t-channel dark matter models at the NLO accuracy in QCD

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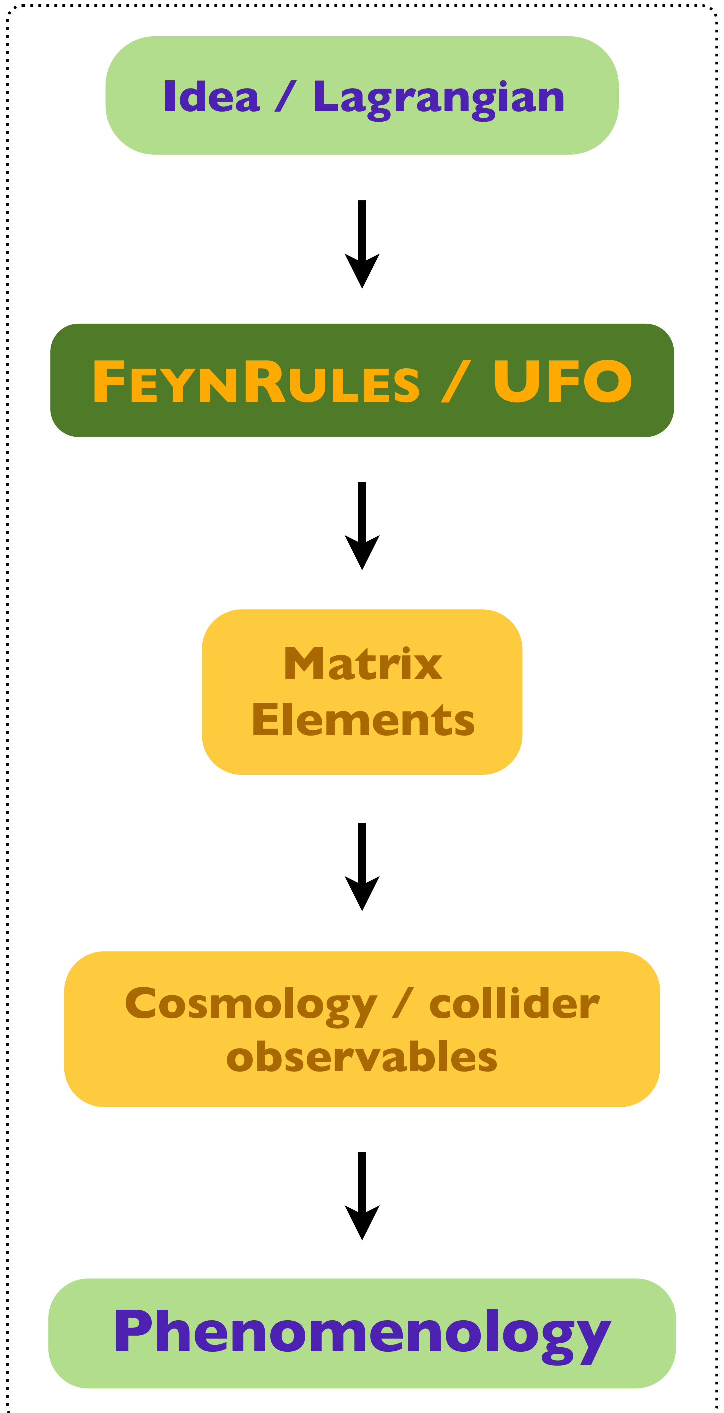
Outline

1. The Über UFO: goal & description
2. Illustrative features: cosmology & colliders@NLO
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)]

