Simplified DM models with the full SM gauge symmetry

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Based on arXiv:1605.07058, JHEP (2017)
w/ A. Natale, M. Park, H. Yokoya

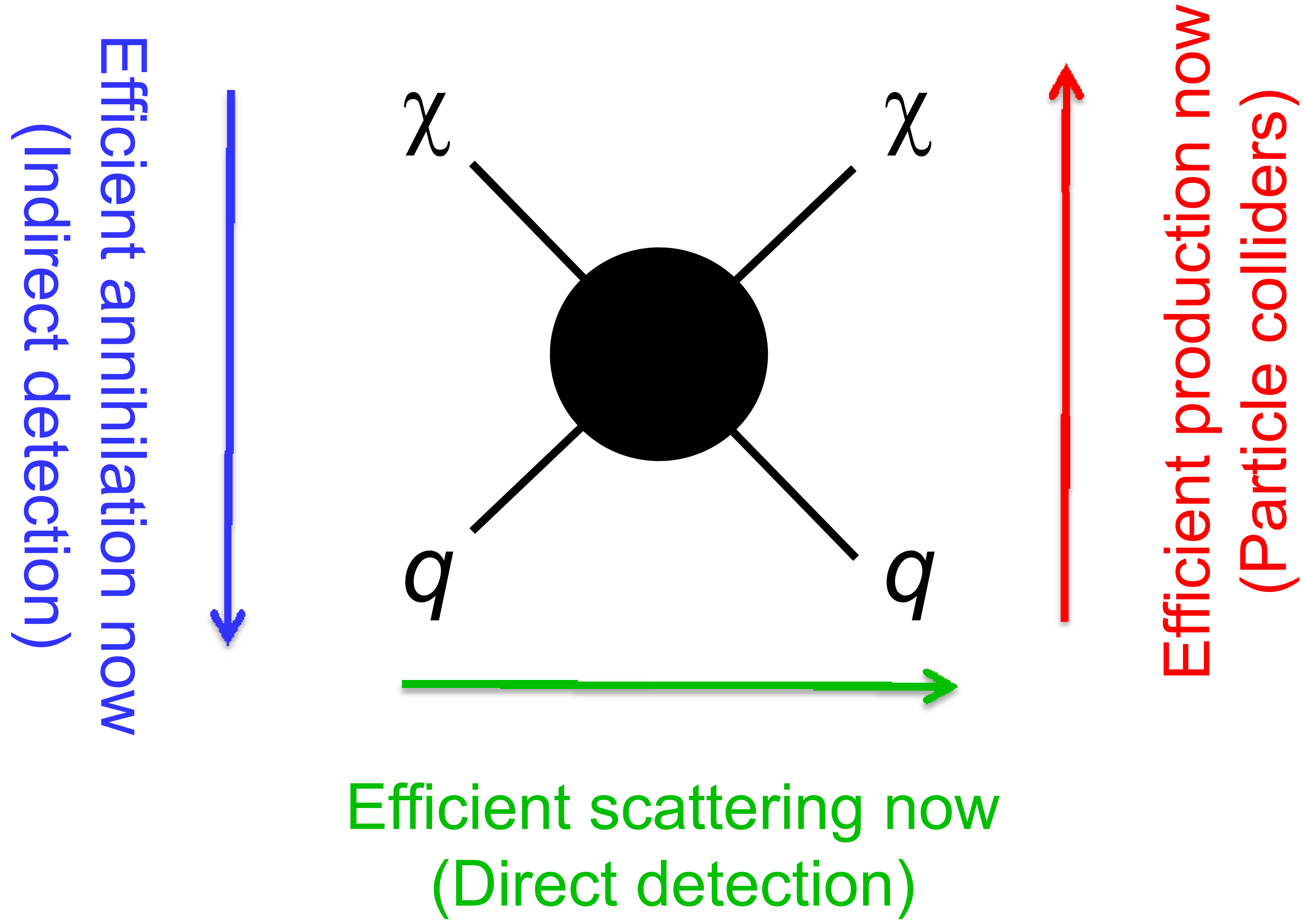
April 26, 2017

Overview

- Key features of the model : the full SM gauge symmetry requires two scalar mediators in general
- Parameters of the model : DM mass, 3 mediator masses, and their Yukawa couplings to the DM and mediators
- List of exp. signatures : mono X (X=jet, gamma, W, Z), Direct detection, Thermal relic

Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Three major approaches

Three major approaches to DM phenomenology:

- EFT: non-renomalizable, higher dimension, DM-SM interactions divided by the mass scale of new physics Λ
  Parameters: Λ, m_χ
- Simplified model: renormalizable, unbroken SM gauge invariant model with a mediator, DM, and SM interactions.
  Parameters: λ_{med}, m_{med}, m_χ
- UV-complete models: full, high energy description of BSM physics
  Parameters: *many*

Limitation and Proposal

- EFT is good for direct detection, but not for indirect or collider searches as well as thermal relic density calculations in general
- Issues : Violation of Unitarity and SM gauge invariance, Identifying the relevant dynamical fields at energy scale we are interested in, Symmetry stabilizing DM etc.

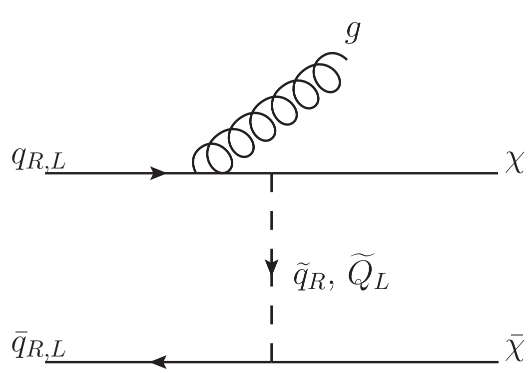
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

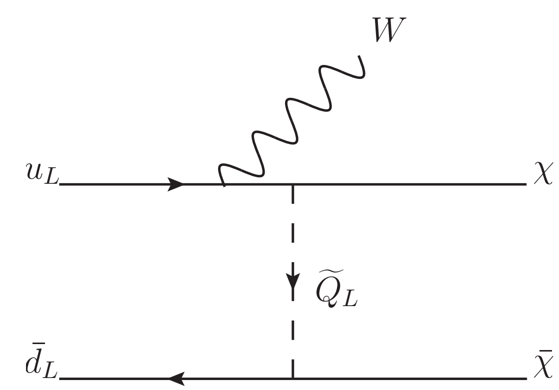
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions in 4-dim spacetime

arXiv:1605.07058 (with A. Natale, M.Park, H.Yokoya)

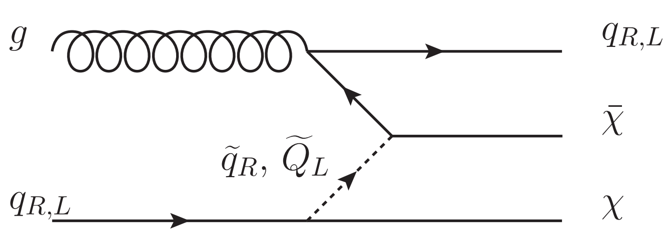
for t-channel mediator

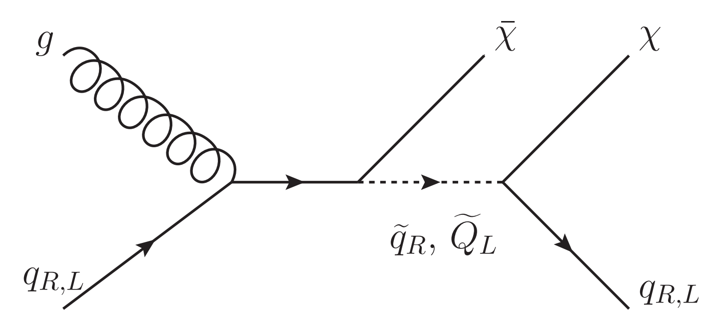
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





W+missing ET : special





$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

- This is good only for W+missing ET, and not for other singatures
- $(g, \gamma, Z^0) + \not{E}_T$ will involve both LH and RH chiral fermions and their scalar partners
- There are no tight correlation between mono-W, mono-(jet, photon, Z0) signatures

The Model

Consider SM-DM quark operator:

$$\frac{1}{\Lambda^2}\overline{\chi}\gamma^\mu\chi\overline{q}\gamma_\mu q = \frac{1}{\Lambda^2}\overline{\chi}\gamma^\mu\chi(\overline{q}_L\gamma_\mu q_L + \overline{q}_R\gamma_\mu q_R)$$

To generate this in a simplified model consider three new scalar types: $\widetilde{Q}_{Li}$, $\widetilde{u}_{Ri}$,$\widetilde{d}_{Ri}$. One Dirac fermion DM particle: χ

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

Isospin violating term:

$$\lambda_4\Phi^\dagger\widetilde{Q}_L\widetilde{Q}_L^\dagger\Phi$$

Previous studies on mono-W enhancement had arbitrary isospin violation among $\widetilde{Q}_L$, but this is actually fixed by λ_4.
$\lambda_4 \leq 4\pi$ has been shown to have small effect on mono-W (Bell, et al arXiv:1503.07874).

UV-complete model

- In general, we need to consider interactions between Dark matter and Standard Model fermions to respect SM chiral structures

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

$$\begin{aligned}
\mathcal{L}_{\text{scalar}} = {} & D_\mu \widetilde{Q}_L^{i\dagger} D^\mu \widetilde{Q}_{Li} - \widetilde{Q}_L^{i\dagger}\left[\left(m^2_{\widetilde{Q}_L,0}\right)_i{}^j + 2\,(\lambda_{Q_L H})_i{}^j\, H^\dagger H\right]\widetilde{Q}_{Lj} \\
& + D_\mu \widetilde{u}_R^{i\dagger} D^\mu \widetilde{u}_{Ri} - \widetilde{u}_R^{i\dagger}\left[\left(m^2_{\widetilde{u}_R,0}\right)_i{}^j + 2\,(\lambda_{u_R H})_i{}^j\, H^\dagger H\right]\widetilde{u}_{Rj} \\
& + D_\mu \widetilde{d}_R^{i\dagger} D^\mu \widetilde{d}_{Ri} - \widetilde{d}_R^{i\dagger}\left[\left(m^2_{\widetilde{d}_R,0}\right)_i{}^j + 2\,(\lambda_{d_R H})_i{}^j\, H^\dagger H\right]\widetilde{d}_{Rj} \\
& - \left[\widetilde{Q}_L^{i\dagger}\,(A_u)_i{}^j\,\widetilde{H}\widetilde{u}_{Rj} + \widetilde{Q}_L^{i\dagger}\,(A_d)_i{}^j\, H\widetilde{d}_{Rj} + H.c\right] \\
& - \lambda_{\widetilde{q}_L}(\widetilde{Q}_L^\dagger \widetilde{Q}_L)^2 - 2\lambda_4 H^\dagger \widetilde{Q}_L \widetilde{Q}_L^\dagger H
\end{aligned}$$

The Philosophy

Our model building guidelines:

- Respect the EW symmetry, not just the unbroken SM gauge $SU(3)_C \times U(1)_{EM}$ (full SM gauge symmetry)
- The dark sector can be more complicated (self-interaction, multipartite, etc.), for DM@LHC assume that χ is stable on lifetime of detector (E_T)
- work with a more 'UV-complete' model than usual Simplified models
- take into account flavor constraints, but loosen assumptions on couplings to mediators/masses relative to usual simplified models

The ultimate goal: try to find optimal balance between simplicity, and UV-complete, that allows us to elucidate DM properties at colliders for broadest possible set of models

Flavor Constraints

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

- Similar to the gluing-mediated FCNC problems in SUSY models
- However there are no SUSY partners of SM gauge bosons here

Mono - W

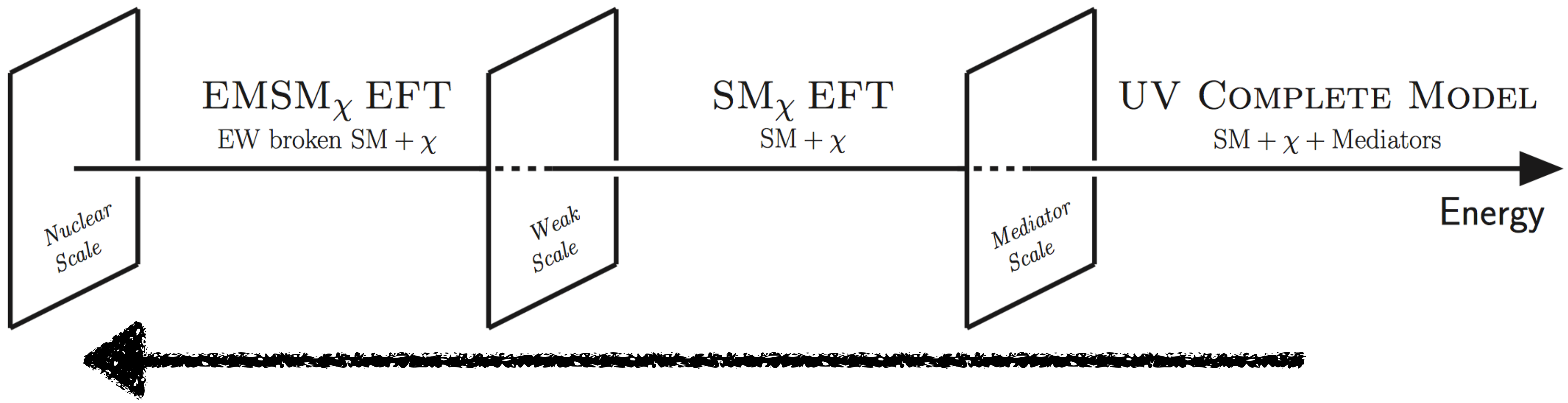
- In this case, there is a handle to have a iso-spin violating operator, the mass gap between

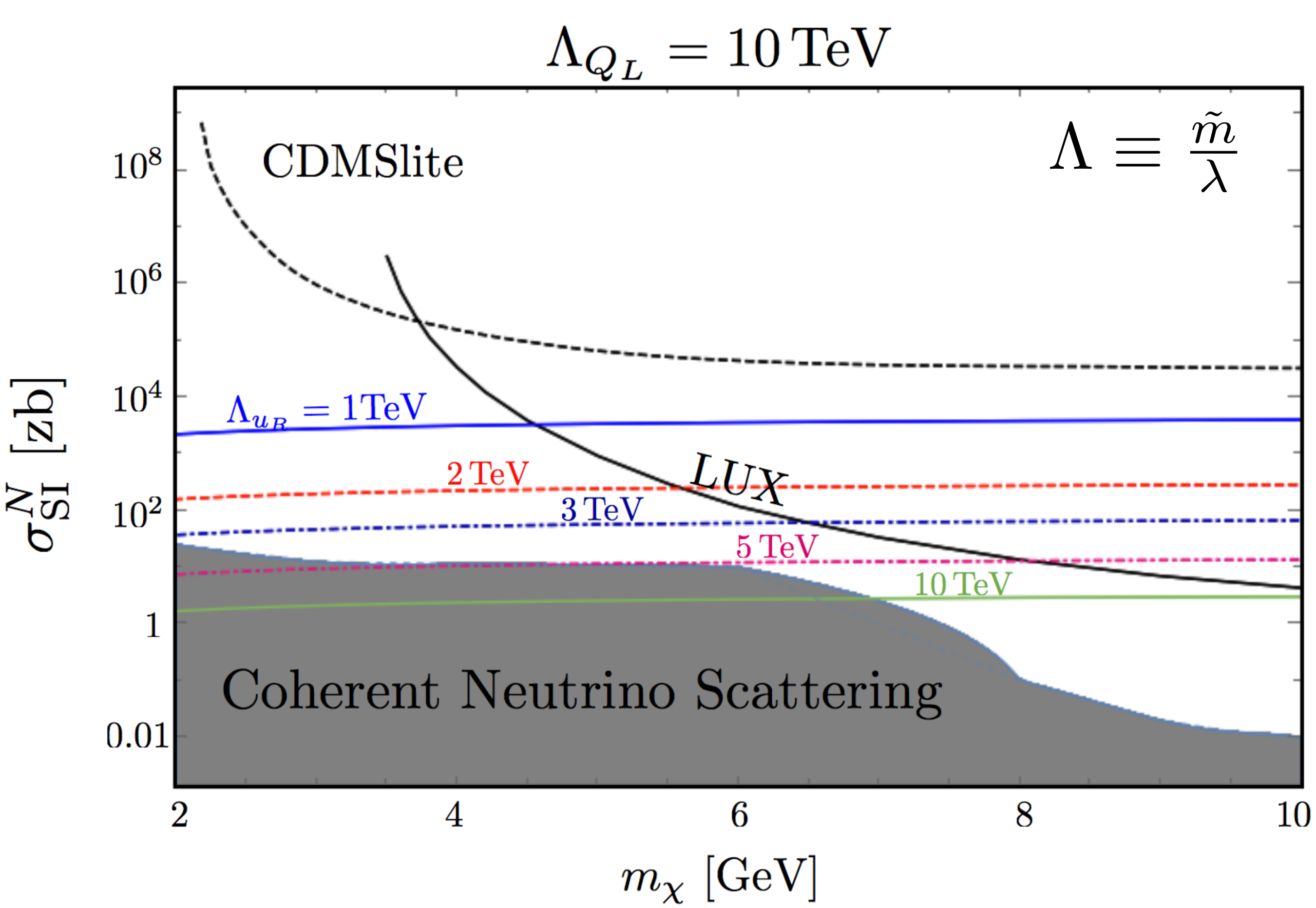
$$m^2_{\tilde{d}_L} - m^2_{\tilde{u}_L} = \lambda_4 v^2,$$

$$\begin{aligned}
m^2_{\tilde{u}_L} &= m^2_{\tilde{Q}_L,0} + \lambda_{Q_L H} v^2 \\
m^2_{\tilde{d}_L} &= m^2_{\tilde{Q}_L,0} + \lambda_{Q_L H} v^2 + \lambda_4 v^2 = m^2_{\tilde{u}_L} + \lambda_4 v^2 \\
m^2_{\tilde{u}_R} &= m^2_{\tilde{u}_R,0} + \lambda_{u_R H} v^2 \\
m^2_{\tilde{d}_R} &= m^2_{\tilde{d}_R,0} + \lambda_{d_R H} v^2
\end{aligned}$$

- It can trigger high PT W-boson enhancement
  - Mono lepton from W-boson

Francesco D'Eramo, Massimiliano Procura, arXiv:1411.3342



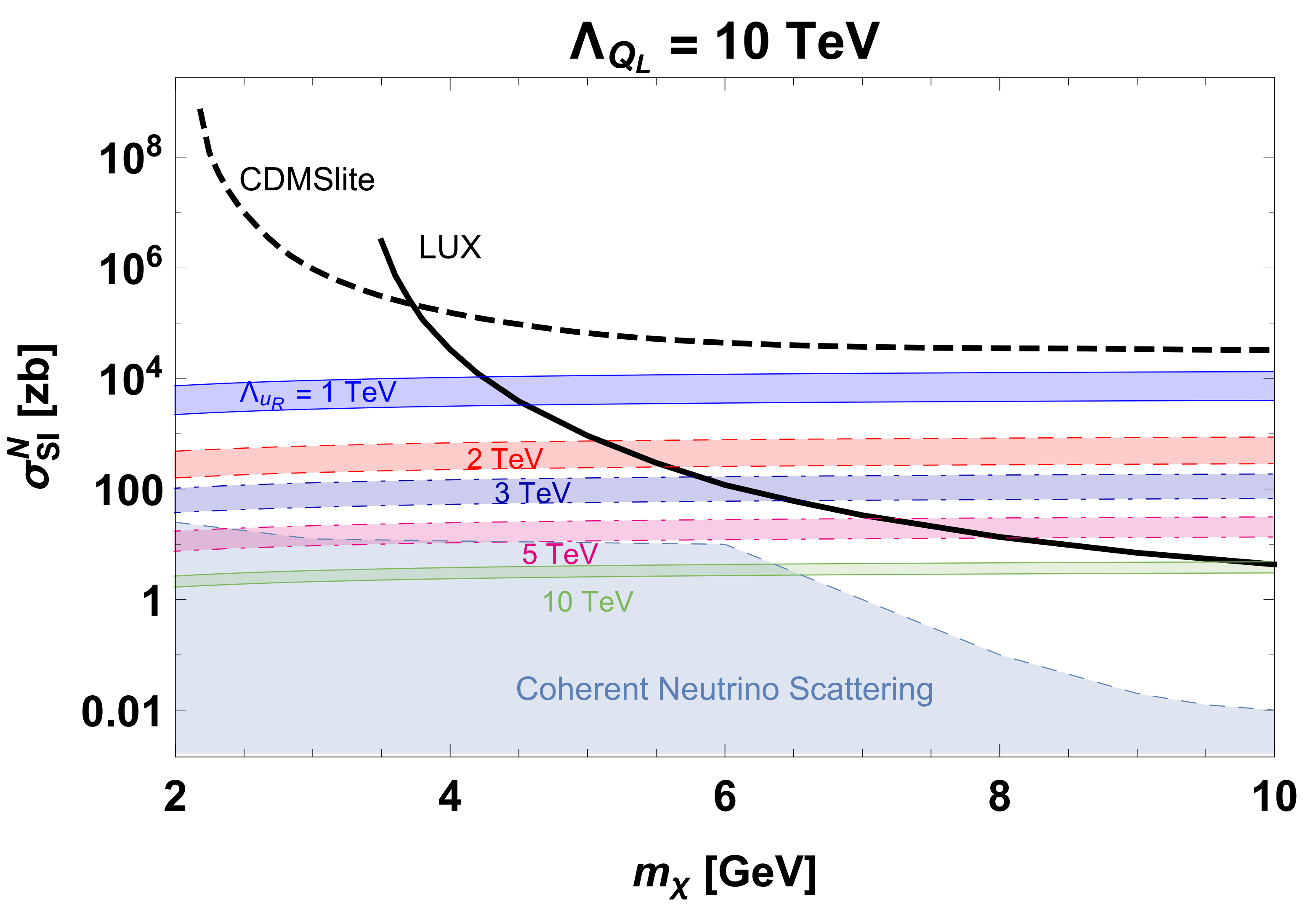


$$\sigma_N^{\mathrm{SI}} = \frac{1}{64\pi}\,\frac{m_N^2 m_\chi^2}{(m_\chi + m_N)^2}\left[\left(\frac{3\,|\lambda_{Q_L}|^2}{2m^2_{\tilde{Q}_L}} + \frac{|\lambda_{u_R}|^2}{2m^2_{\tilde{u}_R}} + \frac{2\,|\lambda_{d_R}|^2}{2m^2_{\tilde{d}_R}}\right) + \frac{Z}{A}\left(\frac{|\lambda_{u_R}|^2}{2m^2_{\tilde{u}_R}} - \frac{|\lambda_{d_R}|^2}{2m^2_{\tilde{d}_R}}\right)\right]^2,$$

$$\lambda_{Q_L} = \lambda_{u_R} = 1,\ \lambda_{d_R} = 0$$

Direct Detection

t-channel colored scalars are highly constrained by direct detection, and the region where $m_\chi > 1$ TeV has significantly reduced mono-X cross sections at the 13 TeV LHC, so the remaining region of interest for DM at the LHC in this model is $m_\chi < 10$ GeV:



Direct Detection

Relaxing the assumptions about coupling constants significantly complicates the direct detection, as there are generic material dependence effects in the SI cross section due to $\lambda_{u_R} \neq \lambda_{d_R}$, as seen 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 $\lambda_{u_R} \neq \lambda_{d_R}$.

Direct Detection

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 quark 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).

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

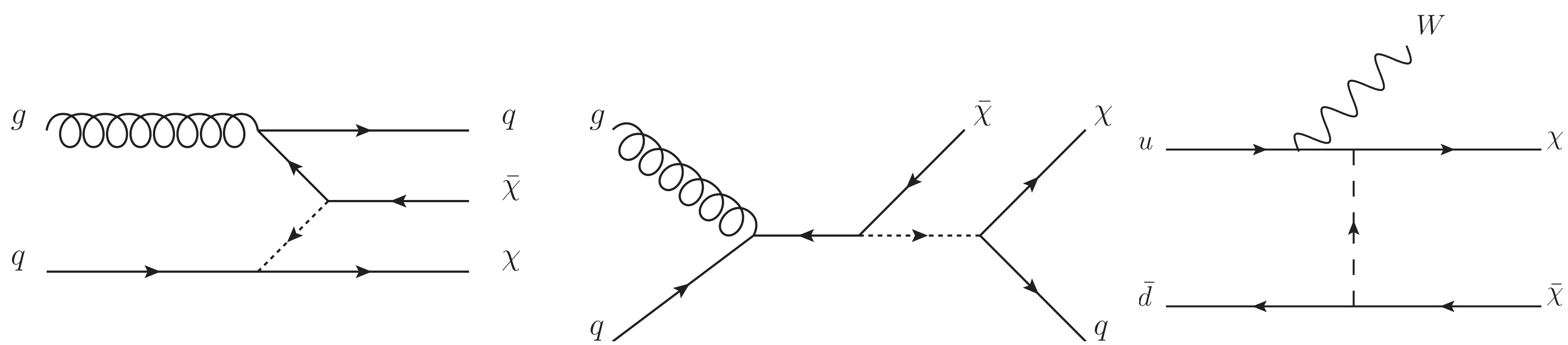
$m_\chi \approx 1$ TeV $\rightarrow$ generically under-produced

- 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

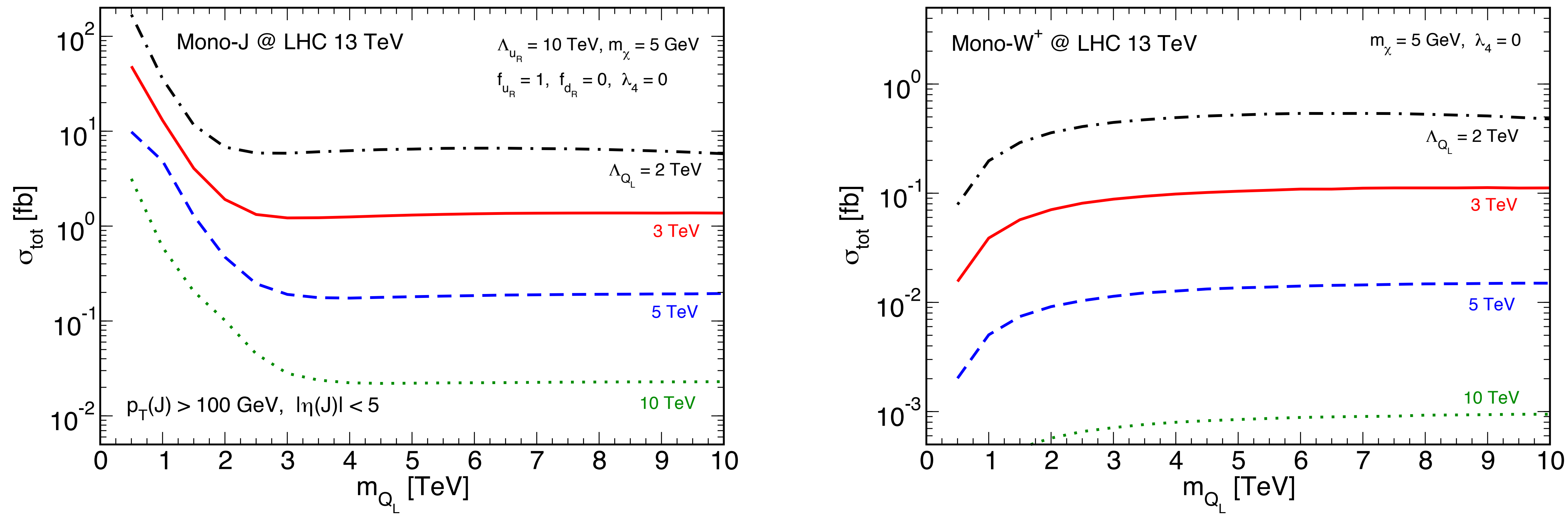
Collider signatures: mono-Jet, mono-W, mono-Z, two jets + ET, etc.



- Mono-W signature depends on $\Lambda_{Q_L} = \frac{\lambda_{Q_L}}{m_{\tilde{Q}_L}}$
- Mono-jet/mono-Z depends on all mediators
- Complementary information from each mono-X when RH/LH quarks reduces complexity

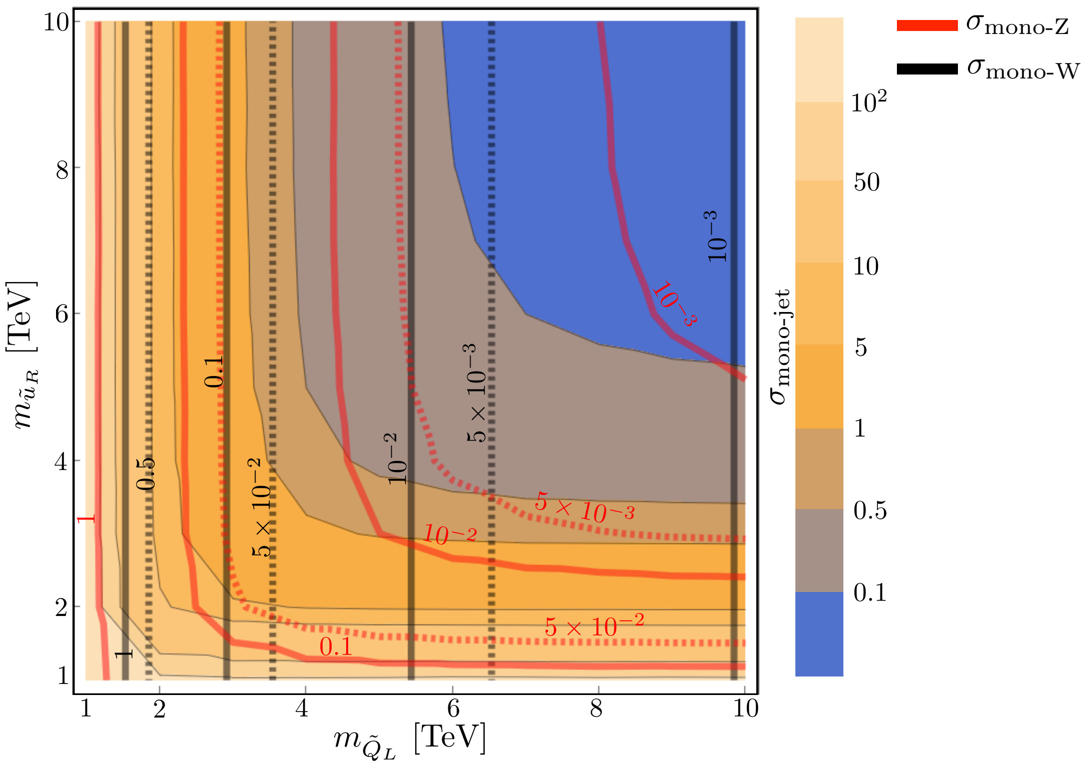
At 13 TeV: No significant difference from σ_{EFT} for $m_{\tilde{q}_{R,L}} \mathcal{O}(10)$ TeV.

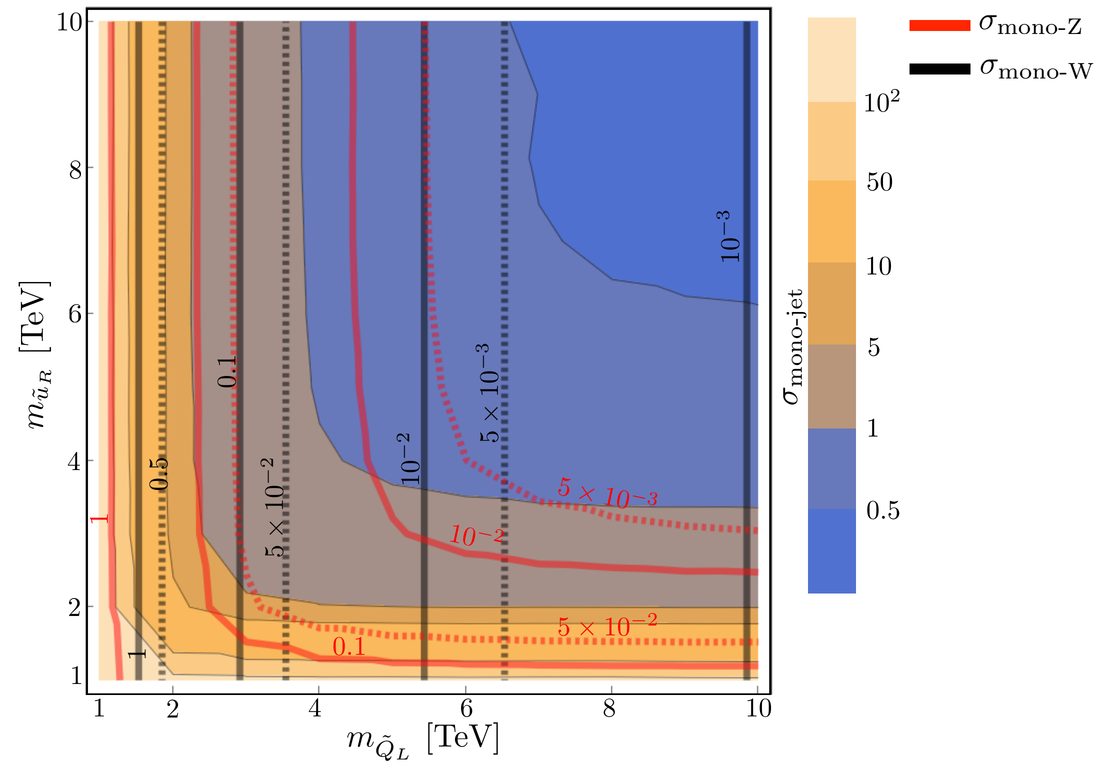
Collider Signatures



Mono-jet and mono-w^+ cross sections for $\lambda_{Q_L} = \lambda_{u_R} = 1$, $m_{u_R} = 10$ 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 : Mono-X



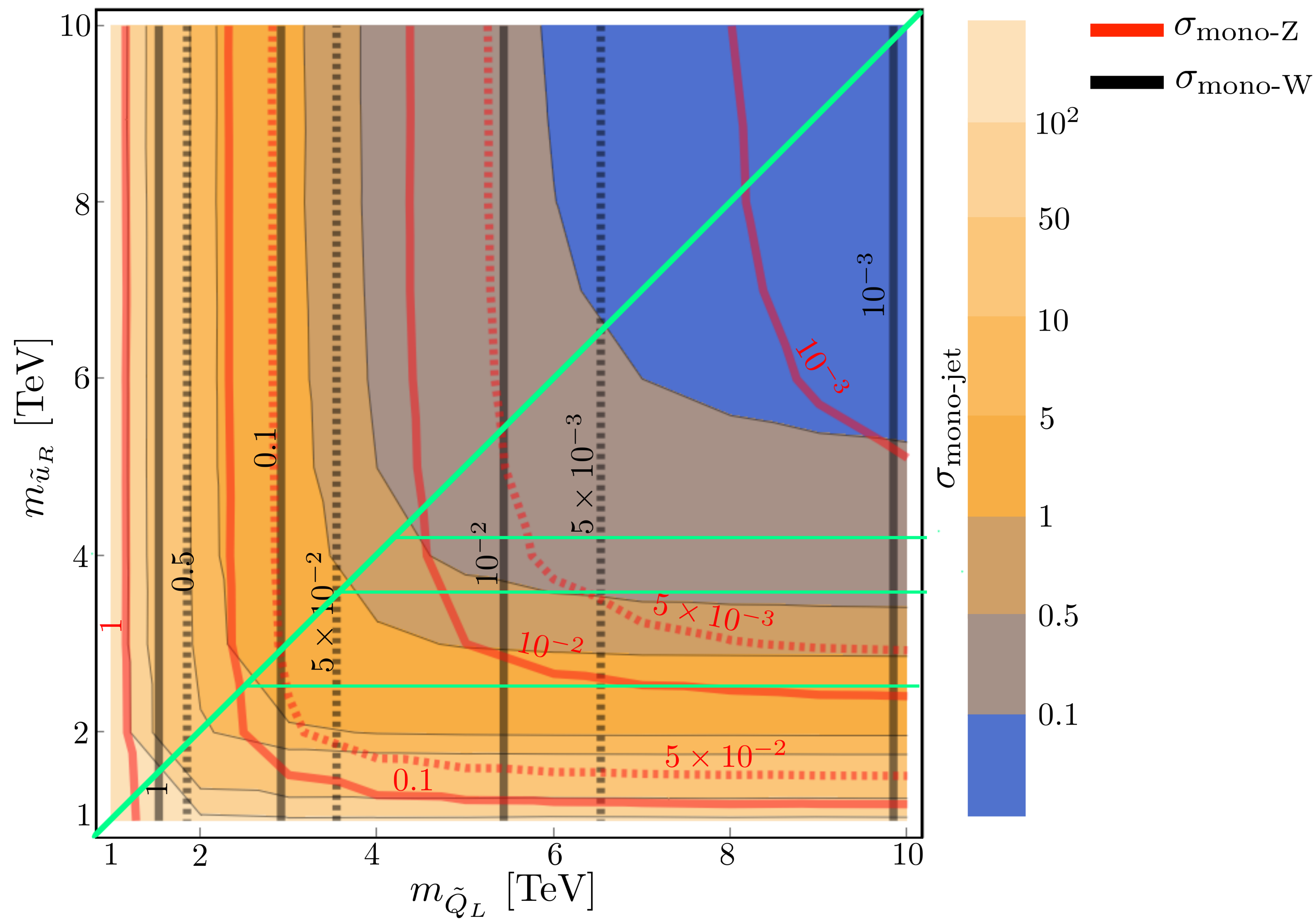


$m_\chi = 5$ GeV, $\lambda_{u_R} = \lambda_{Q_L} = 1$ and $\lambda_4 = 0$

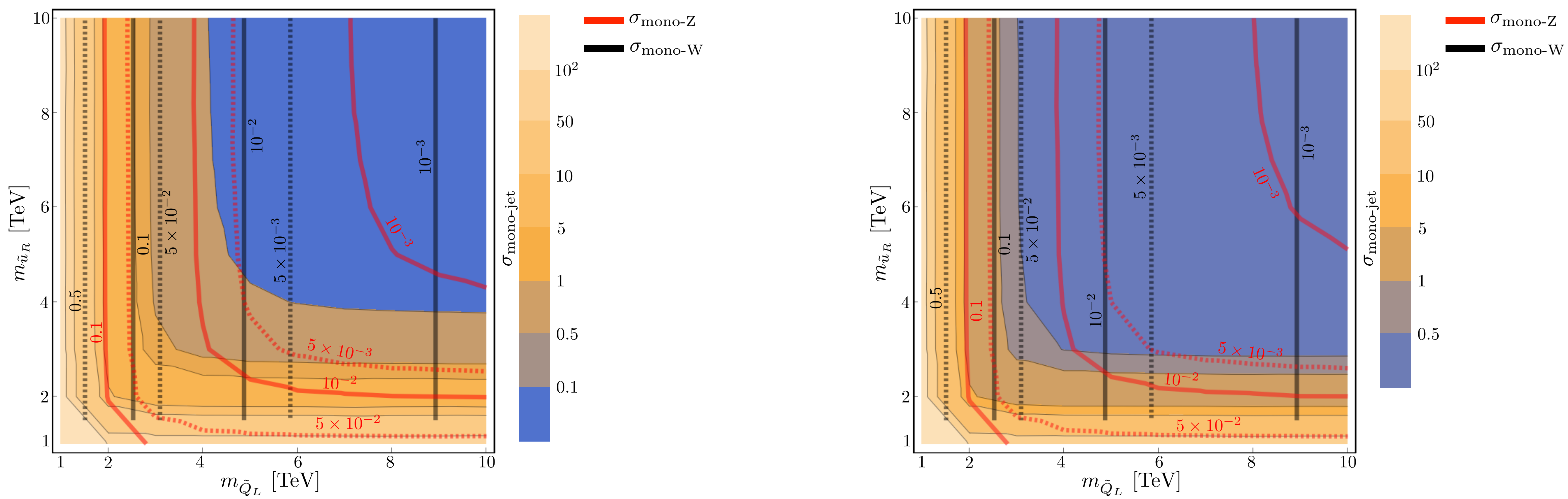
LHS: $\lambda_{d_R} = 0 \to$ RHS: $\lambda_{d_R} = 1$, $m_{d_R} = 3$ TeV

Collider Signatures : Mono-X

Diagonal line represents a previously studied simplified model:



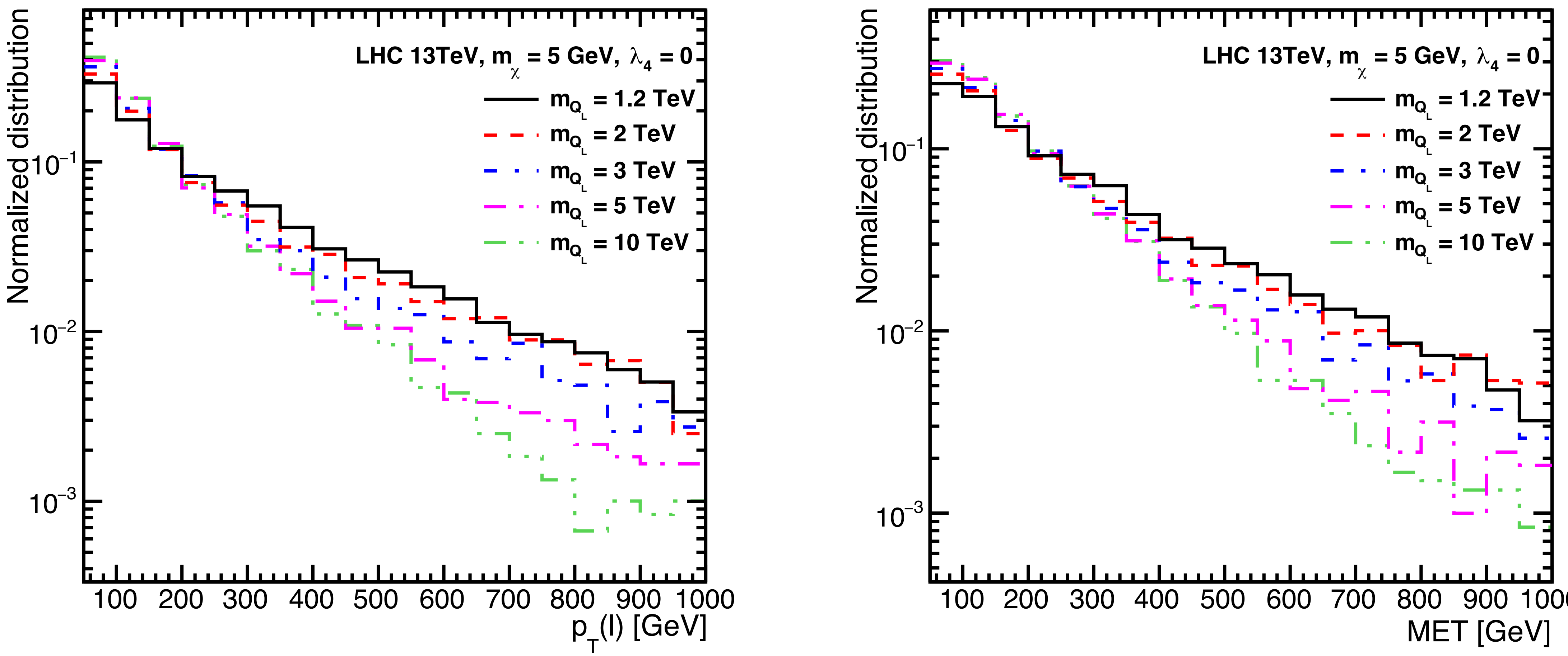
DM mass= 300 GeV



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

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

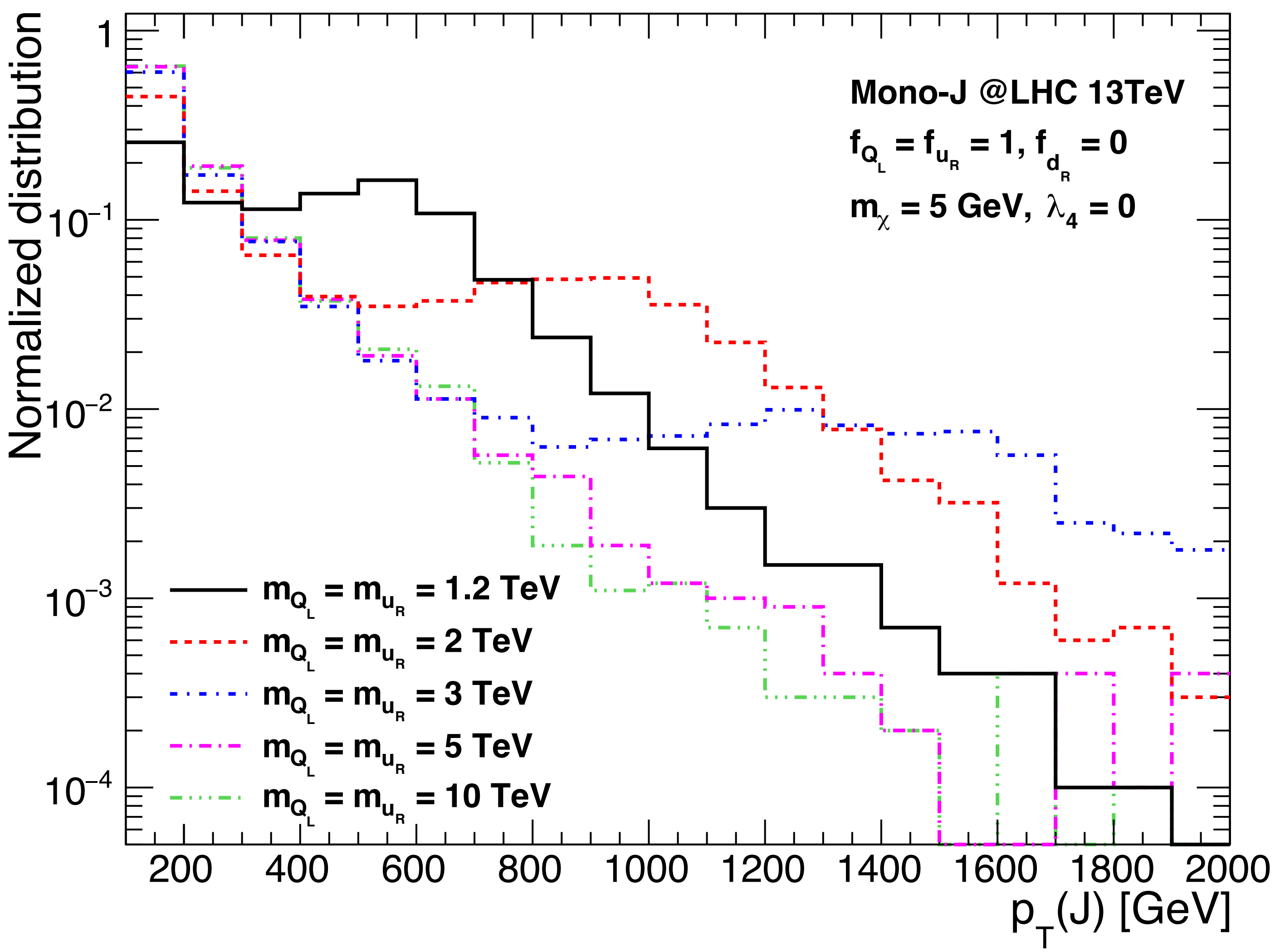
Collider Signatures : Mono-W



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

Collider Signatures : jet pT

Finite mass effects in kinematic mono-Jet p_T:



$$\lambda_{d_R} = \lambda_4 = 0, \lambda_{Q_L} = \lambda_{u_R} = 1, m_{u_R} = m_{Q_L}$$

Summary

- Very important to the full SM gauge symmetry when investigating simplified models for DM at colliders (gauge invariance, unitarity, renormalizability,etc.)

- Broader range of interesting collider signatures, with only modest increase in complication (however tension between thermal relic/direct detection for colored t-channel mediator models)

- In the models with colored scalar mediators, mass plotting of a few TeV are shown to affect collider signatures and in principle could yield material dependence in DD exp’s

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.

Even under simplifying assumptions, these 'less' simplified models allow a practitioner to quickly determine where previously studied simplified models overlap, where they do not, and where 'less' Simplified Models make distinct predictions that may otherwise be missed.

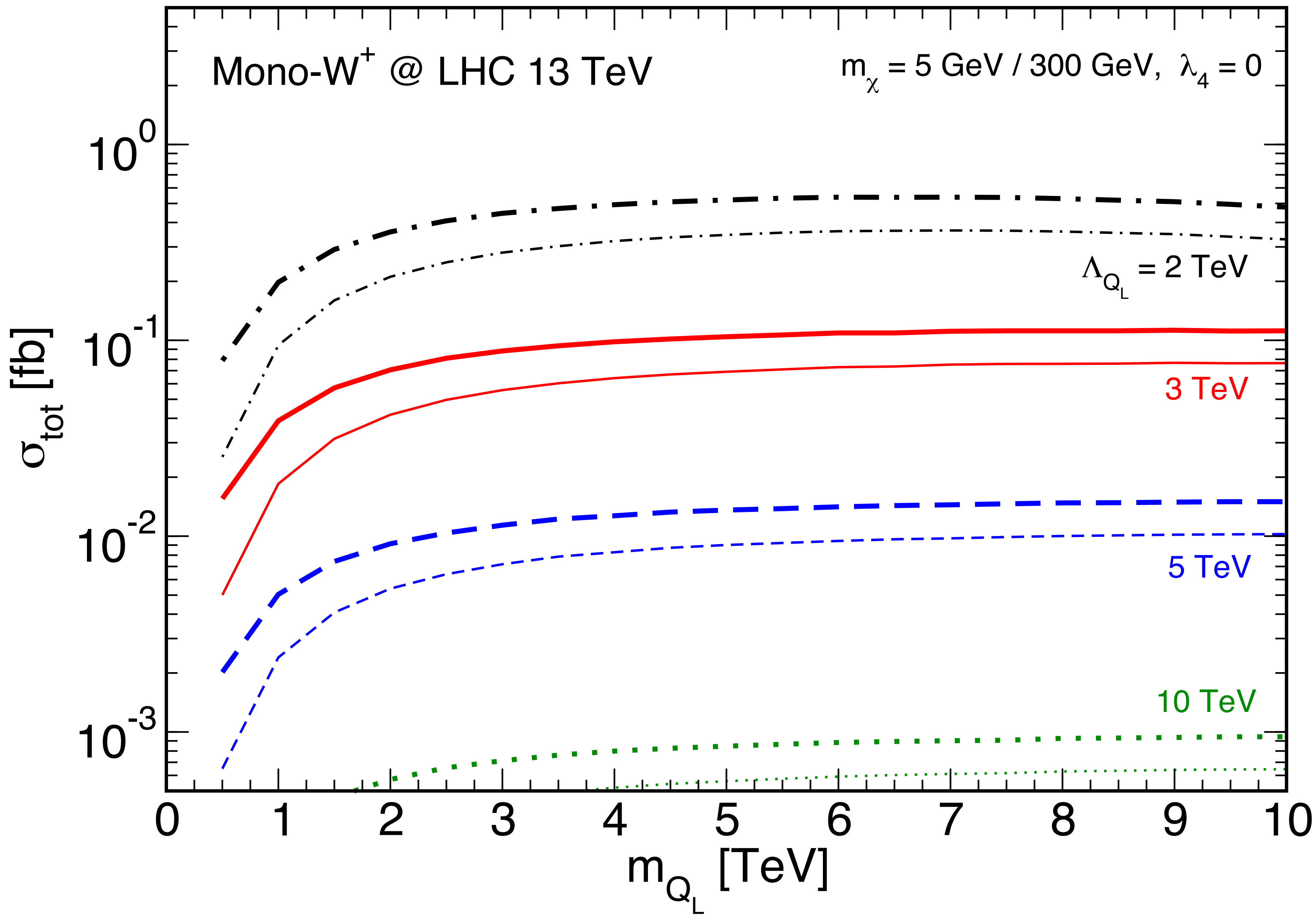
Thank you!

In this talk, I discussed only the t-channel mediator models
In case of the s-channel (pseudo) scalar mediator cases, including the SM Higgs boson can be very important.

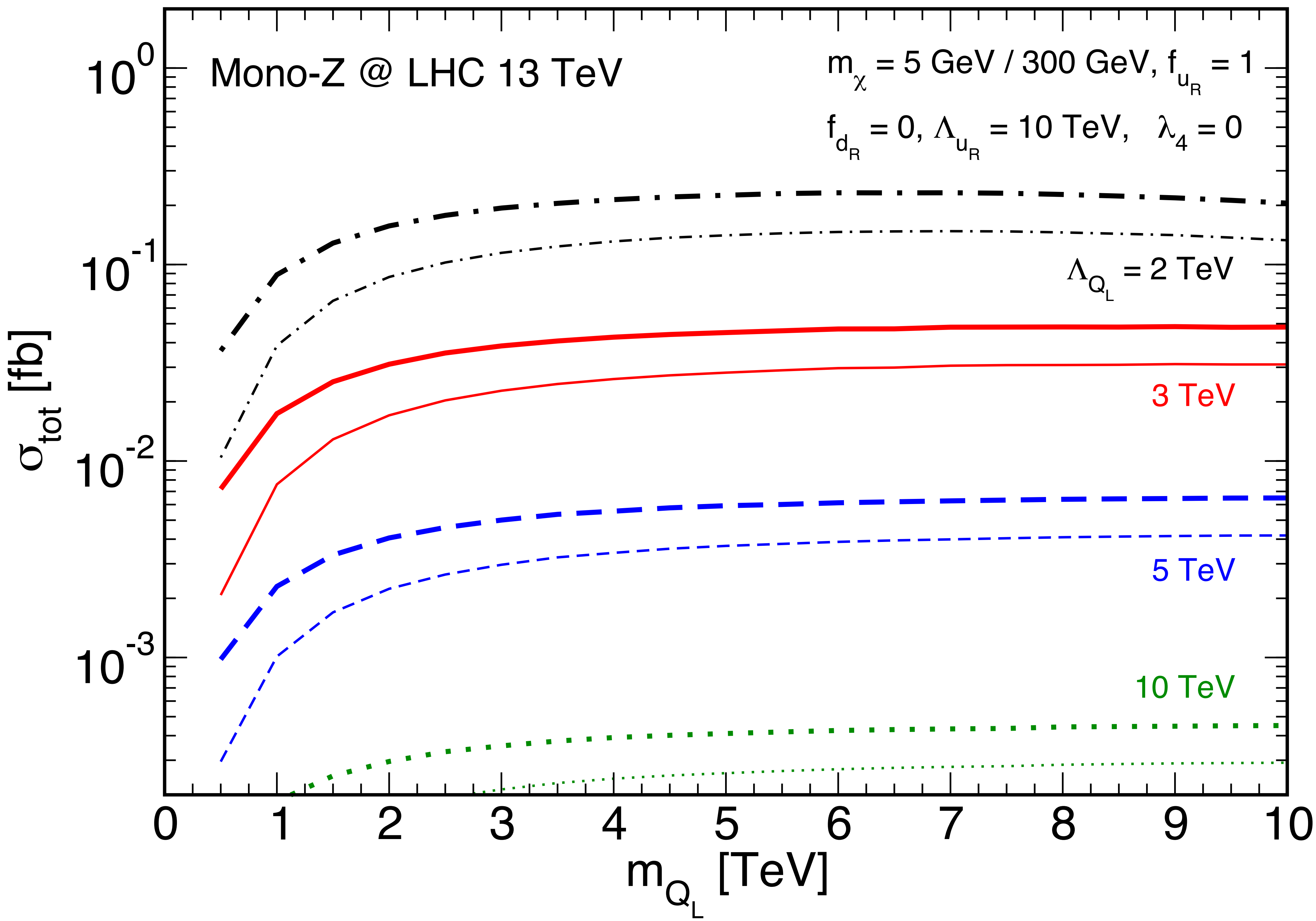
See the following references for more details on this issue: arXiv:1506.06556 (PLB), 1603.04737 (JHEP), 1610.03997 (PLB), 1701.04131(PRD), 1705.02149 (EPJC), 1712.05123 (EPJC), 1807.06697 (PRD)

Backup Slides

Collider Signature : mono-W



Collider Signature : mono-Z



Collider Signatures: mono-X

Diagonal line represents a previously studied simplified model: