A theoretical overview on t-channel models and their phenomenology

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Roadmap of Dark Matter models for Run 3 - CERN 13-17 May 2024

Motivation

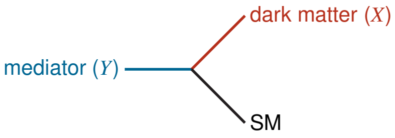
A white paper on t-channel scenarios is being written

Dark Matter via t-channel Production
A Report of the LHC Dark Matter Working Group

Joint effort TH-EXP to provide guidelines and benchmarks for new analysis during Run 3 and future upgrades

More than 50 authors involved

Study of scenarios based on the schematic interaction



Why is this important?

Representative of classes of theoretical scenarios

MSSM

UED

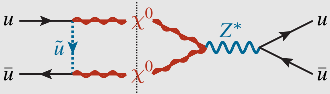
FPVDM

Complementary to s-channel

t-channel
mediator always heavier than DM
even number of mediator+DM in interactions

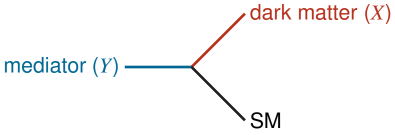
s-channel
mediator can also be lighter than DM
odd mediators allowed in interactions

But interferences can happen in non-minimal/full models. . .



coloured mediators interesting at a hadron collider

Guiding phenomenological questions



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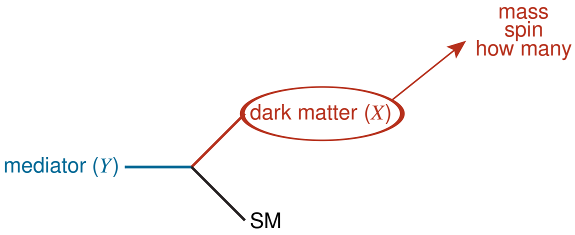

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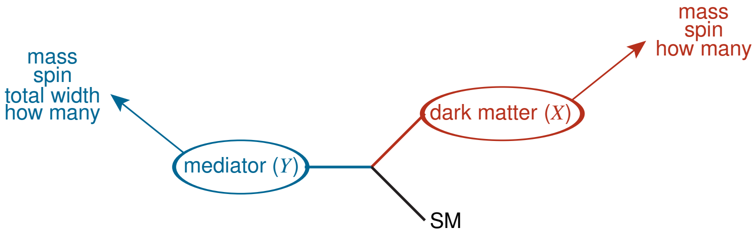

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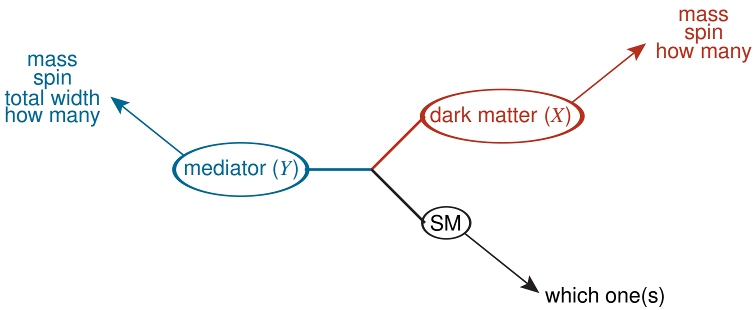

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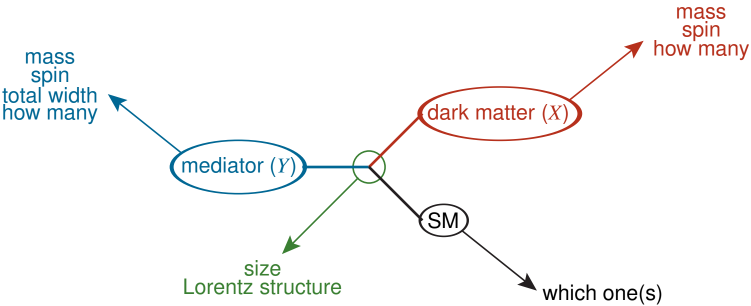

