Determining Dark Matter properties with a XENONnT/LZ signal and LHC-Run3 mono-jet searches

in collaboration with S. Baum, R. Catena, J. Conrad, K. Freese

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Introduction

- Direct Detection and Collider searches effective and complementary way to explore possible DM models
- XENONnT will start 2019
- LHC Run 3 planned start in 2020, 300 fb^{-1} in 2022
- Assuming $\mathcal{O}(100)$ XENONnT events in 2021 (just below current limits) $\rightarrow$ What predictions can be made for LHC Run 3 monojet searches?

Method

1. Identify monojet crosssections compatible with $\mathcal{O}(100)$ XENONnT events in the M_{med} - σ plane.
2. Identify type of DM nucleon interactions and possibly spin $\leftarrow$ observation or lack of mono-jet signal

Simplified models & EFT

$\mathcal{O}_1$	$1_\chi 1_N$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

$$\mathcal{L}_{NR} = \sum_{\alpha=n,p} \sum_{i=1}^{15} c_i^\alpha \mathcal{O}_i^\alpha,$$

[Fitzpatrick et al., 2012]

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[Fitzpatrick et al., 2012]

$$\begin{aligned}
\mathcal{L}_{\chi Z' q} = {} & \mathrm{i}\bar{\chi}\not{D}\chi - m_\chi \bar{\chi}\chi - \frac{1}{4}\mathcal{Z}'_{\mu\nu}\mathcal{Z}'^{\mu\nu} + \frac{1}{2}m'^2_Z Z'_\mu Z'^\mu \\
& - \frac{\lambda_{Z'}}{4}(Z'_\mu Z'^\mu)^2 + \mathrm{i}\bar{q}\not{D}q - m_q\bar{q}q \\
& - \frac{\lambda_3}{2}\bar{\chi}\gamma^\mu\chi Z'_\mu Z^\mu - \mathrm{i}\lambda_4\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu \\
& - h_3(\bar{q}\gamma_\mu q)Z'^\mu - h_4(\bar{q}\gamma_\mu\gamma^5 q)Z'^\mu\,.
\end{aligned}$$

Simplified models & EFT

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$\rightarrow$

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& - \frac{\lambda_{Z'}}{4}(Z'_\mu Z'^\mu)^2 + i\bar{q}\not{D}q - m_q \bar{q}q \\
& - \frac{\lambda_3}{2}\bar{\chi}\gamma^\mu\chi Z'_\mu Z^\mu - i\lambda_4 \bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu \\
& - h_3(\bar{q}\gamma_\mu q)Z'^\mu - h_4(\bar{q}\gamma_\mu\gamma^5 q)Z'^\mu \,.
\end{aligned}$$

$\downarrow$

[Dent et al., 2015]

