Probing Light Nonthermal Dark Matter @ LHC

Yu Gao

Mitchell Institute for Fundamental physics and Astronomy
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, $t\bar{t}$ + MET

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) :

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

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

X index α=1,2. At least two Xs are required for successfully baryogenesis
Quark generation indices ρ δ =1,2,3
SU(3) color indinces 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[†],

$$\frac{n_B}{s} = \frac{Y_S}{8\pi}\frac{1}{M_{X2}^2 - M_{X1}^2}\sum_{i,j,k}\mathrm{Im}(\lambda_1^{1,ij*}\lambda_1^{2,ij}\lambda_2^{1,k*}\lambda_2^{2,k})$$

$$\times\left[\frac{M_{X1}^2\mathrm{BR}_1}{\sum_{ij}|\lambda_1^{1,ij}|^2+\sum_k|\lambda_2^{1,k}|^2}+\frac{M_{X2}^2\mathrm{BR}_2}{\sum_{ij}|\lambda_1^{2,ij}|^2+\sum_k|\lambda_2^{2,k}|^2}\right]$$

Baryon # violating decay

All decays

Y_S: dilution factor from a heavy S (~100TeV) 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.

$$\frac{n_{n_{DM}}}{s} = Y_S \left[\frac{\mathrm{BR}_1 \sum_k |\lambda_2^{1,k}|^2}{\sum_{ij} |\lambda_1^{1,ij}|^2 + \sum_k |\lambda_2^{1,k}|^2} + \frac{\mathrm{BR}_2 \sum_k |\lambda_2^{2,k}|^2}{\sum_{ij} |\lambda_1^{2,ij}|^2 + \sum_k |\lambda_2^{2,k}|^2} \right]$$

Decays into DM

All decays

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

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

$$= \frac{1}{8\pi} \frac{M_{X1}^2}{M_{X2}^2 - M_{X1}^2} \frac{\sum_{i,j,k} \mathrm{Im}(\lambda_1^{1,ij*} \lambda_1^{2,ij} \lambda_2^{1,k*} \lambda_2^{2,k})}{\sum_k |\lambda_2^{1,k}|^2} \sim 0.2.$$

For $\lambda_2 \sim O(1)$ and MX ~ TeV, DM decoupling temperature is ~ 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.

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

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

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

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

ds db

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

sb

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

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

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

top

Light jets

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 λ.

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.

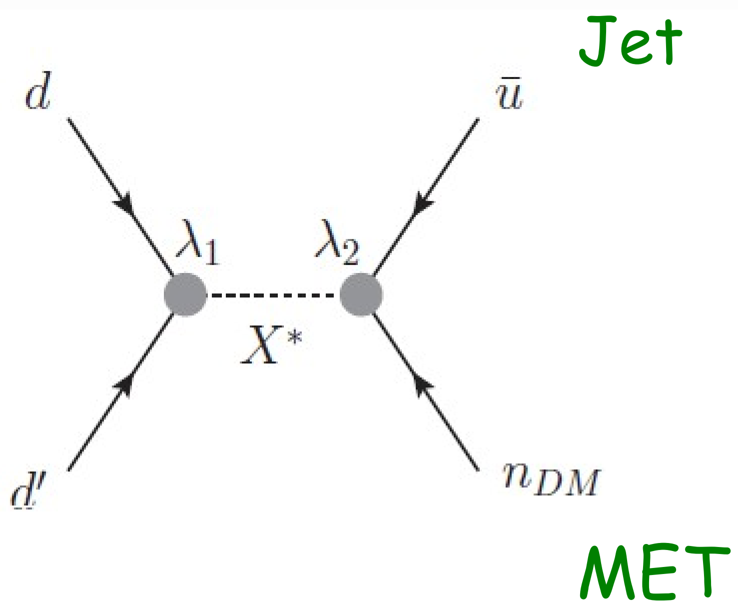
$$| M_{DM} - M_p | < M_e$$

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

- 1 GeV DM mass evades direct detection.