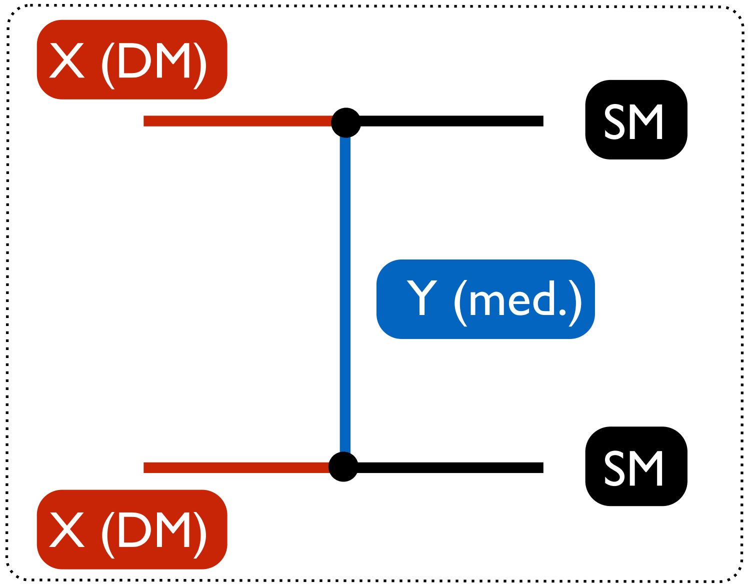
✦ Colliders with MG5_aMC

- ✤ 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 (1907.04898)]

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
S	0	yes	ψ_Q, ψ_u, ψ_d	1/2
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
V_μ	1	yes	ψ_Q, ψ_u, ψ_d	1/2

- Missing (for now):
  - Complex scalar/vector DM
    → trivial to add
  - Vector mediators
    → coloured vector @ NLO?

Lagrangian and restrictions

✦ The model

✤ Fields:

X (DM)	Spin	Self-conj.	Y (med.)	Spin	
S	0	yes	ψ_Q, ψ_u, ψ_d	1/2	→ F3S
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0	→ S3M
χ	1/2	no			→ S3D
V_μ	1	yes	ψ_Q, ψ_u, ψ_d	1/2	→ F3V

✤ Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\lambda_{\bf Q}\ [(\bar{\tilde{\chi}} + \bar{\chi})Q_L]\ \varphi_Q^\dagger + \lambda_{\bf u}\ [(\bar{\tilde{\chi}} + \bar{\chi})u_R]\ \varphi_u^\dagger + \lambda_{\bf d}\ [(\bar{\tilde{\chi}} + \bar{\chi})d_R]\ \varphi_d^\dagger + {\rm h.c.}\Big]$$
$$+ \Big[\hat{\lambda}_{\bf Q}\Big([\bar{\psi}_Q Q_L]\ S + [\bar{\psi}_Q \not{V} Q_L]\Big) + \hat{\lambda}_{\bf u}\Big([\bar{\psi}_u u_R]\ S + [\bar{\psi}_u \not{V} u_R]\Big) + \hat{\lambda}_{\bf d}\Big([\bar{\psi}_d d_R]\ S + [\bar{\psi}_d \not{V} d_R]\Big) + {\rm h.c.}\Big]$$

✦ 12 sets of restrictions

✤ Selection of one spin combination: S3D, S3M, F3S, F3V

✤ 2 masses: m_Y, m_X; 1 coupling parameter λ

✤ Coupling texture:

- ★ Universal couplings: 12 degenerate mediators
- ★ 3rd generation couplings: 3 degenerate mediators
- ★ Coupling to u_R: 1 mediator

