A universal framework for t-channel dark matter models

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Special thank to Chiara for some of the slides

In collaboration with:
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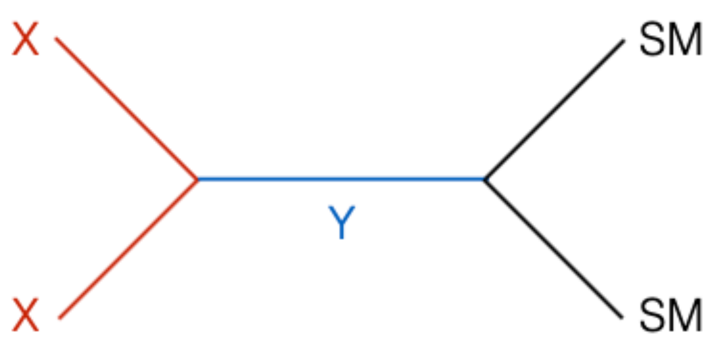
based on arXiv:2001.05024 [hep-ph]

UCLouvain

Extend the Standard model by adding a mediator particle in addition to Dark Matter.

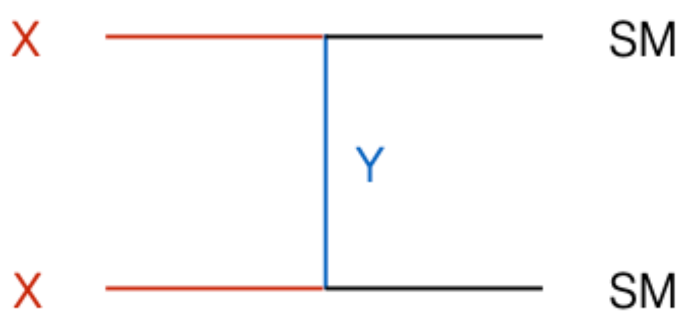
- ❖ **Dark Matter particle stable and neutral**
- ❖ **The Lagrangian has to respect gauge symmetries**

s-channel models



- Y is even under dark symmetries
- Y is a colour singlet and neutral
- X is a SM gauge singlet

t-channel models



- Y is odd under dark symmetries
- Y is a coloured and charged
- Y is heavier than X
- X is a SM gauge singlet

DM simplified model

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM}(Y, X)$$

UFO model @ NLO

FeynRules + NLOCT
[Alloul et al. (CPC 2014); Degrande (CPC 2015); Degrande et al. (CPC 2012)]

- MG5_aMC
  Allwall et al. (JHEP 2014)

Dark matter observables:
- relic density
- direct detection
- indirect detection

Collider signatures:
- Decays
- Parton shower

- MadDM [Ambrogi, CA, et al. (PDU 2019)]
- MicrOmegas [Belanger at al. (CPC 2018)]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde{\chi}) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde{S}) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde{V})$$

A very generic model with 6 dark matter candidates and 2 kind of mediators

	Field	Spin	Repr.	Self-conj.
X	$\tilde{S}$	0	$(\mathbf{1},\mathbf{1},0)$	yes
X	S	0	$(\mathbf{1},\mathbf{1},0)$	no
X	$\tilde{\chi}$	1/2	$(\mathbf{1},\mathbf{1},0)$	yes
X	χ	1/2	$(\mathbf{1},\mathbf{1},0)$	no
X	$\tilde{V}_\mu$	1	$(\mathbf{1},\mathbf{1},0)$	yes
X	V_μ	1	$(\mathbf{1},\mathbf{1},0)$	no
Y	$\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$	0	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no
Y	φ_u	0	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no
Y	φ_d	0	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no
Y	$\psi_Q = \begin{pmatrix} \psi_Q^{(u)} \\ \psi_Q^{(d)} \end{pmatrix}$	1/2	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no
Y	ψ_u	1/2	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no
Y	ψ_d	1/2	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no

$$\mathcal{L}_F(X) = \left[\lambda_{\mathbf{Q}} \bar{X} Q \varphi_Q^\dagger + \lambda_{\mathbf{u}} \bar{X} u \varphi_u^\dagger + \lambda_{\mathbf{d}} \bar{X} d \varphi_d^\dagger + \text{h.c.}\right]$$

$$\mathcal{L}_S(X) = \left[\hat{\lambda}_{\mathbf{Q}} \bar{\psi}_Q Q X + \hat{\lambda}_{\mathbf{u}} \bar{\psi}_u u X + \hat{\lambda}_{\mathbf{d}} \bar{\psi}_d d X + \text{h.c.}\right]$$

$$\mathcal{L}_V(X) = \left[\hat{\lambda}_{\mathbf{Q}} \bar{\psi}_Q \not{X} Q + \hat{\lambda}_{\mathbf{u}} \bar{\psi}_u \not{X} u + \hat{\lambda}_{\mathbf{d}} \bar{\psi}_d \not{X} d + \text{h.c.}\right]$$

couplings
3x3 matrices in flavour space
real and flavour diagonal

Model files and documentation are available here:
http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt

The model is provided with restrictions where undesired particles and couplings are set to zero.

