



# A universal framework for t-channel dark matter models

---

**Luca Mantani**

In collaboration with:  
C. Arina, B. Fuks  
based on [arXiv:2001.05024 \[hep-ph\]](https://arxiv.org/abs/2001.05024)

Special thank to Chiara  
for some of the slides

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

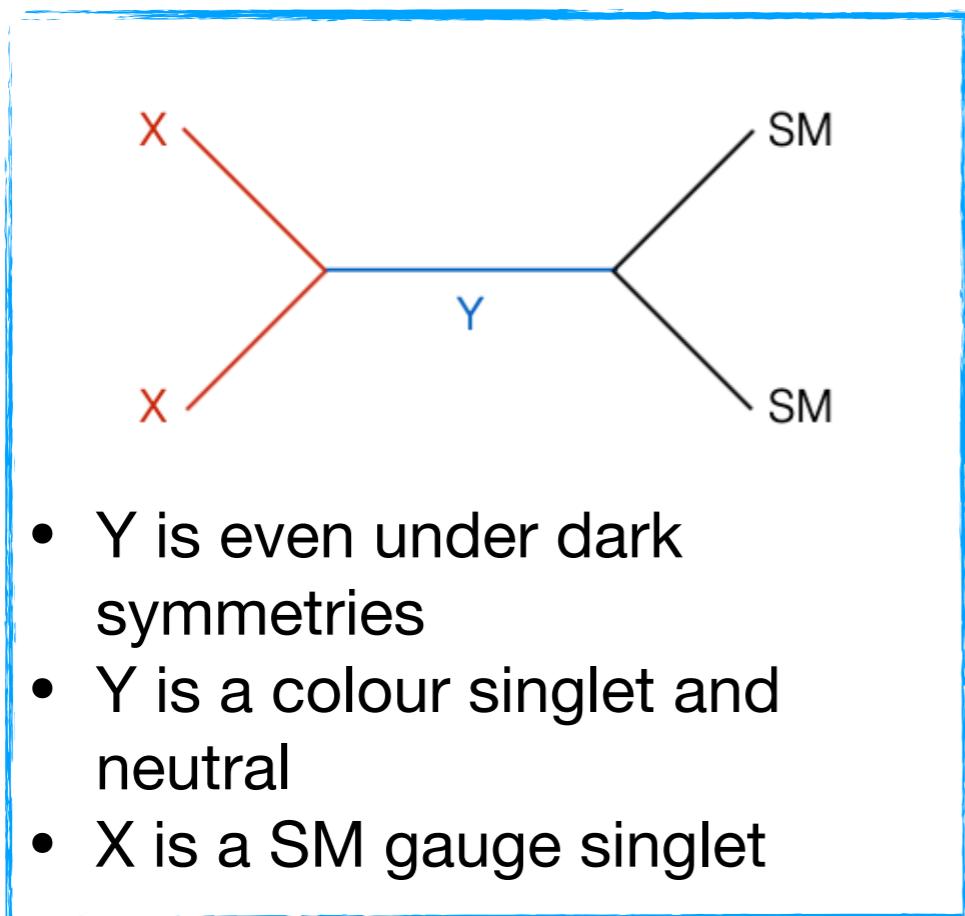
- ❖ **Dark Matter particle stable and neutral**
- ❖ **The Lagrangian has to respect gauge symmetries**



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

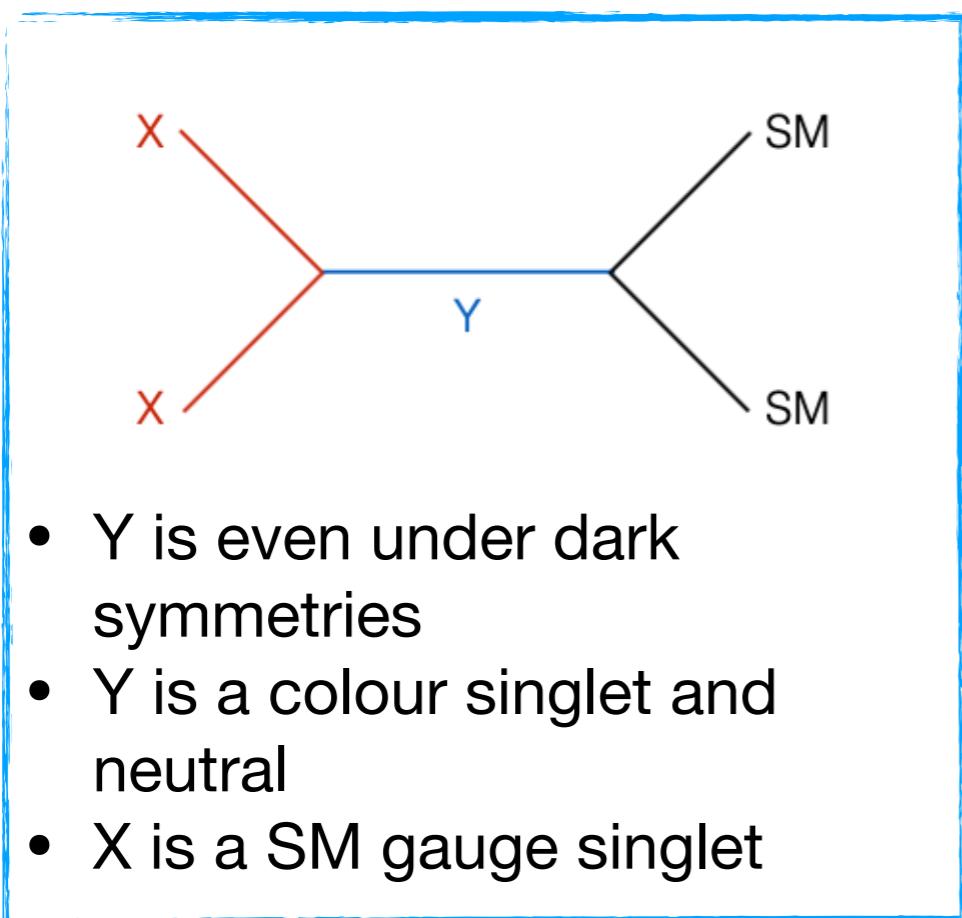
## s-channel models



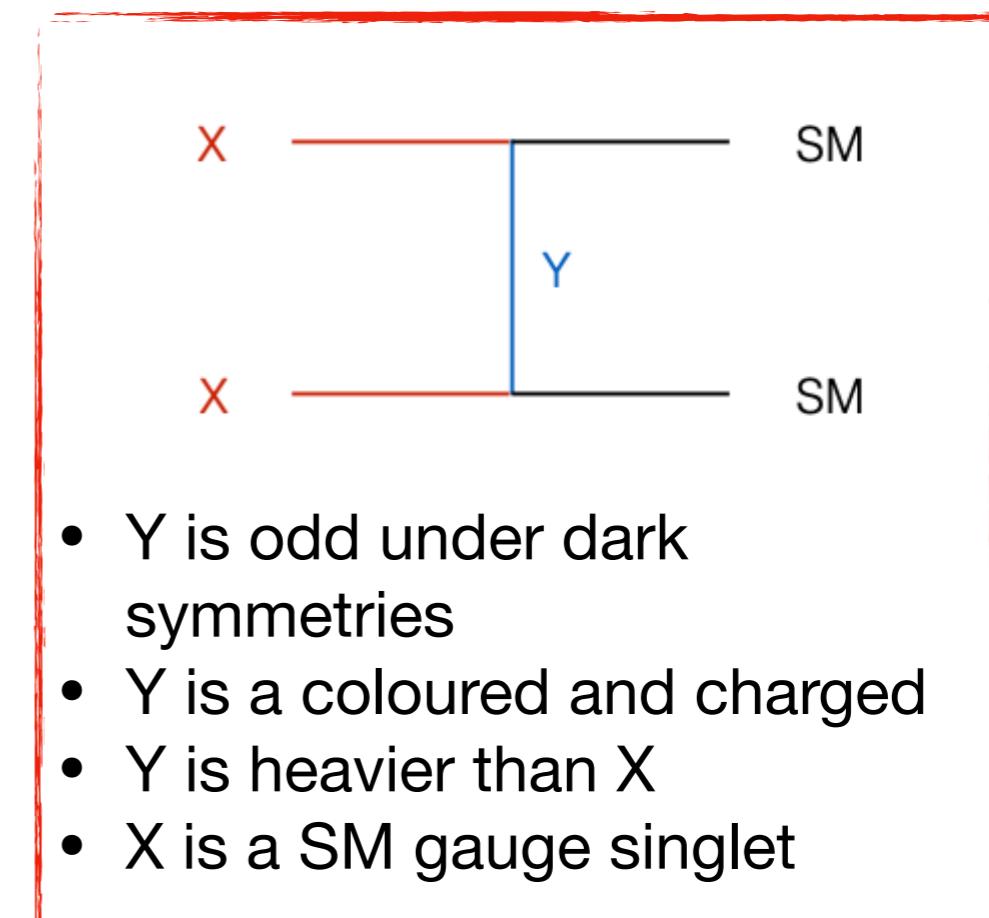
Extend the Standard model by adding a mediator particle in addition to Dark Matter.

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

### s-channel models



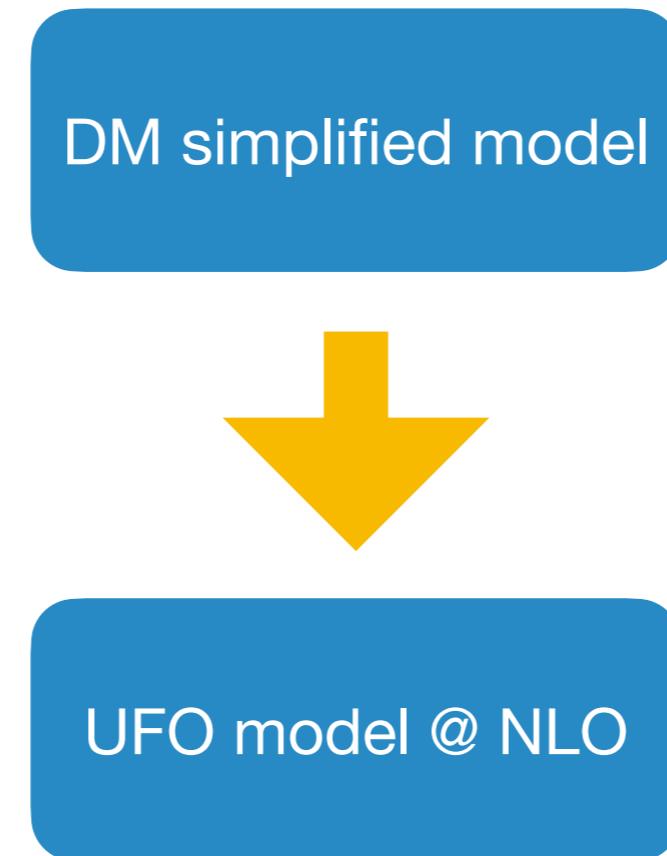
### t-channel models



DM simplified model

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

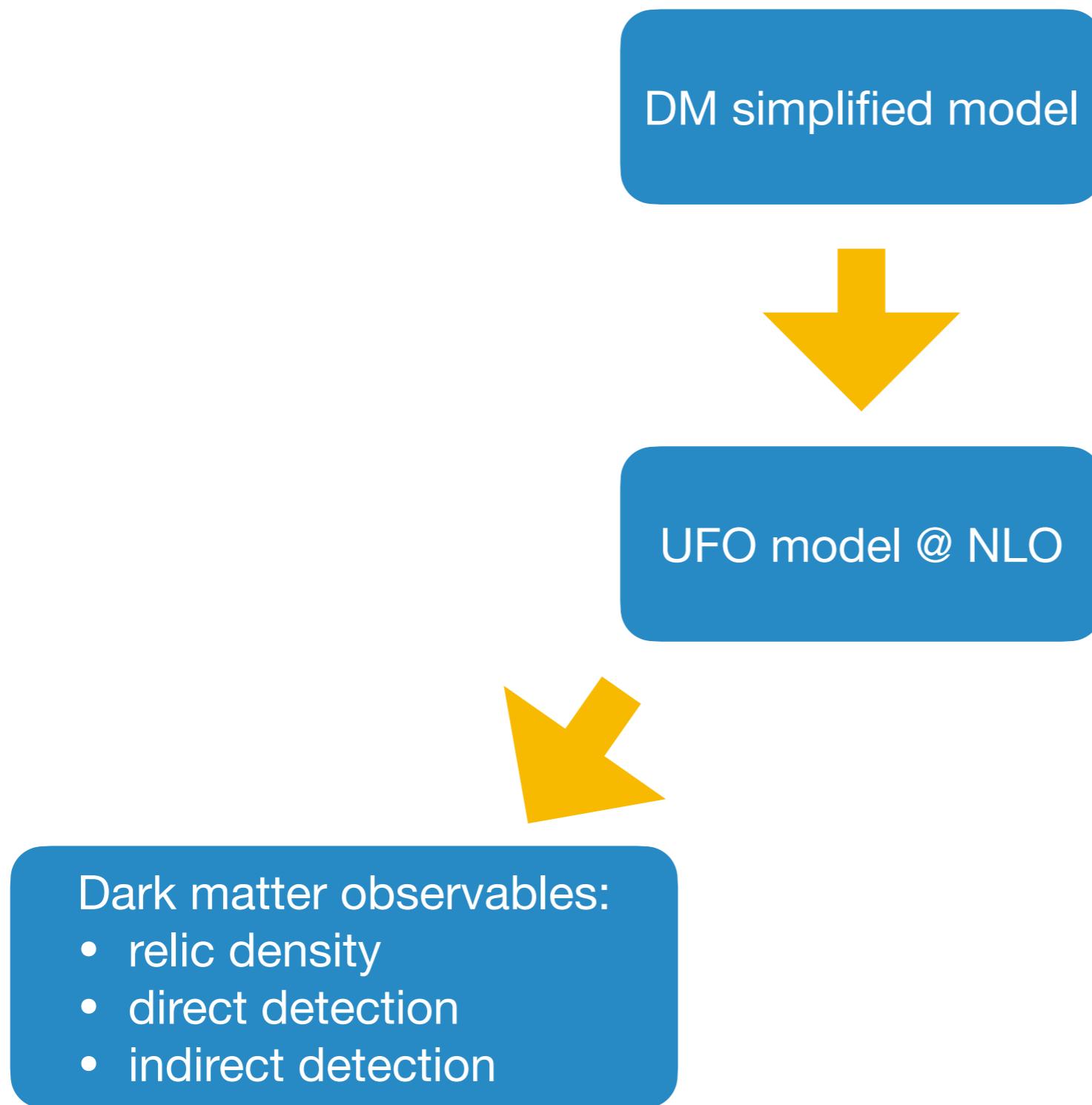




$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM}(Y, X)$$

**FeynRules + NLOCT**

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



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

**FeynRules + NLOCT**

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

Dark matter observables:

