A universal framework for *t*-channel dark matter

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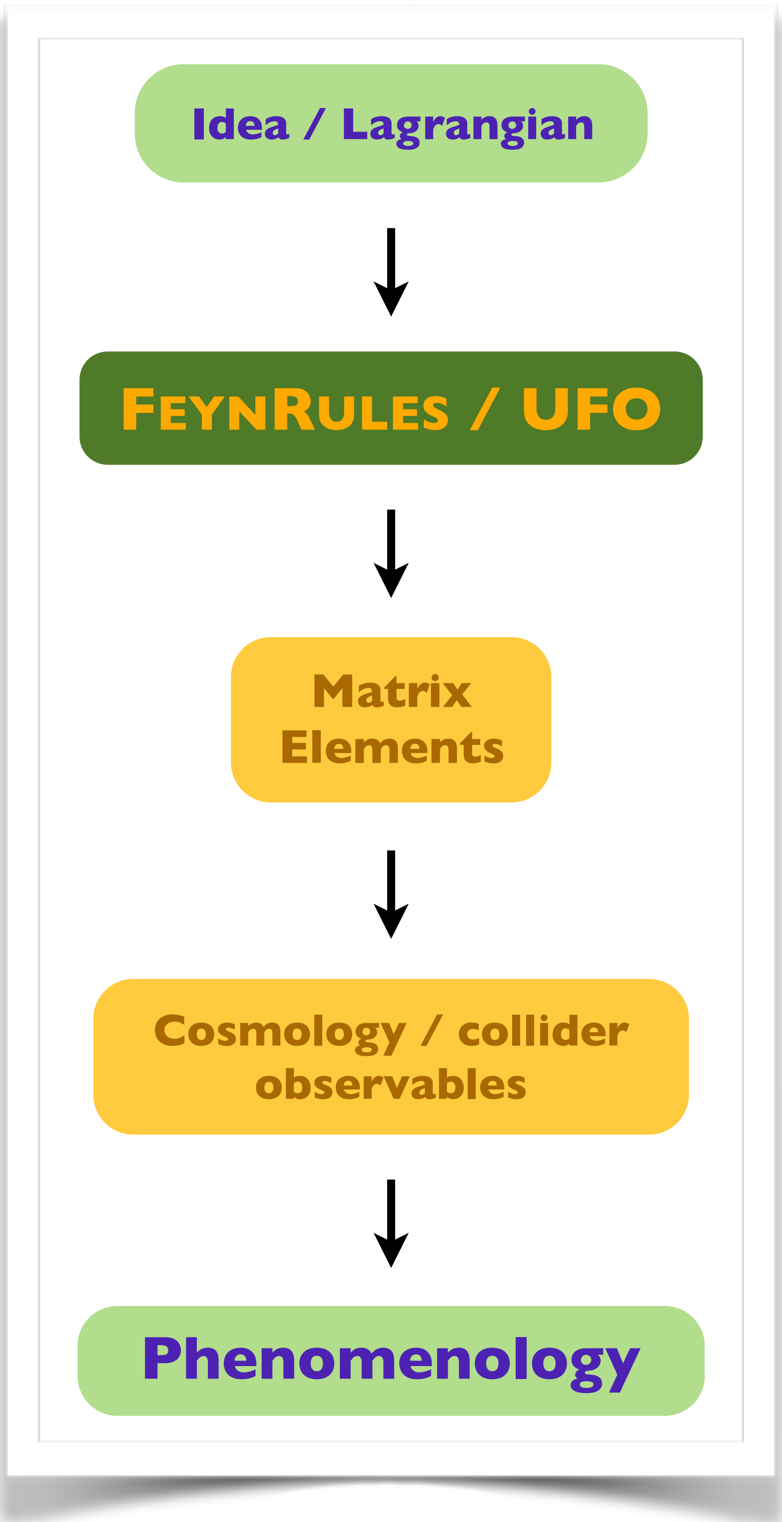
Outline

1. The Über UFO: reminders
2. Illustrative features: a *t*-channel DM signal at the LHC
3. Outlook

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 + NLOCT → UFO @ NLO
- On-shell renormalisation scheme

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]

✦ Hard scattering

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

[Belyaev, Christensen & Pukhov (CPC'13)]
[Alwall *et al.* (JHEP'14)]

