Potential for dark matter searches with the SND@LHC experiment

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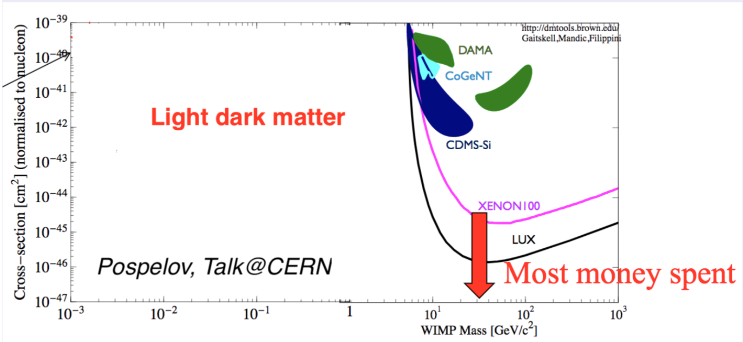
Explaining BSM phenomena

Our questions with no answer so far:

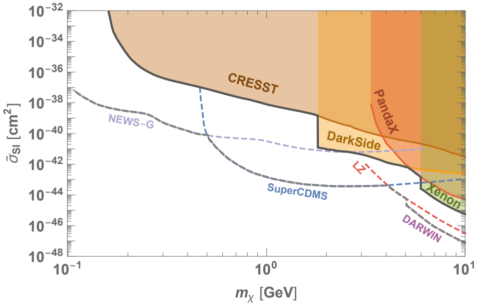
- what is dark matter?
- where has the antimatter gone?
- how do neutrinos acquire a mass?

What is the energy scale of New Physics?

- not the one we are focusing on currently, as e.g. for dark matter:



Light dark matter

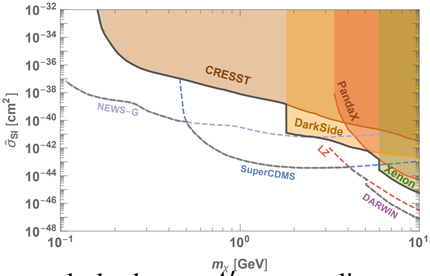


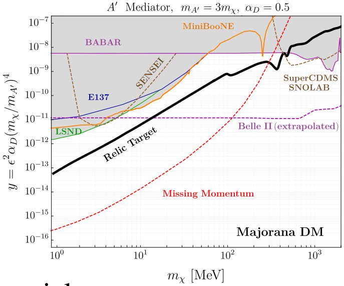
- weakly interacting dark matter is heavily constrained
- Lee-Weinberg bound $m_{DM} > 2$ GeV
  - can be lifted by introducing new light boson mediators
  - DM-SM coupling reduced, DM annihilation cross section increased
- “mediators” as “portals” to a “dark sector”
  - feebly interacting (“FIPs”) and low mass

arXiv:1909.08632

Example: dark photon framework

Translation between direct detection and accelerator searches:

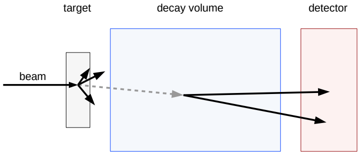




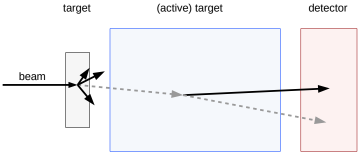
- dark photon A' as a mediator, and DM particles χ:
  - α_D - a coupling constant between A' and χ
  - ϵ - mixing parameter between A' and SM photon
  - m_χ and $m_{A'}$ - the masses of two new particles
  - parameter $y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$
  - in the $(m_{A'}, y)$ plane, the relic abundance curves are invariant under a change of the the α_D and the mass ratio

arXiv:1909.08632 arXiv:1808.05219

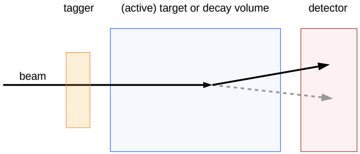
Man-made Light dark matter



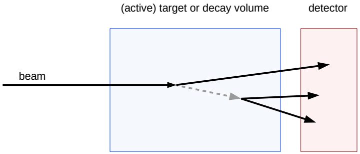
hidden particle decaying into visible particles



