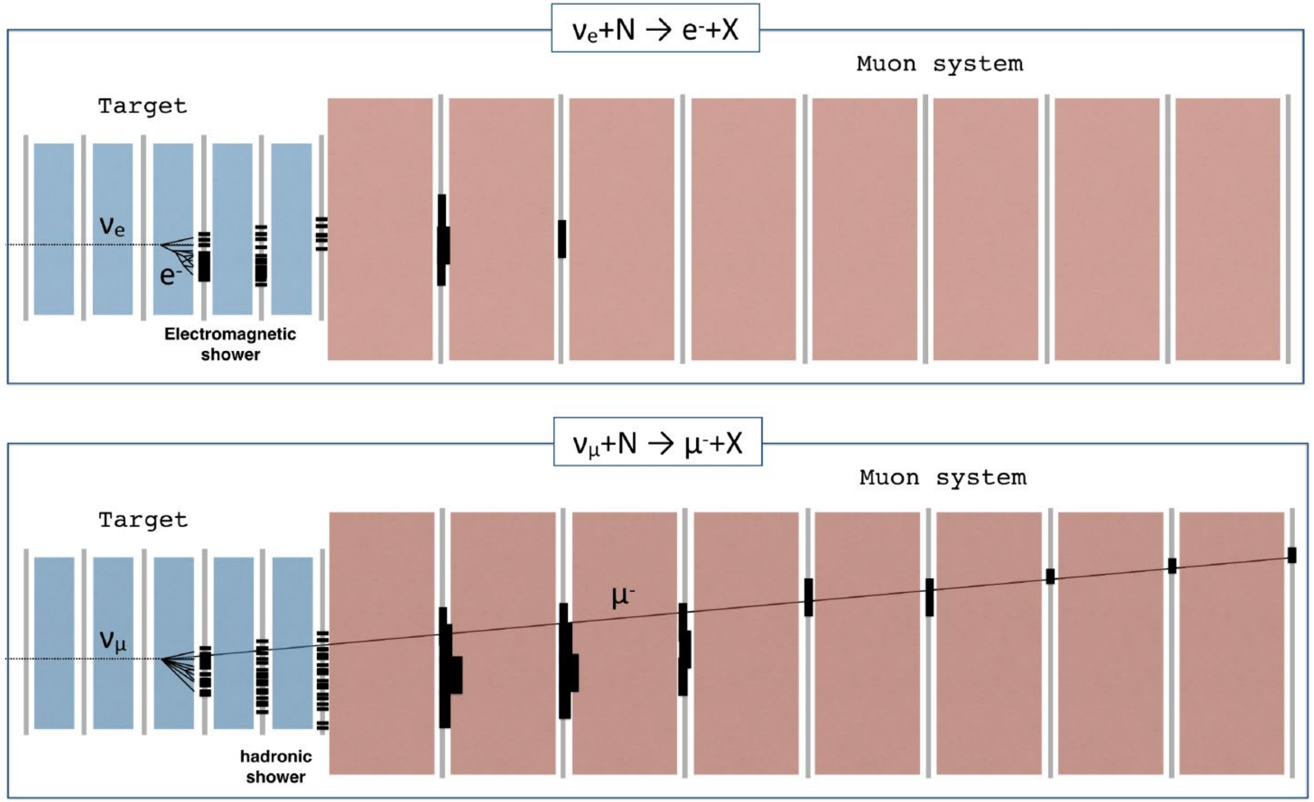


Figure 53: Schematic drawing of the reconstruction of a ν_e (top) and a ν_μ (bottom) charged-current interaction in the SND@LHC detector.

SND@LHC

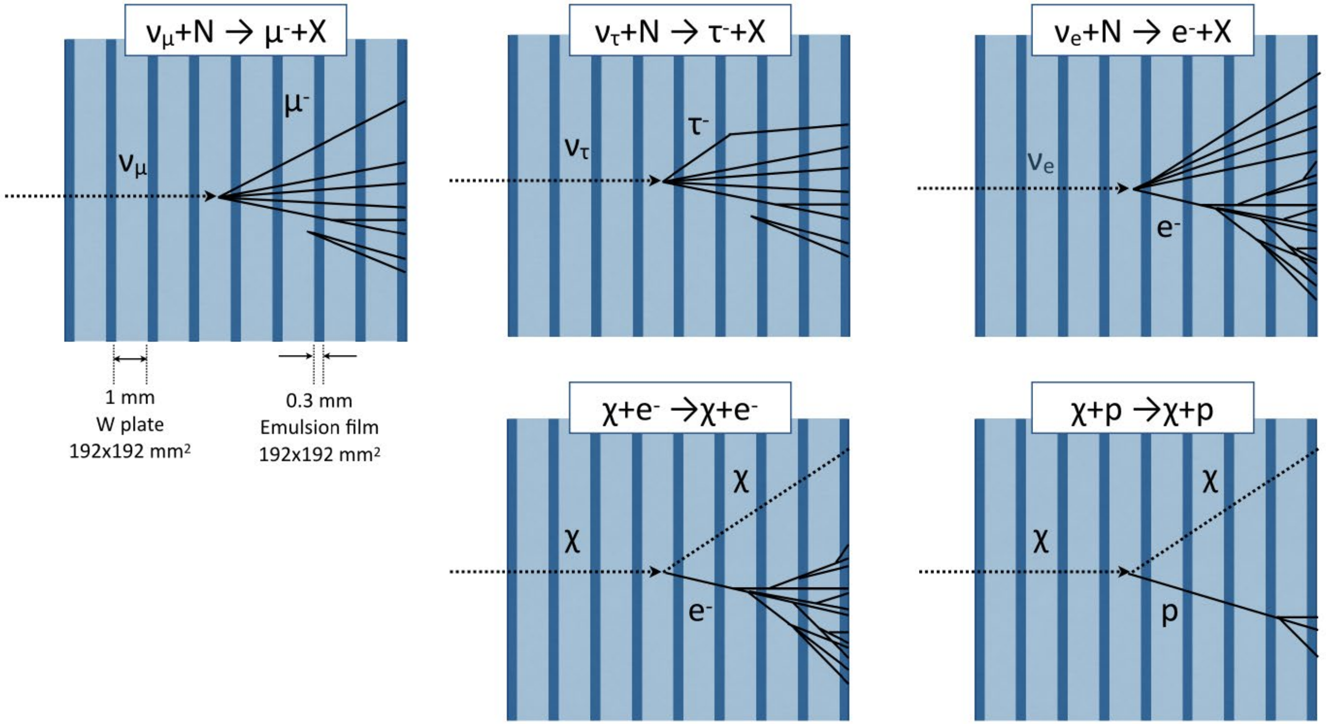


Figure 54: Illustration of some of the signal topologies that can be reconstructed in the SND@LHC brick.