Collider phenomenology: Monojet

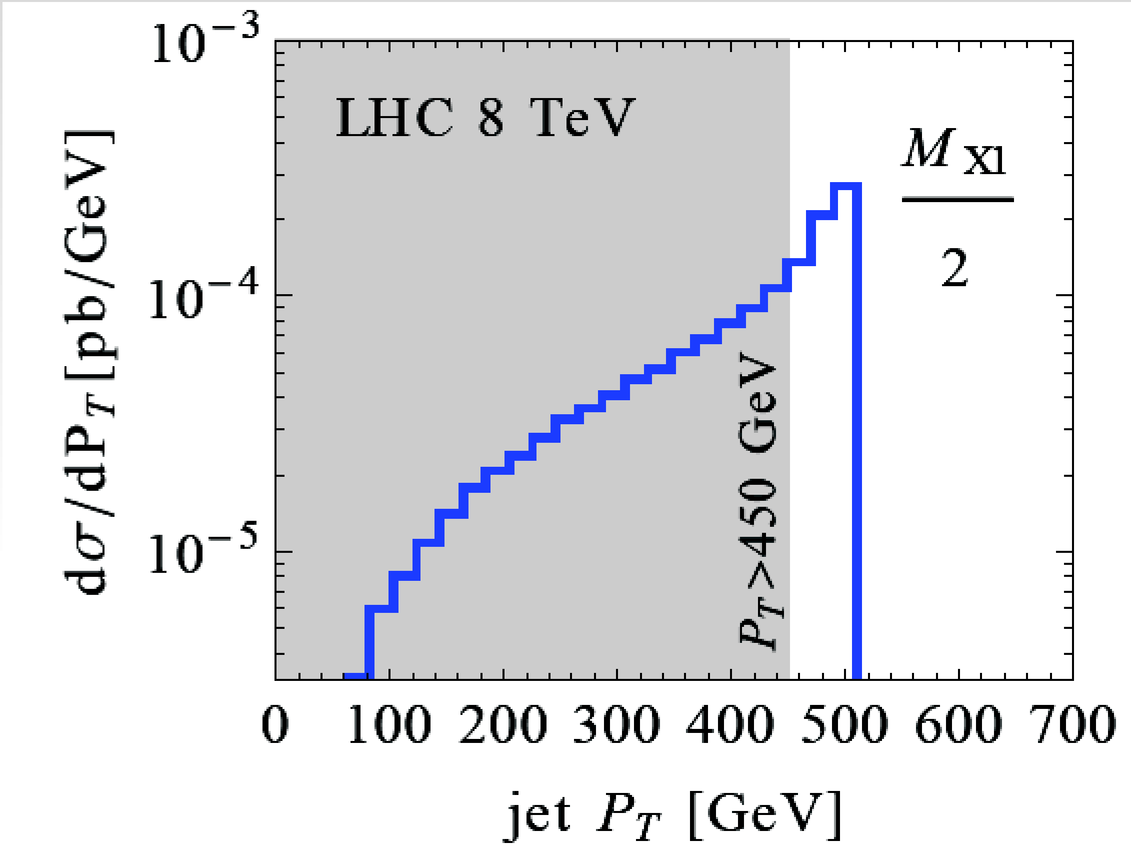
- X couples to two d-quarks or one u-quark and DM: A s-channel resonant process ($d\,d' \to X^* \to \bar{u}\,n$)
- A monojet + MET event without ISR.



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

How different from ISR + Effective Operator?

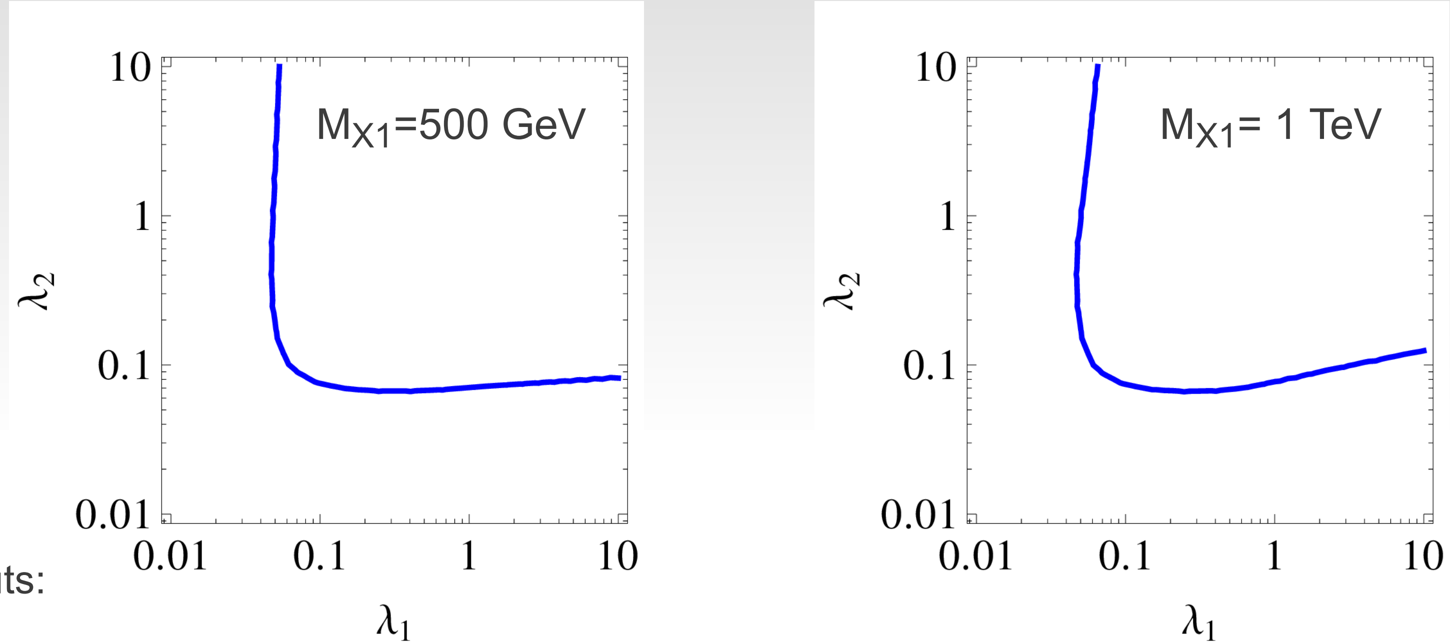
- Jet energy ~ ½ new scalar mass: a Jacobian peak in P_T distribution.
- No preference for lower jet P_T : High P_T cut can be very effective against SM background.
- Effective operator ($\sim \bar{d}\, d^c\, \bar{u}\, n/\Lambda^2$) approach is also non-ISR, but less favorable, since it loses the peak 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



