DM@LHC Workshop
Chicago - 19 Sept 2013

Validity of EFT for DM @ LHC

Andrea De Simone

based on:

Busoni, DS, Morgante, Riotto - arXiv:1307.2253

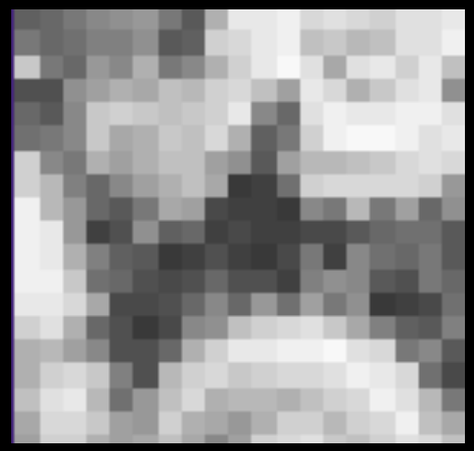
Outline

Searches for Dark Matter @ LHC

- is the EFT approach reliable?
- dead end? improvements in sight?

Effective Field Theory Description

effective low-energy description



M_Z

(Λ~1 TeV)

New States

(say, 10 TeV)

E

EFT OK

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.:

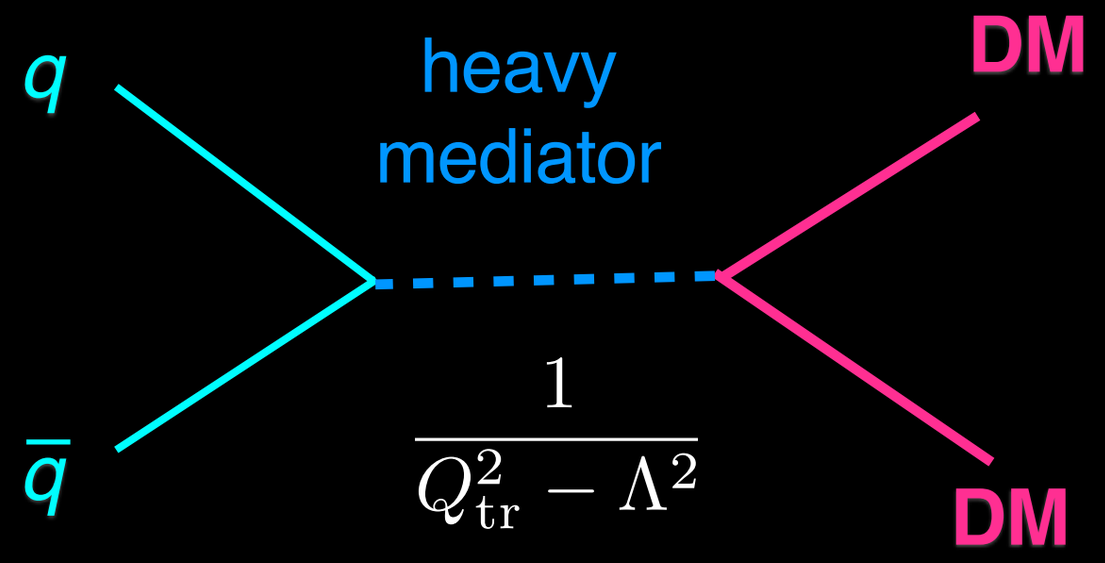
$$\frac{1}{\Lambda^2}(\bar{\chi}\Gamma^A\chi)(\bar{q}\Gamma_A q)$$

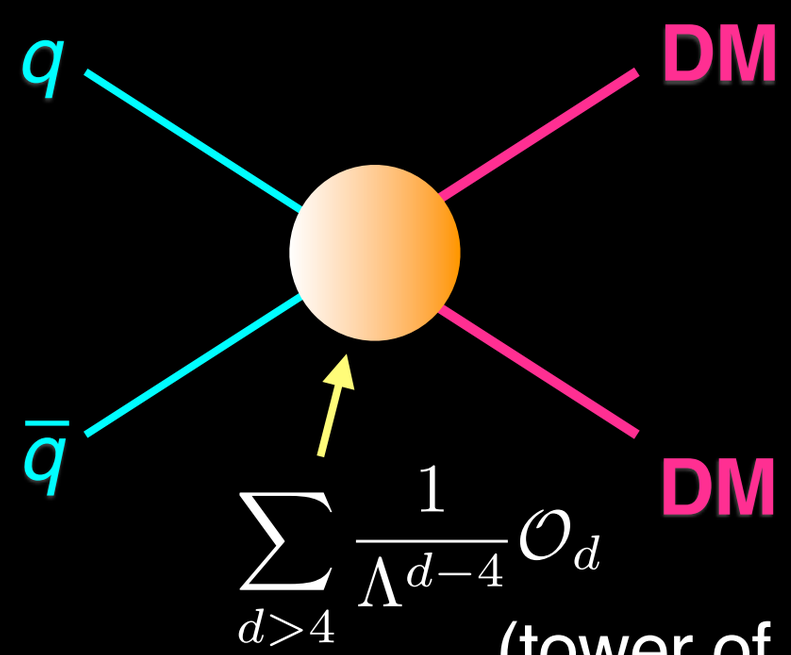
LHC can access regions beyond the validity of the eff. description

→ need to use EFT carefully and consistently

Effective Field Theory Description

- the momentum transfer in the relevant process must be $Q_{\rm tr} \lesssim \Lambda$





(tower of ops.)

$$\frac{1}{Q_{\rm tr}^2 - \Lambda^2} = -\frac{1}{\Lambda^2}\left[\overbrace{1}^{\text{dim-6}} + \frac{Q_{\rm tr}^2}{\Lambda^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{\Lambda^4}\right)\right]$$

- $Q_{\rm tr}/\Lambda$ measures the badness of the truncation of the tower of effective ops to the lowest dimensional ones

- Usually, lowest order is OK. Not a problem for direct/indirect searches. Situation can be different @ LHC.