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		

coupling to all quarks

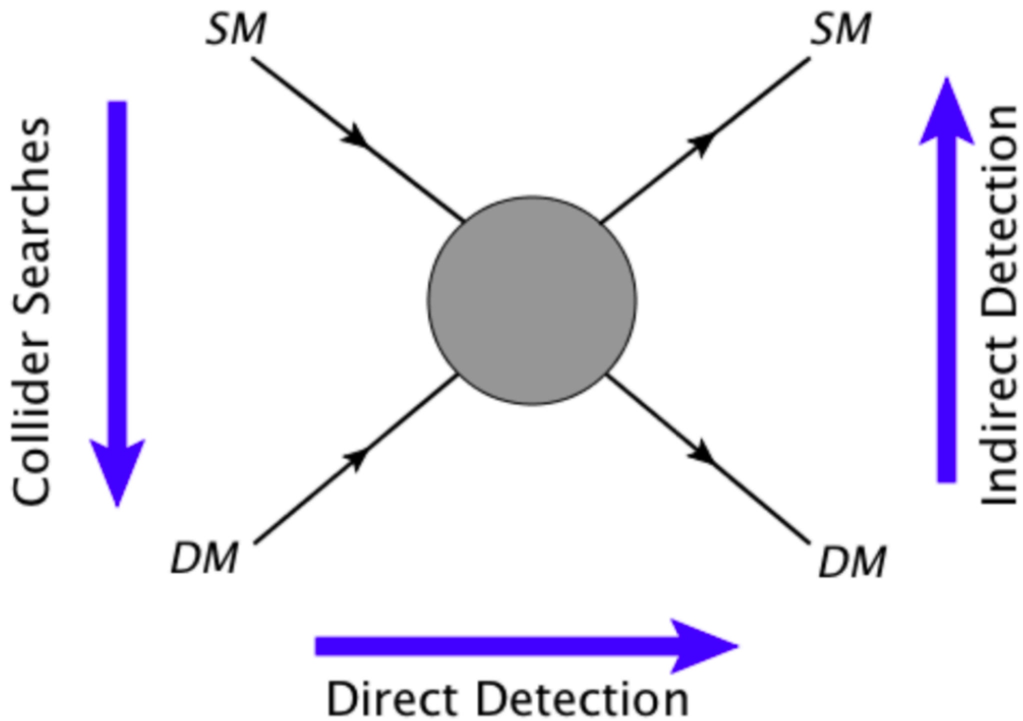
coupling only to b and t quarks

coupling only to quark up-right

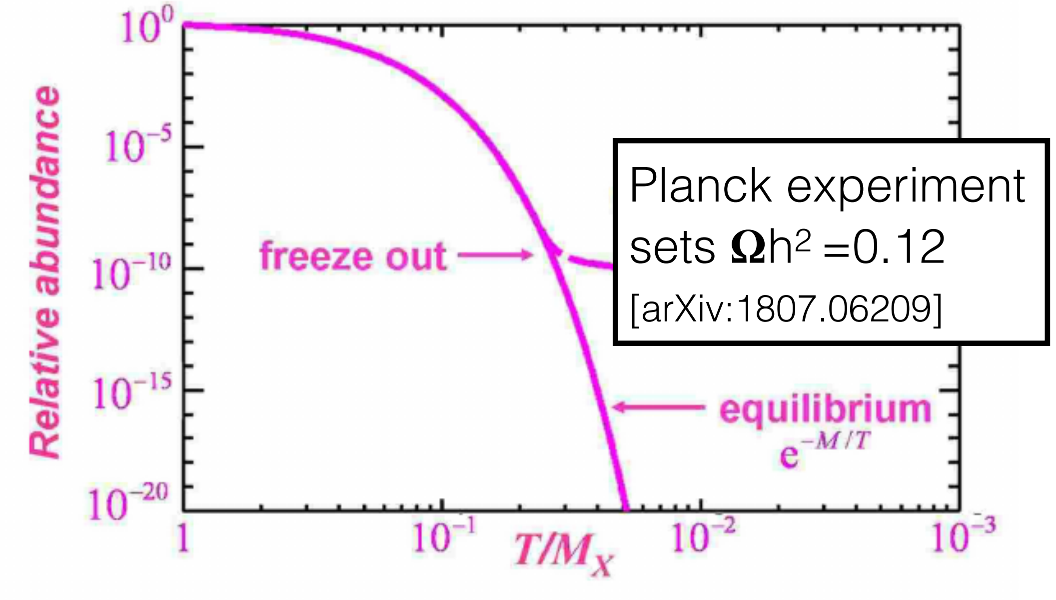
Each restriction has 3 free parameters.

Three broad classes:

- Fermionic DM
- Scalar DM
- Vector DM



Relic abundance

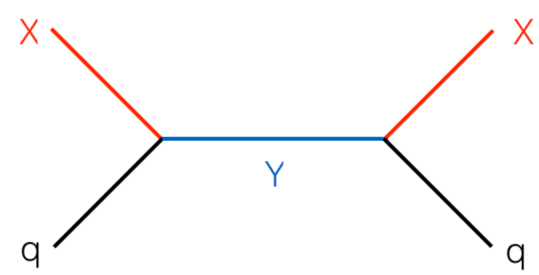


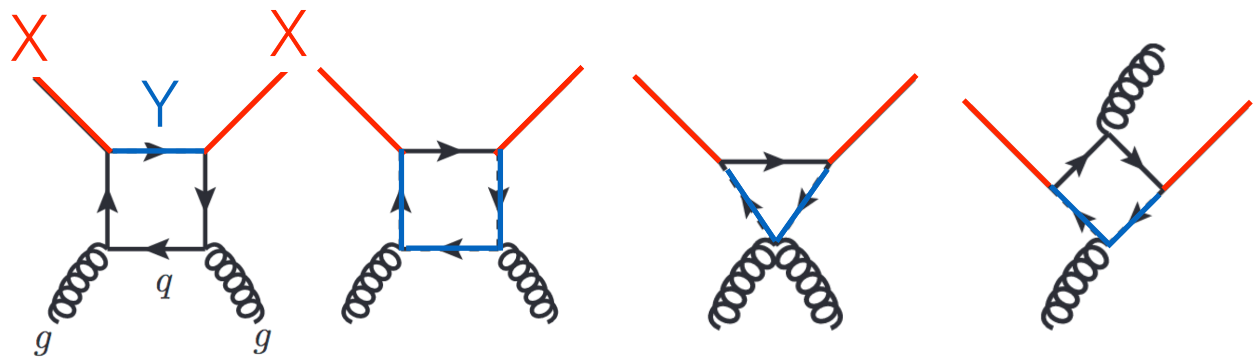
These observables can severely constrain the parameter space of the model and help identify interesting regions of the parameter space for the LHC