hidden particle scattering

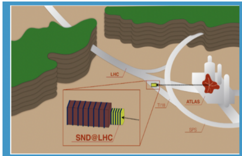


missing energy or momentum

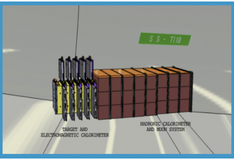


displaced vertex and/or peculiar final state

- provides sensitivity to extremely small couplings ϵ^2
- imperative: small or no background
- E^{miss} or p^{miss} techniques sensitive to ϵ^2, others to ϵ^4



SND-LHC: Scattering and Neutrino Detector at the LHC



A newly proposed, compact and stand-alone experiment designed to:

- perform measurements with neutrinos
- and search for new feebly interacting particles,

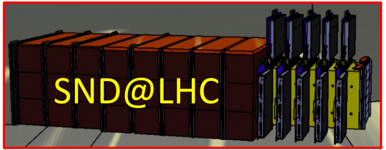
produced at the LHC, in an unexplored range of $7.2 < \eta < 8.6$

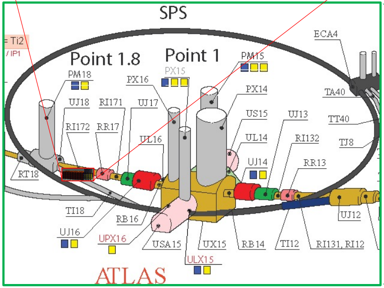
- Letter of intent: LHCC-I-037, 27 Aug 2020
- Technical proposal: LHCC-P-016, 22 Jan 2021
- Experiment approval: Grey Book database, 17 Mar 2021
- Experiment website: http://snd-lhc.web.cern.ch/
- First phase: operation in Run 3 to collect 150 fb^{-1}

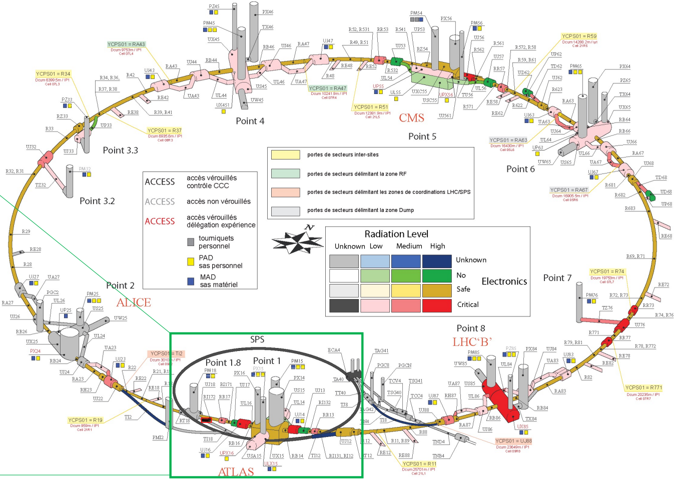
SND@LHC is currently a collaboration of 180 members from 20 institutes

Location: (LEP) Injection Tunnel 18, TI18

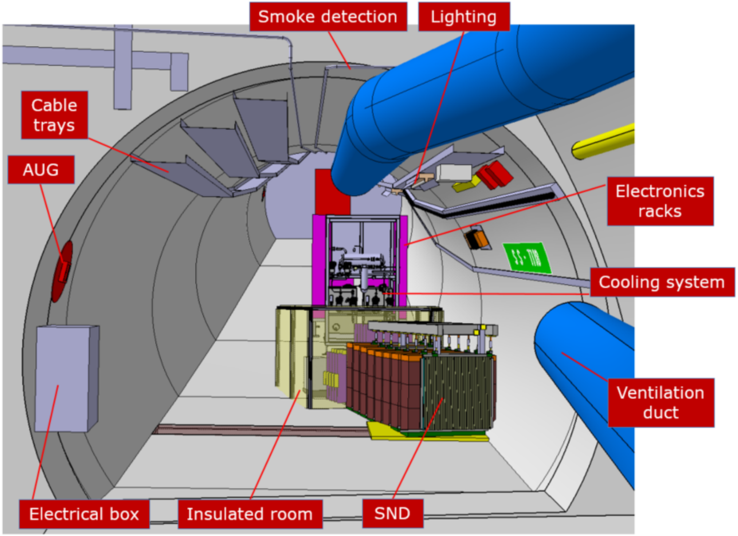
- $\sim$480 m away from the ATLAS IP: shielding from the IP provided by 100 m rock
- charged particles are deflected by the LHC magnets







