A universal framework for *t*-channel dark matter models

Benjamin Fuks
(LPTHE / Sorbonne Université)

With Chiara Arina & Luca Mantani - 2001.05024 [hep-ph] (EPJC`20)

Phenomenology 2020 Symposium

Virtually @ PITT, 4 May 2020

Outline

1. A short overview of the framework
2. Illustrative example: Dirac dark matter
3. Summary

Simplified dark matter models @ LHC

✦ Generic simplified models for dark matter

✤ Minimality in action: SM + 1 DM candidate + 1 mediator

✤ DM (X) is stable

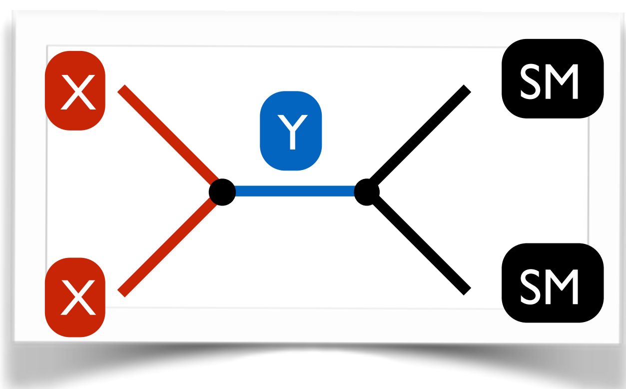
→ Odd under some $\mathbb{Z}_2$ discrete symmetry

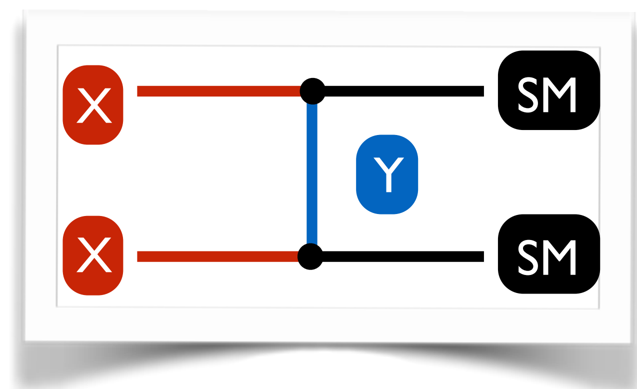
→ SM states even

✤ The mediator (Y) connects DM and quarks/gluons

★ $\mathbb{Z}_2$-even: *s*-channel models → colour singlet and electrically neutral

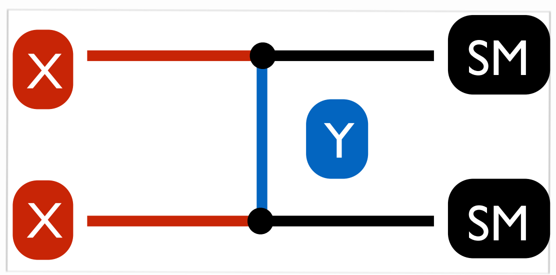
★ $\mathbb{Z}_2$-odd: *t*-channel models → colour triplet and electrically charged





A generic t-channel DM

✦ A generic t-channel DM modelling



Many parameters / spin combination
→ simplifications/restrictions

- ✤ 2 spins: J_X, J_Y
- ✤ 13 masses:
  - ★ 1 DM mass: m_X
  - ★ 12 mediator masses (SM = Q_L, u_R, d_R)
- ✤ 9 couplings
  - ★ 3 vectors in flavour space
  - ★ SM = Q_L, u_R, d_R

