Improving limits on a Simplified Model of Dark Matter

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With
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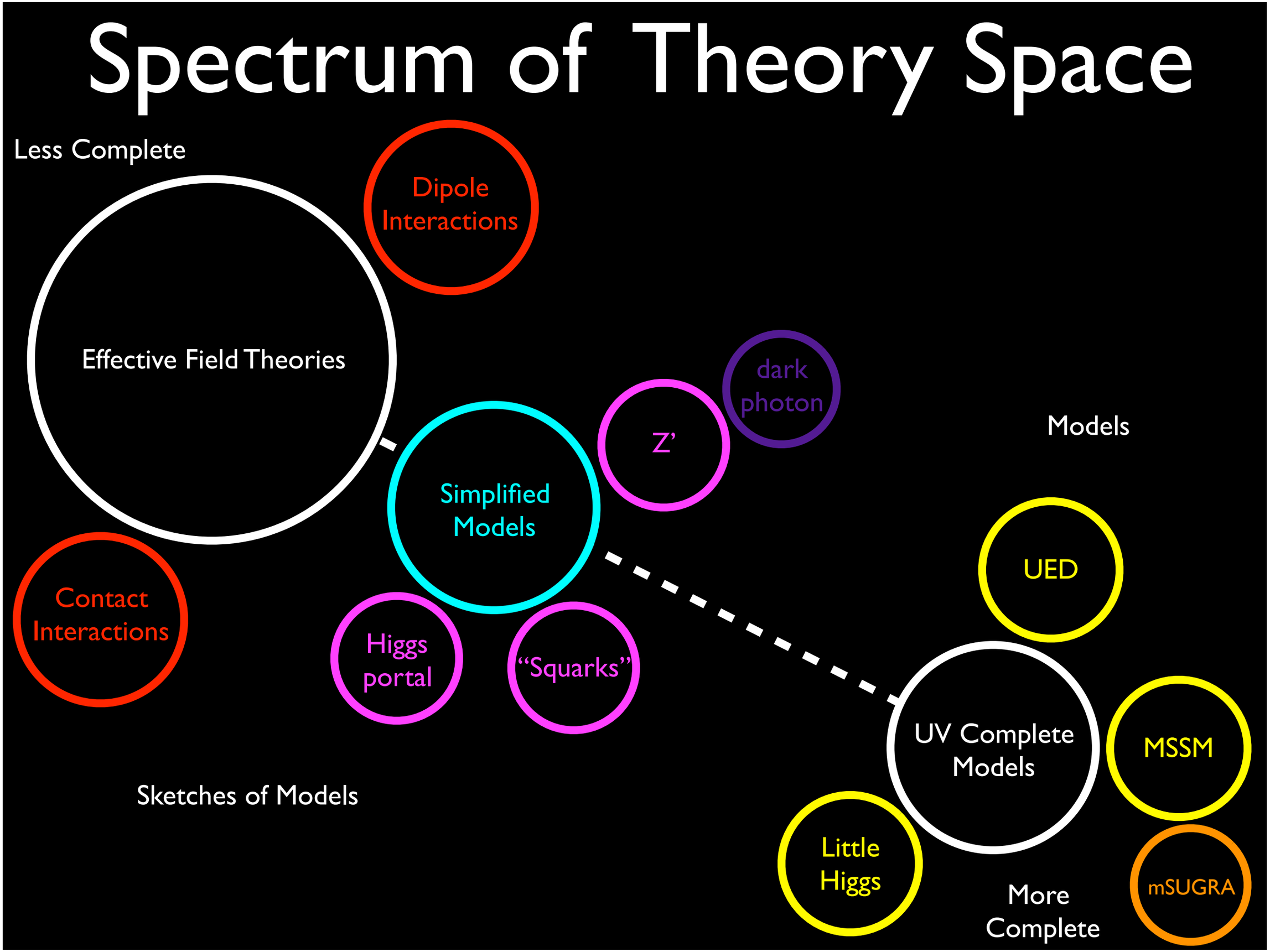
Why a Simplified Model?

- Many models feature a Dark Matter candidate.
- Many models; many parameters; difficult drawing general conclusions.
- An EFT approach is very general and could cover all models; Validity of EFT at large momentum transfer? Not UV complete. Limitations when comparing between experiments that operate at different energy scales.
- Simplified model — A UV complete theory (not necessarily simplification of a more complete/complicated theory). Captures essential features of classes of models.



From Tim Tait

Outline

- Objective: Take a Simplified model and calculate everything with better precision.
- Direct Detection constraints @ 1-loop.
- Include Renormalization Group Evolution effects.
- LHC constraints @NLO.
- Understand importance of improving precision. <u>Is it worth the effort</u>?

A Simplified Model

- Construction—Inspired by more complete models, consider models that contain dark matter as well as the most important mediator(s).

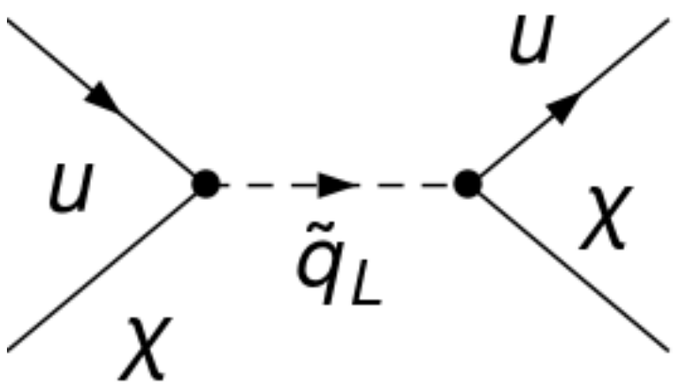
- Example—Consider a class of models in which dark matter interacts with quarks through colored scalar mediators—looks like the MSSM, but simpler with <u>three parameters</u>; dark matter mass, mediator mass, coupling strength.

$$\boxed{\{M_\chi, M_{\tilde{q}_L}, g_{DM}\}} \qquad \mathcal{L}_{int} = \sum_{q=u,d,s,c,b,t} g_{DM} \left(\tilde{q}_L^* \bar{\chi} P_L q + h.c.\right)$$

- Dark matter can be Dirac or <u>Majorana</u> fermion.

A. DiFranzo, K. Nagao, A. Rajaraman, T. Tait 2013

Direct Detection



$$\mathcal{M}_{DD} \approx \frac{i g_{DM}^2}{M_{\tilde{q}_L}^2 - M_\chi^2} \frac{1}{8} [(\bar{\chi}\gamma^\mu\chi)(\bar{u}\gamma_\mu u) - (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{u}\gamma_\mu\gamma_5 u)]$$