✦ Cosmology

- Relic density, scattering off nuclei rates, *etc.*
- MICROMEGAS / MADDM

[Bélanger, Boudjema, Goudelis, Pukhov & Zaldivar (CPC'18)]
[Ambrogi *et al.* (PDU'19)]

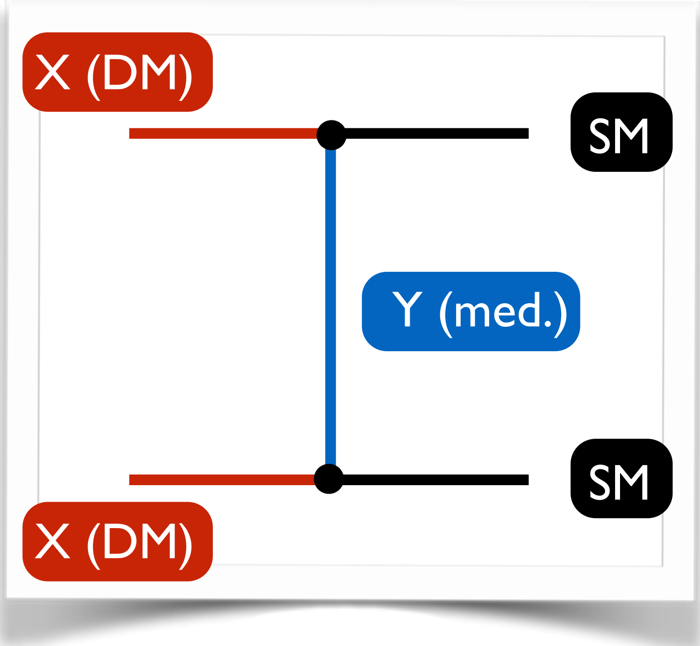
✦ Colliders with MG5_aMC

- Matching matrix elements with parton showers
- Heavy particle decays: MADSPIN/MADWIDTH
- Simplified treatment of the resonances (MADSTR)

[Artoisenet *et al.* (JHEP'13); Alwall *et al.* (CPC`15)]
[Alwall *et al.* (JHEP'14)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

A generic implementation for *t*-channel DM

✦ A generic *t*-channel DM modelling



- 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

Many free parameters / spin combination

✦ 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
- Mediators
  - ★ Spin 0 or 1/2 (no spin 1)
  - ★ Independent couplings to all gauge eigenstates

Model restrictions

✦ 18 restrictions with 3 parameters each

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f},\ \varphi_{u_f},\ \varphi_{d_f}$	$M_\varphi,\ M_\chi,\ \lambda_\varphi$
S3D_uni	χ		
S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3},\ \varphi_{u_3},\ \varphi_{d_3}$	
S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f},\ \psi_{u_f},\ \psi_{d_f}$	$M_S,\ M_\psi,\ \hat{\lambda}_\psi$
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3},\ \psi_{u_3},\ \psi_{d_3}$	
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f},\ \psi_{u_f},\ \psi_{d_f}$	$M_V,\ M_\psi,\ \hat{\lambda}_\psi$
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3},\ \psi_{u_3},\ \psi_{d_3}$	
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

✤ Universal models (uni):

- ★ 1 dark matter particle
- ★ 12 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

$$\mathcal{L}_{\texttt{X\_uni}}(X) = \sum_{F=Q,u,d} \sum_{f=1}^{3} \Big[\lambda_\varphi \bar{X} F_f \varphi^\dagger_{F_f} + \text{h.c.}\Big]$$

✤ 3rd generation models (3rd):

- ★ 1 dark matter particle
- ★ 4 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

$$\mathcal{L}_{\texttt{X\_3rd}}(X) = \sum_{F=Q,u,d} \Big[\lambda_\varphi \bar{X} F_3 \varphi^\dagger_{F_3} + \text{h.c.}\Big]$$

