Dark Matter searches with CMS
XXVII International Workshop on Deep Inelastic Scattering

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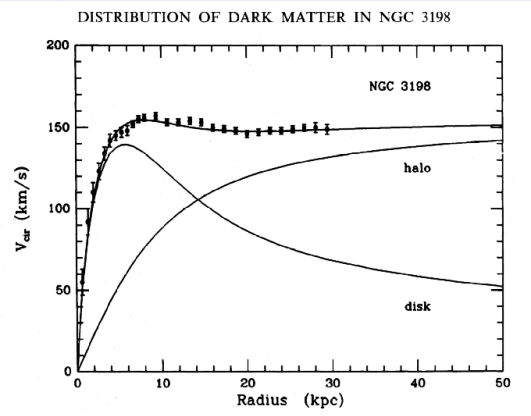
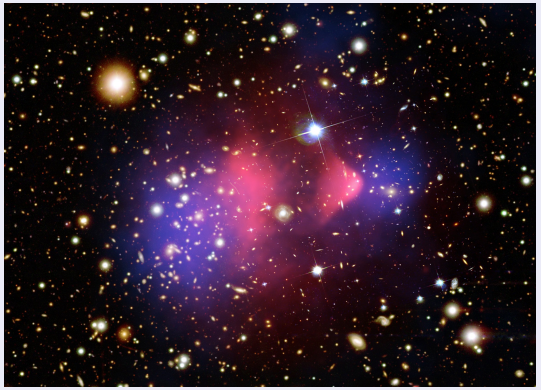
Dark Matter?

Many evidence

- Cosmic Microwave Background
- Galaxy rotation curves
- The Bullet cluster
- ...



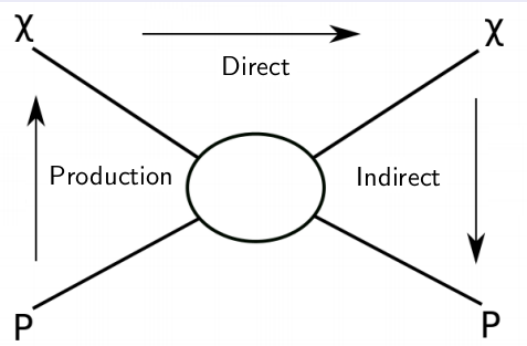


Potential solutions

- **Weakly interacting matter**
- Primordial black holes
- New gravity
- ...

Many ways of investigating

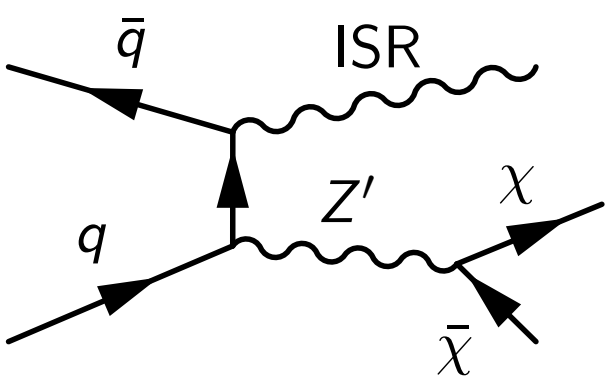
- **Collider searches**
- Direct detection (PandaX-II, LUX, Xenon1T, ...)
- Indirect detection (Auger, IceCube, Fermi, ...)

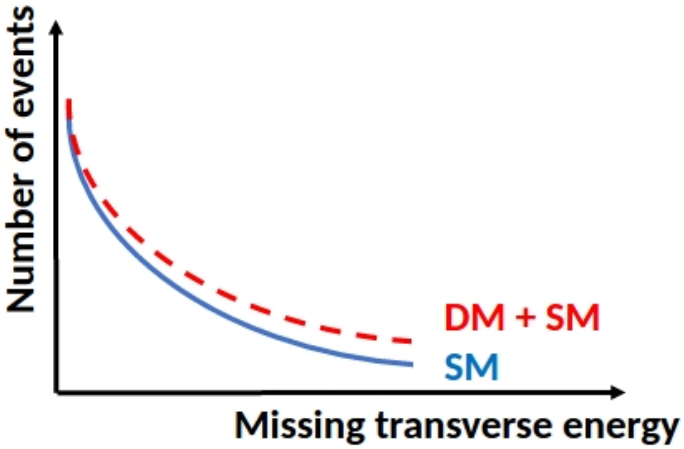


Dark Matter searches at pp colliders

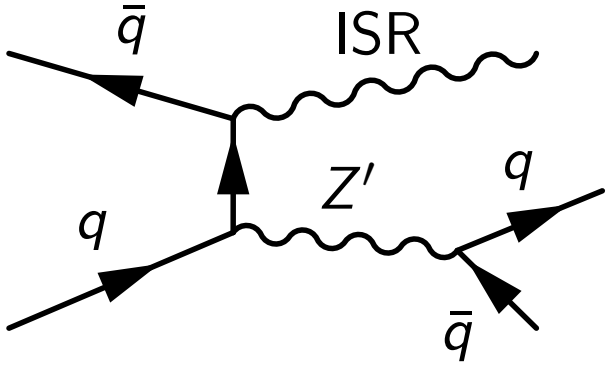
"Mono-X": ISR + E_T^{miss}

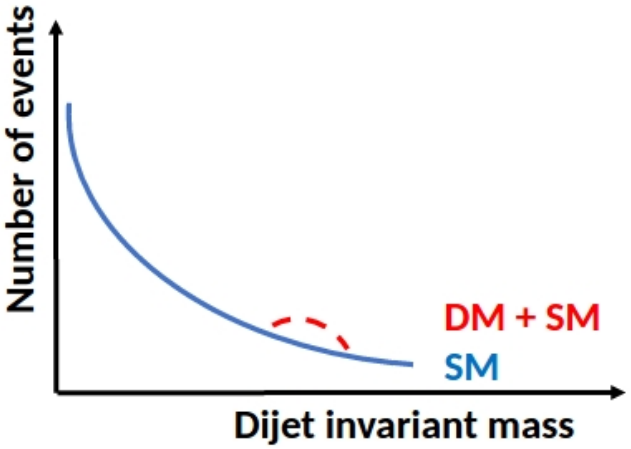
$E_T^{miss} = |\vec{p}_T^{miss}|$





Mediator searches: boosted resonance (here Z')





However, other search strategies exist that we will mention

Definitions

Variables

- Missing transverse momentum $\vec{p}_T^{miss} = -\Sigma_{i=1}^{N_{\text{objects}}} \vec{p}_T^{i}$, Missing transverse energy $E_T^{miss} = |\vec{p}_T^{miss}|$
- $H_T = \Sigma_{i=1}^{N_{\text{jets}}} p_T^i$ (scalar sum!), $H_T^{miss} = |\Sigma_{i=1}^{N_{\text{jets}}} \vec{p}_T^{i}|$ (vector sum!)
- Jet clustering algorithms:
  - Jets from light quarks/gluon: anti-k_T with radius 0.4 (AK4)
  - Jets with substructure (t-/b-jets): AK8, Cambridge-Aachen with radius 0.15 (CA15)
- N-subjettiness $\tau_N = \frac{1}{d_0} \Sigma_k p_{T,k} \min \left\{ \Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k} \right\}$
  - 1, 2, 3, ... : subjet indices
  - k: subjet constituent particles
  - $\Delta R_{i,k} = \sqrt{\Delta \eta_{ik}^2 + \Delta \phi_{ik}^2}$
  - $d_0 = \Sigma_k p_{T,k} R_0$, R_0 is the jet radius

Theoretical concepts

- Simplified models: between EFT and complete models in terms of details. A mediator is implemented and the full kinematics of the Dark Matter production is described.

