

Looking for a Light Nonthermal Dark Matter @ LHC

Yu Gao

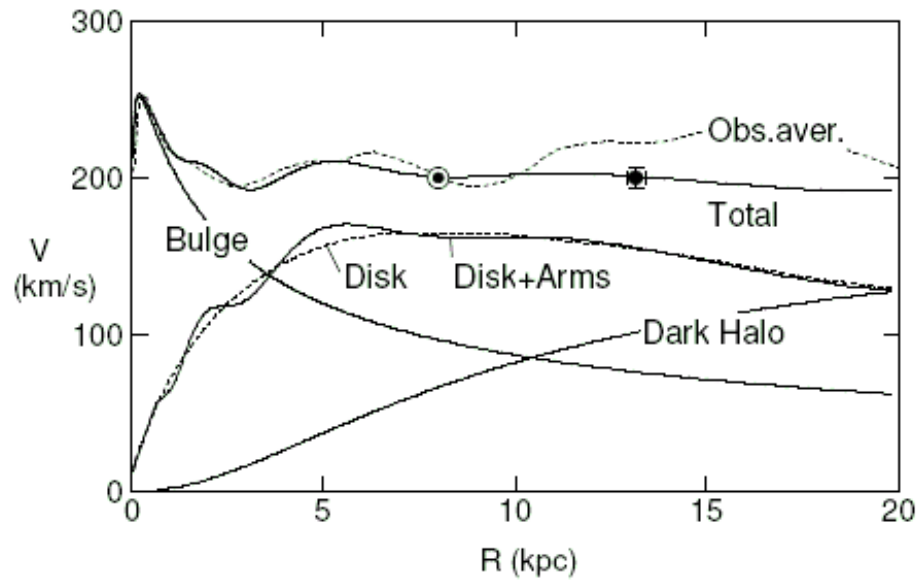
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Texas A&M University

Outline

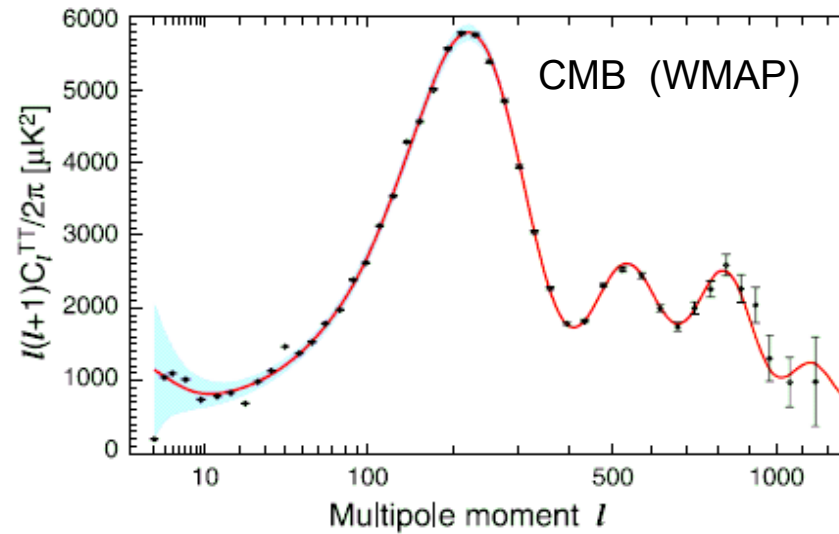
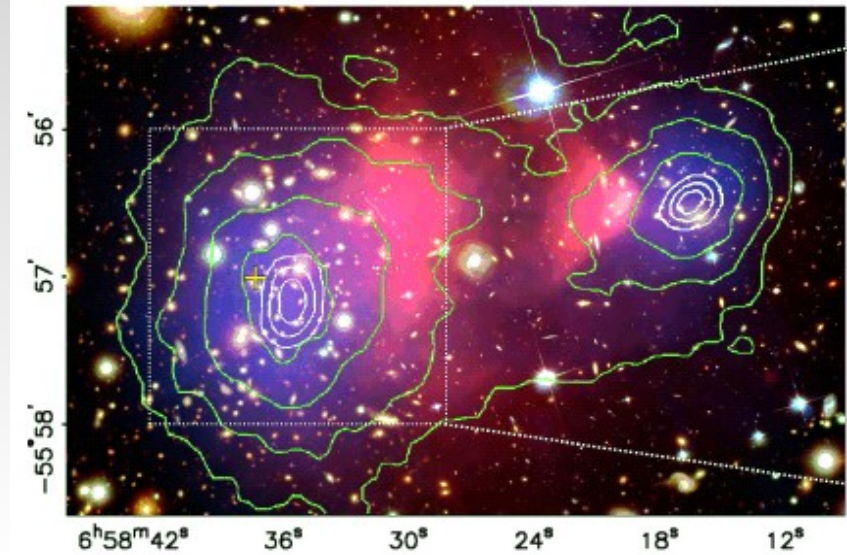
- Minimal extension to SM for baryogenesis & dark matter
- Current constraints from *Monojet*, dijet, 2 jets +MET, paired dijets
- Heavy favor outlook:
single top +MET, $t \bar{t} + \text{MET}$

Astrophysical Dark Matter Implications ...

Galactic rotation curves

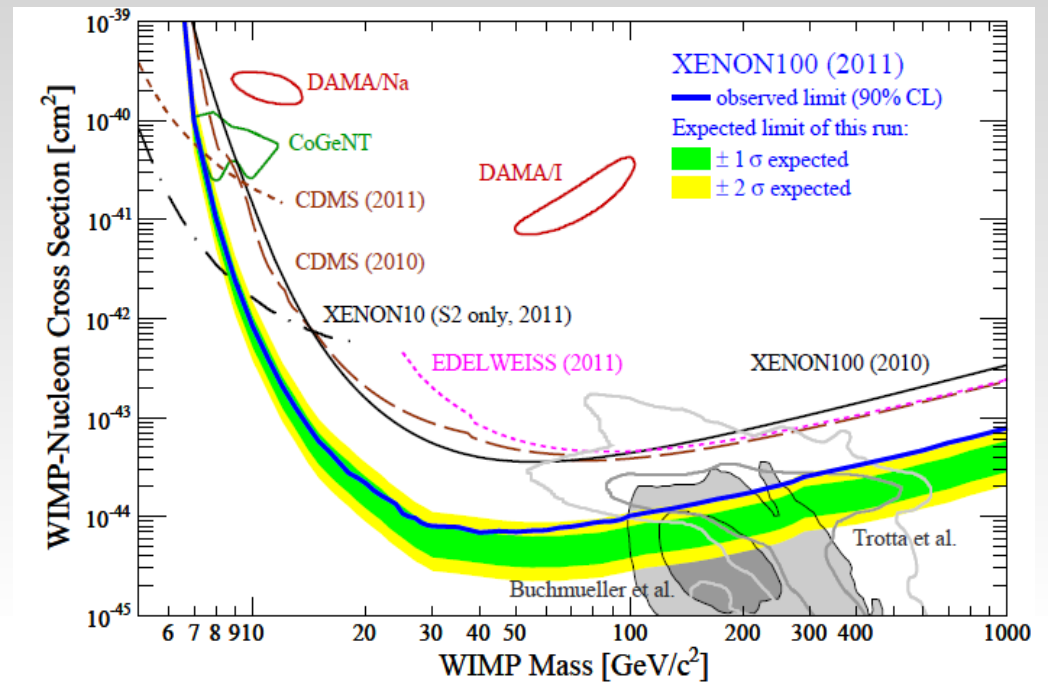


1E0657-56 'Bullet cluster'



