Nonthermal Dark Matter & Top polarization at Collider

Yu Gao

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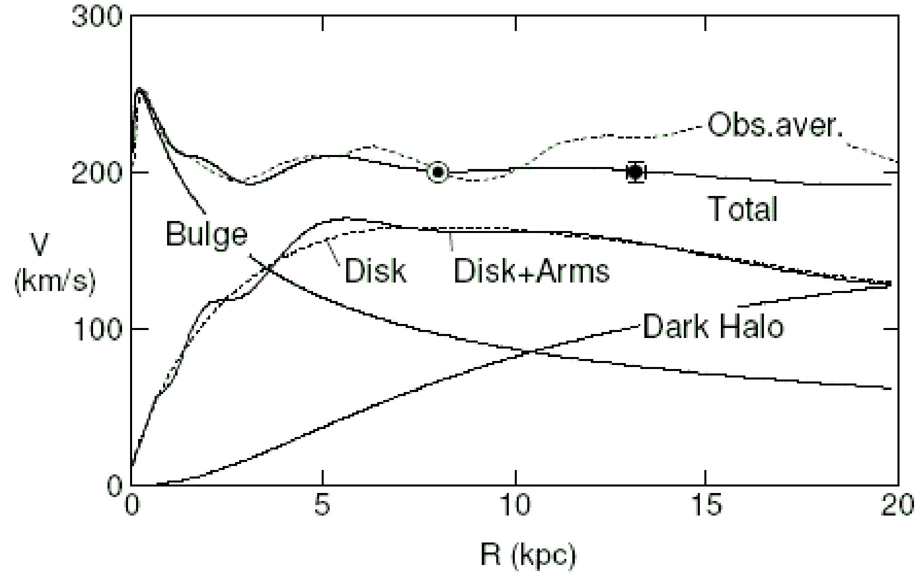
R.Allahverdi, M. Dalchenko, B.Dutta, YG, T. Kamon, in progress
B. Dutta, YG, T. Kamon, arXiv: PRD 89 (2014) 9, 096009
R. Allahverdi, B. Dutta, PRD 88 (2013) 023525

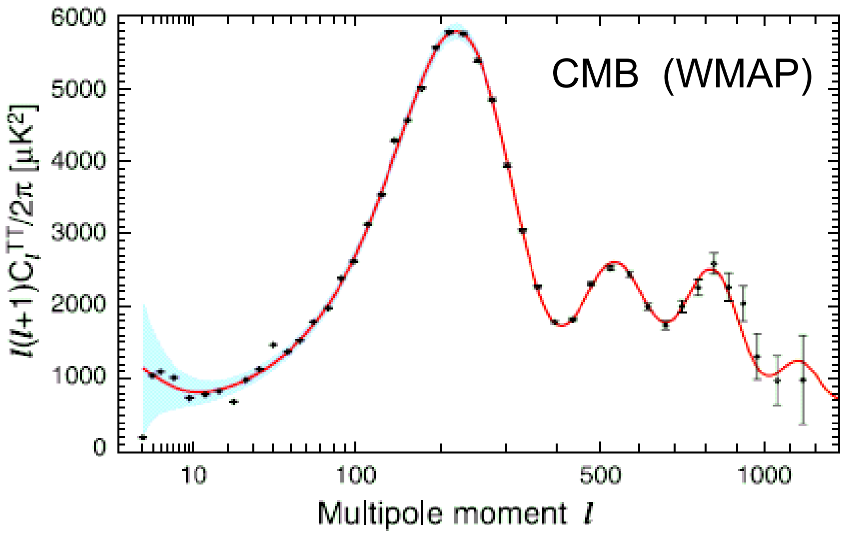
Outline

- A nonthermal dark matter with its coupling to (some) quarks being Chiral
- Collider prospects of the nonthermal DM interactions
- Top polarization as a discriminator
- Left versus right handed DM scenarios

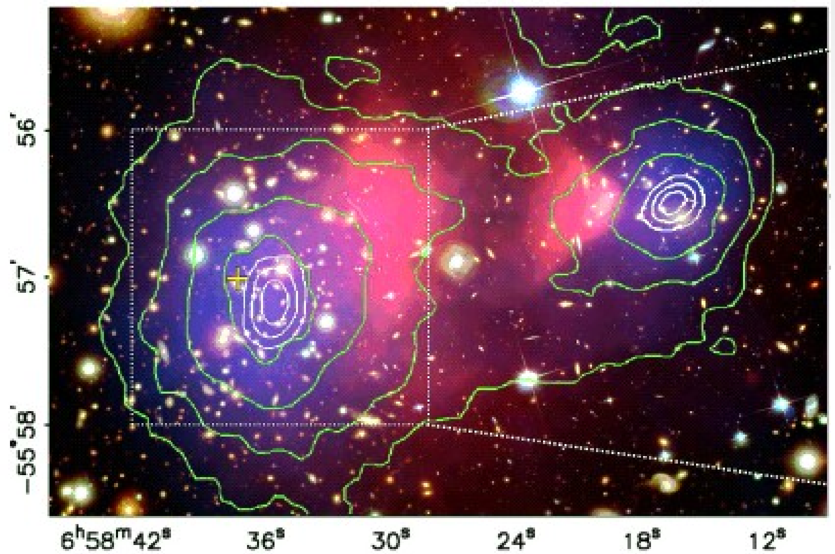
Astrophysical Dark Matter Implications ...

Galactic rotation curves





1E0657-56 'Bullet cluster'



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) :

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

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 a low temperature 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†,

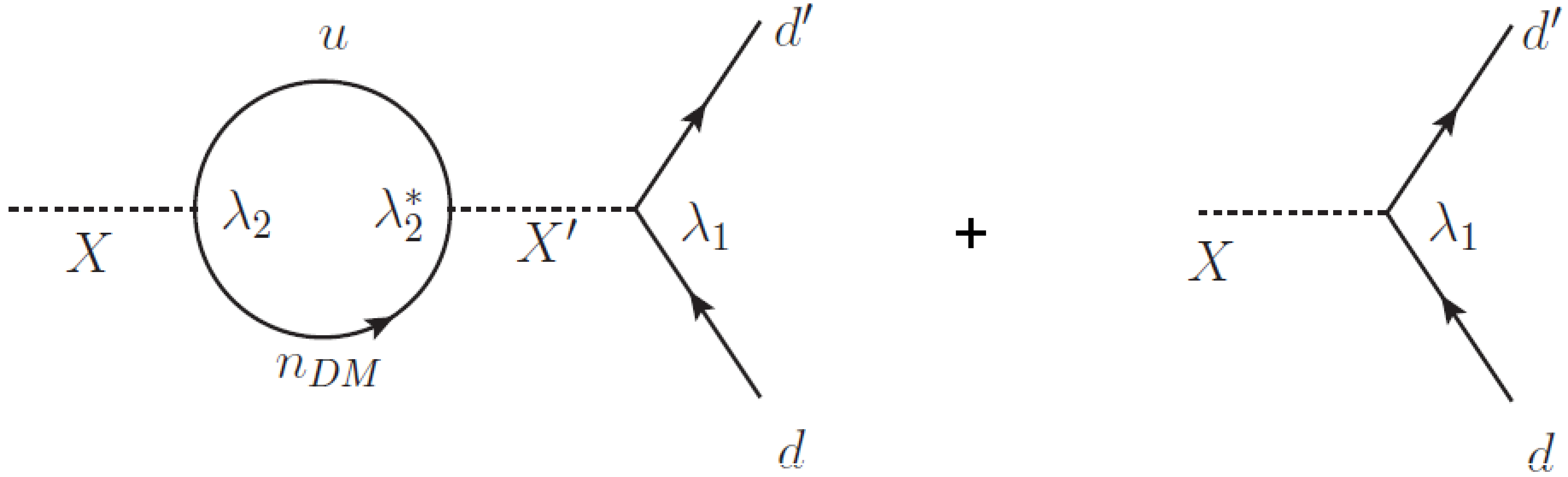
$$\frac{n_B}{s} = \frac{Y_S}{8\pi}\frac{1}{M_{X2}^2 - M_{X1}^2}\sum_{i,j,k}\underbrace{\mathrm{Im}(\lambda_1^{1,ij*}\lambda_1^{2,ij}\lambda_2^{1,k*}\lambda_2^{2,k})}_{\text{Baryon \# violating decay}}$$

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

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

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

The CP violating process



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

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

Baryon asymmetry and DM density

- (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 λ_2~*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.

