The Mono-jet *t*-channel Simplified Model

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Content

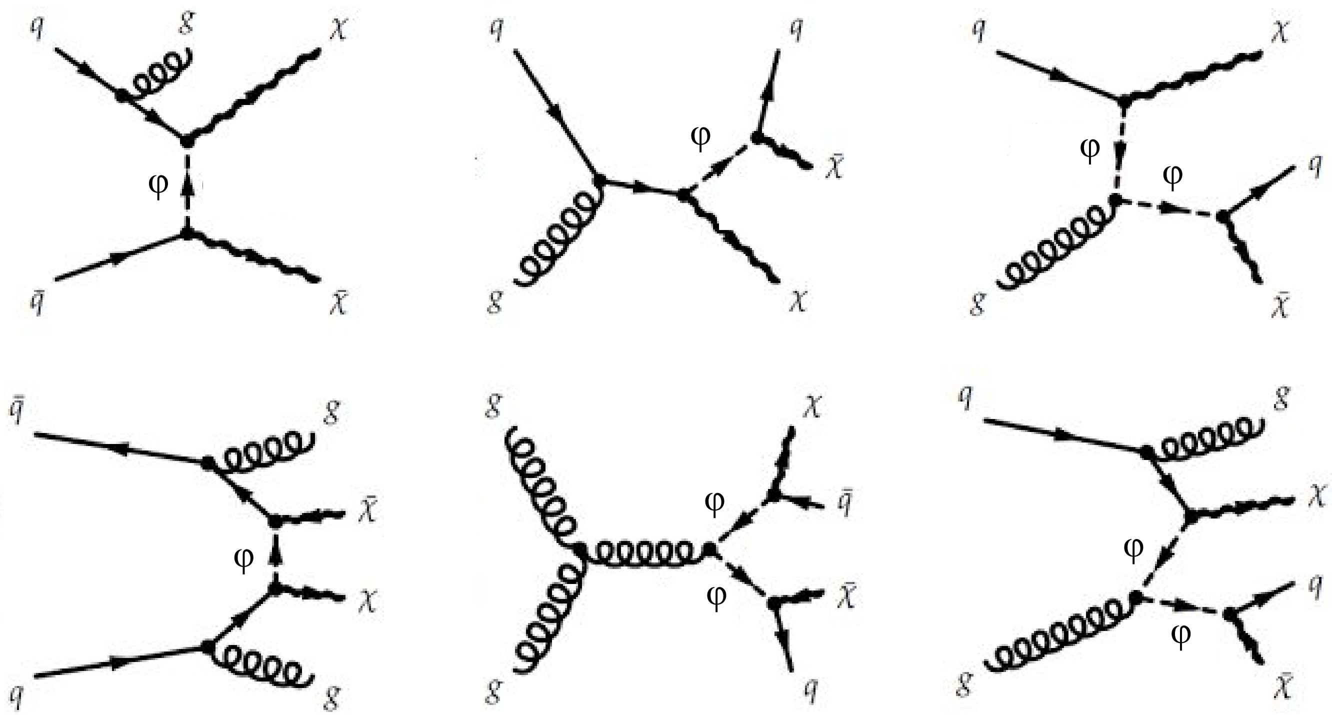
The *t*-channel Model: Introduction (1/3)

A '*t*-channel model' was first discussed in the ATLAS/CMS Dark Matter Forum

➔ '*t*-channel model' synonym for 'colored scalar mediator model'

➔ Introduces signatures not covered by the conventional *s*-channel models

	***t*-channel mediation**	***s*-channel mediation**	***s*-/*t*-channel mediation**
1-jet case			
2-jet case			



Ref. [arXiv:1507.00966](https://arxiv.org/abs/1507.00966)

The t-channel Model: Introduction (2/3)

DMF report model:

$$\mathcal{L}_{\text{int}} = g \sum_{i=1,2} (\phi_{(i),L}\bar{Q}_{(i),L} + \phi_{(i),u,R}\bar{u}_{(i),R} + \phi_{(i),d,R}\bar{d}_{(i),R})\chi$$