Direct & collider searches for dark matter

Nuclear recoils:
Upper bound on WIMP-nucleon scattering cross-section



Collider searches

Search for large 'missing energy'

A non-thermal DM & Baryogenesis

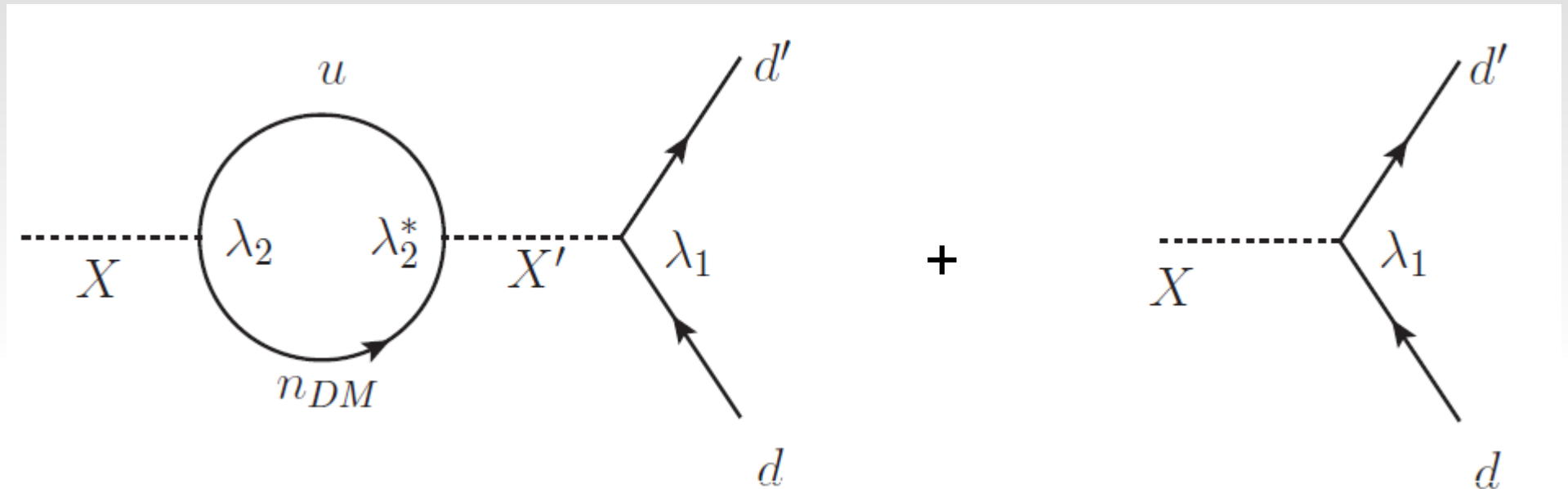
- A 'minimal' extension to SM with \sim TeV scalar color triplet(s) and a fermionic DM candidate
- Baryon-number violating interaction mediated by heavy scalars (X) :

$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta} \epsilon^{ijk} X_{\alpha,i} \bar{d}_{\rho,j}^c \mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho} X_{\alpha}^* \bar{n}_{DM} \mathbf{P}_R u_{\rho} + C.C.$$

R. Allahverdi, B. Dutta, PRD 88 (2013) 023525
B. Dutta, Y. Gao, T. Kamon, arXiv: 1401.1825

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 $i,j,k =1,2,3$

The CP violating process



$$\sim \sum_{i,j,k} \text{Im}(\lambda_1^{1,ij*} \lambda_1^{2,ij} \lambda_2^{1,k*} \lambda_2^{2,k})$$

- * Heavy scalar couplings carry CPV phases
- * At least two (different) Xs are need

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[†],

$$\frac{n_B}{s} = \frac{Y_S}{8\pi} \frac{1}{M_{X_2}^2 - M_{X_1}^2} \sum_{i,j,k} \text{Im}(\lambda_1^{1,ij*} \lambda_1^{2,ij} \lambda_2^{1,k*} \lambda_2^{2,k})$$

Baryon # violating decay

$$\times \left[\frac{M_{X_1}^2 \text{BR}_1}{\sum_{ij} |\lambda_1^{1,ij}|^2 + \sum_k |\lambda_2^{1,k}|^2} + \frac{M_{X_2}^2 \text{BR}_2}{\sum_{ij} |\lambda_1^{2,ij}|^2 + \sum_k |\lambda_2^{2,k}|^2} \right]$$

All decays

Y_S : dilution factor from a heavy S ($\sim 100\text{TeV}$) that decays into Xs.

BR: decay branching of S into X_1 or X_2 .

[†] R. Allahverdi, B. Dutta, K. Sinha PRD 82 (2010) 035004
R. Allahverdi, B. Dutta, PRD 88, 023525 (2013)

Baryon asymmetry and DM density

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

$$\frac{n_{n_{DM}}}{s} = Y_S \left[\frac{BR_1 \sum_k |\lambda_2^{1,k}|^2}{\sum_{ij} |\lambda_1^{1,ij}|^2 + \sum_k |\lambda_2^{1,k}|^2} + \frac{BR_2 \sum_k |\lambda_2^{2,k}|^2}{\sum_{ij} |\lambda_1^{2,ij}|^2 + \sum_k |\lambda_2^{2,k}|^2} \right]$$

Decays into DM

All decays

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

$$\begin{aligned} n_B/n_{n_D} &= \frac{m_{n_{DM}}}{m_p} \frac{\Omega_B}{\Omega_{n_{DM}}} \\ &= \frac{1}{8\pi} \frac{M_{X1}^2}{M_{X2}^2 - M_{X1}^2} \frac{\sum_{i,j,k} \text{Im}(\lambda_1^{1,ij*} \lambda_1^{2,ij} \lambda_2^{1,k*} \lambda_2^{2,k})}{\sum_k |\lambda_2^{1,k}|^2} \sim 0.2. \end{aligned}$$

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.

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

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

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

$$\lambda_{1X}^{\alpha} = (1, 1) \quad \lambda_{1R}^{\rho\delta} = \begin{pmatrix} 0 & \text{ds} & \text{db} \\ 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{sb}$$

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

$$\lambda_{2R}^{\alpha} = (1, 1, 1) \quad \begin{matrix} \nearrow \nearrow \\ \text{top} \end{matrix}$$

- For simplicity: **Light jets**
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 λ .

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

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.

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

kinematically stabilizes the DM and the proton.

