Simplified Models for Dark Matter and Missing Energy Searches at the LHC

GIORGIO BUSONI

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Outline

1. **Problems with EFT approach in Mono-X searches**
2. From EFT to Simplified models
3. Mediator Searches
4. Comments and Recommendations
5. Conclusions

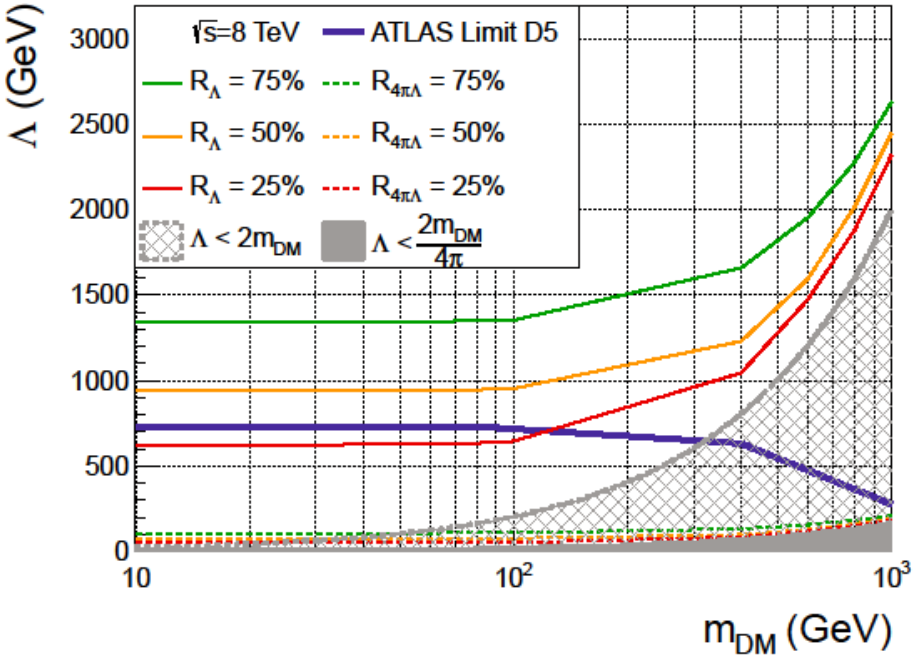
Problems with EFT approach in Mono-X searches

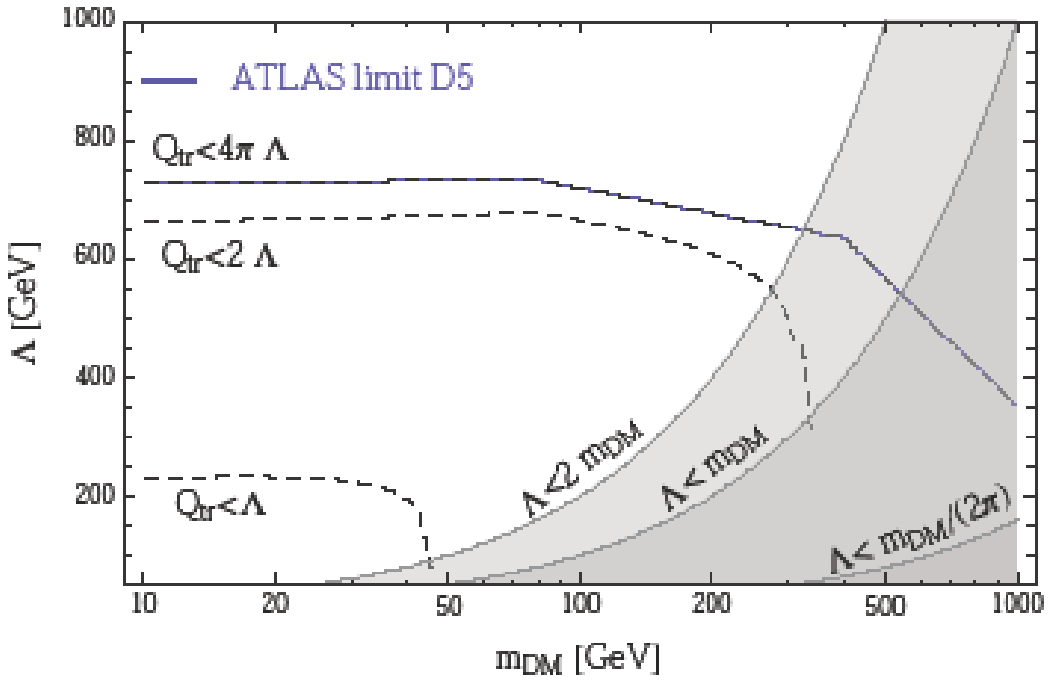
- Minimal number of degrees of freedom
- Heavy particles are «integrated out»
- High-Lambda and Low-DM mass zone of parameters space is safe for EFT (for RUN II: $\Lambda \gtrsim 3\ TeV, m_{DM} \lesssim 1\ TeV$)
- Unconstrained zones of parameters space (Low-Lambda, High-DM mass) are **not** EFT-safe
- Limits can be recast and be calculated by only using the EFT-safe events $\Lambda \gtrsim Q_{transf}$
- This procedure leads to weaker constrains
- This means that we have «integrated out» too much, and some degrees of freedom should be «integrated in» back in the theory
- This is why Simplified Models come in!!!

Problems with EFT approach in Mono-X searches

To quantify how many events pass the EFT validity condition we study the ratio

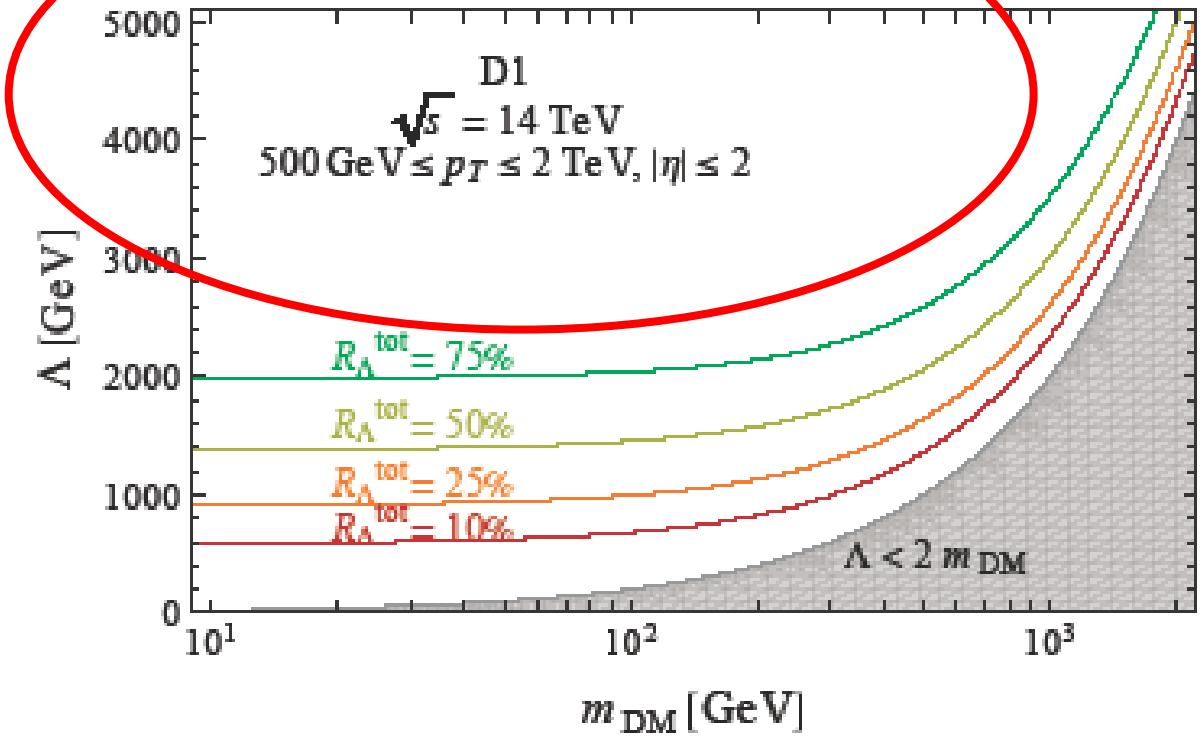
$$R_{\Lambda}^{tot} = \frac{\sigma_{eff}\big|_{Q_{transf}<\Lambda}}{\sigma_{eff}}$$