CMS analyses

Run-2 DM efforts in CMS cover a broad range of signatures:

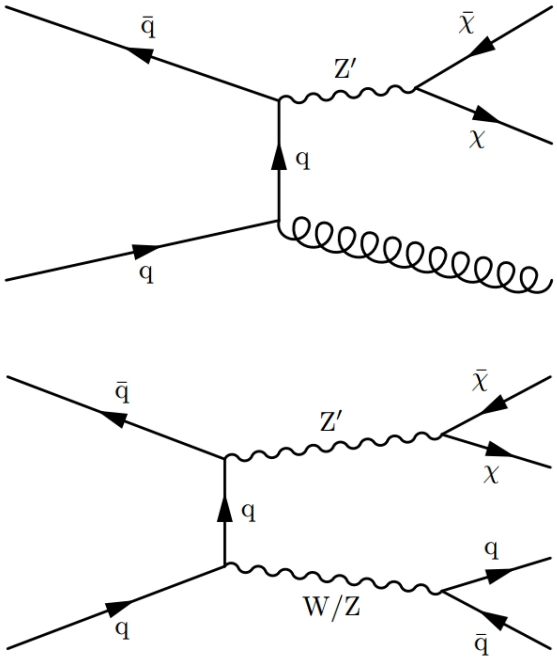
	CADI	Channel	Dataset
Standard Mono-X	EXO-16-048	Jet + E_T^{miss}	2016 (35.9 fb^{-1})
	EXO-16-052	Z(ll) + E_T^{miss}	2016 (35.9 fb^{-1})
	EXO-16-053	γ + E_T^{miss}	2016 (35.9 fb^{-1})
Higgs	EXO-18-011	H($bb/\tau\tau/\gamma\gamma/VV$) + E_T^{miss}	2016 (35.9 fb^{-1})
	HIG-17-023	VBF H(inv.)	2016 (35.9 fb^{-1})
Top	EXO-16-051	t(had.) + E_T^{miss}	2016 (36 fb^{-1})
	EXO-16-049	$t\bar{t}$ + E_T^{miss}	2016 (35.9 fb^{-1})
	EXO-18-010	$t/t\bar{t}$ + E_T^{miss}	2016 (35.9 fb^{-1})
Mediator	EXO-17-015	Leptoquark(l+jet) + E_T^{miss}	2016+2017 (77.4 fb^{-1})
	EXO-17-001	Boosted dijet (jet ISR)	2016 (35.9 fb^{-1})
	EXO-17-027	Boosted dijet (γ ISR)	2016 (35.9 fb^{-1})
Long-lived	EXO-18-001	Emerging jets	2016 (16.1 fb^{-1})
	EXO-16-046	Dijet (angular distrib.)	2016 (35.9 fb^{-1})

Not presented by lack of time

Mono-jet/V(had.) analysis (EXO-16-048)

Signature: **jet(s) + E_T^{miss}**. Combination of two categories:

- Monojet: jets from light quarks/gluons
  - AK4 clustering, $p_T > 100$ GeV, $|\eta| < 2.4$
- Mono-V: "fat" jets from V boson decay
  - AK8 clustering, $p_T > 250$ GeV, $|\eta| < 2.4$
  - Identified with $65 < m_j < 105$ GeV
  - N-subjettiness ratio $\tau_2/\tau_1 < 0.6$



Other main selection criteria are:

- $E_T^{miss} > 250$ GeV (trigger motivated)
- Lepton, photon, b jet veto
- $\Delta\phi(jet, E_T^{miss}) > 0.5$ (QCD BG rejection)

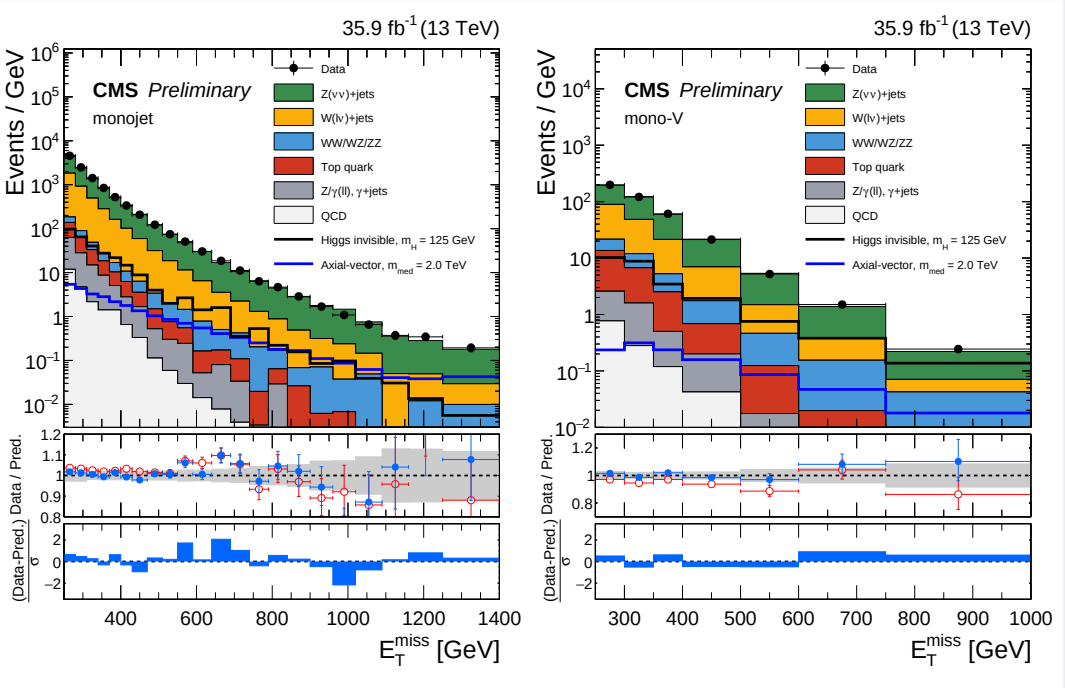
Mono-jet/V(had.) analysis (EXO-16-048)

Signal extraction

Extract signal from data/BG comparison in the E_T^{miss} spectrum

- Main backgrounds (Z($\nu\nu$) and W(lν)) are estimated using 5 CR transfered to data with transfer factors derived from simulations.
- CR are then fitted to data in a combined constrained likelihood fit

Monojet **Mono-V**



Limits are set using many different interpretations:

- Simplified DM models with (axial-)vector or (pseudo-)scalar mediator
- Fermion portal DM
- Nonthermal DM
- Invisible decays of the Higgs boson (see also dedicated HIG-17-023 analysis for VBF production)

Mono-jet/V(had.) analysis (EXO-16-048)

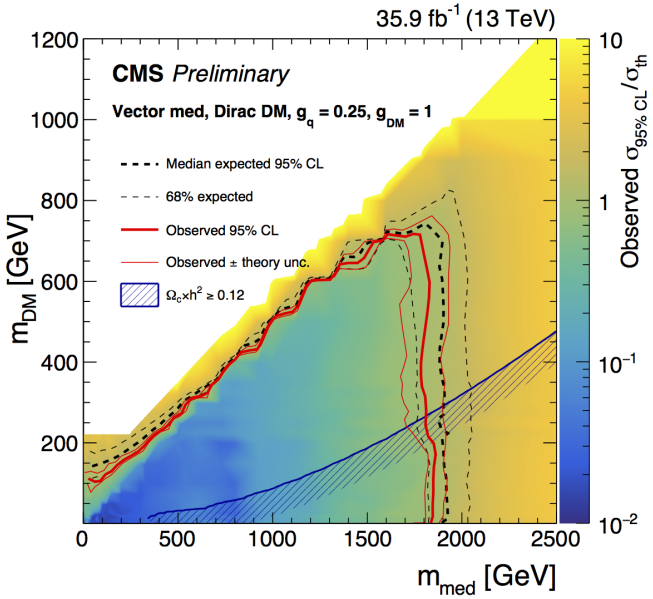
"Simplified models" interpretation:

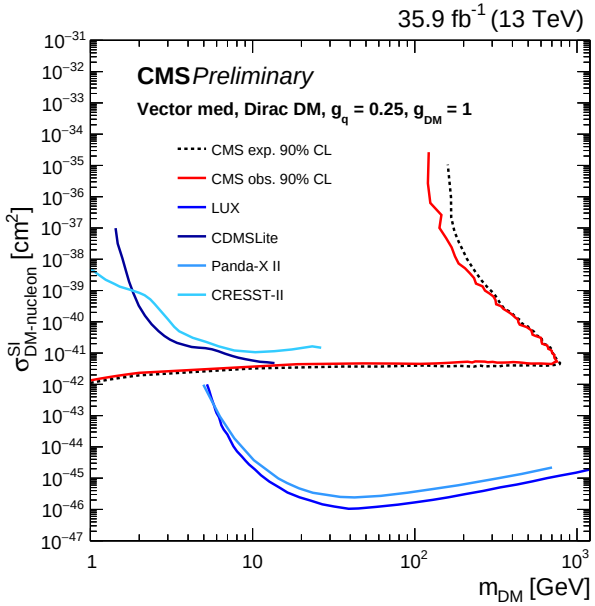
M_{med} masses up to 1.8 TeV are excluded at 95 % CL