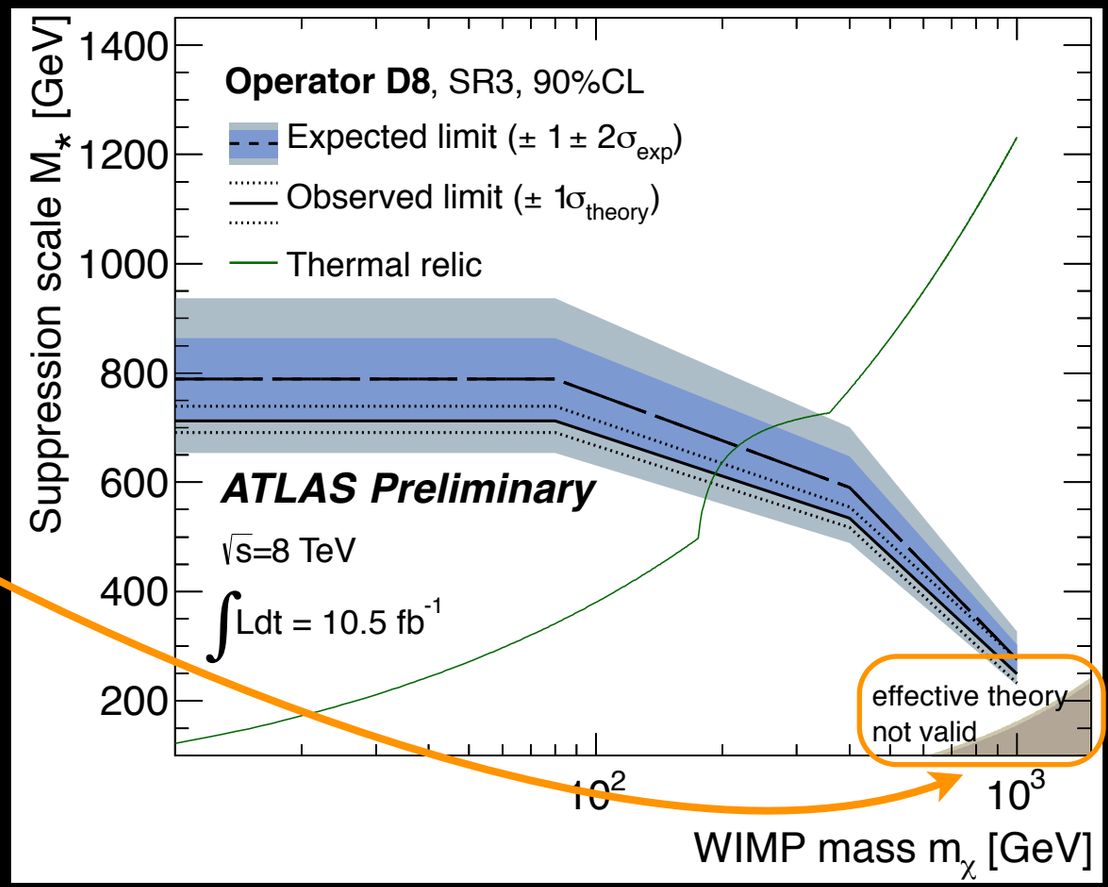
EFT Validity

- Standard lore

mediator mass $M > m_\chi$

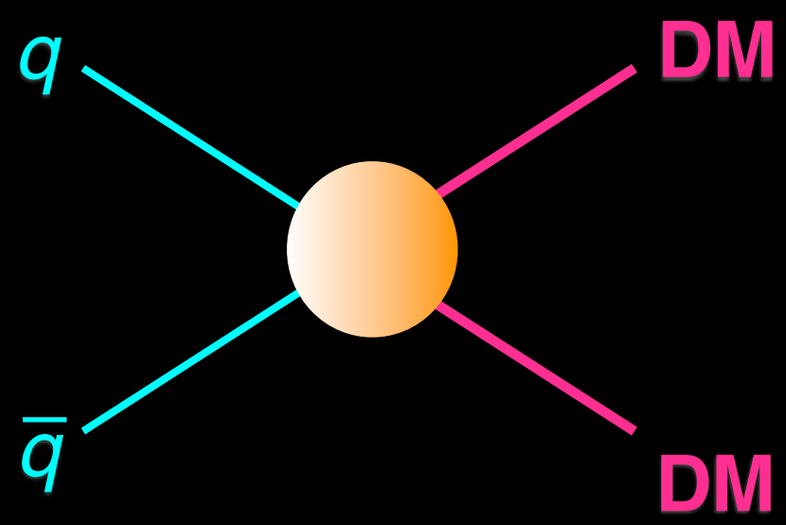
$$\Lambda \simeq \frac{M}{\sqrt{g_{\rm SM}\, g_\chi}} \gtrsim \frac{M}{4\pi} \Bigg\} \Lambda \gtrsim \frac{m_\chi}{4\pi}$$

Actual limits can be stronger (depending on the process)



[ATLAS-CONF-2012-147]

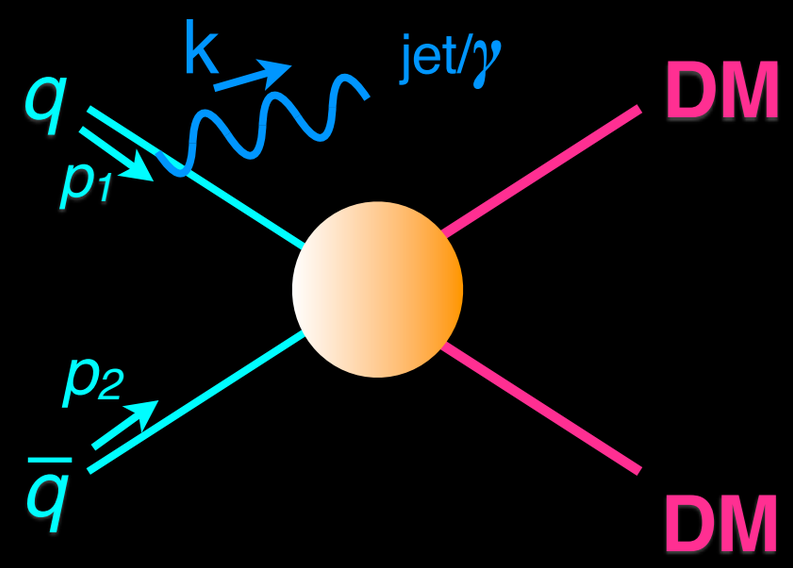
- 2→2 process



$$Q^2_{\rm tr} \geq 4m^2_\chi \longrightarrow \Lambda > 2m_\chi$$

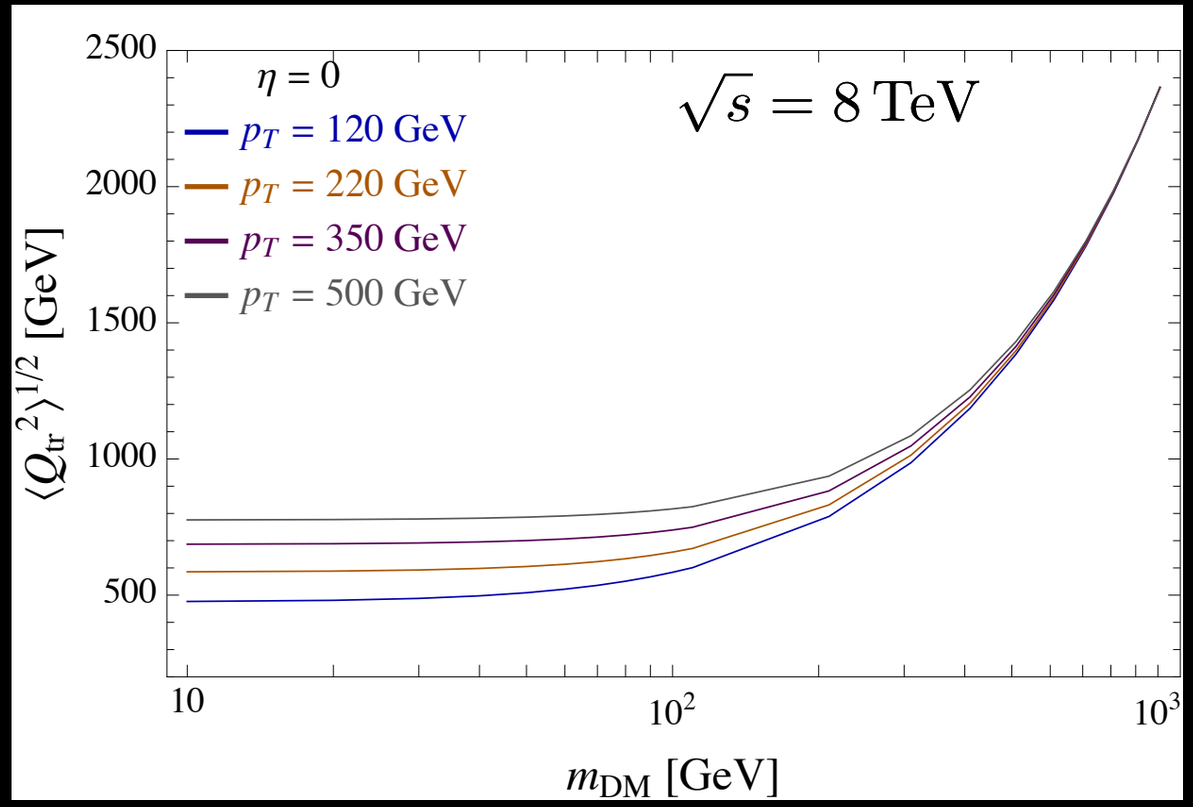
below this bound, the contribution of higher-dim ops becomes important

- 2→3 process



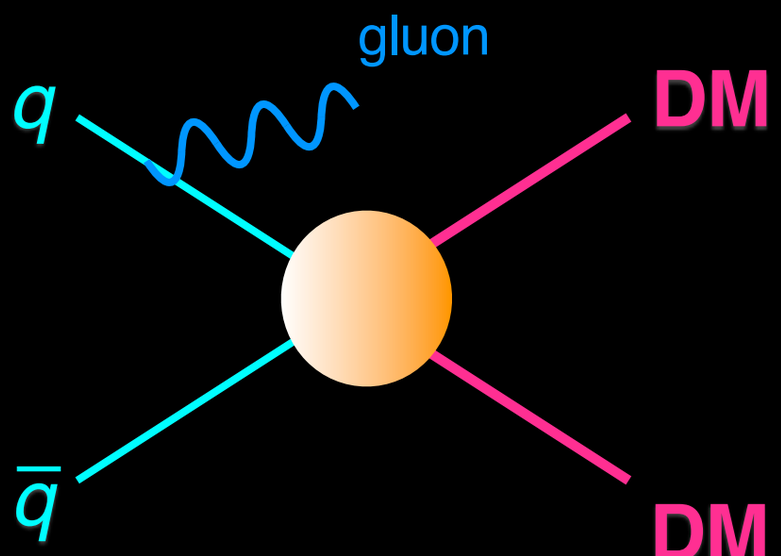
$$Q_{\rm tr}^2 \equiv (p_1 + p_2 - k)^2 = x_1 x_2 s - \sqrt{s}\, p_{\rm T} \left(x_1 e^{-\eta} + x_2 e^{\eta} \right)$$

for s-channel momentum transfer



the momentum trasnfer is larger for larger DM mass

An Example with Scalar Mediator

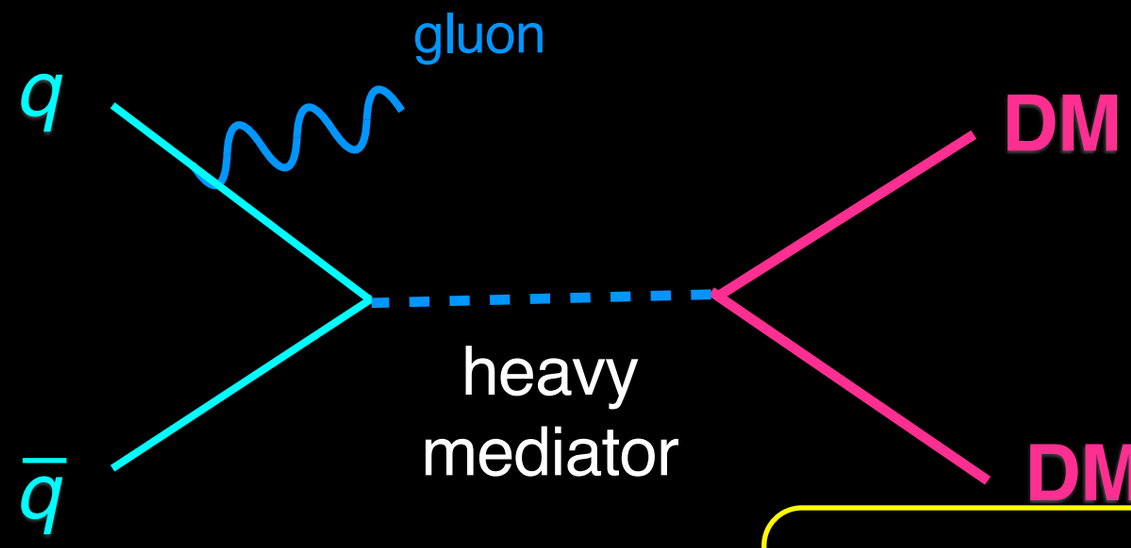


eff. operator $\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$

parton-level differential cross section:

$$\frac{\mathrm{d}^2\hat{\sigma}_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_{\mathrm{T}}}\frac{1}{\Lambda^4}\frac{\left[Q_{\mathrm{tr}}^2 - 4m_{\mathrm{DM}}^2\right]^{3/2}\left[1+\frac{Q_{\mathrm{tr}}^4}{(x_1x_2s)^2}\right]}{Q_{\mathrm{tr}}}$$

matching: $\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$



$$\mathcal{L}_{\mathrm{UV}} \supset \frac{1}{2}M^2S^2 - g_q\bar{q}qS - g_\chi\bar{\chi}\chi S$$

parton-level differential cross section:

$$\frac{\mathrm{d}^2\hat{\sigma}_{\mathrm{UV}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_{\mathrm{T}}}\frac{g_q^2g_\chi^2}{\left[Q_{\mathrm{tr}}^2 - M^2\right]^2}\frac{\left[Q_{\mathrm{tr}}^2 - 4m_{\mathrm{DM}}^2\right]^{3/2}\left[1+\frac{Q_{\mathrm{tr}}^4}{(x_1x_2s)^2}\right]}{Q_{\mathrm{tr}}}$$

EFT Validity

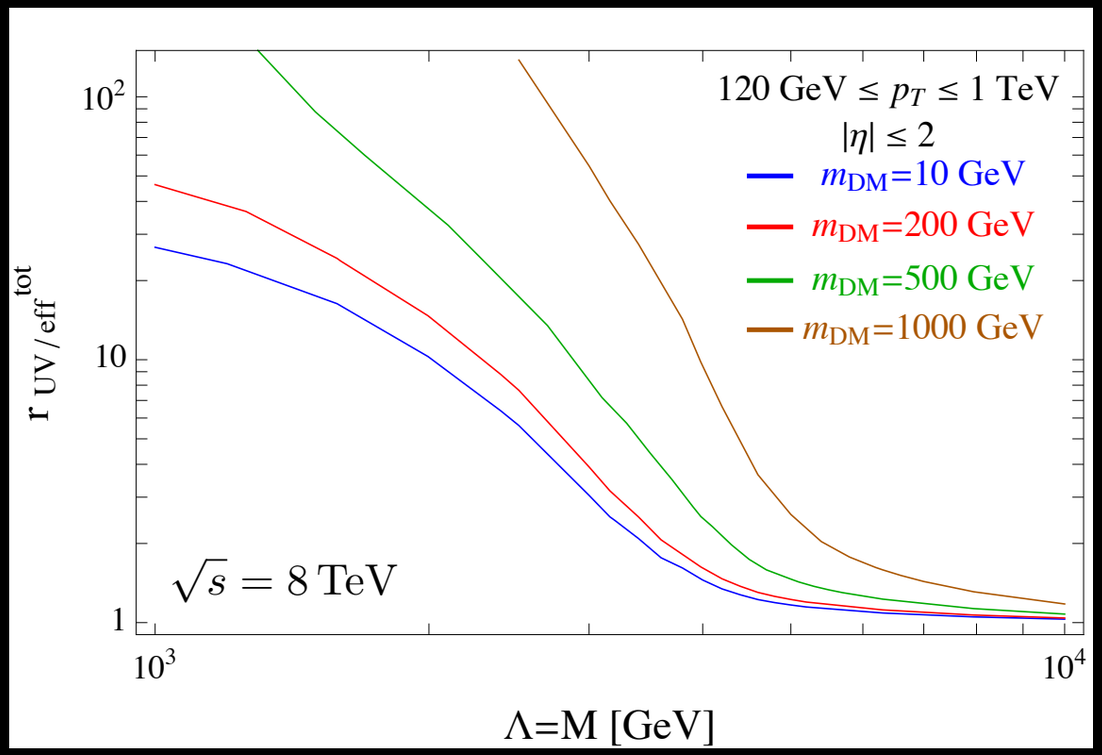
1. What is the difference between interpreting data with an effective operator and with its UV completion?

