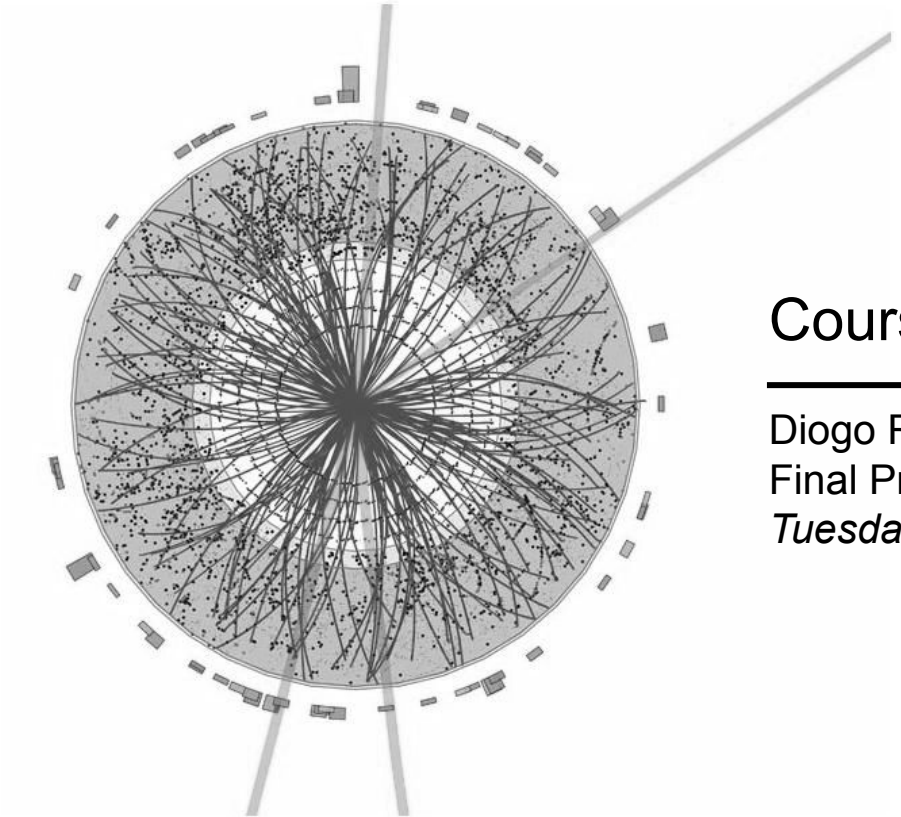


Course on Physics at the LHC

Diogo Ribeiro

Final Presentation

Tuesday , 15 June 2021

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-311
2019/04/02

CMS-EXO-18-010

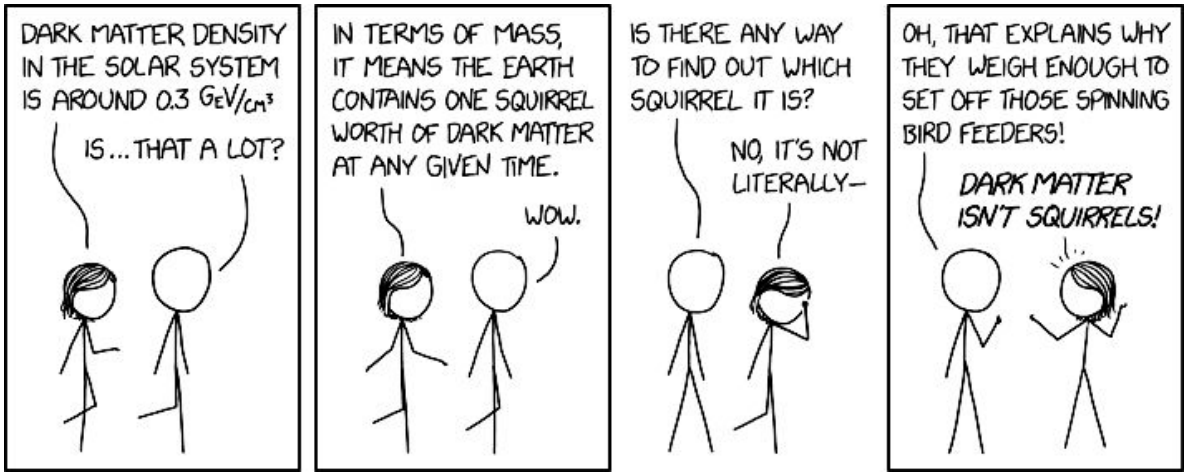
Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

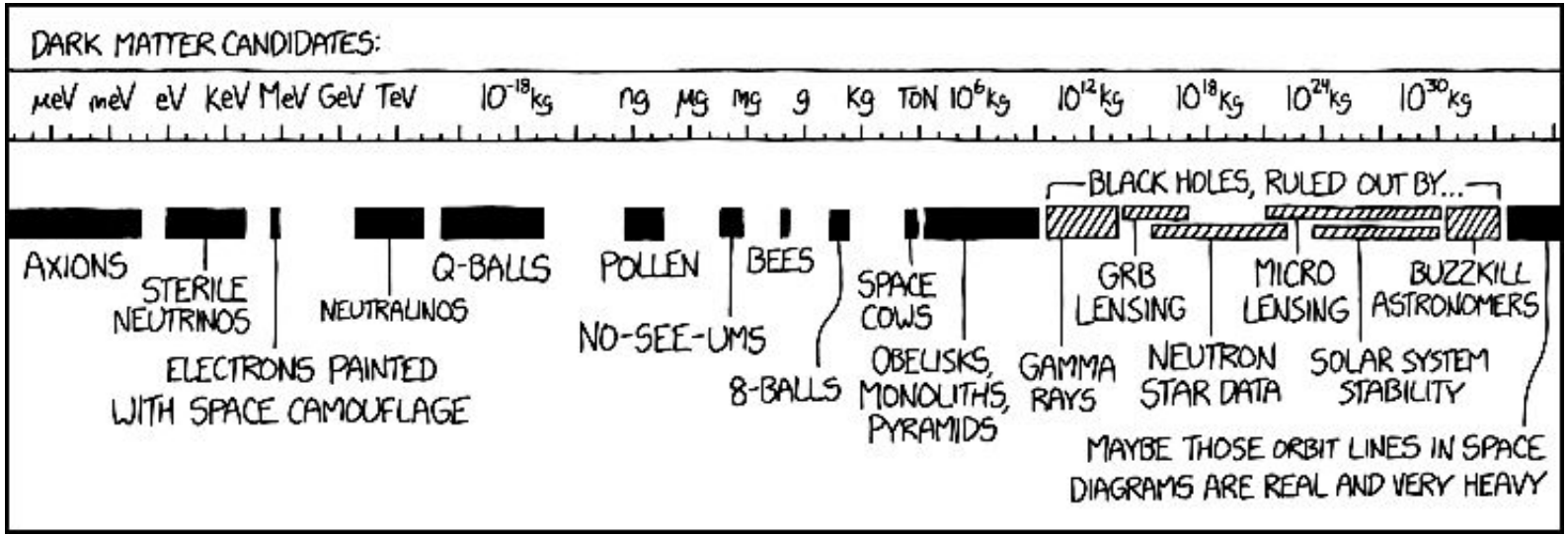
Abstract

A search for dark matter produced in association with top quarks in proton-proton collisions at a center-of-mass energy of 13 TeV is presented. The data set used corresponds to an integrated luminosity of 35.9 fb^{-1} recorded with the CMS detector at the LHC. Whereas previous searches for neutral scalar or pseudoscalar mediators considered dark matter production in association with a top quark pair only, this analysis also includes production modes with a single top quark. The results are derived from the combination of multiple selection categories that are defined to target either the

