COLORED SCALAR MEDIATOR MODELS

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Disclaimer

- This talk is not a conclusion for the white paper.
- I was not involved in any Atlas and CMS wide discussions of colored scalar mediator (t-channel) models.
    - https://lpcc.web.cern.ch/sites/lpcc.web.cern.ch/files/wg_docs/20160919-20_publicmeeting.pdf
    - https://lpcc.web.cern.ch/sites/lpcc.web.cern.ch/files/wg_docs/20160622_publicmeeting.pdf
    - https://lpcc.web.cern.ch/sites/lpcc.web.cern.ch/files/wg_docs/20151210-11_publicmeeting.pdf
- I know, for the 2HDM+pseudoscalar model, Atlas and CMS people met many times and detailed discussions were done about the contents of the white paper.
- But, as far as I know this was not the case for colored scalar mediator models.

Colored scalar mediator models

- Papucci model (1402.2285[hep-ph]):

$$\mathcal{L} = \mathcal{L}_{SM} + g_M \sum_{i=1,2} \left(\tilde{Q}_L^i \bar{Q}_L^i + \tilde{u}_R^i \bar{u}_R^i + \tilde{d}_R^i \bar{d}_R^i \right) \chi + \text{mass terms} + c.c.$$

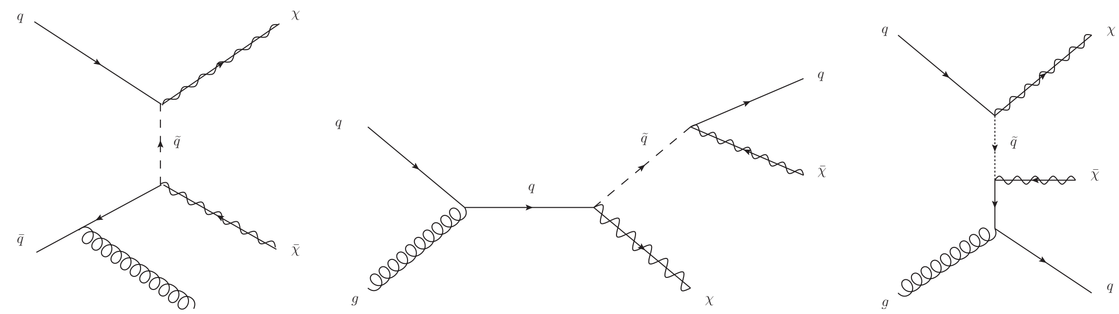
  - 8 Mediators: $\tilde{Q}_L^i$, $\tilde{u}_R^i$, $\tilde{d}_R^i$ (i = flavor, only first two generations)
    - MLV(Minimal Flavor Violation) ➔ universal coupling, same mass.
  - 3 free parameters (mediator widths are given by minimal requirement):
    - 1 coupling, 1 mediator mass, 1 DM mass.
- Bell model (1209.0231[hep-ph]):

$$\begin{aligned} \mathcal{L}_{\text{int}} &= f_{ud} \bar{Q}_{\text{L}} \eta \chi_{\text{R}} + h.c \\ &= f_{ud} \left(\eta_u \overline{u}_{\text{L}} + \eta_d \overline{d}_{\text{L}} \right) \chi_{\text{R}} + h.c., \end{aligned}$$

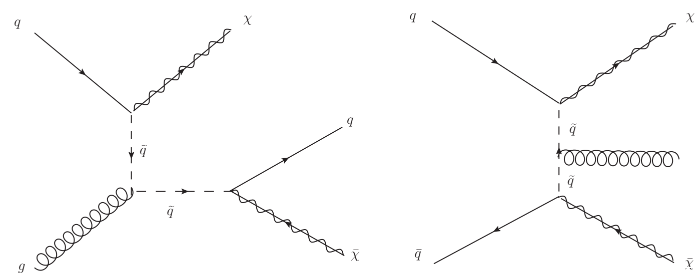
  - 6 Mediators (do not couple to right hand quarks, couple to all 3 generations).
  - 3 free parameters (mediator widths are given by minimal requirement):
    - 1 coupling, 1 mediator mass, 1 DM mass.

Diagrams

- Mono-jet diagrams.
  - Many variations.

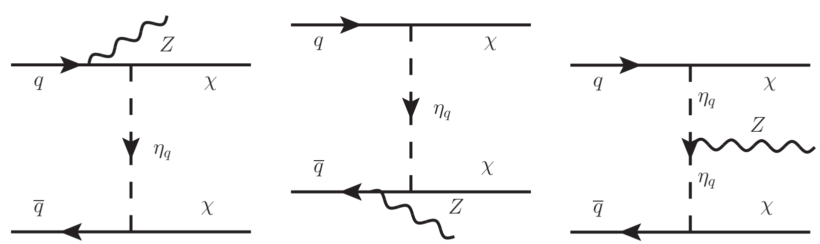


(a) (b) (c)



(d) (e)

- Mono-Z diagrams.
  - Only (a) ISR and (e) mediator emission are possible for mono-Z.



