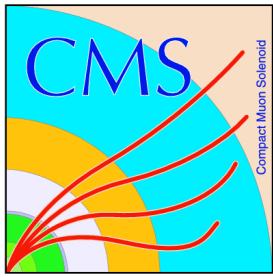


Dark Matter Searches in CMS

Kelly Beernaert

DESY LHC Physics Discussion

November 6th 2017

HELMHOLTZ ASSOCIATION

Public Results on 2015+2016 Data

> Mono-Higgs

- h(γγ)
  [CMS-PAS-EXO16-011]
  [CMS-PAS-EXO-16-054]
- h($b\bar{b}$)
  [arxiv:1703.05236]

> Heavy Flavor + MET

- $t\bar{t}$ + MET, $b\bar{b}$ + MET
  [arxiv:1706.02581]
- tt(ll) + MET
  [CMS-PAS-EXO-16-028]
- Top + MET
  [CMS-PAS-EXO-16-051]
- Boosted top + MET
  CMS-PAS-EXO-16-017
  [CMS-PAS-EXO-16-040]
- Top squarks & DM search
  [arxiv:1711.00752]

> Invisible Higgs decays

- Z + h(inv)
  [arxiv:1711.00431]

> Mono-X searches

- Mono-photon
  [arxiv:1706.03794]
  [CMS-PAS-EXO-16-014]
- Mono-Z(ll)
  [arxiv:1701.02042]
- Mono-jet, W(had), Z(had)
  [CMS-EXO-PAS-16-013]
  [arxiv:1703.01651]
  [CMS-EXO-PAS-16-048]

> Mediator searches

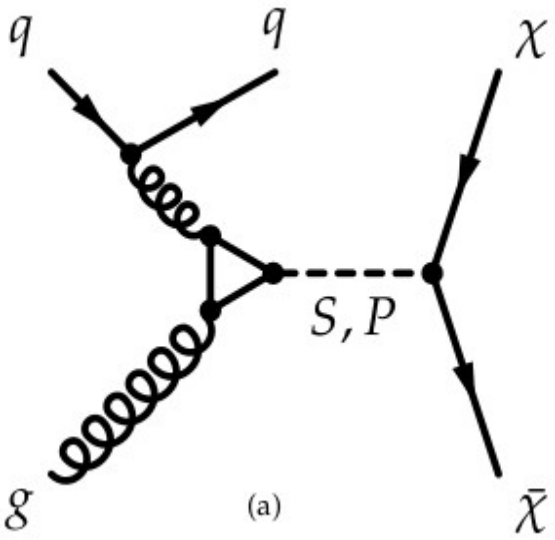
- Dijet resonances
  [CMS-EXO-PAS-16-046]
  [arxiv:1611.03568]
- Dilepton resonances
  [CMS-PAS-EXO-16-031]

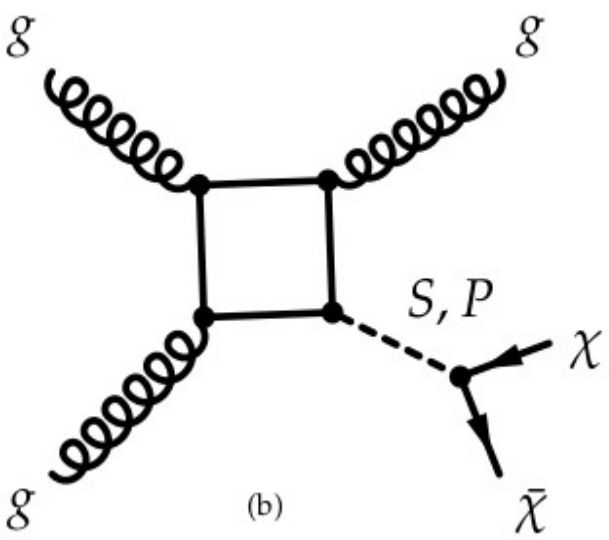
Outline

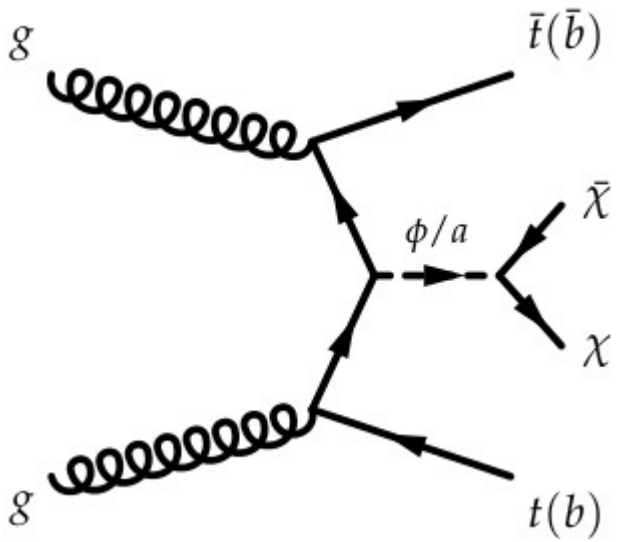
Focus on following models and final states:

> Simplified model with a scalar or pseudoscalar mediator

- Mono-jet/mono-V + MET signatures
- $t\bar{t}$ and $b\bar{b}$ + MET signatures
- Mono-top

