Search for the production of dark matter in association with top-quark pairs in the single-lepton final state in proton-proton collisions at $\sqrt{s} = 8$ TeV (CMS)

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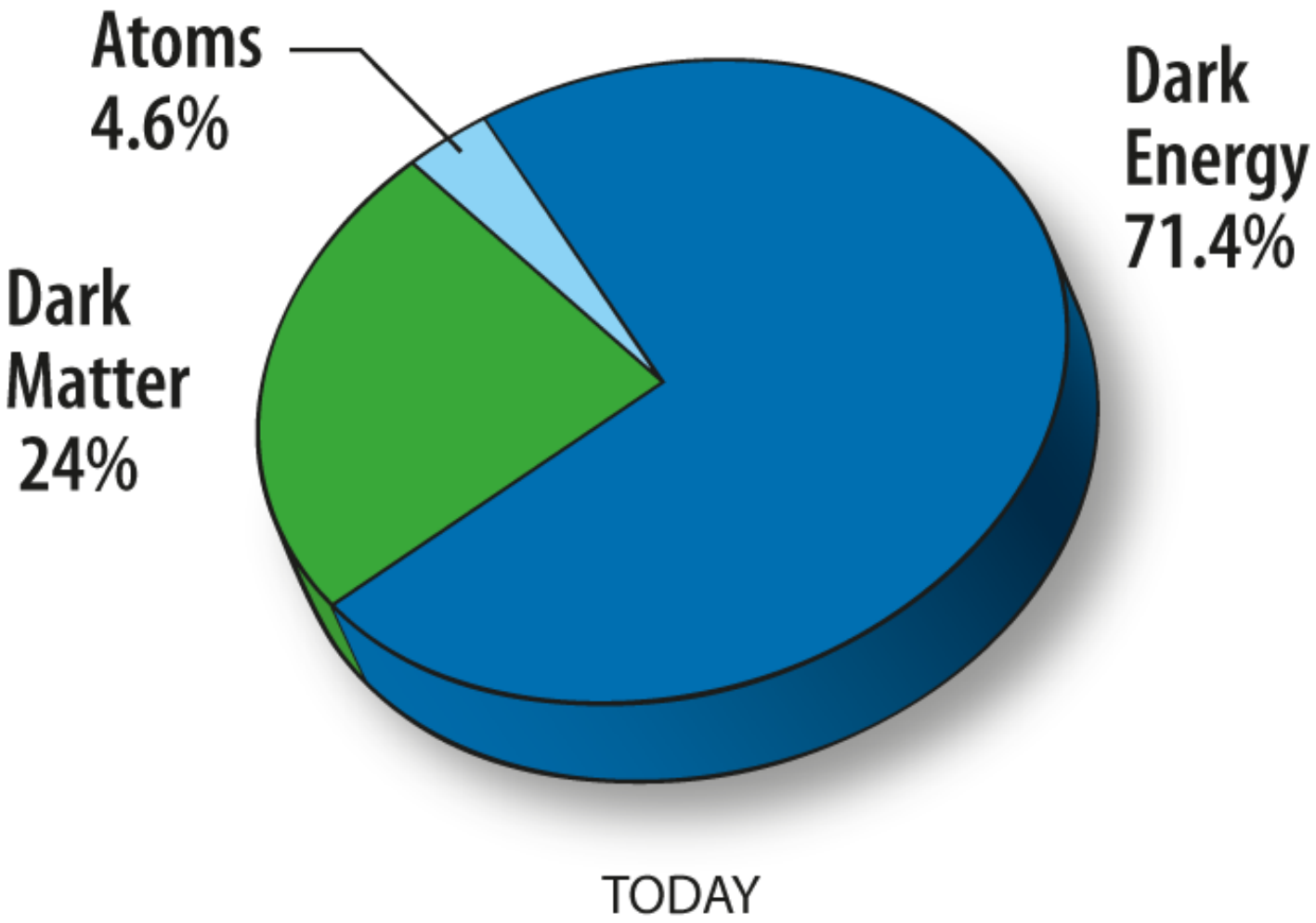
Outline

Introduction

- Dark Matter (DM) is estimated to account for about 24% of the total mass of the universe
- Five times more abundant than the known baryonic matter



Introduction

- Assume DM has a particle explanation
- There is only one new Dirac fermion which is related to DM within LHC energy reach
- Fermions interact with quarks via a four-fermion contact interaction, this is described by a EFT Lagrangian

$$L_{int} = \sum_{q} \sum_{i} C_{qi} \left(`\bar{q} \Gamma_i^q q \right) \left(\bar{\chi} \Gamma_i^\chi \chi \right) \tag{1}$$

Introduction

- Exclusion limit for a scalar interaction between DM particles and scalar is the most relaxed of all the interaction types probed so far
- In this interaction the coupling strength is proportional to the mass of the quark:

$$L_{int} = \frac{m_q}{M_\star^3} \bar{q} q \bar{\chi} \chi \tag{2}$$

- Coupling to light quarks $\rightarrow$ suppressed
- Sensitivity to scalar interaction can be improved by searching in final states with third-generation quarks

Objective

- This paper reports on the search of the production of DM particles in association a pair of top quarks
- Consider the scalar interaction only
- Focus on the events with one lepton (electron or muon) in the final state

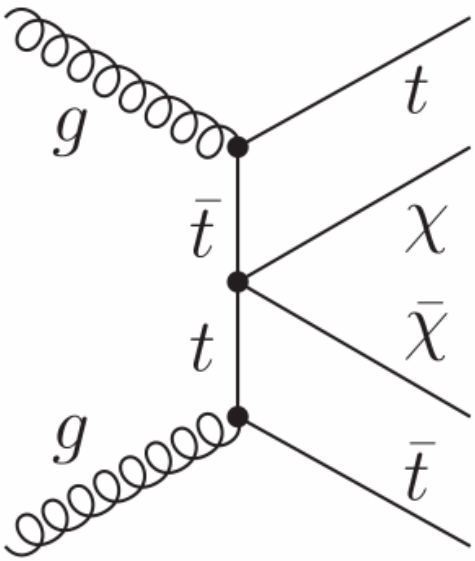
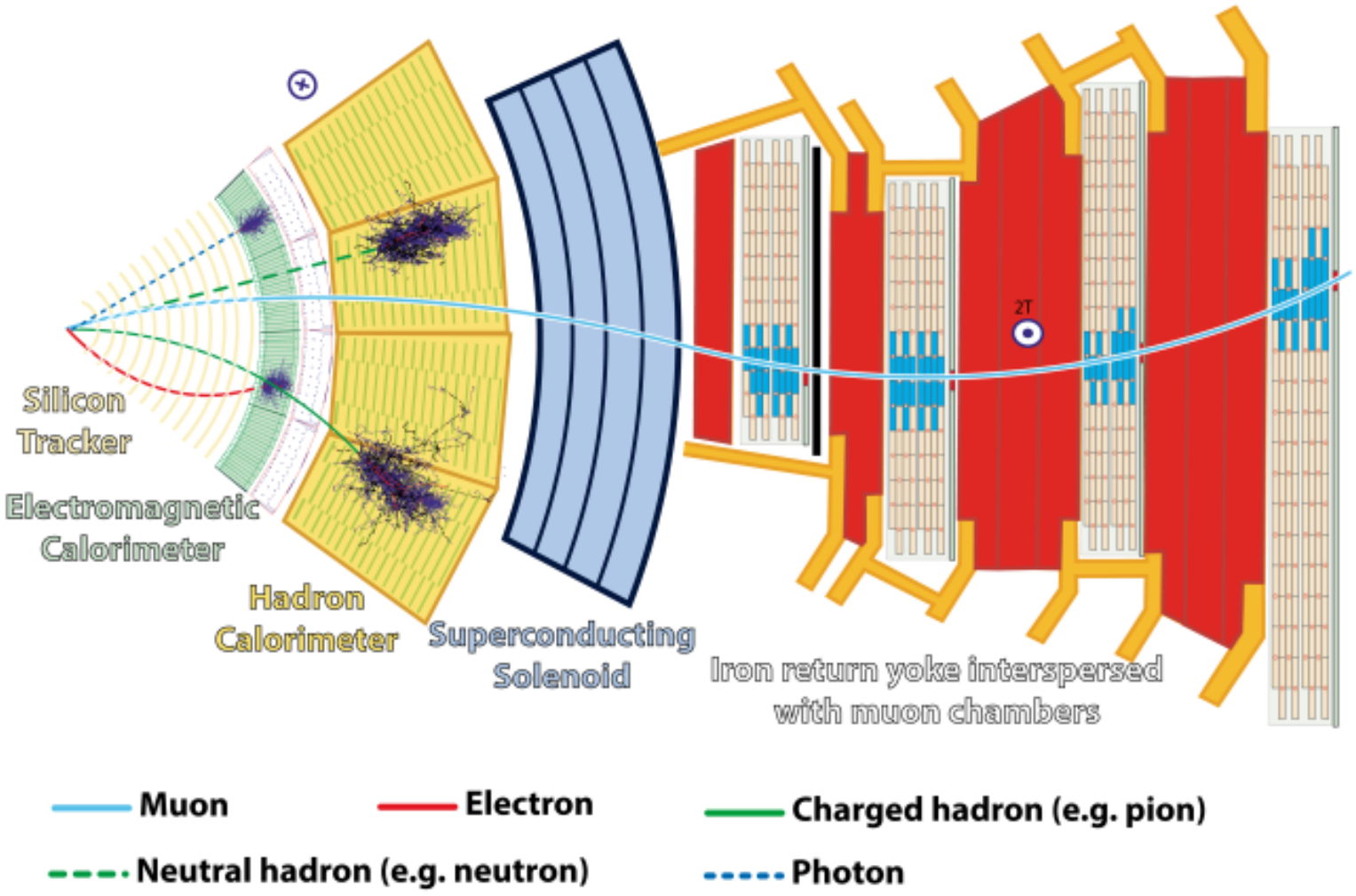


Figure 1: Dominant diagram contributing to the production of DM particles in association with top quarks at the LHC.

CMS Detector



Data and simulated samples: Data

- Data used in this search was recorded with the CMS detector at the LHC with a $\sqrt{s} = 8$ TeV
- Integrated Luminosity corresponds to 19.7 fb^{-1}
- Data was collected using single-electron and single-muon triggers, with the P_T thresholds of 27 and 24 GeV respectively
- Efficiencies of the triggers of the data and the simulation are compared and the correction factors are applied to the simulation

Data and simulated samples: Simulation

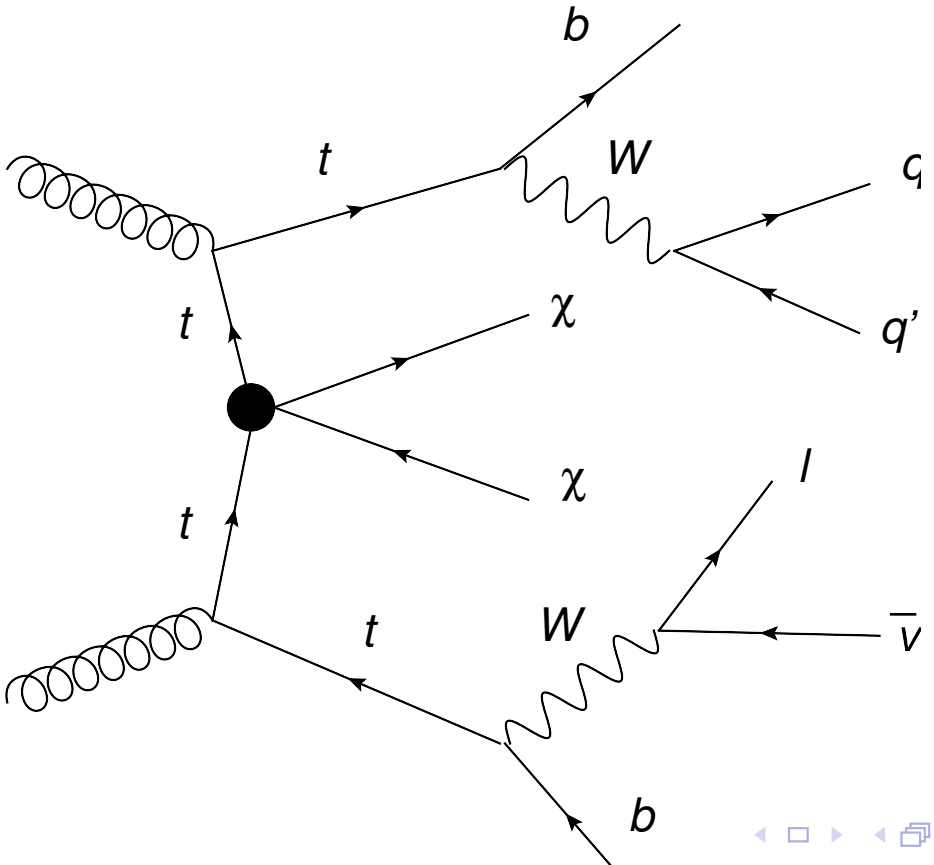
- DM signal is generated with MADGRAPH v5.1.5.11
- Dominant standard model (SM) background processes for this search are:
  - $t\bar{t}$+jets
  - $t\bar{t} + \gamma/W/Z$
  - single top quark
  - diboson (WW, WZ. and ZZ)
  - Drell-Yan events
- All these backgrounds, except single top quark and WW events, are generated with MADGRAPH
- Single top quark processes are generated with NLO generator POWHEG v1.0 & WW background are generated with PYTHIA v6.242
- All events are:
  - matched to the PYTHIA parton shower description.
  - passed through detailed simulation of CMS detector based on GEANT4 v9.4

Object reconstruction

- A particle-flow (PF) based event reconstruction is used by CMS, takes into account information from all the subdetectors
- All particles in the events are classified into mutually exclusive categories: electrons, muons, photons, charged and neutral hadrons.
- Electrons (Muons) are selected if they satisfy P_T >30 GeV (P_T >30 GeV) and $|\eta| < 2.5$ ($|\eta| < 2.1$)
- Jets clustered using anti-k_t algorithm and Jet candidates required to have $P_T > 30$ GeV and $|\eta| < 4.0$
- E_T^{miss} is measured as magnitude of the vectorial P_T sum of all PF candidates, takes into account the jet energy corrections

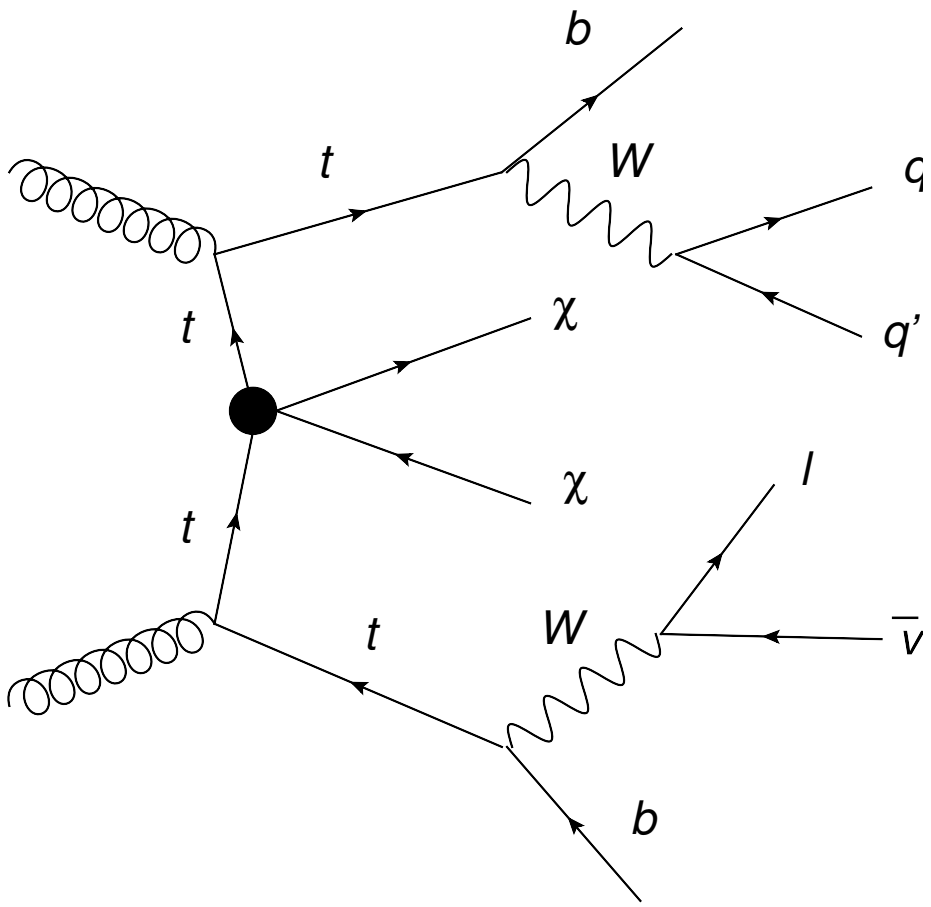
Event selection: preselection cut

- In semileptonic $t\bar{t}$ decays, two b quarks and two light quarks are produced (four jets produced, $N_j = 4$)
- Search sensitivity is in fact better by 10 % for $N_j \geq 3$ than $N_j \geq 4$
- Require at least one b-tagged jet in the event and only one identified isolated lepton



Event selection: preselection cut

- Signal normally has larger E_T^{miss} than the backgrounds because of the two DM particles
- Events required to have $E_T^{miss} > 160$ GeV
- The cuts discussed so far are called the preselection cut



Event selection: final selection

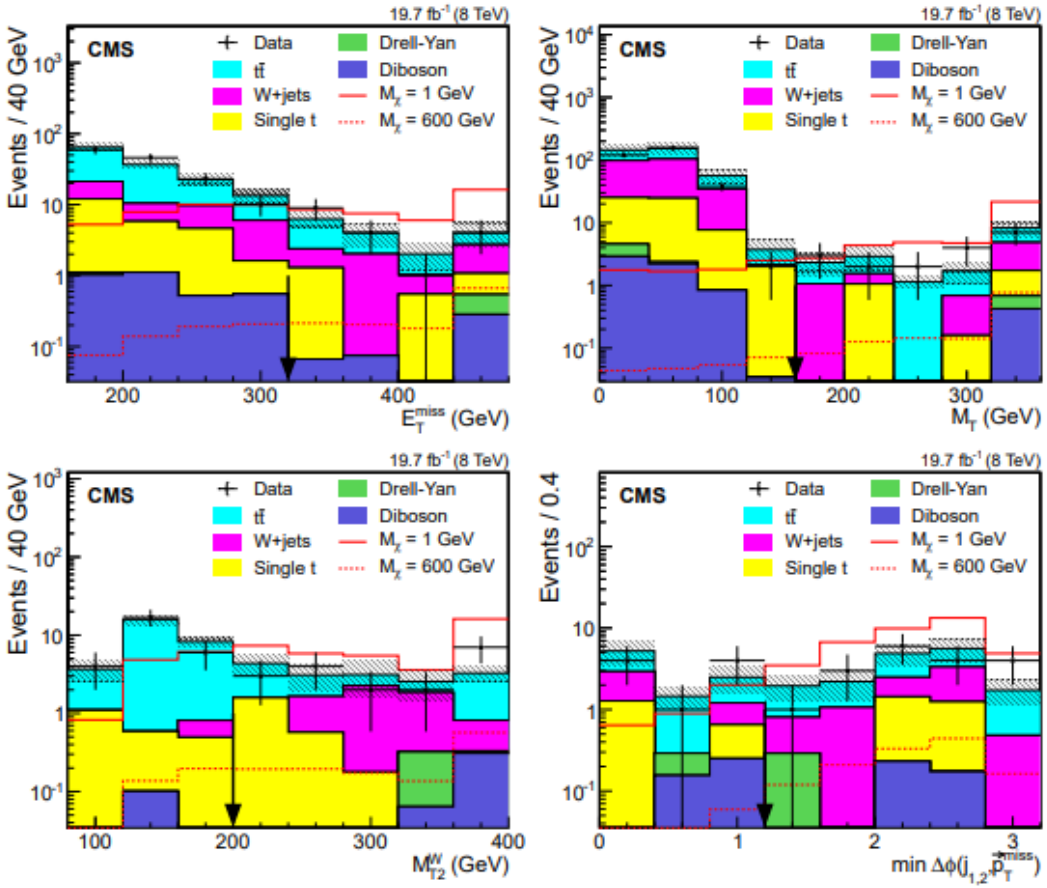
- After preselection, the main backgrounds are $t\bar{t}$ and $W+$ jets
- QCD multijet background cut greatly due to preselection cut

To improve search sensitivity:

- $E_T^{\text{miss}} > 320$ GeV
- $M_T > 160$ GeV, where for background $M_T < M_W$ and for signal $M_T > M_W$
- $M_{T2}^W > 200$ GeV
- In addition, jets and $\vec{p}_T^{miss}$ are usually more separated in ϕ in signal events than in $t\bar{t}$ background, therefore a min $\Delta\phi(j_{1,2}, \vec{p}_T^{miss}) > 1.2$
- All of the above selection cuts are optimized based on expected significance for DM masses between 1 and 1000 GeV

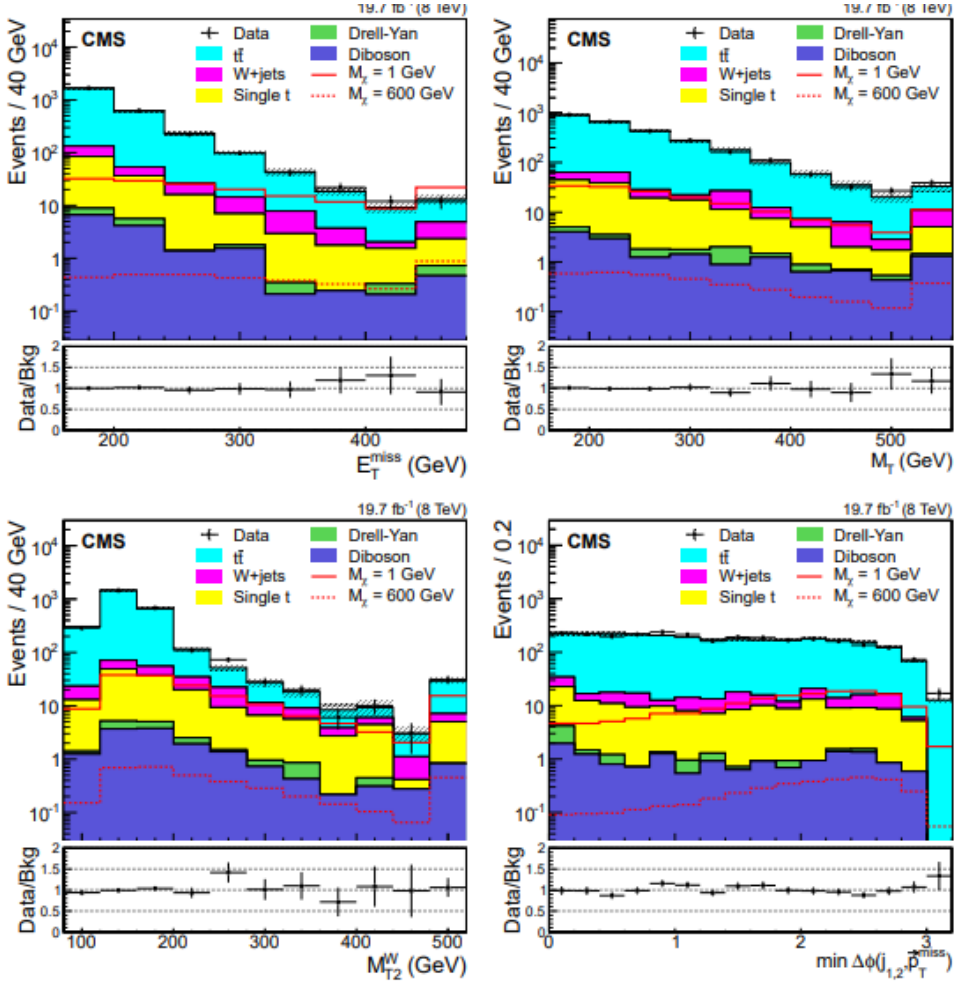
Event selection

- Distributions of E_T^{miss}, M_T, M_{T2}^W and min $\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$
- Distributions after applying all other selections, this is so that we can see power of discrimination.
- In distributions, the $t\bar{t}$ + jets and W + jets backgrounds have been adjusted by Scale Factors (SF)



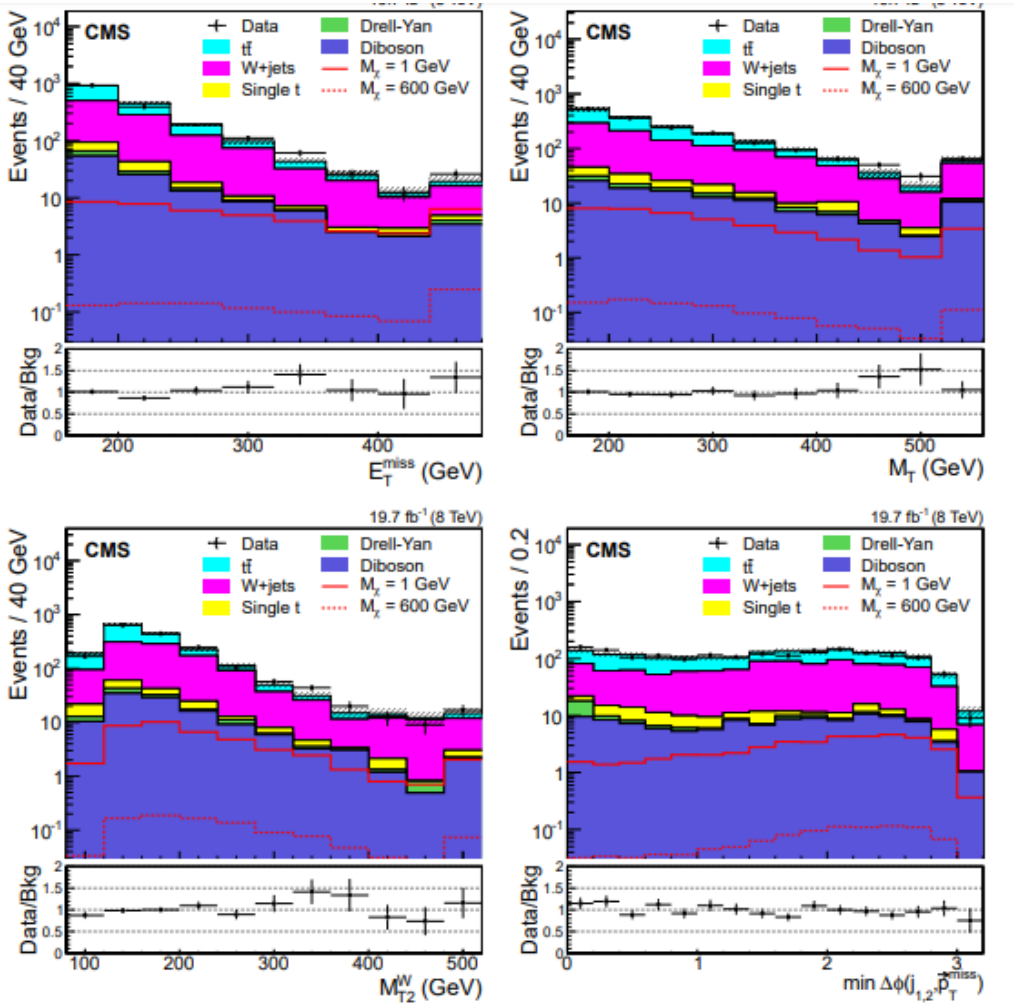
Background Estimation

- Two control regions (CR) defined to extract these SF
- CR1 is the preselection cuts with the additional requirement of M_T >160 GeV (SF applied in figure)
- Dominated by $t\bar{t}$ jets background



Background Estimation

- Two control regions (CR) defined to extract these SF
- CR2 is the same as CR1 except there is no b-tag requirement (SF applied in figure)
- Increase amount of W+jets events.



Background Estimation: Conclusion

- The subdominant backgrounds are subtracted from data distributions and obtain a sample which only has $t\bar{t}$ +jets and W+jets background contributions
- The $t\bar{t}$ + jets and W + jets SFs are obtained by matching the data from the M_T distributions in CR1 and E_T^{miss} distributions in CR2
- The SF for $t\bar{t}$ + jets and W + jets are 1.11 ± 0.02(stat) and 1.26 ± 0.06(stat) respectively

Systematic Uncertainties

- Main systematic uncertainties sources are the normalization uncertainty of other background in deriving the SF and the CR tests.
- Other uncertainties include the Jet energy scale & resolution and the b-tagging correction factors.

Table 1: Systematic uncertainties from various sources and their impact on the total background prediction.

Source of systematic uncertainties	Relative uncertainty on total background (%)
50% normalization uncert. of other bkg in deriving SFs	10
SF_{W+jets} (CR tests)	13
$t\bar{t}$+jets top-quark p_T reweighting	3.9
Jet energy scale	4.0
Jet energy resolution	3.0
b-tagging correction factor (heavy flavour)	1.0
b-tagging correction factor (light flavour)	1.8
Pileup model	2.0
PDF	2.6

Results: Number of Expected Events

- Data agrees with our background within the uncertainties

Table 2: Expected number of background events in the SR, expected number of signal events for a DM particle with the mass $M_\chi = 1\,\text{GeV}$, assuming an interaction scale $M_* = 100\,\text{GeV}$, and observed data. The statistical and systematic uncertainties are given on the expected yields.

Source	Yield ($\pm$stat $\pm$syst)
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.8 \pm 2.1$
Single top	$2.3 \pm 1.1 \pm 1.1$
Diboson	$0.5 \pm 0.2 \pm 0.2$
Drell–Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.9$
Data	18

Results: Cross section limits

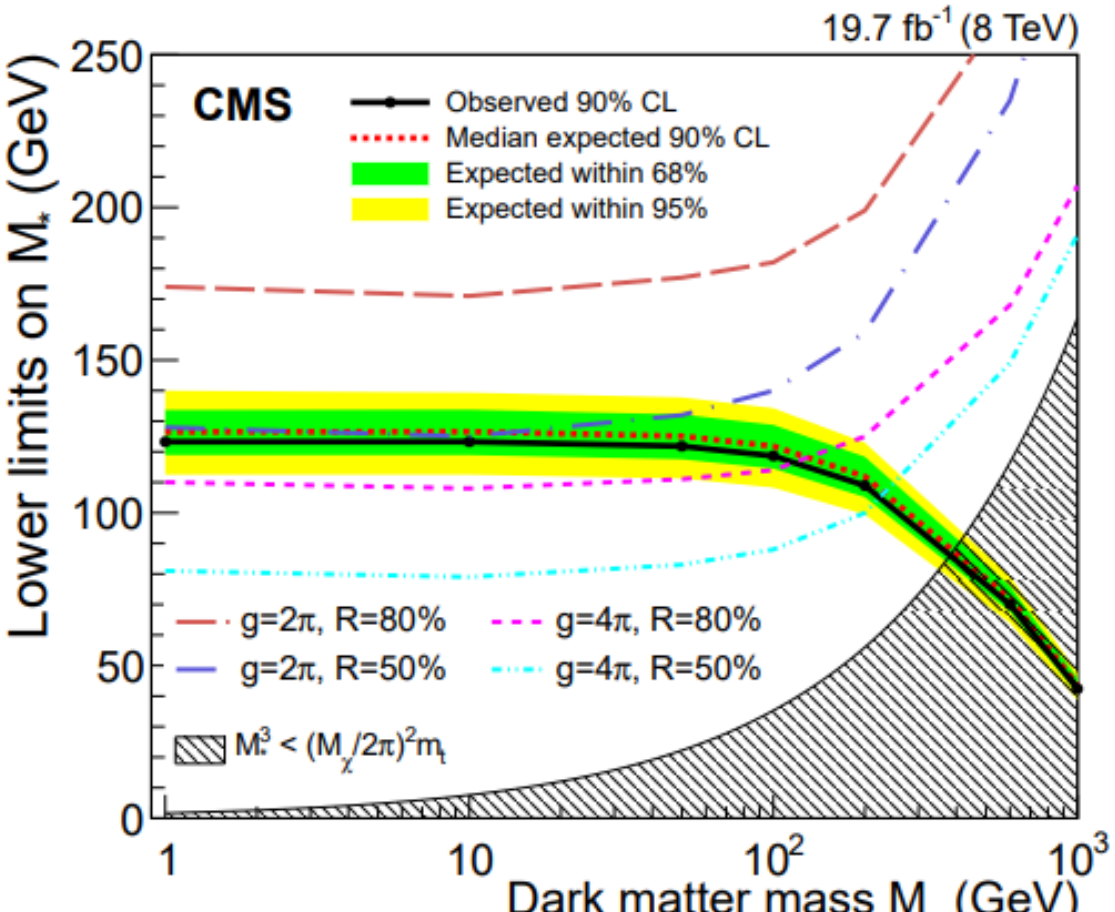
- Obtain the signal efficiencies for various masses of M_χ and also the upper limit of the cross section at a 90 CL interval which range from 20 to 55 fb

Table 3: Expected number of signal events in SR assuming an interaction scale $M_* = 100\,\text{GeV}$, signal efficiencies, and observed and expected limits at 90% CL on production cross sections for $pp \to t\bar{t} + \chi\bar{\chi}$, for various DM particle masses.

M_χ (GeV)	Yield ($\pm$stat $\pm$syst)	Signal efficiency (%) ($\pm$stat $\pm$syst)	$\sigma^{\text{lim}}_{\text{exp}}$ (fb)	$\sigma^{\text{lim}}_{\text{obs}}$ (fb)
1	$38.3 \pm 0.7 \pm 2.1$	$1.01 \pm 0.02 \pm 0.05$	47^{+21}_{-13}	55
10	$37.8 \pm 0.7 \pm 2.1$	$1.01 \pm 0.02 \pm 0.05$	46^{+21}_{-13}	54
50	$35.1 \pm 0.6 \pm 1.9$	$1.20 \pm 0.02 \pm 0.06$	39^{+18}_{-11}	45
100	$30.1 \pm 0.4 \pm 1.7$	$1.46 \pm 0.02 \pm 0.07$	32^{+14}_{-9}	37
200	$18.0 \pm 0.2 \pm 1.0$	$1.73 \pm 0.02 \pm 0.08$	27^{+12}_{-8}	32
600	$1.26 \pm 0.02 \pm 0.07$	$2.40 \pm 0.03 \pm 0.11$	19^{+9}_{-6}	23
1000	$0.062 \pm 0.001 \pm 0.003$	$2.76 \pm 0.04 \pm 0.13$	17^{+8}_{-5}	20

Results: Limitations of EFT

- The EFT approximation is only valid when momentum transfer is small compared to the mediator mass
- The couplings should not exceed the perturbative limit
- Both conditions depend on the details of the new physics approximated by EFT



Summary

- Search for production of dark matter particles in association with top quarks in single lepton events in the CMS detector at $\sqrt{s} = 8$ TeV.
- No excess of events above the SM expectation is found and place cross section upper limits
- See in figure below that upper limits on cross section are more sensitive for masses below 6 GeV than the direct DM detectors (at 90 CL level).

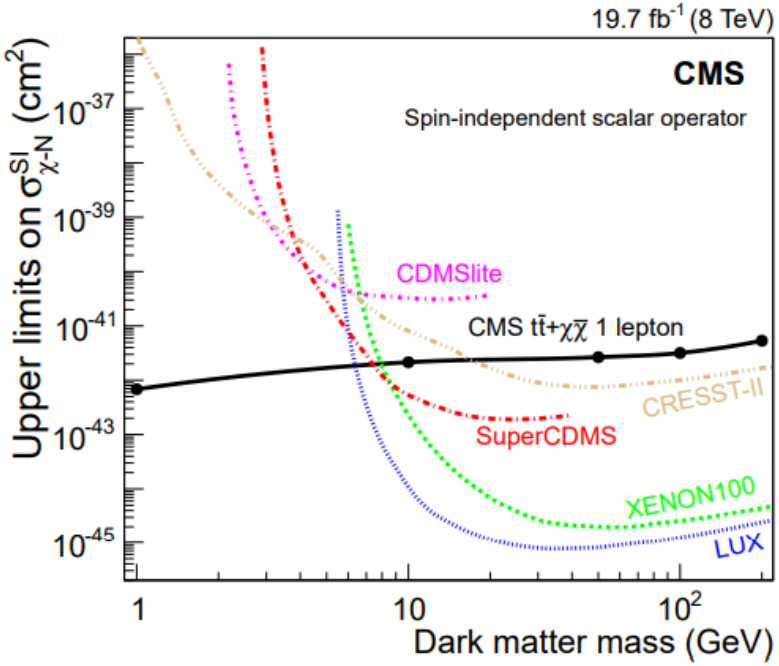


Figure 8: The 90% CL upper limits on the DM-nucleon spin-independent scattering cross sec-