Less simplified models of dark matter for direct detection and the LHC

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The Lancaster, Manchester, Sheffield Consortium for Fundamental Physics

Plan of the Talk :

- Brief introduction to Simplified Dark Matter Models.
- Combining Two Models.
- Results.
- Conclusions.

Talk based on : A. Choudhury, K. Kowalska, L. Roszkowski, E. M. Sessolo, A. J. Williams; JHEP **1604**, 182 (2016) [arXiv:1509.05771].

Different approaches :

- Complete Models like mSUGRA or cMSSM etc. (the lightest neutralino $\rightarrow$ good candidate for WIMP)
- Effective field theory (EFT) framework $\rightarrow$ advantage of providing bounds in terms of a common contact operator $\rightarrow$ a good approximation as long as the interaction is mediated by particles with masses well above the collision energy.
- Simplified Dark Matter Models.
    - Vector mediator $\rightarrow Z'$.
    - Scalar mediator or Higgs portal $\rightarrow H$.
    - Scalar **t**-channel mediators $\longrightarrow \tilde{\mathbf{q}}$.

    Goodman and Shepherd (2011); J. Abdallah et al. (2014), (2015) .....

Models with Vector mediator:

- The mediator $\rightarrow$ leptophobic Z'.
- The Dirac fermion singlet DM particle $\chi \rightarrow$ couples to the new gauge boson, Z'.
- Z' is assumed to have negligible mixing with the Z boson of the SM, and to not couple to the SM leptons.

The terms in the Lagrangian relevant to DM searches

$$\mathcal{L} \supset Z'_\mu \bar{\chi}\gamma^\mu (g^V_\chi - g^A_\chi \gamma_5)\chi + \sum_i Z'_\mu \bar{q}_i \gamma^\mu (g^V_q - g^A_q \gamma_5) q_i$$

- Described By 4 (3) parameter $\rightarrow \{m_\chi, m_{Z'}, g^V_\chi, g^V_q\}$

- We limit ourselves $\rightarrow$ WIMPs are produced at the LHC through an on-shell mediator: $m_{Z'} > 2m_\chi$.
- In this regime the production cross section and mediator width are largely independent of the spin structure of the couplings, so that we can set either $g^V_{\chi/q}$ or $g^A_{\chi/q}$ to zero without loss in generality.

Scalar mediator/Higgs portal:

- The Dirac fermion singlet DM particle (χ) $\rightarrow$ couples to a new singlet real scalar (s).
- Scalar mediators have also been studied extensively in literature.

The terms in the Lagrangian relevant to DM searches

$$\mathcal{L} \supset -y_\chi \bar{\chi}\chi s - \mu_s s|\Phi|^2 - \lambda_s s^2 |\Phi|^2$$

- y_χ is the Yukawa coupling between the DM and the singlet
- μ_s is a mass term $\rightarrow$ induces mixing between s and the SM Higgs doublet Φ $\rightarrow$ gives rise to the Higgs boson after EWSB.

- Φ develops the SM VEV v: $\Phi \rightarrow 1/\sqrt{2}\,(0, v+h)^T$, which can be determined in terms of the SM mass and quartic couplings.

Scalar mediator/Higgs portal:

- The μ_s and λ_s Lagrangian terms produce an off-diagonal component in the (h, s) mass matrix.
- The mass matrix is diagonalized by a mixing matrix parametrized by a mixing angle θ

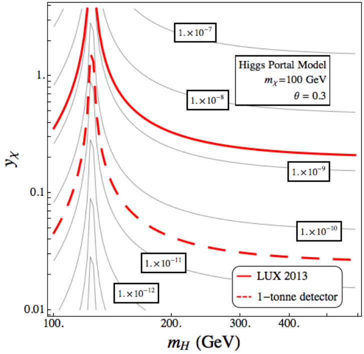
$$\begin{pmatrix} h_{\rm SM} \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

After diagonalization the relevant terms for DM phenomenology

$$\mathcal{L} \supset -y_\chi \left(h_{\rm SM} sin\theta + H\cos\theta \right) \bar{\chi}\chi - \frac{1}{\sqrt{2}} \left(h_{\rm SM} cos\theta - H\sin\theta \right) \sum_f y_f f \bar{f}$$

- In the spirit of phenomenology one can trade λ_s and μ_s for θ and m_H to produce a simplified model of DM.
- The DM simplified model is finally described by 4 parameters, $\{m_\chi, m_H, \sin 2\theta, y_\chi\}$

$\sigma_p^{\rm SI}$ for Higgs portal model



- For $m_H \approx m_{h_{\rm SM}}$ the contributions due to $h_{\rm SM}$ and H cancel out and $\sigma_p^{\rm SI}$ is suppressed.
- This creates a blind spot for Direct Detection.

