A simplified model for gluphilic scalar Dark Matter

Ambresh Shivaji

CP3, UCL, Louvain-la-Neuve

with
Gaurav Mendiratta, Rohini Godbole and Tim M.P. Tait

Based on 1506.01408, 1605.04756

LHC Dark Matter WG public meeting

September 19-20, 2016

The model

- Simplest DM model includes a standard model singlet scalar (χ) which is odd under a Z_2 symmetry for stability.

- In the literature, the coupling of such a dark matter with heavy electroweak bosons is widely discussed. However, the possibility of its coupling with gluons is not very popular.

- The simplified model proposed by GRT (1506.01408) allows the DM to couple with gluons via scalars (ϕ) charged under $SU(3)_c$,

$$\mathcal{L} \supset \partial_\mu \chi^* \partial^\mu \chi - m_\chi^2 |\chi|^2 + (D_\mu \phi)^* (D^\mu \phi) - m_\phi^2 |\phi|^2 + \lambda_d |\phi|^2 |\chi|^2, \tag{1}$$

$$D_\mu \phi = \partial_\mu \phi - i g_s \frac{\lambda_r^a}{2} G_\mu^a \phi. \tag{2}$$

The model

- In general, ϕ may belong to any representation of $SU(3)_c$. The coupling to quarks can be governed by the principle of MFV. When ϕ is a color triplet which couples to a pair of up-type quarks, MFV suggests it is a flavor triplet under $SU(3)_{u_R}$ ($y_i \, \epsilon_{ijk}\phi_i u_j u_k$).
- The symmetries of the model also permit additional quartic interactions such as,

$$\lambda_{\chi H}|H|^2|\chi|^2 + \lambda_{\phi H}|H|^2|\phi|^2. \tag{3}$$

- In our discussion, we would assume $\lambda_{\chi H}, \lambda_{\phi H} << \lambda_d$, and the relevant parameters of the model are $\{m_\chi,\ m_\phi,\ \lambda_d,\ r,\ y_i\}$.

The model

- In 1506.07110, the colored scalar mediator is studied in octet representation, however, the analysis is carried out in an EFT framework.
- Another case where dark matter interacts with colored particles includes the possibility where the mediator couples with top or bottom quarks 1508.00564.
- GSDM is a simple and UV complete model for dark matter.
- We would consider both the astrophysical and collider searches for GSDM discussed in 1506.01408, 1605.04756.

What has been done...

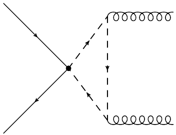
- In 1506.01408, the authors study
  a) Constraints from relic density
  b) Direct detection searches and LUX bound
  c) Collider signals: 1) production of colored mediators at tree level, 2) monojet searches at the LHC in EFT framework.
- The strongest constraints typically come from direct searches. The usual monojet is suppressed, but of course exists and a careful calculation is required.
- In 1605.04756, the monojet searches at the LHC and FCC is studied performing the exact one-loop calculation for monojet signal.

Annihilation cross section and Relic density (1506.01408)

- $m_\phi < m_\chi$, $\chi^*\chi \to \phi^*\phi$ ($\to$ hadrons)

$$< \sigma v_\chi >= \frac{\lambda_d^2 r}{64\pi m_\chi^2}\sqrt{1 - \frac{m_\phi^2}{m_\chi^2}} \tag{4}$$

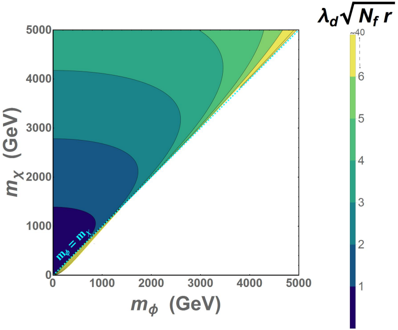
- $m_\phi > m_\chi$, $\chi^*\chi \to gg$ (via ϕ loop)



$$< \sigma v_\chi >= \frac{\lambda_d^2 T_r^2 \alpha_s^2}{64\pi^3 m_\chi^2}|(1 + 2m_\phi^2 C_0)|^2 \tag{5}$$

- In a standard $\Lambda\mathrm{CDM}$ cosmology,

$$< \sigma v > \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \tag{6}$$



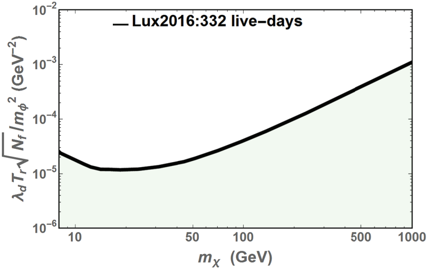
- By invoking large Yukawa (y_i) or $\lambda_{\chi H}$, a larger parameter space can be allowed in region where $m_\phi > m_\chi$.

- Spin independent cross section combined with $\chi\chi^* \to gg$ matrix element for $m_\phi >> m_\chi$,

$$\sigma_{\rm SI} = 5.2 \times 10^{-44} {\rm cm}^2 (\lambda_d T_r)^2 \left(\frac{\mu_\chi m_\chi}{10~{\rm GeV}^2}\right) \left(\frac{200~{\rm GeV}}{m_\phi}\right)^4 \qquad (7)$$

where, μ_χ is the reduced mass of the nucleon-dark matter system.

- Bound from LUX experiment with a liquid Xenon target:

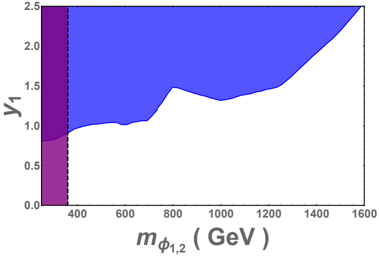


Production of colored mediators (1506.01408)

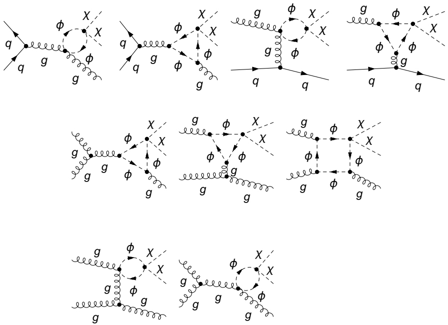
- Since the mediating scalar interacts directly with gluons, it would have large pair production cross section. Depending on its coupling strength with quarks (y_i), we can have different signatures at LHC.
- The mediators may be long-lived on collider scales in the small Yukawa limit. The best bounds come from searches for colored particles stopping in the detector material, and then later decaying out of time.
- Searches for such objects which are colored triplets or octets result in bounds on their masses of roughly $m_\phi \gtrsim 900$ and $m_\phi \gtrsim 1200$ GeV, respectively.

Color triplet mediators (1506.01408)

- Yukawa interaction of color triplet mediators with up-type quarks, $y_1\ (\phi_1 c_R - \phi_2 u_R)\, t_R + y_2\ \phi_3 u_R c_R + h.c.$
- The CMS bound (1412.7706) on pairs of dijet resonances $(\mathrm{gg} \to \phi_3^* \phi_3,\ \phi_3 \to \mathrm{u_R c_R})$ requires $m_{\phi_3} \gtrsim 350$ GeV.
- Top-rich signatures: $\mathrm{gg} \to \phi_{1,2}^* \phi_{1,2} \to \mathrm{t\bar{t}} + 2\ \mathrm{jets}$, $\mathrm{qg} \to \mathrm{t}\phi_{1,2}^* \to \mathrm{t\bar{t}} + 1\ \mathrm{jet}$. Bounds from ATLAS and CMS,

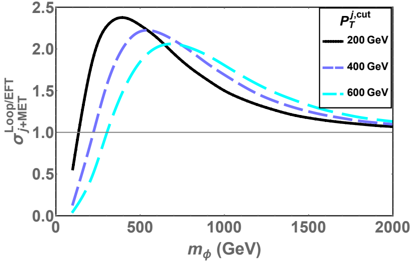


- Monojet search at colliders is intimately connected with dark matter and is most model independent probe.
- Monojet signal in GSDM: $\mathrm{pp} \to \chi\chi^{*}\mathrm{j}$ (monojet+mET)
- It is a one-loop process mediated by ϕ and receives contributions from qq, qg, and gg initial states.



Calculation & EFT limit (1605.04756)

- We have calculated the amplitudes using in-house code integrated with OneLOop library of scalar integrals. As a cross-check the calculation is repeated using FormCalc and LoopTools.
- Taking the advantage of the automation of one-loop calculation in Madgraph, we have also prepared the UFO library of the model using NLOCT in FeynRules.
- We have also compared the exact one-loop calculation with the EFT calculation (often used for heavy mediator case) for the monojet.



- We obtain bounds on the cross section at 95% C.L. for a set of p_T^j cuts used in the experiments.

$$m_\chi = 1 \text{ GeV}, \;\; \lambda_d = 1, \;\; |\eta_j| < 2.0 \tag{8}$$

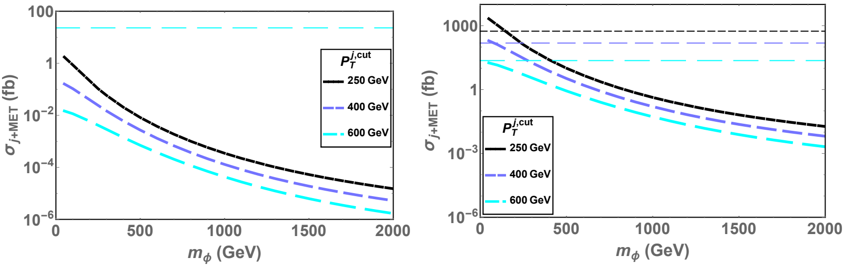


Figure : ATLAS data 13 TeV (3.2 fb^{-1}), $r = 3$(left) and $r = 15$(right).

- We consider the main SM background $\mathrm{pp} \to \mathrm{Zj},\ \mathrm{Z} \to \nu\bar{\nu}$ to the monojet and access the collider reach to discover GSDM for different values of m_ϕ.

$$|\eta_j| < 2.4,\ p_T^j > 200\ \mathrm{GeV} \tag{9}$$

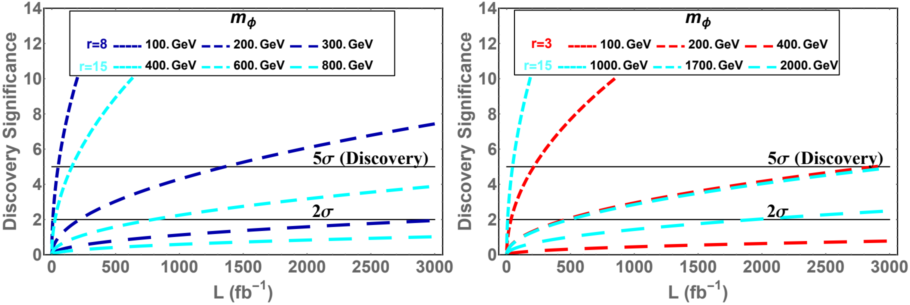


Figure : Significance $(S/\sqrt{B})$ at 13 (left) and 100 (right) TeV.

Summary

- GSDM is a viable UV complete model for dark matter.
- It has many astrophysical and collider signatures.
- It can be probed at gluon machines like LHC and its future upgrades.
- There are many collider signatures for the colored mediators in the model, which constrain the mediator mass and its coupling with quarks.
- For monojet searches, the high luminosity LHC can easily probe higher representation of ϕ with masses up to 500 GeV. A much large parameter space can be explored at FCC.

Backup

- The effective interaction of dark matter with gluons in heavy m_ϕ limit,

$$\mathcal{L}_{\rm EFT} = \frac{\lambda_d \alpha_s T_r}{48\pi} \frac{1}{m_\phi^2} \; |\chi|^2 G^a_{\mu\nu} G^{a\mu\nu}. \tag{10}$$

- Bounds from the CMS monojet analysis (1408.3583) with $\not{E}_T > 500$ GeV,

$$\frac{\lambda_d T_r}{48\pi} \frac{1}{m_\phi^2} \leq \frac{1}{(207 \text{ GeV})^2}, \tag{11}$$

for $m_\chi \lesssim 200$ GeV.

Backup

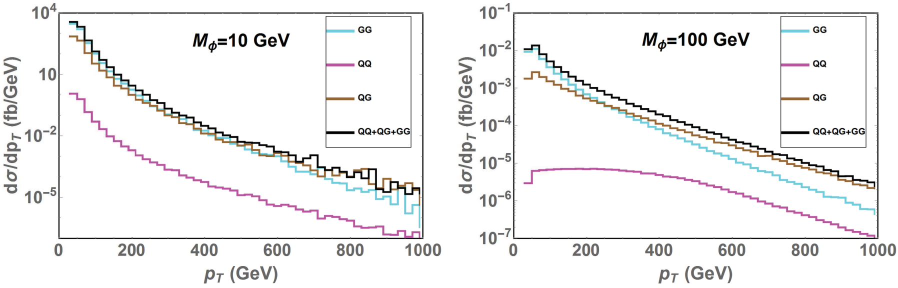


Figure : p_T^j distribution and initial state dependence for different m_ϕ masses.

Backup

$$m_\chi = 1 \text{ GeV}, \;\; \lambda_d = 1, \;\; |\eta_j| < 2.4 \tag{12}$$

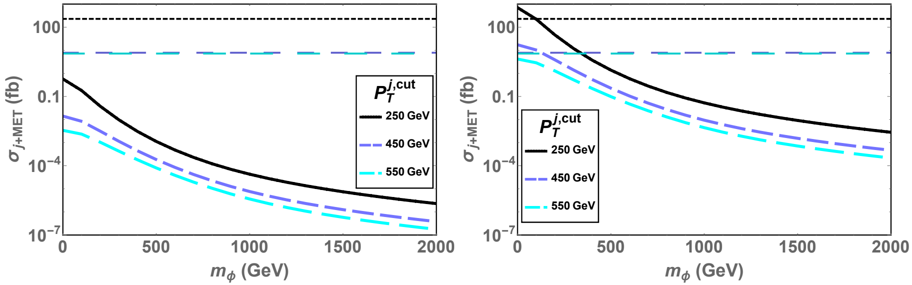


Figure : CMS data 8 TeV, $r = 3$(left) $r = 15$(right).