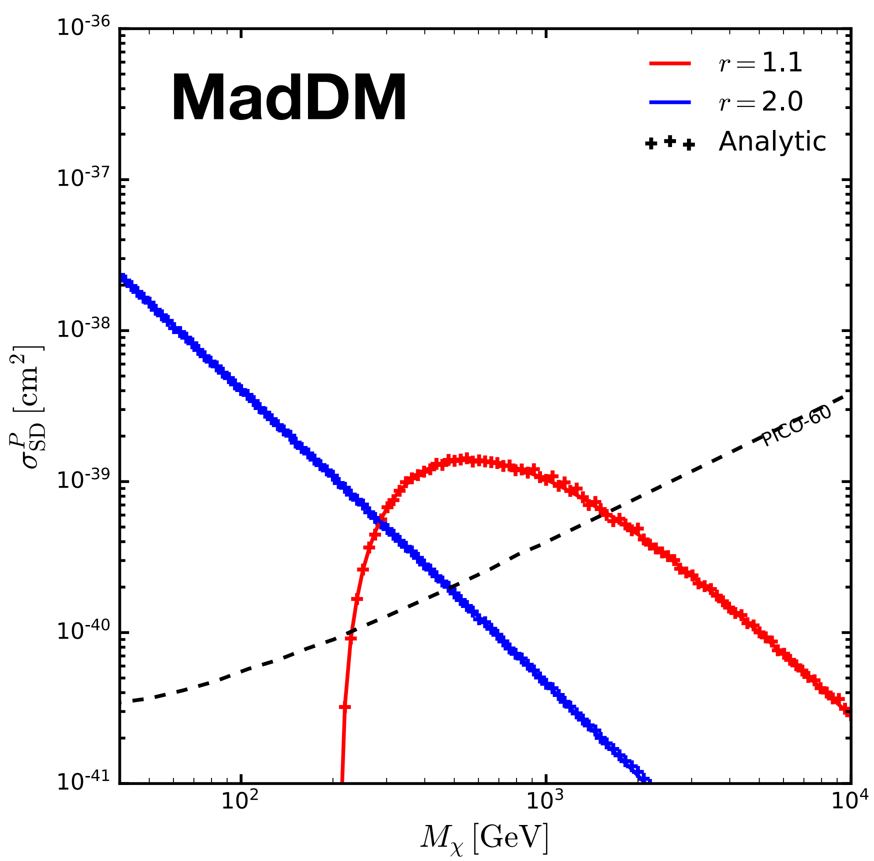
$$\mathcal{L}_{\texttt{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$

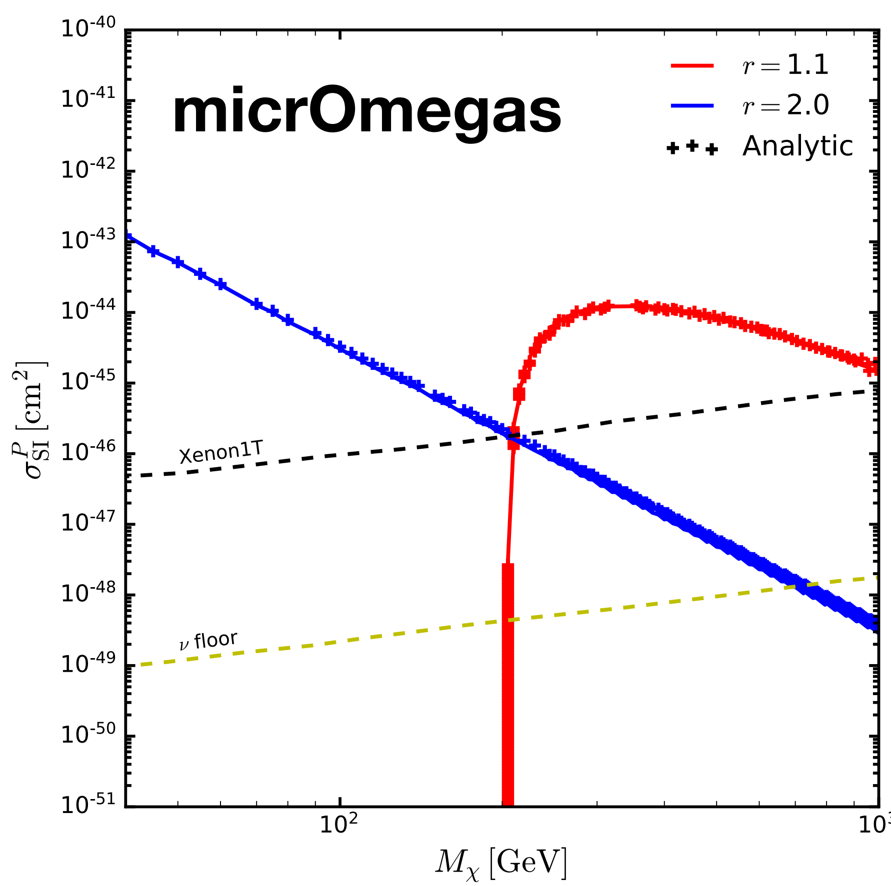
Direct detection analytic expressions [Hisano et al. (JHEP 2015)]