Neutrinos in SND@LHC acceptance

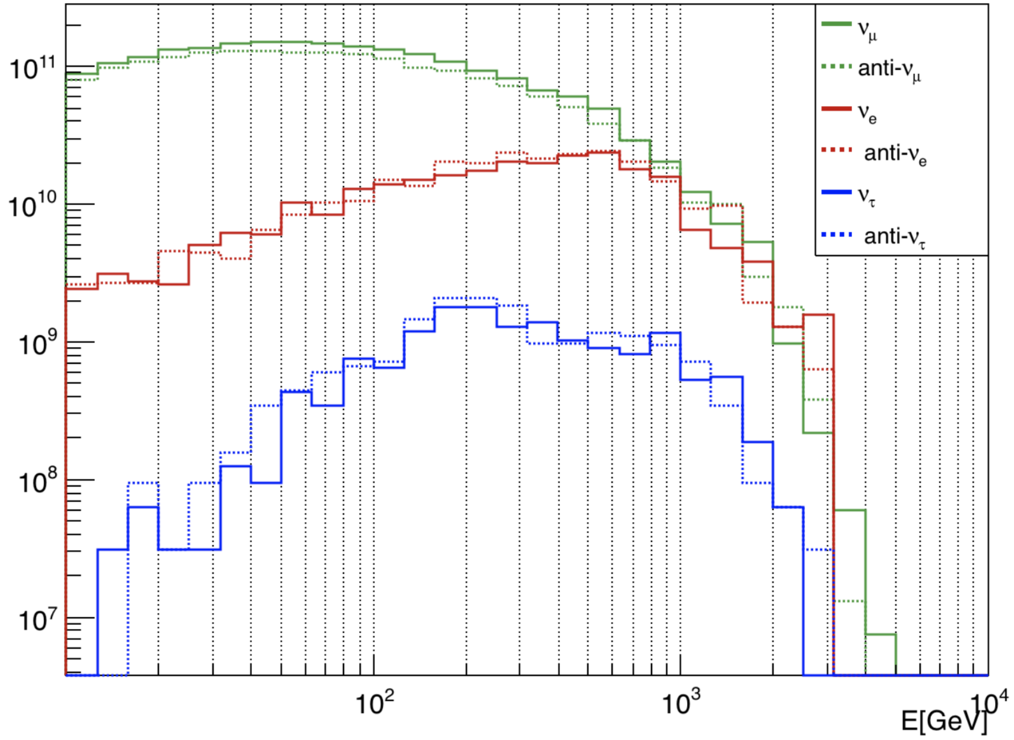
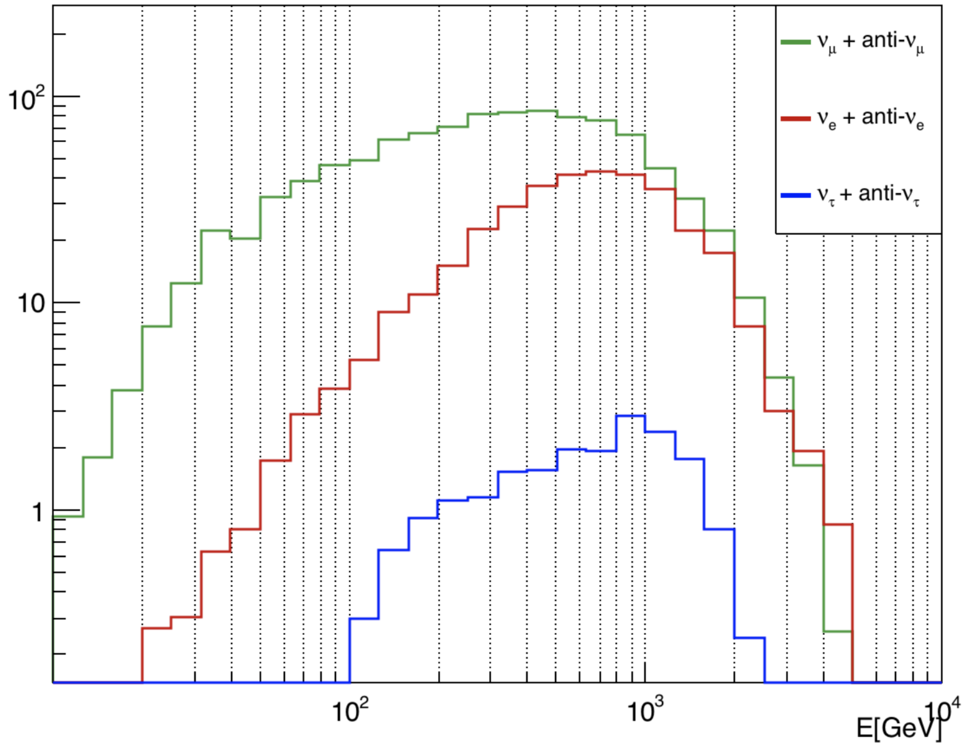


Figure 3: Energy spectrum of the different types of incoming neutrinos and anti-neutrinos as predicted by the DPMJET/FLUKA simulation. The normalisation corresponds to $150\,\mathrm{fb}^{-1}$.

CC DIS neutrino-induced events



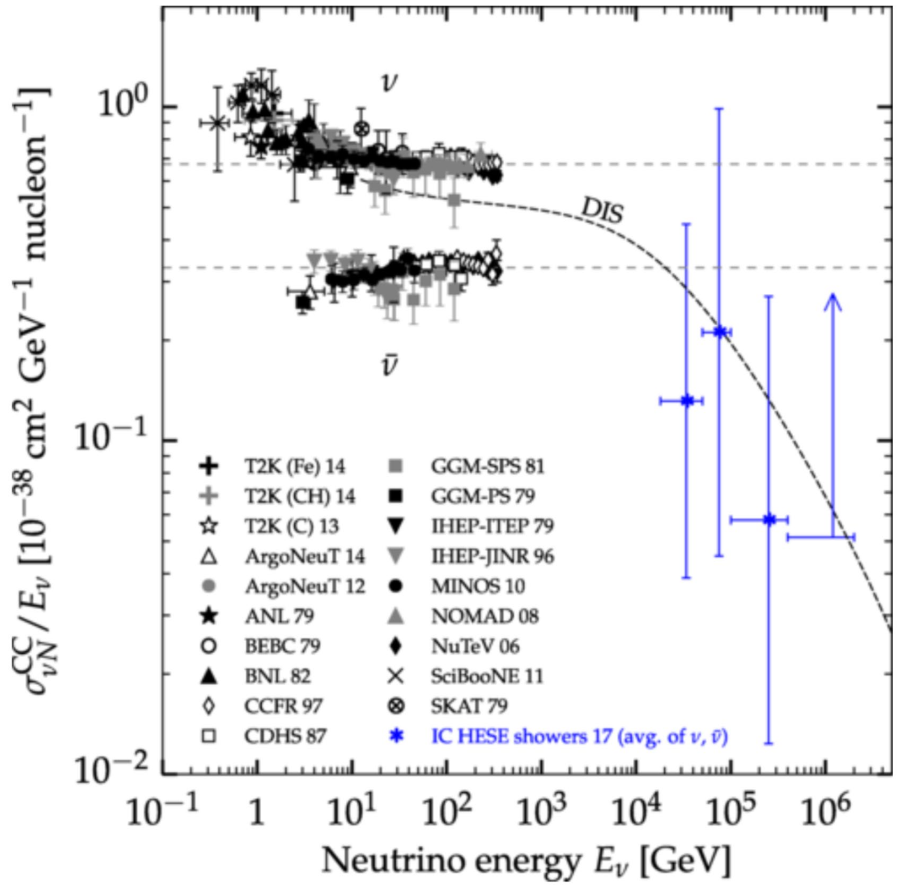
Tungsten 850 kg

Figure 59: Energy spectra of the different types of CC DIS interacting neutrinos. The normalisation corresponds to $150\,\mathrm{fb}^{-1}$.

Unexplored Area

- LHC neutrinos range from 10^2 GeV to TeV
- First detection of collider TeV neutrinos
- Measure pp → νX cross-section

Unexplored Area



Number of neutrinos in SND@LHC

Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
ν_μ	145	2.1×10^{12}	450	730	480	220
$\bar{\nu}_\mu$	145	1.8×10^{12}	485	290	480	110
ν_e	395	2.6×10^{11}	760	235	720	70
$\bar{\nu}_e$	405	2.8×10^{11}	680	120	720	44
ν_τ	415	1.5×10^{10}	740	14	740	4
$\bar{\nu}_\tau$	380	1.7×10^{10}	740	6	740	2
TOT		4.5×10^{12}		1395		450

Table 15: Number of neutrinos in the SND@LHC acceptance, charged-current and neutral-current neutrino interactions in the detector target, assuming $150\,\mathrm{fb}^{-1}$. Average energies are also reported.

SM physics in SND@LHC

Charmed-hadron production at LHC

- Electron neutrinos in $7.2<\eta<8.4$ mainly come from the decay of charmed hadrons produced in the LHC pp collisions.
- Provide insight into the heavy-quark production in an unexplored domain.
- Dominant partonic process for associated charm production at the LHC is gluon-gluon scattering.
- Electron neutrino measurements can constrain the uncertainty on the gluon PDF in the very small (below 10^{-5}) x region.

Charmed-hadron production at LHC

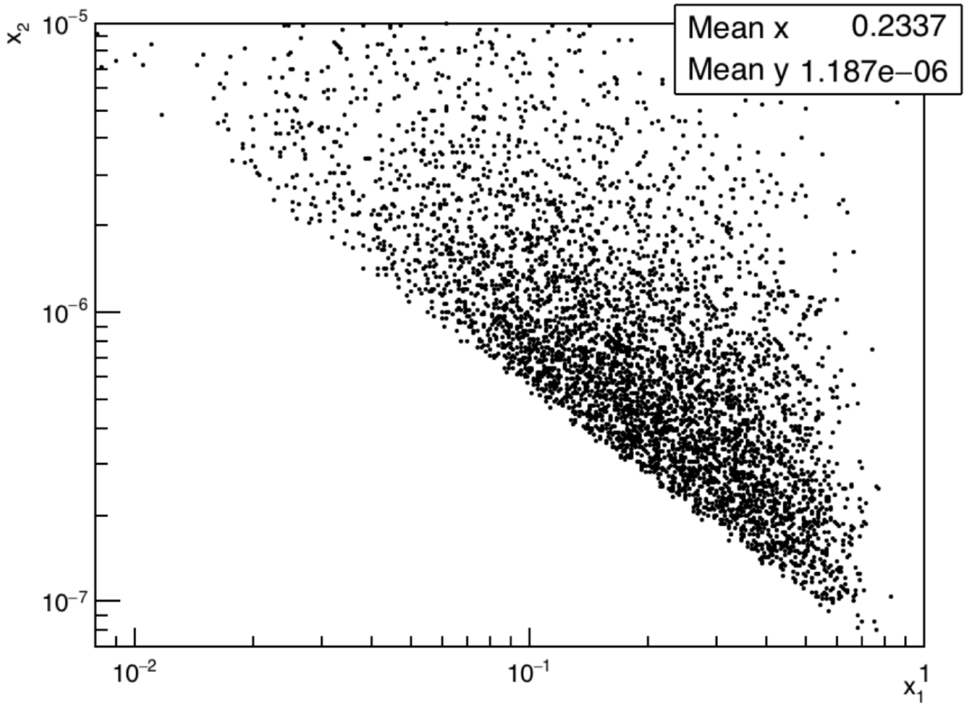


Figure 65: Correlation between x_1 and x_2 momentum fractions for events with neutrinos in the SND@LHC acceptance.

Neutrino-induced charm production

- High-energy neutrino interactions produce charmed hadrons at the level of 10 percent of the total rate at the SND@LHC energies.
- The nuclear emulsion technology offers a unique possibility to identify charmed hadrons through the observation of a two vertex topology, such that no kinematic cuts are required.

Neutrino-induced charm production

- Charmed-hadron production in anti-neutrino interactions selects the anti-strange quark in the nucleon. Measure the s-quark content of the nucleon.

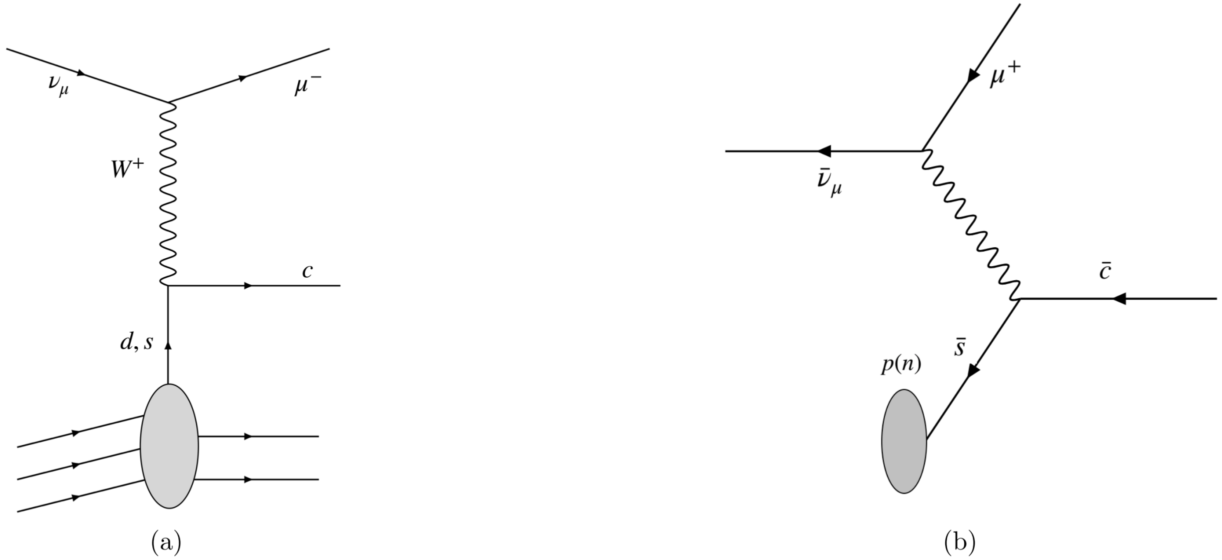


Figure 71: Charm production in neutrino (a) and anti-neutrino (b) charged-current interactions.

BSM physics in SND@LHC

Example: leptophobic DM

- A theory with a scalar LDM χ coupled to the SM via a vector mediator V that interacts with the baryon current J^B

$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_\chi V^\mu (\partial_\mu \chi^\dagger \chi - \chi^\dagger \partial_\mu \chi), \quad J^B_\mu = \frac{1}{3} \sum_q \bar{q} \gamma_\mu q$$

Experimental Setup

- Consider experimental setup:

  detector thickness = 30cm (for scattering)

  exposed to pp collision (13 TeV, 150 fb^{-1})

Scattering

- LDM scattering off protons

- Two types of scattering off protons:
elastic and inelastic producing an isolated proton or hadronic showers, respectively.

- Most of neutrino scattering events are inelastic.
$N_{NC,el}/N_{NC,inel} \sim 4 \cdot 10^{-3}$, which correspond to 1.7 elastic neutrino scattering events expected during Run3.

The ratio of $\sigma_{el}/\sigma_{inel}$

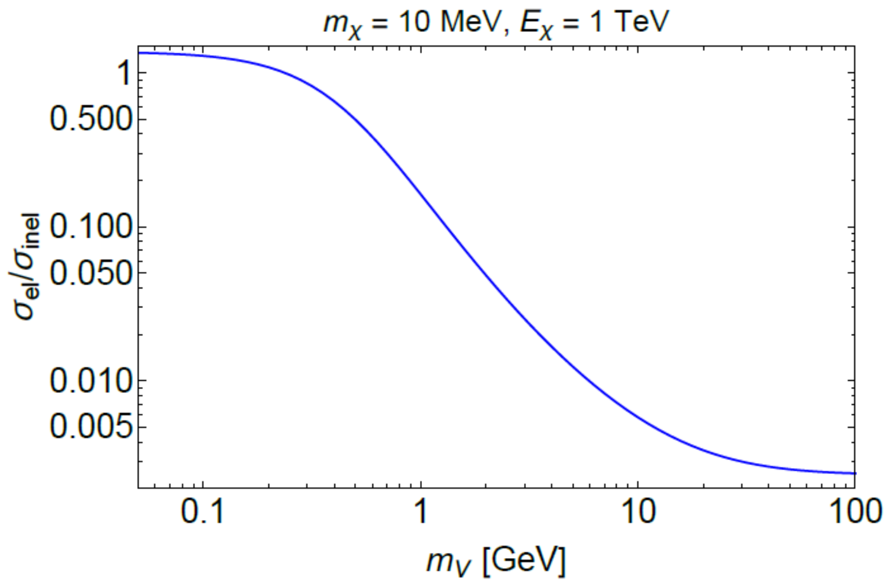


Figure 2. The ratio $\sigma_{\rm el}/\sigma_{\rm inel}$ of elastic and inelastic cross sections in the model with a vector-like mediator V interacting with protons and a scalar dark sector particle χ of mass $m_\chi = 10$ MeV and energy $E_\chi = 1$ TeV. The minimal proton recoil energy $E_p > 100$ MeV is required. For the description of the elastic and deep inelastic scattering (DIS), see Appendix D.

Scattering

- For $m_V \leq 1$ GeV, the elastic and inelastic scattering yields may be comparable, therefore the background-free elastic signature is more sensitive.

- For $m_V \geq 1$ GeV, LDM is more likely to scatter inelastically. In this case, we need to see the events over the numerous neutrino scattering background.

Scattering

- The total number of NC neutrino events is a subject of theoretical uncertainties.

- The ratio of N_{NC}/N_{CC} for neutrino is uniquely predicted within the SM.
  (Overall uncertainty at SND@LHC ~ 10%)
  (N_{CC} = 1395, N_{NC} = 450 from simulation for the SND@LHC setup)

Number of events

$$N_{\text{events}} = 2 \cdot N_{\chi}^{\text{SND@LHC}} \times n_{\text{detector}} \times \begin{cases} Z\sigma^{\text{el}}_{\text{scatt}}(\langle E_\chi \rangle) \cdot l^{\text{scatt}}_{\text{det}}, & \text{elastic signature} \\ A\sigma^{\text{inel}}_{\text{scatt}}(\langle E_\chi \rangle) \cdot l^{\text{scatt}}_{\text{det}}, & \text{inelastic signature} \end{cases}$$

- $N_\chi^{SND@LHC}$: the number of χ particles produced in the direction of the SND@LHC detector volume
- $n_{detector}$: the detector's atomic number density (the tungsten material is considered)
- Z, A : atomic and mass numbers of the target material
- σ : the elastic or inelastic scattering cross section of χ particles

