Search for feebly-interacting particles with SND@LHC at CERN

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on behalf of the SND@LHC collaboration

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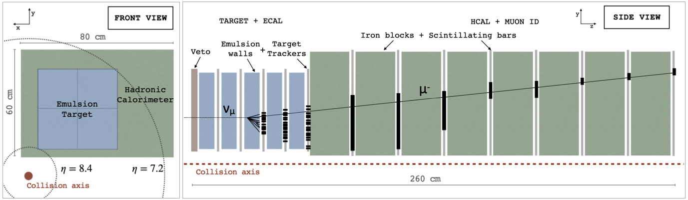
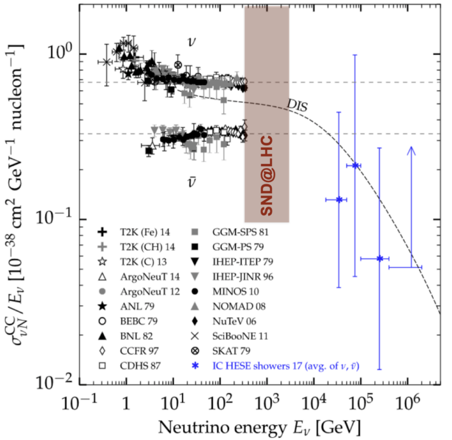
Scattering and Neutrino Detector at the LHC

Karlsruher Institut für Technologie

SNDLHC

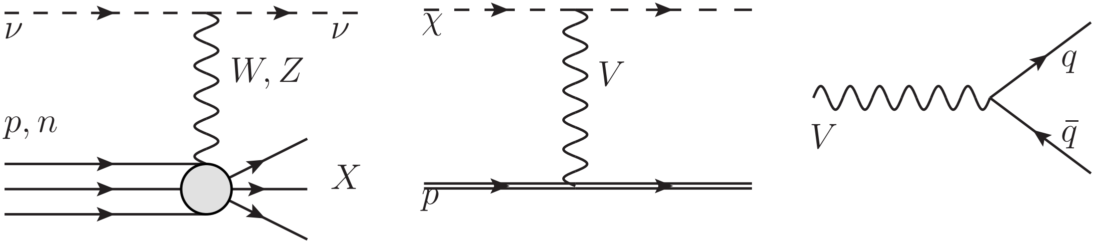




- SND@LHC is a far-forward experiment covering $7.2 < \eta < 8.4$
- Its main goal is to study interactions of neutrinos in the range $E_\nu \sim 100 - 1000$ GeV
- Recently, the first 8 ν_μ events have been observed

[2305.09383], accepted for PRL

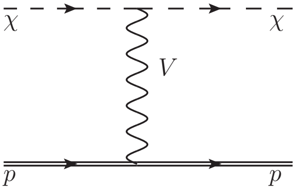
Signatures with new physics

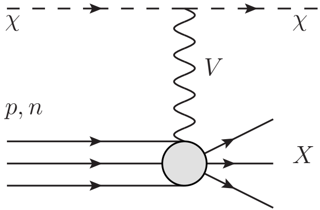


- Apart from neutrinos, SND@LHC may search for new physics produced in the far-forward direction
- **How to distinguish these events from neutrino scatterings?**

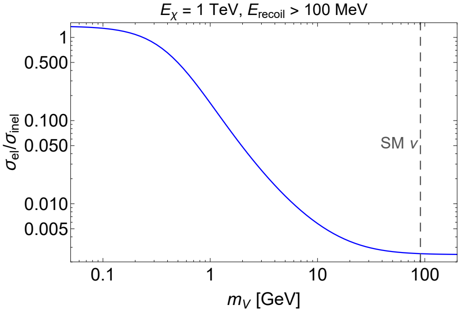
[2104.09688],[2203.05090]