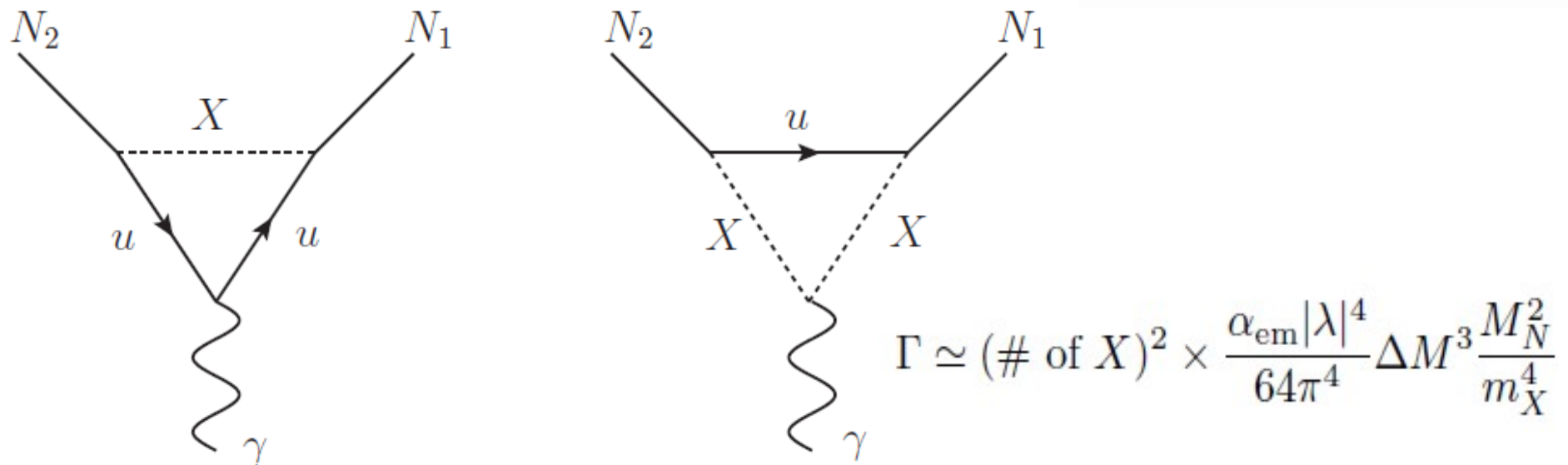
DM mass stability: For $\lambda_2 \sim 0.1$ and $M_X \sim \text{TeV}$, radiative correction to M_{DM} is less than M_e .

- 1 GeV DM mass evades direct detection.

3.5 keV line

- 3.5 keV emissions from galaxy clusters
- Two DM fermions with $\sim \text{keV}$ mass splitting
- $\lambda \sim O(10^{-2} \sim 10^{-3})$, $m_X \sim O(\text{TeV})$

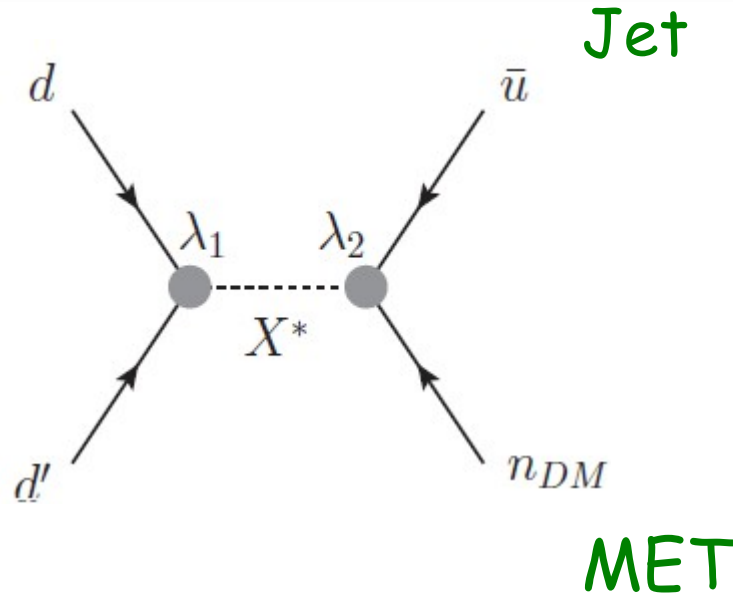
E. Bulbul, et.al. arXiv:1402.2301
A. Boyarsky, et.al. arXiv:1402.4119



R. Allahverdi, B. Dutta, Y.G.
arXiv:1403.5717

Collider phenomenology: Monojet

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



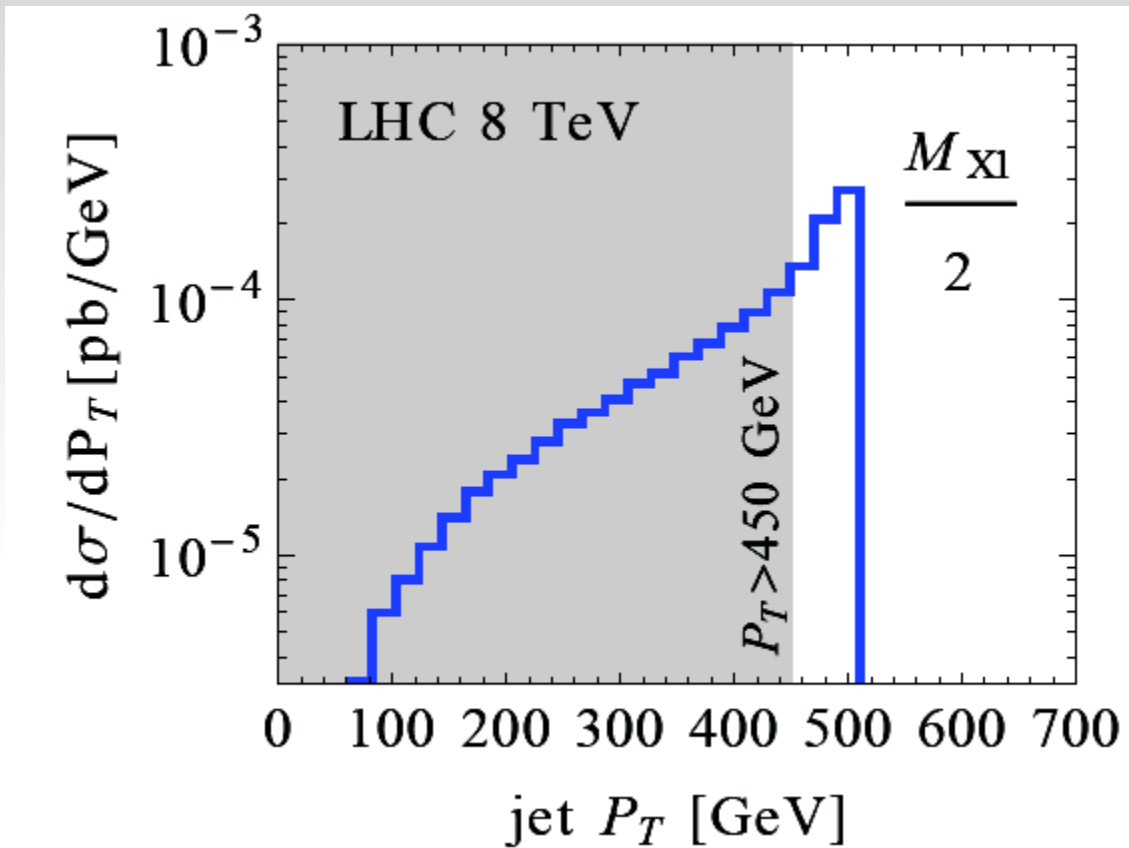
$$\mathcal{L}_{int} = \lambda_1^{\alpha, \rho \delta} \epsilon^{ijk} X_{\alpha, i} \bar{d}_{\rho, j}^c \mathbf{P}_R d_{\delta, k} + \lambda_2^{\alpha, \rho} X_{\alpha}^* \bar{n}_{DM} \mathbf{P}_R u_{\rho} + \text{C.C.}$$

How different from ISR + Effective Operator?