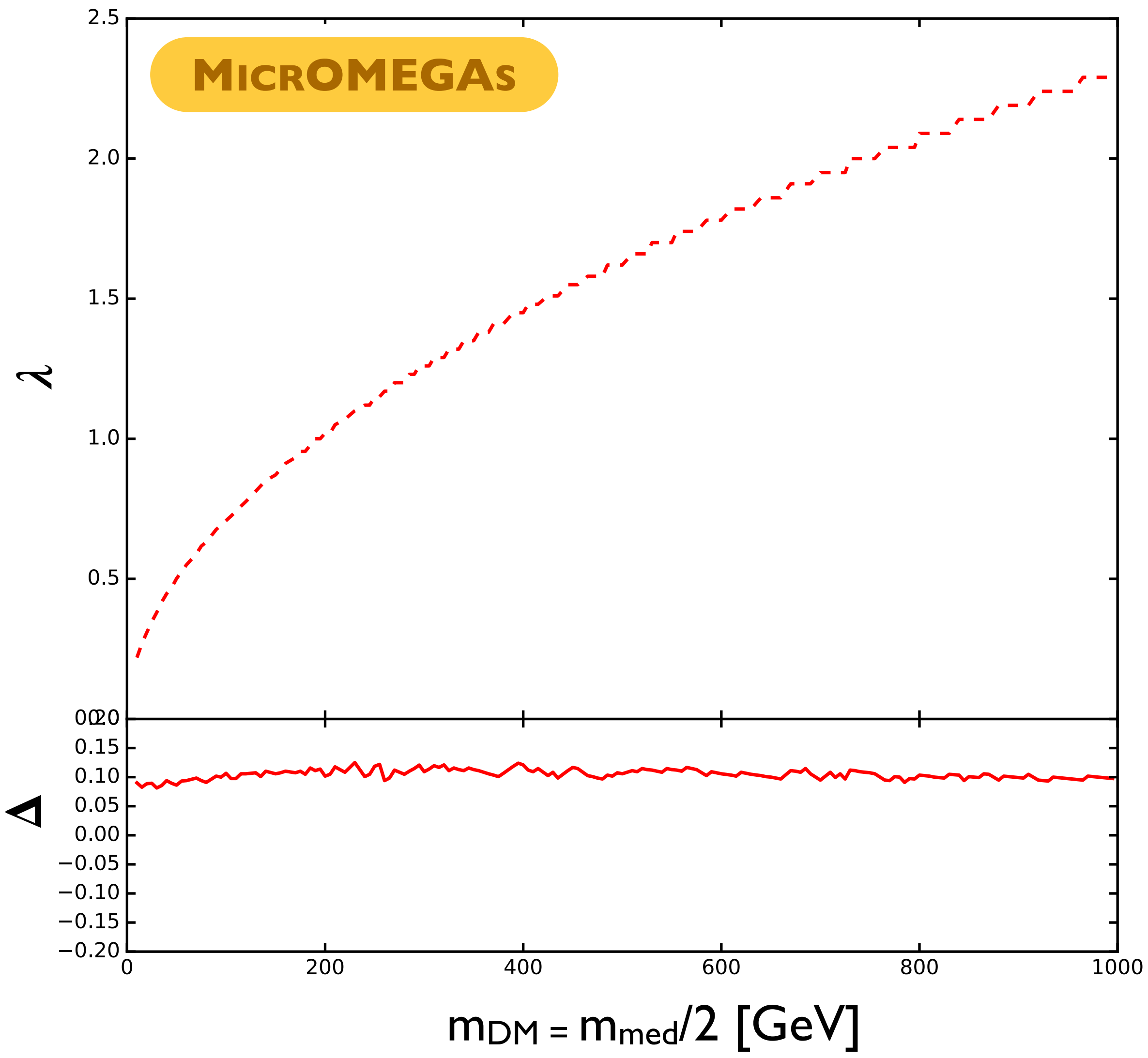
import model DMSimp_t-S3D_uni --modelname

Relic density in the S3M_uR model

✦ The S3M_uR model: coupling to the right-handed up-quark only

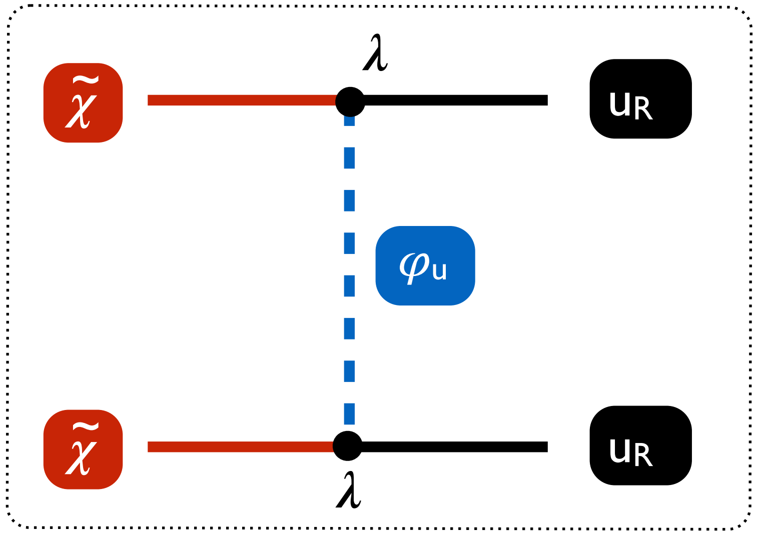
X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\lambda_{\bf u}\ \bar{\tilde{\chi}} u_R\ \varphi_u^\dagger + {\rm h.c.}\Big]$$