➔ Adaptation of model by **Papucci et al.** in arXiv:1402.2285 (MSSM where only the squarks and the neutralino are light)

➔ LH + RH couplings

➔ 2 generations of spin-0 mediators, φ_i, forming color triplets, SU(2) doublets

➔ DM-mediator-quark couplings, g

➔ SM singlet Dirac fermion DM particle, χ

➔ Minimal decay widths:

$$\Gamma(\phi_{(i)} \to \bar{u}_{(i)}\chi) = \frac{g_{(i)}^2}{16\pi M_{\phi_{(i)}}^3}(M_{\phi_{(i)}}^2 - m_{u_{(i)}}^2 - m_\chi^2)\sqrt{(M_{\phi_{(i)}}^2 - (m_{u_{(i)}} + m_\chi)^2)(M_{\phi_{(i)}}^2 - (m_{u_{(i)}} - m_\chi)^2)}$$

Additional models studied in the literature:

➔ Coupling to $\varphi_{(i),u,R}$ (arXiv:1308.2679) and $\varphi_{(i),d,R}$ (arXiv:1402.2285, arXiv:1409.2893)

➔ LH coupling only by **Bell et al.** in arXiv:1307.8120 (also in arXiv:1405.3101)

The *t*-channel Model: Introduction (3/3)

By construction, UFO of Papucci model doesn't include couplings to W bosons

➔ Interest from mono-W group prompted move to Bell et al. model

The Bell Model: [UFO files]

$$\mathcal{L}_{\text{int}} = g \sum_{i=1,2,3} \phi_{(i),L} \bar{Q}_{(i),L} \chi$$

Model is in general a subset of the Papucci model with a few key differences:

1. **RH coupling switched off**
2. **Coupling to 3rd generation of quarks switched on (fTB ≠ 0)**
3. **Coupling to W bosons switched on**

Ref. arXiv:1307.8120

- Compatibility check of models performed by Amelia Brennan with:
  - ➔ fTB = 0 for the Bell Model, RH coupling off for the Papucci Model
  - ➔ Outcomes: models yield the same cross-sections for mono-jet and mono-Z signatures
  - ➔ Full details in ref. link
- Bell model is equivalent to the model by Y. Bai et al. (arXiv:1308.0612)
  - ➔ 'Fermion Portal DM Model' studied by CMS

The *t*-channel Model: Mono-jet Implementation

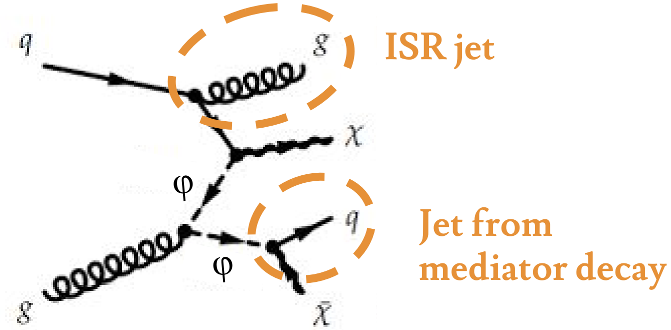
The mono-jet group uses the Bell Model with a set of simplifying assumptions:

- MFV and therefore $m_\varphi = M$
- Leave **fTB = 0** and omit $\varphi_{(3),L}$ from hard scatter processes
  - ➔ Model aligns better with DMF model
  - ➔ Inclusion of b- and t-quarks requires significant additional work
  - ➔ Already performed some preliminary studies towards future inclusion [link]
- Require $m_\chi < M$
  - ➔ Ensures stability of DM particle
- Require $m_\chi^2 + m_q^2 \leq M^2$ and $4m_\chi^2/M^2 \leq \left(1 - m_q^2/M^2 + m_\chi^2/M^2\right)^2$
  - ➔ Ensures mediator width is always defined

Split Sample Generation Procedure (1/2)

Considerations:

1. DM-mediator-quark vertices allow for simultaneous FS partons with different hard scales

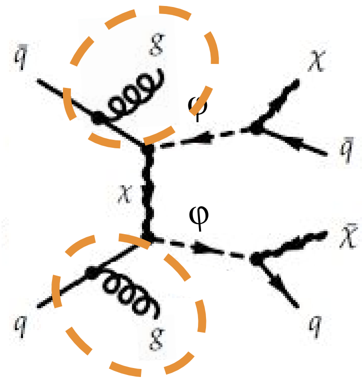


Events with p_T(FS parton) < matching scale vetoed

➔ Problematic when $M \approx m_\chi$ and φ produced on-shell

2. Without including any additional jets, ISR is suppressed for the inclusive process pp > χχ + {0, 1, 2}j

➔ Hard ISR important when $\Delta m = M - m_\chi$ is small



Split Sample Generation Procedure (2/2)

<u>Treatment:</u>

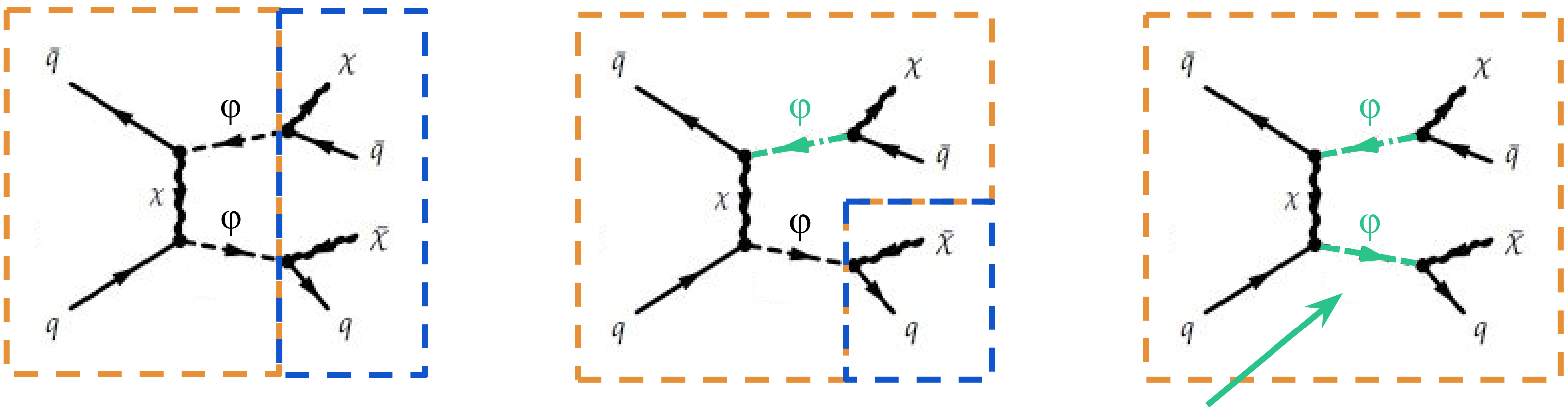
Split sample generation for each mass and coupling point according to the number of on-shell mediators in the MadGraph process:

1. $\varphi\varphi + \{0, 1, 2\}j$
2. $\varphi\chi + \{0, 1, 2\}j\ \$\ \mathrm{med}$
3. $\chi\chi + \{0, 1, 2\}j\ \$\ \mathrm{med}$

□ Decay of mediators performed by Pythia (assume 100% BR for $\varphi \rightarrow q\chi$)

Adapted from Papucci et al., ref. [arXiv:1402.2285](https://arxiv.org/abs/1402.2285)

<u>Sub-sample 1</u> **<u>Sub-sample 2</u>** **<u>Sub-sample 3</u>**



MadGraph Pythia MadGraph Pythia Internal s-channel mediators off-shell MadGraph

<u>Note:</u> Following Papucci et al, we neglect interference

Split Sample Recombination Procedure

Omitting on-shell mediators in samples 2 and 3 removes the phase space **M ± Γ*BWcutoff**

➔ Require Γ∗BWcutoff ≤ O(50 GeV)

- ❑ For narrow Γ, BWcutoff = 15
- ❑ For points with 50/Γ < 1, BWcutoff capped at 1

For broad Γ, a narrow BWcutoff leads to event duplication among the samples - accounted for as follows:

1. Assume mediator is well-modelled by a Breit-Wigner propagator:

$$BW(x) = \frac{1}{\pi\Gamma/2\left(1+\left(\frac{x-x_0}{\Gamma/2}\right)^2\right)}$$

2. Scale samples 1 and 2 by the factors w^2 and w respectively, where:

$$w = \frac{\int_I BW(x)dx}{\int_{-\infty}^{\infty} BW(x)dx}$$

with $I \equiv [M - \Gamma * \mathrm{BWcutoff}, M + \Gamma * \mathrm{BWcutoff}]$

3. Weight samples by cross-sections and add together

Adapted from ref. arXiv:1402.2285

Additional documentation in Section 3.2.1 and Appendix C of mono-jet internal note

Generation Parameters

MadGraph setup:

- MadGraph5 v2.3.3
- Exclude photons and EW/Higgs bosons
  - ➔ Save on computation time/resources
  - ➔ Added diagrams yields correction of < 8 % but increase computation time by ~80%
- NNPDF23 PDF
- CKKW-L merging scheme
- ktDurham = $M/8$ when both FS mediators on-shell and 30 GeV otherwise
  - ➔ Studied impact on different values and combinations of ktDurham values [link]
  - ➔ Best values yield minimal variation in kinematics, σ, and A when varied by 0.5 or 2
  - ➔ Optimisation achieved for the quoted merging scales in (non-)compressed regions
  - ➔ Systematic uncertainty added to account for any inconsistencies
- 100 GeV MET filter

Pythia setup:

- Pythia8.212
- nJetMax = 2
- A14 NNPDF23LO tune

Full details of validation studies listed on mono-jet twiki [link]

Comparison with SUSY Strong Production

Sub-sample 1 resembles closely direct squark production with RH squarks switched off

- ➔ DM ⇔ neutralino -
- ➔ Mediator ⇔ squark
- ➔ Squarks couple to 1 flavor of quark

m_{χ} = 450 GeV, M = 500 GeV					
	Process	0-j	1-j	2-j	sum{0-j,1-j,2-j}
Sp1, g = 0.1	pp > sq sq	1.4e+00	4.9e-01	1.1e-01	2.0e+00
SUSY sample	pp > sq sq	1.4e+00	4.9e-01	1.1e-01	2.0e+00

Performed a comparison of cross-sections/ kinematics for different values of g [link]

- ➔ Sub-sample 1 recovers MSSM cross-sections for g=0.1
- ➔ MSSM kinematics recovered for a range of couplings
- ➔ For larger g, the other sub-samples become more important

