Simplified Models for $t\bar{t}$ + Dark Matter

T. du Pree, P. Harris, J. Marrouche, N. Wardle
CERN

B. Jayatilaka
FNAL

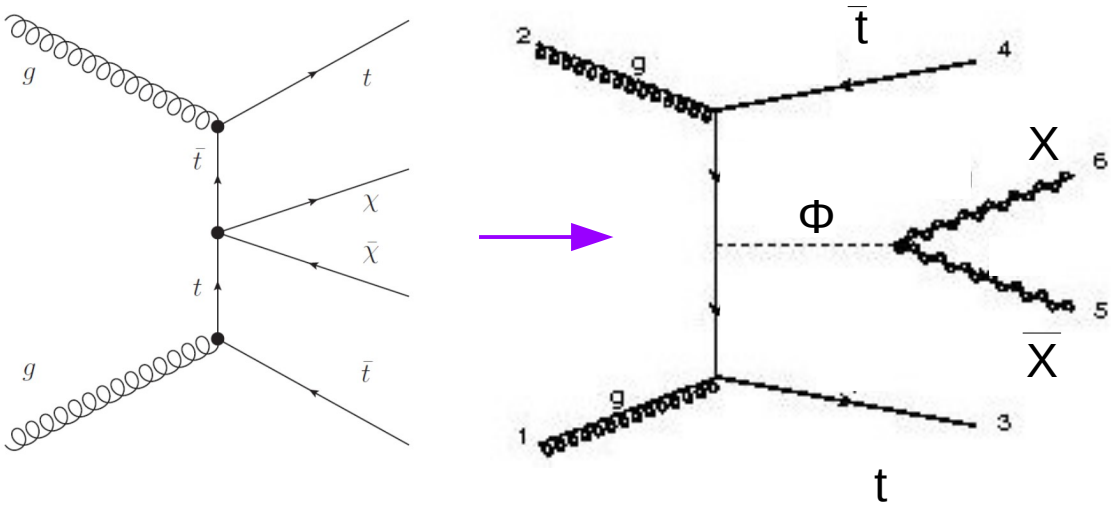
D. Abercrombie, B. Allen, K. Bierwagen, L. Di Matteo,
G. Gómez-Ceballos, D.G. Hsu, M. Klute, S. Narayanan, C. Paus,
J. Veverka
MIT

K. Hahn, S. Sevova, *K. Sung*
Northwestern University

M. Zanetti
Universita' di Padova

Introduction

- Preliminary studies on simplified models for $t\bar{t}$ + Dark Matter
  - Run-I $t\bar{t}$+DM analyses utilized an EFT / contact interpretation
  - Limitations of the EFT interpretation now widely recognized
  - *Simplified models* (ie: with an explicit mediator) more appropriate at the LHC, as the DM mediator can be directly produced



Overview

- Models & Implementation
- Validation
  - Gen-level Comparison with EFT
- Analysis
  - Gen-level simplified model scan
- Summary & Outlook

Models

- Focus on spin-0 mediator, scalar / pseudoscalar couplings
  - Minimal Flavor Violation → couplings proportional to SM Yukawas

$$\mathcal{L}_S = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - g_\chi\phi\bar{\chi}\chi - \sum_{\rm fermions} g_v\frac{y_f}{\sqrt{2}}\phi\bar{f}f\,,$$

$$\mathcal{L}_A = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2}m_A^2A^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - ig_\chi A\bar{\chi}\gamma^5\chi - \sum_{\rm fermions} ig_v\frac{y_f}{\sqrt{2}}A\bar{f}\gamma^5 f.$$

  - Monojet sub-optimal for this scenario, loop suppressed
  - Pseudo-scalar coupling velocity suppressed in Direct Detection
- Using model conventions of 1411.0535
  - Coupling strength g_q scales SM Yukawa

$$g_{\rm SM}^q \equiv g_q y_q\,, \quad g_{\rm DM} \equiv g_\chi y_\chi\,, \quad \text{where} \quad y_\chi \equiv \frac{m_\chi}{v} = \frac{m_{\rm DM}}{v}$$

  - Coupling strength g_χ set to 1, facilitates re-scaling of results

Model Implementation

- Extend MadGraph SM to incorporate mediated DM production
  - Introduce spin-0 PS mediator, use SM Higgs for scalar
  - Implement messenger-SM couplings to top only
  - Minimum mediator widths a la 1411.0535

$$\Gamma^{S,P}_{\mathrm{MED,min}} = \Gamma^{S,P}_{\chi\bar{\chi}} + N_c \Gamma^{S,P}_{t\bar{t}}$$

$$\Gamma^{S}_{f\bar{f}} = \frac{g_f^2 m_f^2 m_{\mathrm{MED}}}{8\pi v^2}\left(1-\frac{4m_f^2}{m^2_{\mathrm{MED}}}\right)^{\frac{3}{2}}$$

$$\Gamma^{P}_{f\bar{f}} = \frac{g_f^2 m_f^2 m_{\mathrm{MED}}}{8\pi v^2}\left(1-\frac{4m_f^2}{m^2_{\mathrm{MED}}}\right)^{\frac{1}{2}}$$