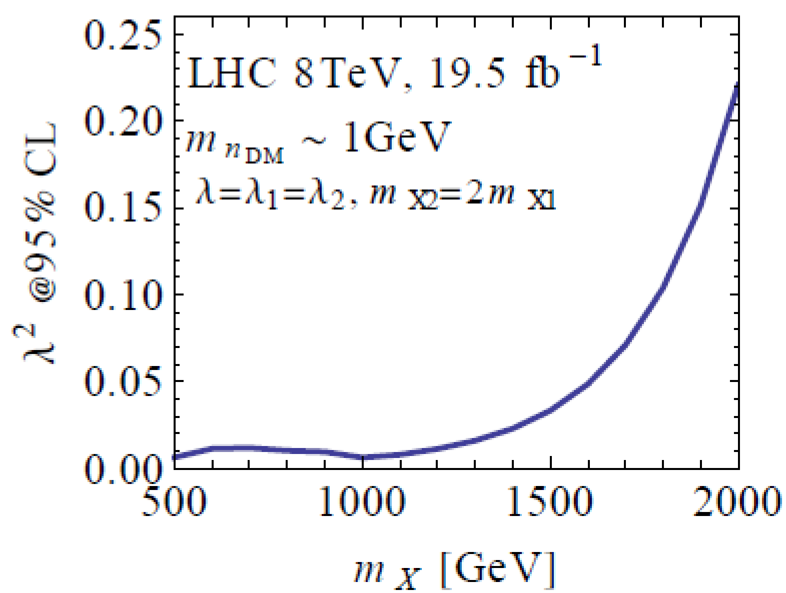
Parton level cuts:

* $|\eta_j| < 2.4$
* 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 abd λ_2

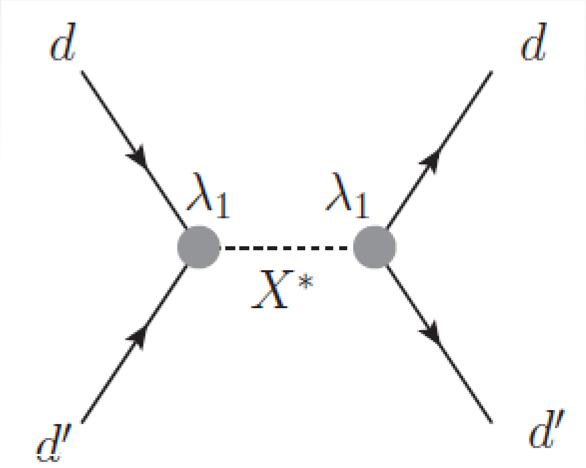
$$\sigma \propto |\lambda_1|^2|\lambda_2|^2/(2|\lambda_1|^2 + |\lambda_2|^2)$$



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

Collider phenomenology: Dijet

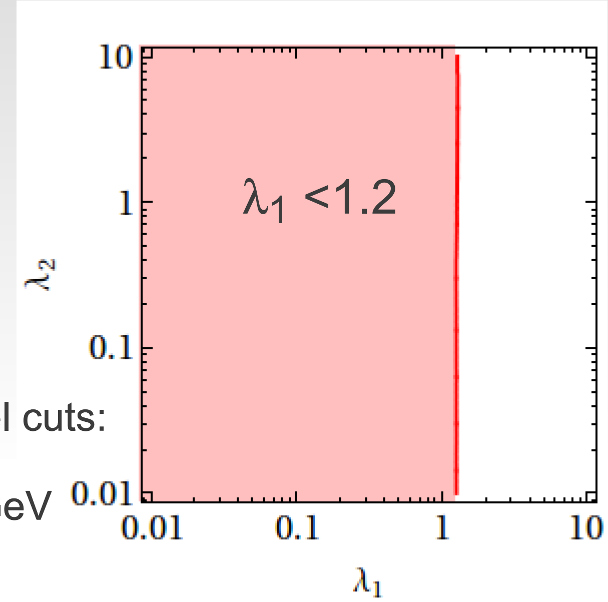
- Similar to the monojet process but with two (different generation) down-type quarks in the final state:



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

Dijet cross section only depends on λ_1.

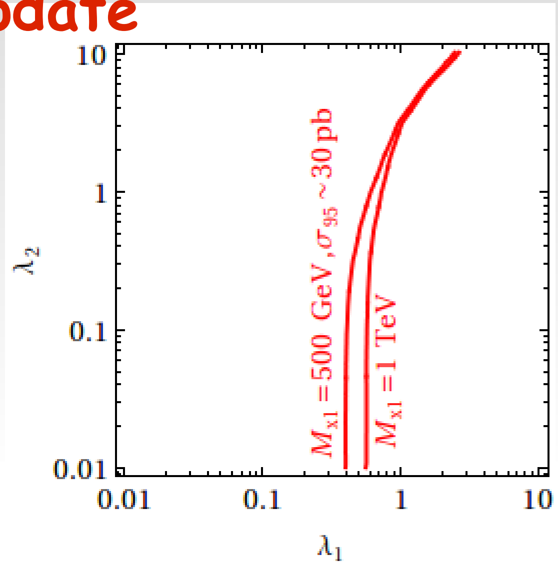
Dijet constraints



Parton level cuts:

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

update



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 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.