Production of χ particles

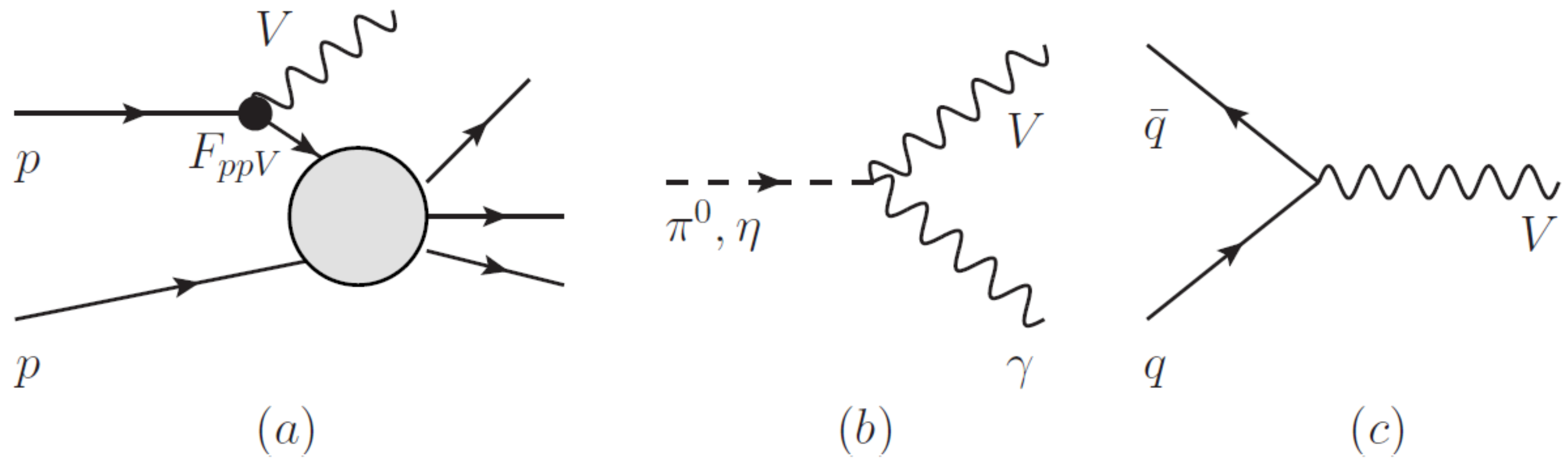
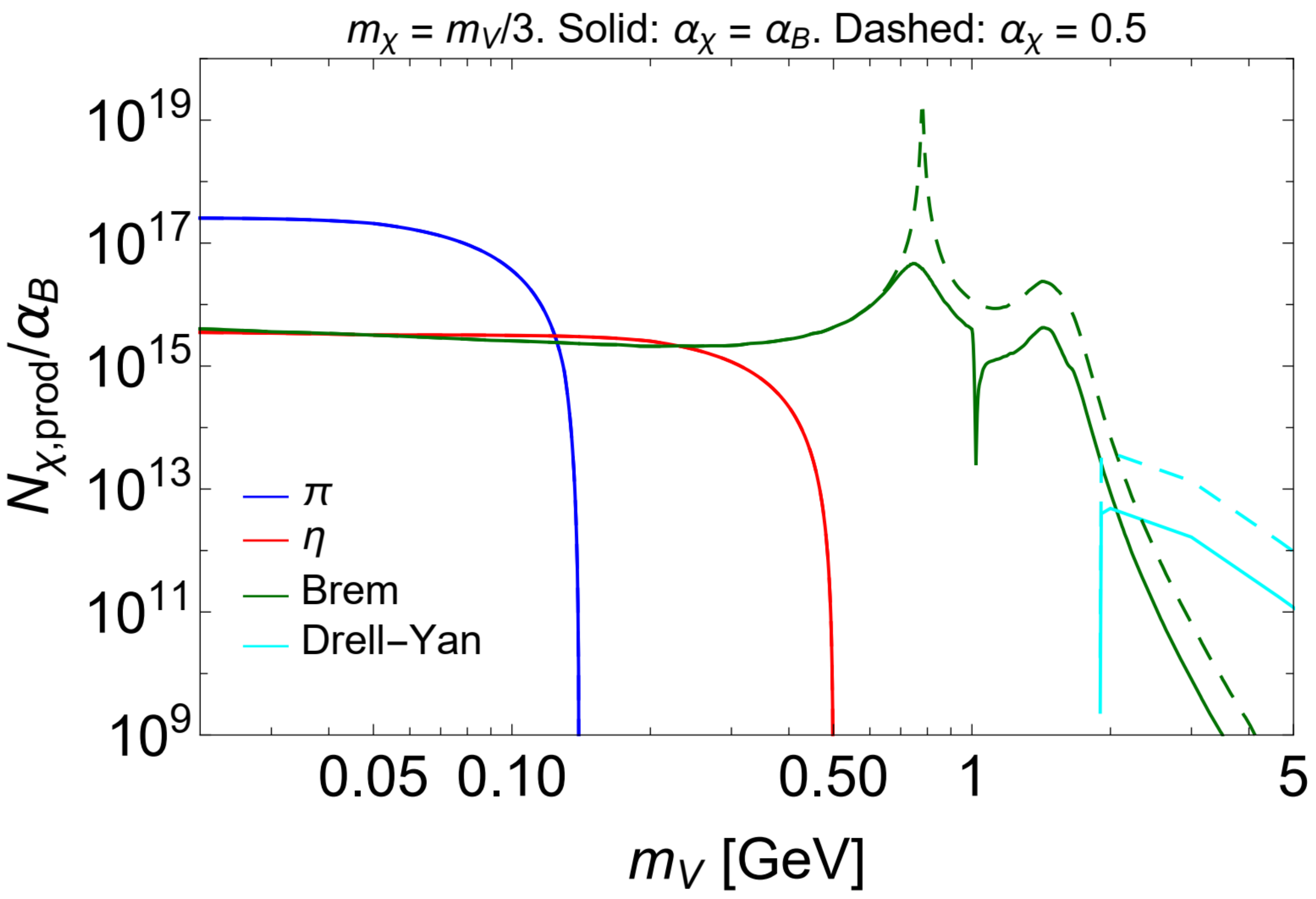


Figure 4. Diagrams of the production of the leptophobic mediator V (a) by proton bremsstrahlung, (b) in decays of light unflavored mesons, and (c) in Drell-Yan process.