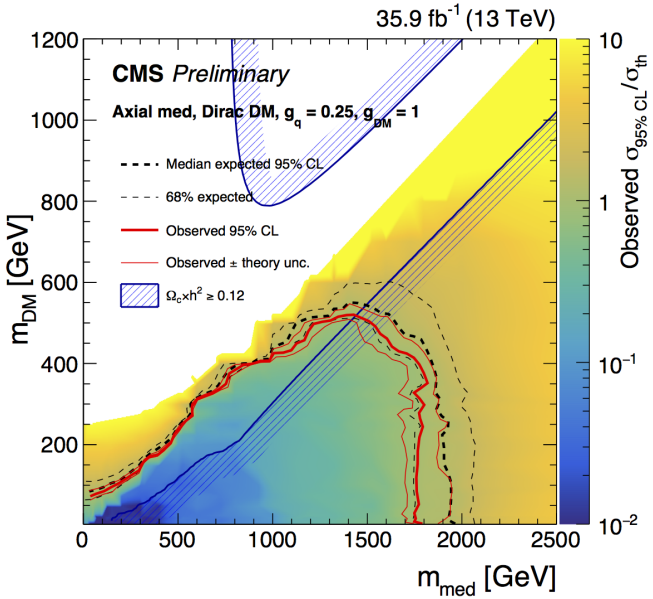
M_{DM} masses up to 700 GeV (vector, top) and 500 GeV (axial-vector, bottom) are excluded at 95 % CL

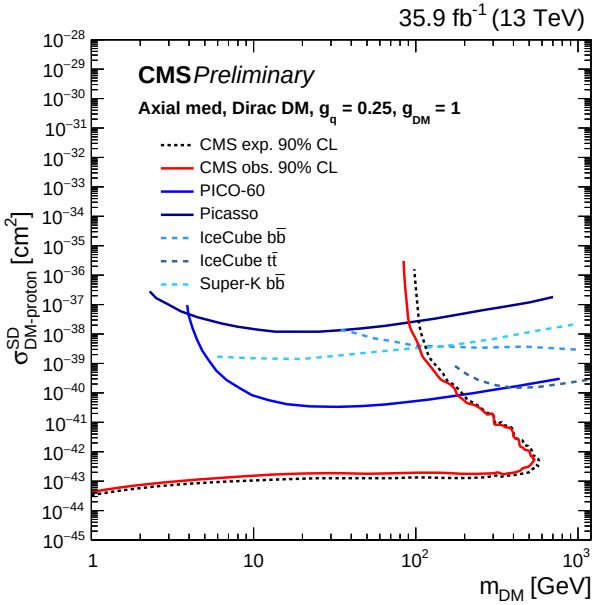
Limits are also given in terms of DM-nucleon cross-section (right column)

It is assumed that $g_q = 0.25$ and $g_{DM} = 1$ for all presented limits





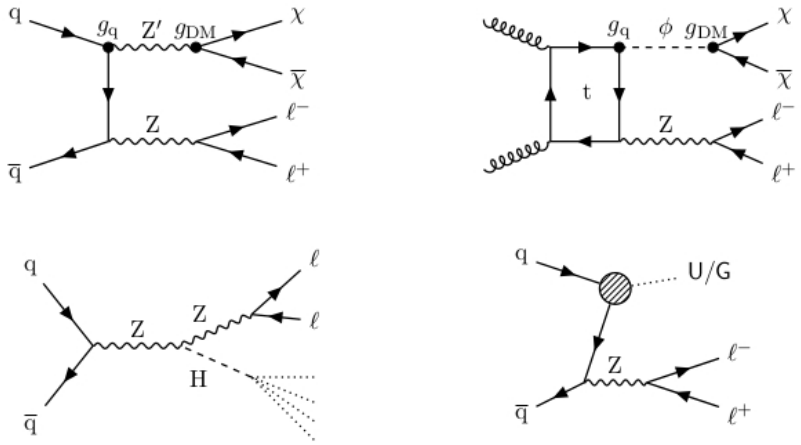




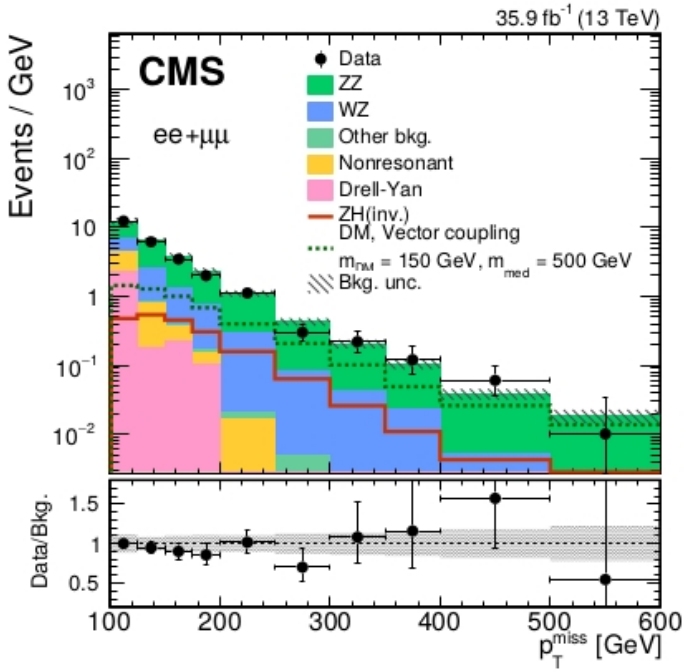
Mono-Z(ll) analysis (EXO-16-052)

Optimized selection on well-identified isolated lepton pairs:

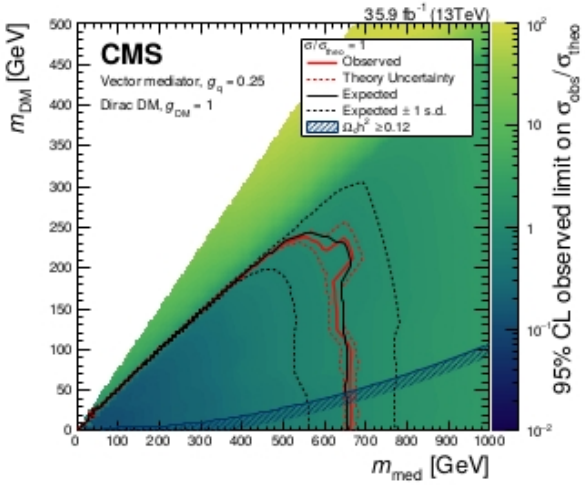
- $E_T^{miss} > 100$ (lower threshold w.r.t to Monojet!)
- $\Delta\phi(\vec{p}_T^{ll}, \vec{p}_T^{miss}) > 2.6$
- $|E_T^{miss} - p_T^{ll}|/p_T^{ll} < 0.4$

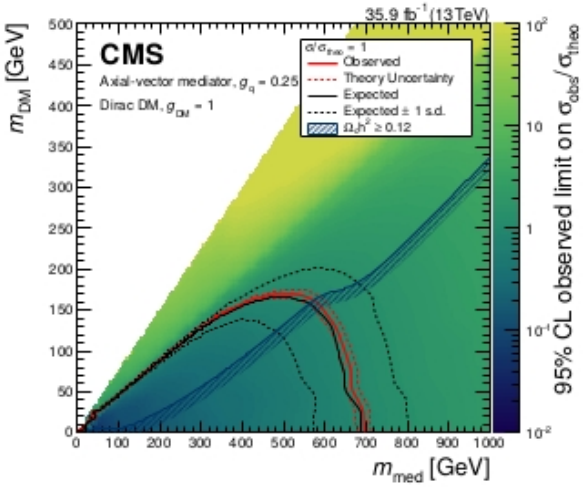


E_T^{miss} spectrum:



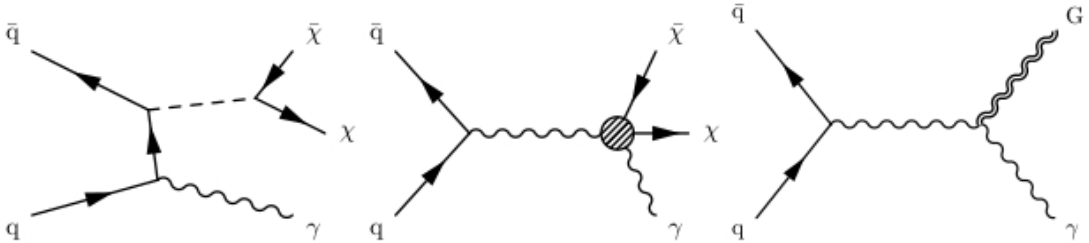
Limits in $M_{med} - M_{DM}$ plane for simplified DM (top-left diagram):