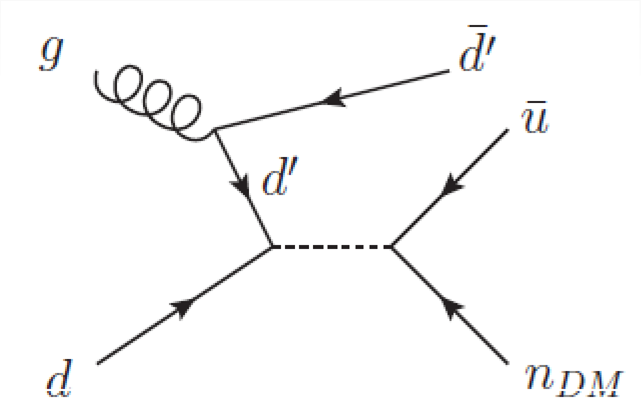
CMS dijet low mass analysis with 0.13 fb^{-1} data @ 7 TeV
CMS-PAS-EXO-11-094, 2012

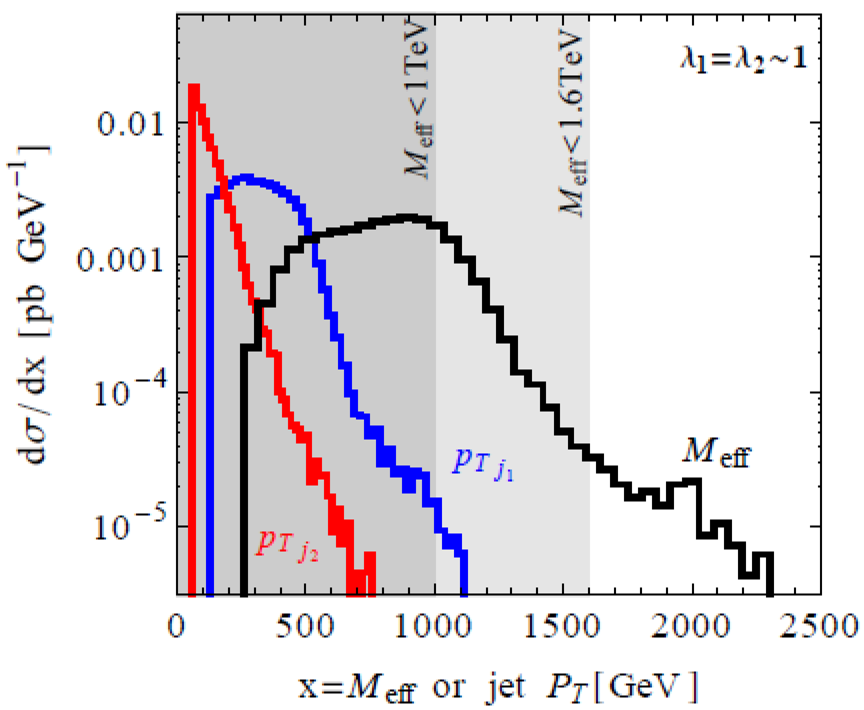
Use the bound from a qq final state

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)

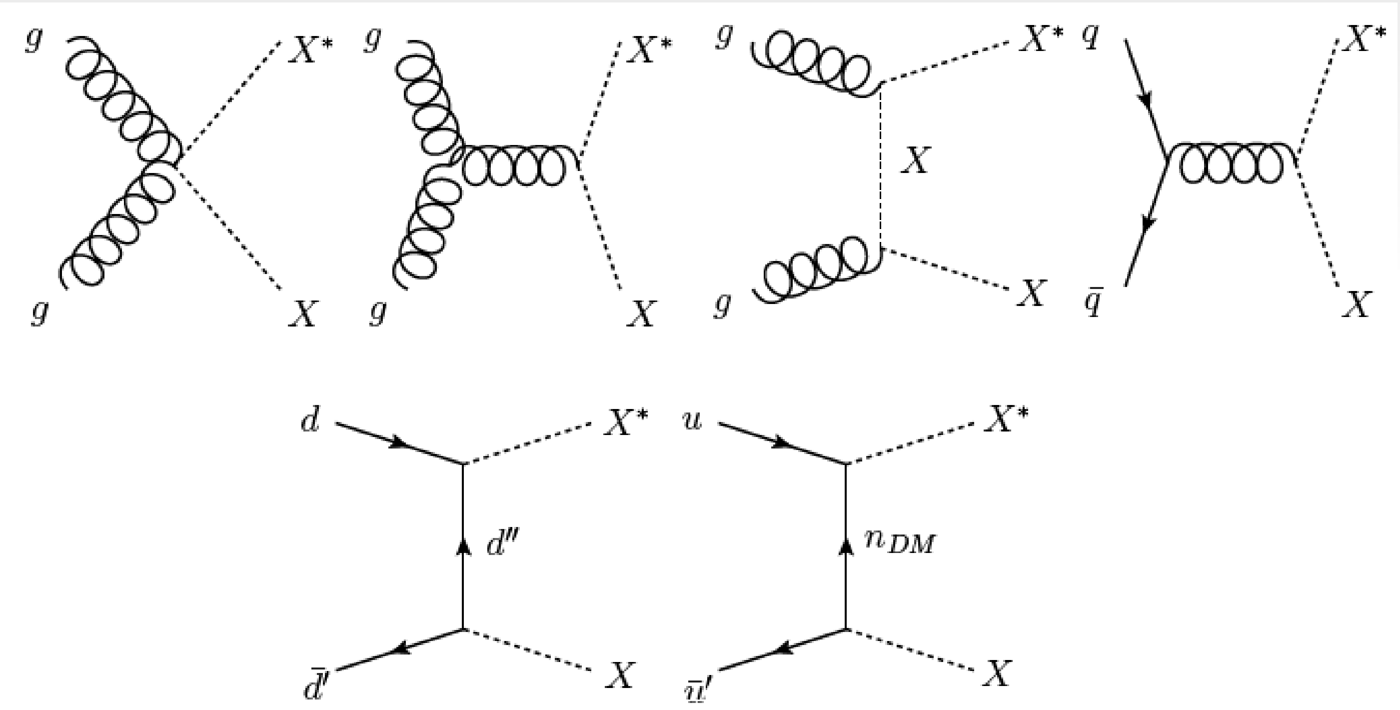




M_{eff} drops quickly above M_{X1}.