- relic density
- direct detection
- indirect detection

- MadDM [Ambrogi, CA, et al. (PDU 2019)]

- MicrOmegas [Belanger et al. (CPC 2018)]

DM simplified model



UFO model @ NLO

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

FeynRules + NLOCT

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



Dark matter observables:

- relic density
- direct detection
- indirect detection

Collider signatures:

- Decays
- Parton shower

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

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

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

Field	Spin	Repr.	Self-conj.
$\tilde{S}$	0	(1, 1, 0)	yes
$S$	0	(1, 1, 0)	no
$\tilde{\chi}$	1/2	(1, 1, 0)	yes
$\chi$	1/2	(1, 1, 0)	no
$\tilde{V}_\mu$	1	(1, 1, 0)	yes
$V_\mu$	1	(1, 1, 0)	no

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

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

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

X

Y

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

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

Field	Spin	Repr.	Self-conj.
$\tilde{S}$	0	(1, 1, 0)	yes
$S$	0	(1, 1, 0)	no
$\tilde{\chi}$	1/2	(1, 1, 0)	yes
$\chi$	1/2	(1, 1, 0)	no
$\tilde{V}_\mu$	1	(1, 1, 0)	yes
$V_\mu$	1	(1, 1, 0)	no
$\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$	0	(3, 2, $\frac{1}{6}$ )	no
$\varphi_u$	0	(3, 1, $\frac{2}{3}$ )	no
$\varphi_d$	0	(3, 1, $-\frac{1}{3}$ )	no

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

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

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

X

Y

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

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

Field	Spin	Repr.	Self-conj.
$\tilde{S}$	0	(1, 1, 0)	yes
$S$	0	(1, 1, 0)	no
$\tilde{\chi}$	1/2	(1, 1, 0)	yes
$\chi$	1/2	(1, 1, 0)	no
$\tilde{V}_\mu$	1	(1, 1, 0)	yes
$V_\mu$	1	(1, 1, 0)	no

$\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$	0	(3, 2, $\frac{1}{6}$ )	no
$\varphi_u$	0	(3, 1, $\frac{2}{3}$ )	no
$\varphi_d$	0	(3, 1, $-\frac{1}{3}$ )	no

$\psi_Q = \begin{pmatrix} \psi_Q^{(u)} \\ \psi_Q^{(d)} \end{pmatrix}$	1/2	(3, 2, $\frac{1}{6}$ )	no
$\psi_u$	1/2	(3, 1, $\frac{2}{3}$ )	no
$\psi_d$	1/2	(3, 1, $-\frac{1}{3}$ )	no

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

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

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

**X****Y**

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

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

Field	Spin	Repr.	Self-conj.
$\tilde{S}$	0	(1, 1, 0)	yes
$S$	0	(1, 1, 0)	no
$\tilde{\chi}$	1/2	(1, 1, 0)	yes
$\chi$	1/2	(1, 1, 0)	no
$\tilde{V}_\mu$	1	(1, 1, 0)	yes
$V_\mu$	1	(1, 1, 0)	no

$\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$	0	(3, 2, $\frac{1}{6}$ )	no
$\varphi_u$	0	(3, 1, $\frac{2}{3}$ )	no
$\varphi_d$	0	(3, 1, $-\frac{1}{3}$ )	no

$\psi_Q = \begin{pmatrix} \psi_Q^{(u)} \\ \psi_Q^{(d)} \end{pmatrix}$	1/2	(3, 2, $\frac{1}{6}$ )	no
$\psi_u$	1/2	(3, 1, $\frac{2}{3}$ )	no
$\psi_d$	1/2	(3, 1, $-\frac{1}{3}$ )	no

$$\mathcal{L}_F(X) = [\lambda_Q \bar{X} Q \varphi_Q^\dagger + \lambda_u \bar{X} u \varphi_u^\dagger + \lambda_d \bar{X} d \varphi_d^\dagger + \text{h.c.}]$$

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

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

couplings

3x3 matrices in flavour space  
real and flavour diagonal

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

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

Field	Spin	Repr.	Self-conj.
$\tilde{S}$	0	(1, 1, 0)	yes
$S$	0	(1, 1, 0)	no
$\tilde{\chi}$	1/2	(1, 1, 0)	yes
$\chi$	1/2	(1, 1, 0)	no
$\tilde{V}_\mu$	1	(1, 1, 0)	yes
$V_\mu$	1	(1, 1, 0)	no

$\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$	0	(3, 2, $\frac{1}{6}$ )	no
$\varphi_u$	0	(3, 1, $\frac{2}{3}$ )	no
$\varphi_d$	0	(3, 1, $-\frac{1}{3}$ )	no

$\psi_Q = \begin{pmatrix} \psi_Q^{(u)} \\ \psi_Q^{(d)} \end{pmatrix}$	1/2	(3, 2, $\frac{1}{6}$ )	no
$\psi_u$	1/2	(3, 1, $\frac{2}{3}$ )	no
$\psi_d$	1/2	(3, 1, $-\frac{1}{3}$ )	no

$$\mathcal{L}_F(X) = [\lambda_Q \bar{X} Q \varphi_Q^\dagger + \lambda_u \bar{X} u \varphi_u^\dagger + \lambda_d \bar{X} d \varphi_d^\dagger + \text{h.c.}]$$

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

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

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

Each restriction has 3 free parameters.

Three broad classes:

- Fermionic DM
- Scalar DM
- Vector DM

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

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

Each restriction has 3 free parameters.

Three broad classes:

- Fermionic DM
- Scalar DM
- Vector DM

coupling only to quark up-right

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

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

Each restriction has 3 free parameters.

Three broad classes:

- Fermionic DM
- Scalar DM
- Vector DM

coupling only to b and t quarks

coupling only to quark up-right

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

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

Each restriction has 3 free parameters.

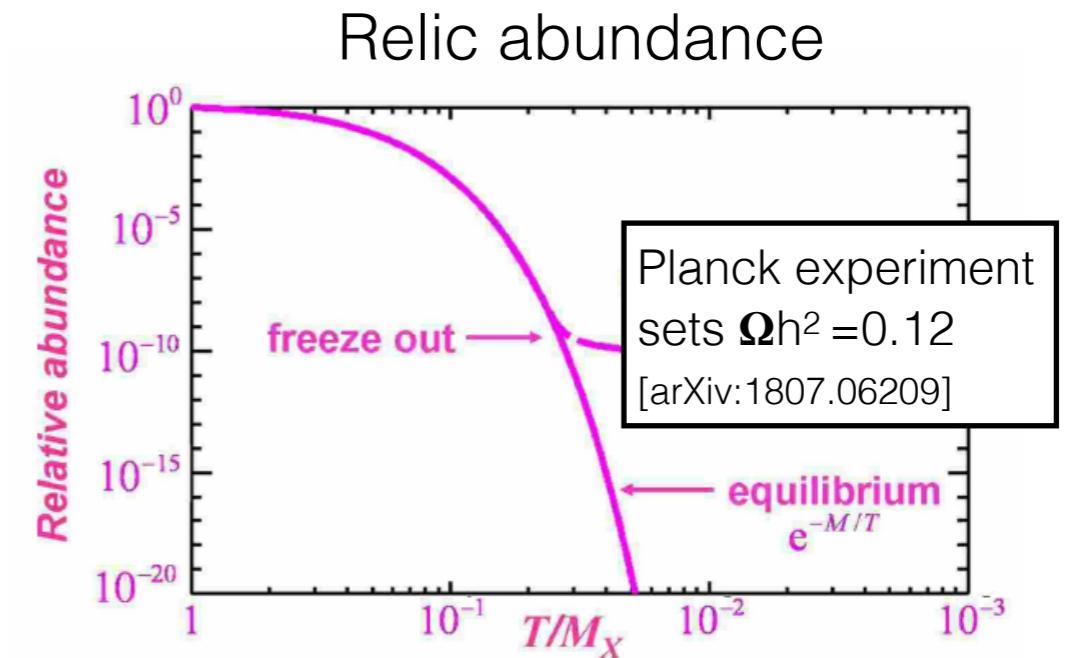
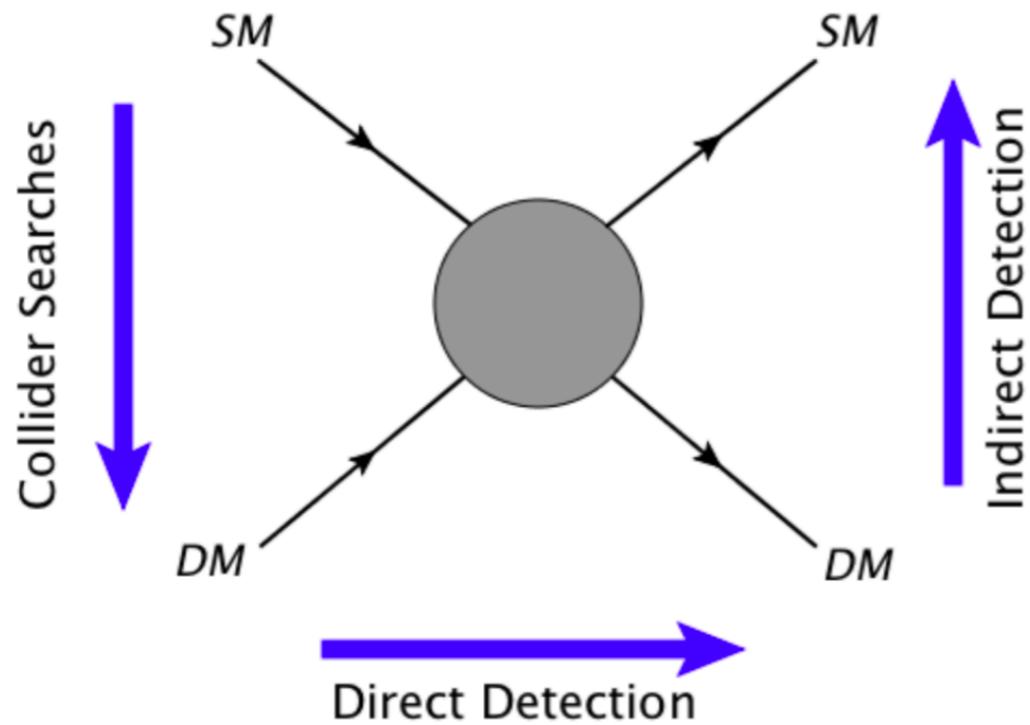
Three broad classes:

- Fermionic DM
- Scalar DM
- Vector DM

coupling to all quarks

coupling only to b and t quarks

coupling only to quark up-right



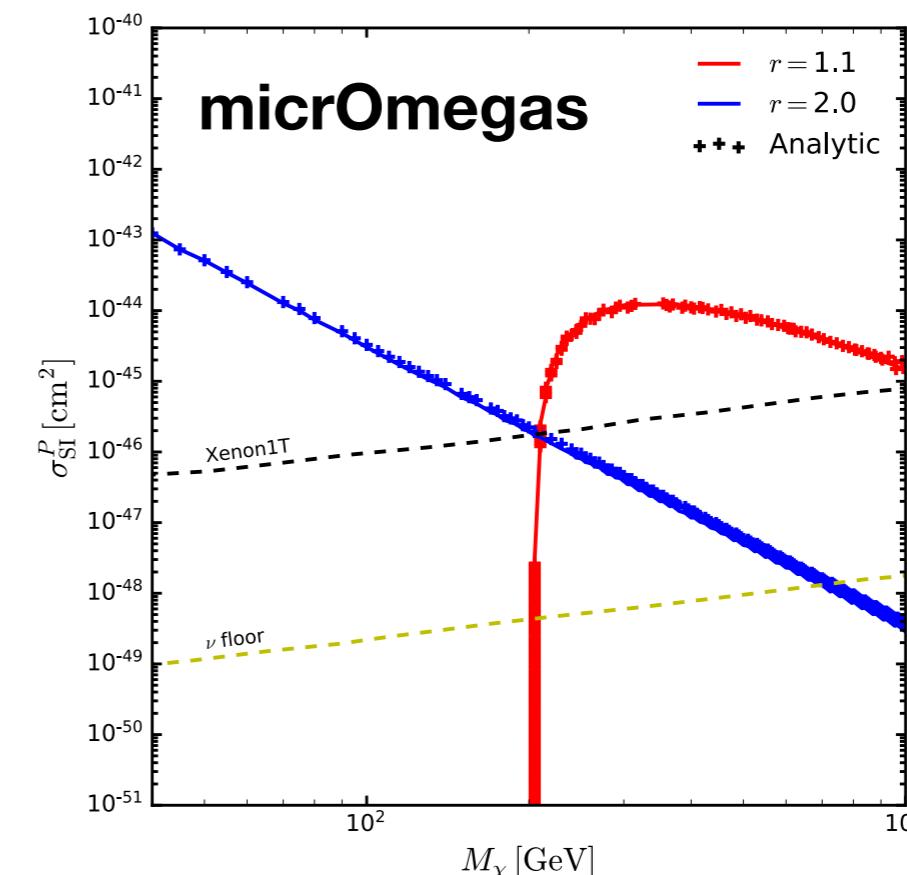
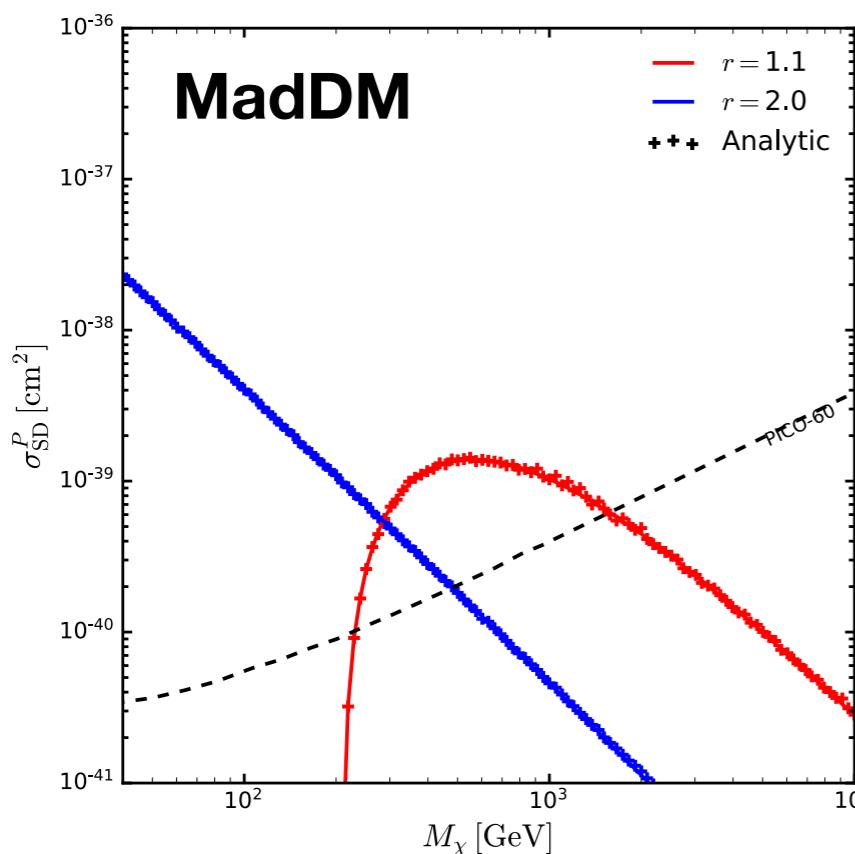
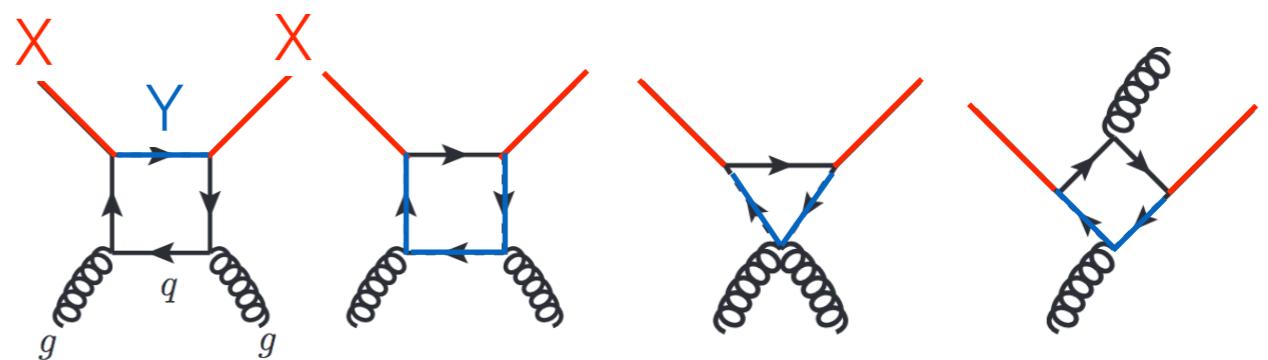
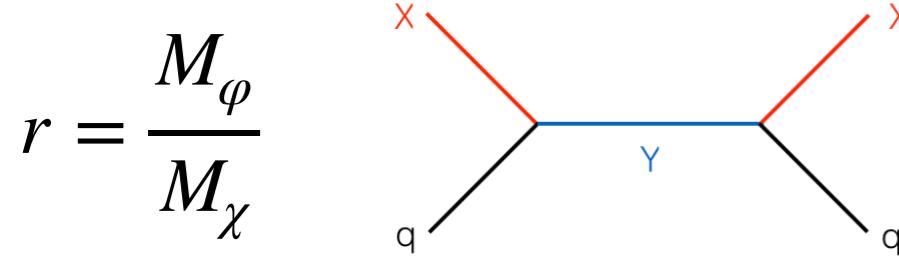
These observables can severely constrain the parameter space of the model and help identify interesting regions of the parameter space for the LHC

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

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

## Direct detection

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

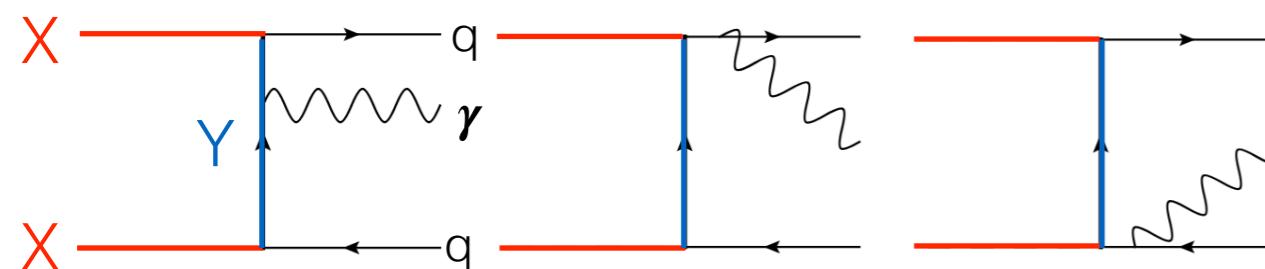


$$\mathcal{L}_{X\_uR}(X) = \left[ \lambda_\varphi \bar{X} u_1 \varphi_{u_1}^\dagger + \text{h.c.} \right]$$

Indirect detection

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

Virtual internal bremsstrahlung (VIB)

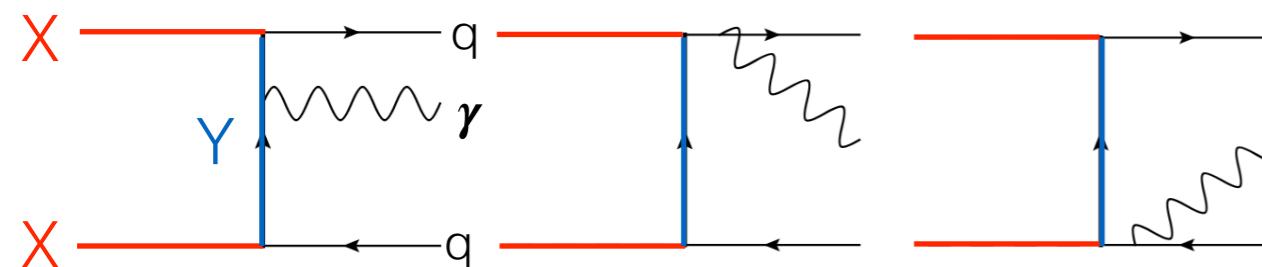


$$\mathcal{L}_{X\_uR}(X) = \left[ \lambda_\varphi \bar{X} u_1 \varphi_{u_1}^\dagger + \text{h.c.} \right]$$

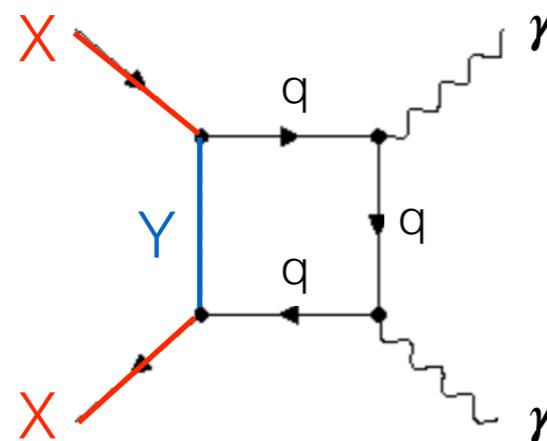
Indirect detection

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

Virtual internal bremsstrahlung (VIB)



Loop-induced diphotons

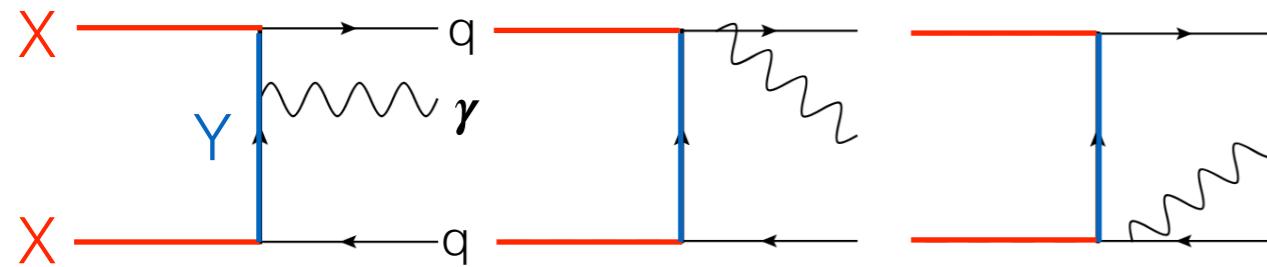


$$\mathcal{L}_{X\_uR}(X) = \left[ \lambda_\varphi \bar{X} u_1 \varphi_{u_1}^\dagger + \text{h.c.} \right]$$

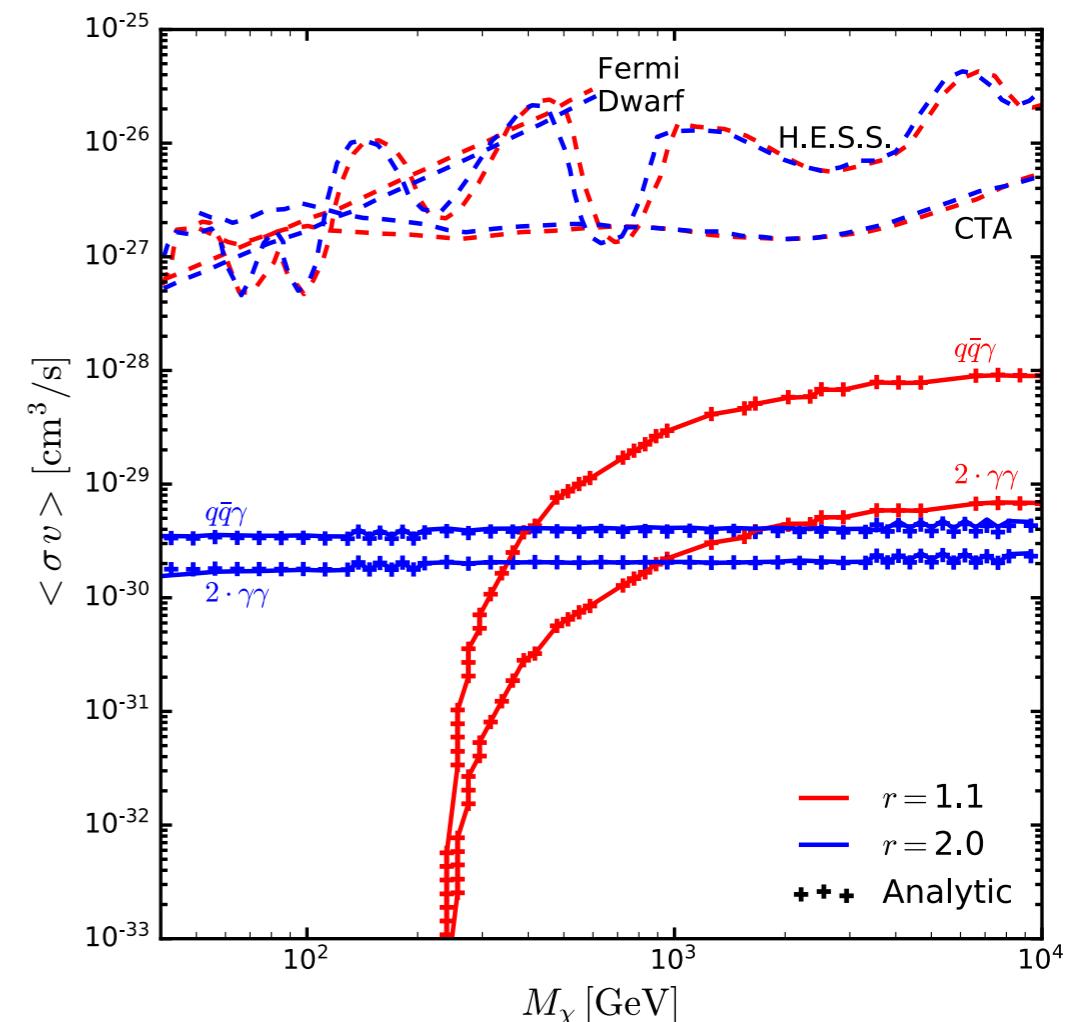
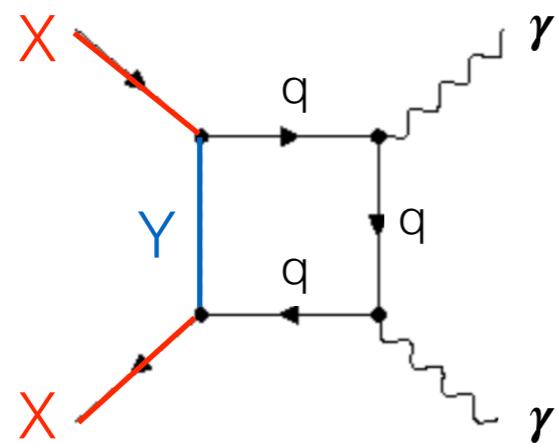
## Indirect detection