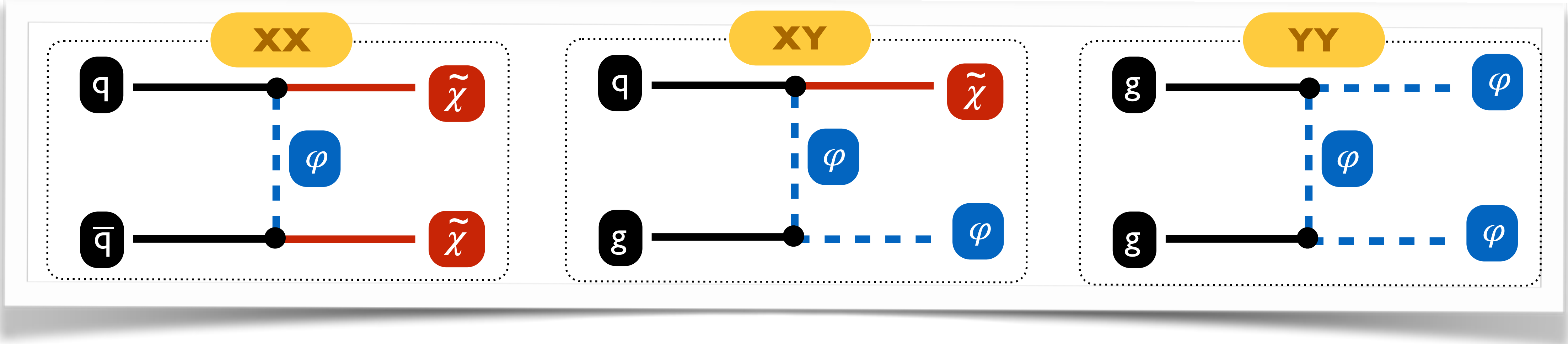
✤ uR models (uR):

- ★ 1 dark matter particle
- ★ 1 mediator
- ★ Coupling to the right-handed up-quark

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

DM production at colliders: generalities

✦ Three contributing classes of processes



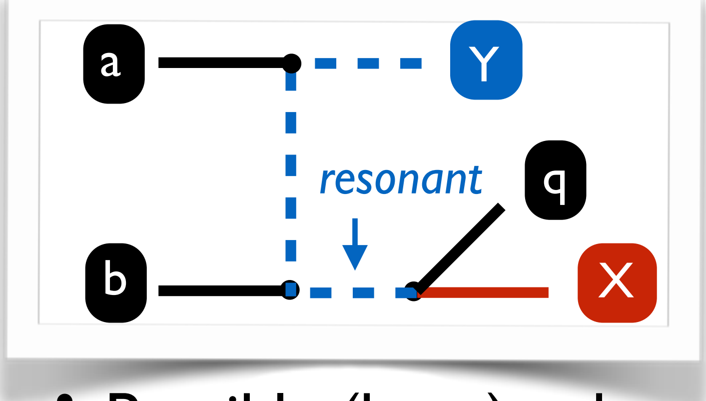
- ✤DM pair production
- ✤DM/mediator associated production (+ mediator decays into DM+jet)
- ✤Mediator pair production (+ mediator decays into DM+jet)

✦ Dark matter signal

- ✤Each subprocess contributes to signal region population
  - ★Jets generated from ISR or in the mediator decays
- ✤The signal is less naive than from considering YY production only