$$r = \frac{M_\varphi}{M_\chi}$$







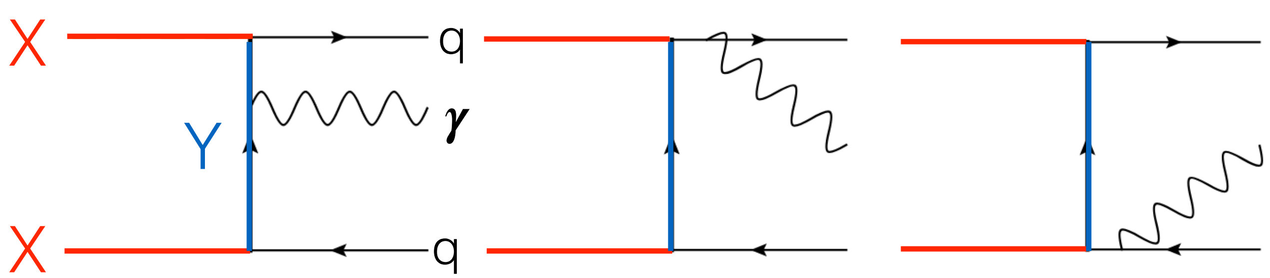


$$\mathcal{L}_{\texttt{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$

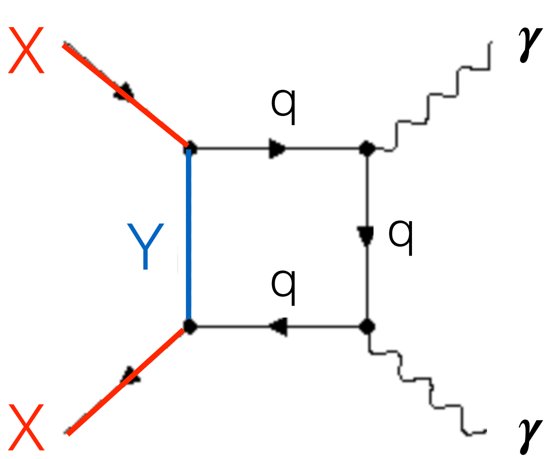
Indirect detection

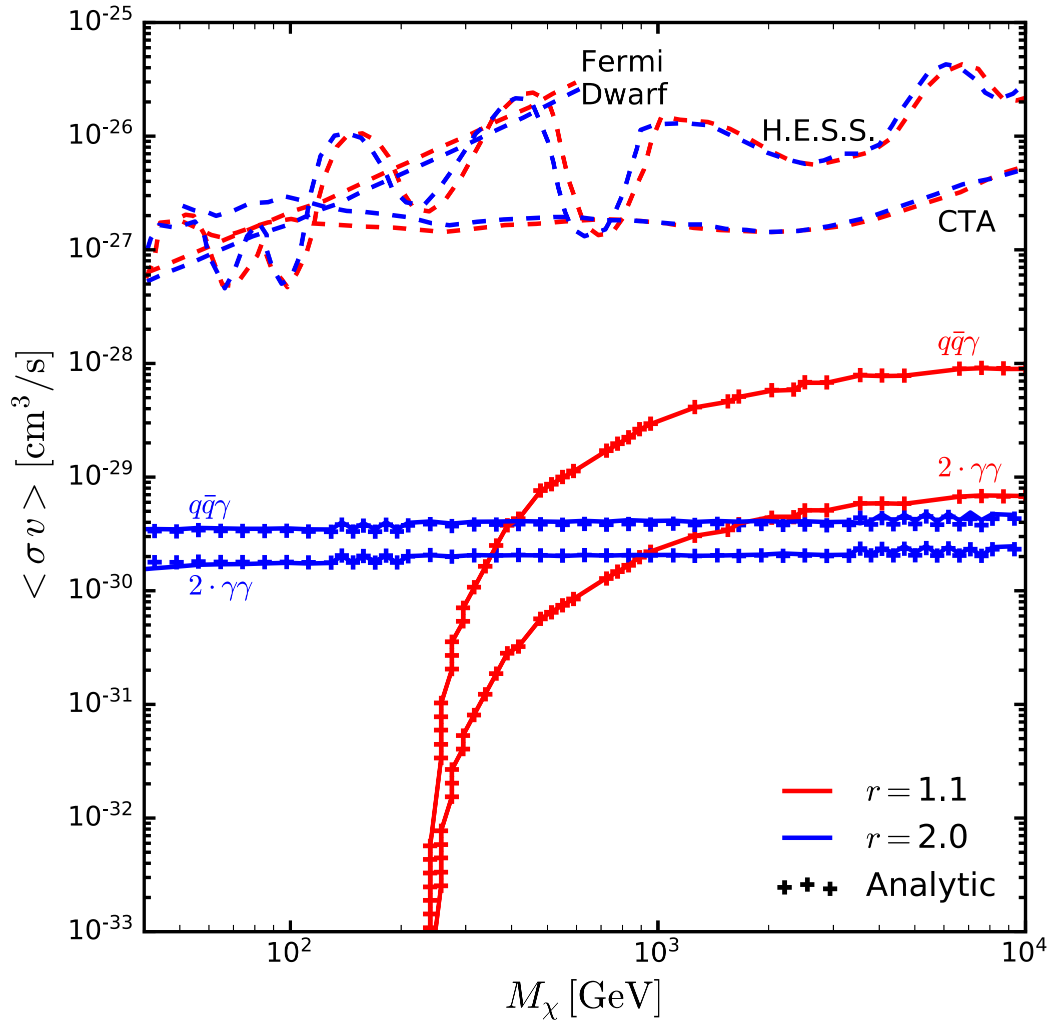
- LO: helicity suppression
- NLO: dominant, sharp signal

Virtual internal bremsstrahlung (VIB)



