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

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The Dark Arts:

Something exists, we can see DM's gravitational effects, but we have no idea what DM is made of, what interactions DM can have (modulo existing constraints), whether we can even detect DM directly or produce it at colliders

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A Light in the Tunnel:

Compliments: Use direct detection, colliders, and precision to constrain models of DM/BSM physics
Building DM models: unitary, renormalizable models with full SM gauge symmetry and general mediator structure important for DM collider phenomenology

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*

Simplest Approach is appealing...but has pitfalls:

- EFTs at colliders: can lead to spurious mono-W signals at the LHC (Bell, Cai, Dent, Leane, Weiler PRD 2015)
- Simplified Models of Z': naive couplings violate $SU(2)_L$ (Haisch, Kahlhoefer, Tait PLB 2016) and dark higgs significantly alters DM pheno (Bell, Cai, Leane JCAP 2016)
- Running Effects: Even in EFTs of DM-SM interaction, SM effects from Λ to nuclear scale have significant impacts on direct detection (D'Eramo, Procura JHEP 2015)

Model Building Philosophy

Our model building guidelines:

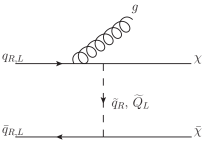
- Respect the full EW symmetry, not just the unbroken SM gauge (ie $SU(3) \times SU(2) \times U(1)$)
- Assume that χ is stable at least lifetime of detector ($\not{E}_T$)
- Use most general DM-SM operator given the mediator choice
- Consider direct detection (+ running), and thermal relic constraints, but goal is ultimately looking at collider signatures for new physics through mono-X signatures

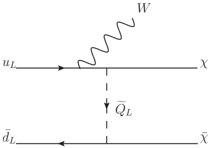
The ultimate goal: Try to find some balance between simplicity and high energy description that allows insight into DM properties at colliders for broadest possible set of models

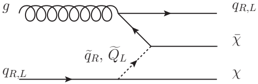
The most general DM-SM operator has *two mediators*:

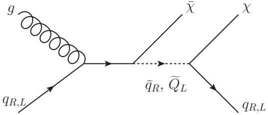
$$\frac{1}{\Lambda^2}\overline{\chi}\Gamma_i\chi\overline{q}\Gamma^j q = \overline{\chi}\Gamma_i\chi\left(\frac{1}{\Lambda_L^2}\overline{q}_L\Gamma^j q_L + \frac{1}{\Lambda_R^2}\overline{q}_R\Gamma^k q_R\right)$$

Thus for mono-X + E_T signatures with a colored t-channel scalar:









Our Model:

$$\overline{\chi}\widetilde{Q}_L^{i\dagger}\left(\lambda_{Q_L}\right)_i^{\ j} Q_{Lj} + \overline{\chi}\widetilde{u}_R^{i\dagger}\left(\lambda_{u_R}\right)_i^{\ j} u_{Rj} + \overline{\chi}\widetilde{d}_R^{i\dagger}\left(\lambda_{d_R}\right)_i^{\ j} d_{Rj} + H.C., \qquad (1)$$

$\widetilde{Q}_{Li}$ are doublets, $\widetilde{u}_{Ri}$ and $\widetilde{d}_{Ri}$ are singlets, and $i, j = 1, 2, 3$.
Generally, $\lambda_{Q_L} \neq \lambda_{u_R} \neq \lambda_{d_R}$, and $m_{\widetilde{q}}$ are free to vary.

Example of previous t-channel model (LHCDMWG July 2015):
$\lambda_{Q_L} = \lambda_{u_R} = \lambda_{d_R}$, and $m_{\widetilde{Q}_L} = m_{\widetilde{u}_R} = m_{\widetilde{d}_R}$

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 JCAP 2015), so set $\lambda_4 = 0$

Direct Detection

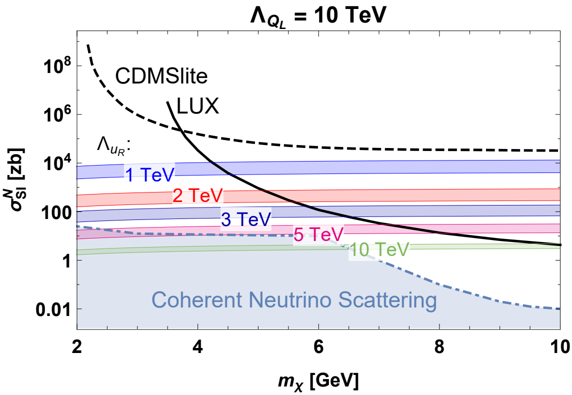
Running effects form EFT scale to Hadronic scale generically mix operators. Usual method in simplified models of going to EFT to determine direct detection misses these effects (can be sizable):

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

A practitioner friendly guide for these effects can be found in D'Eramo, Procura JHEP 2015.

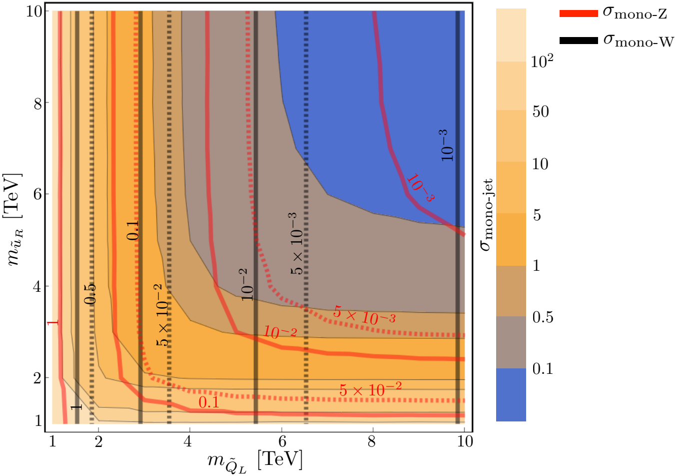
Direct Detection

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):



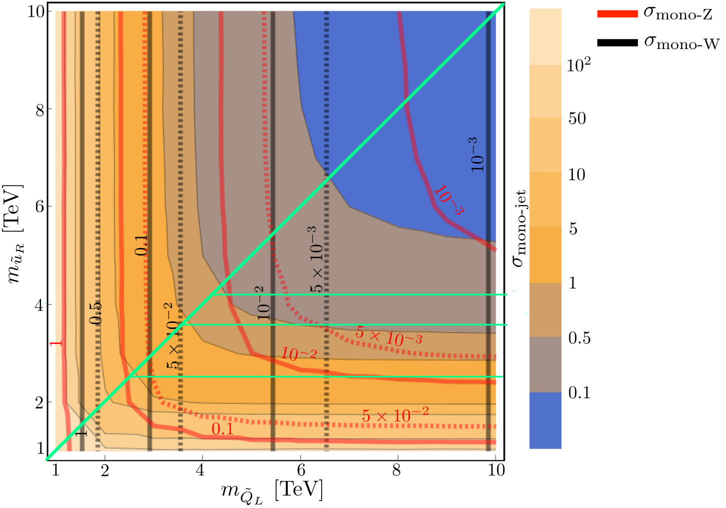
Region where $m_\chi > 1$ TeV has significantly reduced mono-X

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

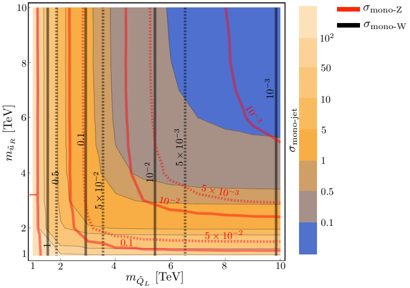


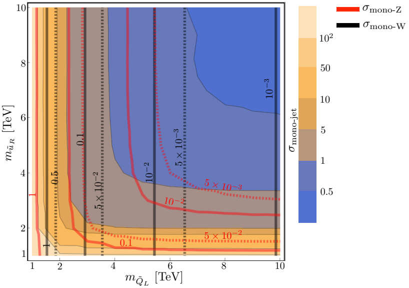
$m_\chi = 5$ GeV, $\lambda_{u_R} = \lambda_{Q_L} = 1$ and $\lambda_4 = 0$

Diagonal line represents a previously studied simplified model:

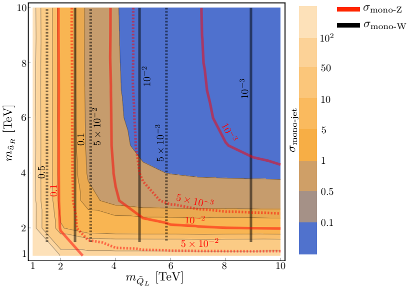


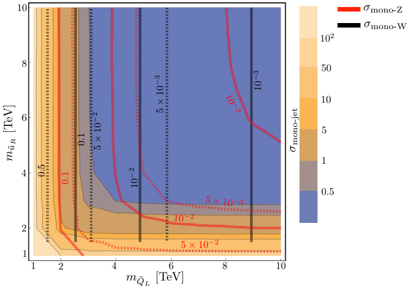
Collider Signatures: $\lambda_{d_R} \neq 0$





$m_\chi = 5$ 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





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

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

Summary:

- Very important to use the full SM gauge group when investigating simplified models at colliders (gauge invariance, unitarity, etc.)
- Constraints from simplified models in direct detection and at the LHC are not easily related if mediator structure is taken to be the most general
- ‘Less simplified’ models are a useful tool for understanding DM searches with a comparatively 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!

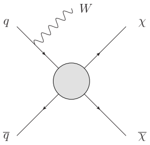
Backup Slides

$SU(2)_L$ and mono-W

EFTs break down when E_{CM} approaches Λ, however breakdown of EFT can happen in other situations.

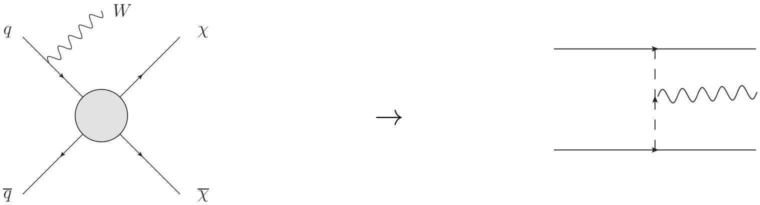
See Bell, Cai, Dent, Leane, Weiler PRD 2015:

$$\frac{1}{\Lambda^2}(\overline{\chi}\gamma^\mu\chi)(\overline{u}_L\gamma_\mu u_L + \xi\overline{d}_L\gamma_\mu d_L)$$



$\xi = -1$ leads to mono-W enhancement from inteference between u_L and d_L couplings $\rightarrow$ this violates $SU(2)_L$!

$SU(2)_L$ and mono-W



Comes from enhancement from spurious W_L contributions at high E:
$\xi - 1 \to 0$ as $E \to v_{EW}$, so $\xi \approx 1$ with 'full' SM gauge group.

So EFT description with arbitrary ξ can break down on $E_{CM} \to v$.

Bell, Cai, Dent, Leane, Weiler PRD 2015

$SU(2)_L$ and mono-W

Similar problems with EW symmetry can exist in simplified models

Take the following simplified Z' model :

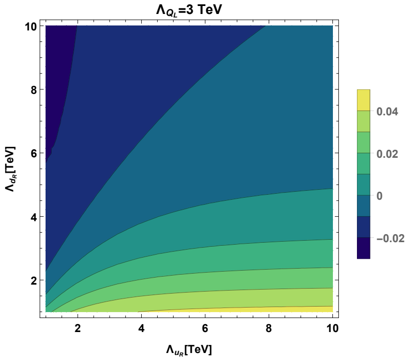
$$\mathcal{L} = -Z'_\mu \overline{\chi}(g^V_{DM}\gamma^\mu + g^A_{DM}\gamma^\mu\gamma_5)\chi - Z'_\mu \overline{f}(g^V_f\gamma^\mu + g^A_f\gamma^\mu\gamma_5)f$$

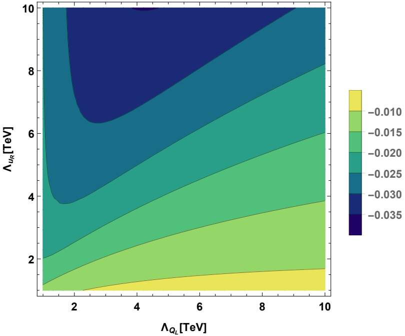
If $g^A_u - g^A_d - g^V_u + g^V_d = -2g^V_u \neq 0$ spurious contributions to $\not{E}_T$ spectrum, enforcing EW symmetry eliminates these.

Haisch, Kahlhoefer, Tait PLB 2016

Direct Detection:Material Dependence

Plot $(\sigma_{Xe} - \sigma_{Ge})/\sigma_{Xe}$ for normalized cross sections (ie nominally no Z/A dependence):





Direct Detection

Material Dependence:

Relaxing the assumptions about coupling constants with more than one mediator 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

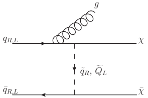
- if χ couples to Leptons, this can be alleviated

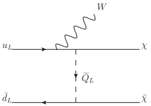
$m_\chi \approx 1$ TeV $\rightarrow$ generically under-produced

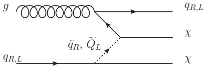
- if χ is not the only thermal relic this can be accommodated

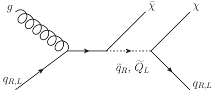
For the LHC phenomenology we assume $m_\chi = 5$ GeV, but $m_\chi \mathcal{O}(100)$ GeV can be accommodated if there are additional thermal relics (reduced direct detection constraints via t-channel mediator).

Recall the mono-X + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):









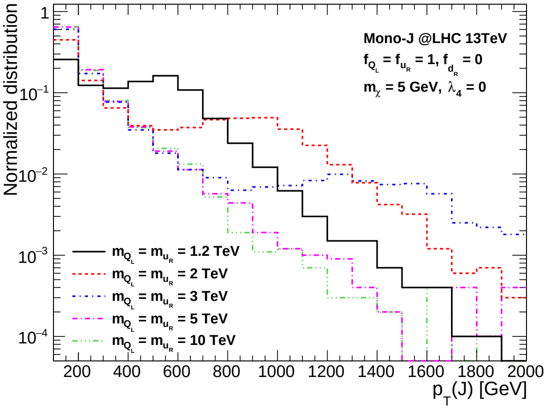
- Mono-W signature depends on $\Lambda_{Q_L} = \frac{\lambda_{Q_L}}{m_{\widetilde{Q}_L}}$
- Mono-jet/mono-Z depends on all mediators
- Complementary information from each mono-X when RH/LH quarks reduces complexity

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

Collider Signatures: Methods

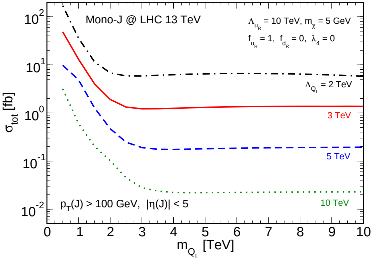
$$\mathcal{L}_{t-channel} = \overline{\chi}\widetilde{Q}_L^{i\dagger}\,(\lambda_{Q_L})_i{}^j\,Q_{Lj} + \overline{\chi}\widetilde{u}_R^{i\dagger}\,(\lambda_{u_R})_i{}^j\,u_{Rj} + \overline{\chi}\widetilde{d}_R^{i\dagger}\,(\lambda_{d_R})_i{}^j\,d_{Rj} + H.C.$$

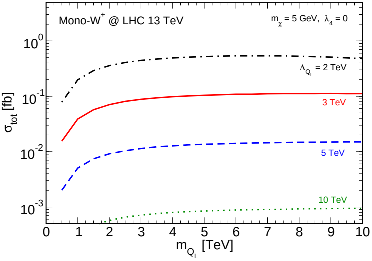
- Implement $\mathcal{L}$ in Feynrules (scalar widths implemented as internal parameter, function of $\lambda_{q_{(L,R)}}$, $m_{\widetilde{q_{(L,R)}}}$)
- Generate events with Madgraph 5 ($|\,\eta\,| < 5$, $p_T > 100$ GeV for mono-jet)
- For kinematic distributions analyze with Delphes/Root
- Make assumptions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



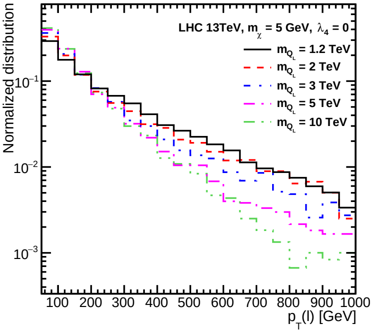
$$\lambda_{d_R} = \lambda_4 = 0, \lambda_{Q_L} = \lambda_{u_R} = 1, m_{\tilde{u}_R} = m_{\tilde{Q}_L}$$

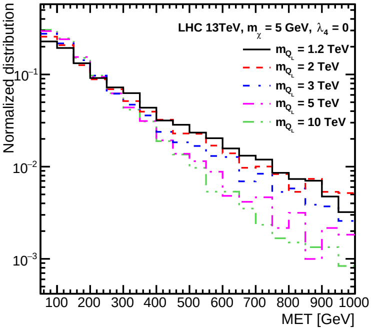
Collider Signatures: mono-J





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

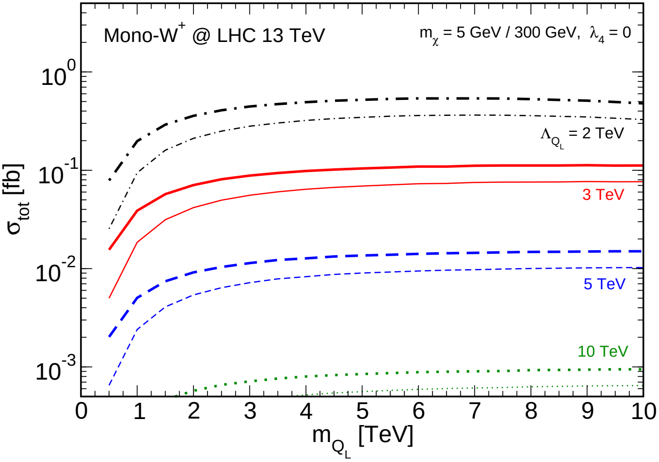


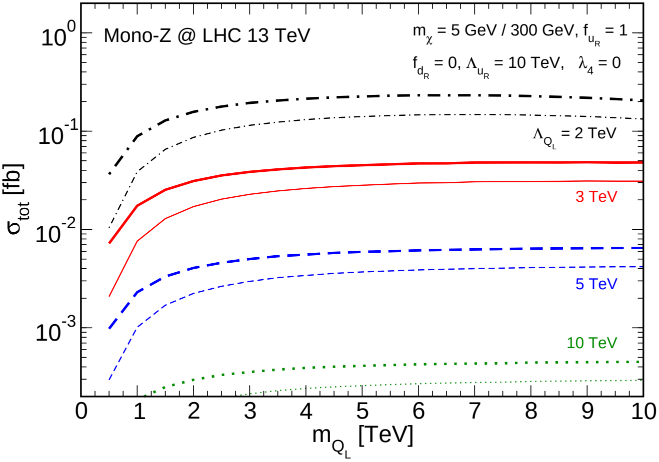


Lepton mono-W kinematics produced in Delphes for $\lambda_4 = 0$, $m_\chi = 5$ GeV

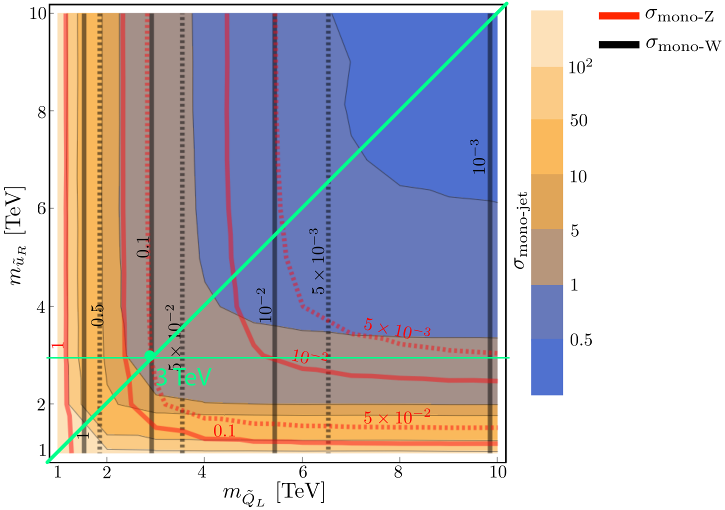
Simplified models with lighter scalar mass has broader p_T and E_T

Collider Signatures:mono-X




Mono-Z @ LHC 13 TeV
m_χ = 5 GeV / 300 GeV, f_uR = 1
f_dR = 0, Λ_uR = 10 TeV, λ_4 = 0
Λ_QL = 2 TeV
3 TeV
5 TeV
10 TeV
σ_tot [fb]
m_QL [TeV]
10^0
10^-1
10^-2
10^-3
0
1
2
3
4
5
6
7
8
9
10

Diagonal line represents a previously studied simplified model:



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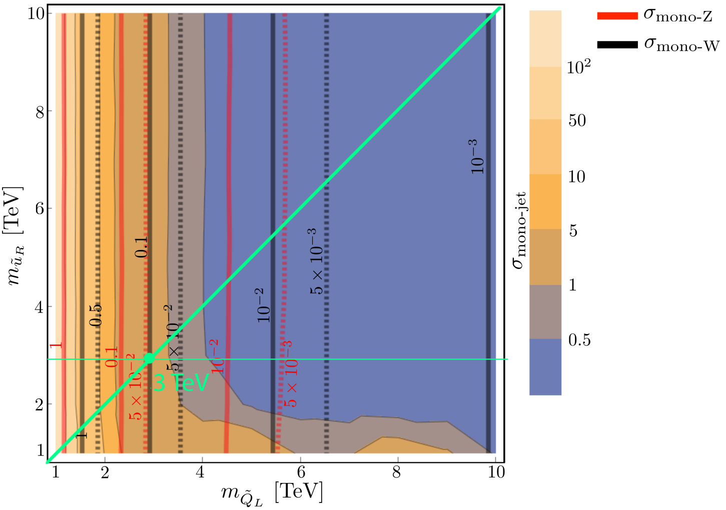

Flavor Constraints

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