Benchmark models for Dark Matter searches at the LHC

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in preparation

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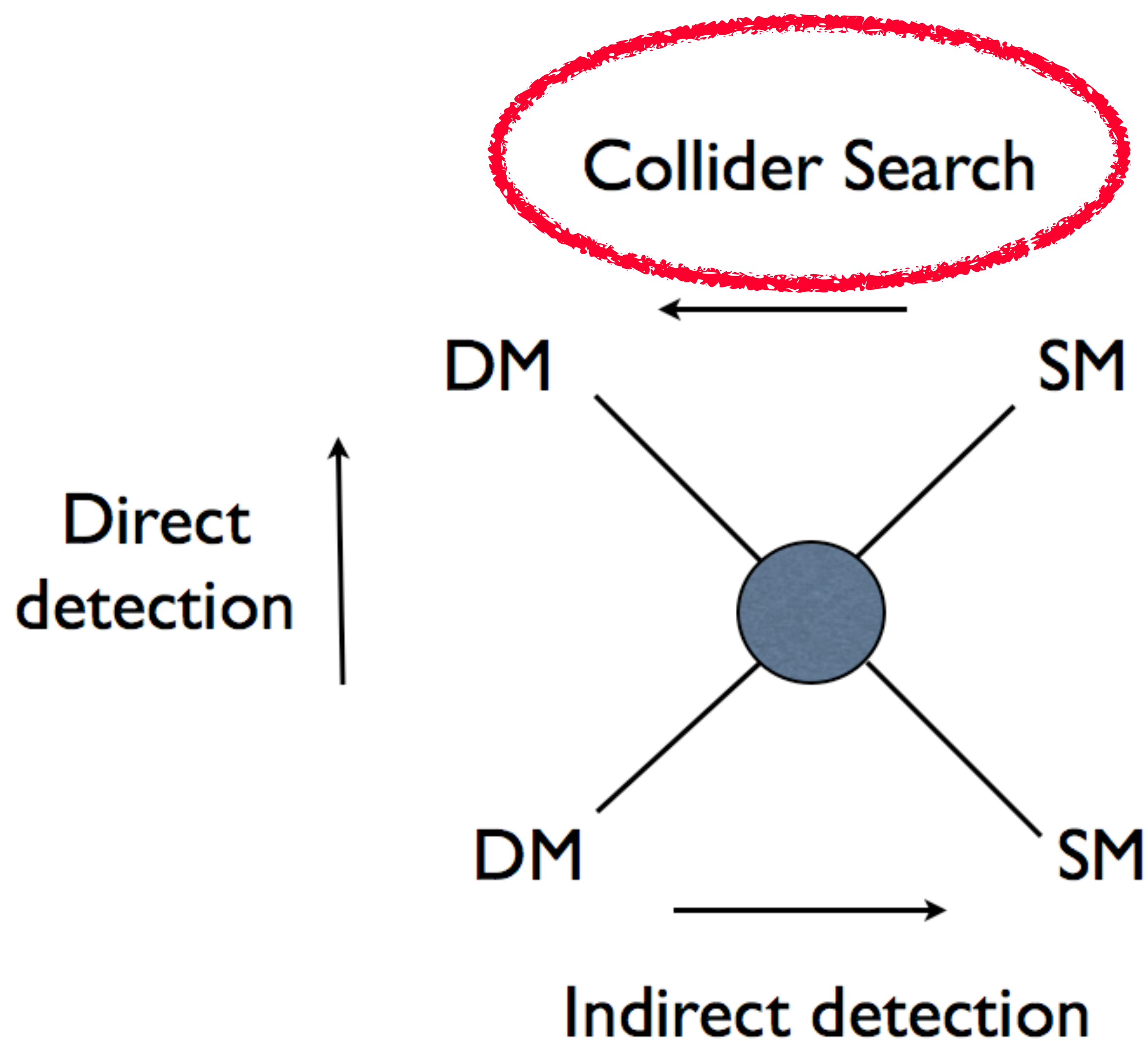
Detecting Dark Matter Signals



Two approaches

Top-down

Supersymmetry

Extra dimensions

etc.

relatively well known

bottom-up

Effective Field Theory

Simplified models

relatively new

Bottom-up approach: Effective Field Theory

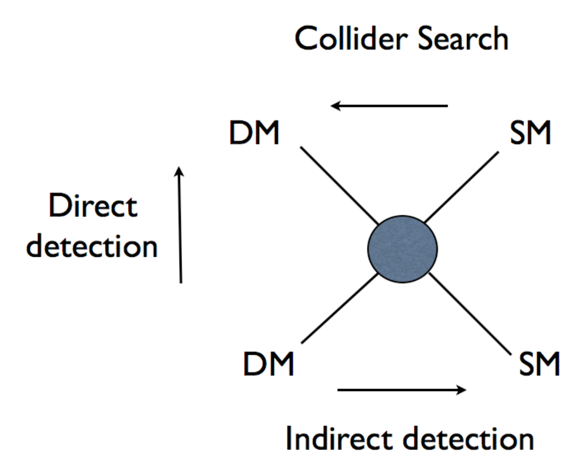
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
M1	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$
M2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$
M3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
M8	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/8M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

[Goodman et al. '10]

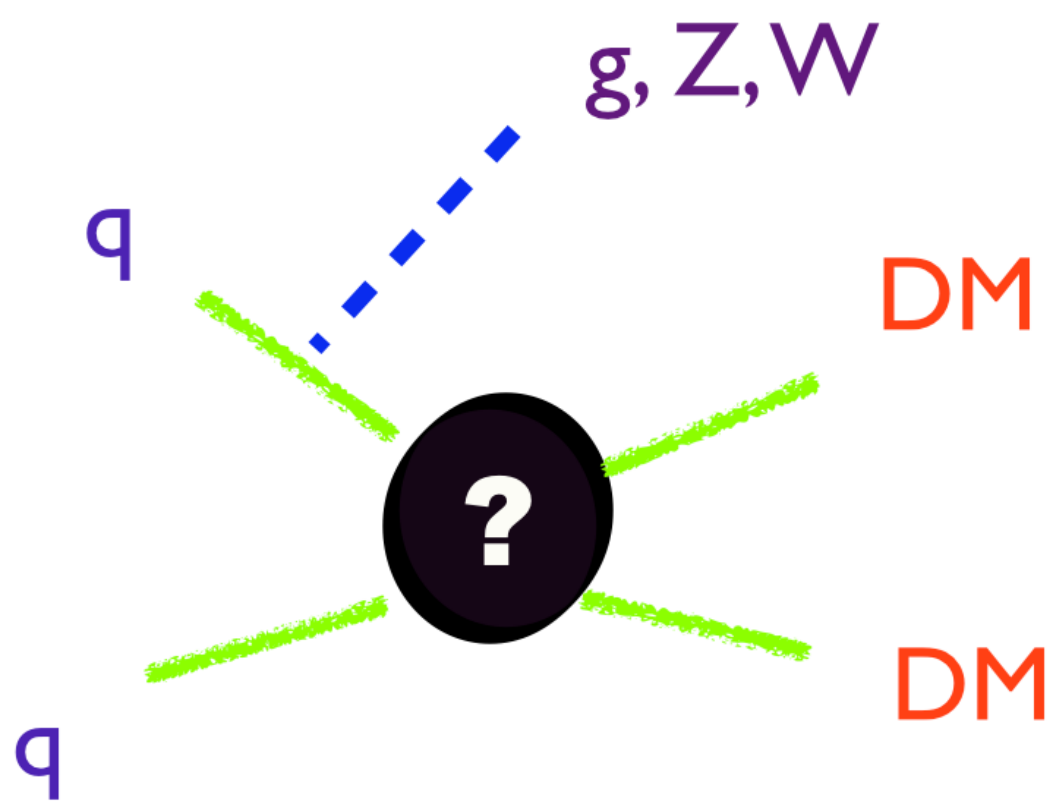
- DM is an SM singlet
- DM is odd under a Z2 symmetry
- DM is either scalar or fermion



Bottom-up approach: Effective Field Theory

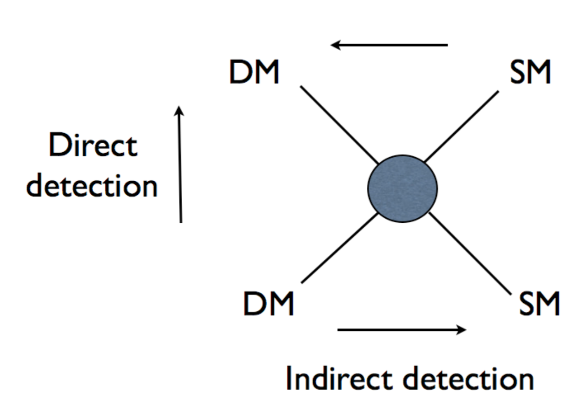
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3