Detector integration in the tunnel

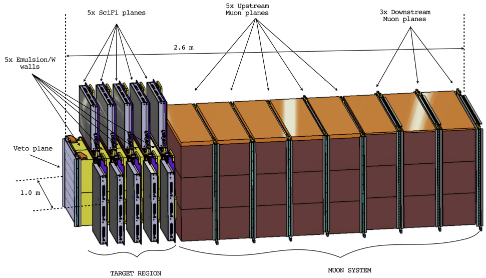


Detector design

Hybrid detector designed for:

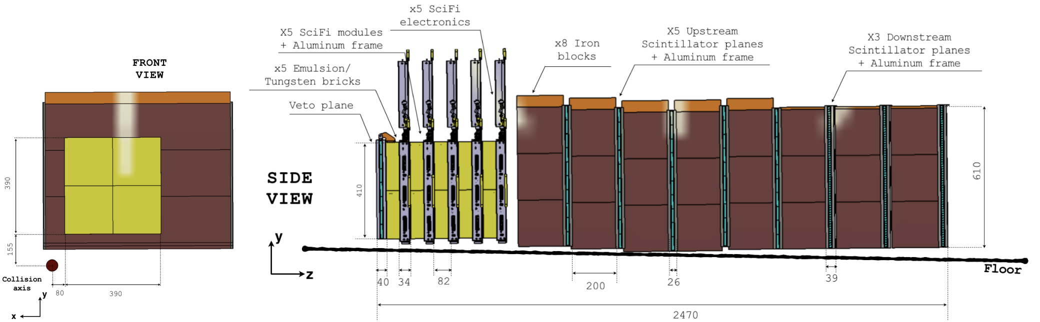
- identification and measurement of the three neutrino flavours, ν_e, ν_μ, ν_τ
- detection of feebly interacting particles, χ

1. **Veto plane** to tag incoming muons
   - scintillating bars
2. **Target region** for ν or χ scattering
   - emulsion cloud chambers (emulsion and tungsten)
   - SciFi (scintillating fibres) planes
3. **Muon system** for produced μ ID
   - iron walls interleaved with scintillating bars

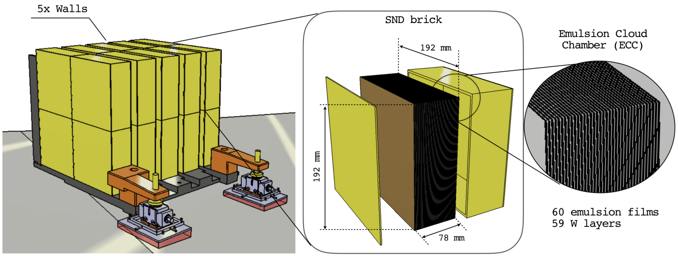


Detector key numbers

- target: 830 kg of tungsten
- angular acceptance: $7.2 < \eta < 8.6$, off-axis location
- electromagnetic calorimeter: $\sim 84X_0$, sampling every $17X_0$
- hadronic calorimeter: $\sim 10\lambda$ (muon system alone – 8λ), sampling every λ

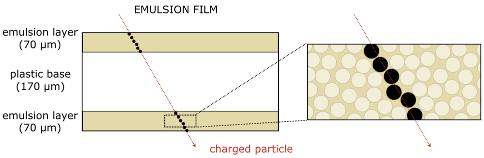


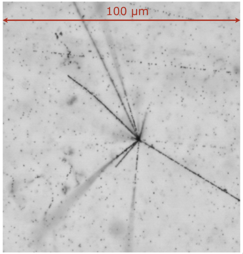
Target and vertex detector: Emulsion



Emulsion cloud chamber (ECC) technique for the target: tungsten layers (1mm thick) alternated with nuclear emulsion films