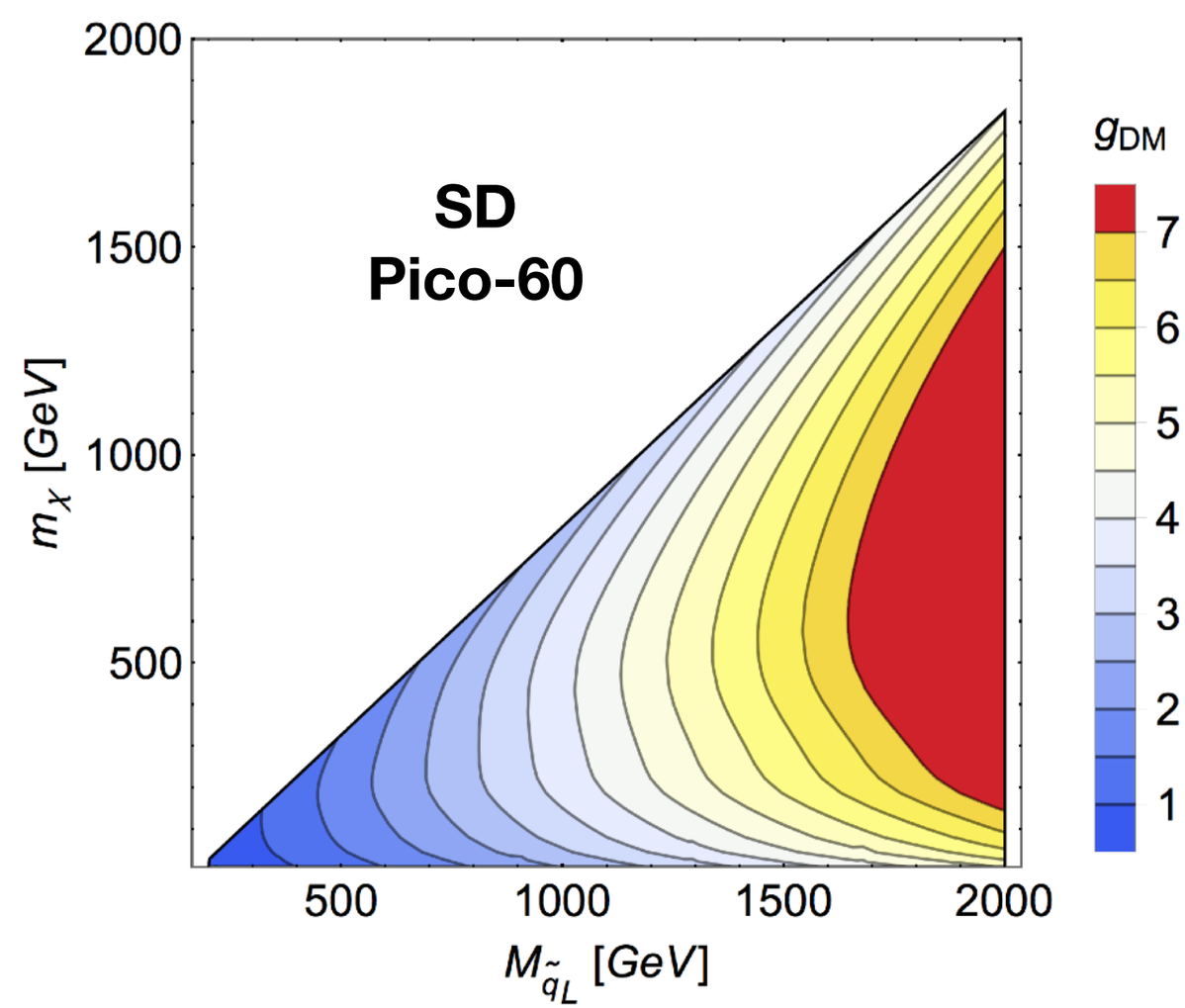
SI — **0 for Majorana**

SD

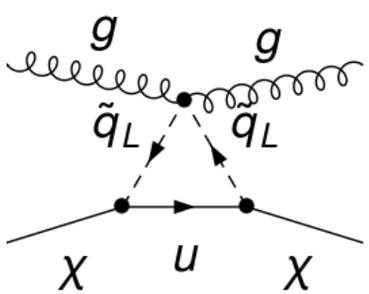
$$\sigma_p = \frac{4}{\pi}\left(\frac{M_\chi m_p}{M_\chi + m_p}\right)^2 |\langle \mathcal{M}_{DD}\rangle_{NR}|^2 \ .$$

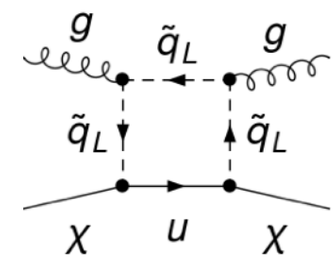
- Tree level calculation tells us that model has <u>only</u> a spin dependent cross-section.

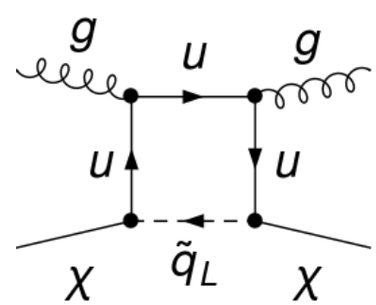
- Limits from direct detection are weak—large values of g_{DM} allowed.



DD @ 1-Loop







Determine Wilson Coefficients for effective operators

$$\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2}\bar{q}i\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{D}\right)q$$
$$\mathcal{O}^g_{\mu\nu} \equiv \left(G^{a\rho}_\mu G^a_{\rho\nu} + \frac{1}{4}g_{\mu\nu}G^a_{\alpha\beta}G^{a\alpha\beta}\right) .$$

Spin-2 Operators

$$\mathcal{L}^{\rm eff}_q = \boxed{f_q m_q\ \bar{\tilde{\chi}}\tilde{\chi}\ \bar{q}q} + \frac{g_q^{(1)}}{m_\chi}\ \bar{\tilde{\chi}}i\partial^\mu\gamma^\nu\tilde{\chi}\ \mathcal{O}^q_{\mu\nu} + \frac{g_q^{(2)}}{m_\chi^2}\ \bar{\tilde{\chi}}(i\partial^\mu)(i\partial^\nu)\tilde{\chi}\ \mathcal{O}^q_{\mu\nu}\ ,$$
$$\mathcal{L}^{\rm eff}_g = \boxed{f_G\ \bar{\tilde{\chi}}\tilde{\chi}G^a_{\mu\nu}G^{a\mu\nu}} + \frac{g_G^{(1)}}{m_\chi}\ \bar{\tilde{\chi}}i\partial^\mu\gamma^\nu\tilde{\chi}\ \mathcal{O}^g_{\mu\nu} + \frac{g_G^{(2)}}{m_\chi^2}\ \bar{\tilde{\chi}}(i\partial^\mu)(i\partial^\nu)\tilde{\chi}\ \mathcal{O}^g_{\mu\nu}\ .$$

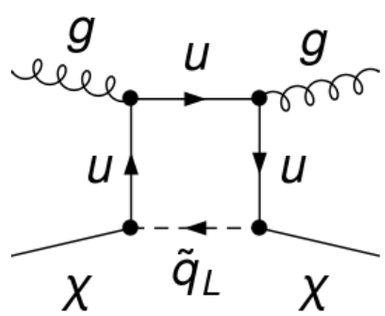
Spin 0
Dimension 6

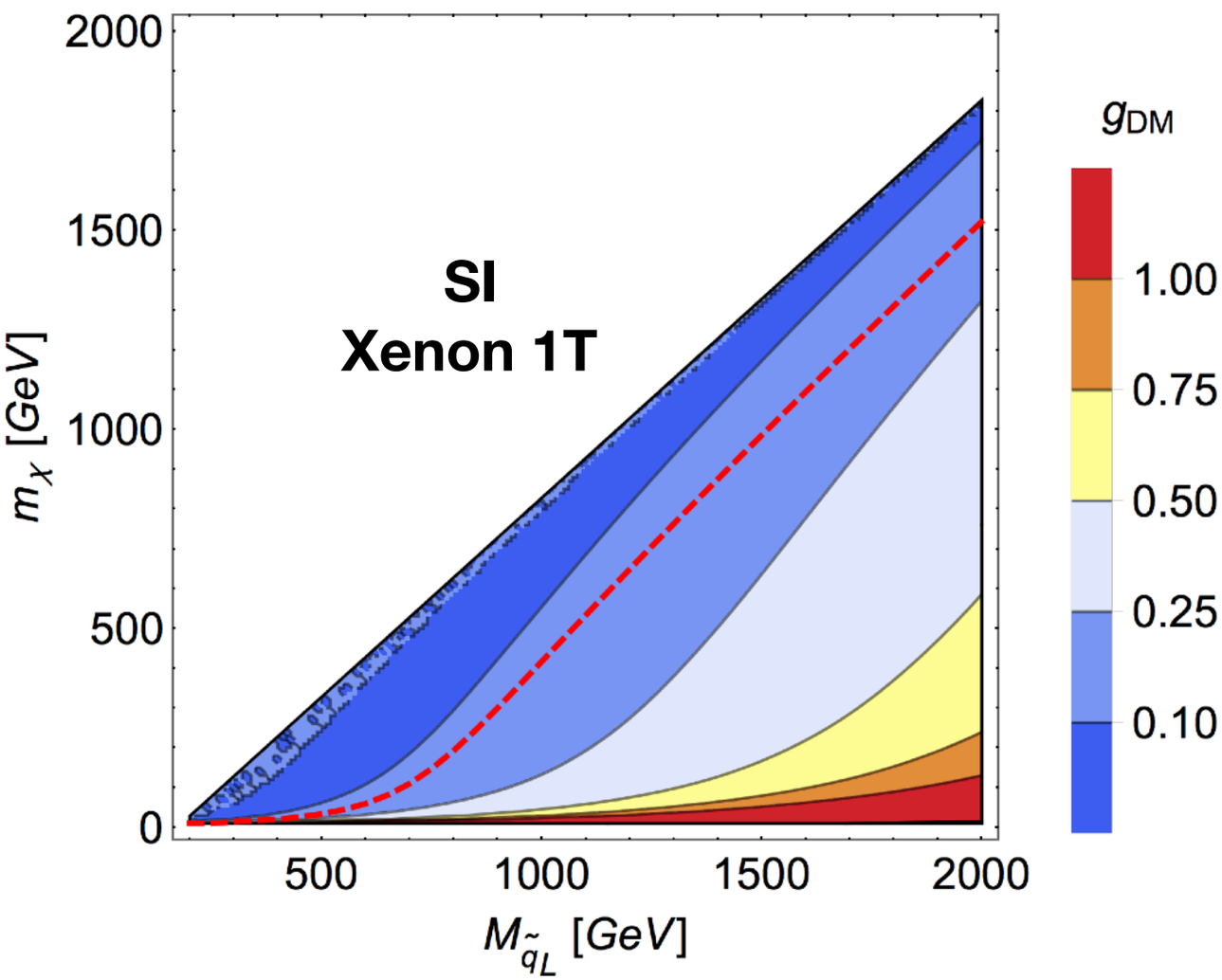
Evaluate matrix element for the elastic scattering process in the non-relativistic limit.

$$f_N/m_N = \sum_{q=u,d,s} f_q f_{Tq} + \sum_{q=u,d,s,c,b} \frac{3}{4}\left(q(2)+\bar{q}(2)\right)\left(g_q^{(1)}+g_q^{(2)}\right) - \frac{8\pi}{9\alpha_s}f_{TG}f_G + \frac{3}{4}G(2)\left(g_G^{(1)}+g_G^{(2)}\right)\ .$$