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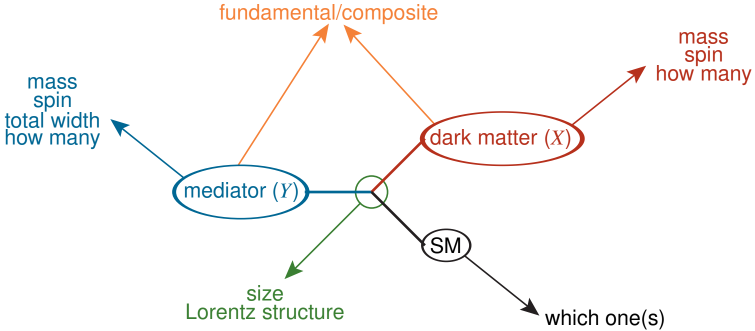

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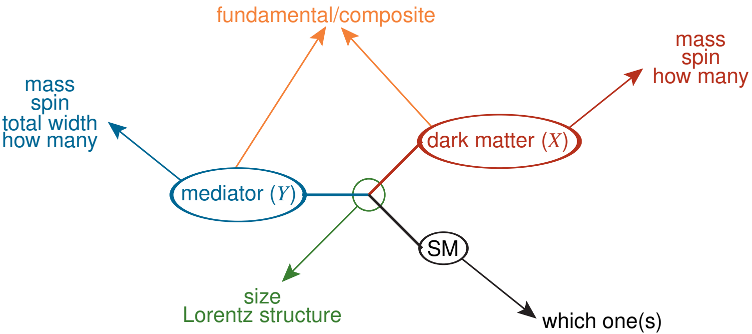
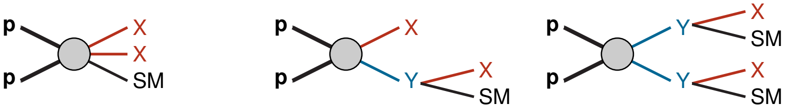


Depending on the possibilities:

- Can we observe a signal? And how?
- How does cosmology constrain the parameters?
- How do we reinterpret results?
- Can we define benchmarks for LHC to cover the widest range of possibilities?

Which signatures

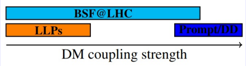


Not all processes might be possible at tree-level

depending on coupling or mass splitting

Long-lived mediators

Bound states
Displaced vertices
Delayed jets/photons



Mediators with prompt decay

MET+SM

depending on which SM particle

quark-philic { 1st generation, 2st generation, 3st generation, universal, . . . } **lepto-philic**

Interacting with SM gauge bosons (Z/W) or the Higgs boson

This talk: quark-philic scenarios with prompt-decay mediators

Classification of simplified scenarios

Real DM

		Mediator spin		
		0	$1/2$	1
DM spin	0	$\times$	**F3S**	$\times$
	1/2	**S3M**	$\times$	to be done
	1	$\times$	**F3V**	$\times$

Complex DM

		Mediator spin		
		0	$1/2$	1
DM spin	0	$\times$	**F3C**	$\times$
	1/2	**S3D**	$\times$	to be done
	1	$\times$	**F3W**	$\times$

Examples of theories which can be described by these simplified models

S3M	SUSY: squarks+neutralino (Majorana fermion)
S3D	Right-handed neutrino portals with extended scalar sectors
F3S	UED: KK quark partners + KK photon (real scalar)
F3C	SUSY: sleptons+sneutrinos (not aware of quark-philic models)
F3V	?
F3W	FPVDM: vector-like quark + vector DM (non-abelian gauge boson)

Complex DM scenarios excluded by cosmology for interactions with light quarks

Is it true also for non-minimal models?

Is it true also for bottom and top?

Numerical models

Simplified models suitable for performing MC simulations at NLO in QCD and testing against cosmological observables

Coloured mediators

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 includ
or bosonic dark matter) or 0 (fermionic dark matter). The model Lagrangian is given by

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

The first term consists in the Standard Model Lagrangian, the second one includes gauge-invariant kinetic
Dirac fermion, Majorana fermion, complex scalar, real scalar, complex vector and real vector dark matter,

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

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

http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt

	Spin	
Mediator	0	1/2
Dark matter	1/2	0 or 1

- DM real or complex
- Couplings with any SM quark
- Restrictions to select representations or coupling hierarchies (only one generation, universal couplings. . .)

C. Arina, B. Fuks and L. Mantani, Eur. Phys. J. C **80** (2020) no.5, 409, [arXiv:2001.05024 [hep-ph]].

Other models available for specific problems (leptophilic DM, multi-component DM. . .)