Scattering signature 1: elastic/inelastic ratio I

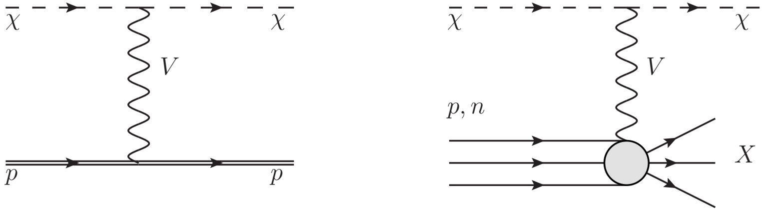




- The ratio of cross sections $\sigma_{\text{el}}/\sigma_{\text{inel}}$ drops with the mediator's mass
- For SM neutrinos, the mediator (Z) is heavy $\Rightarrow$ most of events are inelastic
- **An excess of elastic events is a good signature for light mediators,** $m_V \lesssim \mathcal{O}(1\ \textbf{GeV})$

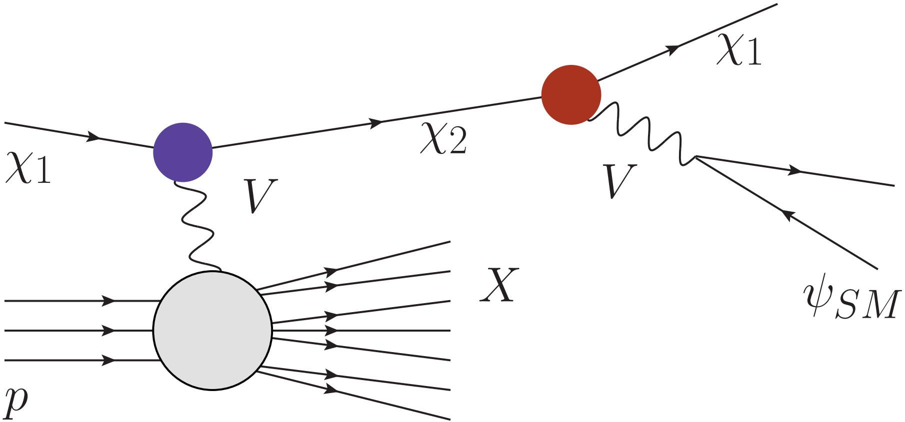


Scattering signature 2: increase of the NC/CC ratio



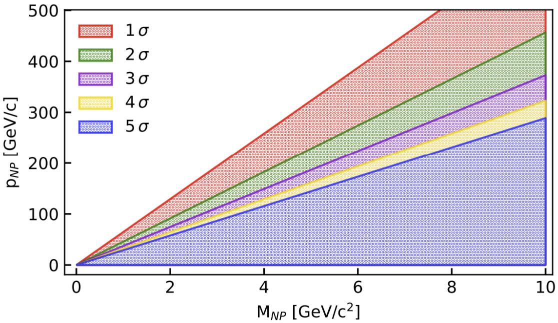
- Heavier mediators, inelastic events dominate. They compete with numerous ν DIS – CC and NC
- LDM contributes only to NC events
- SM predicts the ratio $N_{\text{NC}}/N_{\text{CC}} \approx 0.33$ (measured at SND@LHC with 10% accuracy)
- **An increase of the NC/CC ratio is a good signature!**

Scattering signature 3: double bang



- Consider the model: two particles χ_1, χ_2 coupled to SM via mediator V
- More massive χ_2 is unstable and decays as $\chi_2 \to \chi_1 + V^* \to \chi_2 + \psi_{\text{SM}}$
- **DIS+displaced decay, like *"double bang"* at IceCube**

Possible background rejection: timing



– Depending on the γ factor of the produced FIP, the background may be rejected using TOF measurements

Model example: leptophobic portal

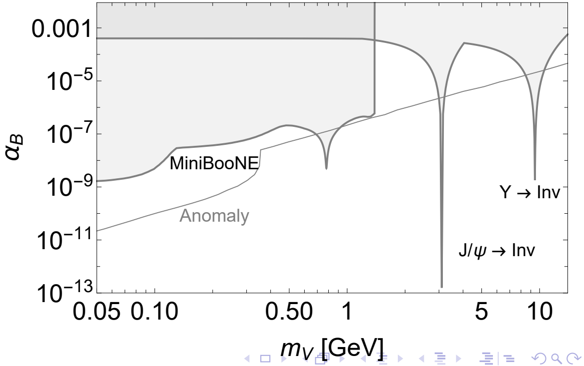
Leptophobic portal (also $B-3L_\tau$):

$$\mathcal{L}_{\text{leptophob}} = -g_B V_\mu J_B^\mu + |D_\mu\chi|^2, \quad D_\mu = \partial_\mu + ig_\chi V_\mu, \quad J_B^\mu = \frac{1}{3}\sum_q \bar{q}\gamma_\mu q \tag{1}$$

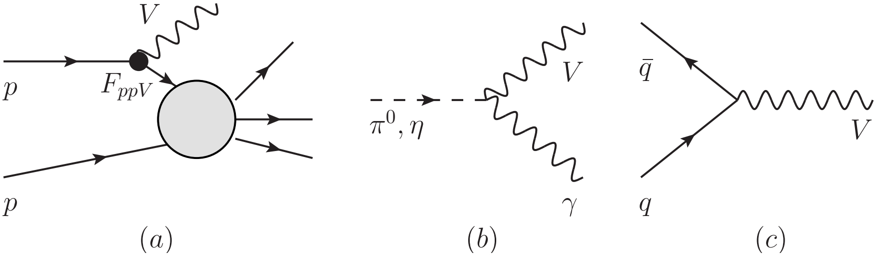
- 4 parameters: m_V, m_χ, $\alpha_D = g_\chi^2/4\pi$, $\alpha_B = g_B^2/4\pi$
- $\alpha_D = 0.5$
- Choose $m_\chi < 150$ MeV (to avoid DM direct detection bounds)

No bounds from EM processes as for dark photon

- Invisible/visible $J/\psi, \Upsilon$ decays at BaBar [2005.03594]
- Monojet signatures at CDF [2004.10996]
- Scatterings at MiniBooNE [1807.06137]

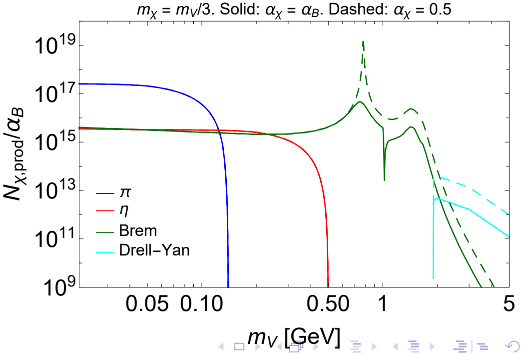


Phenomenology of the leptophobic portal at the LHC



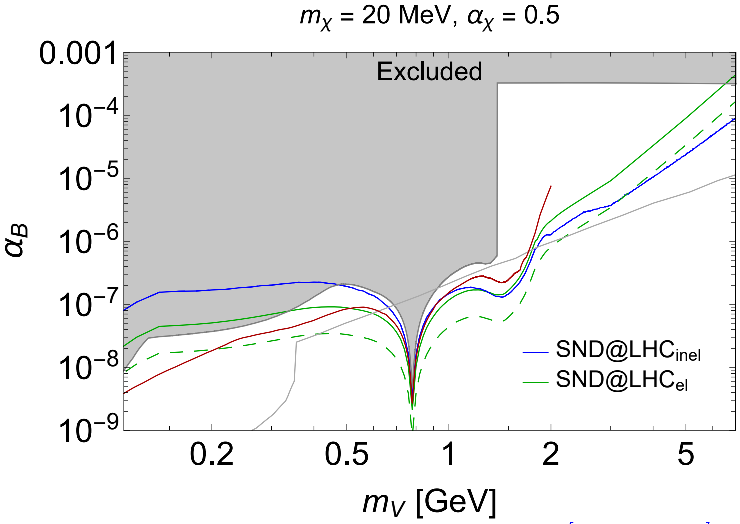
Production channels:

- by proton bremsstrahlung (a)
- in decays of light unflavored mesons (b)
- by Drell-Yan process (c)