ATLAS mono-jet group

(Mono-jet) Model 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 (No 3rd generation)
  - ➔ Model aligns better with DMF model
  - ➔ Inclusion of b- and t-quarks requires significant additional work
  - ➔ Already performed some preliminary studies towards future inclusion
- 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
  - ➔ Minimal decay widths:

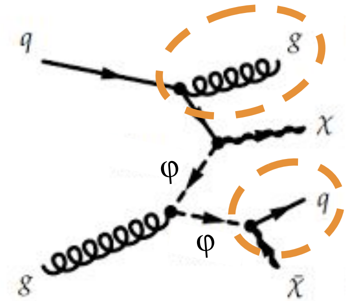
$$\Gamma(\phi_{(i)} \to \bar{u}_{(i)}\chi) = \frac{g_{(i)}^2}{16\pi M_{\phi_{(i)}}^3}(M_{\phi_{(i)}}^2 - m_{u_{(i)}}^2 - m_\chi^2)\sqrt{(M_{\phi_{(i)}}^2 - (m_{u_{(i)}} + m_\chi)^2)(M_{\phi_{(i)}}^2 - (m_{u_{(i)}} - m_\chi)^2)}$$

(Mono-jet) Split Sample Generation Procedure

ATLAS mono-jet group

Considerations:

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

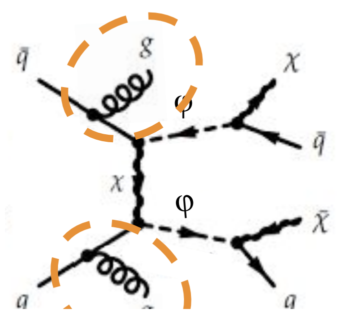


Events with p_T(FS parton) < matching scale vetoed

➔ 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



(Mono-jet) Split Sample Generation Procedure

ATLAS mono-jet group

Treatment:

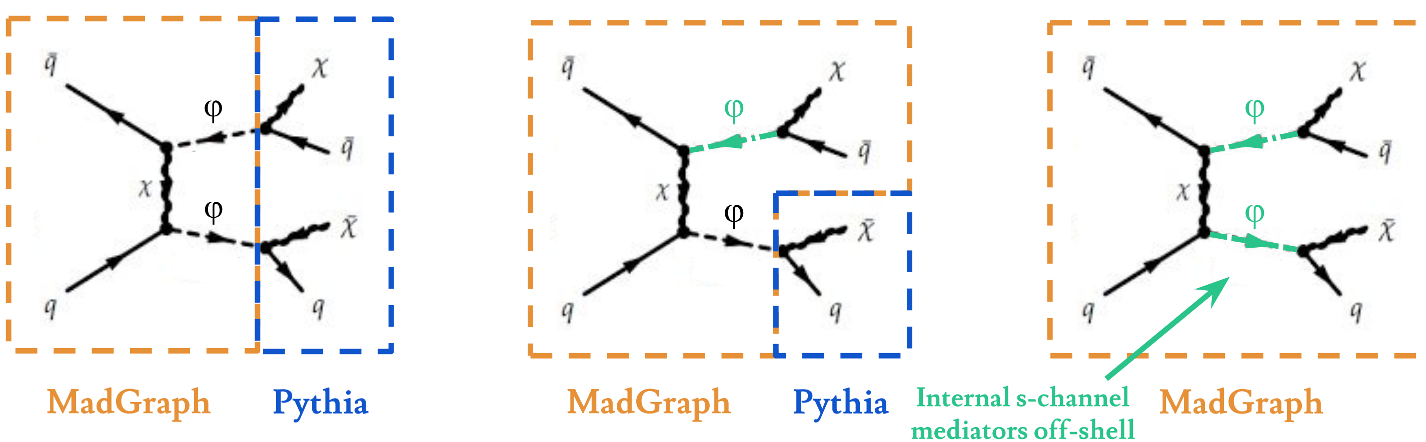
Split sample generation for each mass and coupling point according to the number of on-shell mediators in the MadGraph process:

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

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

Adapted from Papucci et al., ref. arXiv:1402.2285

Sub-sample 1 **Sub-sample 2** **Sub-sample 3**



Note: Following Papucci et al, interference is neglected

Note: Excludes photons and EW/Higgs bosons in the hard scatter.

(Mono-jet) Split Sample Recombination Procedure

ATLAS mono-jet group

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:

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

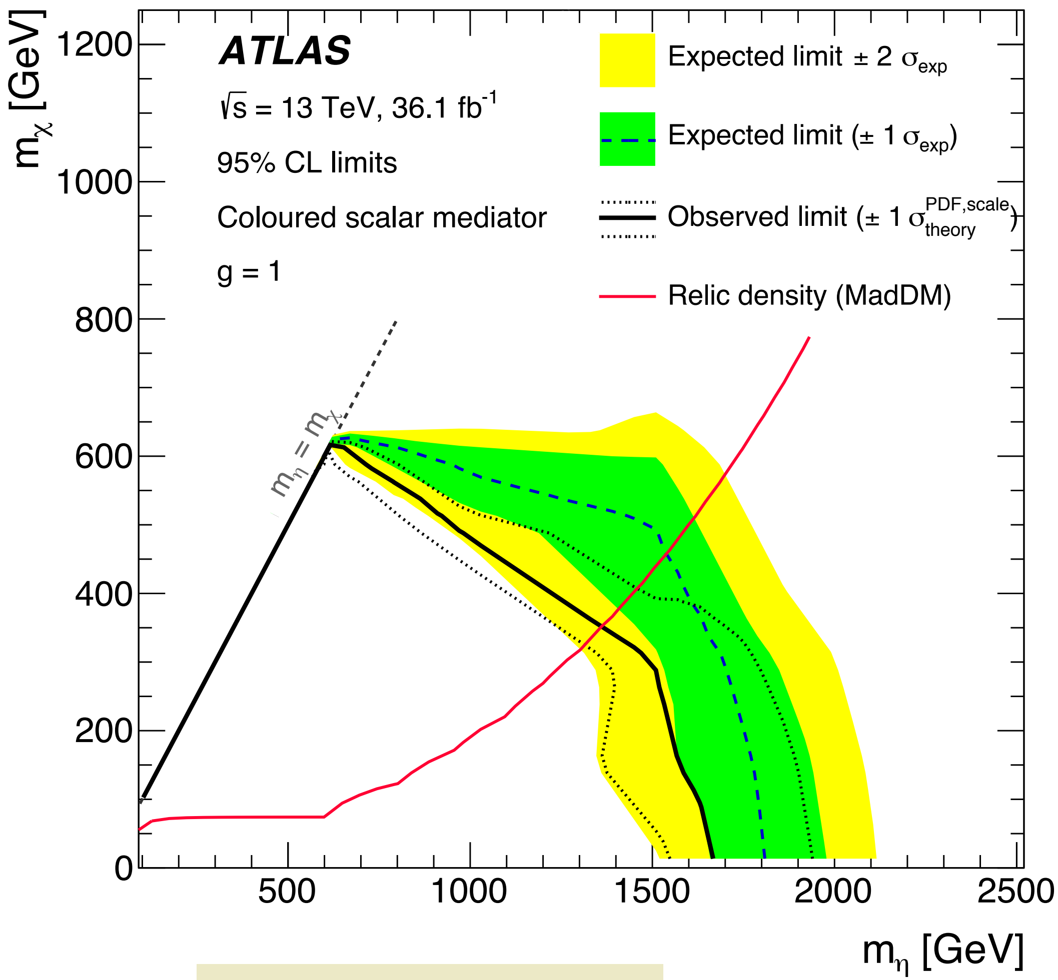
2. Scale samples 1 and 2 by the factors w^2 and w respectively, where:

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

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

3. Weight samples by cross-sections and add together

(Mono-jet) Limits for g=1



1711.03301[hep-ex]

2015+2016 data. 36.1 fb^{-1}

Mediator masses of ~1.65 TeV are excluded for light DM.

DM masses up to 600 GeV are excluded.

Setting g=1:
→ Distinguish the t-channel model from SUSY squark production
→ Interesting in terms of relic density.

Less Simplified model

- Simplified DM models with the full SM gauge symmetry (1605.07058[hep-ph]).

$$\mathcal{L}_{t-channel} = -\left[\overline{\chi}\widetilde{Q}_L^{i\dagger}\left(\lambda_{Q_L}\right)_i{}^j Q_{Lj} + \overline{\chi}\widetilde{u}_R^{i\dagger}\left(\lambda_{u_R}\right)_i{}^j u_{Rj} + \overline{\chi}\widetilde{d}_R^{i\dagger}\left(\lambda_{d_R}\right)_i{}^j d_{Rj} + H.c.\right]$$

- Left handed mediator masses relation:

$$m^2_{\widetilde{d}_L} - m^2_{\widetilde{u}_L} = \lambda_4 v^2$$

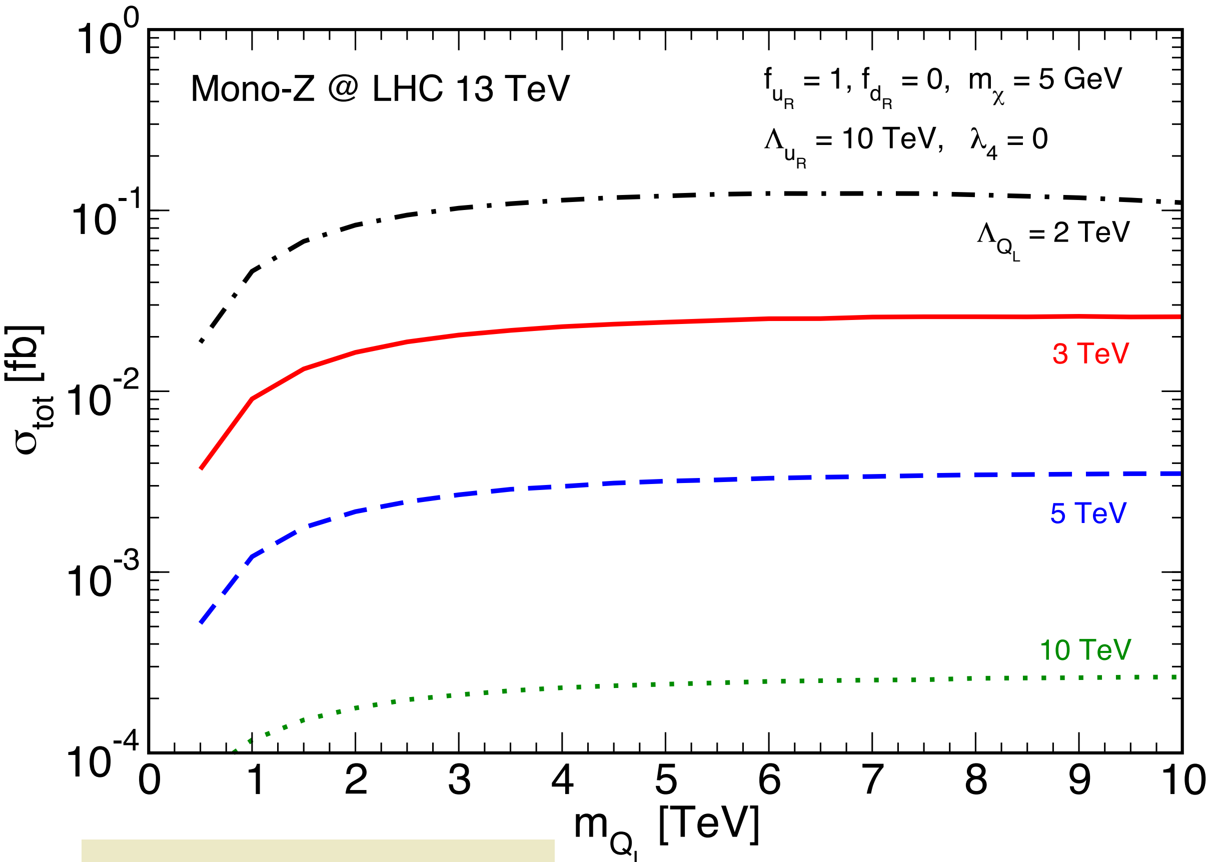
- Different couplings and masses for Q_L, u_R and d_R.
  - The mediators have SU(2) charges like quarks.
- Parameters:
  - 1 DM mass
  - 3 couplings: λ_{QL}, λ_{uR}, λ_{dR}
  - 12 mediator masses: 4 kind (m_{QLu}, m_{QLd}, m_{uR}, m_{dR}) * 3 generations
  - Mediator widths are given by minimal requirements.
- Sleptons are not included in this model.

Benchmark point (LS model)

- Only the first generation is relevant to collider search.
  - Set second and third generation mediator mass heavy.
- 8 free parameters:
  - 1 DM mass
  - 4 couplings: λ_{QL}, λ_{uR}, λ_{dR}, λ_4
  - 3 mediator masses in the 1st genaration: m_{QLu}, m_{uR}, m_{dR}
  - The m_{QLd} is given by m_{QLu} and λ_4
- Benchmark values
  - $\lambda_4 = 0 \rightarrow m_{QLd} = m_{QLu}$
  - $\lambda_{dR} = 0 \rightarrow m_{dR}$ is not relevant.
  - This leaves with 5 free parameters.

Benchmark point (LS model)

- Mono-Z cross section



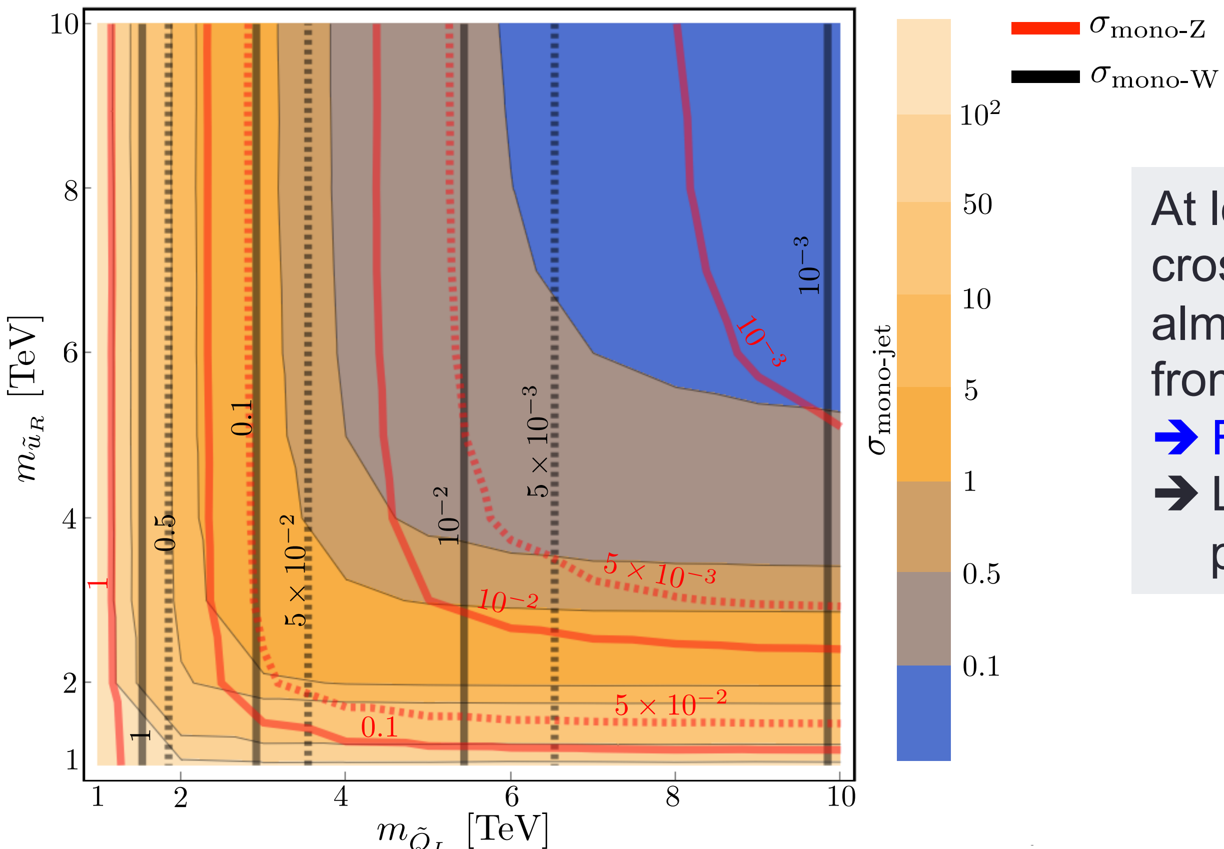
1605.07058[hep-ph]