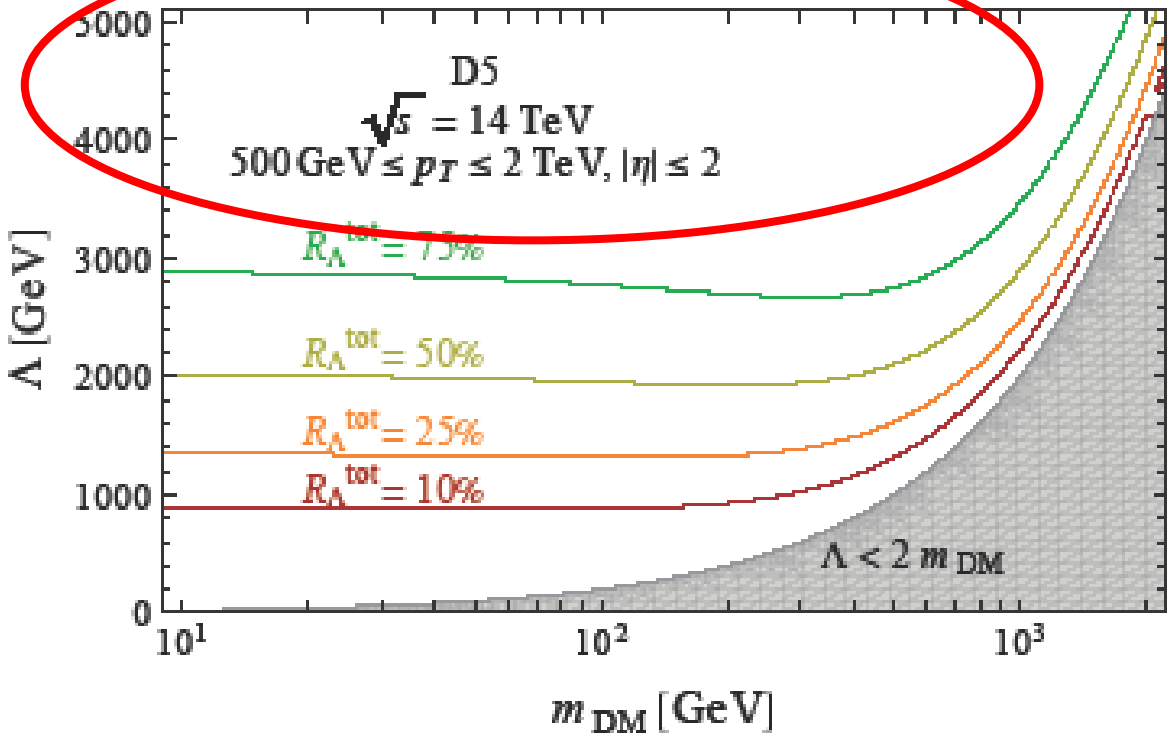




Problems with EFT approach in Mono-X searches

EFT SAFE





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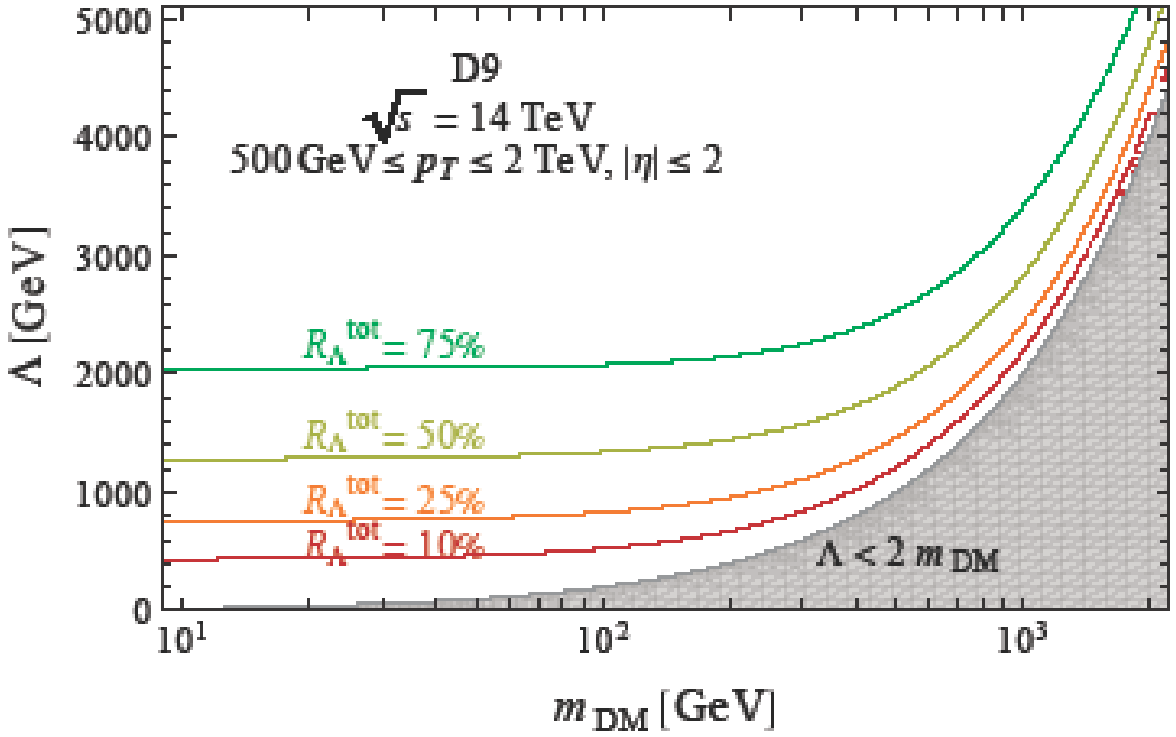