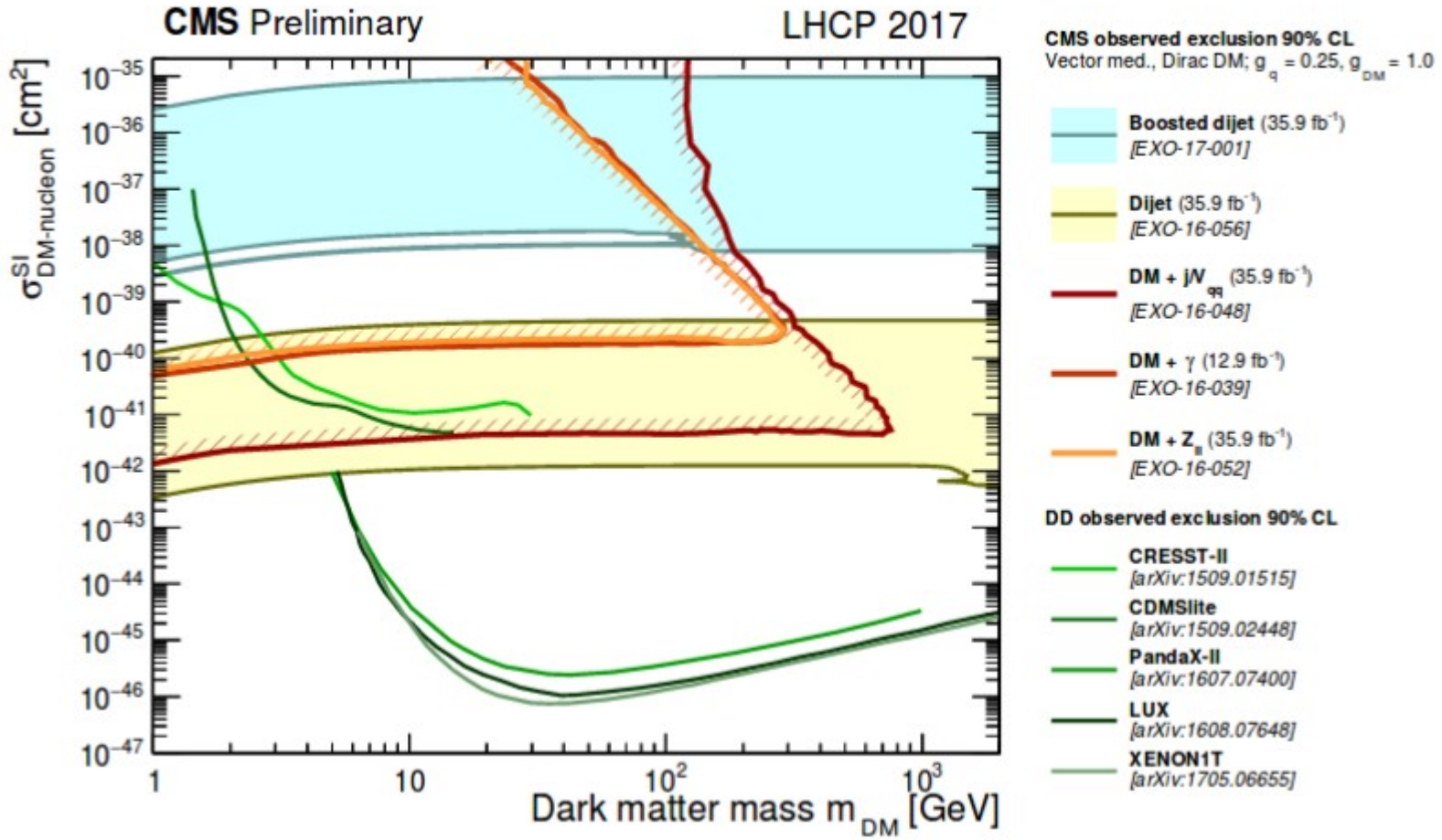






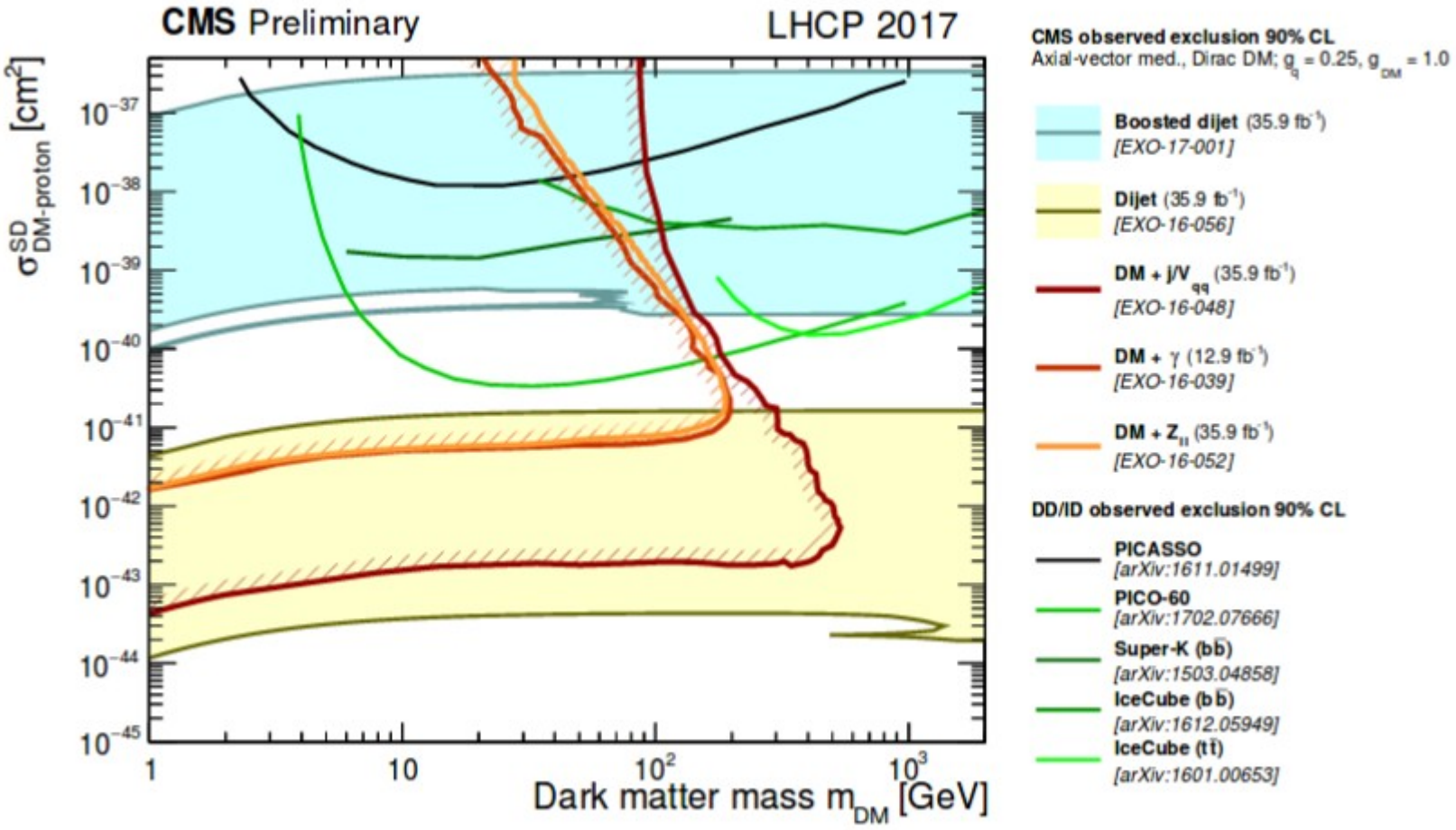
Comparison with Direct Detection – Vector mediator

- CMS and Direct Detection exclusion limits at 90% CL
- DM-nucleon interaction, $g_q = 0.25$, $g_l = 0.0$, $g_{DM} = 1.0$



Comparison with Direct Detection – Axial-vector mediator

- CMS and Direct Detection exclusion limits at 90% CL
- DM-proton interaction, $g_q = 0.25$, $g_l = 0.0$, $g_{DM} = 1.0$

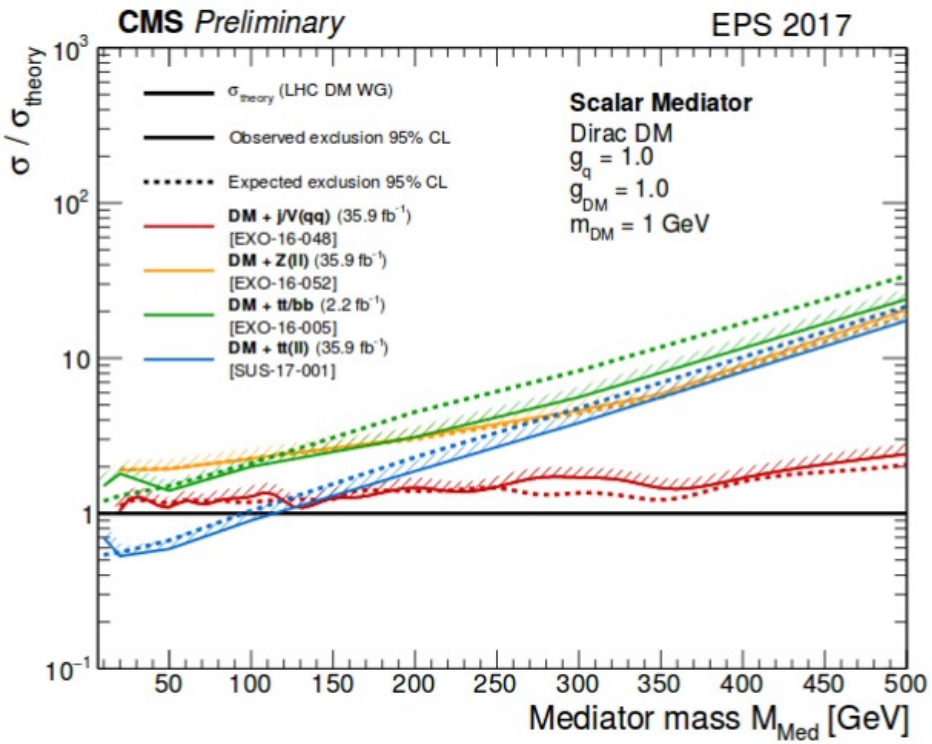


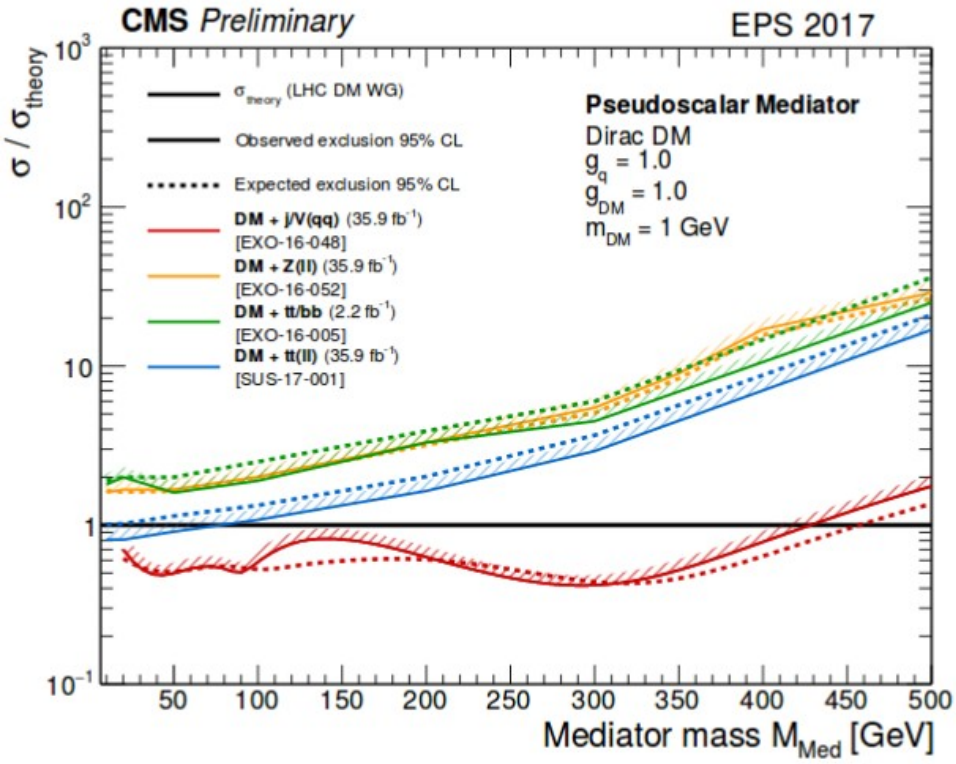
Scalar or Pseudoscalar Mediator

- Simplified Model
- Mediator with scalar or pseudoscalar interactions (s-channel)
- Probed by mono-X and Heavy Flavor + MET
- Mediator couplings: g_u, g_d, g_l , g_{DM}
  - Unlike vector and axial-vector models, scalar mediators can couple to leptons, although contribution is negligible in most of the parameter space considered
  - For simplicity: $g_q = g_u = g_d = g_l$
- Masses $m_{\Phi/a} = m_{MED}$ and m_{DM}
- Minimal set of 4 parameters
- Mediator width $\Gamma_{\Phi/a}$ fixed minimal allowed value for chosen masses and couplings

Results for Scalar and Pseudoscalar

- Benchmark models suggested by LHC DMWG
- m_{DM} = 1 GeV, g_q = 1.0, g_{DM} = 1.0
- Coupling to leptons is negligible