- Jet energy $\sim 1/2$ 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.

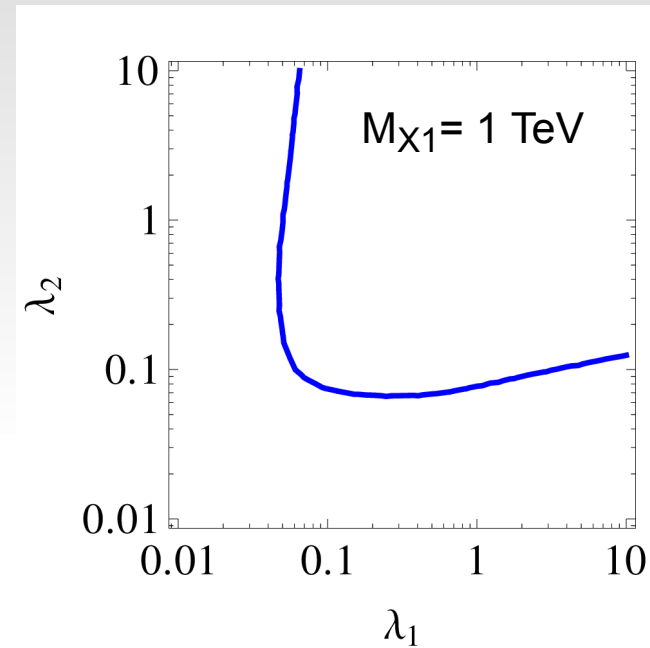
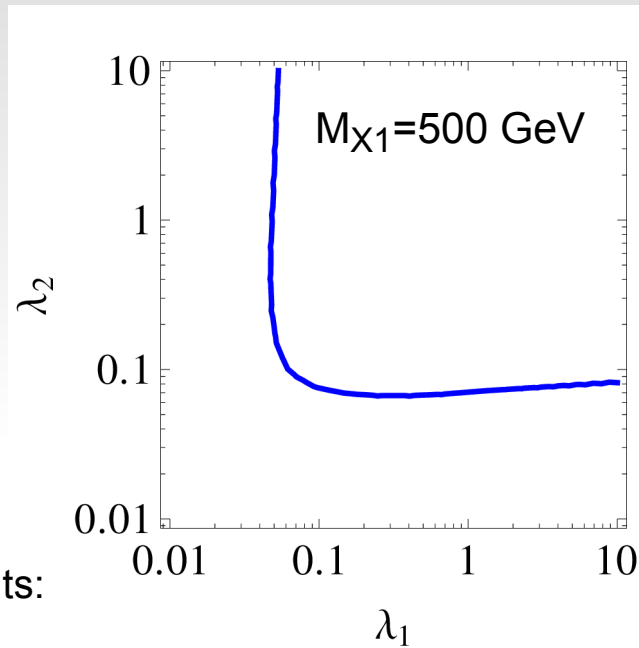
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A sample (mono) jet p_T distribution with X_1 mass at 1 TeV.
 A high p_T cut near the Jacobian peak picks out (most of) the signal

Monojet constraint @ LHC



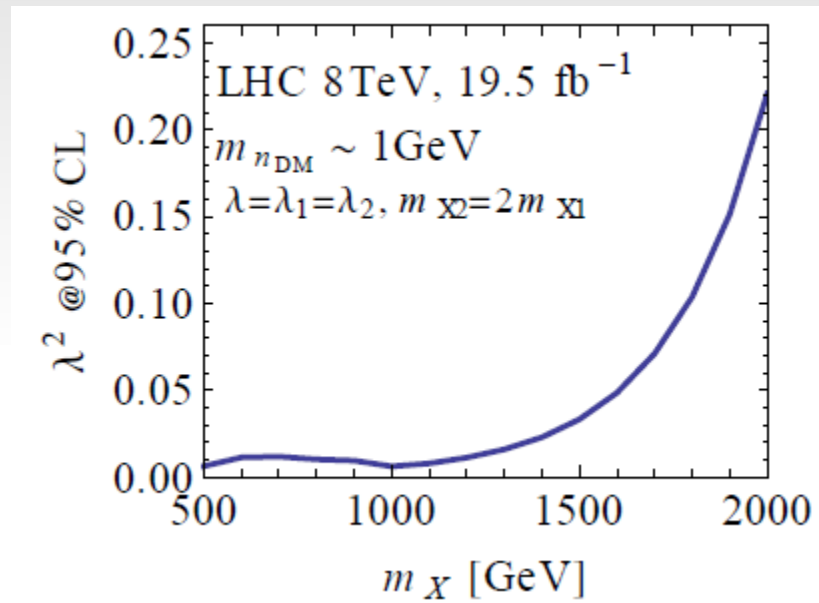
Parton level cuts:

- * $|\eta_j| < 2.4$
- * Minimal $\sigma/\sigma_{95\%}$ from all listed p_T cuts

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 λ_1 and λ_2

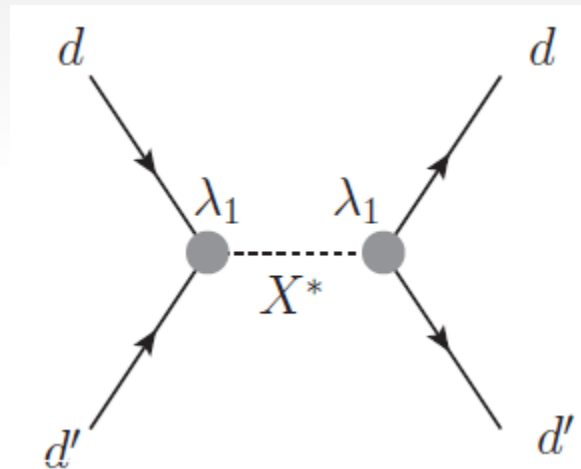
$$\sigma \propto |\lambda_1|^2 |\lambda_2|^2 / (2|\lambda_1|^2 + |\lambda_2|^2)$$



A further simplified case: $\lambda_1 = \lambda_2$
 Constrained to $O(0.1)$ for X_1 below $\sim 1.3 \text{ TeV}$

Collider phenomenology: Dijet

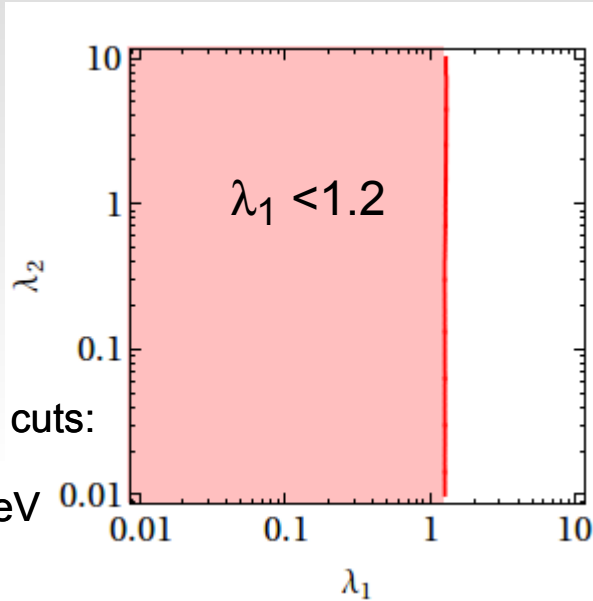
- Similar to the monojet process but with two (different generation) down-type quarks in the final state:



$$\lambda_1^{\alpha, \rho\delta} \epsilon^{ijk} X_{\alpha, i} \bar{d}_{\rho, j}^c \mathbf{P}_R d_{\delta, k}$$

Dijet cross section only depends on λ_1 .