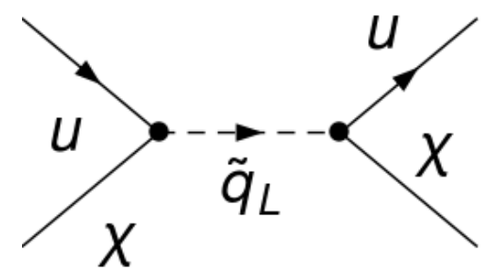
Tools: FeynArts, FORM, PackageX

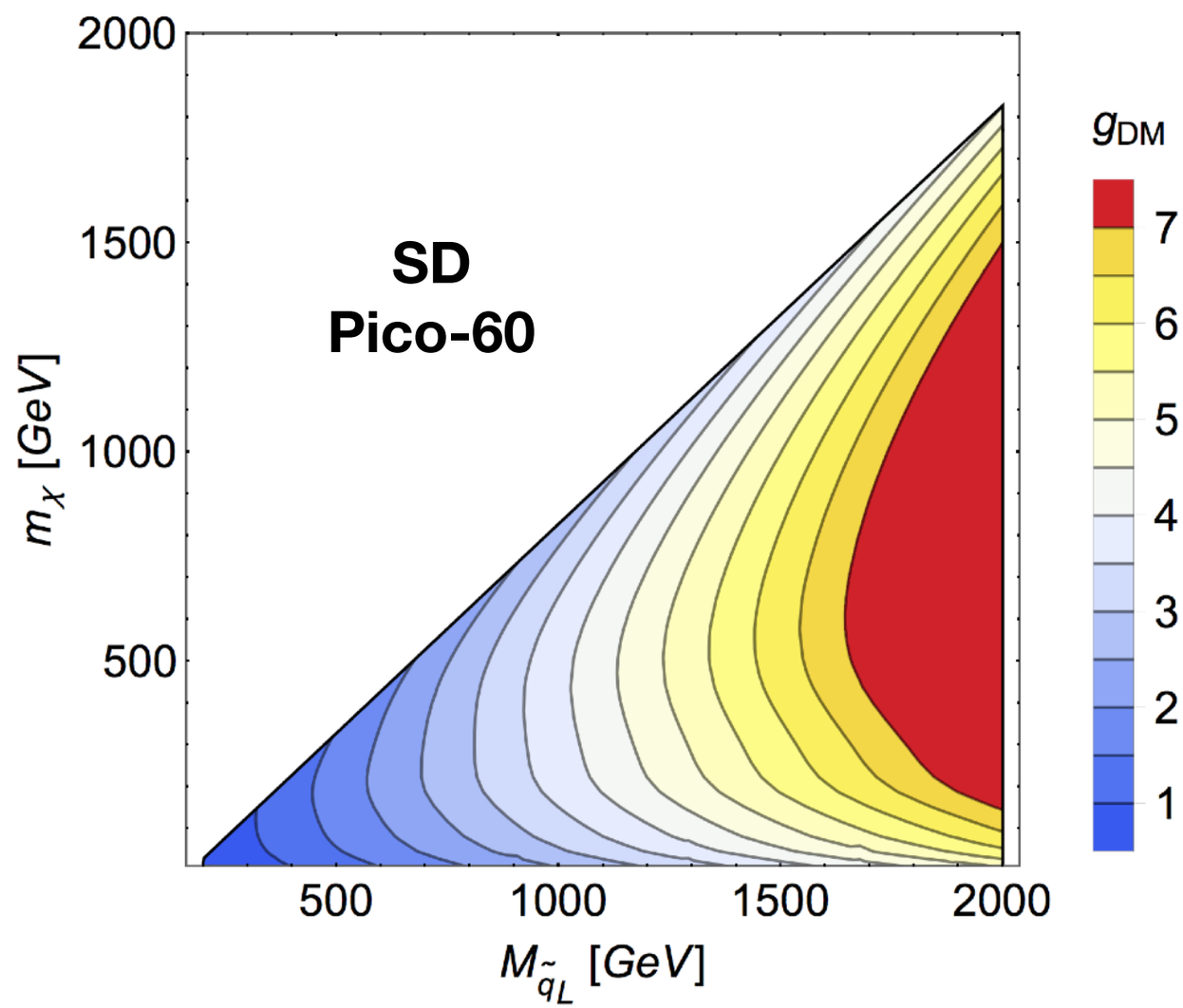
SI Limits (Loop)





SD Limits (Tree)





Constraints improve by an order of magnitude.

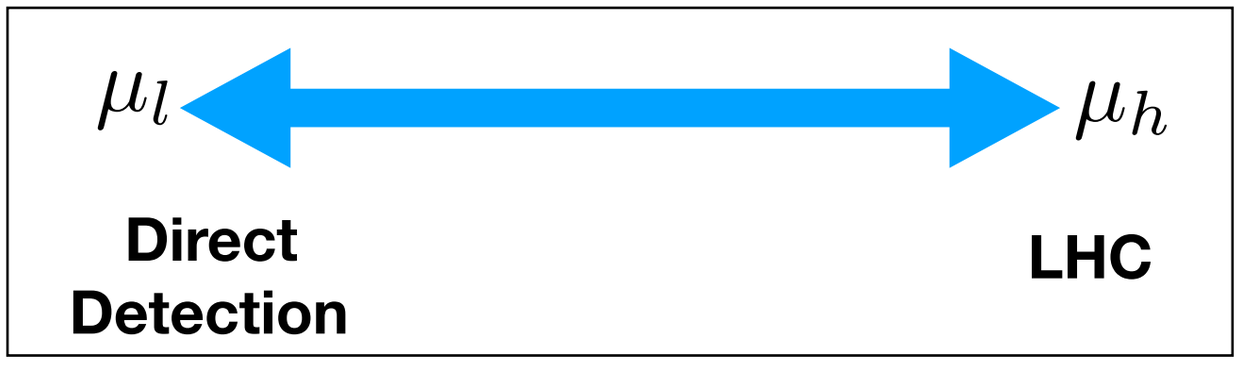
RGE of Wilson Coefficients

- Nucleon DM cross-sections at Non-Relativistic velocities.
- At what scale do we define coupling and masses? If at scale μ~0, then to compare with LHC we should run up. If at μ~LHC energy, then to compare we should run down.
- RGE not necessary if no comparisons being made at different energy scales.

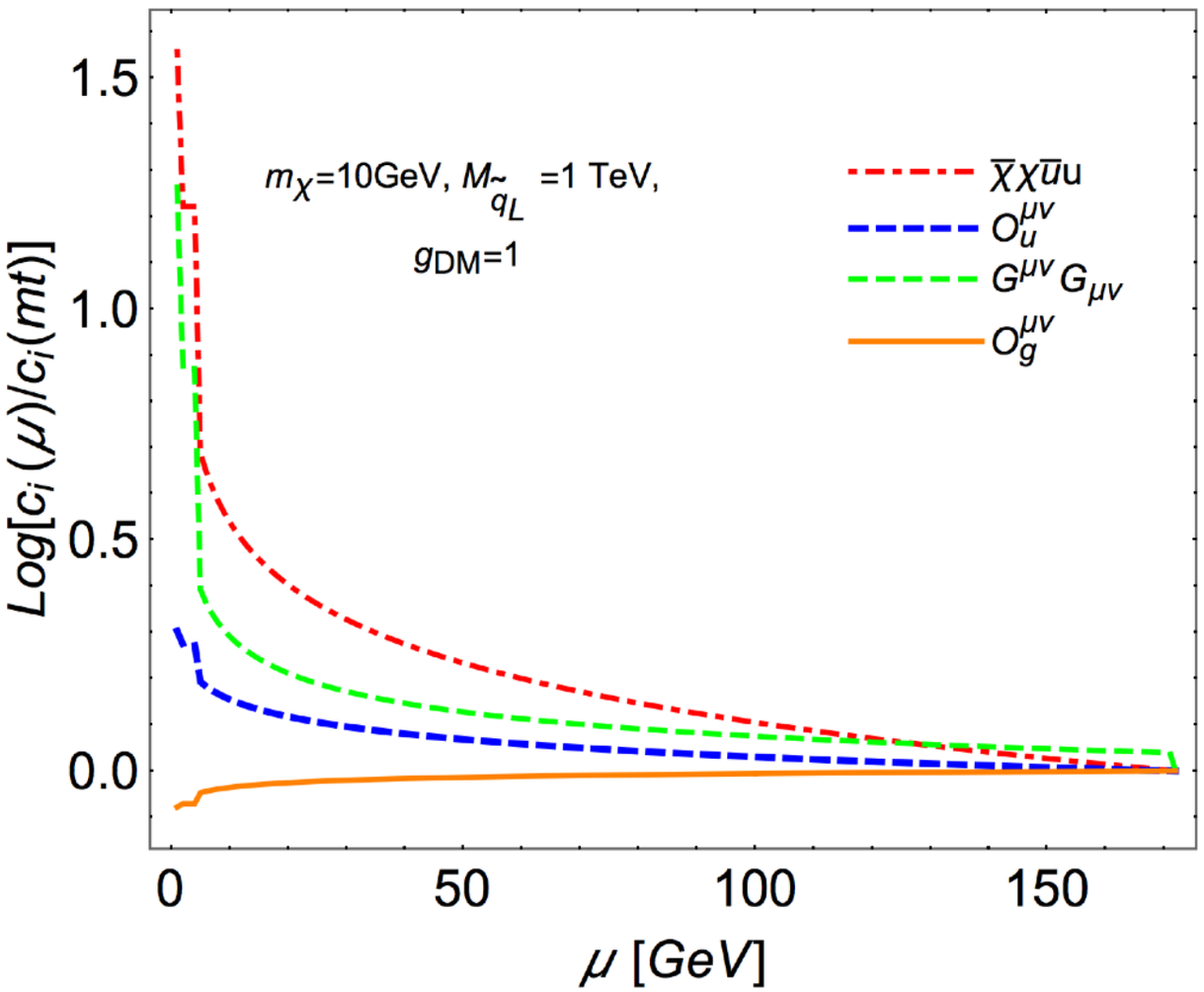
$$c_i(\mu_l) = R_{ij}(\mu_l, \mu_h) c_j(\mu_h) \ .$$