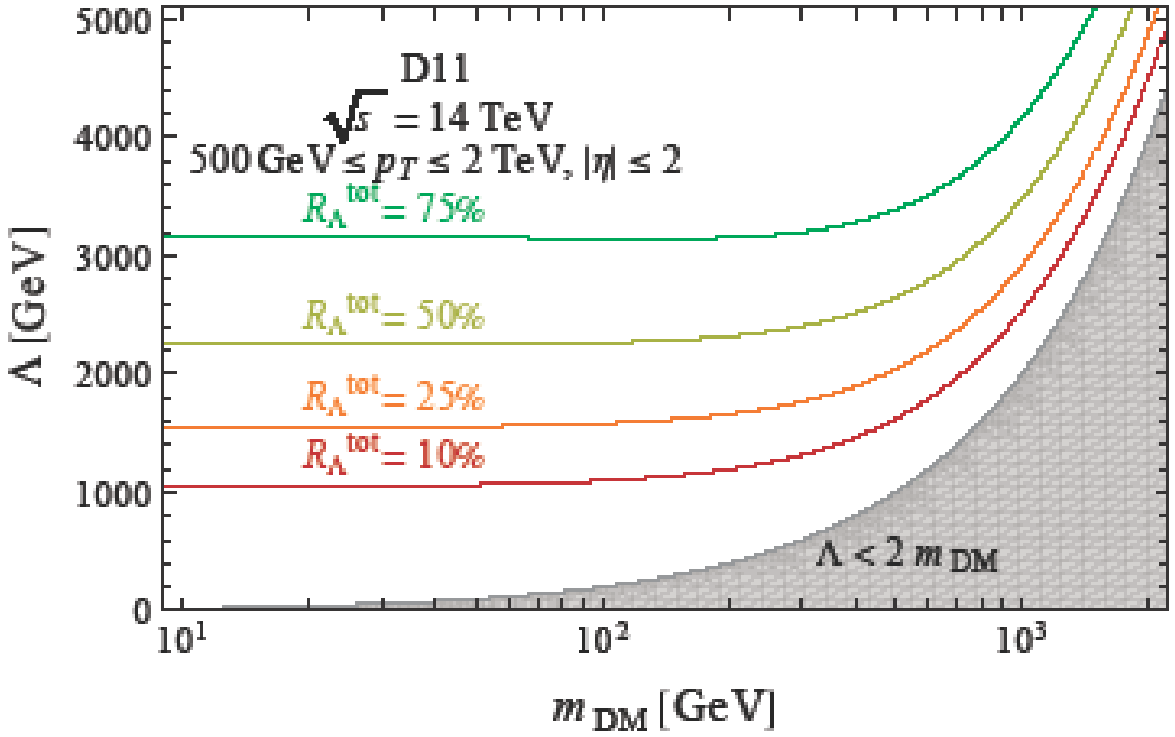

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EFT vs Simplified Models

- Only 1 new particle, the DM
- Heavier particles integrated out
- Only 2 parameters (Λ, m_{DM})
- Non-renormalizable theory
- Useful in Mono-X Searches

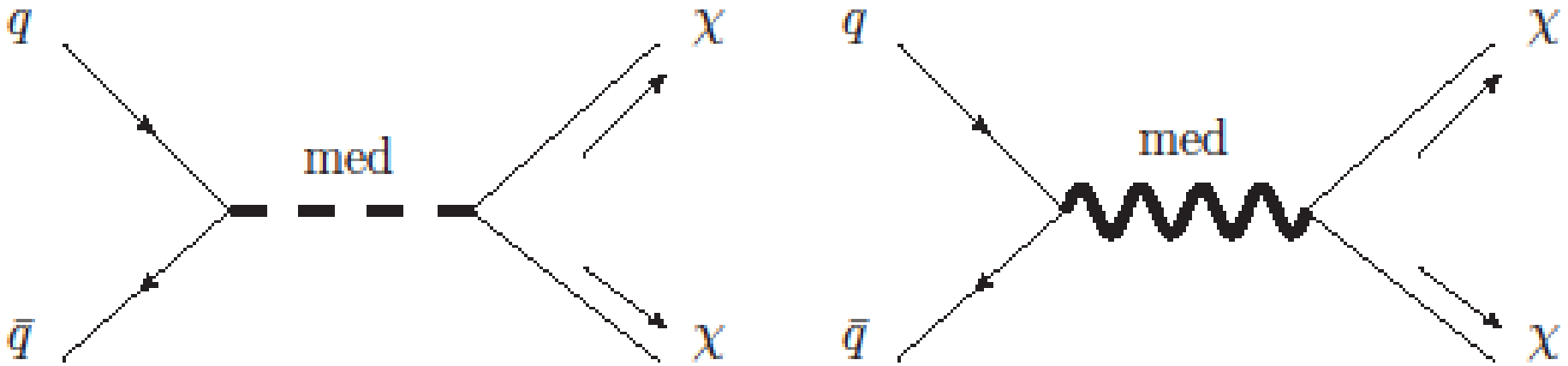
- 2 (or more) new particles, the DM and a new mediator
- Agnostic about heavier particles
- Small number of parameters (M, m_{DM}, Γ, g_i)
- Renormalizable (usually)
- Useful in Mono-X, Di/multi-Jet Searches

From EFT to Simplified models

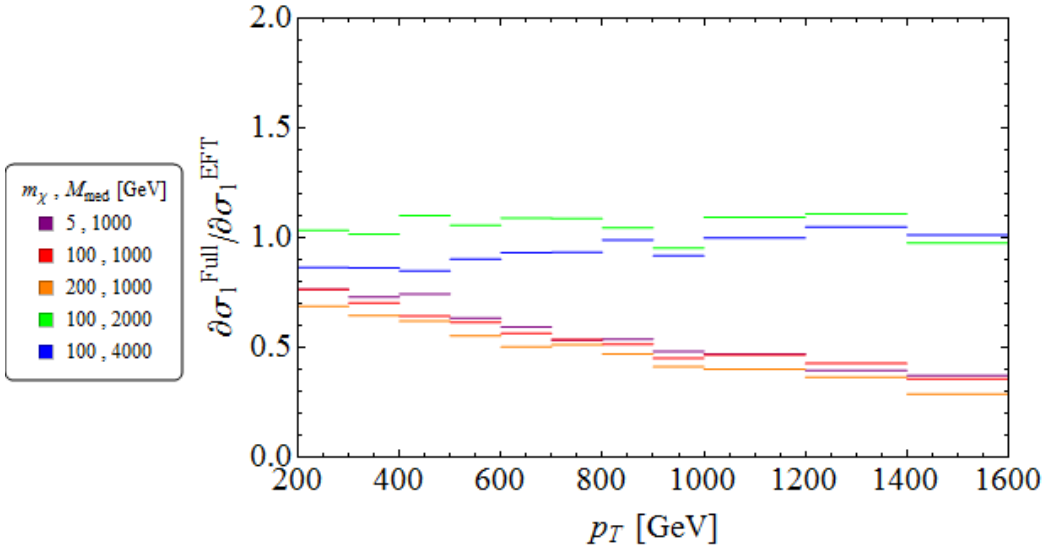
Name	Operator	Coefficient
D1,(D3)	$\bar{\chi}\chi\bar{\psi}\psi$	m_q/Λ^3
D4,(D2)	$\bar{\chi}\gamma^5\chi\bar{\psi}\gamma^5\psi$	m_q/Λ^3
D1',(D3')	$\bar{\chi}\chi\bar{\psi}\psi$	$1/\Lambda^2$
D4',(D2')	$\bar{\chi}\gamma^5\chi\bar{\psi}\gamma^5\psi$	$1/\Lambda^2$
D5,(D7)	$\bar{\chi}\gamma_\mu\chi\bar{\psi}\gamma^\mu\psi$	$1/\Lambda^2$
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	$\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\alpha_s/4\Lambda^3$

From EFT to Simplified models – s channel

- These models generate the D1-D8 and D1'-D4'
- New (Pseudo)Scalar or (Axial) Vector uncolored mediator coupling to (u,d) quarks
- Simplified models may provide rather different cross sections or p_T distributions
- Similar to EFT only when $\mathrm{M} \gtrsim Q_{transf} > 2m_{DM}$. For LHC Run II: $\mathrm{M} \gtrsim 3\ TeV, m_{DM} \lesssim 1\ TeV$

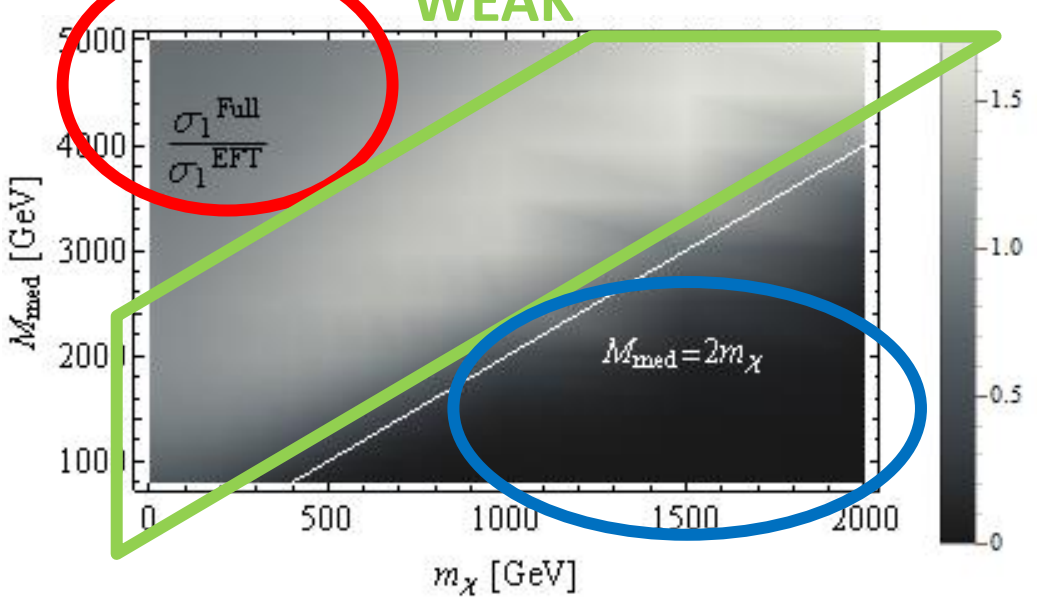


Simplified Models – s channel - scalar



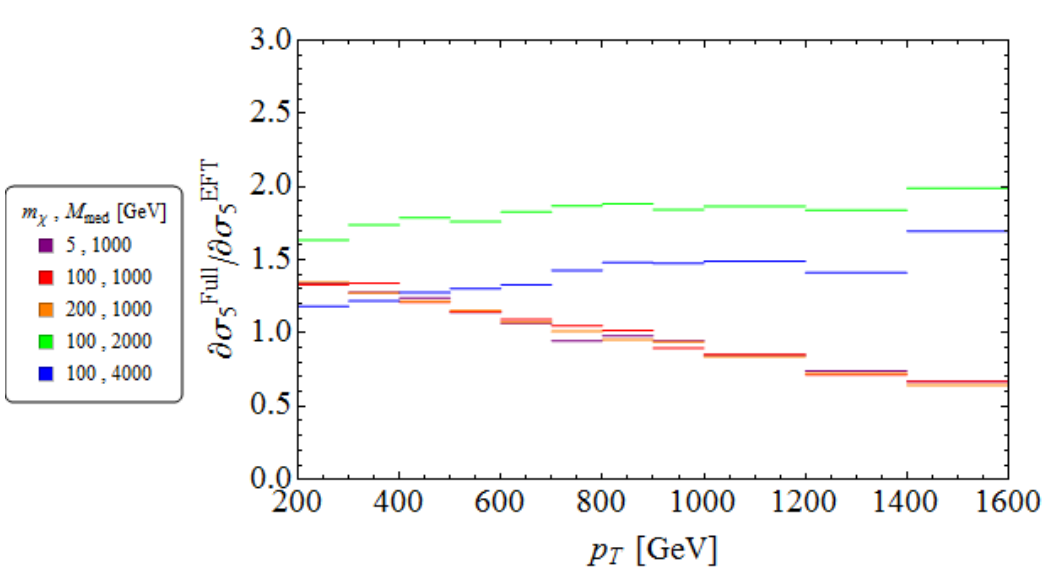
EFT SAFE