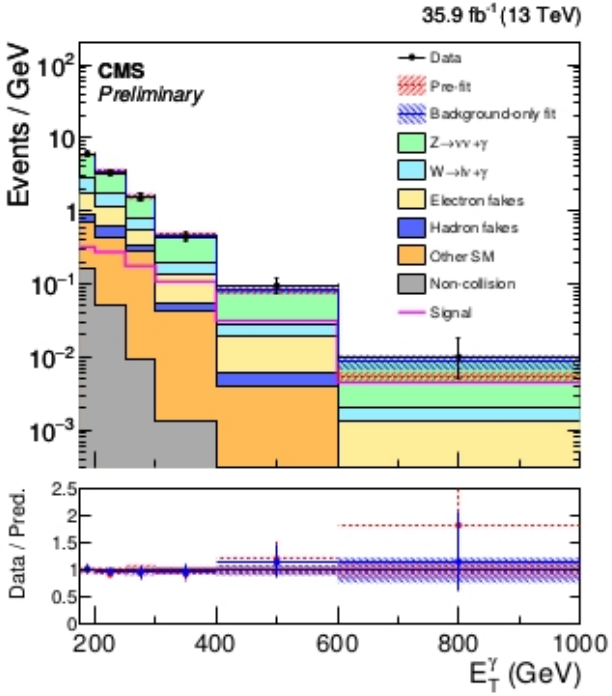


Monophoton analysis (EXO-16-053)

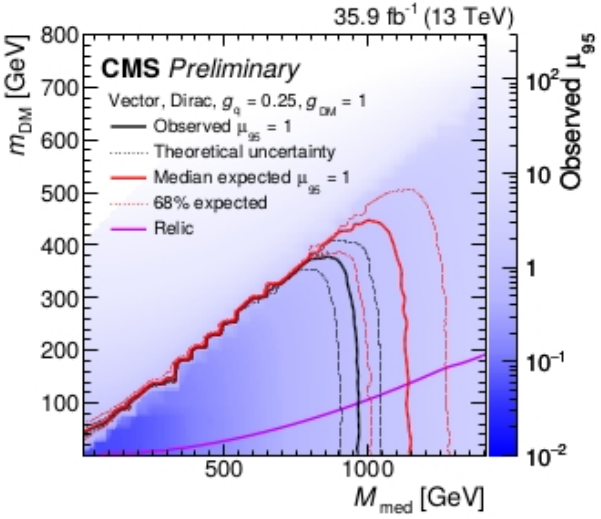
- Trigger on single photon events
- Photon H/E< 0.05 and $\sigma_{\eta\eta} < 0.0102$
- $E_T^{\gamma} > 175$ GeV
- $E_T^{miss} > 170$ GeV

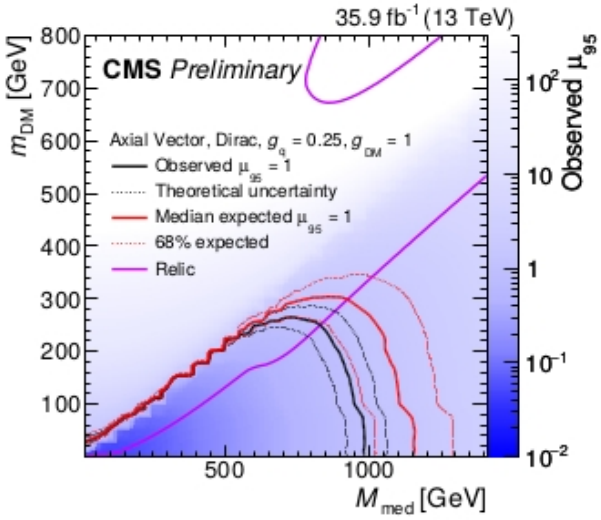


E_T^{γ} spectrum:



Limits in $M_{med} - M_{DM}$ plane for simplified DM (left diagram):





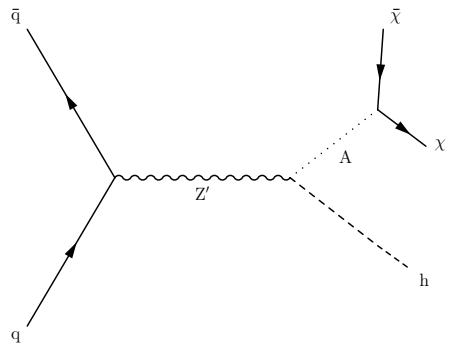
Mono-Higgs - combination (EXO-18-011)

Because of the:

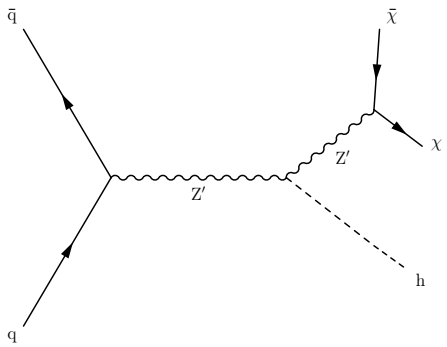
- small Yukawa coupling of H to light q
- loop-supressed coupling of H to gluons

$\Rightarrow$ Mono-Higgs $\neq$ ISR radiation but involves coupling to BSM mediators

Z'-2HDM



Baryonic Z'



Complementarity of the combined channels

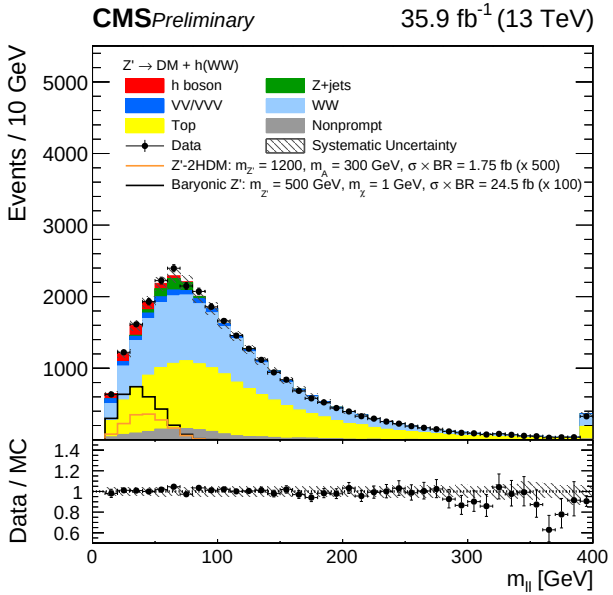
Decay channel	Subsequent decay or category	Model
$h \to b\bar{b}$	AK8 jet	Z'-2HDM
	CA15 jet	Baryonic Z'
$h \to \gamma\gamma$	$p_T^{miss} \in 50$–130 GeV, > 130 GeV	Z'-2HDM and baryonic Z'
$h \to \tau\tau$	$\tau_h\tau_h$	Z'-2HDM and baryonic Z'
	$\mu\tau_h$	Z'-2HDM and baryonic Z'
	$e\tau_h$	Z'-2HDM and baryonic Z'
$h \to WW$	$e\nu\mu\nu$	Z'-2HDM and baryonic PZp
$h \to ZZ$	4e	Z'-2HDM and baryonic Z'
	4μ	Z'-2HDM and baryonic Z'
	$2e2\mu$	Z'-2HDM and baryonic Z'

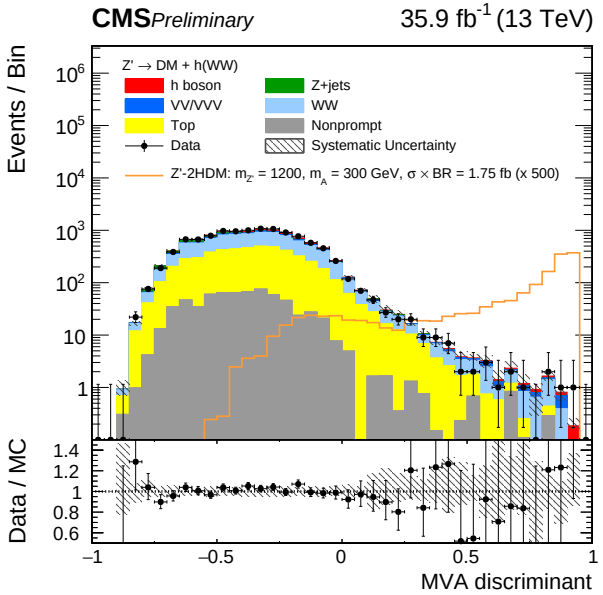
- H(bb): larger branching ratio
- H($\gamma\gamma$) and H(ZZ): better reconstructed M_H resolution
- H($\tau\tau$), H(VV): lower SM BG $\rightarrow$ higher sensitivity to lower p_T signals