Collider phenomenology: 2 jets + MET

- X pair-production



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

ISGS vs Pair-production

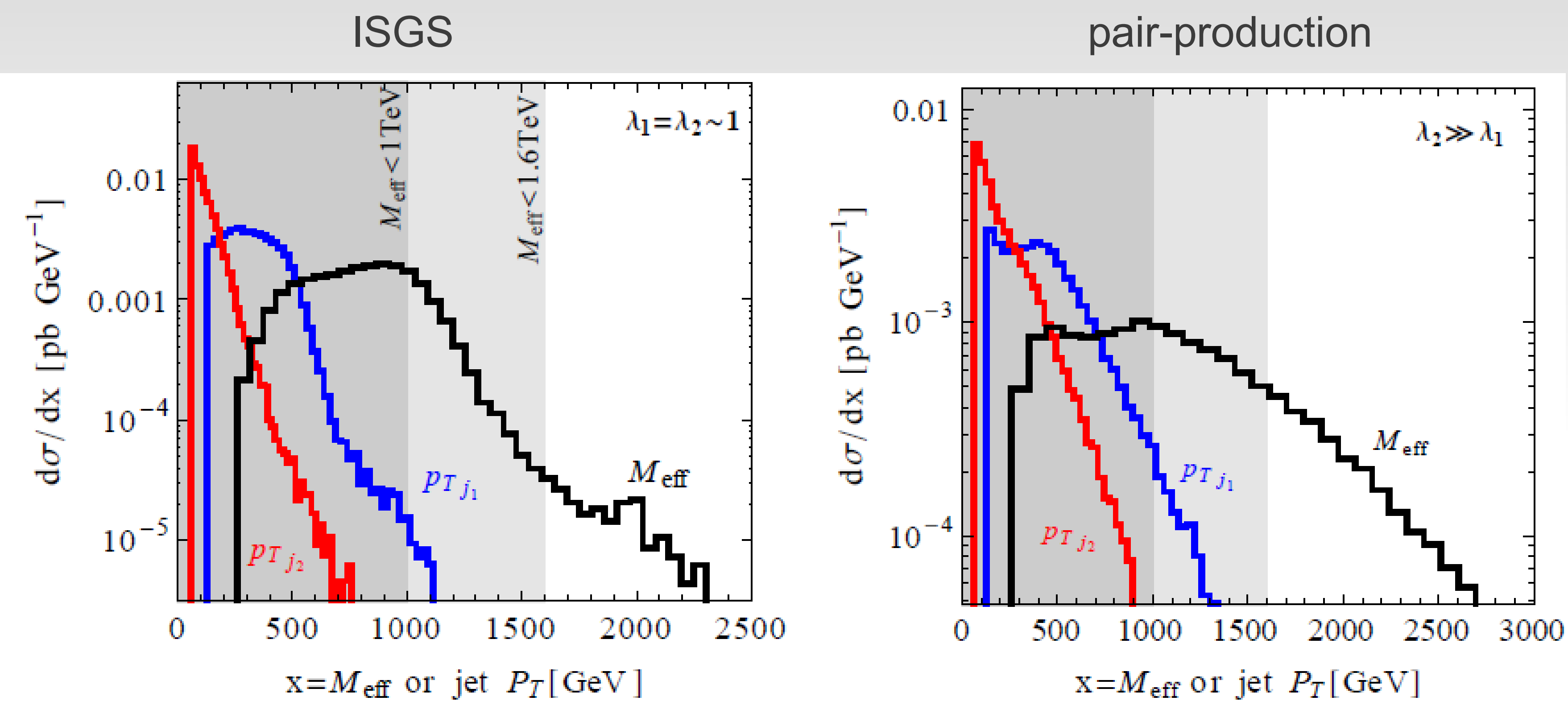
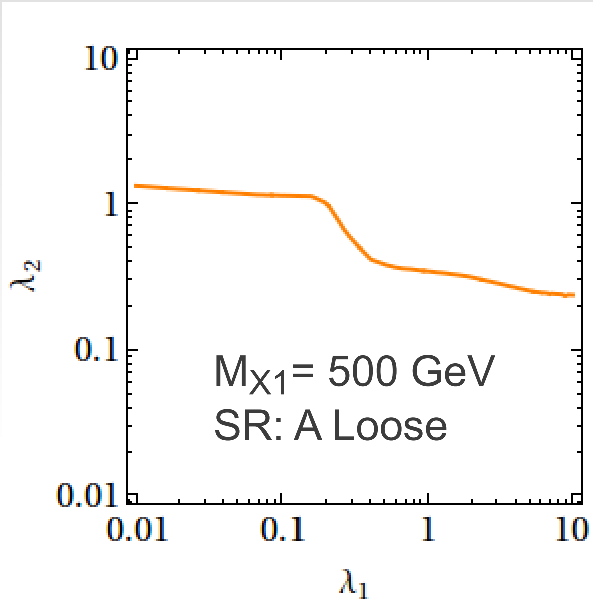
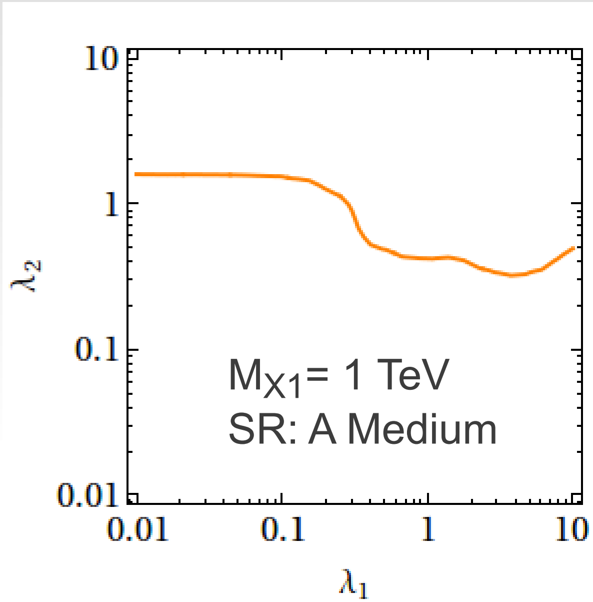


