Simplified DM models: a case with t-channel colored scalar mediators.

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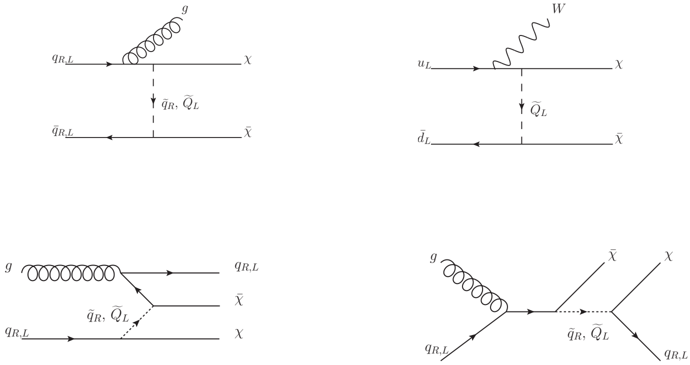
Model Building Philosophy

Our model building guidelines:

- Respect the full EW symmetry, not just the unbroken SM gauge (ie $SU(3)_C \times U(1)_{EM}$)
- The dark sector can be more complicated (self-interaction, multipartite, etc.), for DM at LHC we assume that χ is stable at least lifetime of detector (E_T)
- Take into account flavor constraints, but loosen assumptions on couplings to mediators and masses compared to other simplified models
- Consider direct detection (+ running), and thermal relic constraints, but goal is ultimately looking at collider signatures for new physics through mono-X signatures

The ultimate goal: Try to find some balance between simplicity and UV-completeness that allows insight into DM properties at colliders for broadest possible set of models

Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):



The Model

Example of previous t-channel model (LHCDMWG arXiv:1507.00966):

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

Our Model:

$$\overline{\chi}\widetilde{Q}_L^{i\dagger}\left(\lambda_{Q_L}\right)_i^{\ j} Q_{Lj} + \overline{\chi}\widetilde{u}_R^{i\dagger}\left(\lambda_{u_R}\right)_i^{\ j} u_{Rj} + \overline{\chi}\widetilde{d}_R^{i\dagger}\left(\lambda_{d_R}\right)_i^{\ j} d_{Rj} + H.C., \quad (2)$$

$\widetilde{Q}_L \to \phi_L$, $\widetilde{u}_R \to \phi_{u,R}$, $\widetilde{d}_R \to \phi_{d,R}$ with $i, j = 1, 2, 3$. Generally, $\lambda_{Q_L} \neq \lambda_{u_R} \neq \lambda_{d_R}$, and $m_{\widetilde{q}}$ are free to vary.

Scalar Interactions:

$\lambda_4 \Phi^\dagger \widetilde{Q}_L \widetilde{Q}_L^\dagger \Phi$, $\lambda_4 \leq 4\pi$ has small effect on mono-W signal (Bell, Cai, Leane arXiv:1512.00476), so set $\lambda_4 = 0$.

Cannot simultaneously diagonalize λ and m for scalars and $\widetilde{q}^\dagger q H^\dagger H$ terms yield:

- Rare Higgs decays: $H \to \widetilde{q}_i^* \widetilde{q}_j^* \to \overline{q}_i q_j \overline{\chi} \chi$
- Modified Higgs branching ratios to gg, $\gamma\gamma$, Z γ, etc.
- **FCNC**

χ is Dirac (no helicity flip in loop), and only one species (reduces FCNC as compared to MSSM)

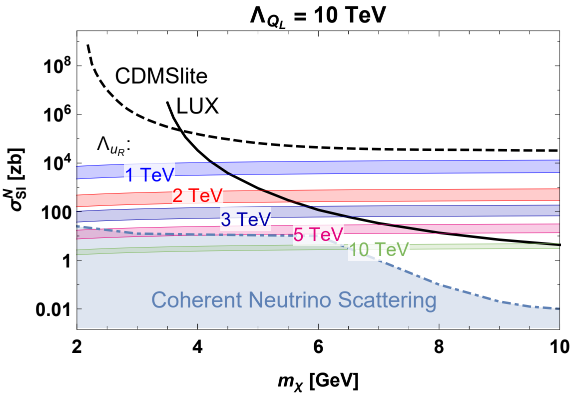
Assume: $m_{\widetilde{d}} \approx m_{\widetilde{s}}$, allows reduced $K^0 - \overline{K}^0$ mixing constraints

Running effects form EFT scale to Hadronic scale generically mix operators. These effects come from EW loops, quark-threshold scales, etc. Usual method in simplified models of going to EFT to determine direct detection misses these effects (can be sizable):

- Running introduces additional dependence on Λ so cannot re-scale constraints to eliminate coupling constants
- Generally mixes RH and LH couplings, and introduces slight isospin violation in SI cross section (in addition to the source from $\lambda_{u_R} \neq \lambda_{d_R}$)

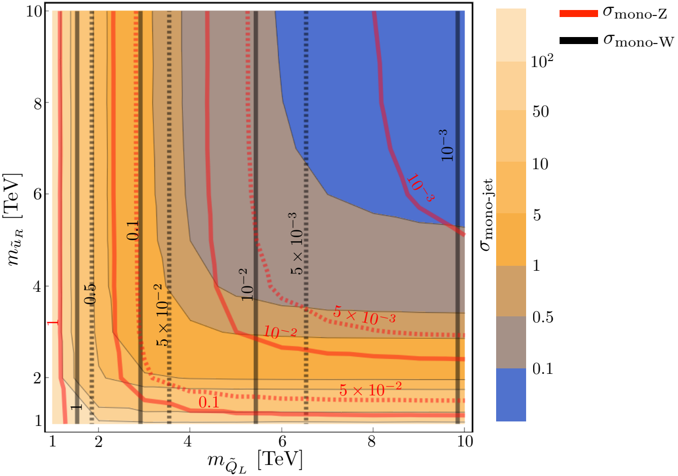
A practitioner friendly guide for these effects can be found in D'Eramo et al (arXiv:1411.3342).

Models with t-channel colored scalars are highly constrained by direct detection (10 GeV $< m_\chi <$ 1 TeV excluded by LUX for $\Lambda \leq 10$ TeV):



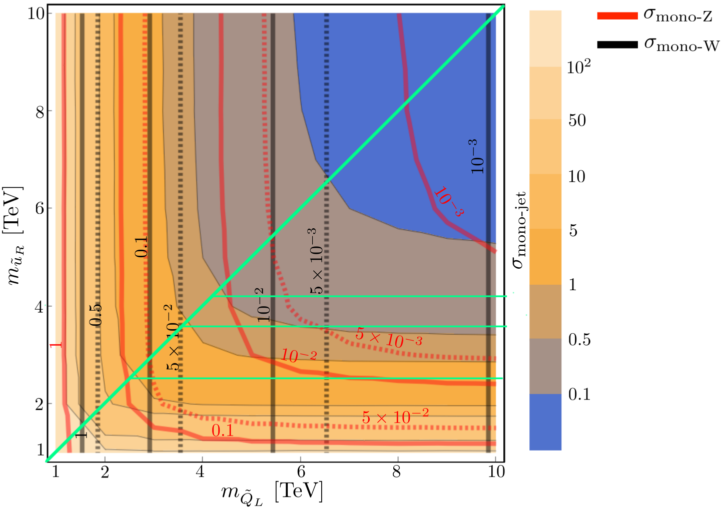
Region where $m_\chi > 1$ TeV has significantly reduced mono-X

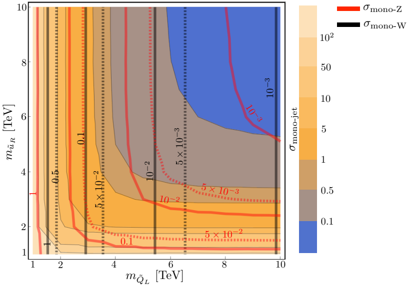
Contour plots for mono-X when $\lambda_{q_i}/m_{\widetilde{q}_i}$ are allowed to vary ($\lambda_{d_R} = 0$):

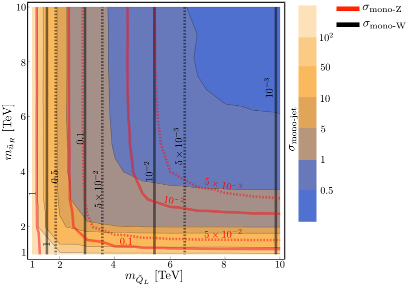


$m_\chi = 5$ GeV, $\lambda_{u_R} = \lambda_{Q_L} = 1$ and $\lambda_4 = 0$

Diagonal line represents a previously studied simplified model:







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

LHS: $\lambda_{d_R} = 0 \rightarrow$ RHS: $\lambda_{d_R} = 1$, $m_{\widetilde{d}_R} = 3$ TeV

Summary & Conclusions

Summary:

- Very important to use the full SM gauge group when investigating simplified models at colliders (gauge invariance, unitarity, etc.)
- 'Less simplified' models: broader range of interesting collider signatures, with only modest increase in complication (however tension between thermal relic/direct detection for colored t-channel)

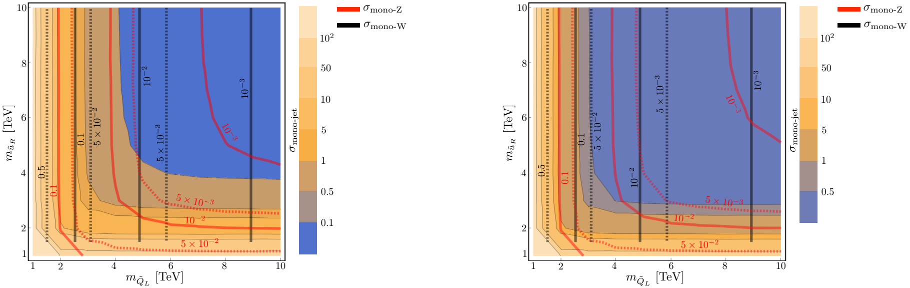
Conclusion:

Loosening constraints from the usual simplified models (ie $\Lambda_{Q_L} \neq \Lambda_{u_R} \neq \Lambda_{d_R}$) allows for the clear presentation of mono-X cross sections.

Thank you!

Thank you!

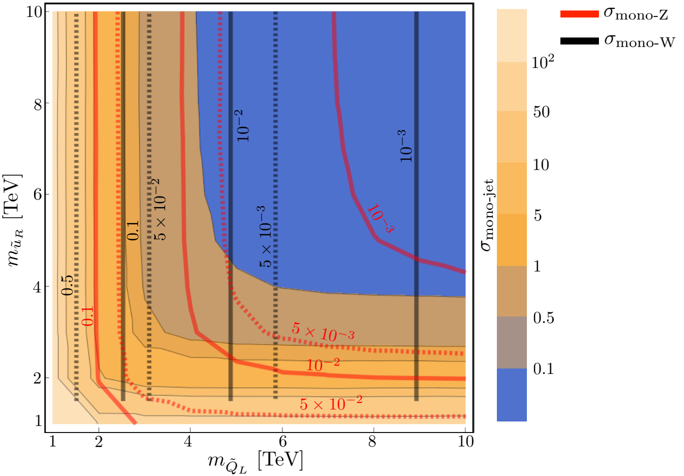
Backup Slides



$m_\chi = 300$ GeV, $\lambda_{u_R} = \lambda_{Q_L} = 1$ and $\lambda_4 = 0$

LHS: $\lambda_{d_R} = 0 \rightarrow$ RHS: $\lambda_{d_R} = 1$, $m_{\tilde{d}_R} = 3$ TeV

Collider Signatures:mono-X ($m_\chi = 300$ GeV)



$m_\chi = 300$ GeV, $\lambda_{u_R} = \lambda_{Q_L} = 1$ and $\lambda_4 = 0$

Relaxing the assumptions about coupling constants significantly complicates the direct detection, as there are generic material dependence effects in the spin independent cross section:

$$\frac{1}{64\pi}\frac{m_N^2 m_\chi^2}{(m_\chi+m_N)^2}\left[\left(\frac{3|\lambda_{\widetilde{Q}_L}|^2}{m^2_{\widetilde{Q}_L}}+\frac{|\lambda_{\widetilde{u}_R}|^2}{m^2_{\widetilde{u}_R}}+\frac{|\lambda_{\widetilde{d}_R}|^2}{m^2_{\widetilde{d}_R}}\right)+\frac{1}{2}\frac{Z}{A}\left(\frac{|\lambda_{\widetilde{u}_R}|^2}{m^2_{\widetilde{u}_R}}-\frac{|\lambda_{\widetilde{d}_R}|^2}{m^2_{\widetilde{d}_R}}\right)\right]$$

Without considering running effects, the direct detection probes λ/m_{med}, but there are isospin violating effects from $\lambda_{u_R} \neq \lambda_{d_R}$.

Thermal Relic

Known tension between thermal relic and direct detection for t-channel, colored, scalar mediators and from existing LHC constraints ($m_{med} > 1.2$ TeV).

$m_\chi \approx 5$ GeV $\rightarrow$ generically over-produced

- if χ couples to Leptons, this can be alleviated

$m_\chi \approx 1$ TeV $\rightarrow$ generically under-produced

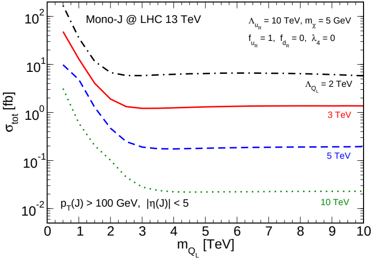
- if χ is not the only thermal relic this can be accommodated

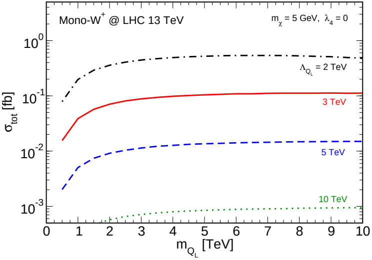
For the LHC phenomenology we assume $m_\chi = 5$ GeV, but $m_\chi \mathcal{O}(100)$ GeV can be accommodated if there are additional thermal relics (reduced direct detection constraints via t-channel mediator).

Collider Signatures: Methods

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

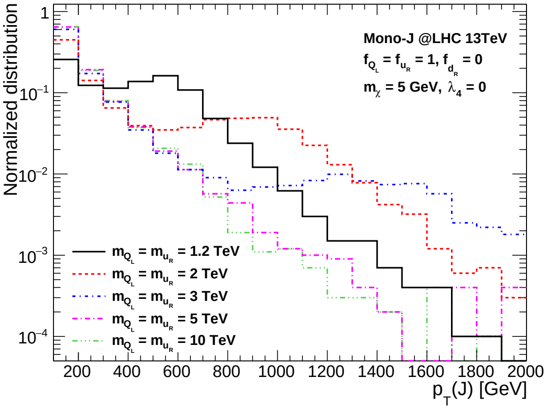
- Implement $\mathcal{L}$ in Feynrules (scalar widths implemented as internal parameter, function of $\lambda_{q_{(L,R)}}$, $m_{\widetilde{q_{(L,R)}}}$)
- Generate events with Madgraph 5 ($\mid \eta \mid < 5$, $p_T > 100$ GeV for mono-jet)
- For kinematic distributions analyze with Delphes/Root
- Make assumptions about coupling constants, masses, to simplify parameter space but look at parameter choices different from previous simplified models





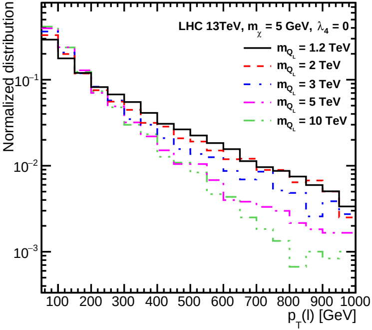
Mono-jet and mono-w^+ cross sections for $\lambda_{Q_L} = \lambda_{u_R} = 1$, $m_{\tilde{u}_R} = 10$ TeV, mono-W^- will be $1/2$ mono-W^+ due to PDFs. For mono-jet: $\mid \eta \mid < 5$, $p_T > 100$ GeV.

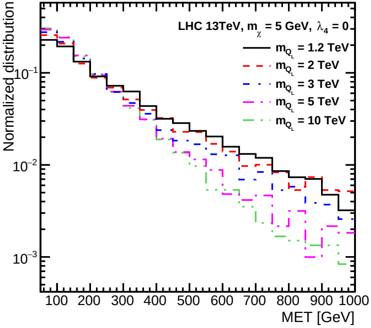
Collider Signatures: Jet p_T



$$\lambda_{d_R} = \lambda_4 = 0, \lambda_{Q_L} = \lambda_{u_R} = 1, m_{\tilde{u}_R} = m_{\tilde{Q}_L}$$

Collider Signatures: mono-W

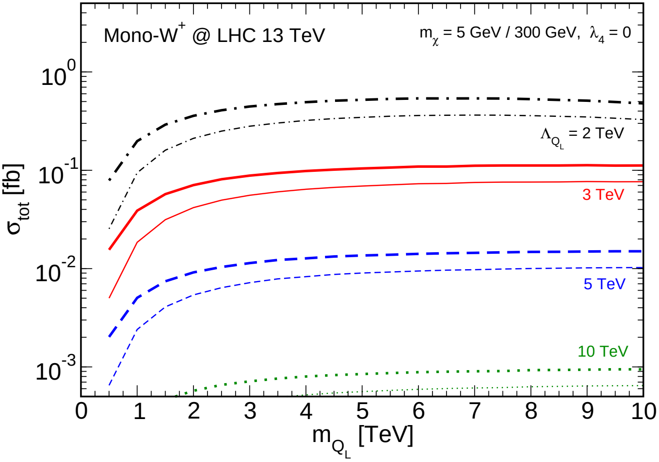




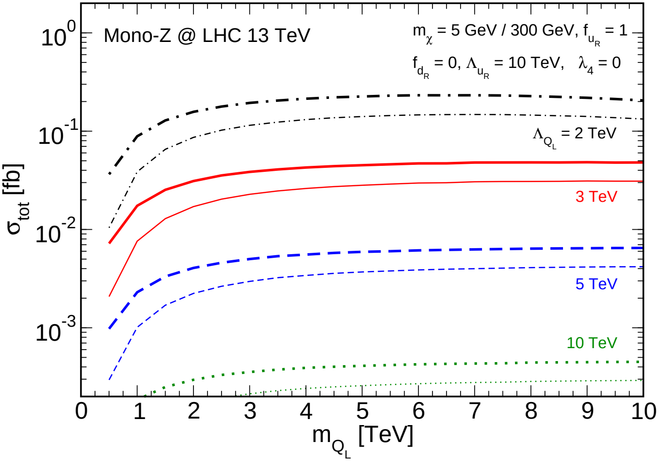
Lepton mono-W kinematics produced in Delphes for $\lambda_4 = 0$, $m_\chi = 5$ GeV

Simplified models with lighter scalar mass has broader p_T and E_T

Collider Signatures:mono-X



Collider Signatures:mono-X



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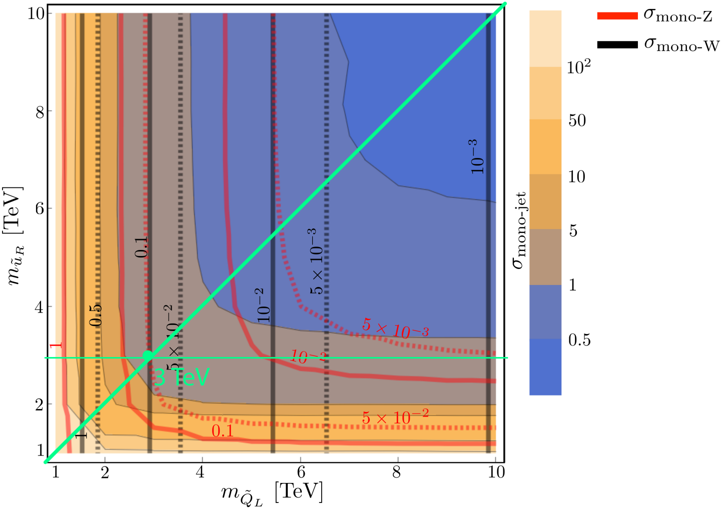

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