Nonthermal Dark Matter and LHC Monojet

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A non-thermal DM & Baryogenesis

- Relic density and baryon asymmetry are produced non-thermally from the decay of some heavy states (e.g. moduli).
- A `minimal' extension to SM with ~TeV scalar color triplet(s) and a ~GeV fermionic DM candidate.
- Baryon-number violating interaction mediated by new scalars:

\[
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\text{new}}
\]

\[
\mathcal{L}_{\text{new}} = (\lambda_{\alpha i} X_{\alpha}^* N u_i^c + \chi'_{\alpha ij} X_{\alpha} d_i^c d_j^c + \frac{1}{2} m_N N N + \text{h.c.})
\]

\[
+ m_\alpha^2 |X_\alpha|^2 + \text{(kinetic terms)}.
\]

and couples to \( N \) the dark matter candidate.

• (Baryogenesis) when $X_1$ and $X_2$ decay, baryon asymmetry is caused by the interference b/w their tree-level and one loop decay diagrams, baryon asymmetry becomes related to the DM abundance as $X$ decay also produces $N$.

• (Non-thermal) $X$ needs to stay out-of-equilibrium (from $XX^* \leftrightarrow gg$) to yield sufficient baryon asymmetry: $X$ can be the decay product of some heavier states during a relatively late reheating process.


• (GeV DM mass) for proton stability DM – proton mass difference less than electron mass. For $\lambda \sim 0.1$ and $m_X \sim \text{TeV}$, one loop correction to $m_N \leq m_e$. 
**LHC phenomenology: Monojet**

- X couples to two d-quarks or one u-quark and DM: A s-channel resonant process \((d \ d' \rightarrow X \rightarrow u \ \bar{N})\)
- A monojet event without ISR.
**How different from ISR + Effective Operator?**

- Jet energy $\sim \frac{1}{2} X$ mass: a peak in $P_T$ distribution.
- No preference for lower jet $P_T$: High $P_T$ cut can be very effective against SM background.
- Effective operator ($\sim \bar{d} d^c \bar{u} N/\Lambda^2$) approach is also non-ISR, but not favorable as it loses the peak feature in $P_T$ distribution.
A Madgraph5 package

- SM extended with two SU(3) triplet scalars and a DM
  STripletBaryogen_X2N1.tar.gz

- Implemented: $X^* d^c d^c$, $X u^c N$ Interaction terms (and $X$ couplings to gluons)

$$\mathcal{L}_{int} = \lambda_1^{\alpha, \rho \delta} \epsilon^{ijk} X^*_\alpha \bar{d}_{\rho, j} P_R d^c_{\delta, k} + \lambda_2^{\alpha, \rho} X_\alpha \bar{u}_\rho P_R n + C.C.$$  

$$\lambda_1^{\alpha, \rho \delta} = \lambda_1 \cdot \lambda_{1X}^{\alpha} \cdot \lambda_{1R}^{\rho \delta}$$  

$$\lambda_2^{\alpha, \rho} = \lambda_2 \cdot \lambda_{2X}^{\alpha} \cdot \lambda_{2R}^{\rho}$$

$$\lambda_{1X}^{\alpha} = (1, 1)$$  

$$\lambda_{1R}^{\rho \delta} = \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$  

$$\lambda_{2X}^{\alpha} = (1, 1)$$  

$$\lambda_{2R}^{\alpha} = (1, 1, 1)$$

Xdd term forbids symmetric quark generation structure

Can make $X_1$ much lighter than $X_2$ so that one scalar is more relevant for LHC.
High jet $P_T$ cut can be effective

The light scalar dominates the signal and sets the characteristic jet $P_T$ scale.

Processes and Feynman diagrams

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24 diagrams (12 independent).
Constraint from CMS Monojet @ 8 TeV & 19.5 fb$^{-1}$ at Parton/MG5 level

A special case $\lambda = \lambda_1 = \lambda_2$
so that the integrated s-channel cross-section scales with $\lambda^2$

parton level:
correction from secondary jet(s) not included

Cuts:

* $E_j > 30$ GeV
* $|\eta_j| < 2.4$
* Minimal $\sigma/\sigma_{95\%}$ from all 7 CMS Pt cuts

$|\lambda_1 \lambda_2|$ constrained to $10^{-2}$. 

CMS@8TeV 19.5 fb$^{-1}$

$m_N \sim 1$ GeV

$\lambda = \lambda_1 = \lambda_2$, $m_{X_2} \rightarrow 2m_{X_1}$
Prospects at LHC

- **Monojet**: s-channel X resonance with a u+DM final state, constrains $|\lambda_1 \lambda_2|$.

- **Dijet**: s-channel X resonance with a dd' final state, constrains $\lambda_1$.

- **X pair production**: two jets +MET & 4 jets.

- **X coupling to heavy quarks**: single c/t + MET, b+light quark, etc.
A possible variation in theory...

- $X'^c u d^c$ (instead of $X^c d d^c$ where $u$ is replaced) can also give nonthermal DM and baryogenesis.
- Need `some' symmetry to forbid the QLX' term which causes proton decay.
- Allow symmetric quark generation structure in, i.e. same generation process ($u d \rightarrow X' \rightarrow$ jet +MET):
  Both initial quarks are valence quarks.
SUMMARY

- Strong motivation in DM & Baryon asymmetry
- Non-ISR, resonant monojet events in LHC
- Madgraph5 package available.