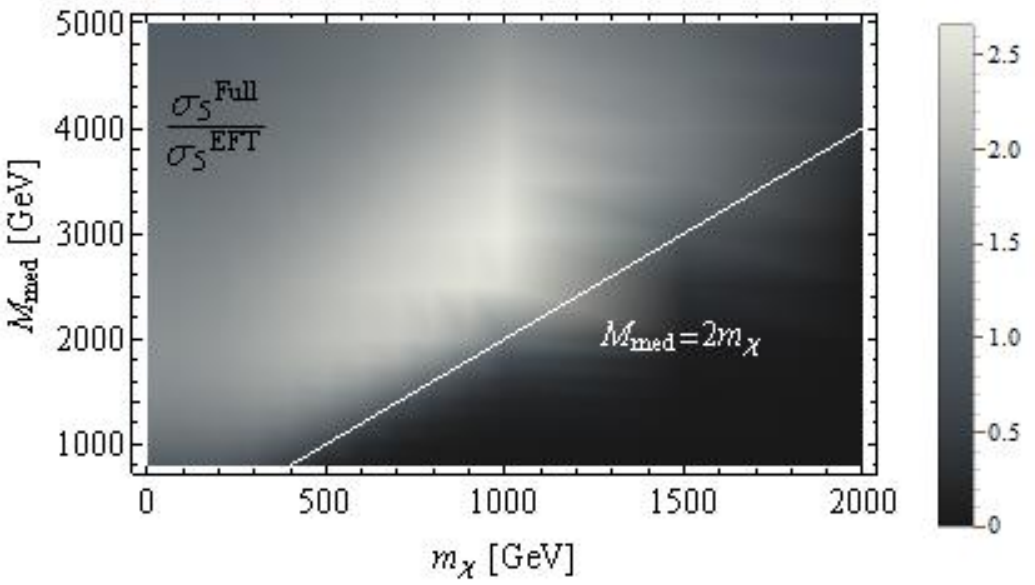
RESONANCE – EFT LIMITS TOO WEAK



HEAVY DM REGION – EFT LIMITS TOO STRONG

Simplified Models – s channel - vector

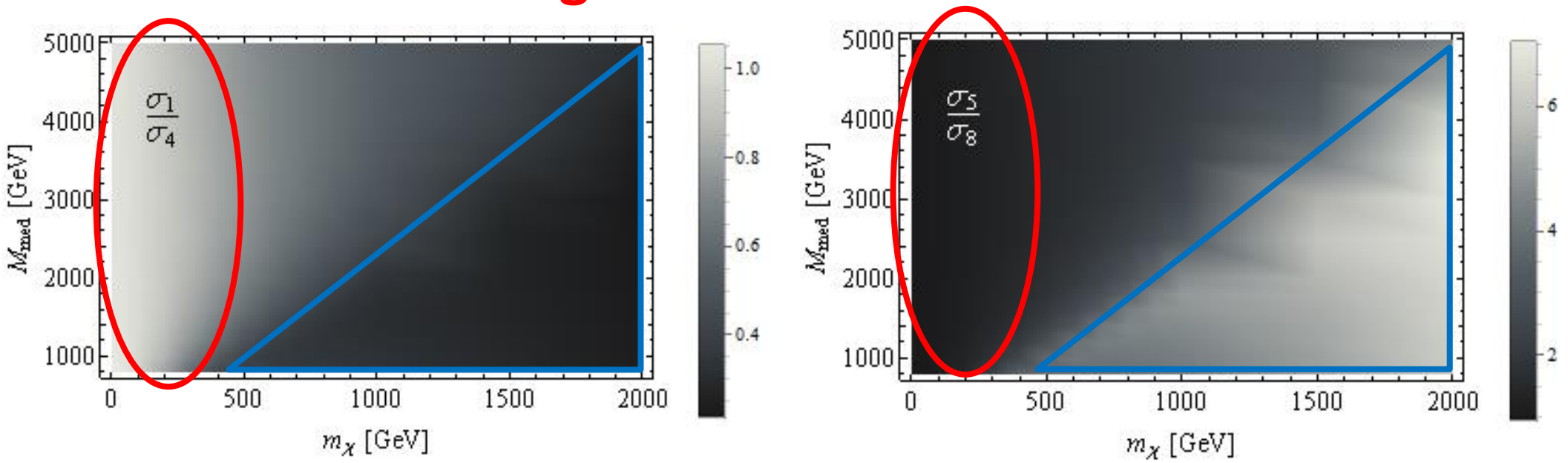




Precedent Talk from M. Dolan already discussed this case

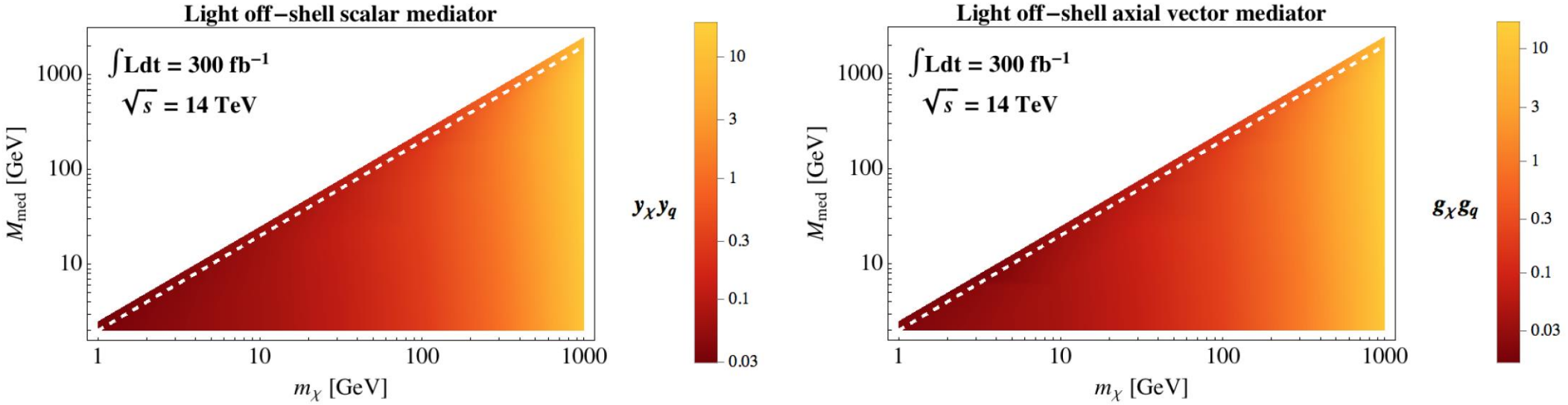
From EFT to Simplified models – s channel

Similar Strengths



Scalar and Axial Mediator give weaker signals → Weaker Bounds

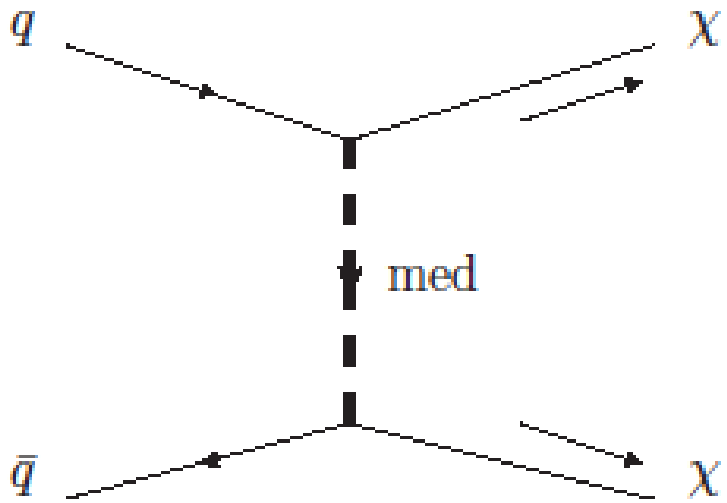
From EFT to Simplified models – s channel – Expected Sensitivity