Scalar t-channel mediators:

- Scalar **t**-channel mediators $\longrightarrow$ charged under **SU(3)**.
- Borrow the notation "squarks" ($\tilde{\mathbf{q}}$) as in MSSM.
- Our model is not necessarily SUSY based.
- We assume universality between the first two generations for the masses and couplings to the DM ($\mathbf{m}_{\tilde{\mathbf{q}}}$, $\mathbf{g}_{\tilde{\mathbf{q}}}$).

The terms in the Lagrangian relevant to DM searches

$$\mathcal{L} \supset \sum_{i=1,2} g_{\tilde{q}} \left(\tilde{u}^{\dagger}_{i,R} \bar{\chi} P_R u_i + \tilde{u}^{\dagger}_{i,L} \bar{\chi} P_L u_i + \tilde{d}^{\dagger}_{i,R} \bar{\chi} P_R d_i + \tilde{d}^{\dagger}_{i,L} \bar{\chi} P_L d_i \right) + \mathrm{h.c.}$$

- We assume that the stability of the DM is protected by a discrete symmetry similar to R-parity.
- This simplified model is described by 3 parameters:

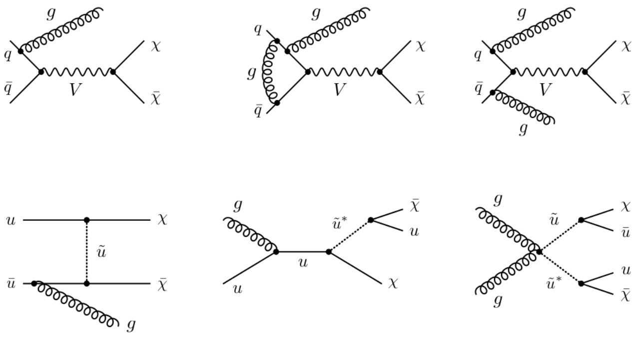
$$\{m_{\chi}, m_{\tilde{q}}, g_{\tilde{q}}\}$$

Methodology and analysis of the combined models:

- Model 1. Combining vector and Higgs portal mediators.
  (6 free parameters: $m_\chi, m_{Z'}, m_H, \theta, y_\chi, g^V_{\chi/q}$)

- Model 2. Combining Higgs portal and t-channel mediators.
  (6 free parameters: $m_\chi, m_{\tilde{q}}, m_H, \theta, y_\chi, g_{\tilde{q}}$)

- Model 3. Combining vector and t-channel mediators.
  (6 free parameters: $m_\chi, m_{\tilde{q}}, m_{Z'}, g^V_\chi, g^V_q, g_{\tilde{q}}$)



- LHC Bounds : Mono-jet searches, searches with jets + missing E_T (MET), invisible branching fraction of the Higgs boson, and bounds on new heavy Z' resonances from the $t\bar{t}$ and di-jet invariant mass distributions. • Bounds from DD searches.
- Implemented by: `FeynRules`,`CalcHEP`, `micrOMEGAs`, MadGraph5_aMC@NLO, PYTHIA and `CheckMATE`

