



Discussion on Monte Carlo tools for DM@LHC

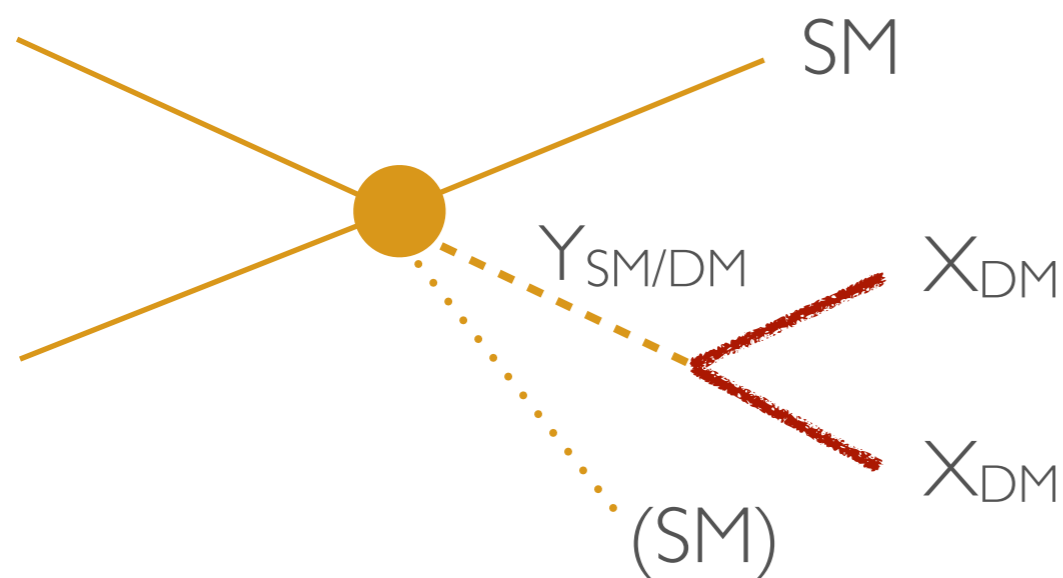
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Outline

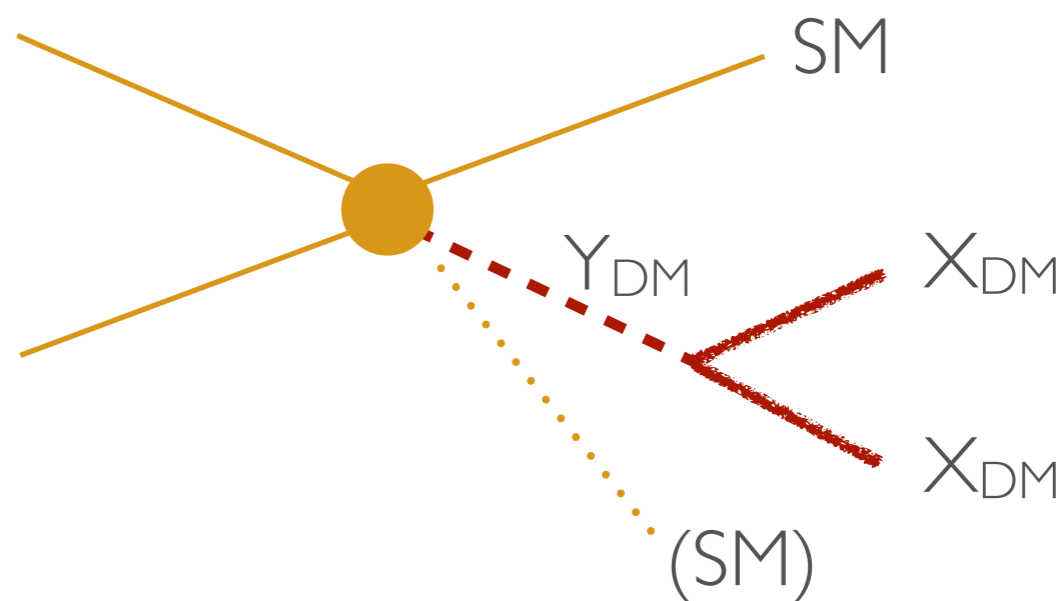
- s-channel simplified models : status and directions
- t-channel simplified models : status and directions
- What more is needed?
- Towards a DM-MC-wishlist

Search for DM at the LHC: s-channel mediators

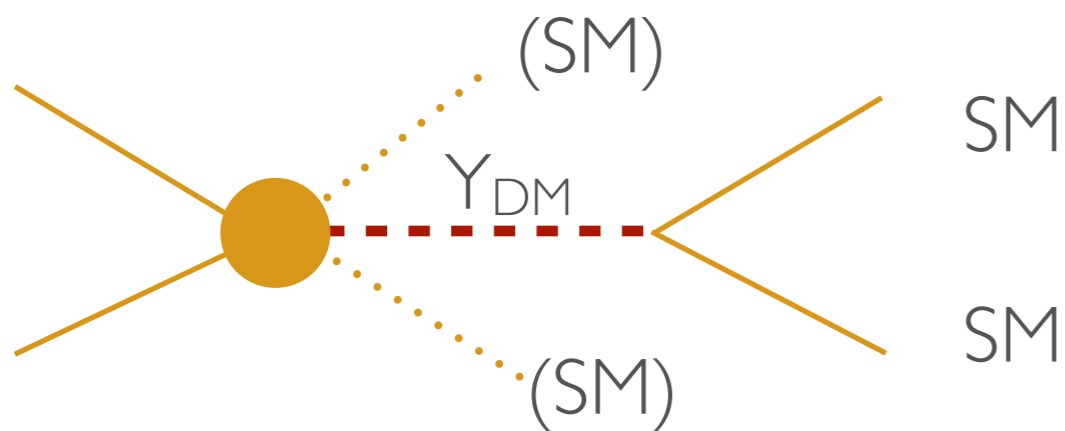
Portals



MET+SM



Direct mediator search



$Y_{SM/DM}$ = mediators mixing with SM Z or H
 $\dots (SM)$ = other SM particles, such as QCD radiation

s-channel spin-0 mediators

spin-0 (A/P)	MCFM	POWHEG-BOX	MG5aMC
$X_{DM} X_{DM} + \text{jets}$	1-jet at NLO "HEFT"	1-jet at NLO+PS	NLO+PS and FxFx in the HEFT. MEPS@LO loop induced [Backovic et al., 2015]
$X_{DM} X_{DM} + \gamma$	NLO (light quarks)		NLO+PS and FxFx in the HEFT. MEPS@LO loop induced
$X_{DM} X_{DM} + Z \text{ or } W$			NLO+PS and FxFx in the HEFT. MEPS@LO loop induced [M. Neubert, J. Wang, C. Zhang, 2015]
$X_{DM} X_{DM} + \text{heavy quarks}$			NLO+PS [Backovic et al., 2015]

s-channel spin-1 mediators

spin-1 (A/P)	MCFM	POWHEG-BOX	MG5aMC
$X_{DM} X_{DM} + \text{jets}$	1-jet at NLO	1-jet at NLO+PS	NLO+PS and FxFx <small>[Backovic et al., 2015]</small>
$X_{DM} X_{DM} + \gamma$ (+jets)	NLO		NLO+PS (and FxFx)
$X_{DM} X_{DM} + Z$ or W (+jets)			NLO+PS (and FxFx) <small>[M. Neubert, J. Wang, C. Zhang, 2015]</small>
$X_{DM} X_{DM} + \text{heavy quarks}$			NLO+PS <small>[Backovic et al., 2015]</small>