Submicrometric position resolution for event topology reconstruction:

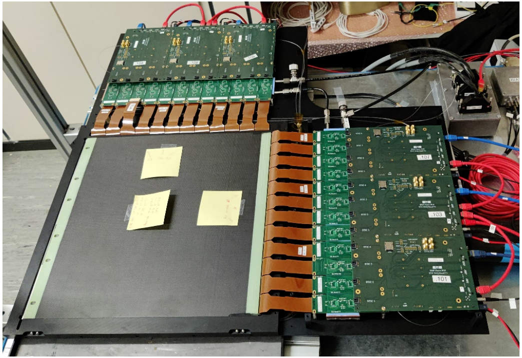


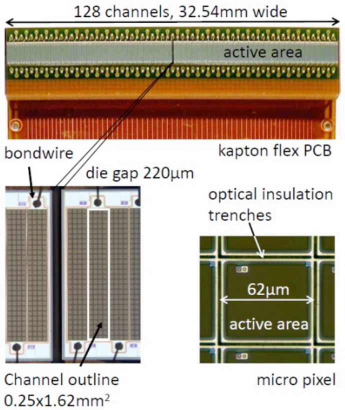


SciFi planes

5 xy $390 \times 390\text{mm}^2$ SciFi planes used for:

- tracking and combining information from ECC
- active layers of sampling calorimeter for energy measurement
- timing information for global event reconstruction and ToF from the IP1 measurement





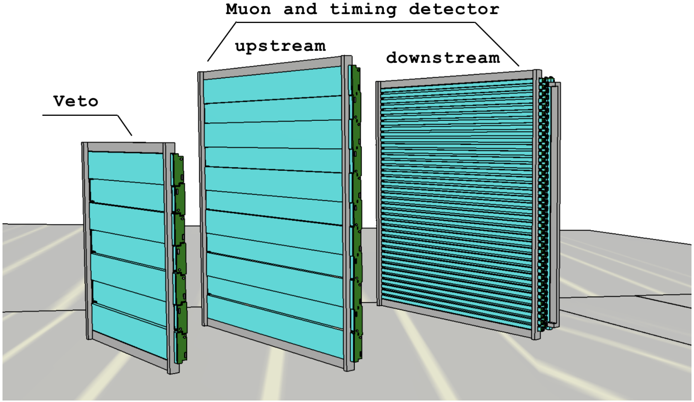
SiPM array for light detection: 60μm spatial resolution

Muon stations (+veto plane)

1. upstream:
   - 5 planes
   - 10 bars per plane

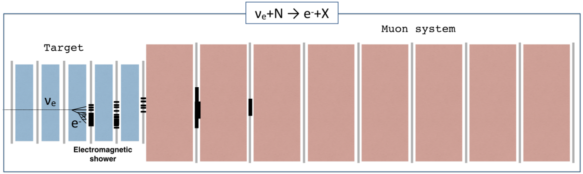
   $\Longrightarrow$ HCAL
2. downstream
   - 3 planes
   - 2 layers per plane
   - 60 bars layer

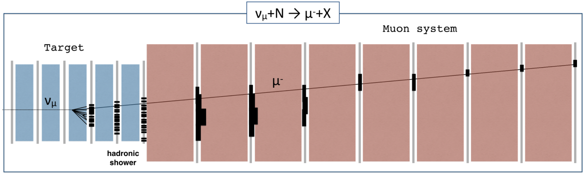
   $\Longrightarrow$ μ ID



Event reconstruction: first phase

Using information from electronic detectors (veto, SciFi, muon system):

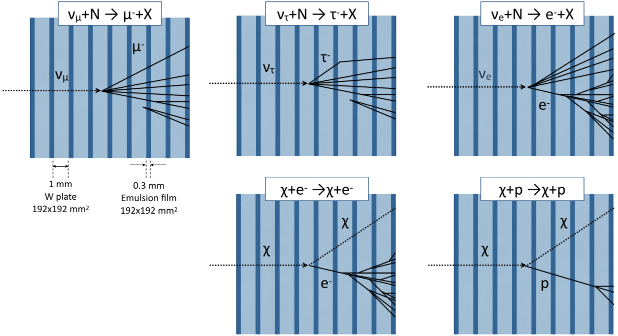




- identify neutral scattered candidates
- identify muons in the final state
- identify electrons/hadrons
- reconstruct EM and hadronic showers
- measure neutrino/χ energy

Event reconstruction: second phase

Using nuclear emulsions:



- identify EM showers
- ν/χ vertex reconstruction and secondary search
- match with candidates from electronic detectors
- complement SciFi for EM energy measurement

Neutrino physics in Run 3

ν production with DPMJET3, propagation with FLUKA, interaction with GENIE:

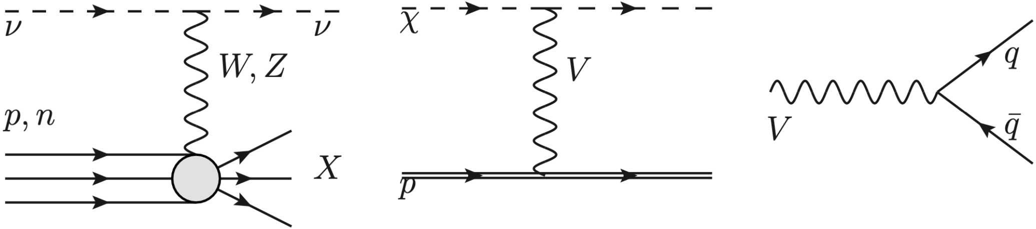
Flavour	Neutrinos in acceptance		CC neutrino interactions		NC neutrino interactions	
	$\langle E \rangle$ [GeV]	Yield	$\langle E \rangle$ [GeV]	Yield	$\langle E \rangle$ [GeV]	Yield
ν_μ	145	2.1×10^{12}	450	730	480	220
$\bar{\nu}_\mu$	145	1.8×10^{12}	485	290	480	110
ν_e	395	2.6×10^{11}	760	235	720	70
$\bar{\nu}_e$	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

Neutrino physics programme detailed in the technical proposal LHCC-P-016:

Measurement	Uncertainty		Signal/Background
	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%	
Observation of high-energy ν_τ			4

Dark matter signatures

SM NC interactions | **DM scattering** | **Mediator decay**



1. DM scattering in the target volume: $pp \to V + X, V \to \chi\chi$
   - **elastic**: background-free signature with one charged track $\chi + p/e \to \chi + p/e$
   - **inelastic**: $\chi + p/n \to \chi + X$ signature is similar to ν NC

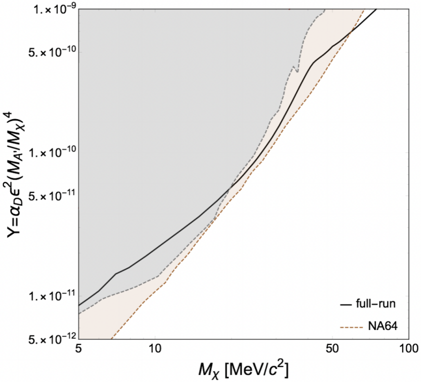
     $\Longrightarrow$ exploit kinematical features, look for an excess in NC events
2. visible mediator decay within the detector volume: $V \to q\bar{q}$:
   - look for an isolated decay vertex
   - exploit time of flight from the IP1 (480 m)

Scattering off atomic electrons (150 fb^{-1})

Vector portal in a minimal SM extension, with the production of a dark photon $\mathcal{A}'$:

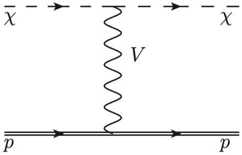
$$\mathcal{L}_{\mathcal{A}'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{\mathcal{A}'}}{2}A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} \quad (1)$$

- $\mathcal{A}' \to \chi\chi$, with $\chi + e \to \chi + e$ in the target
- study with full simulation: 0 SM background expected
- sensitivity dominated by small couplings: DM scattering acquires additional ϵ^2 in the yield
  $\Longrightarrow$ SND@LHC is an ϵ^4 experiment
- NA64 is an ϵ^2 experiment
  $\Longrightarrow$ has better sensitivity

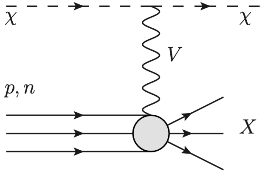


Scattering off nucleons: elastic signature

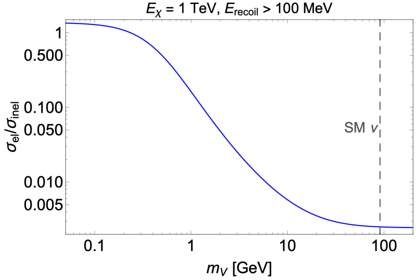
elastic scattering



inelastic scattering



- the ratio of cross sections $\sigma_{\text{el}}/\sigma_{\text{inel}}$ drops with the mediator mass
- for SM neutrinos, mediator (Z) is heavy $\implies$ most of events are inelastic, only $\mathcal{O}(1)$ of elastic events is expected at SND@LHC during Run 3
- elastic scattering off protons is background-free

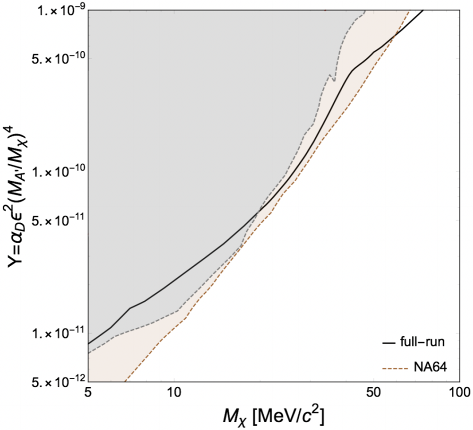


Scattering off nucleons: inelastic signature

- deep inelastic scattering (DIS) off nucleons is important for heavier mediators
- these inelastic DM scattering events compete with much more numerous neutrino inelastic events
- the total flux of neutrinos in the far-forward direction is unknown – will be measured by the SND@LHC
- however, SM predicts the ratio $N_{NC}/N_{CC} \approx 0.33$
- envisioned precision for the N_{NC}/N_{CC} measurement with SND@LHC is 10%
- $\implies$ if LDM contributes only to NC events – an increase of NC/CC is a good signature!
- at 2σ, around 100 LDM events are required in the inelastic signature

Other experiments

- with coupling to new physics ϵ, SND@LHC is ϵ^4 experiment
- there are many other ϵ^2 experiments:
  - NA64 for $m \lesssim 1$ GeV
  - BaBar and Belle for $m \lesssim 8$ GeV



But there are no bounds from these experiments if mediator does not interact with electrons and photons

Leptophobic portal

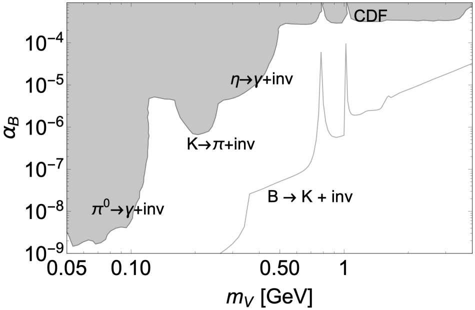
Leptophobic portal is currently less constrained:

$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J_\mu^B + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi), \quad J_\mu^B = \frac{1}{3} \sum_q \bar{q} \gamma_\mu q \tag{2}$$

Current bounds are from 2005.03594:

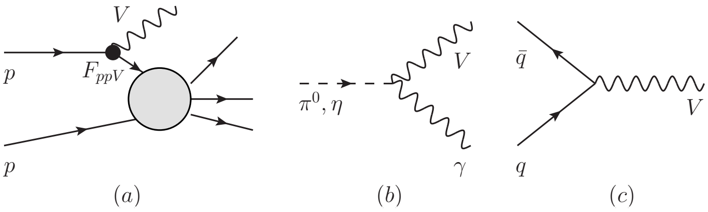
- invisible π, K, η decays at NA62, CB and E949
- CDF monojet in 2004.10996

Constraint from $B \to K$+invisible at LHCb is model-dependent, 1707.01503



Leptophobic portal: DM production at the LHC

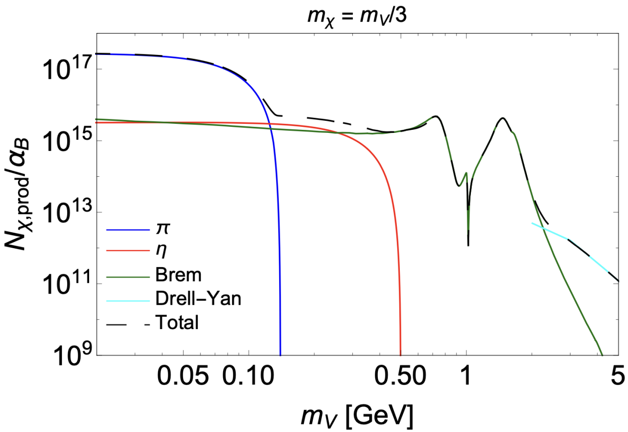
DM χ is produced in decays of mediator V:



Similarly to dark photon, the mediator is produced:

1. by proton bremsstrahlung: $p + p \to V + X$
2. in decays of unflavored mesons π, η: $\pi \to V + \gamma, \quad \eta \to V + \gamma$
3. by Drell-Yan process: $q + \bar{q} \to V + X$

Leptophobic portal: DM production at the LHC



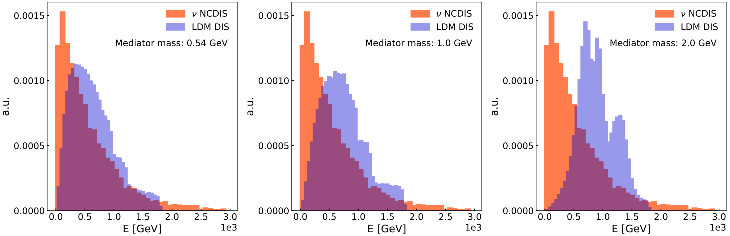
- the dominant production channel for $m_V < m_\pi$ is decays of pions,
- for masses $m_\phi < m_V < 2$ GeV is the proton bremsstrahlung
- at larger masses, the Drell-Yan channel dominates

Studies with full simulation

1. elastic scattering:

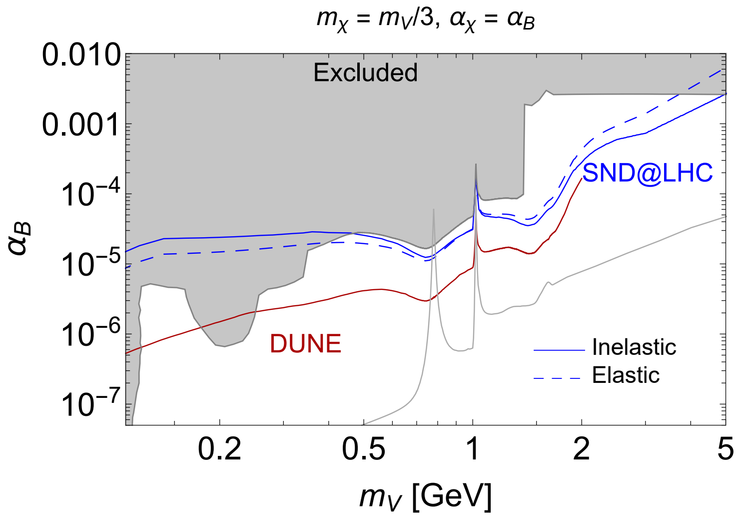
	$\chi p \to \chi p$ Selection eff.	Background
NC DIS	2.8×10^{-3}	1.26
NC RES	1.7×10^{-1}	0.48