FIG. 6. Two sample jet p_T (blue and red) and $M_{\rm eff}$ (black) distributions for $\lambda_1 = \lambda_2 \sim 1$ (left) and $\lambda_2 \gg \lambda_1$ (right). The ISGS process singly produces $X1$ and $M_{\rm eff}$ drops quickly above M_{X1}. In the pair-production case $M_{\rm eff}$ is easier to be above M_{X1}. A properly placed $M_{\rm eff}$ cut above M_{X1} 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 (1TeV)

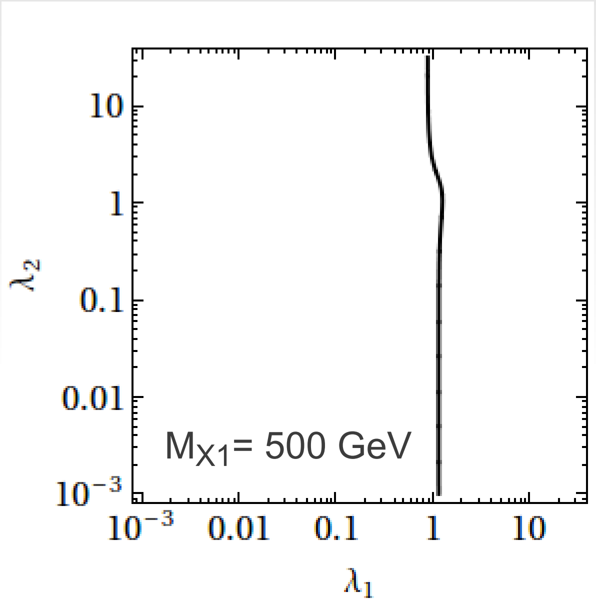
2 jets + MET (95% C.L.) *exclusive* bounds selected from ATLAS multi-jet analysis with 20.3 fb^{-1} at 8 TeV:
ATLAS-CONF-2013-047, 16 May, 2013

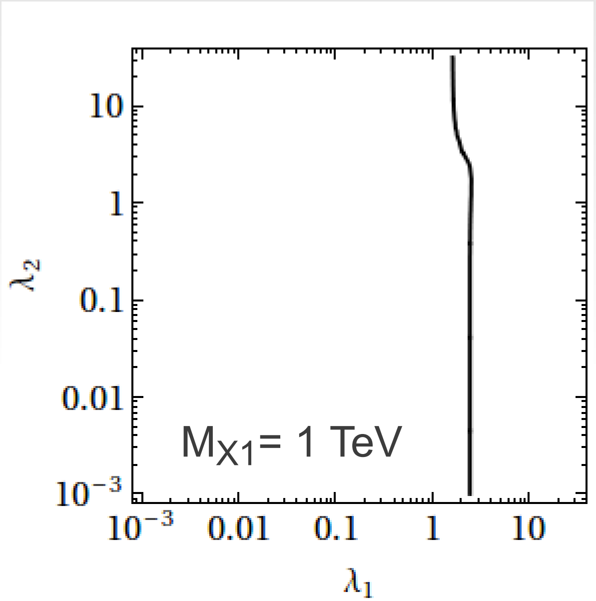
Turn over at small λ_1:
Due to pair-production diagrams becoming dominant when $\lambda_1 \ll \lambda_2$.