Dijet constraints

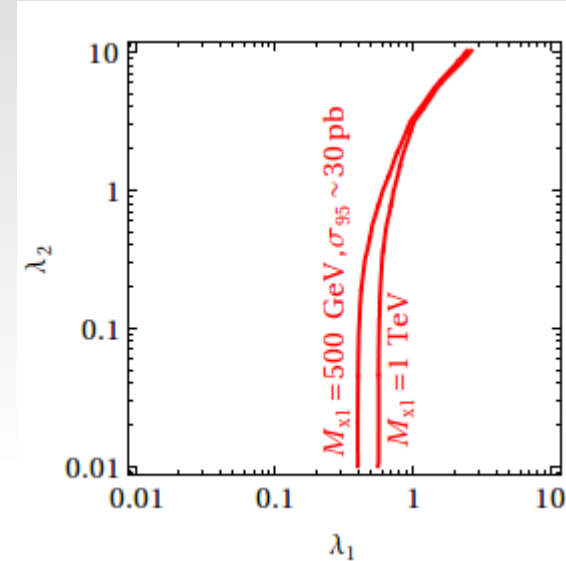


Parton level cuts:

- * $E_j > 10$ GeV
- * $|\eta_j| < 1$

Data: **CDF** 1.13 fb^{-1} at 1.96 TeV, 95 C.L.
 T. Aaltonen et al. [CDF Collaboration],
 Phys. Rev. D 79, 112002 (2009)

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.



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

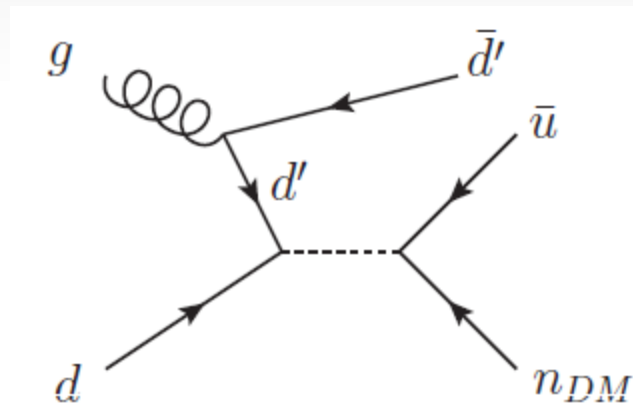
Use the bound from a qq final state

Parton level cuts:

- * $p_{Tj} > 30$ GeV
- * $H_T > 100$ GeV, $|\Delta\eta_{jj}| < 2$

Collider phenomenology: 2 jets + MET

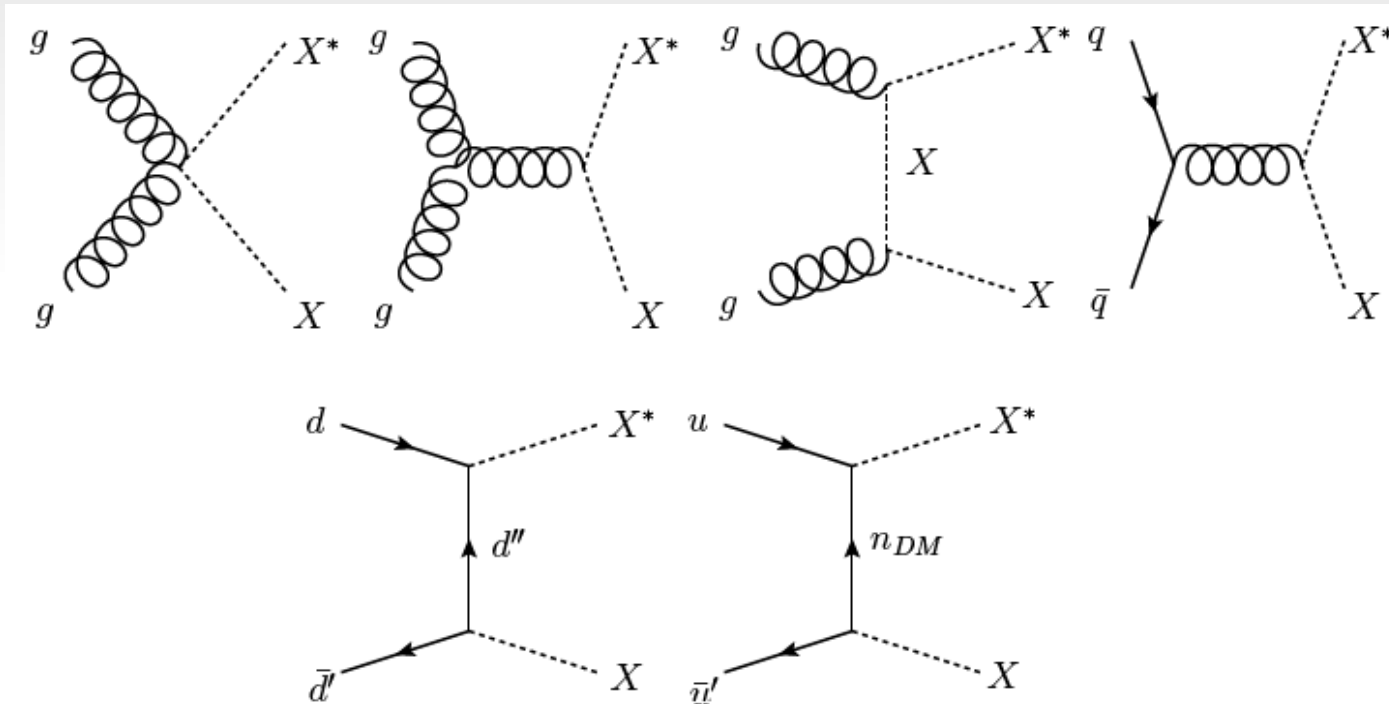
- Initial state gluon splitting (ISGS)



M_{eff} drops quickly above M_{χ_1} .

Collider phenomenology: 2 jets + MET

- X pair-production



Two heavy scalars: M_{eff} can be large compared to ISGS.