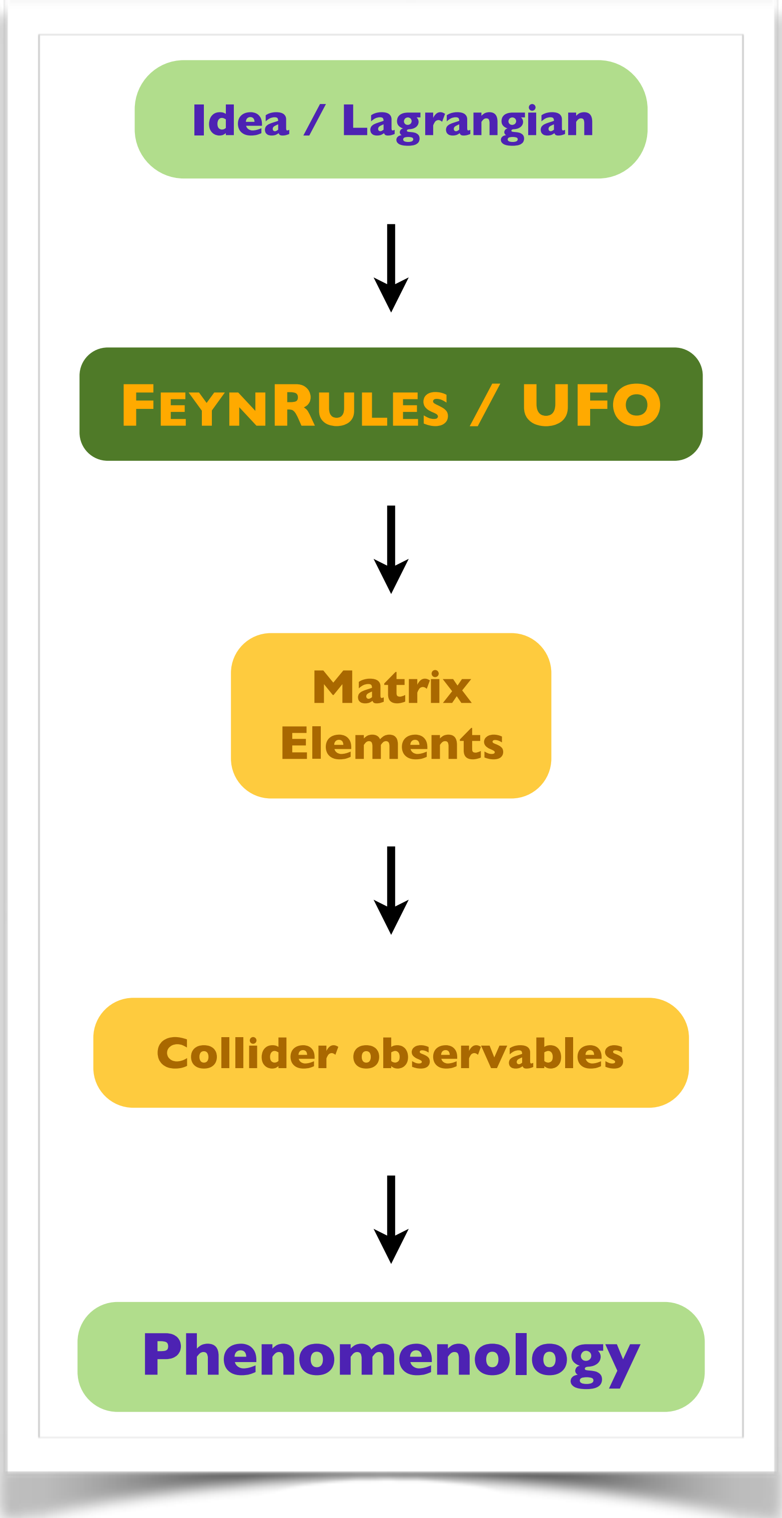
✦ Spin options

X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{S}$	0	yes	ψ_Q, ψ_u, ψ_d	1/2
S	0	no		
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
$\tilde{V}_\mu$	1	yes	ψ_Q, ψ_u, ψ_d	1/2
V_μ	1	no		

- ✤ Dark matter
  - ★ Spin 0, 1/2 and 1
  - ★ Majorana or not
- ✤ 12 mediators
  - ★ Spin 0 or 1/2 (no spin 1)
  - ★ Independent couplings to all gauge eigenstates

A comprehensive approach to new physics calculations

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]



✦ Model building: from Lagrangian to tools

- ✤ FEYNRULES ⊕ MOGRE ⊕ NLOCT → UFO @ NLO
- ✤ General on-shell renormalisation scheme

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

✦ Hard scattering

- ✤ Feynman diagram, matrix elements
- ✤ MG5aMC/MadDM → cosmology/colliders at LO/NLO

[Alwall *et al.* (JHEP'14)]
[Ambrogi *et al.* (PDU'19)]