✦ Relic density matching Planck data

- ✤ λ: MICROMEGAs gives $\Omega_{\rm CDM}$ = 0.12
- ✤ MADDM *vs.* MICROMEGAs (Δ)
  - ★ 10% difference for the same benchmark
    - → being investigated



Direct detection in the S3M_uR model

✦ The S3M_uR model: coupling to the right-handed up-quark only

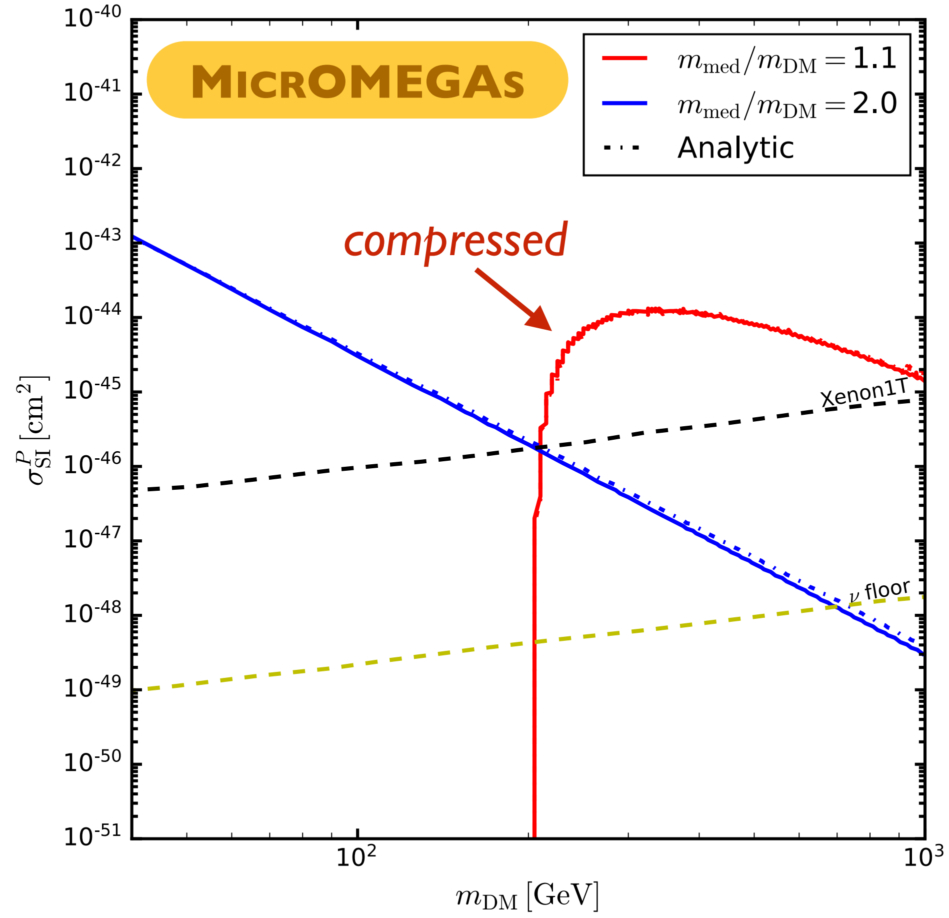
X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0