DM signal production at NLO

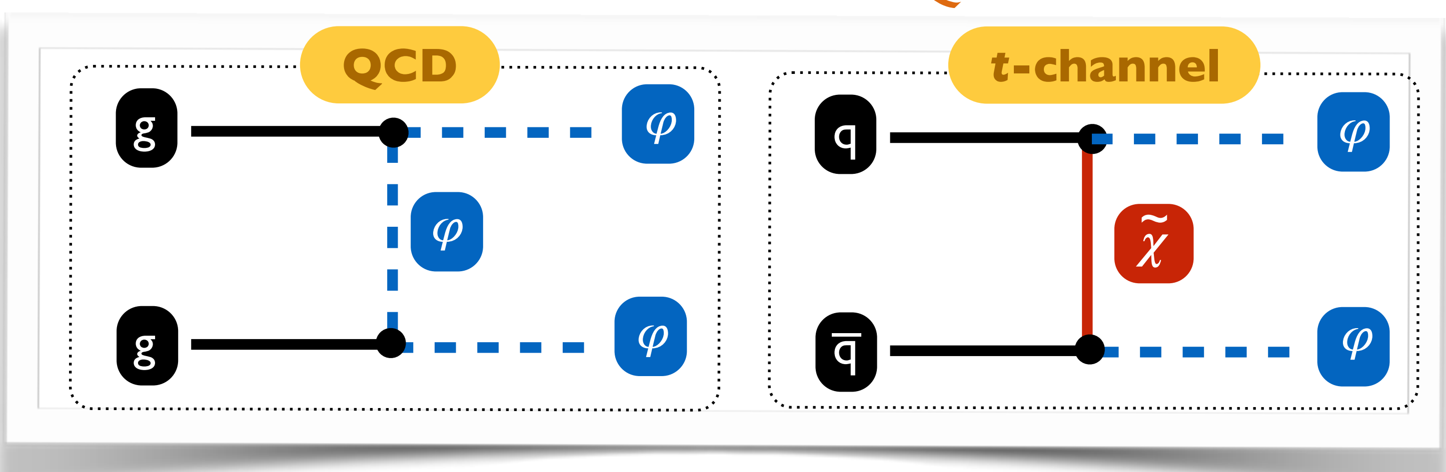
✦ NLO computations are not trivial



- ✤ 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

✦ Mediator pair production

- ✤ Two classes of contributions: QCD and *t*-channel DM-induced



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

Example: the S3D_uR case

The S3D_uR model: 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

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

- 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

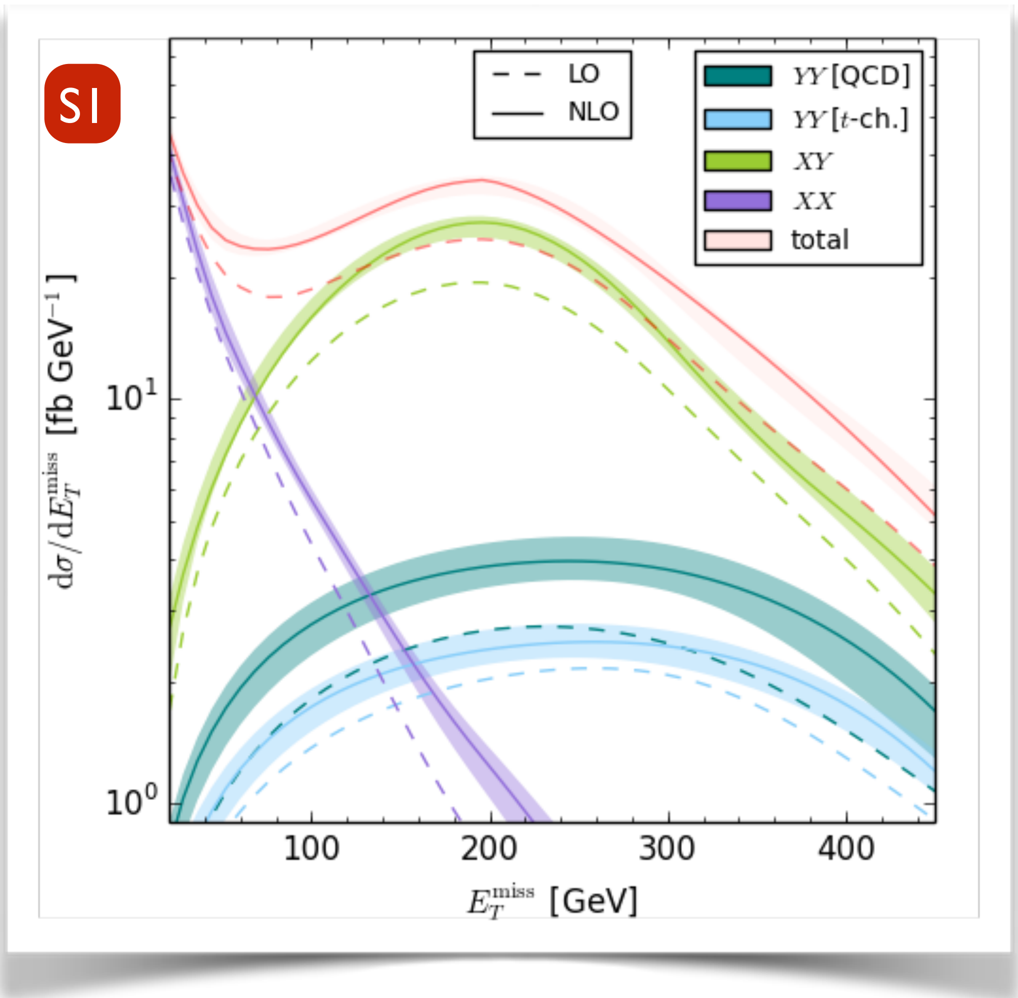