A unified model will also be released

How the analysis is performed

We need to provide useful information for both TH and EXP community

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- **Accurate kinematical description of the signal**
  → LO vs NLO

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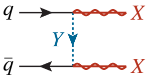
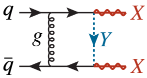
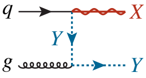
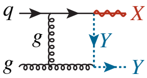
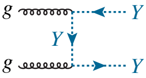
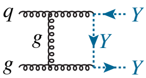
XX		
XY		
YY		

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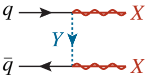
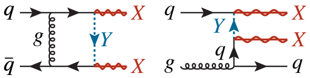
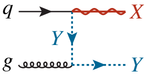
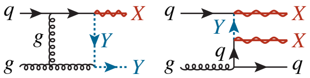
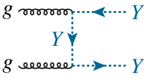
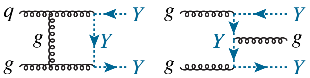
XX		
XY		
YY		

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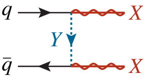
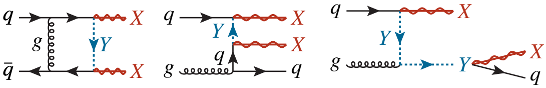
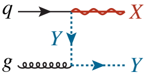
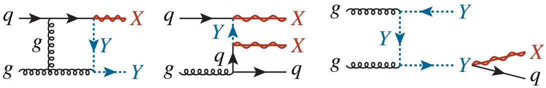
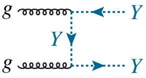
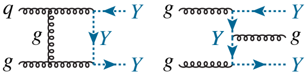
XX		
XY		
YY		

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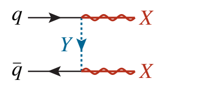
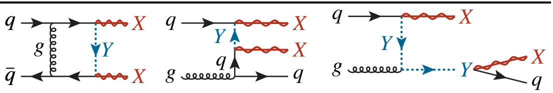
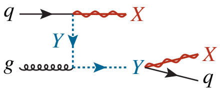
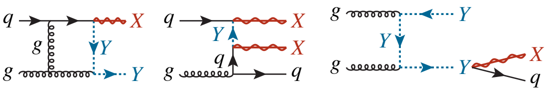
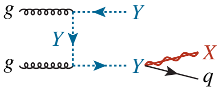
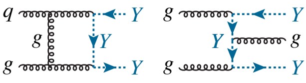
XX		
XY		
YY		

Double-counting between real emission and tree-level processes
Removed through suitable algorythm in MadGraph (MadSTR)

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  → LO vs NLO
  → beware of limitations: **narrow width approximation** $\Gamma_Y \ll m_Y$

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  - → recasts using publicly available codes in MadAnalysis 5
  - → is there any model-independent conclusion we can make?

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- **Provide public models and simulated data for (at least) Run 3 studies**
  → Writing easy-to-use tools to map simplified model parameters to any theory

```
S3M_XX_NLO_SMd_MY100_MX95_recast.tar.gz      S3M_YYi_LO_SMd_MY3200_MX3195_recast.tar.gz   S3M_YYtMM_NLO_SMd_MY2000_MX1995_recast.tar.gz  S3M_YYtPP_LO_SMd_MY100_MX95_recast.tar.gz
S3M_XX_NLO_SMd_MY100_MX99_recast.tar.gz      S3M_YYi_LO_SMd_MY3200_MX3199_recast.tar.gz   S3M_YYtMM_NLO_SMd_MY2000_MX1999_recast.tar.gz  S3M_YYtPP_LO_SMd_MY100_MX99_recast.tar.gz
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```

Database of simulated samples and recast data under construction (not public yet)

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People involved in the analysis
E. Bagnaschi, F. Benoit, A. Cagnotta, A. Desai, B. Fuks, O. Iorio, L. Munoz
S. Manohar Dogra, A. Moreno, Y. Sheng
(limitations mostly due to accessibility to HPC resources)

Relevance of the different processes

Master equation to reconstruct signal for any flavour hypothesis

$$
\begin{aligned}
\sigma^{eff}_{\rm Tot}(M_Y, M_X, \lambda) = & \lambda^0 \, \hat{\sigma}_{Y\bar{Y}_{QCD}}(M_Y) \quad \epsilon_{Y\bar{Y}_{QCD}}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{YY_t}(M_Y, M_X) \; \epsilon_{YY_t}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{Y\bar{Y}_t}(M_Y, M_X) \; \epsilon_{Y\bar{Y}_t}(M_Y, M_X) \\
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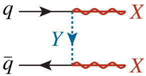
& + \lambda^2 \, \hat{\sigma}_{Y\bar{Y}_i}(M_Y, M_X) \; \epsilon_{Y\bar{Y}_i}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{XX}(M_Y, M_X) \; \epsilon_{XX}(M_Y, M_X) \\
& + \lambda^2 \, \hat{\sigma}_{XY}(M_Y, M_X) \; \epsilon_{XY}(M_Y, M_X)
\end{aligned}
$$

$\hat{\sigma}$ are the cross-sections after factorizing the new coupling

ϵ are the efficiencies associated with a given experimental signal region

Example with XX



$$\mathcal{M} \propto \lambda^2 \rightarrow \sigma \propto \lambda^4$$

The kinematic properties are driven **only** by the masses

λ just **rescales** the cross-sections without affecting the shape of distributions

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$$
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\end{aligned}
$$

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Channel	Scaling	Key features
XX	λ^4	strong dependence on coupling, but requires emission of visible objects
XY	λ^2	phase-space advantage: potentially competitive
$Y\bar{Y}_{QCD}$	1	only depends on masses, baseline contribution
YY_t $Y\bar{Y}_t$ $\bar{Y}\bar{Y}_t$	λ^4	enhanced by PDFs for u and d but present only for real DM strong dependence on coupling and interferes with QCD always PDF suppressed and present only for real DM
$Y\bar{Y}_i$	λ^2	unphysical by itself, but potentially negative contribution

Do we need to study all interactions?

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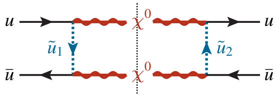
Possibility to combine individual result to describe
universal scenarios
$\mathcal{L} \sim \lambda\, Y_f X q_f$ with same λ for each q_f

Actually, results can be recombined in almost any way
Simulated samples can also be recycled using appropriate weights

Potential to reconstruct complex models
with multiple mediators or DM candidates

Missing some interference contributions at the moment

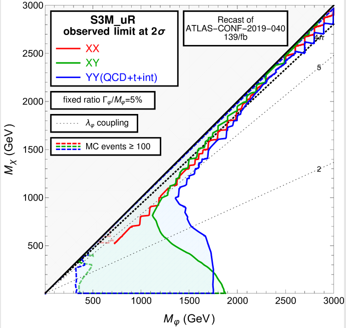


Current results

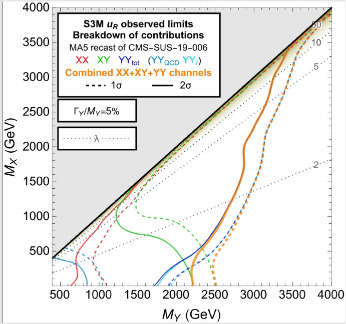
Interaction with the up quark

Goals

- Go beyond existing results



C. Arina, B. Fuks, L. Mantani, H. Mies, LP and J. Salko, Phys. Lett. B **813** (2021), 136038



C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, Phys.Rev.D 108 (2023),

Combination of all channels, relevance of NLO corrections and interference effects

Interaction with the up quark

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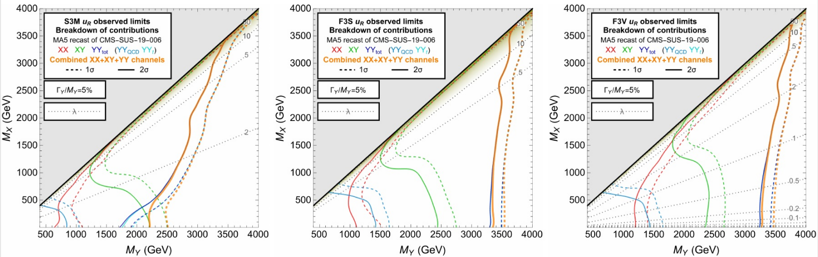

C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, Phys.Rev.D 108 (2023)

Discrimination between spin configurations

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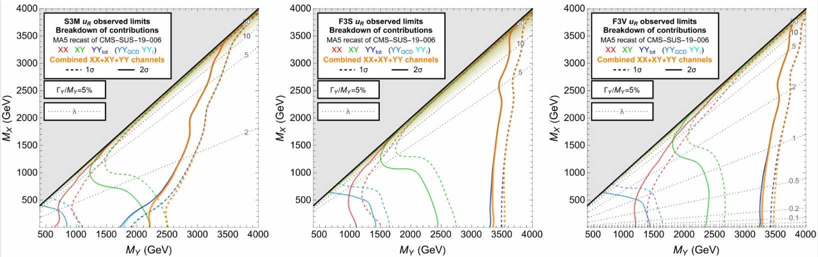


C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, Phys.Rev.D 108 (2023)

Discrimination between spin configurations

For fixed Γ_Y/m_Y bounds poorly depend on m_X, especially for fermion Y, even if λ decreases.

$$\texttt{S3M\_uR}: \begin{cases} \mathcal{M}^2_{uu} \propto \lambda^4 \frac{tu-M_Y^2}{(t-M_X^2)^2} \\ \mathcal{M}^2_{u\bar{u}} \propto \lambda^4 \frac{sM_X^2}{(t-M_X^2)^2} \end{cases},$$

$$\texttt{F3S\_uR}: \mathcal{M}^2_{uu} = \mathcal{M}^2_{u\bar{u}} \propto \lambda^4 \frac{(t-M_Y^2)^2}{(t-M_X^2)^2},$$

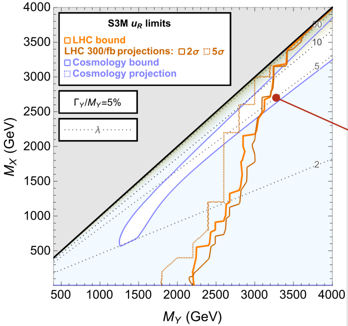
$$\texttt{F3V\_uR}: \begin{cases} \mathcal{M}^2_{uu} \propto \lambda^4 \frac{\left[2M_X^2(t-M_Y^2)+M_Y^2(t+2u-3M_Y^2)\right]^2}{M_X^4(t-M_X^2)^2} \\ \mathcal{M}^2_{u\bar{u}} \propto \lambda^4 \frac{\left[2M_X^2(M_Y^2-t)+M_Y^2(s-u+M_Y^2)\right]^2}{M_X^4(t-M_X^2)^2} \end{cases}$$

- **F3S** and **F3V**: the YY_t all amplitudes become independent of m_X for $m_X \to 0$
- **S3M**: the $u\bar{u}$-initiated amplitude decreases with m_X and leaves only the m_X-independent uu-initiated one for low DM masses

Interaction with the up quark

Goals

- Go beyond existing results
- Identify benchmarks allowed by LHC and cosmology observables



C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, arXiv:2307.10367, to appear on PRD

	M_Y	M_X	λ
S3M_uR	3300	2700	4.79563
F3S_uR	3400	2500	4.88088
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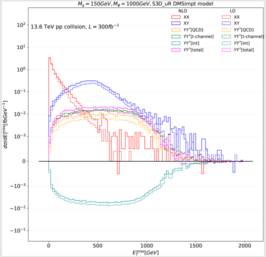
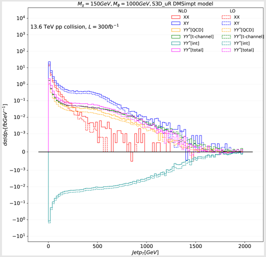
- Kinematical studies for subsequent analyses (preliminary, courtesy of A. Desai)

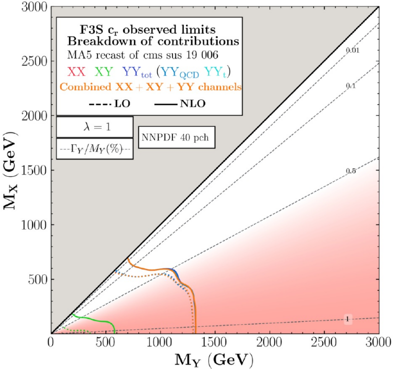


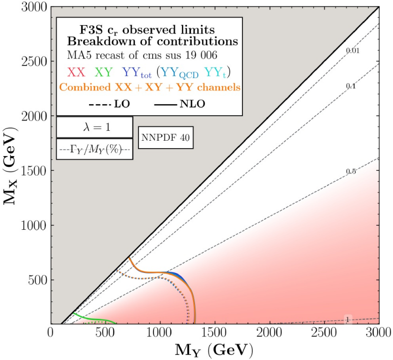


Do we need differential K-factors or can we just apply a constant one?
Which process dominates in which region, and how to emphasize its significance?

Interaction with the charm quark

preliminary results courtesy of F. Benoit and L. Munoz

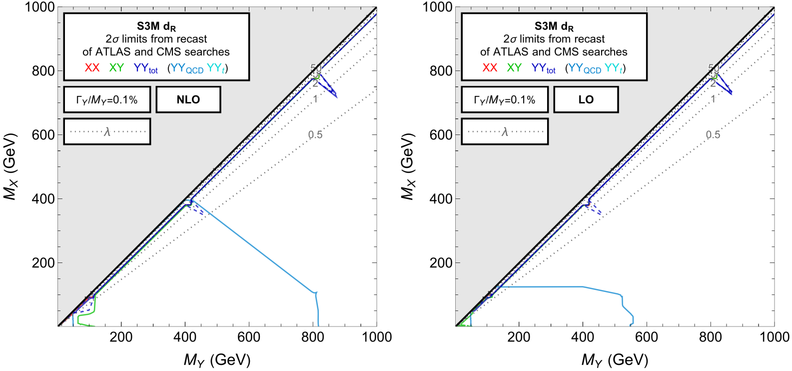




- Exploring difference by using perturbative/intrinsic charm PDFs
- Results in the red area have large mediator width: care must be taken

Interaction with down-type quarks

preliminary results with many thanks to A. Desai



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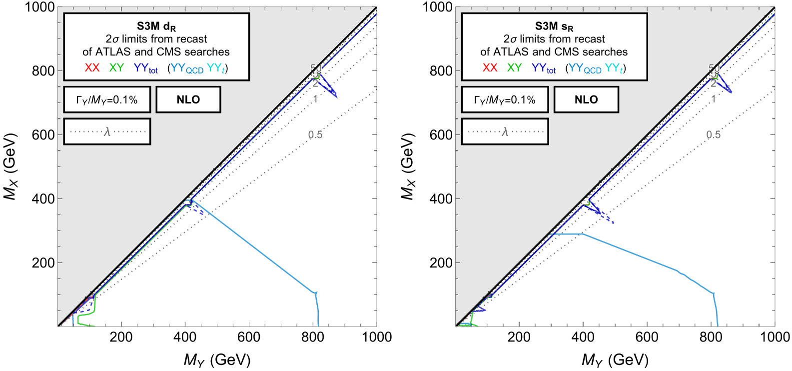

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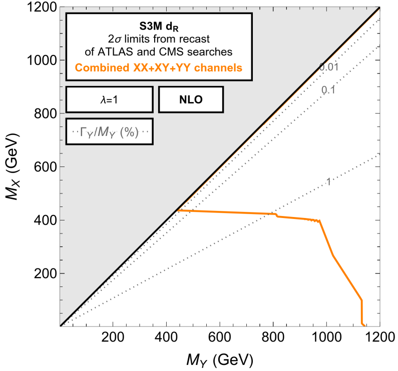

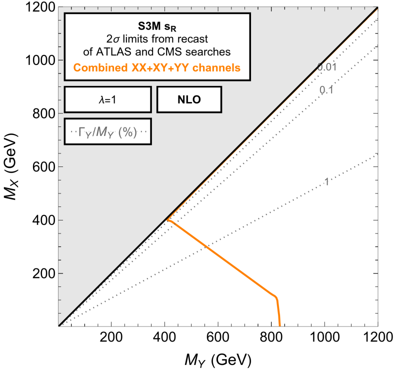

- Simulations done with fixed $\Gamma_Y/m_Y = 0.1\%$: small λ overall, baseline QCD pair production bound dominates.
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- Rescaling for $\lambda = 1$: PDF-enhancement for down, increasing constraints

Outlook

Systematic study of t-channel scenarios and their phenomenology at LHC

Analysis with Run 2 data

focus on kinematically relevant parameters (masses, spins)
accurate description of the processes and determination of current bounds
recombination of samples to determine bounds for different hypotheses

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Wishlist

Combine with s-channel
Include lepto-philic DM scenarios
Include flavoured DM scenarios
Include interferences for non-minimal scenarios

Further pheno and experimental input will be needed in due course