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

### Virtual internal bremsstrahlung (VIB)



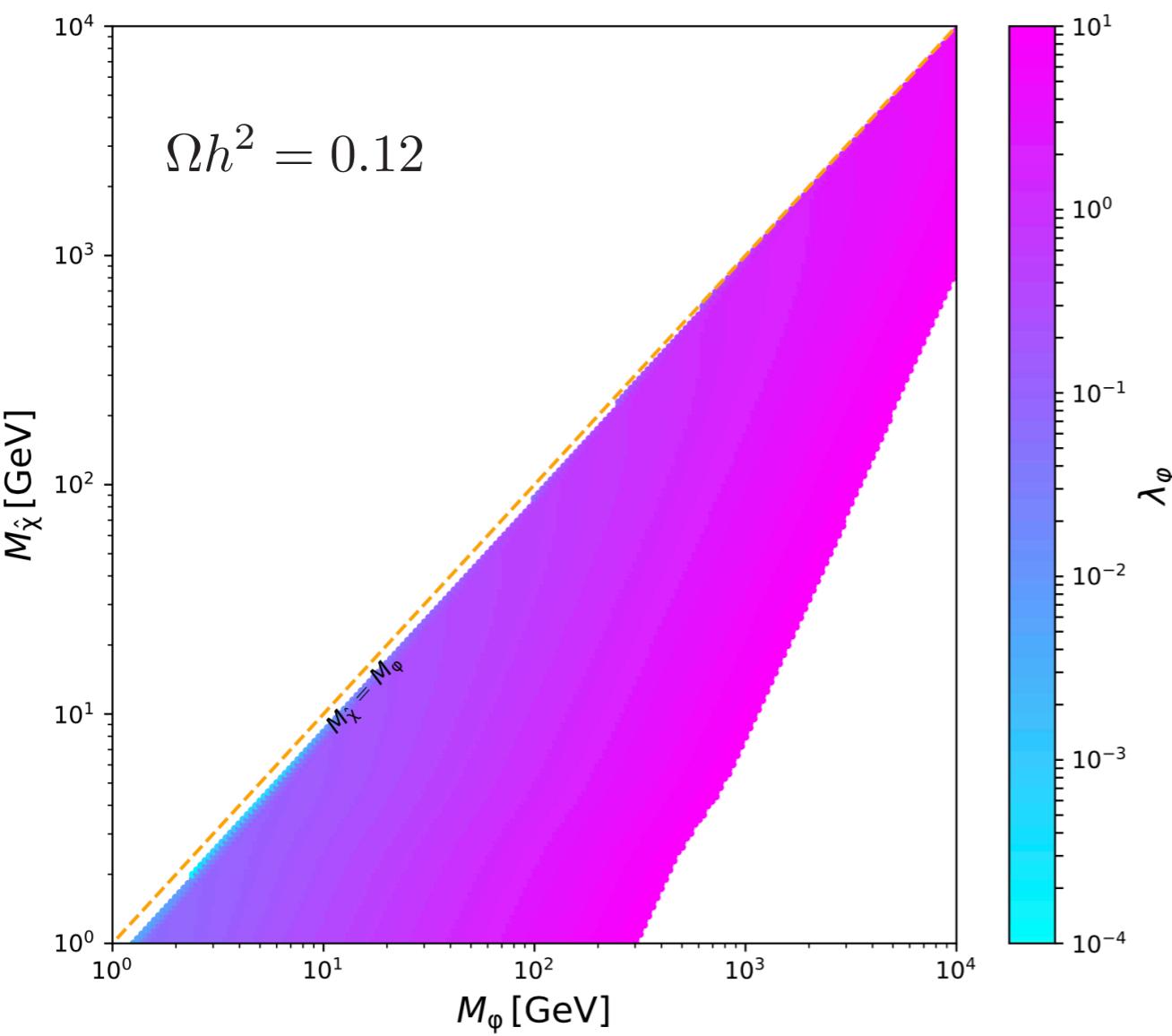
### Loop-induced diphotons



- 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

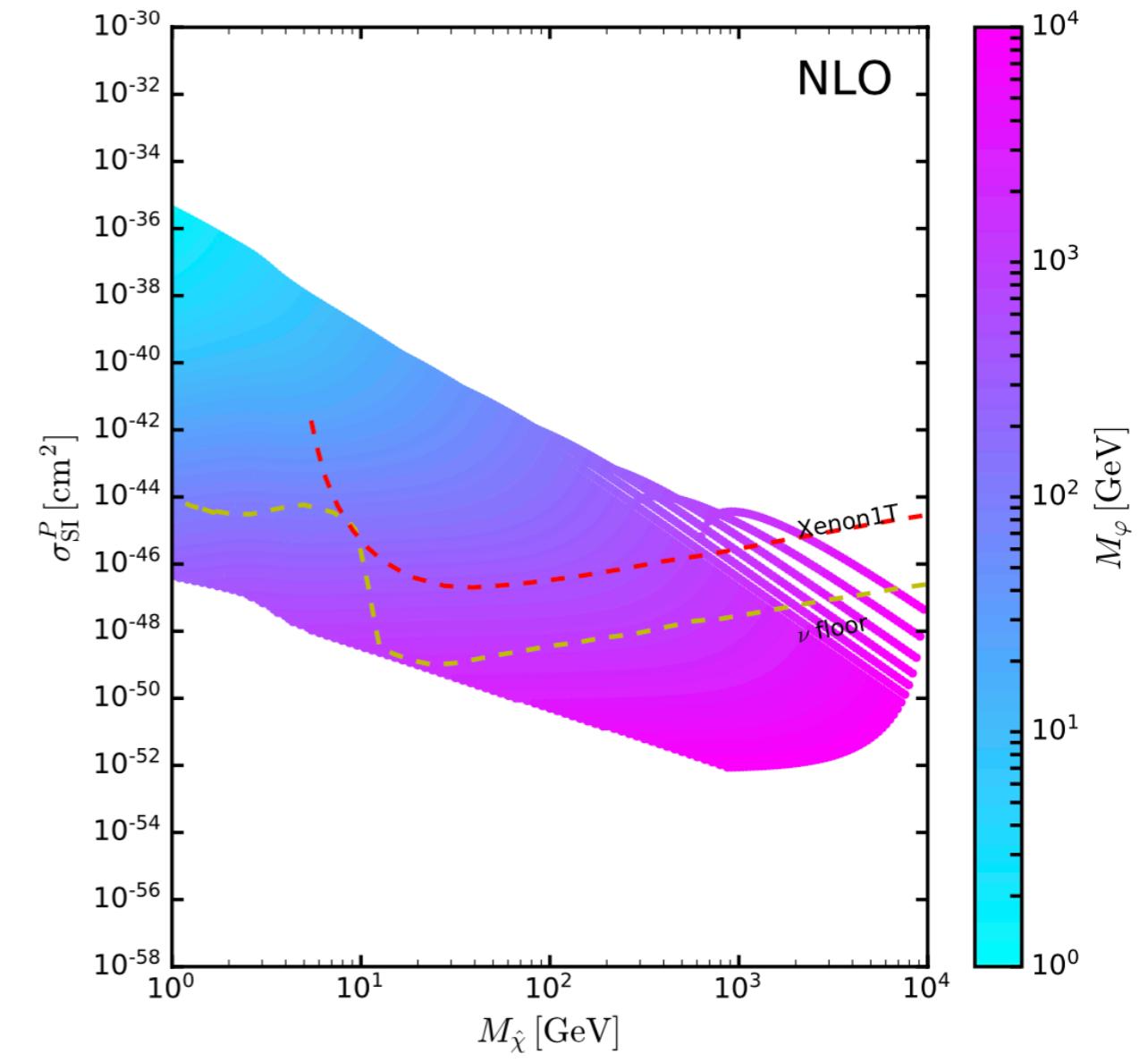
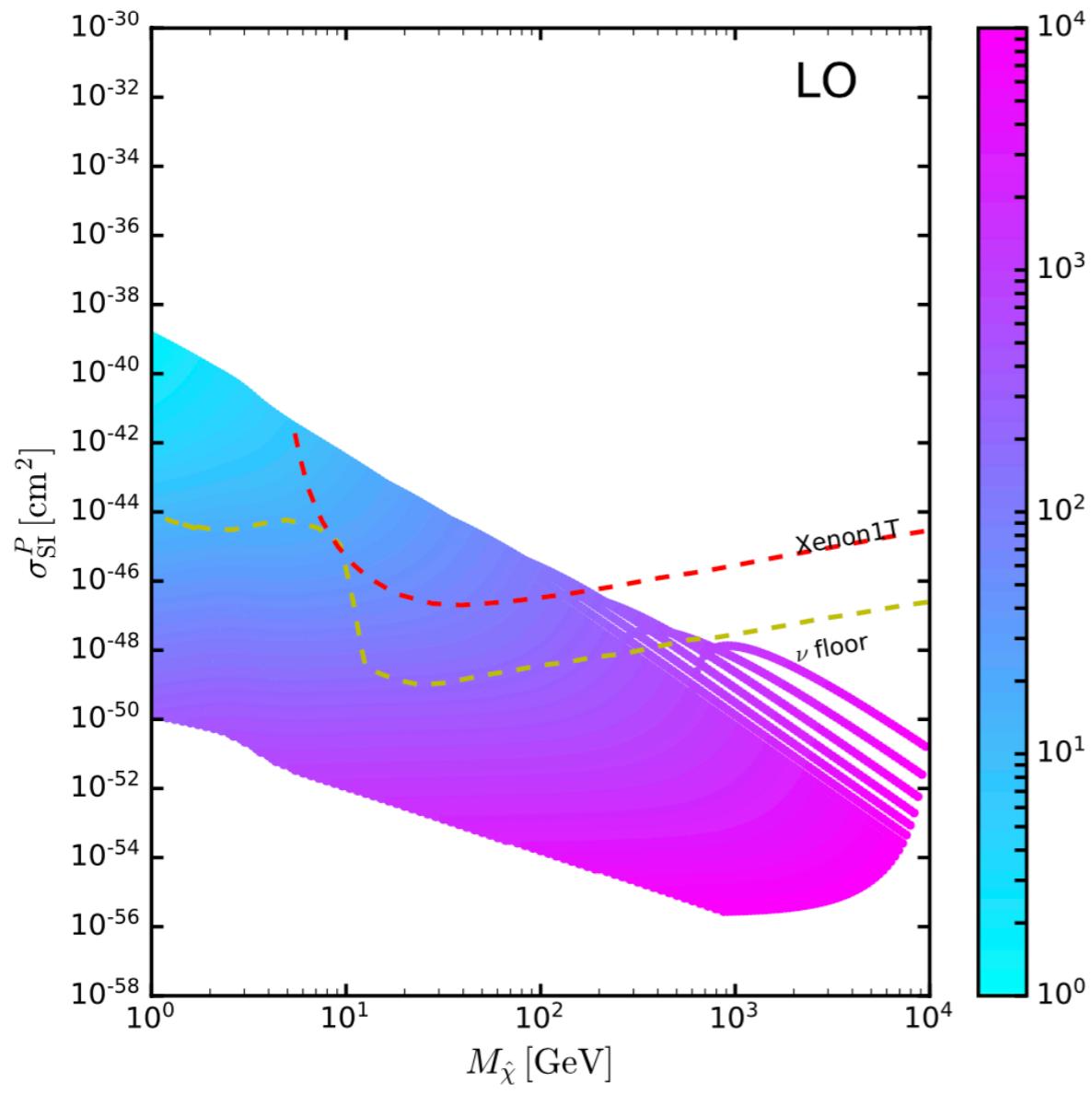
Preliminary

Relic density



Preliminary

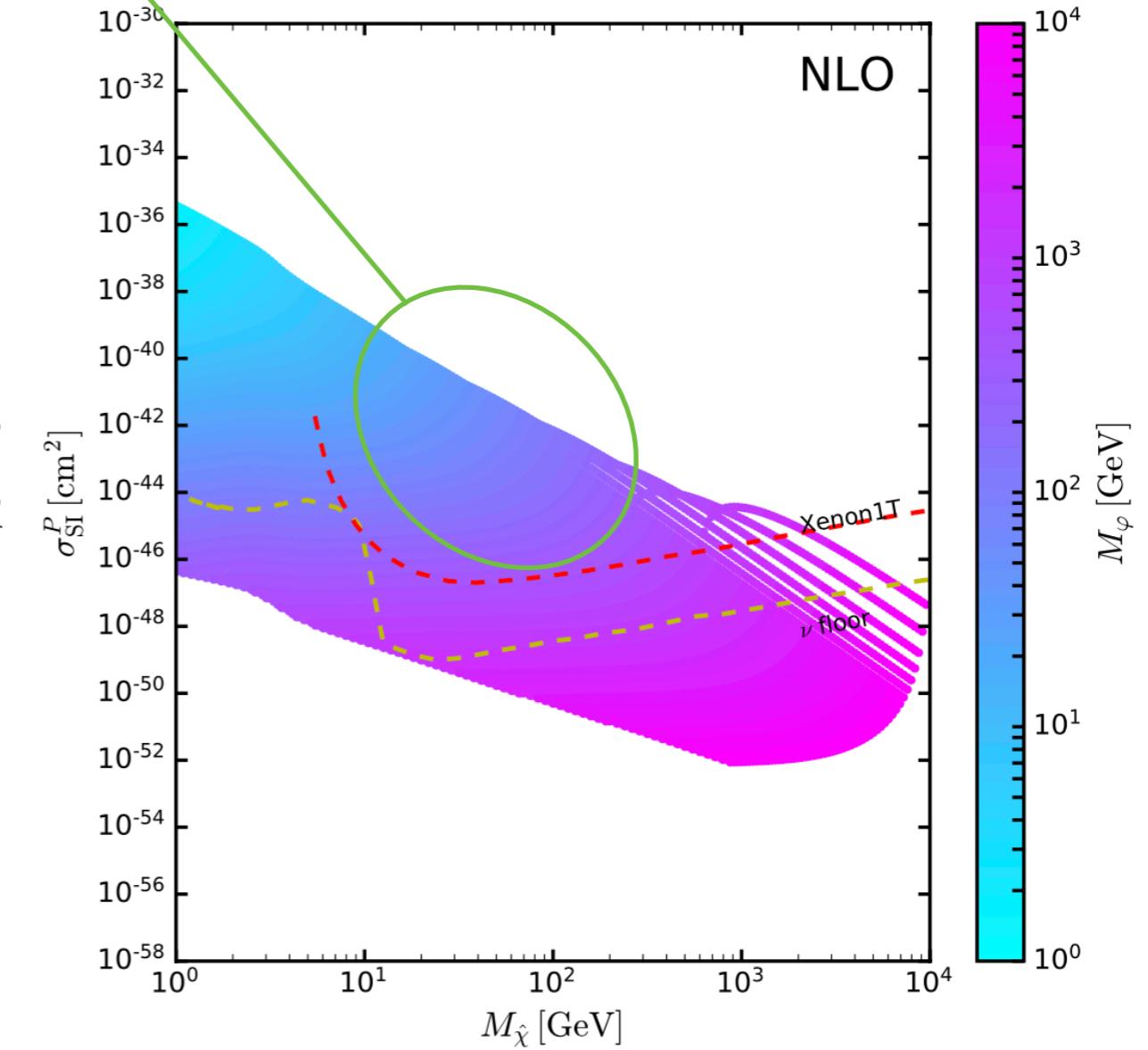
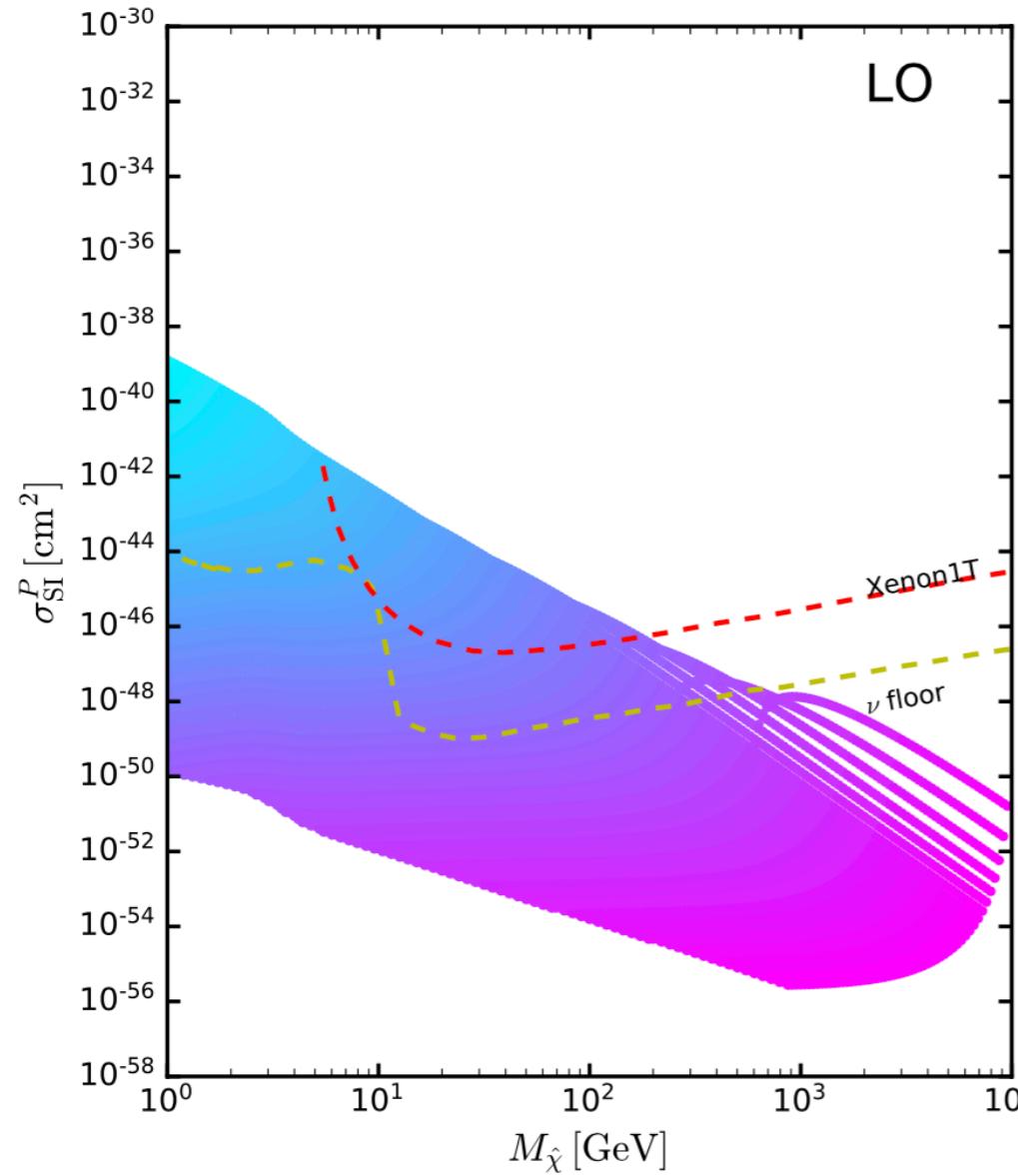
## SI direct detection