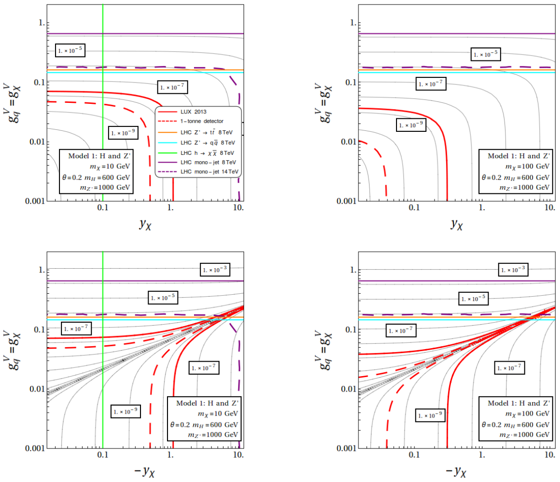
Model 1: combining $\mathbf{Z'}$ and Higgs portal

- Many UV complete models with a Z' also contain an extended scalar sector. (see for example: Basso, Fischer and vd Bij 2013)
- We consider a Z' vector boson associated to a new symmetry $U(1)_X$.
- A hypothetical extended scalar sector that will include, among others, a $U(1)_X$-neutral SM singlet field s that couples to the SM Higgs and the DM particle.
- If all other degrees of freedom are decoupled, the low energy Lagrangian is just the sum of:

$$\mathcal{L} \supset Z'_\mu \bar{\chi}\gamma^\mu (g_\chi^V - g_\chi^A \gamma_5)\chi + \sum_i Z'_\mu \bar{q}_i \gamma^\mu (g_q^V - g_q^A \gamma_5) q_i$$

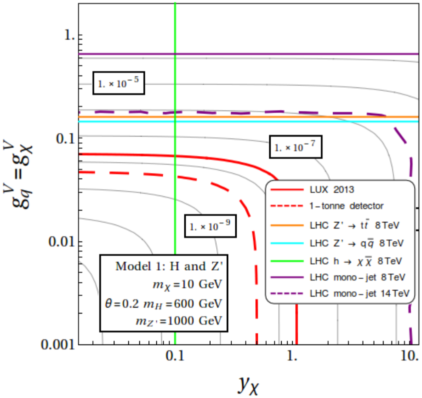
$$\mathcal{L} \supset -y_\chi \left(h_{\rm SM} sin\theta + H\cos\theta\right)\bar{\chi}\chi - \frac{1}{\sqrt{2}}\left(h_{\rm SM} cos\theta - H\sin\theta\right)\sum_f y_f f\bar{f}$$

Model 1: combining $\mathbf{Z'}$ and Higgs portal



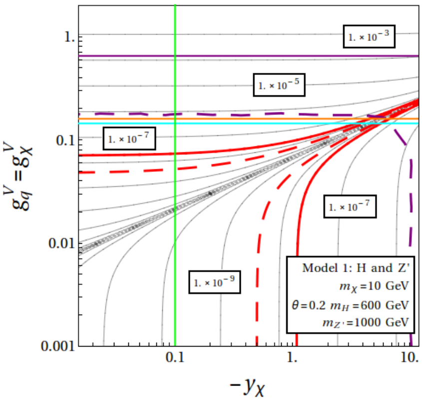
- (a) $m_\chi = 10\ GeV$, $m_{Z'} = 1000$, $\theta = 0.2$ and $m_H = 600$; (b) $m_\chi = 100\ GeV$.
- (c) Same as (a) but the sign of y_χ is negative. (d) Same as (c) but $m_\chi = 100\ GeV$.

Model 1: combining $\mathbf{Z'}$ and Higgs portal



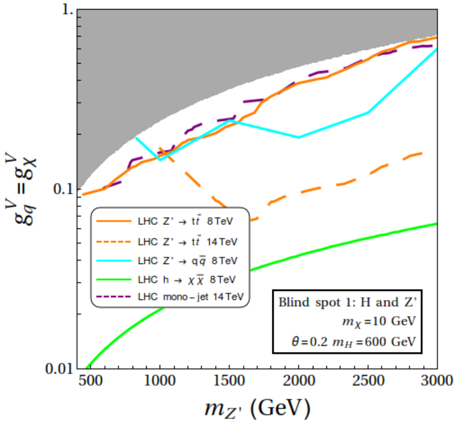
- the DD detection bound on $g^V_{\chi/q}$ from LUX is significantly more constraining then any of the collider limits.
- For $m_\chi \lesssim 62\ GeV$, the invisible width of $h \rightarrow$ places an upper bound on y_χ $\rightarrow$ stronger than the projected reach of tonne-scale detectors.