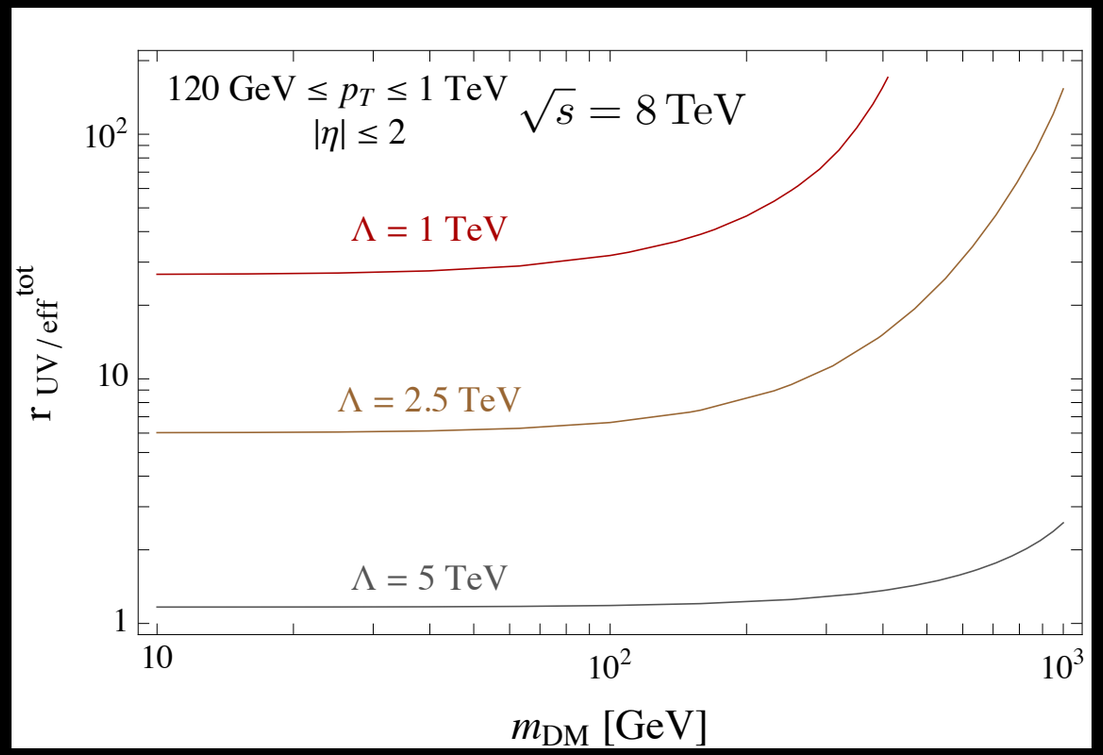
2. In what regions of the parameter space $\{\Lambda, m_{\rm DM}\}$ is the effective description accurate/reliable?

EFT vs UV completion

$$r^{\rm tot}_{\rm UV/eff} \equiv \frac{\sigma_{\rm UV}\big|_{Q_{\rm tr}<M}}{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}$$

error of using EFT (truncated at dim-6) instead of full theory





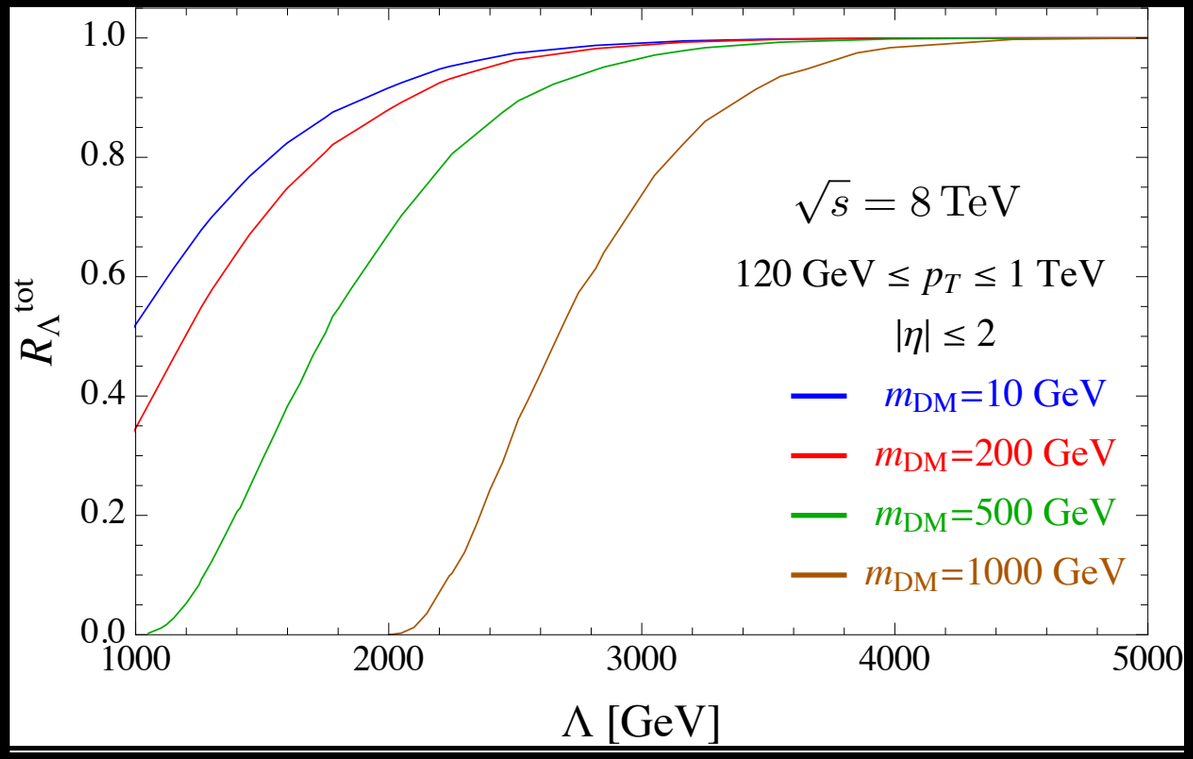
- $\sigma_{\rm UV}$ easily larger than $\sigma_{\rm eff}$ → mono-jet data can place more stringent bounds on mediator masses

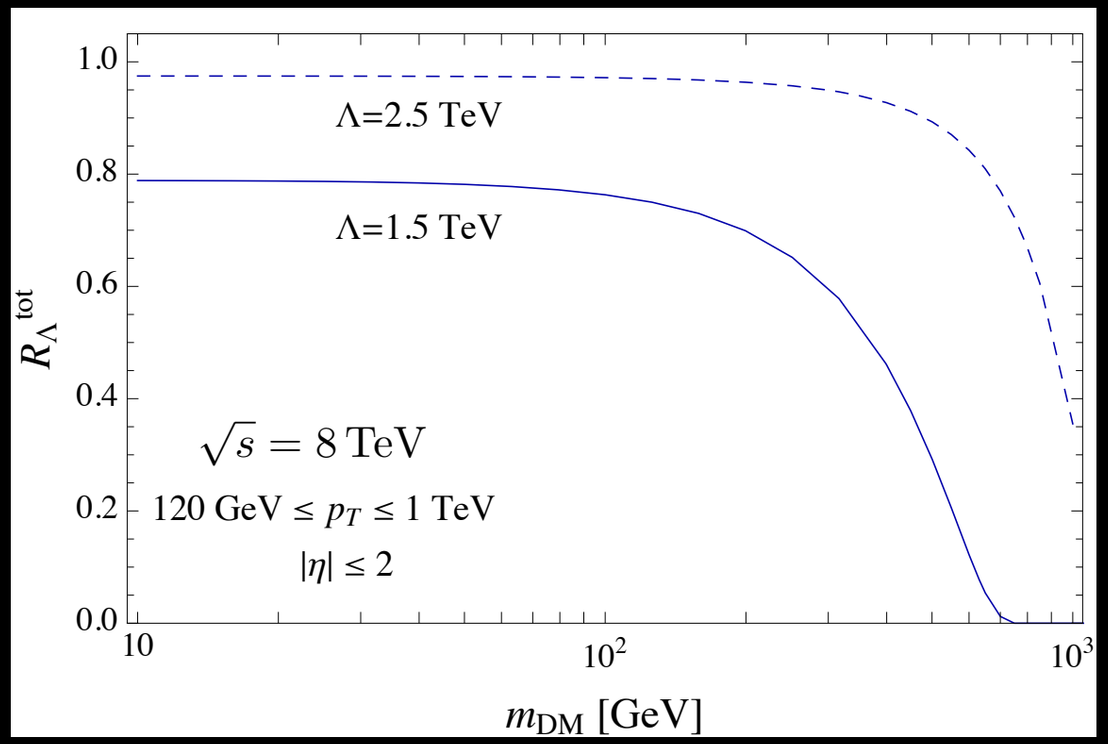
- **direct** exclusion bounds from negative searches of heavy mediators? (e.g. di-jet searches)

The effect of the EFT Cutoff

$$R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$$

fraction of eff. cross section at low momentum transfer





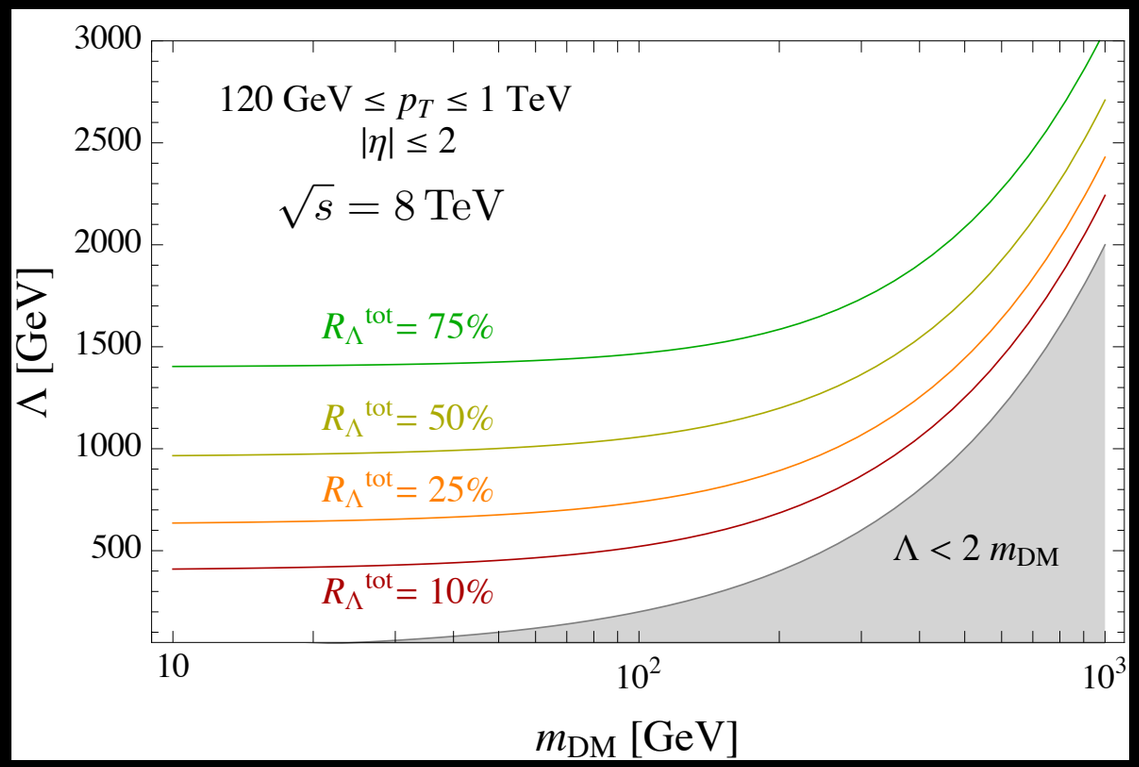
- Ratio ~ 1: negligible contribution from higher-dim ops.
  Accurate cross sections can be extracted without considering the cutoff on the momentum transfer.

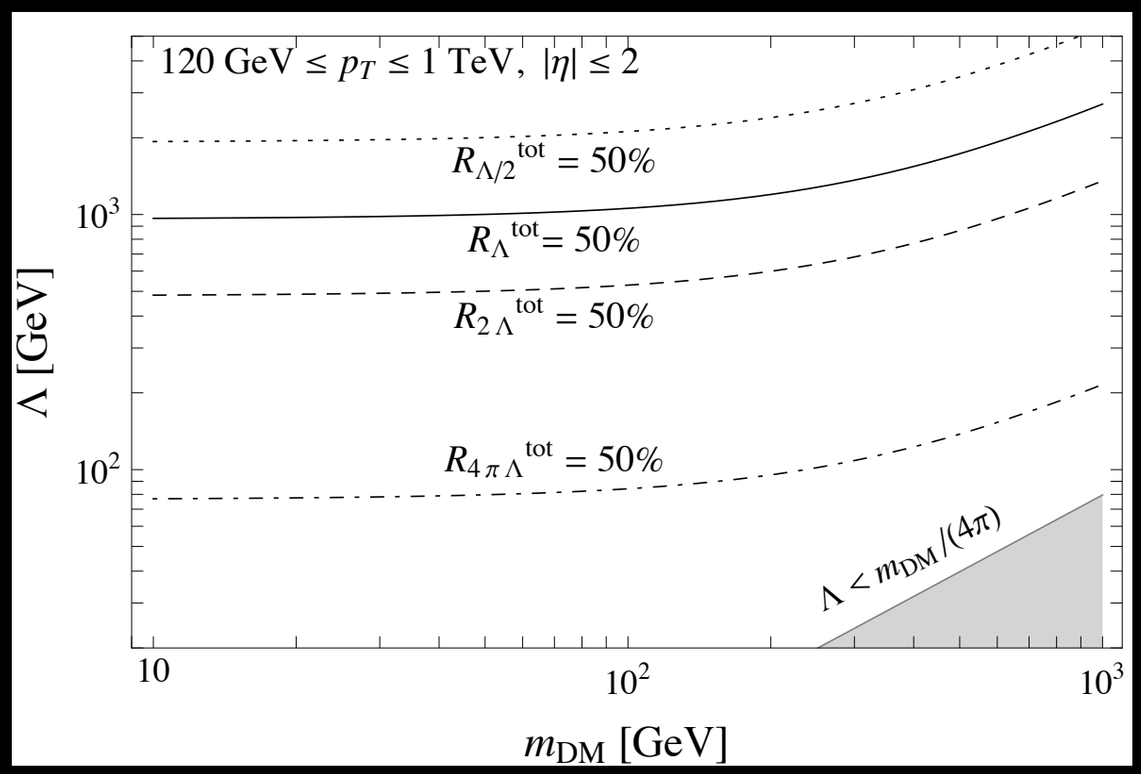
- EFT works better for larger Λ and smaller $m_{\rm DM}$

