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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– 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 $\nu_\mu$ events have been observed [2305.09383], accepted for PRL
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]
The ratio of cross sections $\sigma_{el}/\sigma_{inel}$ 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, $m_V \lesssim O(1 \text{ GeV})$. 

Graph showing the ratio $\sigma_{el}/\sigma_{inel}$ as a function of mediator mass $m_V$. The graph indicates a sharp decrease in the ratio as $m_V$ increases, with a sharp cutoff at $m_V \approx O(1 \text{ GeV})$. The horizontal line at $E_\chi = 1 \text{ TeV}$ and $E_{\text{recoil}} > 100 \text{ MeV}$ is also shown.
Scattering signature 2: increase of the NC/CC ratio

- Heavier mediators, inelastic events dominate. They compete with numerous $\nu$ DIS – CC and NC
- LDM contributes only to NC events
- SM predicts the ratio $N_{NC}/N_{CC} \approx 0.33$ (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 $\chi_1, \chi_2$ coupled to SM via mediator $V$
- More massive $\chi_2$ is unstable and decays as $\chi_2 \rightarrow \chi_1 + V^* \rightarrow \chi_2 + \psi_{SM}$
- DIS+displaced decay, like “double bang” at IceCube
Depending on the $\gamma$ factor of the produced FIP, the background may be rejected using TOF measurements.
Model example: leptophobic portal

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

$$\mathcal{L}_{\text{leptophob}} = -g_B V_\mu J_B^\mu + |D_\mu \chi|^2, \quad D_\mu = \partial_\mu + i g_\chi V_\mu, \quad J_B^\mu = \frac{1}{3} \sum_q \bar{q} \gamma_\mu q$$  \hspace{1cm} (1)

- 4 parameters: $m_V$, $m_\chi$, $\alpha_D = g_\chi^2/4\pi$, $\alpha_B = g_B^2/4\pi$
- $\alpha_D = 0.5$
- 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]
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

$\alpha_B = 0.5$, $m_\chi = 20$ MeV

[2104.09688]
“Double bang” signature relies on reconstructing isolated events with a few tracks
- Complicated with emulsion, but may be possible with fully electronic detectors
AdvSND: an extension of SND@LHC to be run during HNL-LHC

- Two detectors:
  1. AdvSND\textsubscript{far} (to be located at FPF)
  2. AdvSND\textsubscript{near} (to be located much closer and covered the LHCb $\eta$ range)

- AdvSND\textsubscript{near}: benefits from precise measurements of the charm production at LHCb
- Possible option to be equipped with fully electronic detectors

\cite{2203.05090}
Assuming that the “double bang” signature is bg free, it may be possible to probe an order of magnitude lower $\alpha_B$ than with NC/CC signature.

- Also, TOF may be efficient for AdvSND$_{\text{near}}$.
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 $\nu$ interaction vertex and secondary vertices
  - Match event with electronic detectors
  - Complement EM energy measurement
Potential of AdvSND I

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<th>Detector</th>
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<th>AdvSND$_{\text{near}}$</th>
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<td>(7.2, 8.4)</td>
<td>(4, 5)</td>
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<td>Run 4</td>
<td>Run 4</td>
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Potential of AdvSND II

- AdvSND$_\text{near}$ 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$_{\text{far}}$ is better for probing bremsstrahlung and decays of light mesons.
- AdvSND$_{\text{near}}$ is better for probing decays of heavy mesons.
Production of $\chi$ 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 $\chi$
- For getting the spectrum of $\chi$ particles from the Drell-Yan process, we have implemented the model (1) in MadGraph using FeynRules, and then simulated the leading-order process $p + p \rightarrow V, \ V \rightarrow \chi \bar{\chi}$
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

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

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

- Only one constant is known: $f_{\omega(780)} = 0.5f_{\omega}^{EM}(780) \approx 0.5$ (the coupling $g_{V\omega}$ of $V$ to $\omega$ 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 $\omega$ resonances have been used.
Resonances

$V$ mixes with vector isoscalar mesons $\omega$, $\phi$. 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
$B \rightarrow K + \text{inv}$

Model-dependent constraints:

- Constraint from $B \rightarrow K + \text{invisible}$ 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]
Consider now the inelastic DM:

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

\( \chi_2 \) is heavier than \( \chi_1 \): \( m_{\chi_2} = m_{\chi_1}(1 + \Delta) \)

- 5 parameters: \( m_V, m_{\chi_1}, \alpha_D, \alpha_B, \Delta \)
- \( V \) interacts with quarks similarly to \( \omega \), which decays into \( \pi^0 \gamma, 3\pi \). Therefore, decays of \( \chi_2 \) are

\[ \chi_2 \rightarrow \chi_1 + \begin{cases} \pi^0 \gamma/3\pi, & \Delta m_{\chi_1} \lesssim 1 \text{ GeV}, \\ q\bar{q}, & \Delta m_{\chi_1} \gg 1 \text{ GeV} \end{cases} \quad (5) \]
Inelastic model II

• The number of events is

\[ N_{\text{events}}(m_V, m_\chi, \alpha_B, \alpha_D, \Delta) \approx N_{\chi_1,\text{prod}}^{\text{SND}} \times P_{\text{DIS}} \times P_{\text{decay}} \]  

(6)

where \( P_{\text{decay}} \) is the decay probability:

\[ P_{\text{decay}} \approx e^{-l_{\text{min}}/c\tau_2\langle \gamma_2 \rangle} - e^{-l_{\text{max}}/c\tau_2\langle \gamma_2 \rangle} \]  

(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 $l_{\text{min}} \approx 5 \text{ cm} (=\text{scattering length of hadrons in tungsten})$ and $l_{\text{max}} = 15 \text{ cm}$
- 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 $\Delta, \alpha_D$ as $\Gamma_{\chi_2} \propto \alpha_D\Delta^{1-5}m_{\chi_1}^5/m_V^4$
- Marginalization: choose $\Delta$ to maximize $P_{\text{decay}} \rightarrow P_{\text{decay,max}}$
Inelastic model IV

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

\[
\frac{N^{\text{AdvSND}\textsubscript{far}}_{\text{CC}}}{N^{\text{SND@LHC}}_{\text{CC}}} \approx \frac{m_{\text{AdvSND}\textsubscript{far}}}{m_{\text{SND@LHC}}} \times \frac{\mathcal{L}_{\text{Run 4}}}{\mathcal{L}_{\text{Run 3}}} \approx 125
\]  

(8)

- Assuming that the resolution for NC/CC at AdvSND\textsubscript{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 \( \alpha_B \):

\[
\frac{\alpha_B^{\text{DIS+decay}}}{\alpha_B^{\text{NC/CC}}} \sim \sqrt{\frac{3}{10^3 P_{\text{decay, max}}}} \sim 0.1
\]  

(9)