  - Showering with Pythia8

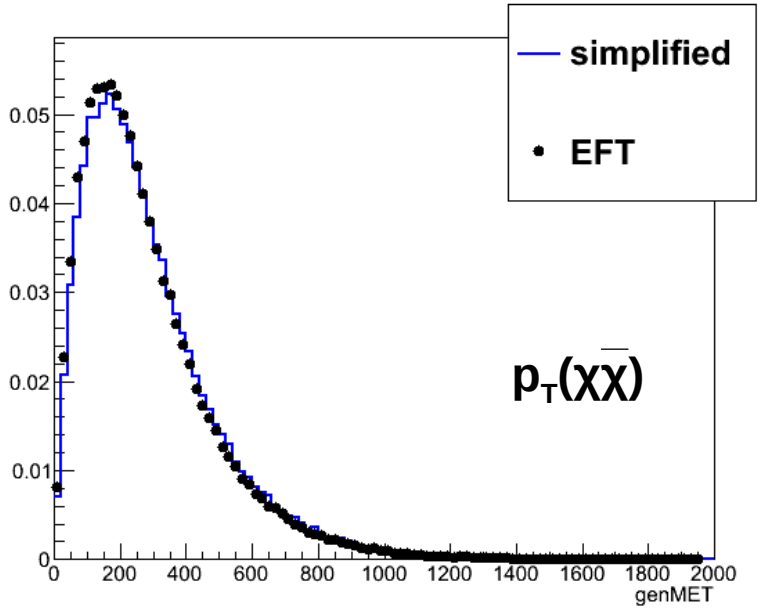
- Free parameters in the model: m_{DM}, m_{MED} and g_q

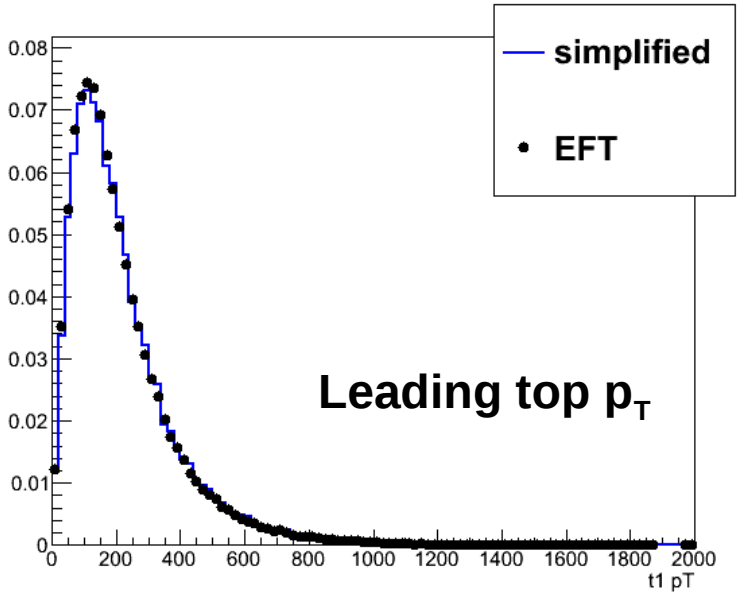
(private) Production

- Scan m_{DM}:
  - 1, 10, 50, 100, 200, 600, 1000 GeV
- Scan m_{MED} over range similar to recent monojet/mono-V study:
  - 350, 525, 725, 925, 1125, 1325, 1525, 1725, 1925, 2000, 3000, 4000, 5000, 7000, 10000, 11000, 12000 GeV
- Same with g_q ...
  - 0.3, 0.5, 1.0, 1.5, 2.0, 3.0
- Study @ 13 TeV: validation with EFT and first look at effects from parameter scans

Validation (1)

- Compare official CMS EFT samples to simplified model with m_{MED} = 12 TeV and g_q = 3

