Probing Light Nonthermal Dark Matter @ LHC

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Outline

- Minimal extension to SM for baryogenesis & dark matter

- Current constraints from *Monojet*, dijet, 2 jets +MET, paired dijets

- Heavy favor outlook: single top +MET, t t + MET
A non-thermal DM & Baryogenesis

- A `minimal' extension to SM with \( \sim \) TeV scalar color triplet(s) and a fermionic DM candidate

- Baryon-number violating interaction mediated by heavy scalars (X):

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


\( X \) index \( \alpha=1,2 \). At least two Xs are required for successfully baryogenesis
Quark generation indices \( \rho \delta =1,2,3 \)
SU(3) color indices \( i,j,k =1,2,3 \)
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 the interference b/w tree-level and one-loop self-energy diagrams$^\dagger$,

\[
\frac{n_B}{s} = \frac{Y_S}{8\pi} \frac{1}{M_{X_2}^2 - M_{X_1}^2} \sum_{i,j,k} \text{Im}(\lambda_{1,i}^1 \lambda_{2,i}^2 \lambda_{2,k}^2 \lambda_{2,k}^2) \\
\times \left[ \frac{M_{X_1}^2 \text{BR}_1}{\sum_{i,j} |\lambda_{1,i}^1|^2 + \sum_{k} |\lambda_{2,k}^2|^2} + \frac{M_{X_2}^2 \text{BR}_2}{\sum_{i,j} |\lambda_{1,i}^1|^2 + \sum_{k} |\lambda_{2,k}^2|^2} \right]
\]

$Y_S$: 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.

\[ \frac{n_{n_{DM}}}{s} = Y_S \left[ \frac{\text{BR}_1 \sum_k \lambda_2^{1,k} \lambda_2^{1,k} \lambda_2^{1,k} \lambda_2^{1,k}}{\sum_{i,j} |\lambda_2^{i,j}|^2 + \sum_k |\lambda_2^{1,k}|^2} \right] \]

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

\[ n_B/n_D = \frac{m_{n_{DM}}}{m_p} \frac{\Omega_B}{\Omega_{n_{DM}}} \]

\[ = \frac{1}{8\pi} \frac{M^2_{X_1}}{M^2_{X_2} - M^2_{X_1}} \sum_{i,j,k} \text{Im}(\lambda_1^{i,j} \lambda_2^{i,j} \lambda_1^{1,k} \lambda_2^{2,k}) \frac{\sum_k |\lambda_2^{1,k}|^2}{\sum_k |\lambda_2^{2,k}|^2} \sim 0.2. \]

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

- Implemented in MadGraph5: New interaction terms and gluon-X couplings.

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

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

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

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

\[ \lambda_{1R}^{\rho\delta} = \begin{pmatrix} ds & db \\ 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \]

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

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

Xdd term forbids symmetric quark generation structure (b/c antisymmetry in color indices)

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.

DM mass stability: For $\lambda_2 \sim 0.1$ and $M_X \sim$ 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 $\bar{\text{DM}}$: A s-channel resonant process $(d\ d' \rightarrow X^* \rightarrow u\ n)$
- A monojet + MET event without ISR.

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

\[
\sigma \propto \frac{|\lambda_1|^2 |\lambda_2|^2}{(2|\lambda_1|^2 + |\lambda_2|^2)}
\]

Parton level cuts:
* \(|\eta| < 2.4\)
* Minimal \(\sigma/\sigma_{95}\%\) from all listed \(p_T\) cuts
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:

\[
\lambda_1^\alpha, \rho \delta \epsilon^{ijk} X_{\alpha,i} \bar{d}_{\rho,j}^c P_{Rd,\delta,k}
\]

Dijet cross section only depends on \( \lambda_1 \).
Dijet constraints

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

Note: CDF uses the $p_T$ 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.

Parton level cuts:
* $E_j > 10$ GeV
* $|\eta_j| < 1$

CMS dijet low mass analysis with 0.13 fb$^{-1}$ data @ 7 TeV
CMS-PAS-EXO-11-094, 2012

Use the bound from a qq final state
Parton level cuts:
* $p_{Tj} > 30$ GeV
* $H_T > 100$ GeV, $|\Delta \eta_{jj}| < 2$
Collider phenomenology: 2 jets + MET

- Initial state gluon splitting (ISGS)

\[ M_{\text{eff}} \] drops quickly above \( M_{X_1} \).

\[ \text{d} \sigma / \text{d}x \text{ [pb GeV}^{-1}] \]

\[ x = M_{\text{eff}} \text{ or jet } P_T [\text{GeV}] \]

\[ \lambda_1 = \lambda_2 \sim 1 \]

\[ P_T j_1 \]

\[ P_T j_2 \]
Collider phenomenology: 2 jets + MET

- X pair-production

Two heavy scalars: $M_{\text{eff}}$ can be large compared to ISGS.
**ISGS vs Pair-production**

![Graph comparing ISGS and pair-production](image)

**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 singly produces $X_1$ and $M_{\text{eff}}$ drops quickly above $M_{X_1}$. In the pair-production case $M_{\text{eff}}$ is easier to be above $M_{X_1}$. A properly placed $M_{\text{eff}}$ cut above $M_{X_1}$ can be effective to separate the ISGS from pair production.
2 jets + MET constraint @ LHC

Signal Region (SR):
`A Loose (Medium)`' cuts
for X1 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

![Graphs showing combined collider bounds for different mass values](image)
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)
From current bounds ...

- 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)
Outlook: the 3rd generation quarks

- Baryogenesis & DM production are indiscriminate in quark flavor

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

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

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Couplings to d-quarks: constrained w/o distinguishing the bottom quark

Light jets: constrained

Top: NOT constrained
Mono-top + MET

Like monojet, single top can be produced via s-channel resonance

\[ M_{X1} = 1 \text{ TeV} \]
Other possibilities: Top + jet(s) + MET

- ISGS (also ISR diagrams)
*Other possibilities: $t \bar{t} + \text{MET}*$

- From $X$ pair production both $X \rightarrow t, n_{DM}$
- Analogous to SUSY stop pair production in the low neutralino mass limit

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CMS-SUS-13-011,

$M_{DM} = 1 \text{ GeV}$

**SUSY stop pair:** QCD dominated production

**$X$ pair:** QCD + NP (via $\lambda_2$),

*large $\lambda^3_2$ for significant $X$ decay BR into $t$*