A Real Problem: Dark Matter



A Real Problem: Lots of Candidates

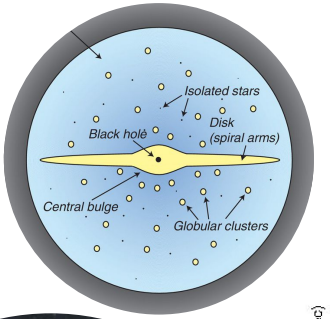


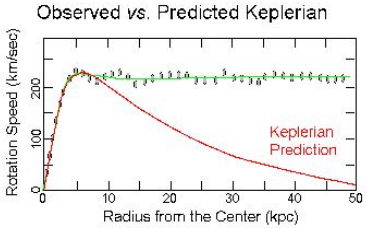
Evidence from outer space

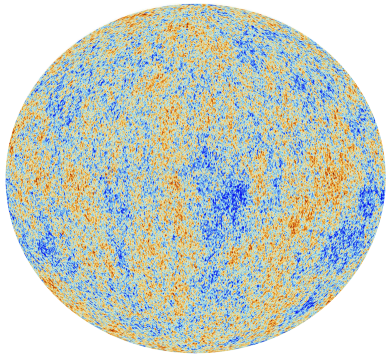


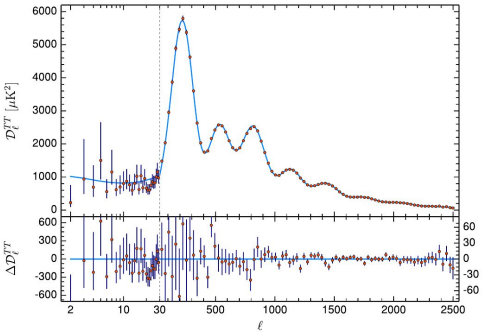



Evidence from outer space



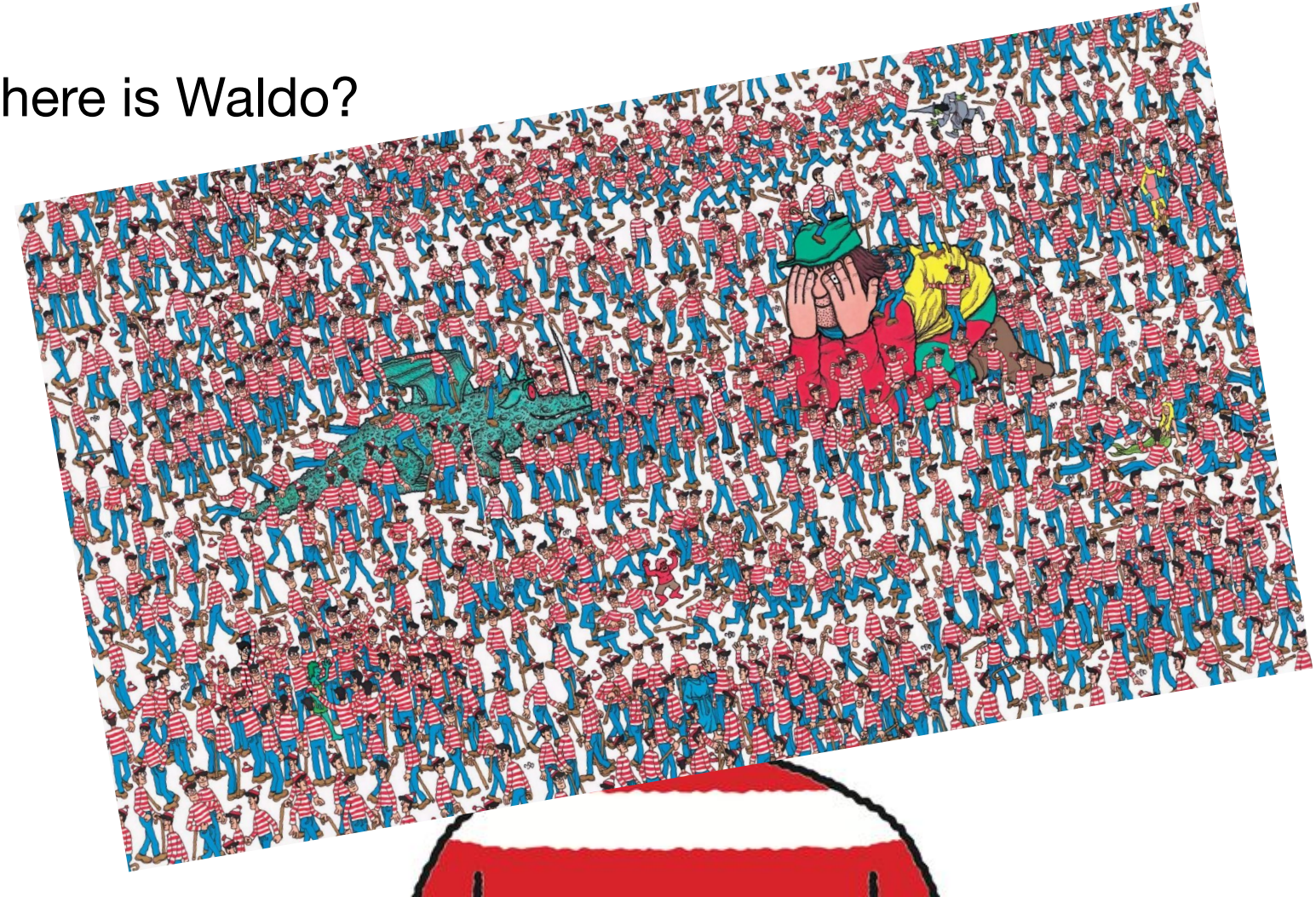






Where is Waldo?

Where is Waldo?



What is Waldo?

What is Waldo?

What is Waldo like:

- Has mass
- Cold (non-relativistic) matter
- Weakly coupled to the SM
- Stable

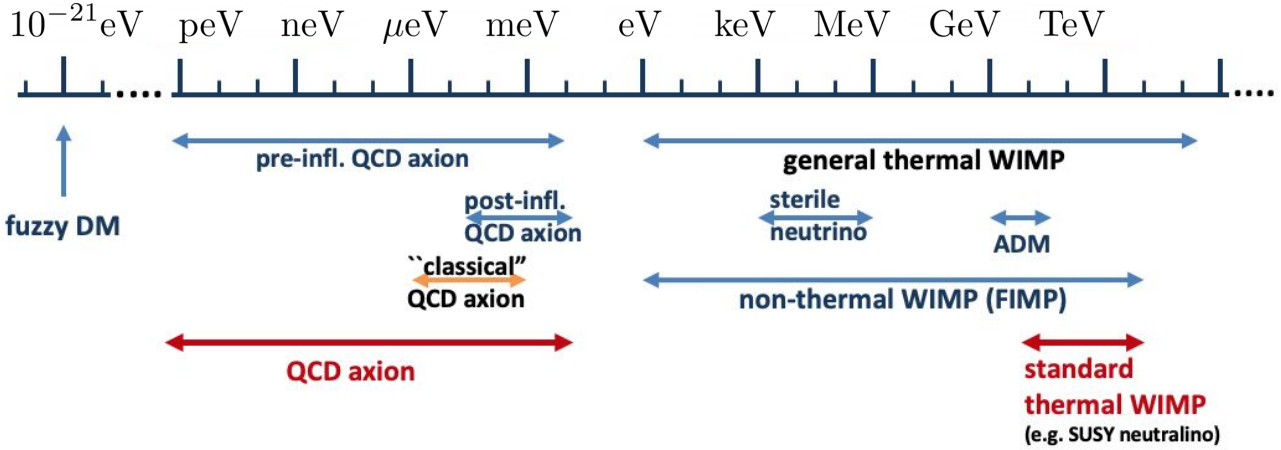
What is Waldo?