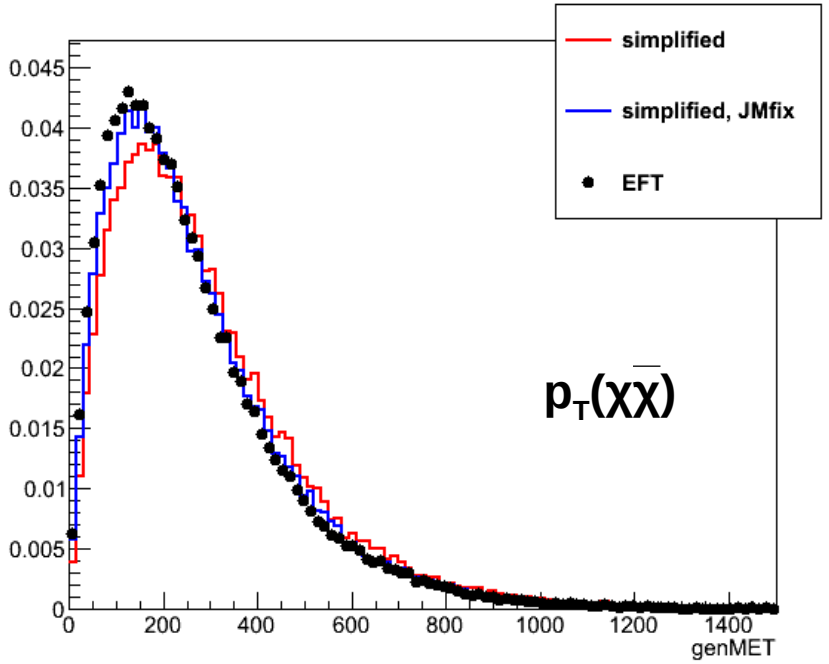


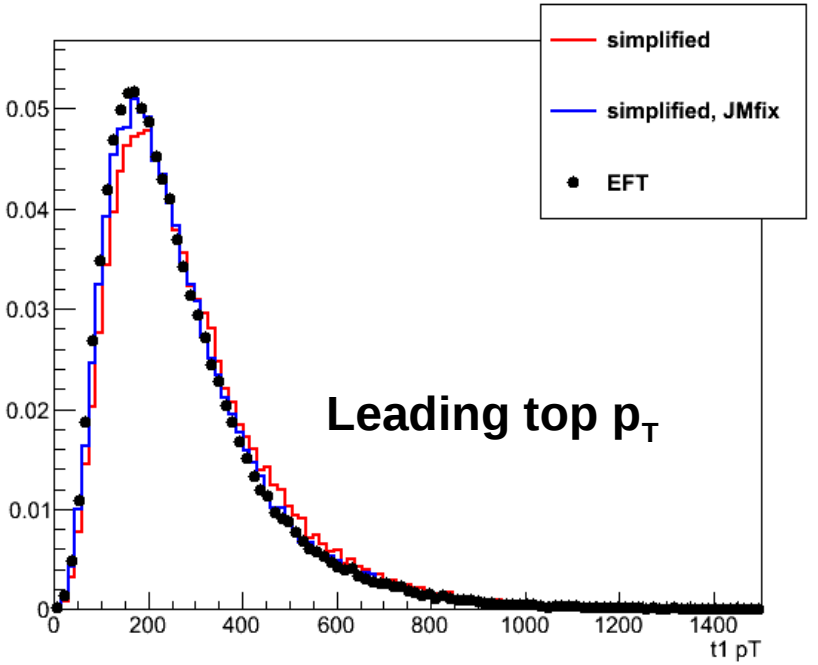


- Comparison above at LHE level
  - Implementation of the MG model validated

Validation (2)

- Compare official CMS EFT samples to simplified model with m_{MED} = 12 TeV and g_q = 3





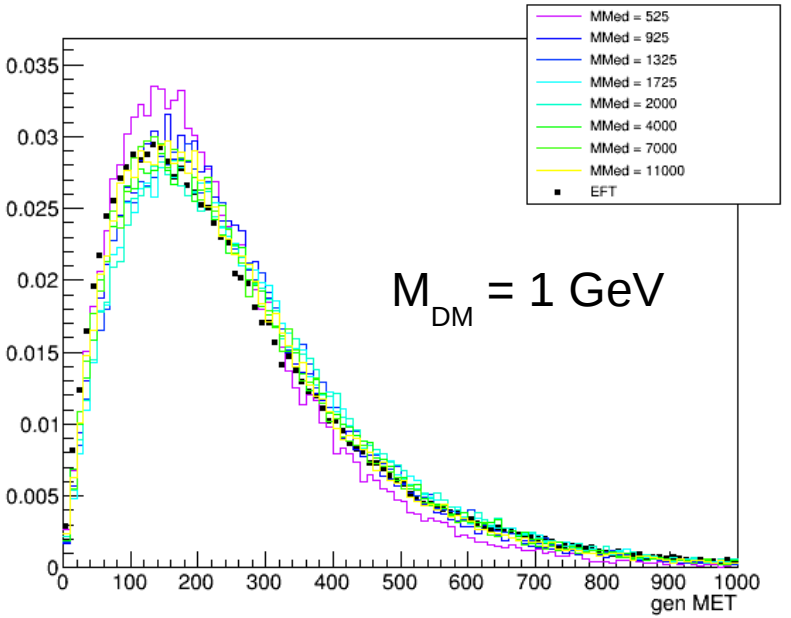
- Comparison above after Pythia8
  - Initially generated samples where jet-matching parameters differed from official CMS config
  - In following, will show results before fix, as not yet propagated to all our samples...

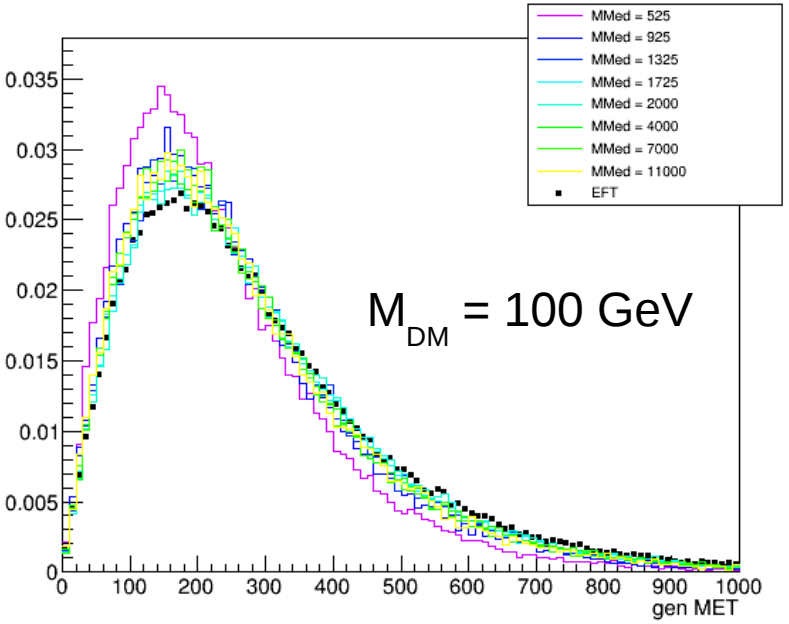
Model Scan

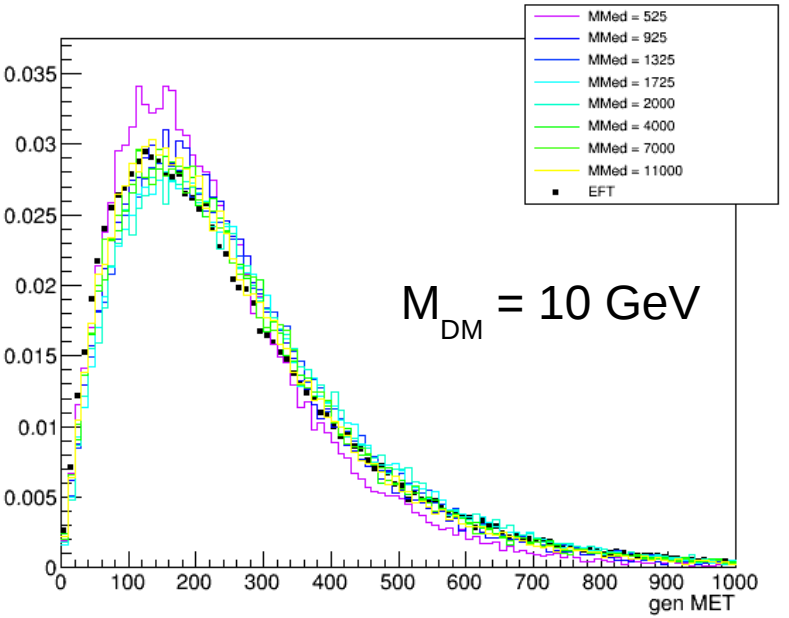
- Scans over model parameters
  1) m_{MED} for fixed g_q and m_{DM}
  2) g_q for fixed m_{DM} and m_{MED}
  3) Scalar vs pseudoscalar
- Caveat
  - Validation performed with 0,1,2 additional jets, as in the EFT
  - ***But*** scan samples generated with 0 additional jets
    - Higher multiplicity prohibitively time consuming for private production
    - But should be do-able in an official scenario

M_{MED} Scan (1)

- M_{DM} = 1, 10, 100 GeV @ g_q = 3, scalar
  - *MET distribution* broadens with increasing mediator mass, as expected
  - Hadronization differences more apparent with increasing m_{DM}

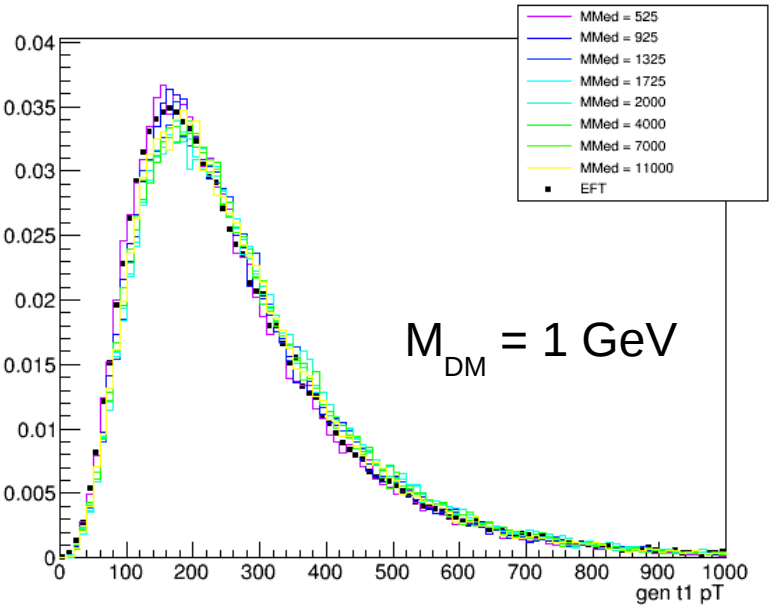


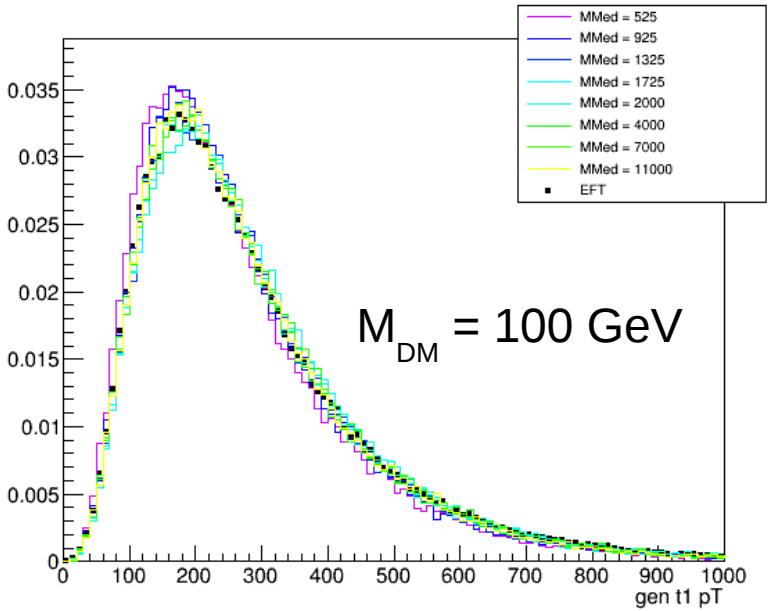


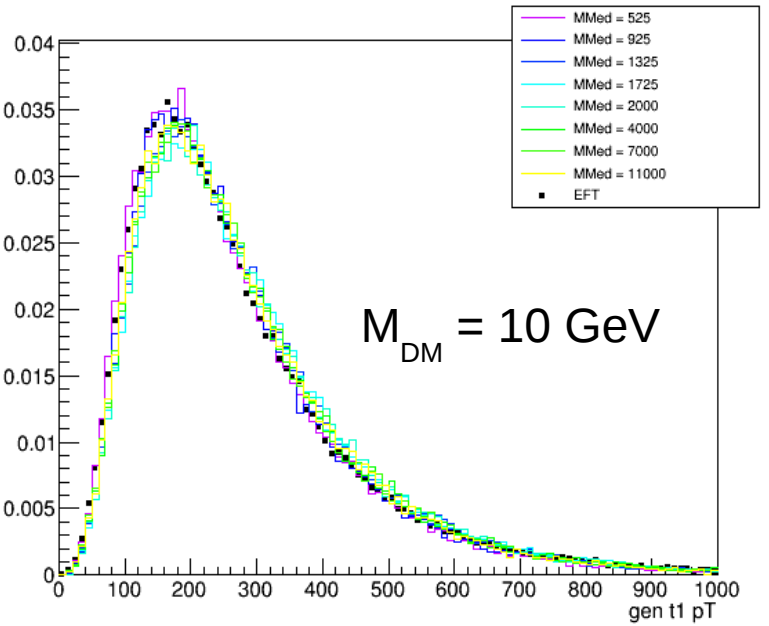


M_{MED} Scan (2)

- M_{DM} = 1, 10, 100 GeV @ g_q = 3, scalar
  - *Top p_T distribution* also broadens with increasing mediator mass, as expected

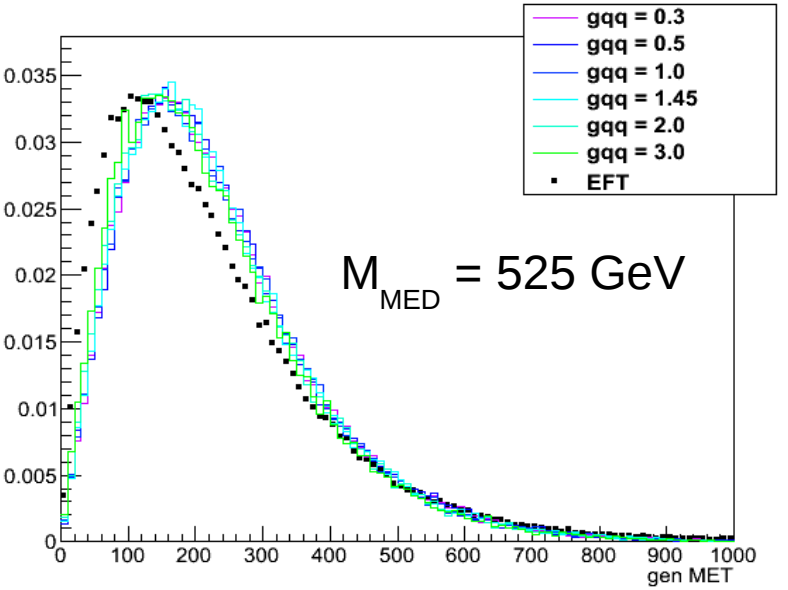


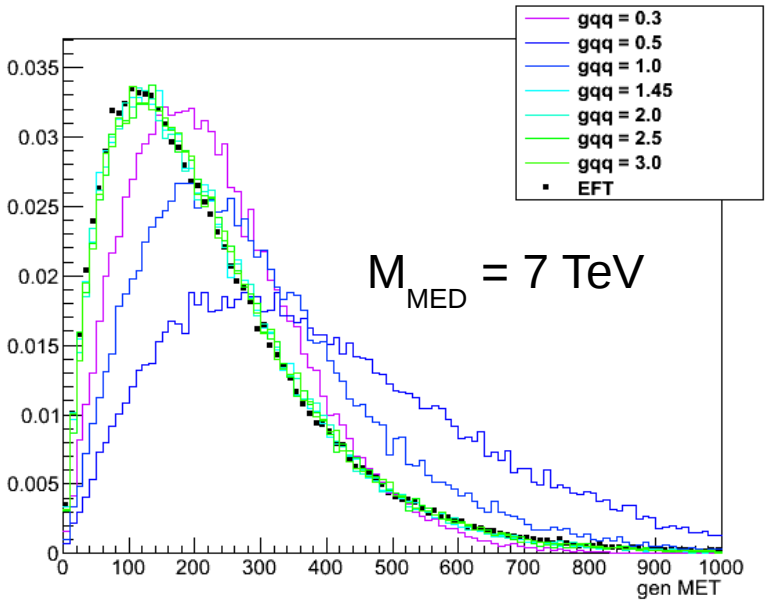


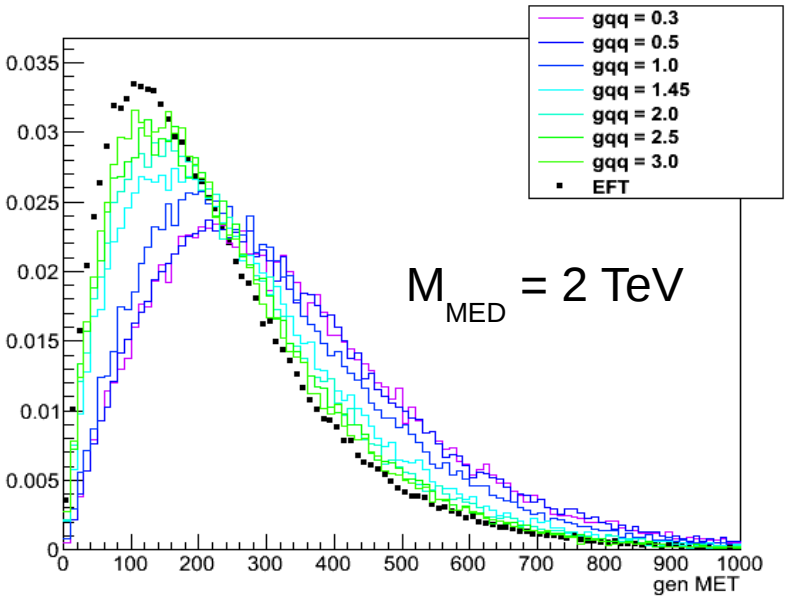


g_q Scan (1)

- M_{DM} = 1 GeV, M_{MED} = .525, 2, 7 TeV, scalar
  - Little difference in MET distributions for light mediators
  - Large couplings: pdf suppression of large $s_{\chi\chi}$, narrows MET distribution

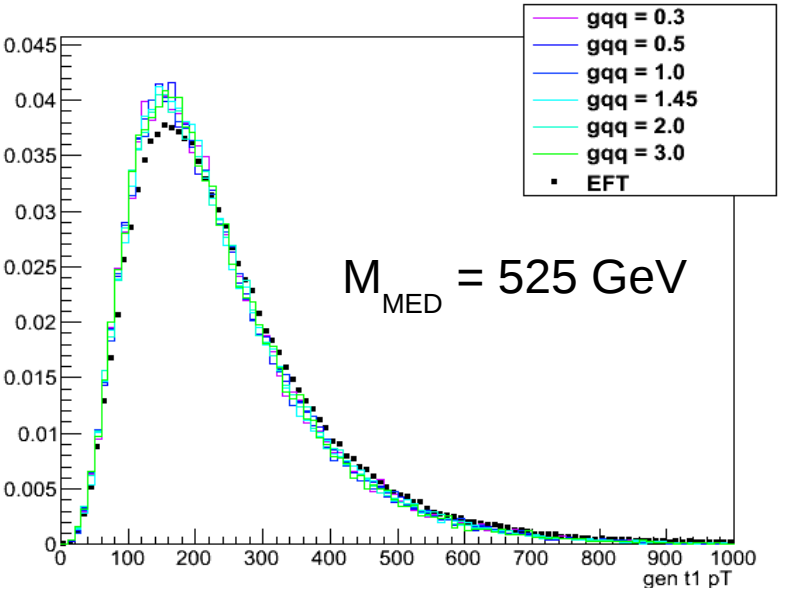


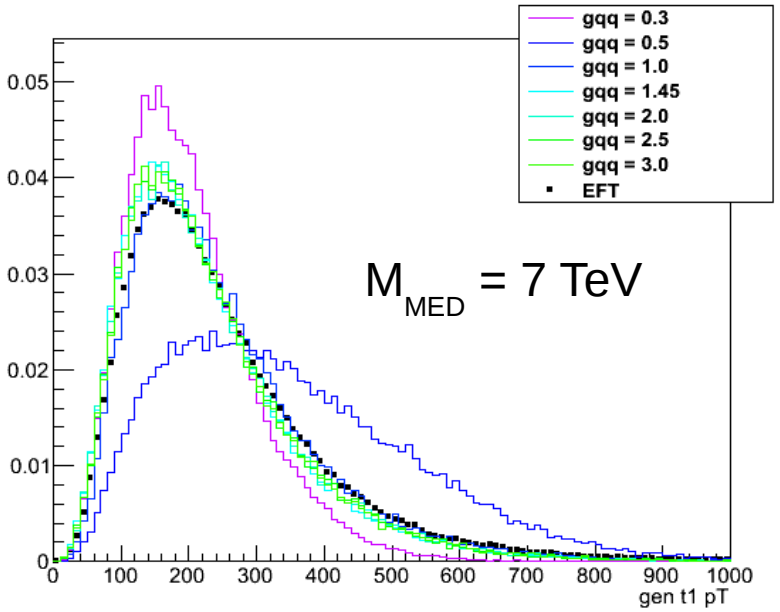


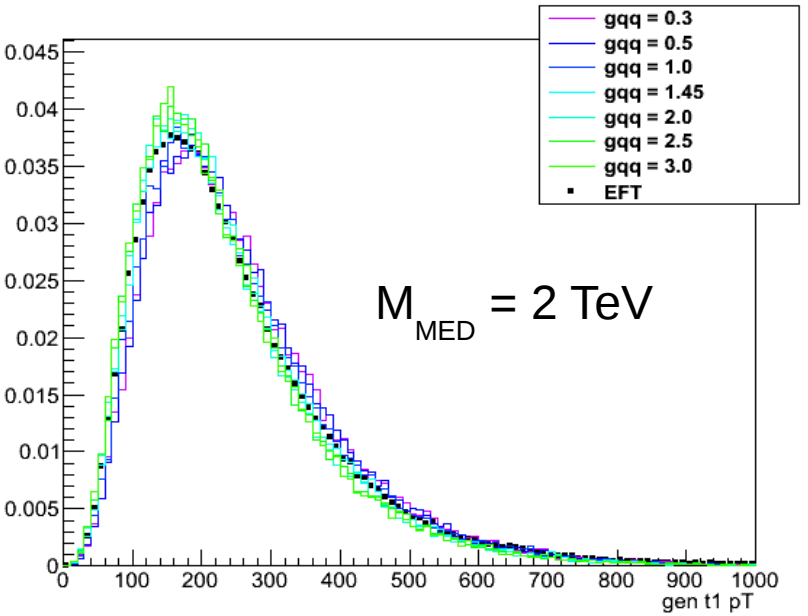


g_q Scan (2)

- M_{DM} = 1 GeV, M_{MED} = .525, 2, 7 TeV, scalar
  - Similar situation for top p_T

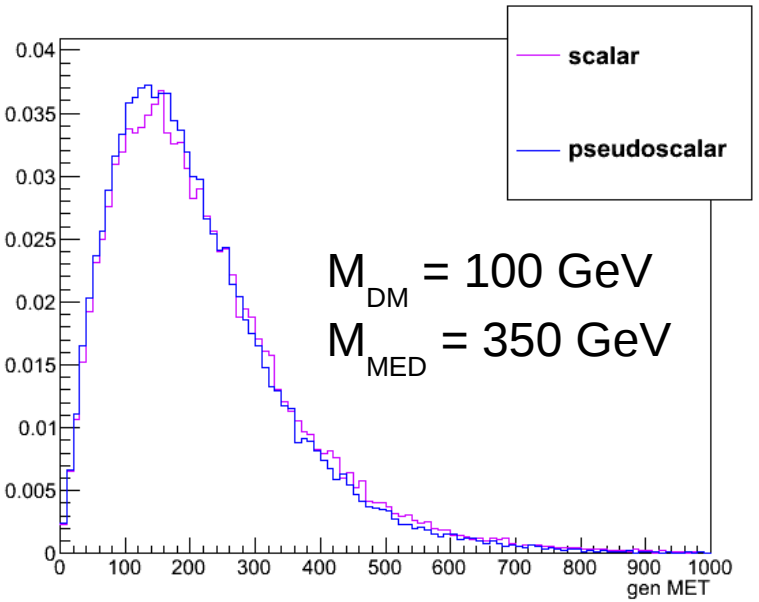


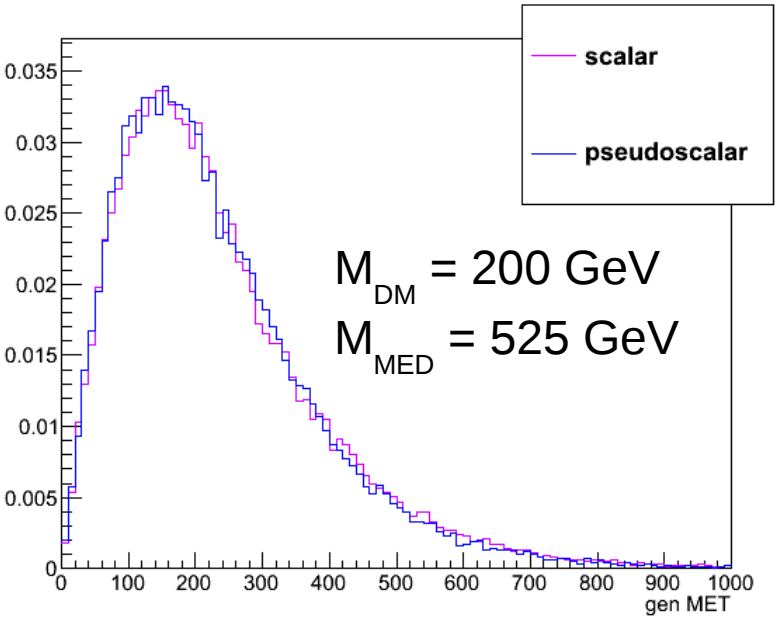




Scalar vs Pseudoscalar

- Small effects from difference in widths
  - $\Gamma_{PS} > \Gamma_{S}$, leads to narrowing of PS MET distribution
    - Again, pdf suppression
  - More apparent near threshold(s), as below
  - Note: only comparing shapes; cross sections will be different





Summary & Outlook

- First look at simplified models for DM + heavy flavor pair
  - Implementation validated against 13 TeV EFT
  - Kinematics from simplified modeling consistent with expectations
  - Machinery in place to turn around LHEs for a 13 TeV scan

- Open issues:
  - Double check / synchronize coupling strength convention
    - Important for obtaining consistent cross sections (not yet checked) with monojet/mono-V models

- In progress:
  - Explore model predictions following basic kinematic selections
  - Develop LHE/GEN re-weighting scheme to avoid full reconstruction of many model points
    - Techniques from monojet / mono-V a good starting point
  - Simplified $b\bar{b}$ + DM implemented, generation recently finished
    - Validation on-going
    - Looking at consistency with relic density constraints using MadDM

Backup

- M_{MED} for central value of 2 TeV, various coupling strengths