Consequences of a XENONnT/LZ signal for the LHC and thermal dark matter production

in collaboration with S. Baum, R. Catena, J. Conrad, K. Freese
[arXiv:1709.06051, 1712.07969]

CHALMERS
UNIVERSITY OF TECHNOLOGY

Martin B. Krauss

DESY Theory Workshop 2018

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Hamburg

Overview

- After potential DM discovery, what can we learn about DM properties?
- XENONnT will start 2019
- LHC Run 3 planned start in 2020, 300 fb^{-1} in 2022
- Assuming $\mathcal{O}(100)$ XENONnT events in 2021 (˜20 ton$\times$year exposure) (just below current limits)
- Non-relativistic EFT and simplified DM models as framework

$\rightarrow$ What predictions can be made for LHC Run 3 monojet (and dijet) searches?

$\rightarrow$ Is a discovery compatible with thermal production?

$\rightarrow$ Using complementarity in DM searches, what can we learn about DM properties? (mass, couplings, spin,...)

Simplified models & EFT

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[Fitzpatrick et al., 2012]

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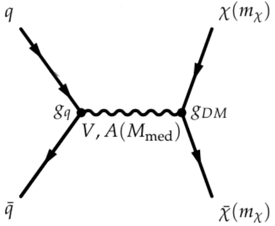
$\downarrow$ [Dent et al., 2015]



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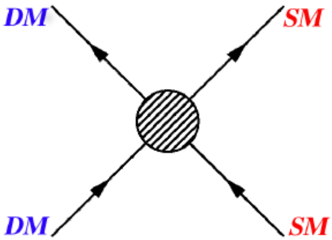

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$\downarrow$

[Dent et al., 2015]

spin 1/2 DM	Coeff.	Scalar med.	Vector med.
	c_1	$\frac{h_1^N\lambda_1}{M_\Phi^2}$	$-\frac{h_3^N\lambda_3}{M_G^2}$
	c_4		$4\frac{h_4^N\lambda_4}{M_G^2}$
	c_6	$\frac{h_2^N\lambda_2}{M_\Phi^2}\frac{m_N}{m_\chi}$	
	c_7		$2\frac{h_4^N\lambda_3}{M_G^2}$
	c_8		$-2\frac{h_3^N\lambda_4}{M_G^2}$
	c_9		$-2\frac{h_4^N\lambda_3}{M_G^2}\frac{m_N}{m_\chi} - 2\frac{h_3^N\lambda_4}{M_G^2}$
	c_{10}	$\frac{h_2^N\lambda_1}{M_\Phi^2}$	
	c_{11}	$-\frac{h_1^N\lambda_2}{M_\Phi^2}\frac{m_N}{m_\chi}$	

Benchmark points from direct detection

Direct detection can only constrain

$$M_{\mathrm{eff}} \equiv 0.1 \frac{M_{\mathrm{med}}}{\sqrt{g_q g_{\mathrm{DM}}}} \,.$$

Assume XENONnT(/LZ) detects $\mathcal{O}(100)$ (S1) signal events with an exposure of $\varepsilon = 20$ton $\times$ year

$\rightarrow$ Calculate M_{eff} for various combinations of couplings and mediators.

Operators with larger supression

$\downarrow$

smaller M_{eff}

Benchmark points

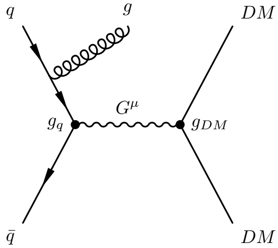
Spin 0 DM	Op.	g_q	g_{DM}	M_{eff} [GeV]
	1	h_1	g_1	14564.484
	1	h_3	g_4	10260.217
	7	h_4	g_4	4.509
	10	h_2	g_1	10.706

Spin 1/2 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

Spin 1/2 DM	Op.	g_q	g_{DM}	M_{eff} [GeV]
	1	h_1	b_1	14564.484
	1	h_3	b_5	10260.216
	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	4.509
	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

Impact on LHC monojet searches

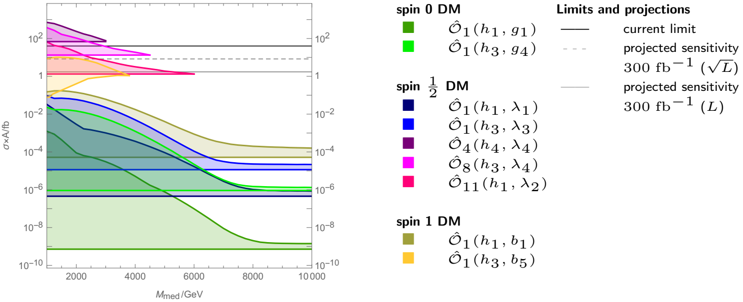
- Translating the $\mathcal{O}(100)$ XENONnT events into regions in the M_{med}-σ plane
- Mediator necessarily couples to quarks. $\rightarrow$ Can be produced in pp collisions
- Can decay into pair of DM particles (E^T_{miss})
- Initial state radiation (e.g., gluon) $\rightarrow$ jet in detector



