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

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Martin B. Krauss

Preparing for Dark Matter
Particle Discovery

June 11th, 2018
Chalmers, Göteborg

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?

Two types of spectra:

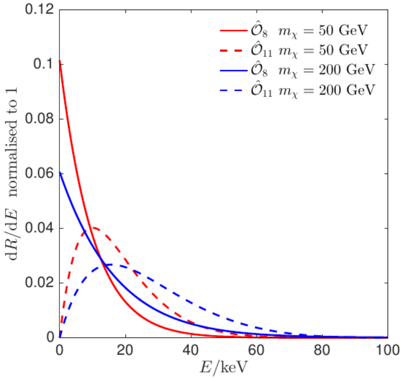
Type A: maximum at E=0 (q=0)

Type B: maximum at E≠0 (q≠0)

Canonical SI and SD interactions are of type A.

Use test statistic for model selection

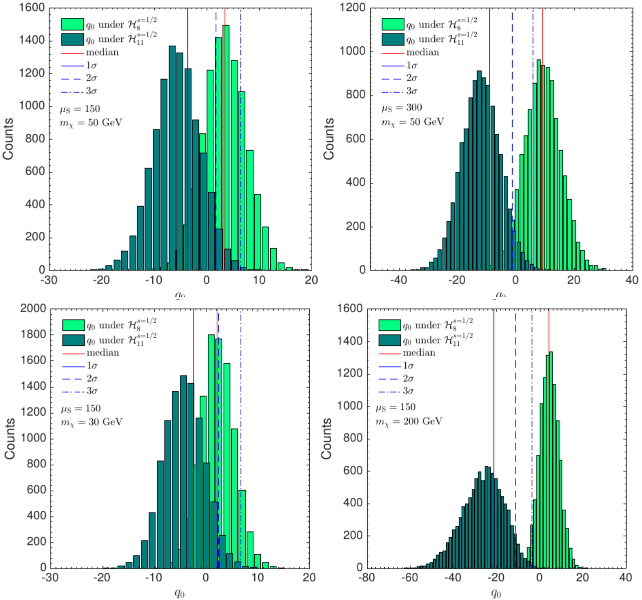
$$q_0 = -2\ln\left[\frac{\mathcal{L}(\boldsymbol{d}\,|\,\widehat{\boldsymbol{\Theta}}_0, \mathcal{H}_0)}{\mathcal{L}(\boldsymbol{d}\,|\,\widehat{\boldsymbol{\Theta}}_a, \mathcal{H}_a)}\right]$$



Assumptions:

neglect operator evolution and chiral EFT corrections,

no charged mediators and universal quark-mediator couplings



10000 pseudo-experiments each

Simplified models & EFT

$$\hat{\mathcal{O}}_1 = \mathbb{1}_\chi \mathbb{1}_N$$
$$\hat{\mathcal{O}}_3 = i\hat{\boldsymbol{S}}_N \cdot \left(\frac{\hat{\boldsymbol{q}}}{m_N} \times \hat{\boldsymbol{v}}^\perp\right) \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_4 = \hat{\boldsymbol{S}}_\chi \cdot \hat{\boldsymbol{S}}_N$$
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$$\hat{\mathcal{O}}_7 = \hat{\boldsymbol{S}}_N \cdot \hat{\boldsymbol{v}}^\perp \mathbb{1}_\chi$$
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$$\hat{\mathcal{O}}_{15} = -\left(\hat{\boldsymbol{S}}_\chi \cdot \frac{\hat{\boldsymbol{q}}}{m_N}\right) \left[\left(\hat{\boldsymbol{S}}_N \times \hat{\boldsymbol{v}}^\perp\right) \cdot \frac{\hat{\boldsymbol{q}}}{m_N}\right]$$
$$\hat{\mathcal{O}}_{17} = i\frac{\hat{\boldsymbol{q}}}{m_N} \cdot \boldsymbol{\mathcal{S}} \cdot \hat{\boldsymbol{v}}^\perp \mathbb{1}_N$$
$$\hat{\mathcal{O}}_{18} = i\frac{\hat{q}}{m_N} \cdot \boldsymbol{\mathcal{S}} \cdot \hat{S}_N$$

[Fitzpatrick et al., 2012]

Simplified models & EFT

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[Fitzpatrick et al., 2012]