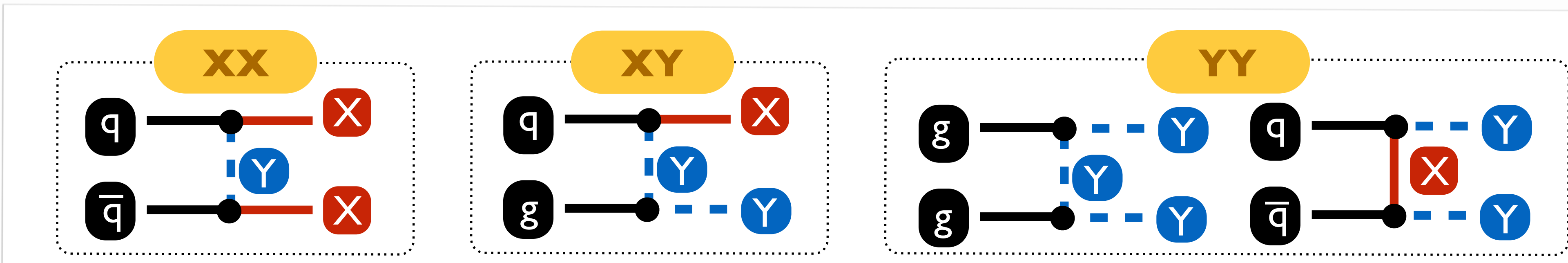
✦ BSM phenomenology @ colliders with MG5_aMC

- ✤ Matching matrix elements with parton showers
- ✤ Simplified treatment of the resonances (MADSTR)

[Alwall *et al.* (JHEP'14)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

DM production at colliders: generalities

✦ Three classes of processes → jets generated from ISR or mediator decays



✤ The signal is less naive than from considering XX production only

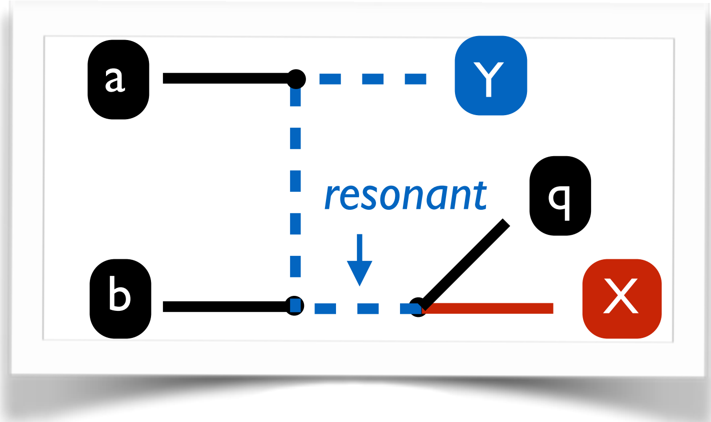
- ★ DM pair production
- ★ DM/mediator associated production (+ mediator decays into DM+jet)
- ★ Mediator pair production (+ mediator decays into DM+jet)

✤ Mediator pair-production: *t*-channel and QCD contributions

- ★ Model-dependent relative dominance → couplings, masses
- ★ Mixed order situation → to be simulated separately
- ★ Problem of the interference → re-weighted LO simulations

Resonance subtraction: generalities

✦ NLO computations are not trivial



✤ Overlap
- ★ YY @ LO ⊗ Y → Xq decay
- ★ YX @ NLO (real emission)

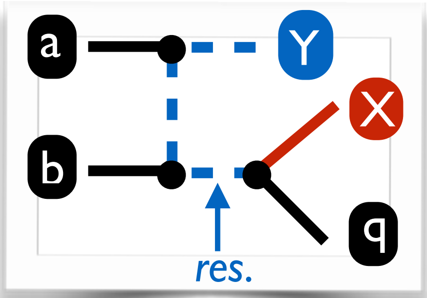
✤ Possible (huge) enhancement w.r.t. LO (if YY dominates over XY)
- ★ Spoiling the perturbative expansion for the original process

✤ All three subprocesses need to be considered separately to avoid double counting
- ★ Resonances must be subtracted

Resonance treatment in practice

✦ Matrix element: resonant and non-resonant pieces

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\rm non-res.)}\right|^2 + 2\Re\Big(\mathcal{A}^{(\rm non-res.)}\mathcal{A}^{(\rm res.)\dagger}\Big) + \left|\mathcal{A}^{(\rm res.)}\right|^2$$



