Probing Light Nonthermal Dark Matter @ LHC

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A non-thermal DM & Baryogenesis

- A `minimal' extension to SM with ~TeV scalar color triplet(s) and a fermionic DM candidate
- Baryon-number violating interaction mediated by heavy scalars (X):

\[ \mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta} \epsilon^{ijk} X_{\alpha,i} \bar{d}^{c}_{\rho,j} P_R d_{\delta,k} + \lambda_2^{\alpha,\rho} X^*_{\alpha} \bar{n}_{DM} P_R u_{\rho} + \text{C.C.} \]


X index \(\alpha=1,2\). At least two Xs are required for successfully baryogenesis
Quark generation indices \(\rho, \delta =1,2,3\)
SU(3) color indeces \(i,j,k =1,2,3\)
Baryon asymmetry and DM density

- Xs are the decay products from some heavy particles during the reheating process.

- (Baryogenesis) when $X_1$ and $X_2$ decay, baryon asymmetry arises from the interference between tree-level and one-loop self-energy diagrams $^\dagger$,

\[
\frac{n_B}{s} = \frac{Y_S}{8\pi} \frac{1}{M_{X_2}^2 - M_{X_1}^2} \sum_{i,j,k} \text{Im}(\lambda_{1,i}^1\lambda_{1,j}^1\lambda_{2,k}^1\lambda_{2,j}^2) \\
\times \left[ \frac{M_{X_1}^2 BR_1}{\sum_{i,j} |\lambda_{1,i}^1|^2 + \sum_k |\lambda_{2,k}^1|^2} + \frac{M_{X_2}^2 BR_2}{\sum_{i,j} |\lambda_{1,i}^2|^2 + \sum_k |\lambda_{2,k}^2|^2} \right]
\]

$Y_S$: dilution factor from a heavy S (~100TeV) that decays into Xs.
BR: decay branching of S into $X_1$ or $X_2$.

$^\dagger$ R. Allahverdi, B. Dutta, K. Sinha PRD 82 (2010) 035004
Baryon asymmetry and DM density

- (Non-thermal) dark matter are also the decay product of Xs.

\[
\frac{n_n_{DM}}{s} = Y_S \left[ \frac{\text{BR}_1 \sum_k |\lambda^{1,k}_2|^2}{\sum_{ij} |\lambda^{1,ij}_1|^2 + \sum_k |\lambda^{1,k}_2|^2} + \frac{\text{BR}_2 \sum_k |\lambda^{2,k}_2|^2}{\sum_{ij} |\lambda^{2,ij}_1|^2 + \sum_k |\lambda^{2,k}_2|^2} \right]
\]

Thus the relic density becomes related to that of baryonic asymmetry,

\[
n_B/n_n_D = \frac{m_{n_{DM}}}{m_p} \frac{\Omega_B}{\Omega_{n_{DM}}} \approx \frac{1}{8\pi} \frac{M^2_{X_1}}{M^2_{X_2} - M^2_{X_1}} \frac{\sum_{i,j,k} \text{Im}(\lambda^{1,ij}_1 \lambda^{2,ij}_1 \lambda^{1,k*}_2 \lambda^{2,k}_2)}{\sum_k |\lambda^{2,k}_2|^2} \sim 0.2.
\]

For \(\lambda_2 \sim O(1)\) and \(M_X \sim \text{TeV}\), DM decoupling temperature is \(\sim \text{MeV}\). \(M_X\) isn't tightly constrained by the relic density. We consider sub-TeV cases.
A minimal parametrization

- SM extended with two SU(3) triplet scalars and a DM
- Implemented in MadGraph5: New interaction terms and gluon-X couplings.

\[
\lambda_1^{\alpha, \rho \delta} = \lambda_1 \cdot \lambda_{1X}^{\alpha} \cdot \lambda_{1R}^{\rho \delta}
\]
\[
\lambda_2^{\alpha, \rho} = \lambda_2 \cdot \lambda_{2X}^{\alpha} \cdot \lambda_{2R}^{\rho}
\]

\[
\lambda_{1X}^{\alpha} = (1, 1)
\]
\[
\lambda_{1R}^{\rho \delta} = \begin{pmatrix}
0 & 1 & 1 \\
0 & 0 & 1 \\
0 & 0 & 0 \\
\end{pmatrix}
\]
\[
\lambda_{2X}^{\alpha} = (1, 1)
\]
\[
\lambda_{2R}^{\alpha} = (1, 1, 1)
\]

Xdd term forbids symmetric quark generation structure

For simplicity:
1. we made $X_1$ lighter than $X_2$ so that $X_1$ is more relevant for LHC
2. we made a minimal, flavor blind structure in $\lambda$. 
A light dark matter

• (GeV DM mass) $n_{DM}$ is not protected by a parity, yet coupled to light quarks. For proton stability, DM – proton mass difference less than electron mass.

$$| M_{DM} - M_p | < M_e$$

kinematically stabilizes the DM and the proton. For $\lambda_2 \sim 0.1$ and $M_X \sim \text{TeV}$, radiative correction to $M_{DM}$ is less than $M_e$.