- Further constrains may come from Di-Jet searches for the mediator

From EFT to Simplified models – t channel

- These models generate mixtures of D1-D8 and D1'-D4' (Fierz transformation)
- New mediator is colored, coupling to u,d (s,c)
- An example is Squarks exchange in SUSY
- EFT safe only when $\mathrm{M} \gtrsim 1\ TeV$
- Bounds from other searches (Di/Multi-Jet+MET) can be stronger than Mono-Jet

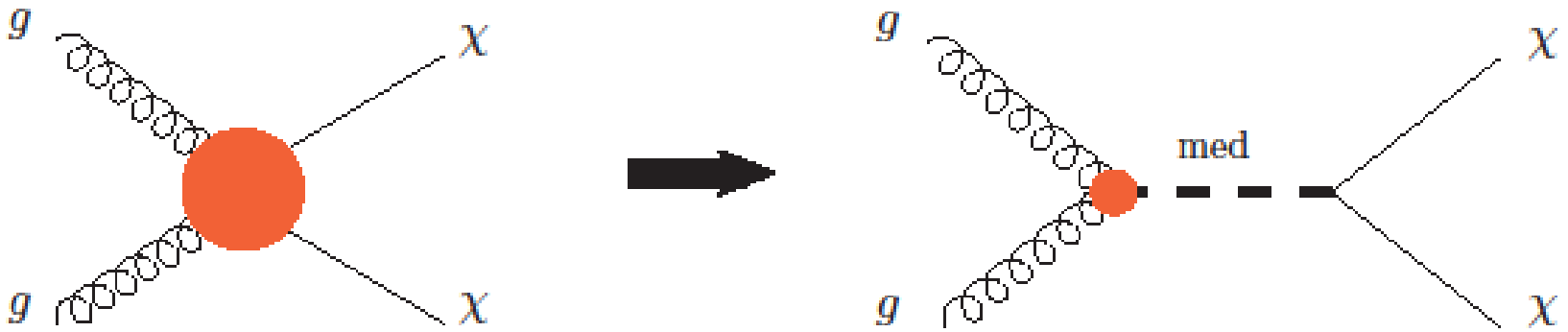


From EFT to Simplified models – Gluon operators

- Resolving the D11-D14 operators **is not straight-forward as for D1-D8**
- These operators have stronger problems with EFT validity as $\Lambda \gtrsim 350\ GeV$
- Simplest way involves an s-channel scalar mediator and dim-5 operator

$$\frac{1}{4\Lambda^3} = \frac{y_\chi}{M_{med}^2 \Lambda_5}$$

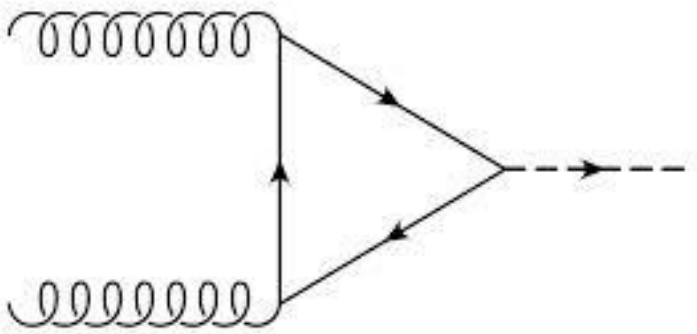
- Light M_{med} allows low Λ while retaining high (EFT-safe) Λ_5



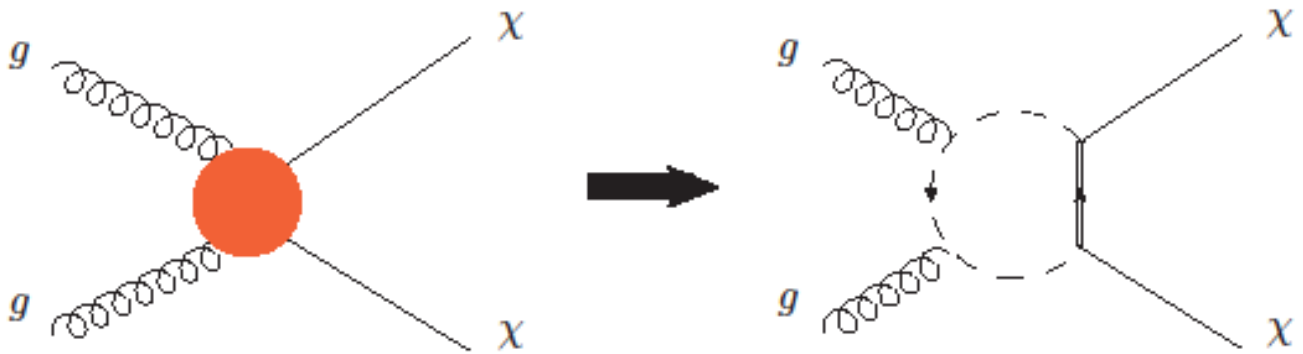
From EFT to Simplified models – Gluon operators

- The dim-5 operator can be resolved by gluon fusion through some new heavy colored states

$$\frac{1}{\Lambda_5} = \frac{1}{8\pi}\sum \frac{y_f}{m_f}$$



- Alternatively, the dim-7 operator can be resolved directly by adding a new colored scalar and fermion



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Mediator Searches

- Simplified Models are most needed when mediators are light enough to be produced at LHC
- It is therefore natural to consider the searches for the mediator as an important additional channel to look at
- Possible channels:

1. Di-Jet Narrow resonance searches
2. Di-Jet Angular distribution
3. Di-Jet central-to-forward/total ratio
4. Multi-Jet

- Mediator too heavy to be produced → H. Dreiner talk of Friday (yesterday)

Mediator Searches – s channel

- Monojet signal is proportional to $g_q g_\chi$, while Di/Multi-Jet signal is more sensitive to g_q
- For fixed $g_q g_\chi$, higher g_q → Di-Jet, while lower g_q → Mono-Jet
- Narrow resonances searches can probe

$$\Gamma/M \lesssim 0.15(Gaussian), 0.05\ (B-W)$$

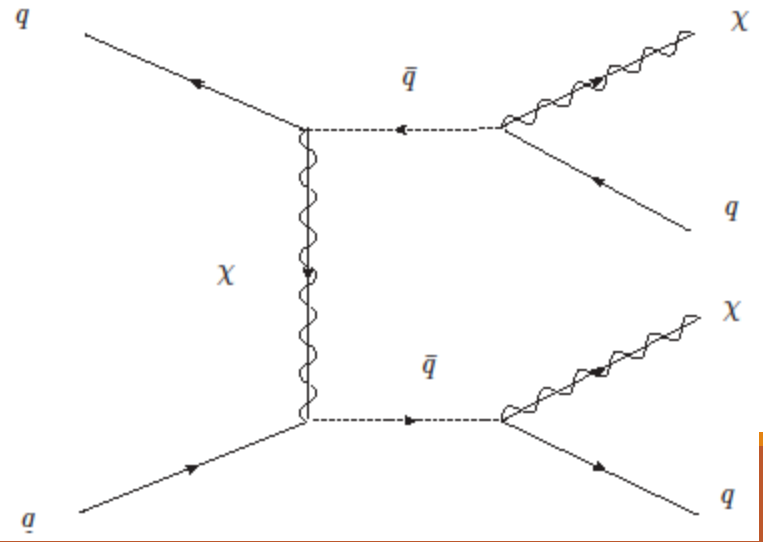
- →Maximum value of coupling that can be probed in this way (Z') (scalar case is similar)

