Search for dark matter produced in association with a single top quark or a top quark pair in pp collisions @13 TeV

COURSE: PHYSICS BEYOND THE STANDARD MODEL

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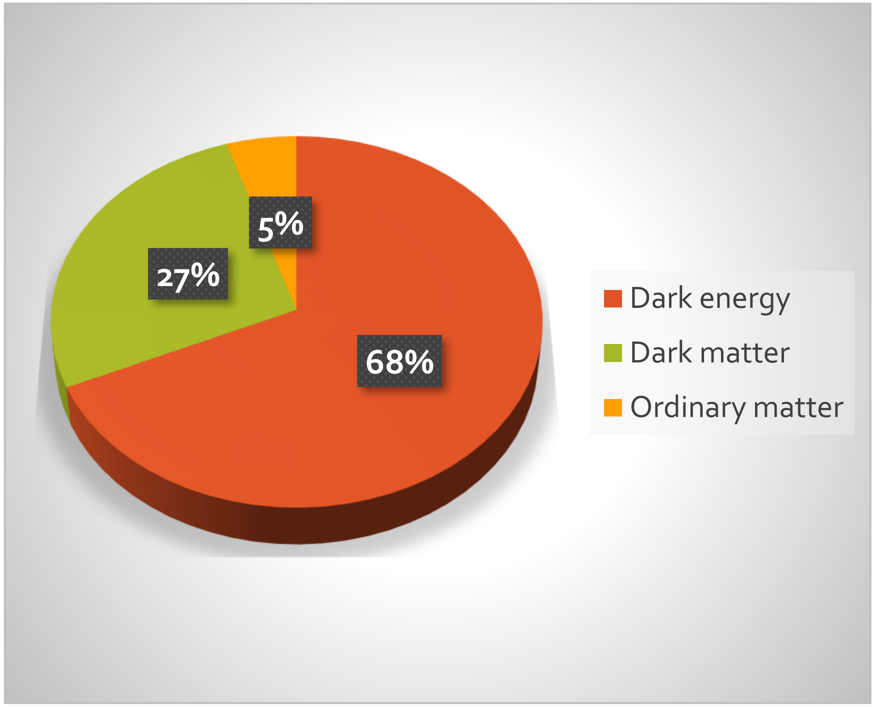
Dark matter



Dark matter is:

- **Massive**→gravitationally attractive
- **Cold** →slow moving
- **Collisionless** →passes through itself and other matter
- **Dark** → does not emit or absorb light
- **Weakly**-(Non-)interacting

While the nature of this dark matter (DM) is still unknown, a compelling candidate is the so called **weakly interacting massive particle (WIMP)**
This new particle is predicted to have weak interactions with standard model (SM) particles, allowing for direct- and indirect-detection experiments

Introduction: model

- Interactions between the SM and DM sectors are assumed to be mediated by a **new neutral scalar or pseudoscalar particle** that decays into DM
- The **new spin-0 mediator particle** follow the same Yukawa coupling structure as in the SM
- The mediator would couple preferentially to **heavy third-generation quarks** and the DM particles are assumed to be Dirac fermion
- The integration Lagrangian is:

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

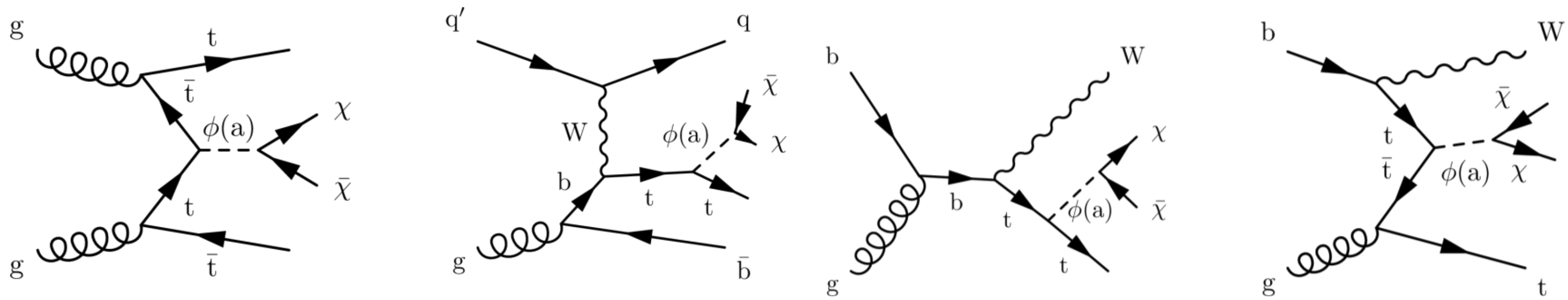
$$\mathcal{L}_a \supset i g_\chi a \bar{\chi}\gamma^5 \chi + \frac{i g_q a}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f),$$ **PSEUDOSCALAR mediator**

- Where where the sum runs over the SM fermions f, $y_f = \sqrt{2m_f/v}$ represents the Yukawa couplings, v = 246 GeV is the Higgs field vacuum expectation value, $\boldsymbol{g_\chi}$ is the **DM-mediator coupling**, and $\boldsymbol{g_q}$ is the **fermion-mediator coupling**
- The mediator particle subsequently decays into DM particles, which escape detection and leave an imbalance of momentum in the transverse plane, referred to as p_T^{miss}

Introduction

The data set used corresponds to an integrated luminosity of 35.9 fb^{-1} recorded with the CMS detector at the LHC

Principal production diagrams for the associated production at the LHC of dark matter with a **top quark pair** or a **single top quark** with associated t channel W boson production or with associated tW production



$t/\bar{t}$+DM processes are investigated for the first time

An excess of events above the SM background in the p_T^{miss} spectrum is expected for events that contain:

- **exactly one lepton** (electron or muon) → **single-lepton (SL)** region
- **zero leptons** →"**all-hadronic**" (AH) region

Event selection

For $t\bar{t} \rightarrow DM$ and $t/\bar{t}$+DM events, several orthogonal signal regions are defined and statistically combined in a **simultaneous global fit of the p_T^{miss} spectrum**

At the analysis level:

- **Jet candidates** are required to have $p_T > 30\ GeV$ and are categorized as "central" if they lie within |η| < 2.4 and as "forward" if they are within 2.4 < |η| < 4.0
- **b-tagged jets** are also required to have $p_T > 30\ GeV$ and to lie within |η| < 2.4
- **Electrons** and **muons** are selected with $p_T > 30\ GeV$ and |η| < 2.1
- Events containing additional leptons with $p_T > 10\ GeV$ and |η| < 2.1 are vetoed

Leptons are required to be isolated from hadronic activity in order to classify events into two channels based on the number of leptons in the final state from top quark decay:

1. The **single-lepton SL channel** that contains events with exactly one electron or muon with $p_T > 30\ GeV$
2. The **all-hadronic AH channel** that contains events with exactly zero leptons with $p_T > 10\ GeV$

The considered signal events are either $\boldsymbol{t/\bar{t} + DM}$ **events** for a region that contains exactly **one b-tagged jet** $n_b = 1$ or $\boldsymbol{t\bar{t} \rightarrow DM}$ **events** for a region that contains **two or more b-taggerd jets** $n_b \geq 2$. For $n_b = 1$ category, the region is further divided into exactly zero or ≥ forward jets

Signal regions-SL

Events in the **SL channel** are required to:

- contain ≥1 identified b-tagged jet
- at least 2 jets with $p_T > 30\ GeV$
- the $p_T^{miss} > 160\ GeV$

Background sources: tt, W+jets, and Z → νν processes. Other backgrounds include QCD multijet events, single top quark, Drell–Yan, and diboson production

	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}	$=1$	$=1$	$=1$	$= 0$	$=0$	$=0$
$p_{\mathrm{T}}(\mathrm{j}_1)/H_{\mathrm{T}}$	—			—		<0.5
n_{jet}	≥2			≥3		
$p_{\mathrm{T}}^{\mathrm{miss}}$	>160 GeV			>250 GeV		
m_{T}	>160 GeV			—		
$m_{\mathrm{T2}}^{\mathrm{W}}$	>200 GeV			—		
$\min\Delta\phi(\mathrm{j}_{1,2}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	>1.2 rad.			>1.0 rad.		
$m_{\mathrm{T}}^{\mathrm{b}}$	>180 GeV			>180 GeV		

Signal regions-AH

Events categorized into the **AH channel** must contain

- at least 1 identified b-tagged jet
- at least 3 jets with $p_T > 30\ GeV$
- $p_T^{miss} > 250\ GeV$
- minΔϕ($j_{1,2}$, ~ p_T^{miss}) greater than 0.4 radians

The dominant backgrounds after this selection arise from tt, W+jets, and Z → νν processes. Other backgrounds include QCD multijet events, single top quark, Drell–Yan, and diboson production

	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	

Control regions

In order to improve the estimation of these main SM backgrounds, methods based on control samples in data are used

In particular, **control regions (CRs)** enhanced in the different background sources are used to derive correction factors as a function of the p_T^{miss} from the comparison of the p_T^{miss} distribution between the data and the simulation

- **In the SL SRs**, the main backgrounds are dileptonic tt events, where one lepton is not identified, and W+jets events
- **For the AH regions** the main backgrounds arise instead from single-lepton tt and W+jets events, where the lepton is not identified, and Z boson production, where the Z boson decays into two neutrinos .

The background CRs for the SL and AH channels are designed to be statistically independent from the corresponding SRs.

Control regions-SL

The first set of CRs is defined to isolate dileptonic tt events by requiring

- exactly two leptons (1 electron and 1 muon, 2 electrons, or 2 muons)
- $n_{jet} \geq 2$
- $n_b \geq 1$
- $p_T^{miss} > 160\ GeV$

In order to statistically enhance these CRs the m_T, m_{T2}^{W} , and forward jet selections are removed

The second set of CRs is designed to isolate W+jets events by requiring:

- exactly one lepton (electron or muon),
- $n_{jet} \geq 2$
- $n_b \geq 1$
- $p_T^{miss} > 160\ GeV$
- $m_T > 160\ GeV$.

The nb = 0 requirement makes this CR orthogonal to the SL SR

	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
$p_{\mathrm{T}}^{\mathrm{miss}}$	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m_{T}	—	>160 GeV	<160 GeV	<160 GeV	—
$\min\Delta\phi(\mathrm{j}_{1,2}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	—	—	>1.0 rad.	—	—
$m_{\ell\ell}$	—	—	—	—	$[60, 120]$ GeV

Control regions-AH

The first set of CRs is enhanced in **single-lepton tt events** selecting events with:

- exactly one lepton (electron or muon)
- $n_{jet} \geq 3$
- $n_b \geq 1$
- $p_T^{miss} > 250\ GeV$
- In order to avoid overlap with the SL SRs, $m_T > 160\ GeV$

The second set of CRs is defined to enhance **single-lepton W+jets events**.

- exactly one lepton (electron or muon),
- $n_{jet} \geq 3$
- $n_b = 0$
- $p_T^{miss} > 250\ GeV$
- in order to avoid overlap with the SL W+jets CR, $m_T > 160\ GeV$

The third set of CRs are designed to model the background due to **Z+jets** where **Z → νν**
To emulate the kinematic properties of the Z+jets process, we use $Z \rightarrow ll$

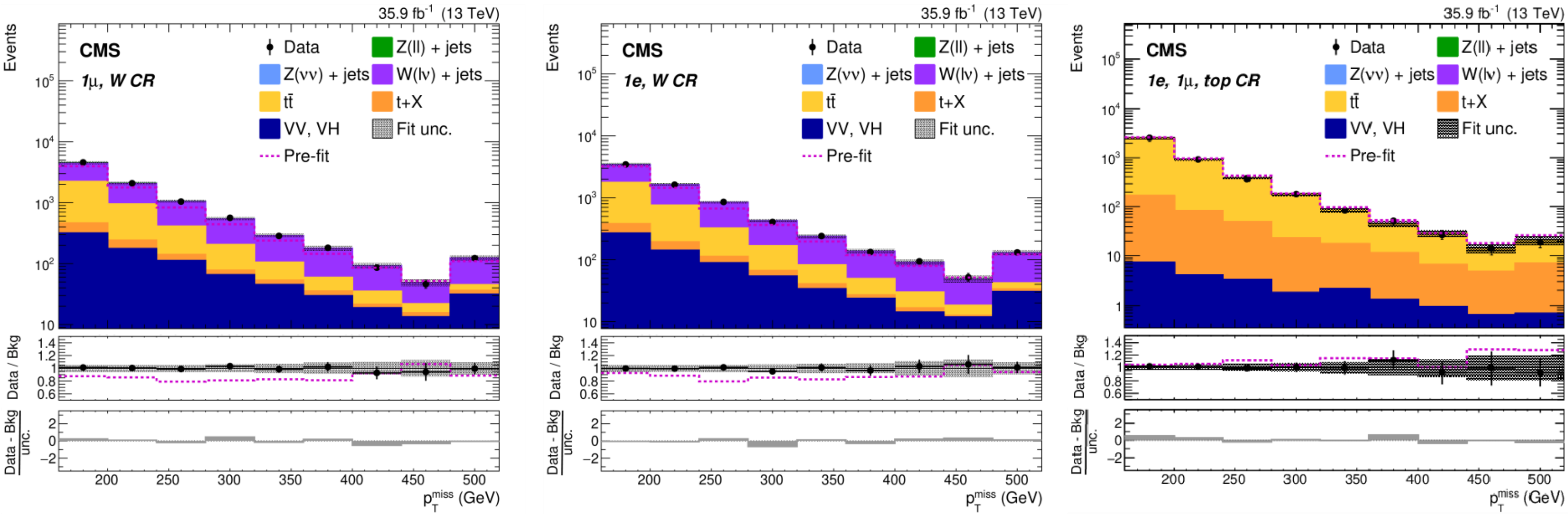
- $60 < m_{ll} < 120\ GeV$
- $n_{jet} \geq 3$
- $n_b = 0$

	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

Signal extraction-CRs

The DM signal is extracted from a simultaneous fit to the binned p_T^{miss} distribution in the various SRs and CRs

Example of post-fit distributions assuming the background only fit for the **SL CRs**

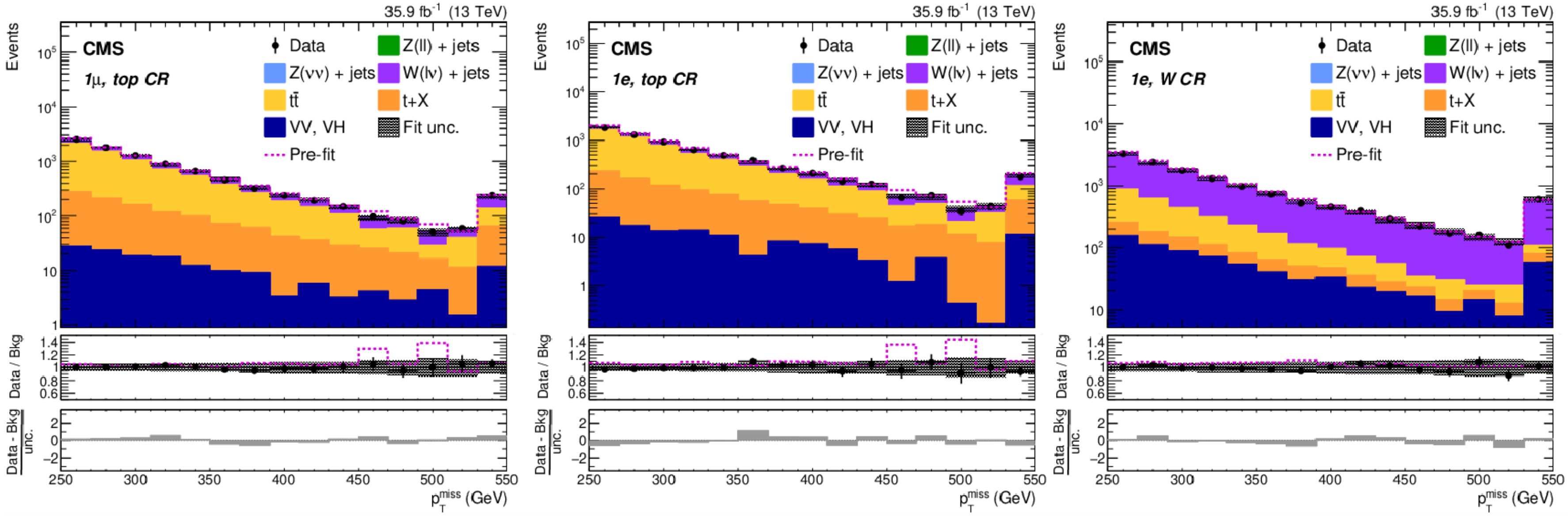


- The lower panels show the ratio of data and the post-fit prediction
- The bottom panels show the difference between the observed data events and the post-fit total background, divided by the full statistical and systematic uncertainty

Signal extraction-CRs

The DM signal is extracted from a simultaneous fit to the binned p_T^{miss} distribution in the various SRs and CRs

Example of post-fit distributions assuming the background only fit for the **AH CRs**

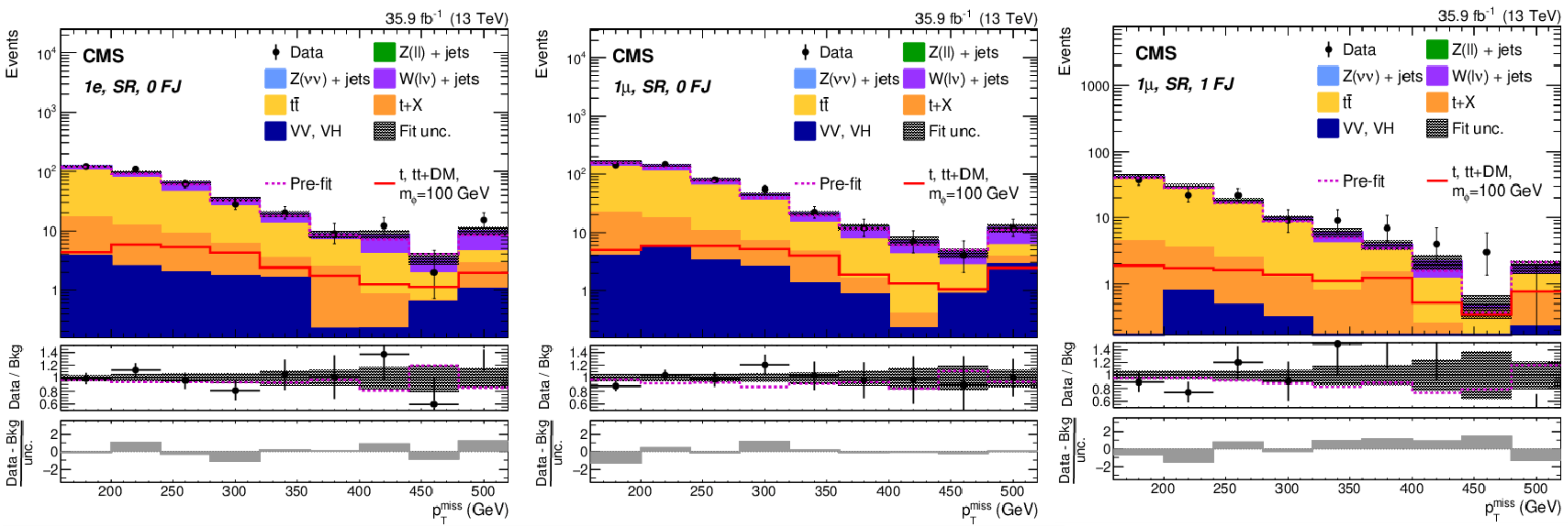


- The lower panels show the ratio of data and the post-fit prediction
- The bottom panels show the difference between the observed data events and the post-fit total background, divided by the full statistical and systematic uncertainty

Signal extraction-SRs

The DM signal is extracted from a simultaneous fit to the binned p_T^{miss} distribution in the various SRs and CRs

Example of post-fit distributions assuming the background only fit for the **SL SRs**

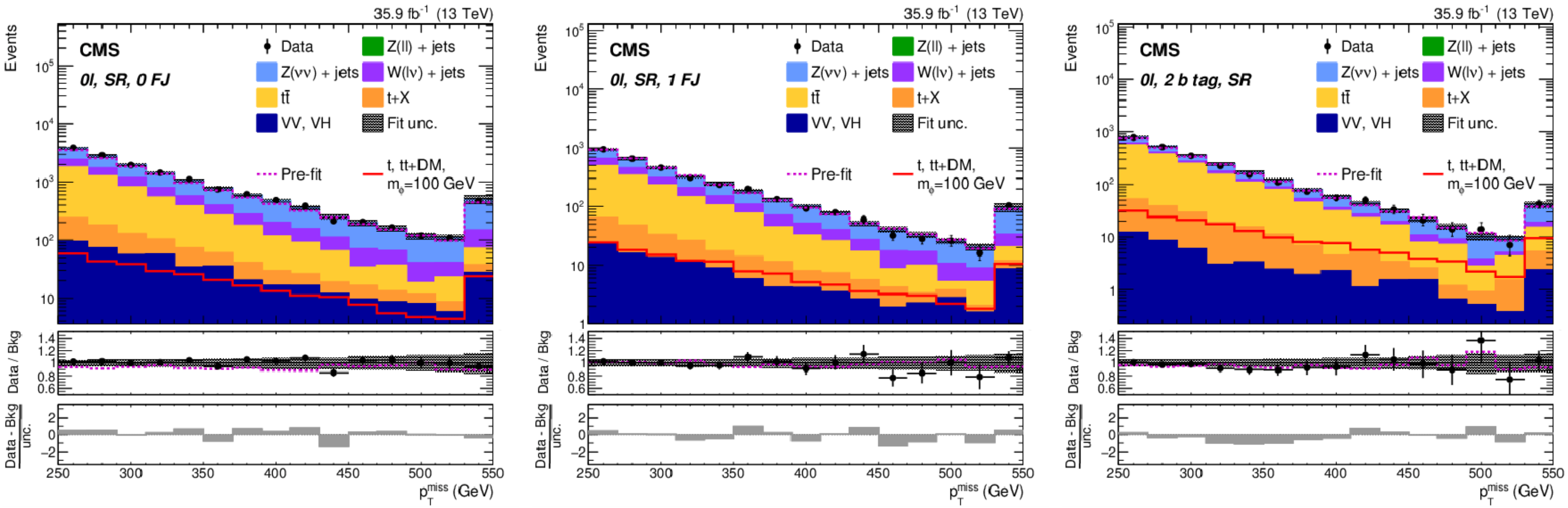


- The **total theory signal** (t/t+DM and tt+DM summed together) is presented by the red solid lines for a scalar mediator mass of 100 GeV
- The lower panels show the ratio of data and the post-fit prediction
- The bottom panels show the difference between the observed data events and the post-fit total background, divided by the full statistical and systematic uncertainty

Signal extraction-SRs

The DM signal is extracted from a simultaneous fit to the binned p_T^{miss} distribution in the various SRs and CRs

Example of post-fit distributions assuming the background only fit for the **AH SRs**



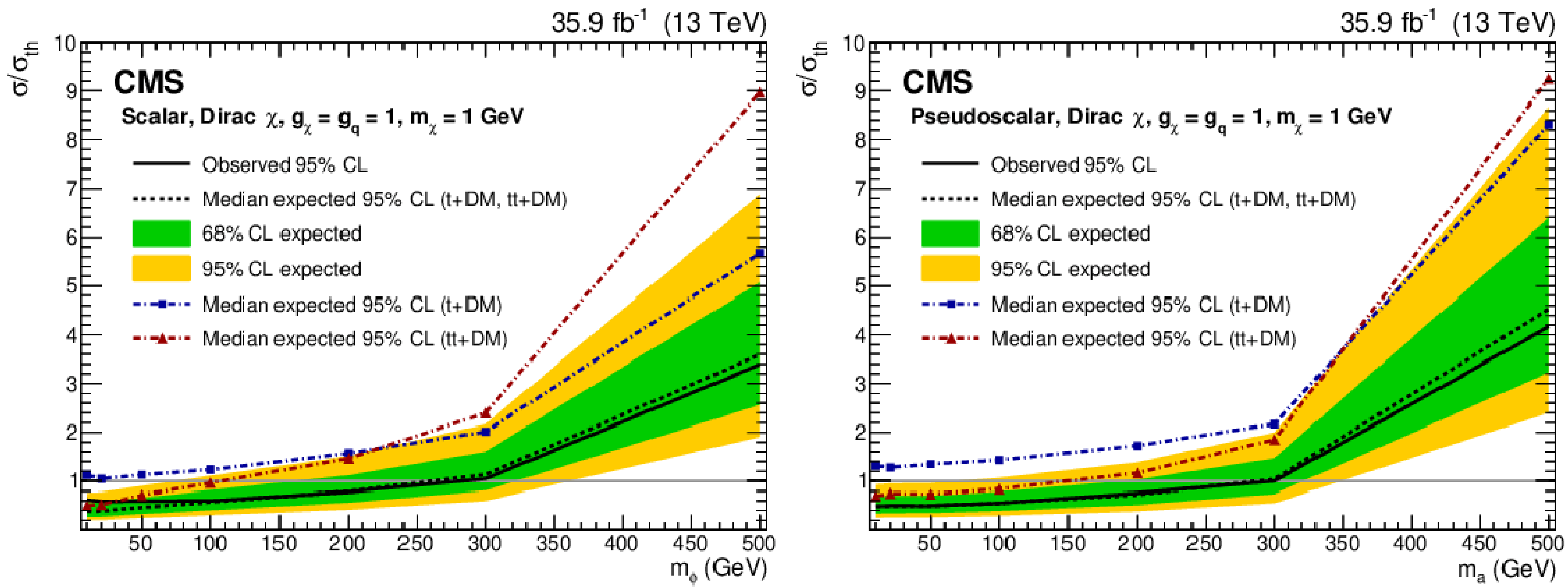
- The **total theory signal** (t/t+DM and tt+DM summed together) is presented by the red solid lines for a scalar mediator mass of 100 GeV
- The lower panels show the ratio of data and the post-fit prediction
- The bottom panels show the difference between the observed data events and the post-fit total background, divided by the full statistical and systematic uncertainty

Results:

<u>Data are found to be in agreement with the expected SM background in the SRs</u>

Upper limits at 95% confidence level (CL) are computed on the ratio between the measured and theoretical cross sections μ

Different mediator mass scenarios with $m_\chi = 1\ GeV$ and $g_q = g_\chi = 1$ are tested



Overall**, mediator masses below 290 and 300 GeV** for the **scalar** and **pseudoscalar hypotheses** are excluded, respectively

Summary:

- The first search at the LHC for dark matter (DM) produced in association with a **single top quark** or **a top quark pair** in interactions mediated by a **neutral scalar** or **pseudoscalar particl**e in proton-proton collisions at $\sqrt{s} = 13TeV$ has been presented

- The results are interpreted in the context of a simplified model in which the **scalar** or **pseudoscalar mediator** particle couples to the top quark and subsequently decays into two DM particles

- <u>No significant deviations with respect to SM predictions are observed!</u>

- **Scalar** and **pseudoscalar mediator masses** below **290 and 300 GeV** are excluded at 95% confidence level assuming a DM particle mass of 1 GeV and mediator couplings to fermions and DM particles equal to unity

Thank you for your attention!

Back up slides:

Questions:

- Which fundamental open question - not answered by the SM - is this search trying to answer? Dark matter nature as a WIMP particle
- Which type of search for NP is it (direct vs indirect, resonant vs not-resonant), i.e. using the categorization I used during the lectures. Indirect search
- Can it be performed also in other final states? Is it already performed in other final states? If yes which is the most sensitive channel and why?
- Which is(are) the experimental challenge(s) of this search? Which are the experimental limitation on the results? (acceptance vs uncertainties)
- Can the same search (meaning the same final state, and acceptance) be used for other NP interpretations (other BSM models)?
- Compare with the results on the same search performed by other experiments (if any) Previous results for ATLAS and CMS
- What are the future prospects of this search (i.e. is it useful to add more data, or what is needed to be done to improve its sensitivity)? And does it still make sense to keep performing this search in the future?