Collider phenomenology: Paired dijets

- X pair production with both Xs 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



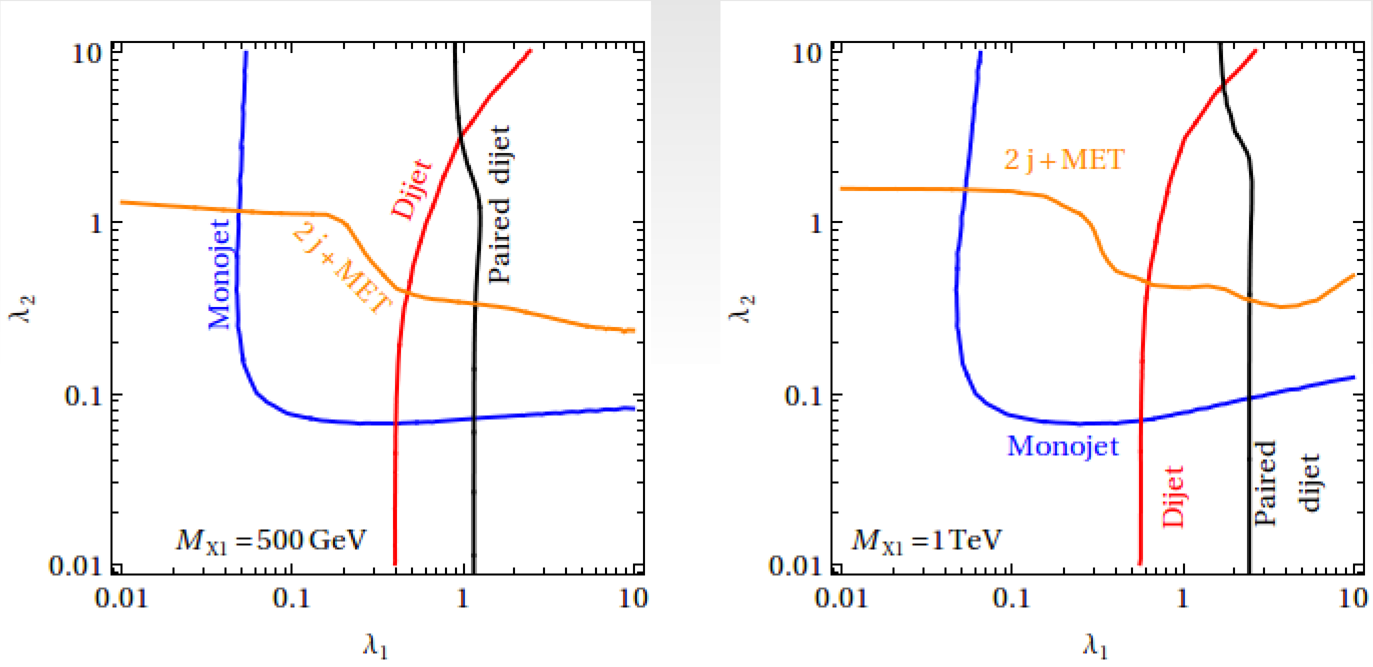


Parton level cuts:

* p_{Tj} > 110 GeV
* $|\eta_j|$ < 2.5
* ΔR_{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}~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

