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

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Dark Matter Working Group

February 4th 2020

* Based on C. Arina, B. Fuks and L. Mantani, arXiv:2001.05024 [hep-ph]

Outline

- Follow up from Benjamin talk
- Dark Matter (DM) observables: validation and tool comparison
- Summary and outlook

Über-UFO model file restrictions

The generic model is shipped with several restrictions where the undesired fields are decoupled and interactions 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		

Any restriction has
3 free model parameters:
DM and mediator masses + coupling

coupling only to quark up-right

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The generic model is shipped with several restrictions where the undesired fields are decoupled and interactions are set to zero

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

This talk Fermionic dark matter

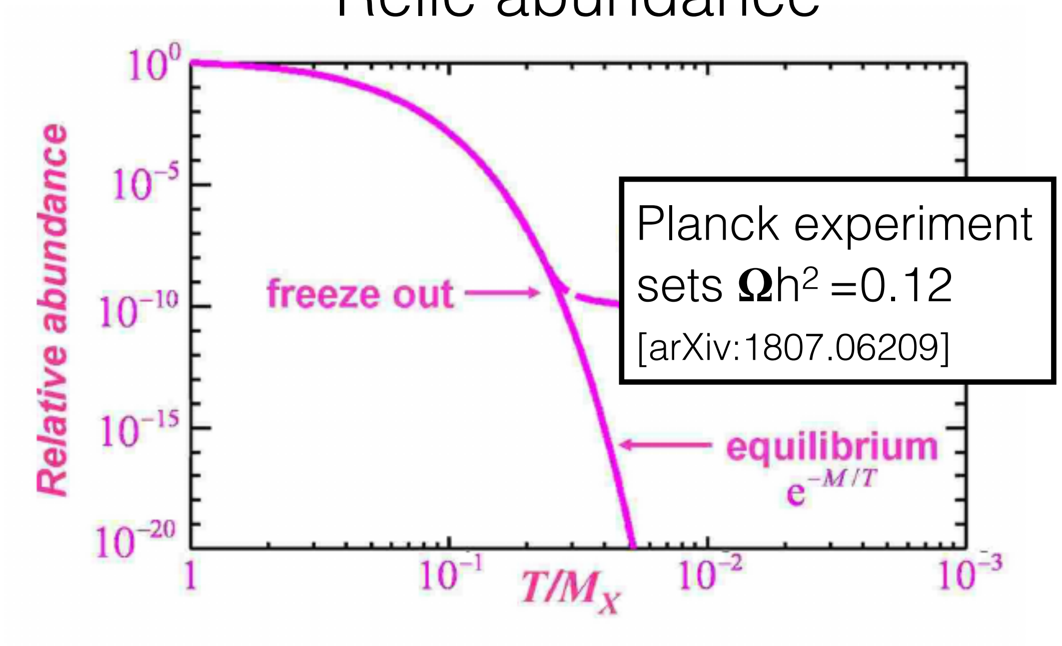
- Nice complementary pheno
- SUSY like benchmarks (neutralino bino like + squark)

Any restriction has 3 free model parameters: DM and mediator masses + coupling

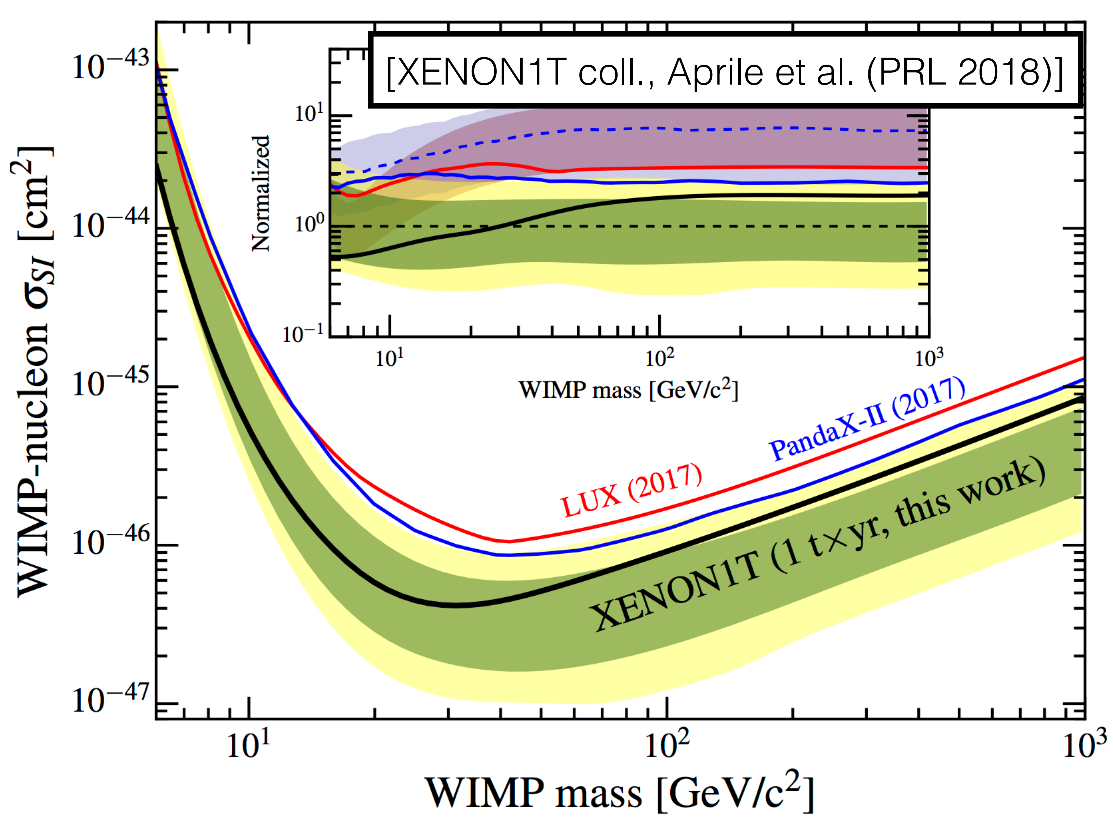
coupling only to quark up-right

Dark Matter observables

Relic abundance

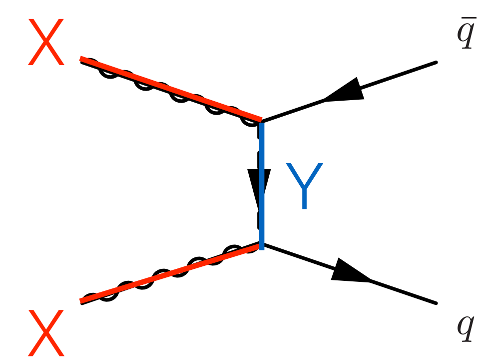


Direct detection



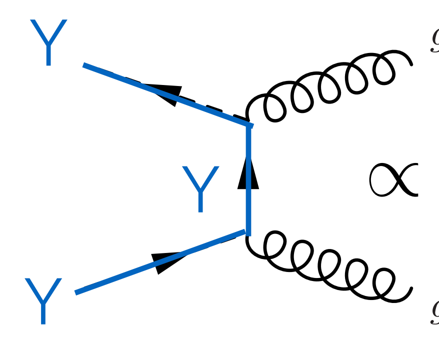
LO processes (for the restriction used in the talk)

DM annihilation

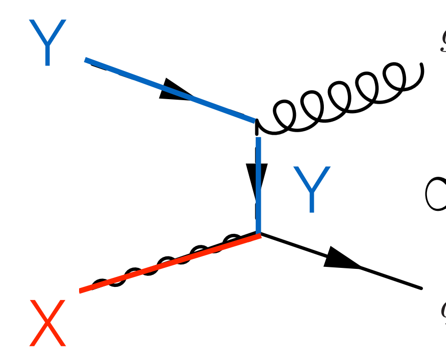


$\propto \lambda_\varphi^4$

coannihilation (compressed spectrum)

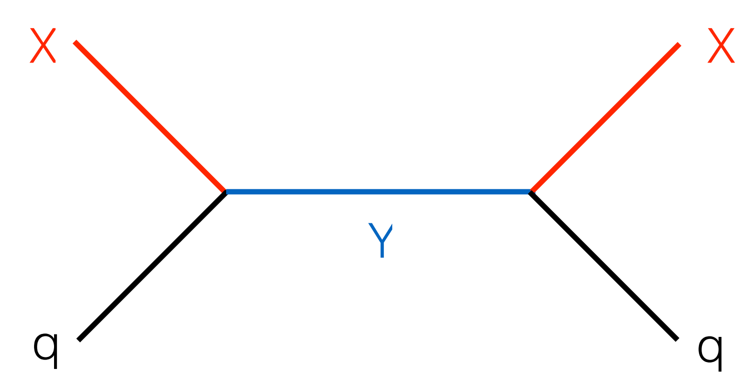


$\propto \alpha_s^2$



$\propto \lambda_\varphi^2 \alpha_s$

LO (or NLO) processes

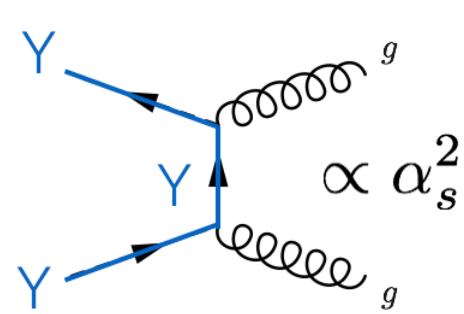


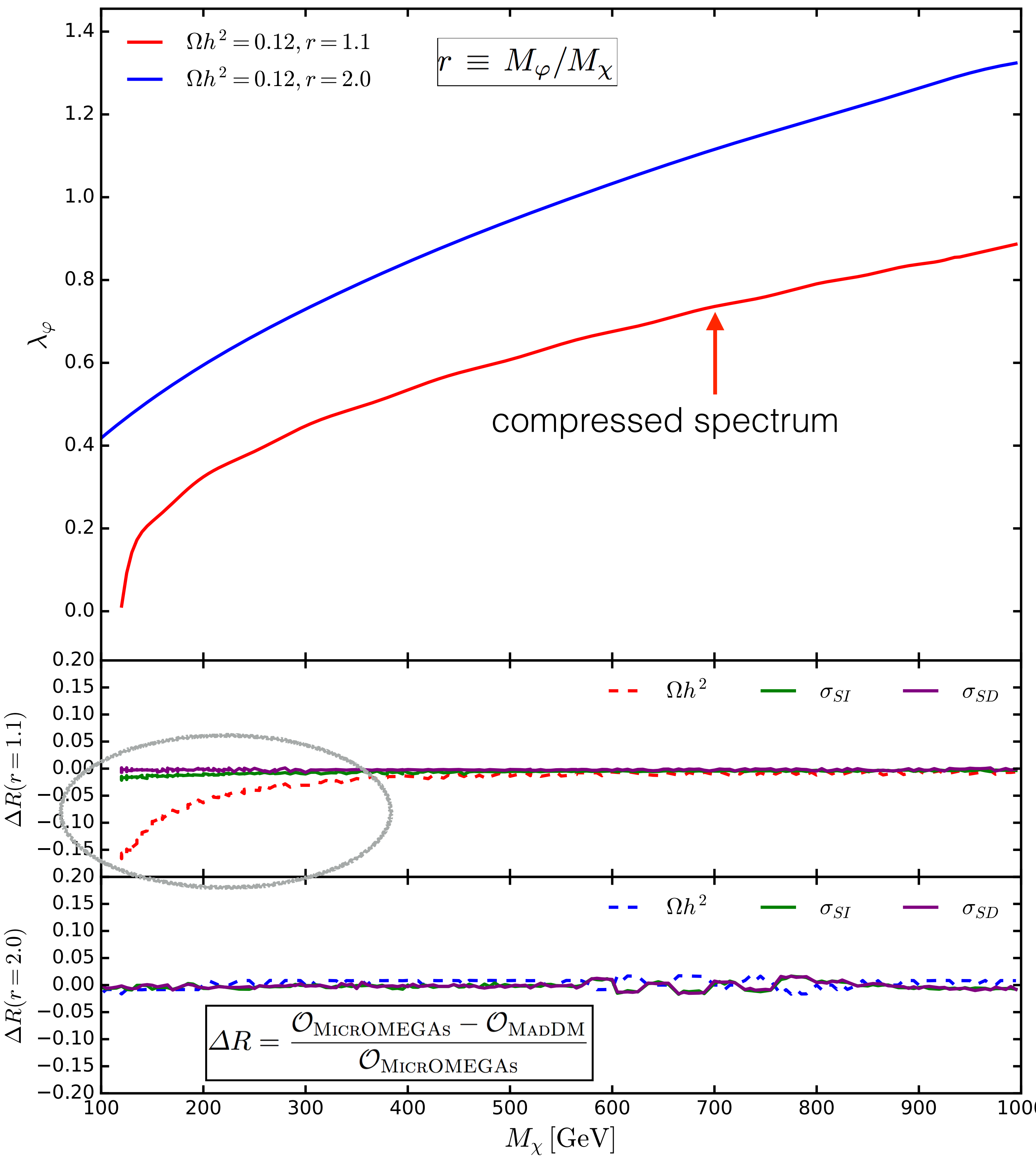
Validation of dark matter observables: S3D_uR case