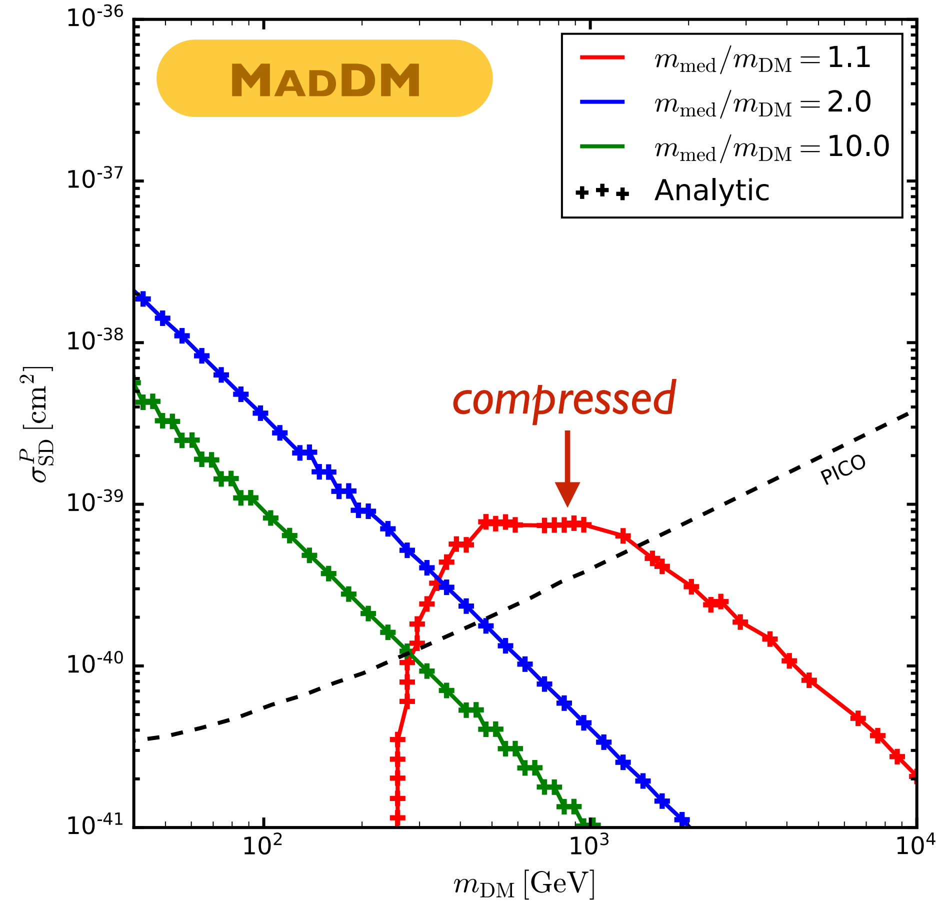
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\lambda_{\mathbf{u}} \overline{\tilde{\chi}} u_R \, \varphi_u^\dagger + {\rm h.c.} \Big]$$

Fixed by $\Omega_{\rm CDM}$

✦ Direct detection

✤ Validation: analytical calculations *vs.* MADDM/MICROMEGAS → excellent agreement





Indirect detection in the S3M_uR model

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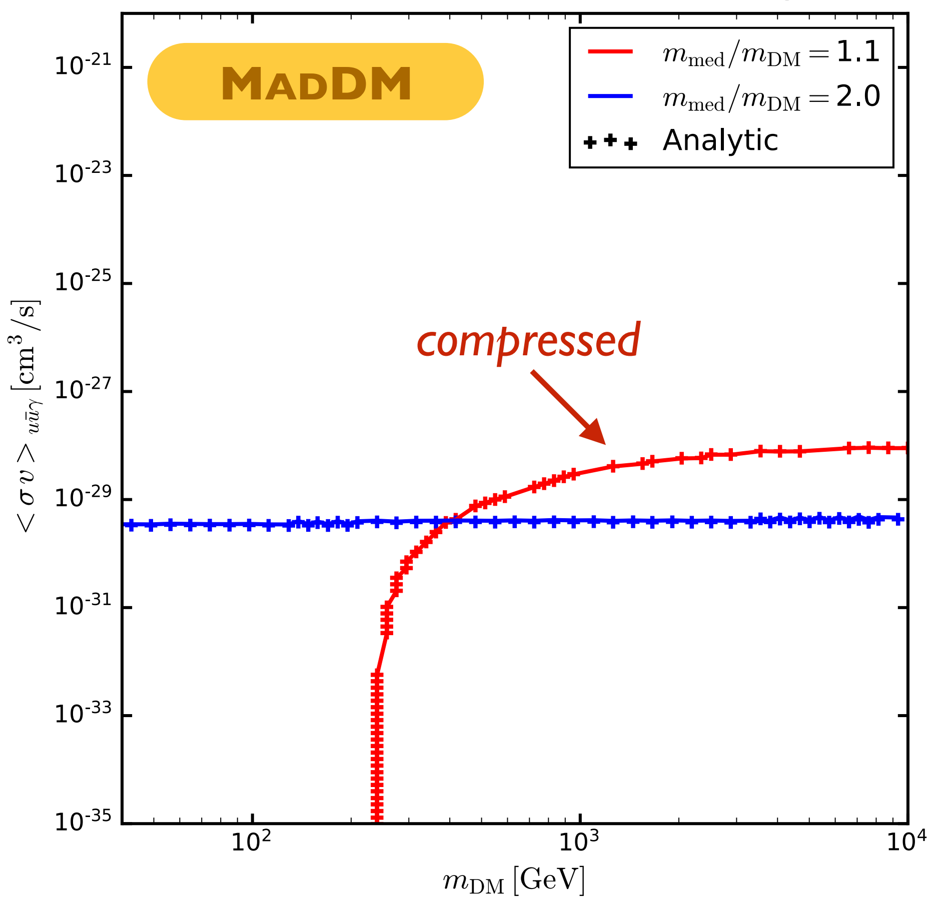
Fixed by $\Omega_{\rm CDM}$