Loop-induced diphotons

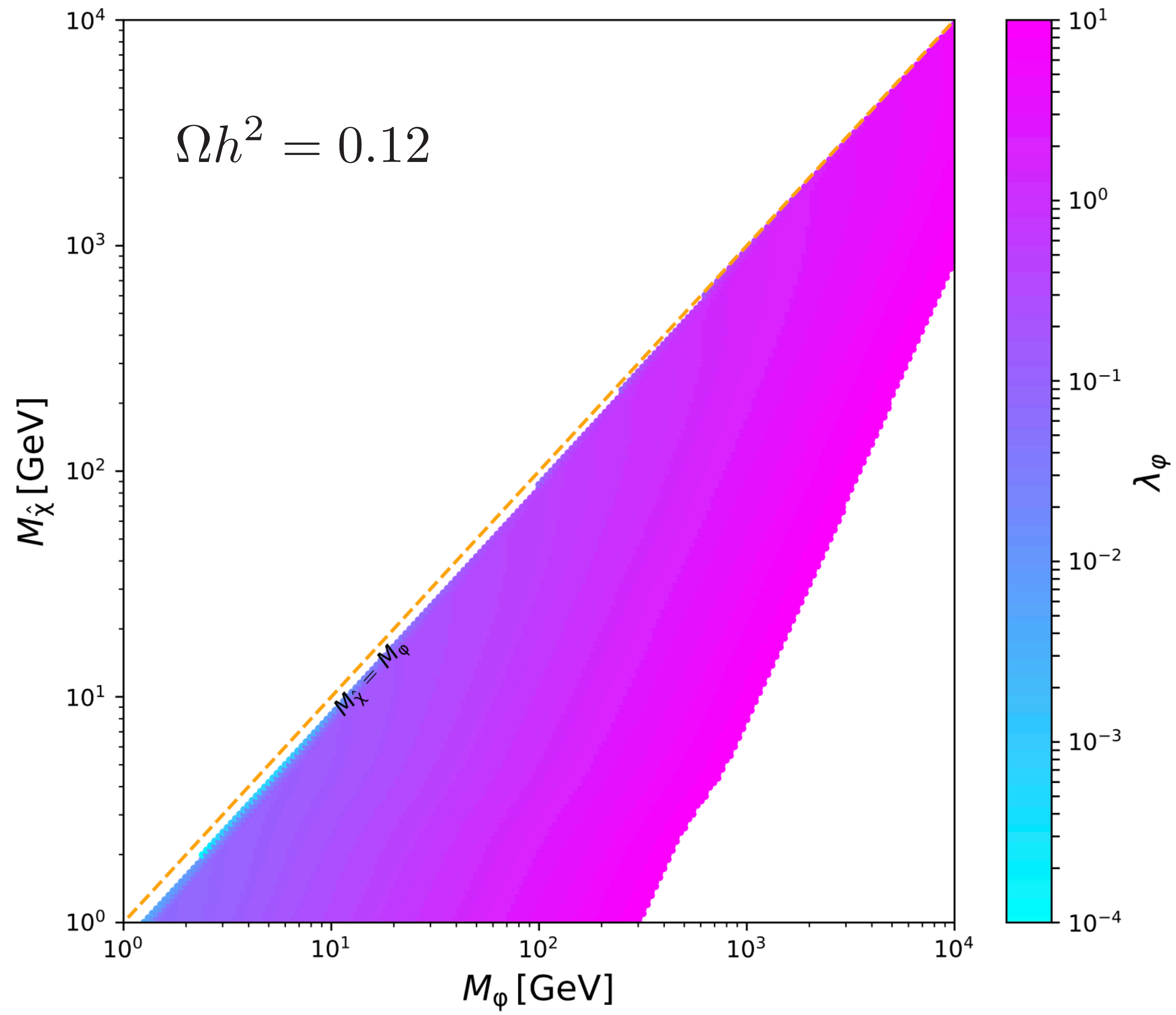




- VIB analytic expression [Giacchino et al. (JCAP 2014)]
- Gamma-ray line expression [Giacchino et al. (JCAP 2013)]
- Experimental constraints from [Garny et al. (JCAP 2013)]
- Numerical computation with MadDM and NLO UFO files