At the LHC: a minimal parametrization

`baryon # violating piece':
→ leading single X production

`DM piece':
→ monojet/tops

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

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

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

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

$$\lambda_{1R}^{\rho\delta} = \begin{array}{c} \begin{array}{ccc} & ds & db \end{array} \\ \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \end{array}$$

sb

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

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

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

Light jets

top

For simplicity:
1. If more than one Xs are present, their resonances don't overlap
2. flavor blind couplings

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.

  $$| M_{DM} - M_p | < 2M_e$$

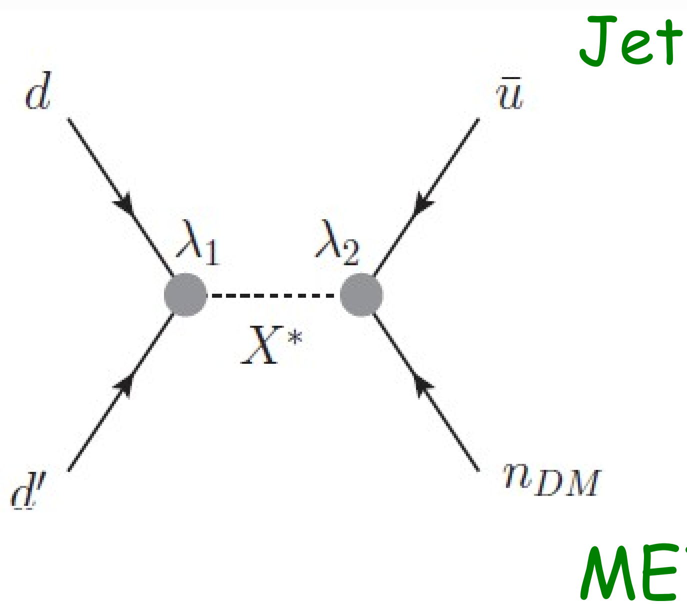
  kinematically stabilizes the DM and the proton.
  DM mass stability: For $\lambda_2 \sim 0.1$ and $M_X \sim$TeV, radiative correction to M_{DM} is less than M_e.

- 1 GeV DM mass evades direct detection.

For (in)direct detection & neutron osc., see:
R. Allahverdi, B. Dutta, PRD 88 (2013) 023525
R. Allahverdi, B. Dutta, Y.G,, RD 89 (2014) 127305

Collider phenomenology: Single X production

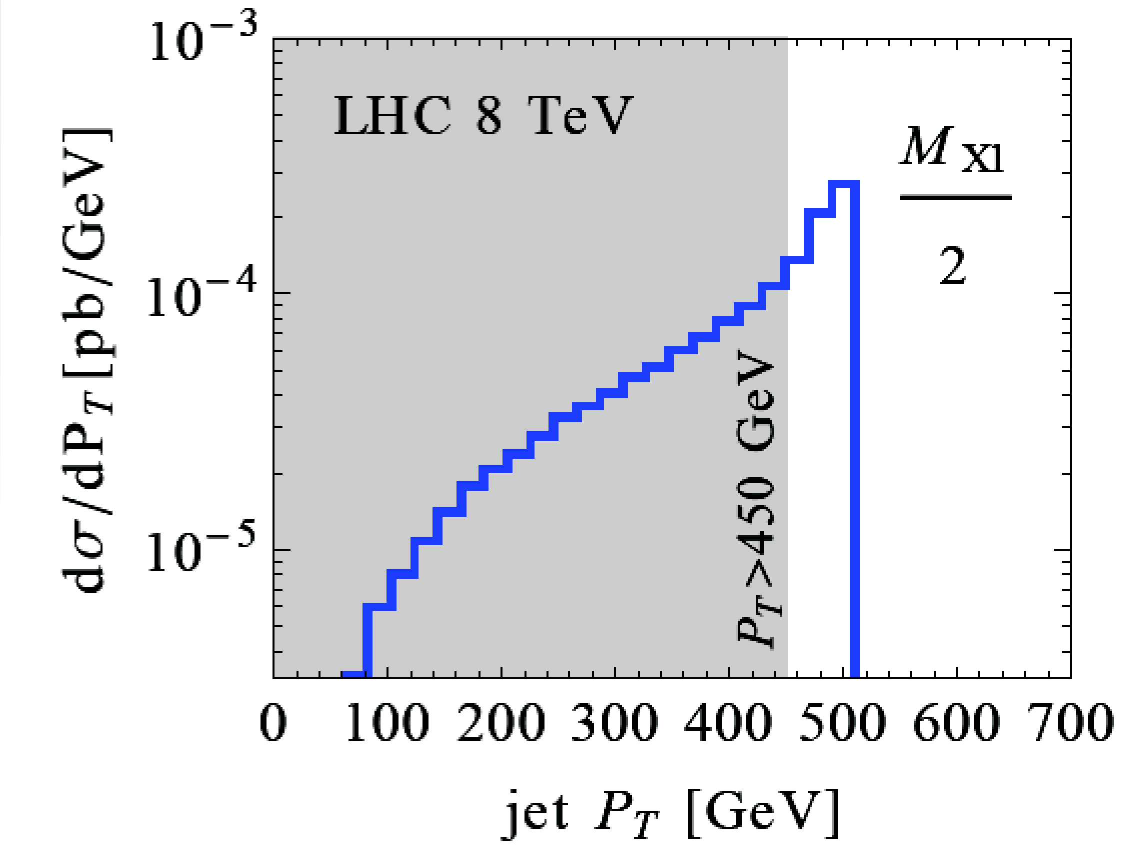
- X couples to two d-quarks or one u-quark and DM:
  A s-channel resonant process ($d\, d' \rightarrow X^* \rightarrow \bar{u}\, n$)
- A monojet + MET event without ISR.



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

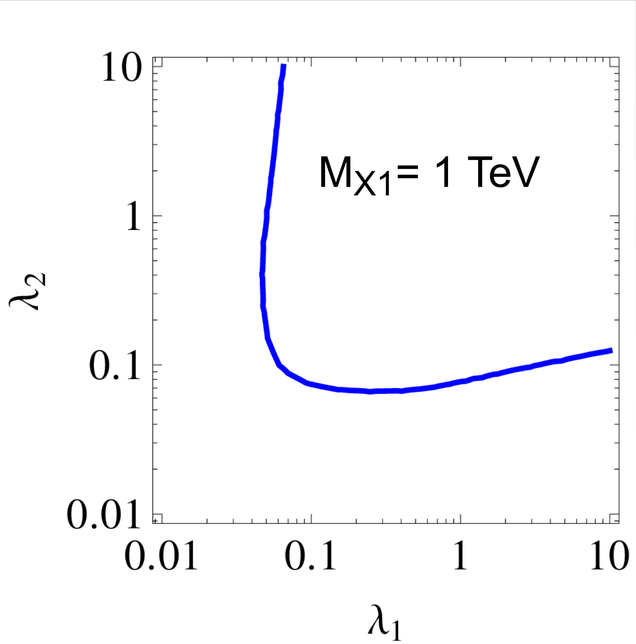
How different from ISR + Effective Operator?