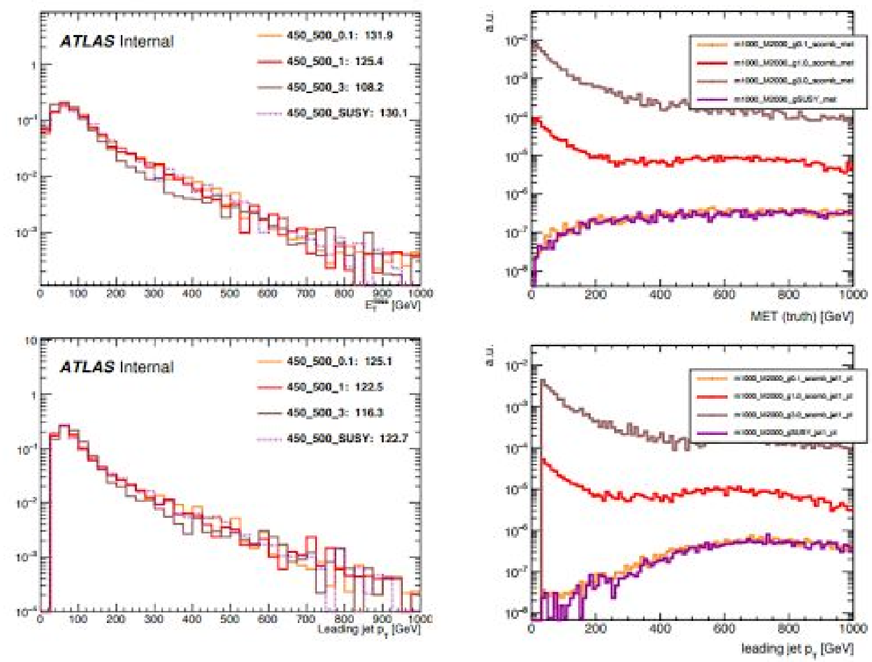


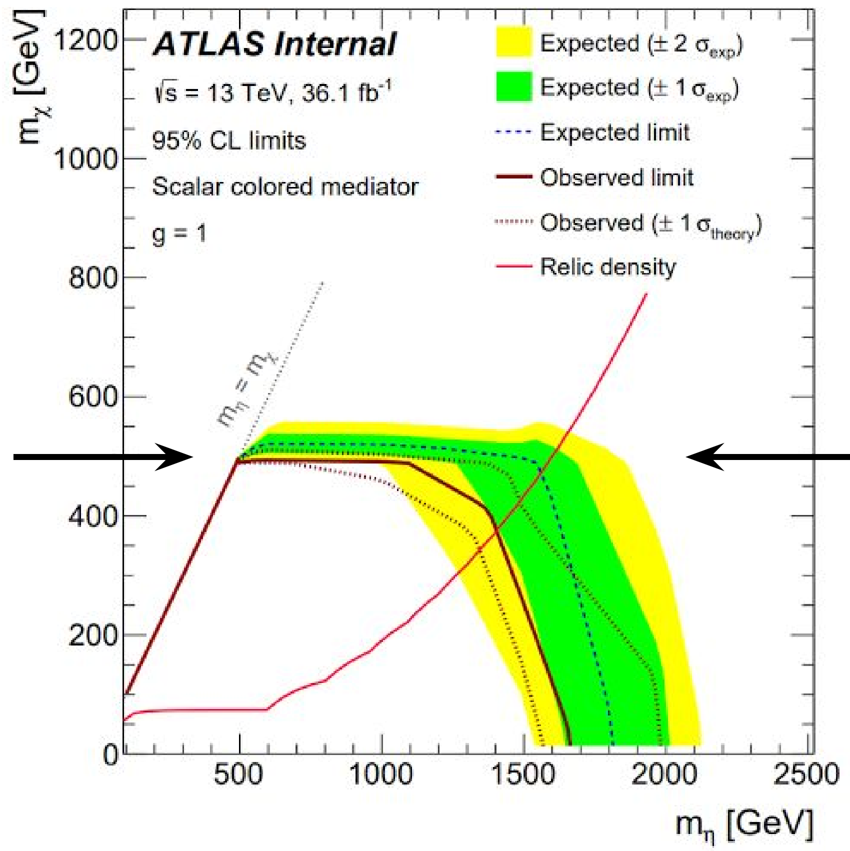
Fig: Kinematics comparison for sub-sample 1 (L) and sub-sample 2 (R)

Setting g = 1:

- ➔ Distinguishes the *t*-channel model from SUSY squark production
- ➔ Interesting in terms of relic density

Limits for g = 1

DM particle unstable when $m_\chi > M$



Mediator masses of ~1.65 TeV are excluded for light DM. For $m_\chi \simeq M$, masses up to 500 GeV are excluded

Note:

- This limit plot generated with initial set of mass points [link] (extended set nearly complete [link])
- For the 1σ band on the observed limit, only the uncertainty on the PDF and scale are included

Outstanding Points

- Full set of replies to draft 1 comments (in particular Dave Charlton's comments) on the *t*-channel now being finalised
- *t*-channel introduction and signal simulation sections rephrased to better encapsulate the complexity of the model and generation procedure
- Appendix C of the internal note has been updated wrt the Exotics-circulated version, now includes:
  - ➔ Additional details on the *t*-channel generation procedure and validation
  - ➔ Full set of *t*-channel studies performed