ISGS vs Pair-production

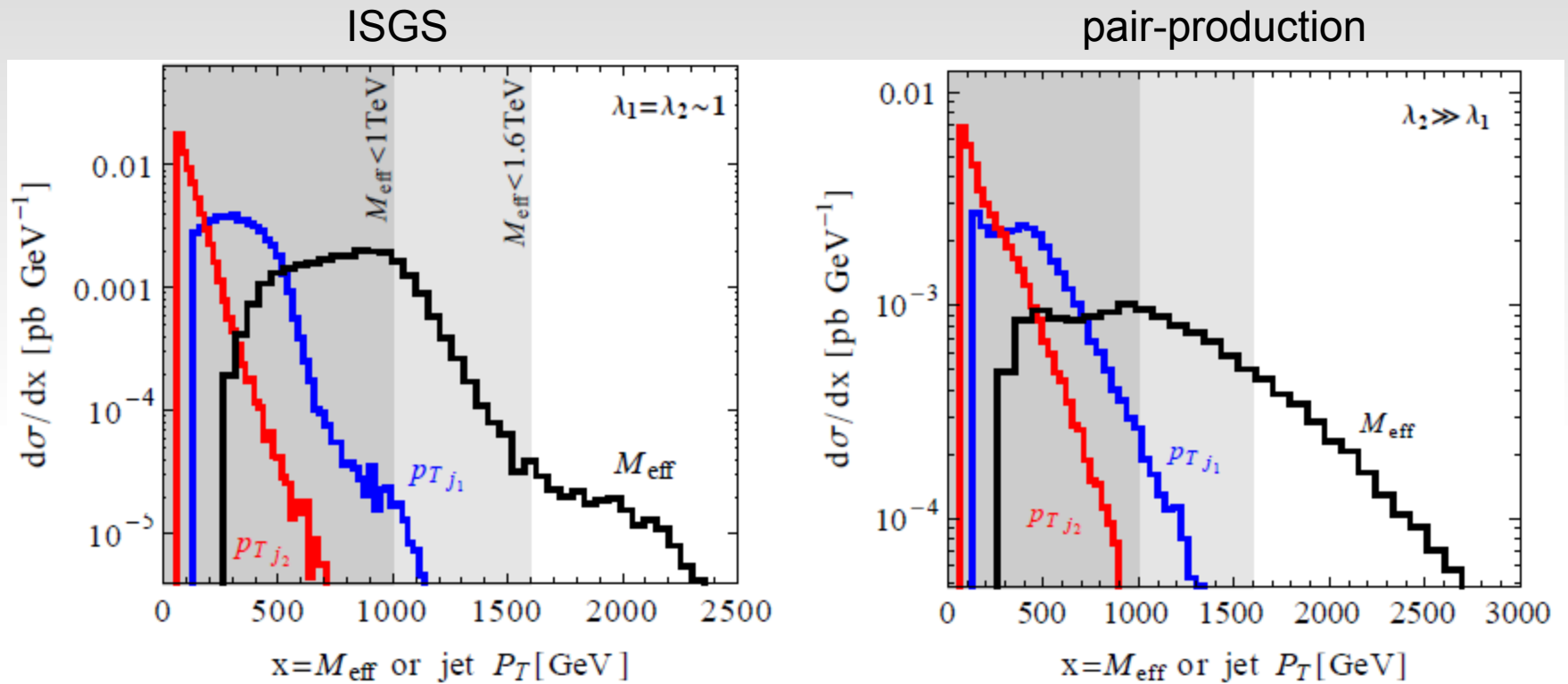
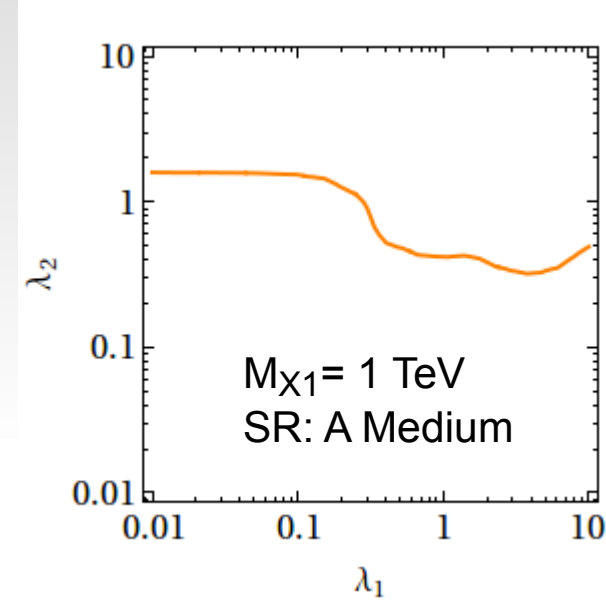
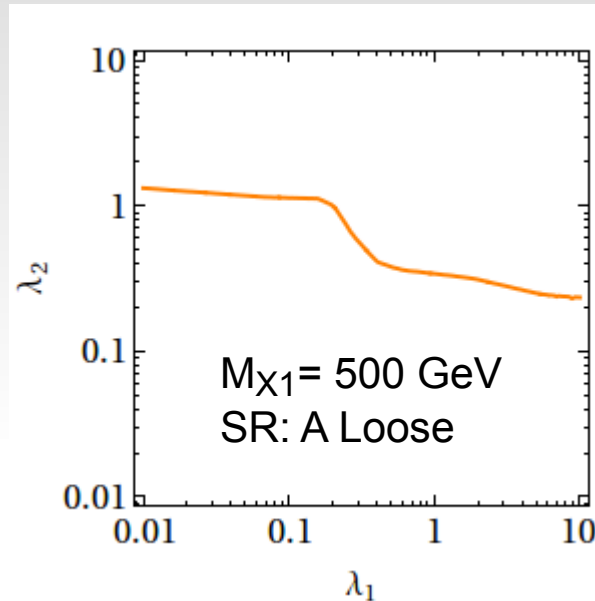


FIG. 6. Two sample jet p_T (blue and red) and M_{eff} (black) distributions for $\lambda_1 = \lambda_2 \sim 1$ (left) and $\lambda_2 \gg \lambda_1$ (right). The ISGS process singly produces X_1 and M_{eff} drops quickly above M_{X_1} . In the pair-production case M_{eff} is easier to be above M_{X_1} . A properly placed M_{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 χ_1 mass at 500 GeV (1TeV)

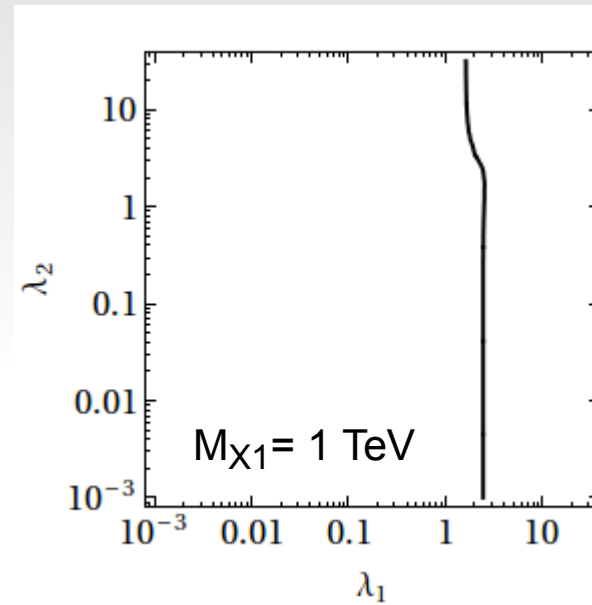
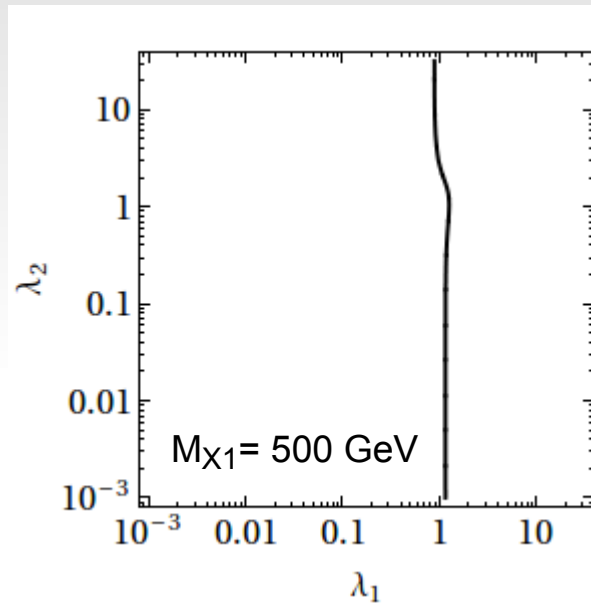
2 jets + MET (95% C.L.) *exclusive*
bounds selected from ATLAS multi-jet
analysis with 20.3 fb^{-1} at 8 TeV:
[ATLAS-CONF-2013-047, 16 May, 2013](#)