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

Simplified models & EFT

$$
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\end{aligned}
$$

[Fitzpatrick et al., 2012]

$\rightarrow$

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

$\downarrow$

[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

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

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

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

Operators with larger supression

$\downarrow$

smaller $M_{\rm eff}$

Benchmark points

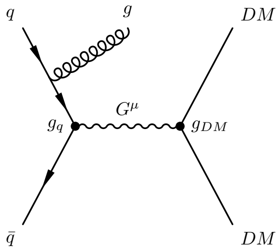
Spin 0 DM	Op.	g_q	$g_{\rm DM}$	$M_{\rm eff}$ [GeV]
	1	h_1	g_1	14564.484
	1	h_3	g_4	10260.217
	7	h_4	g_4	4.509
	10	h_2	g_1	10.706

Spin 1/2 DM	Op.	g_q	$g_{\rm DM}$	$M_{\rm eff}$ [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	$g_{\rm DM}$	$M_{\rm eff}$ [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

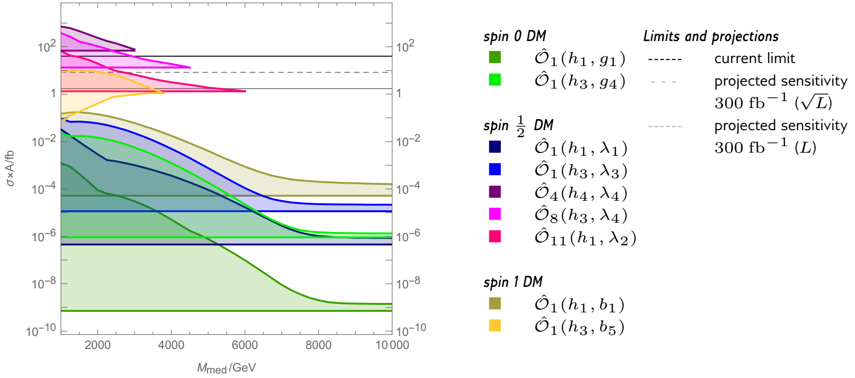
- Translating the $\mathcal{O}(100)$ XENONnT events into regions in the M_{med}-σ plane
- Mediator necessarily couples to quarks.
  $\rightarrow$ Can be produced in pp collisions
- Can decay into pair of DM particles (E^T_{miss})
- Initial state radiation (e.g., gluon)
  $\rightarrow$ jet in detector



Current Limits and projections

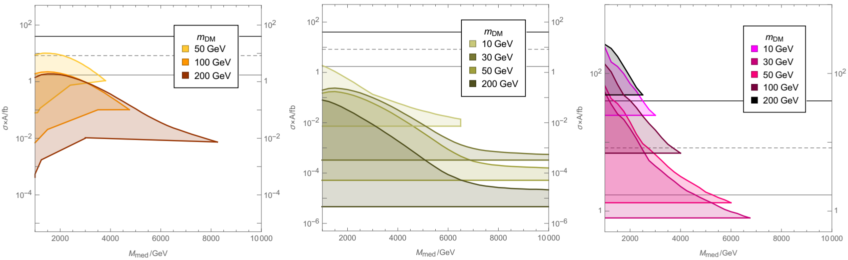
For $12.9\,\text{fb}^{-1}$ integrated luminosity $\rightarrow$ monojet limit $\sigma \times \mathcal{A} \approx 40\,\text{fb}$
(Event level with selection cuts).
For projections after Run 3 we consider scaling with L and $\sqrt{L}$.

Monojet predictions



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

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.

Results

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

Case 1

Featureless energy distribution

- Monojet signal $\rightarrow$ spin 1/2 DM, interaction via $\mathcal{O}_8$
- No monojet $\rightarrow$ canonical SI interaction ($\mathcal{O}_1$)

Case 2

Bump in energy distribution

- Monojet signal must be detected ($\mathcal{O}_{11}$)
- DM must have spin 1/2

- Observation of XENONnT/LZ signal + detection/lack of monojet signal
  $\rightarrow$narrows range of possible DM-nucleon interactions
- Provides information on DM spin

DM thermal production

DM in the early Universe in thermal equilibrium

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

Boltzmann equation

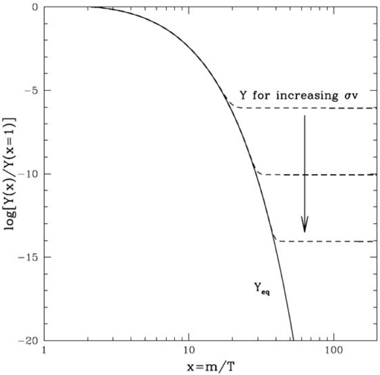
$$\dot{n} + 3Hn = -\langle \sigma v_{\text{Møl}} \rangle (n^2 - n_{\text{eq}}^2)$$

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

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



When the expansion rate becomes larger than the annihilation rate

$$\Gamma \equiv n\langle \sigma v_{\mathrm{M\o l}} \rangle \lesssim H$$

DM departs from thermal equilibrium and "freezes out".

Can be approximated as

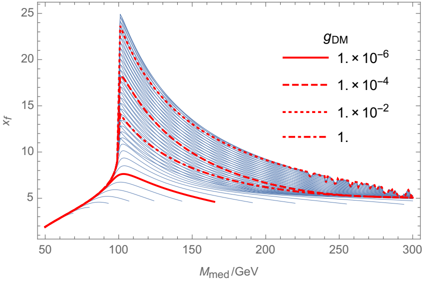
$$Y_0 = 3.79 \frac{\sqrt{g_*}}{h_{\mathsf{eff}}(T)} \frac{x_f}{M_{\mathsf{Pl}} m_{\mathsf{DM}} \sigma_0} \qquad x_f = \ln\left(0.038 \frac{g}{\sqrt{h_{\mathsf{eff}}}} M_{\mathsf{Pl}} m_{\mathsf{DM}} \sigma_0\right)$$

DM relic density today (as fraction of the critical density)

$$\Omega_{\mathsf{DM}} h^2 = 0.1199 \pm 0.0022$$

Parameter scan

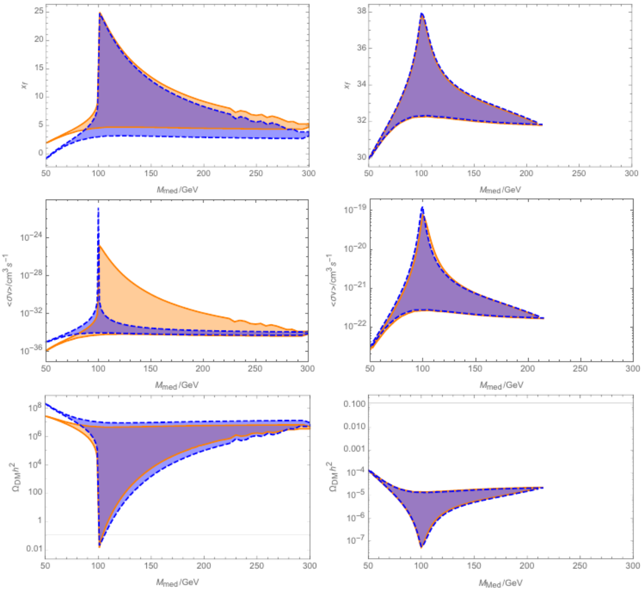
Scan over M_{med} and g_{DM}:



Quark coupling g_q determined by M_{eff}.

Assume g_{DM}, $g_q < \sqrt{4\pi}$ and $\Gamma_{\text{med}} < M_{\text{med}}$.

Defines region in paramater space which is compatible with the observation of $\mathcal{O}(100)$ signal events at XENONnT/LZ.

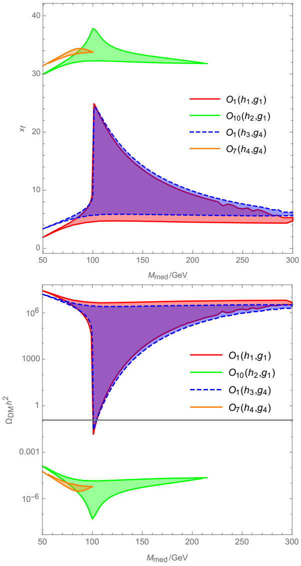


Comparison of the models $\hat{\mathcal{O}}_1(h_1, g_1)$ (left) and $\hat{\mathcal{O}}_{10}(h_2, g_1)$ (right)

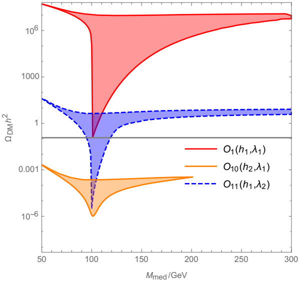
Results for scalar DM

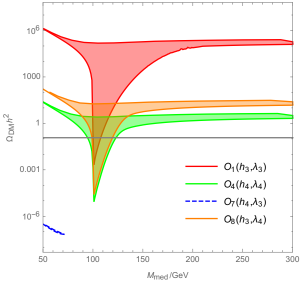
Simplified models corresponding to spin 0 DM.

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

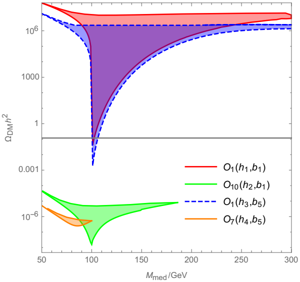


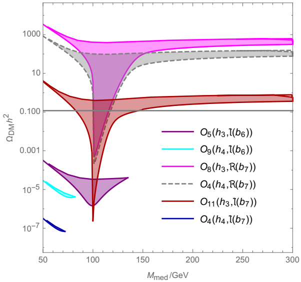
Fermionic DM



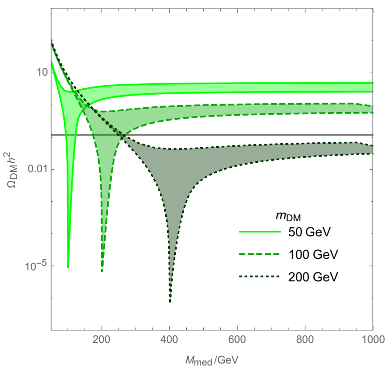


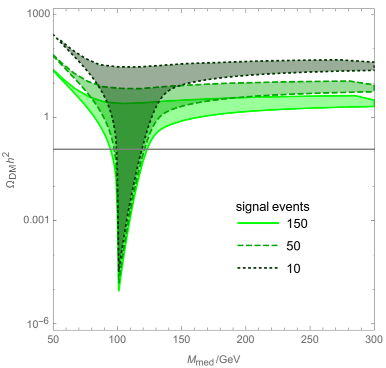
Vector DM





Dependence on m_{DM} and number of signal events





Results

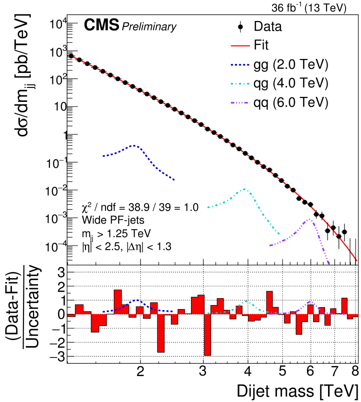
- Relic density calculation within most general set of renormalisable models that preserve Lorentz and gauge symmetries
- Extend SM by one DM candidate + mediator
- Compatibility regions in the $M_{\rm med} - \Omega_{\rm DM}h^2$ defined
- For spin 0: DM thermal production and detection at XENONnT/LZ
  $\rightarrow$ compatible only for $\hat{\mathcal{O}}_1(h_1, g_1)$ and $\hat{\mathcal{O}}_1(h_3, g_4)$
- For spin 1/2 DM $\rightarrow$ 5 models:
  $\hat{\mathcal{O}}_1(h_1, \lambda_1)$, $\hat{\mathcal{O}}_1(h_3, \lambda_3)$, $\hat{\mathcal{O}}_4(h_4, \lambda_4)$, $\hat{\mathcal{O}}_8(h_3, \lambda_4)$ and $\hat{\mathcal{O}}_{11}(h_1, \lambda_2)$.
- For spin 1 DM $\rightarrow$ 5 models:
  $\hat{\mathcal{O}}_1(h_1, b_1)$, $\hat{\mathcal{O}}_1(h_3, b_5)$, $\hat{\mathcal{O}}_4(h_4, \Re(b_7))$, $\hat{\mathcal{O}}_8(h_3, \Re(b_7))$ and $\hat{\mathcal{O}}_{11}(h_3, \Im(b_7))$.
- Increasing DM mass $\rightarrow$ regions move towards bottom right
- Move upwards if the number of signal events decreases.
- Correct DM relic density only at resonance $\rightarrow$ reconstruct DM and mediator mass simultaneously

Dijet searches

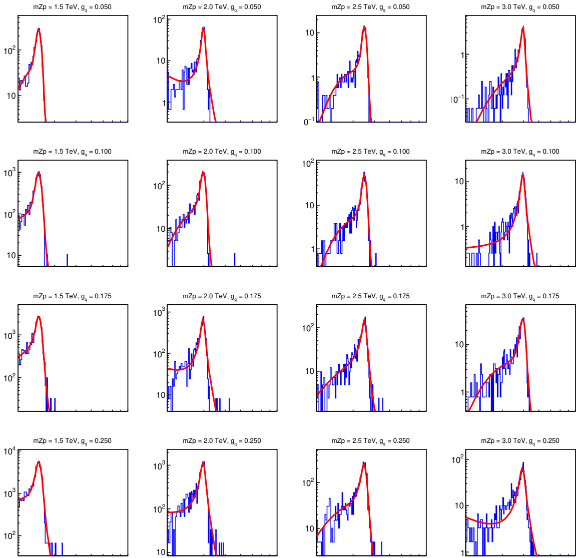
- Instead of pair of DM, mediator can decay in pair of quarks
  $\rightarrow$ Pair of jets in the detector
- Reconstuct mediator mass from jet invariant mass m_{jj}

Dijet Simulation:

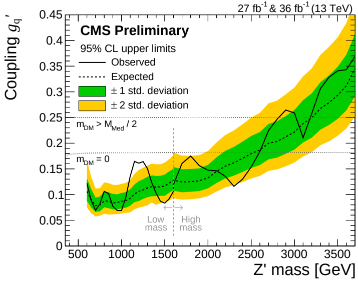
WHIZARD
(event generation)
$\downarrow$
PYTHIA6
(hadronization)
$\downarrow$
DELPHES
(detector simulation)
$\downarrow$
C++/ROOT
(analysis)

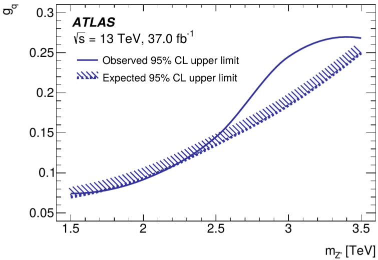


Dijet searches II

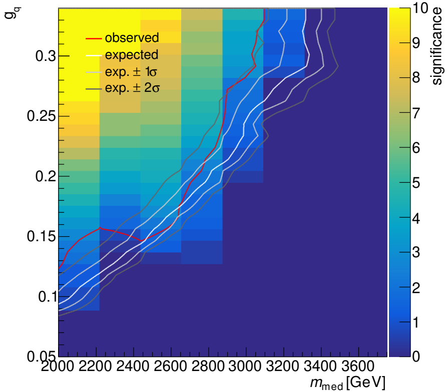


Dijet searches III





preliminary

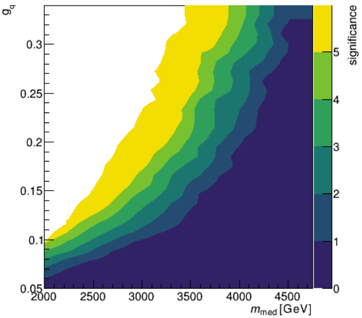


95% C.L. exclusion limits for vector mediator
$36\,\mathrm{fb}^{-1}(\sqrt{s} = 13\,\mathrm{TeV})$

Dijet searches IV

Discovery reach Run 3
(vector mediator, fermionic DM):

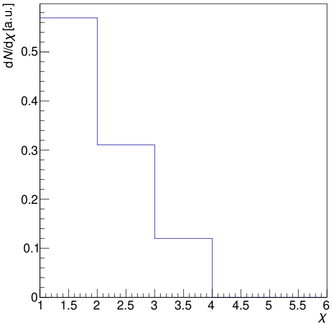
preliminary



$$300\,\text{fb}^{-1}(\sqrt{s} = 13\,\text{TeV})$$

Angular searches:

preliminary



$\chi = e^{2|y^*|}$, $|y^*| = |y_{j1} - y_{j2}|/2$,
y_j: jet rapidity

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
- Possible information about DM spin
- 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)