Total rates

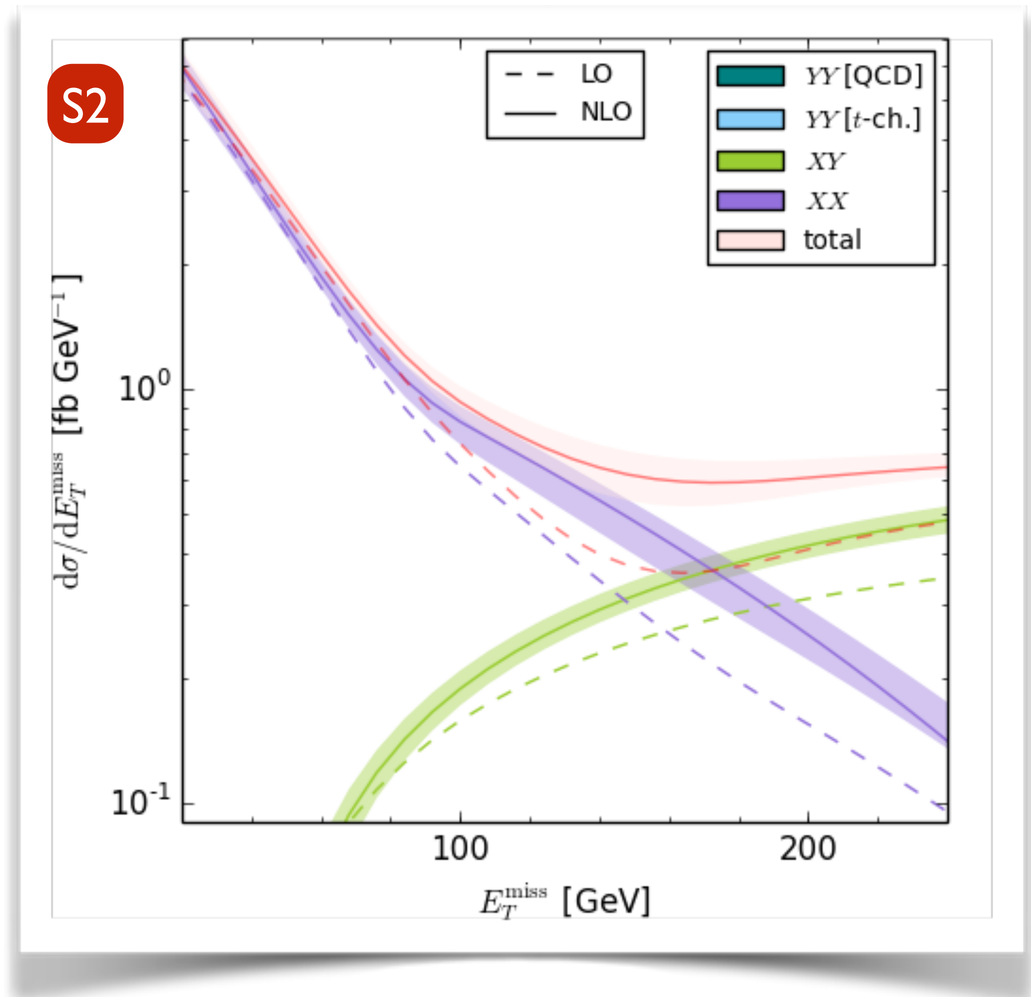
	Scen.	XX [fb]	XY [fb]	YY (total) [fb]	YY (QCD) [fb]	YY (t-channel) [fb]
LO	**S1**	$775.3^{+0.4\%}_{-0.8\%} \pm 1.9\%$	$1617^{+16.5\%}_{-13.4\%} \pm 1.0\%$	$473.5^{+23.6\%}_{-16.9\%} \pm 3.0\%$	$324.2^{+34.2\%}_{-23.8\%} \pm 3.4\%$	$261.5^{+7.1\%}_{-6.3\%} \pm 2.5\%$
LO	**S2**	$122.0^{+1.8\%}_{-2.0\%} \pm 1.9\%$	$74.1^{+20.3\%}_{-15.8\%} \pm 1.2\%$	$7.452^{+19.8\%}_{-14.5\%} \pm 5.6\%$	$3.545^{+37.3\%}_{-25.4\%} \pm 7.2\%$	$6.939^{+11.1\%}_{-9.4\%} \pm 5.0\%$
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