✦ Diagram removal

$$\left|\mathcal{A}\right|^2 = \left|\mathcal{A}^{(\rm non-res.)}\right|^2 + 2\Re\Big(\mathcal{A}^{(\rm non-res.)}\mathcal{A}^{(\rm res.)\dagger}\Big) + \left|\mathcal{A}^{(\rm res.)}\right|^2$$

- DR: removal of the resonant diagrams
- DR+I: interferences are kept

✦ Projection of the kinematics on the resonance

$$\left|\mathcal{A}^{(\rm res.)}\right|^2 d\Phi \quad\Rightarrow\quad \left|\mathcal{A}^{(\rm res.)}\right|^2 d\Phi - f(m^2)\,\mathbb{P}\Big(\left|\mathcal{A}^{(\rm res.)}\right|^2 d\Phi\Big)$$

★ *t*-channel example: $m = m_{Xq} \sim m_Y$

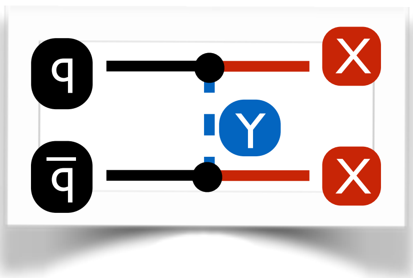
- The projector operator $\mathbb{P}$
  - ★ From an *n*-body kinematics to an $(n\text{-}1) \otimes (1 \to 2)$ kinematics

$$\left|\mathcal{A}^{(\rm res.)}(ab\to XYq)\right|^2 = \left|\mathcal{A}(ab\to YY)\right|^2 \otimes \left|\mathcal{A}(Y\to Xq)\right|^2$$

- The pre-factor f is arbitrary (tends to 1 in the resonant limit)
- DS: Initial-state or final-state reshuffling

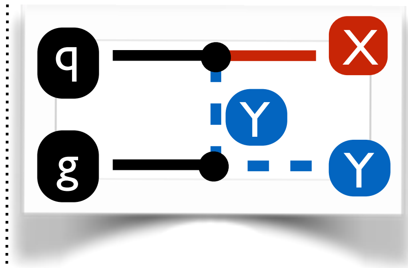
Monojets - a fivefold event generation process

XX @ NLO



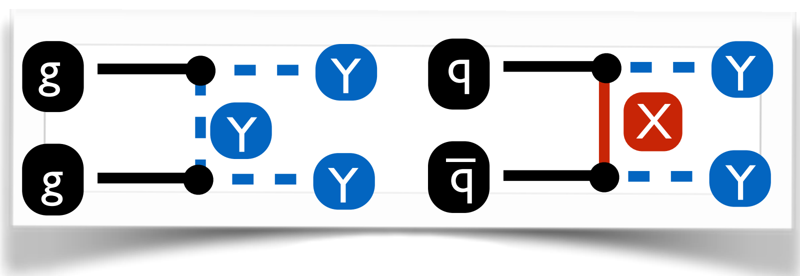
- ★ Jet activity → QCD radiation
- ★ Resonance: XY prod. + decay

XY @ NLO



- ★ Jet activity → QCD radiation
  → mediator decay
- ★ Resonances: YY/XX prod. + decay (benchmark dependent)

YY @ NLO



- ★ Jet activity → QCD radiation and mediator decay
- ★ Resonance: YX production + (off-shell) decay
- ★ 2 interfering channels (from qqbar initials states)

Example: Dirac dark matter @ LHC

✦ Dirac DM couplings to the right-handed up quark

X (DM)	Spin	Self-conj.	Y (med.)	Spin
χ	1/2	no	φ_{u_1}	0

$$\mathcal{L}_{\texttt{X\_uR}}(X) = \Big[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\Big]$$

- ✤ Benchmark BM1: m_X = 150 GeV, m_Y = 500 GeV, λ=1
- ✤ Benchmark BM2: m_X = 150 GeV, m_Y = 1000 GeV, λ=1
- ✤ Large DM-mediator coupling