Model 1: combining $\mathbf{Z'}$ and Higgs portal



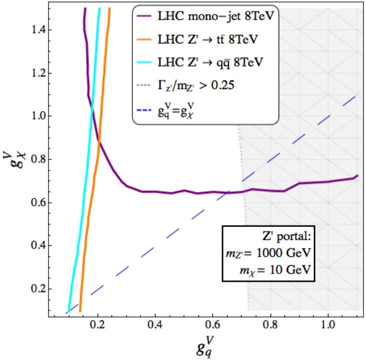
- the DD detection bound on $g^V_{\chi/q}$ from LUX is significantly more constraining then any of the collider limits.
- For $m_\chi \lesssim 62\ GeV$, the invisible width of $h \to$ places an upper bound on $y_\chi \to$ stronger than the projected reach of tonne-scale detectors.
- For $y_\chi < 0$, or if it is positive but $g^V_\chi = -g^V_q$, the diagrams corresponding to the Z' and Higgs portal interfere destructively and $\sigma_p^{\rm SI}$ becomes suppressed.
- the condition for the blind spot: $y_\chi \approx -\left(\frac{8.22\times 10^7\ \mathrm{GeV}^2}{m^2_{Z'}}\right) \frac{g^V_\chi g^V_q}{\sin 2\theta \left(1 - \frac{m^2_{h_{\rm SM}}}{m^2_H}\right)}$.

Model 1: combining Z′ and Higgs portal



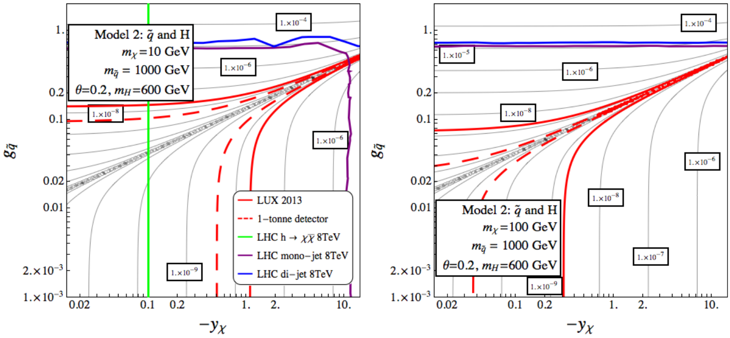
- Interplay of LHC constraints for the blind spot.
- for most of the parameter space the di-top and di-jet searches for heavy resonances are more sensitive to $g^V_{\chi/q}$ than the mono-jet search for DM.
- There remains a significant dependence on the underlying assumptions.

Comparison of the limits from mono-jet Vs Di-top(jet)



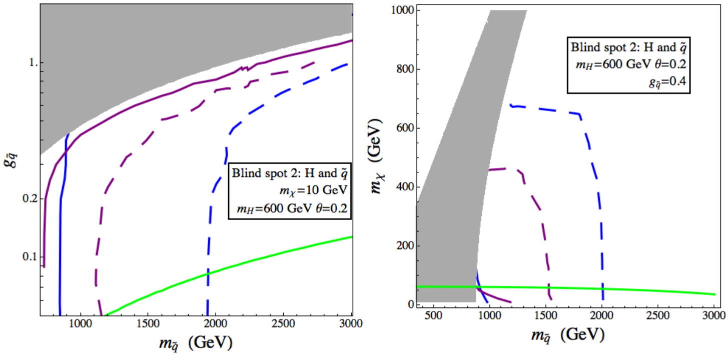
- For $g_\chi^V \neq g_q^V$ the upper bounds will move in the $(y_\chi, \sqrt{g_q^V g_\chi^V})$ plane.
- for $g_\chi^V < g_q^V$ the upper bounds from di-top and di-jet searches will become stronger.
- For $g_\chi^V > g_q^V$ it will be the other way around.