✦ Indirect detection

- ✤ MadDM *vs.* (approximate) analytical calculations → excellent agreement
- ✤ 2-to-3 matrix elements integrated with MadEvent



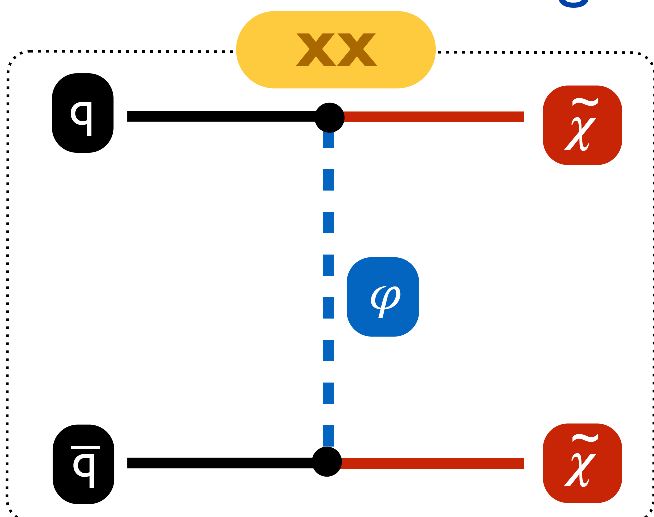
DM production at colliders: the S3D_uni case