	Uncharged Mediator	Charged Mediator
c_1	$\frac{h_1^N\lambda_1}{m_\phi^2} - \frac{h_3^N\lambda_3}{m_G^2}$	$\left(\frac{l_2^\dagger l_2 - l_1^\dagger l_1}{4m_\Phi^2} + \frac{d_2^\dagger d_2 - d_1^\dagger d_1}{4m_V^2}\right) f_T^N + \left(-\frac{l_2^\dagger l_2 + l_1^\dagger l_1}{4m_\Phi^2} + \frac{d_2^\dagger d_2 + d_1^\dagger d_1}{8m_V^2}\right)\mathcal{N}^N$
c_4	$\frac{4h_4^N\lambda_4}{m_G^2}$	$\frac{l_2^\dagger l_2 - l_1^\dagger l_1}{m_\Phi^2}\delta^N - \left(\frac{l_1^\dagger l_1 + l_2^\dagger l_2}{m_\Phi^2} + \frac{d_2^\dagger d_2 - d_1^\dagger d_1}{2m_V^2}\right)\Delta^N$
c_6	$\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}$	$(\frac{l_1^\dagger l_1 - l_2^\dagger l_2}{4m_\Phi^2} + \frac{d_2^\dagger d_2 - d_1^\dagger d_1}{4m_V^2})\frac{m_N}{m_\chi}\tilde{\Delta}^N$
c_7	$\frac{2h_4^N\lambda_3}{m_G^2}$	$(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} + \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\Delta^N$
c_8	$-\frac{2h_3^N\lambda_4}{m_G^2}$	$(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} - \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\mathcal{N}^N$
c_9	$-\frac{2h_4^N\lambda_3 m_N}{m_\chi m_G^2} - \frac{2h_3^N\lambda_4}{m_G^2}$	$(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} - \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\mathcal{N}^N - (\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{2m_\Phi^2} - \frac{d_1^\dagger d_2 + d_2^\dagger d_1}{4m_V^2})\frac{m_N}{m_\chi}\Delta^N$
c_{10}	$\frac{h_2^N\lambda_1}{m_\phi^2}$	$i(\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{4m_\Phi^2} + \frac{d_2^\dagger d_1 - d_1^\dagger d_2}{4m_V^2})\tilde{\Delta}^N - i\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{m_\Phi^2}\delta^N$
c_{11}	$-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}$	$i(\frac{l_2^\dagger l_1 - l_1^\dagger l_2}{4m_\Phi^2} + \frac{d_2^\dagger d_1 - d_1^\dagger d_2}{4m_V^2})\frac{m_N}{m_\chi}f_T^N + i\frac{l_1^\dagger l_2 - l_2^\dagger l_1}{m_\Phi^2}\frac{m_N}{m_\chi}\delta^N$
c_{12}	0	$\frac{l_2^\dagger l_1 - l_1^\dagger l_2}{m_\Phi^2}\delta^N$

DM Detection of XENONnT

Scalar DM	Op.	g_q	g_{DM}	M_{eff} [GeV]
	1	h_1	g_1	14564.484
	1	h_3	g_4	10260.217
	7	h_4	g_4	4.509
	10	h_2	g_1	10.706
Fermionic DM	**Op.**	g_q	g_{DM}	M_{eff} [GeV]
	1	h_1	λ_1	14564.484
	1	h_3	λ_3	7255.068
	4	h_4	λ_4	147.354
	6	h_2	λ_2	0.286
	7	h_4	λ_3	3.188
	8	h_3	λ_4	225.159
	10	h_2	λ_1	10.706
	11	h_1	λ_2	351.589
Vector DM	**Op.**	g_q	g_{DM}	M_{eff} [GeV]
	1	h_1	b_1	14564.484
	1	h_3	b_5	17771.216
	4	h_4	$\Re(b_7)$	188.302
	4	h_4	$\Im(b_7)$	3.215
	5	h_3	$\Im(b_6)$	6.946
	7	h_4	b_5	7.809
	8	h_3	$\Re(b_7)$	287.728
	9	h_4	$\Im(b_6)$	3.674
	10	h_2	b_1	10.706
	11	h_3	$\Im(b_7)$	223.794

Value for the effective mediator mass

$$M_{\text{eff}} \equiv M_{\text{med}} \sqrt{\frac{(0.1)^2}{g_q g_{\text{DM}}}}$$

needed to generate 150 signal events at XENONnT (20 ton$\times$year exposure)

Model selection with XENONnT

Two types of spectra:

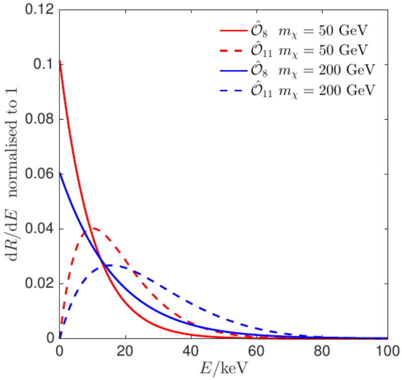
Type A: maximum at E=0 (q=0)