The effect of the EFT Cutoff

$$R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$$

fraction of eff. cross section at low momentum transfer





- Cross sections are measured experimentally with ~O(10%) accuracy. Worry about EFT validity is justified.
- The precise definition of cutoff scale is somewhat arbitrary (*Λ/2, 2Λ?)*
  Most conservative choice: $Q_{\rm tr} < 4\pi\Lambda$
- Numerical simulations: see next talk by J. Gramling.

A WAY-OUT: SIMPLIFIED MODELS

1-1 correspondence:
eff ops ⟷ simple toy models

✘ 1 or 2 more parameters (g's)
✘ direct detection limits must be re-expressed

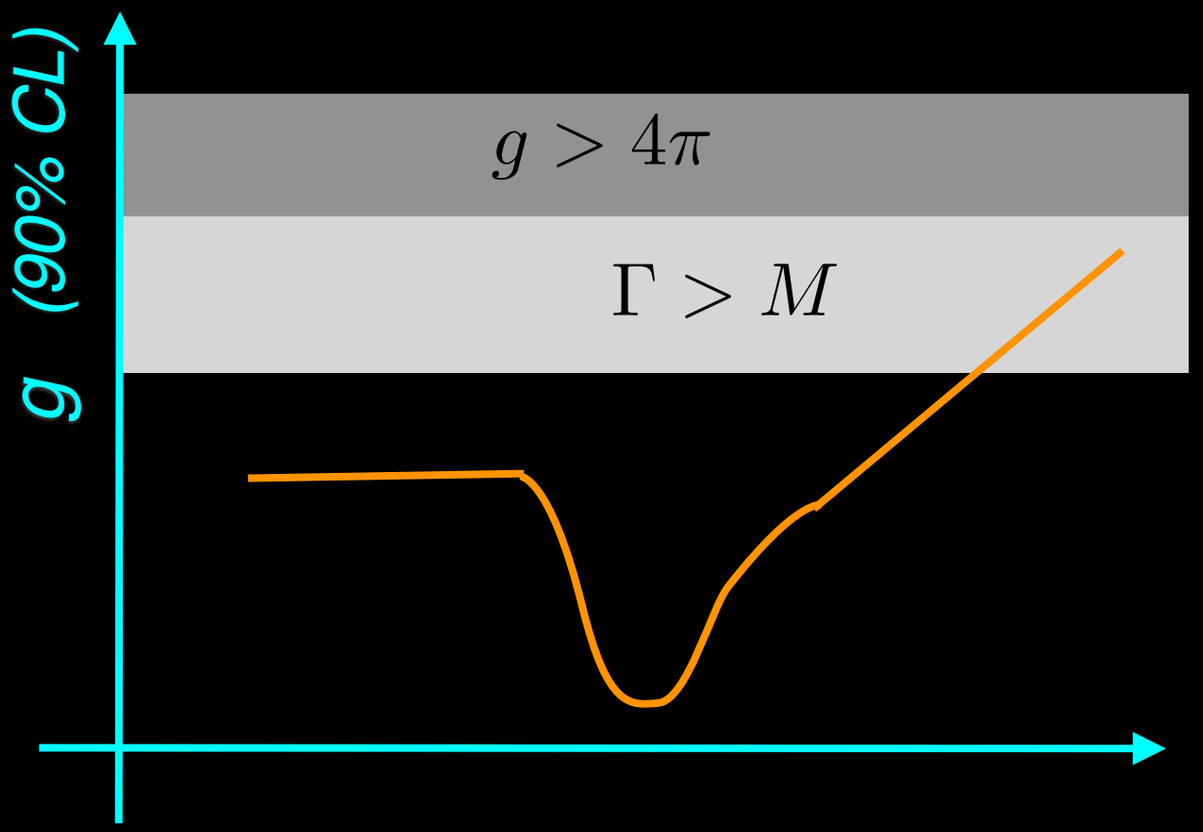
✓ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet
✓ theoretically consistent, no worries about EFT, widths, etc.