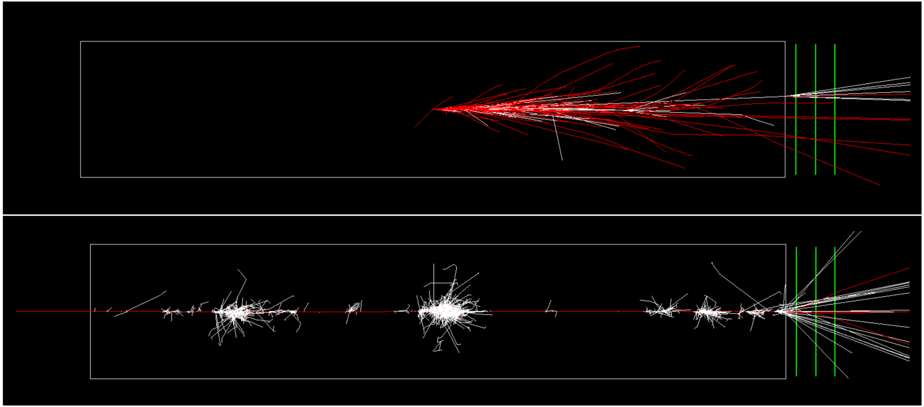
Sensitivity to NC/CC and elastic signatures

- 90% CL sensitivity to elastic and inelastic signatures
- SND@LHC may be sensitive to large masses of leptophobic mediator $m_V \gtrsim 1$ GeV



[2104.09688]

Signatures at AdvSND I



[2001.03073]

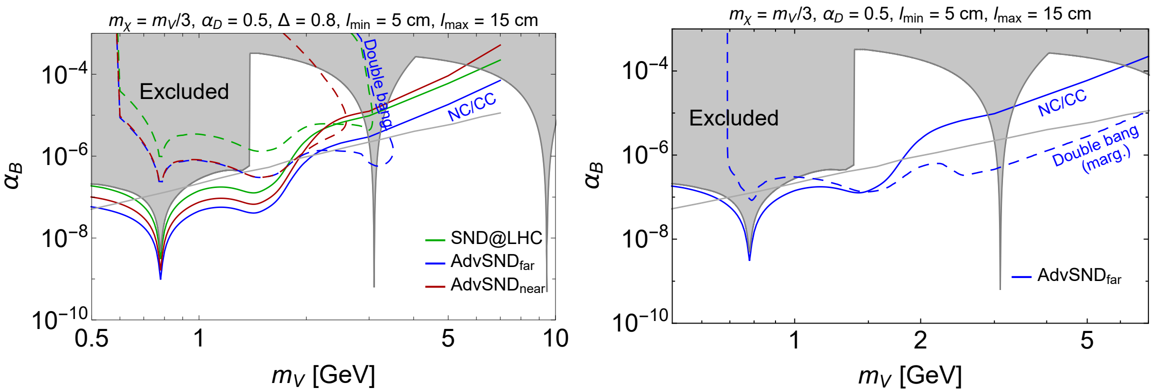
- "Double bang" signature relies on reconstructing isolated events with a few tracks
- Complicated with emulsion, but may be possible with fully electronic detectors

Signatures at AdvSND II

- **AdvSND**: an extension of SND@LHC to be run during HNL-LHC
- Two detectors:
  1. $\text{AdvSND}_{\text{far}}$ (to be located at FPF)
  2. $\text{AdvSND}_{\text{near}}$ (to be located much closer and covered the LHCb η range)
- $\text{AdvSND}_{\text{near}}$: benefits from precise measurements of the charm production at LHCb
- Possible option to be equipped with fully electronic detectors

[2203.05090]

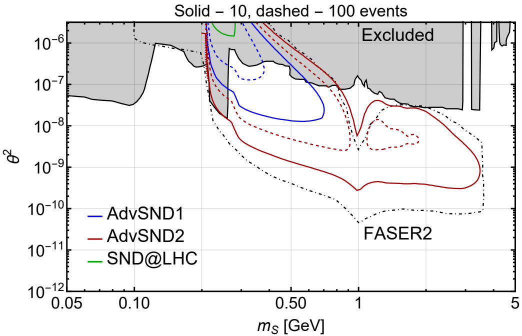
Signatures at AdvSND III



– Assuming that the "double bang" signature is bg free, it may be possible to probe an order of magnitude lower α_B than with NC/CC signature

