Dark Matter with t-channel mediator

A simple step beyond contact interaction

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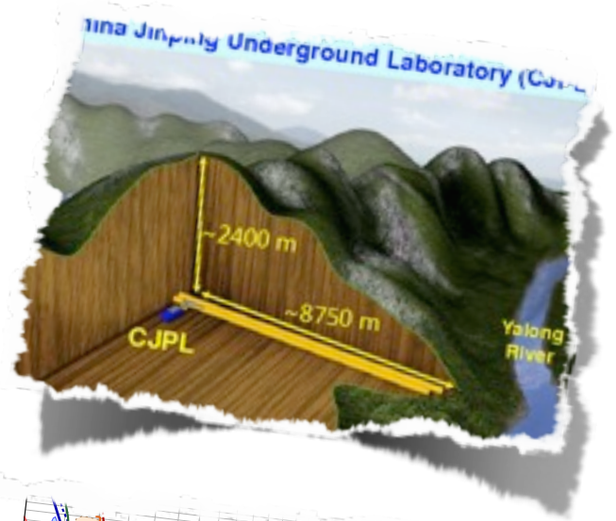
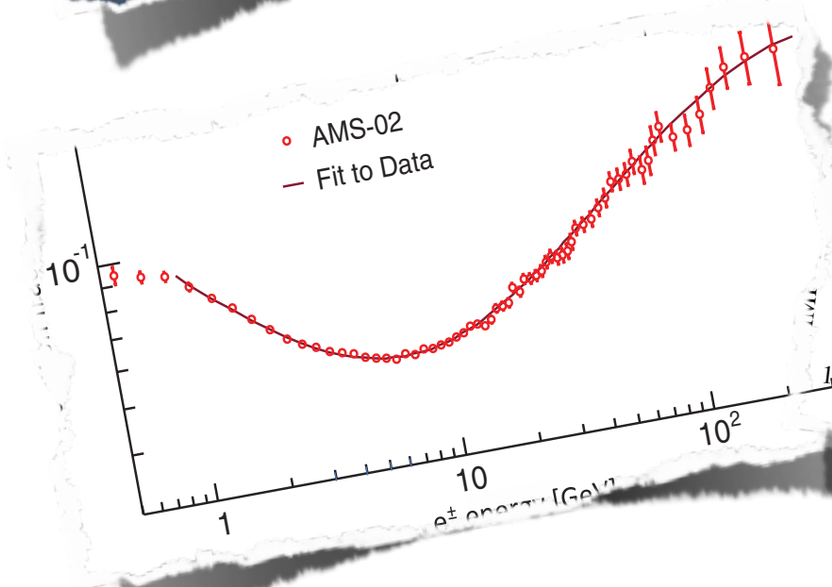
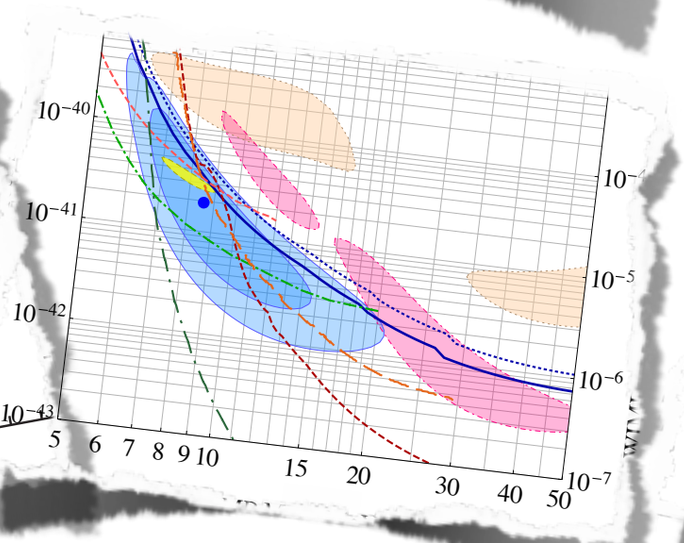
Based on the work arXiv:1308.0592[hep-ph] in collaboration with Haipeng An and Lian-Tao Wang

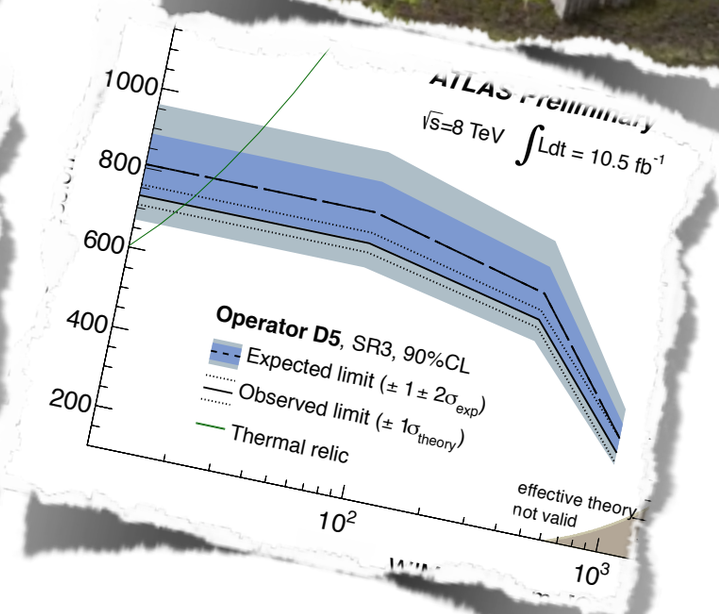
Dark Matter Searching

- Weakly Interacting Massive Particle (WIMP) is one of the most popular dark matter candidates.
- The interaction between WIMP and the SM particles makes it detectable by satellites (indirect detection), underground detectors (direct detection), and colliders.









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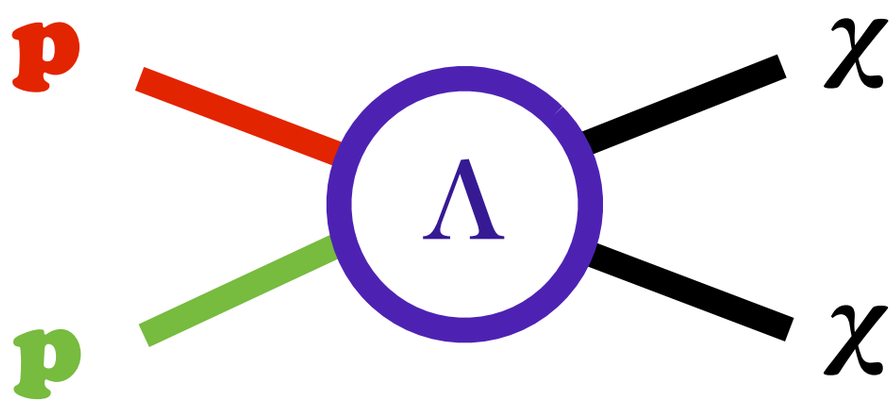
Dark Matter Searching at the LHC

- Effective operator method: model independent, less free parameters.

$$\frac{C_{AB}}{\Lambda^n}\bar{\chi}\Gamma^A\chi\bar{q}\Gamma^B q$$



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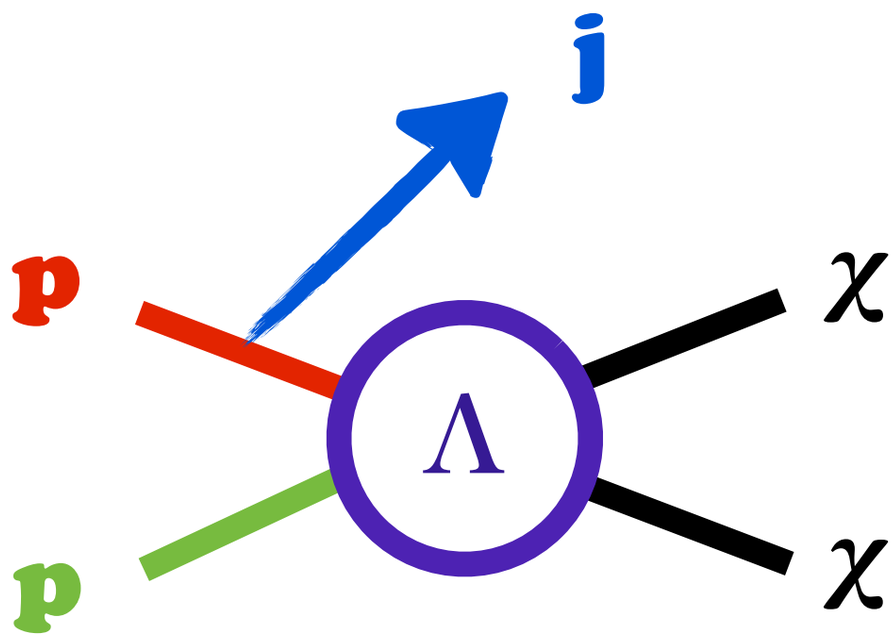

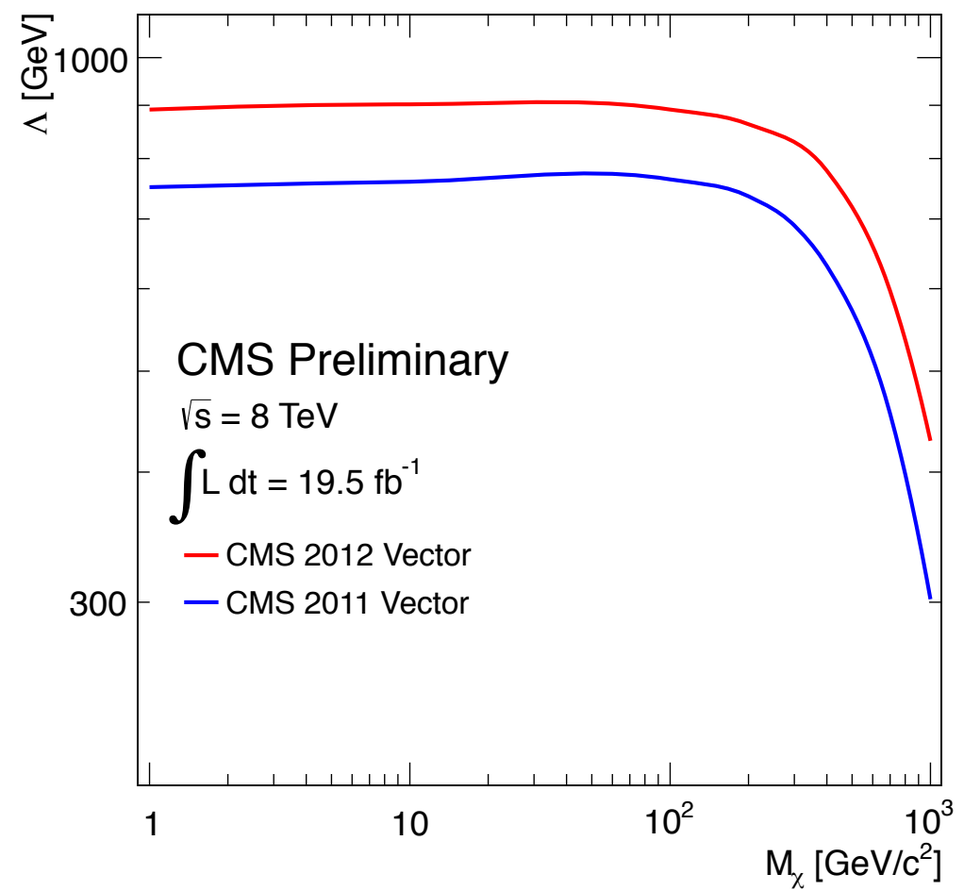

CMS PAS EXO-12-048

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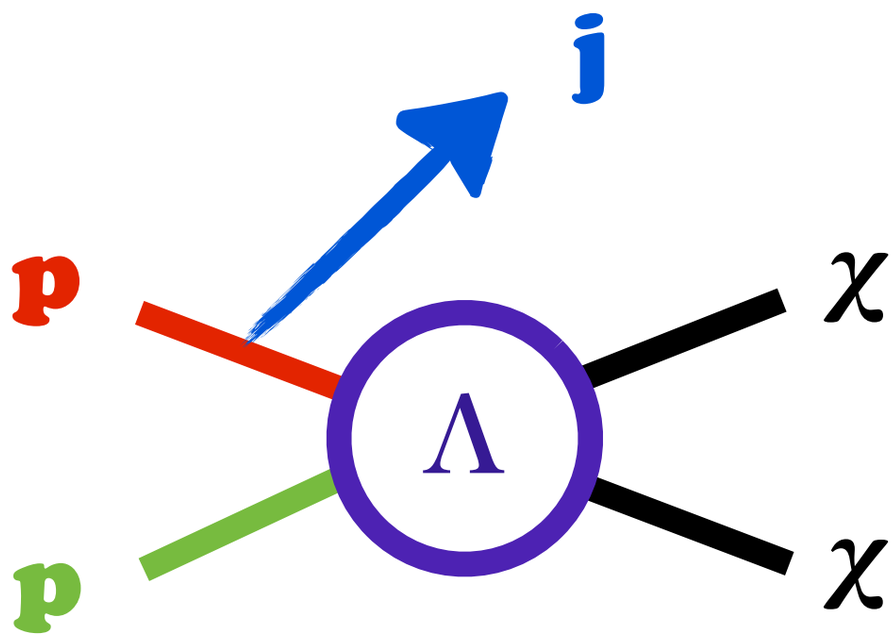

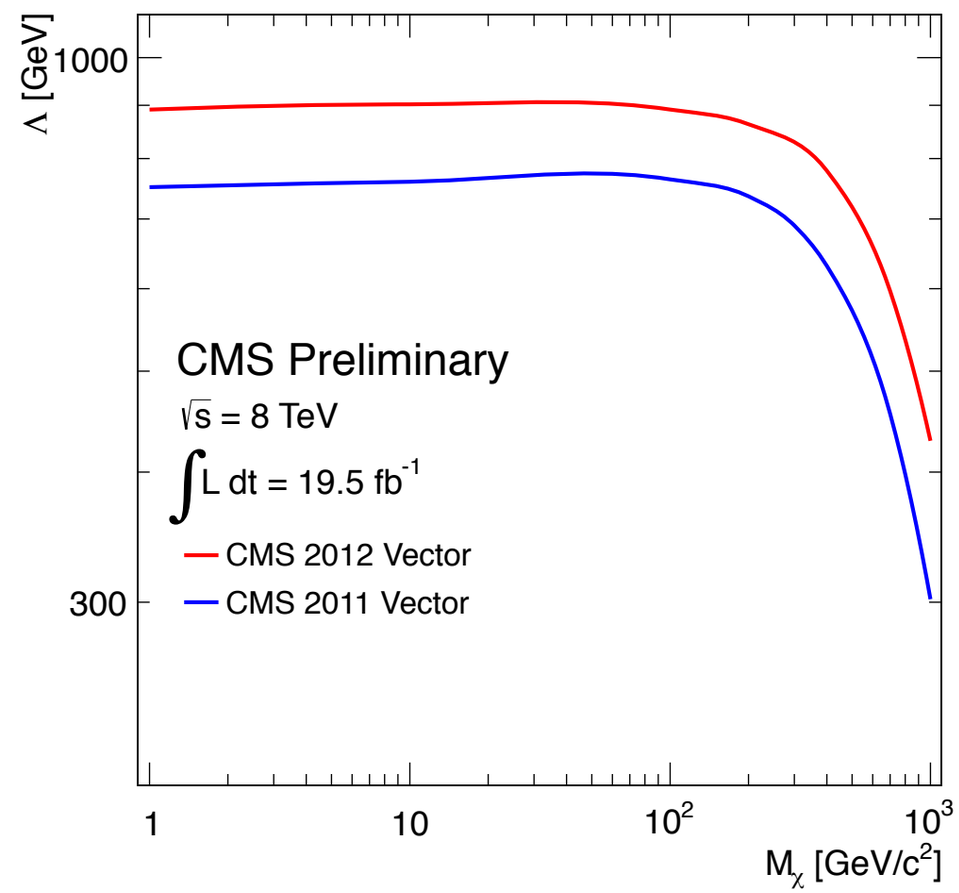

CMS PAS EXO-12-048

- The cutoff scale ~ **hundreds GeV**.
- The typical energy of the jets pass cut ~ **hundreds GeV**.
- The mass of dark matter ~ **hundreds GeV**.
- Effective energy of c.m.s ~ TeV.

Dark Matter Searching at the LHC

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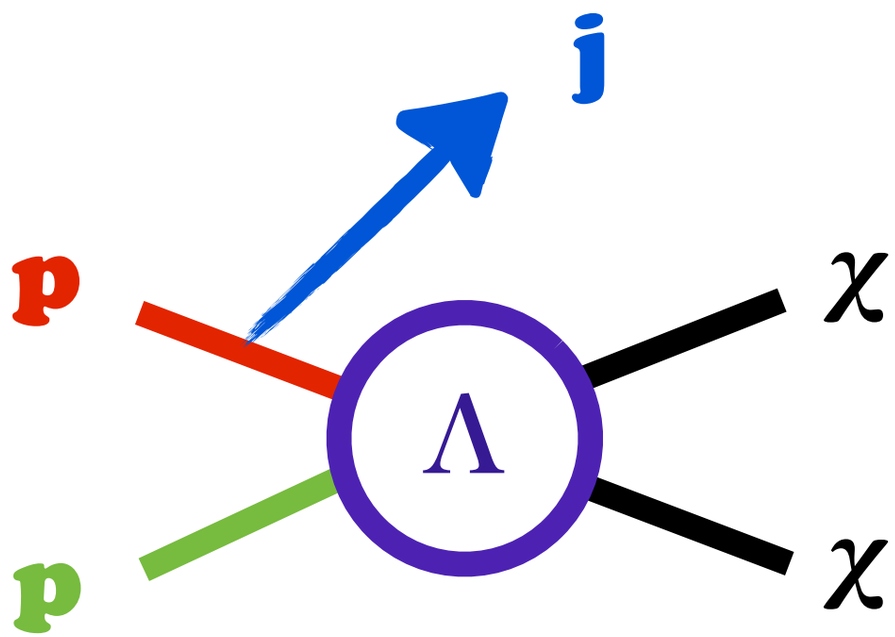
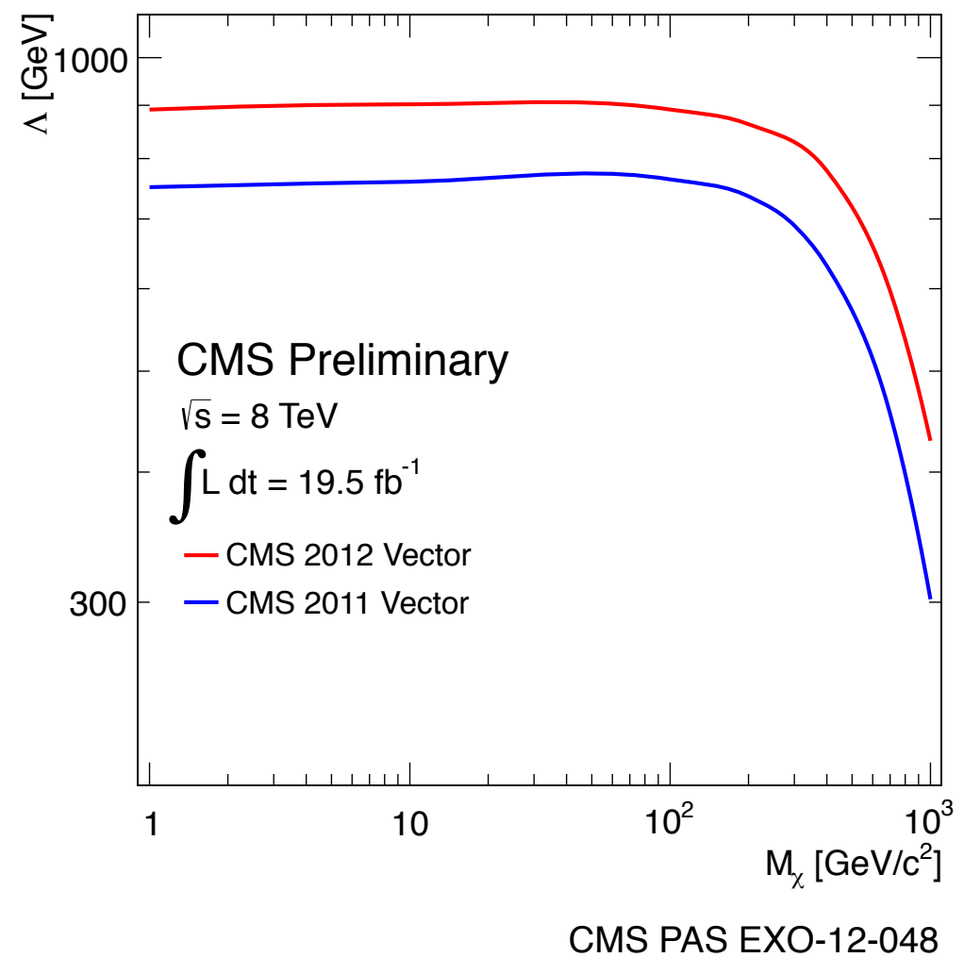
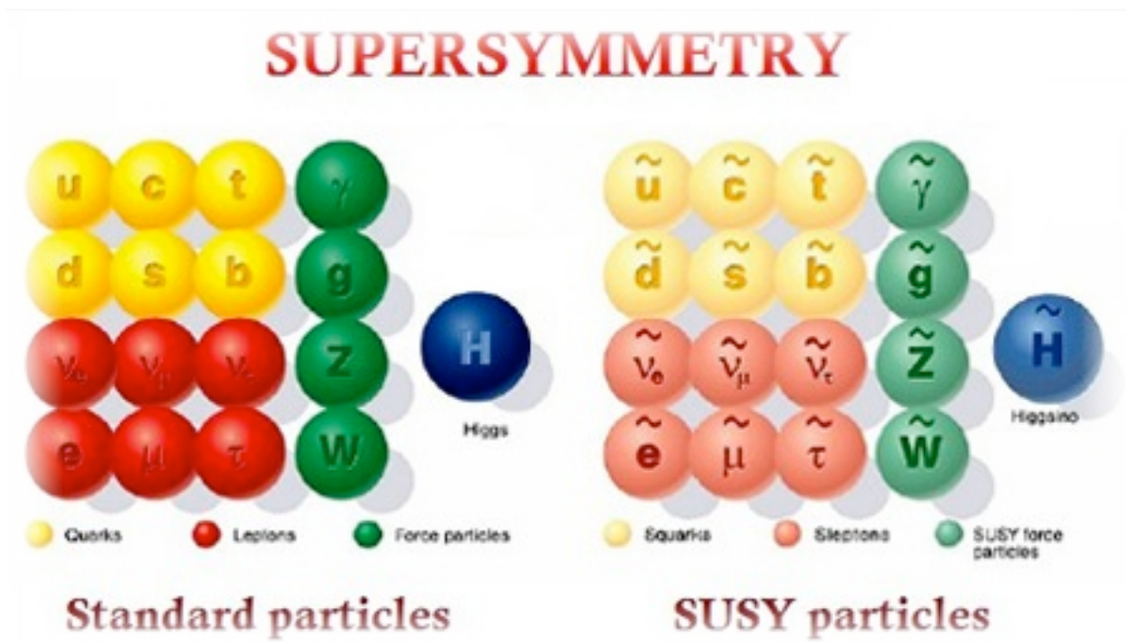


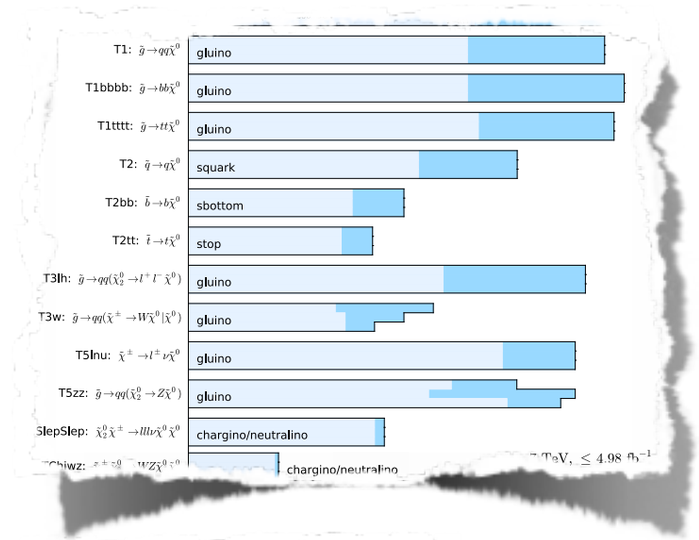


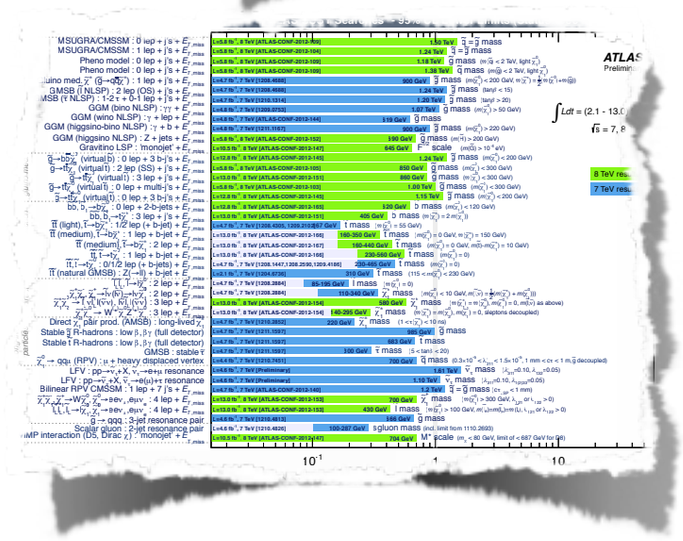
We need to go beyond the EFT!

Dark Matter Searching at the LHC

- Beyond EFT? New physics models?
- Supersymmetry, and etc :)
- More than 100 parameters and tens more particles...
- It is too far than a simple improvement of EFT.

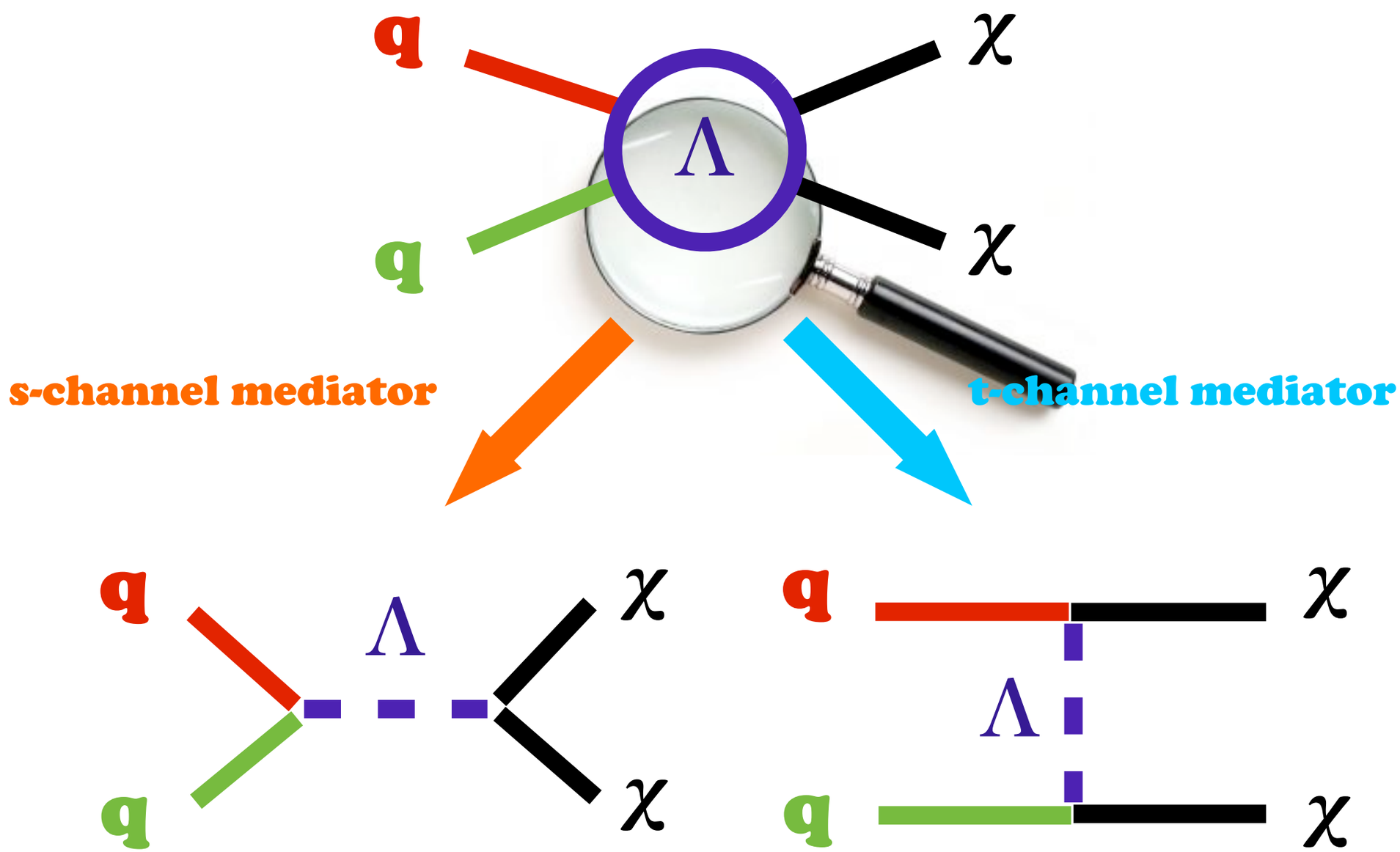






DM with t-channel mediator

- A simple step beyond the EFT.
- Adding a mediator to reduce the dimension of the effective operators in the theory to be smaller than 5.



DM with t-channel mediator

- The effective Lagrangian of a simple t-channel mediator theory can be written as

$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + \text{h.c.}$$

- The quarks in the effective Lagrangian could be right-handed or left-handed. In the MFV scenario,

$$\begin{aligned}
\mathcal{L}_\chi \;=\; & \lambda_Q \bar{\chi} \mathbb{P}_L Q \phi_Q^* + \lambda_u \bar{\chi} \mathbb{P}_R u \phi_u^* + \lambda_d \bar{\chi} \mathbb{P}_R d \phi_d^* \\
& + \frac{\lambda_{Qu}^{(1)} \bar{\chi} H \phi_Q^* Y_u \mathbb{P}_R u}{\Lambda} + \frac{\lambda_{Qd}^{(1)} \bar{\chi} \tilde{H} \phi_Q^* Y_d \mathbb{P}_R d}{\Lambda} \\
& + \frac{\lambda_{Qu}^{(2)} \bar{Q} H Y_u \phi_u \mathbb{P}_R \chi}{\Lambda} + \frac{\lambda_{Qd}^{(2)} \bar{Q} \tilde{H} Y_d \phi_d \mathbb{P}_R \chi}{\Lambda} \\
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Direct detection

- Direct detection

$$\mathcal{O}_1 = \frac{\lambda^2}{2M_\phi^2}\bar{\chi}_L\gamma_\mu\chi_L\bar{q}_R\gamma^\mu q_R$$

- The direct detection cross section from this effective operator has been well studied.

- There are other operators induced by the t-channel mediator!

$$\mathcal{O}_2 = \frac{\alpha_S}{4\pi}G^{a\mu\nu}G^a_{\mu\nu}\chi^2, \qquad \mathcal{O}_3 = m_q\bar{q}q\chi^2$$

- Those operators are dim-7 and loop-induced from the t-channel mediator.

- The chiral symmetry enforces the Wilson coefficients to be proportional to the mass of the WIMP.

$$C_2 \sim \frac{\lambda^2 M_\chi}{M_\phi^4}, \qquad C_3 \sim \frac{\lambda^2 m_t^2 M_\chi}{32\pi^2 M_\phi^2 v_{\rm ew}^2 M_h^2}$$

LHC phenomenology I: monojet

- Dark matter production process: monojet + missing ET.

- New contributions:

  (c) ---- from dim-7 operator $\mathcal{O}_8 = -\frac{i g_S \lambda^2}{M_\phi^4} T^a_{ij} A^a_\mu \left(\bar{\chi} P_R q_j\right) \overleftrightarrow{\partial}^\mu \left(\bar{q}_i P_L \chi\right)$

  - Higher suppressed by the mediator mass
  - No logarithm enhancement as the initial state QCD jet

  (d1-d4) ---- WIMP-mediator associated production

  - Two-body phase space enhancement
  - High pT jet from heavy mediator decay

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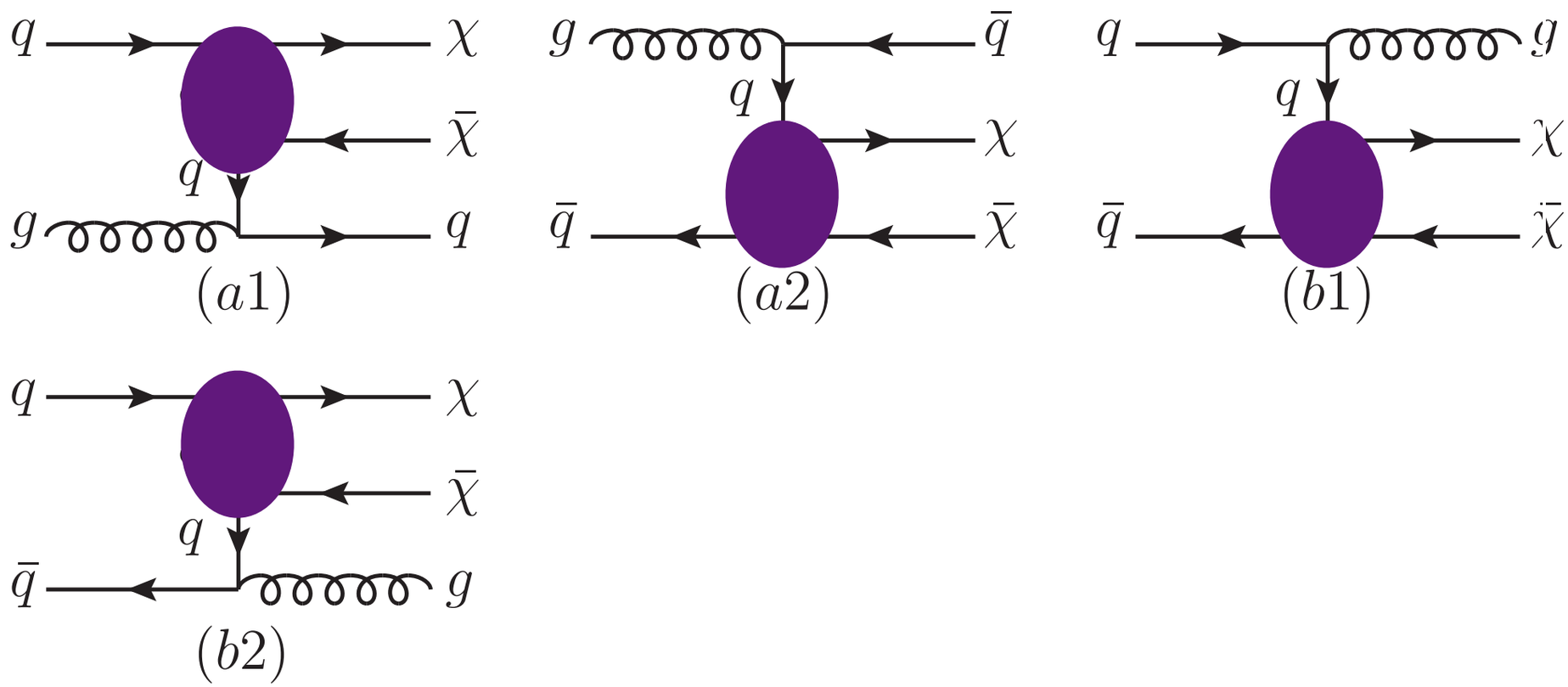

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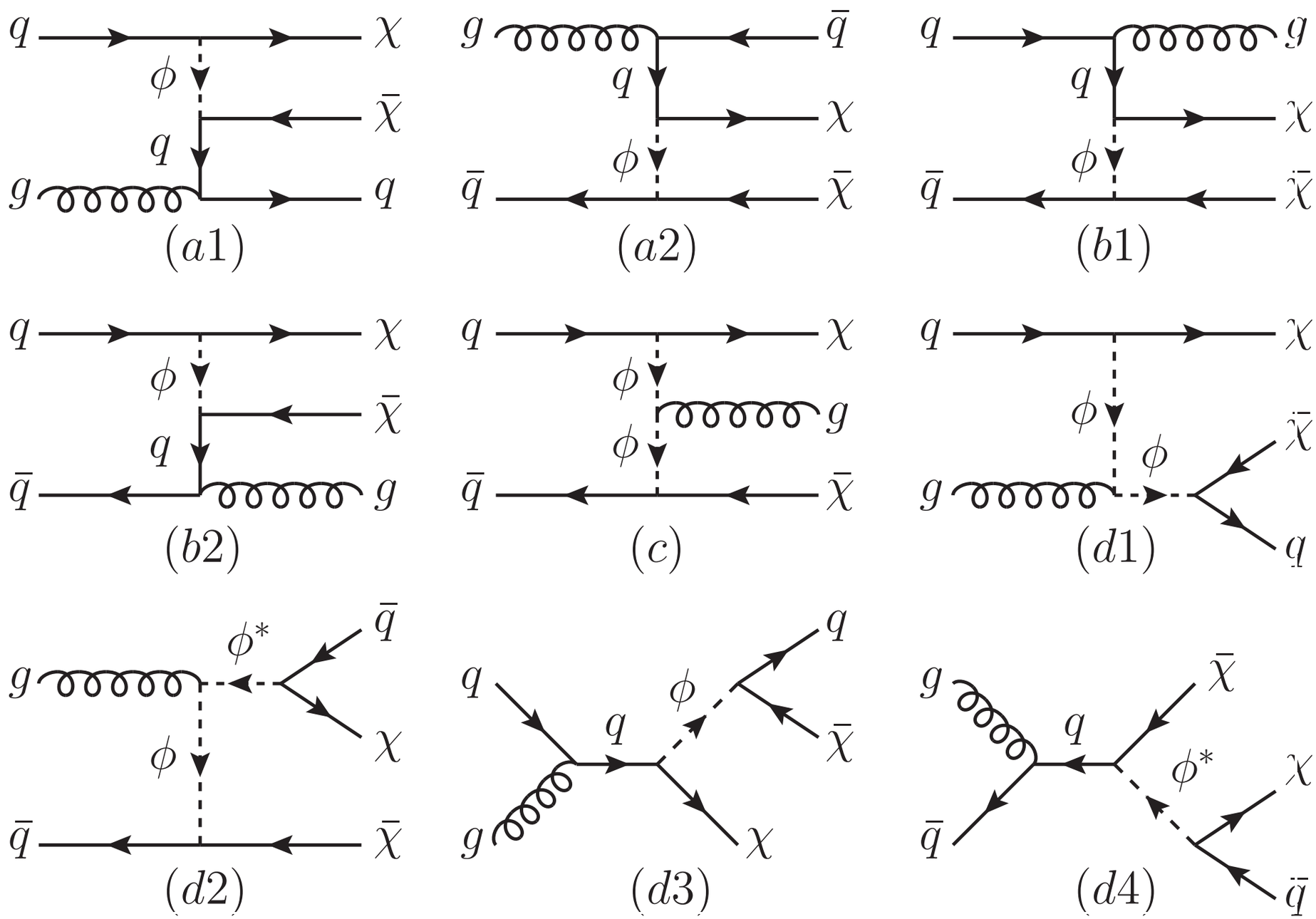

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- The most recent monojet+missing ET constraint from the LHC is from CMS collaboration with 19.5 fb^{-1} dataset from 8 TeV proton-proton collision.

LHC phenomenology I: monojet

- We use MadGraph5/MadEvent generate parton level event, shower it using PYTHIA6.4 and simulate the detector effects using PGS4 with anti-KT jet algorithm with a distance parameter of 0.5.

- Cuts:

Only one central jet $p_T > 110 \text{ GeV}, \ |\eta| < 2.4$

At most two jets s.t. $p_T > 30 \text{ GeV}, \ |\eta| < 4.5$

No isolated electron with $p_T > 10 \text{ GeV}, \ |\eta| < 1.44$ or $1.56 < |\eta| < 2.5$

No isolated muon with $p_T > 10 \text{ GeV}, \ |\eta| < 2.1$

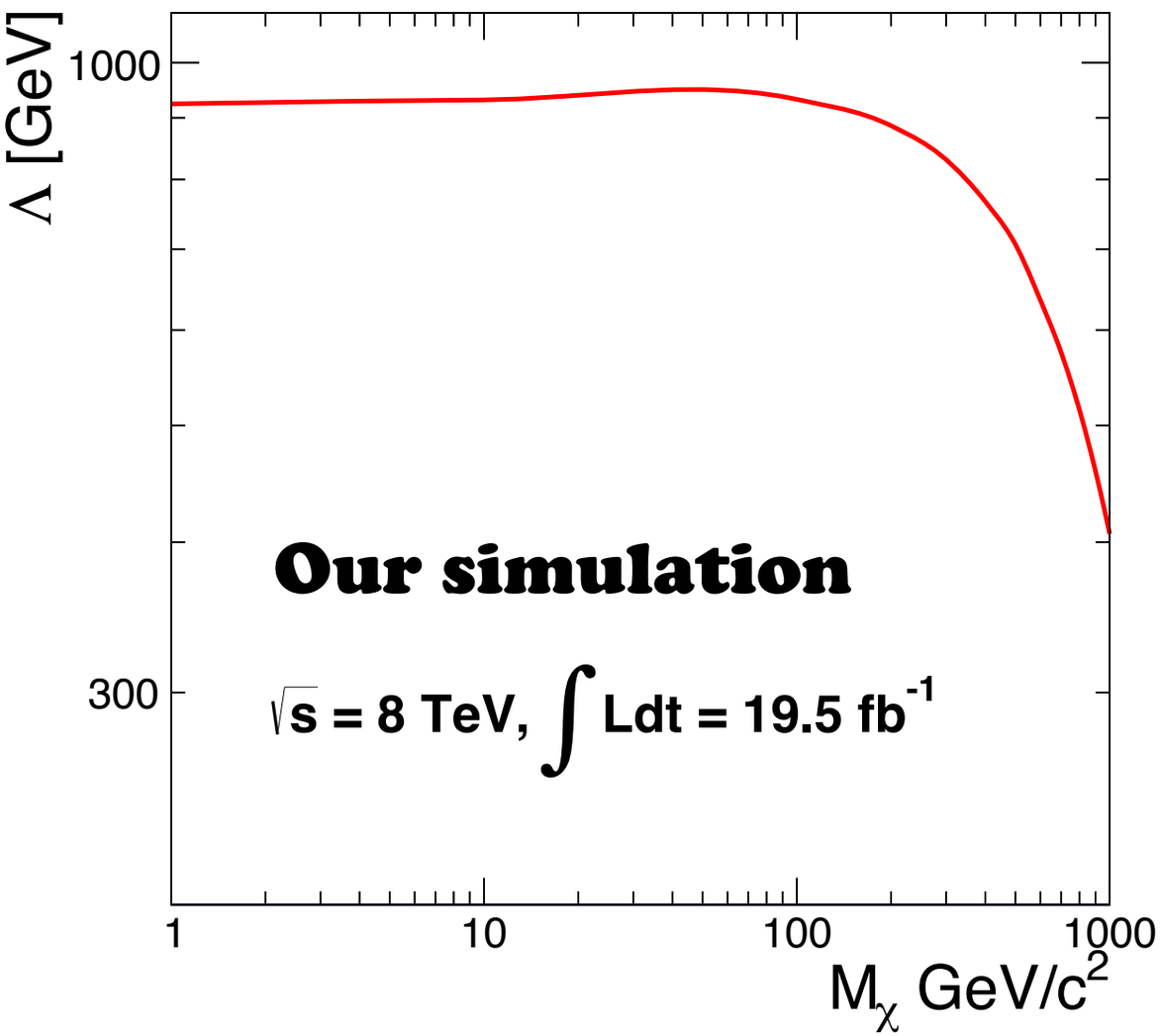
$\not{E}_T > 120 \text{ GeV}$

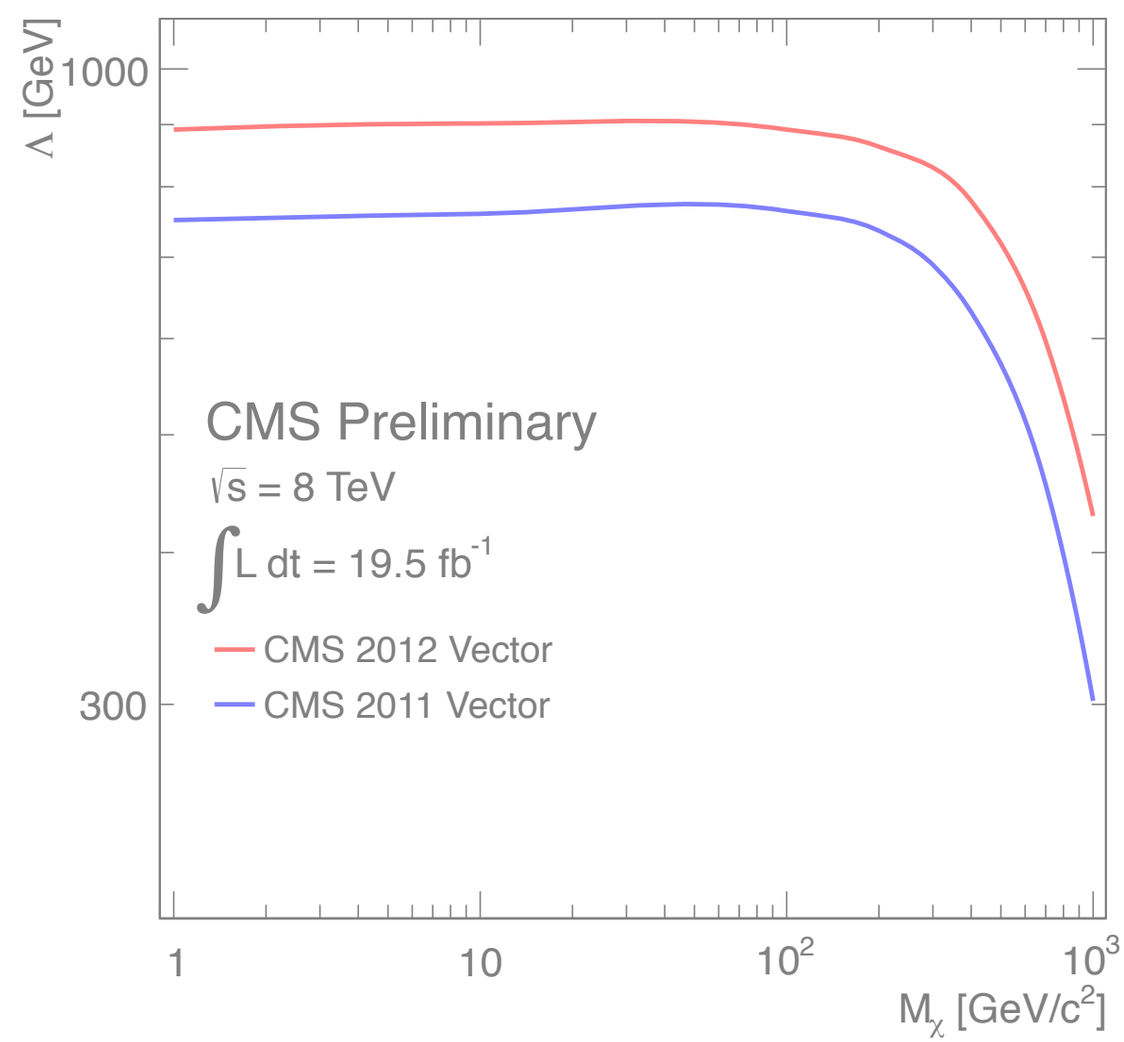
For events with a second jet, $\Delta\phi_{j_1 j_2} < 2.5$

- Events which pass those cuts are separated in seven signal regions according to the missing ET in the event.

LHC phenomenology I: monojet

- Checking our simulation using vector current contact effective operator.





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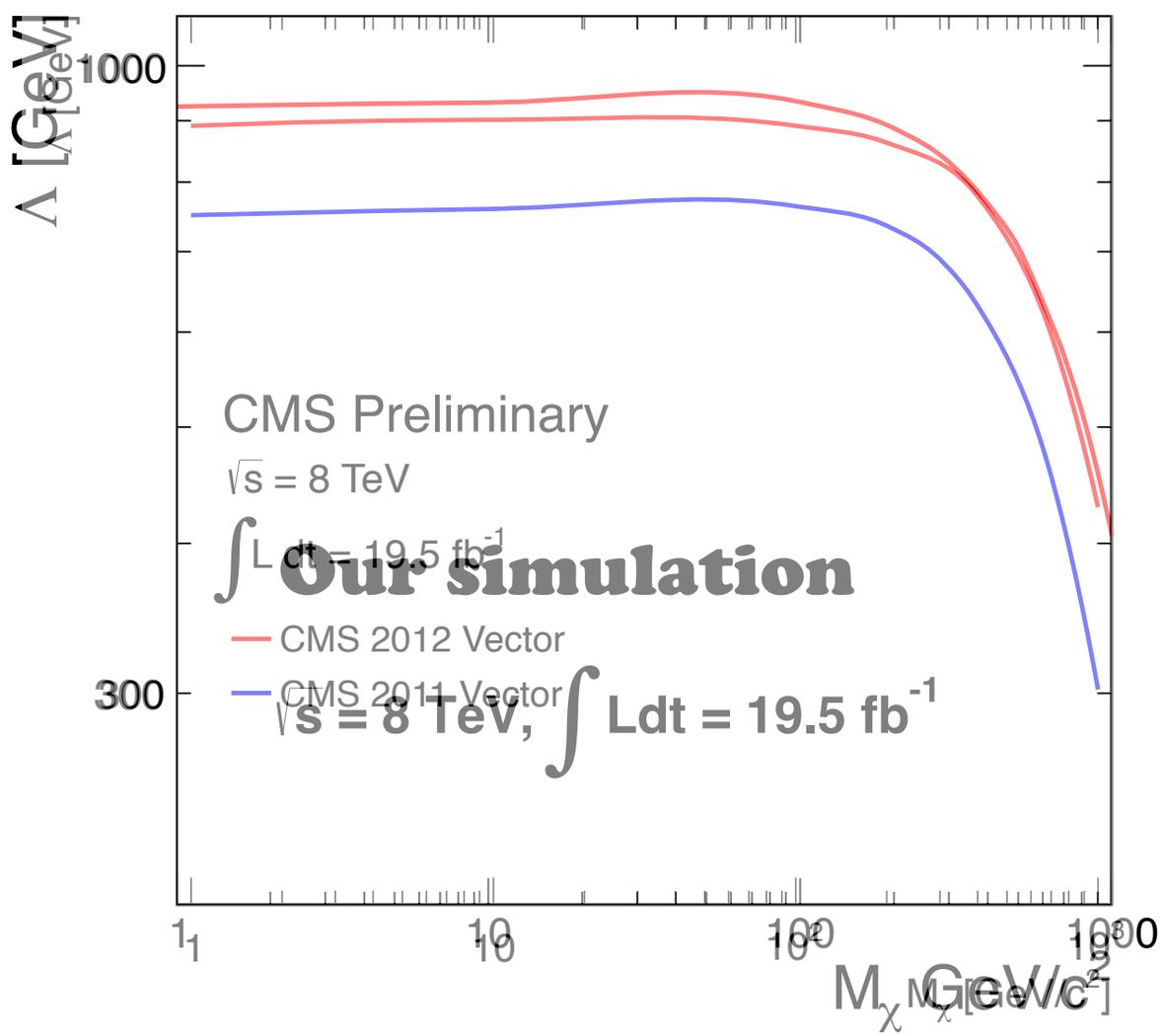
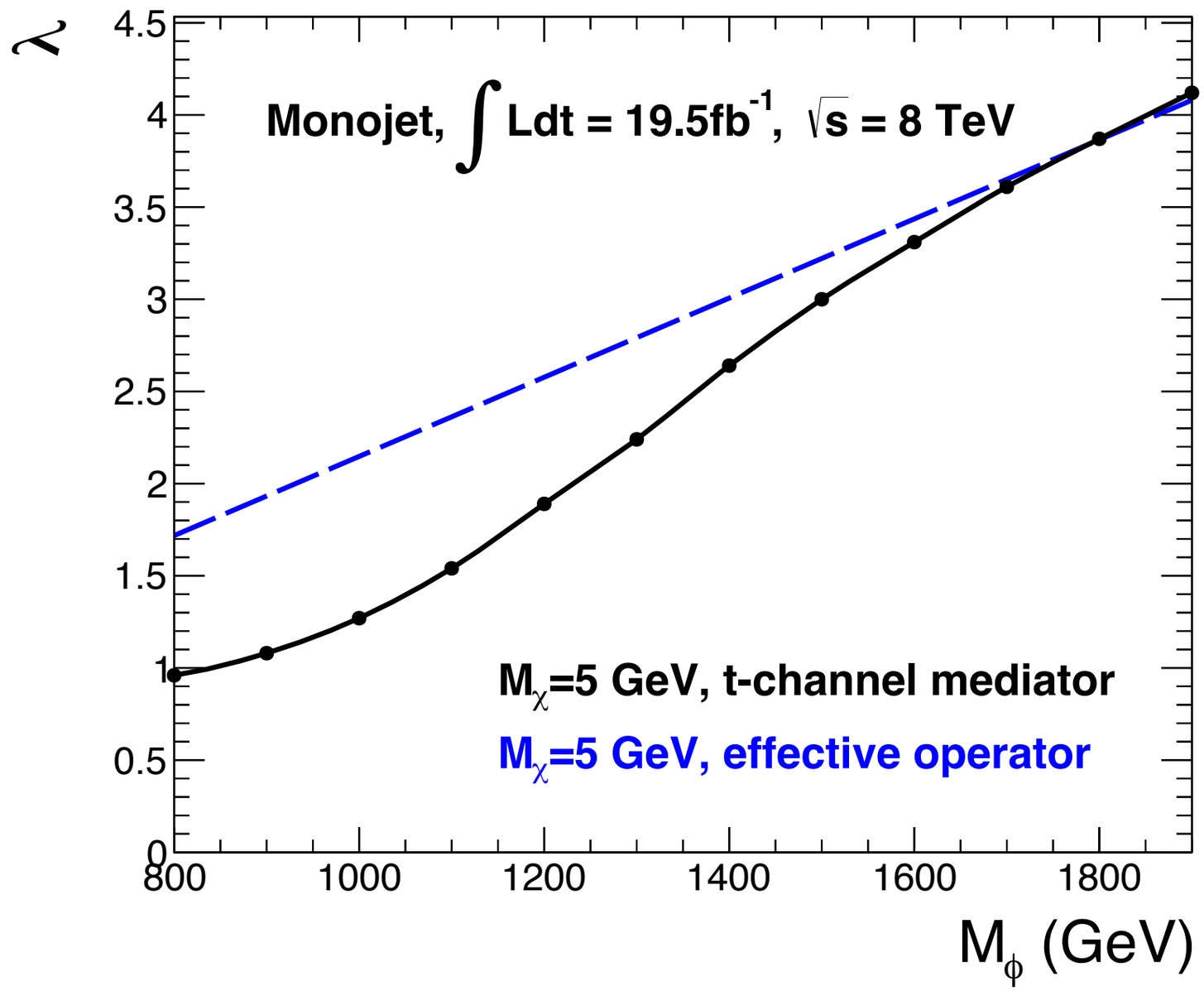


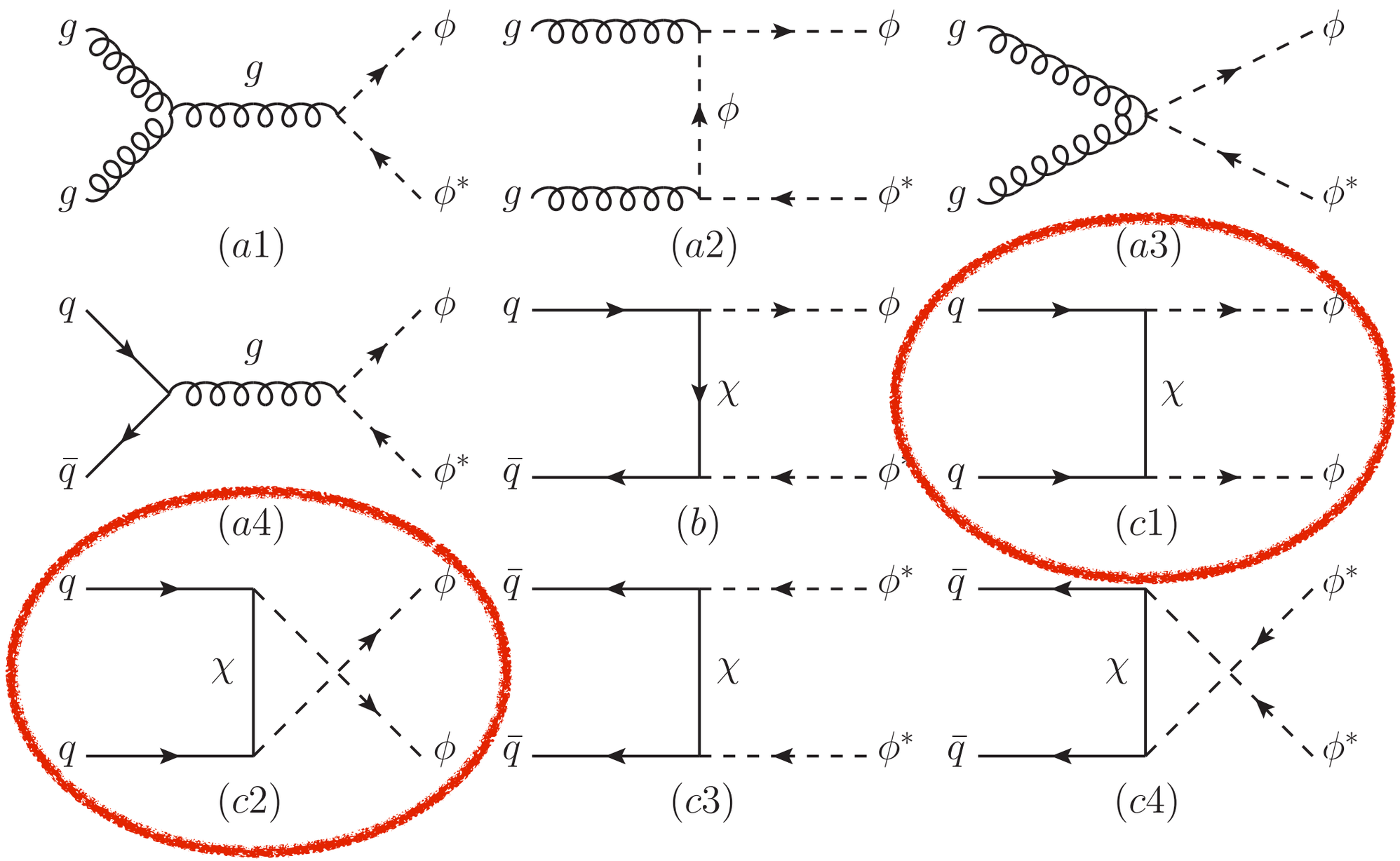
LHC phenomenology I: monojet

- Fix WIMP mass (5 GeV)



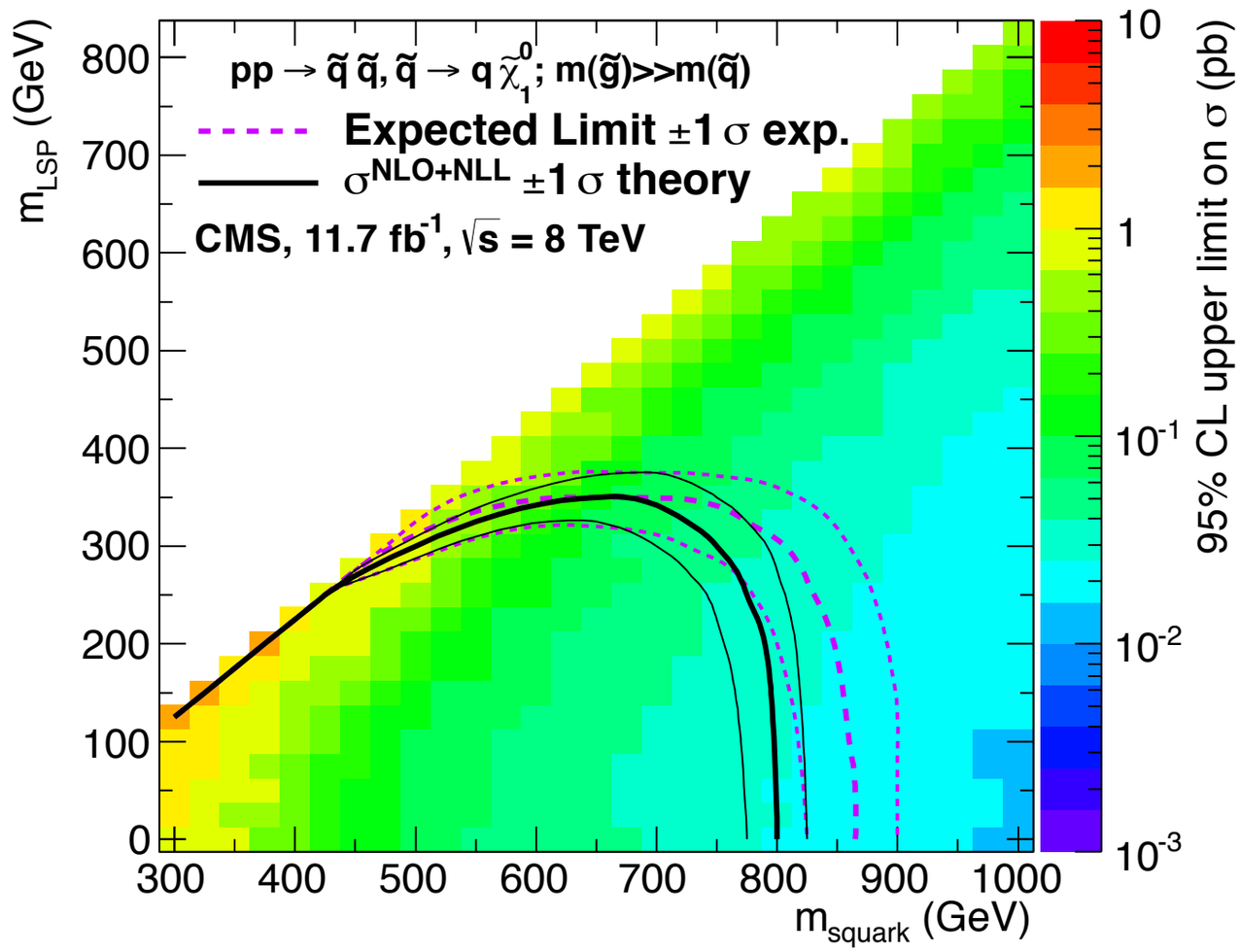
LHC phenomenology II: dijet

- The mediator is colored particle which can be produced by purely QCD process.



LHC phenomenology II: dijet

- The total cross section is calculated using MadGraph5/MadEvent
- A typical value of the K-factor is smaller than 1.05. We will neglect it in our calculation.
- We compare the parton level cross section with the unfolded result of squark search given by the CMS collaboration.



arXiv:1303.2985

LHC phenomenology II: dijet

- The constraint to the mediator mass depends on λ.
- 800 GeV med

  _ _ Dirac

  ..... Majorana
- 1.2 TeV med

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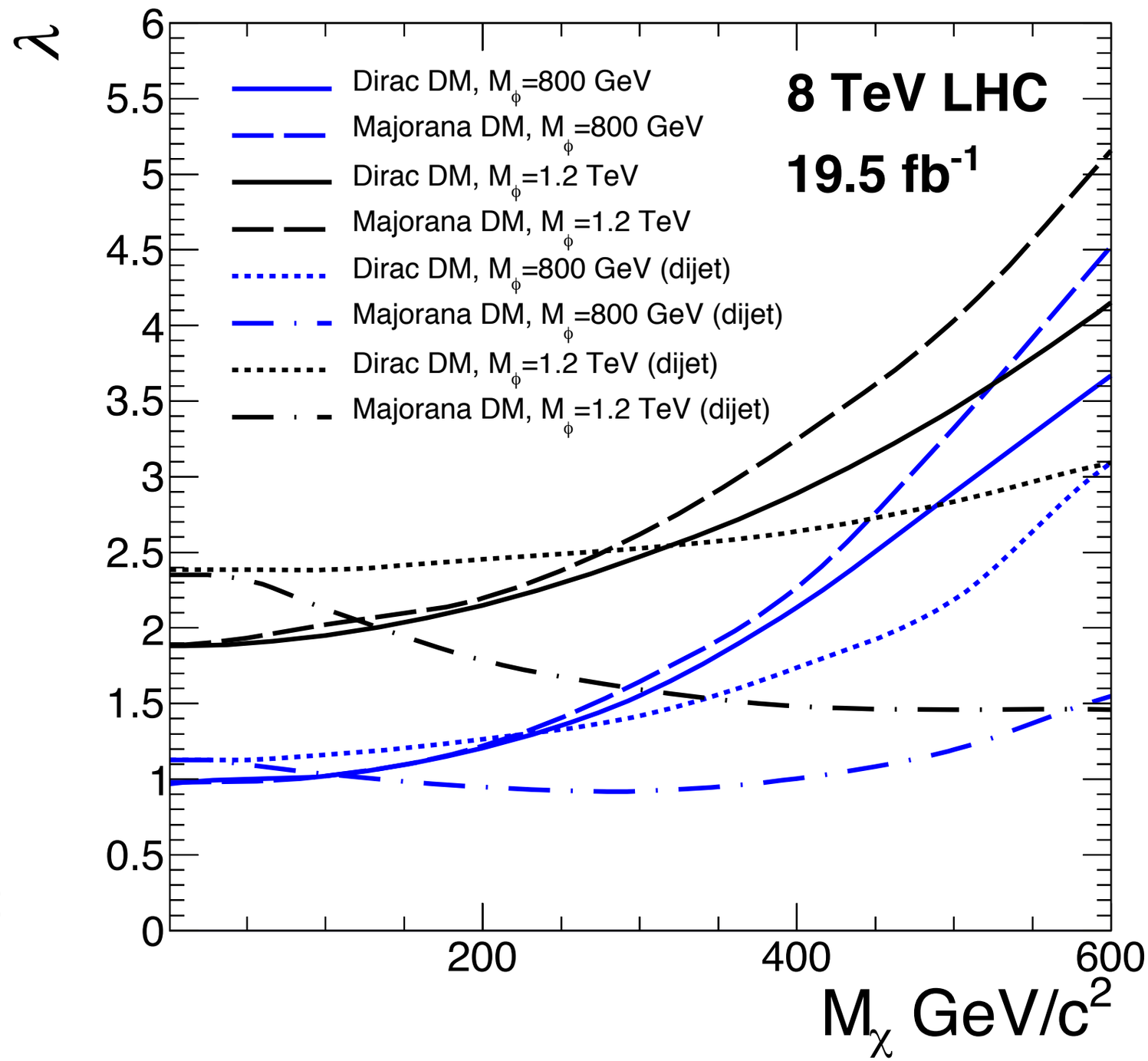
- Light DM: monojet dominant.
- Heavy DM: dijet dominant



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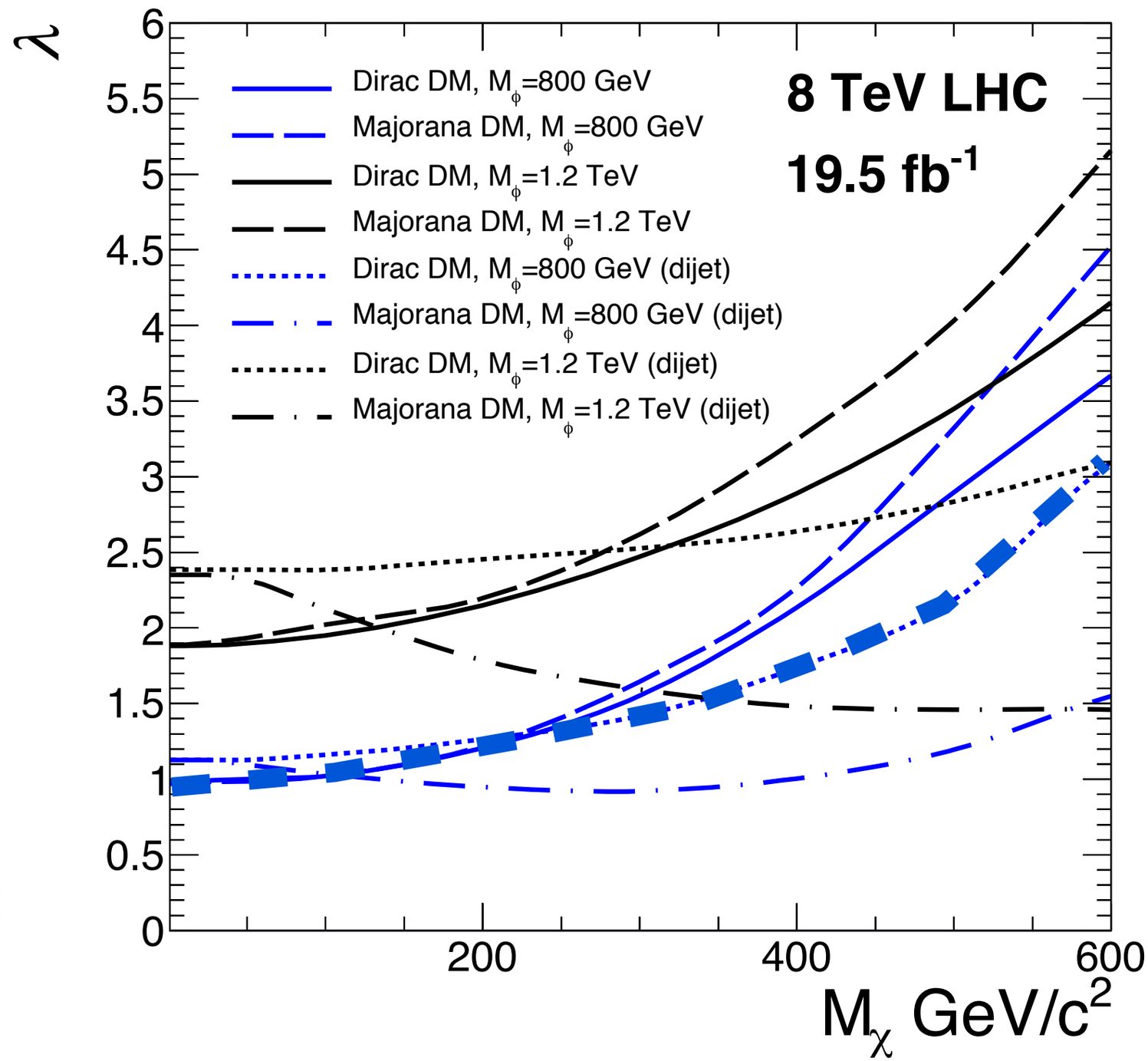

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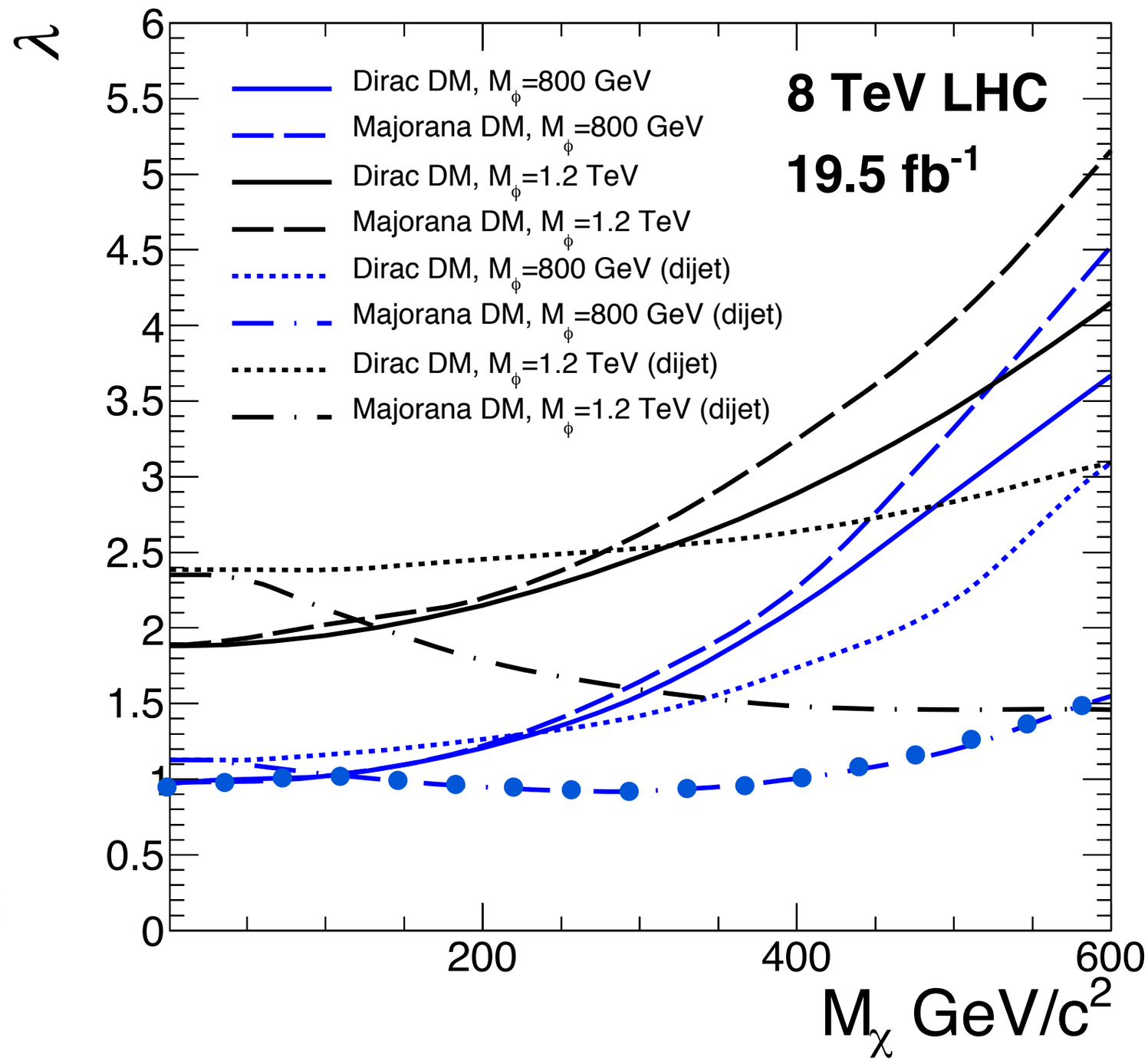

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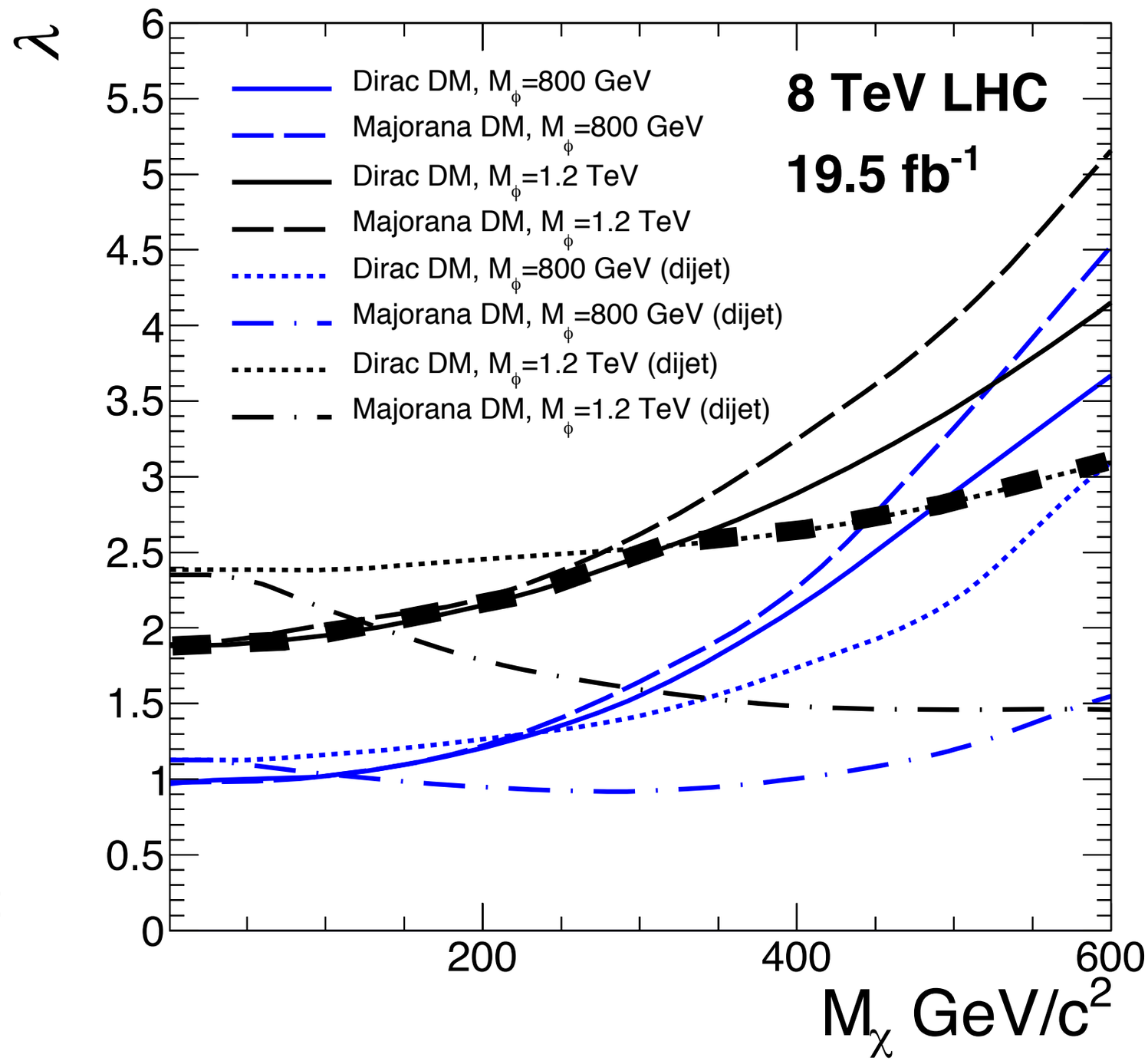

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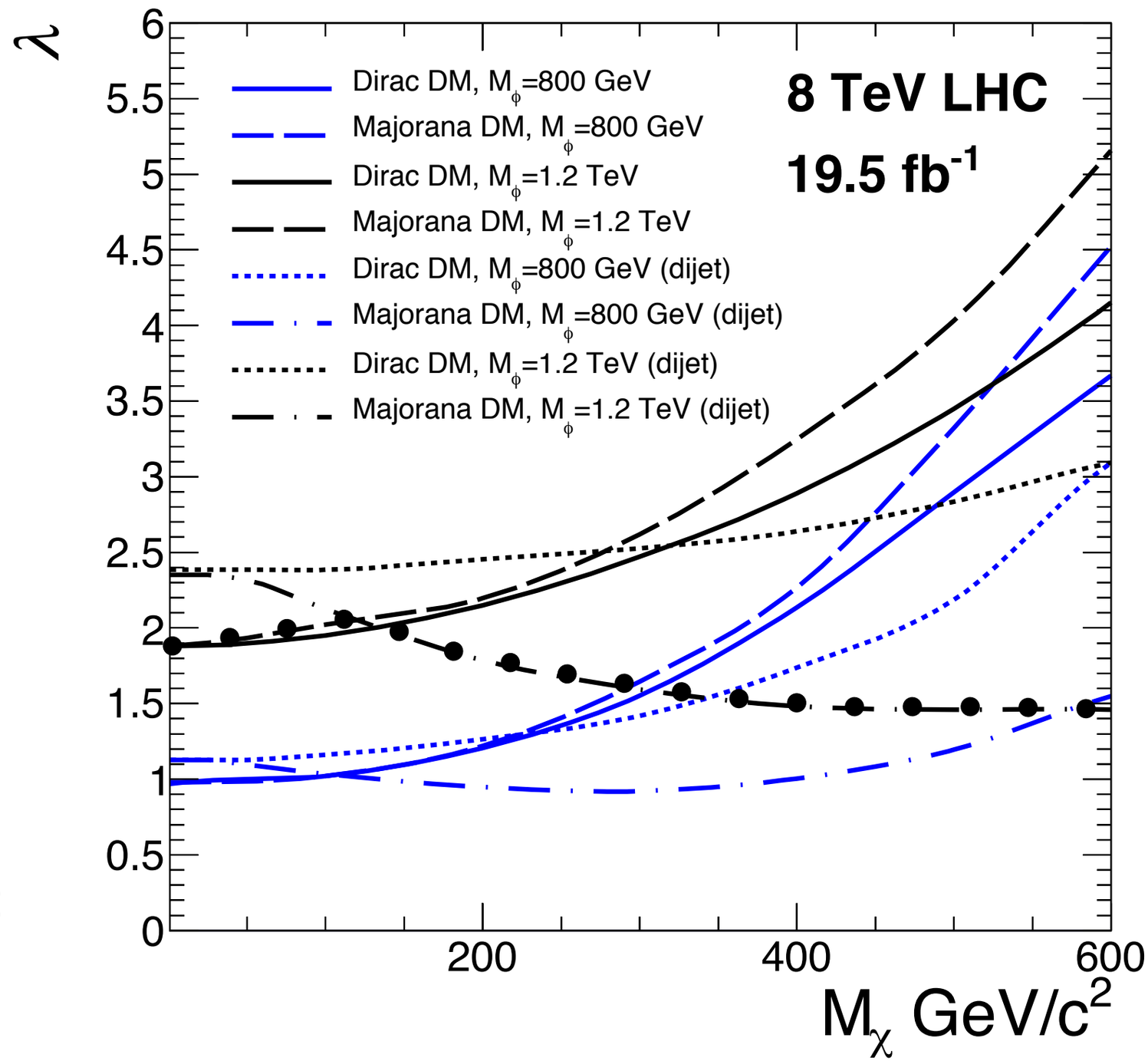
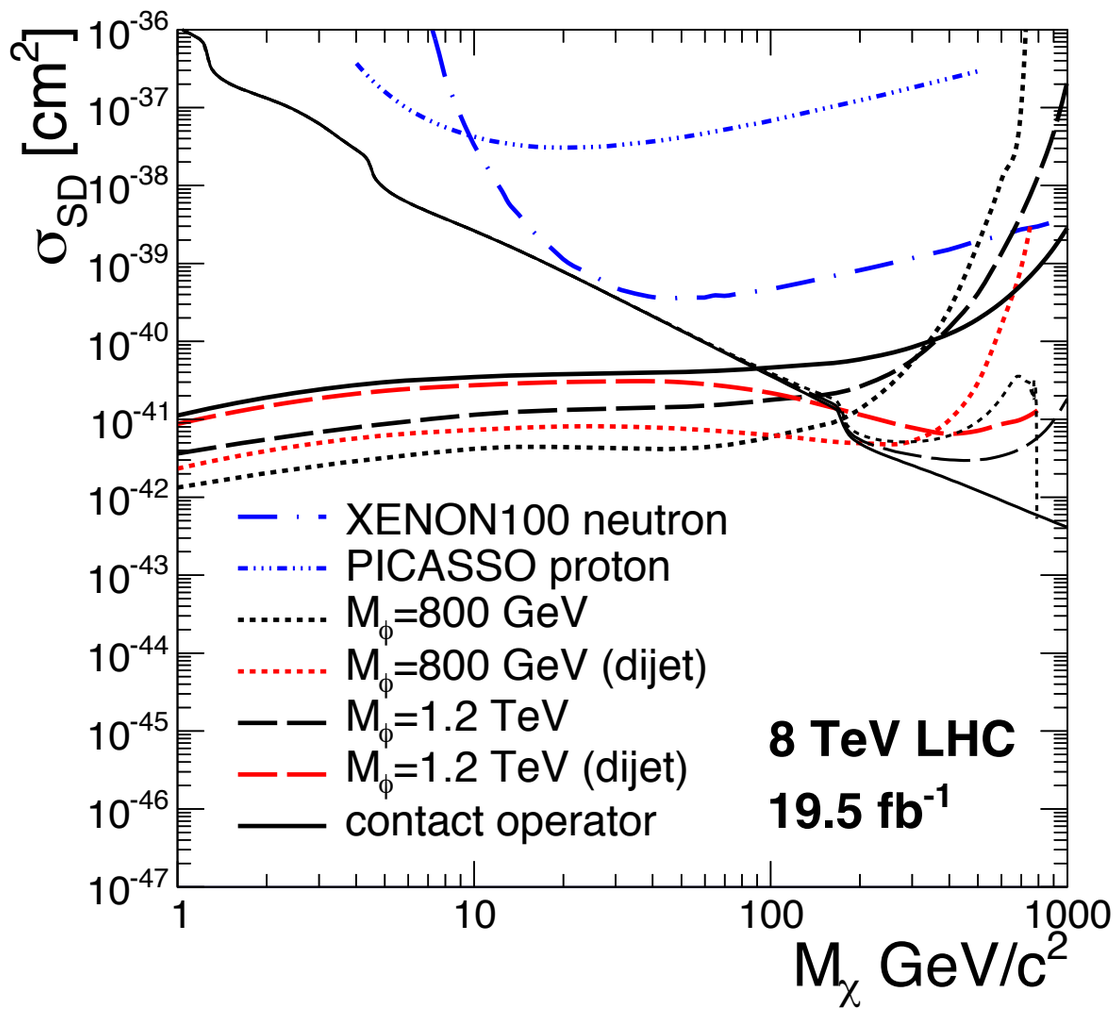
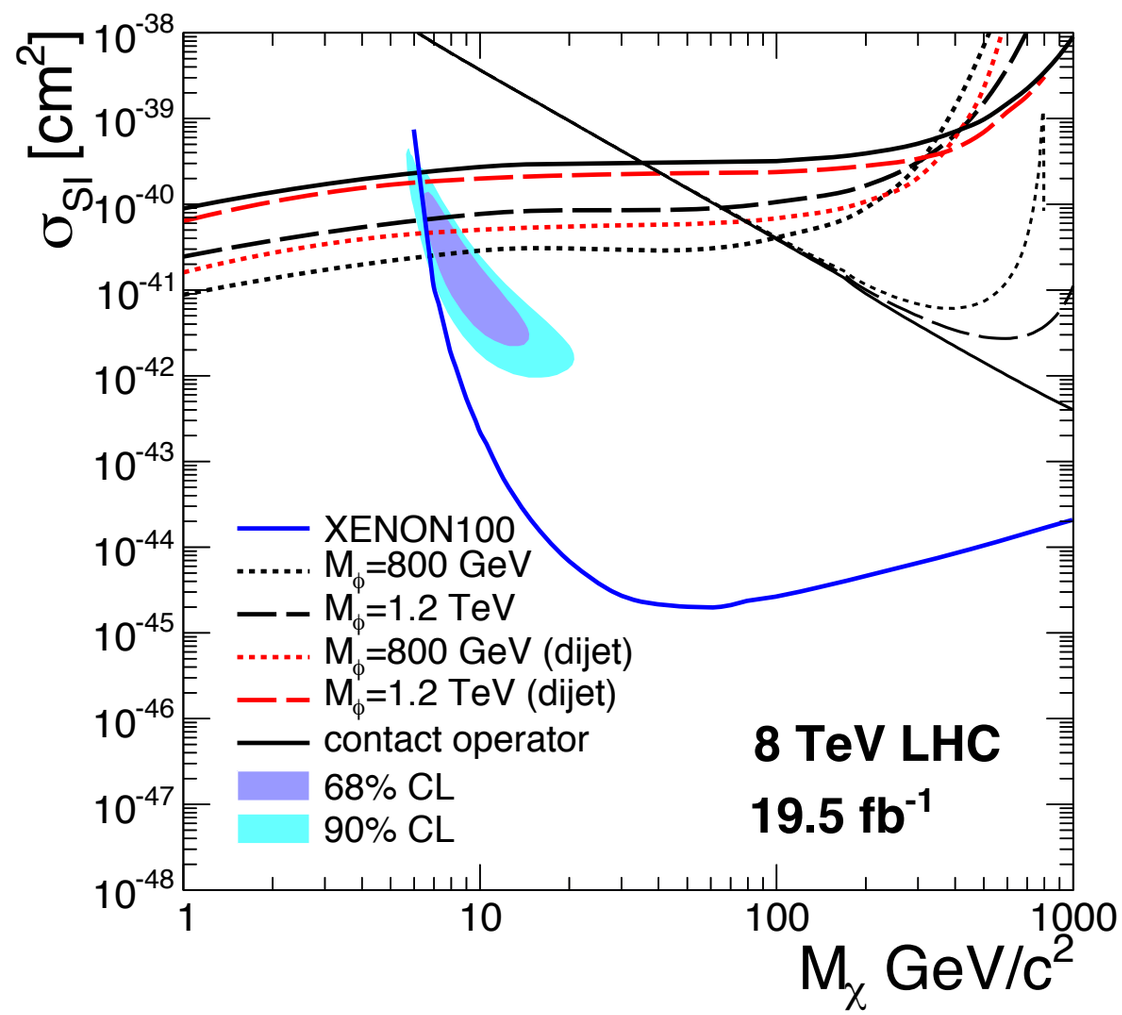


DM with t-channel mediator

- We compare the constraints to the t-channel mediator model from direct detection and 8 TeV LHC.
- The difference between the t-channel mediator model and the effective operator approximation is shown clearly in the figures.





Conclusion

- We study a simplified t-channel UV completion model where the interaction between DM and SM particles are mediated by colored mediators couples to the DM particle and the right-handed quarks.
- In this scenario, if the DM particle is Dirac, the dominant direct detection signal is SI, and the monojet+missing ET search starts to be sensitive to the interesting parameter space in the light DM region.
- In the case that the DM particle is Majorana, the dominant direct detection signal is SD, and the monojet+missing ET signal is stronger in the region that DM mass is smaller than a hundred GeV, and dijet +missing ET is more significant for heavier dark matter.
- Additional annihilation processes are needed for Dirac DM to give correct relic abundance. For Majorana DM, there is still allowed parameter region which can gives correct relic abundance.


Thank you!