• 1 GeV DM mass evades direct detection.
Collider phenomenology: Monojet

- $X$ couples to two $d$-quarks or one $u$-quark and DM:
  A s-channel resonant process ($d\ d'\rightarrow X^*\rightarrow u\ n$)
- A monojet + MET event without ISR.
Collider phenomenology: Monojet

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  A s-channel resonant process ($d d' \rightarrow X^* \rightarrow u \bar{N}$)
- A monojet + MET event without ISR.
How different from ISR + Effective Operator?

- Jet energy $\sim \frac{1}{2}$ new scalar mass: a Jacobian 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 as favorable, since it loses the peak feature in $P_T$ distribution.
A sample (mono) jet $p_T$ distribution with $X_1$ mass at 1 TeV. A high $p_T$ cut near the Jacobian peak picks out (most of) the signal.
**Monojet constraint @ LHC**

Data: CMS 20 fb\(^{-1}\) at 8 TeV, 95 C.L.

CMS-PAS-EXO-12-048, March 8, 2013

PDF integrated cross-section is determined by the lesser between \(\lambda_1\) and \(\lambda_2\)

\[
\sigma \propto |\lambda_1|^2 |\lambda_2|^2 / \left( 2 |\lambda_1|^2 + |\lambda_2|^2 \right)
\]
A further simplified case: $\lambda_1 = \lambda_2$
Constrained to $O(0.1)$ for $X_1$ below $\sim 1.3$ TeV
Collider phenomenology: Dijet

- Similar to the monojet process but with two (different generation) down-type quarks in the final state:

\[
\begin{array}{c}
d \\
\lambda_1 \\
d' \\
\hline
\lambda_1 \\
X^* \\
\lambda_1 \\
d' \\
d
\end{array}
\]

Dijet cross section only depends on $\lambda_1$. 
Dijet constraint @ Tevatron

Data: CDF 1.13 fb\(^{-1}\) at 1.96 TeV, 95 C.L.
T. Aaltonen et al. [CDF Collaboration],

Note: CDF uses the pT distribution near resonance for spin-1 and spin-1/2 states, with O(1) variation in the constrained new physics cross-section. We used the weakest list bounds. Optimization for a spin-0 state can help.
Collider phenomenology: 2 jets + MET

- Initial state gluon splitting (ISGS)

- via X pair-production
Distinguishing Pair-production from ISGS

FIG. 6. Two sample jet $p_T$ (blue and red) and $M_{\text{eff}}$ (black) distributions for $\lambda_1 = \lambda_2 \sim 1$ (left) and $\lambda_2 \gg \lambda_1$ (right). The ISGS process gives a soft secondary jet from gluon splitting, and $M_{\text{eff}}$ near $M_X$. The pair-production process leads to two energy jets and a $M_{\text{eff}}$ peak near $2M_X$. A properly placed $M_{\text{eff}}$ cut can be effective against the ISGS contributions.

$M_{\text{eff}} \sim 2M_X$ is the watershed
Signal Region (SR):
`A Loose (Medium)` cuts for $X_1$ mass at 500 GeV (1 TeV)

2 jets + MET (95% C.L.) exclusive bounds selected from ATLAS multi-jet analysis with 20.3 fb$^{-1}$ at 8 TeV:

Turn over at small $\lambda_1$:
Due to pair-production diagrams becoming dominant when $\lambda_1 \ll \lambda_2$. 
Collider phenomenology: Paired dijets

- X pair production with both Xs decay into dd'.
- Constrain $\lambda_1$. (In contrast, dijet+MET via pair-production constrains $\lambda_2$)
- ISR diagrams negligible due to two heavy masses being reconstructed.
Paired dijet constraint @ LHC

Parton level cuts:
- $p_{Tj} > 110$ GeV
- $|\eta_j| < 2.5$
- $\Delta R_{jj} > 0.7$

Data: CMS 5 fb$^{-1}$ at 7 TeV, 95 C.L.
S. Chatrchyan, et. al. [CMS collaboration]
Combined collider bounds

![Graph showing combined collider bounds for different mass values](image-url)
Notes

• All the presented results are at the parton level, and $b$ quarks considered as jets.

• $X_1$ and $X_2$ can be close in mass. When $M_{X_1} \sim M_{X_2}$, signal cross-section doubles and $\lambda$ constraints improves by up to 40% (non-interference case)
Summary & outlook

- Strong motivation in dark matter & baryon asymmetry
- Non-ISR monojet events, with Jacobian peaks in $p_T$
- Significant constraints on model parameters (lesser $\lambda \sim 0.1$ for a TeV heavy scalar mediator mass)
- A mono-top + MET search?
  The $\lambda_2$ coupling to the 3rd generation is not constrained.