Mono-Higgs - combination (EXO-18-011)

H(WW) NEW

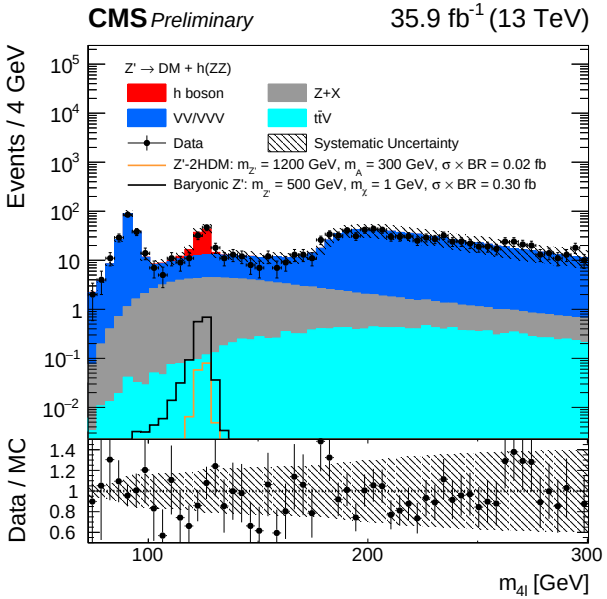
- $e^{\pm}\mu^{\mp} + E_T^{miss}$ events, single-/double-lepton triggers
- $M_{ll} < 76$ GeV, $\Delta R_{ll} < 2.5$
- Missing info (ν): BG estimation with trained BDT

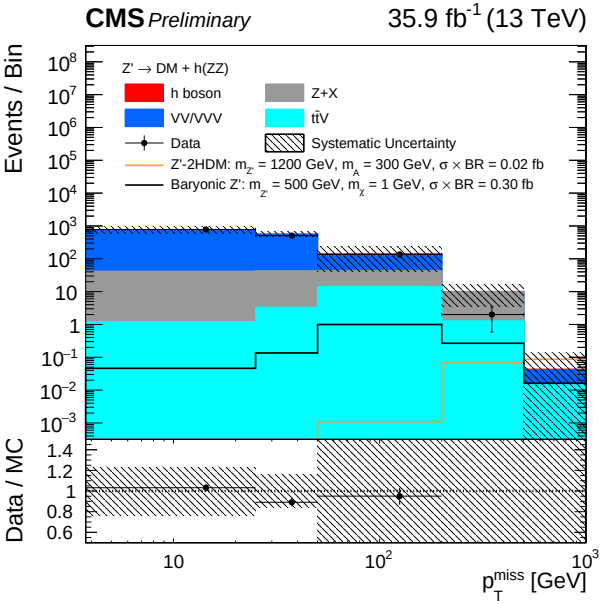




H(ZZ) NEW

- All 4l signatures: double-lepton triggers
- 2 Z with $M_{OS\ ll}$ around M_Z
- Nonres. ZZ main BG estimated from simulations
- Z+X sublead. BG estimated from CR in data

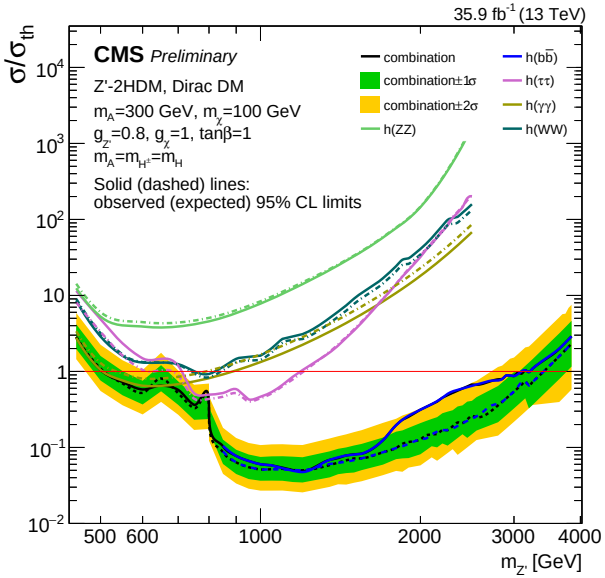


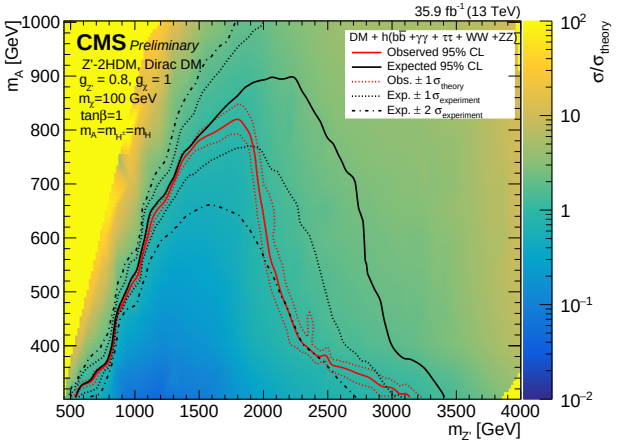


Mono-Higgs - combination (EXO-18-011)

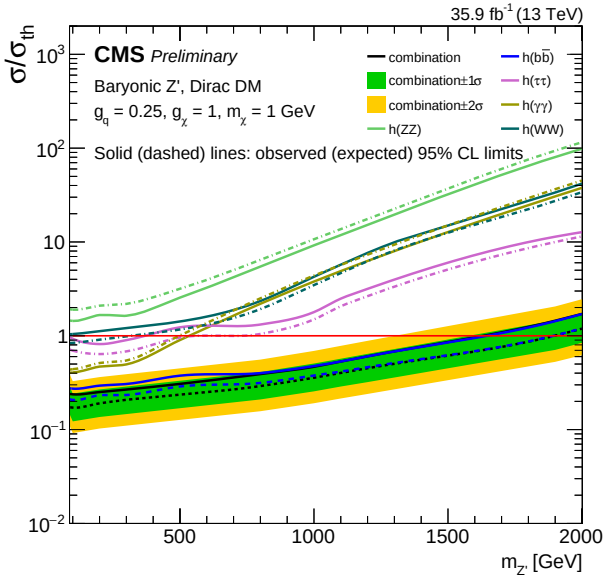
Results:

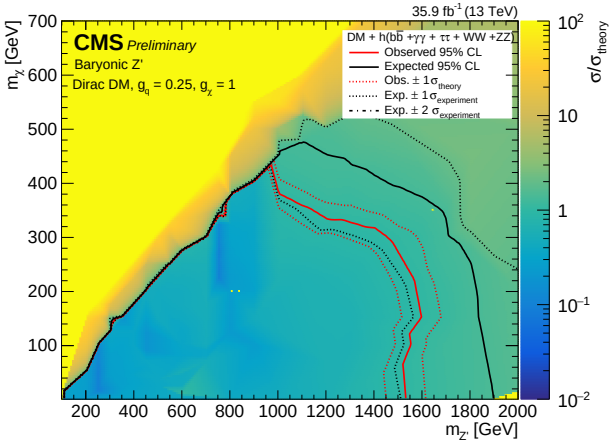
Z'-2HDM





Baryonic Z'



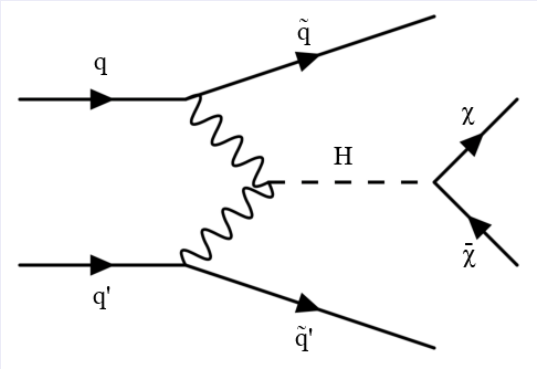


Higgs to invisible final states (EXO-17-023)