2. inelastic scattering:



- kinematic selection alone does not suppress SM bkg
- sensitivity is based on 3σ signal excess over SM bkg

Leptophobic portal sensitivity (150 fb^{-1})



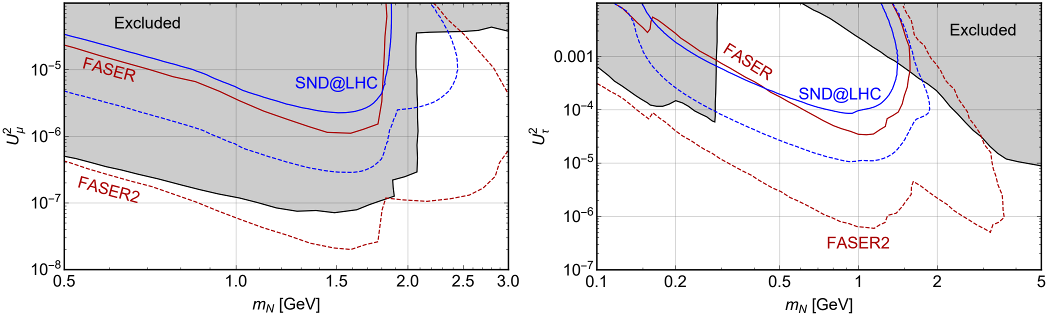
Excluded: results by CDF, BES, E949 and BNL; Projection for DUNE is shown as well

Including decay signatures

- apart from scattering, it is possible to probe decays of mediators V at SND@LHC
- decays should be distinguished from CC and NC scatterings of neutrinos
- decays into a lepton pair, $V \to \ell\ell$, is a background-free signature
- decays into at least one hadron, such as $V \to \pi\ell, \pi\pi$, differ from neutrino events: a very few tracks with a very large energy
- decays into neutral pions and photons look like a high-energy cascade of pairs of highly collimated photons

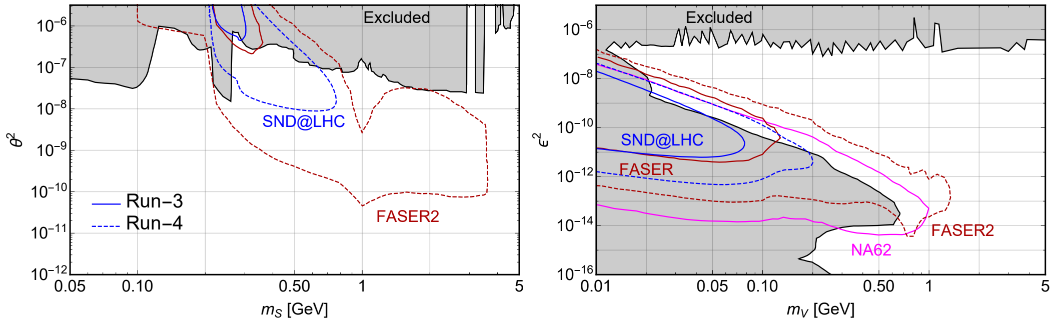
These decay channels are the main for neutrino, scalar and vector portals!

Decay signatures: HNLs



- sensitivity is estimated for
  - $\mathcal{L} = 150\ \text{fb}^{-1}$, $l_{\text{det}} = 0.5$ m (solid line) and
  - $\mathcal{L} = 3000\ \text{fb}^{-1}$, $l_{\text{det}} = 1.25$ m (dashed line)
- sensitivity of FASER (solid) and FASER2 (dashed) from PBC report is shown

Decay signatures: dark scalars and dark photons



For dark scalars and dark photons, the sensitivity is limited:

- these particles, even if being produced in sufficient amounts, decay before reaching the detector

Summary and outlook

- SND@LHC experiment is approved and is quickly advancing with construction
- commissioning and energy calibration for electronic detectors in September
- physics studies for SM and NP searches programme are ongoing

- phenomenological estimates sensitivity to FIPs summarized arXiv:2104.09688