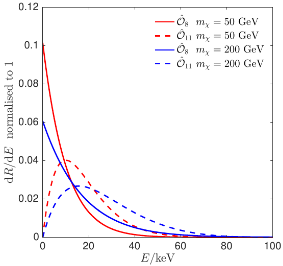
Current Limits and projections

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 predictions



Combining spectral information from direct detection with the discovery or lack of discovery of a monojet signal at the LHC can provide important information about the nature of the DM and mediator.



DM thermal production

DM in the early Universe in thermal equilibrium

$$\mathsf{DM} + \mathsf{DM} \leftrightarrows \mathsf{SM} + \mathsf{SM}\,.$$

Boltzmann equation

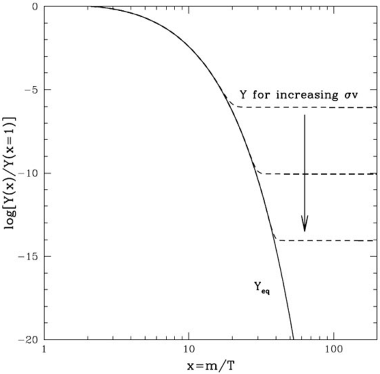
$$\dot{n} + 3Hn = -\langle \sigma v_{\mathsf{Møl}} \rangle (n^2 - n_{\mathsf{eq}}^2)$$

with the thermally averaged annihilation cross-section

$$\langle \sigma v_{\mathrm{Møl}} \rangle = \int_0^\infty \mathrm{d}\epsilon \; \mathcal{K}(x, \epsilon)\, \sigma v_{\mathrm{lab}}$$

and

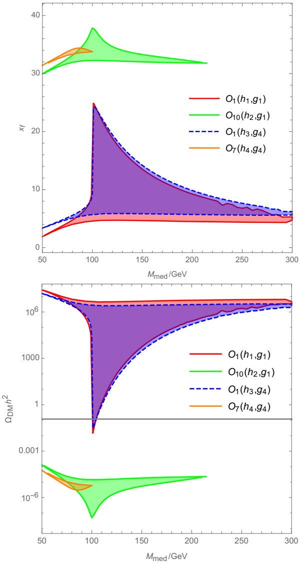
$$x = \frac{m}{T}\,.$$



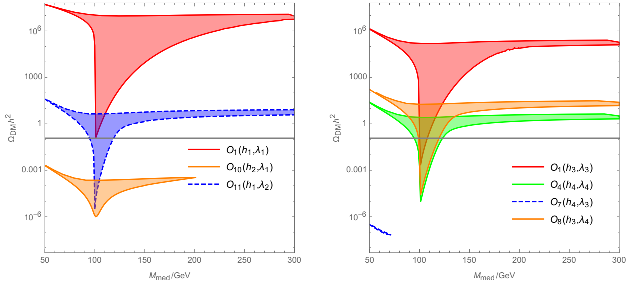
Results for scalar DM

Simplified models corresponding to spin 0 DM.

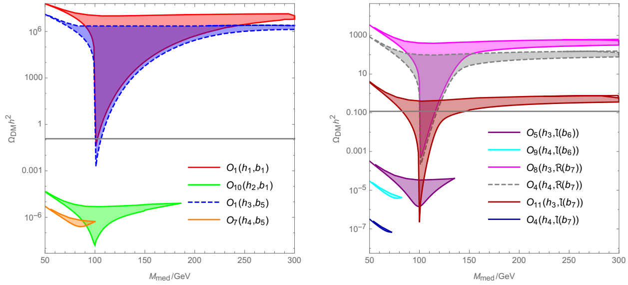
- $\hat{\mathcal{O}}_7(h_4, g_4)$ and $\hat{\mathcal{O}}_{10}(h_2, g_1)$ not compatible with the thermal production mechanism for any value of M_{med}.
- $\Omega_{\text{DM}} h^2$ much smaller than observed.
- $\hat{\mathcal{O}}_1(h_1, g_1)$ and $\hat{\mathcal{O}}_1(h_3, g_4)$ generate values for $\Omega_{\text{DM}} h^2$ which are in general too large
- For $M_{\text{med}} \sim 100$ GeV
  $\rightarrow$ resonant production of DM
  $\rightarrow$ compatible with observed relic density AND XENONnT/LZ signal



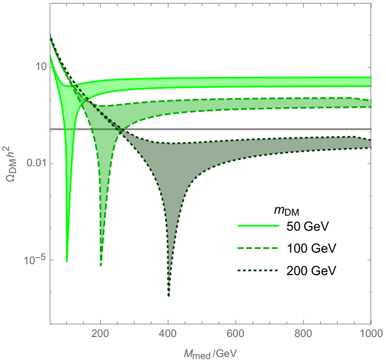
Fermionic DM

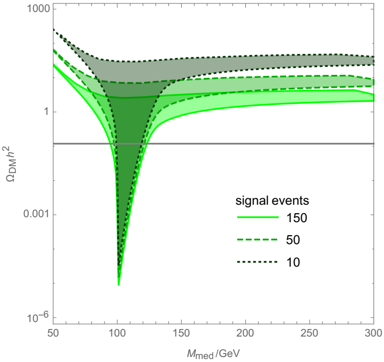


Vector DM



Dependence on m_{DM} and number of signal events



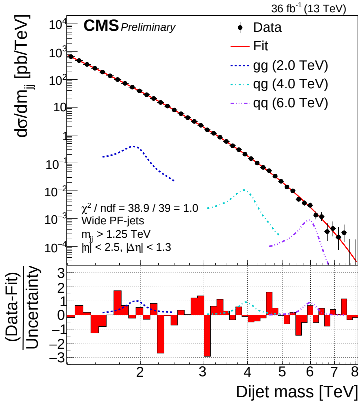


Dijet searches

- Instead of pair of DM, mediator can decay in pair of quarks
  $\rightarrow$ Pair of jets in the detector
- Reconstuct mediator mass from jet invariant mass m_{jj}

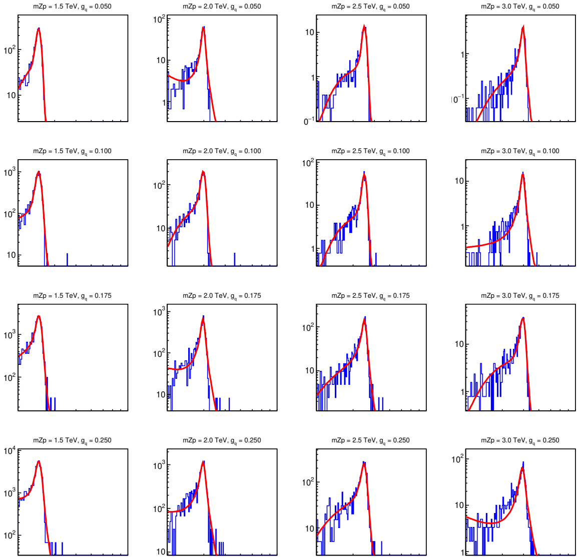
Dijet Simulation:

WHIZARD
(event generation)
$\downarrow$
PYTHIA8
(hadronization)
$\downarrow$
DELPHES
(detector simulation)
$\downarrow$
C++/ROOT
(analysis)



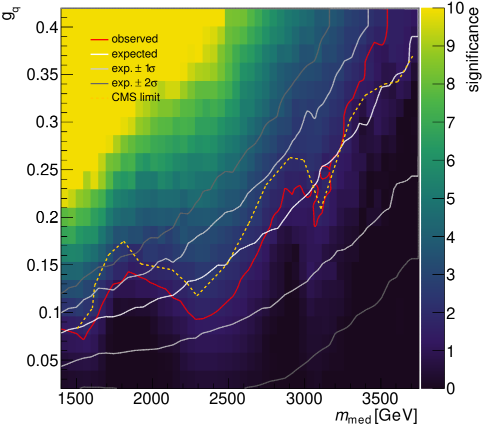
[CMS PAS EXO-16-056]

Simulated Signal



Dijet limits

preliminary

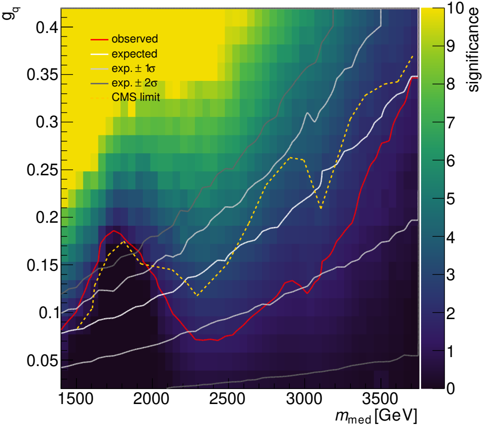


95% C.L. exclusion limits for vector mediator

$36\,\mathrm{fb}^{-1}(\sqrt{s} = 13\,\mathrm{TeV})$

Dijet limits

preliminary

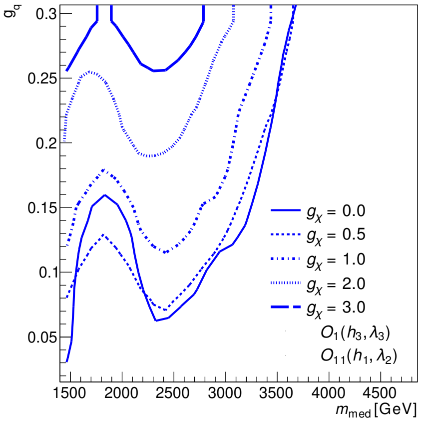


95% C.L. exclusion limits for vector mediator (sideband fit)

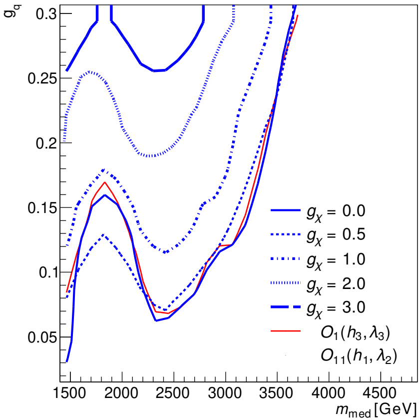
$36\,\mathrm{fb}^{-1}(\sqrt{s} = 13\,\mathrm{TeV})$

Limits for $g_\chi \neq 0$

preliminary

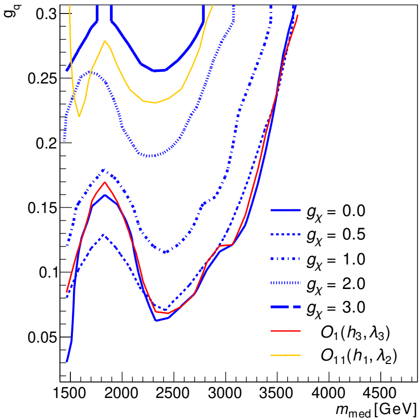


preliminary



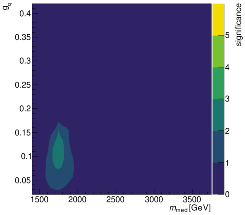
Limits for $g_\chi \neq 0$

preliminary

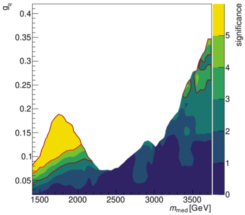


Dijet discovery potential

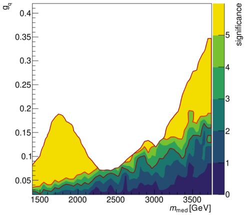
preliminary



$36\,\mathrm{fb}^{-1}$ (current)



$300\,\mathrm{fb}^{-1}$ (LHC Run 3)



$3000\,\mathrm{fb}^{-1}$ (HL-LHC)

Conclusions

- If DM is a WIMP $\rightarrow$ good chance of discovery with next generation of detectors
- Signal at XENONnT/LZ $\rightarrow$ valubale information beyond DM mass and interaction strength
- Predictions for DM searches at the LHC
- Test compatibility with thermal production mechanism
- For most models only resonant production possible ($M_{\text{med}} \simeq 2m_{\text{DM}}$.)
- Analysis will be extended to dijets (work in progress)

Using complimentarity in DM searches, we can learn more about DM properties (couplings,spin,...).

Backup-Slides

Model selection with XENONnT

Two types of spectra:

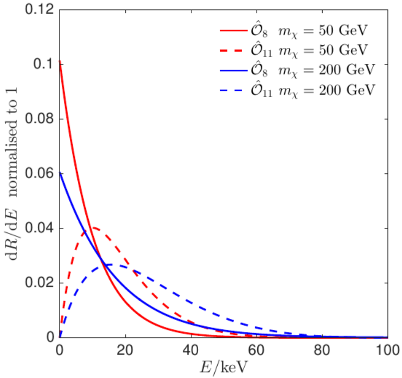
Type A: maximum at E=0 (q=0)

Type B: maximum at E≠0 (q≠0)

Canonical SI and SD interactions are of type A.

Use test statistic for model selection

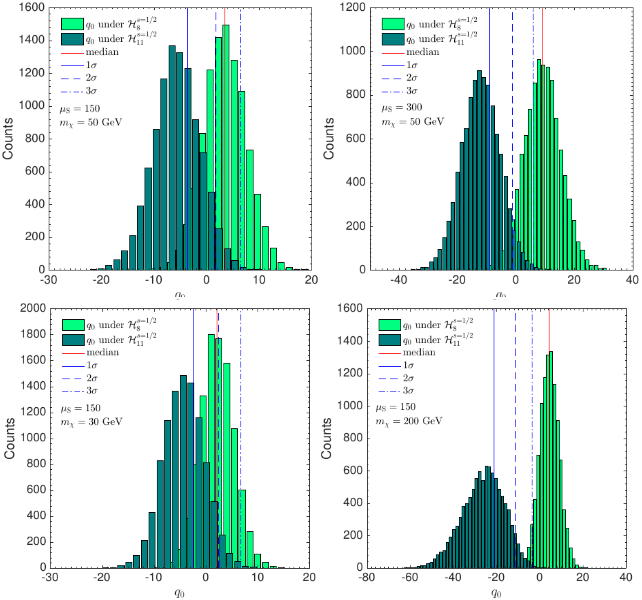
$$q_0 = -2\ln\left[\frac{\mathcal{L}(\boldsymbol{d}\,|\,\widehat{\boldsymbol{\Theta}}_0, \mathcal{H}_0)}{\mathcal{L}(\boldsymbol{d}\,|\,\widehat{\boldsymbol{\Theta}}_a, \mathcal{H}_a)}\right]$$



Assumptions:

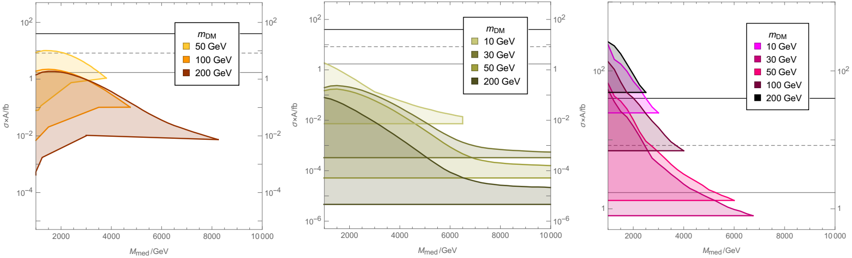
neglect operator evolution and chiral EFT corrections,

no charged mediators and universal quark-mediator couplings

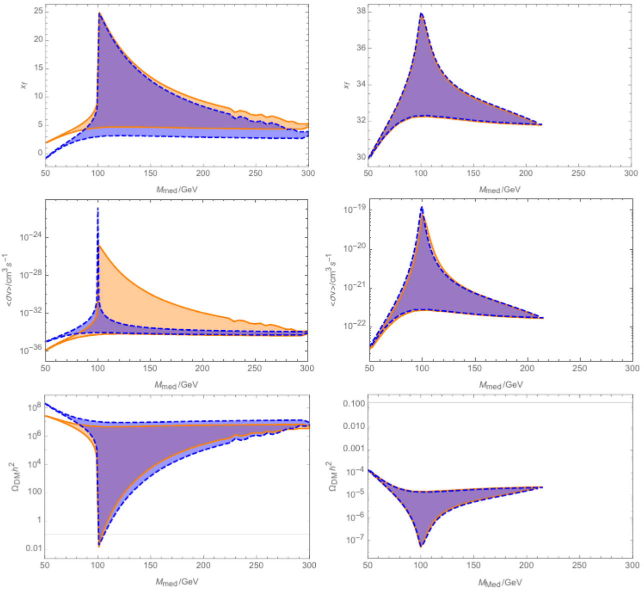


10000 pseudo-experiments each

Dependence on $m_{\rm DM}$



Regions in the $M_{\rm med} - (\sigma \times \mathcal{A})$ 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 $m_{\rm DM} = 10, 30, 50, 100$ and 200 GeV. Where the cases $m_{\rm DM} = 30$ GeV and $m_{\rm DM} = 100$ GeV are omitted, they only marginally differ from the $m_{\rm DM} = 50$ GeV case.



Comparison of the models $\hat{\mathcal{O}}_1(h_1, g_1)$ (left) and $\hat{\mathcal{O}}_{10}(h_2, g_1)$ (right)