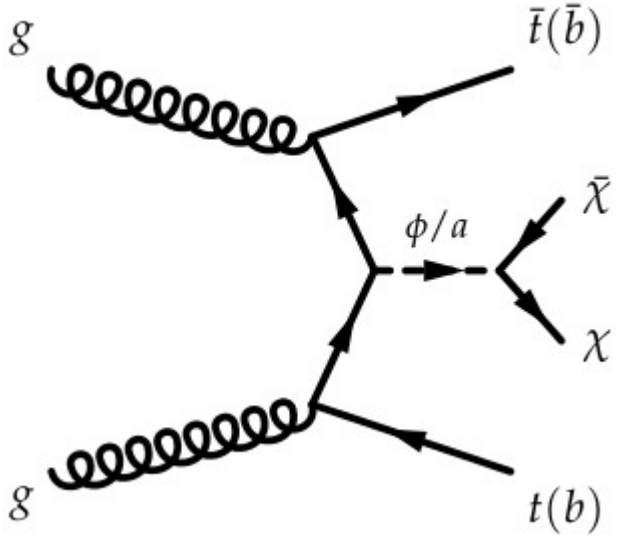




Heavy Flavor + MET final state

arxiv:1706.02581

- Assumption of minimal flavor violation
  → interactions with spin-0 mediators retain Yukawa structure of SM
- Preferential coupling to heavy flavors
  - $t\bar{t}$ + MET
  - $b\bar{b}$ + MET has additional sensitivity to models with suppressed couplings to up-type quarks (e.g. Type-II 2HDM)
- LHC DMF benchmark:
  - m_{DM} = 1 GeV, g_q = 1.0, g_{DM} = 1.0
  - No mixing between Φ scalar and SM Higgs
  - Minimal width is assumed
- MET spectra broaden with mediator masses
  - While $m_{\Phi/a} < 2\, m_{top}$ the MET spectrum of scalar mediators is softer than pseudoscalar mediators at same mass

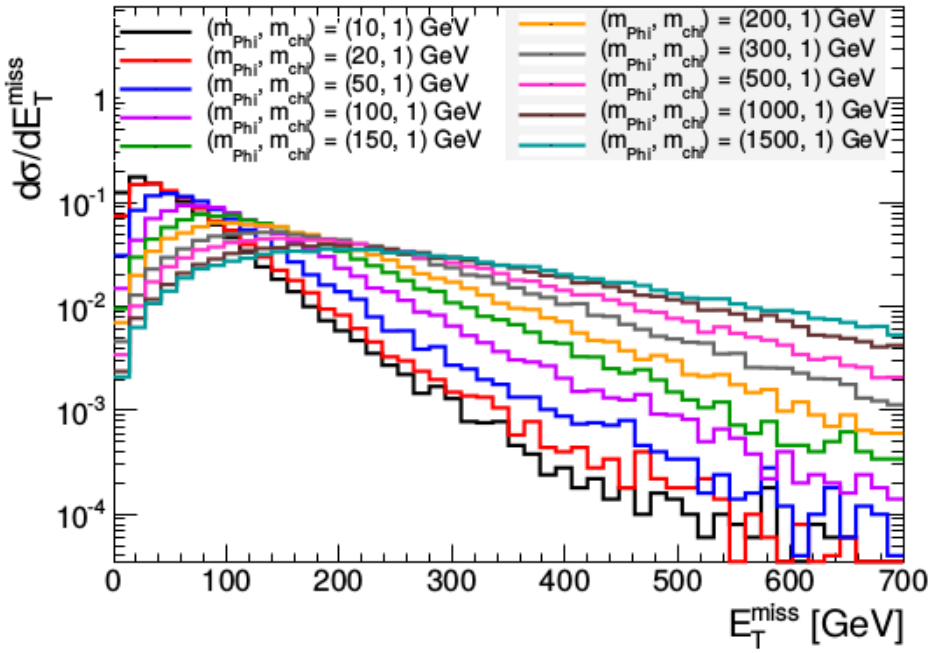


Heavy Flavor + MET final state

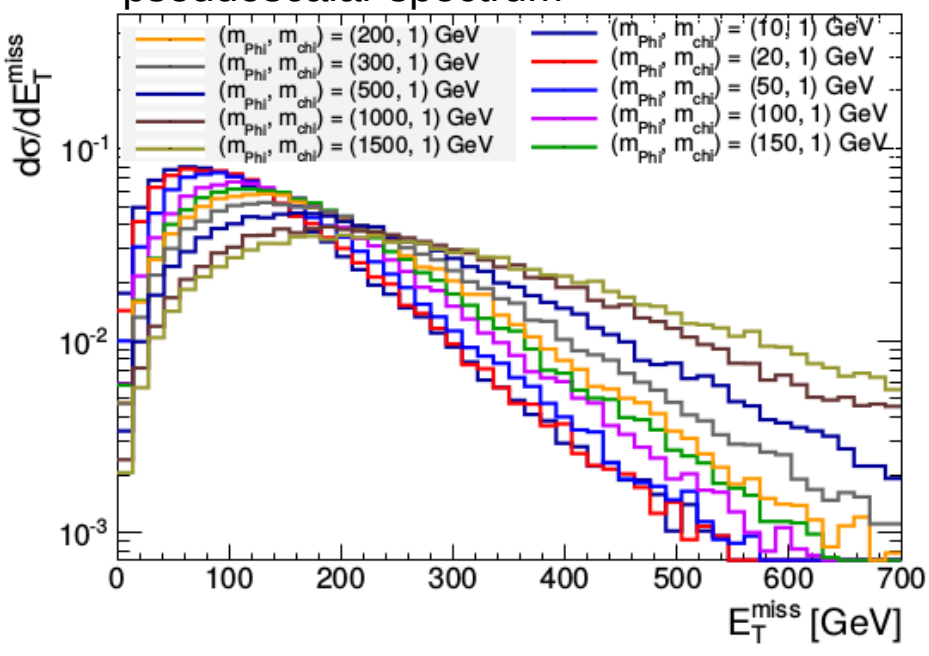
[arxiv:1507.00966]

- MET spectra broaden with mediator masses
  - While $m_{\Phi/a} < 2\, m_{top}$ the MET spectrum of scalar mediators is softer than pseudoscalar mediators at same mass
  - Scalar models at low mediator masses have increased cross section at low p_T

scalar spectrum



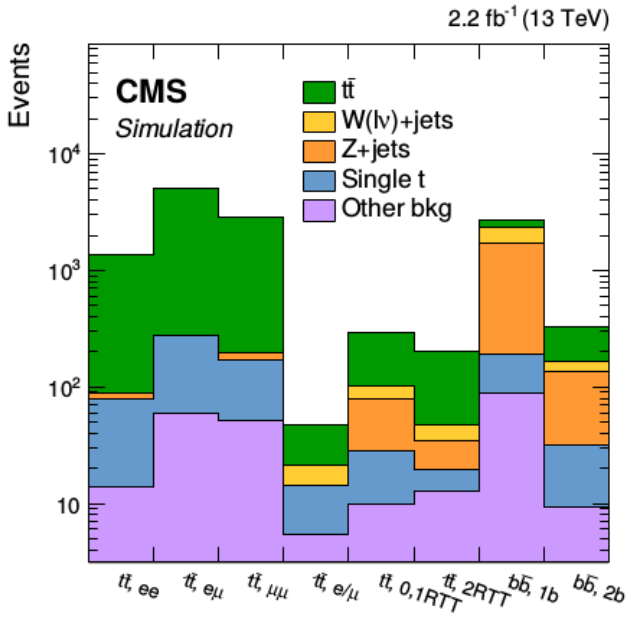
pseudoscalar spectrum



Heavy Flavor + MET final state

arxiv:1706.02581

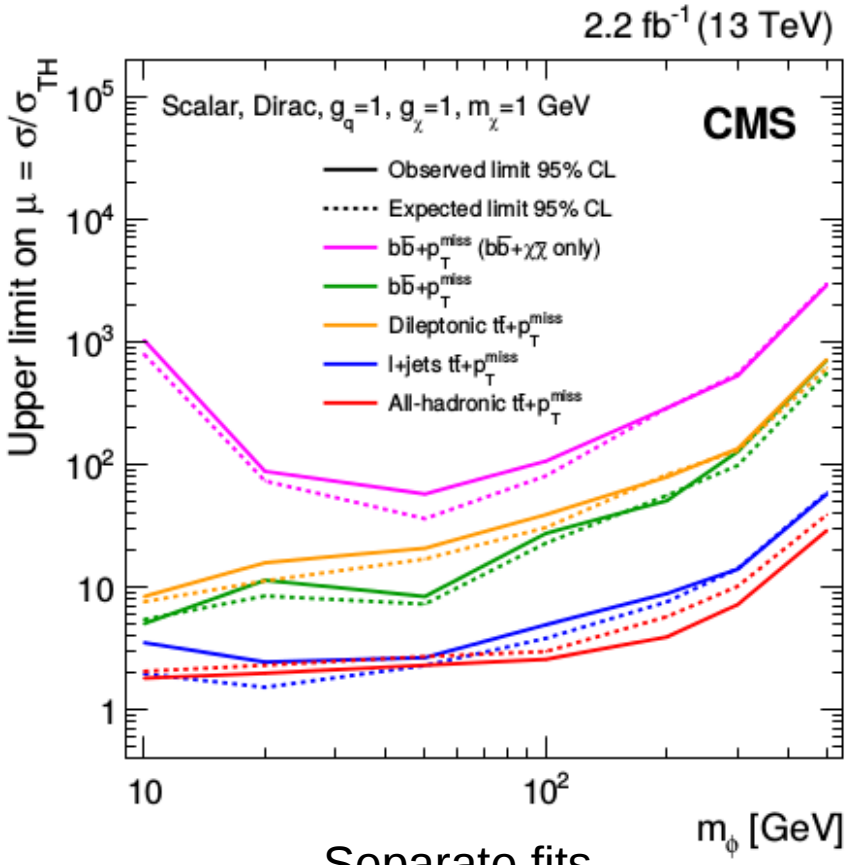
- 2.2 fb^{-1} of data at $\sqrt{s}$ = 13 TeV
- 8 exclusive signal regions
  - 2 $b\bar{b}$ + MET, 3 $t\bar{t}$(ll) + MET, 1 $t\bar{t}$(l+jets) + MET, 2 $t\bar{t}$(had) + MET
  - Resolved Top Tagger (RTT) used in $t\bar{t}$(had) selection
- Multiple control regions per signal region, all mutually exclusive
  - SM ttbar, W/Z + jets backgrounds left floating in fit to data
  - Other subdominant backgrounds estimated from simulation
- Signal extraction:
  - Fit to MET distributions of SRs and associated CRs
  - Independent fit of $b\bar{b}$ + $\chi\bar{\chi}$ and $t\bar{t}$ + $\chi\bar{\chi}$ contributions in each channel
  - Inclusive fit to all SR and CRs using single signal strength for combined $b\bar{b}$ + $\chi\bar{\chi}$ and $t\bar{t}$ + $\chi\bar{\chi}$ contribution