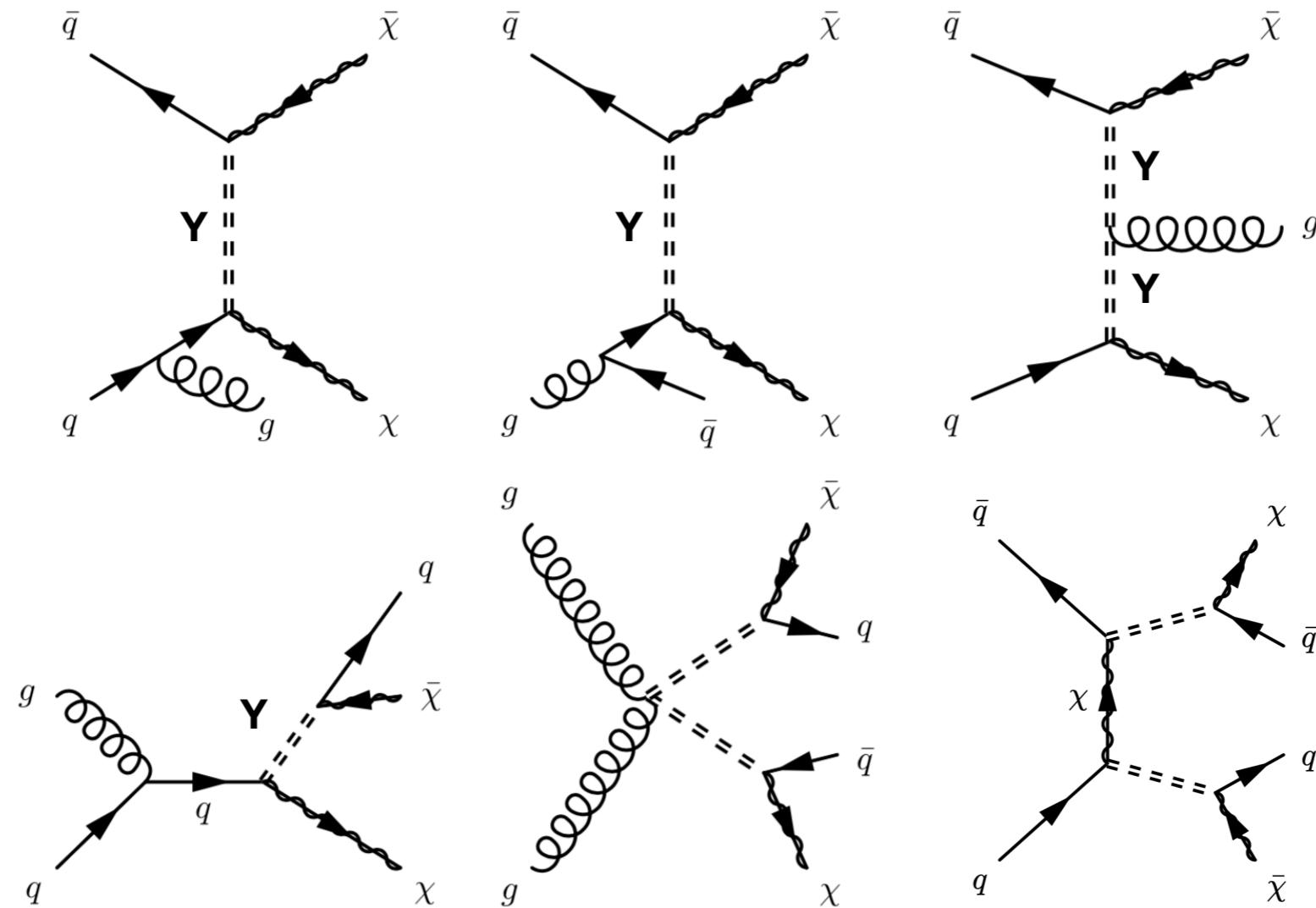


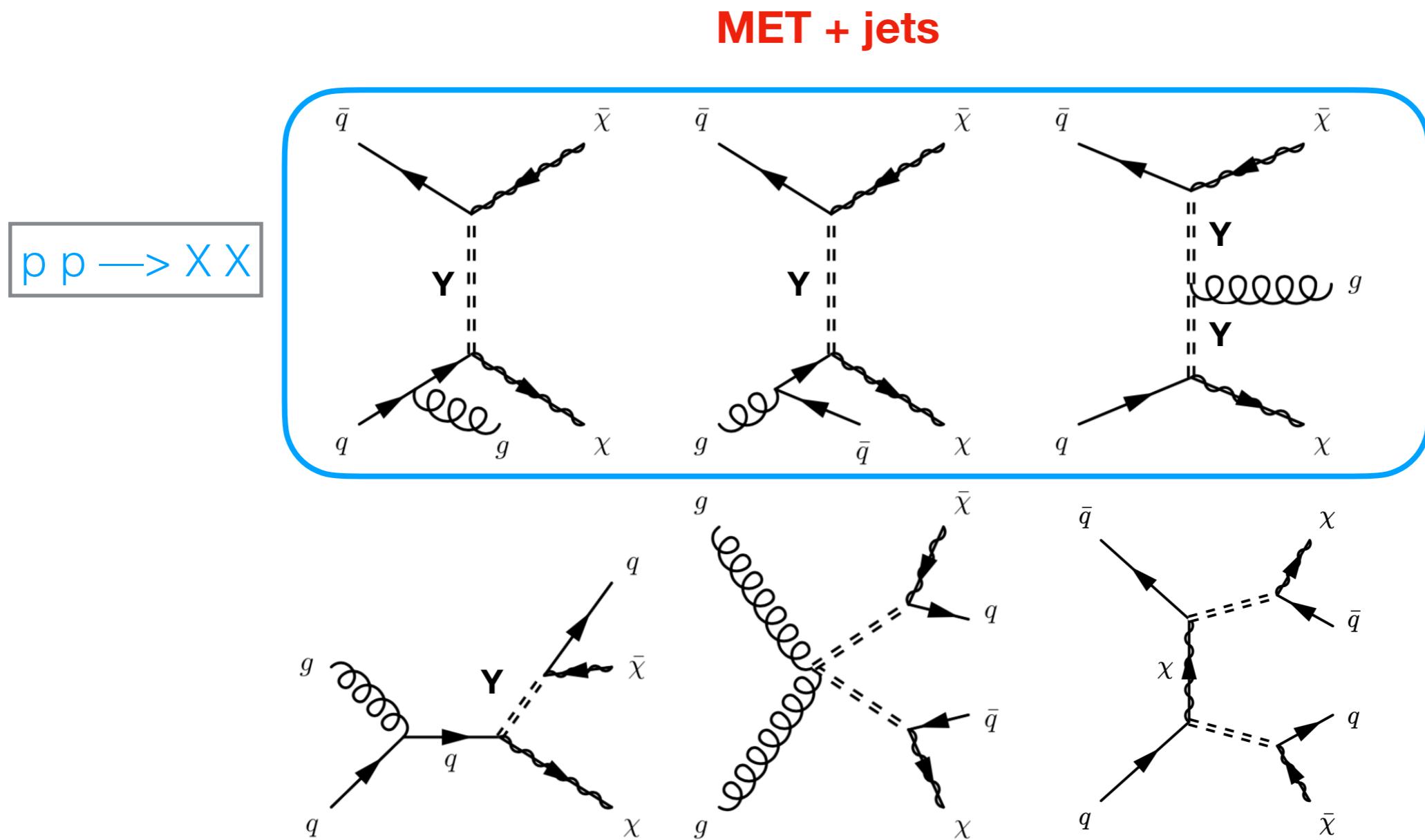
Preliminary

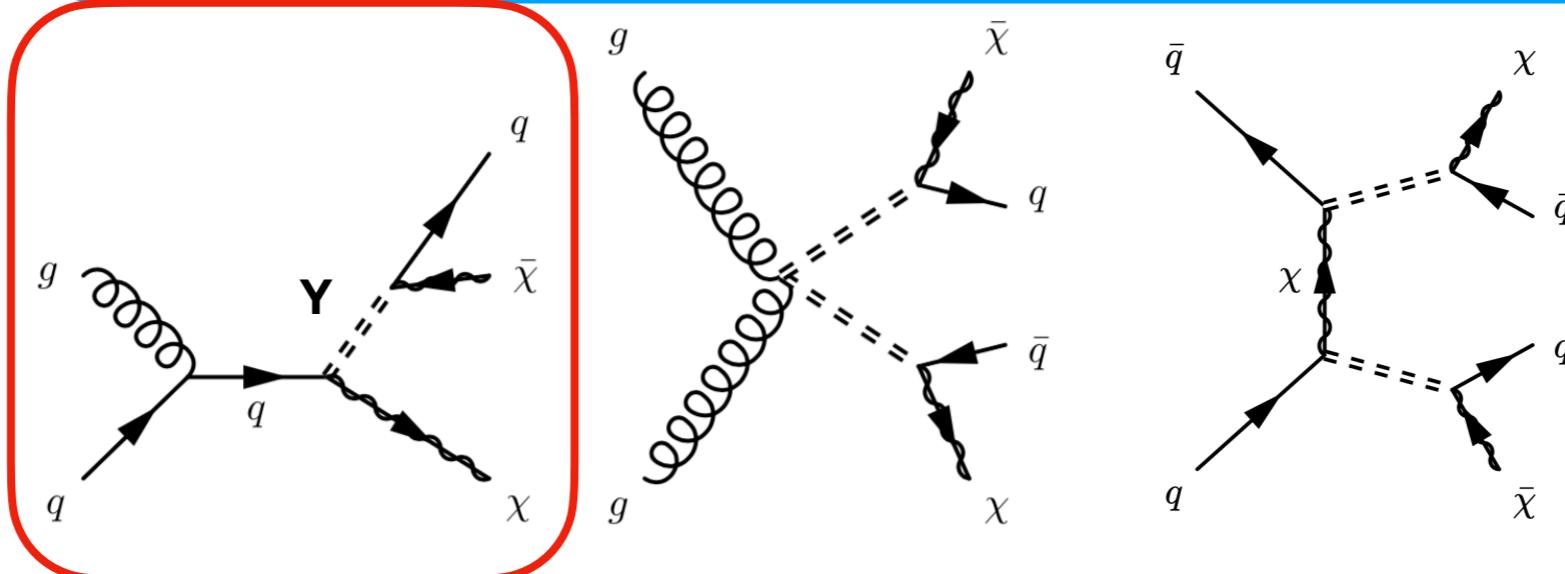
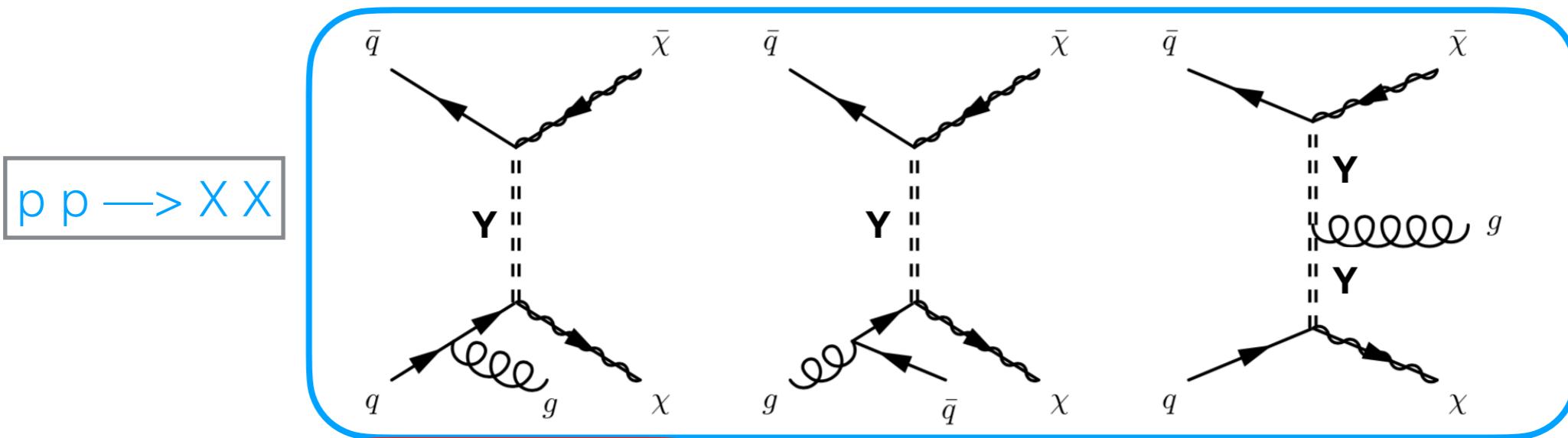
## SI direct detection

