Course on Physics @ the LHC 2020

Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Key reference paper

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Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

Sirunyan, A.M., Tumasyan, A., Adam, W. *et al.* [The CMS Collaboration] Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at √s=13 TeV. *J. High Energ. Phys.* **2019,** 141 (2019).

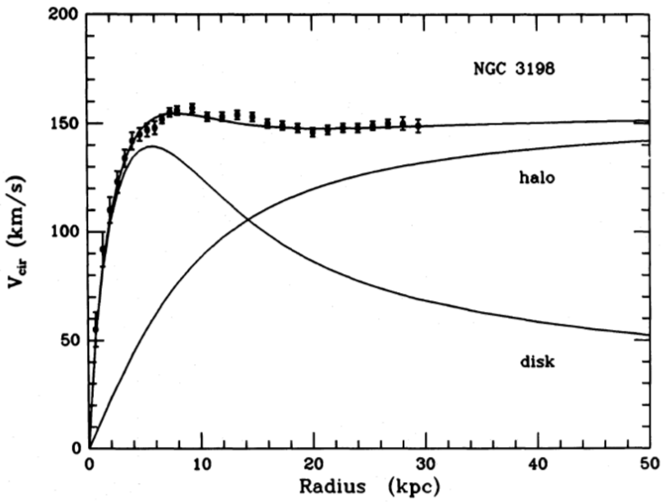
Outline

- Dark matter
- Search framework
- The CMS detector and event reconstruction
- Data sample and simulation
- Event selection
- Systematic uncertainties
- Signal extraction
- Results
- Summary

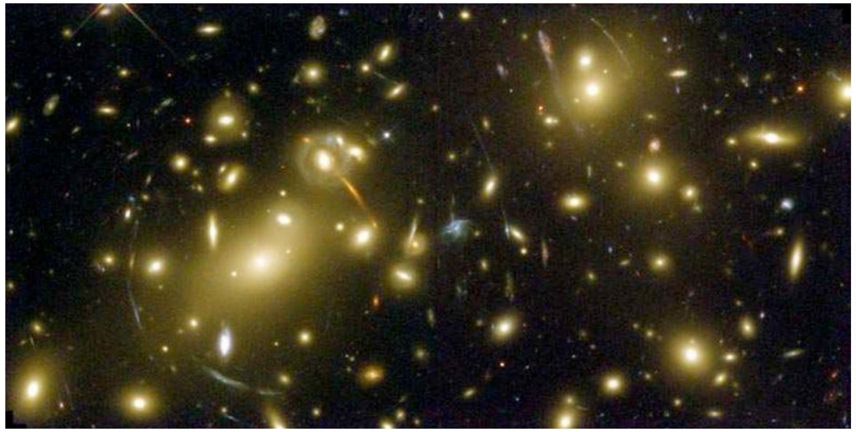
Dark matter

- Open problem in modern physics
- Interface between astrophysics and particle physics

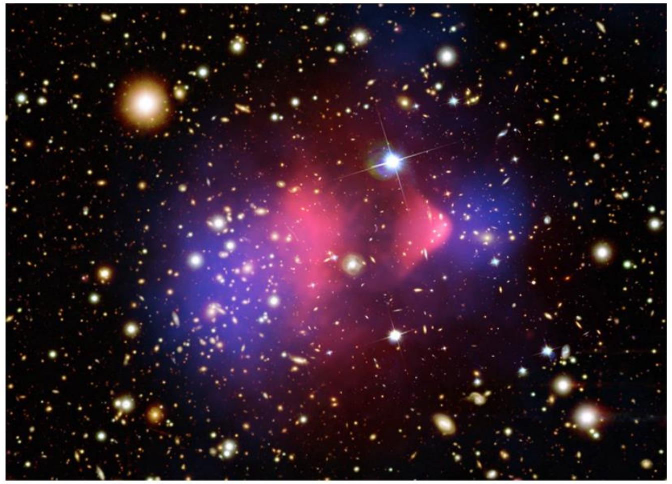
Dark matter



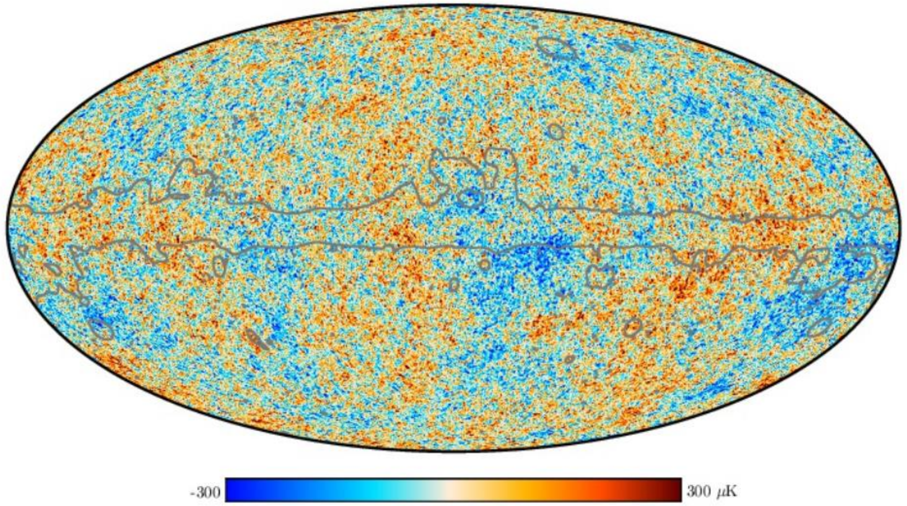
Galactic rotation curve for NGC 3198



Gravitational lensing (image of the galaxy cluster Abell 2218)



The Bullet Cluster



CMB anisotropies

Dark matter

Astrophysical and cosmological evidence

↓

Presence of stable, non-baryonic, non-luminous matter, which interacts weakly or very weakly with SM particles

↓

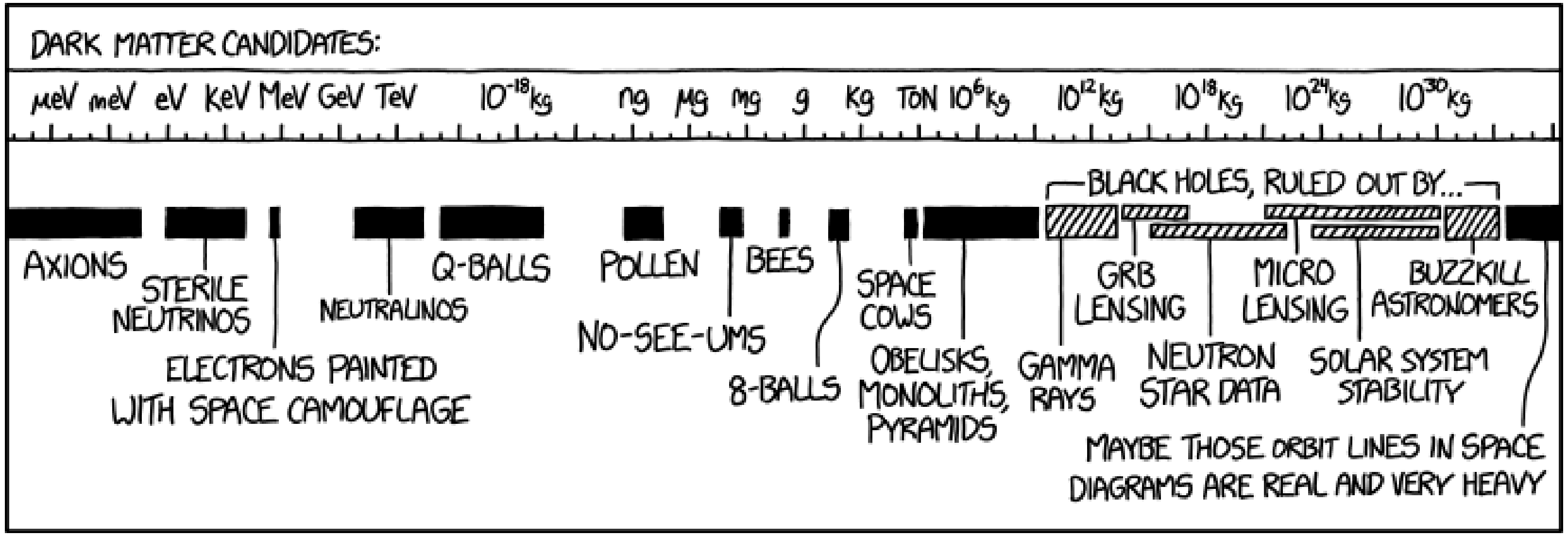
DARK MATTER

Dark energy density (68%)	$\Omega_\Lambda = 0.6847 \pm 0.0073$			
Matter density	$\Omega_m = 0.3153 \pm 0.0073$	{	**Baryonic matter** (5%)	$\Omega_b h^2 = 0.02237 \pm 0.00015$
			(Cold) dark matter (27%)	$\Omega_c h^2 = 0.1200 \pm 0.0012$

Data from the PLANCK Collaboration.

Dark matter

NATURE OF DARK MATTER REMAINS UNKNOWN

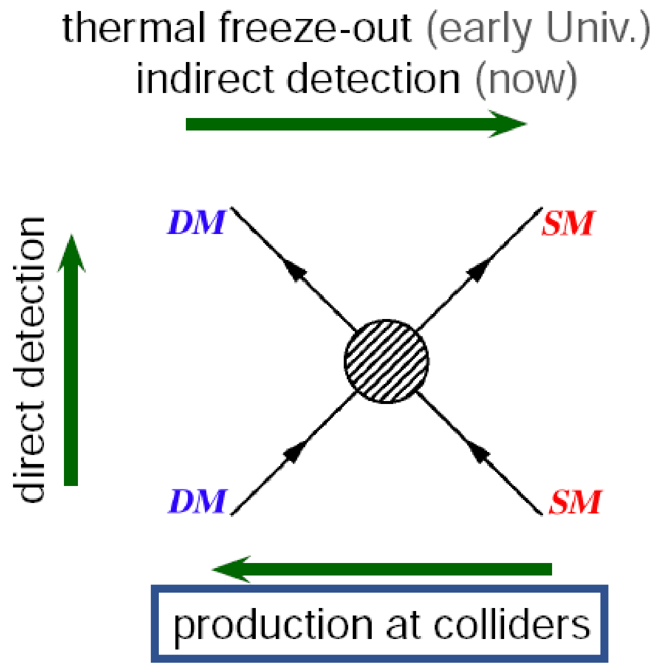


Dark matter

Visualisation of possible solutions to the dark matter problem. From Bertone and Tait.

Weakly Interacting Massive Particle (WIMP)

- Thermal freezout reproduces the cosmological relic abundance (assuming weak-scale cross sections and masses)
- Interacts weakly with SM particles, allowing for several detections possibilities



Dark matter

Complete models

- Model-dependent approach
- *Natural* WIMPs arise in beyond-SM theories (MSSM, ...)

Simplified models

- Simple interaction Lagrangean
- Mediator explicitly modeled in the interaction

Effective field theories

- Model-independent approach
- Based on effective operators

Complexity
Number of parameters
Collider energy needed

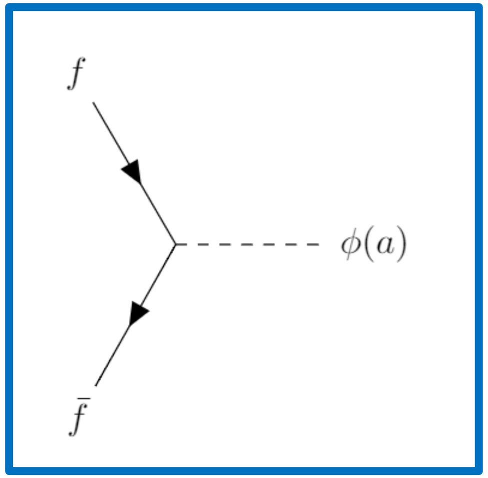
Search framework

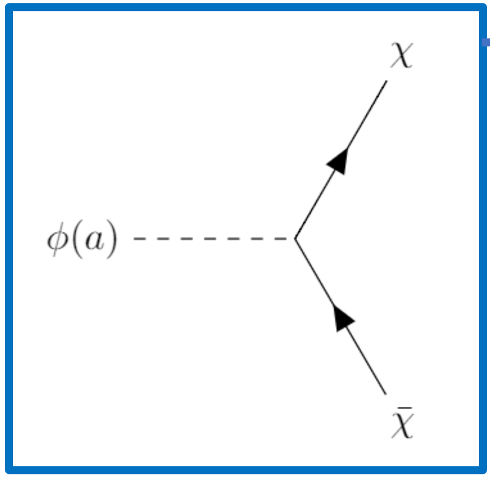
Simplified model → SM-DM interactions mediated by a new **neutral scalar** or **pseudoscalar** particle

Easily accommodated in models containing **extended Higgs sectors**

Scalar mediator $\mathcal{L}_\phi \supset \frac{g_q \phi}{\sqrt{2}} \sum_f (y_f \bar{f} f) + g_\chi \phi \bar{\chi} \chi$

Pseudoscalar mediator $\mathcal{L}_a \supset \frac{i g_q a}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f) + i g_\chi a \bar{\chi} \gamma^5 \chi$





→ Escape detection

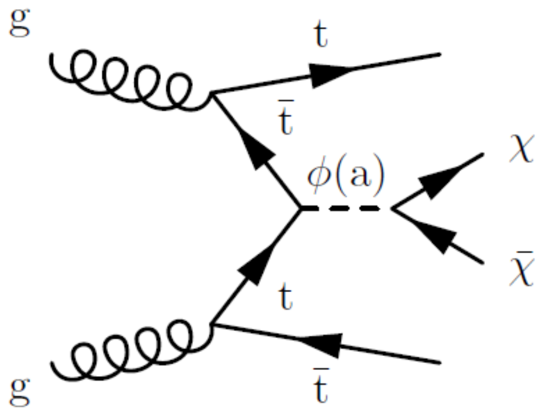
↓

Momentum imbalance in the transverse plane

Missing momentum

Search framework

$t\bar{t} + \text{DM}$



Main production diagram for $t\bar{t} + \text{DM}$

PHYSICAL REVIEW LETTERS **122,** 011803 (2019)

Search for Dark Matter Particles Produced in Association with a Top Quark Pair at $\sqrt{s} = 13$ TeV

A. M. Sirunyan *et al.**
(CMS Collaboration)

(Received 17 July 2018; published 10 January 2019)

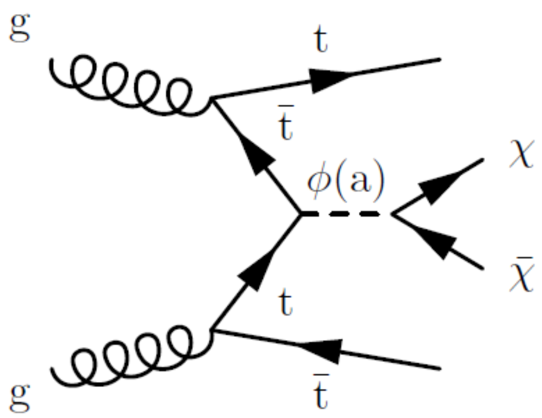
A search is performed for dark matter particles produced in association with a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data correspond to an integrated luminosity of 35.9 fb^{-1} recorded by the CMS detector at the LHC. No significant excess over the standard model expectation is observed. The results are interpreted using simplified models of dark matter production via spin-0 mediators that couple to dark matter particles and to standard model quarks, providing constraints on the coupling strength between the mediator and the quarks. These are the most stringent collider limits to date for scalar mediators, and the most stringent for pseudoscalar mediators at low masses.

DOI: 10.1103/PhysRevLett.122.011803

Previous searches by ATLAS and CMS have so far neglected the contribution from **DM production + single top quark**

Search framework

$t\bar{t}$ + DM



Main production diagram for $t\bar{t}$ + DM

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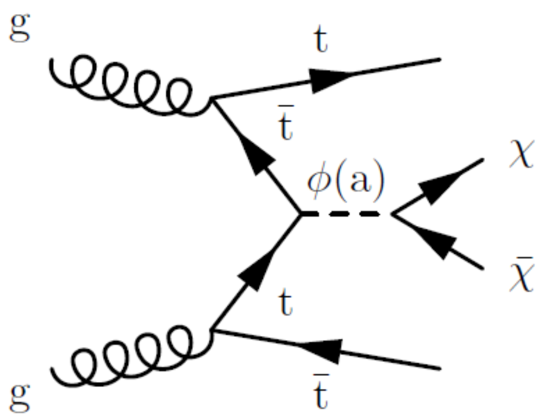
In spite of a generally lower production cross section at LHC when compared to the associated top-pair channel, non-flavour violating single top quark processes are kinematically favored and can significantly increase the sensitivity to these models.

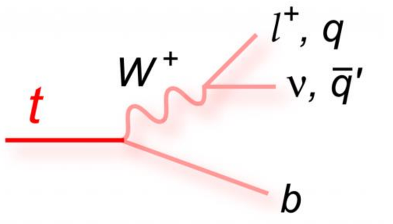
From D. Pinna, A. Zucchetta, M. R. Buckley, and F. Canelli, "Single top quarks and dark matter", Phys. Rev. D **96** (2017) 035031

Search framework

$t\bar{t}$ + DM

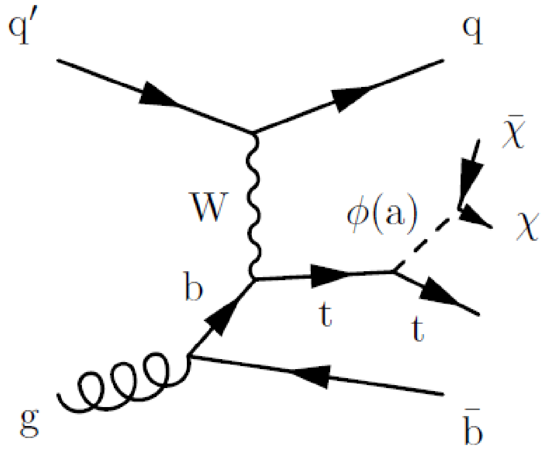


MAIN PRODUCTION DIAGRAMS

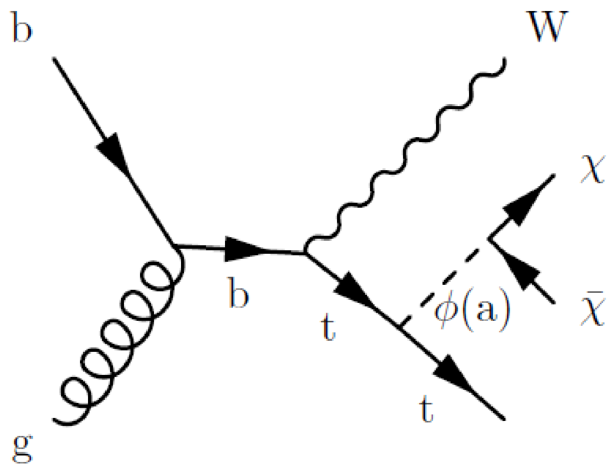


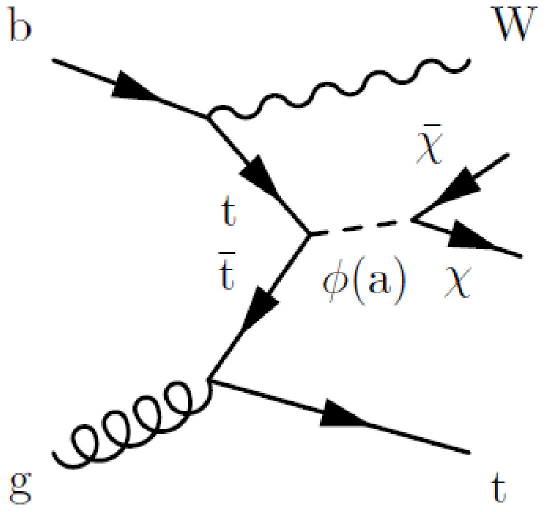
Top quark decay.

$t/\bar{t}$ + DM



Associated t-channel W boson

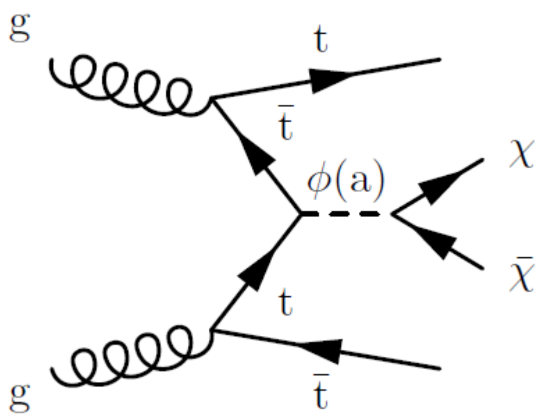




Associated tW production

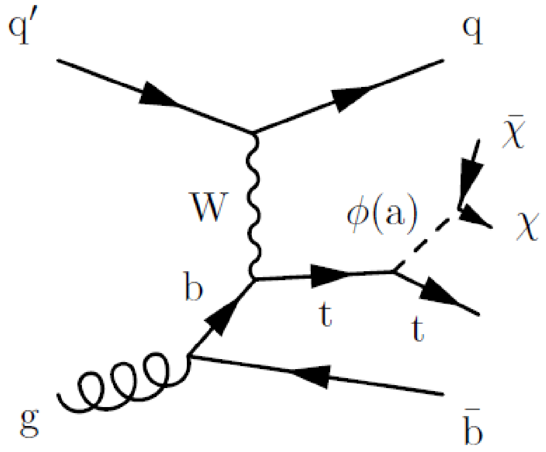
Search framework

$t\bar{t} + \text{DM}$

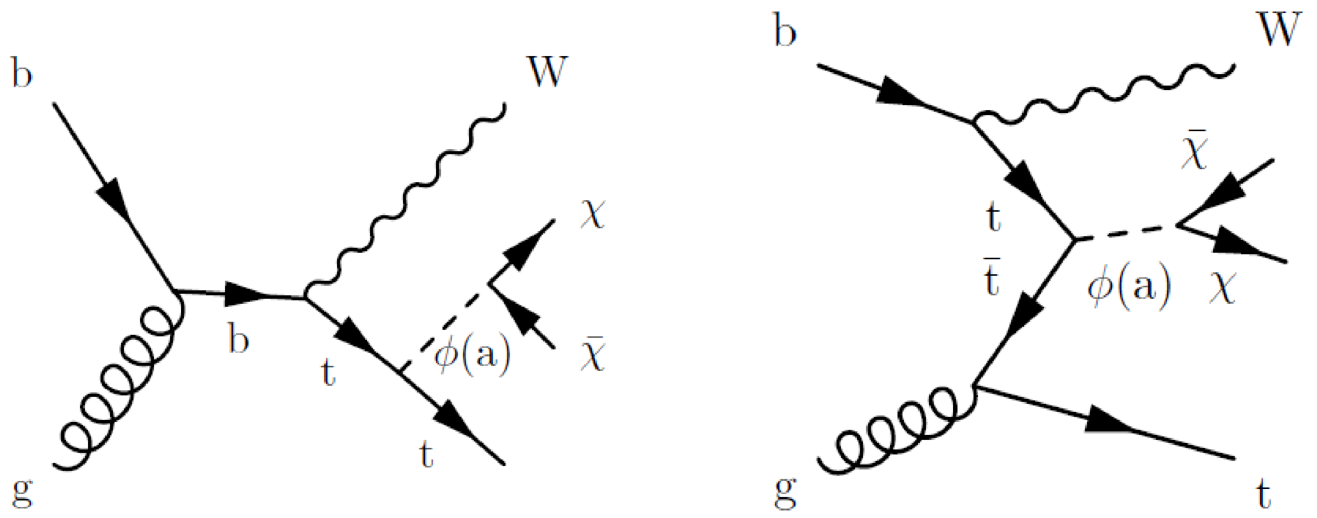


Looking for excess of events above the SM background in the missing momentum spectrum for "single-lepton" (SL) and "all-hadronic" (AH) events

$t/\bar{t} + \text{DM}$

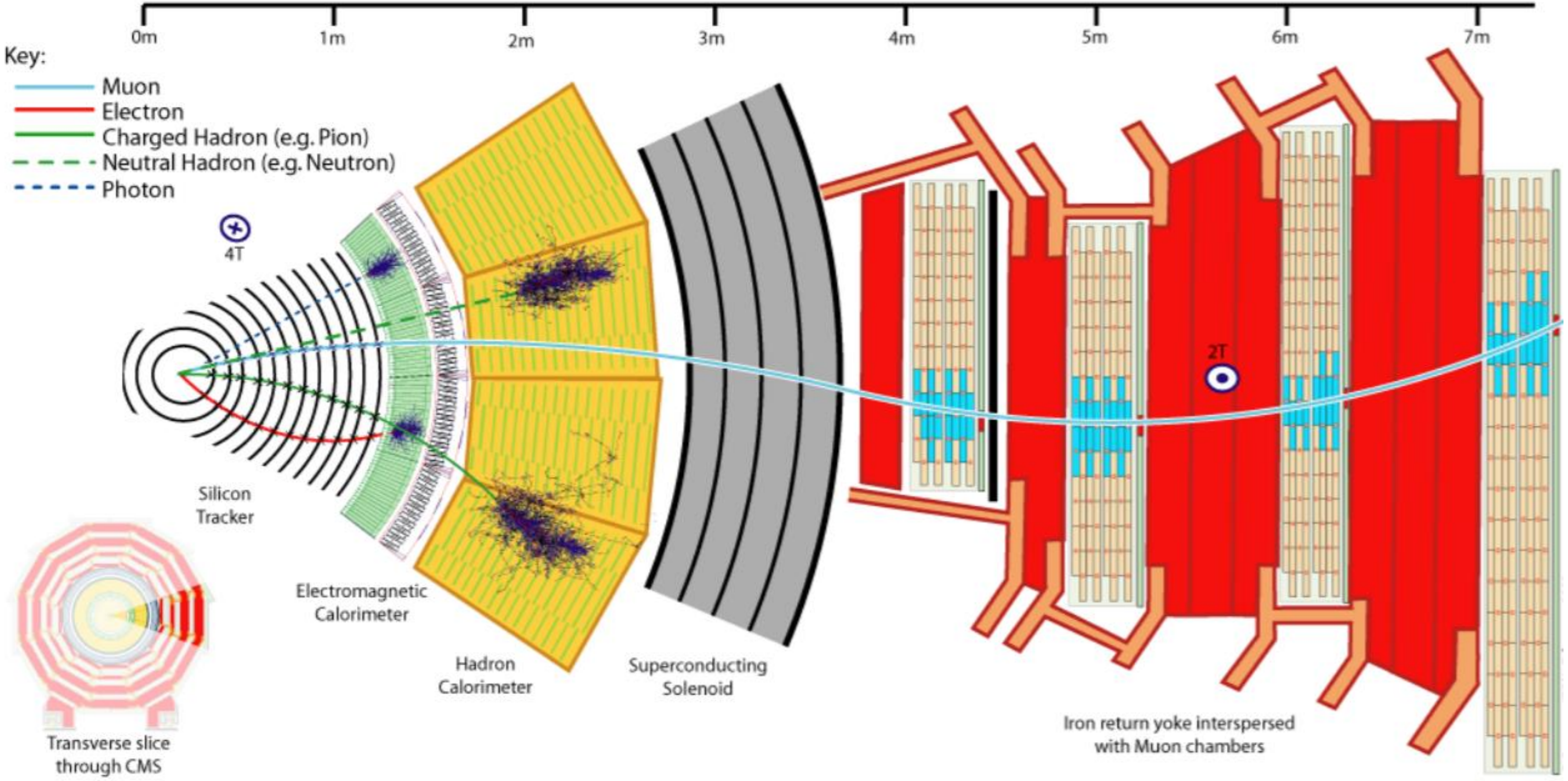


Associated t channel W boson



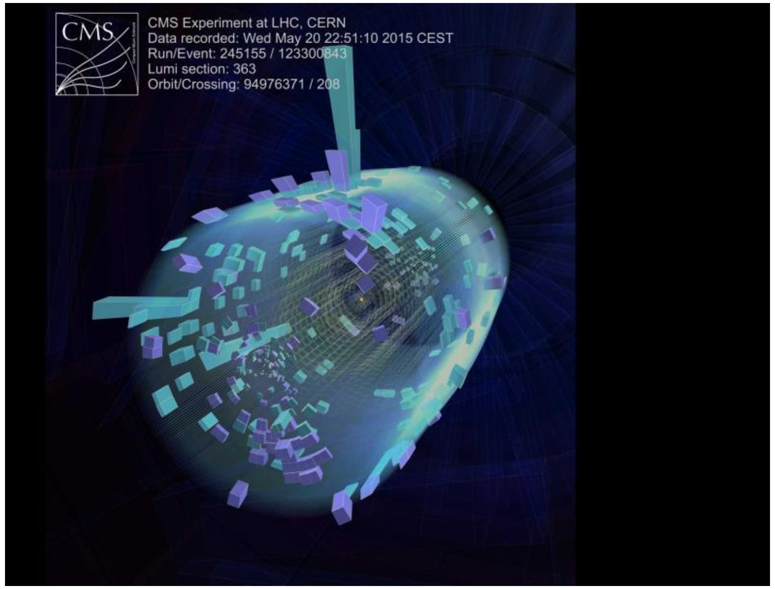
Associated tW production

The CMS detector



Event reconstruction

CMS DETECTOR DATA



Protons collide at 13 TeV sending showers of particles through the CMS detector (Image: CMS).

Event reconstruction

CMS DETECTOR DATA

↓

Two-tiered trigger system

- Consists of two levels designed to select events of potential physics interest from proton-proton collisions
- Performs real-time selection based on a subset of the data to record
- Reduces the rate of interesting events to manageable values

Event reconstruction

CMS DETECTOR DATA

↓

Two-tiered trigger system

↓

Particle-flow algorithm

- Reconstructs and identifies each individual particle in an event, with an optimized combination of information from the several detector elements
- Resulting list of particles (charged hadrons, photons, neutral hadrons, electrons and muons) is used to reconstruct jets, missing transverse energy, etc

Event reconstruction

CMS DETECTOR DATA

↓

Two-tiered trigger system

↓

Particle-flow algorithm

↓

Anti-k_T algorithm

- Clusters hadronic jets from the particles reconstructed with PF
- Jet energy corrections are derived from simulation and applied to calibrate the jet momentum

Event reconstruction

CMS DETECTOR DATA

↓

Two-tiered trigger system

↓

Particle-flow algorithm

↓

Anti-k_T algorithm

↓

CSVv2 algorithm

- Identifies jets originating from the hadronization of bottom quarks, dubbed "b-tagged jets"

Event reconstruction

CMS DETECTOR DATA

↓

Two-tiered trigger system

↓

Particle-flow algorithm

↓

Anti-k_T algorithm

↓

CSVv2 algorithm

↓

Reconstructed events

MISSING TRANSVERSE MOMENTUM

$$\overrightarrow{p_T}^{\text{miss}} = -\sum_{\text{PF particles}} \overrightarrow{p_T}$$

Data sample and simulation

Data	Recorded with the CMS detector in 2016 corresponding to $L_{int} = 35.9\ \text{fb}^{-1}$
Trigger criteria	Events with zero leptons: p_T^{miss} and $H_T^{\text{miss}} > 120$ GeV
	Events with at least one isolated electron (muon): $p_T > 27\ (25)$ GeV
Background	Main sources arise from $t\bar{t}$ + jets, W + jets and Z + jets production

Data sample and simulation

Data simulation	Simulator	Calculation order
$t\bar{t}$ + jets	POWHEGv2	NLO
single top quark processes	POWHEGv1	NLO
Z + jets, W + jets, QCD multijets	MADGRAPH5_aMC@NLO	LO
$t\bar{t} + W/Z$	MADGRAPH5_aMC@NLO and FxFx	NLO
WW, WZ, ZZ, WH, ZH	MADGRAPH5_aMC@NLO or POWHEGv2	NLO
$t\bar{t}$ + DM, $t/\bar{t}$ +DM	MADGRAPH5_aMC@NLO v2.4.2	LO
initial-state partons	NNPDF 3.0	LO or NLO
parton showering and hadronization	PYTHIA 8.205	LO or NLO
CMS detector	GEANT4	-

Signal process simulated using simplified model:

- DM particles assumed to be Dirac fermions
- Spin-0 mediator particles ϕ/a
- Minimal set of four free parameters: $m_\chi, m_{\phi/a}, g_\chi, g_q$

Benchmark scenario:

$$g_\chi = g_q = 1$$
$$m_\chi = 1 \text{ GeV}$$

Event selection

Reconstructed events

Selection criteria

- Jets: $p_T > 30$ GeV; categorized as "central" ($|\eta| < 2.4$) and "forward" ($2.4 < |\eta| < 4.0$)
- b-tagged jets: $p_T > 30$ GeV and $|\eta| < 2.4$
- Electrons and muons: $p_T > 30$ GeV and $|\eta| < 2.1$; required to be isolated from hadronic activity

Separation criteria

- Number of leptons
- Number of b-tagged jets
- Number of forward jets

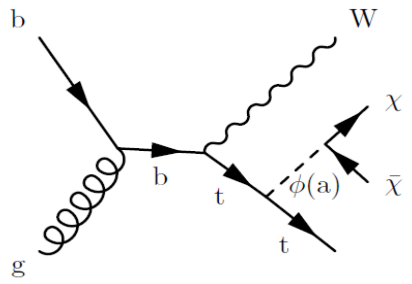
Events are separated into several orthogonal regions

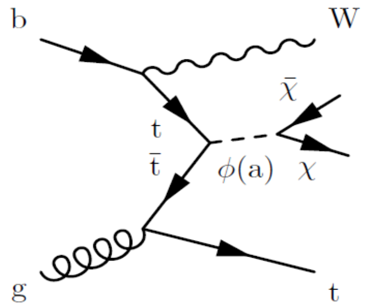
Signal events

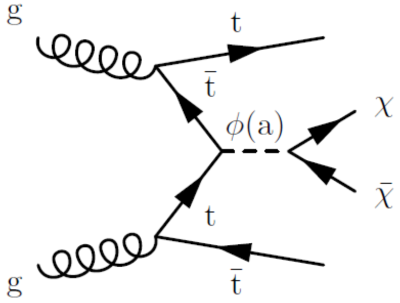
↓

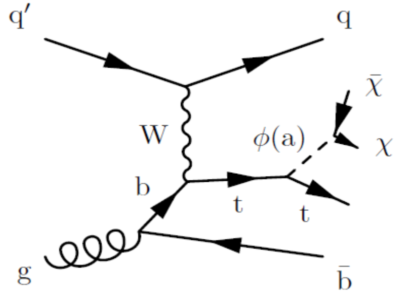
Single-lepton or all-hadronic

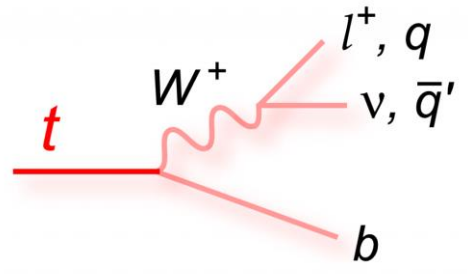
- $t/\bar{t}$ + DM events for a region with exactly one b-tagged jet
  - Exactly zero forward jets
  - One or more forward jets
- $t\bar{t}$ + DM events for a region with two or more b-tagged jet











Top quark decay.

Signal regions

	Exactly one electron or muon with $p_T > 30$ GeV			Exactly zero leptons with $p_T > 10$ GeV		
	Single-lepton SRs			All-hadronic SRs		
	1ℓ, 1 b-tag, 0 FJ	1ℓ, 1 b-tag, 1FJ	1ℓ, 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag
Forward jets	=0	≥1	—	= 0	≥1	—
n_b	=1	=1	≥2	= 1	=1	≥2
n_{lep}	=1	=1	=1	= 0	=0	=0
$p_T(j_1)/H_T$		—			—	<0.5
n_{jet}		≥2			≥3	
p_T^{miss}		>160 GeV			>250 GeV	
m_T		>160 GeV			—	
m_{T2}^{W}		>200 GeV			—	
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$		>1.2 rad.			>1.0 rad.	
m_T^b		>180 GeV			>180 GeV	

To improve the search sensitivity and reduce the dominant background (p_T^{miss} to m_T^b)

Dominant backgrounds:

- SL channel: dileptonic $t\bar{t}$ events and $W+$ jets processes
- AH channel: single-lepton $t\bar{t}$, $W+$ jets and $Z \to \upsilon\upsilon$ processes

What about the expected SM backgrounds?

Control regions

SM backgrounds are estimated by simulation and enhanced by control data samples → **Control regions**: orthogonal to (do not overlap with) signal regions; dominated by SM background

	Single-lepton CRs		All-hadronic CRs		
	CR $t\bar{t}(2\ell)$	CR $W(\ell\nu)$	CR $t\bar{t}(1\ell)$	CR $W(\ell\nu)$	CR $Z(\ell\ell)$
n_b	≥ 1	$=0$	≥ 1	$=0$	$=0$
n_{lep}	$=2$	$=1$	$=1$	$=1$	$=2$
n_{jet}	≥ 2	≥ 2	≥ 3	≥ 3	≥ 3
p_T^{miss}	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m_T	—	>160 GeV	<160 GeV	<160 GeV	—
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$	—	—	>1.0 rad.	—	—
$m_{\ell\ell}$	—	—	—	—	$[60, 120]$ GeV

Parameters are chosen to statistically enhance these regions and avoid overlap with the SRs

Systematic uncertainties

- All uncertainties are included in the global simultaneous fit (described next)
- Uncertainties in the b-tagging scale factors and limited statistical precision of the dilepton $t\bar{t}$ CR have the largest impacts on the final results

Two types of uncertainties

Only affect the normalization of a process

- Lepton reconstruction, selection and trigger
- p_T^{miss} trigger
- b-tagging efficiency scale factors
- Forward jets
- Pileup modeling
- Luminosity
- QCD multijet background normalization
- Single top quark background normalization
- Uncertainty related to ECAL mistiming

Also affect the shape of the p_T^{miss} distribution

- Jet energy scale
- PDF uncertainties
- W/Z + heavy-flavor fraction
- Electroweak and QCD K factors
- Top quark p_T reweighting
- Factorization and renormalization scales
- Simulation sample size

Signal extraction

POTENTIAL DM SIGNAL → **EXCESS OF EVENTS ABOVE SM PREDICTION**

- The DM signal is extracted from a simultaneous fit to the binned missing transverse momentum spectrum in the various SRs and CRs, including all mentioned uncertainties
- The global fit is performed as a binned maximum likelihood fit (ROOSTATS statistical package)

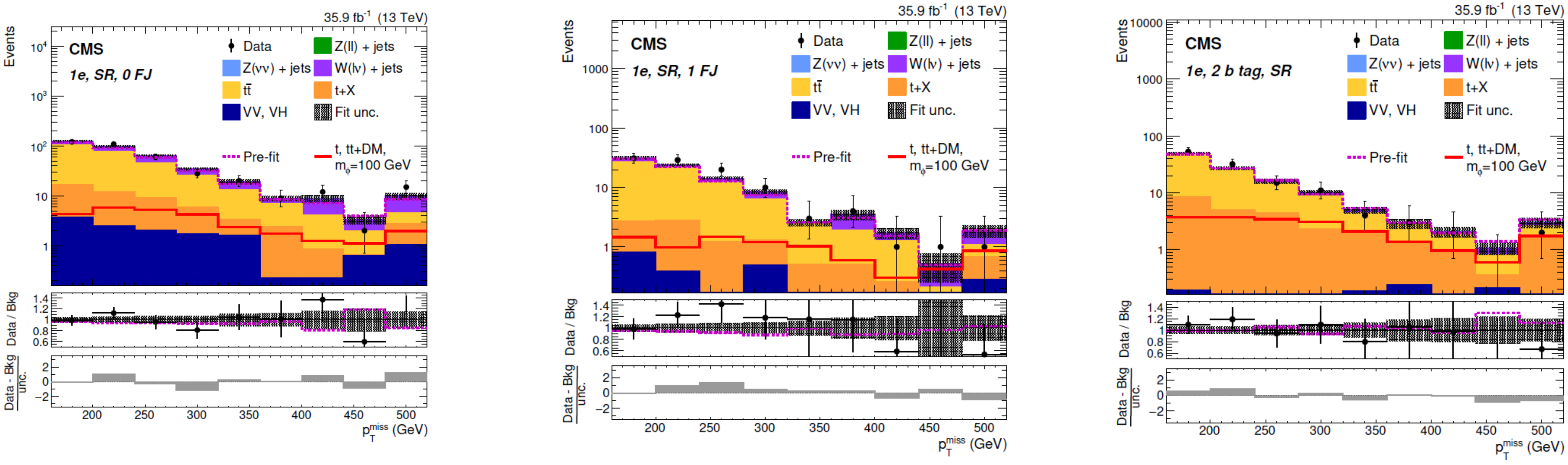
MAIN BACKGROUNDS → Unconstrained multiplicative parameters are assigned to each background for each bin

DM SIGNALS → Scaled by a signal strength modifier $\mu = \sigma/\sigma_{th}$

Signal extraction

- The values for the background multiplicative factors extracted from the fit are on average close to one (root-mean-square deviations from 5% to 21%)
- No significant excess at high missing transverse momentum in the SRs is observed

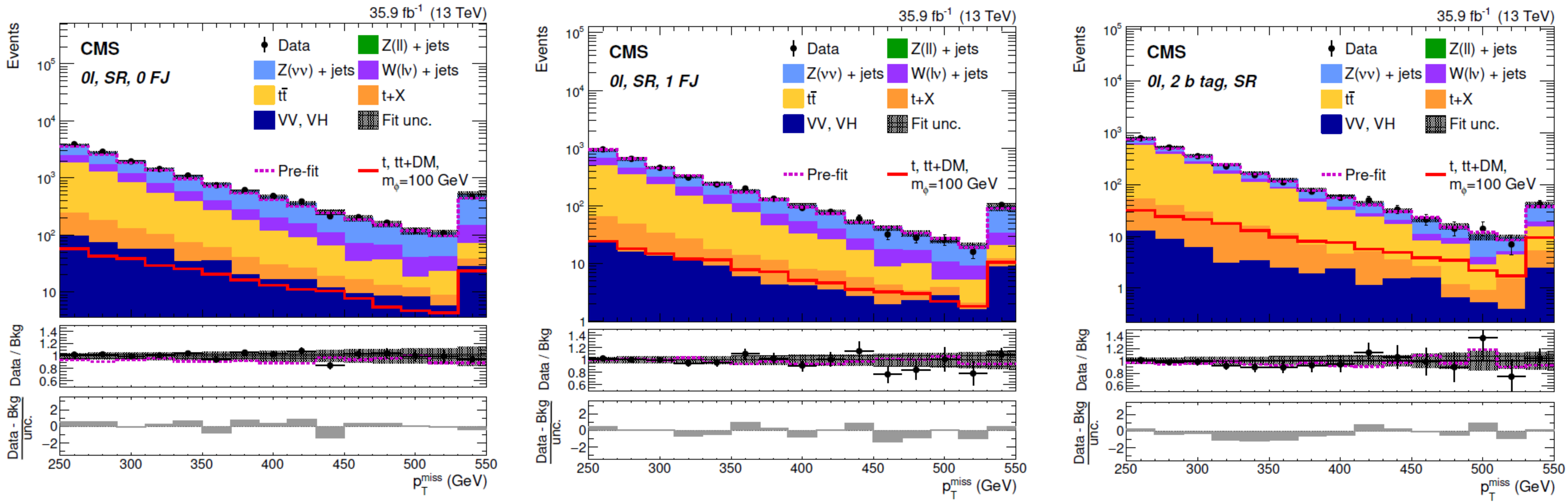
Background-only post-fit missing transverse momentum distributions for the SRs of the SL selection (electron case)



Signal extraction

- The values for the background multiplicative factors extracted from the fit are on average close to one (root-mean-square deviations from 5% to 21%)
- No significant excess at high missing transverse momentum in the SRs is observed

Background-only post-fit missing transverse momentum distributions for the SRs of the AH selection

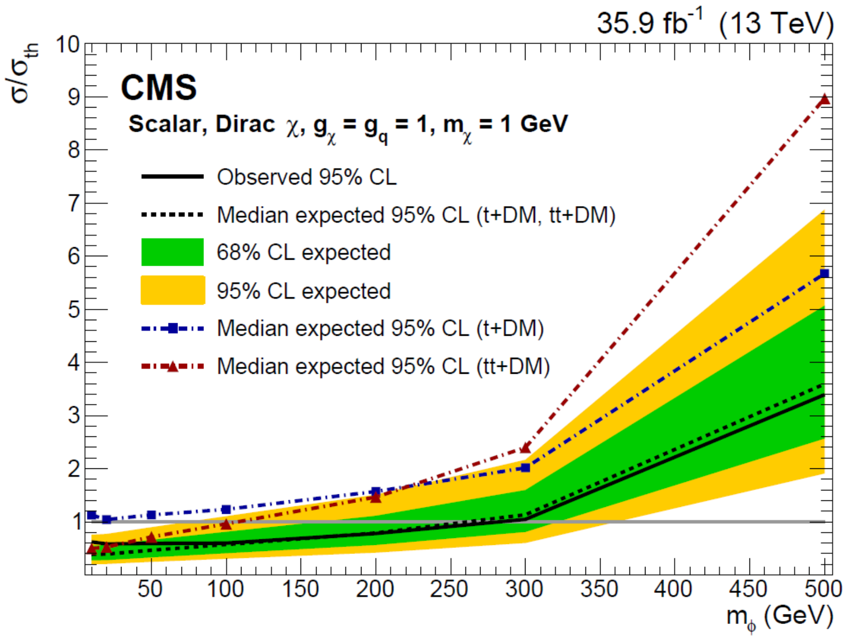


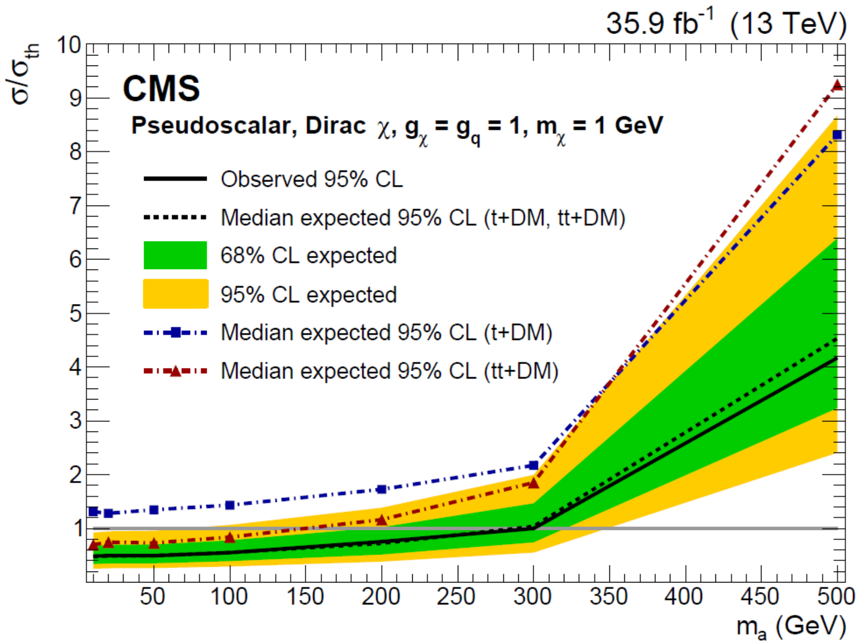
Results

- Data agrees with the expected SM background in the SRs
- Upper limits at 95% CL are computed for $\mu = \sigma/\sigma_{th}$
- For $m_\phi < 200$ GeV and for $m_a < 300$ GeV, the leading contribution stems from $t\bar{t}$ + DM

- $t/\bar{t}$ + DM cross section drops less rapidly in comparison to $t\bar{t}$ + DM
- The p_T^{miss} spectrum for a given mass mediator leans towards higher values for the $t/\bar{t}$ + DM signal

Lead to a factor of two improvement at high mediator masses





Mediator masses below 290 GeV for the scalar and 300 GeV for the pseudoscalar are excluded

Summary

- First search at the LHC for DM together with a single top quark or a top quark pair mediated by a neutral scalar or pseudoscalar
- Results interpreted in the context of a simplified model
- No significant deviations with respect to SM predictions are observed
- Scalar and pseudoscalar mediator masses below 290 and 300 GeV are excluded at 95% CL
- This analysis provides the most stringent limits for these spin-0 mediator particles