✦ Total rates

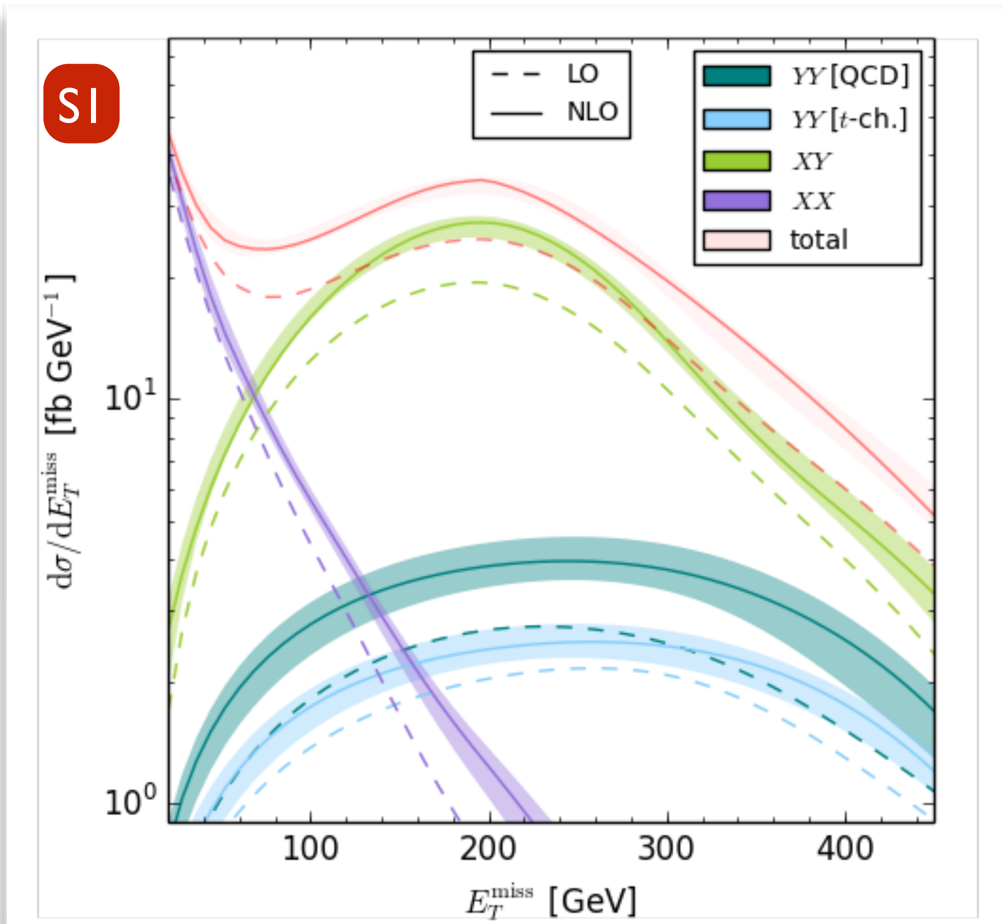
	Scen.	XX [fb]	XY [fb]	YY (total) [fb]	YY (QCD) [fb]	YY (t-channel) [fb]
LO	**S1**	$775.3^{+0.4\%}_{-0.8\%} \pm 1.9\%$	$1617^{+16.5\%}_{-13.4\%} \pm 1.0\%$	$473.5^{+23.6\%}_{-16.9\%} \pm 3.0\%$	$324.2^{+34.2\%}_{-23.8\%} \pm 3.4\%$	$261.5^{+7.1\%}_{-6.3\%} \pm 2.5\%$
LO	**S2**	$122.0^{+1.8\%}_{-2.0\%} \pm 1.9\%$	$74.1^{+20.3\%}_{-15.8\%} \pm 1.2\%$	$7.452^{+19.8\%}_{-14.5\%} \pm 5.6\%$	$3.545^{+37.3\%}_{-25.4\%} \pm 7.2\%$	$6.939^{+11.1\%}_{-9.4\%} \pm 5.0\%$
NLO	**S1**	$929.8^{+1.9\%}_{-1.3\%} \pm 1.9\%$	$2212^{+5.9\%}_{-6.3\%} \pm 1.0\%$	$648.4^{+8.0\%}_{-9.2\%} \pm 3.1\%$	$484.7^{+10.7\%}_{-12.4\%} \pm 3.4\%$	$314.1^{+2.6\%}_{-2.6\%} \pm 2.5\%$
NLO	**S2**	$139.1^{+1.3\%}_{-1.1\%} \pm 2.0\%$	$101.8^{+6.0\%}_{-7.1\%} \pm 1.2\%$	$9.888^{+6.5\%}_{-7.6\%} \pm 5.8\%$	$5.303^{+11.2\%}_{-13.3\%} \pm 7.4\%$	$8.749^{+3.6\%}_{-3.9\%} \pm 4.9\%$