Excluded

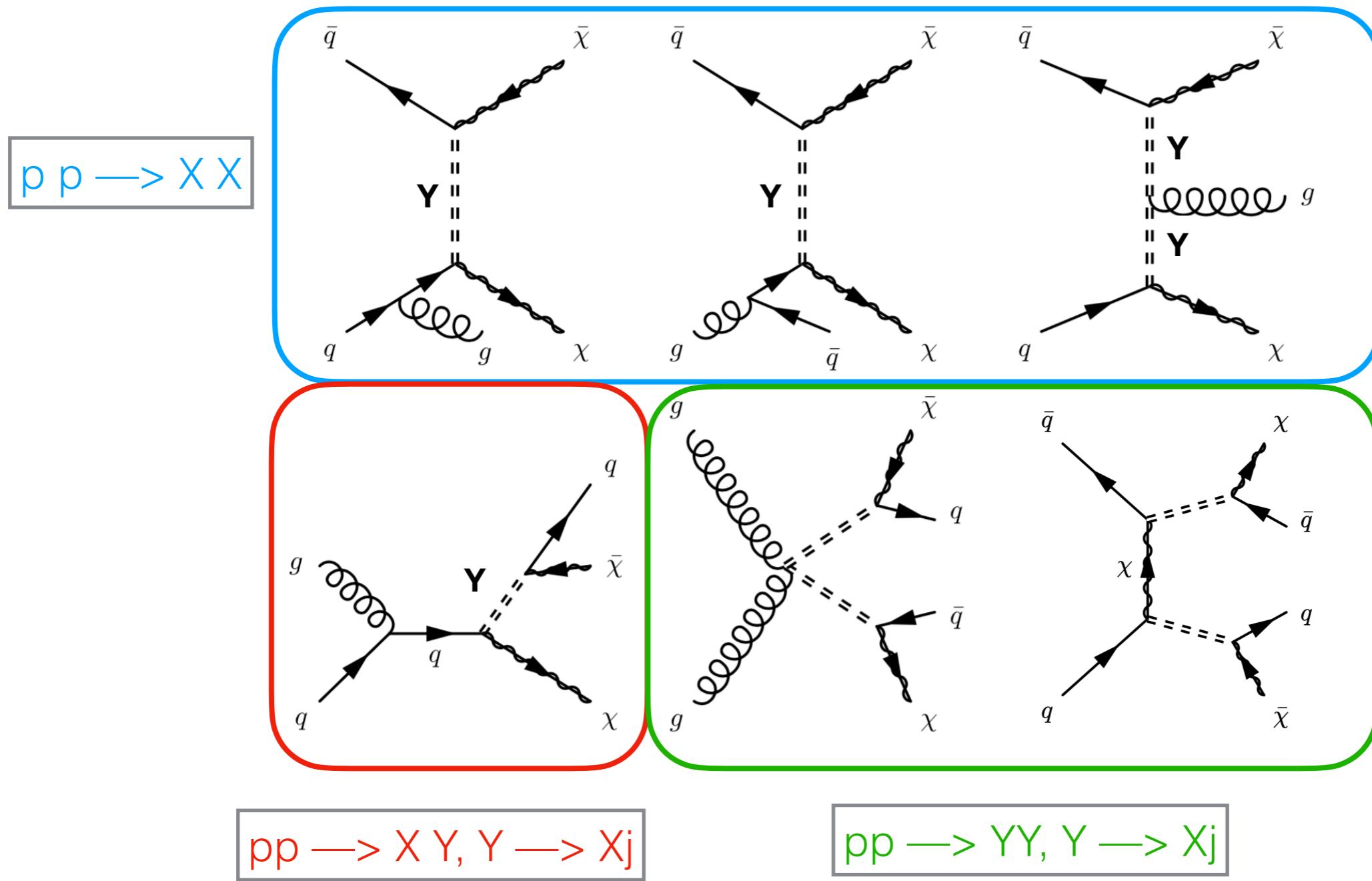


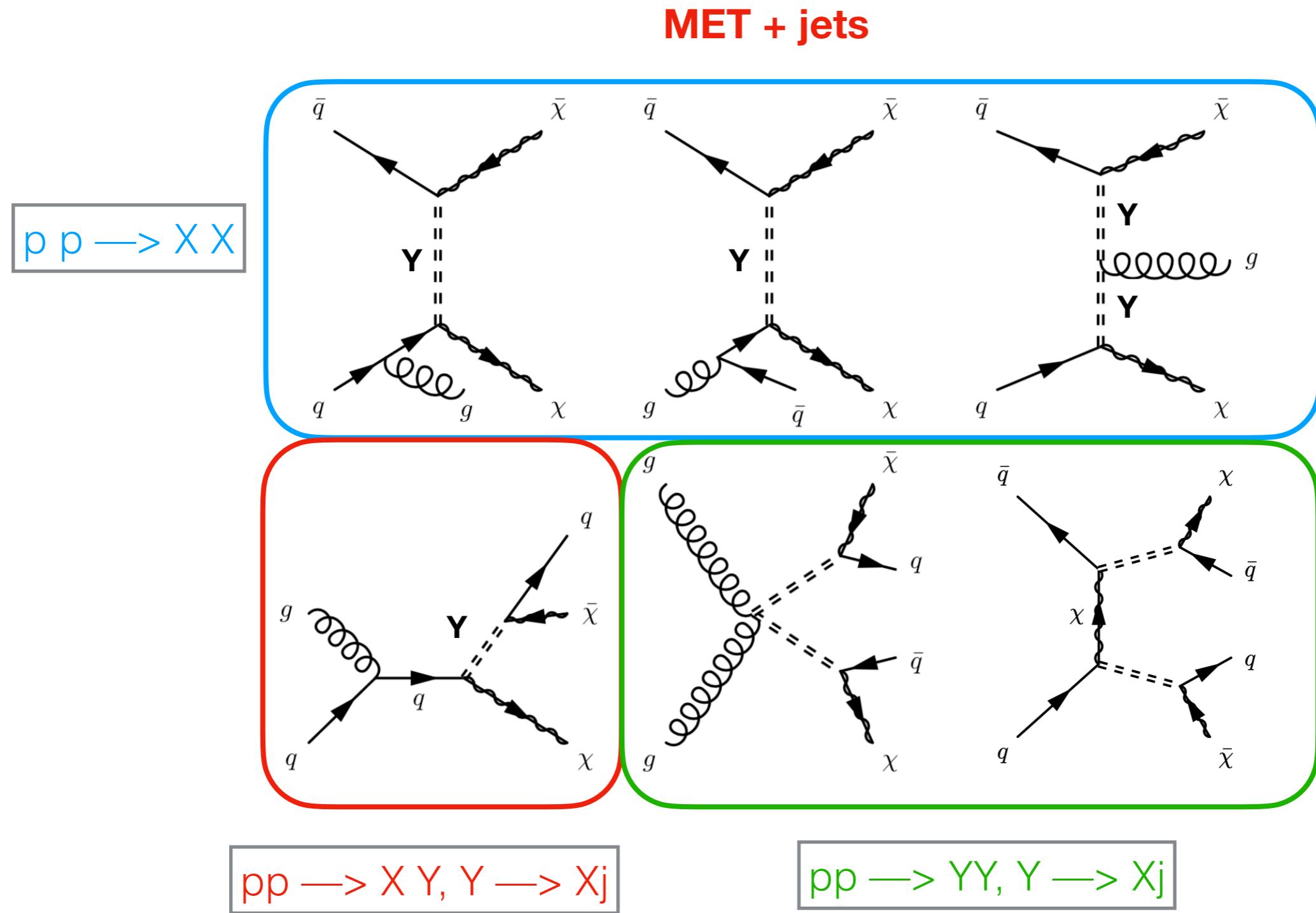
**MET + jets**



**MET + jets** $pp \rightarrow X Y, Y \rightarrow X j$

MET + jets





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

```
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**

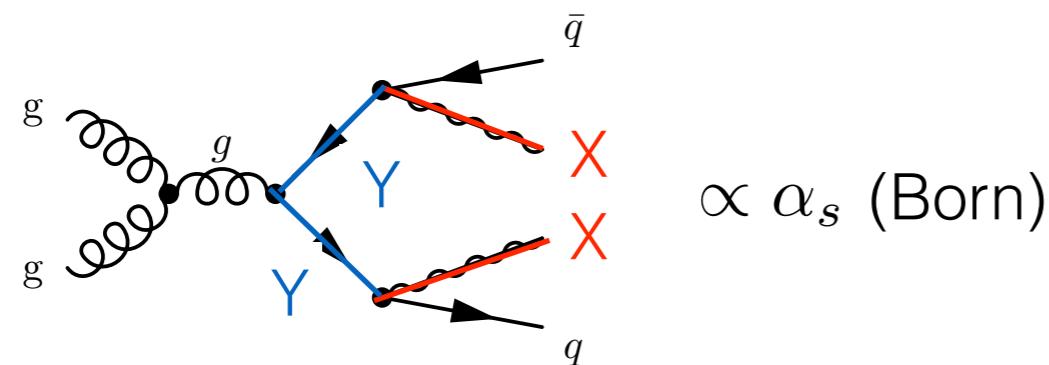
In the prescription used, we removed all square resonant diagram  
Interferences of resonant and non resonant are kept

Shell commands in MG5\_aMC@NLO for  $p p \rightarrow XX$  using MadSTR

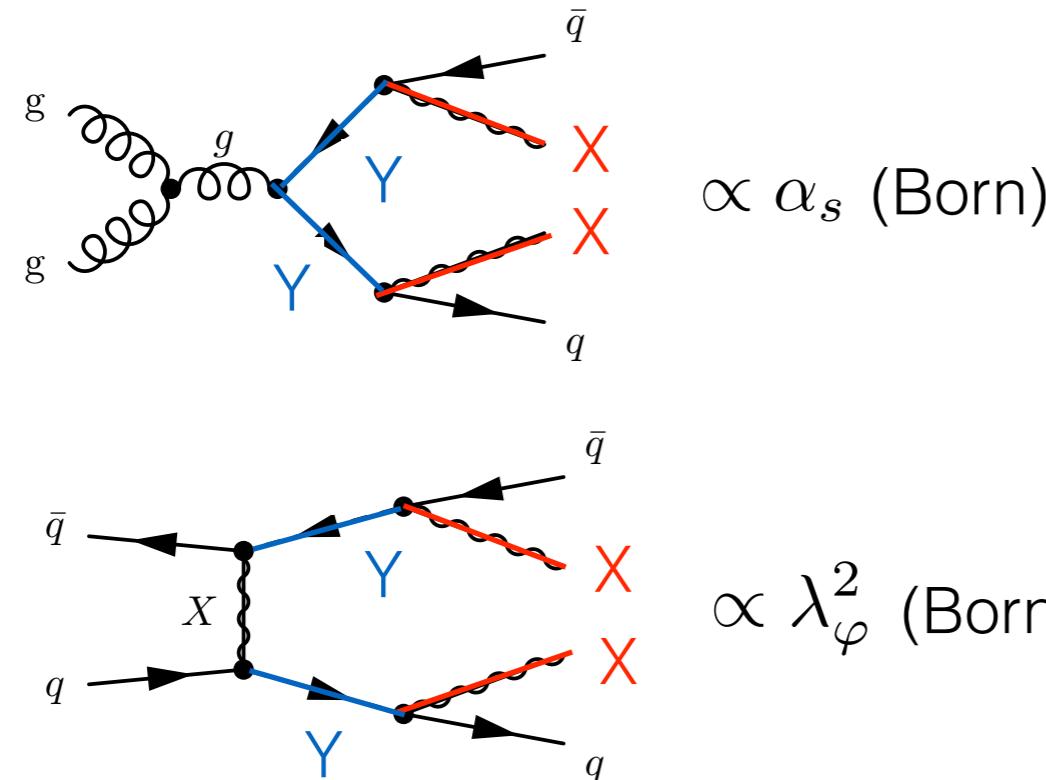
```
import model DMSimpt-S3D_uR --modelname  
generate p p > xd xd~ / yf3qu1 yf3qu2 \  
yf3qu3 yf3qd1 yf3qd2 yf3qd3 yf3u1 yf3u2 \  
yf3u3 yf3d1 yf3d2 yf3d3 ys3qu1 ys3qu2 \  
ys3qu3 ys3qd1 ys3qd2 ys3qd3 ys3u2 ys3u3 \  
ys3d1 ys3d2 ys3d3 xs xm xv xc xw a z [QCD]  
output
```

**Important to forbid decoupled  
particles from loops**

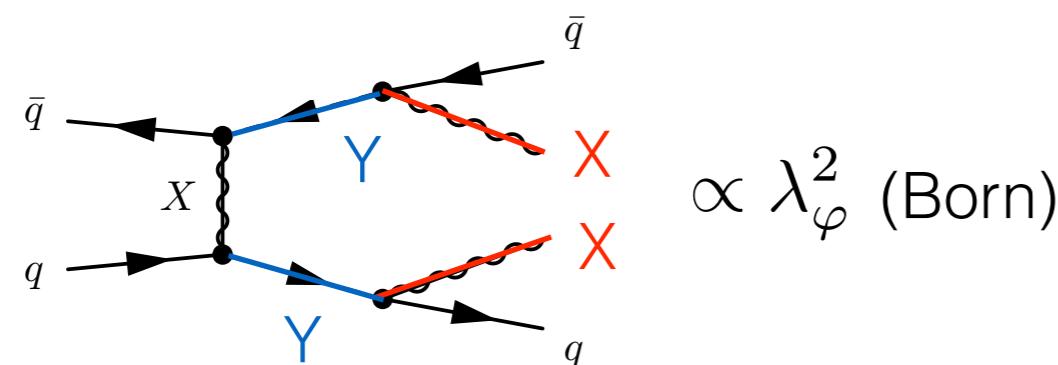




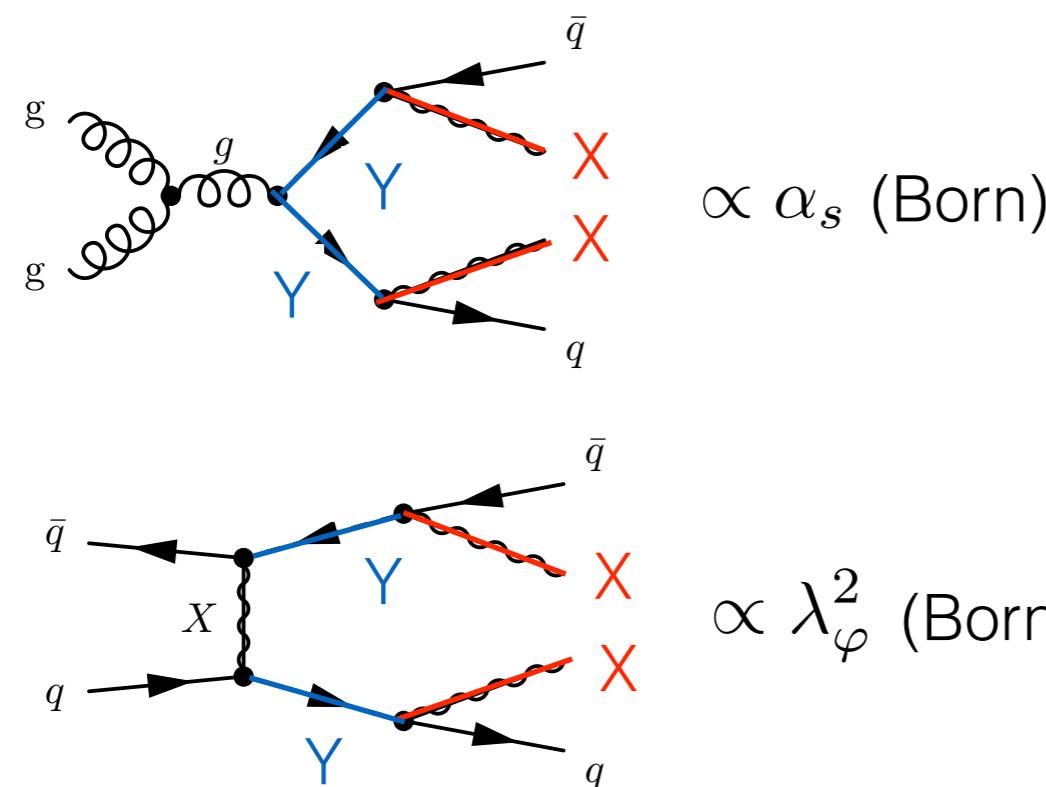
QCD contribution dominates  
Independent of DM mass and coupling



QCD contribution dominates  
Independent of DM mass and coupling



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



QCD contribution dominates  
Independent of DM mass and coupling

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	$m_X = 150 \text{ GeV}$	$m_Y = 500 \text{ GeV}$	$\lambda_\varphi = 1$
S2	$m_X = 150 \text{ GeV}$	$m_Y = 1000 \text{ GeV}$	$\lambda_\varphi = 1$

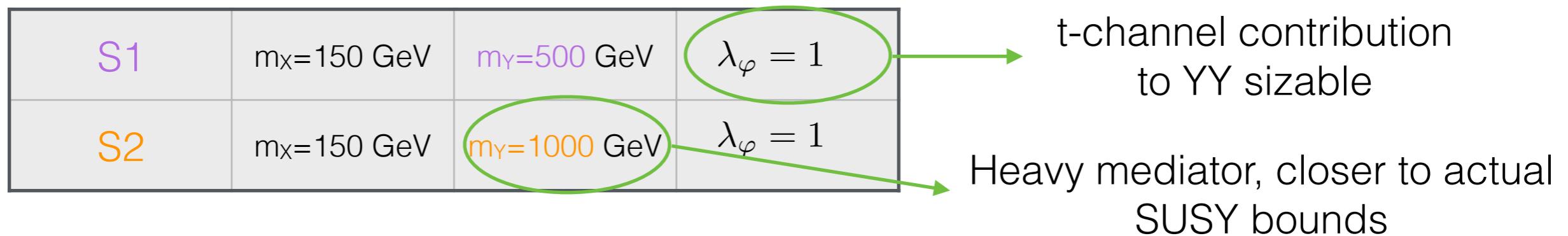
S1	$m_X = 150 \text{ GeV}$	$m_Y = 500 \text{ GeV}$	$\lambda_\varphi = 1$
S2	$m_X = 150 \text{ GeV}$	$m_Y = 1000 \text{ GeV}$	$\lambda_\varphi = 1$

t-channel contribution  
to YY sizable

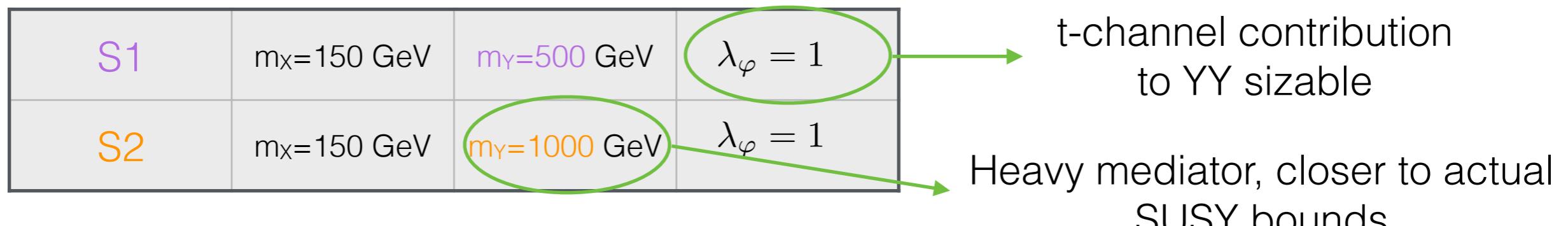
S1	$m_X = 150 \text{ GeV}$	$m_Y = 500 \text{ GeV}$	$\lambda_\varphi = 1$