Turn over at small λ_1 :
Due to pair-production diagrams
becoming dominant when $\lambda_1 \ll \lambda_2$.

Collider phenomenology: Paired dijets

- X pair production with both X s decay into dd' .
- Constrain λ_1 . (In contrast, dijet+MET via pair-production constrains λ_2)
- ISR diagrams negligible due to two heavy masses being reconstructed.

Paired dijet constraint @ LHC

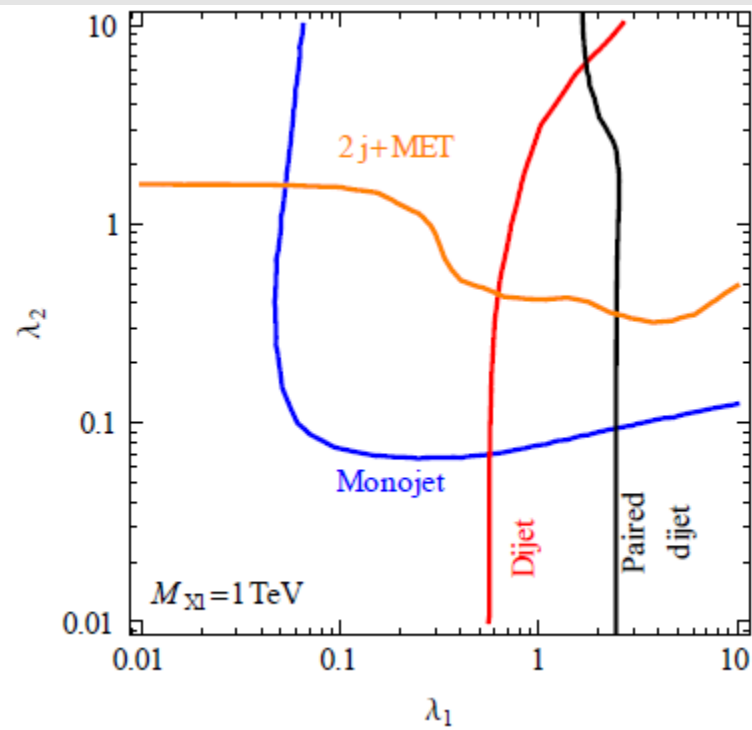
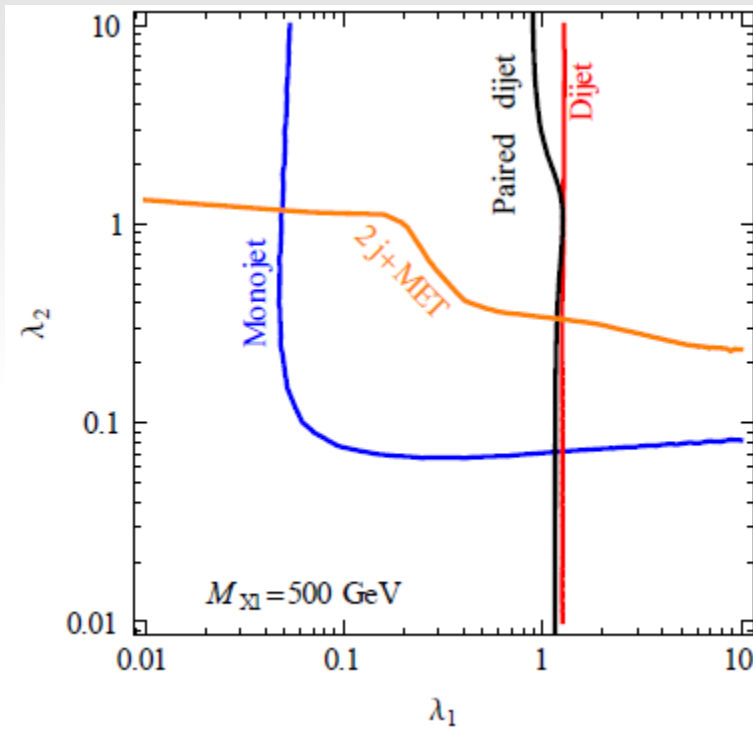


Parton level cuts:

- * $p_{Tj} > 110$ 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]
Phys.Rev.Lett. 110 (2013) 141802

Combined collider bounds



Notes

- All the presented results are at the parton level, and b quarks considered as jets.
- $X1$ and $X2$ can be close in mass. When $M_{X1} \sim M_{X2}$, signal cross-section doubles and λ 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

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

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

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

$$\lambda_{1X}^{\alpha} = (1, 1) \begin{pmatrix} 0 & ds & db \\ 0 & 1 & 1 \\ 0 & 0 & 1 \\ & & sb \\ 0 & 0 & 0 \end{pmatrix}$$