Backup

JobOptions Content

	MadGraph Generated Processes
Sample 1	pp > med med / etab etabbar etat etatbar a h z w+ w- pp > j med med / etab etabbar etat etatbar a h z w+ w- pp > j j med med / etab etabbar etat etatbar a h z w+ w-
Sample 2	pp > dm med / etab etabbar etat etatbar a h z w+ w- $med pp > j dm med / etab etabbar etat etatbar a h z w+ w- $med pp > j j dm med / etab etabbar etat etatbar a h z w+ w- $med
Sample 3	pp > chi chi~ / etab etabbar etat etatbar a h z w+ w- $med pp > j chi chi~ / etab etabbar etat etatbar a h z w+ w- $med pp > jj chi chi~ / etab etabbar etat etatbar a h z w+ w- $med

dm = chi chi~

Merging:mayRemoveDecayProducts = on for sub-samples 1 and 2

➔ Omits resonance decay products from the hard process

➔ Omits mediators from Pythia-internal jet clustering algorithms

	Pythia Merging Process Definition
Sample 1	‘pp>{etad,9000006}{etad~,-9000006}{etau,9000007}{etau~,-9000007}{etas,9000008}{etas~,-9000008} {etac,9000009}{etac~,-9000009}’
Sample 2	‘pp>{chi,1000022}{chi~,-1000022}{etad,9000006}{etad~,-9000006}{etau,9000007}{etau~,-9000007}{etas,9000008}{etas~,-9000008}{etac,9000009}{etac~,-9000009}’
Sample 3	‘pp>{chi,1000022}{chi~,-1000022}’

Validation of Generation Procedure cont.

Validation of merging scales

- Tested CKKW-L merging between MadGraph and Pythia
- Check two possible strategies:
  1. Mediator mass related scale, e.g. Mmed/4, Mmed/8
  2. Jet pt related scale, e.g. analysis-jet-pt-cut/2
- Best strategy is the one which yields:
  1. Minimal variation in MET and leading-/sub-leading jet p_T distributions when the ktDurham value is varied by a factor 0.5 or 2
  2. Minimal variation in the cross-section and acceptances
- Studies performed in two regimes:
  1. Compressed case: $m_\chi = 450$ GeV, $M = 500$ GeV
  2. Non-compressed case: $m_\chi = 100$ GeV, $M = 2$ TeV
- Outcomes:
  - ➔ ktDurham = $M/8$ yields smallest variation in relevant parameters for sub-sample 1 but significant deviation in sample 3
  - ➔ ktDurham = 15 GeV yields large variation in sub-sample 1 but avoids unwanted structure in sub-samples 2 and 3
  - ➔ ktDurham = 30 GeV yields same result as 15 GeV for sub-samples 2 and 3 and is favoured by most DM search analyses
  - ➔ Optimisation achieved for non-uniform merging scales ($M/8$ for sub-sample 1, 30 GeV for sub-samples 2 and 3)

Validation of Generation Procedure cont.

Impact of splitting samples/omitting interference terms:

“However we checked in explicit cases, using analytic formulae, that this introduces up to O(30%) deviations in the rates…” - Papucci et al.

Checks by Caterina Doglioni and Maria Giulia Ratti:

➔ Average impact on cross-section is 10-35% at MadGraph level

m_χ=500, *M*=550 g=1 xsec (pb) bw_weight s1 1,056 0,958 s2 0,639 0,979 s3 0,035 1,000 sum (bw_w included) 1,672 s nom 1,101 diff -34%	m_χ=1, *M*=1000 g=1 xsec (pb) bw_weight s1 0,045 0,717 s2 0,141 0,847 s3 0,082 1,000 sum (bw_w included) 0,233 snom 0,273 diff 17%	m_χ=1, *M*=200 g=1 xsec (pb) bw_weight s1 234,220 0,964 s2 124,360 0,982 s3 5,893 1,000 sum (bw_w included) 353,813 snom 325,210 diff -8%

➔ Take deviation from NWA as a rough idea of interference: for a 30% uncert., signal limits change by roughly 5%

m1_M1500 exp limit on mu: 0.45 -> 0.55 obs limit on mu: 0.66 -> 0.86	m1_M2000 exp limit on mu: 1.32 -> 1.59 obs limit on mu: 1.68 -> 2.09