S2	$m_X = 150 \text{ GeV}$	$m_Y = 1000 \text{ GeV}$	$\lambda_\varphi = 1$

t-channel contribution  
to YY sizable

Heavy mediator, closer to actual  
SUSY bounds



	Scen.	$XX \text{ [fb]}$	$XY \text{ [fb]}$	$YY \text{ (total) [fb]}$	$YY \text{ (QCD) [fb]}$	$YY \text{ (t-channel) [fb]}$
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	$139.1^{+1.3\%}_{-1.1\%} \pm 2.0\%$	$101.8^{+6.0\%}_{-7.1\%} \pm 1.2\%$	$9.888^{+6.5\%}_{-7.6\%} \pm 5.8\%$	$5.303^{+11.2\%}_{-13.3\%} \pm 7.4\%$	$8.749^{+3.6\%}_{-3.9\%} \pm 4.9\%$



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

Uncertainties from parton density fit

S1	$m_X = 150 \text{ GeV}$	$m_Y = 500 \text{ GeV}$	$\lambda_\varphi = 1$	t-channel contribution to YY sizable
S2	$m_X = 150 \text{ GeV}$	$m_Y = 1000 \text{ GeV}$	$\lambda_\varphi = 1$	Heavy mediator, closer to actual SUSY bounds

Theoretical scale uncertainties

Scen.	$XX \text{ [fb]}$	$XY \text{ [fb]}$	$YY \text{ (total) [fb]}$	$YY \text{ (QCD) [fb]}$	$YY \text{ (t-channel) [fb]}$
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

S1	$m_X = 150 \text{ GeV}$	$m_Y = 500 \text{ GeV}$	$\lambda_\varphi = 1$	t-channel contribution to YY sizable
S2	$m_X = 150 \text{ GeV}$	$m_Y = 1000 \text{ GeV}$	$\lambda_\varphi = 1$	Heavy mediator, closer to actual SUSY bounds

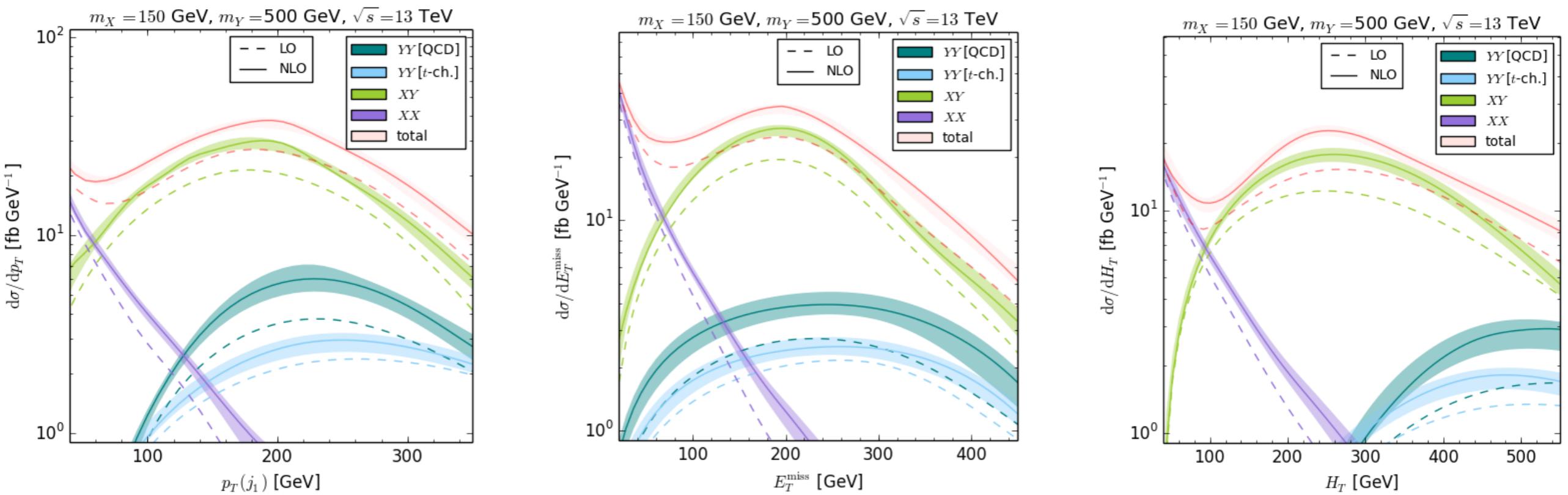
### Theoretical scale uncertainties

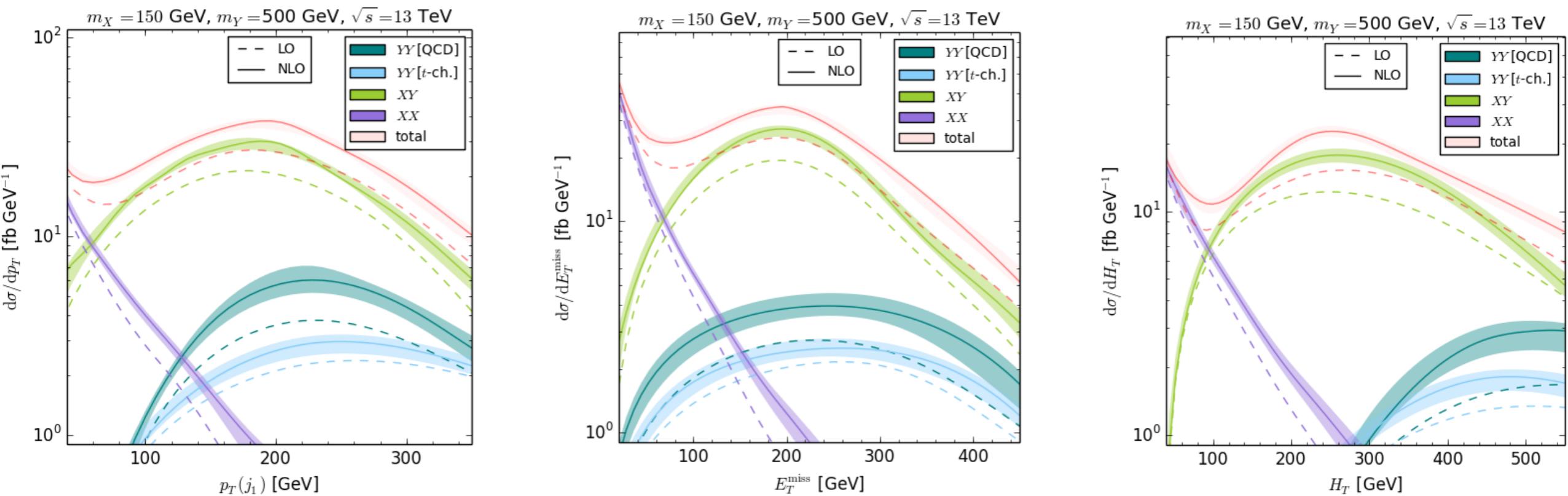
Scen.	$XX \text{ [fb]}$	$XY \text{ [fb]}$	$YY \text{ (total) [fb]}$	$YY \text{ (QCD) [fb]}$	$YY \text{ (t-channel) [fb]}$
LO	S1 $775.3^{+0.4\%}_{-0.8\%} \pm 1.9\%$	$1617^{+16.5\%}_{-13.4\%} \pm 1.0\%$	$473.5^{+23.6\%}_{-16.9\%} \pm 3.0\%$	$324.2^{+34.2\%}_{-23.8\%} \pm 3.4\%$	$261.5^{+7.1\%}_{-6.3\%} \pm 2.5\%$
	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

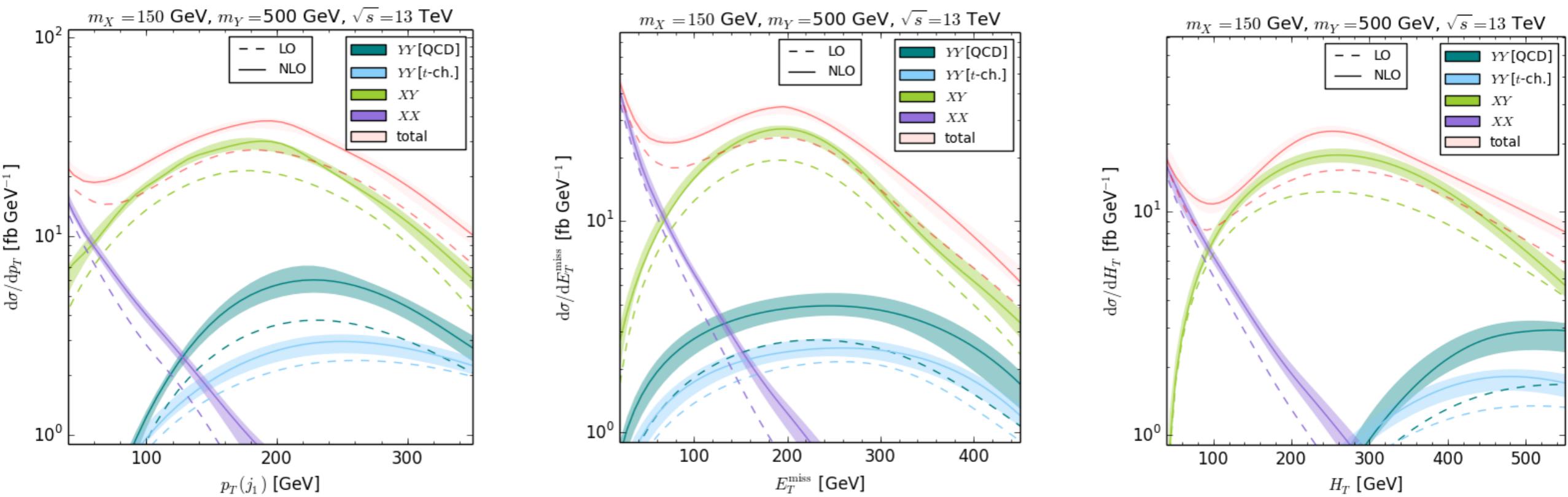
- Large K-factors: avoid underestimating the signal