Vector Boson Fusion

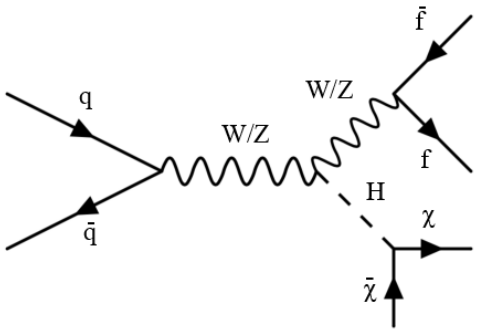
Most sensitive channel for Higgs to invisible final state due to its particular 2 jets signature:

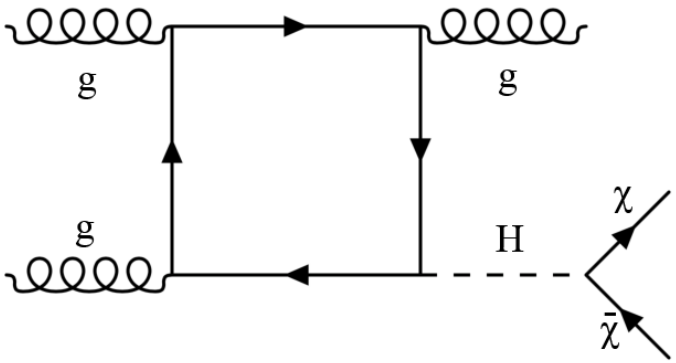
Large $\Delta\eta_{jj}$ and M_{jj}



$\Rightarrow$ Signature: 2 VBF jets + E_T^{miss}

To improve the sensitivity, combination with VH and ggH channels:





Higgs to invisible final states (HIG-17-023)

Strategy

Signal is optimaly extracted via a shape analysis on the $M_{j1,j2}$ spectrum. A cut-and-count (c&c) analysis offers a nice complementarity.

Selection

Trigger on E_T^{miss} and H_T^{miss}. VBF topology selection:

- $\eta_{j1} \times \eta_{j2} < 0$
- $\Delta\phi_{j1,j2} < 1.5$
- $\Delta\eta_{j1,j2} > 1$ (shape), > 4 (c&c)
- $M_{j1,j2} > 200$ GeV (shape), > 1.3 TeV (c&c)

Then: $E_T^{miss} > 250$

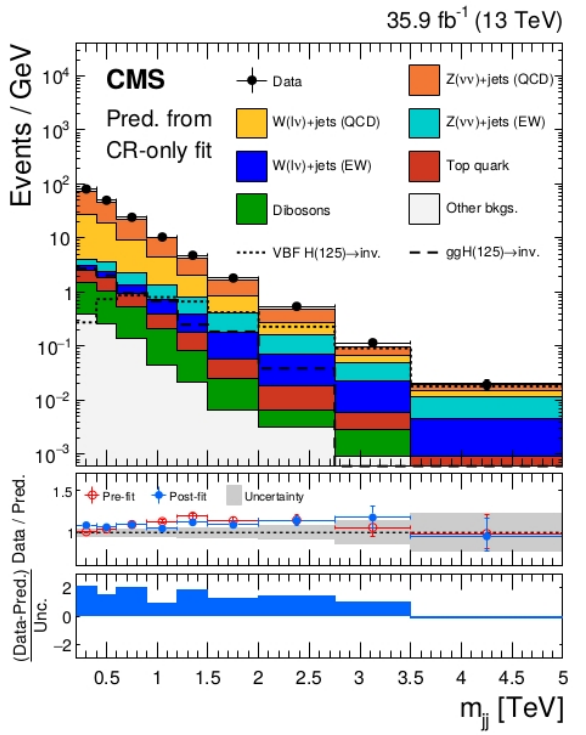
Main BG

VBF Z($\nu\nu$) and W($l\nu$): estimated in CR and transfered to SR using transfer factors derived from simulations. BG is then estimated with a fit to data using a constrained maximum-likelihood (similar to the monojet strategy)

Higgs to invisible final states (EXO-17-023)

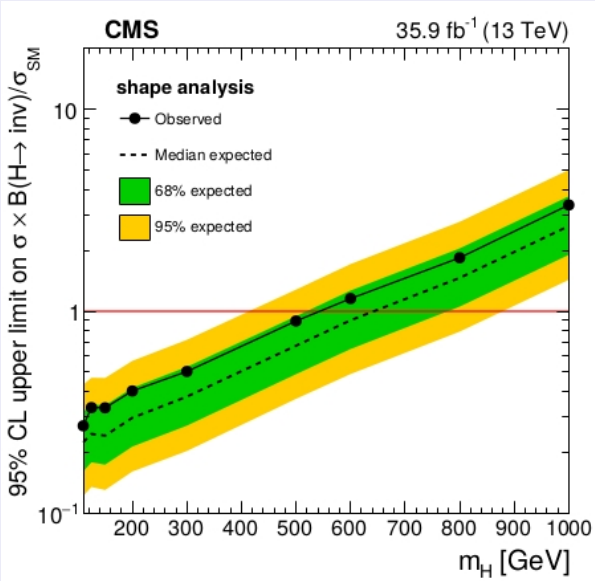
Results:

Signal extraction (M_{jj})

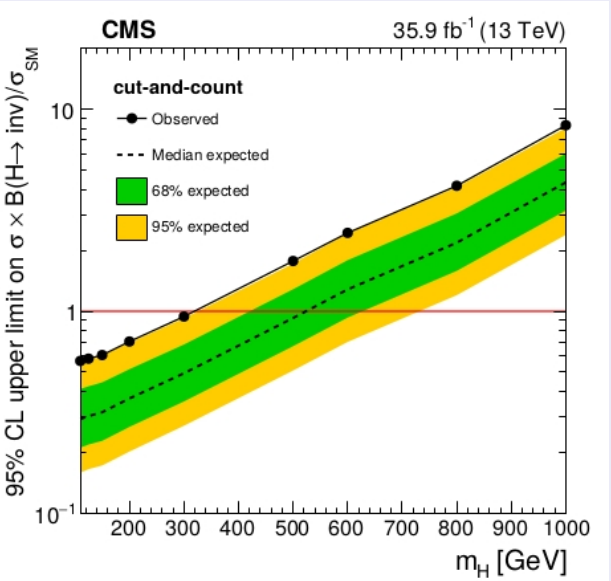


Limits on pp→Higg(inv.) cross-section

Shape



Cut-and-count



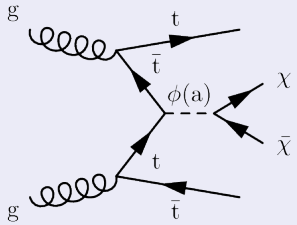
Mono-top/-$t\bar{t}$

Higher sensitivity to scalar mediators ϕ (large $t - \phi$ Yukawa coupling)

EXO-16-049: $t\bar{t} + E_T^{miss}$

$t\bar{t} + E_T^{miss}$

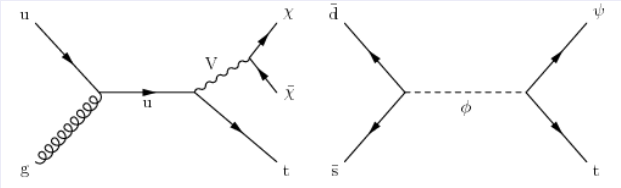
- Coupling to a scalar going to DM



EXO-16-051: boosted single top + E_T^{miss}

$t/\bar{t} + E_T^{miss}$ (heavily suppressed in the SM)

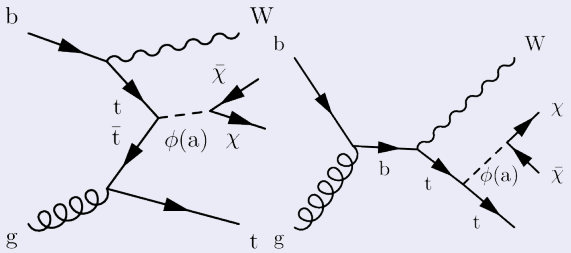
- Through FCNC vector boson or charged colored scalar resonance going to t-DM