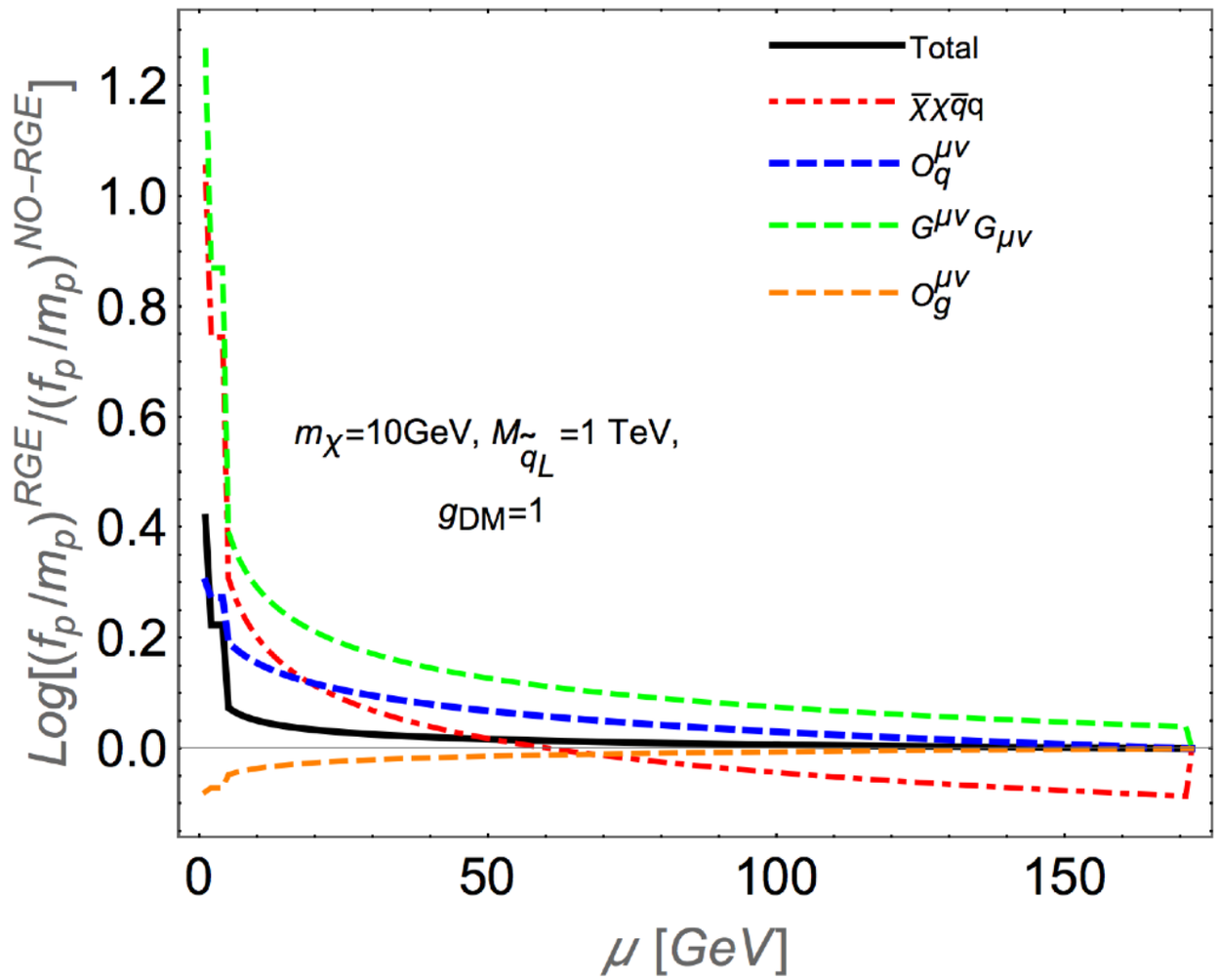
$$c_i(\mu_Q) = M_{ij}(\mu_Q) c'_j(\mu_Q)$$

R. Hill, M. Solon 2014



How important is RGE?





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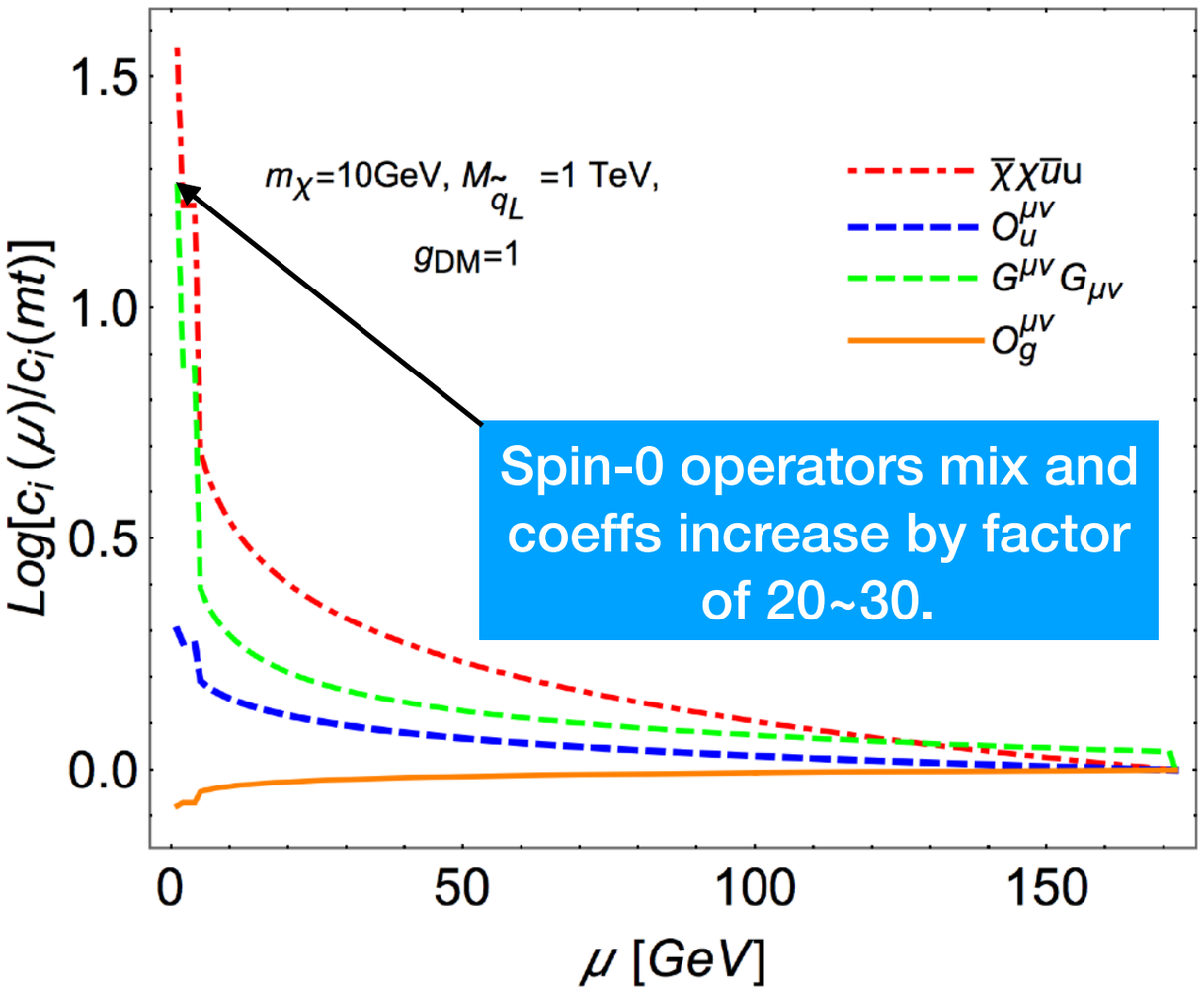