Preliminary

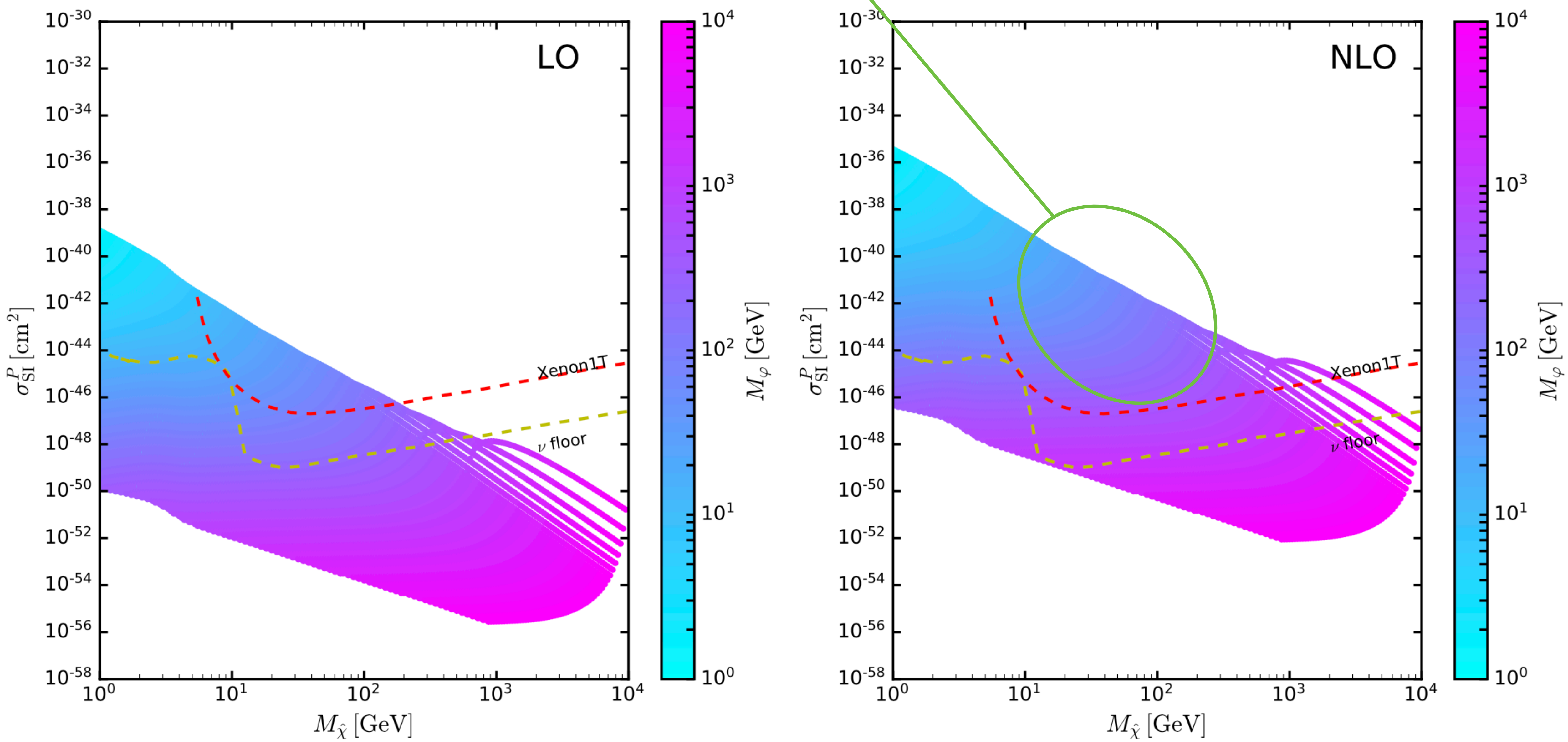
Relic density



Preliminary

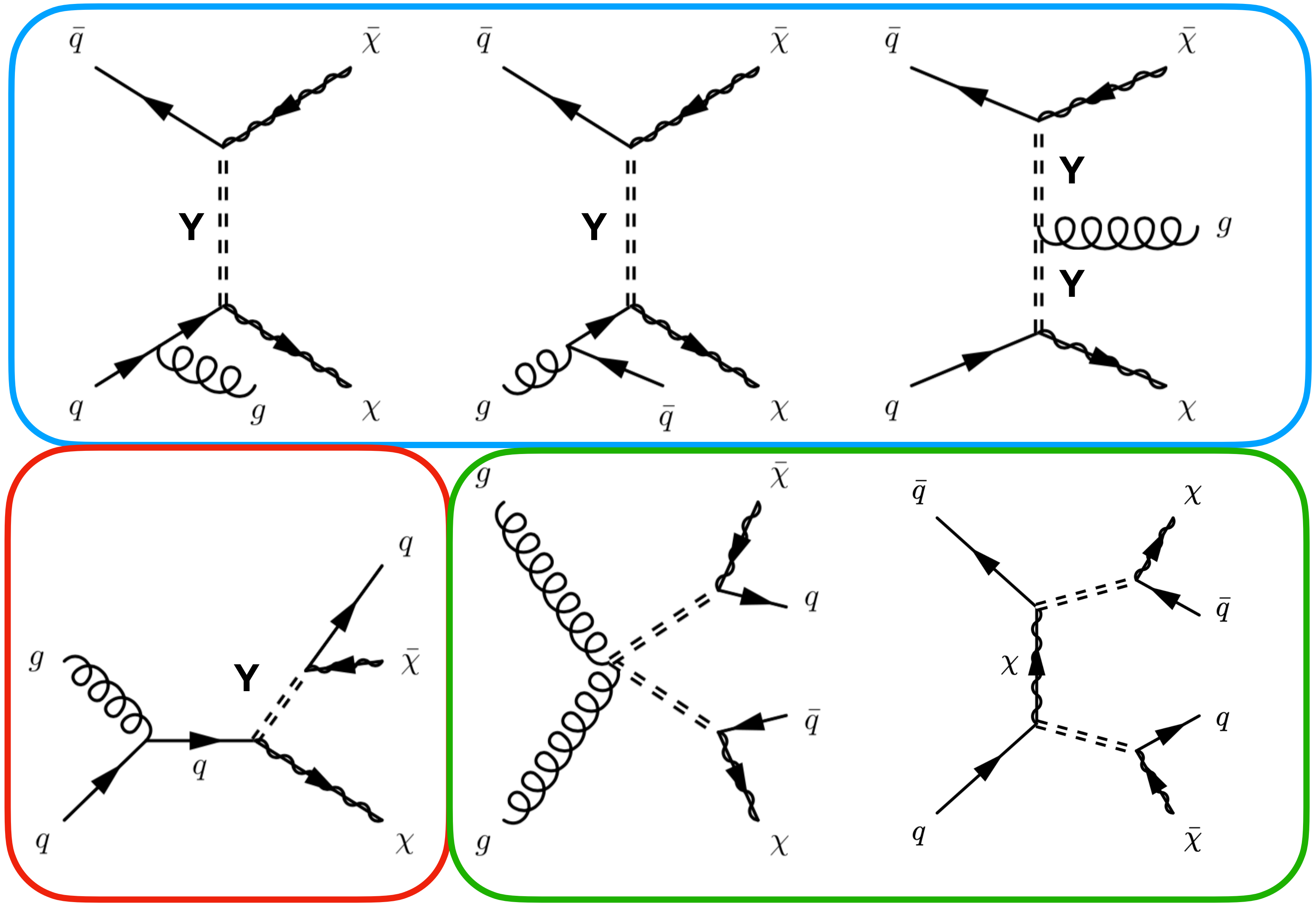
SI direct detection

Excluded



MET + jets

p p —> X X



pp —> X Y, Y —> Xj

pp —> YY, Y —> Xj

Careful handling of resonances at @NLO needed.
Use of MadStr Plugin in mg5_aMC [Frixione et al. (JHEP 2019)]

```
mg5_aMC —mode=MadSTR
generate p p > X X [QCD]
generate p p > X Y [QCD]
generate p p > Y Y [QCD]
decay Y > X j
```

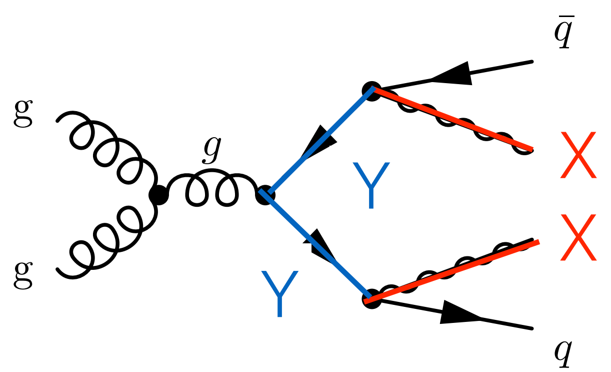
Simulate processes separately
MadSTR takes care double counting

In the prescription used, we removed all square resonant diagram
Interferences of resonant and non resonant are kept

Shell commands in MG5_aMC@NLO for pp —> XX using MadSTR

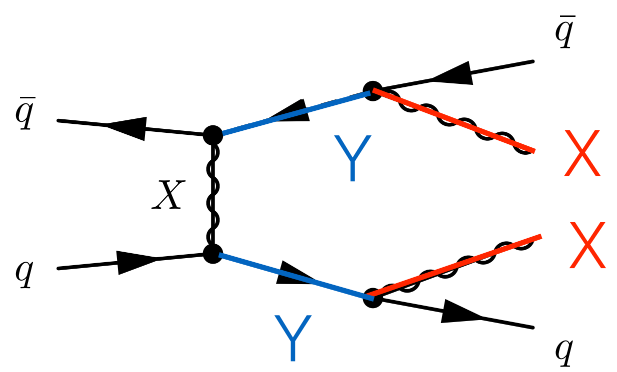
```
import model DMSimpt-S3D_uR --modelname
generate p p > xd xd~ / yf3qu1 yf3qu2 \
yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 \
yf3u3 yf3d1 yf3d2 yf3d3 ys3qu1 ys3qu2 \
ys3qu3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 \
ys3d1 ys3d2 ys3d3 xs xm xv xc xw a z [QCD]

output
```

Important to forbid decoupled particles from loops



$\propto \alpha_s$ (Born)

QCD contribution dominates
Independent of DM mass and coupling



$\propto \lambda_\varphi^2$ (Born)

If DM coupling sizable
t-channel exchange of DM is relevant

Mixed order interference@NLO problematic

1. Simulate Y Y production to get the pure QCD NLO contribution
2. YY production with DMT==2 and QCD==0 coupling computes t-channel dominant contribution
3. Simulate interference at LO and reweight by geometric mean of k-factors (QCD and t-channel) bin by bin

S1	m_X=150 GeV	m_Y=500 GeV	$\lambda_\varphi = 1$
S2	m_X=150 GeV	m_Y=1000 GeV	$\lambda_\varphi = 1$

t-channel contribution to YY sizable

Heavy mediator, closer to actual SUSY bounds

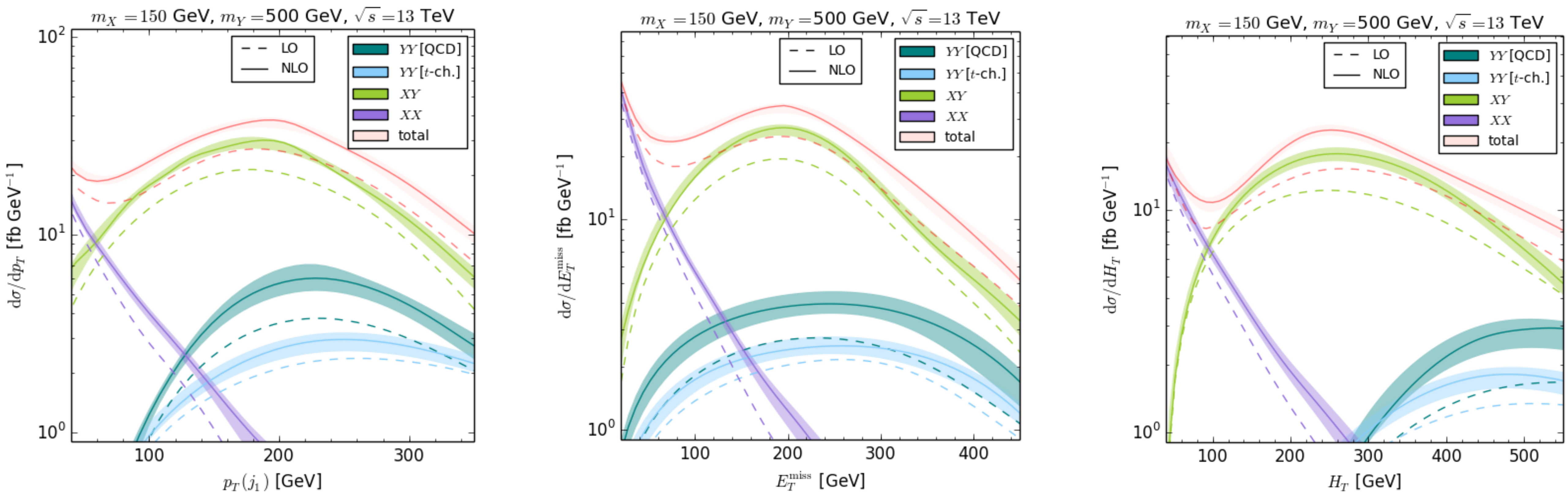
Theoretical scale uncertainties

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

Uncertainties from parton density fit

Benefits of NLO
Large K-factors: avoid underestimating the signal
Reduction of theoretical systematic uncertainties