$f_{qi} = \lambda_{qi}$

$$\Lambda_{q_i} = m_{\tilde{q}_i}/\lambda_{q_i}$$

Benchmark point (LS model)

- Cross sections with various final states.



At lower m_{QL}, the cross section is almost independent from m_{uR}
➔ Fix m_{uR} = 10 TeV
➔ Left with 4 parameters.

$$\lambda_{Q_L} = \lambda_{u_R} = 1,\ \lambda_{d_R} = \lambda_4 = 0, \text{ and } m_\chi = 5\text{ GeV}$$

1605.07058[hep-ph]

Benchmark point (LS model)

- Fix $\lambda_{dR} = \lambda_4 = 0$ and $m_{uR} = 10$ TeV.
- 4 free parameters:
  - 2 couplings: λ_{QL} and λ_{uR}
  - 2 masses: mediator mass $m_{QL} = m_{QLu} = m_{QLd}$ and DM mass
- For given couplings like $\lambda_{QL} = \lambda_{uR} = 1$, we can give 2d mass exclusion limit with DM mass vs mediator mass (m_{QL}).
  - (Mono-Z) Cross section

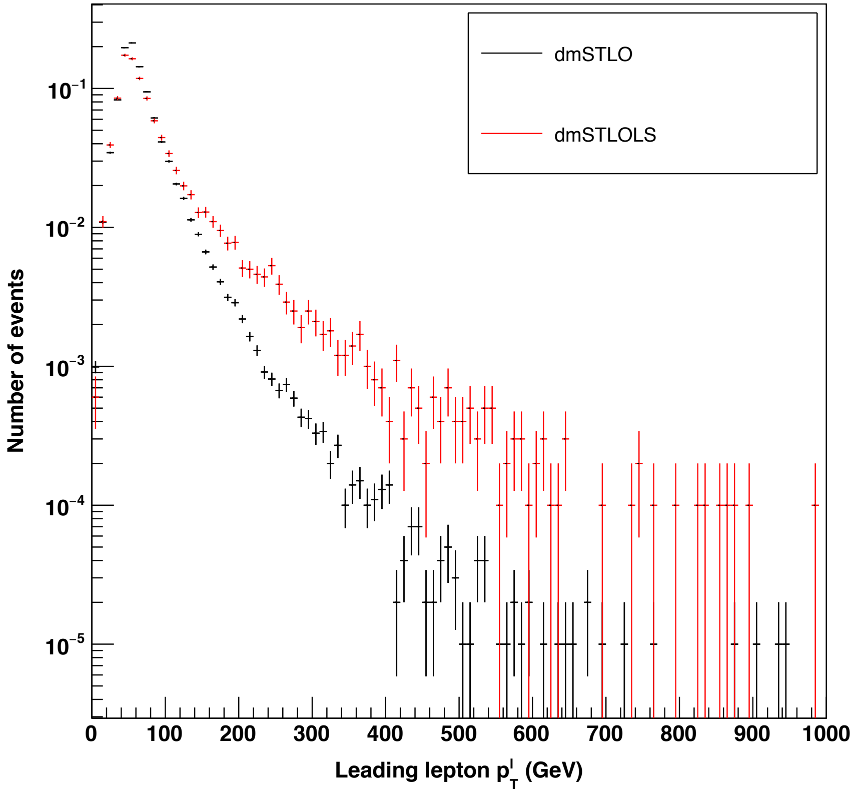
DM mass	m_{QL}	Xsection [fb]	Xsec*BF(Z->ll) [fb]	Bell model [fb] (coupling = 3)
1 GeV	50 GeV	649.0	42.3	90.2
50 GeV	300 GeV	24.3	1.6	2.9