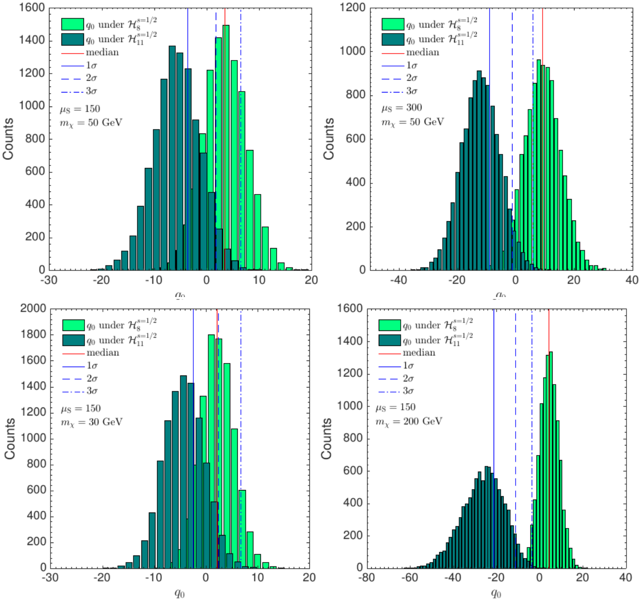
Type B: maximum at E≠0 (q≠0)

Canonical SI and SD interactions are of type A.

Use test statistic for model selection

$$q_0 = -2\ln\left[\frac{\mathcal{L}(\boldsymbol{d}\,|\,\widehat{\boldsymbol{\Theta}}_0, \mathcal{H}_0)}{\mathcal{L}(\boldsymbol{d}\,|\,\widehat{\boldsymbol{\Theta}}_a, \mathcal{H}_a)}\right]$$

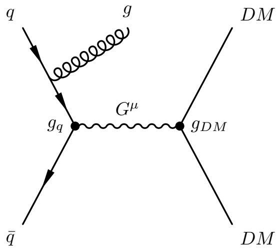




10000 pseudo-experiments each

Impact on LHC monojet searches

- Translating the $\mathcal{O}(100)$ XENONnT events into regions in the M_{med}-σ plane
- Mediator necessarily couples to quarks.
  $\rightarrow$ Can be produced in pp collisions
- Can decay into pair of DM particles (E^T_{miss})
- Initial state radiation (e.g., gluon) $\rightarrow$ jet in detector

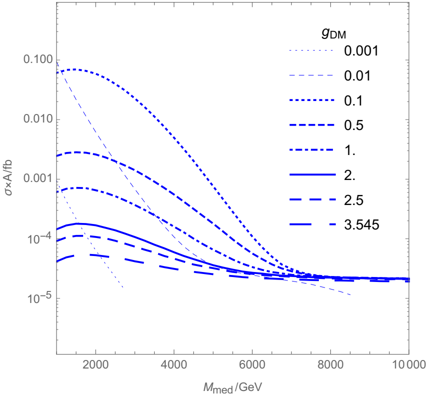


Current Limits and projections

For $12.9\,\text{fb}^{-1}$ integrated luminosity $\rightarrow$ monojet limit $\sigma \times \mathcal{A} \approx 40\,\text{fb}$
(Event level with selection cuts).
For projections after Run 3 we consider scaling with L and $\sqrt{L}$.