Name	Operator	Coefficient



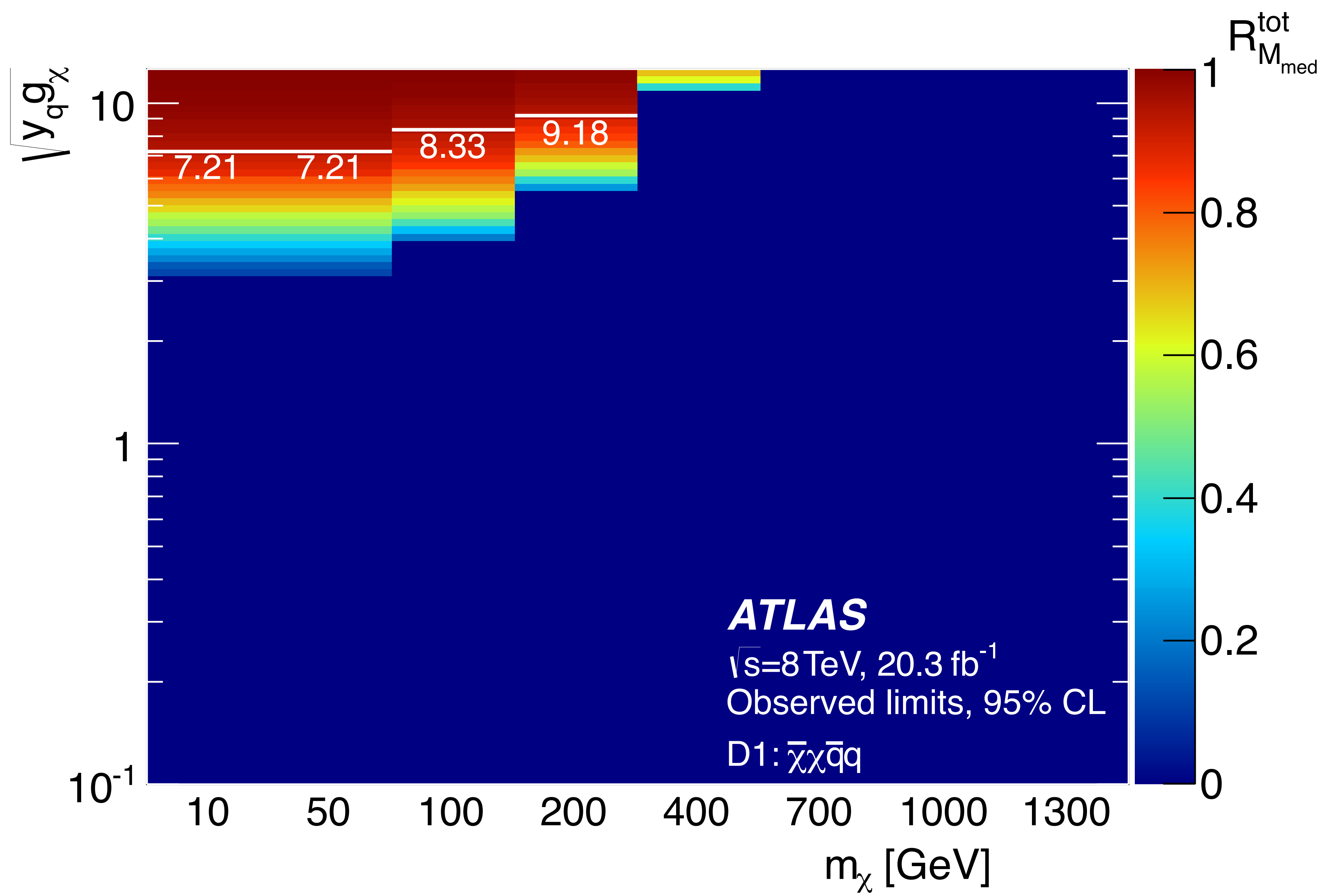
Signature:
Mono-events with missing energy
at the LHC

- DM is an SM singlet
- DM is odd under a Z2 symmetry
- DM is either scalar or fermion



However, in many cases, Effective Field Theory breaks down at LHC energy scales

Q(momentum transfer) > *M* (mediator mass)



fraction of "valid" events

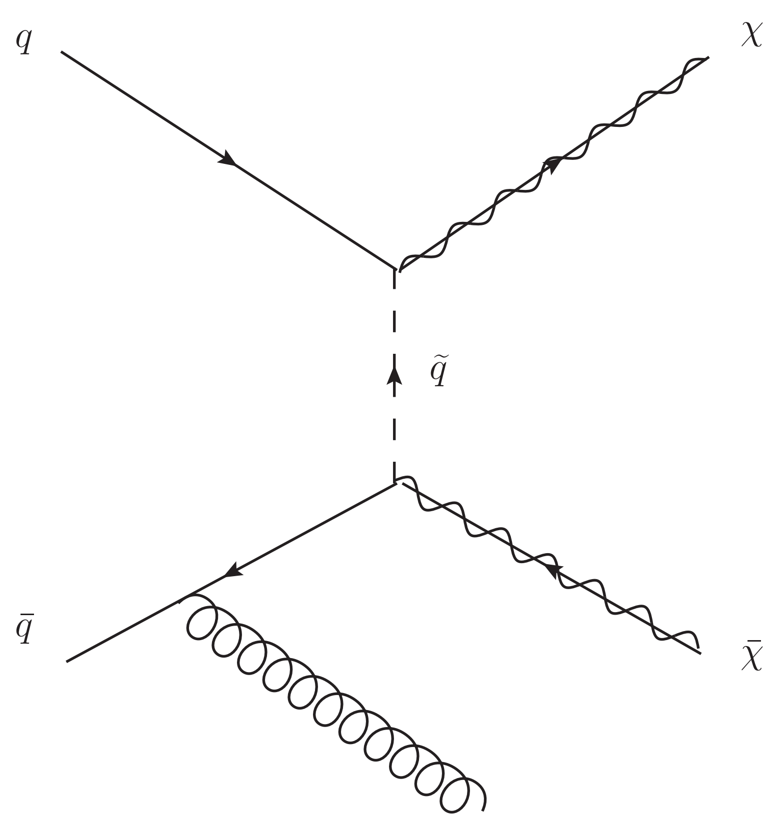
[1502.01518]

(s-channel mediator)

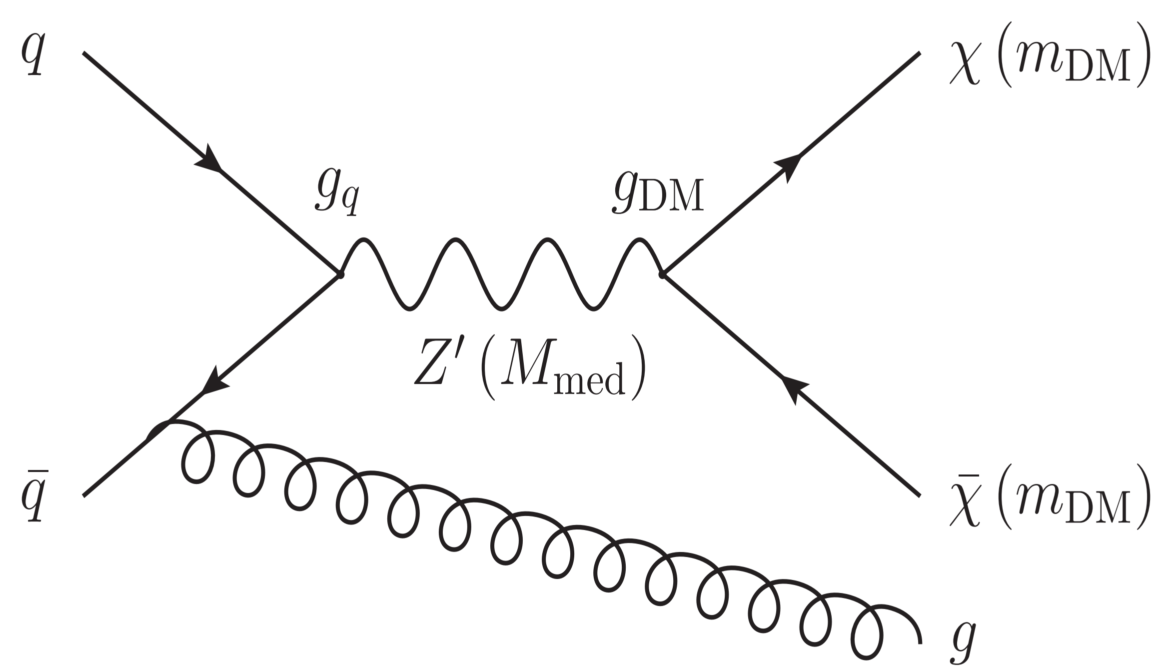
UV-complete models, i.e. simplified DM models are more appropriate.

e.g.

squark-neutralino model



Z' model



[Papucci et al. '14]

[Buchmueller et al. '14]

are the benchmark models to study monojet signatures

Simplified models related to monojet are well known.
How about simplified models for other mono-particle, i.e. mono-*X*, which is also actively looked for at the LHC?

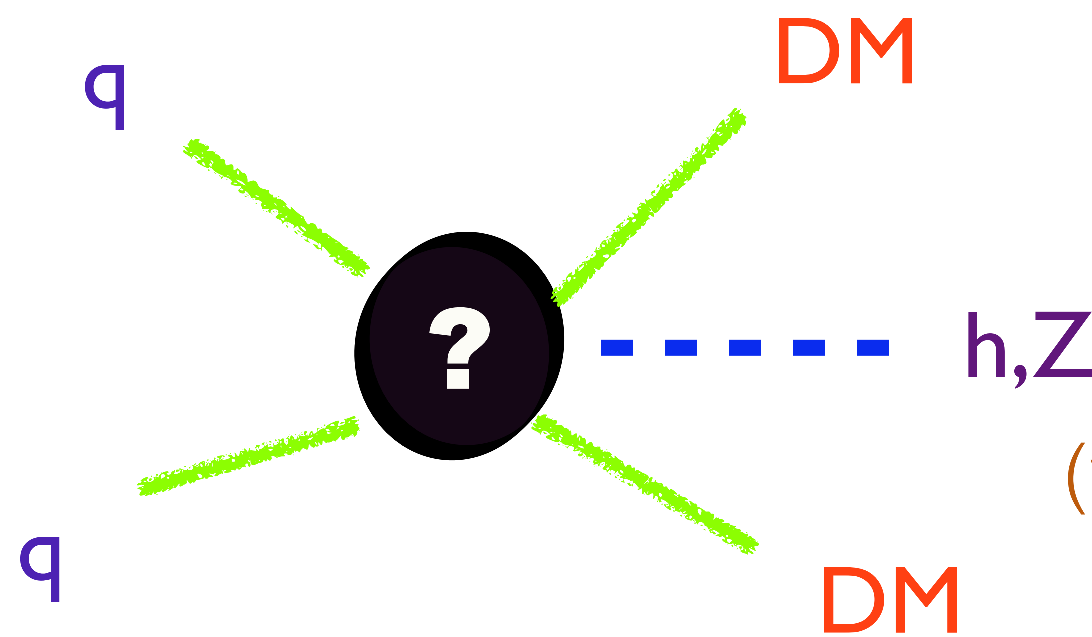
(W, Z boson, photon, Higgs, top, bottom)

firstly, colorless *X* from initial state cannot be dominant over jet from initial state at the **LHC**

monojet >> mono-*X*

simply because QCD processes are more important at the LHC

Simplified models of mono-*X* for colorless *X* must have *X* radiated from the ***final state***