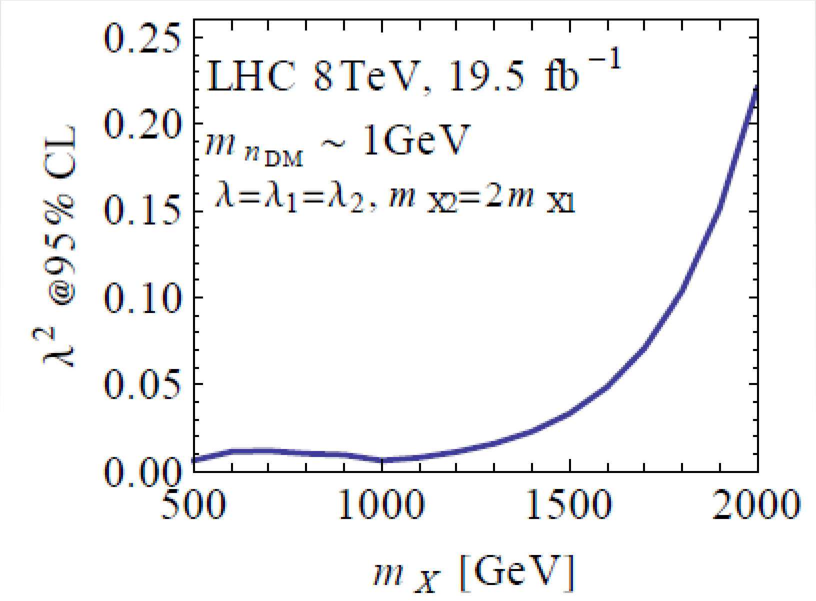
- Jet energy ~ ½ new scalar mass: a Jacobian peak in P_T distribution.
- No preference for lower jet P_T : High P_T cut can be very effective against SM background.
- Effective operator ($\sim \bar{d}\, d^c\, \bar{u}\, n/\Lambda^2$) approach is also non-ISR, but less favorable, since it loses the peak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

A very good constraint





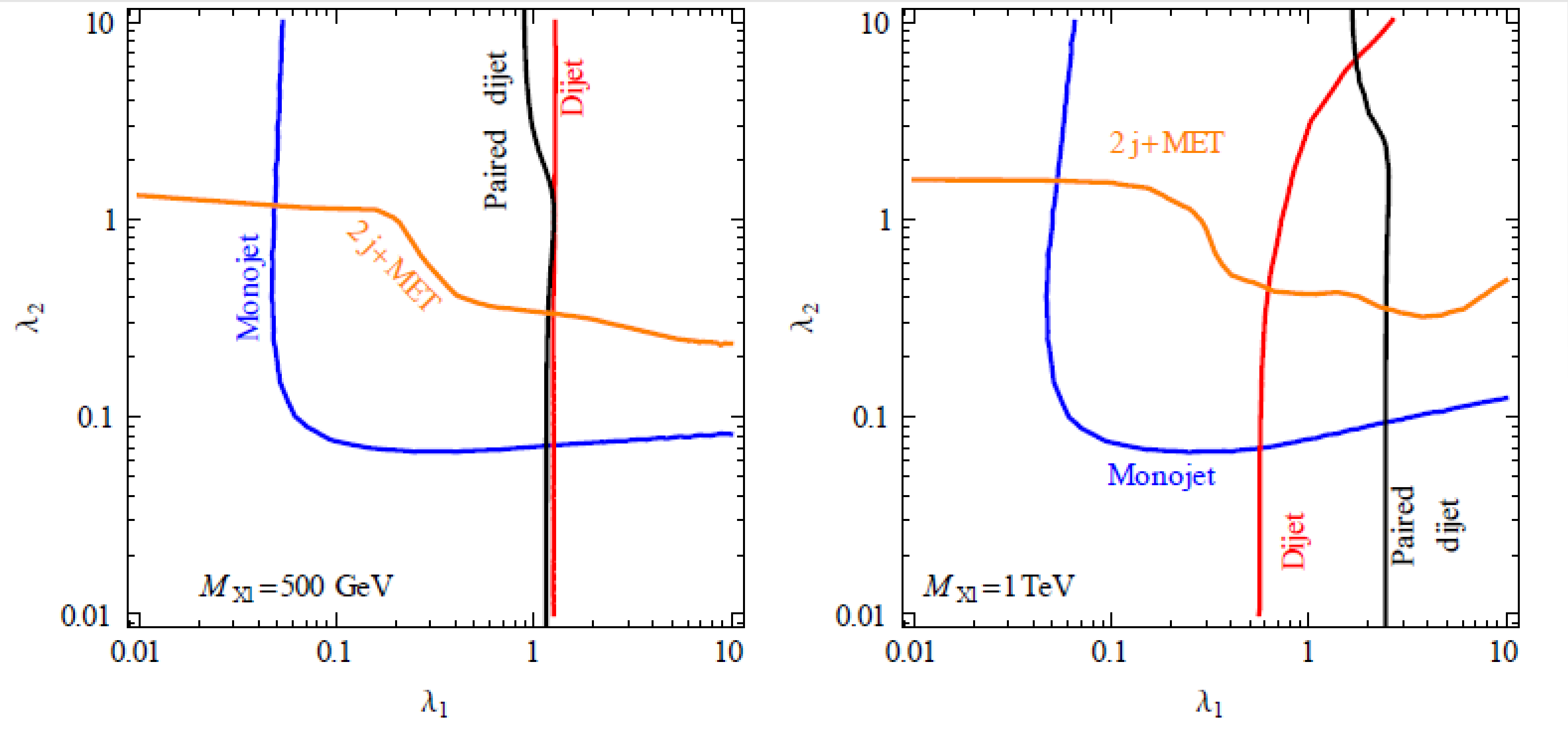
Data: CMS 20 fb^{-1} at 8 TeV, 95 C.L.
CMS-PAS-EXO-12-048, March 8, 2013

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

PDF integrated cross-section is determined by the lesser between λ_1 abd λ_2

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

With more search channels...



Single X production (monojet+ partially 2j+MET) offers better constraint than pair production

How about the 3rd generation quarks?

- Baryogenesis & DM production can involve **all** flavors.
- LHC more sensitive to couplings to light jets

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

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

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

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

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

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

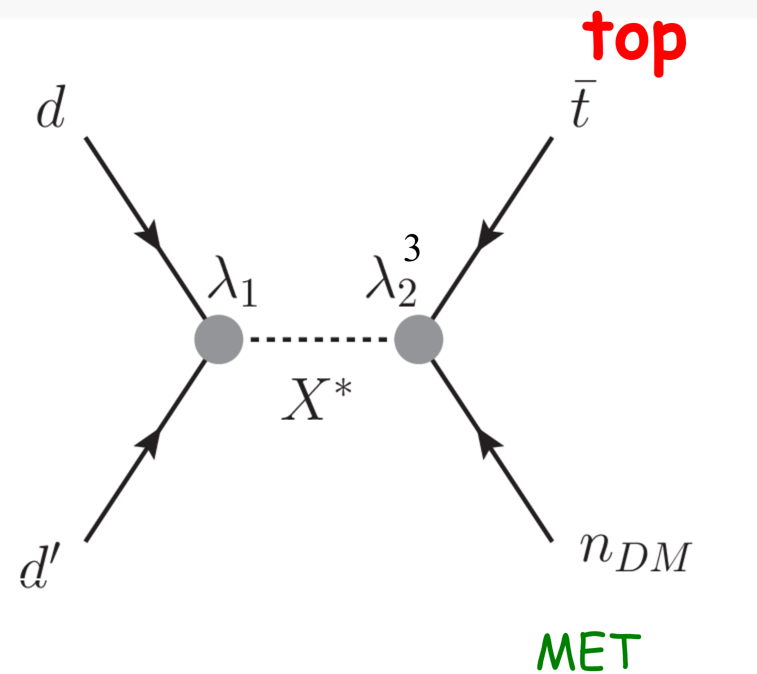
$$\lambda_{2R}^{\alpha} = (1,1,1)$$

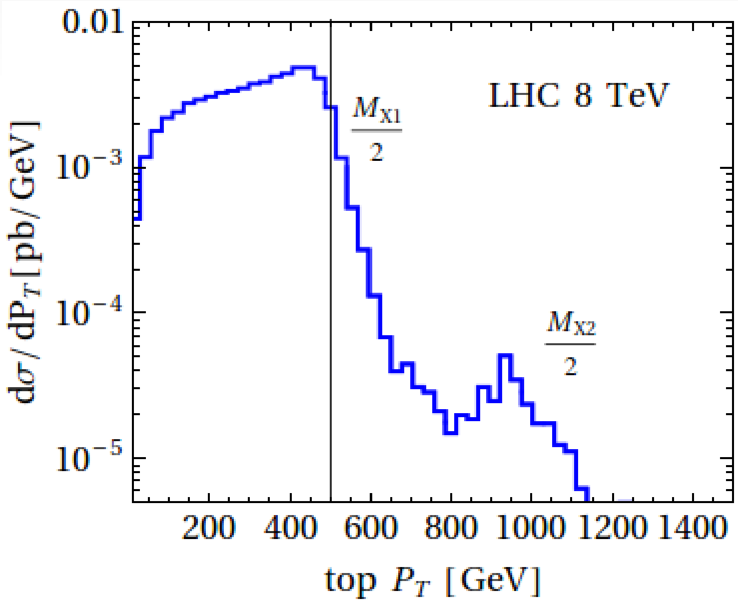
Light jets: constrained

top: NOT constrained

Mono-top + MET

Like monojet, single top can be produced
via s-channel resonance, at certain energy and polarization.



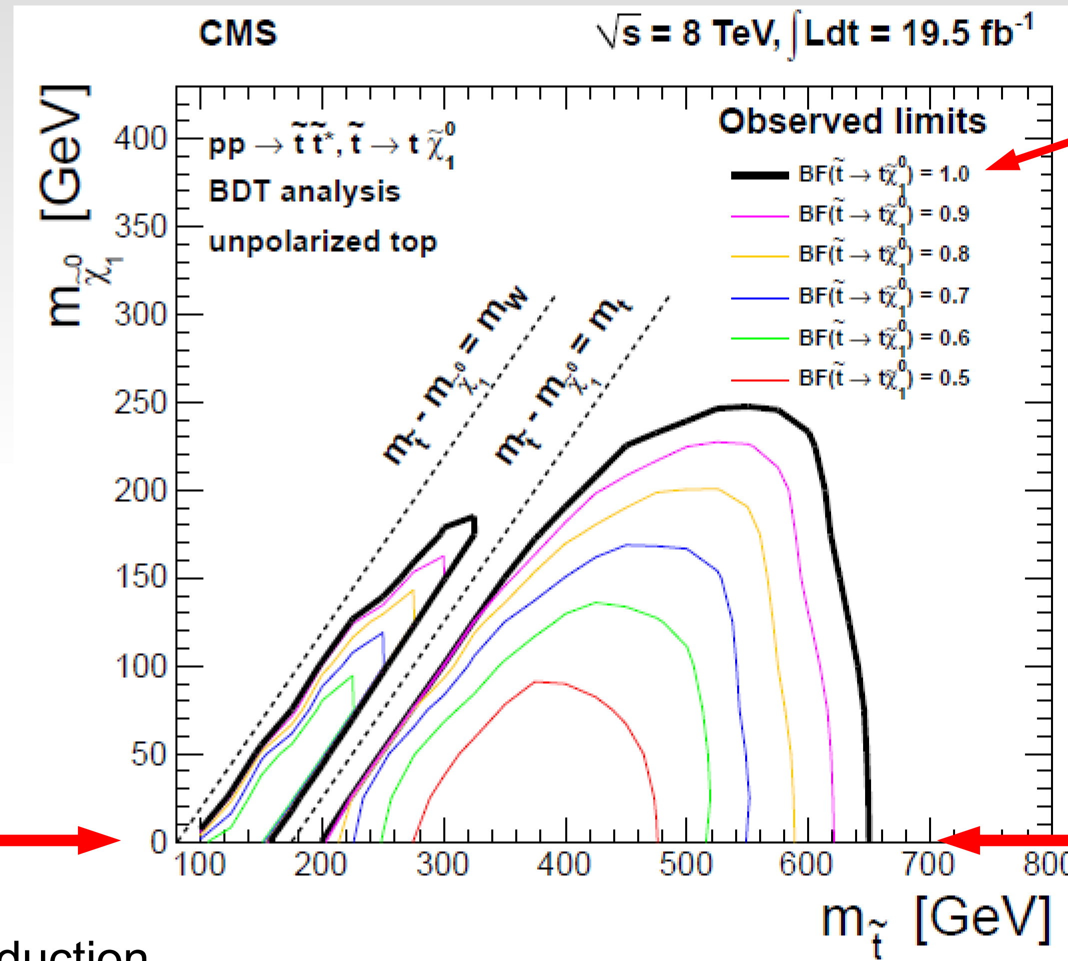


M_{X1} = 1 TeV

Pair production: like the MSSM, $t\,\bar{t}$ + MET

- From X pair production both X→ 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 GeV

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

Top polarization is reconstructible

- Heavy X and light DM allows boosted tops
- The top quark decays before hadronization
  → spin correlation in daughter particle spectra
- Left handed tops decay into more energetic *b* jets.
- Polarized top decay understood to NLO

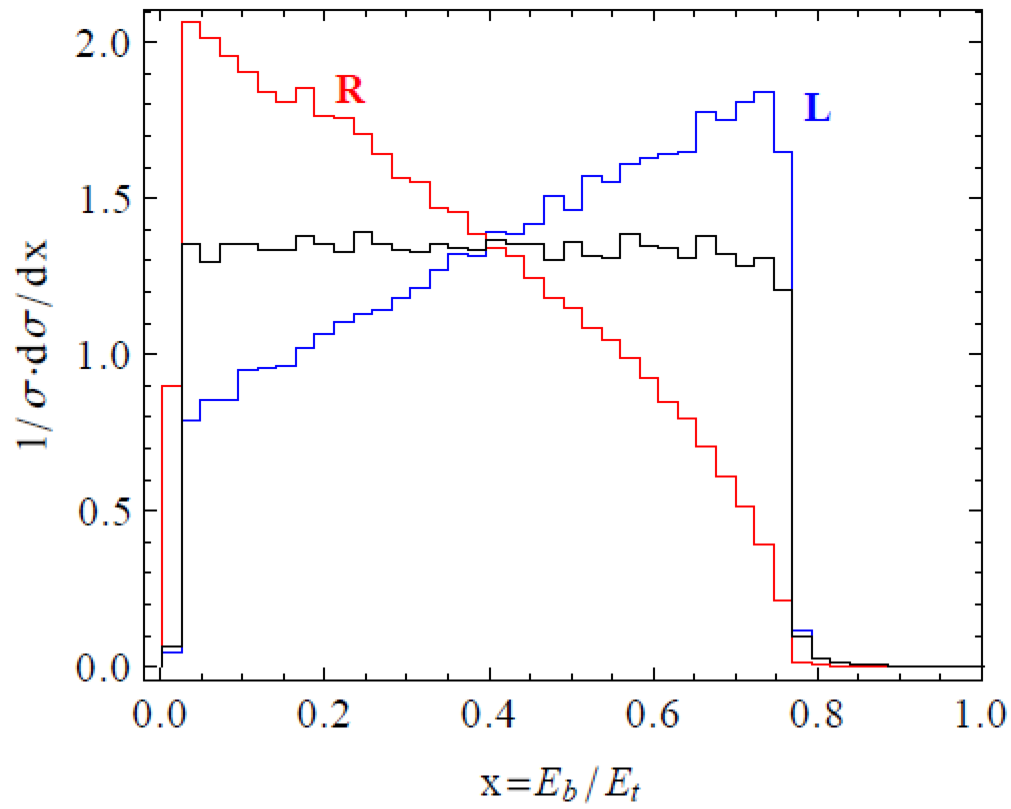
  for a recent study, see
  M. Balali, 1409.1389
- Heavy `top partner' are likely nonrelativistic, and its mass indicate how the tops are boosted.
- Left/right handed tops can be well separated.