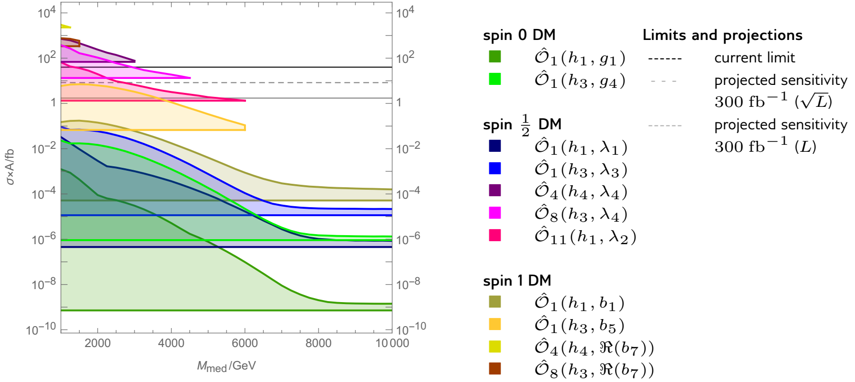
Monojet scan

- Scan over g_{DM}
- M_{eff} as input from DD
- g_q is a function of g_{DM} and M_{eff}
- Require g_{DM}, $g_q < \sqrt{4\pi}$ for perturbativity
- Also require $\Gamma_{\text{med}} < M_{\text{med}}$
- Obtain a region in the M_{med} plane consistent with $\mathcal{O}(100)$ XENONnT events



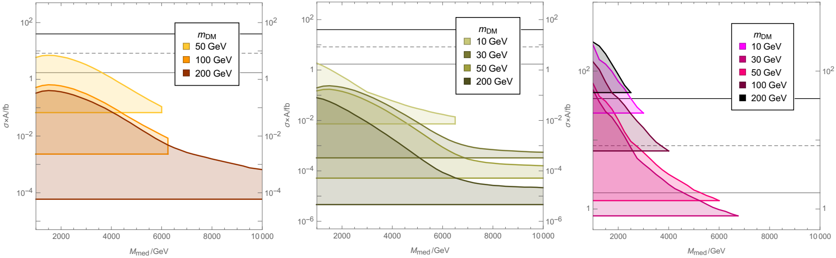
$\mathcal{O}_1(h_3, \lambda_3)$

Monojet predictions



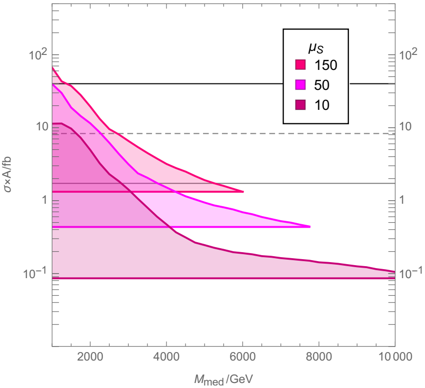
XENONnT-predicted mono-jet cross-sections as a function of M_{med} for various models compared with the LHC current limits and projected sensitivity. We assume $\mathcal{O}(100)$ signal events at XENONnT, $m_{\mathrm{DM}} = 50\,\mathrm{GeV}$ and vary the mediator mass within $1\,\mathrm{TeV} < M_{\mathrm{med}} < 10\,\mathrm{TeV}$.

Dependence on m_{DM}



Regions in the $M_{\text{med}} - (\sigma \times \mathcal{A})$ plane that are compatible with the detection of $\mathcal{O}(100)$ signal events at XENONnT for three representative simplified models, namely $\hat{\mathcal{O}}_1(h_3, b_5)$, $\hat{\mathcal{O}}_1(h_1, b_1)$ and $\hat{\mathcal{O}}_{11}(h_1, \lambda_2)$, and for the DM particle masses $m_{\text{DM}} = 10, 30, 50, 100$ and 200 GeV. Where the cases $m_{\text{DM}} = 30$ GeV and $m_{\text{DM}} = 100$ GeV are omitted, they only marginally differ from the $m_{\text{DM}} = 50$ GeV case.

Dependence on XENONnT events



Discussion & Outlook

For m_{DM} = 50 GeV two mutually exclusive scenarios compatible with $\mathcal{O}(100)$ XENONnT events:

- Models generating $\mathcal{O}_1$ out of reach for Run 3
- Models generating $\mathcal{O}_8$ or $\mathcal{O}_{11}$ can produce observable monojet signals
- Holds also true for $10\,\mathrm{GeV} < m_{\mathsf{DM}} < 100\,\mathrm{GeV}$
  $\rightarrow \mathcal{O}_1$ regions remain below Run 3 reach
  $\rightarrow \mathcal{O}_{11}$ remains (partly) testable

Possible future developments:

- Effects of running couplings and operator mixing
- Constraints from thermal production, indirect DM searches
- Charged mediators
- Non-universal DM coupling