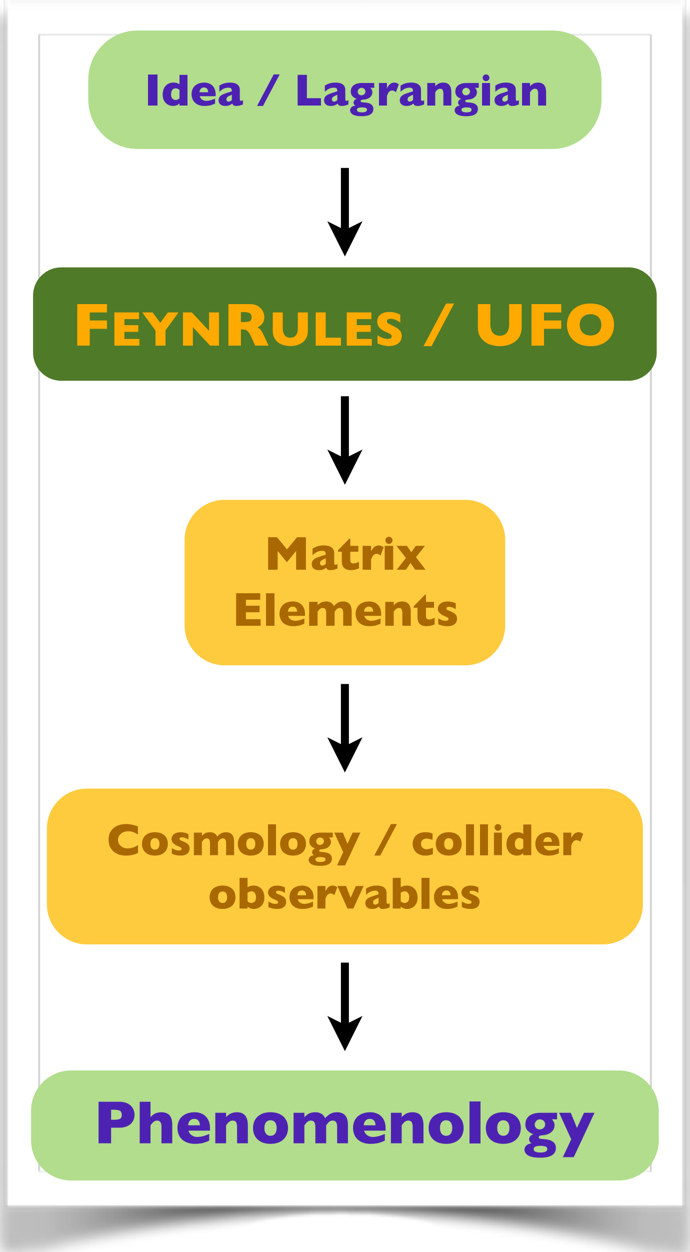
Process	CL_s [LO]	E_T^{miss} constraint	CL_s [NLO]	E_T^{miss} constrtaint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
XX	$0.7^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV	$3.6^{+0.3}_{-0.6}$ %	≥ 900 GeV
XY	$62.7^{+12.3}_{-10.4}$ %	$\in [500, 600]$ GeV	$83.9^{+2.9}_{-4.3}$ %	$\in [700, 800]$ 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



- ✦ The Über UFO is available
  - ✤ LO calculations straightforward (collider + cosmo)
  - ✤ NLO @ colliders → not so straightforward
  - ✤ More information:
    - ★ See the paper (2001.05024) for the syntax
    - ★ Web: http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt
- ✦ Validation
  - ✤ Comparison with the literature
    - ★ Cosmological observables (see Chiara's talk)
    - ★ SUSY cross sections
- ✦ Next steps?