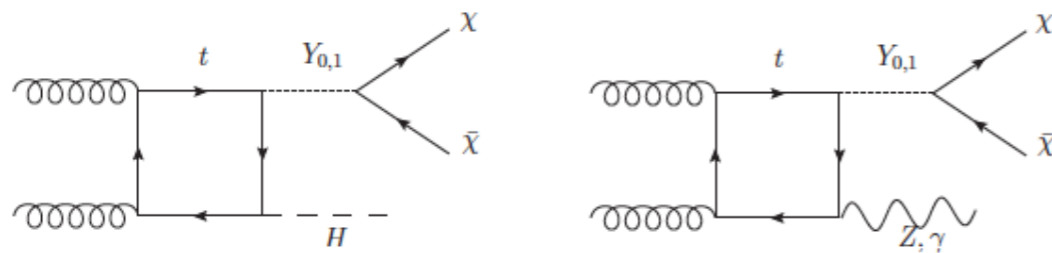
s-channel spin-2 mediator

[Das, Degrande, Hirschi, Shao, 2016]

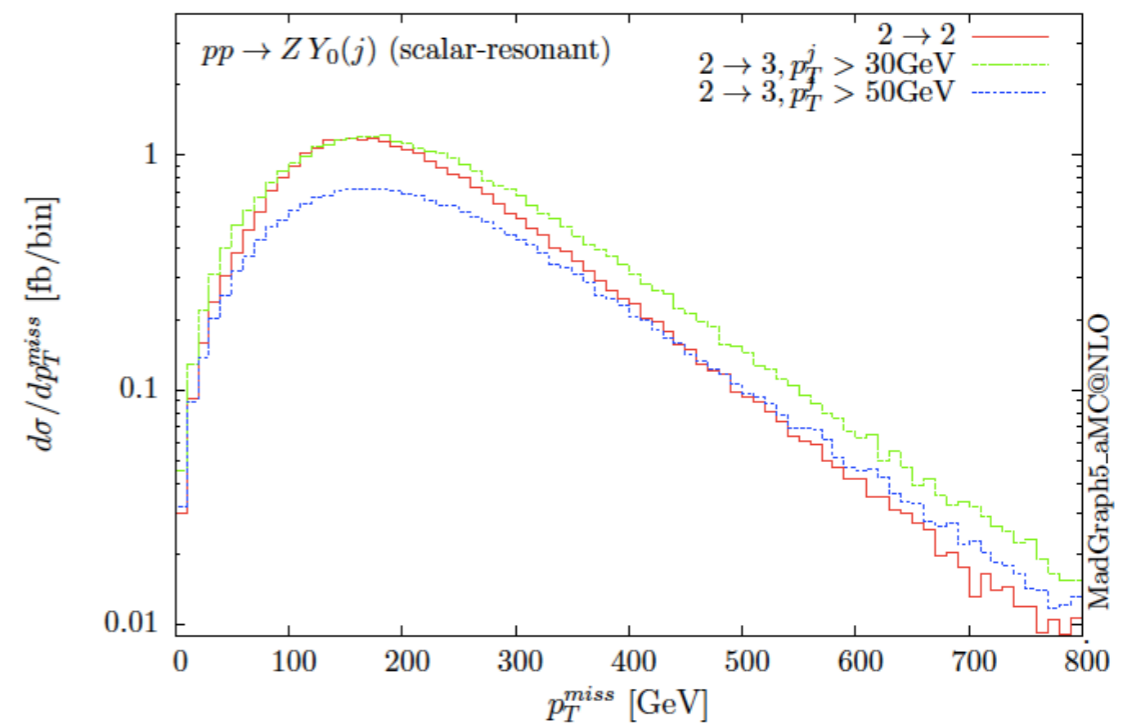
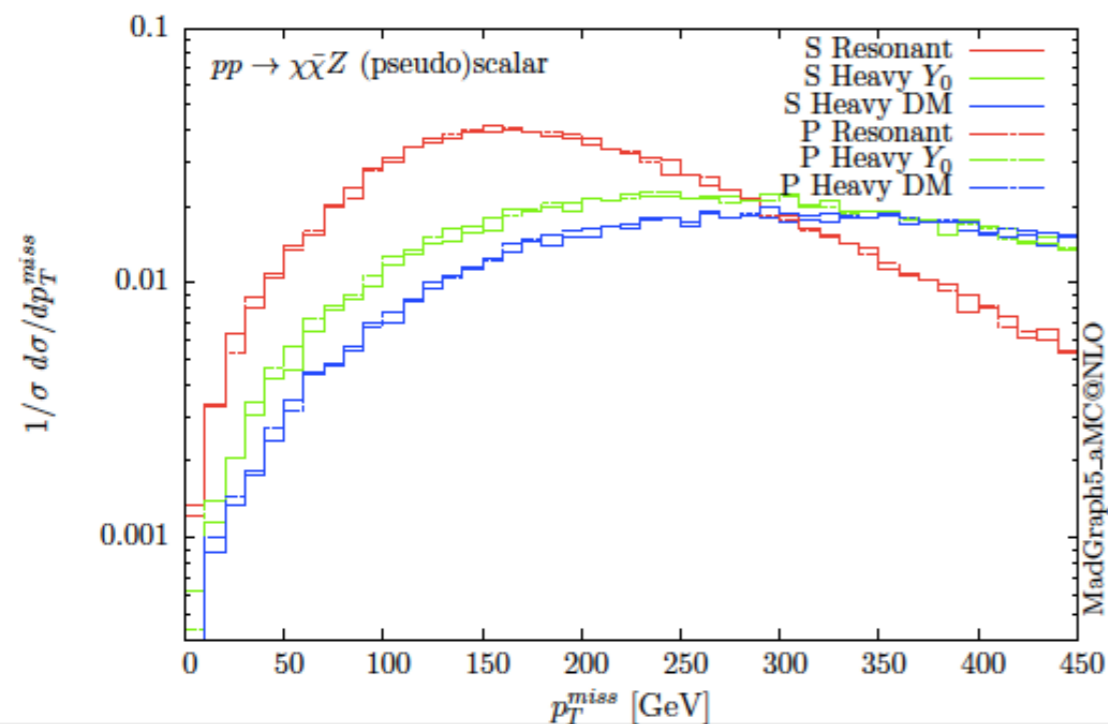
spin-2	MG5aMC
$X_{DM} X_{DM} + 0, 1, (2) \text{ jets}$	NLO+PS (and FxFx)
$X_{DM} X_{DM} + \gamma$	NLO+PS
$X_{DM} X_{DM} + Z$	NLO+PS
$X_{DM} X_{DM} + W^{+-}$	NLO+PS
$X_{DM} X_{DM} + t \bar{t}$	NLO+PS