Shell commands in MadDM:

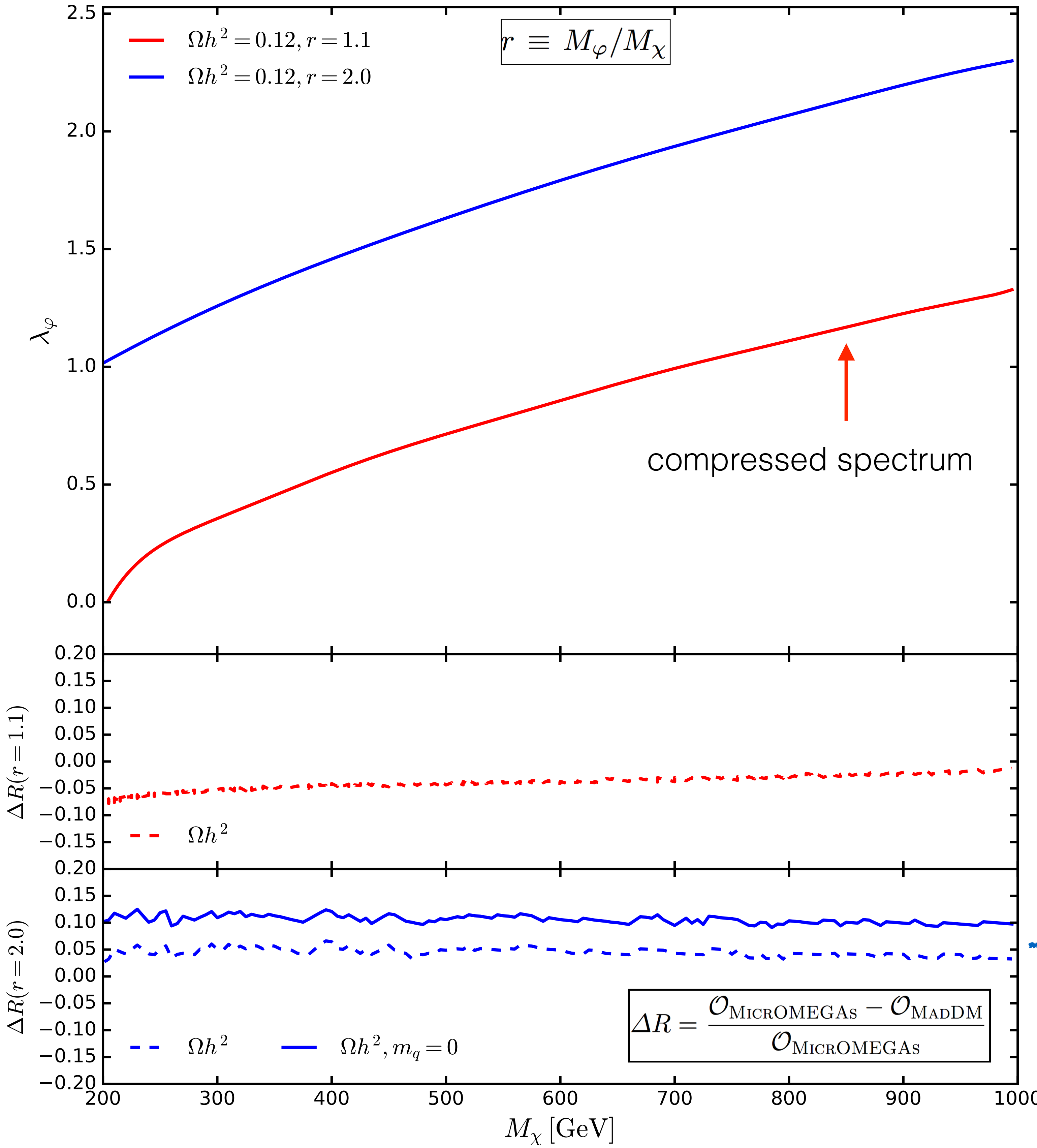
```
import model DMSimp_t-S3D_uR --modelname
define darkmatter xd
define coannihilator ys3u1
generate relic_density
add direct_detection
output my_project
launch
```

Deviations due to different QCD treatment in the two numerical tools compressed spectrum: for small couplings QCD diagrams dominate





Relic density for Majorana DM

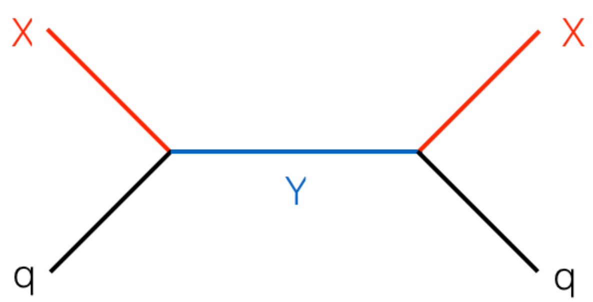


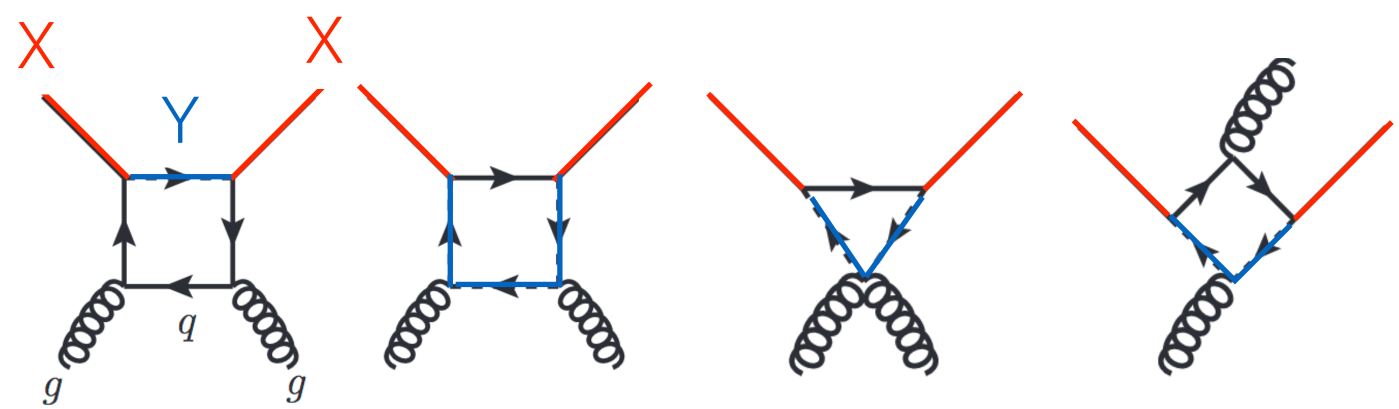
$$\mathcal{L}_{\mathtt{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$

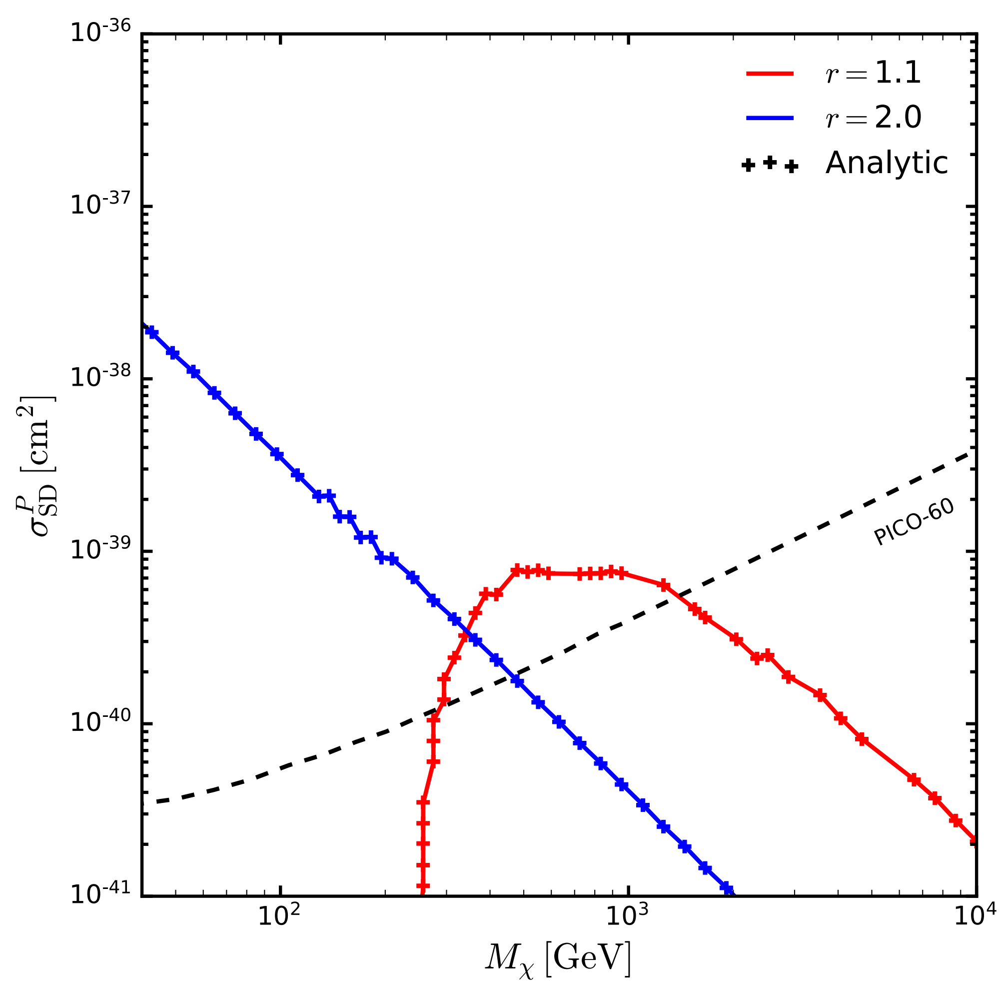
- Similar behavior as for Dirac DM
- UFO file with massless light quarks shows 10% deviation

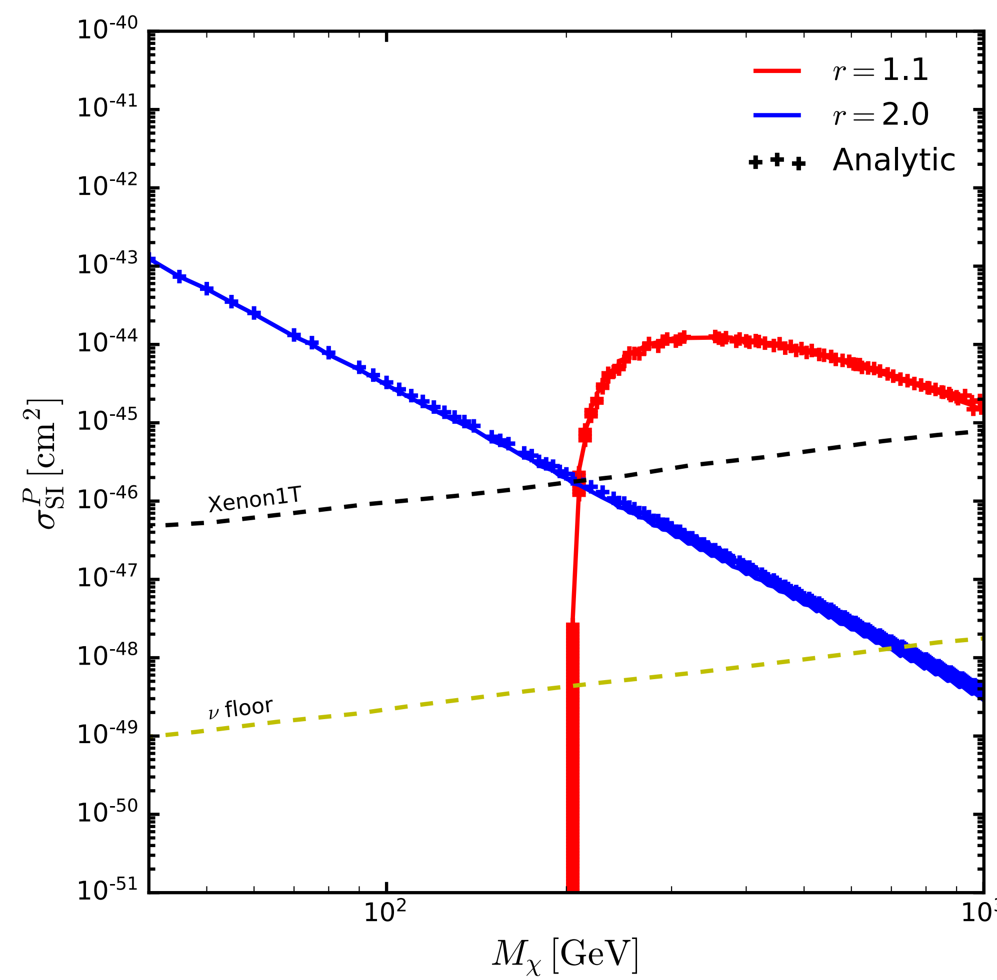
Validation of dark matter observables: S3M_uR case

- Direct detection is LO for spin-dependent (MadDM) and NLO for spin-independent (analytic expressions [Hisano et al. (JHEP 2015)])







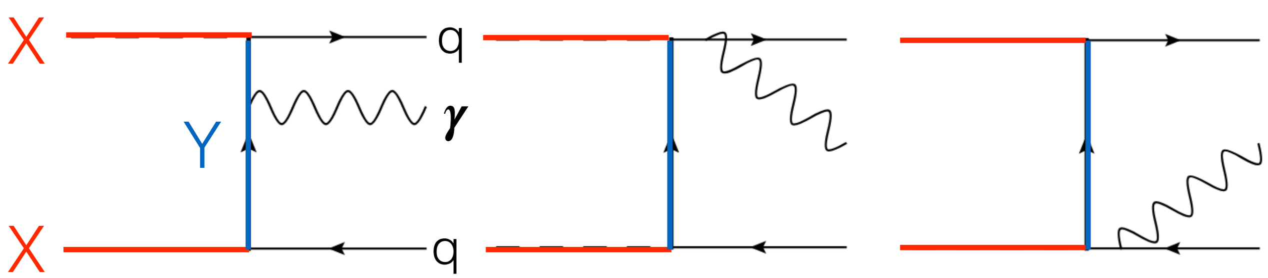


Dark matter automatized NLO processes: S3M_uR case

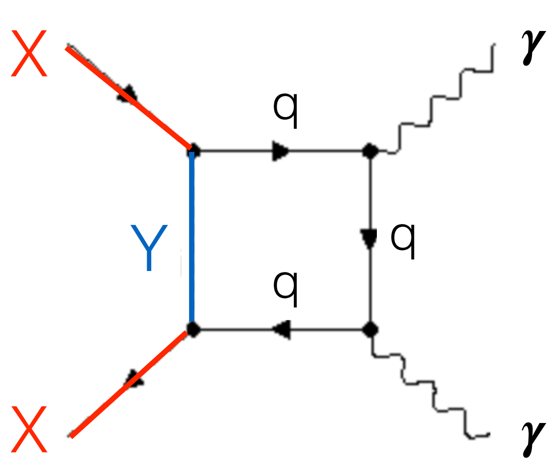
Indirect detection (annihilation at present time)

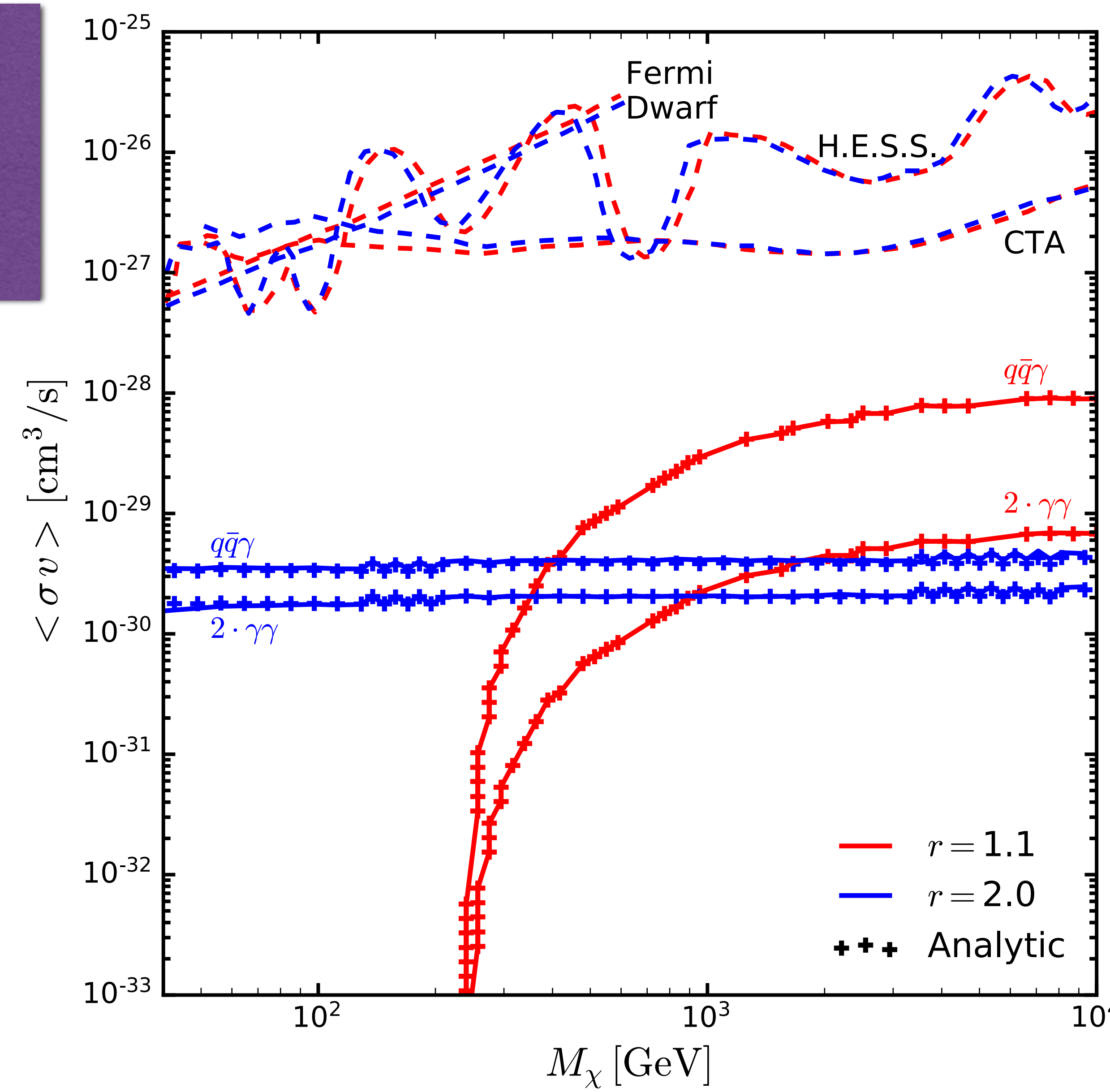
- LO annihilation is p-wave suppressed
- NLO processes uplift the suppression and produce a sharp feature in the gamma-ray energy spectrum

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

Dark matter automatized NLO processes: S3M_uR case

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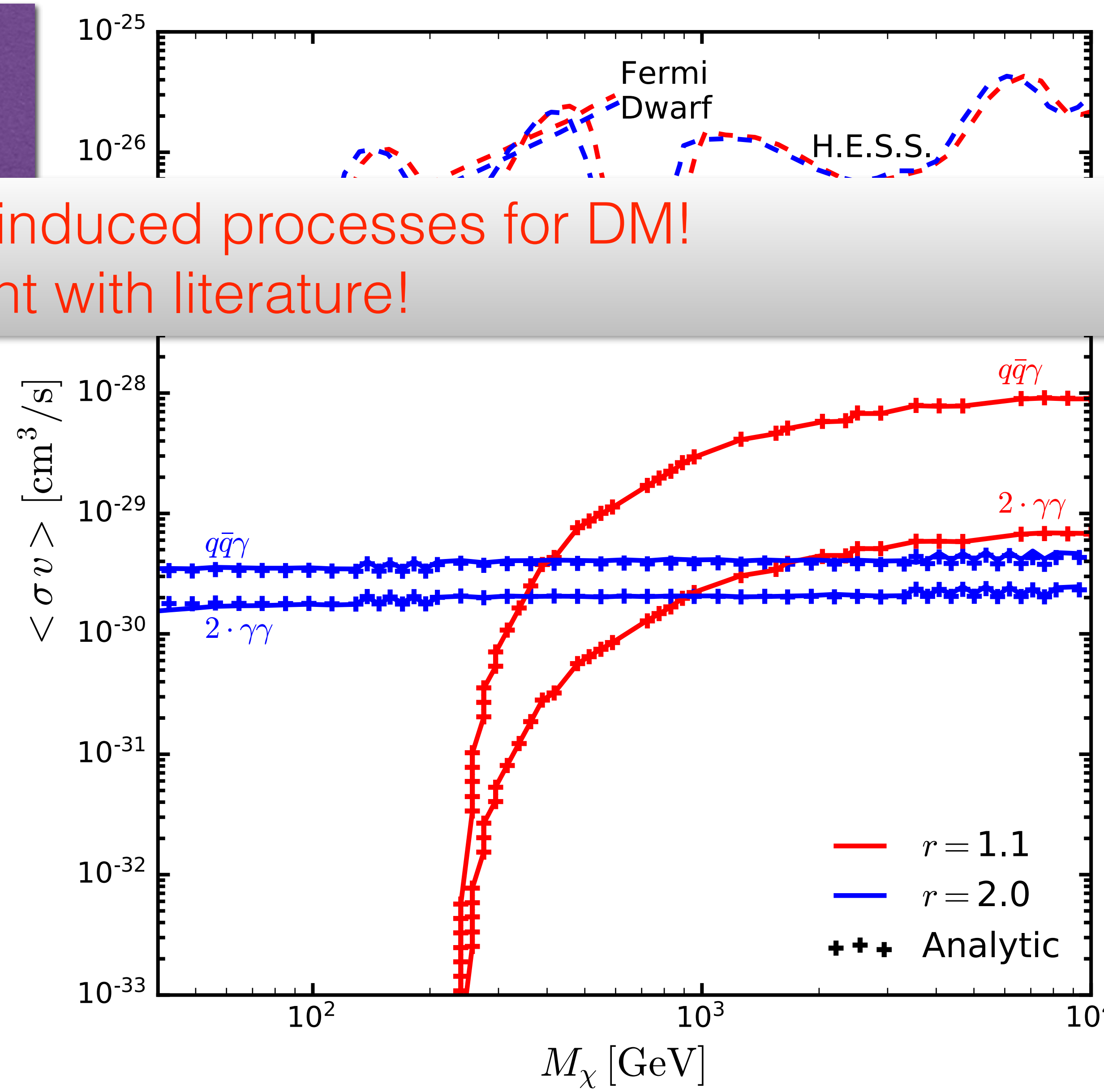
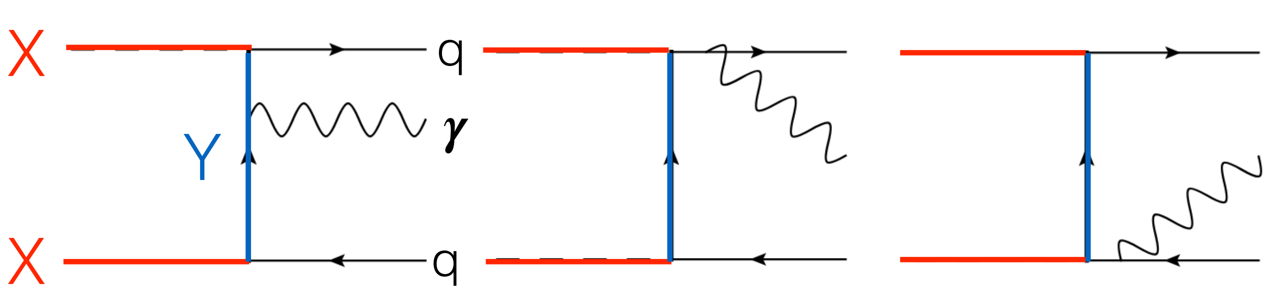
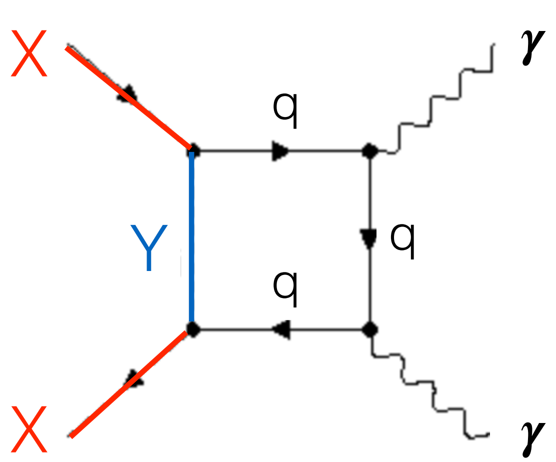
First time automatized loop-induced processes for DM!
Perfect agreement with literature!



Virtual internal bremsstrahlung (VIB)



Loop-induced diphotons



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Summary and outlook

- DMSimpt framework provides a very flexible tool to perform comprehensive analyses
- Über-UFO files contain various set ups of DM particles and mediators and allow for NLO QCD (and QED) predictions (dark matter and collider pheno)
- Dark Matter tools are in agreement for predictions (15% at most deviations)
- MadDM can handle automatized 2 -> 3 annihilation processes and loop-induced computation
- This talk provides a prescription to correctly compute NLO QCD corrections for t-channel models
- NLO QCD corrections at colliders are crucial to perform accurate theoretical predictions and to derive robust exclusion bounds

Thank you for your attention!

Summary and outlook

- DMSimpt framework provides a very flexible tool to perform comprehensive analyses
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- This talk provides a prescription to correctly compute NLO QCD corrections for t-channel models
- NLO QCD corrections at colliders are crucial to perform accurate theoretical predictions and to derive robust exclusion bounds

Suggestions, comments are welcome!
(DM candidates not included in the über-UFO, …)

Thank you for your attention!

Back up slides

Indirect detection for Majorana DM

Shell commands in MadDM for VIB (NLO model files should be used)

```
import model DMSimp_t-S3M_uR --modelname
define darkmatter xm
define coannihilator ys3u1
generate indirect_detection u u~ a
output my_project
launch
```

For the computation of loop-induced processes contact the MadDM authors

DM simplified models and comprehensive approach

DM simplified model

SM + X (DM) + Y (mediator)

Model files (UFO @ NLO)

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

Process Generation
(Feynman diagrams, matrix element)

- MG5_aMC [Allwall et al. (JHEP 2014)]
- CalCHEP [Belayev, Christensen and Pukhov (CPC 2013)]

Dark Matter Observables
(Relic density, direct detection, indirect detection)

- MadDM (allows for comparing with experiments) [Ambrogi, CA, et al. (PDU 2019)]
- MicrOMEGAS [Belanger at al. (CPC 2018)]

Collider signatures at LO/NLO
(matching with parton shower, treatment of resonances)

MG5_aMC@NLO + MadSTR + MadSpin + MadWidth
[Artoisenet et al. (JHEP 2013); Alwall et al. (CPC 2015); Alwall et al. (JHEP 2014); Frixione et al. (JHEP 2019)]

Complete model description

Coupling	FeynRules name	LH block
$(\lambda_Q)_{ij}$	lamS3Q	DMS3Q
$(\lambda_u)_{ij}$	lamS3u	DMS3U
$(\lambda_d)_{ij}$	lamSdD	DMS3D
$(\hat{\lambda}_Q)_{ij}$	lamF3Q	DMF3Q
$(\hat{\lambda}_u)_{ij}$	lamF3u	DMF3U
$(\hat{\lambda}_d)_{ij}$	lamF3d	DMF3D

Field	Spin	Repr.	Self-conj.	FeynRules name	PDG
$\tilde{S}$	0	$(\mathbf{1},\mathbf{1},0)$	yes	Xs	51
S	0	$(\mathbf{1},\mathbf{1},0)$	no	Xc	56
$\tilde{\chi}$	1/2	$(\mathbf{1},\mathbf{1},0)$	yes	Xm	52
χ	1/2	$(\mathbf{1},\mathbf{1},0)$	no	Xd	57
$\tilde{V}_\mu$	1	$(\mathbf{1},\mathbf{1},0)$	yes	Xv	53
V_μ	1	$(\mathbf{1},\mathbf{1},0)$	no	Xw	58
$\varphi_Q = \begin{pmatrix}\varphi_Q^{(u)} \\ \varphi_Q^{(d)}\end{pmatrix}$	0	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no	YS3Q = (YS3Qu, YS3Qd)	$\varphi_Q^{(u)}$: 1000002 1000004 1000006 $\varphi_Q^{(d)}$: 1000001 1000003 1000005
φ_u	0	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no	YS3u	2000002 2000004 2000006
φ_d	0	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no	YS3d	2000001 2000003 2000005
$\psi_Q = \begin{pmatrix}\psi_Q^{(u)} \\ \psi_Q^{(d)}\end{pmatrix}$	1/2	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no	YF3Q = (YF3Qu, YF3Qd)	$\psi_Q^{(u)}$: 5910002 5910004 5910006 $\psi_Q^{(d)}$: 5910001 5910003 5910005
ψ_u	1/2	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no	YF3u	5920002 5920004 5920006
ψ_d	1/2	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no	YF3d	5920001 5920003 5920005

Über-UFO model files in the DMSimpt webpage

`DMSimpt` : A general framework for t-channel dark matter models at NLO in QCD

Contact Information

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See arXiv:2001.05024 [hep-ph].

Model Description and FeynRules Implementation

We extend the Standard Model by a dark matter candidate X and a coloured mediator Y. The model includes several spin possibilities for X and Y, the dark matter being either of a Majorana nature or not and of spin equal to 0, 1/2 or 1. The mediator i

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

The first term consists in the Standard Model Lagrangian, the second one includes gauge-invariant kinetic and mass terms for all new fields and the last ones describe the interactions of the dark matter state with the mediator and the Standard Model.

$$\begin{aligned}
\mathcal{L}_F(X) &= \Big[\lambda_{\mathbf{Q}}\bar X Q_L \varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar X u_R \varphi_u^\dagger + \lambda_{\mathbf{d}}\bar X d_R \varphi_d^\dagger + \text{h.c.}\Big]\ ,\\
\mathcal{L}_S(X) &= \Big[\hat\lambda_{\mathbf{Q}}\bar\psi_Q Q_L X + \hat\lambda_{\mathbf{u}}\bar\psi_u u_R X + \hat\lambda_{\mathbf{d}}\bar\psi_d d_R X + \text{h.c.}\Big]\ ,\\
\mathcal{L}_V(X) &= \Big[\hat\lambda_{\mathbf{Q}}\bar\psi_Q \gamma^\mu X_\mu Q_L + \hat\lambda_{\mathbf{u}}\bar\psi_u \gamma^\mu X_\mu u_R + \hat\lambda_{\mathbf{d}}\bar\psi_d \gamma^\mu X_\mu d_R + \text{h.c.}\Big]\ ,
\end{aligned}$$

where φ and ψ consists in coloured scalar and fermionic mediators.

The above Lagrangian was implemented in the Feynman gauge into FeynRules 2.3.35. QCD renormalisation and R_2 rational counterterms were determined using NLOCT v1.02 and FeynArts 3.9. Feynman rules were collected into a single UFO, in which

The above new physics couplings can be controlled on run-time through the Les Houches blocks DMS3Q, DMS3U, DMS3D (scalar mediator interactions with the Q_L, u_R and d_R quarks), as well as DMF3Q, DMF3U, DMF3D (scalar mediator interactions wit

- Dark matter: 51 (real scalar), 52 (Majorana fermion), 53 (real vector), 56 (complex scalar), 57 (Dirac fermion) and 58 (complex vector).
- Scalar mediators: 1000001 (φ_{dL}), 1000002 (φ_{uL}), 1000003 (φ_{sL}), 1000004 (φ_{cL}), 1000005 (φ_{bL}), 1000006 (φ_{tL}), 2000001 (φ_{dR}), 2000002 (φ_{uR}), 2000003 (φ_{sR}), 2000004 (φ_{cR}), 2000005 (φ_{bR}) and 2000006 (φ_{tR}).
- Fermionic mediators: 5910001 (ψ_{dL}), 5910002 (ψ_{uL}), 5910003 (ψ_{sL}), 5910004 (ψ_{cL}), 5910005 (ψ_{bL}), 5910006 (ψ_{tL}), 5920001 (ψ_{dR}), 5920002 (ψ_{uR}), 5920003 (ψ_{sR}), 5920004 (ψ_{cR}), 5920005 (ψ_{bR}) and 5920006 (ψ_{tR}).

More information can be found in arXiv:2001.05024 [hep-ph].

Model Files (and more)

- FeynRules model files:
  - sm.fr: Accompanying SM implementation.
  - dmsimpt_v1.2.fr: Main DMSimpt FeynRules model.
  - Restriction file relevant for the 5FNS (5 massless quarks).
  - Restriction file relevant for a diagonal CKM matrix.
  - use-DMsimpt.nb: Illustrative Mathematica notebook using the DMSimpt FeynRules model.
- UFO models
  - dmsimpt_v1.2.ufo.tar.gz: Standalone NLO UFO folder in the 5FNS, including all 18 restrictions of arXiv:2001.NNNNN [hep-ph].
  - dmsimpt_v1.2_s3dur.ufo.tar.gz: Standalone UFO LO folder, in the S3D_uR restriction, with 6 massive quarks.
  - dmsimpt_v1.2_s3mur.ufo.tar.gz: Standalone UFO LO folder, in the S3M_uR restriction, with 6 massive quarks.
- CalcHep models
  - dmsimpt_v1.2_s3dur.ch.tar.gz: Standalone CalcHep model files with massive quarks, in the S3D_uR restriction.
  - dmsimpt_v1.2_s3mur.ch.tar.gz: Standalone CalcHep model files with massive quarks, in the S3M_uR restriction.