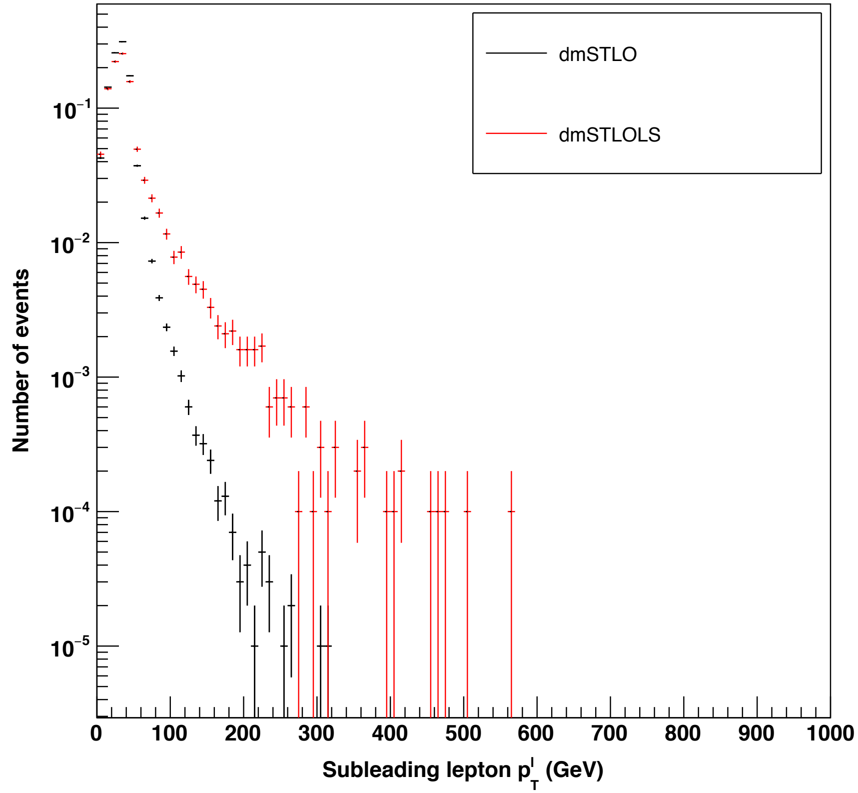
- Mediator mass > 1 TeV by Atlas squark search (2j+MET)?