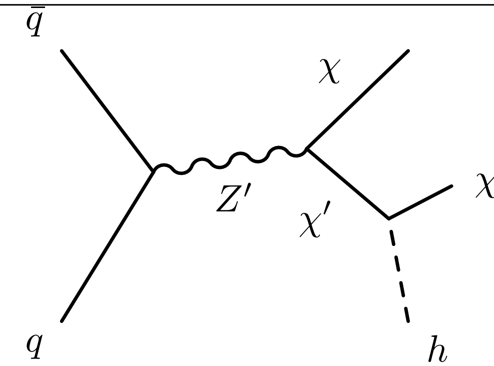
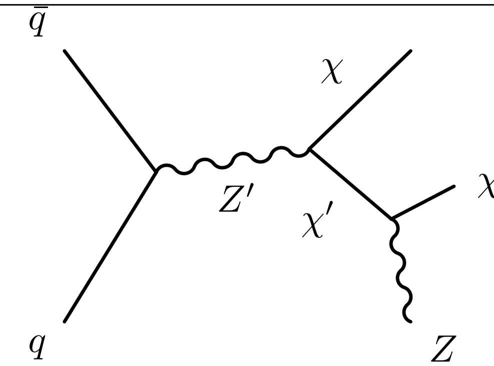
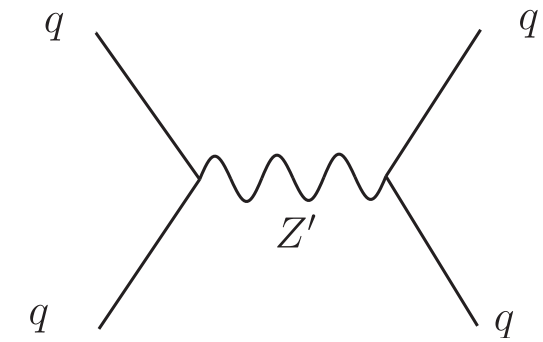
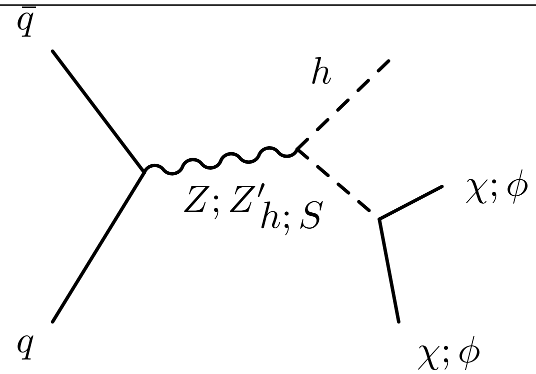
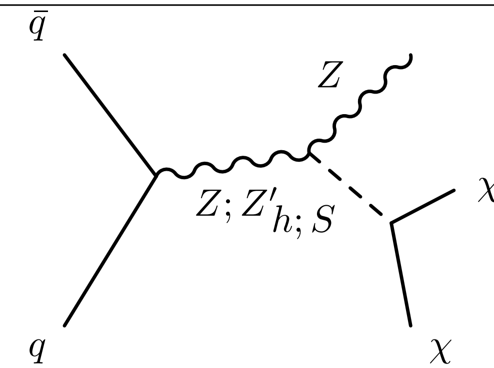
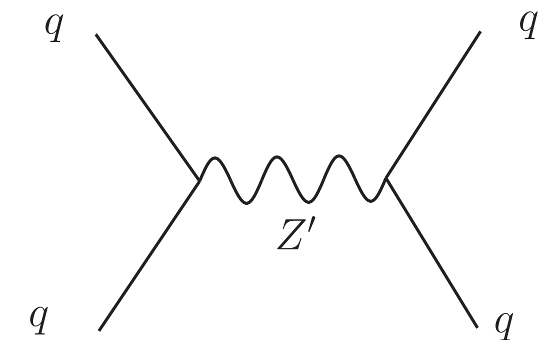
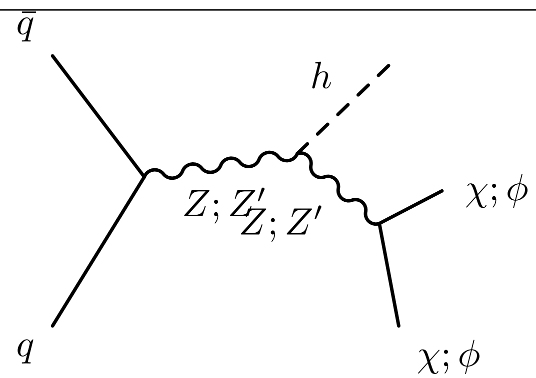
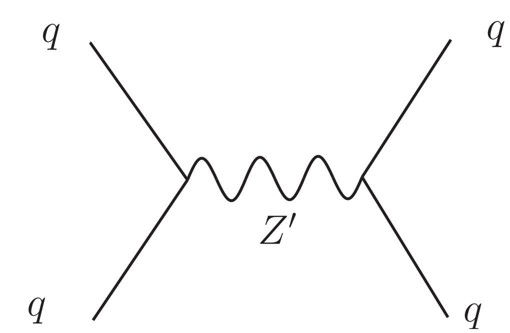
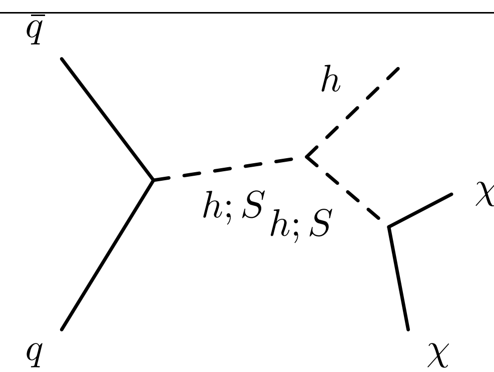
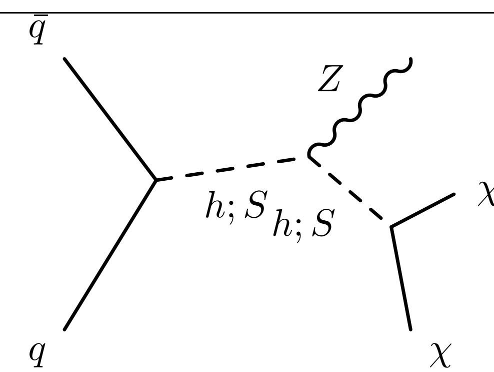
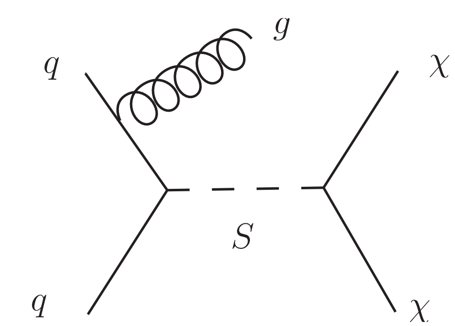
(we focus only on h,Z due to limited time)

We come up with a minimal set of simplified models by imposing the following requirements:

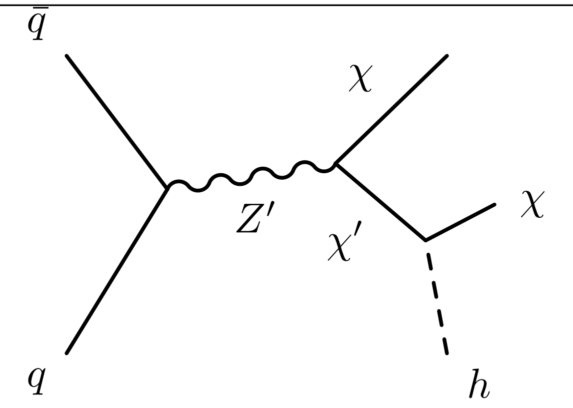
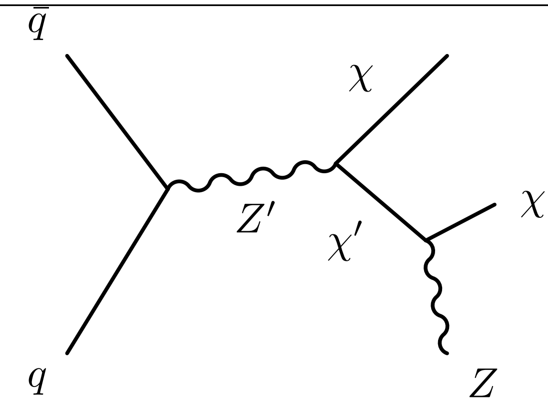
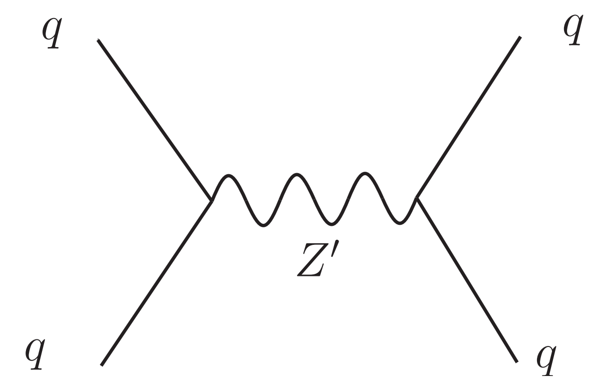
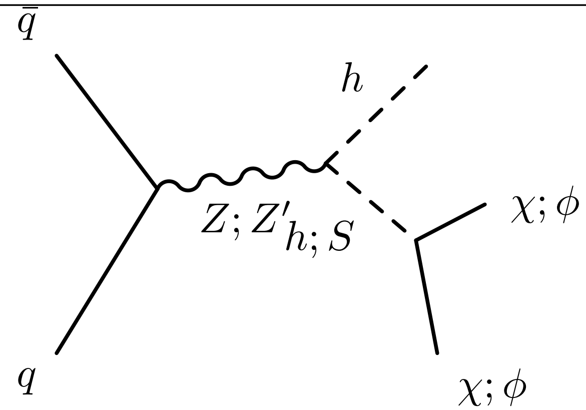
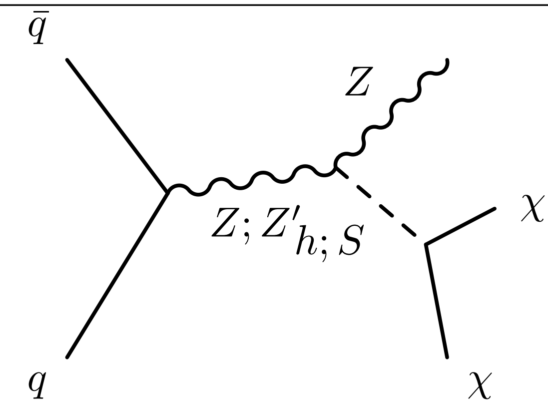
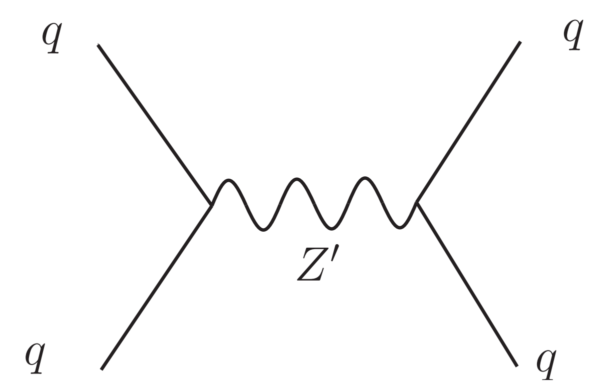
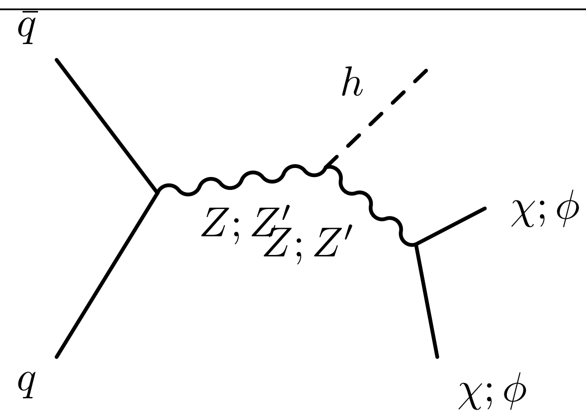
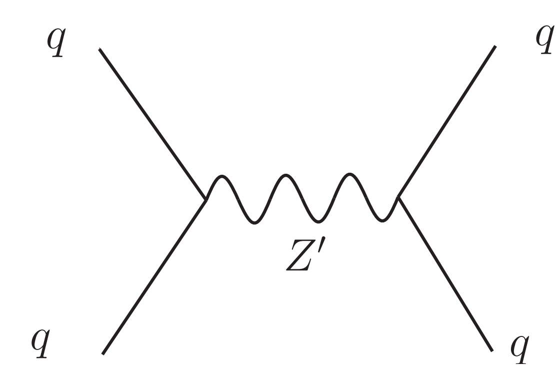
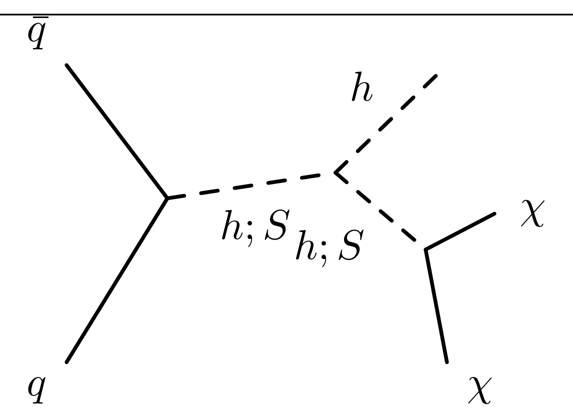
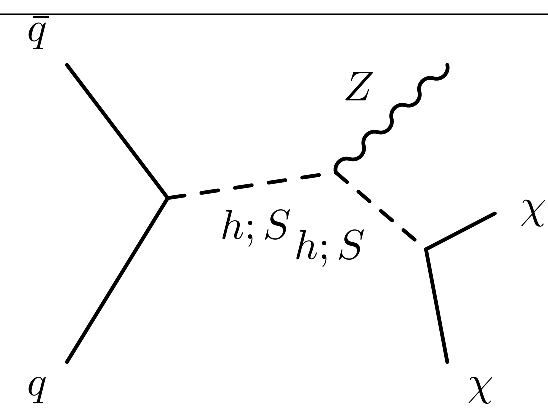
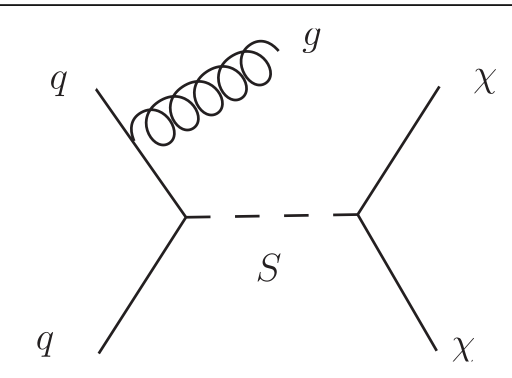
- DM is an SM singlet and is produced in pair
- tree-level topology
- minimal number of mediators

mono-X simplified models I

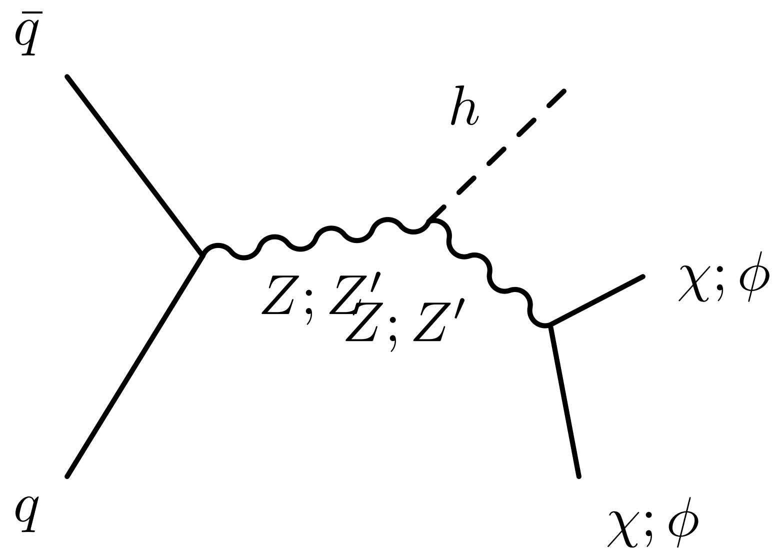
s-channel

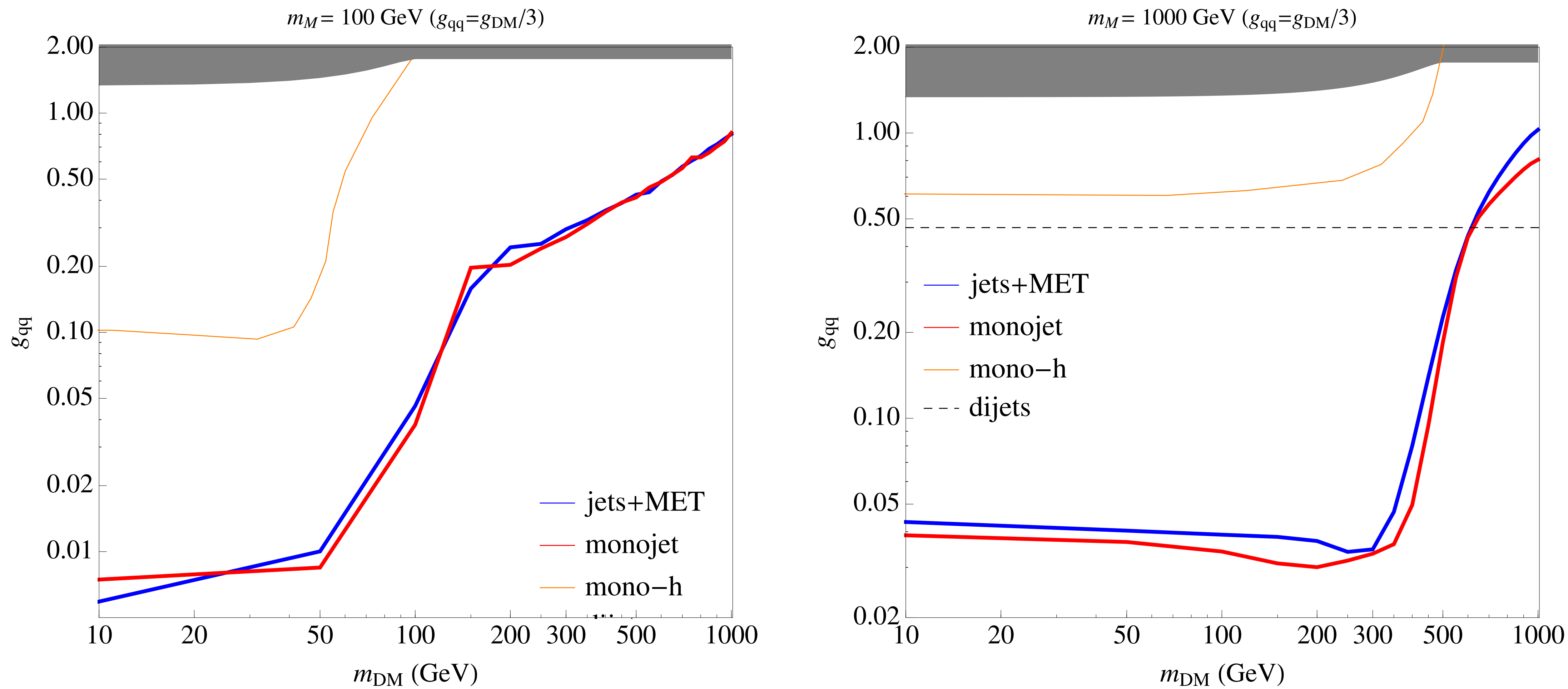
Model	mono-h	mono-Z	direct constraints
Inelastic DM			
2HDM			
s-channel vector			
s-channel scalar			

constraints from direct searches

Model	mono-h	mono-Z	direct constraints	
Inelastic DM				**dijet**
2HDM				**dijet**
s-channel vector				**dijet**
s-channel scalar				**monojet**