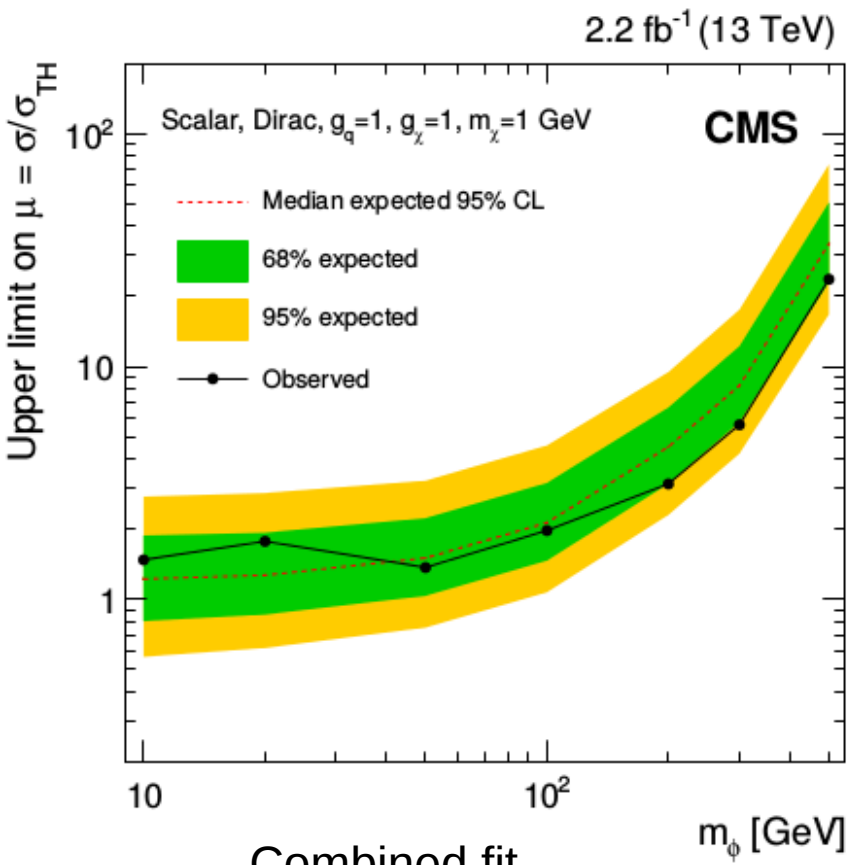
Heavy Flavor + MET final state

arxiv:1706.02581

> M_{DM} = 1 GeV, scalar mediator



Separate fits

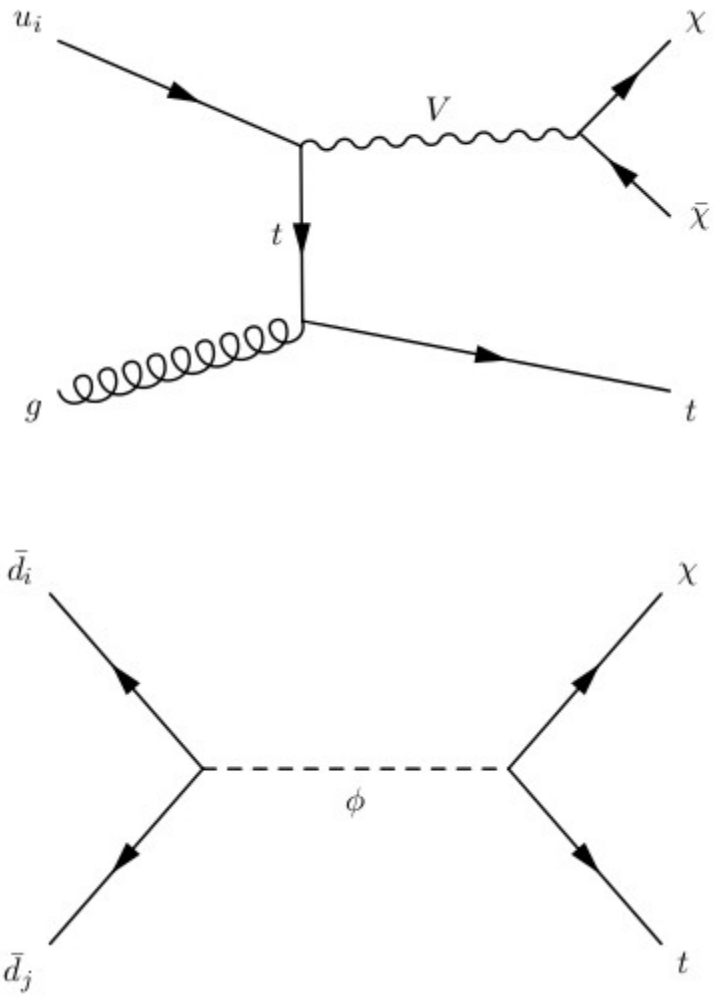


Combined fit

Mono-top

CMS-PAS-EXO-16-051

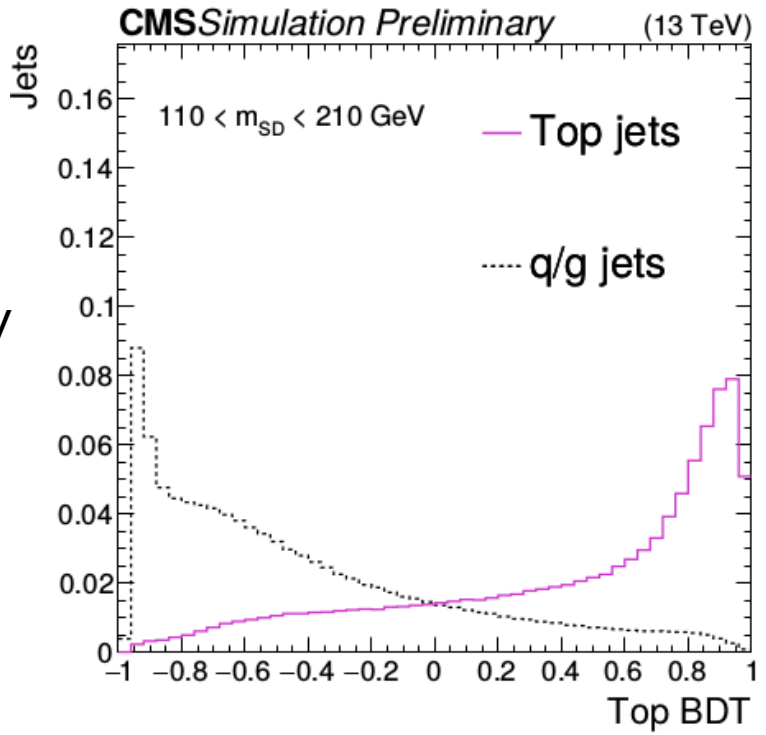
- FCNC model: heavy vector mediator V with flavor-changing couplings to quarks and decays to DM → non-resonant
  - $g_{Vu} = g_{Vd}$; $g_{Au} = g_{Ad}$
  - Only coupling between 1st and 3rd generation considered non-zero
  - m_V > 200 GeV to allow for SM-like top width
- Colored, charged scalar model → resonant
  - Coupling between Φ and quarks: 0.1
  - Φ-t-χ vertex coupling: 0.2
- Mono-top models and parameters described in arXiv:1407.7529



Mono-top

CMS-PAS-EXO-16-051

- 35.8 fb^{-1} at $\sqrt{s}$ = 13 TeV
- Hadronically decaying, boosted top quark
  - One fat jet with $\Delta R = 1.5$, $p_T > 250$ GeV
  - Soft drop jet mass in range 110-210 GeV
  - One b-tagged subjet
  - Top-tagging from BDT
- Veto leptons, b-tagged jets
- Signal extraction:
  - Fit to MET distribution in SR
  - $t\bar{t}$, Z+jets and W+jets backgrounds constrained in CRs by requiring dilepton, single lepton, … events and fitting the hadronic recoil distribution

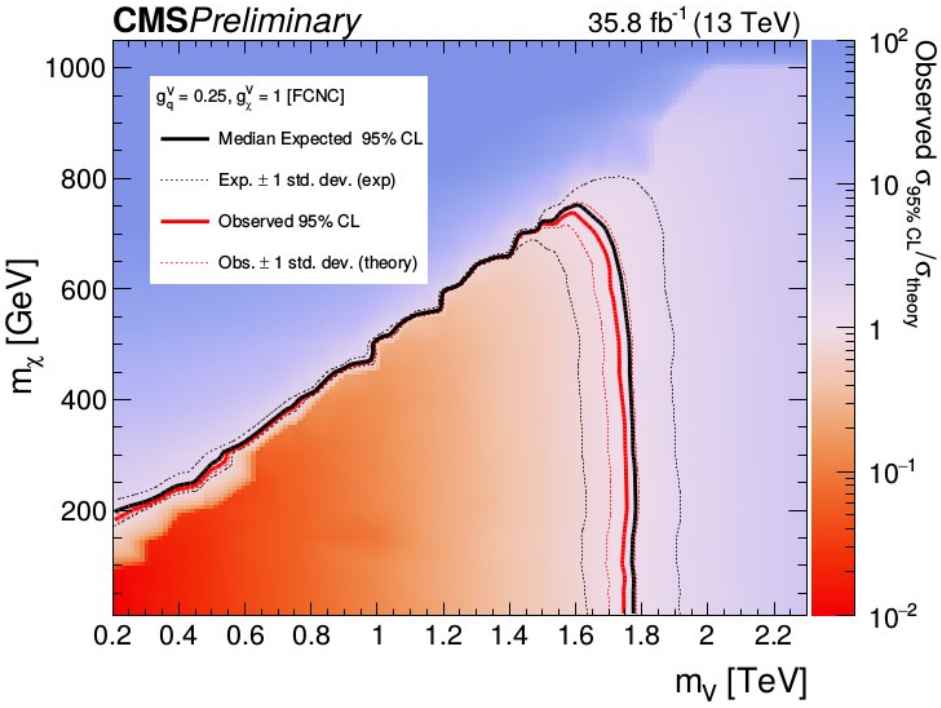


Mono-top

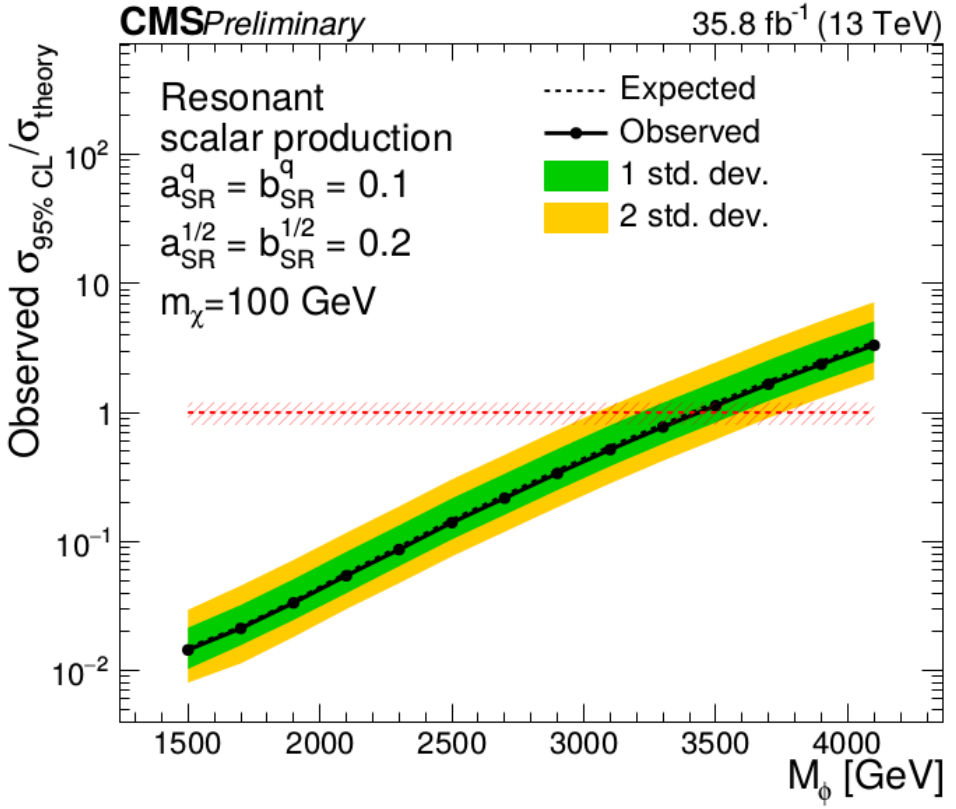
CMS-PAS-EXO-16-051

- FCNC model, m_χ = 1 GeV, g_{Vu} = 0.25 and g_{Vx} = 1: m_V < 1.75 TeV excluded at 95% CL
- Resonant model: m_Φ < 3.4 TeV excluded at 95% CL

FCNC model



Scalar resonance

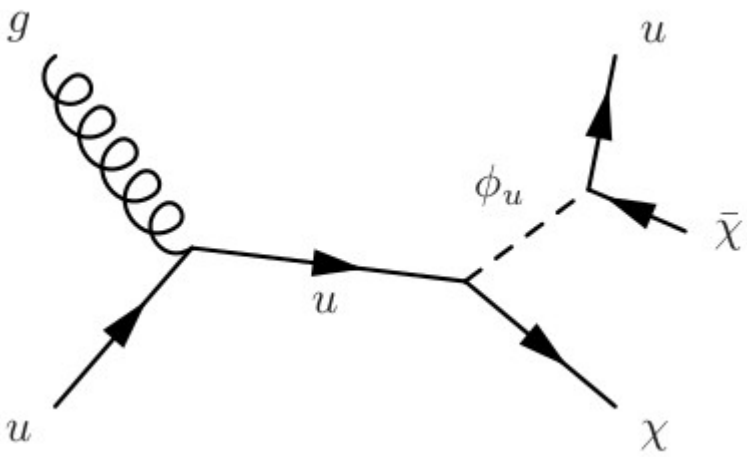


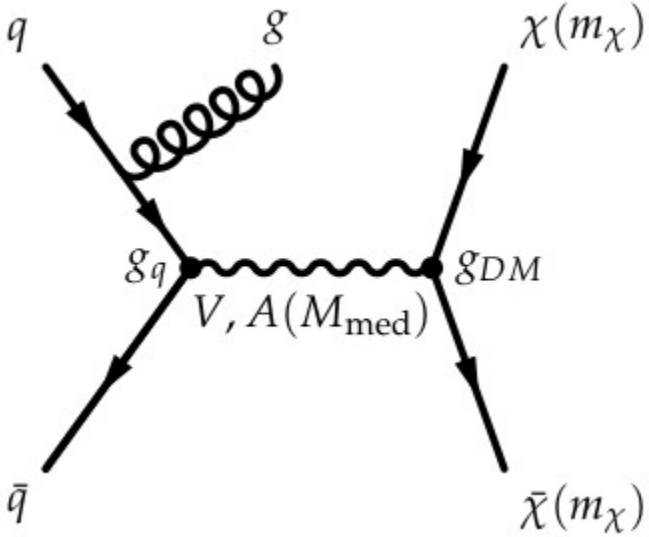
Mono-jet/Mono-V

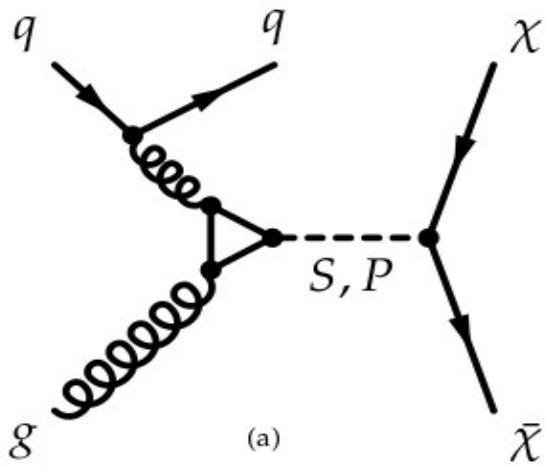
CMS-PAS-EXO-16-048

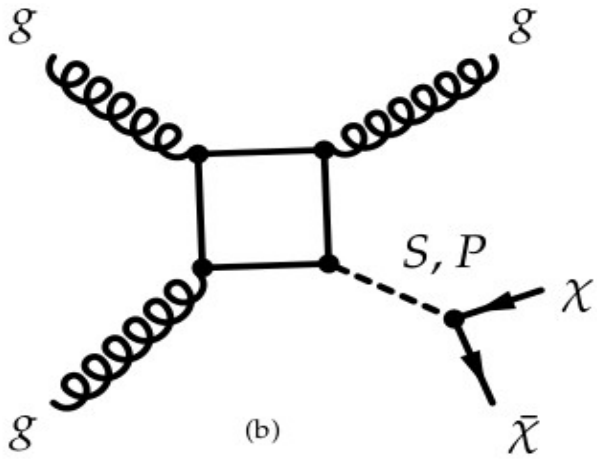
> Many DM models result in a mono-jet signature:

- Vector and axial vector med, s-channel
- Scalar and pseudoscalar med, s-channel
- Colored scalar med, t-channel
- Less simplified models:
  Extra dimensions,
  Nonthermal DM, invisible Higgs, ...





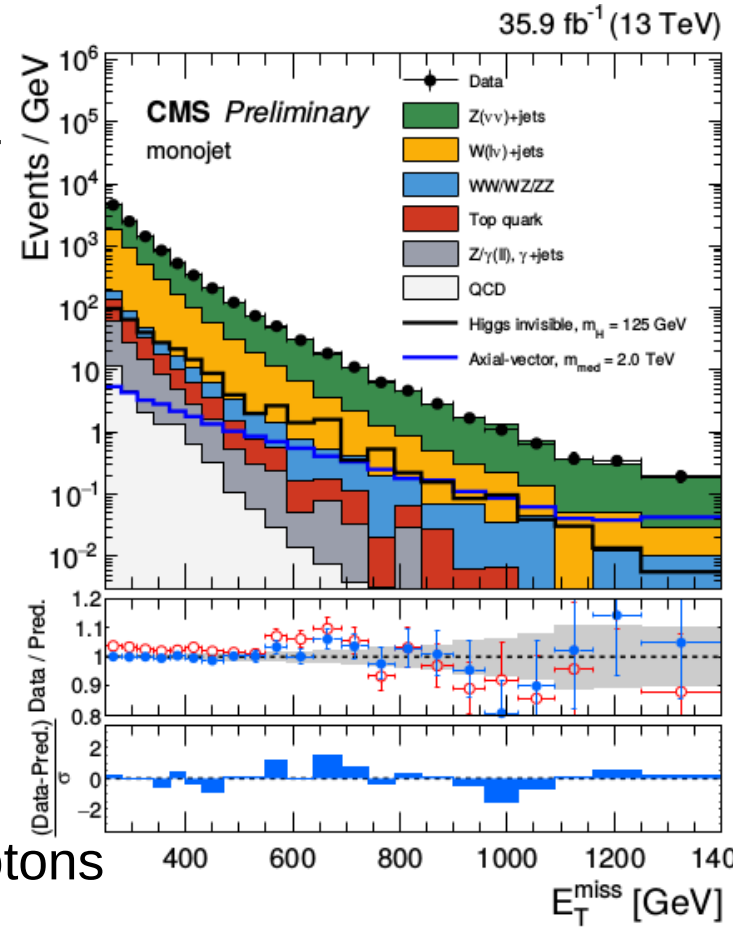




Mono-jet/Mono-V

CMS-PAS-EXO-16-048

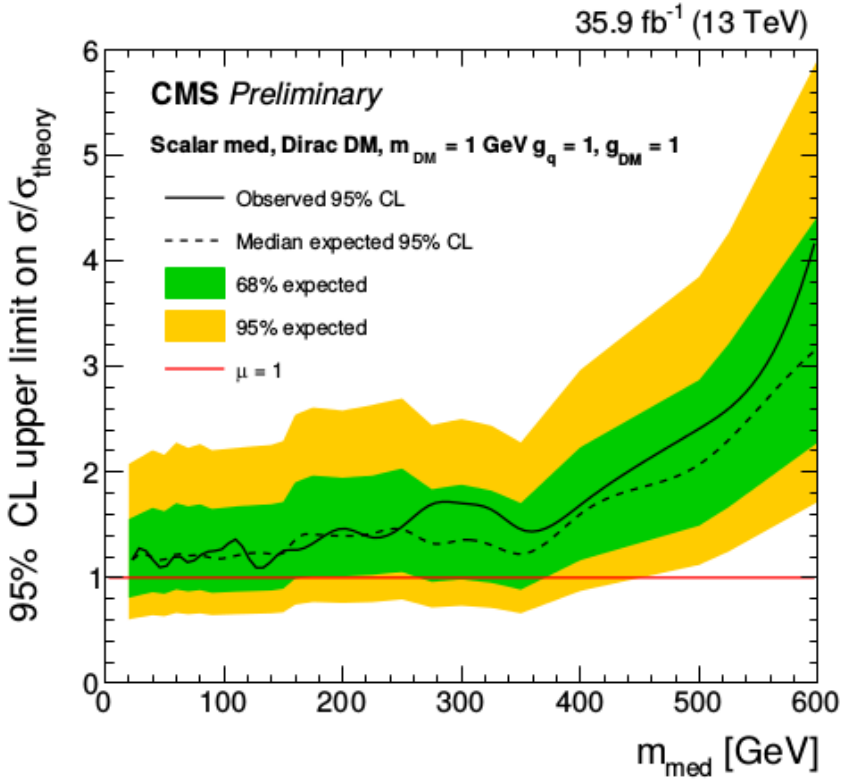
- 35.9 fb^{-1} at $\sqrt{s}$ = 13 TeV
- Finals state of one or more jets + large MET
  - Mono-jet
  - Mono-V with W and Z decaying hadronically
- MET > 250 GeV
- 2 categories, made orthogonally:
  - AK4 jet with p_T > 100 GeV
  - V-tagged jet: AK8 jet with p_T > 250 GeV, mass compatible with W or Z, 2 substructure jets
- Veto on: leptons, tau → hadrons, b-jets, photons
- Mutually exclusive CRs selecting dimuons, dielectron, single lepton, photons → hadronic recoil as proxy for MET distribution
- Combined fit to data in SR and CR

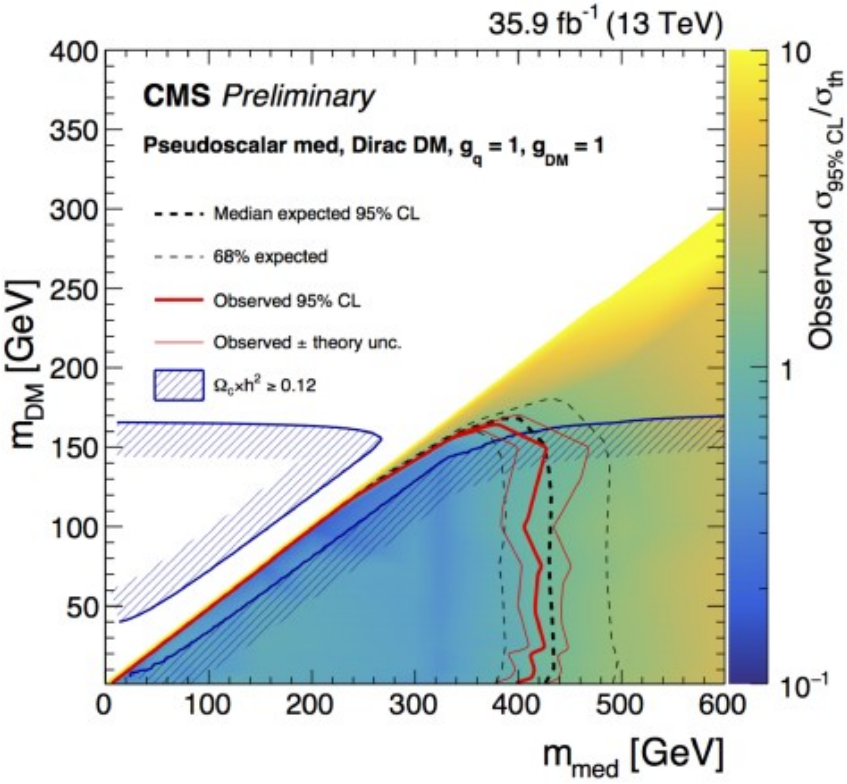


Mono-jet/Mono-V

CMS-PAS-EXO-16-048

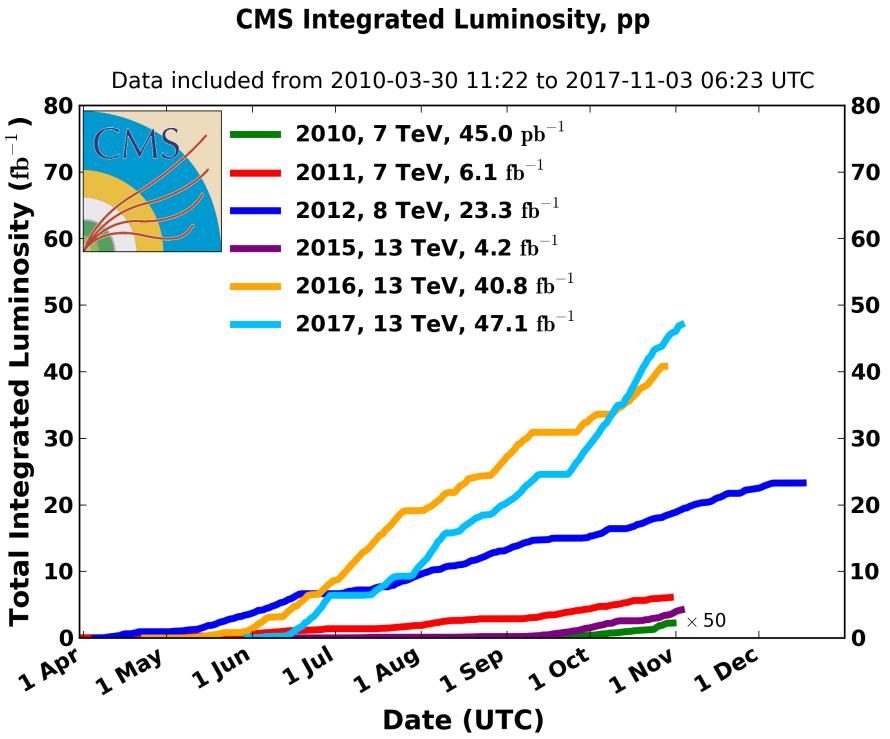
> Interpretation in terms of scalar and pseudoscalar DM mediators





Summary

- Large collection of Benchmark models considered
  - Moving from models sensitive to early Run 2 data to less simplified models as more data is collected
  - Close cooperation between ATLAS and CMS
- Variety of final states considered
- Many new results in the pipeline!

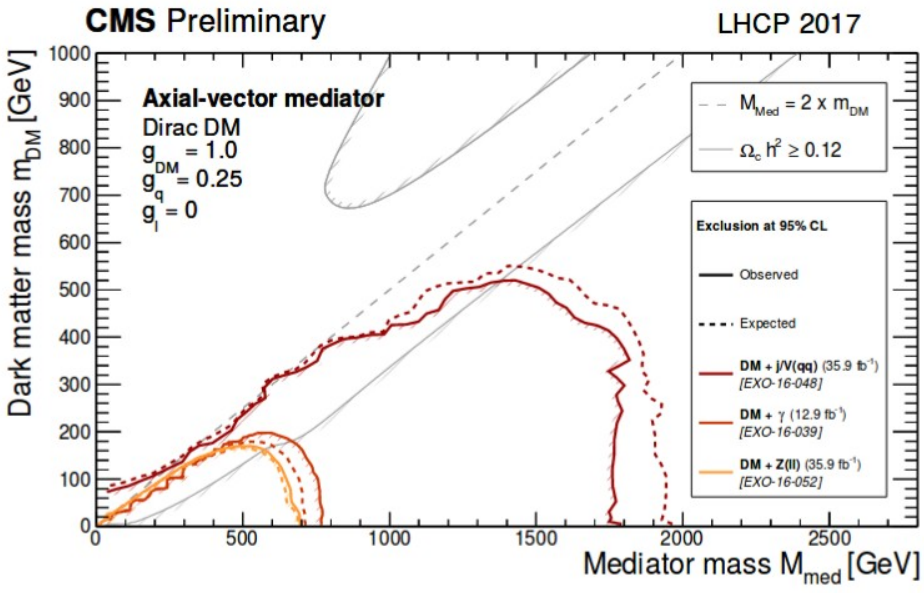


Back-up

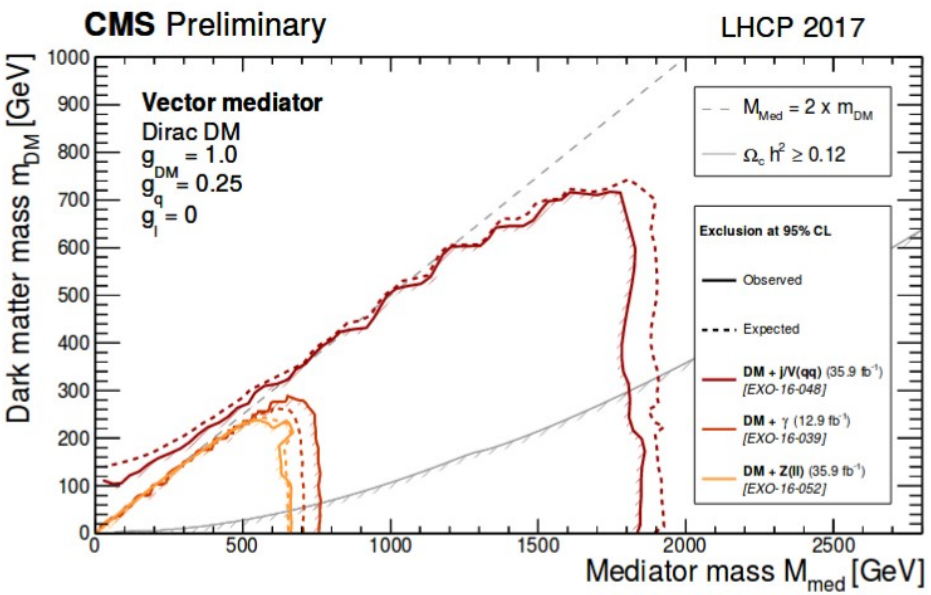
Results for A1 and V1

> No coupling to leptons

A1

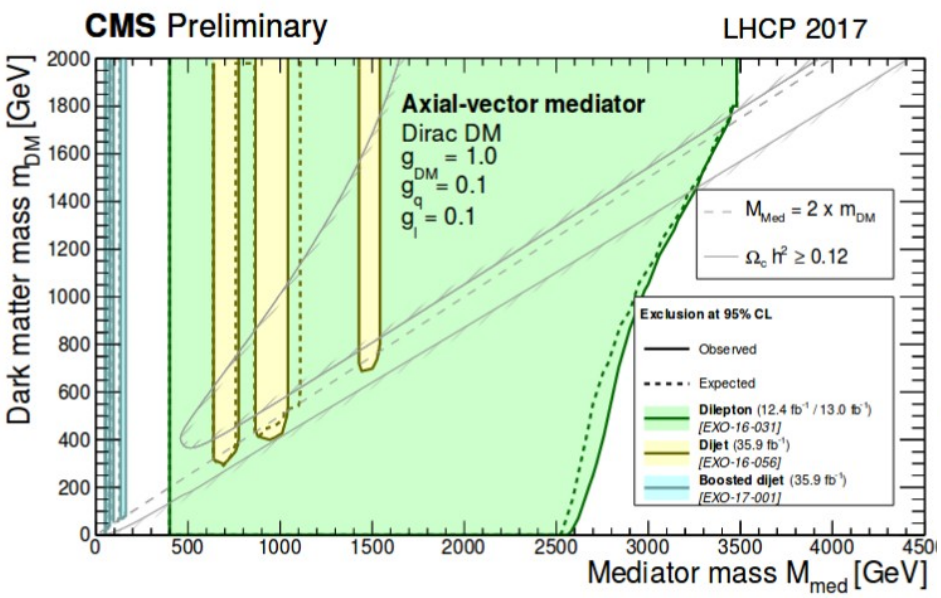


V1

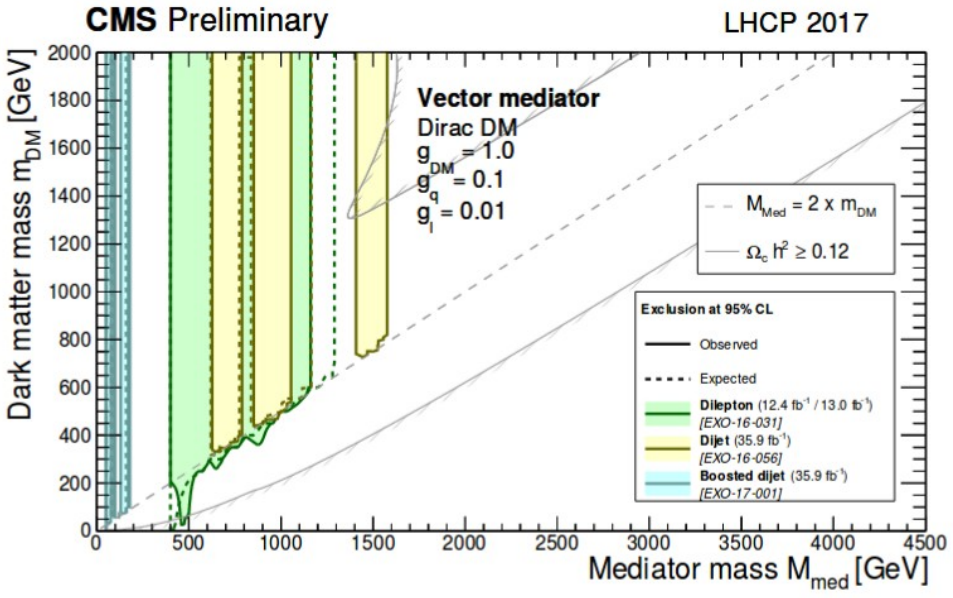


Results for A2 and V2

A2



V2



Minimal mediator width in scalar/pseudoscalar models

> No other quarks but top quarks are considered in the loops

$$\Gamma_{\phi,a} = \sum_f N_c \frac{y_f^2 g_q^2 m_{\phi,a}}{16\pi}\left(1-\frac{4m_f^2}{m_{\phi,a}^2}\right)^{x/2} + \frac{g_\chi^2 m_{\phi,a}}{8\pi}\left(1-\frac{4m_\chi^2}{m_{\phi,a}^2}\right)^{x/2} + \frac{\alpha_s^2 y_t^2 g_q^2 m_{\phi,a}^3}{32\pi^3 v^2}\left|f_{\phi,a}\left(\frac{4m_t^2}{m_{\phi,a}^2}\right)\right|^2$$

where x = 3 for scalars and x = 1 for pseudoscalars

> For mMED > 2mt , dominant contribution is from top quarks

> For mMED < 2mt , Dark Matter dominates

Heavy Flavor: Signal region definition

arxiv:1706.02581

Signal regions	Leptons	Jets	b jets	p_T^{miss}	Other selections
Dileptonic $t\bar{t} + p_T^{miss}$	ee	≥ 2	≥ 1	≥ 50 GeV	$\min \Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{miss}) > 1.2$ rad $m_{\ell\ell} > 20$ GeV $\lvert m_{ee,\mu\mu} - m_Z \rvert > 15$ GeV Dileptonic $t\bar{t}$ control region veto Z + jets control region veto
	eμ				
	$\mu\mu$				
ℓ + jets $t\bar{t} + p_T^{miss}$	e or μ	≥ 3	≥ 1	≥ 160 GeV	$M_T > 160$ GeV $M_{T2}^W > 200$ GeV $\min \Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss}) > 1.2$ rad
All-hadronic $t\bar{t} + p_T^{miss}$	0	≥ 4	≥ 2	≥ 200 GeV	0,1RTT $\min \Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss}) > 1.0$ rad
		≥ 6	≥ 1		2RTT $\min \Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss}) > 0.4$ rad
$b\bar{b} + p_T^{miss}$	0	1 or 2	1	≥ 200 GeV	$\min \Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss}) > 0.5$ rad
		2 or 3	2		

Heavy Flavor: Control region definition

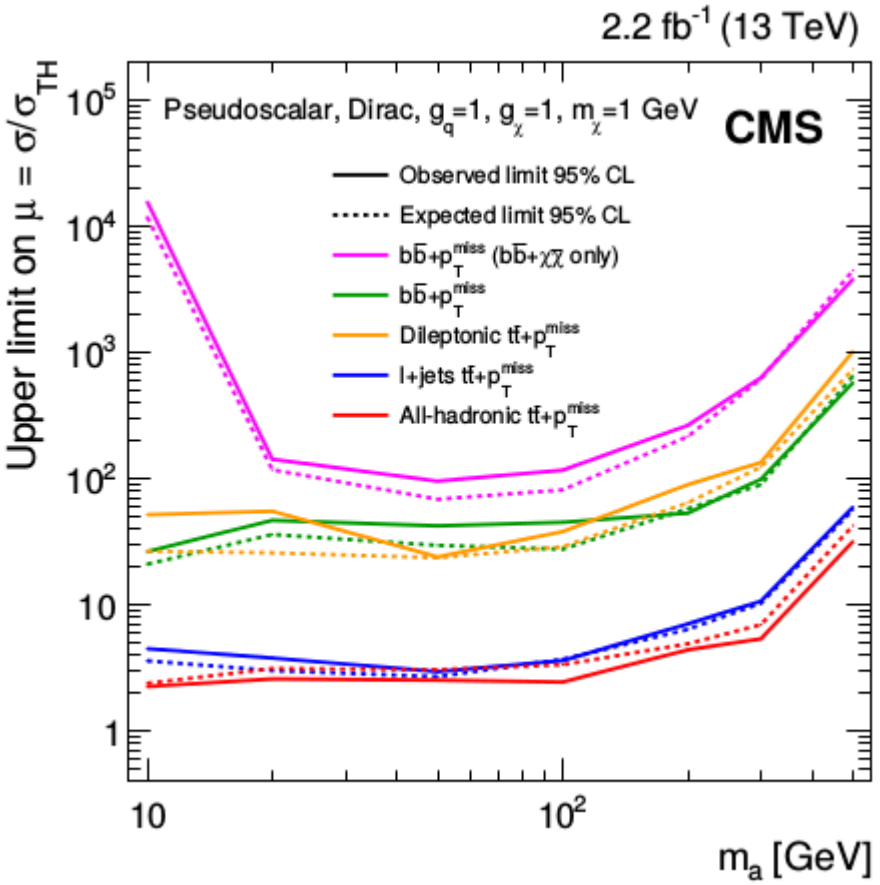
arxiv:1706.02581

Label	Associated signal region(s)	Dominant background	Leptons	Jets	b jets	p_T^{miss}	Additional or modified selections
slA	ℓ + jets $t\bar{t} + p_T^{miss}$	Dileptonic $t\bar{t} + p_T^{miss}$	ee, eμ, $\mu\mu$	≥ 3	≥ 1	$\geq$ 160 GeV	No selection on M_T, M_{T2}^W, min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$ bbC/bbD/bbE/bbH/bbI/bbJ control region veto
slB		W + jets	e or μ		0		No selection on M_{T2}^W, min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
hadA	Hadronic $t\bar{t} + p_T^{miss}$, 0,1RTT	ℓ + jets $t\bar{t} + p_T^{miss}$	e or μ	≥ 4	≥ 2	$\geq$200 GeV	$M_T < 160$ GeV, 0,1RTT
hadB		W/Z + jets	0		0		0,1RTT
hadC		W + jets	e or μ		0		No selection on $M_T < 160$ GeV, min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$, 0,1RTT
hadD		Z + jets	ee or $\mu\mu$		0		$60 < m_{\ell\ell} < 120$ GeV No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
hadE	Hadronic $t\bar{t} + p_T^{miss}$, 2RTT	ℓ + jets $t\bar{t} + p_T^{miss}$	e or μ	≥ 6	≥ 1		$M_T < 160$ GeV, $\geq$ 2RTT
hadF		W/Z + jets	0		0		$\geq$ 2RTT
hadG		W + jets	e or μ		0		No selection on $M_T < 160$ GeV, min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$, $\geq$ 2RTT
bbA	$b\bar{b} + p_T^{miss}$, 1 b tag	W + jets	e	1 or 2	1	$\geq$200 GeV	$50 < M_T < 160$ GeV
bbB		ℓ + jets $t\bar{t}$	μ				No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
bbC		Z + jets	ee				$70 < m_{\ell\ell} < 110$ GeV
bbD			$\mu\mu$				No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
bbE		Dileptonic $t\bar{t}$	eμ				No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
bbF	$b\bar{b} + p_T^{miss}$, 2 b tag	W + jets	e	2 or 3	2		$50 < M_T < 160$ GeV
bbG		ℓ + jets $t\bar{t}$	μ				No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
bbH		Z + jets	ee				$70 < m_{\ell\ell} < 110$ GeV
bbI			$\mu\mu$				No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$
bbJ		Dileptonic $t\bar{t}$	eμ				No selection on min $\Delta\phi(\vec{p}_T^{jet_i}, \vec{p}_T^{miss})$

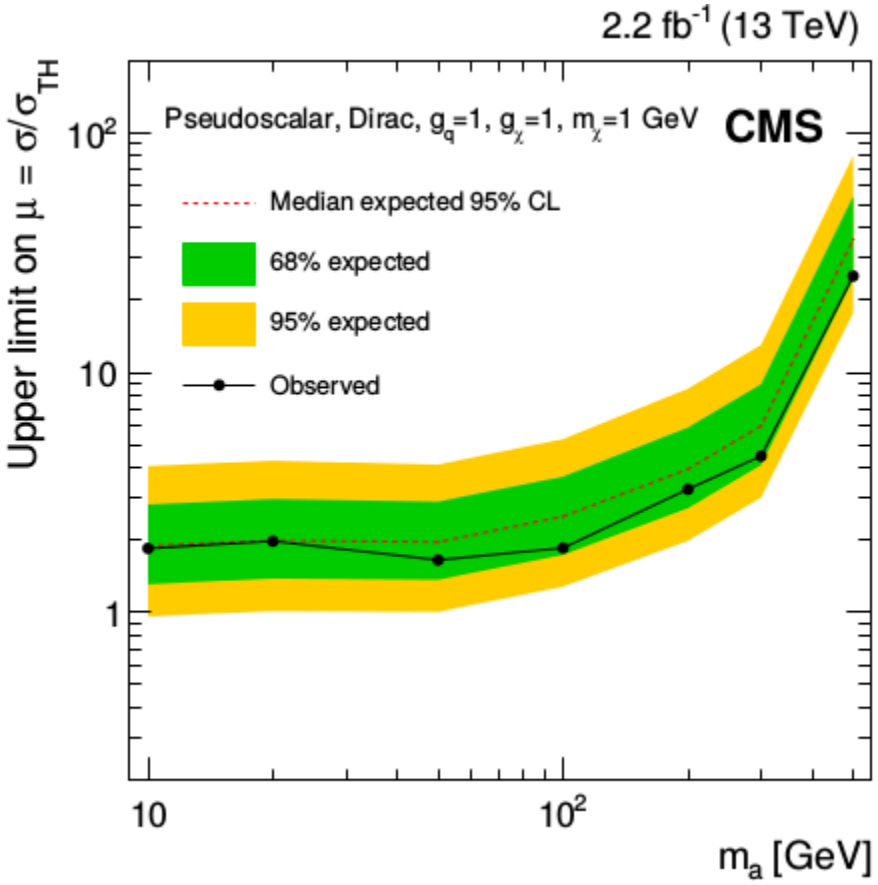
Heavy Flavor + MET final state

arxiv:1706.02581

> M_{DM} = 1 GeV, pseudoscalar mediator



Separate fits



Combined fit

Mono-top

CMS-PAS-EXO-16-051

> FCNC model Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} + V_\mu \bar{\chi}\gamma^\mu(g_{V_\chi} + g_{A_\chi}\gamma_5)\chi + \text{h.c.}$$
$$+ \bar{q}_u\gamma^\mu(g_{V_u} + g_{A_u}\gamma_5)q_u V_\mu + \bar{q}_d\gamma^\mu(g_{V_d} + g_{A_d}\gamma_5)q_d V_\mu + \text{h.c.}$$

$$g_{V_u} - g_{A_u} = g_{V_d} - g_{A_d}.$$

>

> Resonant production Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin}(\phi_s, \chi) + (\phi\bar{d}_i^C[(a_{SR}^q)^{ij} + (b_{SR}^q)^{ij}\gamma^5]d_j + \phi\bar{t}[a_{SR}^{1/2} + b_{SR}^{1/2}\gamma^5]\chi + \text{h.c.}).$$

coupling between mediator and quarks: $a^q_{SR} = b^q_{SR} = 0.1$

Φ-t-x vertex: $a^{1/2}_{SR} = b^{1/2}_{SR} = 0.2$

Mono-top

CMS-PAS-EXO-16-051

> FCNC model