– Also, TOF may be efficient for $AdvSND_{near}$

Signatures at AdvSND IV



– AdvSND may also have the potential of searching for FIPs by their decays

[2203.05090]

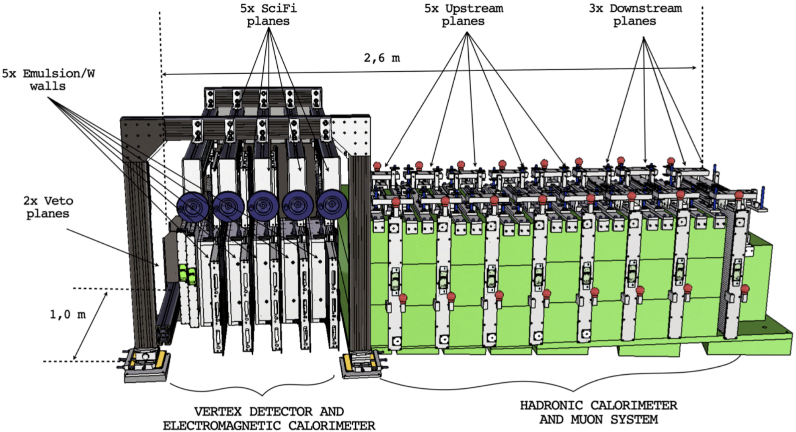
Conclusions

- SND@LHC has a perfect potential for the exploration of the parameter space of FIPs produced in the far-forward direction
- AdvSND may be able to explore more unique signatures

Backup slides

SND@LHC: detailed

- Veto, SciFi Tracker and Muon system
  - Select neutrino interactions
  - Identify muons
  - Reconstruct EM/hadron showers and measure neutrino energy

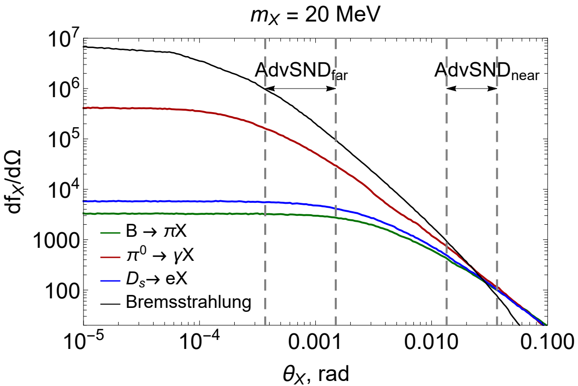


- Emulsion Cloud Chambers
  - Identify ν interaction vertex and secondary vertices
  - Match event with electronic detectors
  - Complement EM energy measurement

Potential of AdvSND I

Detector	SND@LHC	$\text{AdvSND}_{\text{far}}$	$\text{AdvSND}_{\text{near}}$
η	$(7.2, 8.6)$	$(7.2, 8.4)$	$(4, 5)$
Mass, ton	0.8	5	5
$S_\perp$	40×40 cm^2	100×55 cm^2	120×120 cm^2
Ω, sr	$6.7 \cdot 10^{-7}$	$1.6 \cdot 10^{-6}$	$5.8 \cdot 10^{-4}$
$l_{\text{to det}}$	480 m	630 m	55 m
Detector type	Emulsion/SciFi	Electronic	Electronic
Operating time	Run 3	Run 4	Run 4

Potential of AdvSND II



- AdvSND$_{near}$ has the largest solid angle coverage:

$$\Omega_{\text{SND@LHC}} : \Omega_{\text{AdvSND}_{\text{far}}} : \Omega_{\text{AdvSND}_{\text{near}}} = \\ = 1 : 2.4 : 850 \quad (2)$$

- However, the distribution of particles produced by typical processes (decays of mesons, bremsstrahlung) is peaked in the forward direction
- AdvSND$_{far}$ is better for probing bremsstrahlung and decays of light mesons
- AdvSND$_{near}$ is better for probing decays of heavy mesons