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

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

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

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

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

ds *db* *sb*

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

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

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

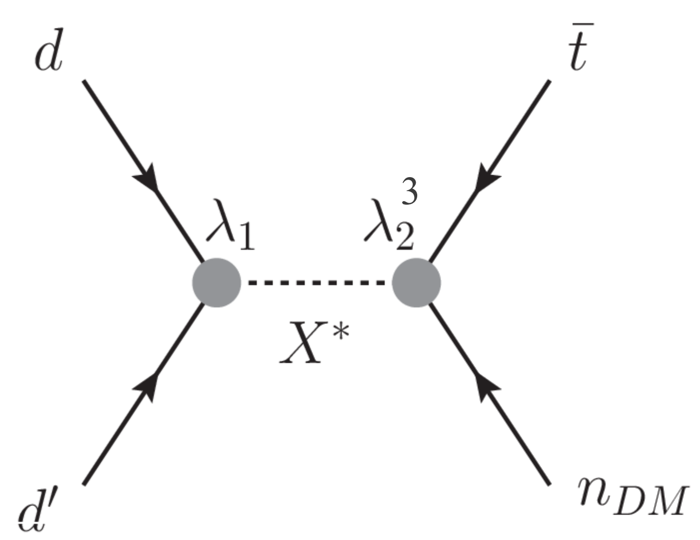
Light jets: constrained

top: NOT constrained

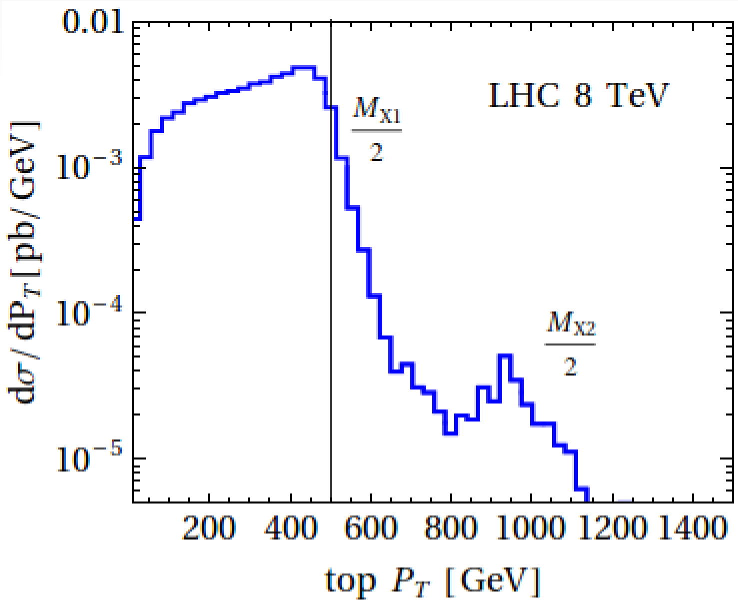
Mono-top + MET

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

Single top



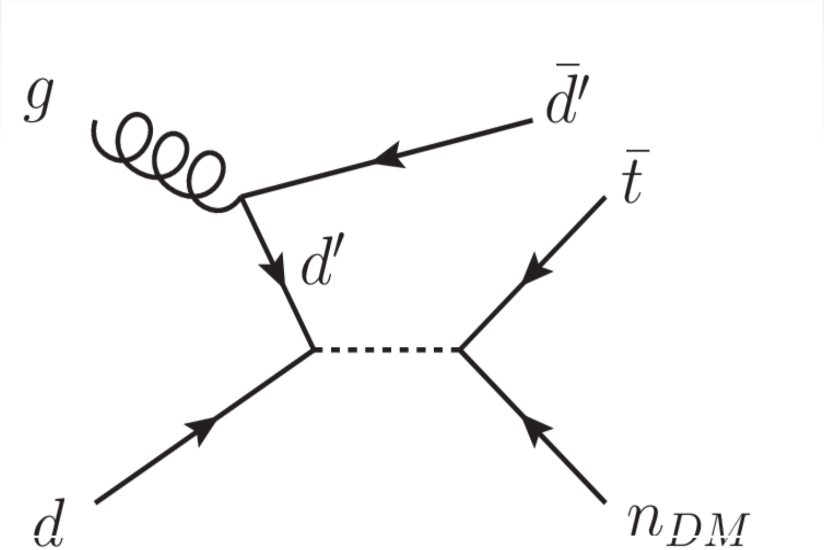
MET



M_{X1} = 1 TeV

Other possibilities: Top + jet(s) + MET

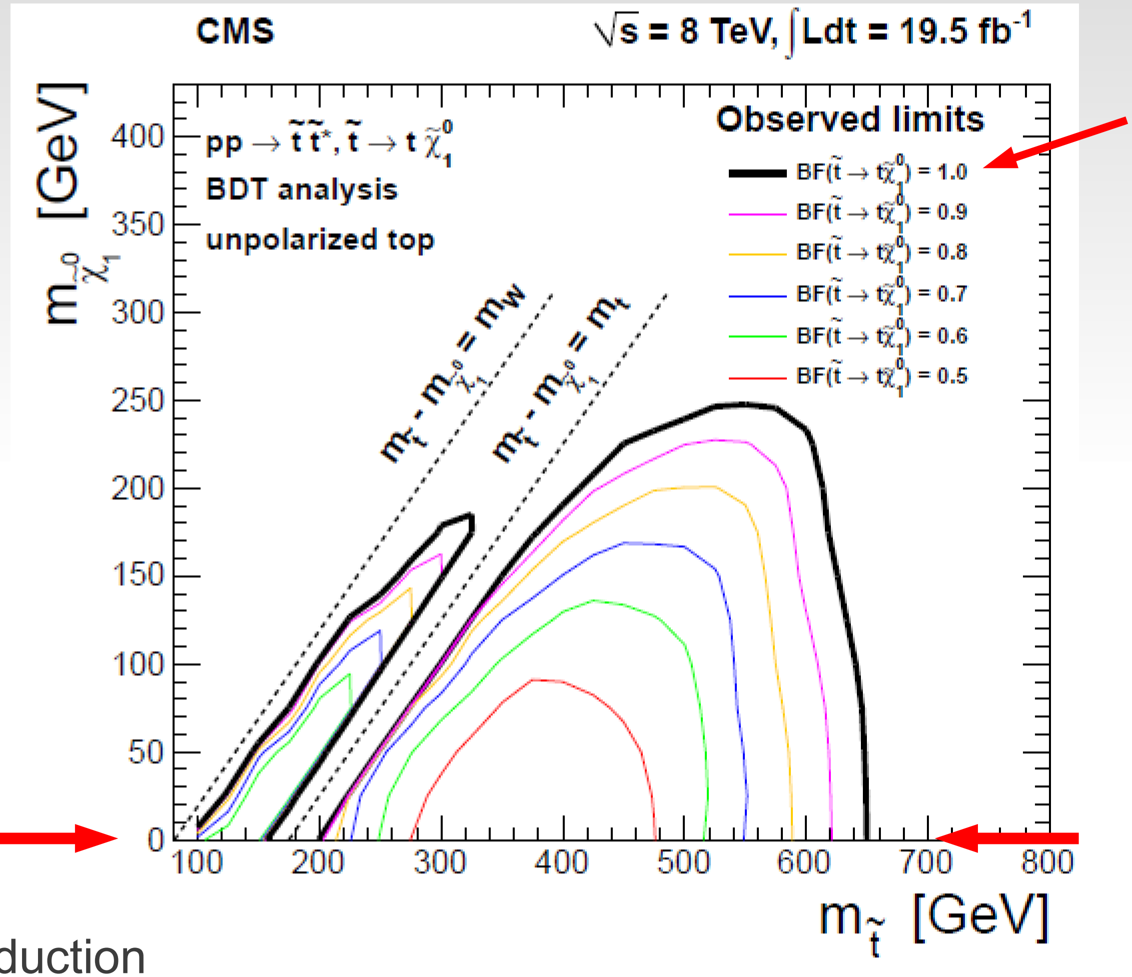
- ISGS (also ISR diagrams)



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

- From X pair production both X$\longrightarrow$ 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,



SUSY stop pair: QCD dominated production
X pair: QCD + NP (via λ_2),
*large $\lambda^3{}_2$ for significant X decay BR into *t*

Comparable final state & cut efficiency