Bell model vs Less Simplified model

- (Mono-Z) Lepton p_T

DM = 1 GeV, Med = 50 GeV





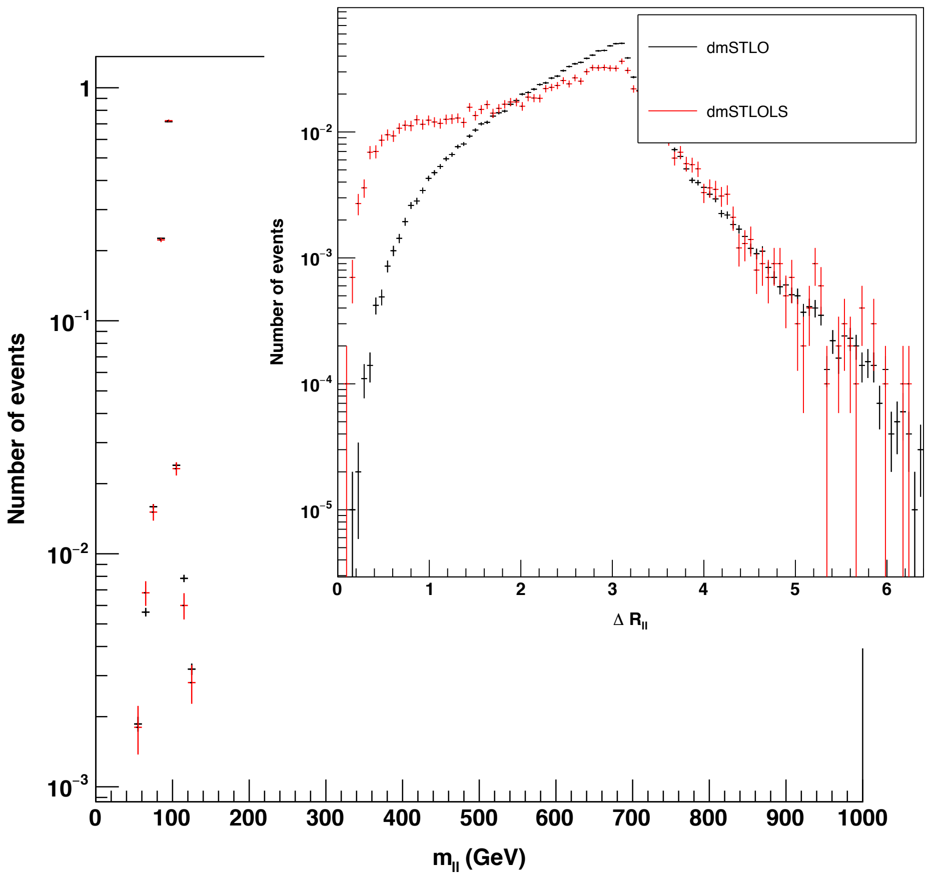
Normalized to integral=1

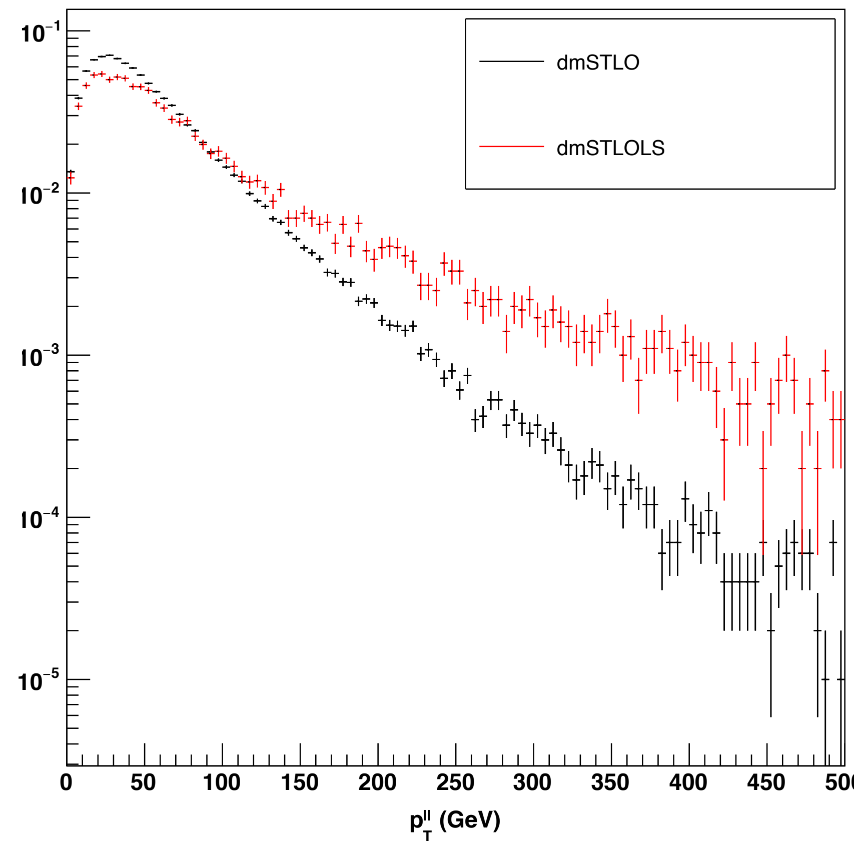
Bell model vs Less Simplified model

- (Mono-Z) Lepton pair

DM = 1 GeV, Med = 50 GeV

Normalized to integral=1

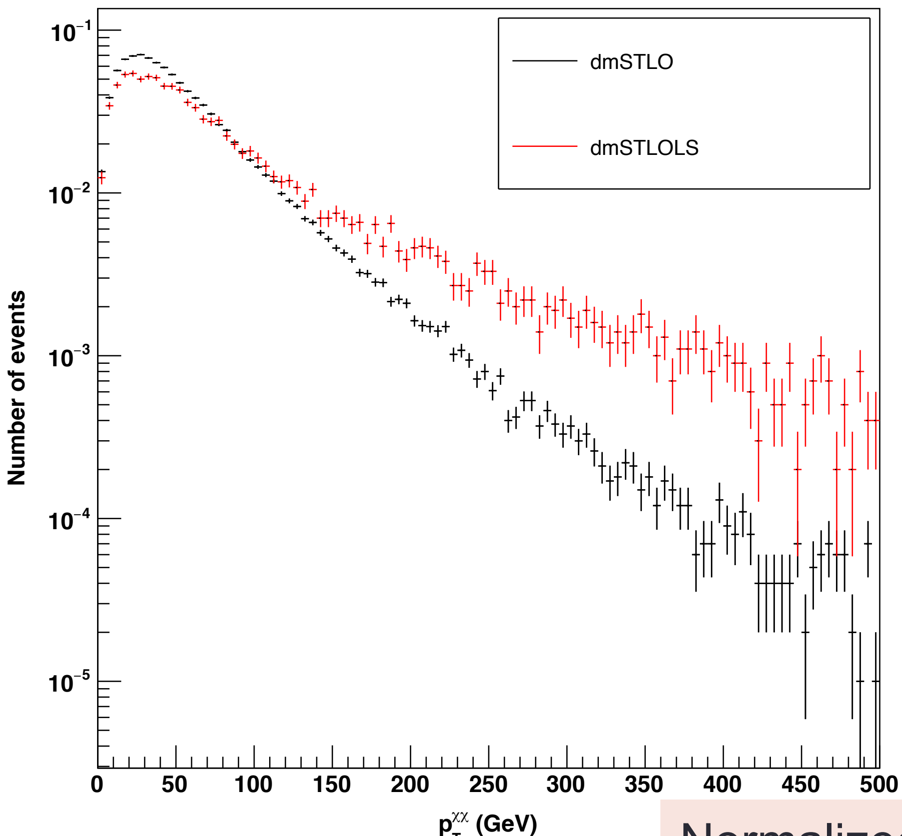




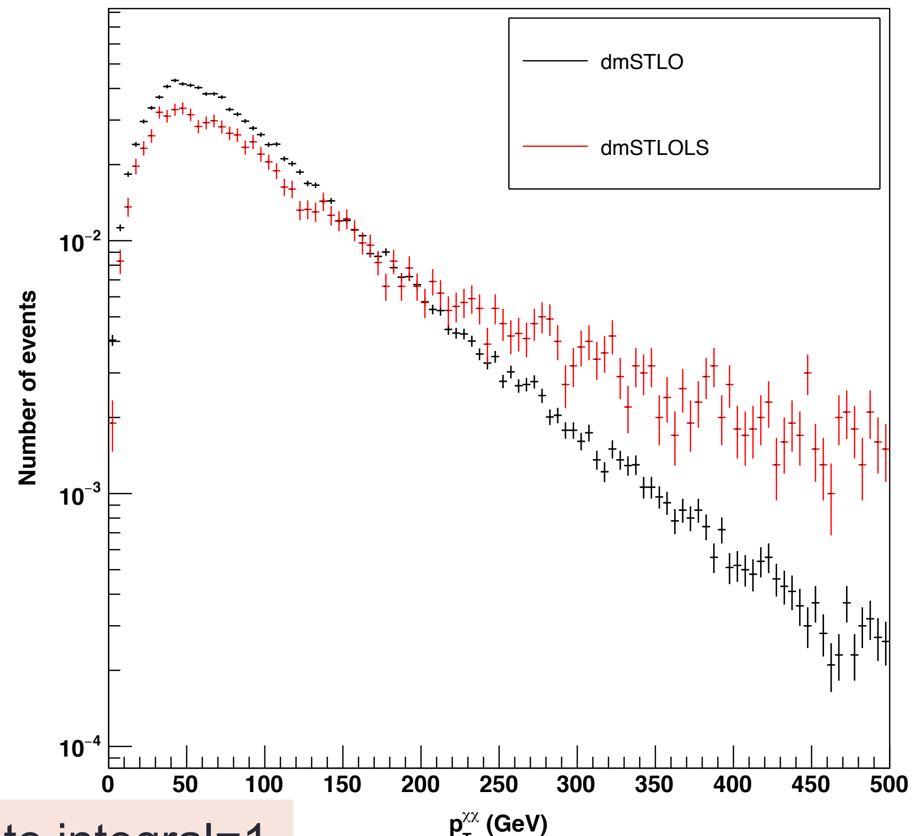
Bell model vs Less Simplified model

- (Mono-Z) Dark matter pair

DM = 1 GeV, Med = 50 GeV



DM = 50 GeV, Med = 300 GeV



Normalized to integral=1

Conclusions

- Various t-channel models were explained.
- Bell model was used in Atlas with 2015+2016 data.
  - Mono-jet set limits on mass-mass plane.
  - Mono-Z did not have enough sensitivity.