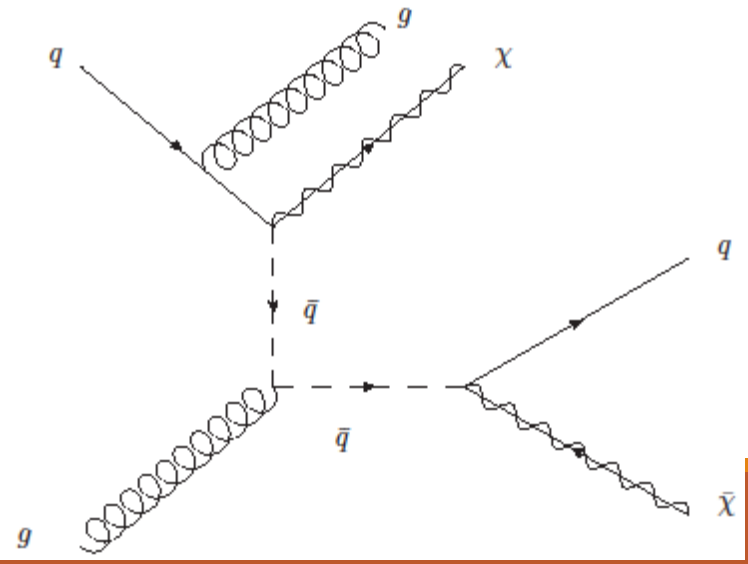
$$g_q < \frac{1.4}{\sqrt{N_q}}(G), \frac{0.79}{\sqrt{N_q}}\ (B-W)$$

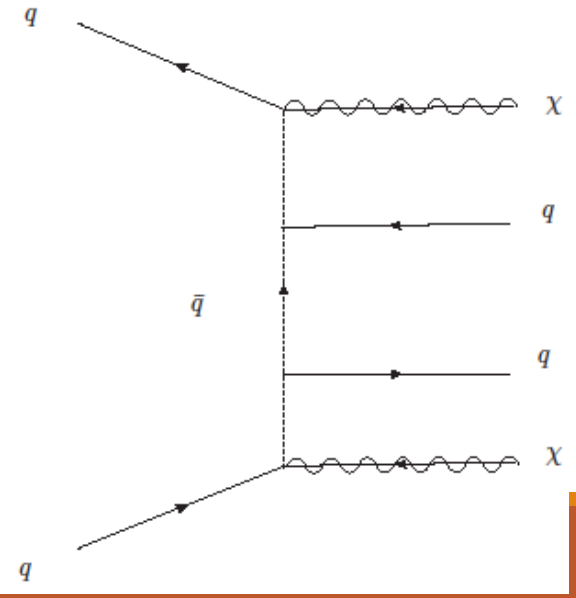
- Wider resonances can be probed using Di-Jet angular distribution or central to forward/total ratios

Mediator Searches – t channel

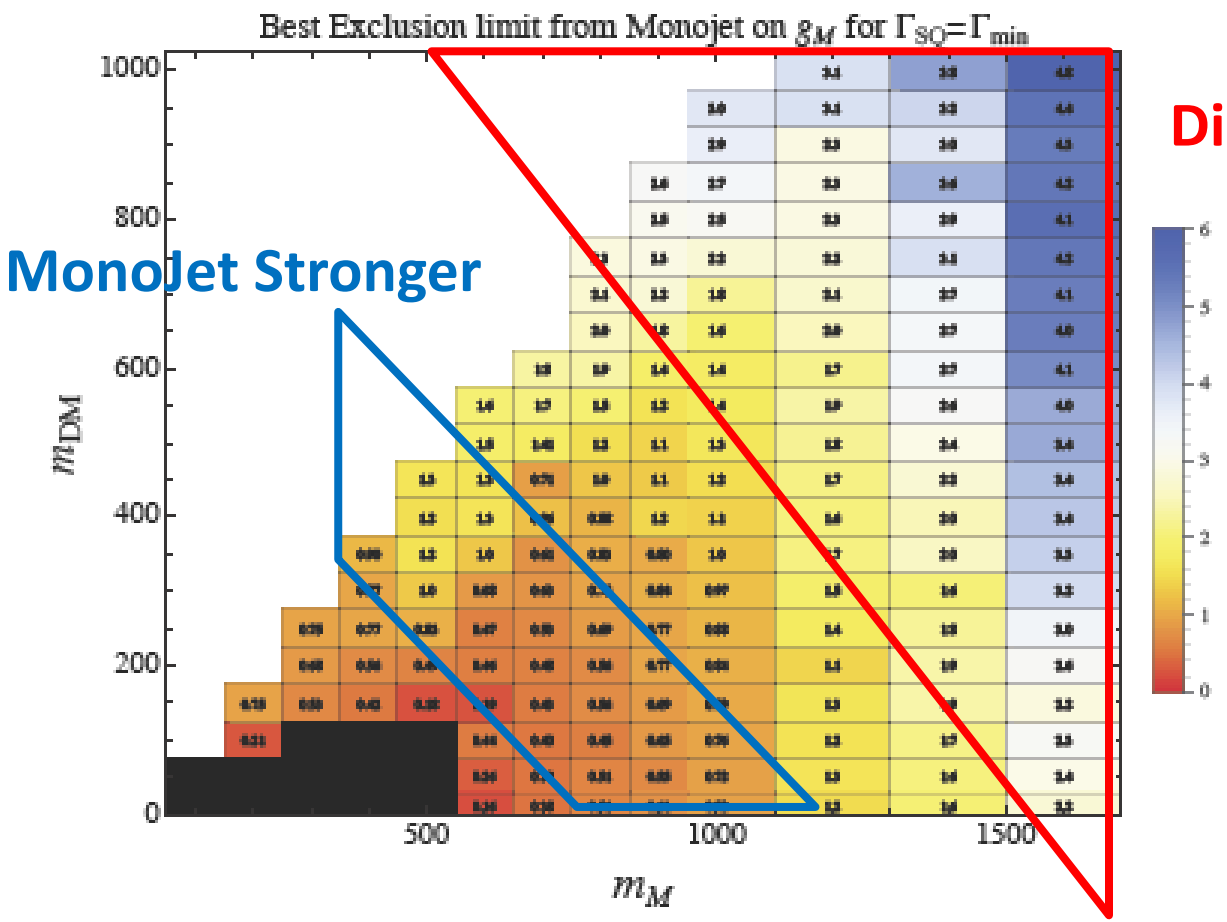
- Di-Jet searches can provide competitive results to Monojet
- Bounds rather different from EFT Mono-Jet
- Largest production at low energy or on resonance (low energy contaminated by SM Background)
- Heavy mediator(but kinematically accessible): resonant production → Stronger bounds
- Light or broad mediator: high background → EFT bounds are too strong