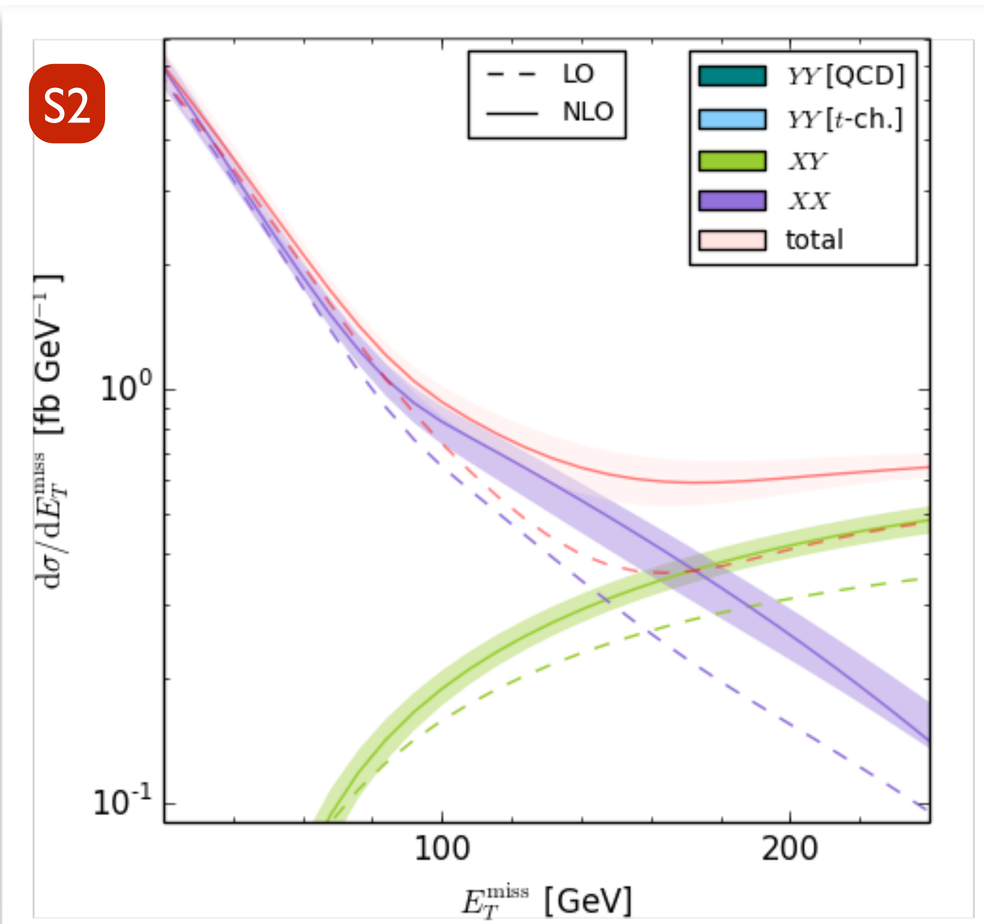
- ✤ Large XX contribution; then XY
  → could be a significant component of the signal
- ✤ YY is smaller
  - ★ QCD and *t*-channel diagrams both important
  - ★ Large destructive interferences

- ✤ Large K-factors
  → NLO rates matter
- ✤ Reduction of the TH errors
  → to a few percents

Differential distributions: missing energy

✦ Properties of the signal at the LHC





✤ XX cross section is large but contribute in the small MET regime
→ irrelevant for the signal (preselection requires large MET)

✤ XY dominates in the intermediate MET regime

✤ YY kicks in at large MET

★ QCD and *t*-channel diagrams both important (but different shapes)

Recasting ATLAS SUSY 2016-27 (monojet; 36 ifb)