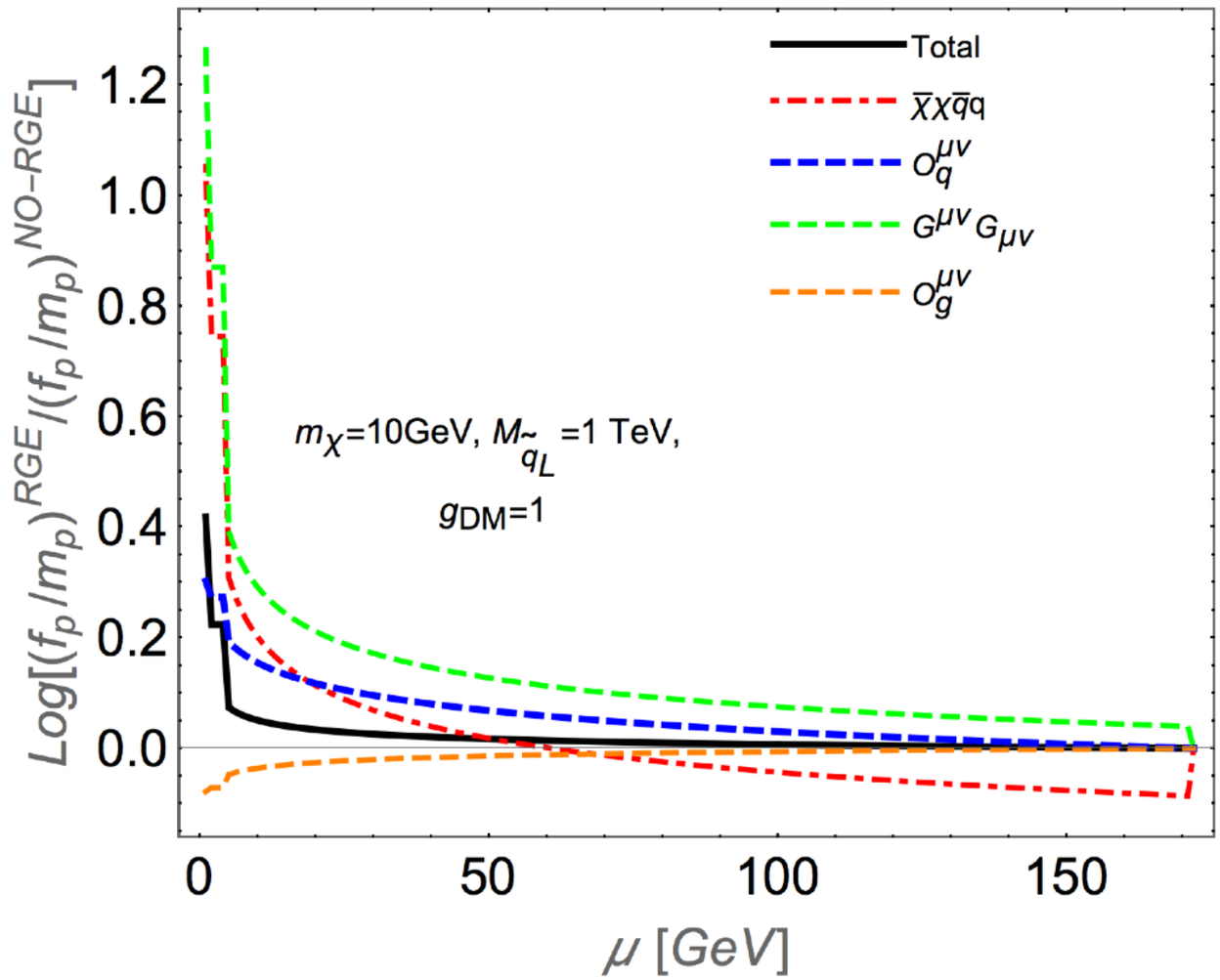

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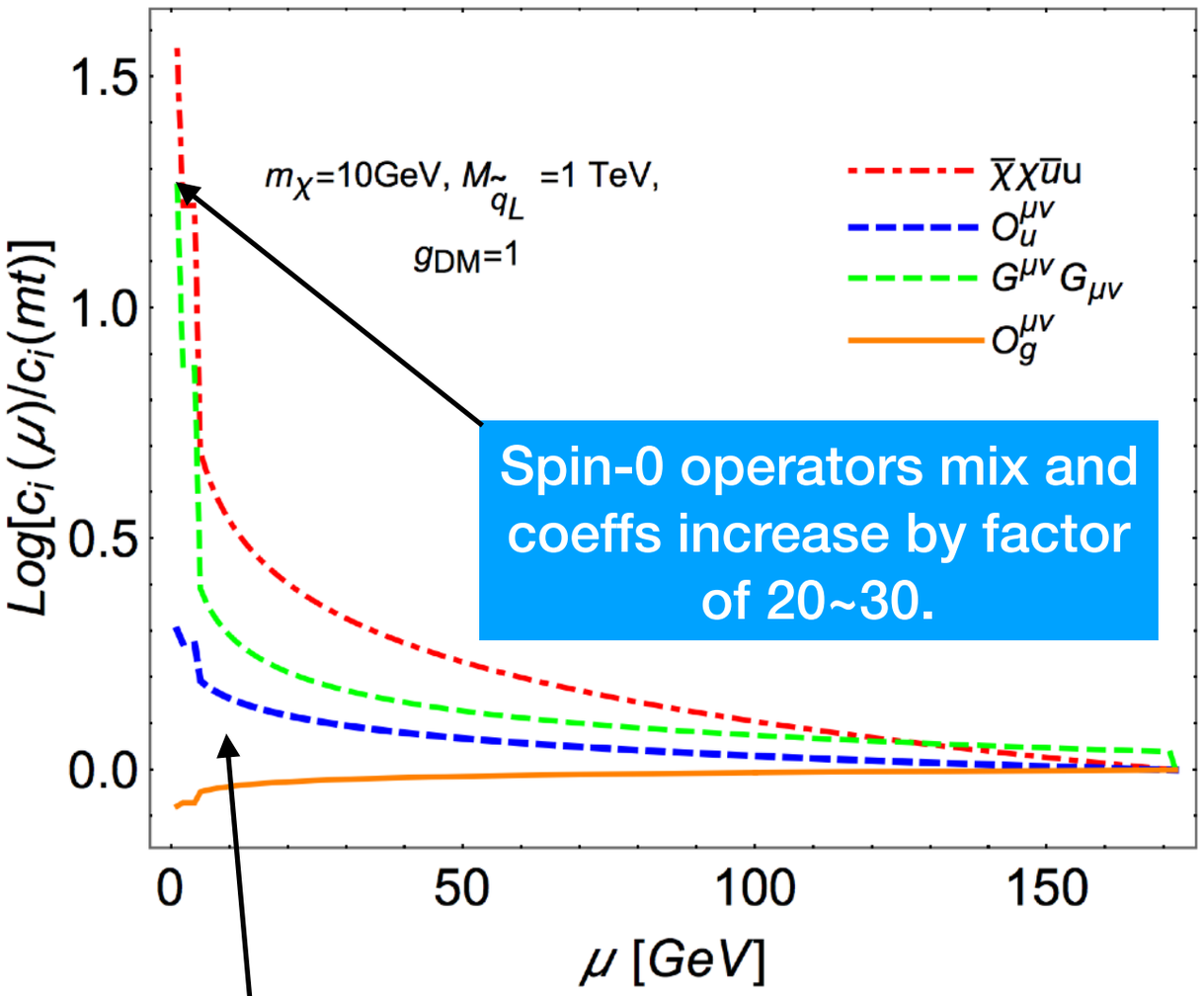
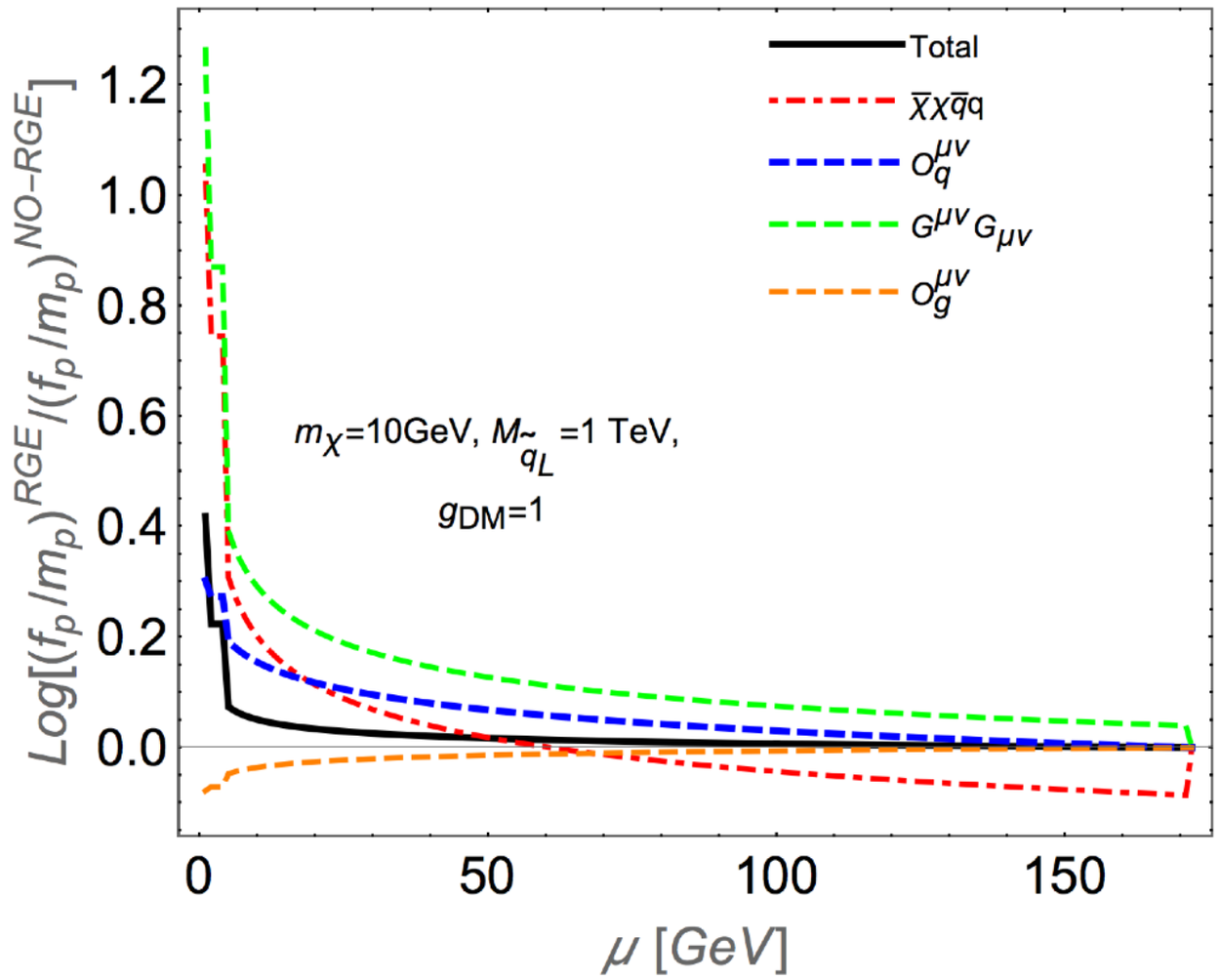