Collider constraints: S1



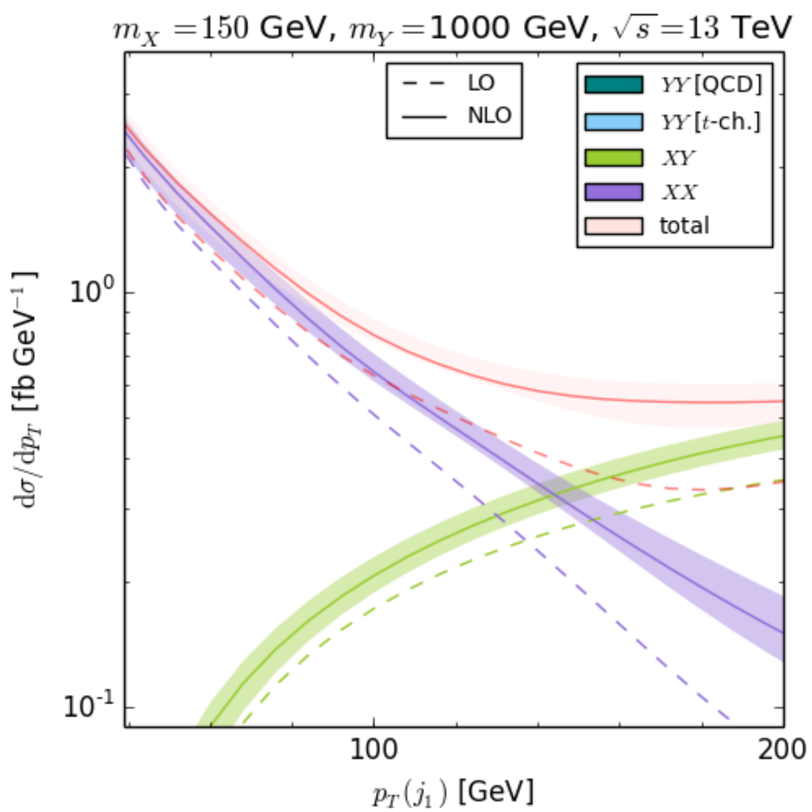
Irrelevant

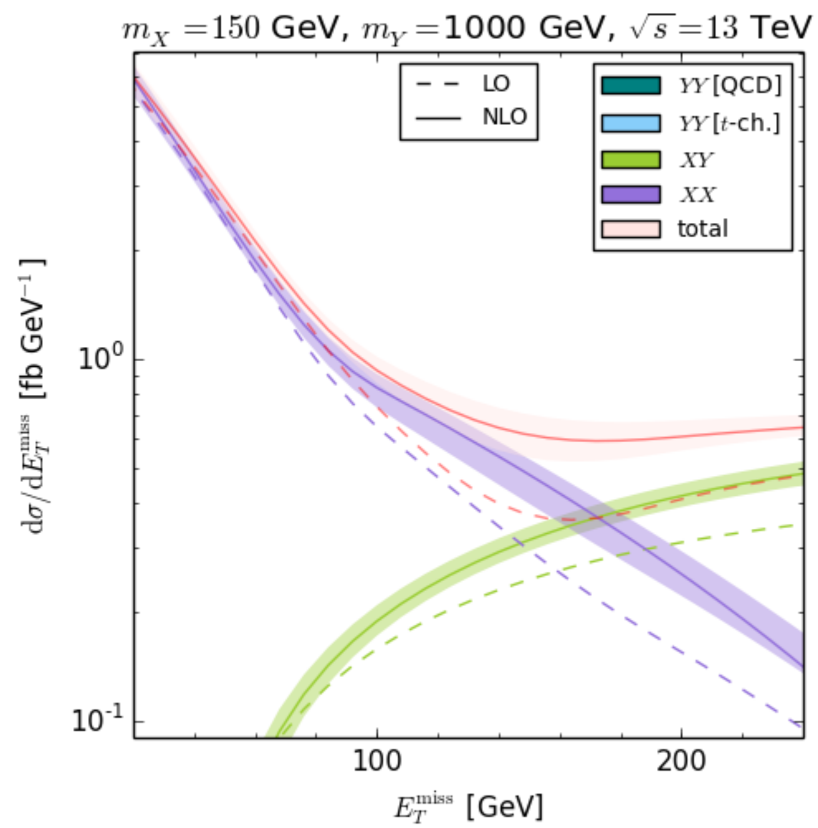
Most important

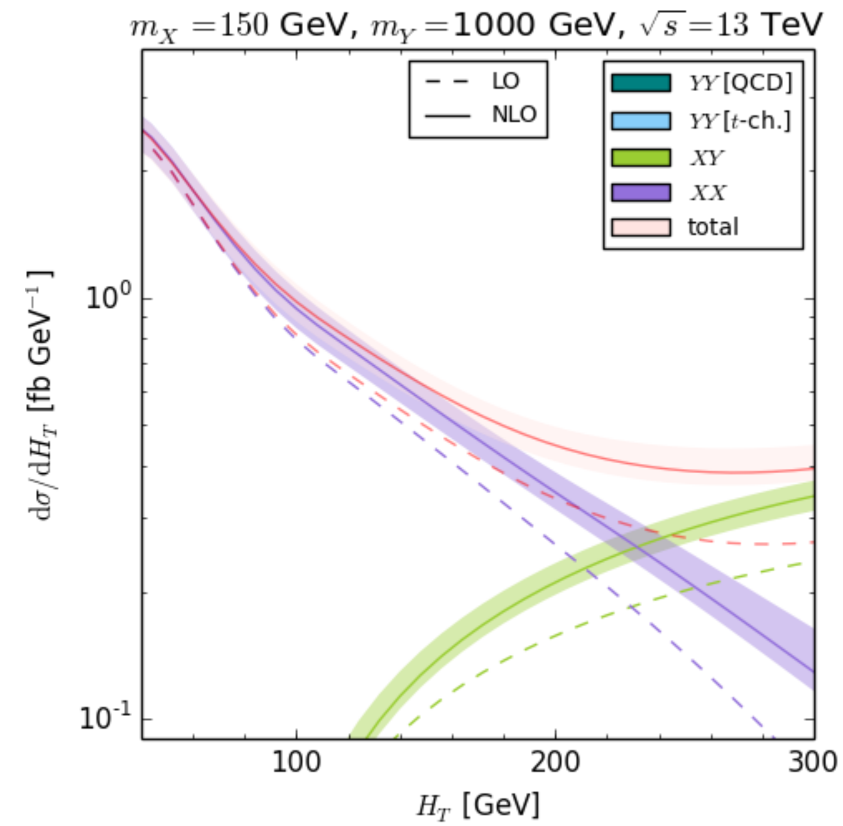
Process	CL_s [LO]	E_T^{miss} constraint	CL_s [NLO]	E_T^{miss} constrtaint
Total	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
XX	$1.6^{+0.2}_{-0.1}$ %	$\in [300, 350]$ GeV	$9.4^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV
XY	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
YY [total]	$91.3^{+6.2}_{-8.8}$ %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
YY [QCD]	$63.0^{+20.0}_{-17.2}$ %	$\in [300, 350]$ GeV	$88.3^{+4.8}_{-7.4}$ %	$\in [300, 350]$ GeV
YY [t-channel]	$70.8^{+5.0}_{-4.6}$ %	$\in [300, 350]$ GeV	$87.2^{+1.0}_{-1.4}$ %	$\in [300, 350]$ GeV

ATLAS-EXOT-2016-27 (most constraining signal region only)

Collider constraints: 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

< 95% CL

Large σ

ATLAS-EXOT-2016-27 (most constraining signal region only)

- DMSimp-t framework provides a flexible tool to perform comprehensive analyses
- UFO provided with several DM candidates and restriction to specific models
- Astrophysical and cosmological constraints can help identify viable regions of parameter space
- NLO QCD corrections are relevant at colliders and should be included
- Special care is needed in simulations for colliders to combine the different channels
- Both NLO and combination of channels are crucial to set robust exclusion bounds
- Part of an on-going effort with a focus on the pheno for all models, complementary between cosmology & LHC and the potential of LHC & future colliders to distinguish between different models.
  [M. Kramer, B. Fuks, C. Arina, K. Mawatari, L. Panizzi, J. Heisig, LM, H. Mies, J. Salko]

Thanks!