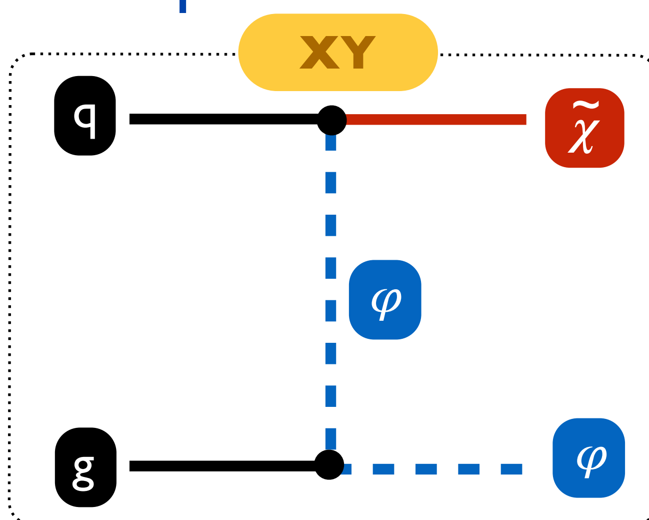
✦ Model

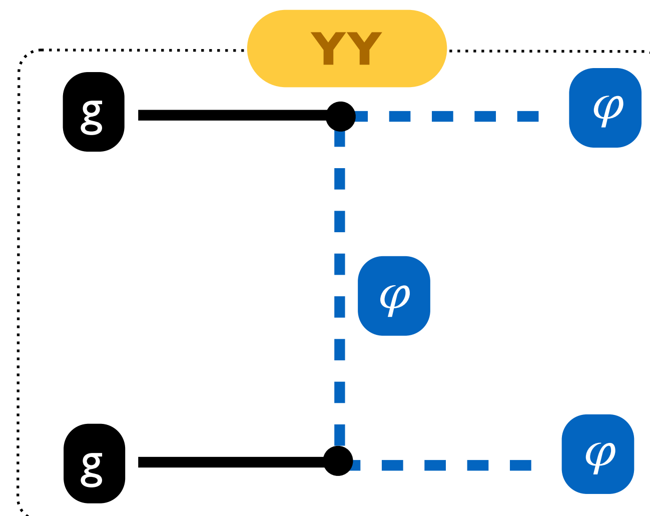
X (DM)	Spin	Self-conj.	Y (med.)	Spin
χ	1/2	no	$\varphi_Q, \varphi_u, \varphi_d$	0

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \lambda\Big[\bar\chi Q_L \varphi_Q^\dagger + \bar\chi u_R \varphi_u^\dagger + \bar\chi d_R \varphi_d^\dagger + {\rm h.c.}\Big]$$

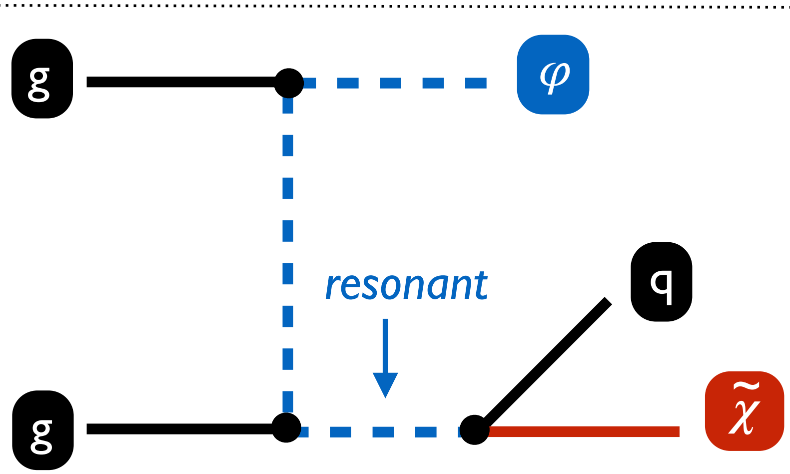
✦ Three contributing classes of processes







✦ NLO computations are not trivial



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

✤ YX @ NLO cannot be evaluated

Resonance subtraction

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]

✦ Different subtraction procedures

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

- **DR**: the resonant diagrams are removed
- **DR+I**: diagram removal while keeping the interferences
- **DS**: subtraction of the purely resonant part from the last term

$$\Big|\mathcal{A}^{(\text{res.})}\Big|^2 d\Phi \ \Rightarrow\ \Big|\mathcal{A}^{(\text{res.})}\Big|^2 d\Phi - f(m^2_{\text{res.}})\ \mathbb{P}\Big(\Big|\mathcal{A}^{(\text{res.})}\Big|^2 d\Phi\Big)$$

  - ★ Different options (momenta projections)
  - ★ The projection $\propto$ 2-to-2 Born

MG5_AMC

Jets + MET @ NLO (I)

✦ Simulation chain

- ✤ Fixed order: XX, XY and YY production at NLO
- ✤ DR+I: diagram removal while keeping the interferences
- ✤ Parton shower matching: PYTHIA 8 (MC@NLO procedure)
- ✤ Detector/reco: DELPHES 3 / FASTJET
- ✤ Recasting: MADANALYSIS 5

[Frixone & Webber (JHEP'02); Sjöstrand et *al.* (CPC'15)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (1907.04898)]
[Cacciari, Salam & Soyez (EPJC'12); de Favereau et *al.* (JHEP`14)]
[Dumont, BF, Kraml et al. (EPJC '15); Conte & BF (IJMPA'18)]

✦ Considered analyses

- ✤ ATLAS SUSY 2016-07: multijet + MET (36 fb^{-1}; 2-6 jets)
- ✤ ATLAS EXOT 2016-27: monojet (36 fb^{-1})

