Direct Detection and LHC constraints on a t -Channel Simplified Model of Majorana Dark Matter at One Loop

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Outline

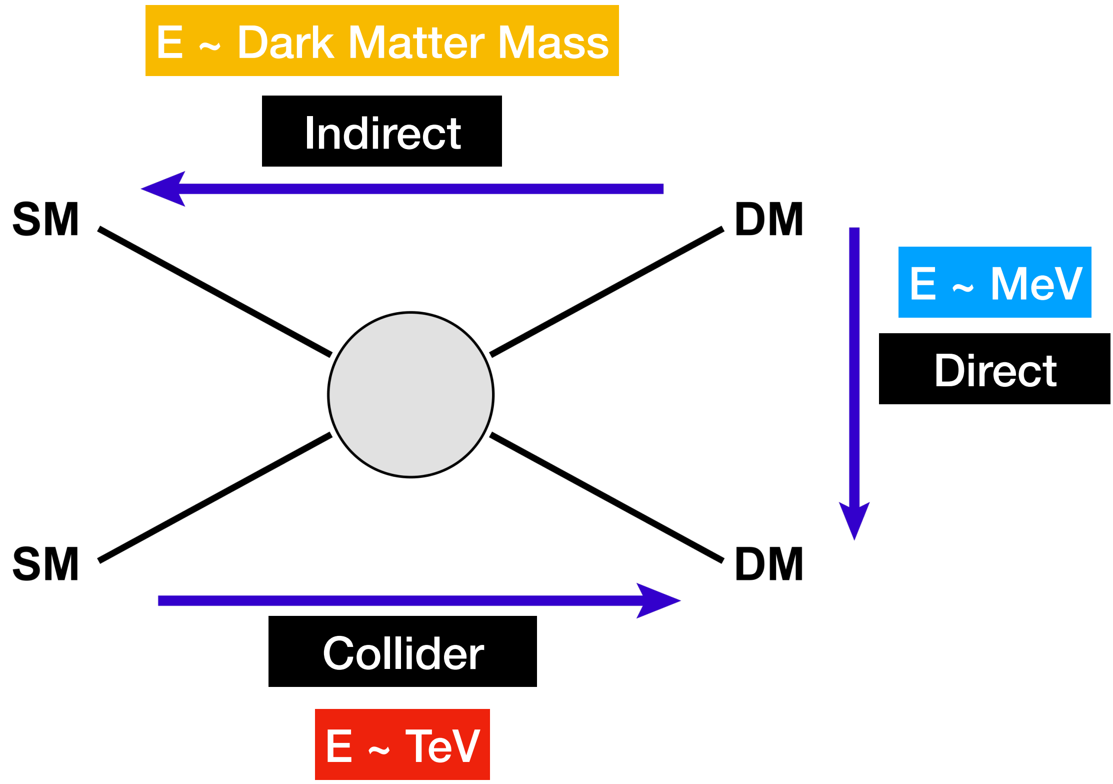
- Objective: Take a Simplified model and calculate everything with better precision.

- Direct Detection constraints @ 1-loop.

- Include Renormalization Group Evolution effects.

- LHC constraints @NLO.

- Understand importance of improving precision. Is it worth the effort?



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 three parameters; 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 Majorana fermion.

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

The Lagrangians

- Colored scalar mediators interact with quarks and singlet dark matter.
- Three possible charges— corresponding to three possible models (u_R, d_R, q_L).
- Motivated by MFV we set all masses and couplings equal.

$$\mathcal{L}_{FV} = \left(\delta g_{DM}\ \tilde{u}^* Y^{u\dagger} Y^u \bar{\chi} P_R u + h.c.\right) + \delta m^2\ \tilde{u}^* Y^{u\dagger} Y^u \tilde{u} + \mathcal{O}(Y^4)$$

$$(3,1)_{2/3}$$

$$\mathcal{L}_{u_R} \supset \sum_{u=u,c,t} \left[(D_\mu \tilde{u})^* (D^\mu \tilde{u}) - M_{\tilde{u}}^2 \tilde{u}^* \tilde{u} + g_{DM} (\tilde{u}^* \bar{\chi} P_R u + \bar{u} P_L \chi)\right]$$

$$(3,1)_{-1/3}$$

$$\mathcal{L}_{d_R} \supset \sum_{d=d,s,b} \left[(D_\mu \tilde{d})^* (D^\mu \tilde{d}) - M_{\tilde{d}}^2 \tilde{d}^* \tilde{u} + g_{DM} (\tilde{d}^* \bar{\chi} P_R d + \bar{d} P_L \chi)\right]$$

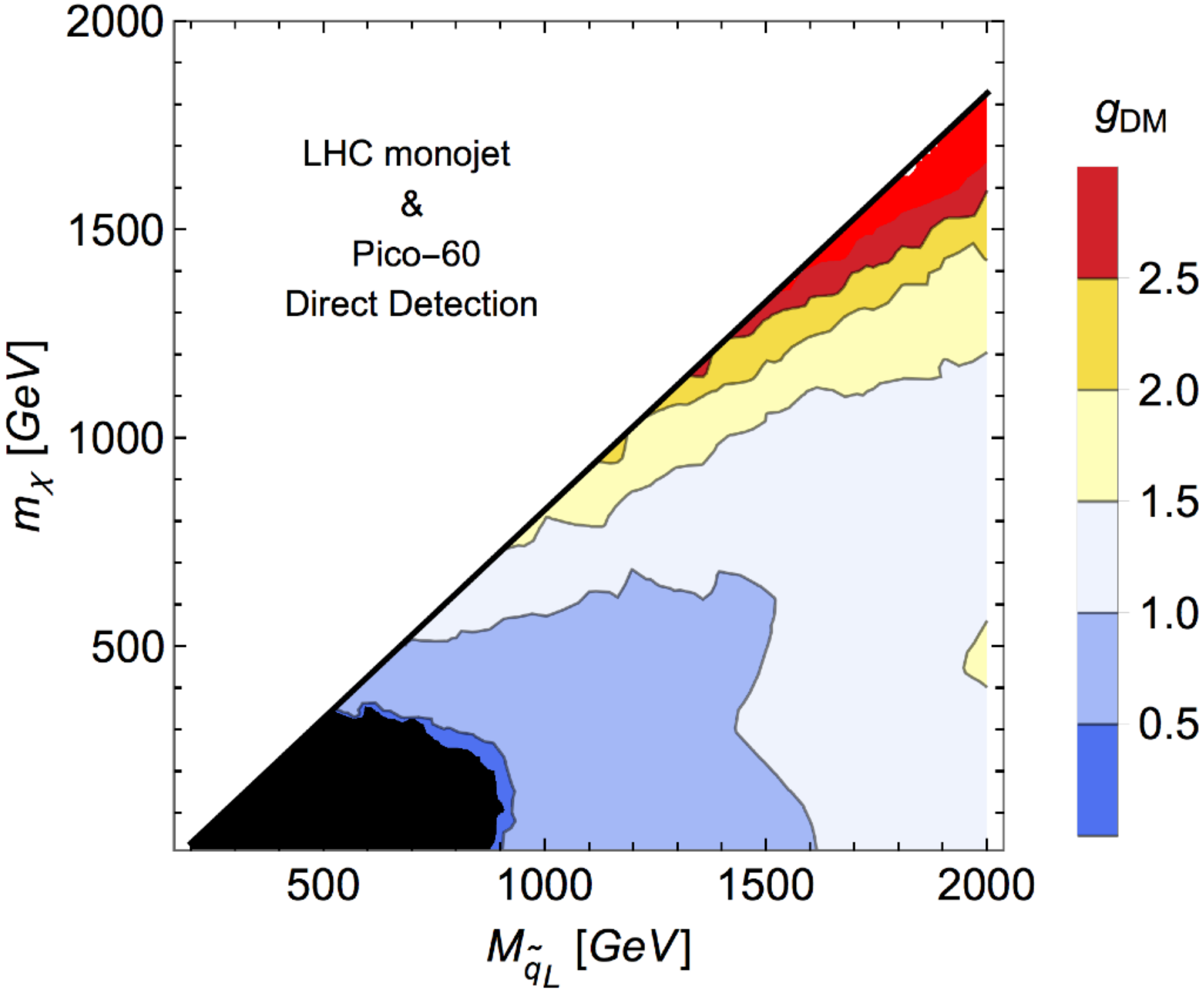
$$(3,2)_{-1/6}$$

$$\mathcal{L}_{q_L} \supset \sum_{q=u,c,t,d,s,b} \left[(D_\mu \tilde{q})^* (D^\mu \tilde{q}) - M_{\tilde{q}}^2 \tilde{q}^* \tilde{u} + g_{DM} (\tilde{q}^* \bar{\chi} P_L q + \bar{q} P_R \chi)\right]$$

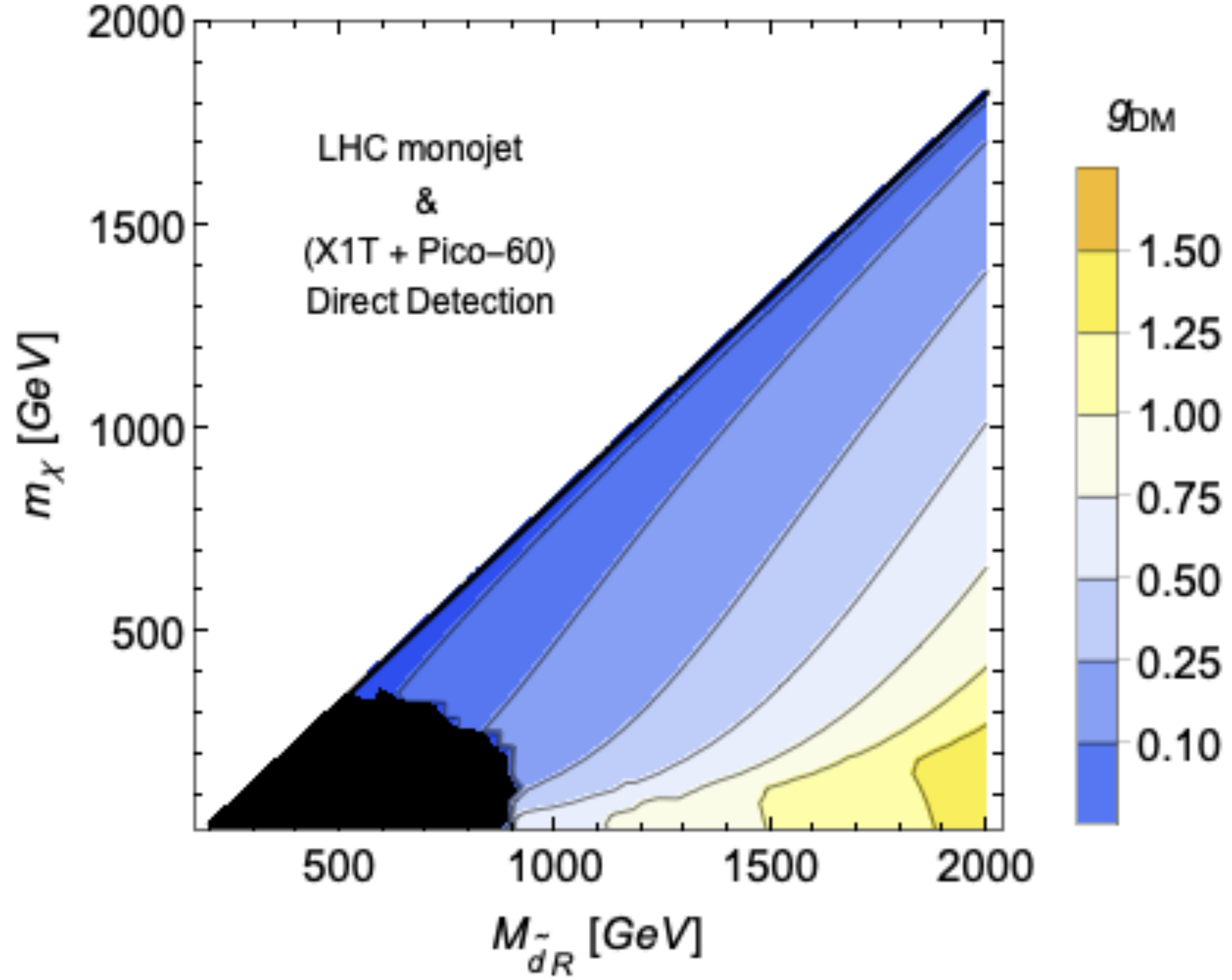
Rest of this talk— We will look at q_L model with majorana fermions.

Before we dive into the details...

Leading Order Constraints



Improved Constraints



Constraints Dominated by LHC

Constraints Dominated by SI Direct Detection

Constraints improve by an order of magnitude in some places.

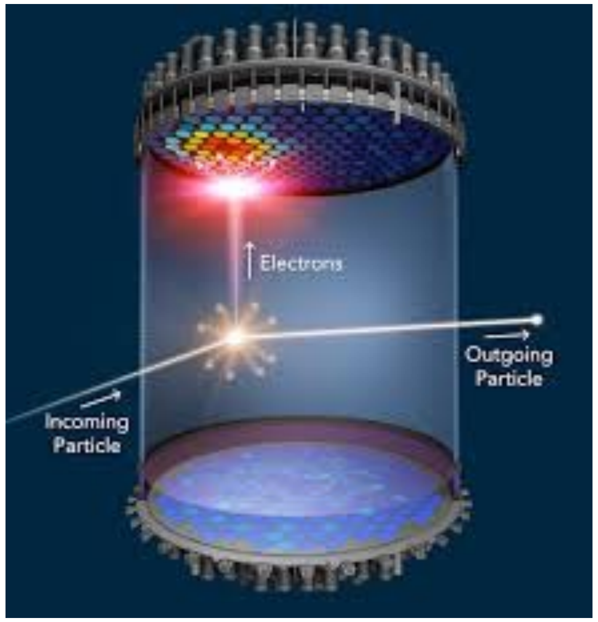
Direct Detection 101

Look for elastic scattering of WIMPS with nuclei.

$$\frac{d\sigma}{dE} = \frac{m_A}{2\mu_A^2 v^2} \cdot (\sigma_0^{\rm SI} \cdot F_{\rm SI}^2(E) + \sigma_0^{\rm SD} \cdot F_{\rm SD}^2(E))$$

$$\sigma_0^{\rm SI} = \sigma_p \cdot \frac{\mu_A^2}{\mu_p^2} \cdot [Z \cdot f^p + (A-Z) \cdot f^n]^2$$

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



Source: KIPAC

$$\langle N|m_q\bar{q}q|N\rangle/m_N \equiv f_{Tq} ,$$

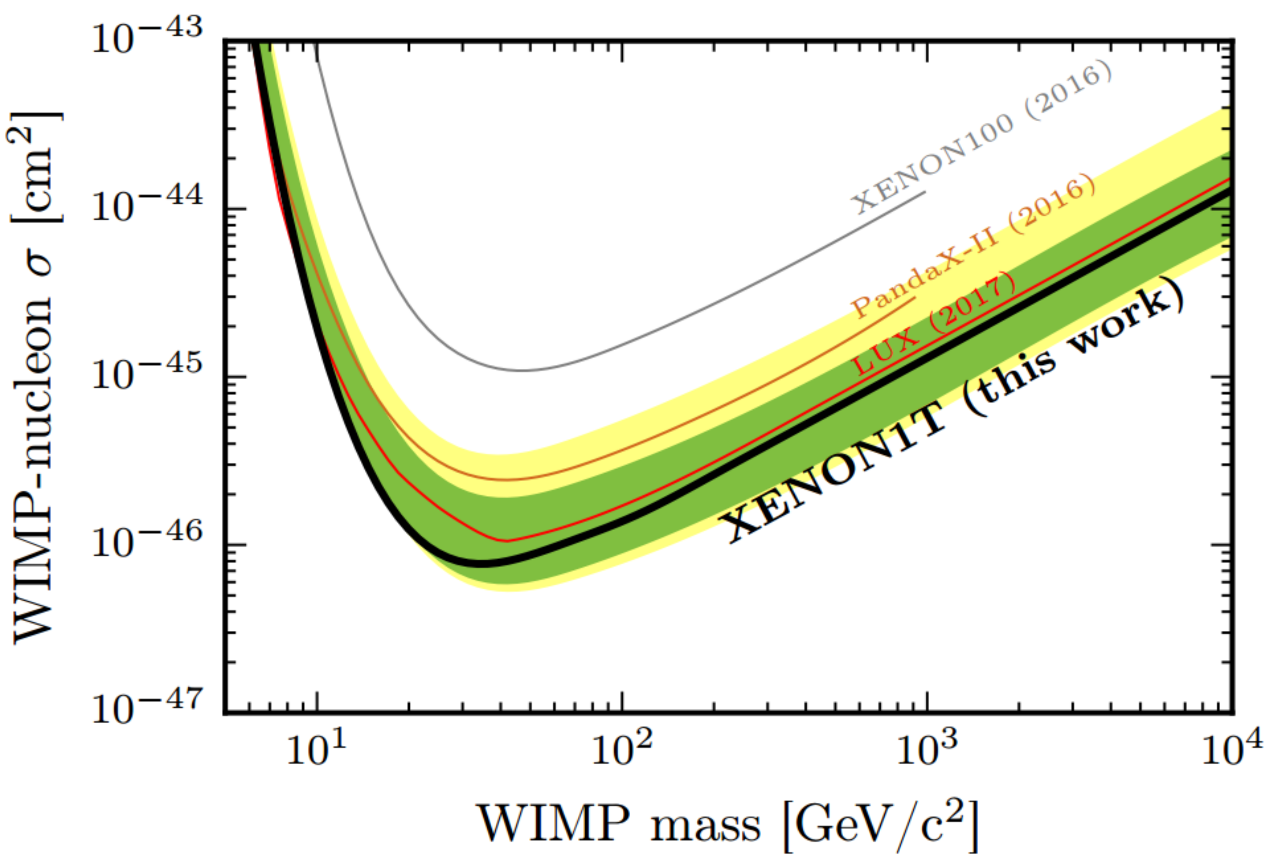
$$1 - \sum_{u,d,s} f_{Tq} \equiv f_{TG} ,$$

$$\langle N(p)|\mathcal{O}_{\mu\nu}^q|N(p)\rangle = \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu})\,(q(2)+\bar{q}(2)) ,$$

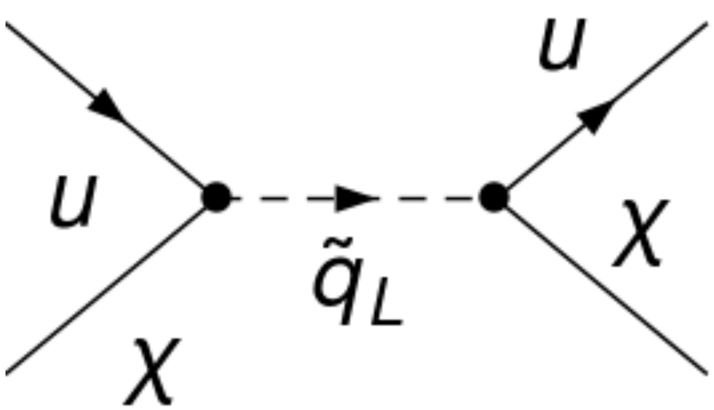
$$\langle N(p)|\mathcal{O}_{\mu\nu}^g|N(p)\rangle = \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu})\,G(2) .$$

Nuclear matrix elements

$$0.94 f_G + 0.09 f_q + 0.29(g_G^{(1)} + g_G^{(2)}) + 0.46(g_q^{(1)} + g_q^{(2)})$$



Direct Detection Leading Order



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

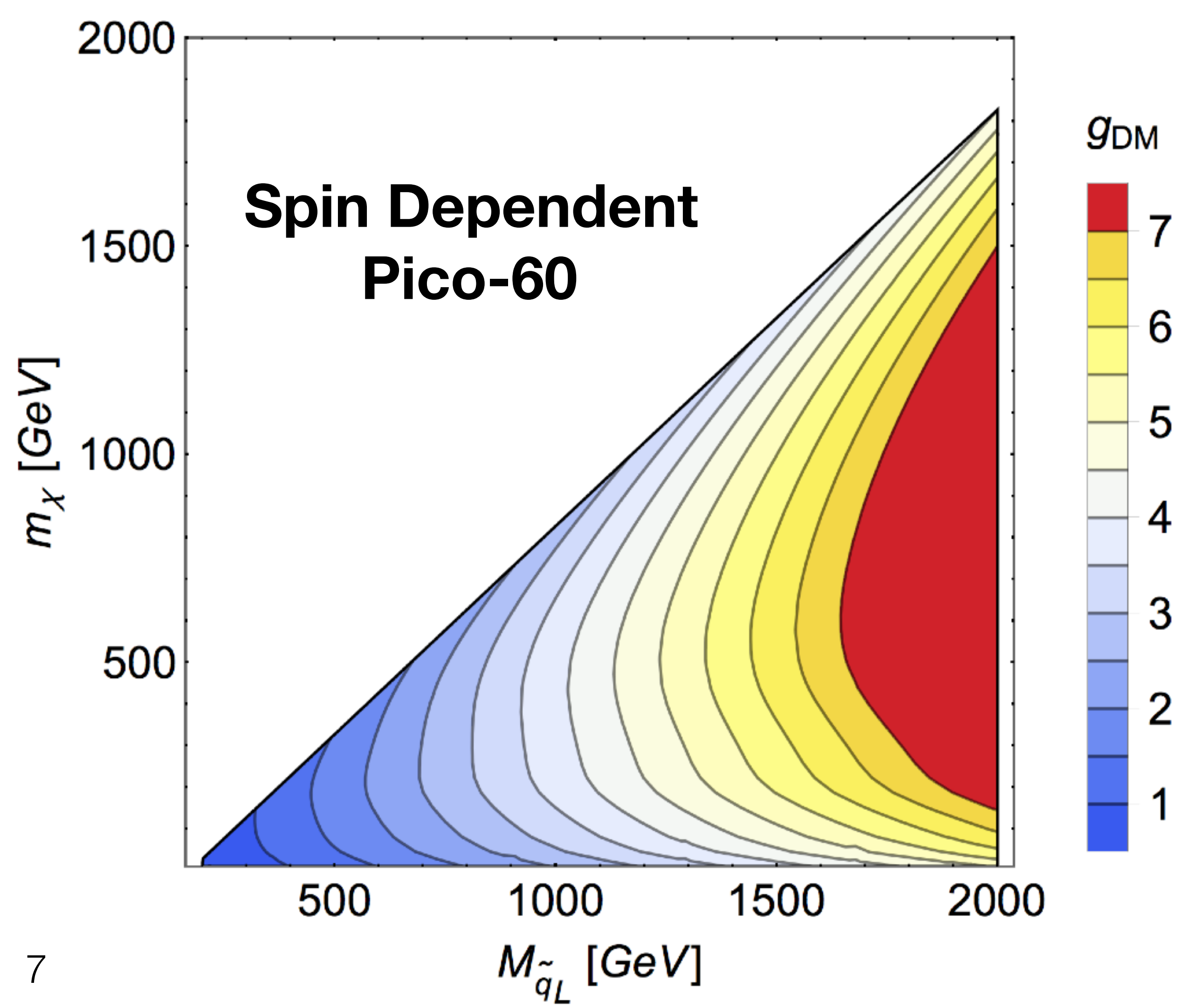
SI
0 for Majorana

SD

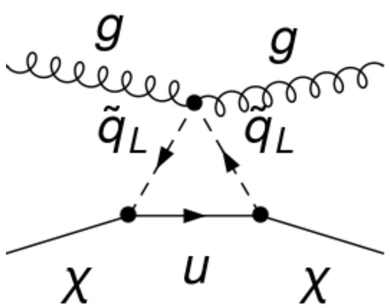
$$\mathcal{L}_{int} = \sum_{q=u,d,s,c,b,t} g_{DM}\,(\tilde{q}_L^*\bar{\chi}P_L q + h.c.)$$

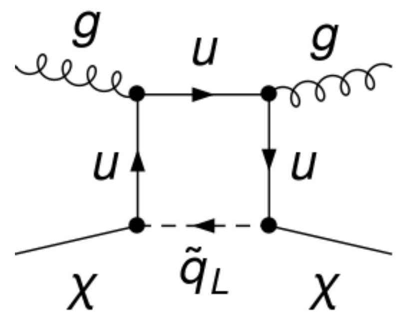
$$\sigma_p = \frac{4}{\pi}\left(\frac{M_\chi m_p}{M_\chi + m_p}\right)^2 |\langle\mathcal{M}_{DD}\rangle_{NR}|^2 \ .$$

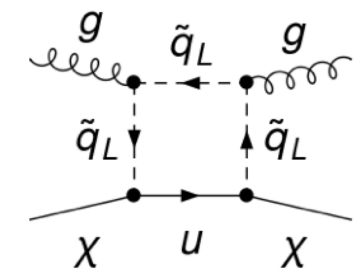
- LO calculation tells us that model has <u>only</u> a spin dependent cross-section.
- Limits from direct detection are weak—large values of g_{DM} allowed.



DD @ 1-Loop







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

Spin-2 Operators

Determine Wilson Coefficients for effective operators

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

Spin 0

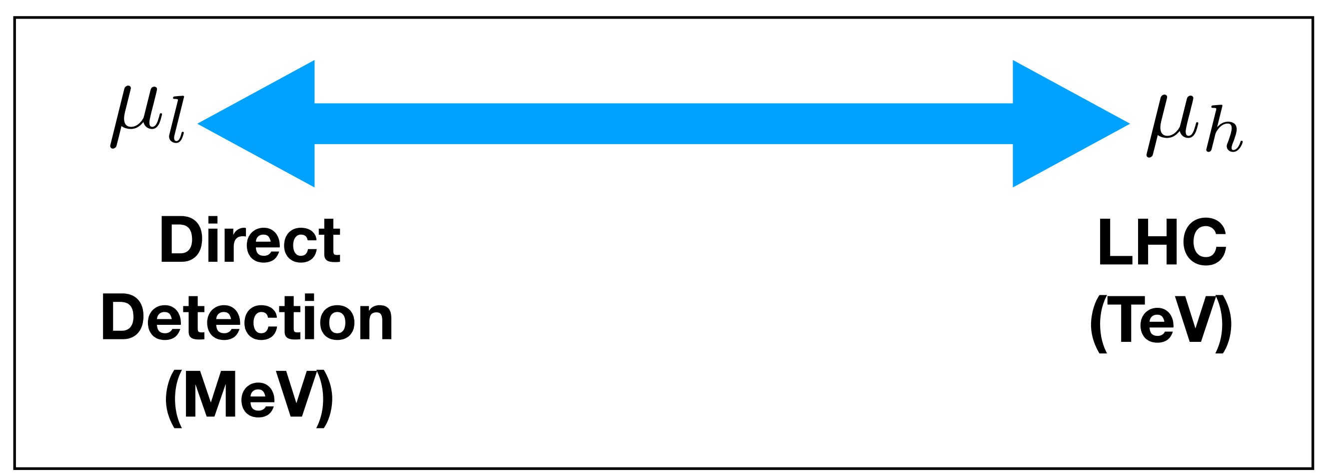
Evaluate matrix element for the elastic scattering process in the non-relativistic limit.

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

Tools: FeynArts, FORM, PackageX

RGE

- 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.



Details of RGE

Operators for Spin Independent Interactions

Quark	Gluon	
$O_q^{(0)} = m_q \bar{q} q$	$O_g^{(0)} = G^A_{\mu\nu} G^{A\mu\nu}$	**Spin 0**
$O_q^{(2)\mu\nu} = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu} iD_-^{\nu\}} - \frac{g^{\mu\nu}}{4} i\not{D}_-\right) q$	$O_g^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_{\lambda} + \frac{g^{\mu\nu}}{4}(G^A_{\alpha\beta})^2$	**Spin 2**

Sum Rules
Relate operators

Spin Dependent Operators

$$A_q^\mu = \bar{q}\gamma^\mu\gamma_5 q$$

Determine Anomalous dimensions

$$\frac{d}{d\log\mu} O_i = -\gamma_{ij} O_j \,, \qquad \frac{d}{d\log\mu} c_i = \gamma_{ji} c_j$$

Evolve and Match at each threshold

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

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

R. Hill, M. Solon 2014

$$R = \left(\begin{array}{ccc|c} & & & R_{qg} \\ & \mathbb{I}(R_{qq} - R_{qq'}) + \mathbb{J} R_{qq'} & & \vdots \\ & & & R_{qg} \\ \hline R_{gq} & \cdots & R_{gq} & R_{gg} \end{array} \right),$$

$$R^{(0)}_{qq} = 1\,, \quad R^{(0)}_{qg} = 2[\gamma_m(\mu_h) - \gamma_m(\mu_l)]/\tilde\beta(\mu_h)\,,$$
$$R^{(0)}_{gq} = 0\,, \quad R^{(0)}_{gg} = \tilde\beta(\mu_l)/\tilde\beta(\mu_h)$$

$$R^{(2)}_{qq} - R^{(2)}_{qq'} = r(0) + \mathcal{O}(\alpha_s)\,, \quad R^{(2)}_{qq'} = \frac{1}{n_f}\left[\frac{16 r(n_f) + 3n_f}{16 + 3n_f} - r(0)\right] + \mathcal{O}(\alpha_s)$$
$$R^{(2)}_{qg} = \frac{16[1 - r(n_f)]}{16 + 3n_f} + \mathcal{O}(\alpha_s)\,,$$
$$R^{(2)}_{gq} = \frac{3[1 - r(n_f)]}{16 + 3n_f} + \mathcal{O}(\alpha_s)\,, \quad R^{(2)}_{gg} = \frac{16 + 3n_f r(n_f)}{16 + 3n_f} + \mathcal{O}(\alpha_s)$$

$$\langle O'^{(0)}_q \rangle = \langle O^{(0)}_q \rangle + \mathcal{O}(1/m_Q)$$

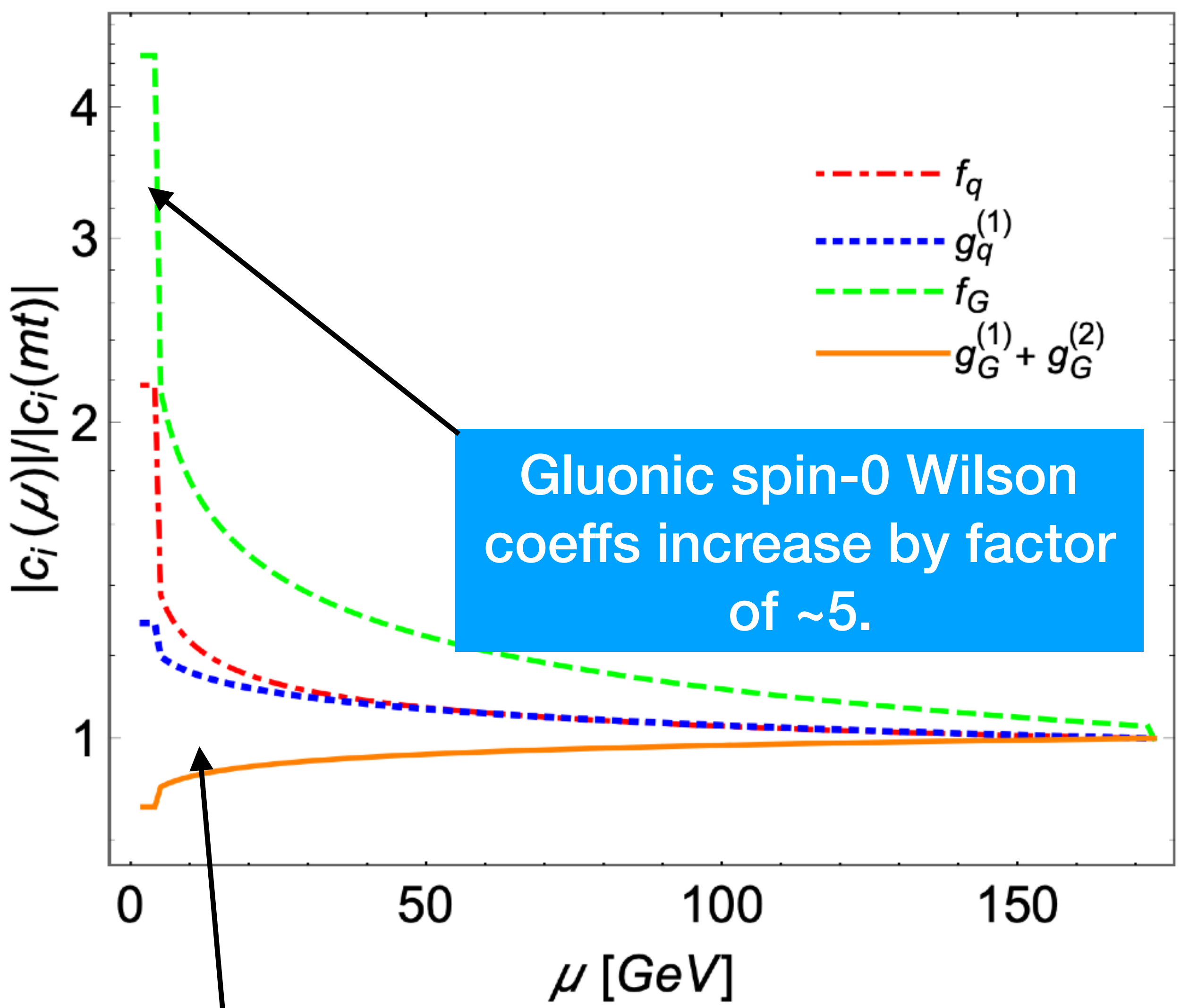
$$M = \left(\begin{array}{ccc|c|c} 1 & & & 0 & 0 \\ & \ddots & & \vdots & \vdots \\ & & 1 & 0 & 0 \\ \hline 0 & \cdots & 0 & M_{gQ} & M_{gg} \end{array} \right)$$

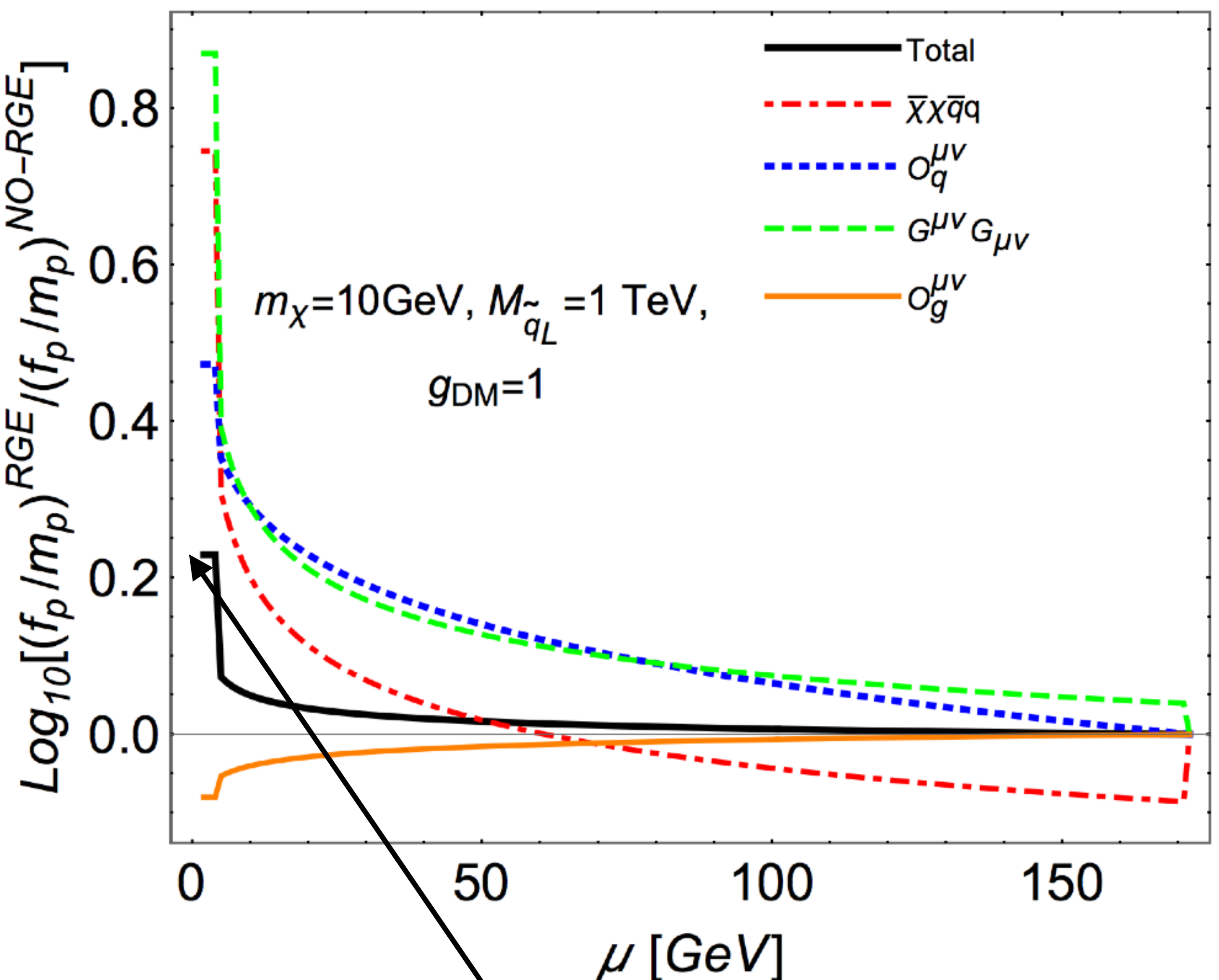
$$M^{(0)}_{gQ} = -\frac{\alpha'_s(\mu_Q)}{12\pi}\left\{1 + \frac{\alpha'_s(\mu_Q)}{4\pi}\left[11 - \frac{4}{3}\log\frac{\mu_Q}{m_Q}\right] + \mathcal{O}(\alpha_s^2)\right\}$$
$$M^{(0)}_{gg} = 1 - \frac{\alpha'_s(\mu_Q)}{3\pi}\log\frac{\mu_Q}{m_Q} + \mathcal{O}(\alpha_s^2)$$

Operators Mix

$$c_j(\mu_0) = R_{jk}(\mu_0, \mu_c) M_{kl}(\mu_c) R_{lm}(\mu_c, \mu_b) M_{mn}(\mu_b) R_{ni}(\mu_b, \mu_t) c_i(\mu_t)$$

How important is RGE?





Gluonic spin-0 Wilson coeffs increase by factor of ~5.

Spin-2 Wilson coefficients do not run as strongly.

Factor ~2 increase in matrix element when performing RGE.

Factor ~4 enhancement in cross-section

A closer look at the Wilson Coefficients

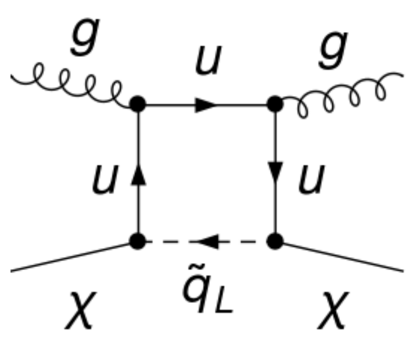
$$\frac{g_G^{(1)}}{m_\chi} = \alpha_s \alpha_{DM} \left[f_1(m_q, M_{\tilde{q}_L}, m_\chi) \log\left(\frac{m_q}{M_{\tilde{q}_L}}\right) + f_2(m_q, M_{\tilde{q}_L}, m_\chi) \right]$$

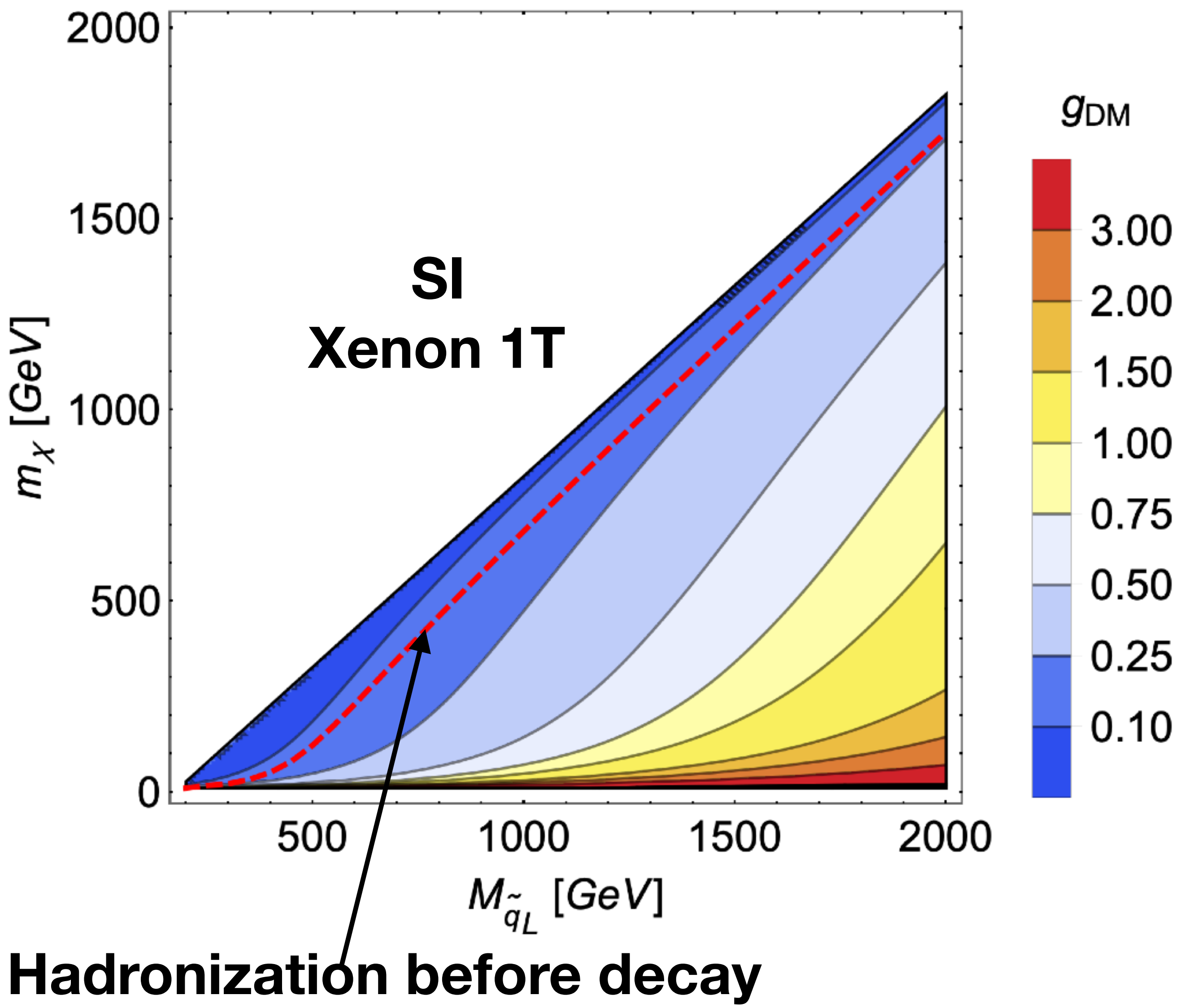
- For light quarks, large logs dominate the loop integral.
- Including RGE ensures large logs cancel

$$\Delta g_G^{(1)} = \frac{\alpha_s g_{DM}^2 m_\chi}{24\pi(M^2 - m_\chi^2)^2} \log\left(\frac{M}{m}\right)$$

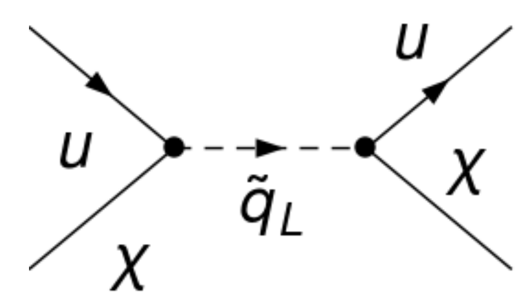
$$\Delta g_G^{(1)}\Big|_{\mu_l} \simeq \frac{m_\chi g_{DM}^2}{72\pi^2(M_{\tilde{q}}^2 - m_\chi^2)^2} \Bigg[3\pi\alpha_s(\mu_h) \log\left(\frac{\mu_l}{\mu_h}\right) + \alpha_s(M_{\tilde{q}}) \log\left(\frac{M_{\tilde{q}}}{m_b}\right) \left(3\pi - 5\alpha_s(\mu_h) \log\left(\frac{\mu_l}{\mu_h}\right)\right) \Bigg]$$

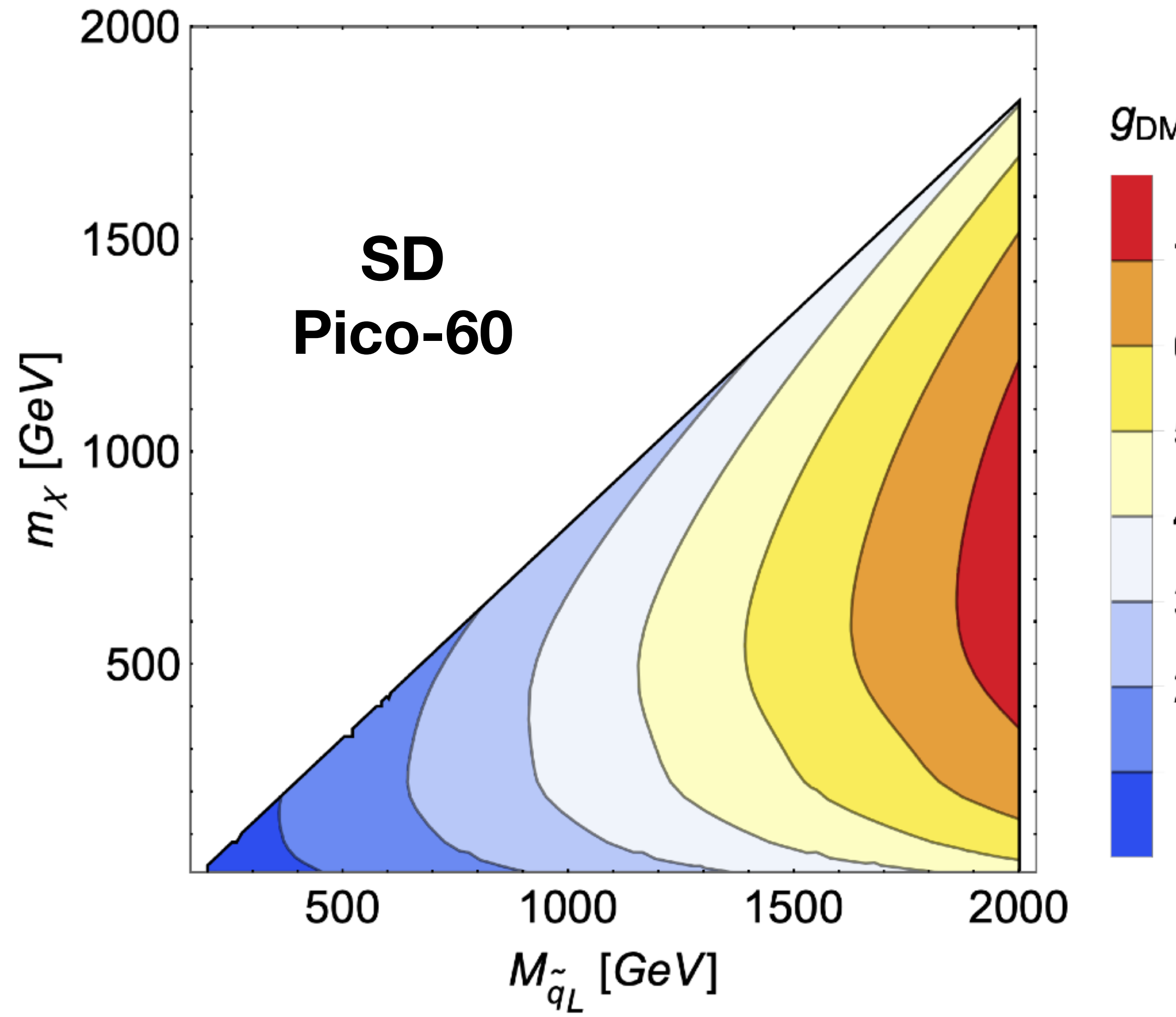
SI Limits (Loop)





SD Limits (LO)



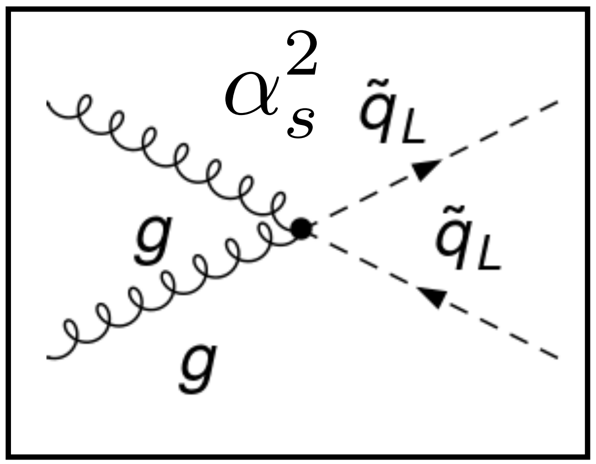


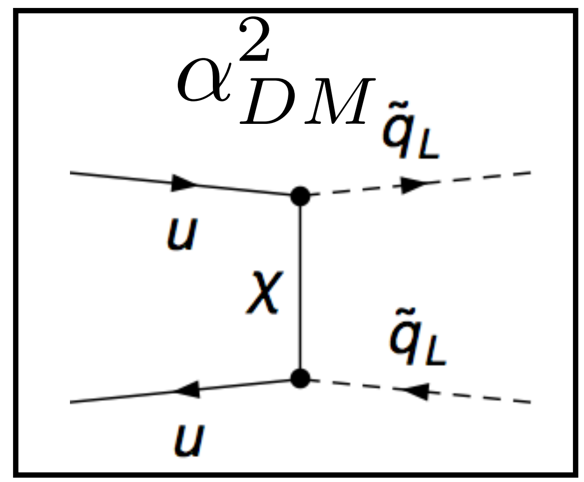
Constraints improve by an order of magnitude.

LHC Constraints

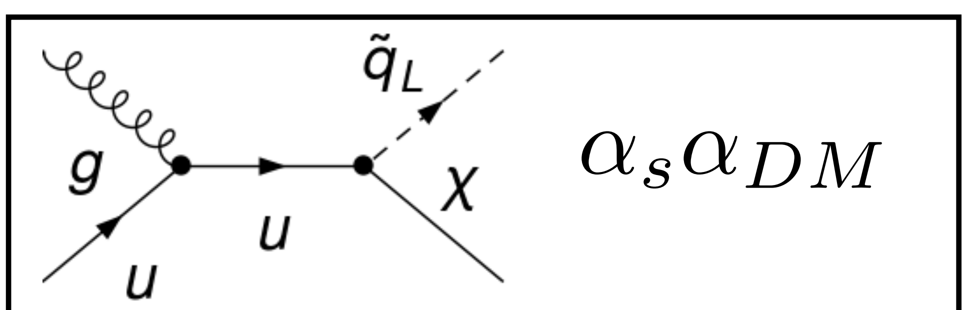
- Colored scalar mediator pair production— production cross-section (mostly QCD) depends on mass of mediator alone.

- Acceptance depends on mass of dark matter candidate also.

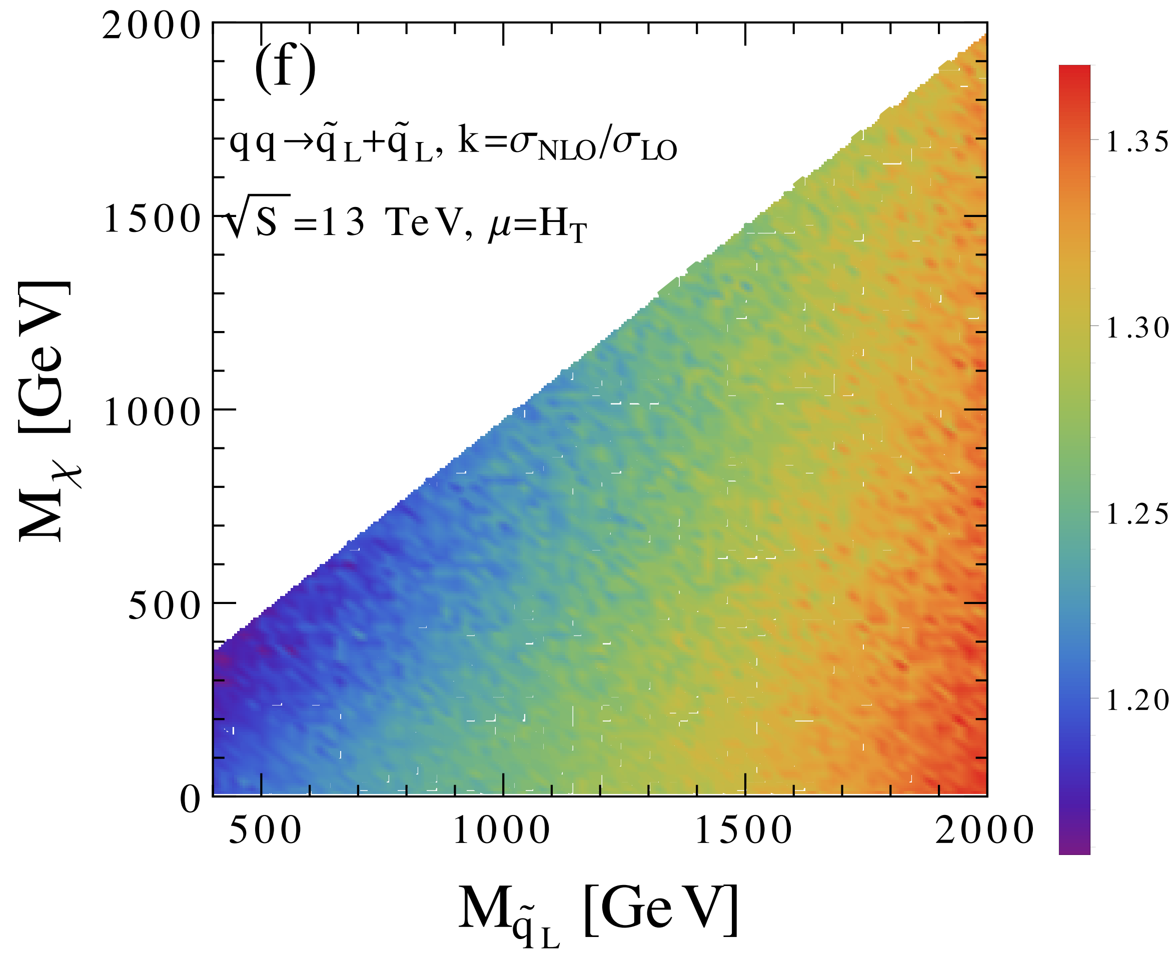


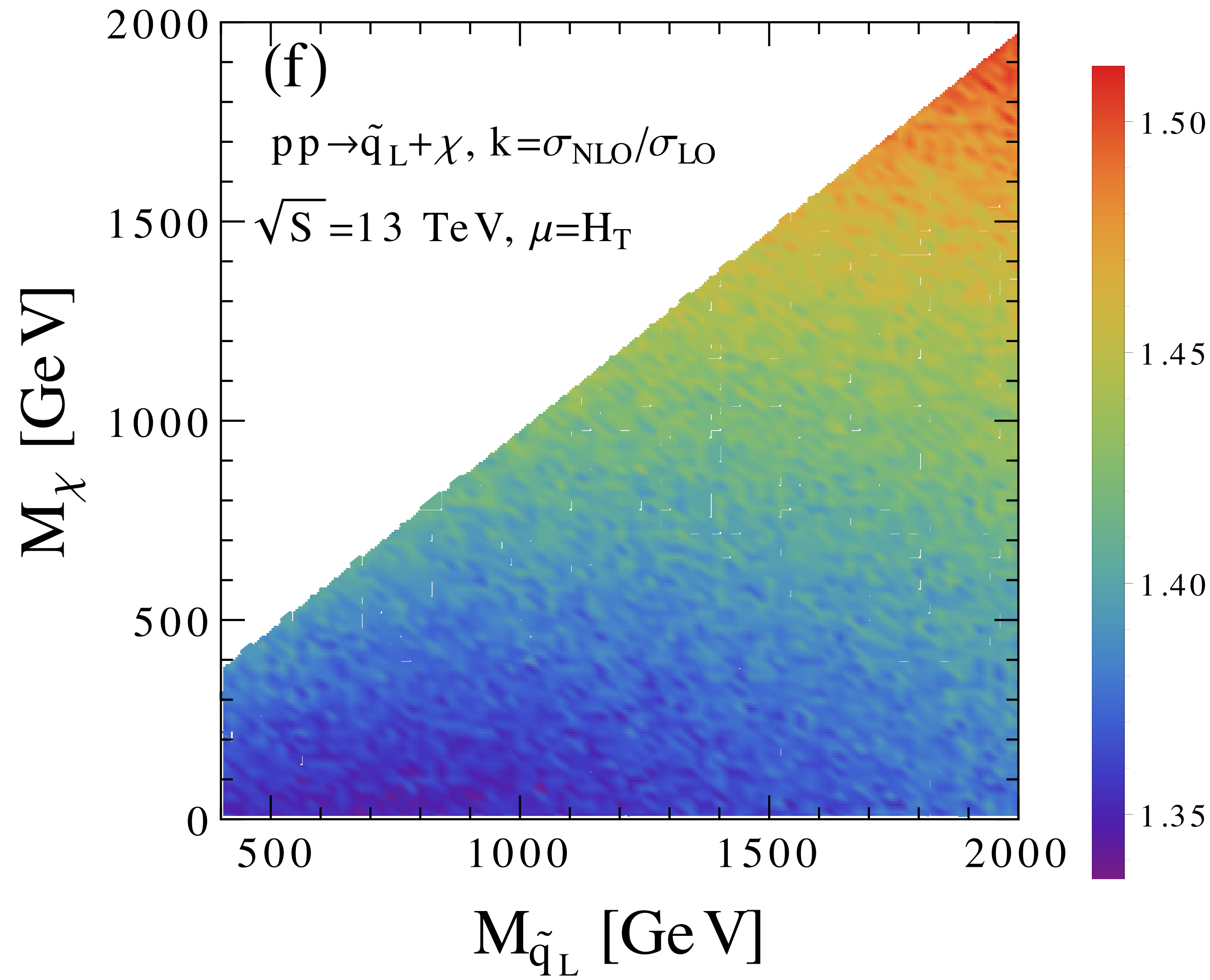


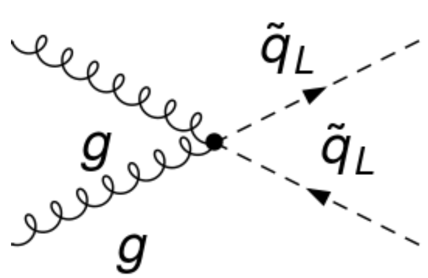
- Associated production of colored mediator and dark matter candidate— depends on all three model parameters.

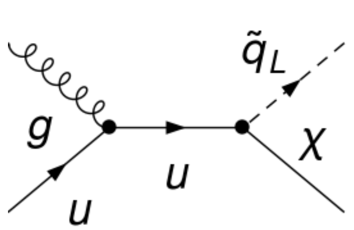


K factors


(f)
qq→q̃L+q̃L, k=σNLO/σLO
√S =13 TeV, μ=HT
MX [GeV]
Mq̃L [GeV]
2000
1500
1000
500
0
500
1000
1500
2000
1.35
1.30
1.25
1.20


(f)
pp→q̃L+χ, k=σNLO/σLO
√S =13 TeV, μ=HT
MX [GeV]
Mq̃L [GeV]
2000
1500
1000
500
0
500
1000
1500
2000
1.50
1.45
1.40
1.35


q̃L
q̃L
g
g


q̃L
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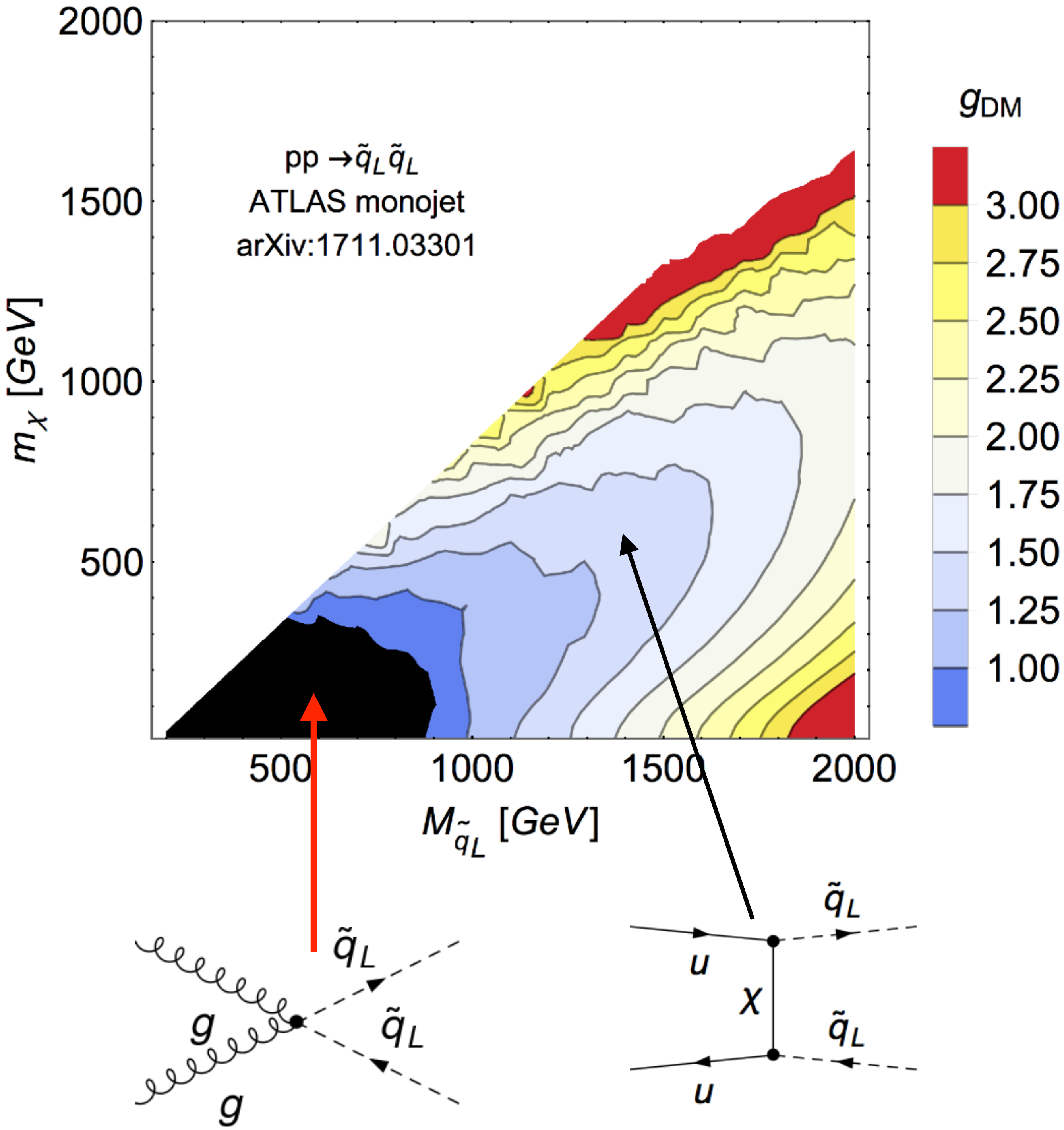
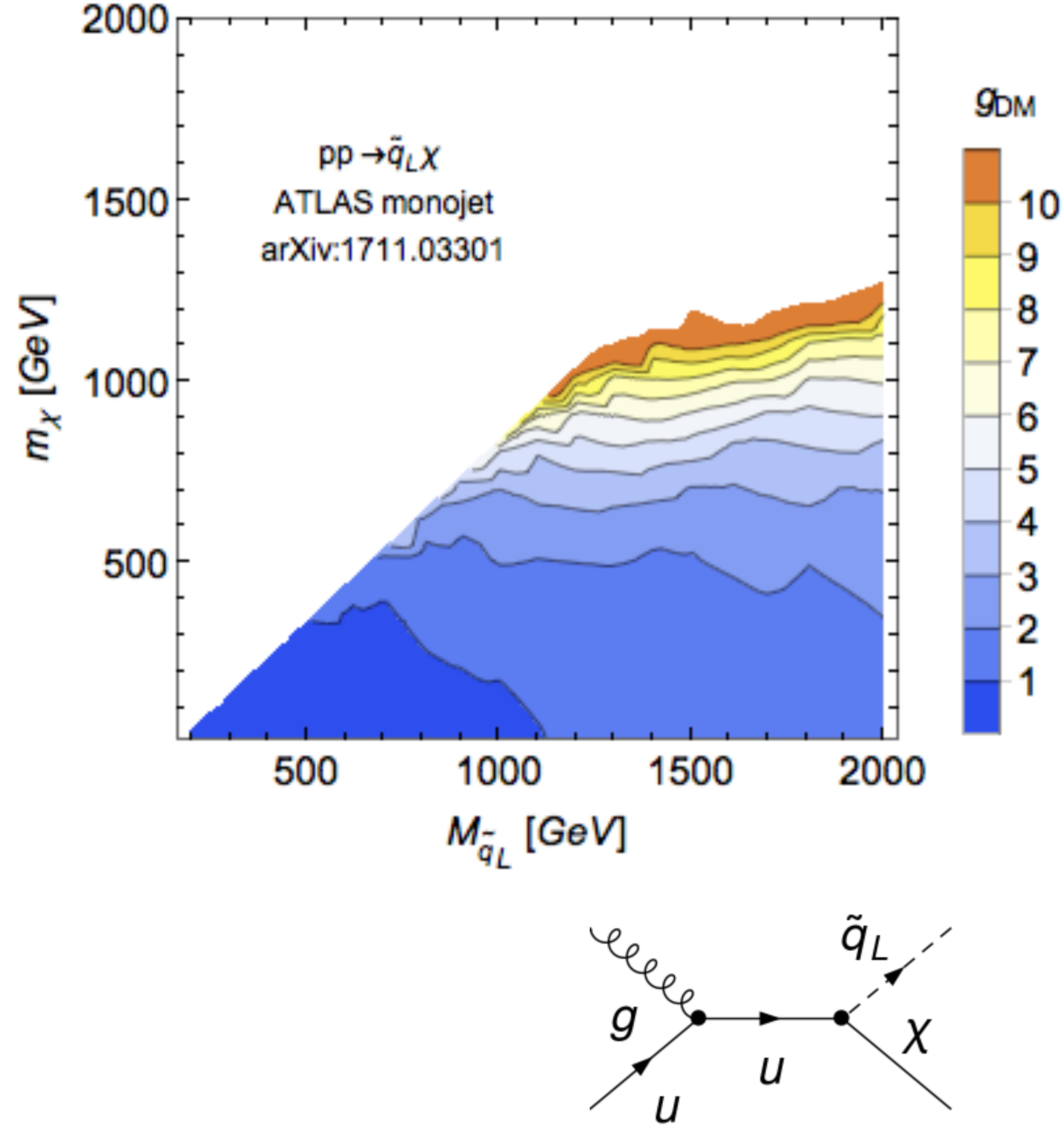
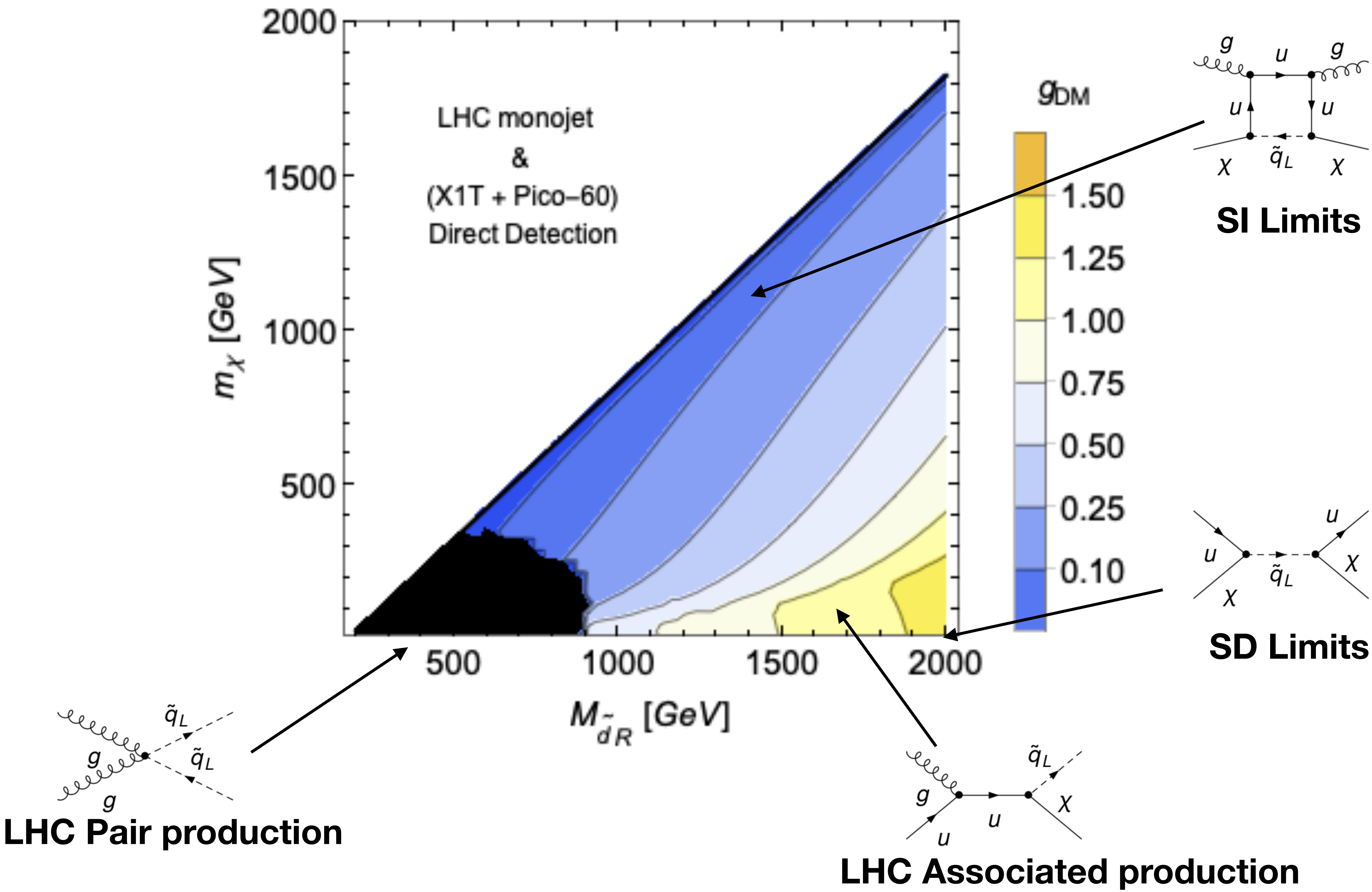




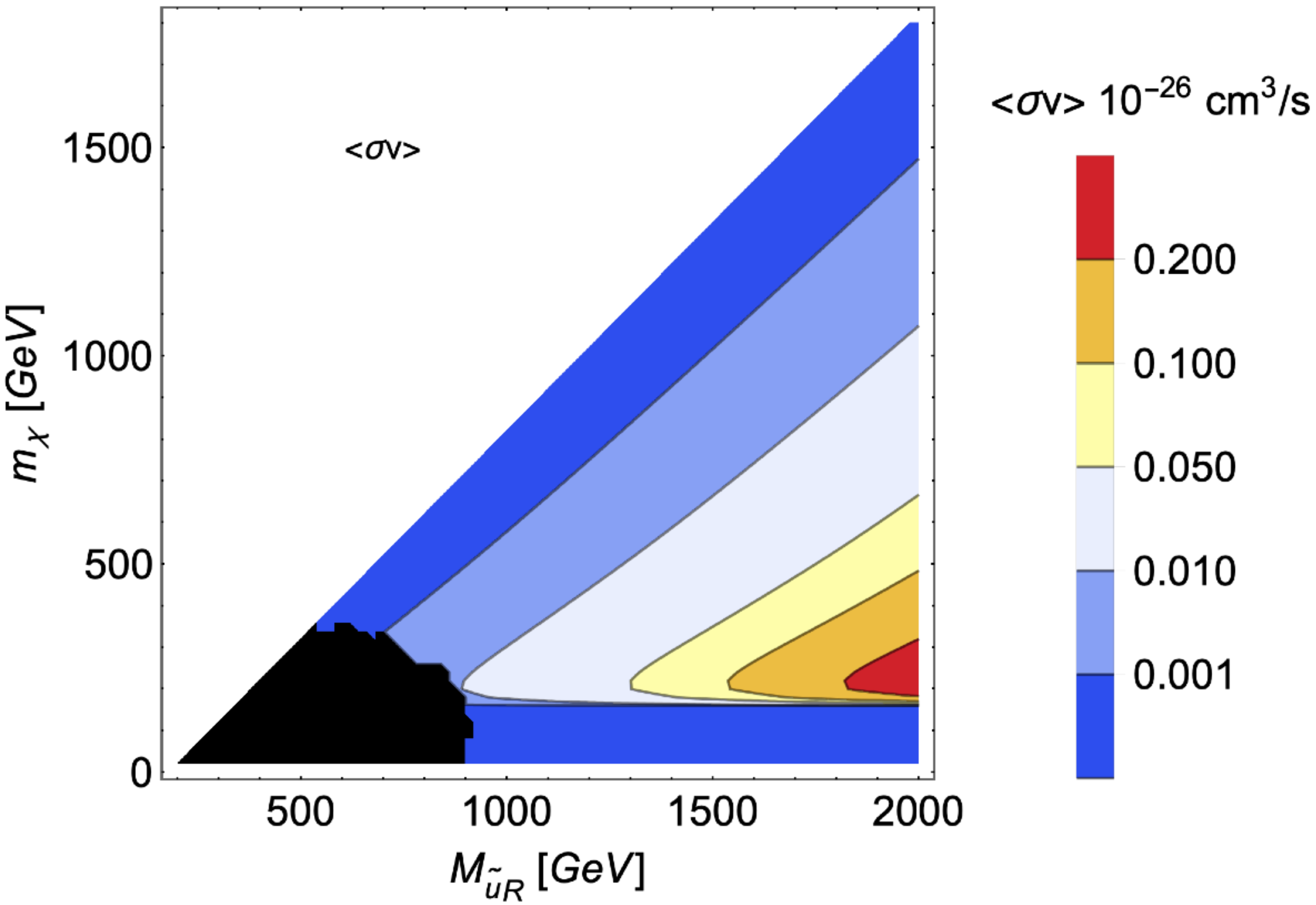
Pure QCD
Independent of
DM coupling (g_{DM})

Tools : FeynRules, NLOCT, MadGraph5_aMC@NLO, MadAnalysis5

Complementarity of DD & LHC experiments



Dark matter annihilation cross-section



$$\langle \sigma v \rangle \simeq N_c^f g_{DM}^4 \left[\frac{m_f^2 \sqrt{1 - \frac{m_f^2}{m_\chi^2}}}{64\pi (m_{\tilde{q}}^2 + m_\chi^2 - m_f^2)^2} + \beta^2 \left\{ \frac{m_\chi^2 \sqrt{m_\chi^4 + m_{\tilde{q}}^4}}{32\pi (m_\chi^2 + m_{\tilde{q}}^2)^4} + \mathcal{O}(m_f^2) \right\} \right]$$

Conclusions

- Simplified models— useful to capture essential features of classes of models; one can make generic statements.
- Importantly - one is able to compare constraints from experiments probing a wide range of energy scales.
- Can easily evaluate LHC constraints @ NLO precision — Madgraph UFO file available.
- Demonstrated importance of going beyond LO for determining direct-detection constraints (order of magnitude increase for this particular model).
- Demonstrated importance of RGE effects (factor 4 increase).
- Able to make proper comparison between experiments that operate at different energy scales.
- Tool to calculate direct detection constraints with RGE will be hosted on the msu website soon. CalcHep model file to run with micromegas also available.

Thank you

$$
\begin{aligned}
&m_u = 2.2 \text{ MeV}, \quad m_d = 4.7 \text{ MeV}, \quad m_s = 95 \text{ MeV}, \\
&m_c = 1.3 \text{ GeV}, \quad m_b = 4.2 \text{ GeV}, \quad m_t = 172 \text{ GeV}, \\
&m_Z = 91.188 \text{ GeV}, \quad \alpha_s(m_Z) = 0.1184, \\
&m_n = 0.9396 \text{ GeV} \quad m_p = 0.9383 \text{ GeV} .
\end{aligned}
$$

$$
\begin{aligned}
&[f_{T_u}]_p = 0.018, \quad [f_{T_d}]_p = 0.030, \quad [f_{T_s}]_p = 0.043, \\
&[f_{T_u}]_n = 0.015, \quad [f_{T_d}]_n = 0.034, \quad [f_{T_s}]_n = 0.043, \\
&f_{T_G}|_{\text{NNNLO}} = 0.80 .
\end{aligned}
$$

$$
f_{T_G} = -\frac{9\alpha_S(\mu)}{4\pi\beta(\mu)}\left[1 - (1+\gamma_m(\mu))\sum_{u,d,s} f_{Tq}\right] .
$$

$$
\begin{aligned}
&[u(2)+\bar{u}(2)]_p = 0.3481, \quad \left[d(2)+\bar{d}(2)\right]_p = 0.1902, \\
&[s(2)+\bar{s}(2)]_p = 0.0352, \quad [c(2)+\bar{c}(2)]_p = 0.0107 , \\
&[G(2)]_p = [G(2)]_n = 0.4159 .
\end{aligned}
$$

$$
\begin{aligned}
&\Delta u^{(p)} = 0.84, \quad \Delta d^{(p)} = -0.43, \quad \Delta s^{(p)} = -0.09, \\
&\Delta u^{(n)} = \Delta d^{(p)}, \quad \Delta d^{(n)} = \Delta u^{(p)}, \quad \Delta s^{(n)} = \Delta s^{(p)}.
\end{aligned}
$$