Model 2: combining Higgs portal and squarks



- $y_\chi > 0 \rightarrow$ no cancellations for σ_p^{SI}.
- The condition for the blind spot: $y_\chi \approx -\left(\frac{2.05\times10^7\ \mathrm{GeV}^2}{m_{\tilde{q}}^2 - m_\chi^2}\right)\frac{g_{\tilde{q}}^2}{\sin 2\theta\left(1-\frac{m_{h_{\mathrm{SM}}}^2}{m_H^2}\right)}$.
- The parameter space that is not in reach of underground DD experiments remains essentially unconstrained.
- $m_{\tilde{q}} = 1000\ GeV \rightarrow$ the 14 TeV jets+MET and mono-jet searches $\rightarrow$ expected to exclude the full parameter space.

Model 2: combining Higgs portal and squarks



- Interplay of LHC constraints for the blind spot.
- Invisible Brs of the Higgs yields the greatest constraint when $m_\chi < 62.5\, GeV$.
- Jets + MET (blue) and mono-jet (purple) searches dominate in different regions of the parameter space.

Model 3: combining $\mathbf{Z'}$ and squarks

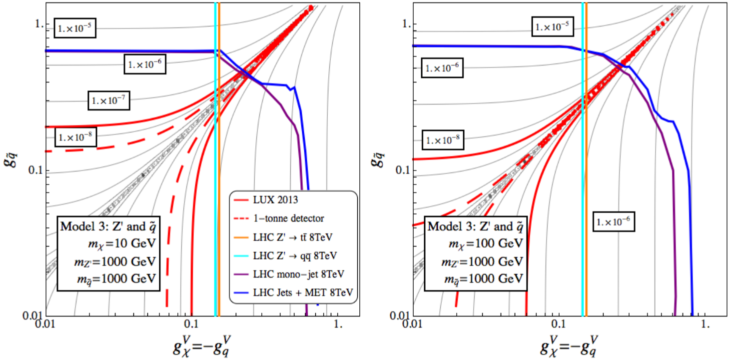
- A first simple way $\rightarrow$ DM particle and the quarks have the same charges under $U(1)_X$ $\rightarrow$ scalar colored particles are instead $U(1)_X$ neutral. $\rightarrow$ the extra scalars do not couple to the Z' $\rightarrow$ No destructive interference between the diagrams with squark exchange and those with a Z' mediator.
- Another way of constructing a gauge invariant LSMS $\rightarrow$ Allow the squarks to have the same coupling to the Z' as the quarks $\rightarrow$ an approximation of a full UV theory involving an extended gauge symmetry and a supersymmetric sector.
- One needs two fermion SM singlet DM candidates, ξ and ζ, such that ξ is coupled to the Z' and ζ is coupled to the squarks. The symmetry is conserved if the fields are charged under $U(1)_X$ according to :

	Ψ	ξ	ζ	q_i	$\tilde{q}_{i,L/R}$
$U(1)_X$ charge	$+1$	$+1$	0	$+1$	$+1$

(1)

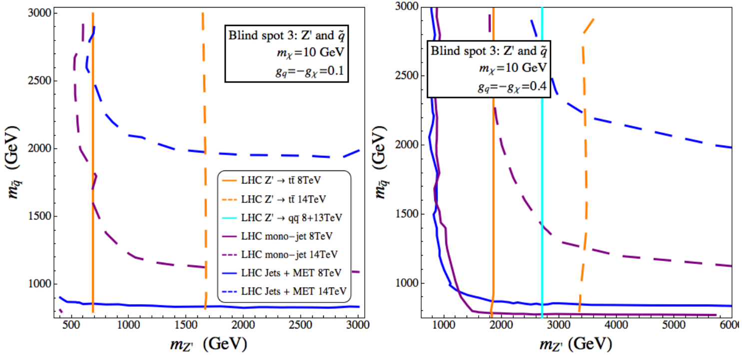
- Despite being apparently rather involved, the phenomenological LSMS is characterized by only 6 free parameters, $\left\{m_\chi, m_{\tilde{q}}, m_{Z'}, g_\chi^V, g_q^V, g_{\tilde{q}}\right\}$.