✦ CLs exclusion from the best region

S2

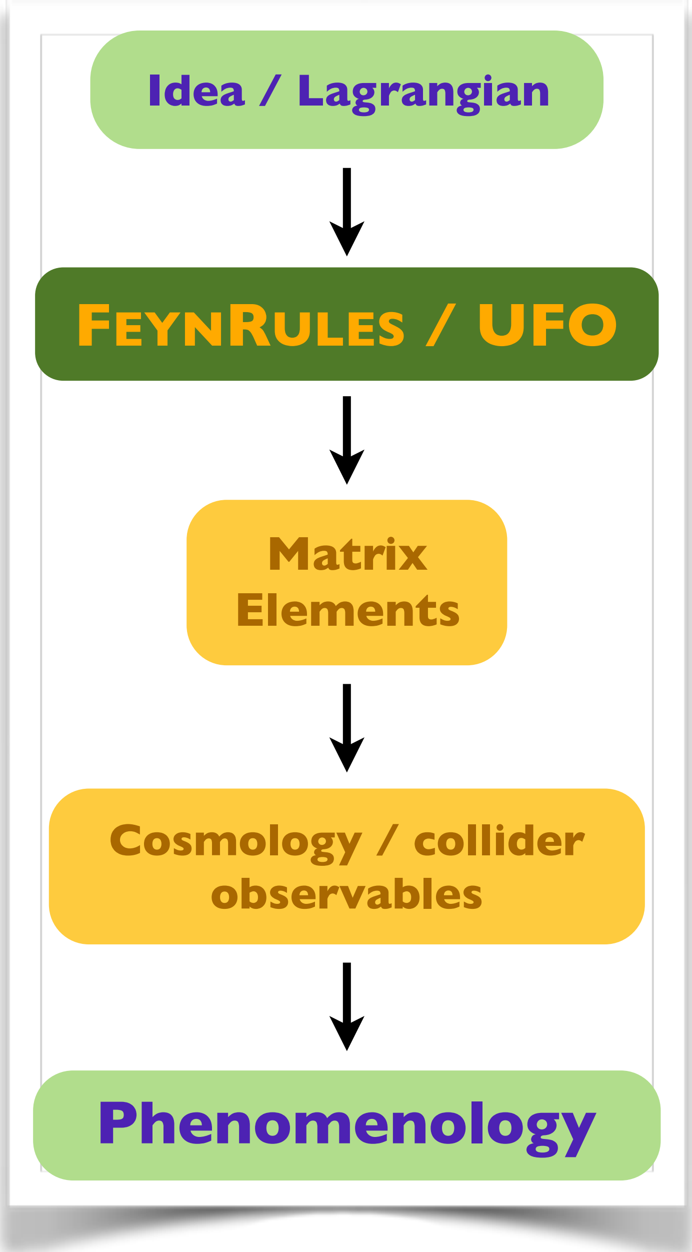
Process	CL_s [LO]	$E_T^{\rm miss}$ constraint	CL_s [NLO]	$E_T^{\rm miss}$ constrtaint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
XX	$0.7^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV	$3.6^{+0.3}_{-0.6}$ %	≥ 900 GeV
XY	$62.7^{+12.3}_{-10.4}$ %	$\in [500, 600]$ GeV	$83.9^{+2.9}_{-4.3}$ %	$\in [700, 800]$ GeV
YY [total]	$24.0^{+3.1}_{-3.1}$ %	≥ 900 GeV	$58.1^{+2.2}_{-3.1}$ %	≥ 900 GeV
YY [QCD]	$10.7^{+4.4}_{-2.6}$ %	≥ 900 GeV	$17.0^{+2.1}_{-2.1}$ %	≥ 900 GeV
YY [t-channel]	$29.6^{+3.3}_{-2.6}$ %	≥ 900 GeV	$38.9^{+1.2}_{-1.8}$ %	≥ 900 GeV

[MadAnalysis 5]

- ✤ NLO simulations are crucial
  - ★ Modification of the rates (larger yields) and shapes (different best region)
  - ★ Better control of the theory errors
- ✤ Considering all signal components is crucial
  - ★ One component alone is not sufficient to exclude the scenario

✦ S1 (lighter mediator) is excluded too (from YX, YY and the total)

Summary- outlook



✦ A generic *t*-channel DM framework

- ✤ Dark matter: spin 0, 1/2 and 1; Majorana or not
- ✤ 12 mediators: spin 0 or 1/2; couplings to all quarks

X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{S}$	0	yes	ψ_Q, ψ_u, ψ_d	1/2
S	0	no		
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
$\tilde{V}_\mu$	1	yes	ψ_Q, ψ_u, ψ_d	1/2
V_μ	1	no		

✦ Automated NLO calculations @ colliders

- ✤ Important impact on the predictions and the bounds
- ✤ More information:
  - ★ See the paper: 2001.05024
  - ★ Web: http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt