On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC

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BASED ON:

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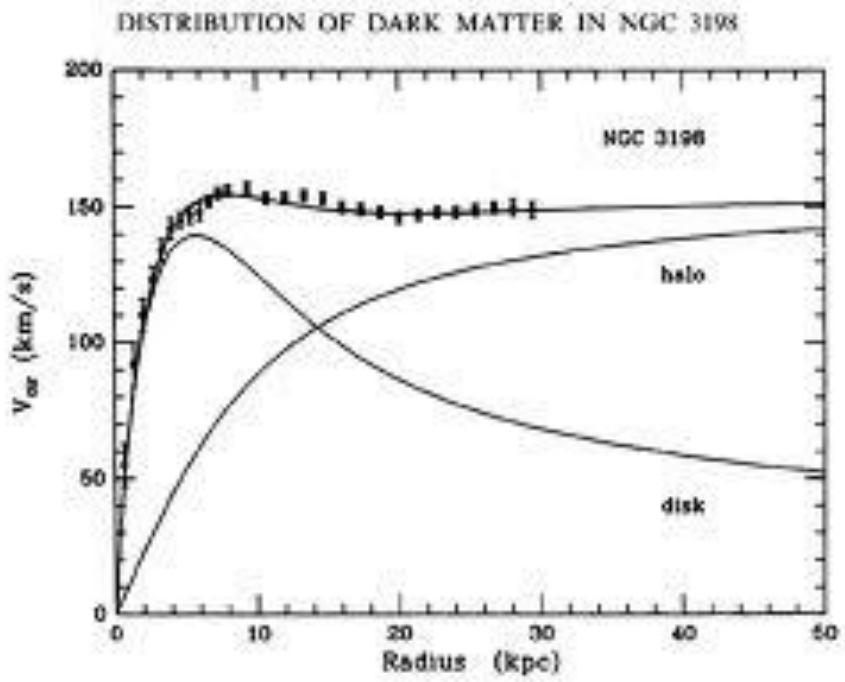
Outline of Presentation

On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC

1. Introduction to Dark Matter Searches
2. Introduction to EFT
3. Collider Searches, general considerations, some estimates
4. Importance of EFT cutoff
5. How to deal with EFT in collider searches
6. Conclusions and future…

Introduction to DM Searches: Observation Evidence

1. Galaxy Rotation Curves
2. Velocity Dispersion of Galaxies
3. Gravitational Lensing
4. CMB
5. More…

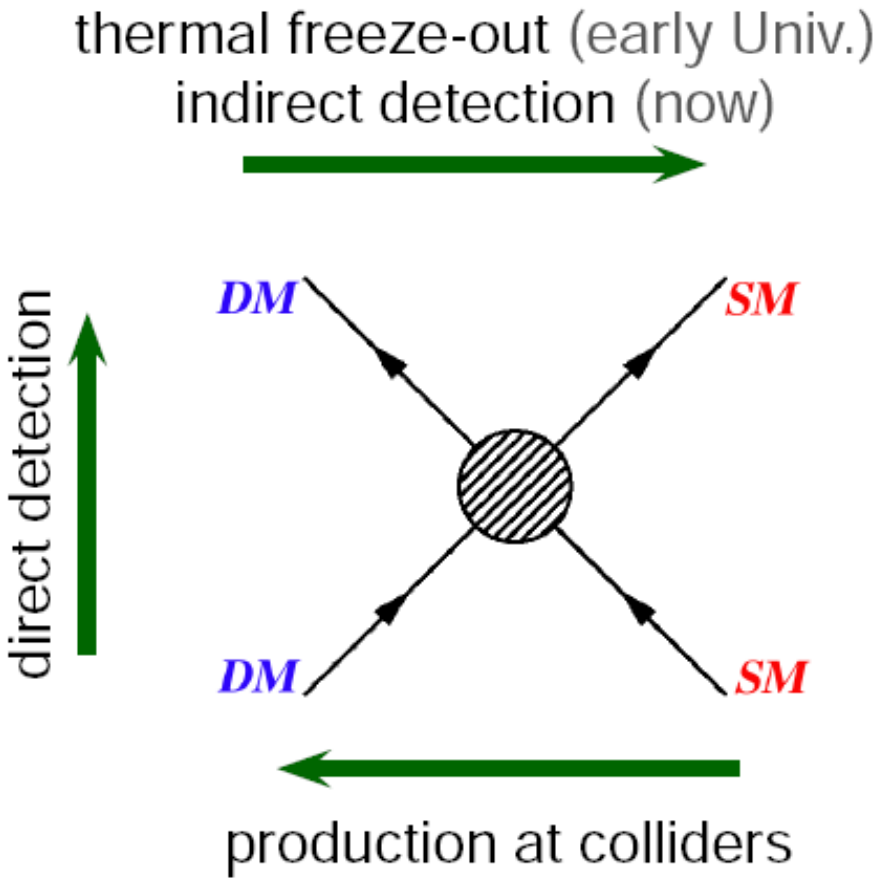


Dark Matter Searches

- 3 kind of searches:

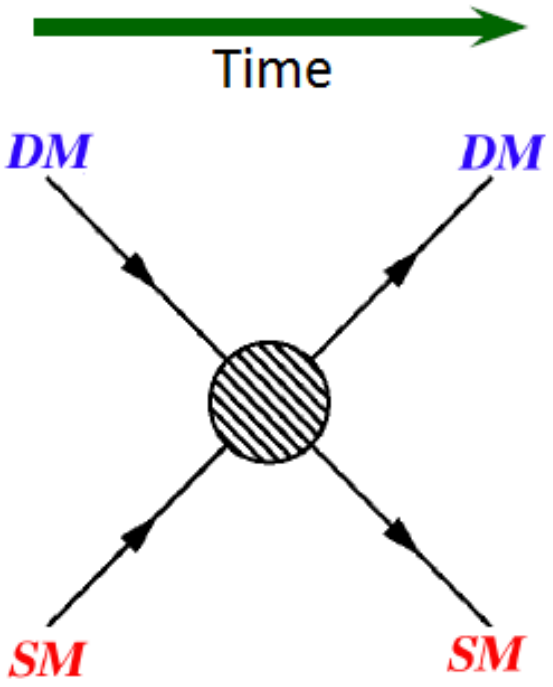
1. Direct Searches
2. Indirect Searches
3. Collider Searches

- We can use the crossing symmetry to relate the 3 searches



Dark Matter Direct Search

- DM Direct Searches →Direct DM-Barion interactions
- Deep underground laboratories → reduce the background from cosmic rays
- **Search for $O(KeV)$ energy deposited in detectors**
- Experiments: SNOLAB, XENON, DAMA, SIMPLE, PICASSO



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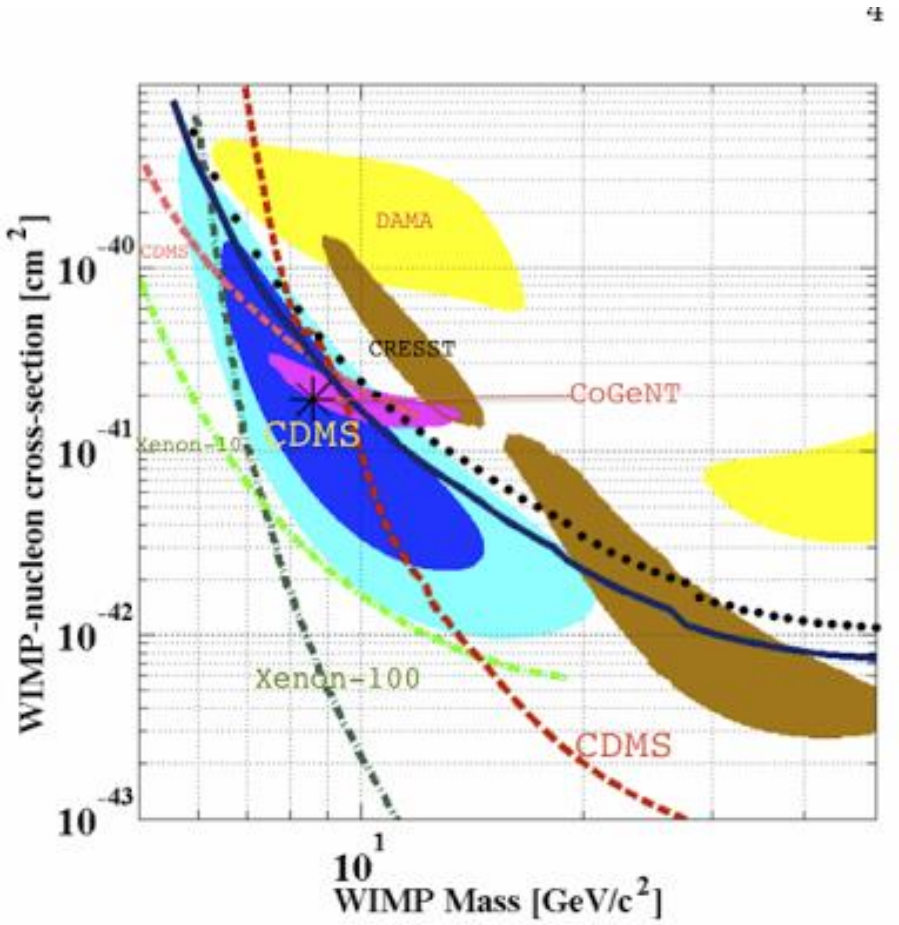
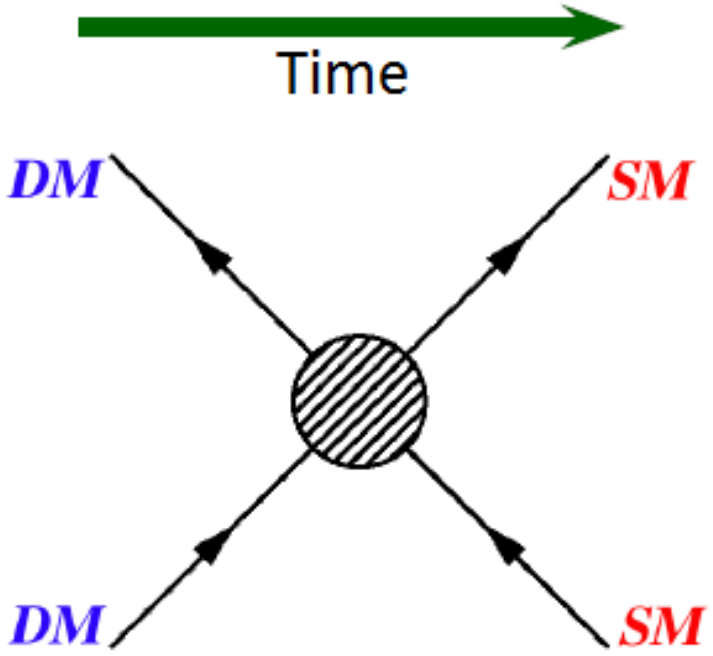


Dark Matter Indirect Search

- Indirect detection experiments → WIMP annihilation or decay
- Annihilation process happens at energies $\sim O(2m_{DM})$
- WIMPs Majorana particles → annihilate to SM particle/antiparticle pairs
- If WIMP unstable → could decay into SM particles ➔identify excesses in fluxes of cosmic rays: $e^+, \bar{p}, \nu$
- Problem: Background known with less precision!!!
- Experiments: PAMELA, AMS, AMANDA, ICECUBE, ANTARES



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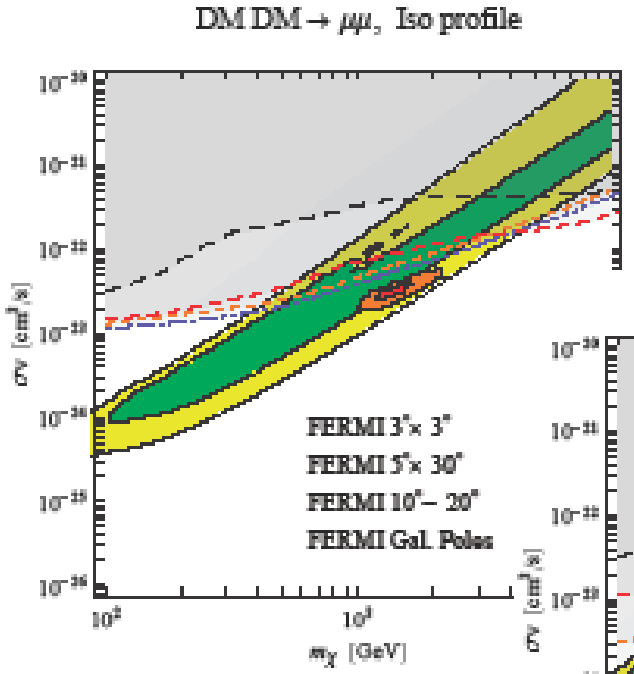
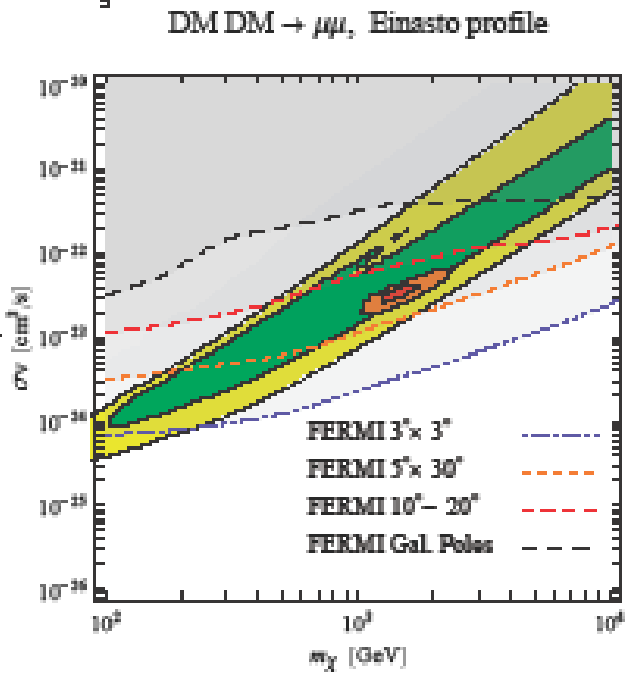
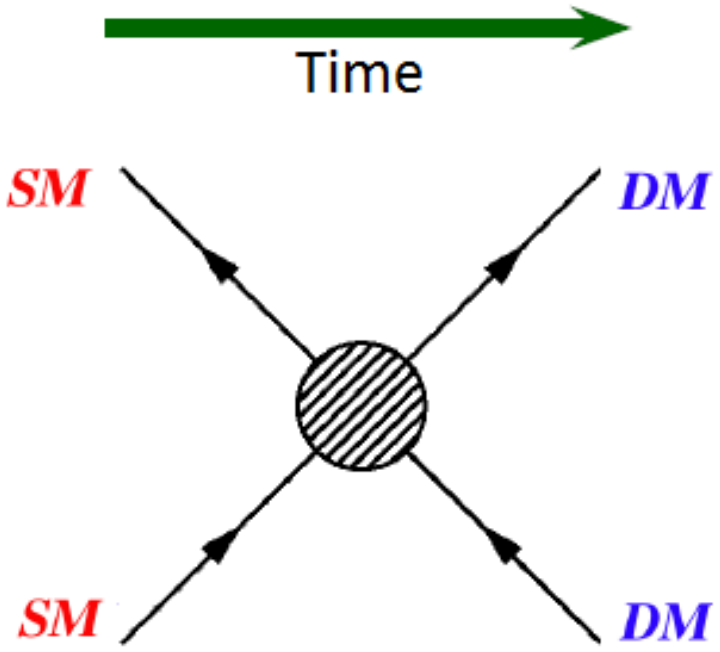




Collider DM Searches

- Search for mono-Jet/photon events with missing p_t
- DM would look like missing energy
- Background due to $Z \to \nu\bar{\nu}, W^{\pm} \to l\nu$
- Background known with better precision
- No energy threshold
- Higher energies involved
- Cannot determine if WIMP is stable or not
- Usually constrained in model-independent way using EFT ➔Bounds on effective operators



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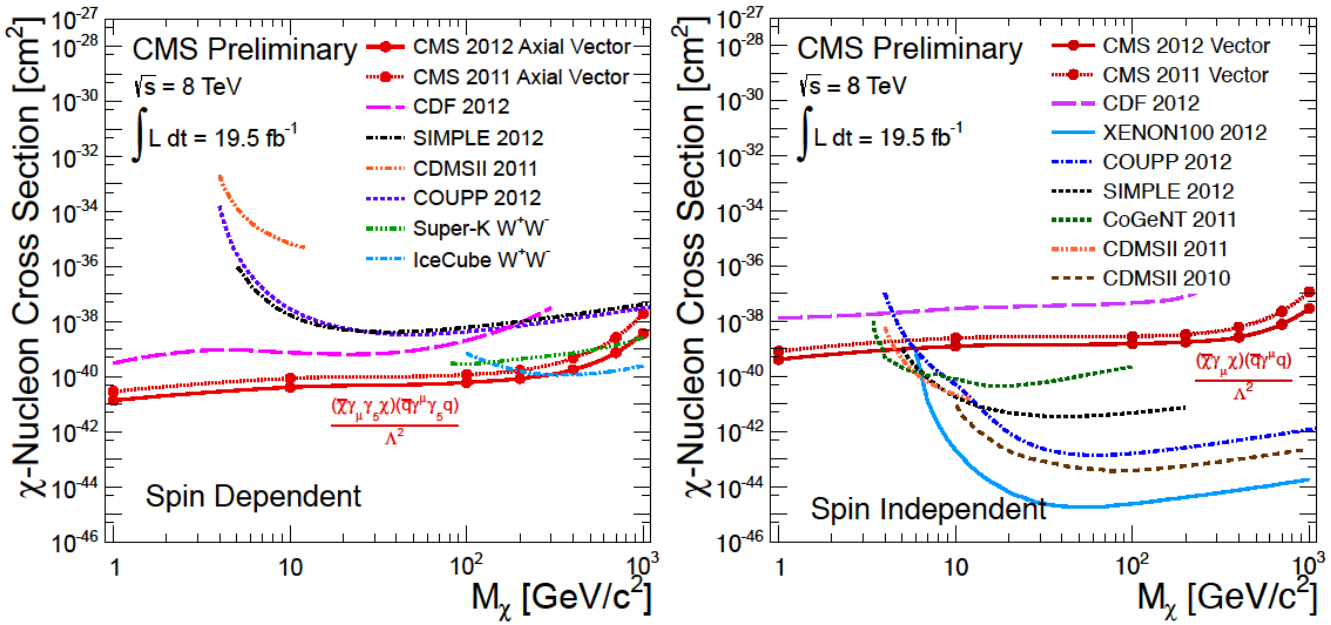


Introduction to EFT: Simple Toy Model

Let's consider a Lagrangian with 2 light fermions and 1 heavy scalar as mediator:

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_1\right)\psi + \bar{\chi}\left(i\gamma^{\mu}\partial_{\mu} - m_2\right)\chi + \frac{1}{2}\partial_{\mu}\phi\partial^{\mu}\phi - \frac{1}{2}M^2\phi^2 + \mathrm{g}(\bar{\psi}\psi + \bar{\chi}\chi)\phi$$

If $M \gg m_1, m_2$, for low energy processes we can "simplify" the model by Integrating Out the heavy scalar mediator by using the Euler-Lagrangian Equations for ϕ

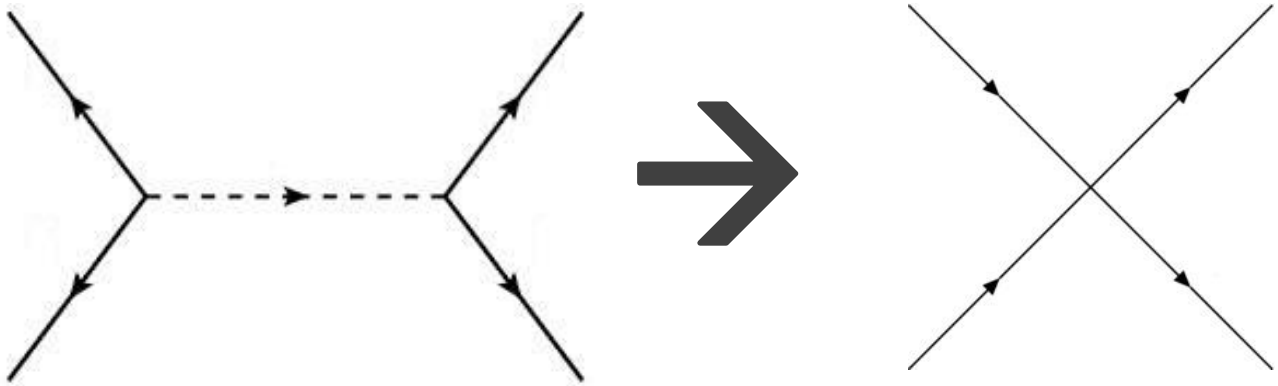
At order 0, we obtain

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_1\right)\psi + \bar{\chi}\left(i\gamma^{\mu}\partial_{\mu} - m_2\right)\chi + \frac{1}{2}\frac{g^2}{M^2}\left(\bar{\psi}\psi + \bar{\chi}\chi\right)^2$$

Introduction to EFT: Simple Toy Model

Operators of Dimension 6 appear in the Lagrangian:

$$\frac{1}{2}\frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\chi}\chi + \frac{1}{2}\frac{g^2}{M^2}\bar{\chi}\chi\bar{\chi}\chi$$



Introduction to EFT: Simple Toy Model

We can obtain the same result by considering the amplitude for the UV model, and expanding the propagator in powers of $\left(\frac{s}{M^2}\right)$ (s-channel process)

$$g^2 \frac{-i}{Q_{transf}^2 - M^2} = \frac{ig^2}{M^2}\left(1 + \frac{Q_{transf}^2}{M^2} + \left(\frac{Q_{transf}^2}{M^2}\right)^2 + \cdots\right) \sim \frac{i}{\Lambda^2}$$

From this expression we can easily understand that this kind of approximation is good only if

$$Q_{transf}^2 \ll M^2$$

This, if also $m \ll M$ (or at east $m < M$), is verified in

- Direct Searches, where kinetic energy is $O(KeV)$, and therefore $Q_{transf}^2 \sim O(KeV)$
- Indirect Searches, where $Q_{transf}^2 \sim O(2m)$

Collider Searches, General considerations

- In general for the EFT to be valid we require $\Lambda \gtrsim Q_{transf}$
- From the previous 2 slides, by Matching the 2 expressions of the propagator, we obtain

$$\frac{1}{\Lambda^2} = \frac{g^2}{M^2}$$

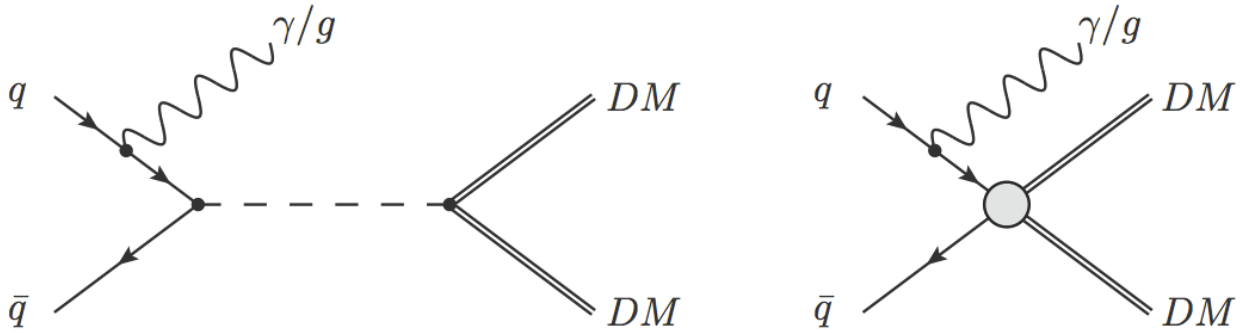
- We want the Mediator to be heavier than DM particle, and the new coupling not to be strong:

$$M > m_{DM}, g^2 < 4\pi, \rightarrow \Lambda > \frac{m_{DM}}{4\pi}$$

- Matching also requires: $M \geq Q_{transf} \rightarrow \Lambda > \frac{Q_{transf}}{4\pi}$
- 2-2 process: DM is produced on shell → $Q_{transf} \geq 2m_{DM}$ → $\Lambda \gtrsim \frac{m_{DM}}{2\pi}$

Some Estimates

2-3 body processes: mono-photon/jet + DM pair

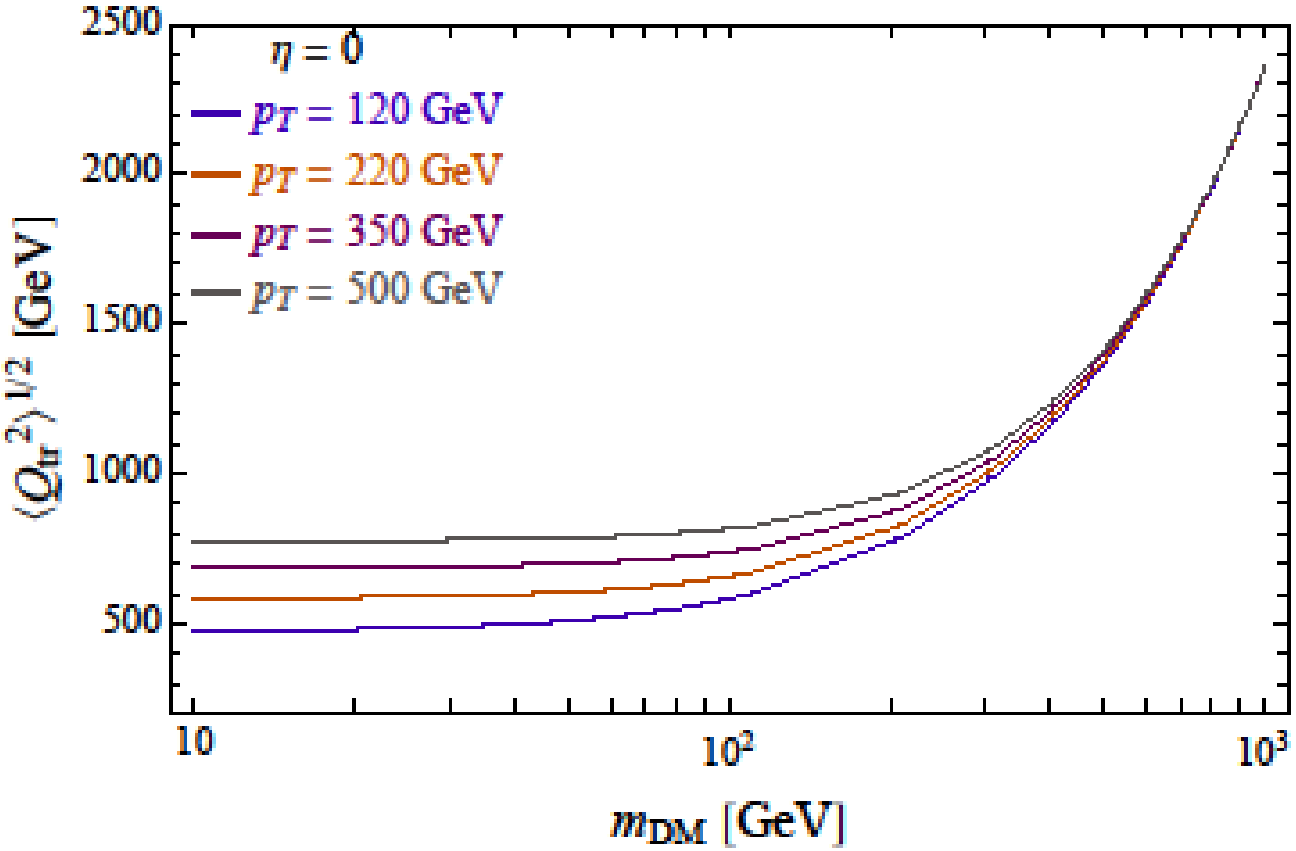


The momentum transfer is $Q^2_{transf} = x_1 x_2 s - \sqrt{s} p_T (x_1 e^{-\eta} + x_2 e^{\eta})$

Simple estimate → averaging Q^2_{transf} on the PDF

$$\langle Q^2_{transf} \rangle = \frac{\sum_q \int dx_1 dx_2 \left(f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1) \right) \theta\left(Q_{transf} - 2m_{DM}\right) Q^2_{transf}}{\sum_q \int dx_1 dx_2 \left(f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1) \right) \theta\left(Q_{transf} - 2m_{DM}\right)}$$

Estimates


$\eta = 0$
$p_T = 120$ GeV
$p_T = 220$ GeV
$p_T = 350$ GeV
$p_T = 500$ GeV
2500
2000
1500
1000
500
$\langle Q_{tr}^2 \rangle^{1/2}$ [GeV]
10
10^2
10^3
m_{DM} [GeV]

EFT Cutoff

The cross sections for the process $\bar{q}q \longrightarrow \bar{\chi}\chi g$ are:

$$\frac{d^2\hat{\sigma}_{eff}}{dp_T d\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_T}\frac{1}{\Lambda^4}\frac{\left(Q_{transf}^2 - 4m_{DM}^2\right)^{\frac{3}{2}}\left(1 + \left(\frac{Q_{transf}^2}{x_1 x_2 s}\right)^2\right)}{Q_{transf}}$$

$$\frac{d^2\hat{\sigma}_{UV}}{dp_T d\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_T}\frac{g_g^2 g_\chi^2}{\left(Q_{transf}^2 - M^2\right)^2}\frac{\left(Q_{transf}^2 - 4m_{DM}^2\right)^{\frac{3}{2}}\left(1 + \left(\frac{Q_{transf}^2}{x_1 x_2 s}\right)^2\right)}{Q_{transf}}$$

The corresponding cross sections for $pp \longrightarrow \bar{\chi}\chi g$ are obtained by integrating over the PDFs and summing over the possible quarks:

$$\frac{d^2\sigma}{dp_T d\eta} = \sum_q \int dx_1 dx_2 dp_T d\eta \left(f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1)\right)\theta\left(Q_{transf} - 2m_{DM}\right)\frac{d^2\hat{\sigma}}{dp_T d\eta}$$

Extract Limits on Lambda

From experiment, we get upper bound on the number of events $N < N_{exp}$

The number of events is calculated as luminosity times cross section:

$$N = \mathcal{L} \int dp_T d\eta \sum_q \int dx_1 dx_2 dp_T d\eta \left(f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1) \right) \theta\left(Q_{transf} - 2m_{DM}\right) \frac{\alpha_s}{36\pi^2} \frac{1}{p_T} \frac{1}{\Lambda^4} \frac{\left(Q_{transf}^2 - 4m_{DM}^2\right)^{\frac{3}{2}} \left(1 + \left(\frac{Q_{transf}^2}{x_1 x_2 s}\right)^2\right)}{Q_{transf}}$$

We can take out of the integral and solve the inequality

$$N = \frac{1}{\Lambda^4} \mathcal{L} \int dp_T d\eta \sum_q \int dx_1 dx_2 dp_T d\eta \left(f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1) \right) \theta\left(Q_{transf} - 2m_{DM}\right) \frac{\alpha_s}{36\pi^2} \frac{1}{p_T} \frac{\left(Q_{transf}^2 - 4m_{DM}^2\right)^{\frac{3}{2}} \left(1 + \left(\frac{Q_{transf}^2}{x_1 x_2 s}\right)^2\right)}{Q_{transf}}$$

$$N = \frac{1}{\Lambda^4} \mathrm{f}(m_{DM}) < N_{exp}$$

$$\Lambda > \sqrt[4]{\frac{1}{N_{exp}} \mathrm{f}(m_{DM})} = \Lambda_{exp}$$

This procedure would be ok if all the events in the integration domain would statisfy $\Lambda \gtrsim Q_{transf}$

This is not the case at LHC!

Extract Limits on Lambda

For $Q_{transf} > \Lambda$, we don't know if the Eft is a good approximation of the unknown UV theory.

It may happen that $\frac{d^2\hat{\sigma}_{eff}}{dp_T d\eta} > \frac{d^2\hat{\sigma}_{UV}}{dp_T d\eta}$ or also that $\frac{d^2\hat{\sigma}_{eff}}{dp_T d\eta} < \frac{d^2\hat{\sigma}_{UV}}{dp_T d\eta}$.

To be conservative, we choose the worst case: $\frac{d^2\hat{\sigma}_{UV}}{dp_T d\eta} = 0$ for such events.

Then

$$N = \mathcal{L} \int dp_T d\eta \sum_q \int dx_1 dx_2 dp_T d\eta \left(f_q(x_1) f_{\bar{q}}(x_2) + f_q(x_2) f_{\bar{q}}(x_1)\right) \theta\left(Q_{transf} - 2m_{DM}\right) \frac{\alpha_s}{36\pi^2} \frac{1}{p_T} \frac{1}{\Lambda^4} \frac{\left(Q_{transf}^2 - 4m_{DM}^2\right)^{\frac{3}{2}} \left(1 + \left(\frac{Q_{transf}^2}{x_1 x_2 s}\right)^2\right)}{Q_{transf}} \theta\left(\Lambda - Q_{transf}\right)$$

$$N = \frac{1}{\Lambda^4} \mathrm{g}(m_{DM}, \Lambda) < N_{exp}$$

$$\Lambda > \sqrt[4]{\frac{1}{N_{exp}} \mathrm{g}(m_{DM}, \Lambda)} = \sqrt[4]{\frac{1}{N_{exp}} \mathrm{f}(m_{DM})} \sqrt[4]{\frac{\mathrm{g}(m_{DM}, \Lambda)}{\mathrm{f}(m_{DM})}} = \Lambda_{exp} \sqrt[4]{\frac{\sigma_{\Lambda > Q_{transf}}}{\sigma}}$$

With this procedure we can obtain limits respecting the EFT assumption from the limits obtained without taking the EFT assumption into account!

EFT Cutoff

Up to which value of m_{DM} is the EFT approach valid? In order to quantify our ignorance about this, we study the ratio

$$R_{\Lambda}^{tot} = \frac{\sigma_{eff}\big|_{Q_{transf}<\Lambda}}{\sigma_{eff}}$$

For as a function of Λ and m_{DM}.

Typical experimental cuts, $500GeV < p_T < 2TeV$ and $|\eta| < 2$.

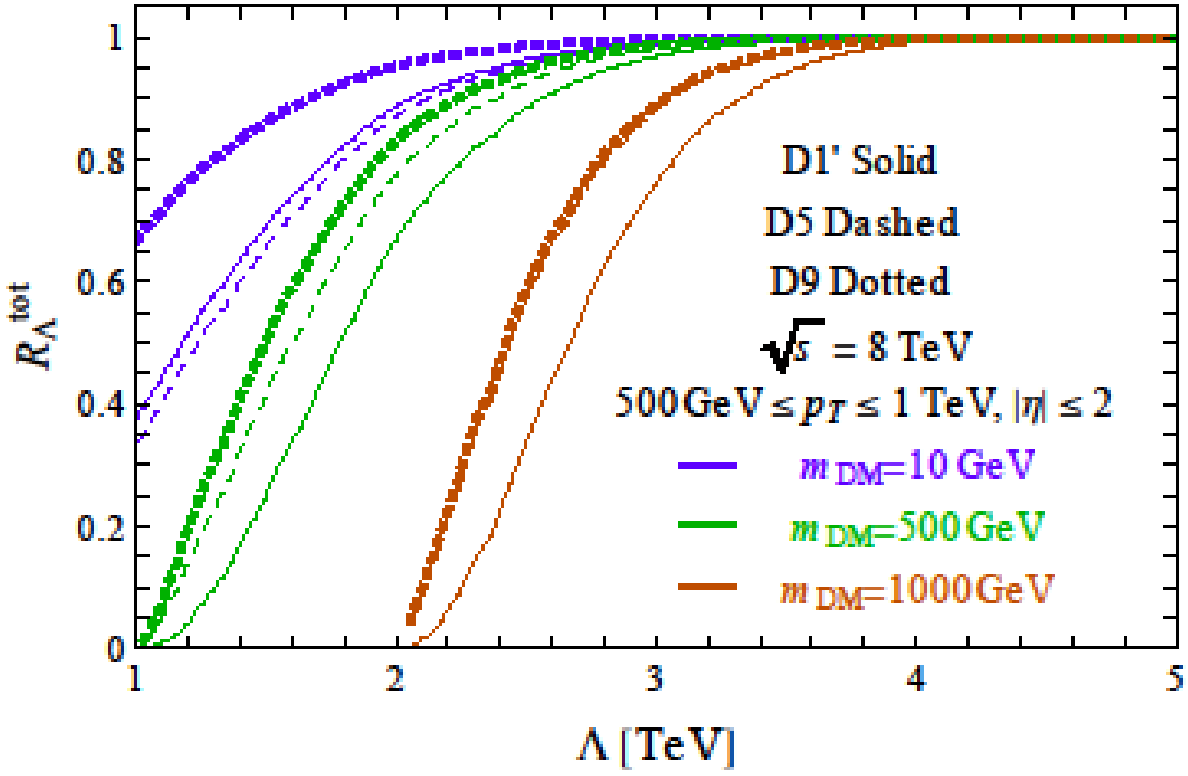
Not putting a cutoff ➔ **<u>May produce up to O(1) Errors</u>**

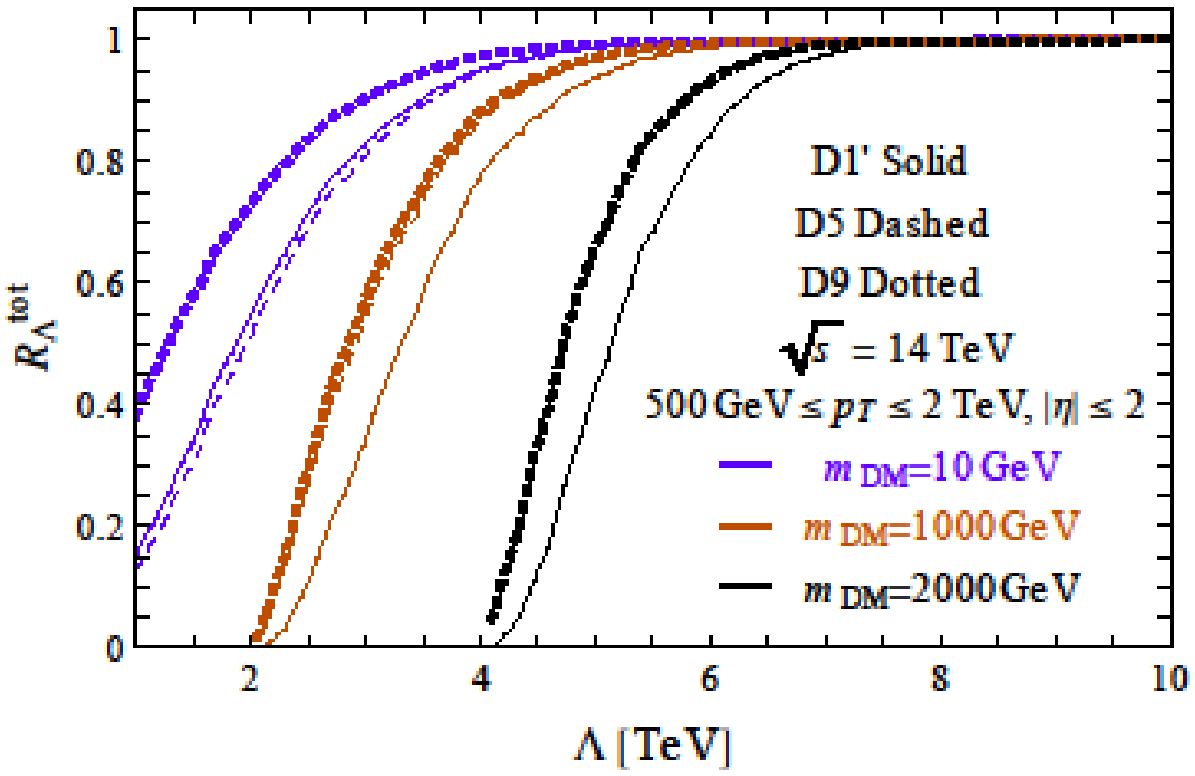
Of course the precision definition of the cutoff scale is somewhat arbitrary, and one should consider these results with a grain of salt

EFT Cutoff: Operators Considered

Name	Operator	Coefficient
D1,(D3)	$\bar{\chi}\chi\bar{\psi}\psi$	m_q/Λ^3
D4,(D2)	$\bar{\chi}\gamma^5\chi\bar{\psi}\gamma^5\psi$	m_q/Λ^3
D1',(D3')	$\bar{\chi}\chi\bar{\psi}\psi$	$1/\Lambda^2$
D4',(D2')	$\bar{\chi}\gamma^5\chi\bar{\psi}\gamma^5\psi$	$1/\Lambda^2$
D5,(D7)	$\bar{\chi}\gamma_\mu\chi\bar{\psi}\gamma^\mu\psi$	$1/\Lambda^2$
D8,(D6)	$\bar{\chi}\gamma_\mu\gamma^5\chi\bar{\psi}\gamma^\mu\gamma^5\psi$	$1/\Lambda^2$
D9,(D10)	$\bar{\chi}\sigma_{\mu\nu}\chi\bar{\psi}\sigma^{\mu\nu}\psi$	$1/\Lambda^2$
D11	$\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	$\alpha_s/4\Lambda^3$
D12	$\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D13	$\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D14	$\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\alpha_s/4\Lambda^3$

EFT Cutoff: Analytic Results





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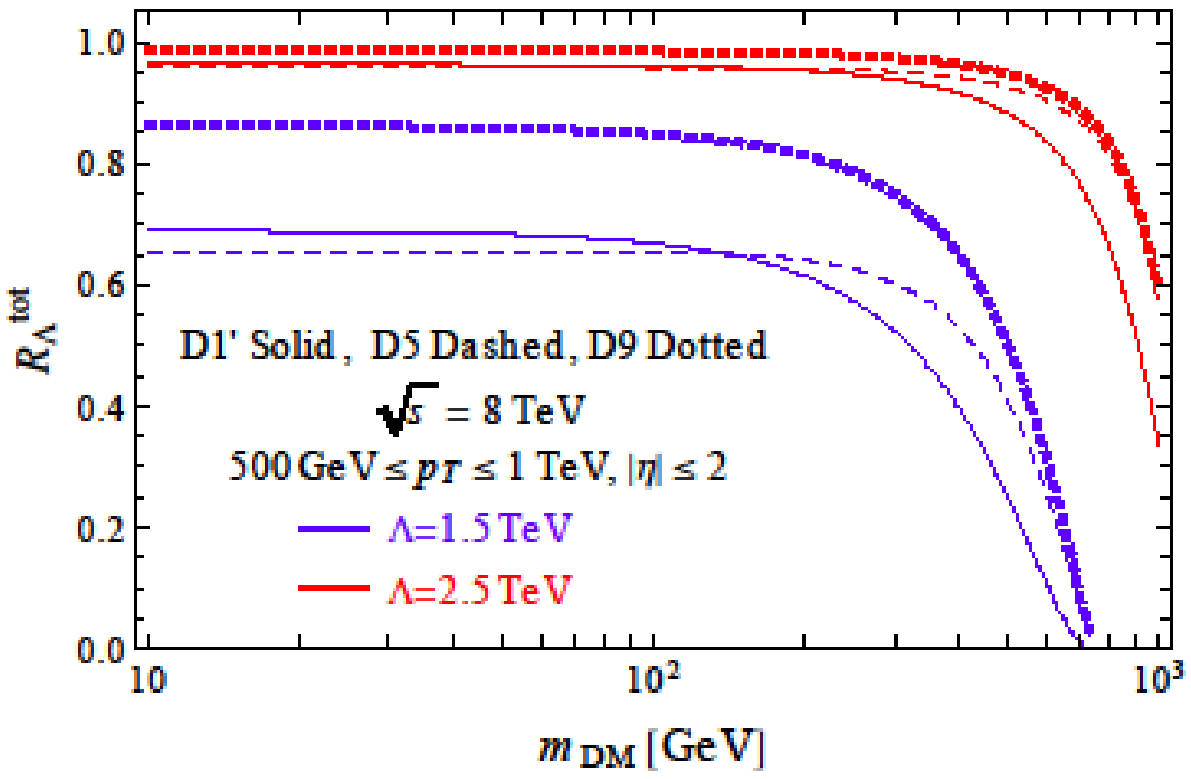

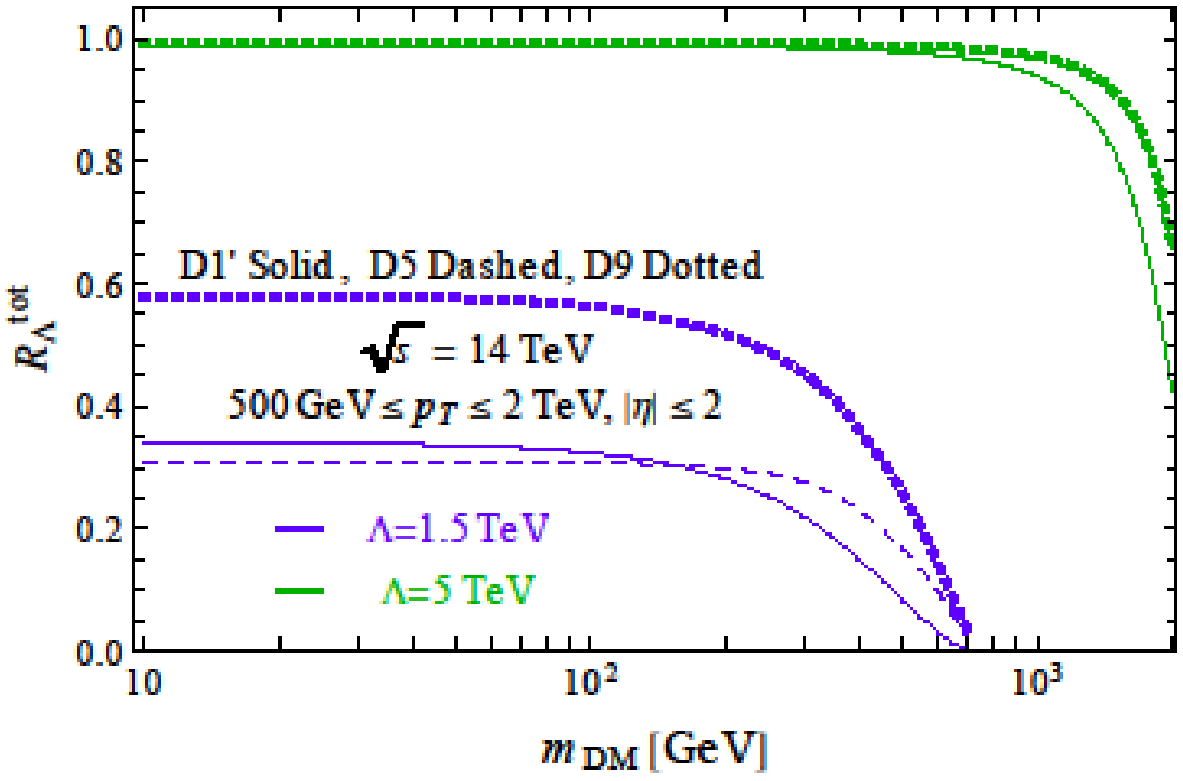

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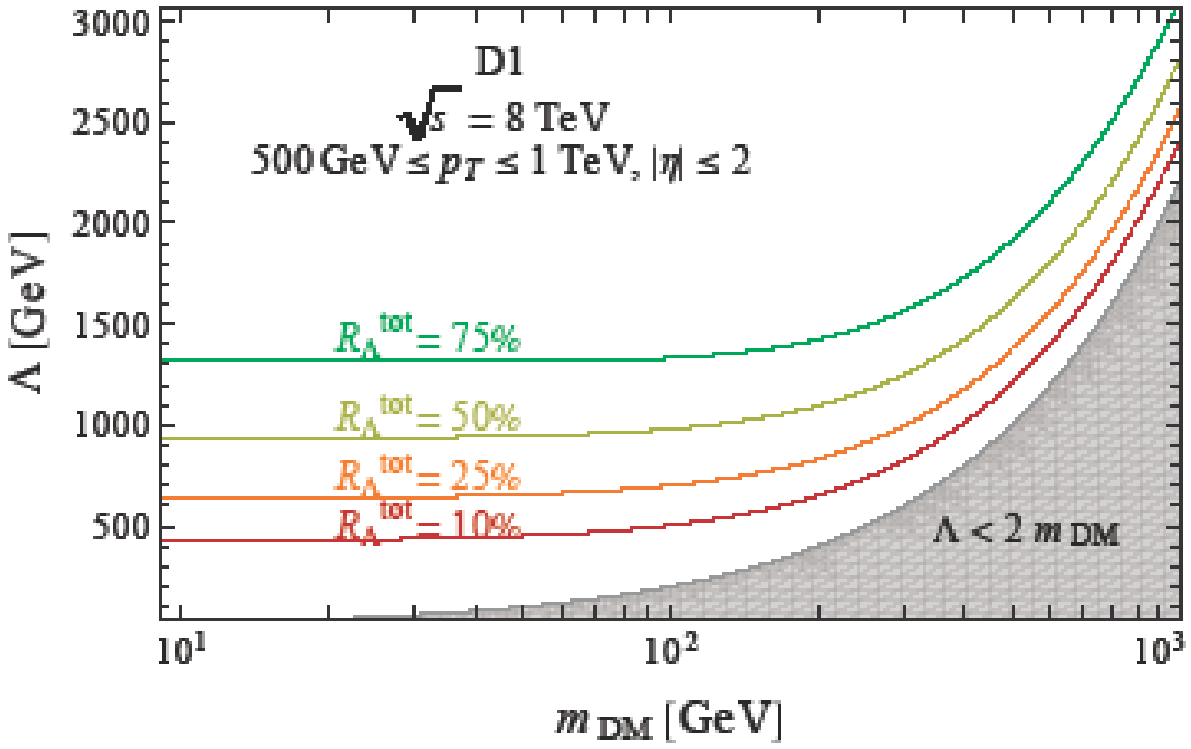

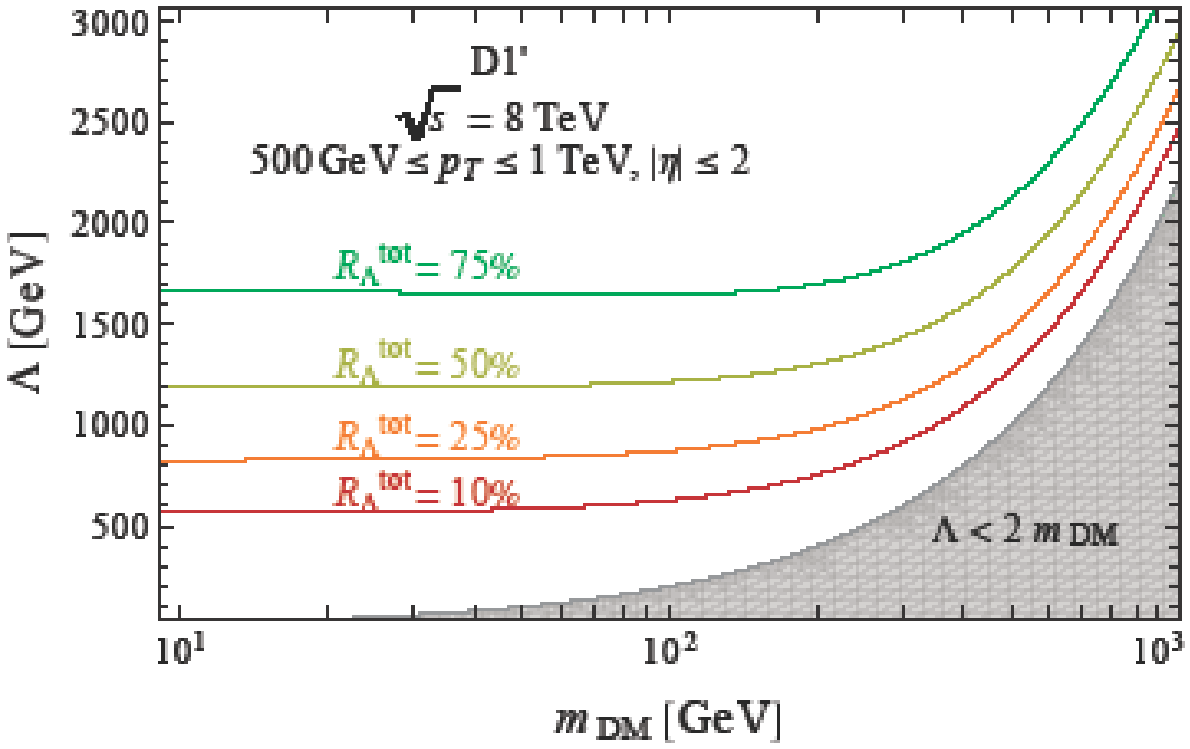

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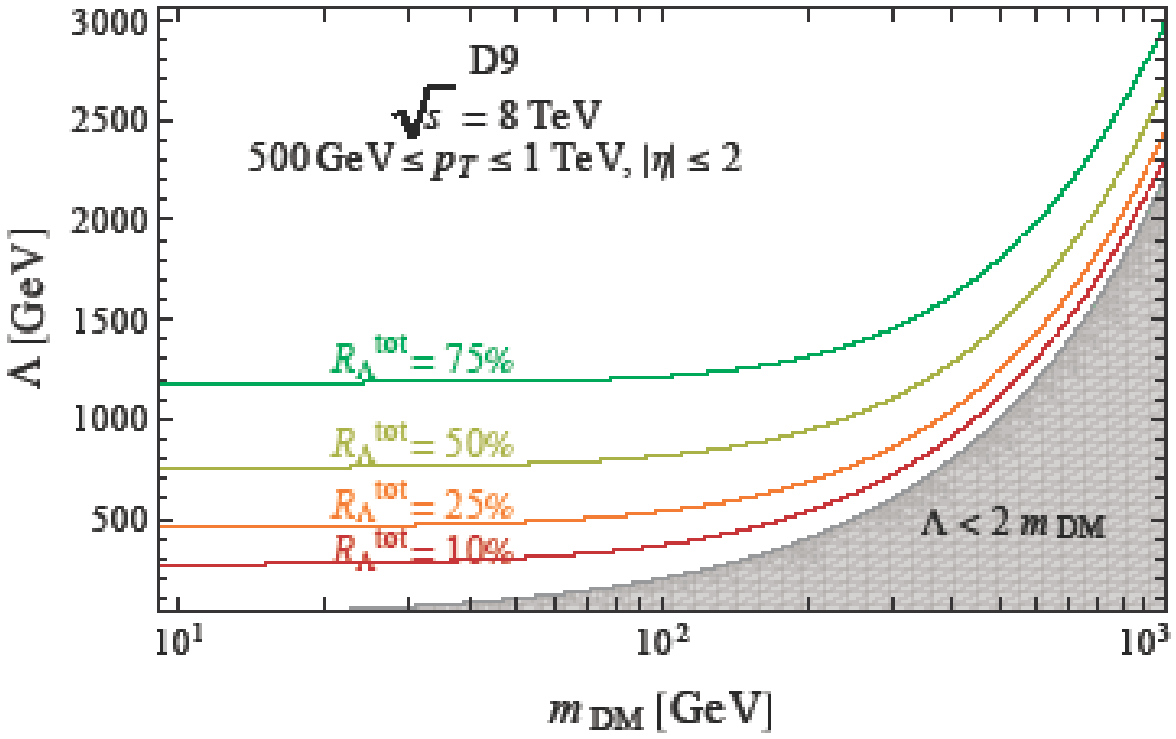
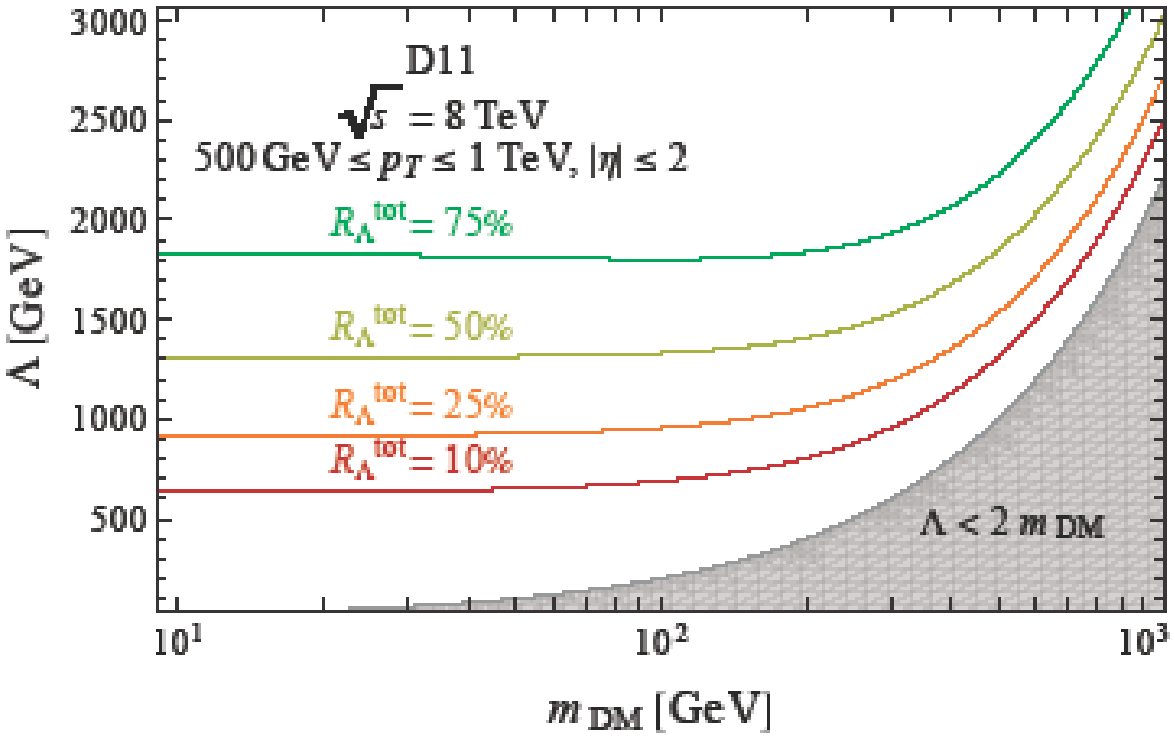
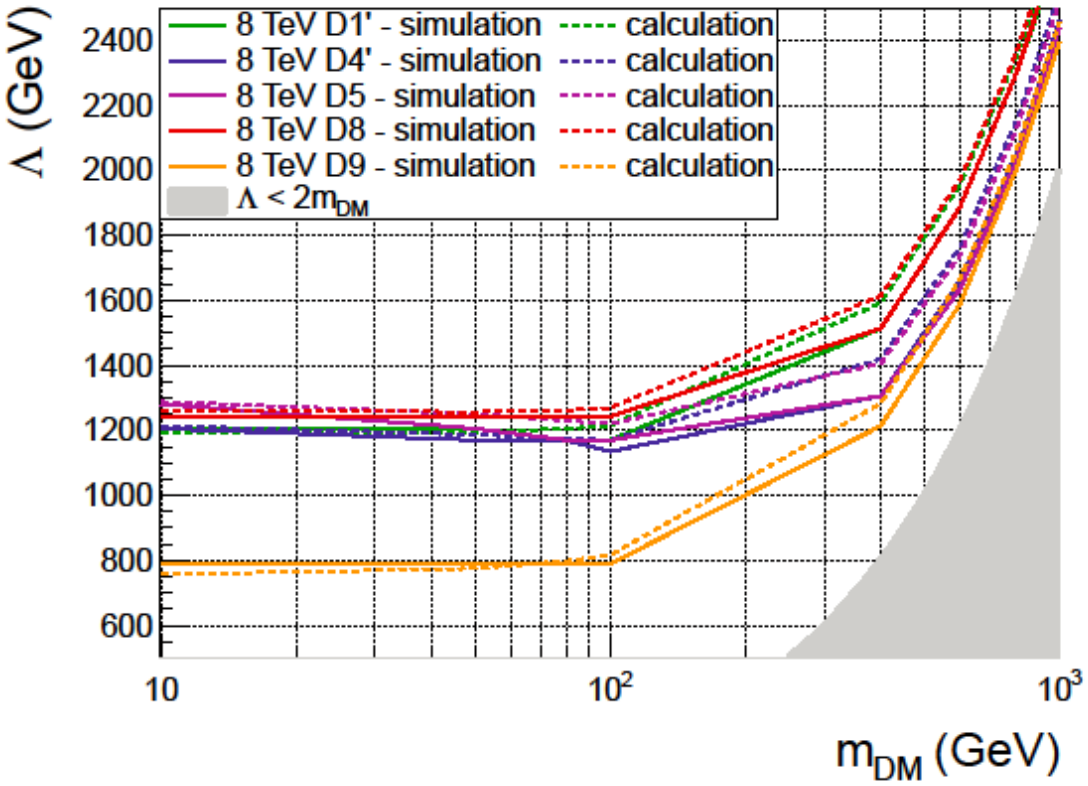


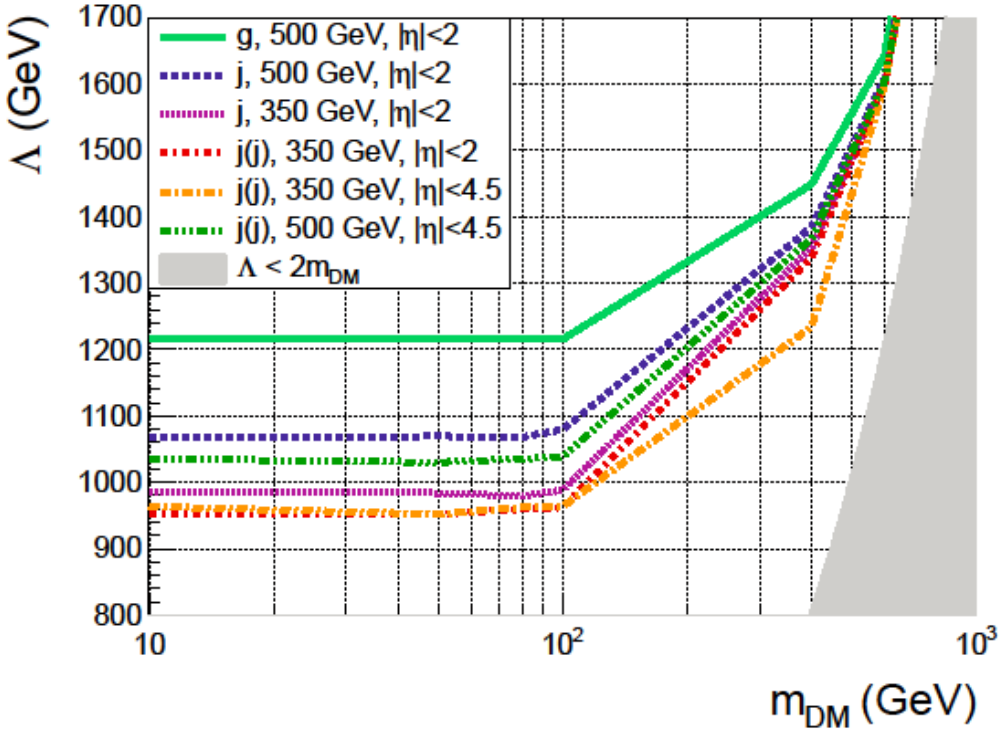


EFT Cutoff: Analytic Results vs Numeric Results (MadGraph)



EFT Cutoff: Numeric Results

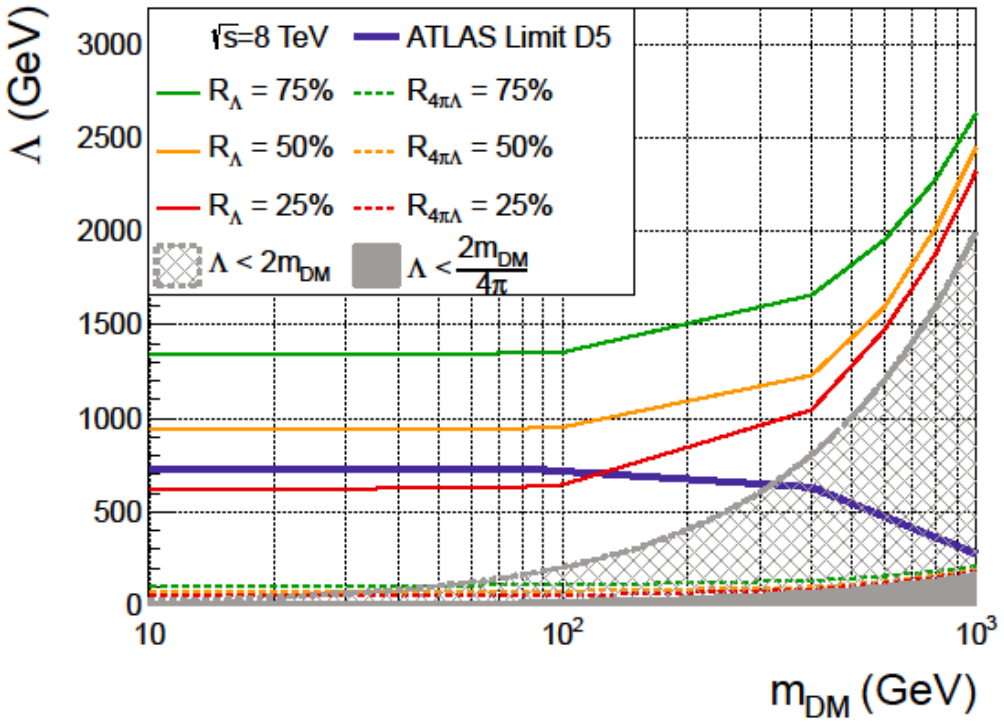
- Use MadGraph
- Simulate several variations from the analytically calculated scenario
- We simulate a scenario close to the cuts used in the ATLAS monojet analysis
- Leading jet is allowed to come from either a gluon or a quark being radiated
- Leading jet p_T cut is changed from 500 GeV to 350 GeV
- A second jet is allowed and its range in η is enlarged to $\eta < 4.5$
- Allowing not only for a gluon jet but also taking into account the possibility of a quark jet changes the contours appreciably



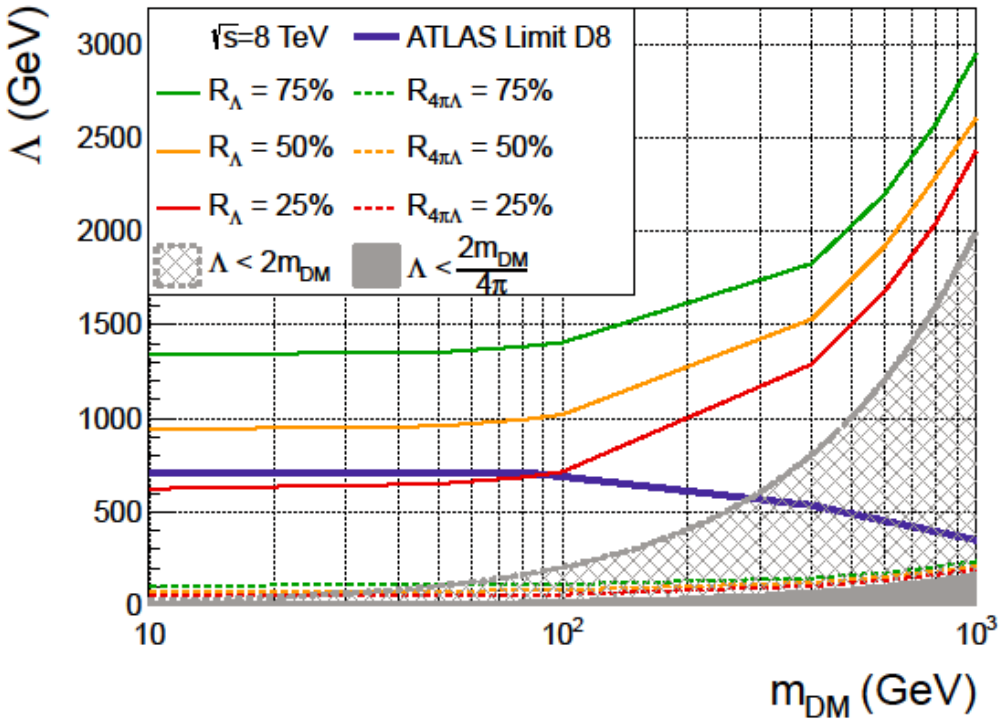
EFT Cutoff: Numeric Results vs Experimental Limits

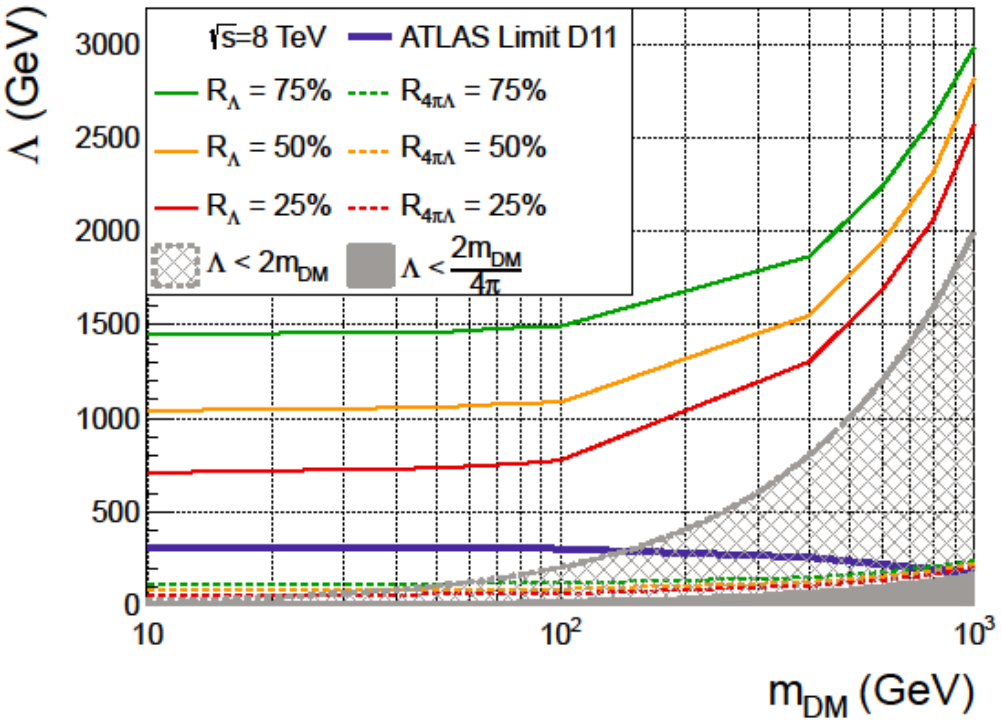
Let's now compare the contours we obtained with the actual experimental limits.

As you can see, we are not in the safe situation where the actual limits are well above the 75% contours



EFT Cutoff: Numeric Results vs Experimental Limits





How to deal with EFT in collider searches

- Very naively, the number of signal events in a given EFT model has to be less than the experimental observation, $N_{signal}(\Lambda, m_{DM}) < N_{expt}$

  The cross section due to an operator of mass dimension d scale like $\Lambda^{-2(d-4)}$, so

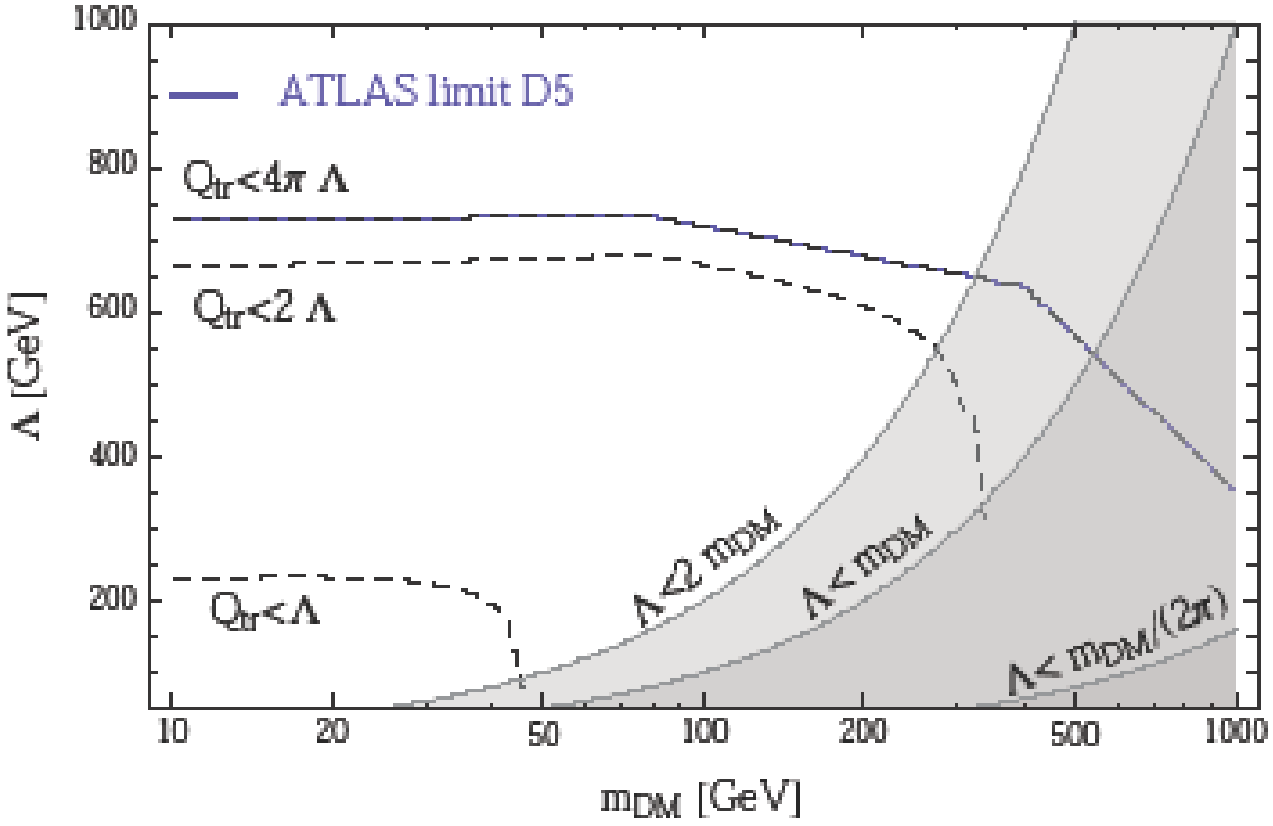
$$N_{signal}(\Lambda, m_{DM}) = \Lambda^{-2(d-4)} \widetilde{N}_{signal}(m_{DM})$$

  and the experimental lower bound in the scale of the operator becomes

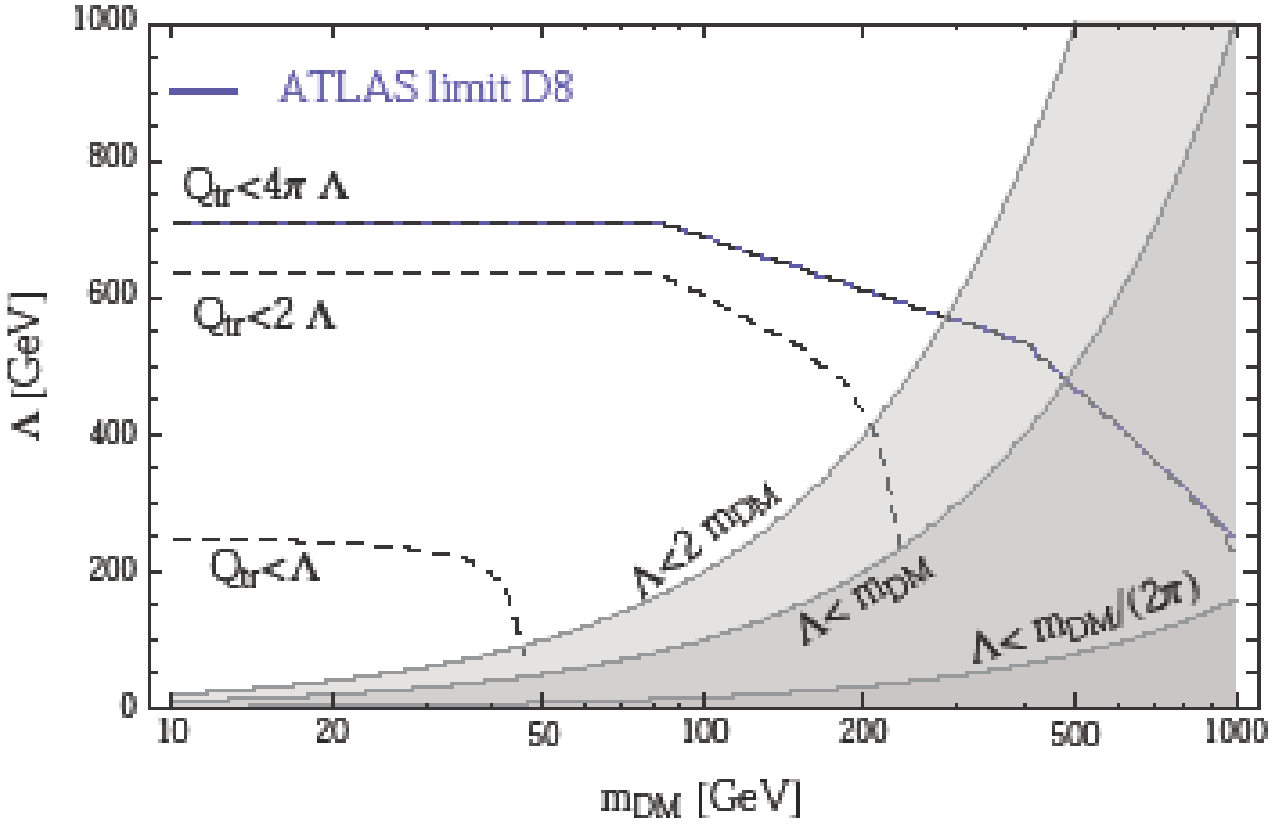
$$\Lambda > \left(\widetilde{N}_{signal}(m_{DM})/N_{expt}\right)^{1/2(d-4)} = \Lambda_{expt}$$

- The fact that a fraction of the events involve a transfer momentum exceeding the cutoff scale of the EFT means that the number of signal events for placing a limit gets reduced by a factor R_{Λ}^{tot}

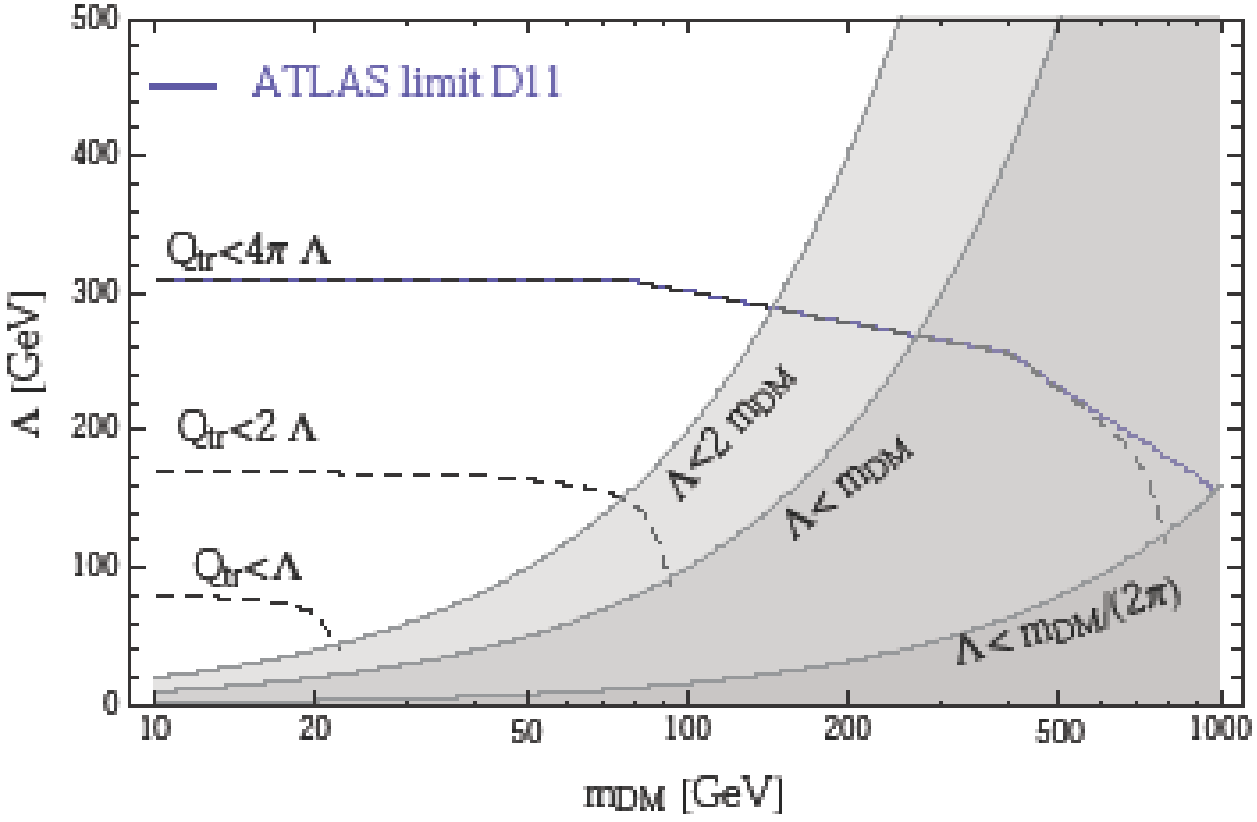
How to deal with EFT in collider searches



How to deal with EFT in collider searches



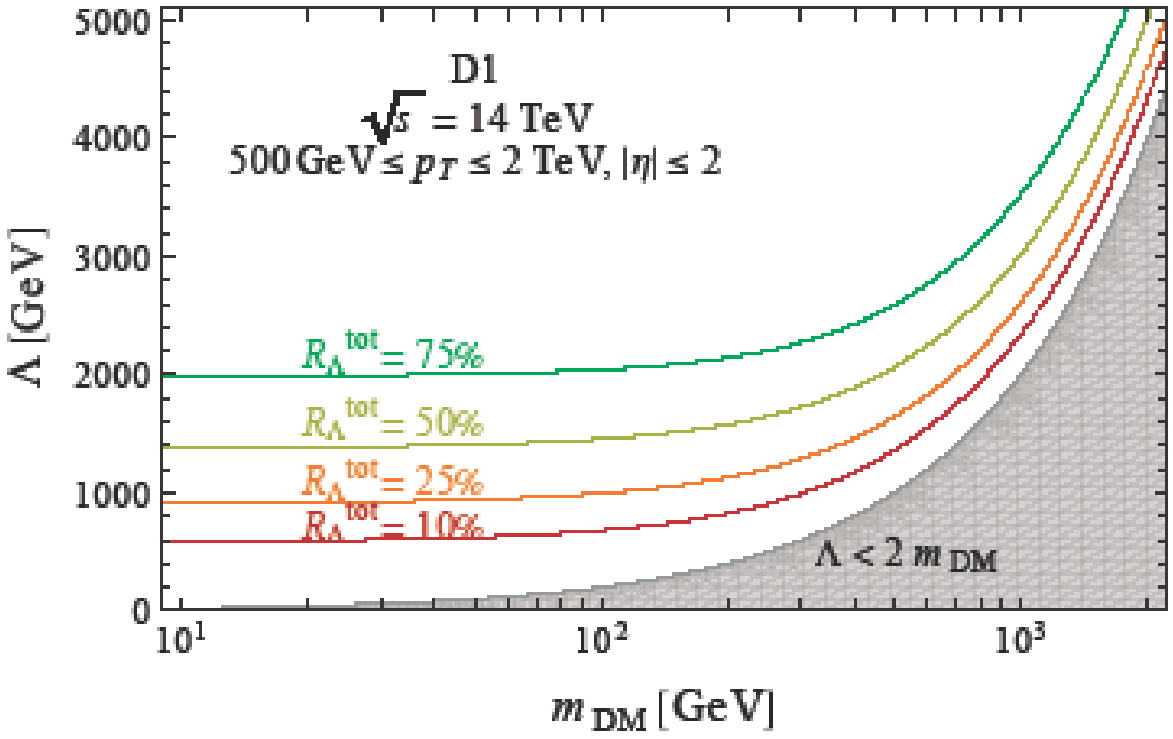
How to deal with EFT in collider searches

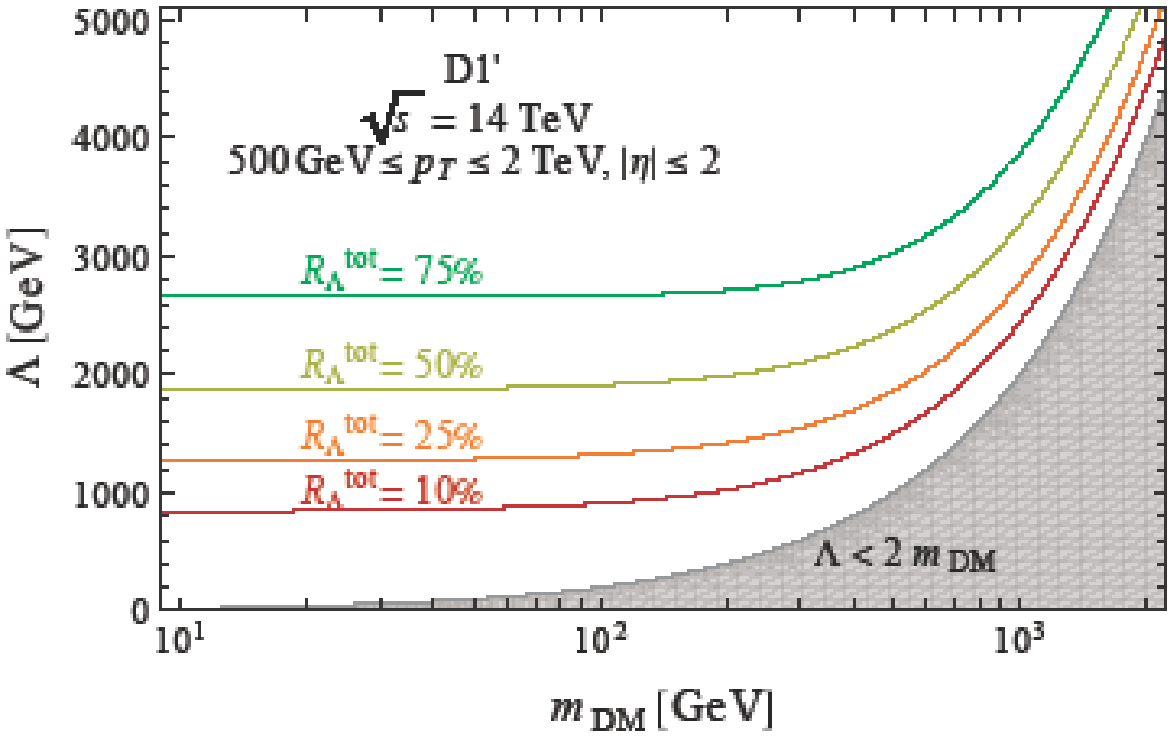


Conclusions and future…

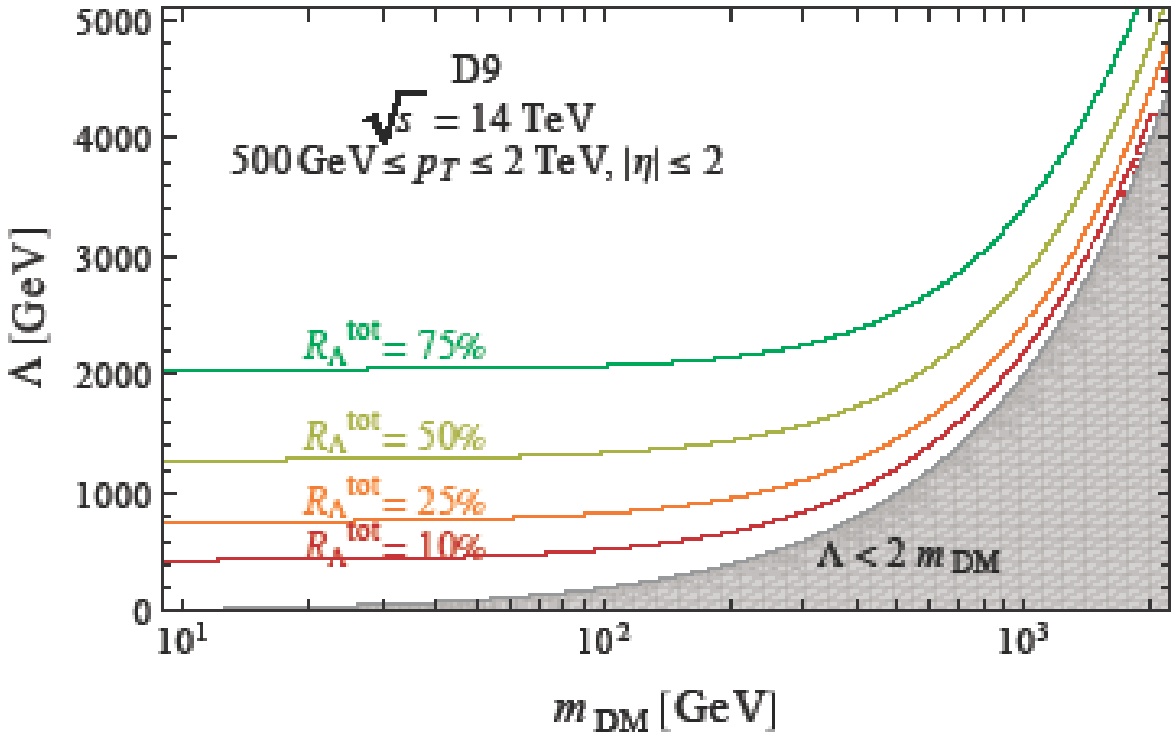
- When using EFT for DM collider searches it is important to check that the bounds obtained are consistent with the EFT low energy process assumption
- Bounds on EFT operators get weakened after taking this into account
- We have done a complete analysis for s-channel, what about t-channel? [Work in progress]
- Using simplified models we could instead get stronger bounds, thanks also to limits on the direct search of the mediator

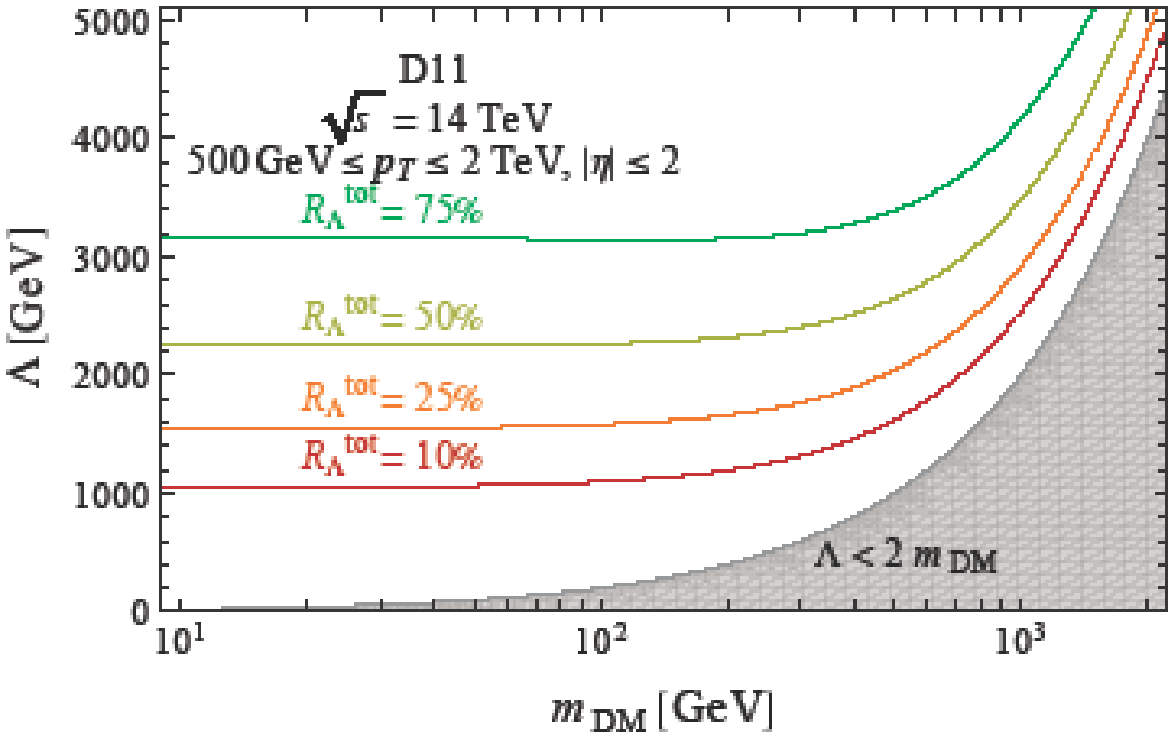
EFT Cutoff: Analytic Results





EFT Cutoff: Analytic Results





EFT vs UV completion

To compare EFT to UV completion, we study the ratios

$$R^{tot}_{UV/eff} = \frac{\sigma_{UV}}{\sigma_{eff}}$$

Same experimental cutoffs, as for R^{tot}_{Λ}.

Regularize UV cross section ➔ small width for the mediator: $\Gamma = \frac{M}{8\pi}$

Avoid production of mediator on shell ➔ appropriate bounds on integration domain for UV and EFT.

EFT vs UV completion