(additional assumption $g_\chi^V = \pm g_q^V \equiv g_{\chi/q}^V$)



- The condition for the blind spot: $|g_{\tilde{q}}| \approx 2 \left| g^V_{\chi/q} \right| \frac{\sqrt{m^2_{\tilde{q}} - m^2_{\chi}}}{m_{Z'}}$.
- mono-jet and jets+MET ATLAS searches yield very comparable bounds.
- for these mediator masses, the 14 TeV projected reach for both searches covers the full parameter space.

Model 3: combining Z′ and squarks



- Dependence of the collider bounds on the mediators' mass.
- The condition for the blind spot: $|g_{\tilde{q}}| \approx 2 \left| g^V_{\chi/q} \right| \frac{\sqrt{m^2_{\tilde{q}} - m^2_\chi}}{m_{Z'}}$.
- For $g^V_{\chi/q} = 0.1$, Z' mass below $\sim 700\, GeV$ is excluded by the di-top search.
- For $g^V_{\chi/q} = 0.4$, one can probe the squark mediator mass up to $\sim$ 2000 GeV and Z' mass up to more than 3000 GeV.

Summary:

- We considered three cases characterized by a Dirac fermion WIMP coupled to more than one mediator.
- Interference between different diagrams $\rightarrow$ gives rise to blind spots for DD experiments.
- The LUX upper bound on $\sigma_p^{\rm SI}$ constrains the coupling constants of WIMP SMS by at least one order of magnitude more strongly (Exceptions $\rightarrow m_\chi \lesssim 1/2\, m_{h_{\rm SM}}$).
- LUX bounds also outperforms projected reach for 14 TeV LHC in most cases.
- The model involving a Z' and Higgs portal $\rightarrow$ not constrained at all by mono-jet searches in the blind spot if $g_\chi^V = g_q^V$.
- For the LHC 14 TeV $\rightarrow$ heavy Z' resonances will constitute the most effective strategy.
- Models involving squark-like mediators the bounds from mono-jet and jets+MET searches on the coupling $g_{\tilde{q}}$ are at present comparable.
- The reach of 14 TeV LHC jets+MET searches for the blind spots significantly outperforms the expectations for mono-jet searches.

THANK YOU

Back Up

Model 1: combining $\mathbf{Z'}$ and Higgs portal

- The differential WIMP-nucleus scattering cross section in the non-relativistic limit:

$$\frac{d\sigma_{\chi N}}{d|\mathbf{q}|^2} = \frac{1}{\pi v_\chi^2}\left[Zf_p + (A-Z)f_n\right]^2 F^2(Q) \qquad \text{Jungman, Kamionkowski and Griest (1996)}$$

$|\mathbf{q}|$ - transferred momentum, Z - atomic number, A the atomic weight, v_χ - average speed of the DM in the halo, and $F(Q)$ is the Wood-Saxon function as a function of $Q = |\mathbf{q}|^2/2m_N$.

$$f_n \approx f_p \approx \frac{y_\chi \sin 2\theta}{4\, m^2_{h_{\rm SM}}}\left(1 - \frac{m^2_{h_{\rm SM}}}{m_H^2}\right)\frac{m_p}{v}\left(\sum_{q=u,d,s} f_{Tq} + \frac{2}{9}\, f_{TG}\right) + \frac{3}{2}\,\frac{g_\chi^V g_q^V}{m^2_{Z'}}$$

In the relativistic WIMP-quark scattering, $q(p_1)\chi(p_3) \to q(p_2)\chi(p_4)$, the squared amplitude reads:

$$\begin{aligned}|\mathcal{A}|^2 \quad &= \quad 2\,\frac{\sin^2 2\theta\, y_q^2 y_\chi^2 (m_p^2 + p_1 p_2)(m_\chi^2 + p_3 p_4)}{[(p_1-p_2)^2 - m^2_{h_{\rm SM}}]^2} + \frac{(g_\chi^V g_q^V)^2\,(16 m_p^2 - 8p_1p_2)(16 m_\chi^2 - 8p_3p_4)}{[(p_1-p_2)^2 - m^2_{Z'}]^2} \\ &+ \quad \frac{16}{\sqrt{2}}\,\frac{\sin 2\theta\, y_q y_\chi g_\chi^V g_q^V m_p m_\chi (p_1+p_2)^\mu (p_3+p_4)_\mu}{[(p_1-p_2)^2 - m^2_{h_{\rm SM}}][(p_1-p_2)^2 - m^2_{Z'}]}\end{aligned}$$

the condition for the blind spot: $y_\chi \approx -\left(\frac{8.22\times 10^7\ \mathrm{GeV}^2}{m^2_{Z'}}\right)\frac{g_\chi^V g_q^V}{\sin 2\theta\left(1 - \frac{m^2_{h_{\rm SM}}}{m_H^2}\right)}$.