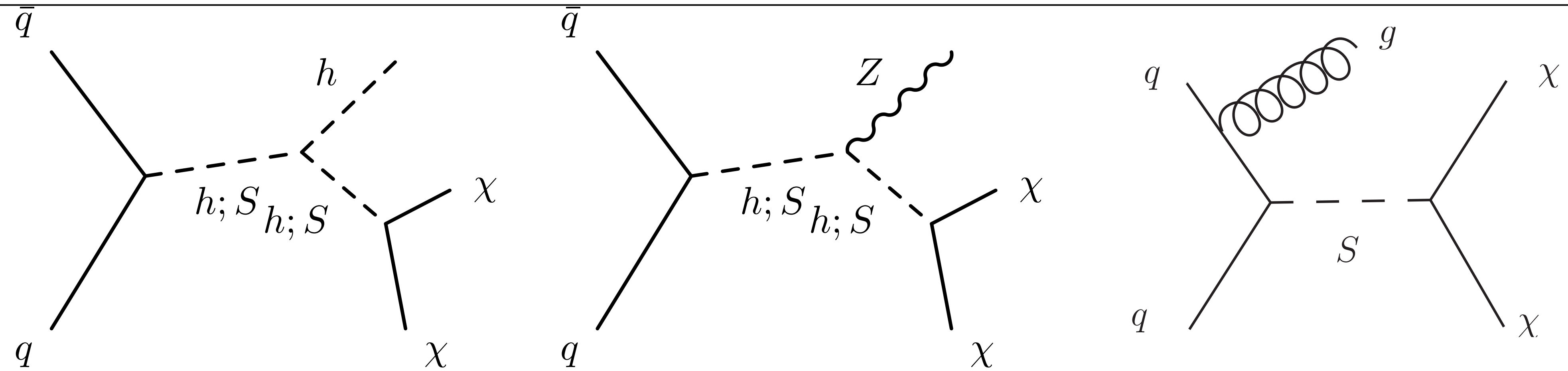
s-channel vector





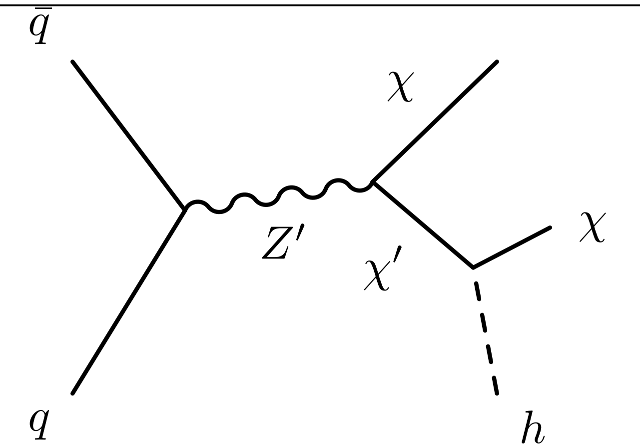
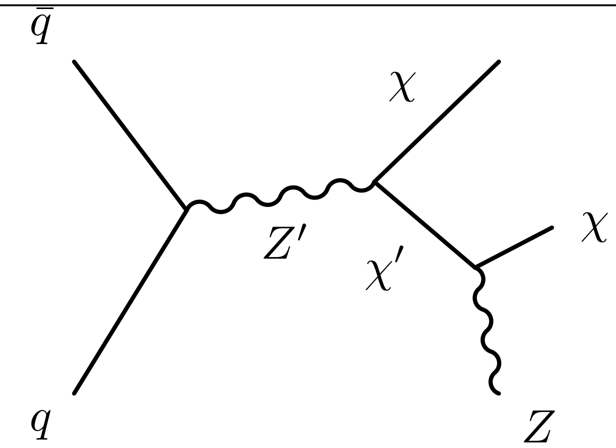
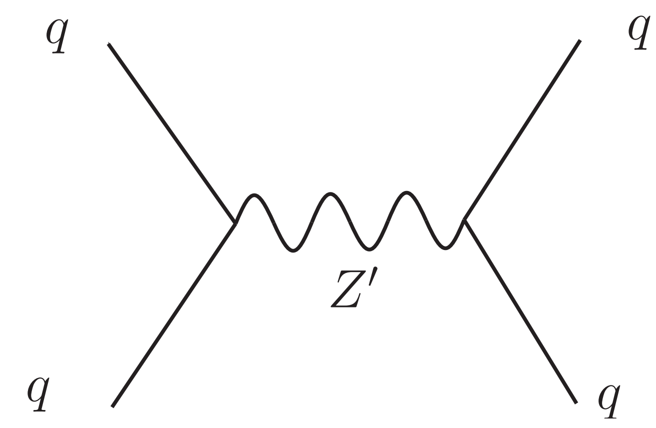
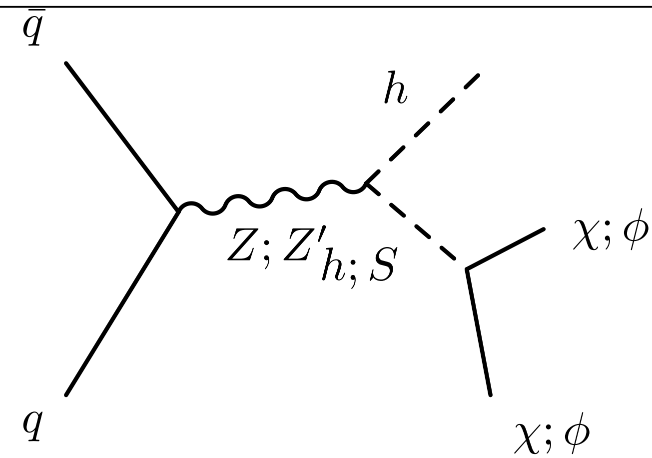
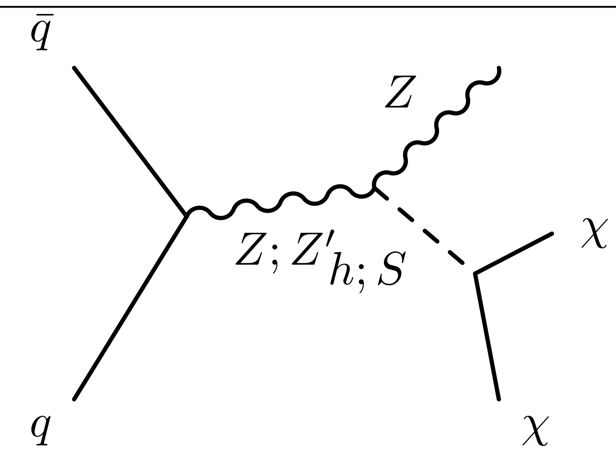
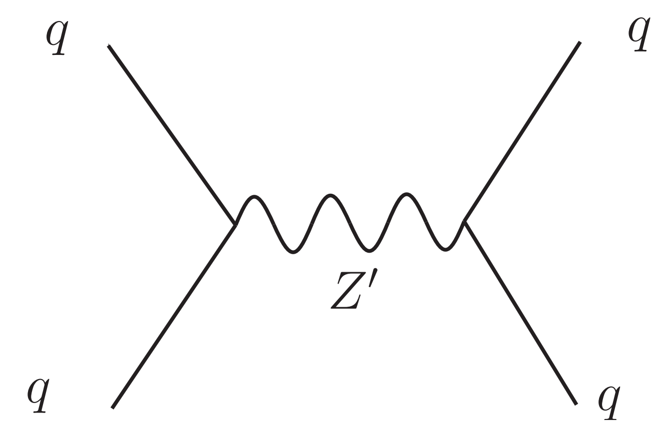
Monojet,dijet, jet + MET searches are more powerful than mono-Higgs

s-channel scalar



no searches can constrain the couplings
up to perturbative level

see also [Carpenter et al. '13]