- Reduction of theoretical systematic uncertainties





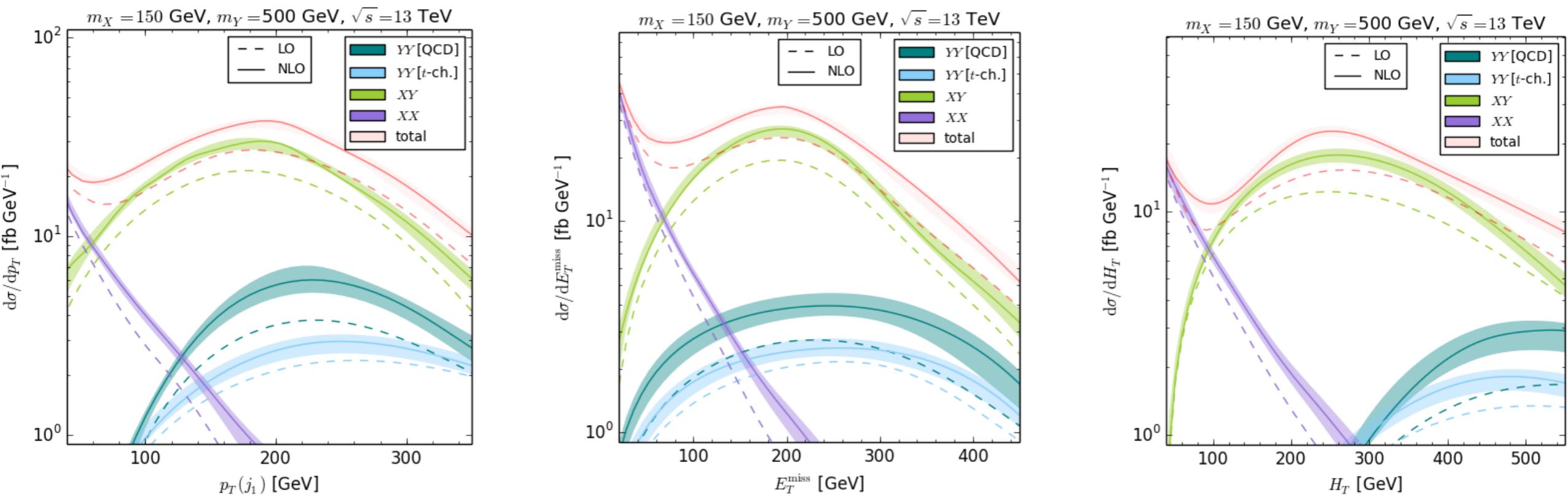
Process	$\text{CL}_s$ [LO]	$E_T^{\text{miss}}$ constraint	$\text{CL}_s$ [NLO]	$E_T^{\text{miss}}$ constraint
Total	100 %	$\in [300, 350] \text{ GeV}$	100 %	$\in [300, 350] \text{ GeV}$
$XX$	$1.6^{+0.2}_{-0.1} \%$	$\in [300, 350] \text{ GeV}$	$9.4^{+0.6}_{-0.6} \%$	$\in [250, 300] \text{ GeV}$
$XY$	100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

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



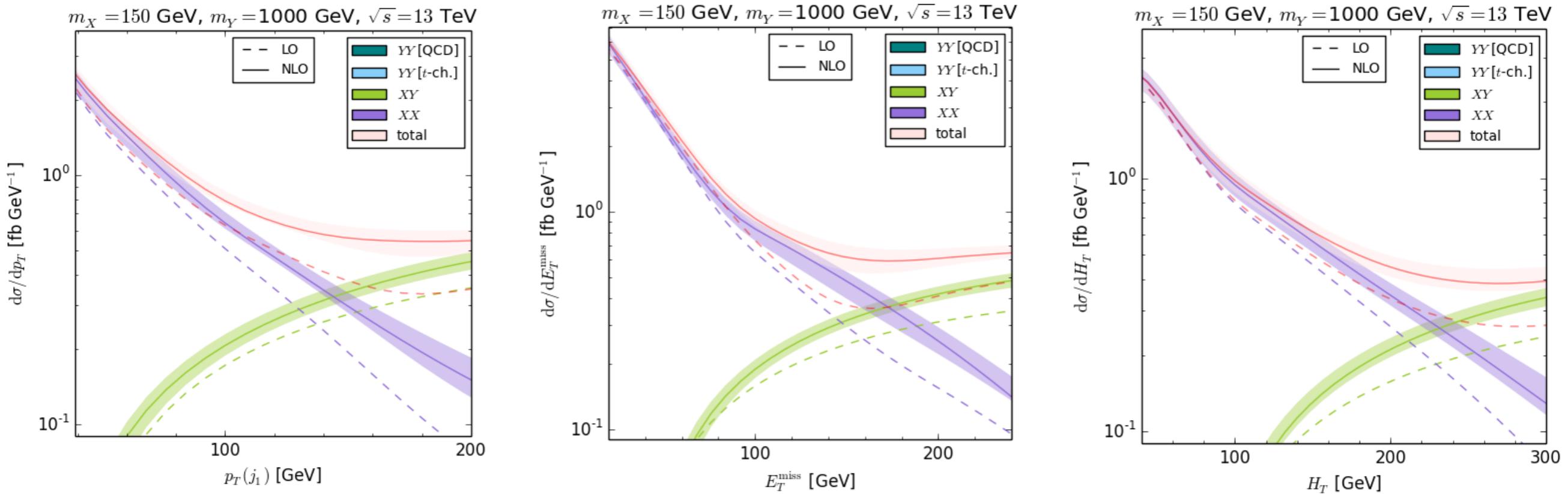
Process	$\text{CL}_s$ [LO]	$E_T^{\text{miss}}$ constraint	$\text{CL}_s$ [NLO]	$E_T^{\text{miss}}$ constraint
Total	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
<b>XX</b>	$1.6^{+0.2}_{-0.1}$ %	$\in [300, 350]$ GeV	$9.4^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV
<b>XY</b>	100 %	$\in [300, 350]$ GeV	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)



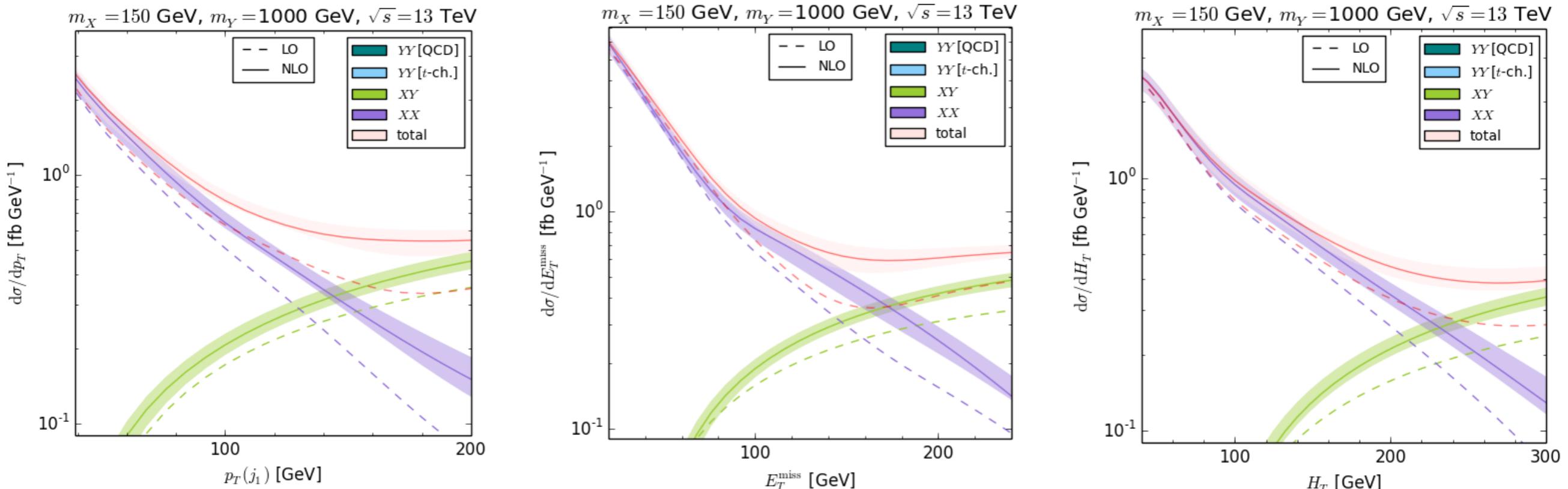
Process	$\text{CL}_s$ [LO]	$E_T^{\text{miss}}$ constraint	$\text{CL}_s$ [NLO]	$E_T^{\text{miss}}$ constraint
Total	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
$XX$	$1.6^{+0.2}_{-0.1}$ %	$\in [300, 350]$ GeV	$9.4^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV
$XY$	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ 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)



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

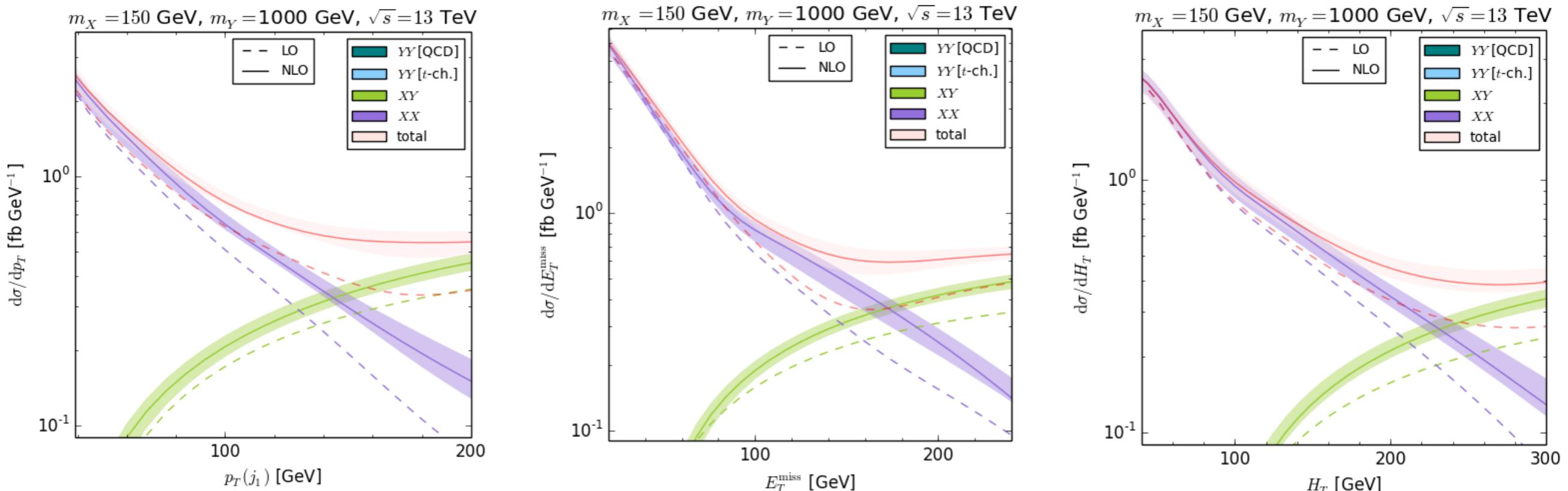
ATLAS-EXOT-2016-27 (most constraining signal region only)



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

< 95% CL ←

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



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

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]



- 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!