Production of t-channel model particles X and Y @LHC

pp —> YY, Y —> Xj

Shell commands in MG5_aMC@NLO for the pure QCD part

```
import model DMSimpt-S3D_uR --modelname
define yy1 = ys3u1 ys3u1~
generate p p > yy1 yy1 / 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 [QCD]
output
```

Shell commands in MG5_aMC@NLO for the t-channel part (MadSTR plugin)

```
import model DMSimpt-S3D_uR --modelname
define yy1 = ys3u1 ys3u1~
generate p p > yy1 yy1 DMT=2 QCD=0 QED=0   \
  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  \
  [QCD]
output
```

Shell commands in MG5_aMC@NLO for the interference

```
import model DMSimpt-S3D_uR --modelname
 define yy1 = ys3u1 ys3u1~
 generate p p > yy1 yy1 DMT^2=2 / 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
 output
```

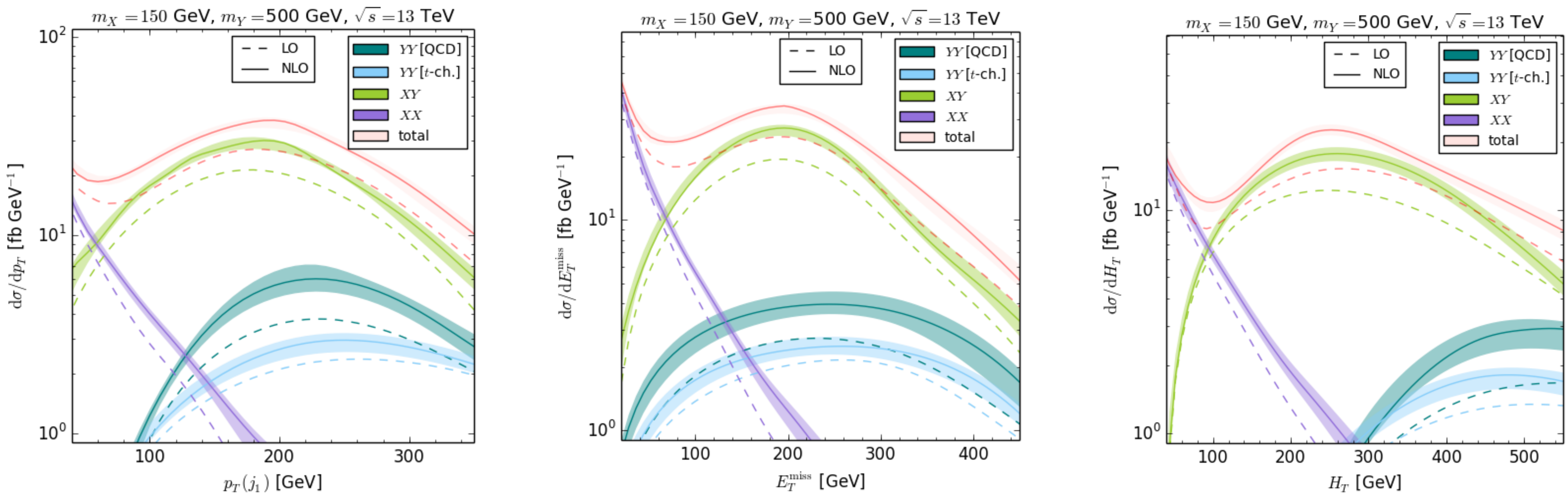
Production of t-channel model particles X and Y @LHC

pp —> XY, Y —> Xj

Shell commands in MG5_aMC@NLO with the use of the MadSTR plugin

```
import model DMSimpt-S3D_uR --modelname
define dm = xd xd~
define yy1 = ys3u1 ys3u1~
generate p p > dm yy1 / 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 [QCD]
output
```

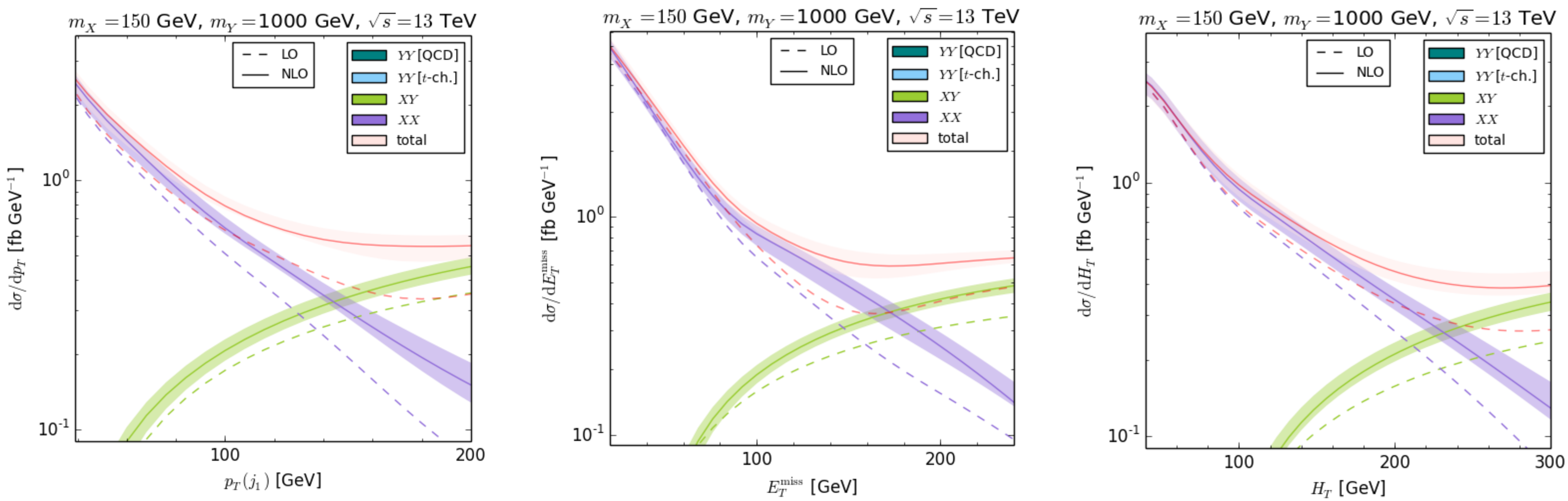
Validation and results for S3D_uR case (S1)



Process	CL_s [LO]	N_j	M_{eff} threshold	CL_s [NLO]	N_j	M_{eff} threshold
Total	$99.5^{+0.4}_{-2.1}$ %	≥ 4	> 1.4 TeV	100 %	≥ 5	> 2 TeV
XX	$0.6^{+0.6}_{-0.6}$ %	≥ 5	> 1.7 TeV	$3.3^{+0.1}_{-0.3}$ %	≥ 2	> 1.6 TeV
XY	$89.2^{+4.5}_{-4.8}$ %	≥ 2	> 1.6 TeV	$99.8^{+0.1}_{-0.2}$ %	≥ 5	> 2 TeV
YY [total]	$96.0^{+3.4}_{-7.6}$ %	≥ 4	> 1.4 TeV	$97.2^{+1.4}_{-2.6}$ %	≥ 4	> 1.4 TeV
YY [QCD]	$88.7^{+8.8}_{-14.5}$ %	≥ 4	> 1.4 TeV	$93.7^{+2.7}_{-5.2}$ %	≥ 4	> 1.4 TeV
YY [t-channel]	$35.1^{+3.4}_{-2.1}$ %	≥ 4	> 1.4 TeV	$29.7^{+0.2}_{-1.4}$ %	≥ 5	> 2 TeV

ATLAS-SUSY-2016-07 (most constraining signal region only)

Validation and results for S3D_uR case (S2)

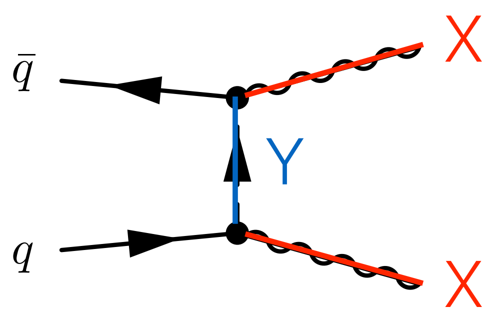


Process	CL_s [LO]	E_T^{miss} constraint		CL_s [NLO]	E_T^{miss} constrtaint	
Total	$95.0^{+3.0}_{-4.3}$ %	≥ 2	> 1.6 TeV	100 %	≥ 2	> 1.6 TeV
XX	$0.6^{+0.6}_{-0.6}$ %	≥ 6	> 2.2 TeV	$1.0^{+0.0}_{-0.2}$ %	≥ 3	> 1.3 TeV
XY	$61.7^{+8.4}_{-7.0}$ %	≥ 2	> 1.6 TeV	$83.6^{+1.5}_{-3.1}$ %	≥ 2	> 2 TeV
YY [total]	$77.4^{+7.9}_{-7.5}$ %	≥ 2	> 1.6 TeV	$97.8^{+0.5}_{-1.1}$ %	≥ 2	> 1.6 TeV
YY [QCD]	$55.3^{+12.0}_{-12.3}$ %	≥ 2	> 2 TeV	$67.7^{+4.1}_{-6.4}$ %	≥ 2	> 1.6 TeV
YY [t-channel]	$75.6^{+4.4}_{-4.8}$ %	≥ 2	> 2 TeV	$80.1^{+0.3}_{-1.6}$ %	≥ 2	> 1.6 TeV

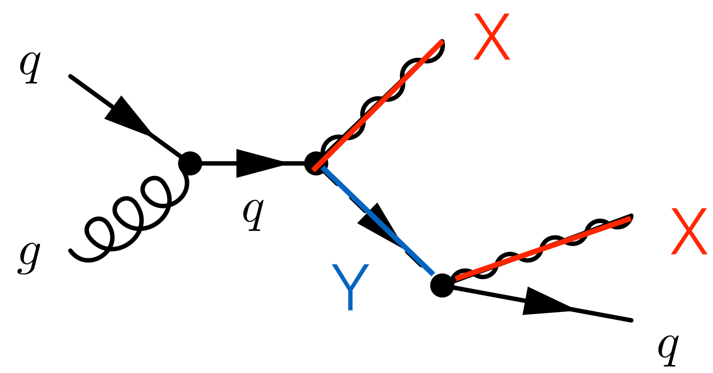
ATLAS-SUSY-2016-07 (most constraining signal region only)

Collider phenomenology @NLO QCD accuracy

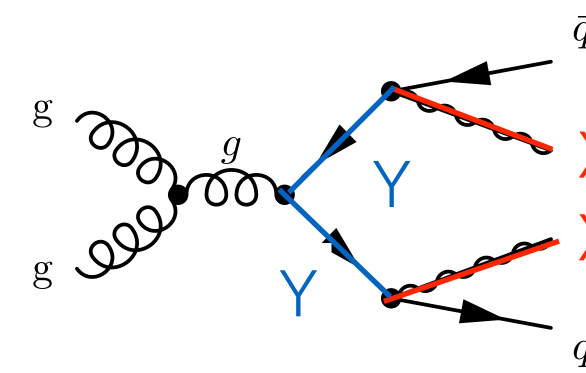
p p —> X X

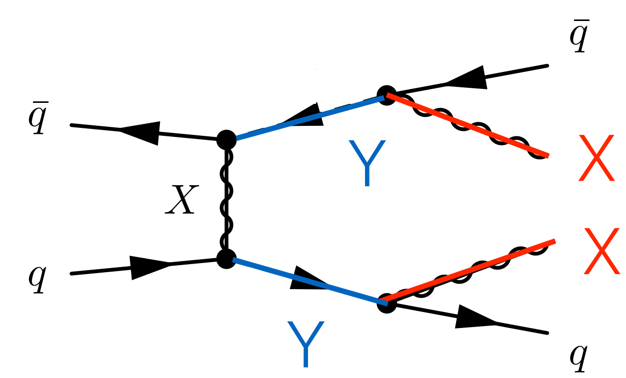


pp —> X Y, Y —> Xj



pp —> YY, Y —> Xj



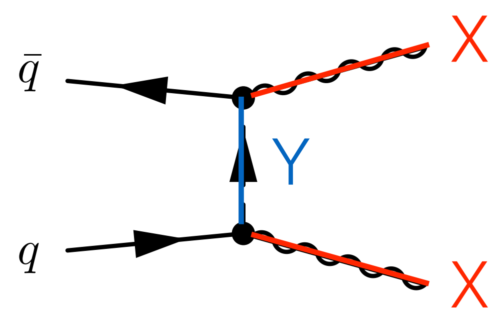


- Simulations of t-channel models at NLO QCD accuracy require a careful handling of resonances
- Use of MadSTR plugin of MG5_aMC@NLO to properly handle resonances and possible associated divergences and to avoid double counting of diagrams [Frixione et al. (JHEP 2019)]

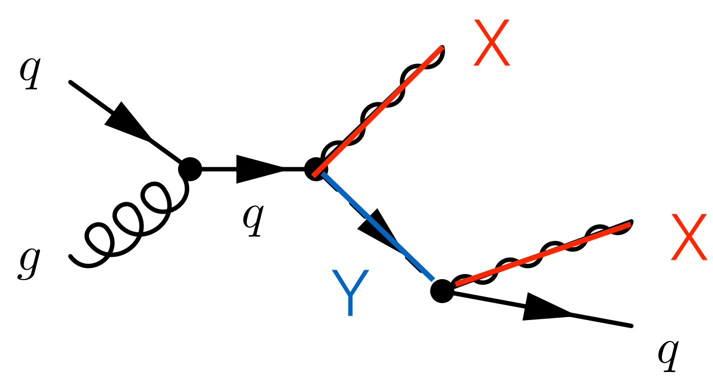
```
mg5_aMC —mode=MadSTR
```

Collider phenomenology @NLO QCD accuracy

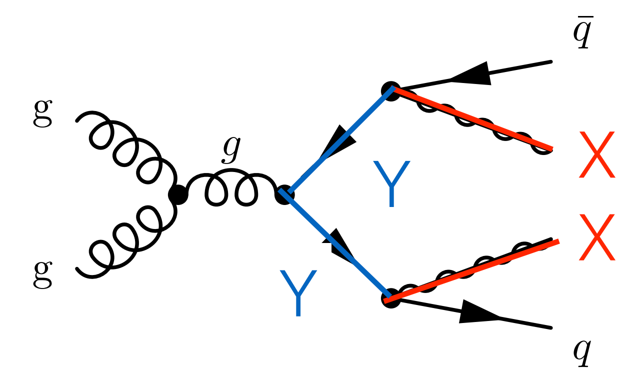
p p —> X X



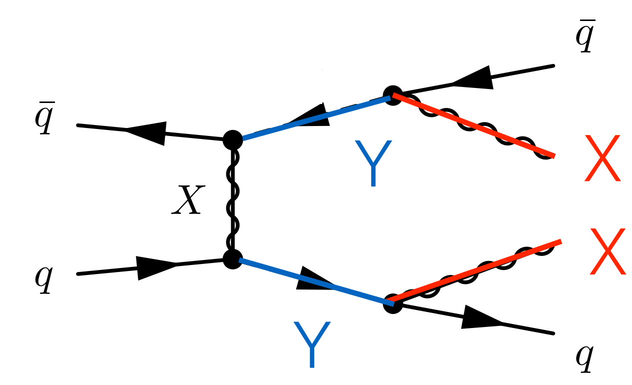
pp —> X Y, Y —> Xj



pp —> YY, Y —> Xj



This is LO for XY production
but NLO for XX production

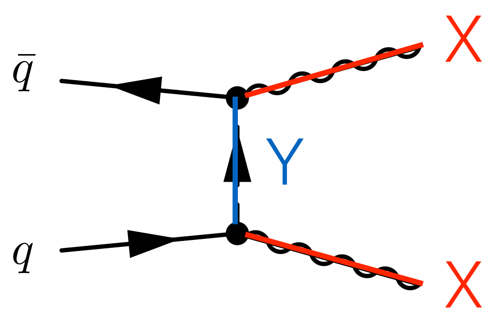


- Simulations of t-channel models at NLO QCD accuracy require a careful handling of resonances
- Use of MadSTR plugin of MG5_aMC@NLO to properly handle resonances and possible associated divergences and to avoid double counting of diagrams [Frixione et al. (JHEP 2019)]