Left versus Right... in bottom energy fraction

$$N_+ = \int_{x_0}^{1} \frac{dN}{dx} dx, \quad N_- = \int_{0}^{x_0} \frac{dN}{dx} dx$$

$$\eta \equiv \frac{N_+ - N_-}{N_{\text{total}}}$$

Left: $\eta > 0$
Right: $\eta < 0$



Top may not always be highly boosted:
Left, right & unpolarized spectra, cross-over point calculable at different energies

Which quark chirality does our DM couple to?

- X scalar as a weak singlet:

$$\mathcal{L}_{\rm S} \supset \lambda_1^{\alpha,\rho\delta}\epsilon^{ijk}X_{\alpha,i}\bar{d}^c_{\rho,j}d_{\delta,k} + \lambda_2^{\alpha,\rho}X^*_\alpha n u_\rho + \mathrm{C.C.},$$

Or as a doublet:

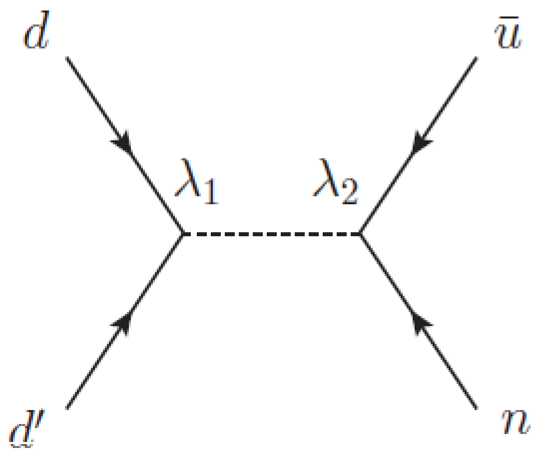
$$\mathcal{L}_{\rm D} \supset y_1^{\alpha,i}\bar{Q}_i n X_\alpha + y_2^{\alpha,i}X^\dagger_\alpha \bar{Y} d_i + y_3^{\alpha,i}X_\alpha \bar{Y} u^c_i + M_Y\bar{Y}Y + M_n nn + \frac{1}{2}M^2_{X_\alpha}|X_\alpha|^2. \quad + \mathrm{C.C.}$$

Both cases give rise to baryogenesis and DM density.
The mediator's non-trivial isospin indicates for more particles
and different phenomenology

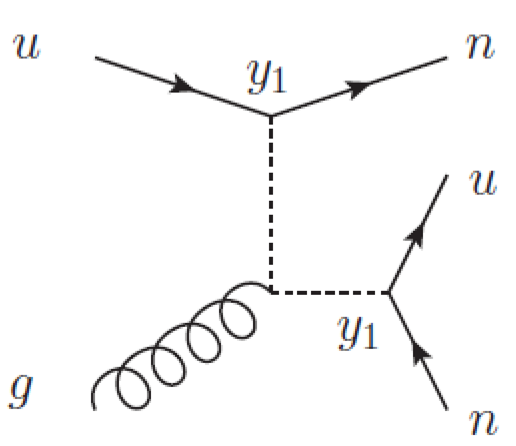
R.Allahverdi, M. Dalchenko,B.Dutta, YG, T. Kamon
in progross

A different monotop process...

- Yet both signals are possible.

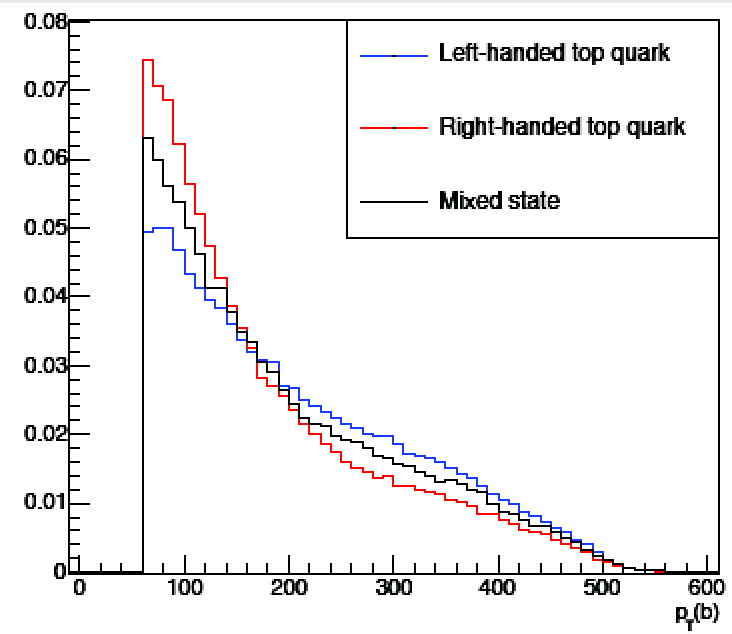


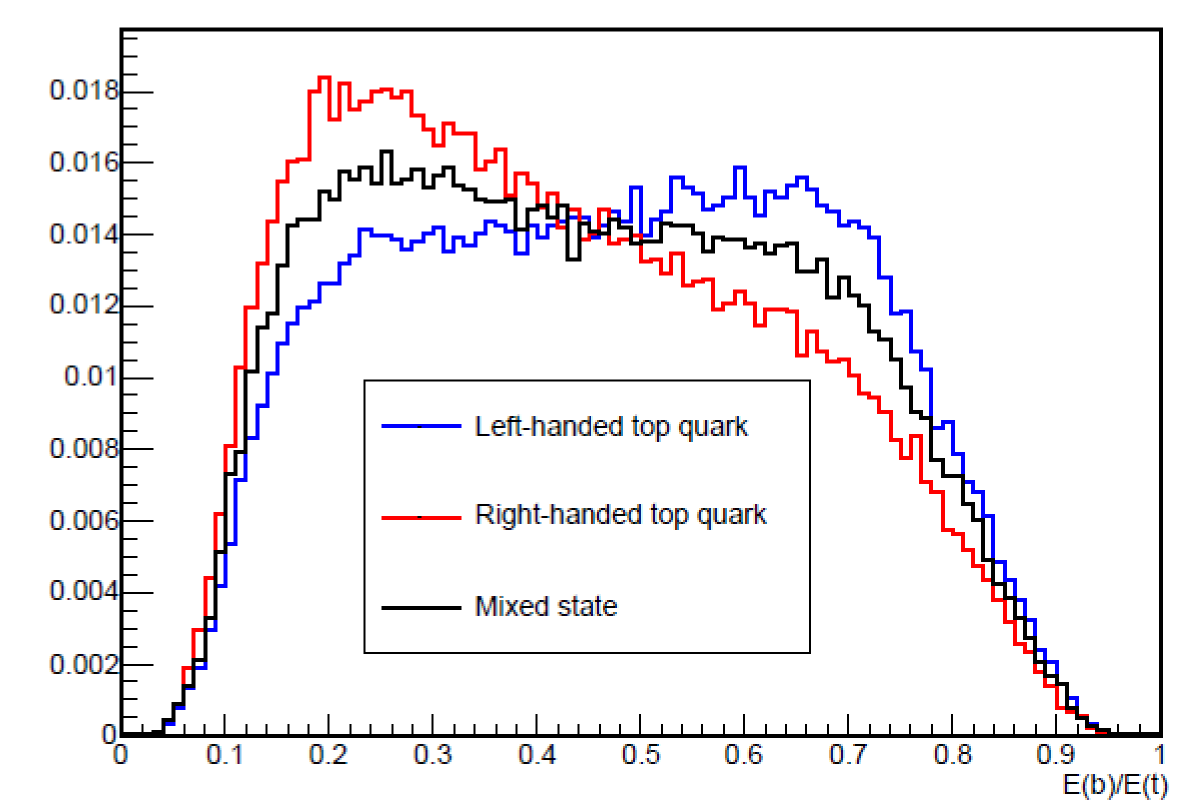
weak singlet case,
has a Xdd term
and s-channel resonance