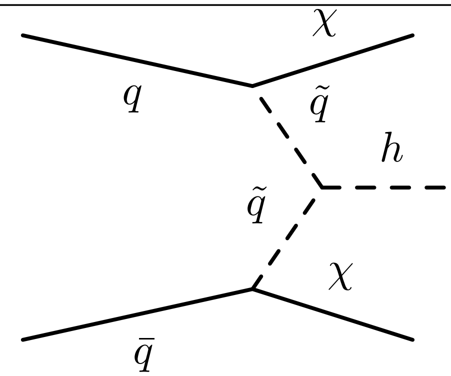
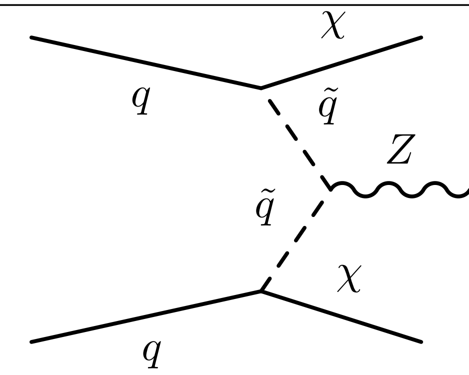
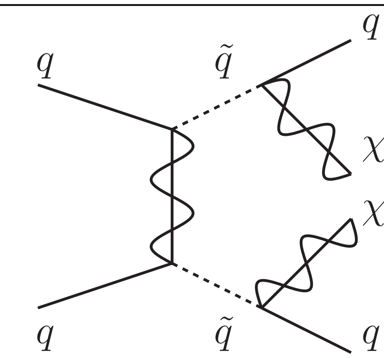
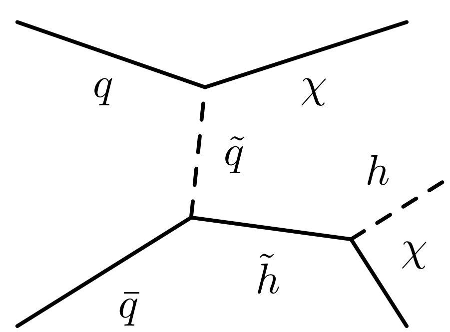
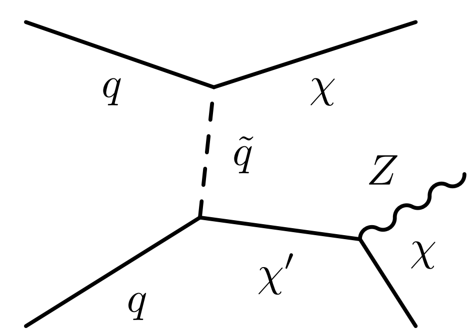
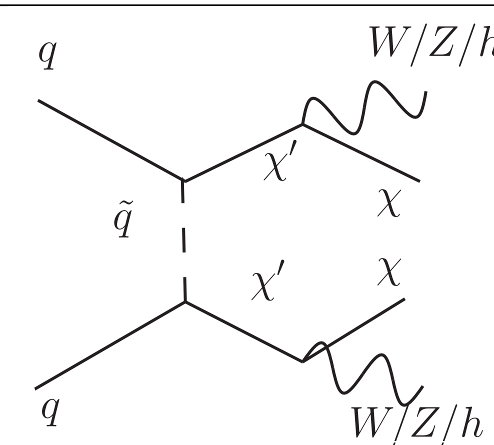
Model	mono-h	mono-Z	direct constraints
Inelastic DM			
2HDM			

mono-*h* and mono-*Z* can overcome dijet constraints -> good benchmark models for mono-*h* and mono-*Z*

(will discuss more later if time allows)

mono-X simplified models II

t-channel

Model	mono-h	mono-Z	direct constraints
Squarks/sbottoms			
Inelastic squark			

mono-*h* and mono-*Z* are weak compared to squark searches (jets + MET etc.)

We have studied a comprehensive list of mono-X simplified models.
The following are the benchmark models giving dominant mono-X signals at the LHC

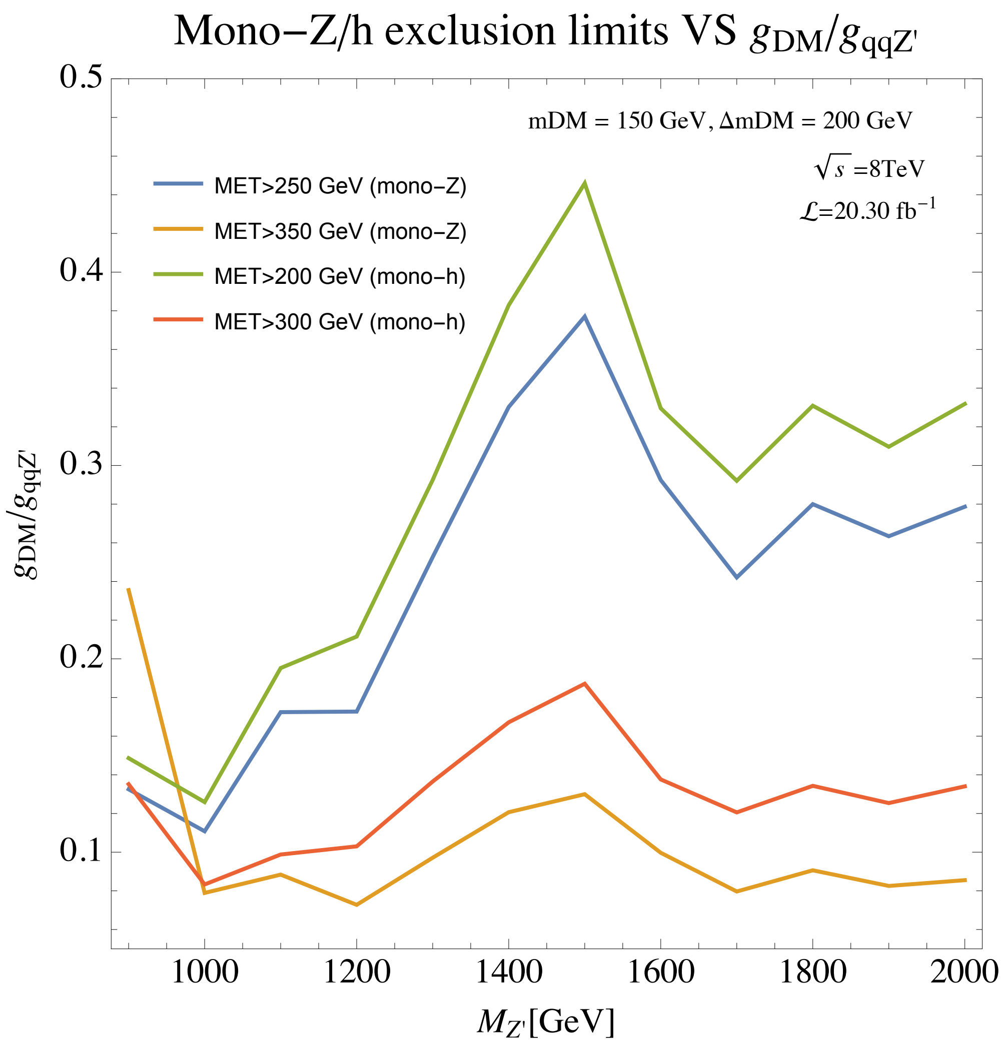
Search	Model where it matters
mono-h	Inelastic DM; 2HDM
mono-z	Inelastic DM; 2HDM
mono-jet	squark mediated production, compressed spectrum; Z'
mono-b	sbottom mediated production, compressed spectrum
mono-t	RPV stops; non-resonant mono-t

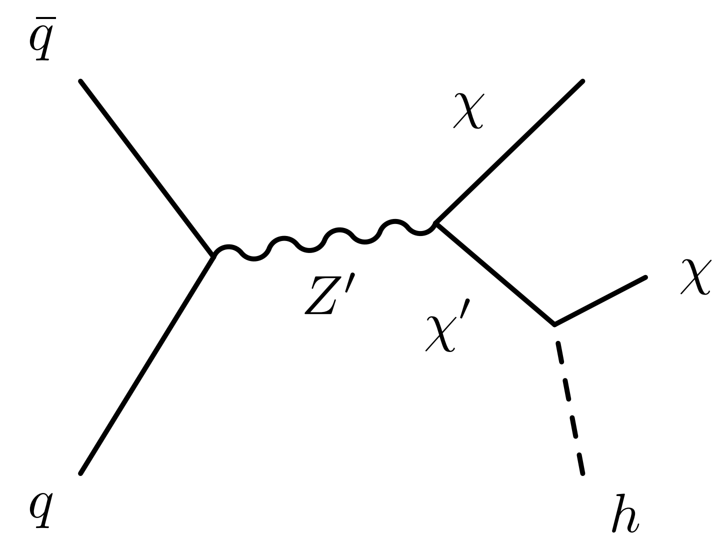
TABLE I: Summary of results: for each mono-X search we list the models where the analysis can exclude part of the parameter space not already ruled out by some other search.

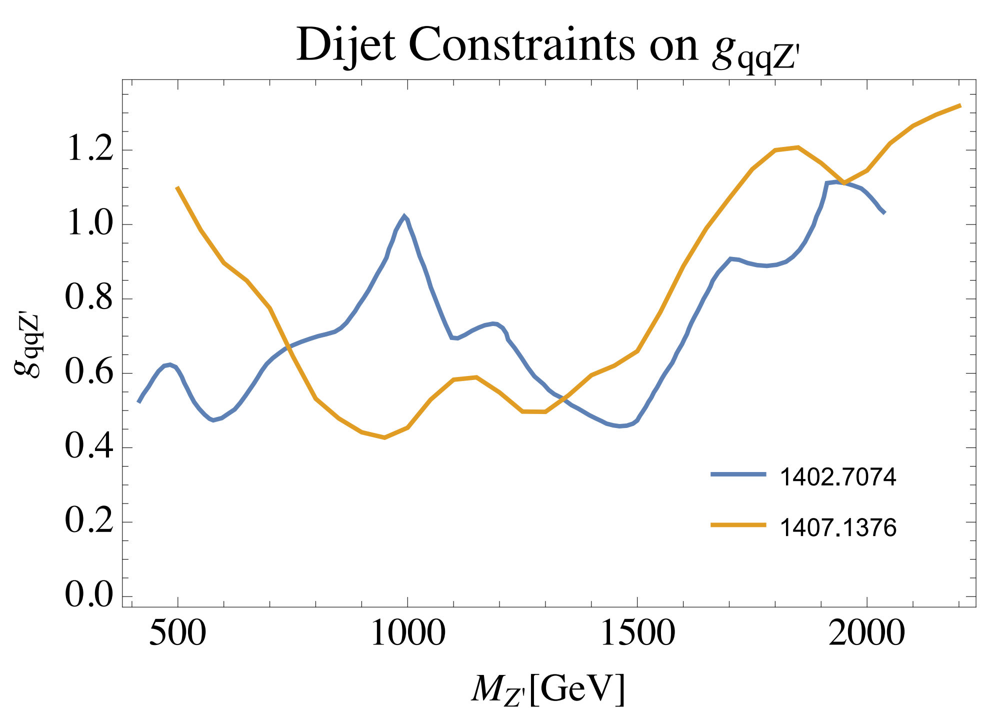
Thank you!