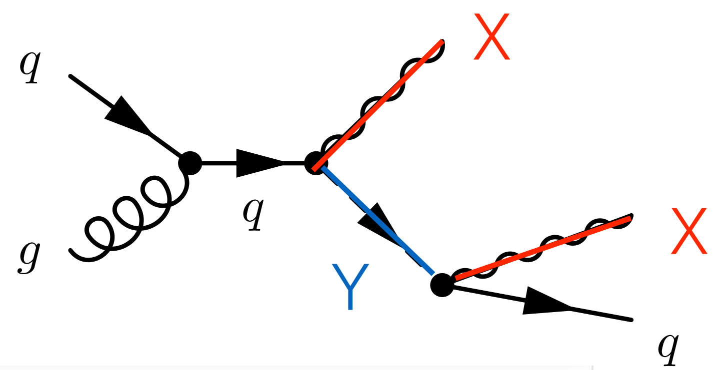
```
mg5_aMC —mode=MadSTR
```

Collider phenomenology @NLO QCD accuracy

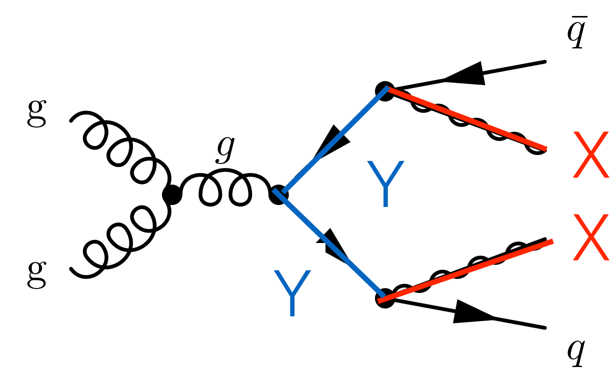
p p —> X X



pp —> X Y, Y —> Xj



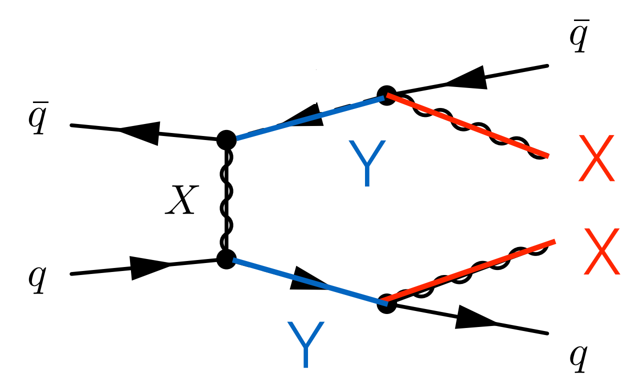
pp —> YY, Y —> Xj



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 [QCD]
output
```

ction
tion



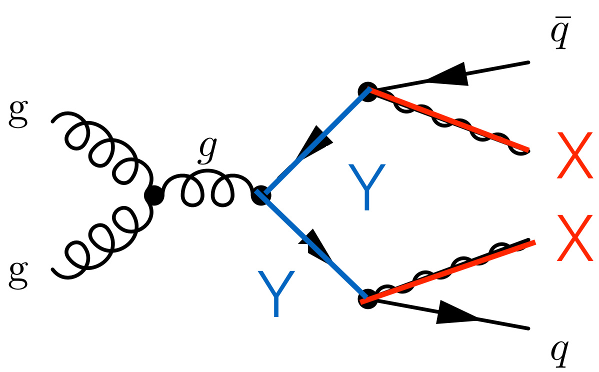
ccuracy require a careful handling of resonances

- Use of MadSTR plugin of MG5_aMC@NLO to properly handle resonances and possible associated divergences and to avoid double counting of diagrams [Frixione et al. (JHEP 2019)]

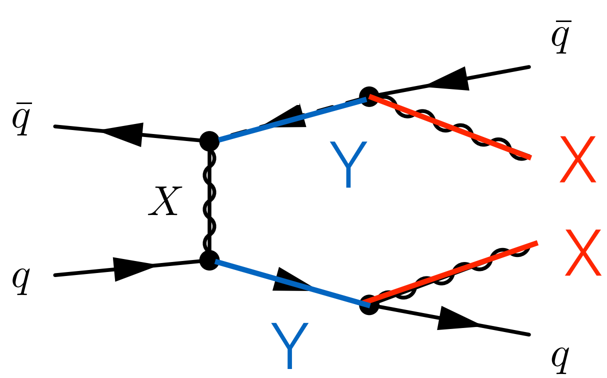
```
mg5_aMC —mode=MadSTR
```

Mediator production and NLO QCD corrections

Simulations of t-channel models at NLO QCD accuracy require a careful handling of interference terms when the mediator is a charged coloured particle



$\propto \alpha_s$ (Born)



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

Pure QCD process, which typically dominates unless the new physics coupling is sizable, in which case the t-channel diagram contributes and interferes

1. Simulate Y Y production (no use of MadSTR plugin) to get the pure QCD NLO contribution
2. YY production with DMT==2 and QCD==0 coupling computes t-channel dominant contribution, use of MadSTR
3. Simulate interference at LO and reweight by geometric mean of k-factors (QCD and t-channel) bin by bin

Results for S3D_uR case

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

	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	$139.1^{+1.3\%}_{-1.1\%} \pm 2.0\%$	$101.8^{+6.0\%}_{-7.1\%} \pm 1.2\%$	$9.888^{+6.5\%}_{-7.6\%} \pm 5.8\%$	$5.303^{+11.2\%}_{-13.3\%} \pm 7.4\%$	$8.749^{+3.6\%}_{-3.9\%} \pm 4.9\%$

Results for S3D_uR case

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

	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**	$929.8^{+1.9\%}_{-1.3\%} \pm 1.9\%$	$2212^{+5.9\%}_{-6.3\%} \pm 1.0\%$	$648.4^{+8.0\%}_{-9.2\%} \pm 3.1\%$	$484.7^{+10.7\%}_{-12.4\%} \pm 3.4\%$	$314.1^{+2.6\%}_{-2.6\%} \pm 2.5\%$
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Results for S3D_uR case

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 (here Dirac DM!)

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

Results for S3D_uR case

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 (here Dirac DM!)

	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

Results for S3D_uR case

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 (here Dirac DM!)

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

Results for S3D_uR case

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 (here Dirac DM!)

Theoretical scale uncertainties

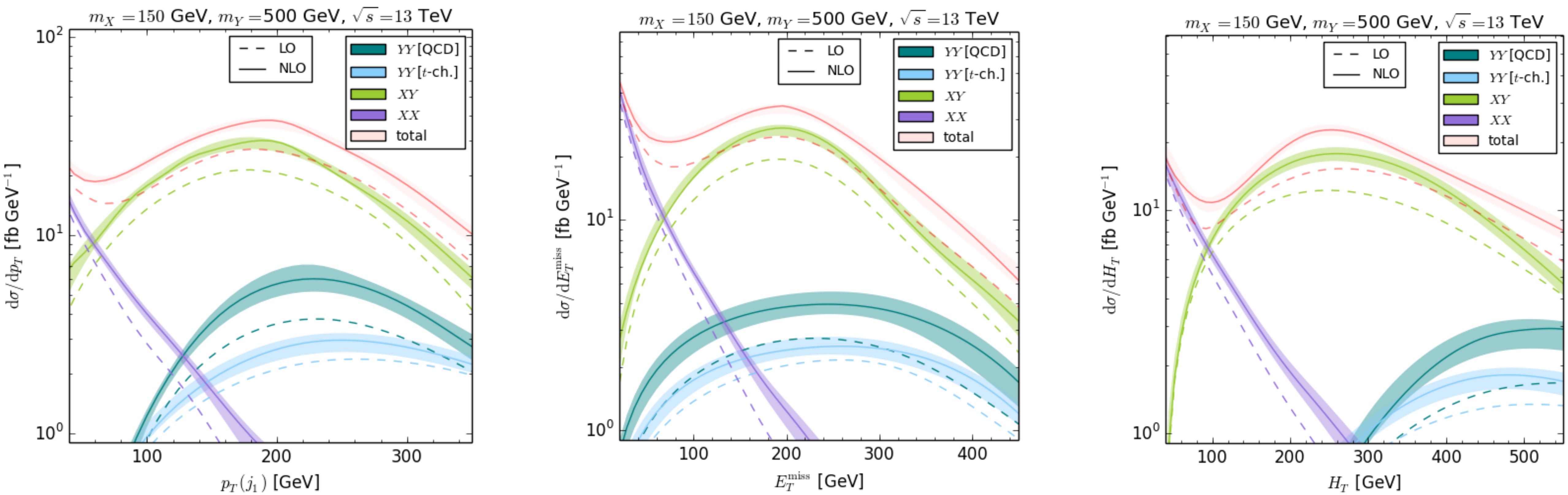
	Scen.	XX [fb]	XY [fb]	YY (total) [fb]	YY (QCD) [fb]	YY (t-channel) [fb]
LO	**S1**	$775.3^{+0.4\%}_{-0.8\%} \pm 1.9\%$	$1617^{+16.5\%}_{-13.4\%} \pm 1.0\%$	$473.5^{+23.6\%}_{-16.9\%} \pm 3.0\%$	$324.2^{+34.2\%}_{-23.8\%} \pm 3.4\%$	$261.5^{+7.1\%}_{-6.3\%} \pm 2.5\%$
	S2	$122.0^{+1.8\%}_{-2.0\%} \pm 1.9\%$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

First take home message

Large K factors: NLO predictions avoid underestimating the signal

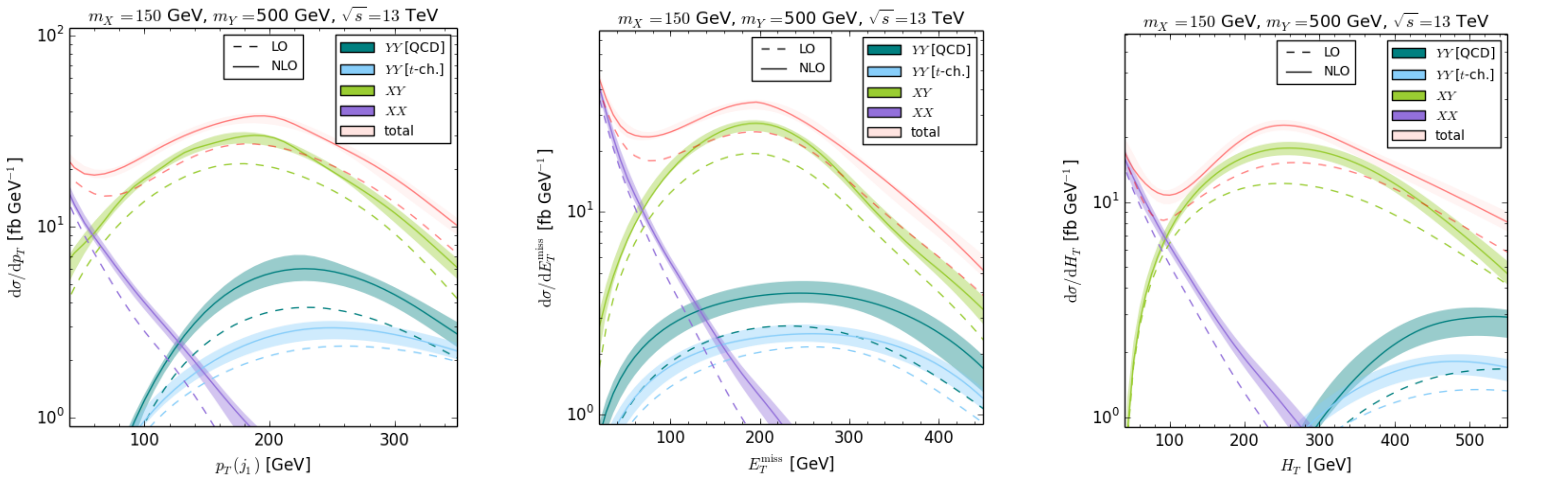
Validation and results for S3D_uR case (S1)



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)

Validation and results for S3D_uR case (S1)

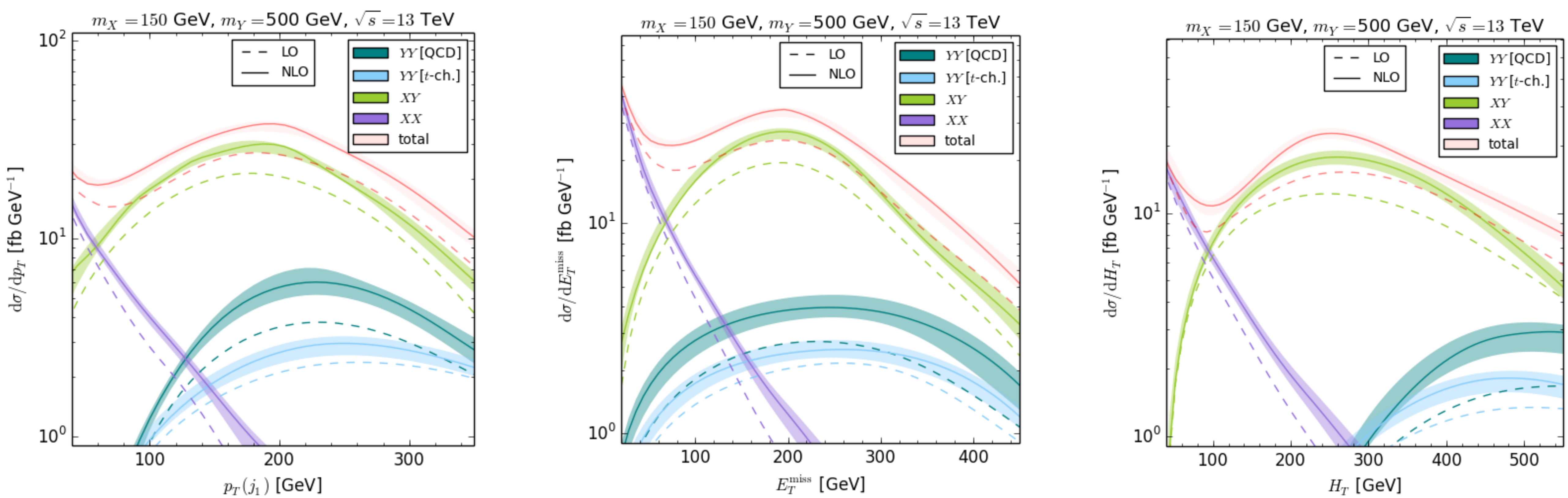


Process	CL_s [LO]	E_T^{miss} constraint	CL_s [NLO]	E_T^{miss} constrtaint
Total	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
XX	$1.6^{+0.2}_{-0.1}$ %	$\in [300, 350]$ GeV	$9.4^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV
XY	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
YY [total]	$91.3^{+6.2}_{-8.8}$ %	$\in [300, 350]$ 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)

Most relevant signal for exclusion → XY

Validation and results for S3D_uR case (S1)



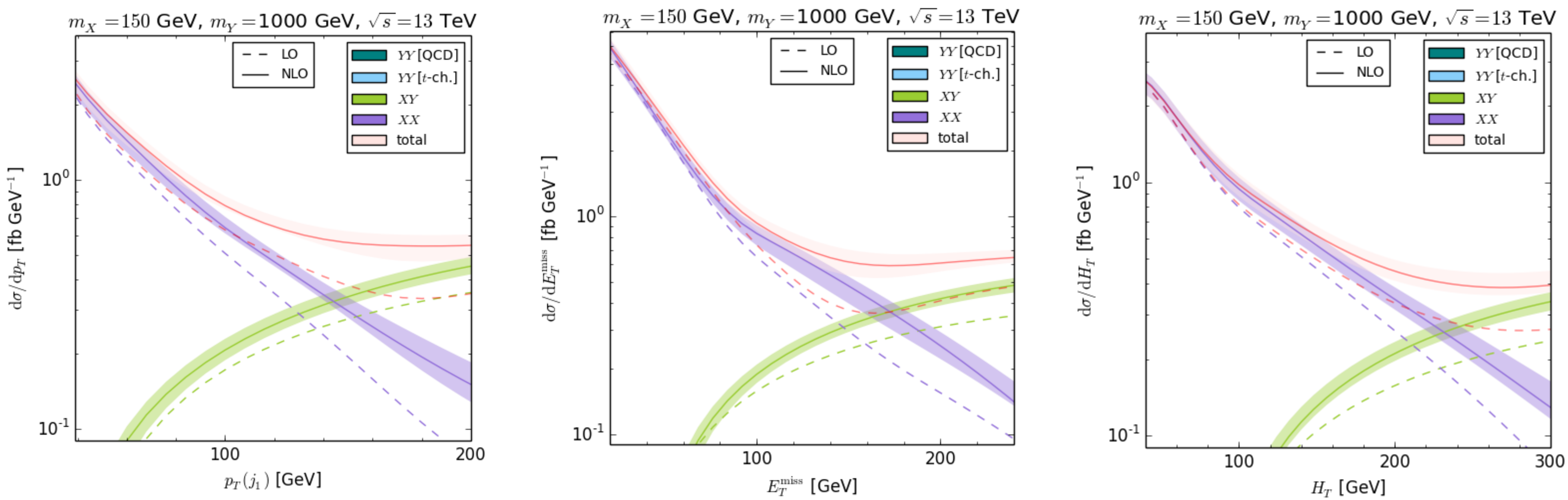
Process	CL_s [LO]	E_T^{miss} constraint	CL_s [NLO]	E_T^{miss} constrtaint
Total	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
XX	$1.6^{+0.2}_{-0.1}$ %	$\in [300, 350]$ GeV	$9.4^{+0.6}_{-0.6}$	[illegible]
XY	100 %	$\in [300, 350]$ GeV	100 %	$\in [300, 350]$ GeV
YY [total]	$91.3^{+6.2}_{-8.8}$ %	$\in [300, 350]$ 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)

Most relevant signal for exclusion

Only at NLO level signal region is sensitive to YY signal

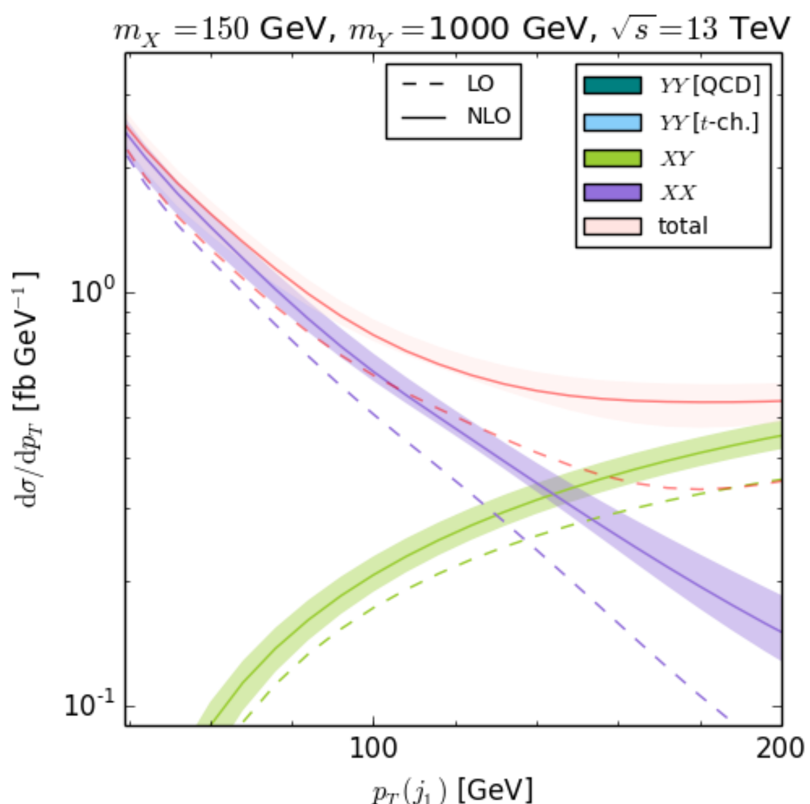
Validation and results for S3D_uR case (S2)

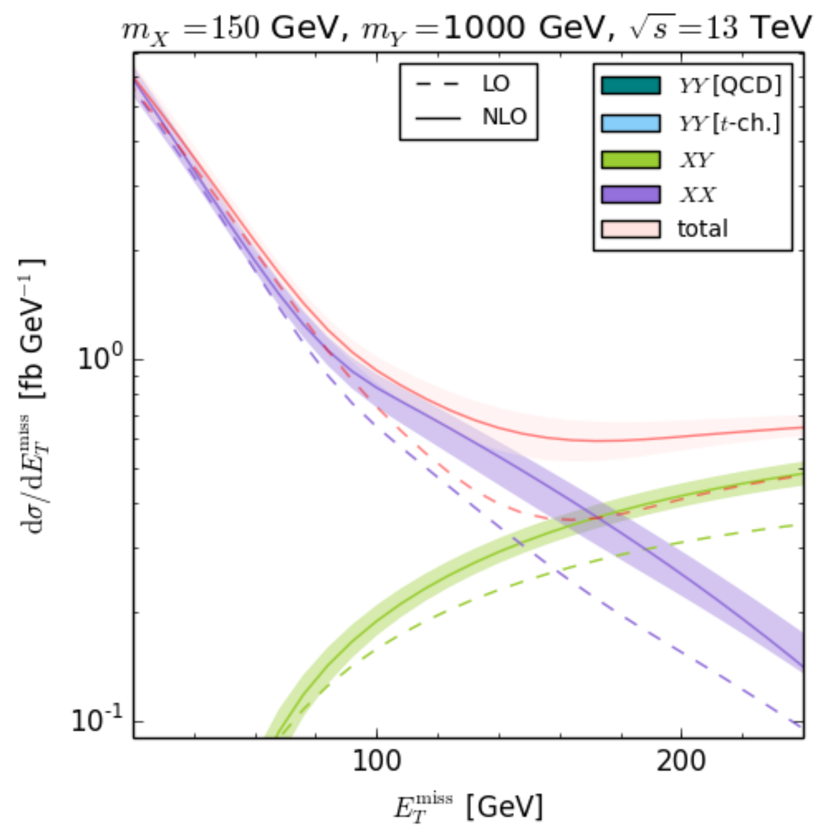


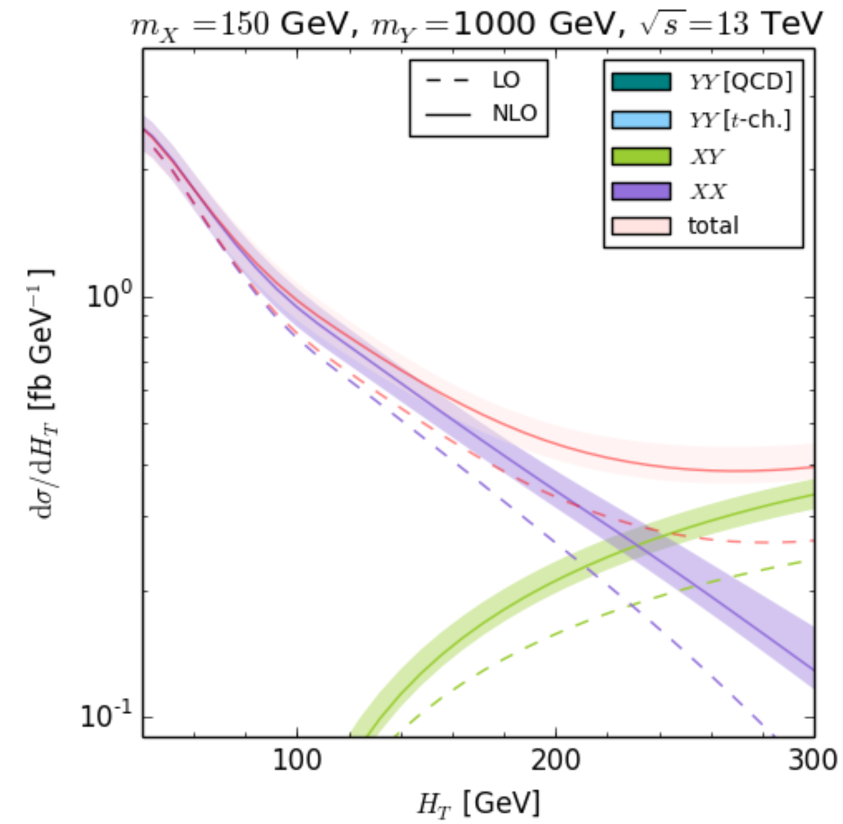
Process	CL$_s$ [LO]	E_T^{miss} constraint	CL$_s$ [NLO]	E_T^{miss} constrtraint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
XX	$0.7^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV	$3.6^{+0.3}_{-0.6}$ %	≥ 900 GeV
XY	$62.7^{+12.3}_{-10.4}$ %	$\in [500, 600]$ GeV	$83.9^{+2.9}_{-4.3}$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

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

Validation and results for S3D_uR case (S2)







Excluded at 1σ

	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

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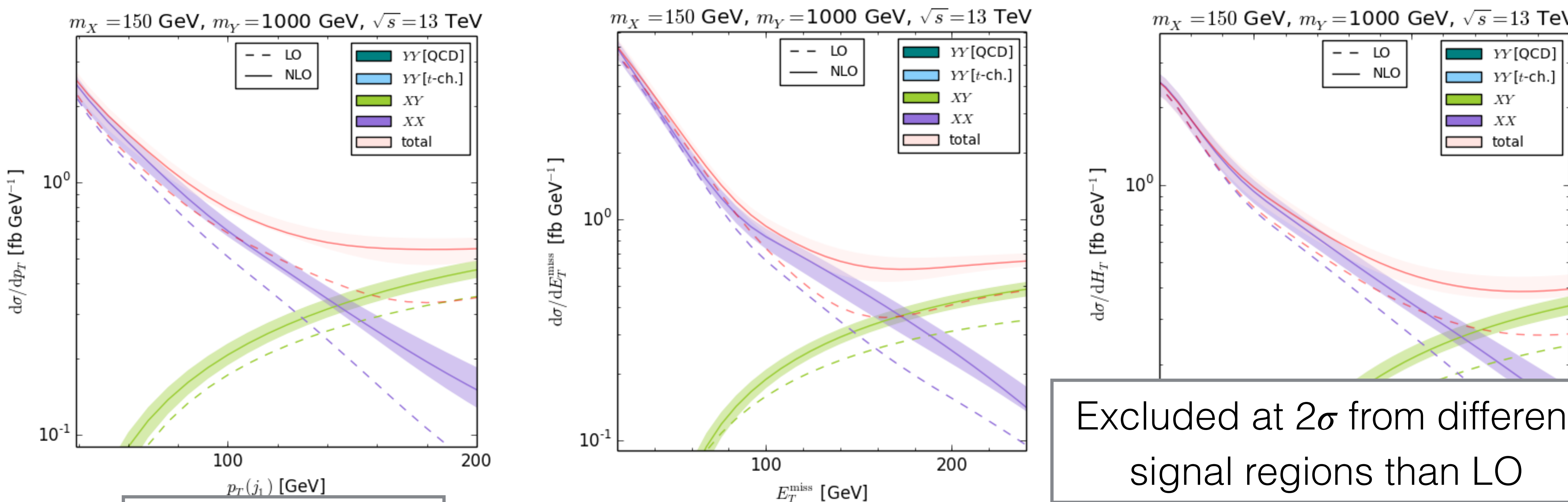
Validation and results for S3D_uR case (S2)



Excluded at 2σ from different signal regions than LO

Excluded at 1σ

	CL_s [LO]	E_T^{miss} constraint	CL_s [NLO]	E_T^{miss} constrtraint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
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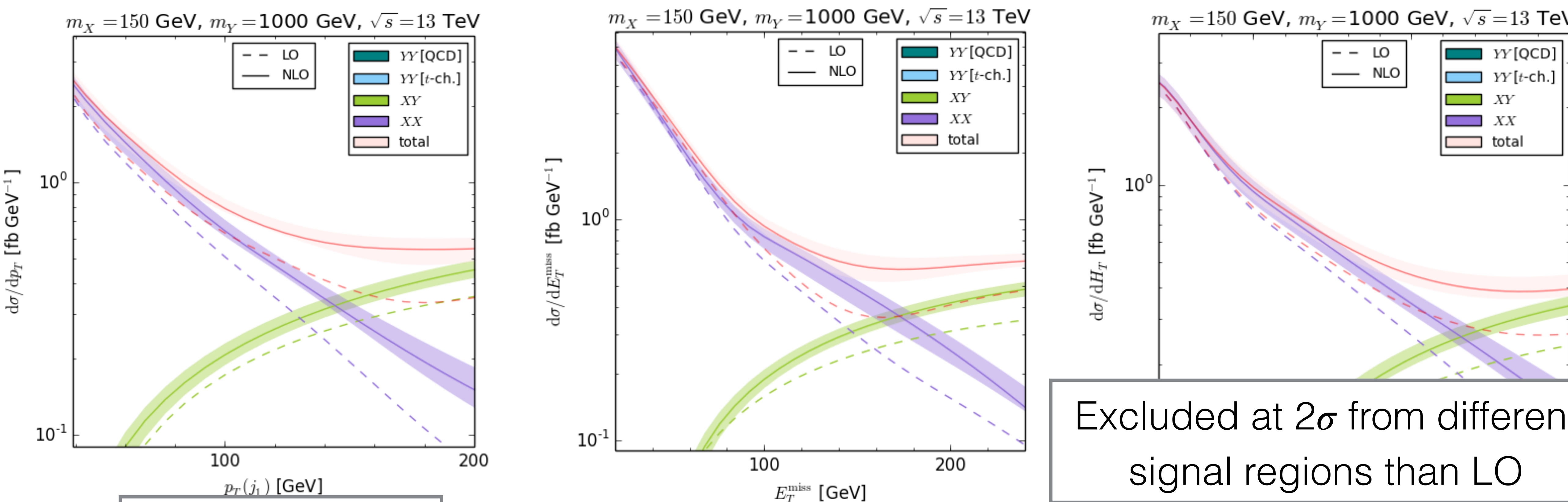
ATLAS-EXOT-2016-27 (most constraining signal region only)

Validation and results for S3D_uR case (S2)



Excluded at 2σ from different signal regions than LO

Excluded at 1σ

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Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
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Second take home message

NLO predictions allow to set robust exclusion bounds

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