Production of χ at LHC I

- We have mainly follow 1609.01770, 1609.01770 when calculating the production of leptophobic mediator
- In order to get the angle-energy distribution of light mesons, we used EPOS-LHC as a part of CRMC package. Having these distributions, we then used the approach from 1908.04635 in order to obtain the distribution of V and χ
- For getting the spectrum of χ particles from the Drell-Yan process, we have implemented the model (1) in MadGraph using FeynRules, and then simulated the leading-order process $p+p\to V,\ V\to\chi\bar{\chi}$

Bremsstrahlung: form-factor I

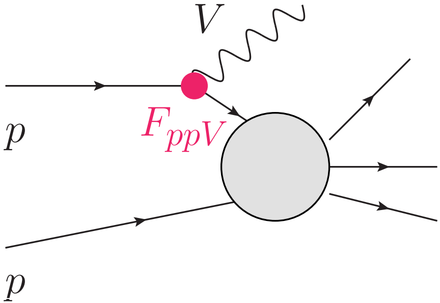
- Similarly to 2005.03594, for the form-factor in the time-like region (with the transferred momentum $q^2 > 0$) we consider

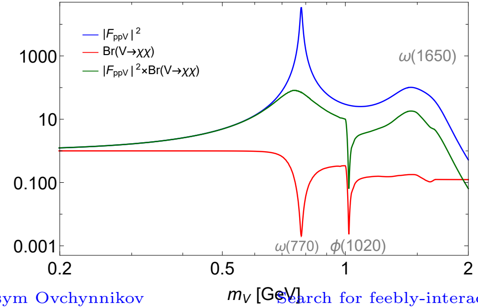
$$F_{ppV}(q^2) = \sum_{\omega} \frac{f_\omega m_\omega^2}{q^2 - m_\omega^2 - i\Gamma_\omega m_\omega}, \tag{3}$$

where the sum goes over all ω resonances with masses $m_\omega < 1.7$ GeV (three resonances: $\omega(780), \omega(1420), \omega(1650)$). The contribution from ϕ is not taken into account, as its interaction with nucleons is suppressed

- Only one constant is known: $f_{\omega(780)} = 0.5 f_\omega^{\mathrm{EM}}(780) \approx 0.5$ (the coupling $g_{V\omega}$ of V to ω meson is twice larger than the EM coupling, while $f_{\omega(780)} \sim 1/g_{V\omega}$). However, the other two couplings may be determined, following 0910.5589, 1) from the requirement $F_{ppV}(q^2 \to \infty) \sim 1/q^4$ in the space-like region, and 2) from $F(0) = 1$
Note that in 0910.5589 outdated masses and widths for ω resonances have been used

Resonances

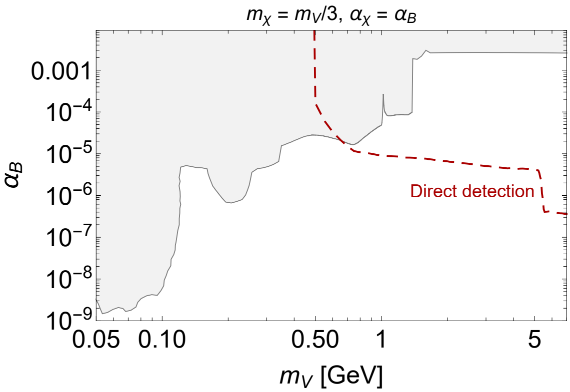




V mixes with vector isoscalar mesons ω, ϕ. This leads to the resonant enhancement of

1. the production by proton bremsstrahlung (via the proton elastic form-factor F_{ppV}), see backup slides
2. The hadronic decay width of V (which causes a drop of the branching ratio $\text{Br}(V \to \chi\bar{\chi})$), see 1801.04847

$B \to K + \text{inv}$



Model-dependent constraints:

- Constraint from $B \to K +$ invisible at LHCb: assumes that the model (1) is effective, and its UV completion has no anomaly in the B current
- Requires knowing the UV completion of the theory (1) [1707.01503]

Inelastic model I

- Consider now the inelastic DM:

$$\mathcal{L}_{\text{leptophob,inel}} = -g_B V_\mu J_B^\mu + g_\chi \bar{\chi}_2 \gamma_\mu \chi_1 V^\mu \quad (4)$$