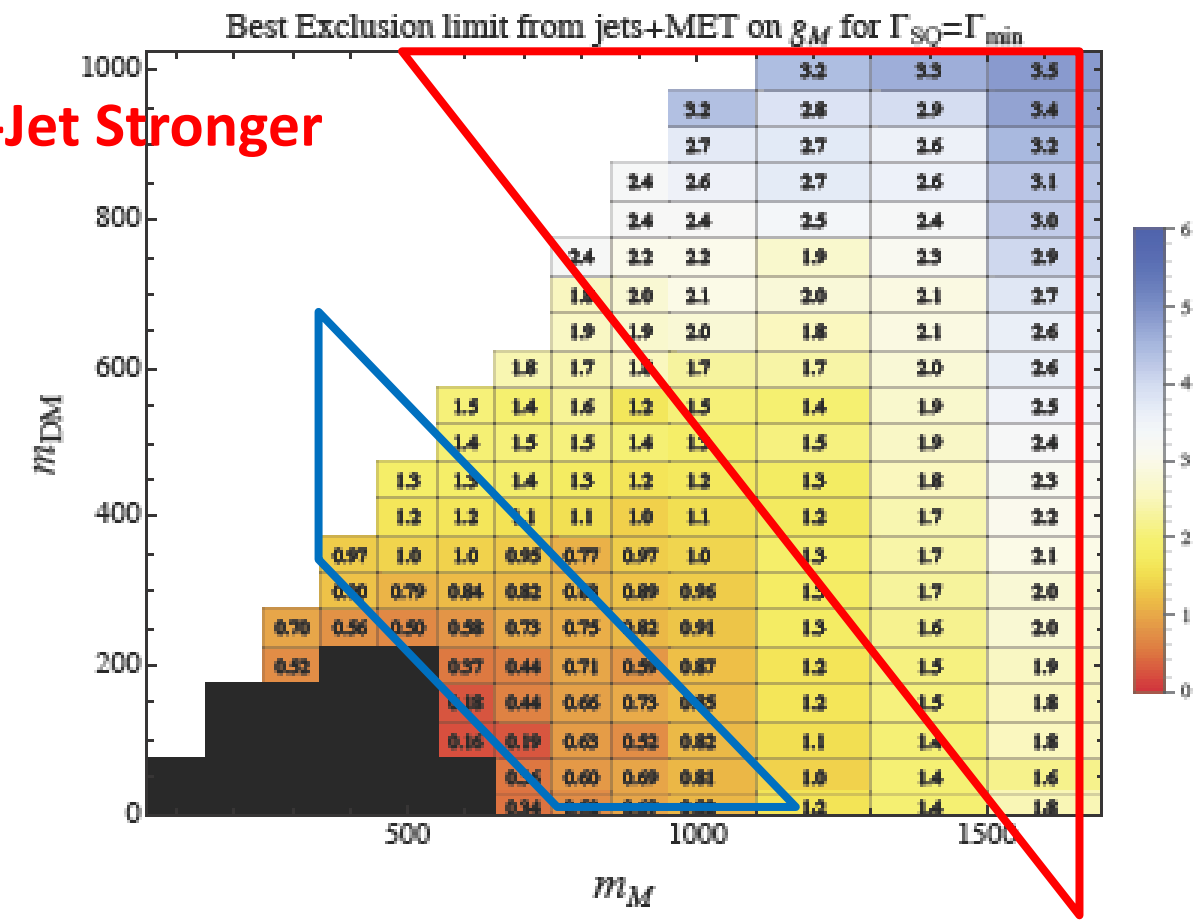






Mediator Searches – t channel





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Comments and recommendations

1. The new mediator in the simplified models has a minimum width that should not be forgot
2. In Monojet analysis, a second jet is allowed, simulating event without it is erroneous → weaker constrains
3. Limits should be expressed as function of all parameters
4. Narrow Width Approximation: finite width effects may be important
5. Important that largest possible part of the phase space is searched for BSM Physics. Extensions of Mono-X topology → giving higher sensitivity?

Comments and recommendations

6. Di-Jet searches constrains for low mass mediators are limited by data taking limitations. High QCD background → small fraction of Di-Jet events with masses below $1\ TeV$ is recorded → An interesting region of the parameter space remains unconstrained.
7. Multi-Jets, tops, Mono-Z, Mono-W, Mono-Higgs can still provide interesting results, thanks to a smaller background. Those searches are important and should be pursued.
8. Despite the PDF suppression, b-Jet plus MET and $t\bar{t}$ plus MET may improve Mono-Jet searches limits in some simplified models

Comments and recommendations

9. Simplified models are incomplete models. This should be kept in mind when comparing different kind of searches. Full theory may contain multiple mediators, one mediator important for one search, and another type relevant for a different search.
10. Because of this, results should be quoted for each channel separately. Combinations can be done separately and the assumptions that go into such combinations should be clearly stated
11. Simplified models not just EFT reinterpretation, should also inform us when additional search channels are necessary, (new qualitatively different final states?). In a full theory, it is possible that more than one process described by the simplified models is relevant for collider searches

Comments and recommendations

12. For the reinterpretation of the LHC results, it is important to clearly specify how the Monte Carlo samples are generated (Parton showering, PDF)
13. Experimental results addressing Simplified models are most useful if they include all information needed to reinterpret the results in the context of a larger theory. At minimum, observed event, SM background and uncertainty in inclusive bins of the key kinematic variables (transverse momentum, rapidity for MonoJet). Results should provide as much numerical detail as possible (auxiliary repositories such as HEPdata)
14. NLO results for production cross section should be implemented only when a strong case for their inclusion is made and their effect are shown to be significant

Comments and recommendations

15. EFT can still be useful. EFT limits should still calculated, as they remain the most generic description for the possible low-energy phenomenology. While calculating EFT limits, the validity conditions for EFT should be kept in mind
16. EFT collider limits could be recast and combined with DD limits. The same reinterpretation can be made by using Simplified models. This should be done for mediator masses above the typical momentum exchange of DD, so $M > 1\ MeV$. In this part of the parameters space the DD process is just a contact interaction. The region below $1\ MeV$ should be left for theorists at this stage
17. Finally, when drawing conclusions about EFT and Simplified Models, it is important to remember that they are incomplete theories. The set of simplified models described are just building blocks out of which a proper theory can be constructed. Constrains on proper, anomaly-free models should be left to theorists.

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Conclusions

- Simplified models are not only reinterpretation of EFT
- New kind of searches (Mediator: Di/Multi-Jet)
- Still quite simple, but much richer phenomenology
- SM basic building blocks for new theory
- New subtleties to consider
- Careful when combining different channels
- Searches such as Mono-Z/W/Higgs/top should be also pursued
- Reinterpretation of results will be very useful to let theorists combine the basic building blocks in a full theory