- Planets? Dark Stars? Black Holes? (MACHOS) ✗
- Baryonic Matter? ✗
- Neutrinos? ✗
- Weakly Interacting Massive Particle? (WIMPS)
- Axion?
- Altered Theories of Gravity?

What is Waldo?

- Planets? Dark Stars? Black Holes? (MACHOS) ✗
- Baryonic Matter? ✗
- Neutrinos? ✗
- **Weakly Interacting Massive Particle? (WIMPS)**
- Axion?
- Altered Theories of Gravity?

Many Candidates

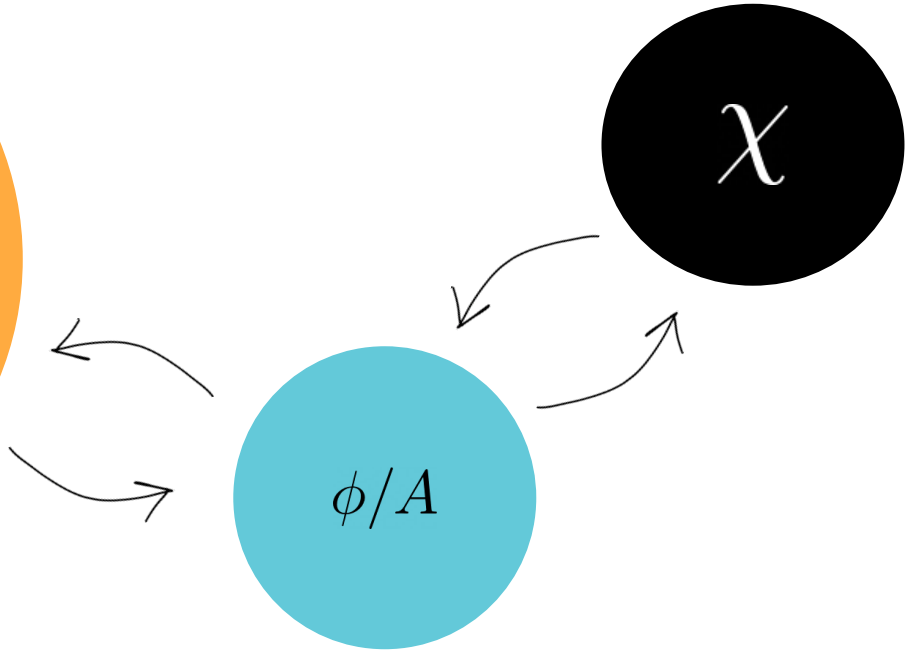


Dark and scalar sectors

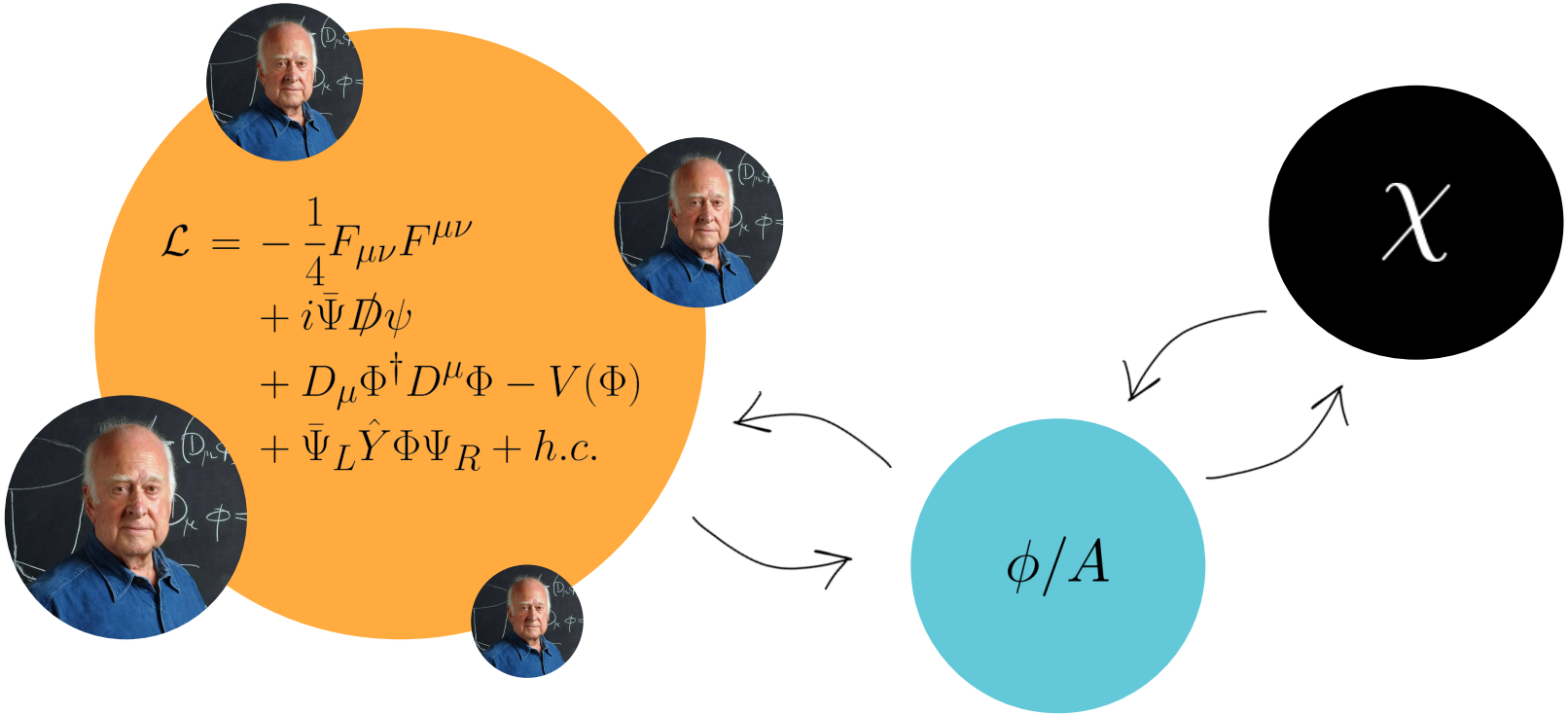
$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ & + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

Dark and scalar sectors

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$



Dark and scalar sectors



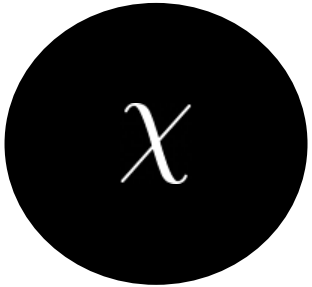
Dark and scalar sectors

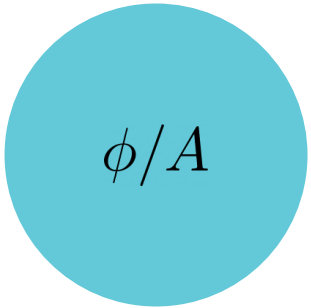
Scalar mediator:

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

Pseudoscalar mediator:

$$\mathcal{L}_\phi \supset i g_\chi A \bar{\chi}\gamma^5 \chi + \frac{i g_q A}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f)$$





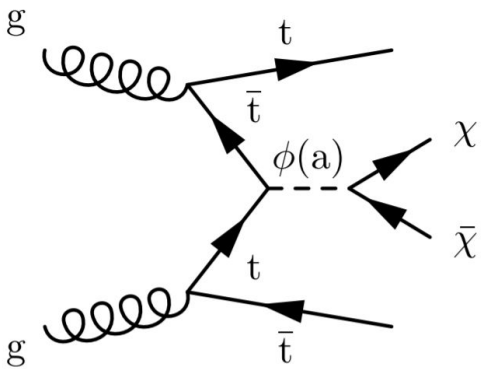
Dark and scalar sectors

Scalar mediator:

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

Pseudoscalar mediator:

$$\mathcal{L}_\phi \supset i g_\chi A \bar{\chi}\gamma^5 \chi + \frac{i g_q A}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f)$$



Dark and scalar sectors

Previously:

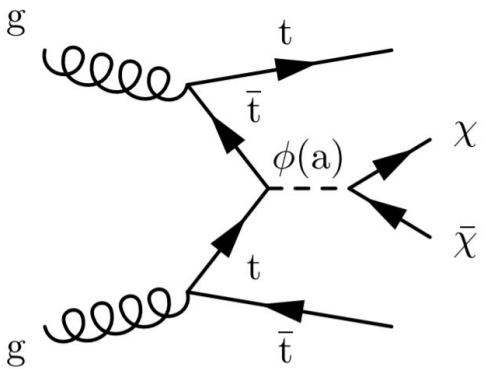
[12] CMS Collaboration, "Search for the production of dark matter in association with top-quark pairs in the single-lepton final state in proton-proton collisions at $\sqrt{s} = 8$ TeV", *JHEP* **06** (2015) 121, doi:10.1007/JHEP06(2015)121, arXiv:1504.03198.

[13] ATLAS Collaboration, "Search for dark matter in events with heavy quarks and missing transverse momentum in pp collisions with the ATLAS detector", *Eur. Phys. J. C* **75** (2015) 92, doi:10.1140/epjc/s10052-015-3306-z, arXiv:1410.4031.

[14] CMS Collaboration, "Search for dark matter produced in association with heavy-flavor quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **77** (2017) 845, doi:10.1140/epjc/s10052-017-5317-4, arXiv:1706.02581.

[15] ATLAS Collaboration, "Search for dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector", *Eur. Phys. J. C* **78** (2018) 18, doi:10.1140/epjc/s10052-017-5486-1, arXiv:1710.11412.

[16] CMS Collaboration, "Search for dark matter particles produced in association with a top quark pair at $\sqrt{s} = 13$ TeV", (2018). arXiv:1807.06522.



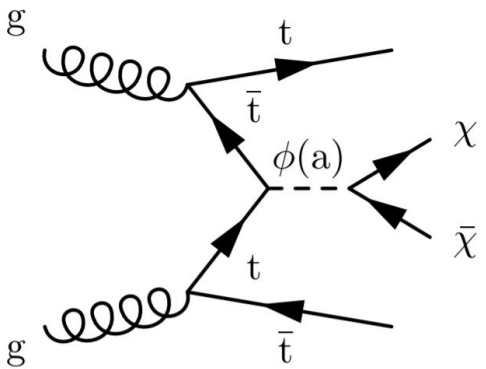
Dark and scalar sectors

Scalar mediator:

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

Pseudoscalar mediator:

$$\mathcal{L}_\phi \supset i g_\chi A \bar{\chi}\gamma^5 \chi + \frac{i g_q A}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f)$$



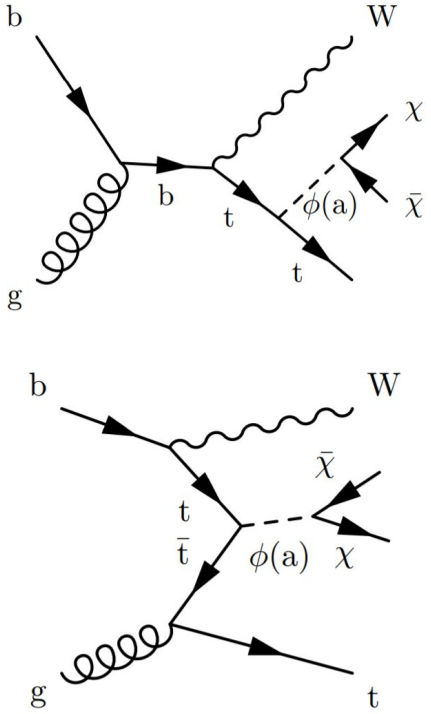
Dark and scalar sectors

Scalar mediator:

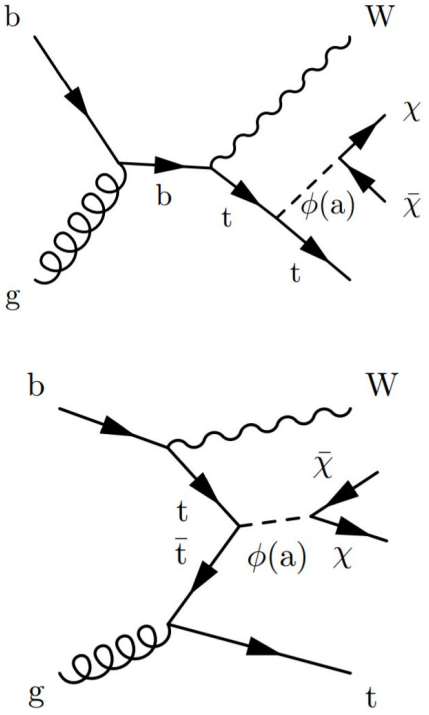
$$\mathcal{L}_\phi \supset g_\chi \phi \bar{\chi}\chi + \frac{g_q \phi}{\sqrt{2}} \sum_f (y_f \bar{f} f)$$

Pseudoscalar mediator:

$$\mathcal{L}_\phi \supset i g_\chi A \bar{\chi}\gamma^5 \chi + \frac{i g_q A}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f)$$



Dark and scalar sectors



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-311
2019/04/02

CMS-EXO-18-010

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

The CMS Collaboration*

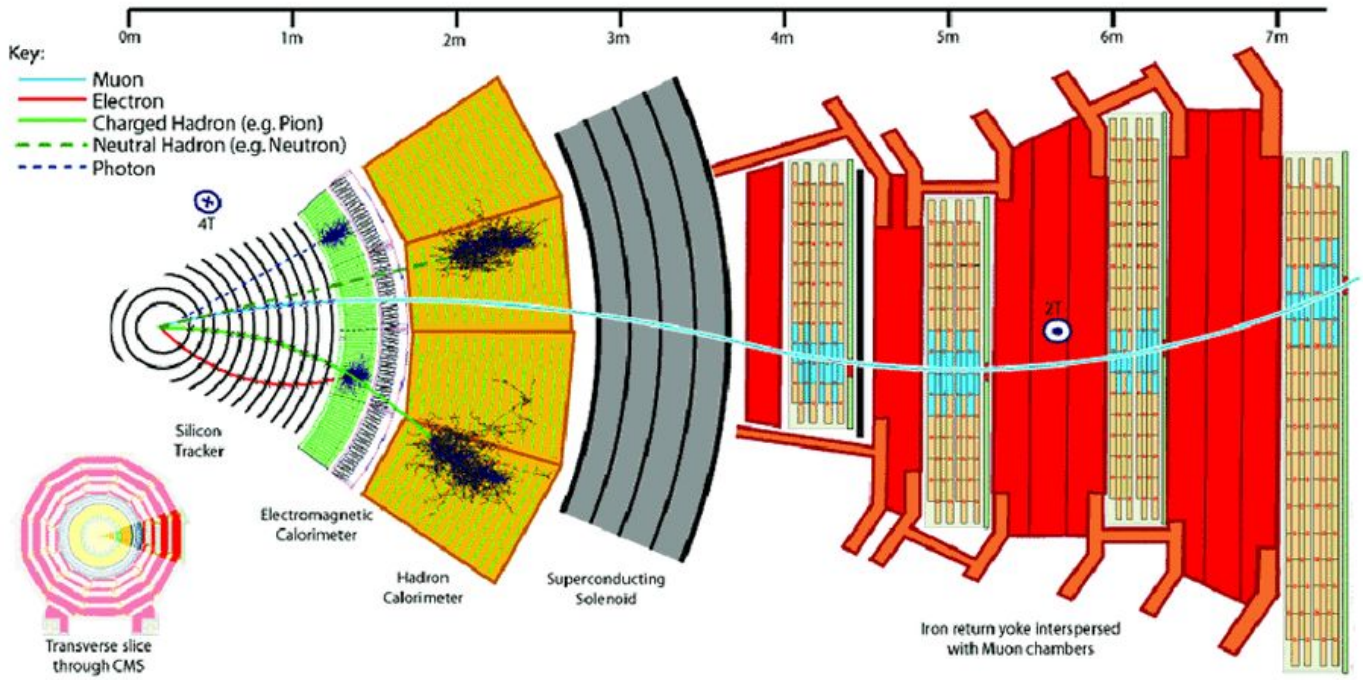
Abstract

A search for dark matter produced in association with top quarks in proton-proton collisions at a center-of-mass energy of 13 TeV is presented. The data set used corresponds to an integrated luminosity of 35.9 fb^{-1} recorded with the CMS detector at the LHC. Whereas previous searches for neutral scalar or pseudoscalar mediators considered dark matter production in association with a top quark pair only, this analysis

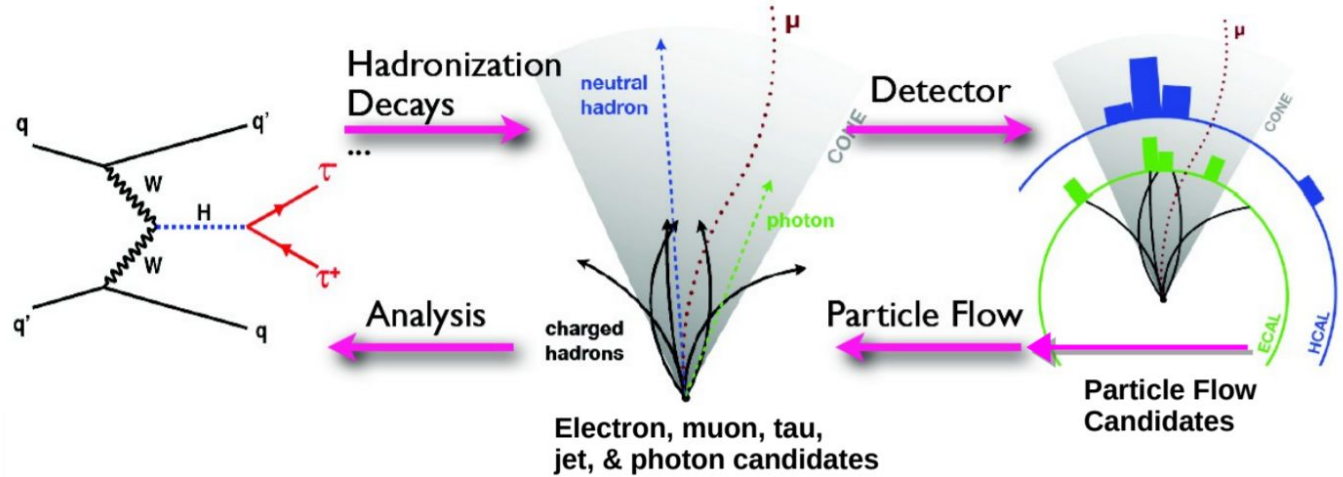
Spoiler Alert:

the combination of multiple selection categories that are defined to target either the single top quark or the top quark pair signature. No significant deviations with respect to the standard model predictions are observed. The results are interpreted in the context of a simplified model in which a scalar or pseudoscalar mediator particle

The CMS detector



Events: Particle Flow



Events: Data Sample

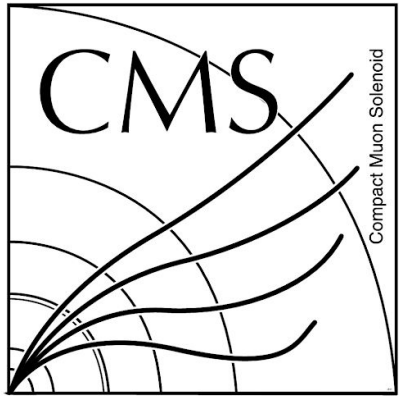
Data:

- CMS 2016
- Integrated Luminosity of 35.9 fb^{-1}

Triggers:

- No lepton and large amounts of p_T^{miss}
  (p_T^{miss} and missing hadronic activity > 120 GeV)

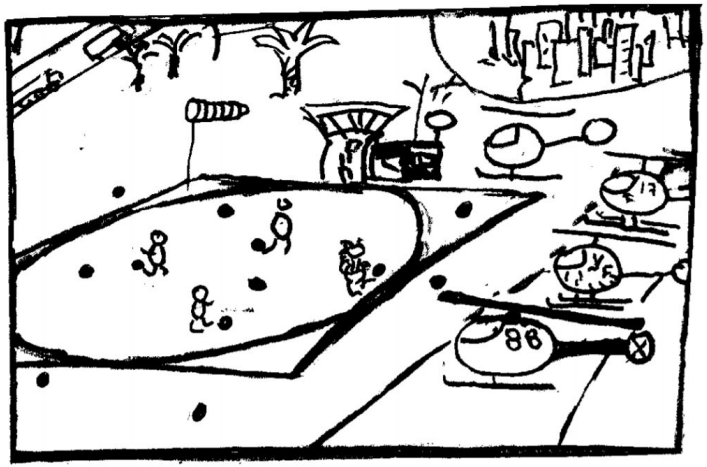
- At least one (isolated) high p_T lepton (pt > 27 GeV)



Events: Data Simulation

Monte Carlo simulation:

- SM Background
- DM Signal

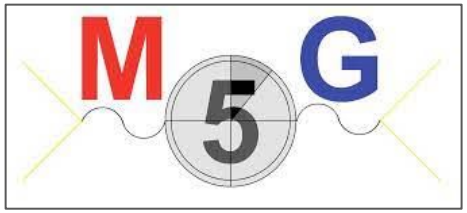


Events: Data Simulation

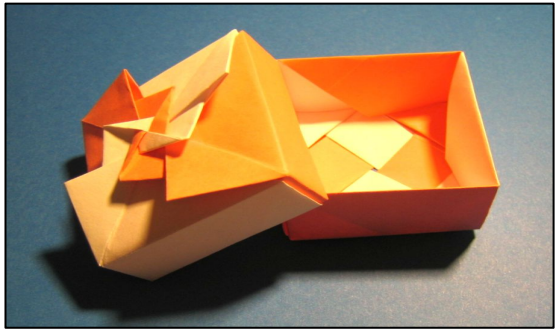
SM Background:

- Main contributions come from:
  - ttbar + jets
  - W + jets
  - Z + jets

- but also some rare processes
  - ttbar + W
  - ttbar + Z



MadGraph5_aMC@NLO



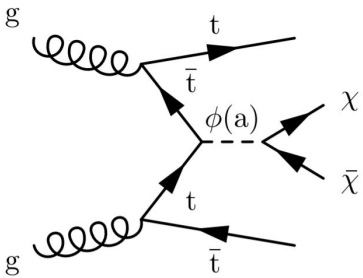
POsitive Weight Hardest Emission Generator (POWHEG)

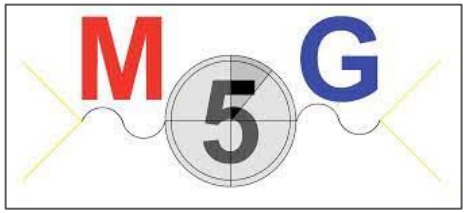
Events: Data Simulation

DM Signal:

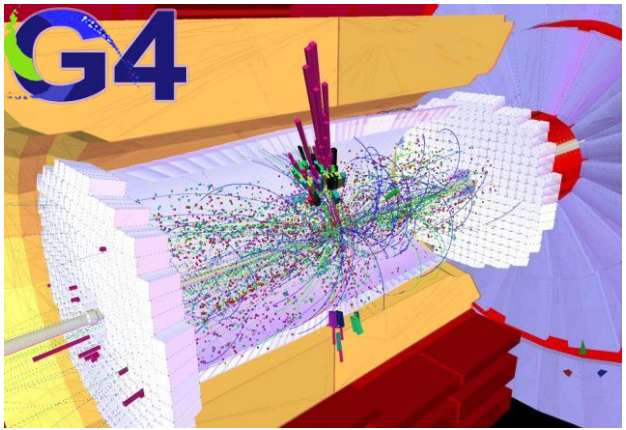
- Four free parameters:

$$(m_\chi, m_\phi, g_\chi, g_q)$$





MadGraph5_aMC@NLO

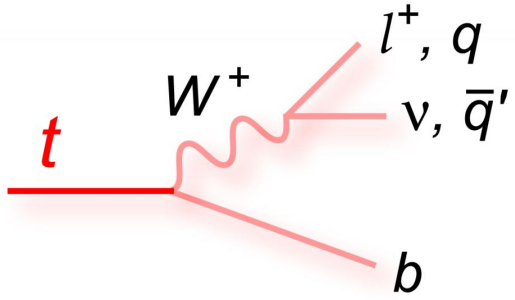


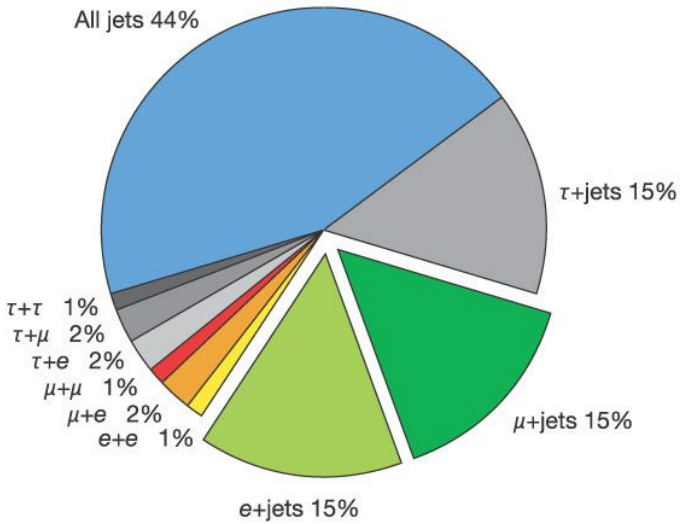
GEANT4

Events: Event Selection

Decay channels:

- Dilepton (BR ~ 5 %)
- Lepton + Jets (BR ~ 30 %)
- All Hadronic (BR ~ 44 %)





Events: Event Selection

- Orthogonal SR for SL and AH cases:

	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	

Events: Control Regions

- Control Regions for SL and AH regions:

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

Systematic Uncertainties

Affect p_T normalization

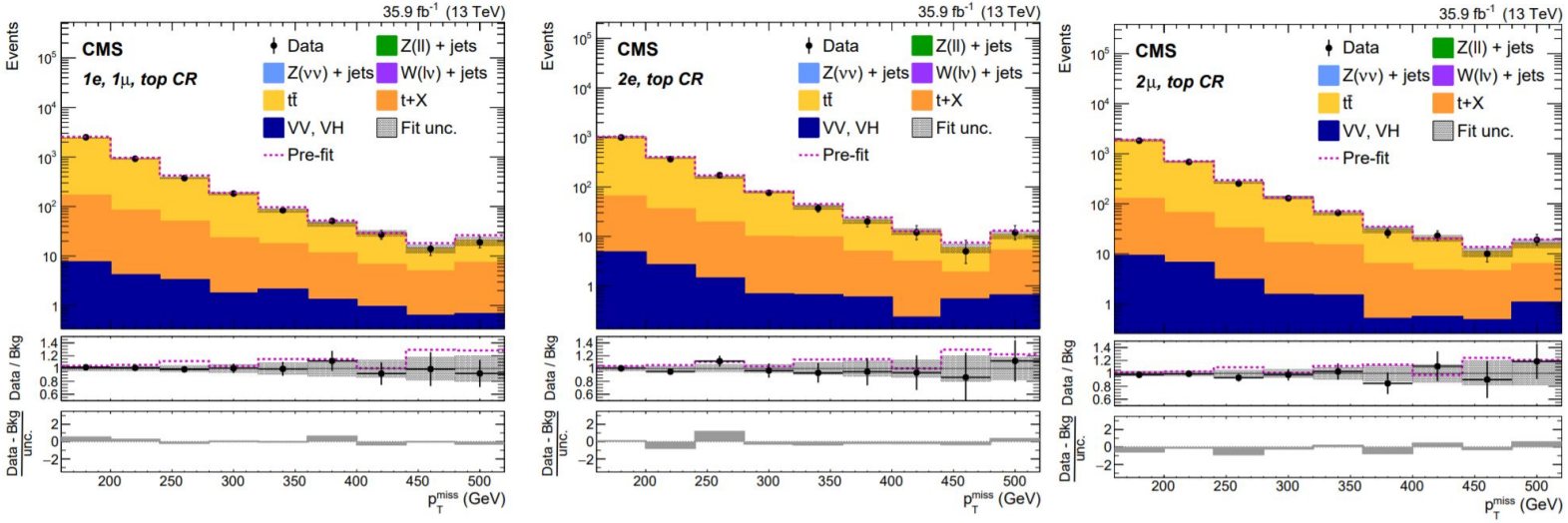
- Lepton reconstruction, selection and trigger
- b-tagging efficiency
- Forward jets
- Pileup
- Luminosity
- ECAL mistiming

Affect p_T normalization & shape

- Jet energy scale
- PDF uncertainties
- W/Z + heavy flavour fraction
- K factors
- top p_T reweighting
- Simulation sample size

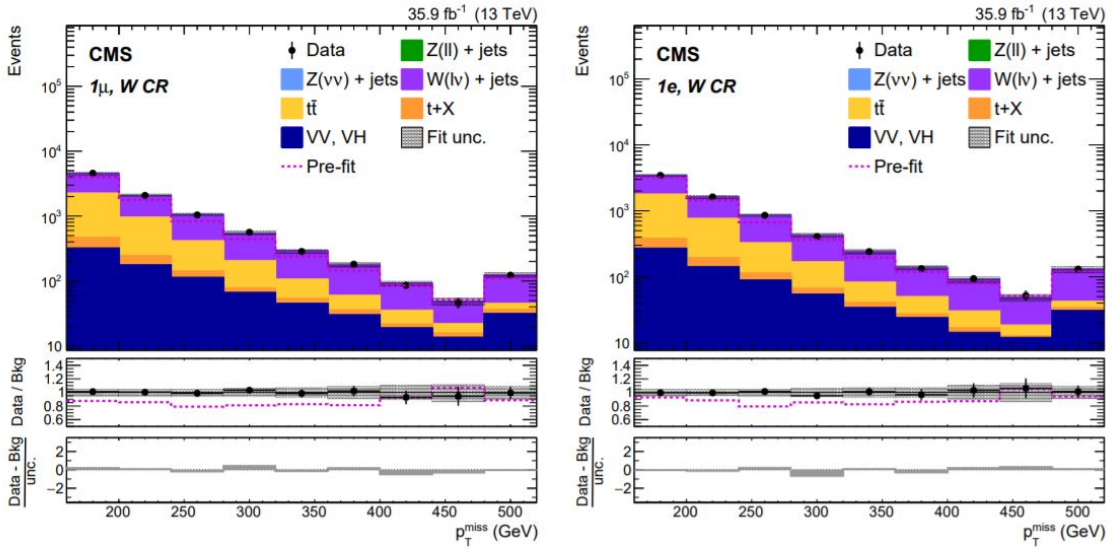
Signal Extraction

Single Lepton , CR Background fit:



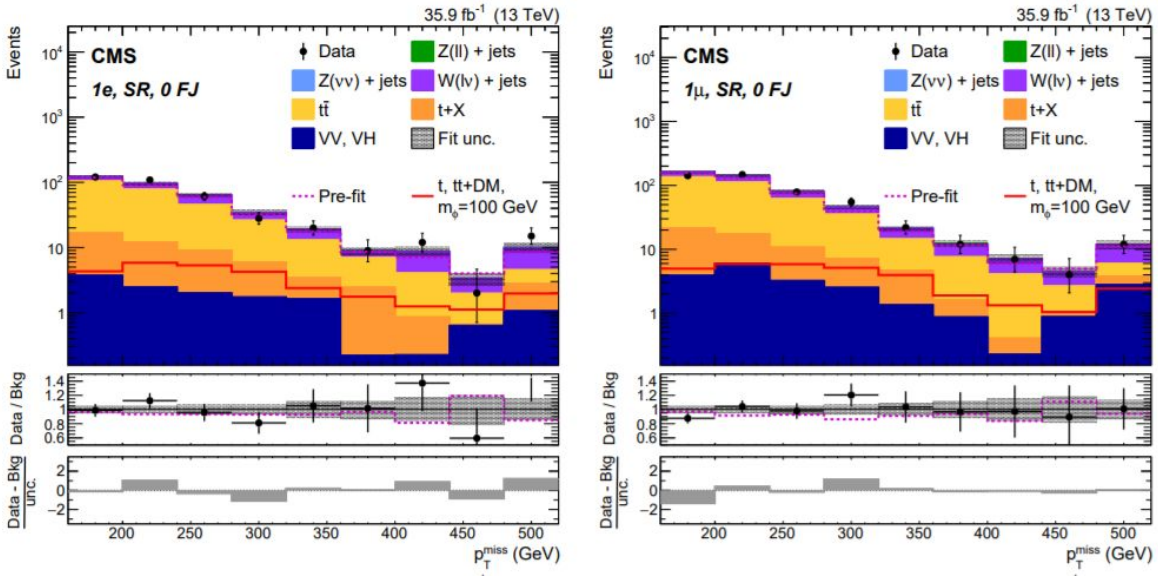
Signal Extraction

Single Lepton , CR Background fit:



Signal Extraction

Single Lepton , SR:



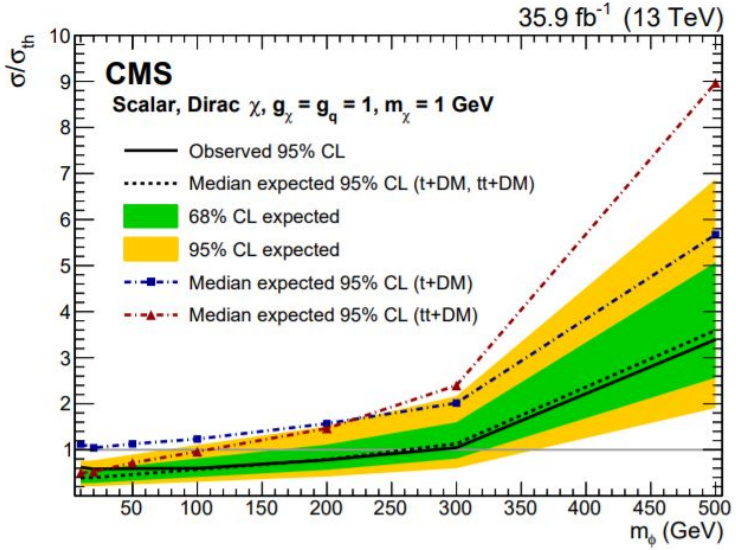
Results

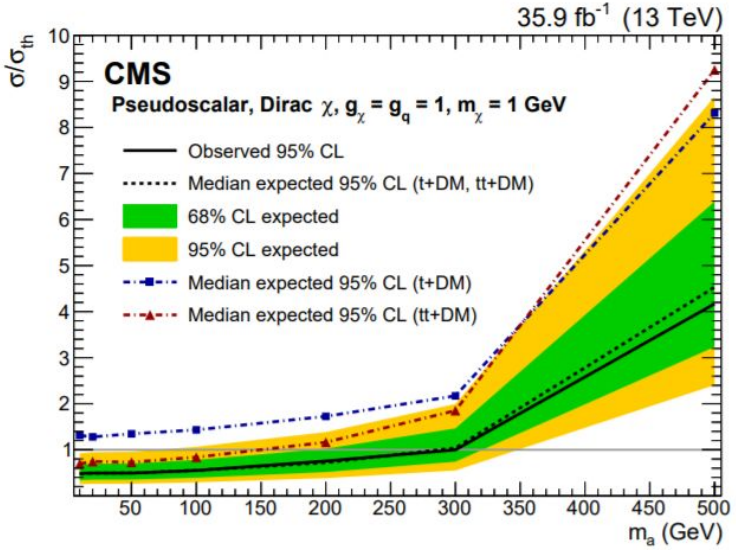
"Overall, data are found to be in agreement with the expected SM background in the SRs"

		t/$\bar{t}$+DM		$t\bar{t}$+DM		t, $t\bar{t}$+DM sum			
	$m_{\phi/a}$(GeV)	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	68% CI	95% CI
Scalar	10	1.59	1.12	0.91	0.50	0.62	0.39	[0.27, 0.55]	[0.21, 0.76]
	20	1.38	1.04	0.84	0.52	0.58	0.39	[0.28, 0.56]	[0.21, 0.77]
	50	1.15	1.13	1.11	0.72	0.59	0.46	[0.33, 0.66]	[0.25, 0.90]
	100	1.43	1.23	0.94	0.96	0.60	0.57	[0.41, 0.81]	[0.30, 1.11]
	200	1.66	1.57	1.37	1.46	0.78	0.79	[0.56, 1.11]	[0.42, 1.51]
	300	1.97	2.02	2.09	2.40	1.05	1.13	[0.81, 1.60]	[0.60, 2.17]
	500	5.84	5.67	7.48	8.97	3.39	3.59	[2.57, 5.07]	[1.91, 6.88]
Pseudoscalar	10	1.43	1.31	0.70	0.70	0.49	0.47	[0.34, 0.67]	[0.25, 0.92]
	20	1.43	1.28	0.71	0.75	0.49	0.49	[0.35, 0.70]	[0.26, 0.95]
	50	1.48	1.35	0.70	0.73	0.49	0.50	[0.35, 0.70]	[0.26, 0.96]
	100	1.53	1.43	0.81	0.84	0.55	0.55	[0.39, 0.78]	[0.29, 1.06]
	200	1.89	1.73	1.18	1.16	0.76	0.72	[0.52, 1.02]	[0.38, 1.38]
	300	2.17	2.17	1.74	1.85	1.00	1.04	[0.74, 1.47]	[0.55, 2.00]
	500	8.22	8.31	8.00	9.25	4.17	4.53	[3.24, 6.39]	[2.41, 8.67]

Results

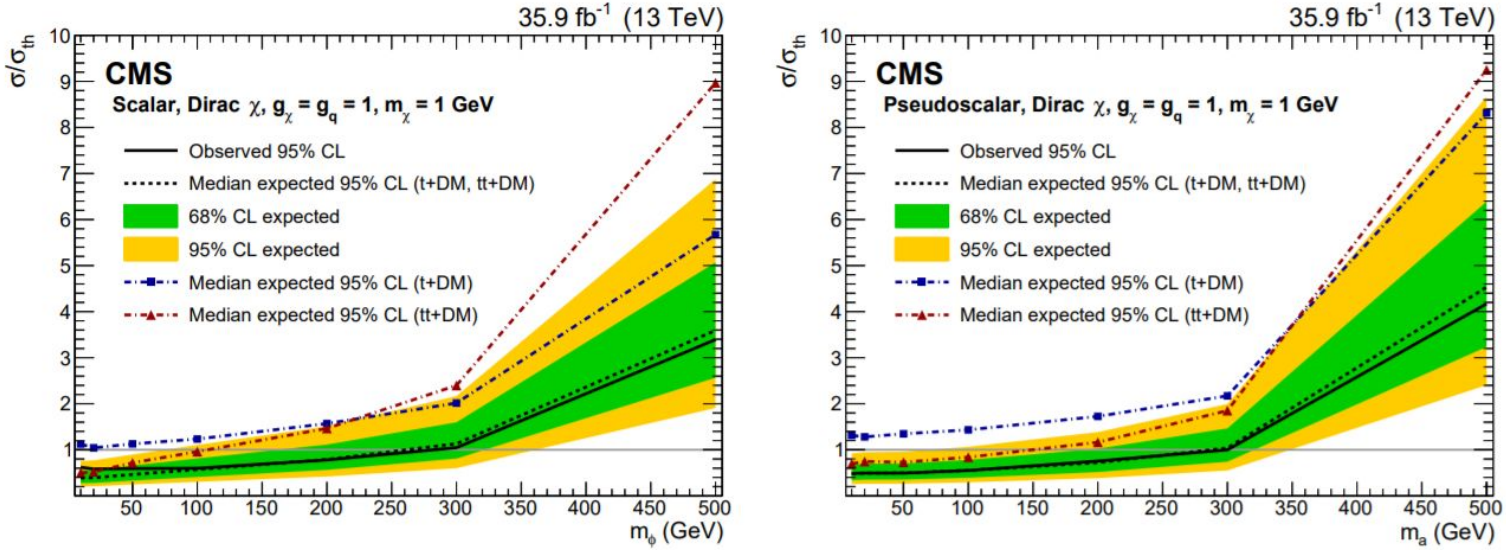
“Overall, data are found to be in agreement with the expected SM background in the SRs”





Results

"Overall, data are found to be in agreement with the expected SM background in the SRs"



Mediator masses below 290 GeV (300 GeV) for the Scalar (Pseudoscalar) are excluded

Where to now?

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Rev. Lett. 126 (2021) 121802
DOI: 10.1103/PhysRevLett.126.121802

CERN-EP-2020-172
December 17, 2020

Search for dark matter produced in association with a dark Higgs boson decaying into $W^{\pm}W^{\mp}$ or ZZ in fully hadronic final states from $\sqrt{s} = 13$ TeV pp collisions recorded with the ATLAS detector

The ATLAS Collaboration

Several extensions of the Standard Model predict the production of dark matter particles at the LHC. An uncharted signature of dark matter particles produced in association with $VV = W^{\pm}W^{\mp}$ or ZZ pairs from a decay of a dark Higgs boson s is searched for using 139 fb^{-1} of pp collisions recorded by the ATLAS detector at a center-of-mass energy of 13 TeV. The $s \to V(q\bar{q})V(q\bar{q})$ decays are reconstructed with a novel technique aimed at resolving the dense topology from boosted VV pairs using jets in the calorimeter and tracking information. Dark Higgs scenarios with $m_s > 160$ GeV are excluded.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-136
2021/01/13

CMS-EXO-19-003

Search for dark matter produced in association with a leptonically decaying Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for dark matter particles is performed using events with a Z boson candidate and large missing transverse momentum. The analysis is based on proton-proton collision data at a center-of-mass energy of 13 TeV, collected by the CMS experiment at the LHC in 2016–2018, corresponding to an integrated luminosity of 137 fb^{-1}. The search uses the decay channels $Z \to ee$ and $Z \to \mu\mu$. No significant excess of events is observed over the background expected from the standard model. Limits are set on dark matter particle production in the context of simplified models with vector, axial-vector, scalar, and pseudoscalar mediators, as well as on a two-Higgs-doublet model with an additional pseudoscalar mediator. In addition, limits are provided for spin-dependent and spin-independent scattering cross sections and are compared to those from direct-detection experiments. The results are also interpreted in the context of

Thank you!