PROPOSAL

provide upper limits on g (or M/g)

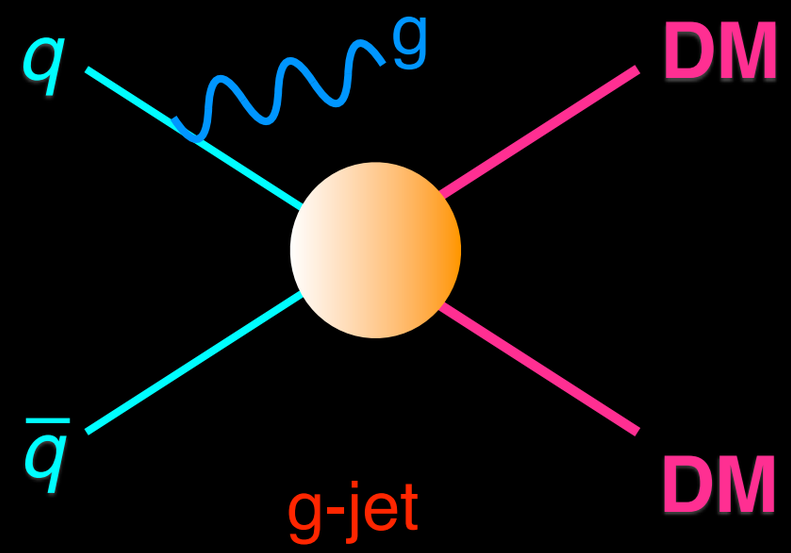
- for each simplified model
- for given m_{DM}

⟶ complete and reliable information

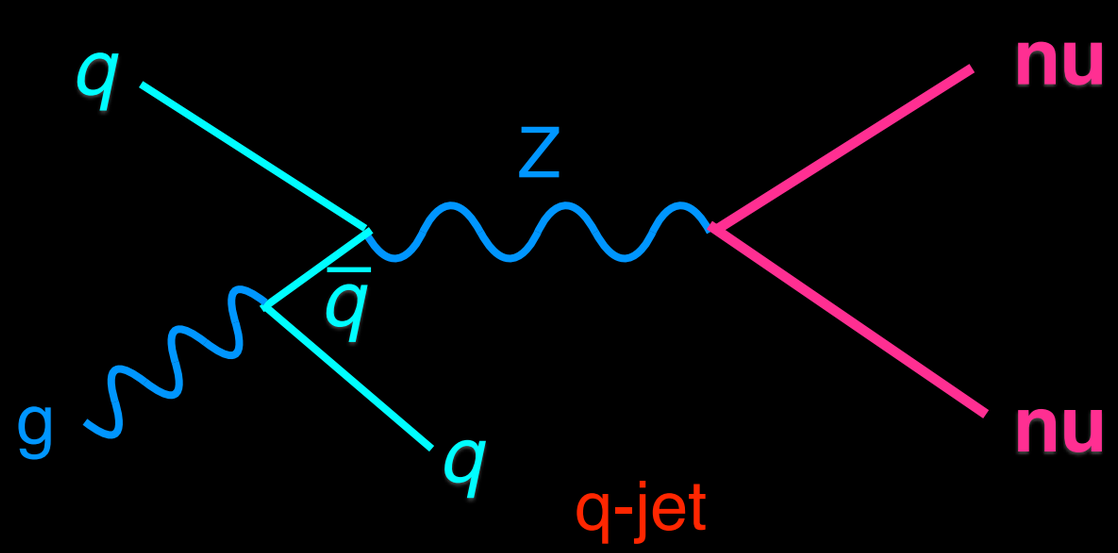


Quarks vs Gluon jets?

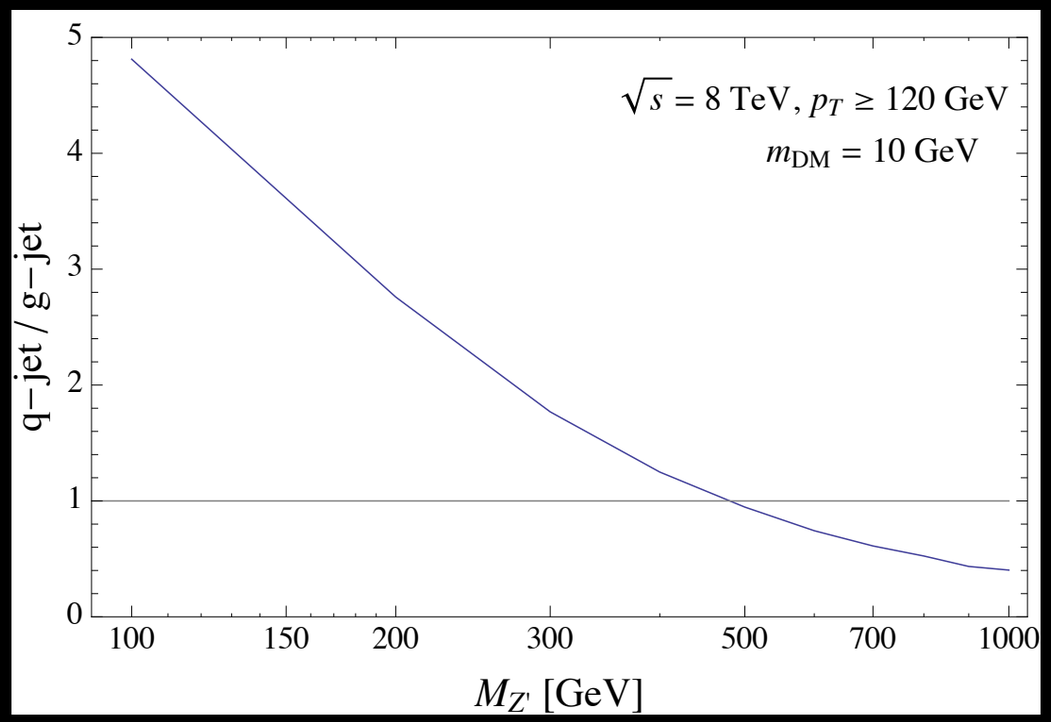
Preferentially:



Main bkg: $Z \to \nu\bar{\nu}$



because of parton luminosities



- Ratio q-jet/g-jet can be: ~ 1/4 for SIGNAL, ~ 5 for BKG
- Challenge: distinguish q/g jets
- This observation can help improving bounds with 14 TeV data

Outlook

14 TeV data?

- stat and syst errors are already comparable
- expect stronger bounds on Λ but also larger Q_{tr}

other ops?

- work in progress (analytically)
- for numerics, see Gramling's talk

t - channel?

- experimental results only for contact s-channel interactions

Scalar DM?

- anybody working on it?

Conclusions

LHC searches for DM using effective operators must be handled with care

without resorting to an explicit model, info about the validity of EFT can be extracted → take it into account when placing bounds

use explicit UV completions rather than EFT → stronger/complementary limits from direct searches of heavy mediators

LHC can discover mediators more easily than effective operators → TIME TO SHIFT FROM EFT TO SIMPLIFIED MODELS