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

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

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

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

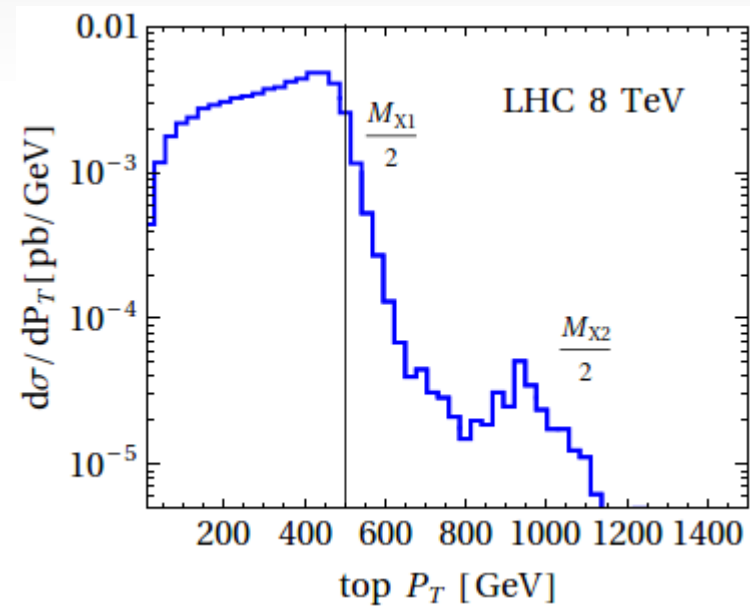
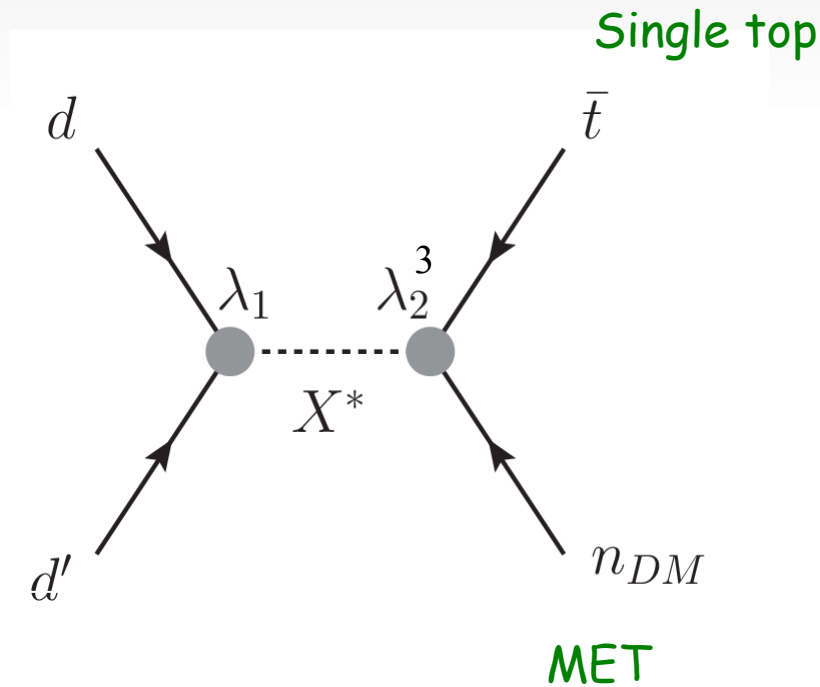
Light jets:

constrained

top: NOT constrained

Mono-top + MET

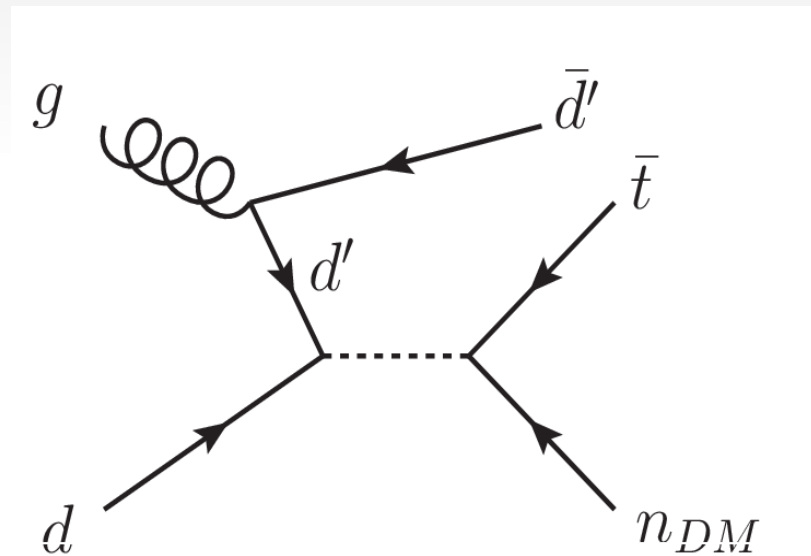
Like monojet, single top can be produced via s-channel resonance



$$M_{X1} = 1 \text{ TeV}$$

Other possibilities: Top + jet(s) + MET

- ISGS (also ISR diagrams)

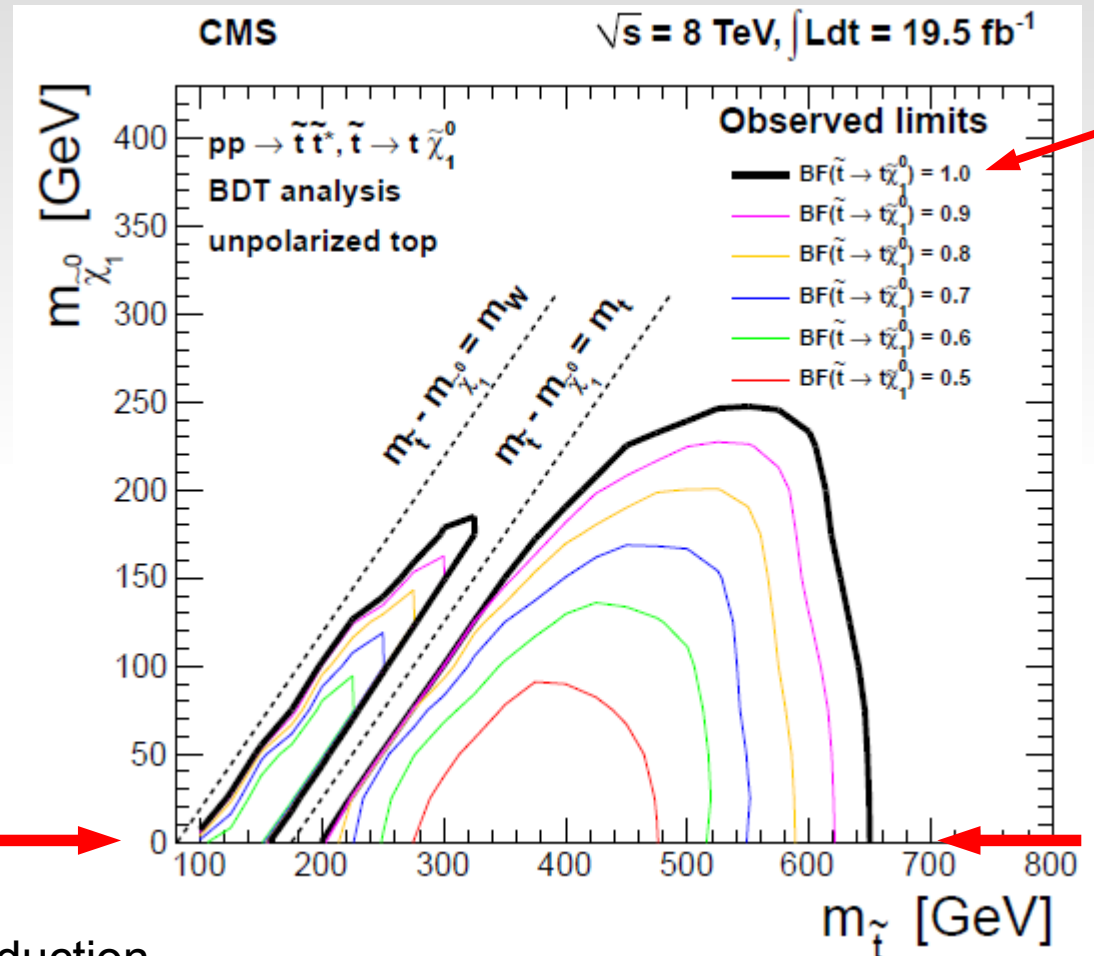


Other possibilities: $t \bar{t} + MET$

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

Eur.Phys.J. C73 (2013) 2677
CMS-SUS-13-011,

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



SUSY stop pair: QCD dominated production

X pair: QCD + NP (via λ_2),

*large λ_2^3 for significant X decay BR into t

Comparable final state & cut efficiency