doublet case:
no XQd term and
single t production
at higher order

Left versus right at detector level

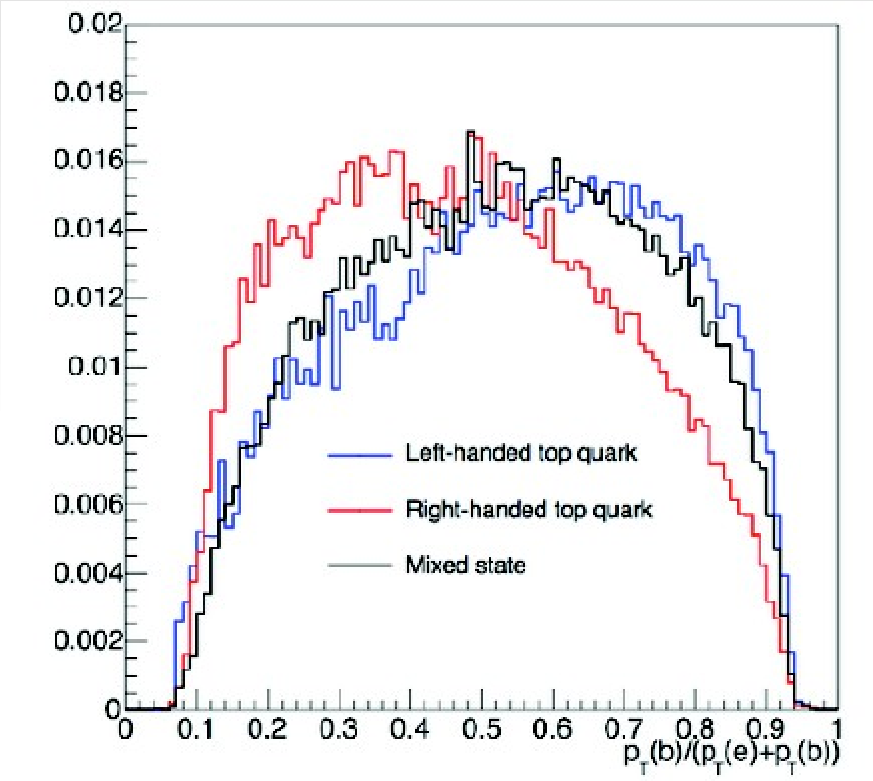


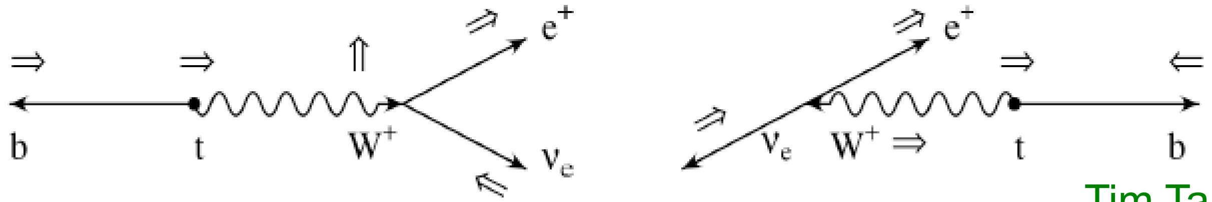


MadGraph+Pythia8+Delphes

More correlation in the W decay, too.

The charged lepton from the W decay tends to align with the top's spin → RH's along the boost and more energetic





Tim Tait 09'

Not only for monotop...

- Chiral coupling in Xqn terms produce highly polarized tops in pair-produced Xs
- Can be used to identify left/right handed top partners,
  e.g. quark portal couplings, supersymmetric stops.

Summary

- A minimal extension of SU(3) triplet scalar X can mediate baryon number violation and DM production at a low reheating temperature.
- Single production of X can be resonant and offer good constraint on its couplings
- In both cases of X being weak singlet/doublet scenarios, single production of X can lead to monotop events with highly polarized tops
- Measurement of top polarization offer insight on the chirality of the mediator-quark-DM coupling and weak structure of the mediator.

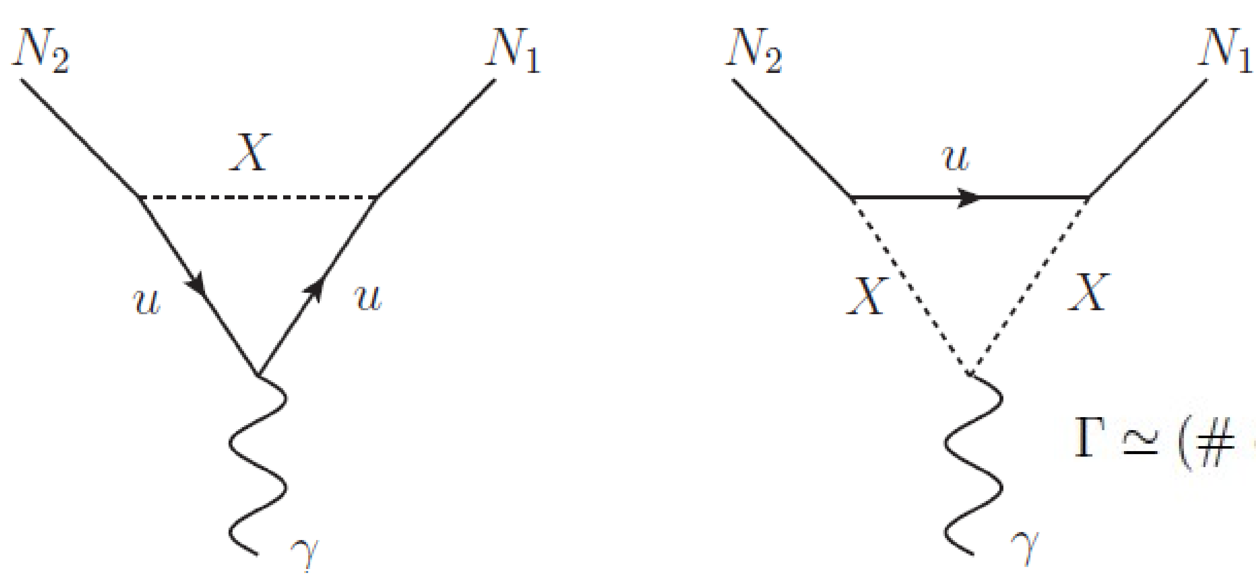
backups

3.5 keV line

- 3.5 keV emissions from galaxy clusters

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

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

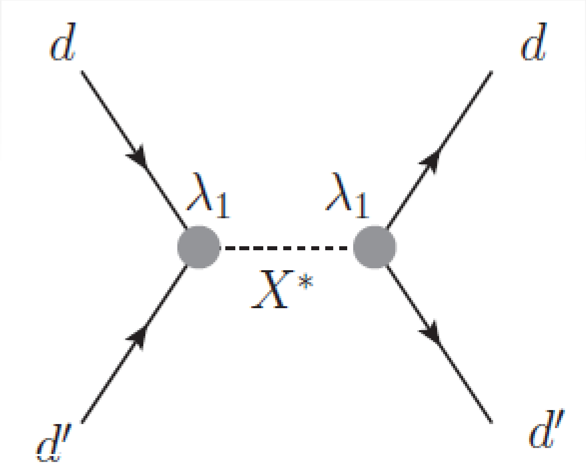


$$\Gamma \simeq (\#\text{ of } X)^2 \times \frac{\alpha_{\text{em}}|\lambda|^4}{64\pi^4}\Delta M^3 \frac{M_N^2}{m_X^4}$$

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

Collider phenomenology: Dijet

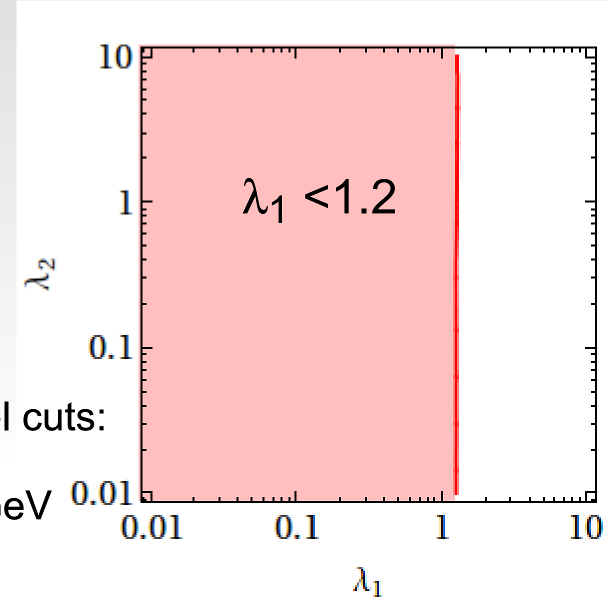
- Similar to the monojet process but with two (different generation) down-type quarks in the final state:



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

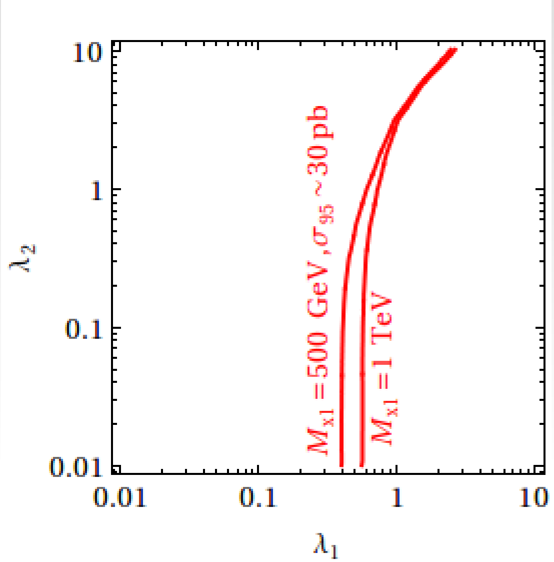
Dijet cross section only depends on λ_1.

Dijet constraints



Parton level cuts:

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



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.

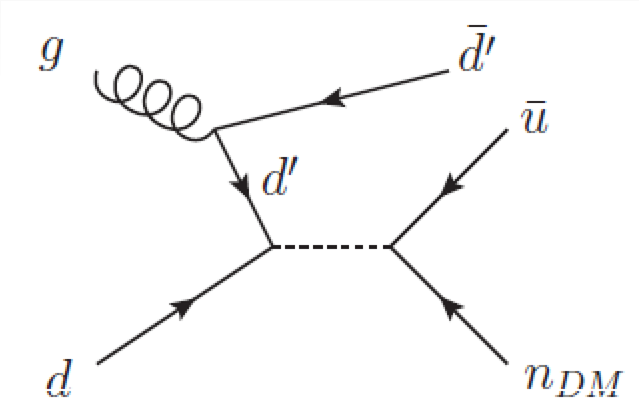
CMS dijet low mass analysis with 0.13 fb^{-1} data @ 7 TeV
CMS-PAS-EXO-11-094, 2012

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

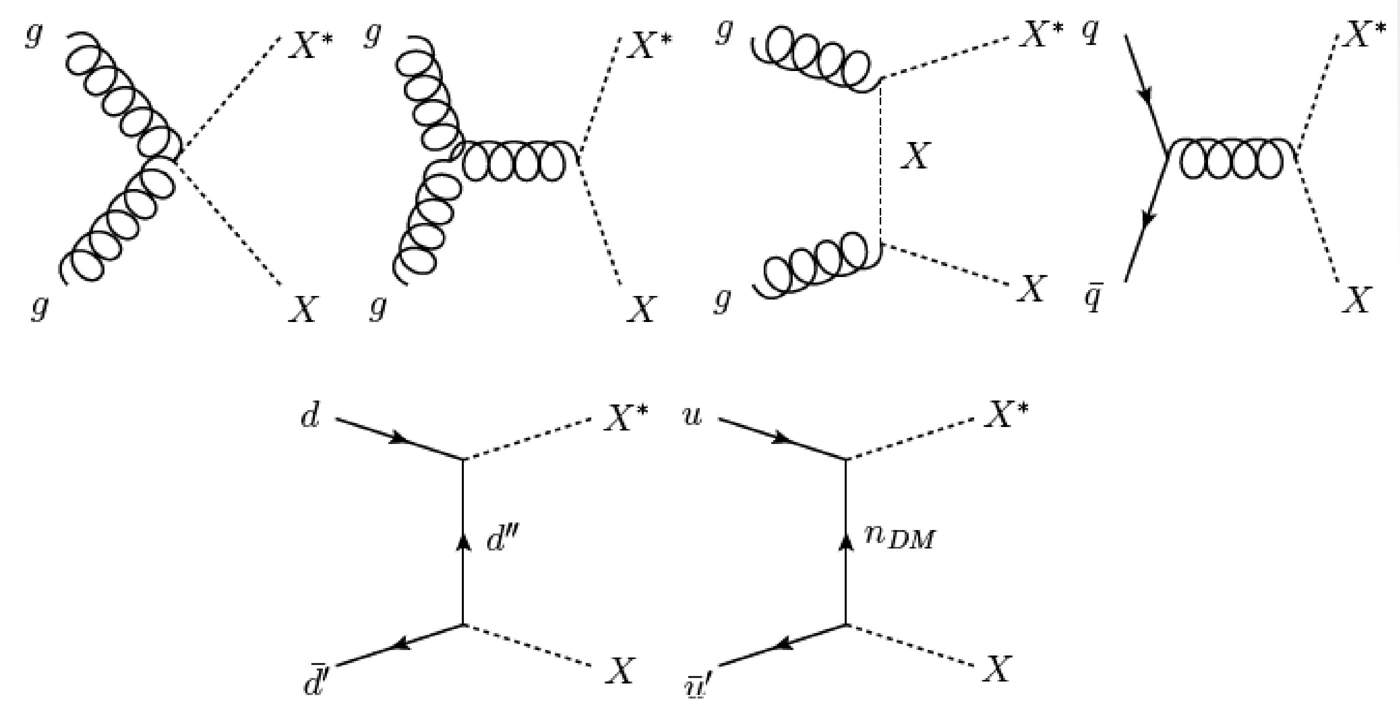
- Initial state gluon splitting (ISGS)