Model 2: combining Higgs portal and squarks

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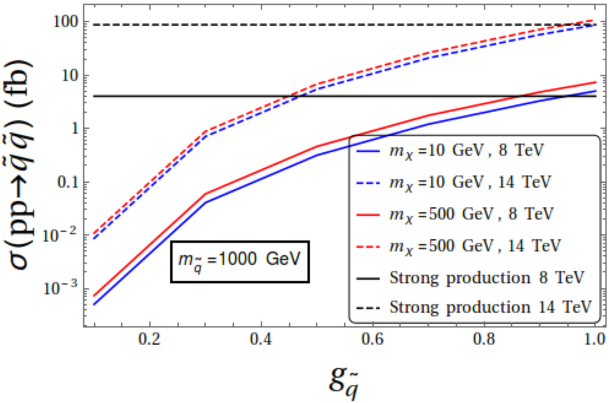
$$f_n \approx f_p \approx \frac{y_\chi \sin 2\theta}{4\, m_{h_{\rm SM}}^2} \left(1 - \frac{m_{h_{\rm SM}^2}}{m_H^2}\right) \frac{m_p}{v} \left(\sum_{q=u,d,s} f_{Tq} + \frac{2}{9}\, f_{TG} \right)$$
$$+ \frac{m_p}{m_q} \left(\mathcal{C}_{\rm tree} \sum_{q=u,d,s} f_{Tq} + \mathcal{C}_{\rm box}\, f_{TG} \right) \frac{g_{\tilde{q}}^2}{m_{\tilde{q}}^2 - m_\chi^2}$$

the condition for the blind spot:

$$y_\chi \approx - \left(\frac{2.05 \times 10^7 \ {\rm GeV}^2}{m_{\tilde{q}}^2 - m_\chi^2} \right) \frac{g_{\tilde{q}}^2}{\sin 2\theta \ \left(1 - \frac{m_{h_{\rm SM}}^2}{m_H^2} \right)} \ .$$

Model 2: Cross section for squark production



- Cross section for squark production through t-channel DM exchange at the LHC.
- Solid black line shows the cross section for strong squark production.
- The cross sections for strong and t-channel DM exchange production of the squarks become of equal size when $g_{\tilde{q}} \approx 0.9$

Model 3: combining $\mathbf{Z'}$ and squarks

- One needs two fermion SM singlet DM candidates, ξ and ζ, such that ξ is coupled to the Z' and ζ is coupled to the squarks. The symmetry is conserved if the fields are charged under $U(1)_X$ according to :

	Ψ	ξ	ζ	q_i	$\tilde{q}_{i,L/R}$
$U(1)_X$ charge	$+1$	$+1$	0	$+1$	$+1$

- The low energy Lagrangian can contain the additional terms,

$$\mathcal{L} \supset y_1 \Psi \bar{\xi}\zeta + \frac{1}{2} m_\xi \bar{\xi}\xi + \frac{1}{2} m_\zeta \bar{\zeta}\zeta + \text{ h.c.}$$

where Ψ is the field that breaks $U(1)_X$ when it gets a vev $\Psi \to v_\Psi + \psi$, with ψ a decoupled physical scalar.

- After the symmetry is broken, ξ and ζ mix giving rise to two mass eigenstates: χ_1 and χ_2 which, if we assume $m_\xi, m_\zeta \ll y_1 v_\Psi$, are almost mass degenerate with a mass $m_\chi = y_1 v_\Psi$ and maximal mixing.
- Despite being apparently rather involved, the phenomenological LSMS is characterized by only 6 free parameters, $\left\{ m_\chi, m_{\tilde{q}}, m_{Z'}, g_\chi^V, g_q^V, g_{\tilde{q}} \right\}$.