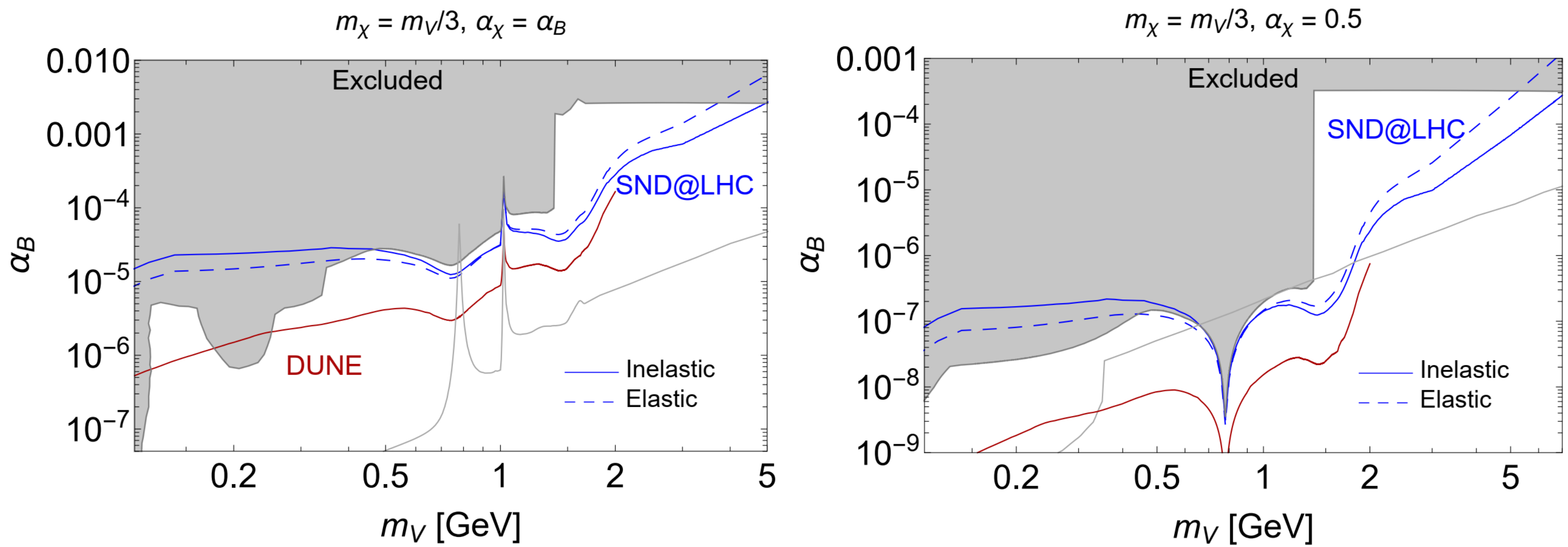
Production of χ particles



Production of χ particles

- The main production channel for masses $m_V \le m_\eta$ is decays of mesons
- For masses $m_\eta \le m_V \le 3$ GeV it is the proton bremsstrahlung
- For $m_V \ge 3$ GeV it is the Drell-Yan process

Sensitivity (scattering)



Summary

- Neurino cross-sections at uncharted energies
- Probe charm production
- SM tests in neutrino sector

- Search for FIPs (feebly interacting particles)

Thank you

Production of χ particles

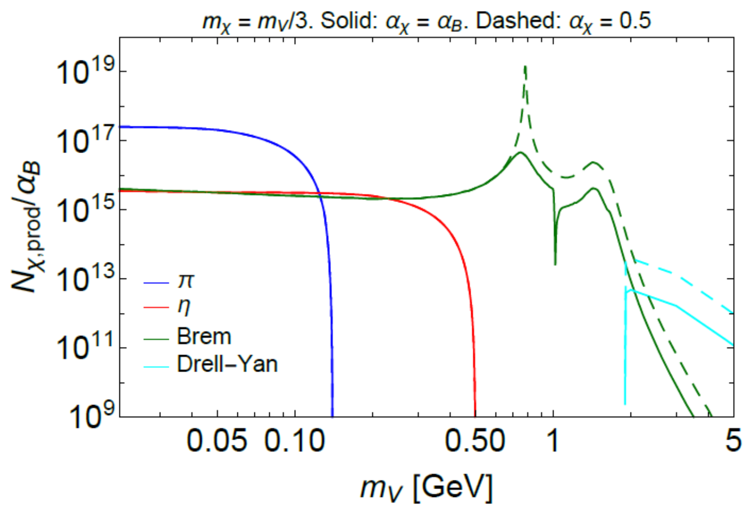


Figure 5. The number of χ particles produced in the direction of the SND@LHC experiment, assuming the integrated luminosity $\mathcal{L} = 150\ \text{fb}^{-1}$. $m_\chi = m_V/3$ is assumed. Wiggles around V masses of 782 MeV, 1020 MeV and $\simeq 1.7$ GeV are caused by the mixing of the mediator with isoscalar vector mesons ω, ϕ, and their excitations, which leads to the resonant enhancement of 1) the ppV form-factor for the production by the proton bremsstrahlung, and 2) the decay width of the leptophobic mediator V into hadrons (and hence to a suppression of $\text{Br}(V \to \chi\bar{\chi})$). See text and Appendix C for details.

Sensitivity (scattering)

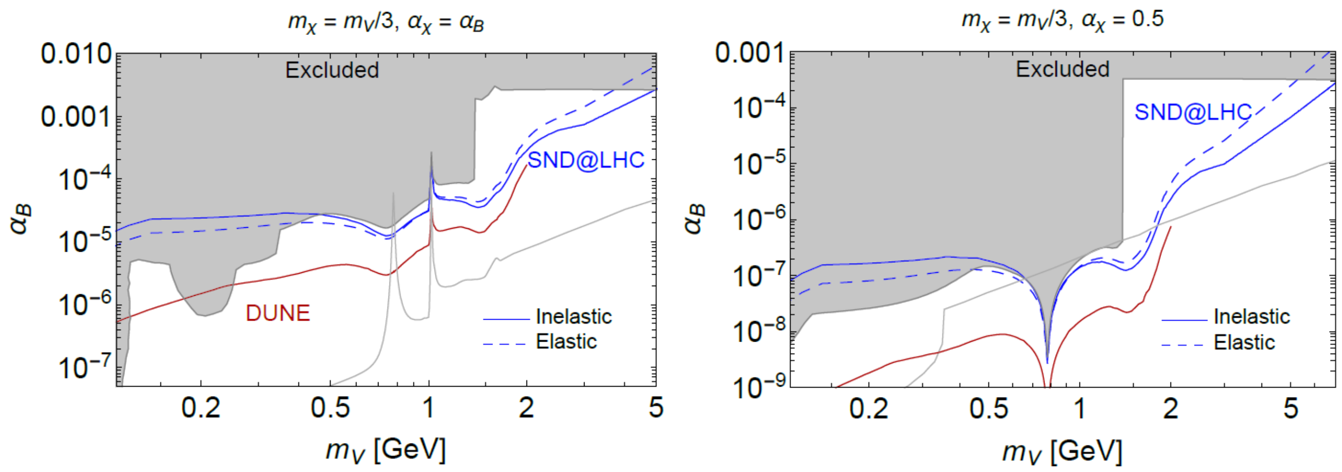


Figure 6. Sensitivity of the SND@LHC experiment to the leptophobic portal (3.2) assuming the integrated luminosity of $\mathcal{L} = 150\ \text{fb}^{-1}$ (2σ CL). The sensitivity is shown under an assumption $m_\chi = m_V/3$ for two different choices of the coupling of mediator to χ particles $\alpha_\chi = \alpha_B$ (left), and $\alpha_\chi = 0.5$ (right). The considered signatures are the elastic scattering off protons (the dashed blue line, corresponding to 5 signal events) and the deep-inelastic scattering (the solid blue line, corresponding to 100 signal events), see text for details. By the red line, we show the sensitivity of the DUNE experiment from Ref. [24], assuming 100 events. We rescale the previous bounds, according to our description of the proton form-factor in bremsstrahlung and $\text{Br}(V \to \chi\chi)$. The thin gray line corresponds to model-dependent constraints from invisible decays $B \to K + \text{inv}$ [50] (see text for details).

Forward Physics Facility

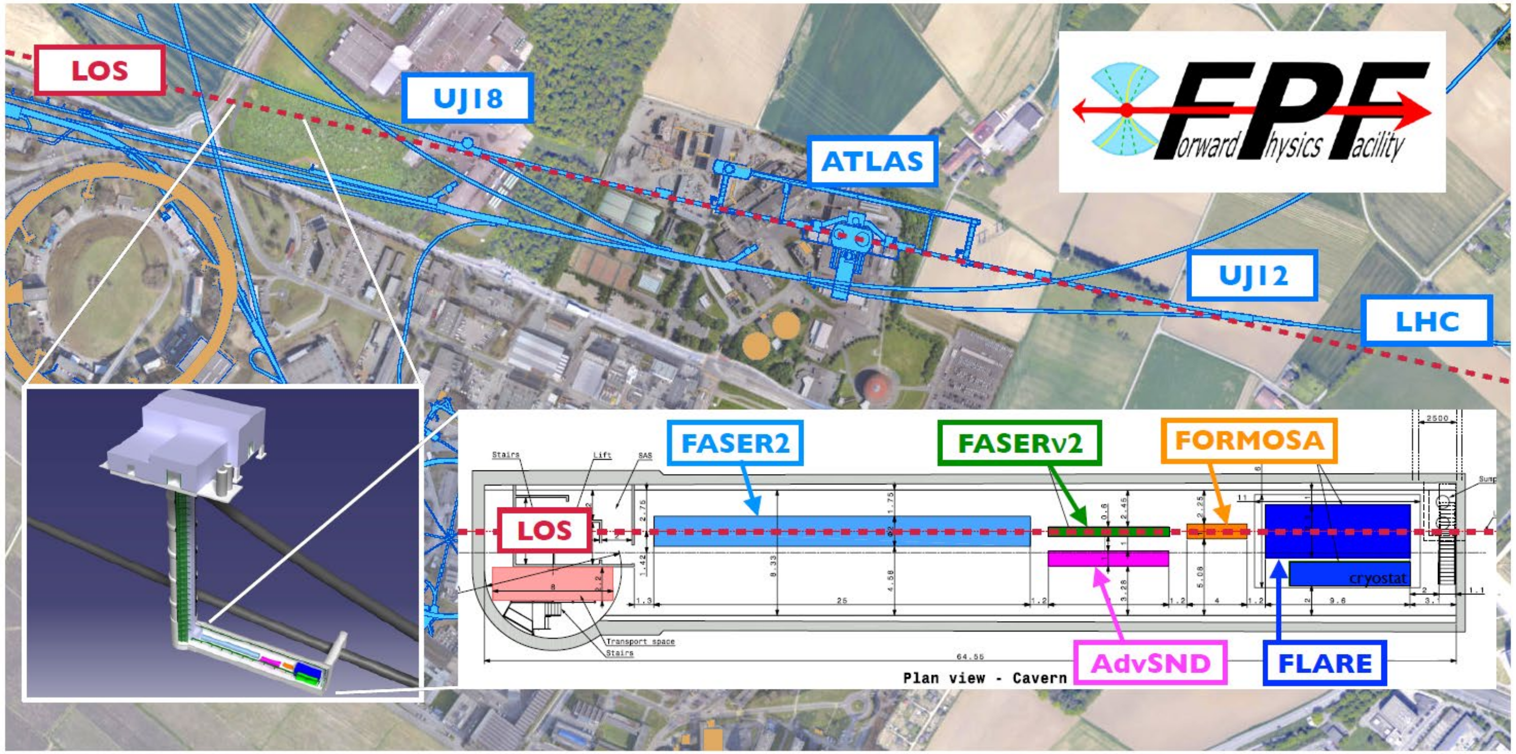
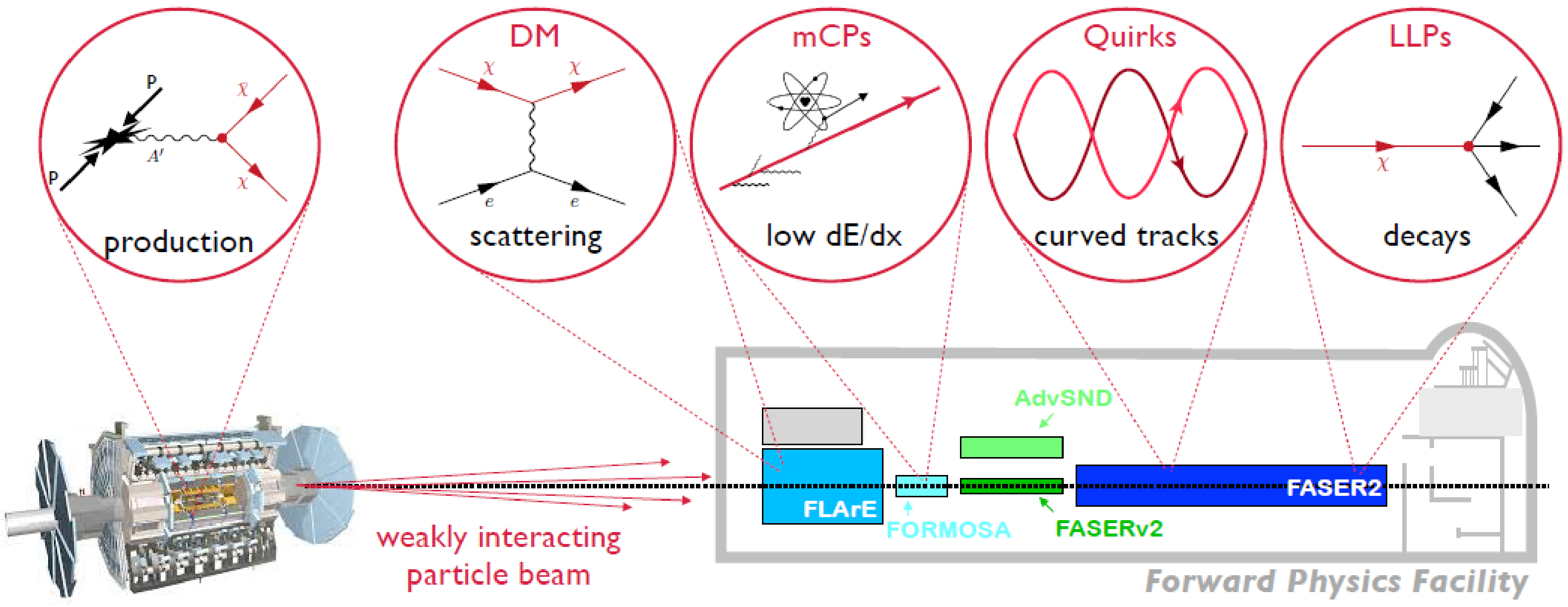


Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

Experiments

- **FASER2, FASERν2, AdvSND, FLArE, FORMOSA**



AdvSND

- **Adv**anced **SND**@LHC
- It will consist of two detectors (NEAR, FAR).
- The FPF would host the FAR detector.

	AdvSND - NEAR	AdvSND - FAR
η	[4.0, 5.0]	[7.2, 8.4]
target mass (tonne)	5	5
front surface (cm^2)	120×120	100×55
distance from IP (m)	55	630

Table 3.6: Parameters of the two AdvSND detectors in the NEAR and FAR locations.

AdvSND

- Both detectors will be made of three elements

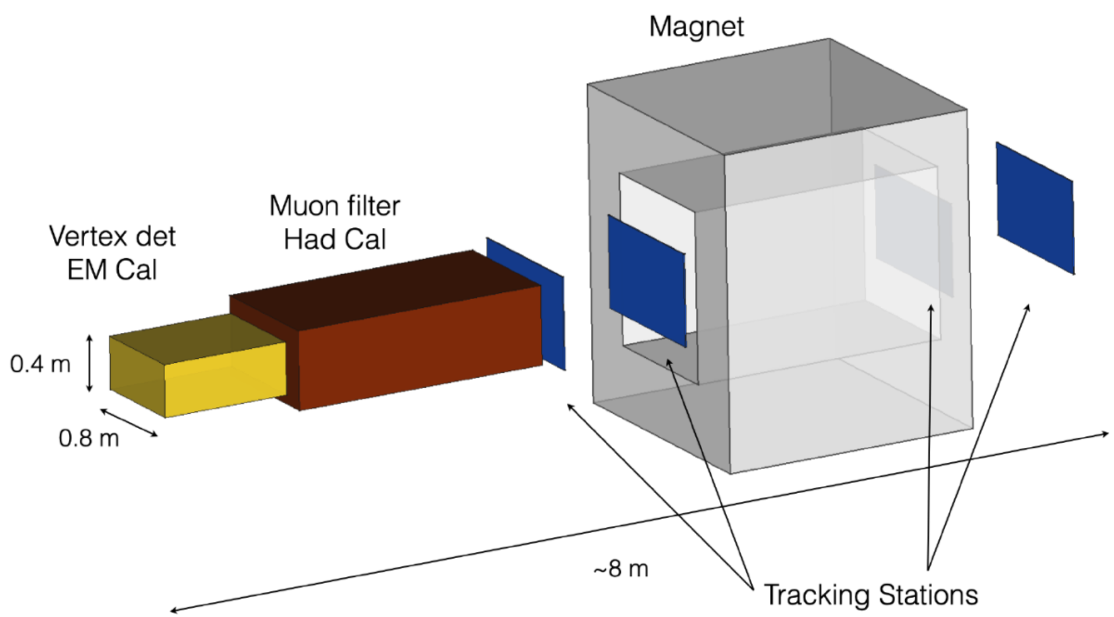


Figure 3.15: Layout of the AdvSND detector.

AdvSND (QCD)

- Electron neutrino measurements can constrain the uncertainty on the gluon PDF in the very small (below 10^{-5}) x region.
- Large systematic uncertainty mostly comes from the procedure linking neutrinos to charm.
- Charm yield was measured with high precision by **LHCb** experiment in the $4.0<\eta<5.0$ region.
- The comparison between neutrino measurements and LHCb direct charm measurements will reduce the systematic uncertainties.

AdvSND (Neutrinos)

- AdvSND will be able to perform neutrino cross section measurements with the NEAR detector, since the neutrino flux from charm and beauty in the 4.0<η<4.5 region is very reliable, given the measurements performed by LHCb.

AdvSND - NEAR				
	ν in acceptance		CC DIS	
Flavour	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	2.1×10^{12}	3.3×10^{11}	980	200
$\nu_e + \bar{\nu}_e$	2.2×10^{12}	3.3×10^{11}	1000	200
$\nu_\tau + \bar{\nu}_\tau$	2.7×10^{11}	1.4×10^{11}	80	50
Tot	5.4×10^{12}		2.5×10^{3}	

Table 3.5: The number of neutrinos passing through the NEAR detector of AdvSND and the number of CC neutrino interactions in the detector target, assuming $3000\,\mathrm{fb}^{-1}$, as estimated with the `Pythia 8` generator.