Loop-induced $X_{\text{DM}} X_{\text{DM}} + (H, Z, \gamma)$

[Haisch et al., 2013] [Fox and Williams, 2013] [Haisch et al., 2014] [Harris et al. 2014] [Haisch and Re, 2015]
 [Mattelaer and Vryonidou, 2015]



Process	S	P	V	A
mono-Z	✓	✓	✓	✓
mono-photon	✗	✗	✓	✗
mono-Higgs	✓	✓	✗	✓



Scalar mediator coupled to the top leads to $X_{\text{DM}} X_{\text{DM}} + H, Z$ or γ . Selection rules are found. Very different shape of E_{miss} depending on the associated production. The effect of extra gluon radiation on the shape E_{miss} can also be studied.

Questions

- What else is needed?
- Does the nature of the DM matter at the LHC? Dirac and Scalar is available? Should we have Majorana? What about vector dark matter?
- Higgs portals (scalar, vector, fermion, tensor...)? see for example [[Endo and Takaesu, 2014](#)]

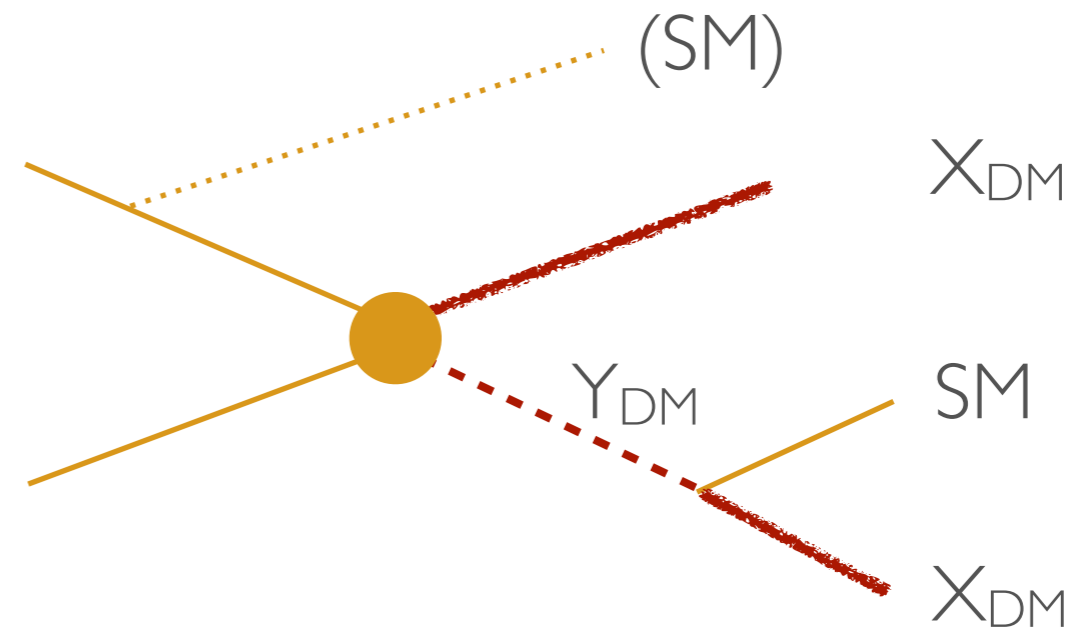
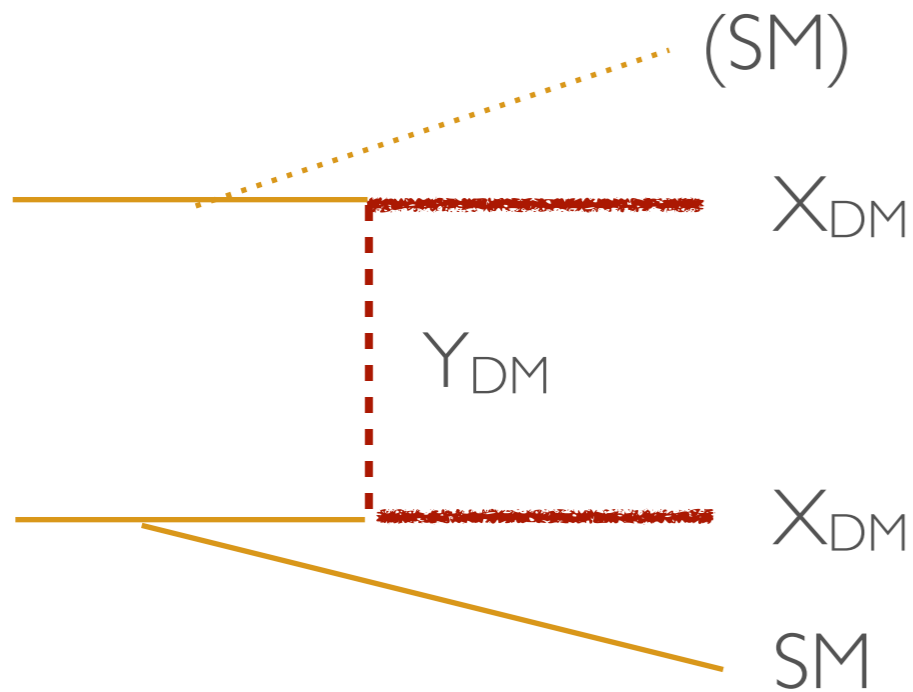
$$\mathcal{L}_S = \frac{1}{2} \partial^\mu S \partial_\mu S - \frac{1}{2} M_S^2 S^2 - \lambda_S S^4 - c_S |H|^2 S^2,$$

$$\mathcal{L}_V = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} M_V^2 V^\mu V_\mu - \lambda_V (V^\mu V_\mu)^2 + c_V |H|^2 V^\mu V_\mu,$$

$$\begin{aligned} \mathcal{L}_B = & \frac{1}{4} \partial_\lambda B^{\mu\nu} \partial^\lambda B_{\mu\nu} - \frac{1}{2} \partial^\mu B_{\mu\nu} \partial_\rho B^{\rho\nu} - \frac{1}{4} M_B^2 B^{\mu\nu} B_{\mu\nu} \\ & - \lambda_B B_{\mu\nu} B^{\nu\lambda} B_{\lambda\rho} B^{\rho\mu} - c_B |H|^2 B^{\mu\nu} B_{\mu\nu}, \end{aligned}$$

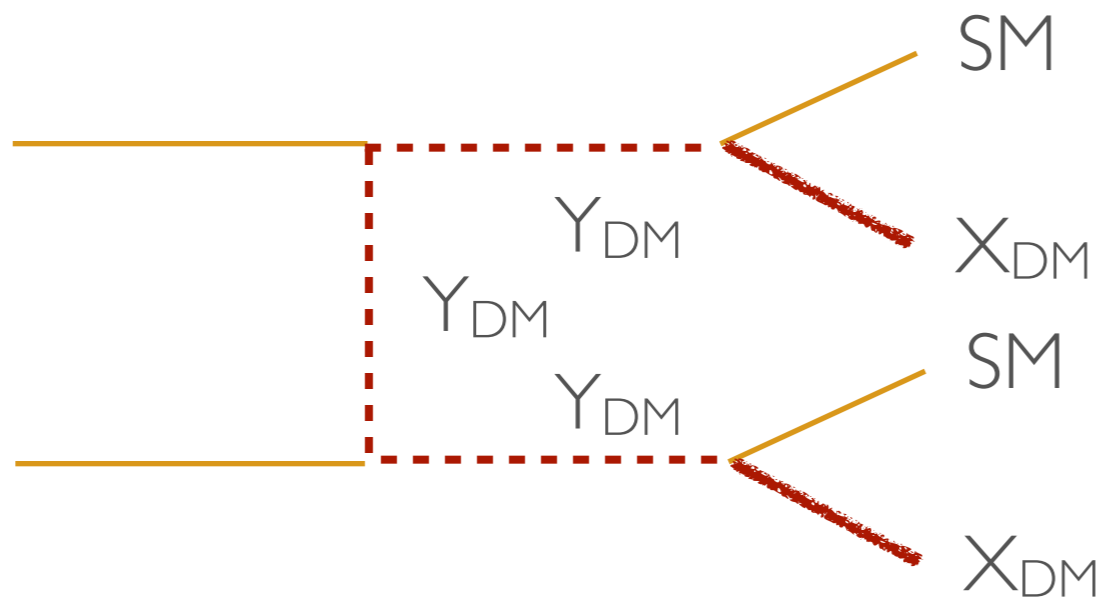
- Less simplified models...set of minimal UV-consistent models? Which ones?

Search for DM at the LHC: t-channel mediators



Rules of the thumb for t-channel-mediator phenomenology at the LHC:

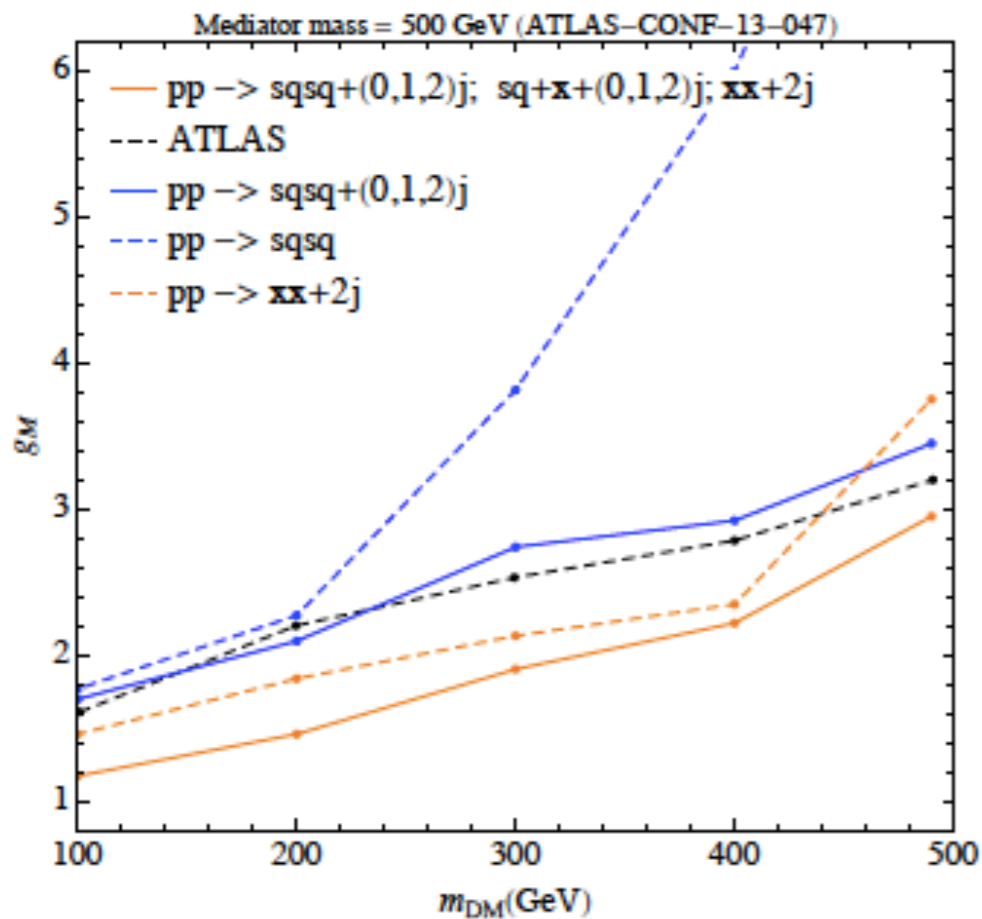
- Search for DM and mediators are normally entangled.
- SUSY-like searches.
- jets+mET golden channel



Search for DM at the LHC: t-channel mediators

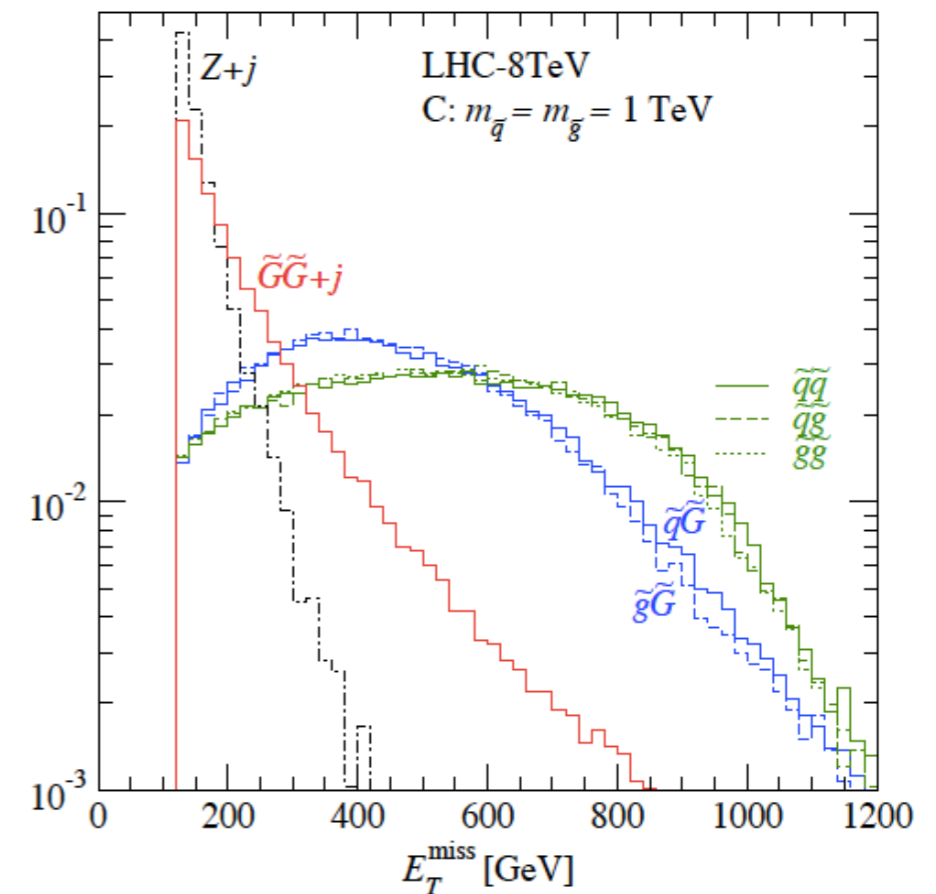
[Alwall et al., 2008]

[Papucci et al. 2014]



1. $pp \rightarrow \tilde{q}\tilde{q}^\dagger + (0, 1, 2)j$;
2. $pp \rightarrow \chi\tilde{q}^\dagger, \bar{\chi}\tilde{q} + (0, 1, 2)j$ with no mass-shell integration for internal squark lines;
3. $pp \rightarrow \chi\bar{\chi} + (0, 1, 2)j$ with no mass-shell integration for internal squark lines.

[De Aquino et al., 2012] [Martini et al., 2015]



$$pp(q\bar{q}, qg, gg) \rightarrow \tilde{G}\tilde{G}j,$$

$$pp \rightarrow \tilde{q}\tilde{G}, \tilde{g}\tilde{G} \rightarrow \tilde{G}\tilde{G}j,$$

$$pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \rightarrow \tilde{G}\tilde{G}jj.$$

Questions

[De Simone and Jacques, 1603.08002]

- Predictions are currently LO (ME+PS) in QCD. Should we improve?
- All simplified models are SUSY-like
What else?
- Is there any “urgent” request?

Mediator spin	Channel	DM spin	Model Name	Discussed in Section
0	s	0	0s0	3.2.1
0	s	$\frac{1}{2}$	0s $\frac{1}{2}$	3.2.2
0	t	0	0t0	3.2.3
0	t	$\frac{1}{2}$	0t $\frac{1}{2}$	3.2.4
$\frac{1}{2}$	t	0	$\frac{1}{2}$ t0	3.3.1
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}$ t $\frac{1}{2}$	3.3.2
1	s	0	1s0	3.4.1
1	s	$\frac{1}{2}$	1s $\frac{1}{2}$	3.4.2
1	t	$\frac{1}{2}$	1t $\frac{1}{2}$	3.4.3

Table 9: Simplified models for scalar and fermion DM.

Towards a DM-MC-wishlist

- What are the most important collider predictions for which an accurate prediction is missing?
- What are the most motivated and urgent simplified model implementations in MC still missing?
- Are there final state signatures which need special care (like mono-top)?
- What about more UV-complete models? Can we make an “ordered” list?
- What about combining LHC results with non-collider constrains? Complete/easy-to-use frameworks (see e.g. [Arina et al., 2016])?
- ...