  → Enough sensitivity with full Run2 (2015+2016+2017+2018) data.
- Less Simplified Model was introduced.
  - Comparison with Bell model in the context of mono-Z was done.
  - Do we want to use this model with entire Run data? Or do we stick to Bell model?

Back up: Comparison with SUSY Strong Production

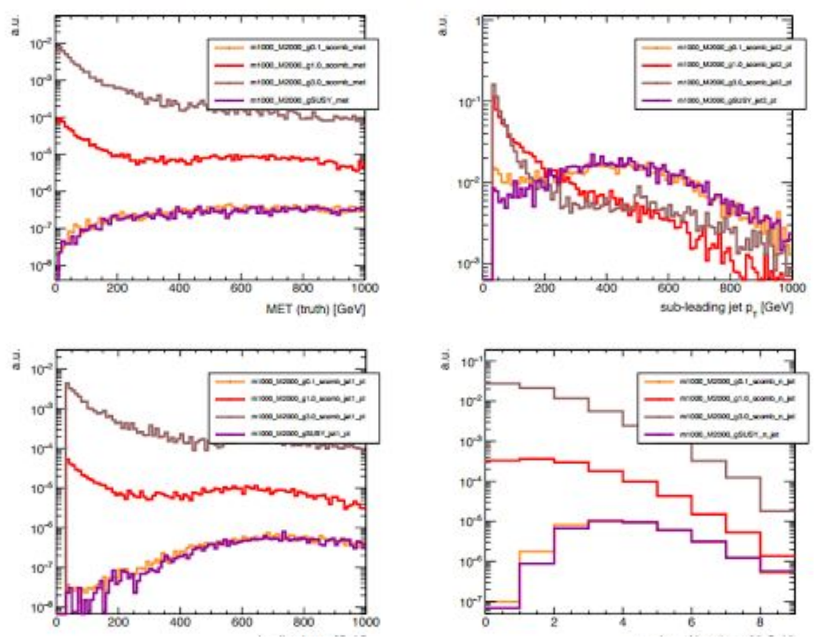
Sub-sample 1 resembles closely direct squark production with RH squarks switched off

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

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

- ➔ 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

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



<u>Setting g = 1:</u>

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