✦ Benchmark: m_X = 150 GeV, m_Y = 500 GeV, λ=1

- ✤ XX production ($p_T(j)$ > 100 GeV): 3.3 pb (1.2% scales, 1.6% PDFs)
  - → monojet sensitivity: 4-6 pb
- ✤ XY_1 production: 6.9 pb (6.2% scales, 1.2% PDFs)
- ✤ XY_2 production: 1 pb (5.6% scales, 5.8% PDFs)
  - → monojet/multijet: excluded at 100% CL (both subprocesses independently)
- ✤ YY production: more tricky…

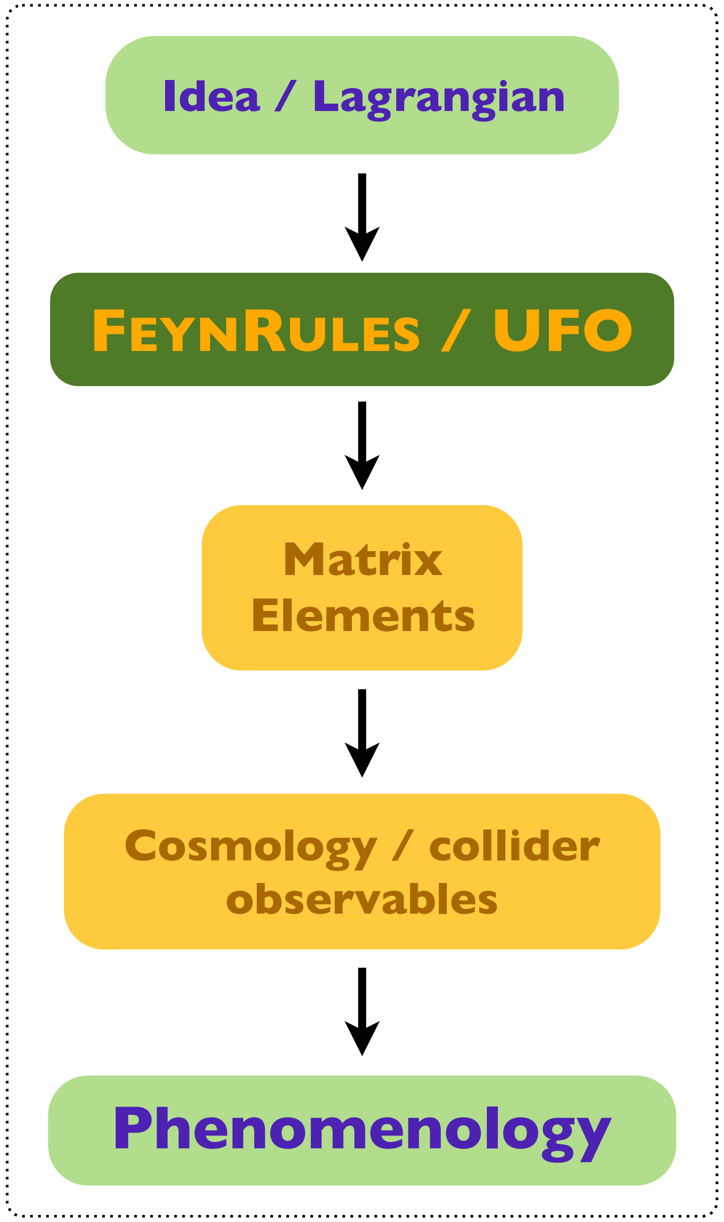
Jets + MET @ NLO (2)

✦ Benchmark: m_X = 150 GeV, m_Y = 500 GeV, λ=1

- ✤ Y_iY_i production (QCD; i=1,2,3): *qq* and *gg* channels (squark pair production)
- ✤ Y_iY_j production (DM *t*-channel; i,j=1,2,3)
- ✤ Interferences between the QCD and DM channels
  - → Mixed orders: interferences @ LO + K-factor rescaling

→ monojet/multijet: excluded at 100% CL

Summary- outlook



- A first version of the Über UFO is available
  - Some spin configurations still missing
  - LO calculations straightforward (collider + cosmo)
  - NLO @ colliders → not so straightforward
- Validation is on-going
  - Comparison with the literature
  - Encouraging first results (cosmo)
  - Issues to be understood
  - Colliders: need to be started