Spin-0 operators mix and coeffs increase by factor of 20~30.

Spin-2 Wilson coefficients do not run as strongly.



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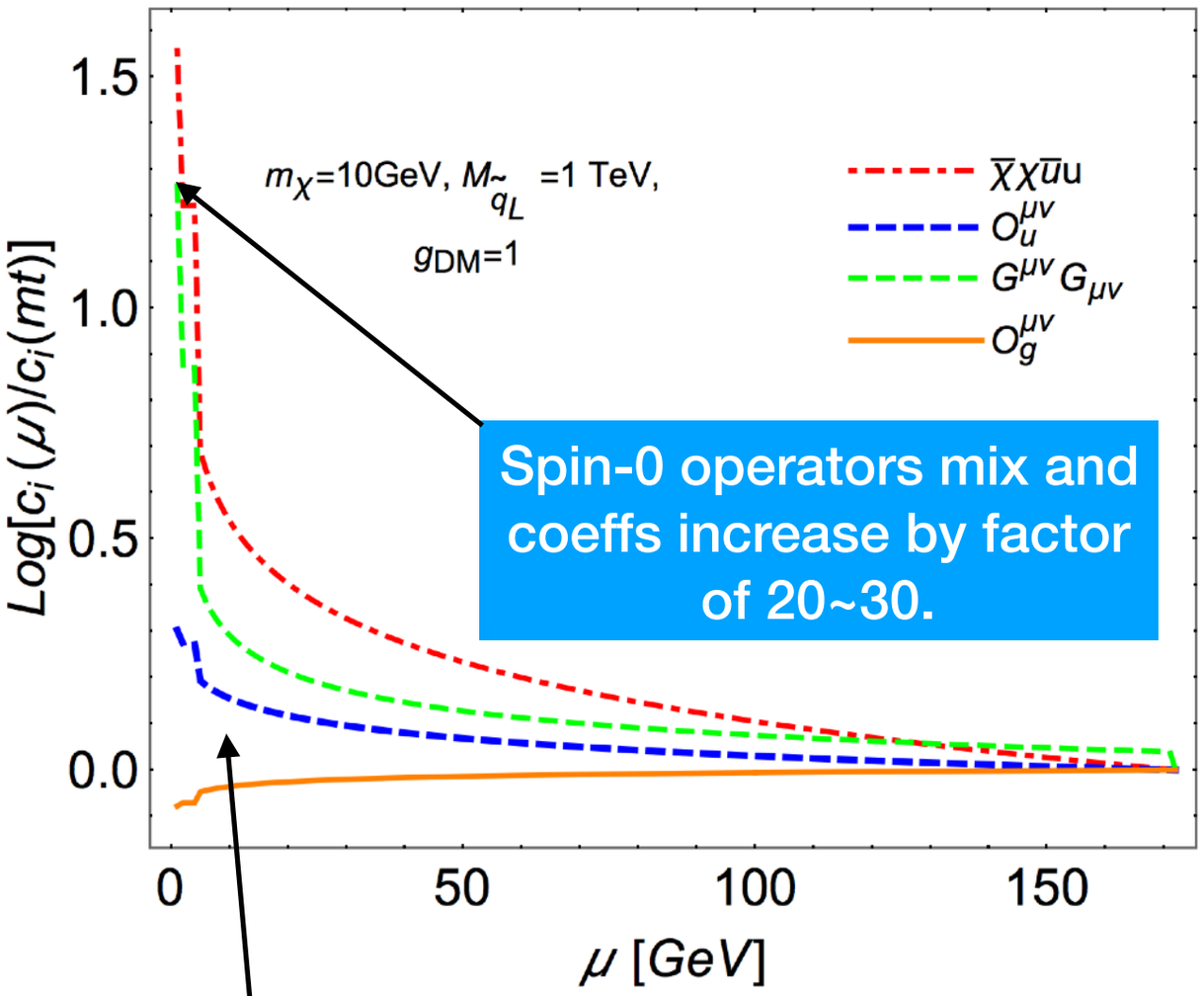

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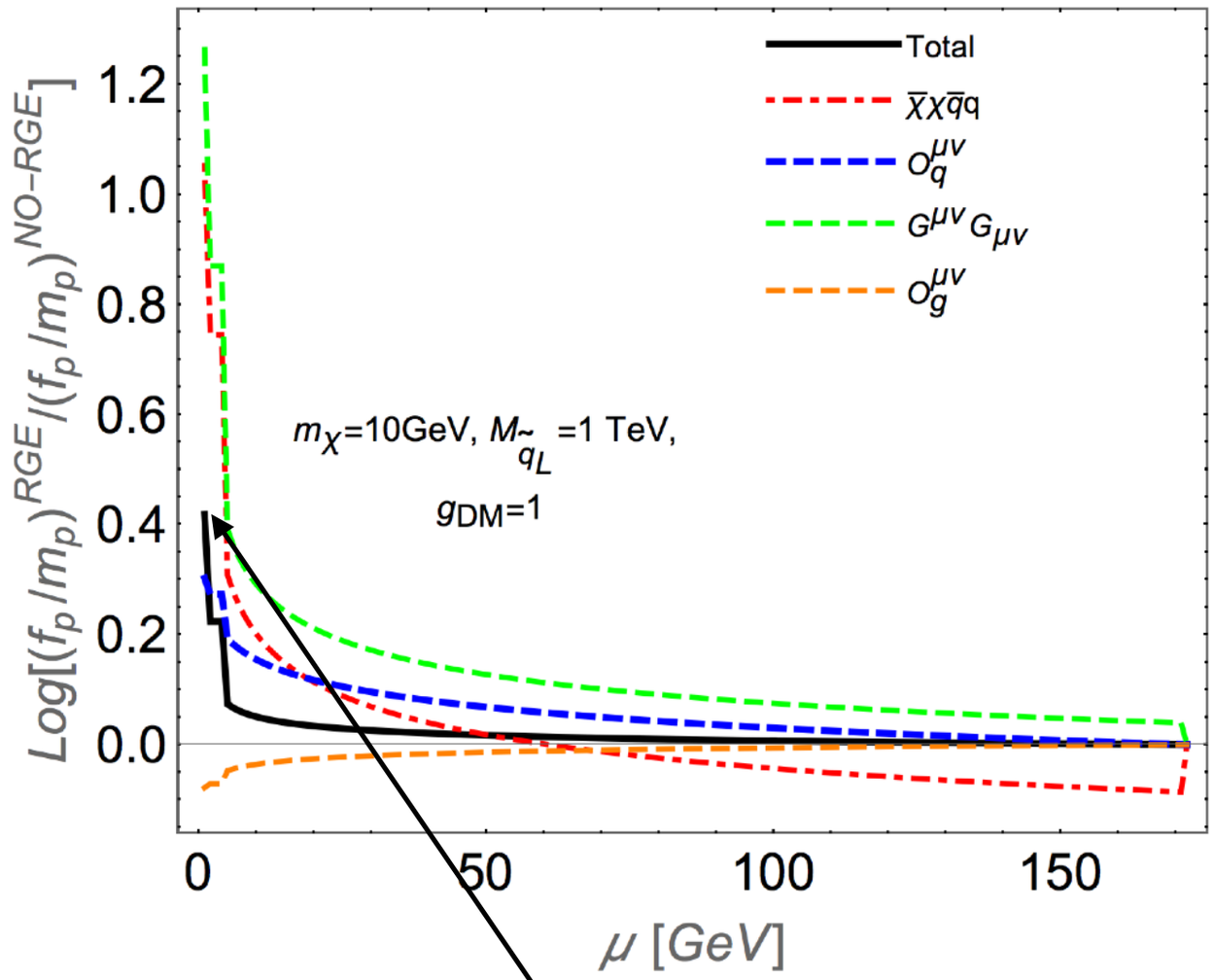
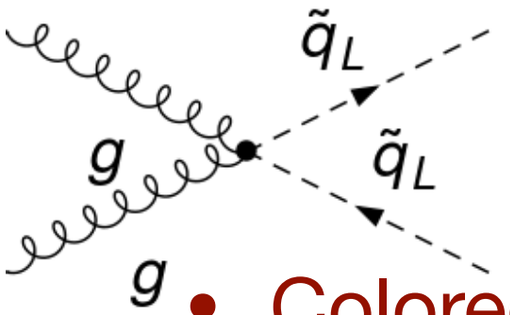


Factor 2~3 increase in matrix element when performing RGE.

Factor 4-9 enhancement in cross-section

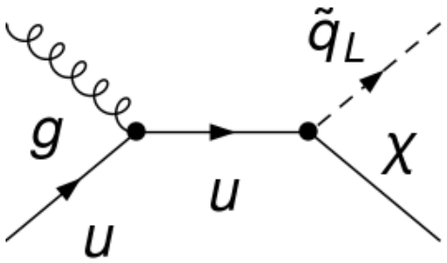
LHC Constraints

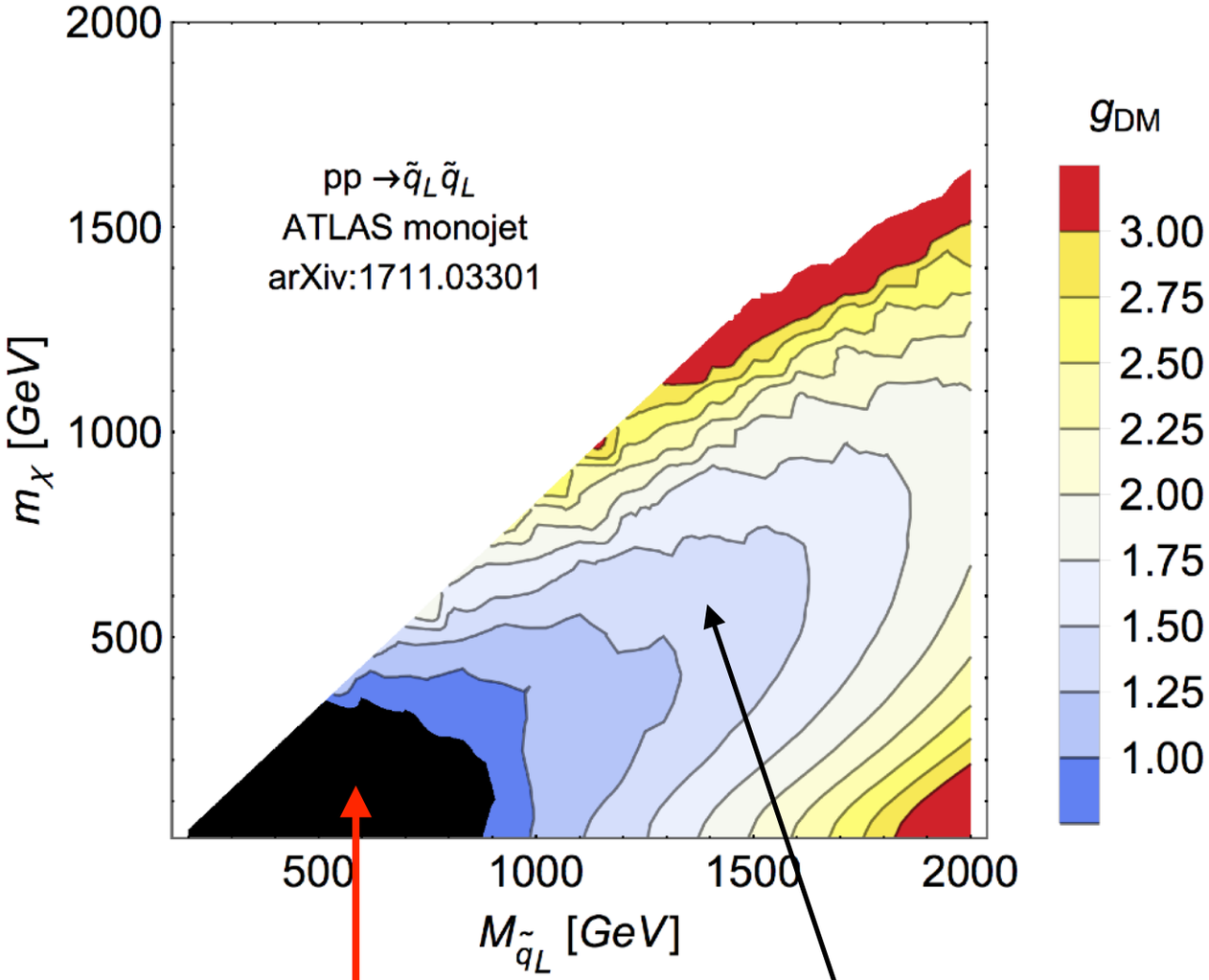


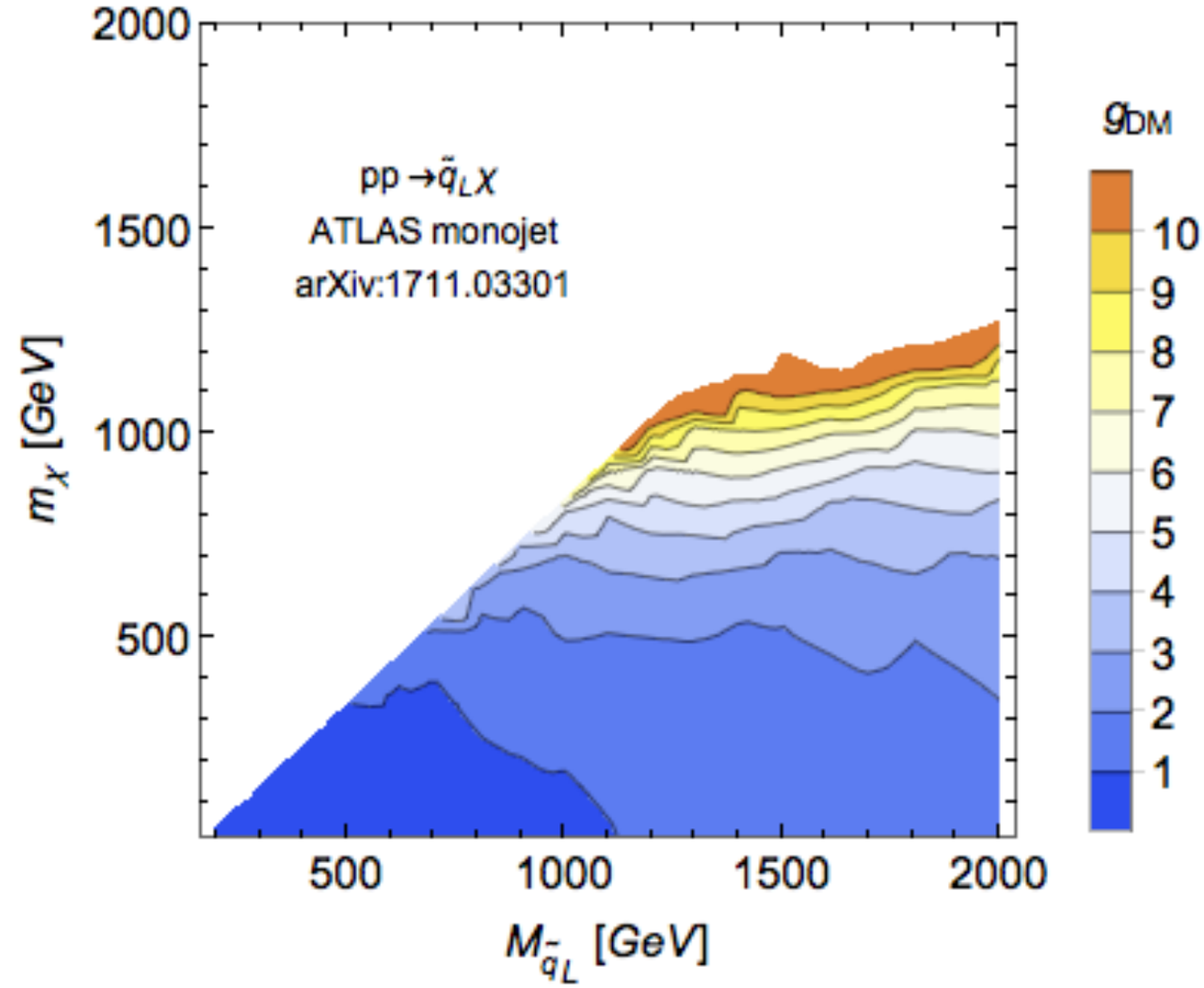
- Colored scalar mediator pair production— production cross-section (mostly QCD) depends on mass of mediator alone.

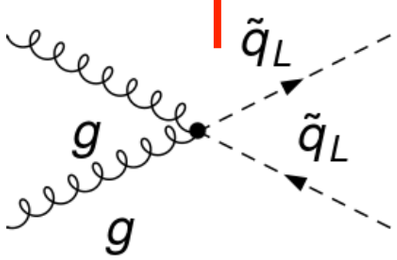
- Acceptance depends on mass of dark matter candidate also.

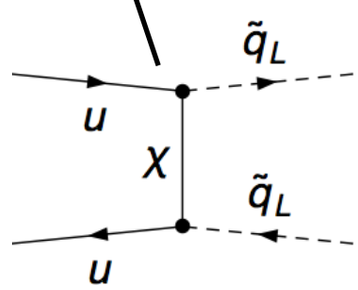
- Associated production of colored mediator and dark matter candidate— depends on all three model parameters.

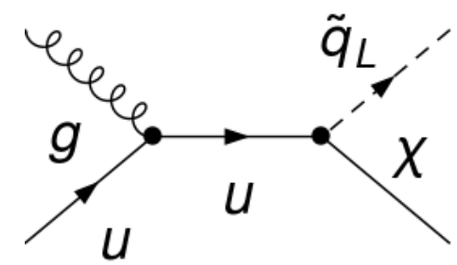








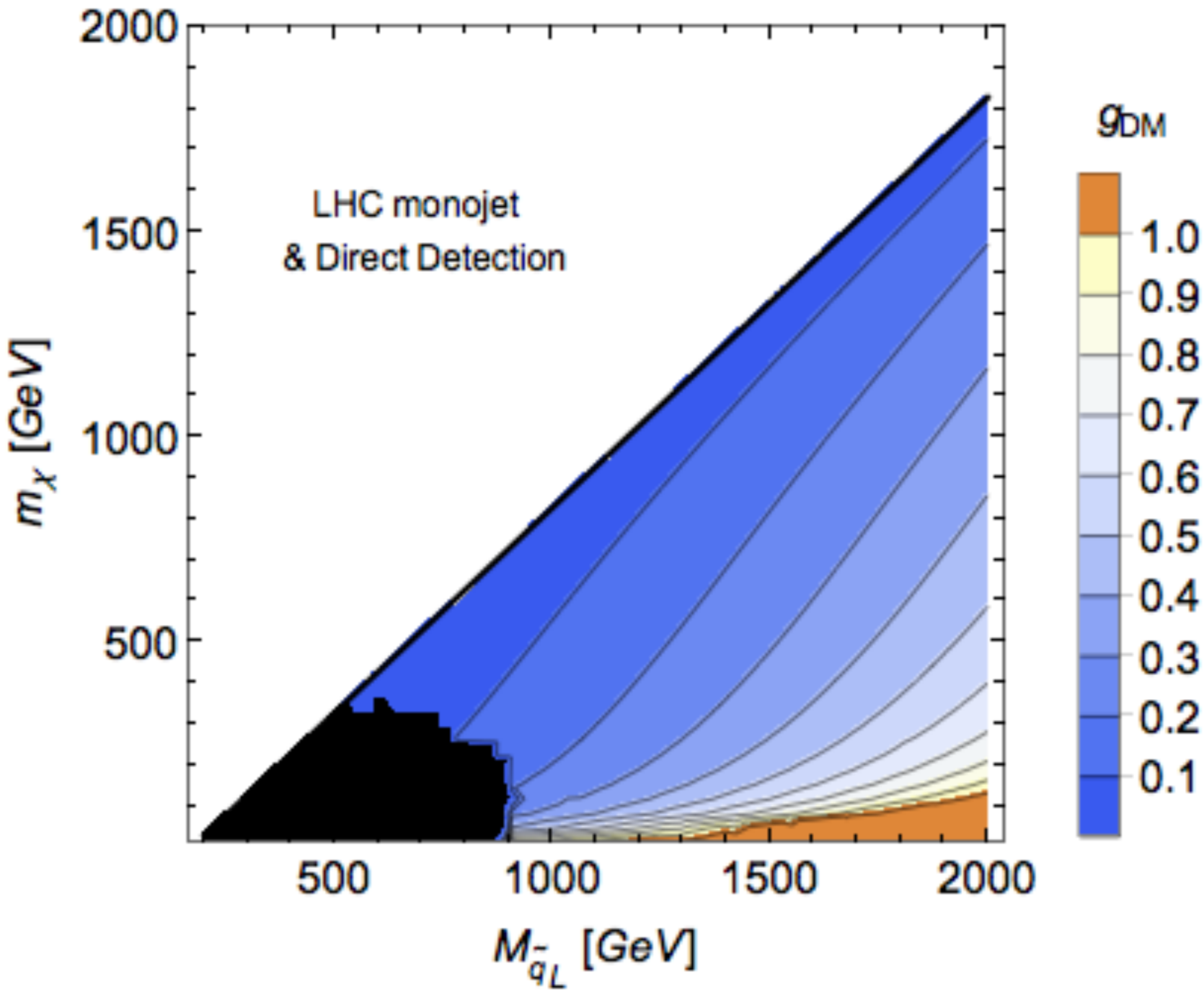




Pure QCD
Independent of
DM coupling (g_{DM})

Tools : FeynRules, NLOCT, MadGraph5_aMC@NLO, MadAnalysis5

Complementarity of DD & LHC experiments



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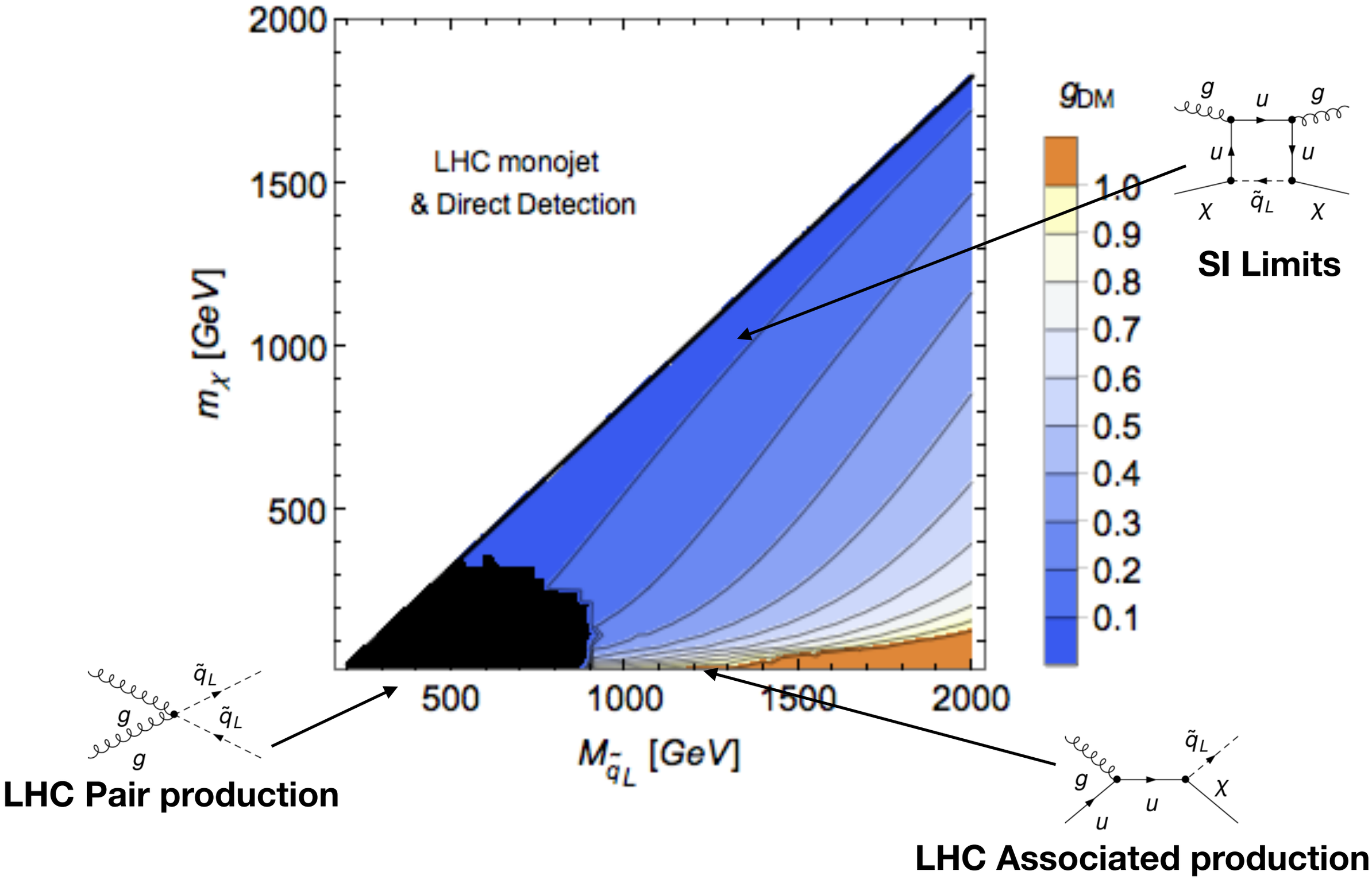

Conclusions

- Simplified models— useful to capture essential features of classes of models; one can make generic statements.
- Can easily evaluate LHC constraints @ NLO precision.
- Demonstrated importance of going beyond LO for determining direct-detection constraints (order of magnitude increase).
- Demonstrated importance of RGE effects (factor 7 increase).
- Able to make proper comparison between experiments that operate at different energy scales.