  χ_2 is heavier than χ_1: $m_{\chi_2} = m_{\chi_1}(1+\Delta)$
- 5 parameters: $m_V, m_{\chi_1}, \alpha_D, \alpha_B, \Delta$
- V interacts with quarks similarly to ω, which decays into $\pi^0\gamma, 3\pi$. Therefore, decays of χ_2 are

$$\chi_2 \to \chi_1 + \begin{cases} \pi^0\gamma/3\pi, & \Delta m_{\chi_1} \lesssim 1 \text{ GeV}, \\ q\bar{q}, & \Delta m_{\chi_1} \gg 1 \text{ GeV} \end{cases} \quad (5)$$

Inelastic model II

- The number of events is

$$N_{\text{events}}(m_V, m_\chi, \alpha_B, \alpha_D, \Delta) \approx N^{\text{SND}}_{\chi_1,\text{prod}} \times P_{\text{DIS}} \times P_{\text{decay}} \tag{6}$$

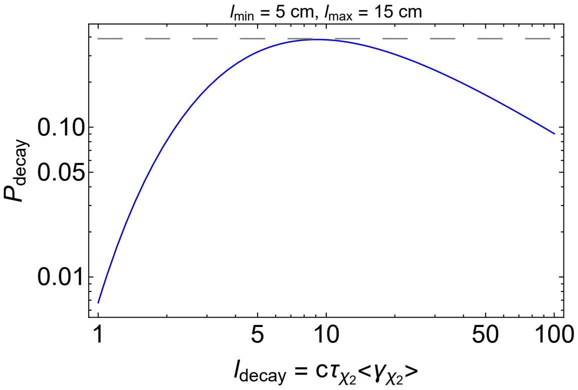
where P_{decay} is the decay probability:

$$P_{\text{decay}} \approx e^{-l_{\min}/c\tau_{\chi_2}\langle\gamma_{\chi_2}\rangle} - e^{-l_{\max}/c\tau_{\chi_2}\langle\gamma_{\chi_2}\rangle} \tag{7}$$

- We marginalize over $\alpha_D, \Delta, m_{\chi_1}$ to maximize the product $P_{\text{DIS}} \times P_{\text{decay}} \sim \alpha_D \cdot P_{\text{decay}}$

Inelastic model III

- We require the minimal displacement $l_{\text{min}} \simeq 5$ cm (=scattering length of hadrons in tungsten) and $l_{\text{max}} = 15$ cm
- In this case, $P_{\text{decay}} < P_{\text{decay,max}} \approx 0.4$ as a function of $l_{\text{decay}} = c\tau_{\chi 2}\gamma_{\chi 2}$



- Decay width scales with Δ, α_D as $\Gamma_{\chi 2} \propto \alpha_D \Delta^{1-5} m_{\chi 1}^5 / m_V^4$
- Marginalization: choose Δ to maximize $P_{\text{decay}} \to P_{\text{decay,max}}$

Inelastic model IV

- For the NC/CC signature, the background constitutes DIS scatterings of neutrinos
- The number of neutrino DIS events at AdvSND$_{\text{far}}$ is

$$\frac{N_{\text{CC}}^{\text{AdvSND}_{\text{far}}}}{N_{\text{CC}}^{\text{SND@LHC}}} \approx \frac{m_{\text{AdvSND}_{\text{far}}}}{m_{\text{SND@LHC}}} \times \frac{\mathcal{L}_{\text{Run 4}}}{\mathcal{L}_{\text{Run 3}}} \approx 125 \tag{8}$$

- Assuming that the resolution for NC/CC at AdvSND$_{\text{far}}$ will be 1%, we need $N_{\text{DIS}} > \mathcal{O}(10^3)$ events
- For the "double bang" signature, we optimistically assume no background and require $N_{\text{decay+DIS}} > 3$. Therefore, if $P_{\text{decay}} = P_{\text{decay,max}}$, the decay+DIS signature would probe smaller couplings α_B:

$$\frac{\alpha_{B,\text{min}}^{\text{DIS+decay}}}{\alpha_{B,\text{min}}^{NC/CC}} \sim \sqrt{\frac{3}{10^3 P_{\text{decay,max}}}} \simeq 0.1 \tag{9}$$