Backups

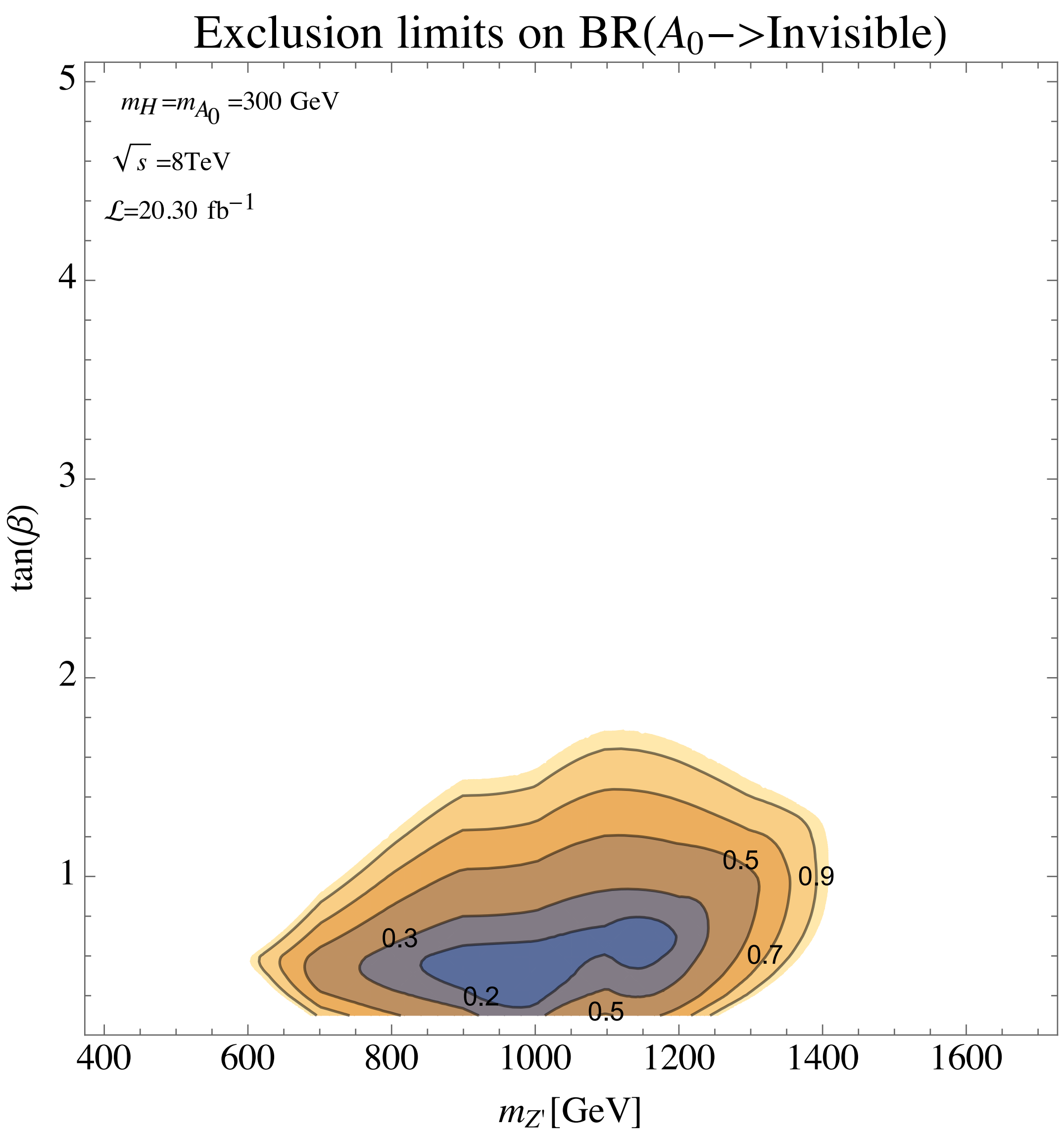
Inelastic DM



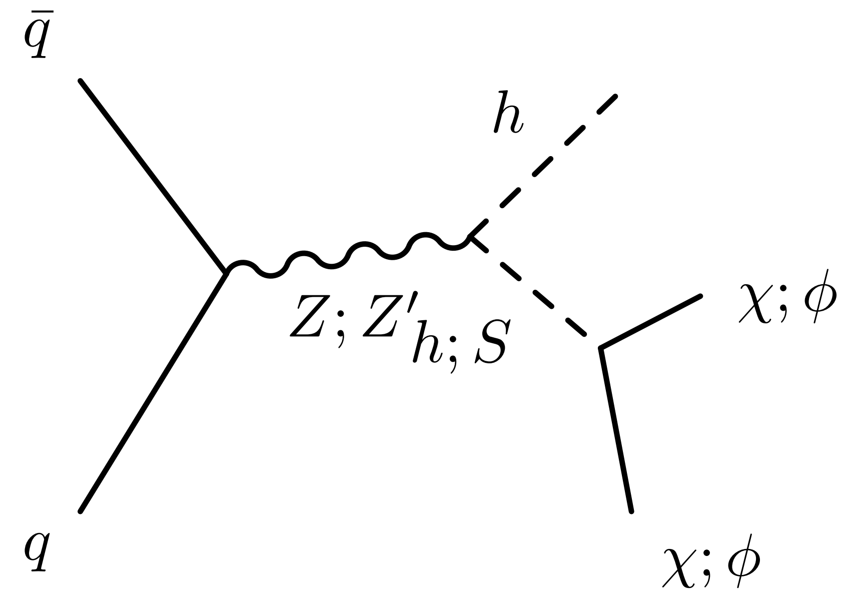


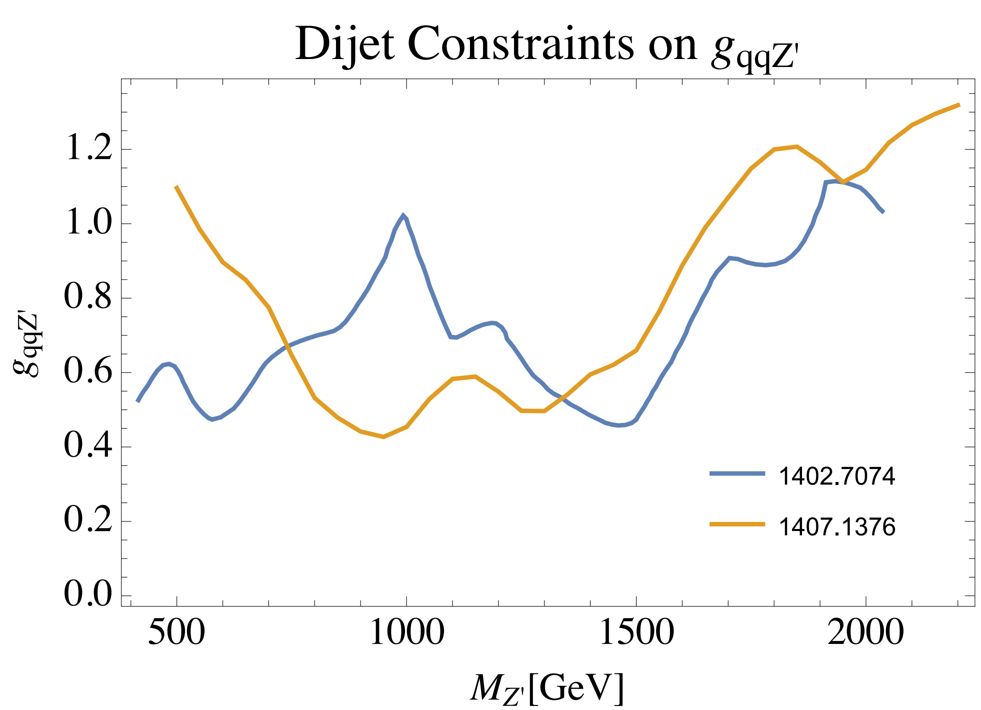


Dijet constraint



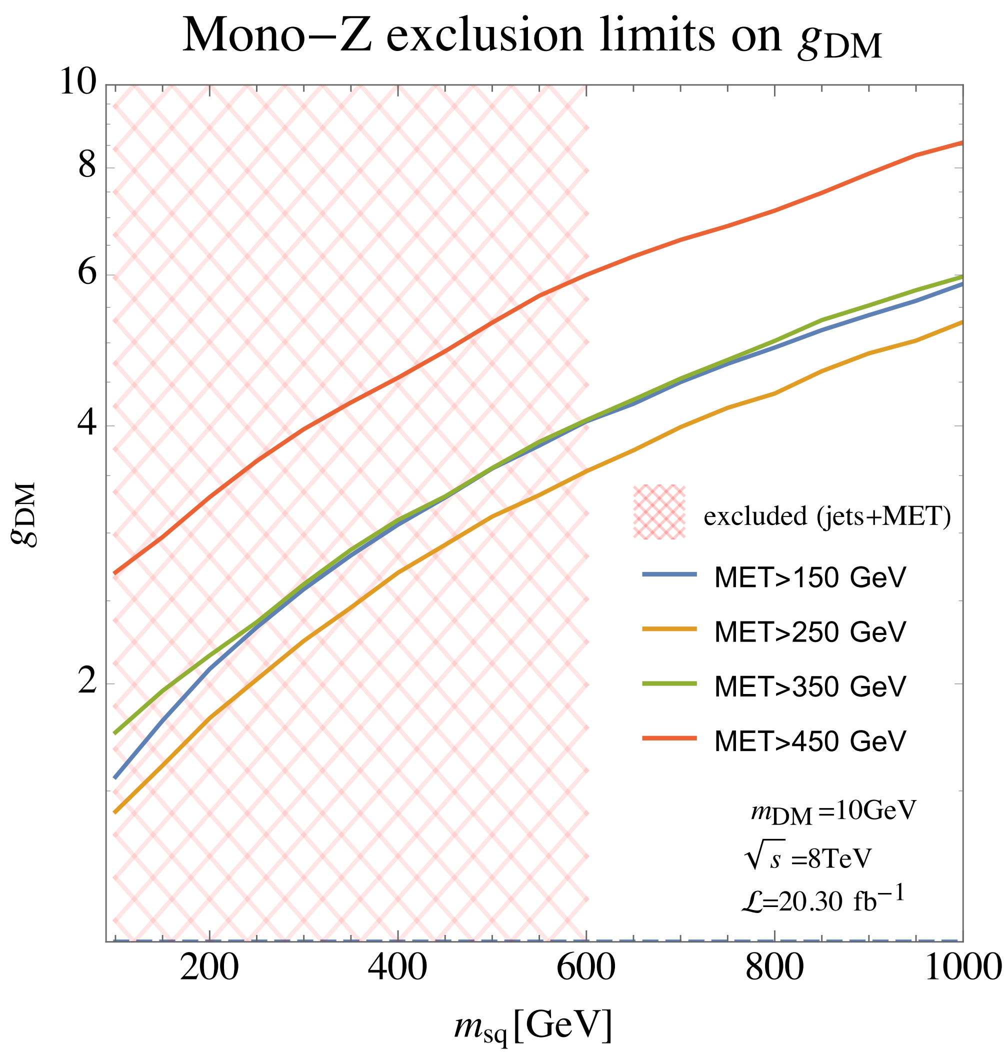
2HDM

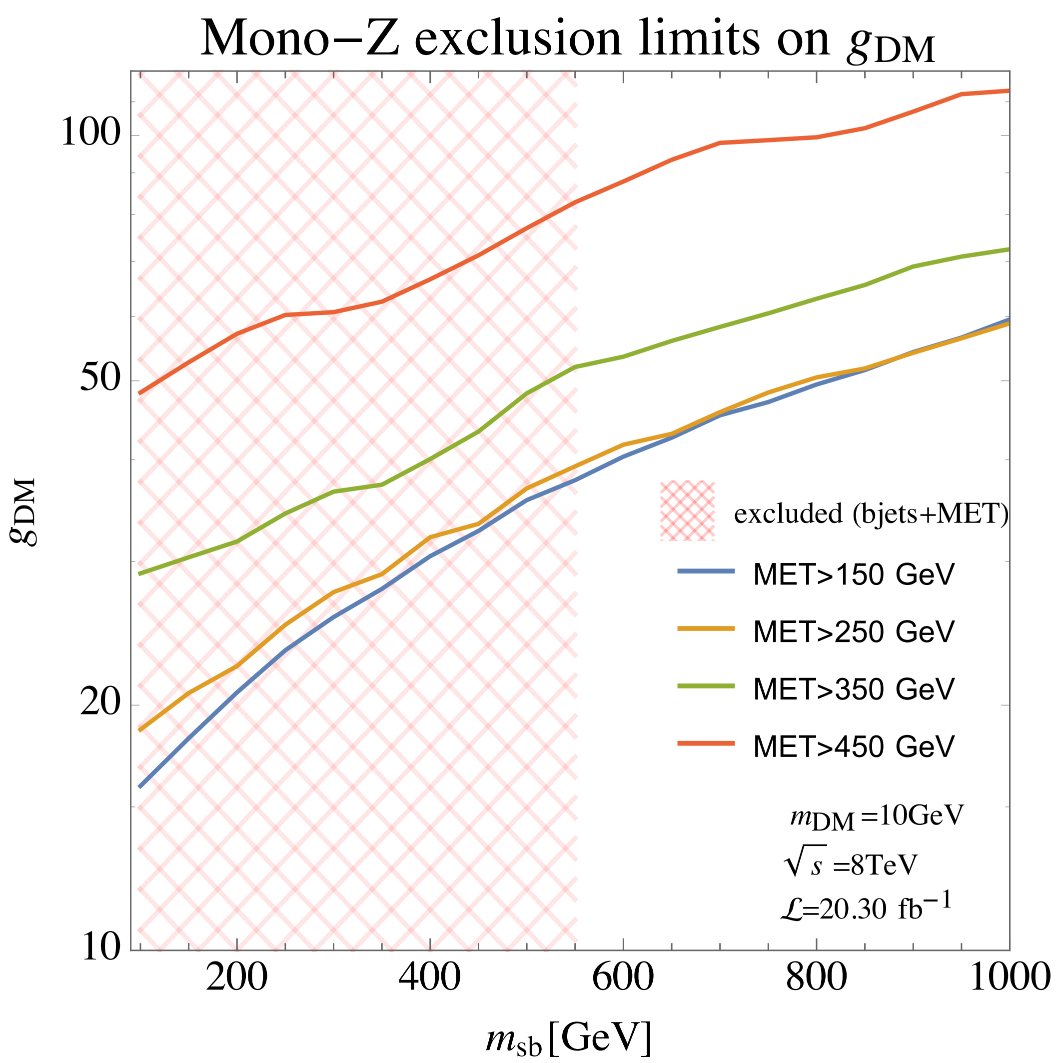




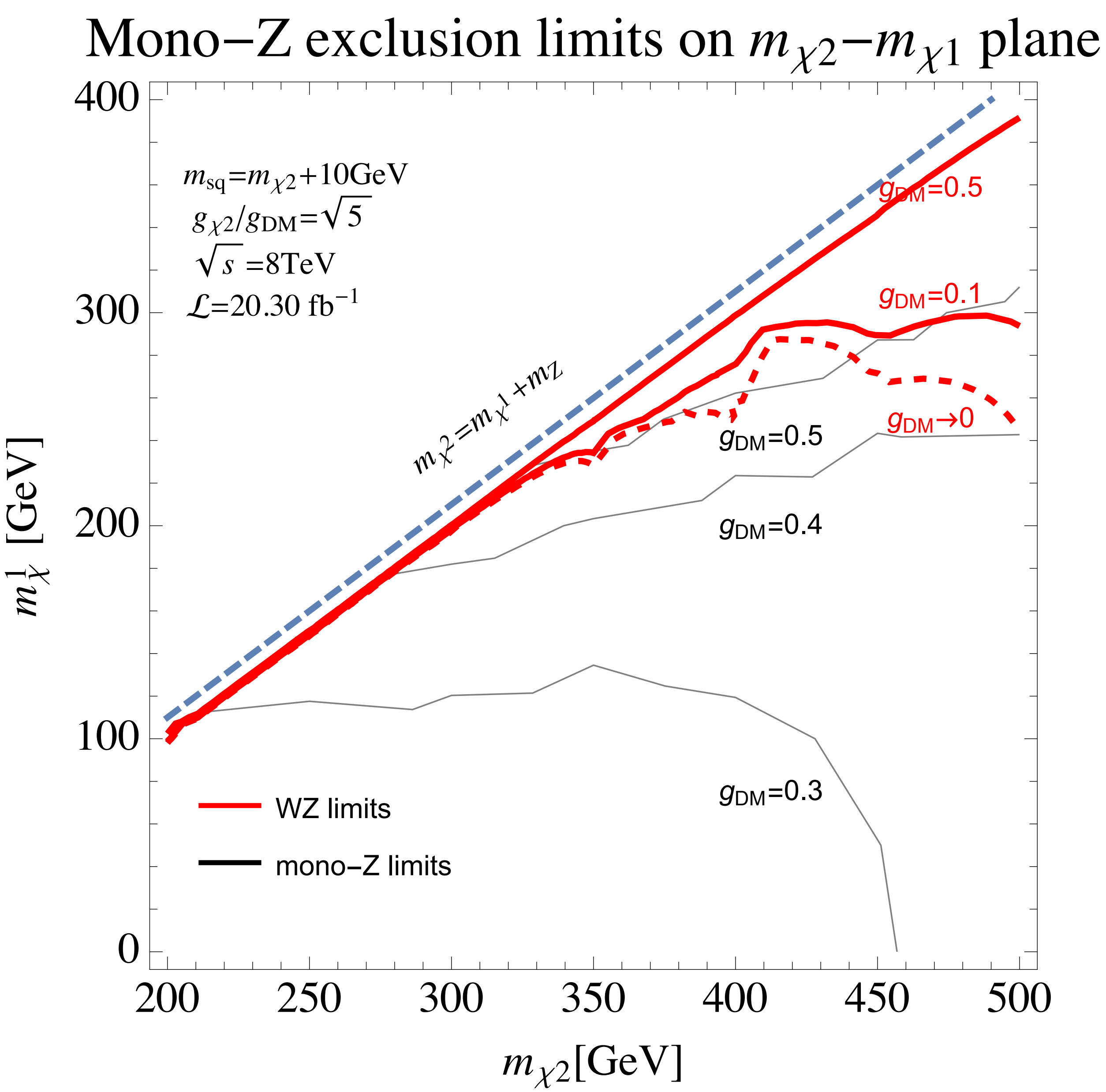
Dijet constraint

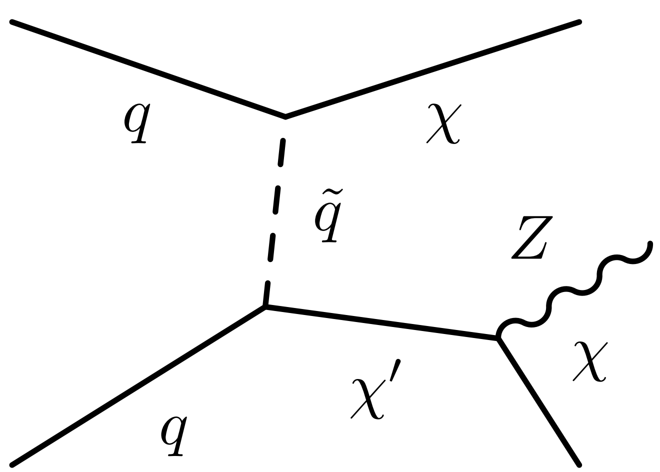
mono-Z for squark/sbottom model





mono-Z
(inelastic squark)





sbottom model (mono-b & b-jets + MET)