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

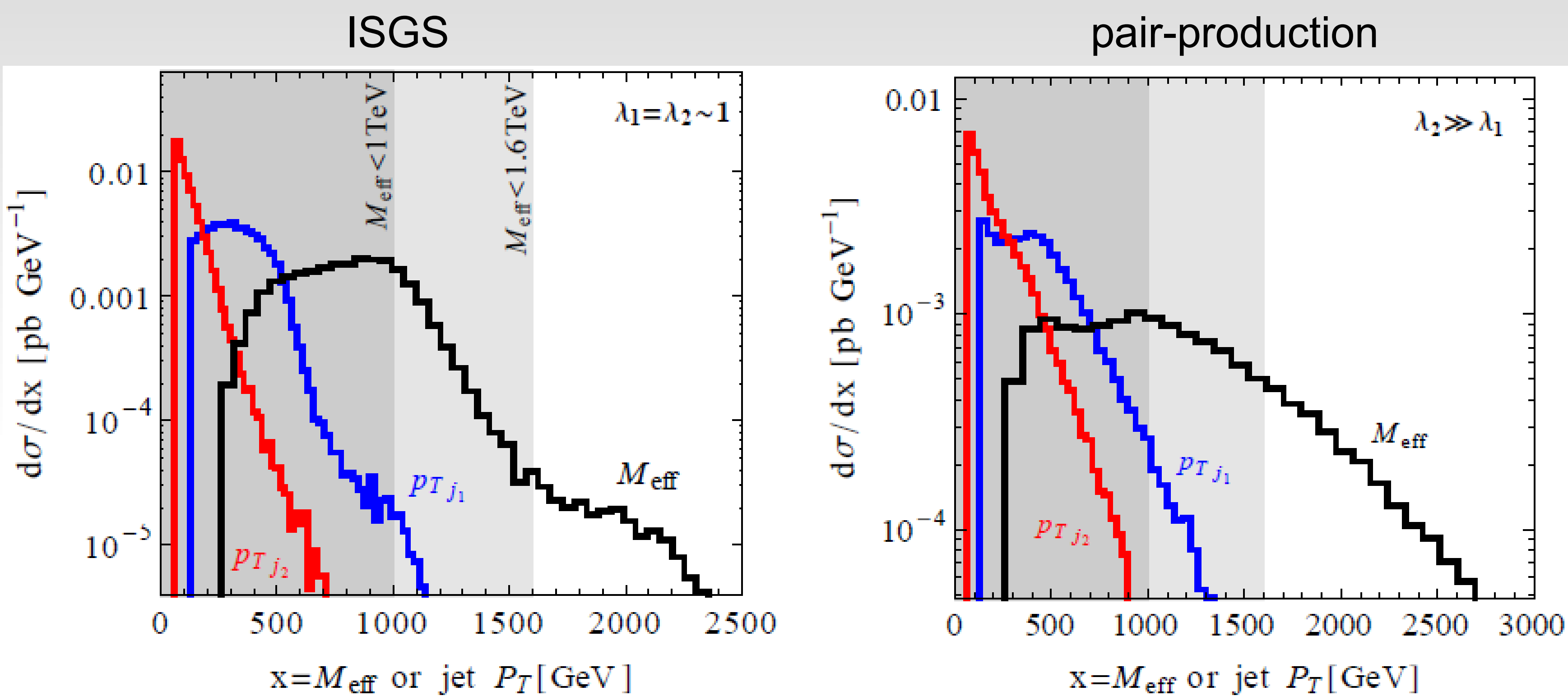
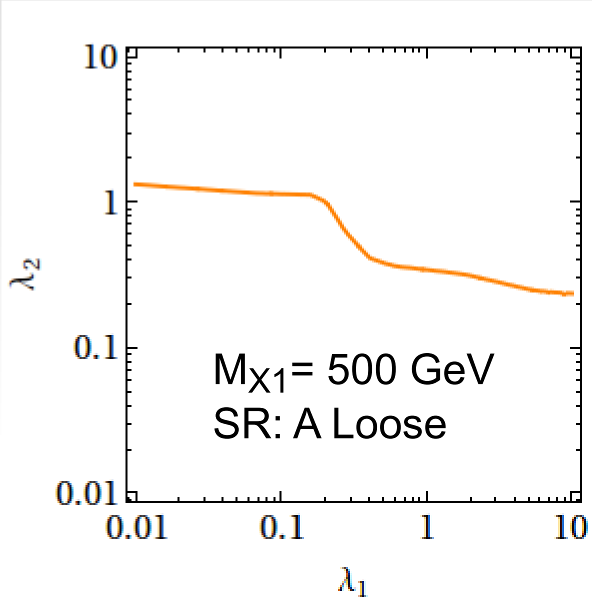
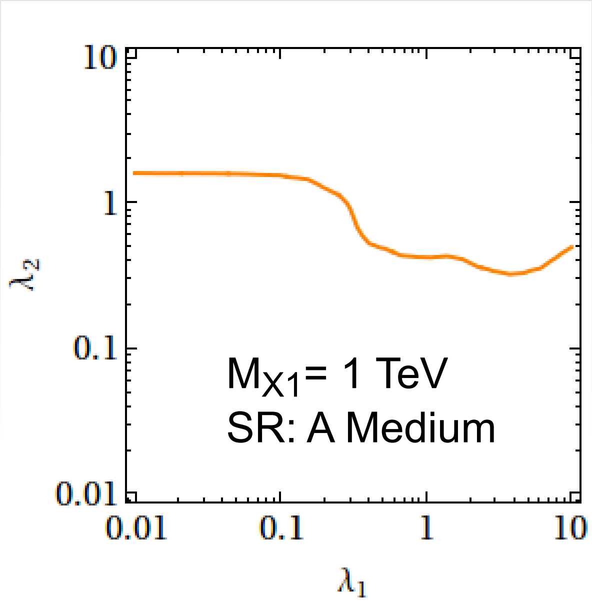


FIG. 6. Two sample jet p_T (blue and red) and $M_{\rm eff}$ (black) distributions for $\lambda_1 = \lambda_2 \sim 1$ (left) and $\lambda_2 \gg \lambda_1$ (right). The ISGS process singly produces $X1$ and $M_{\rm eff}$ drops quickly above M_{X1}. In the pair-production case $M_{\rm eff}$ is easier to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

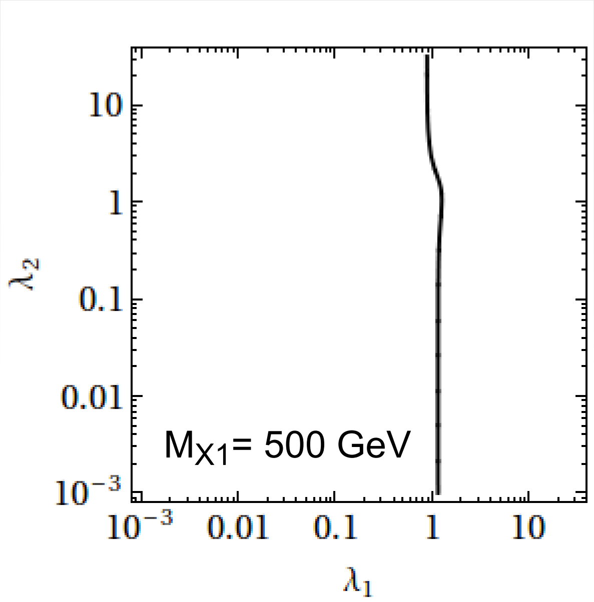
2 jets + MET (95% C.L.) *exclusive* bounds selected from ATLAS multi-jet analysis with 20.3 fb^{-1} at 8 TeV:
ATLAS-CONF-2013-047, 16 May, 2013

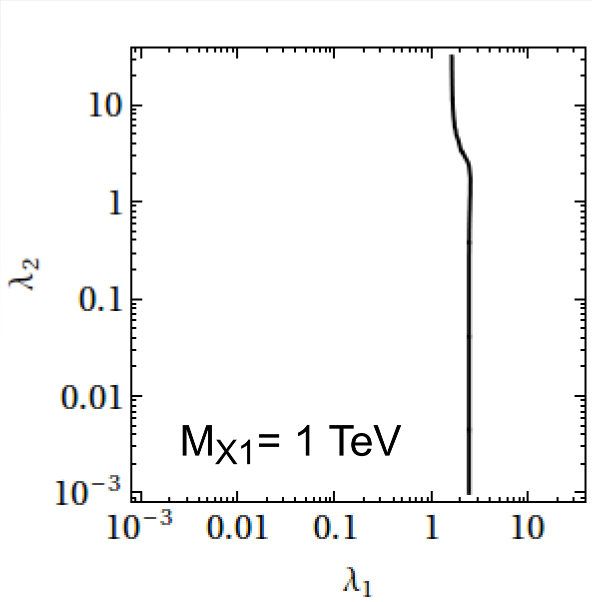
Turn over at small λ_1:
Due to pair-production diagrams becoming dominant when $\lambda_1 \ll \lambda_2$.

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
* $|\eta_j| < 2.5$
* $\Delta R_{jj} > 0.7$

Data:CMS 5 fb^{-1} at 7 TeV, 95 C.L.
S. Chatrchyan, et. al. [CMS collaboration]
Phys.Rev.Lett. 110 (2013) 141802

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)