EXO-18-010: $t\bar{t}$/single top combination

$t/\bar{t} + E_T^{miss}$ **+ W or b/light jets**

- Through SM-like diagrams with a neutral uncolored scalar resonance



$t\bar{t} + E_T^{miss}$ (EXO-16-049)

All-hadronic: trigger on E_T^{miss}/H_T^{miss}

- $E_T^{miss} > 200$ GeV
- $N_{\text{jets}} \geq 4$, $N_{\text{b-jets}} \geq 1$

Lepton+jets: trigger on single leptons

- $E_T^{miss} > 160$ GeV
- $N_{\text{jets}} \geq 3$, $N_{\text{b-jets}} \geq 1$

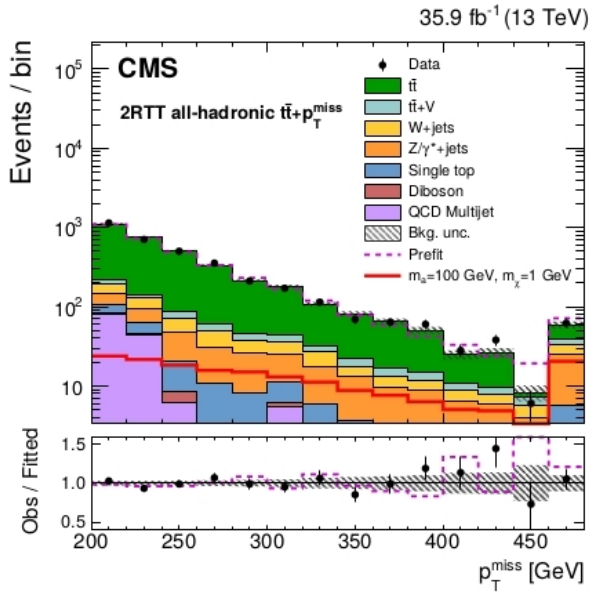
Dilepton: trigger on single-/double-leptons

- $E_T^{miss} > 50$ GeV
- $N_{\text{jets}} \geq 2$, $N_{\text{b-jets}} \geq 1$

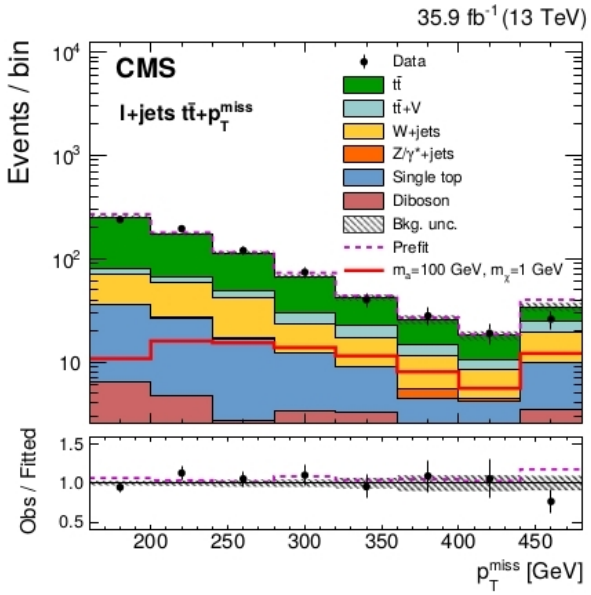
Limits in the $M_{(\text{pseudo})\text{scalar}} - M_{DM}$ plane

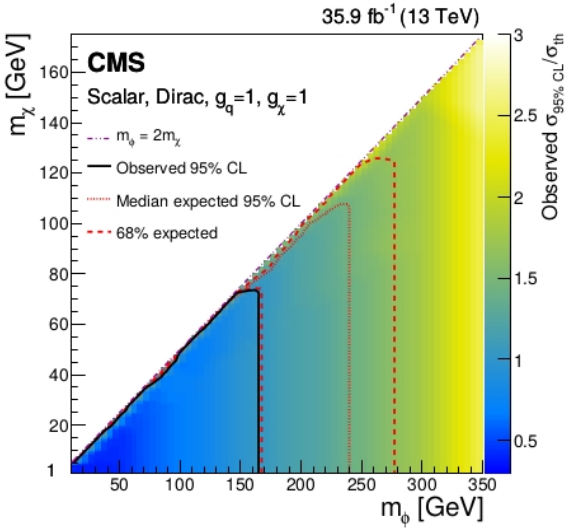
For scalar mediators, $g_q = g_{DM} = 1$ is assumed

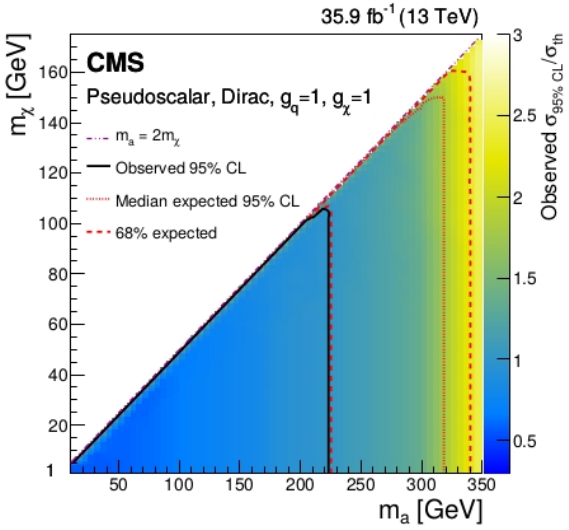
All-hadronic



Lepton+jets







$t\bar{t}$ and single top ($t/\bar{t}$) (EXO-18-010)

First results for $t/\bar{t}$ production through neutral uncolored ϕ mediator
$\Rightarrow$ nice complementarity with previous $t/\bar{t}$ analysis
$\Rightarrow$ combination with $t\bar{t}$ production with the same scalar going to DM

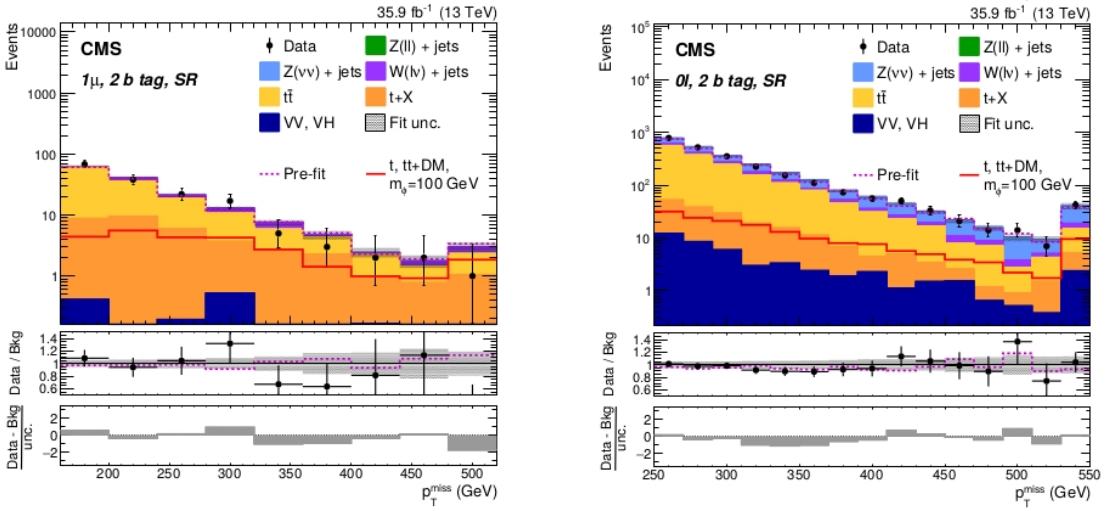
Events are classified in "Single Lepton" (SL) and "All-Hadronic" (AH) categories and also according to $N_{\text{b-jets}}$:

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

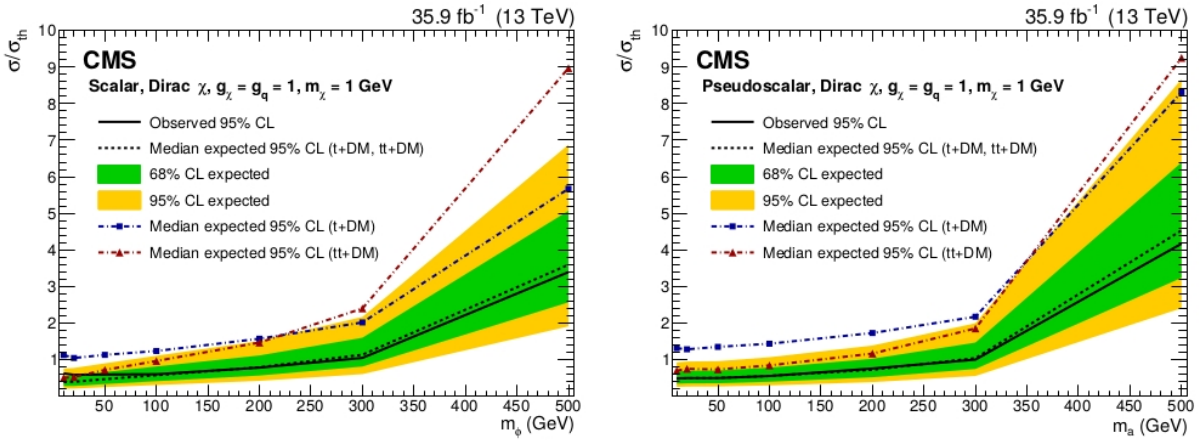
All channels are combined in a simultaneous global fit to the E_T^{miss} spectrum for signal extraction

$t\bar{t}$ and single top ($t/\bar{t}$) (EXO-18-010)

E_T^{miss} spectrum in the SL (μ + 2 b-jets) and the AH (2 b-jets) categories:



Limits for a scalar (left) and pseudoscalar (right) mediator:

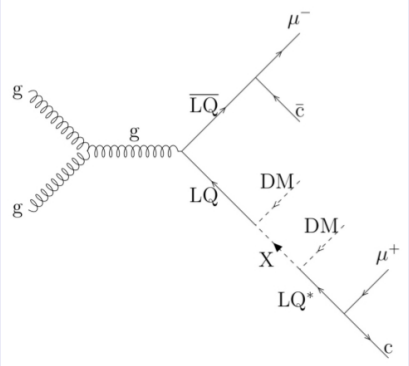


Mediator searches

Leptoquarks (EXO-17-015)

$L_Q \equiv$ color-triplet, fractionally charged Dirac fermion with both n_L and n_B

- Bump hunting in $L_Q(c\mu)$ channel (clean μ signature)
- $M_T(\vec{p}_T^{\mu}, \vec{p}_T^{miss}) > 500$ GeV



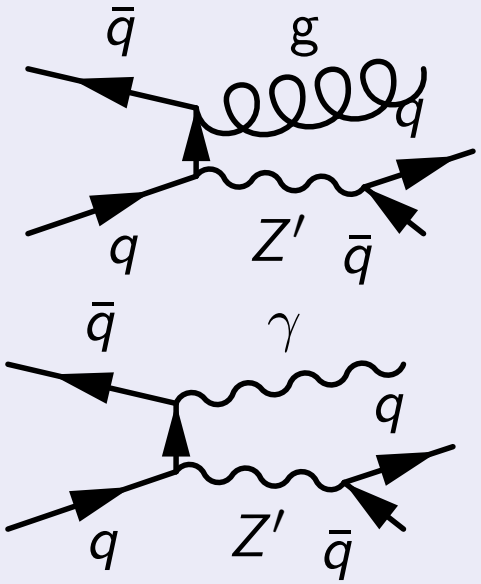
Jet/γ-boosted Z' to dijet (EXO-17-001/EXO-17-027)

Jet ISR:

- Trigger on H_T
- ≥ 1 AK8 jet with $p_T > 500$ GeV

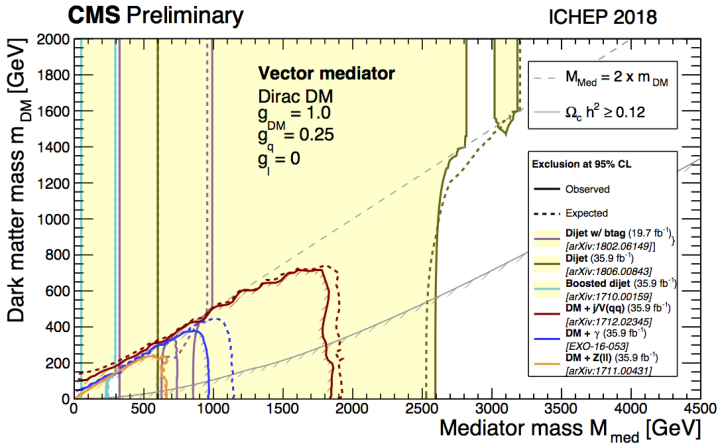
γ ISR:

- Trigger on γ (lower p_T threshold!)
- ≥ 1 AK8 jet with $p_T > 200$ GeV

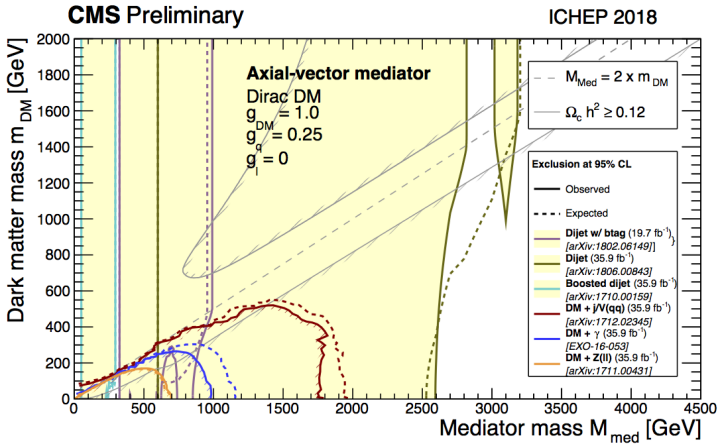


Summary plots

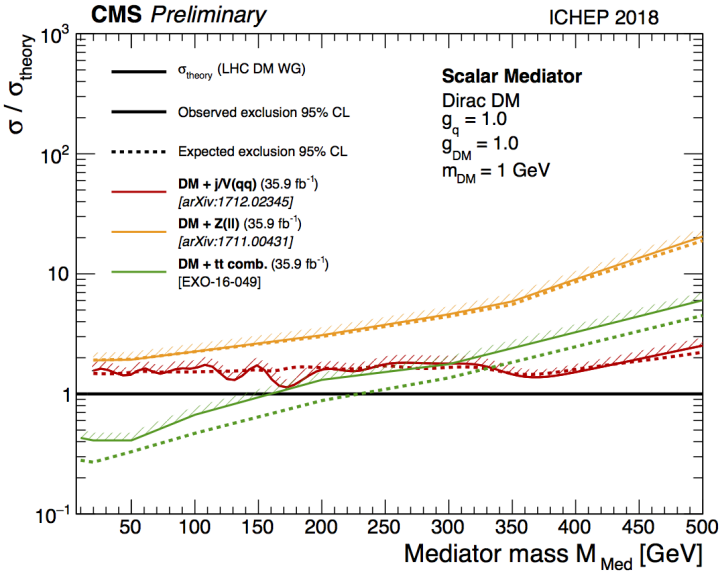
Vector med.



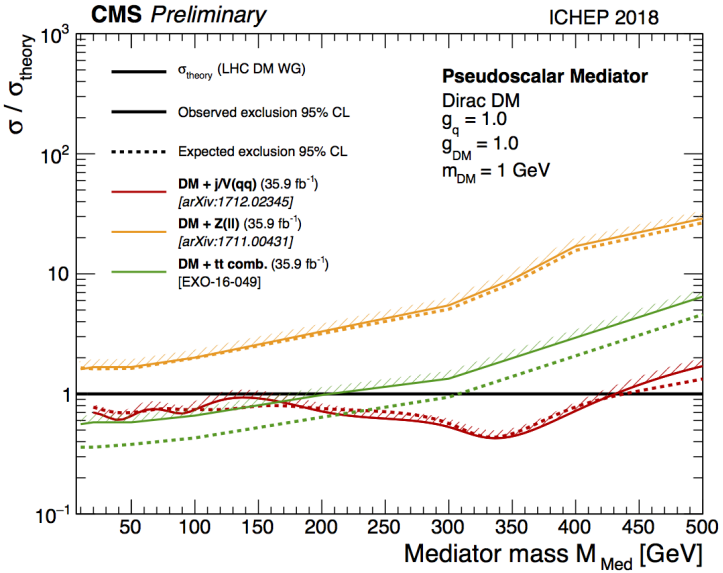
Axial med.



Scalar med.



Pseudoscalar med.

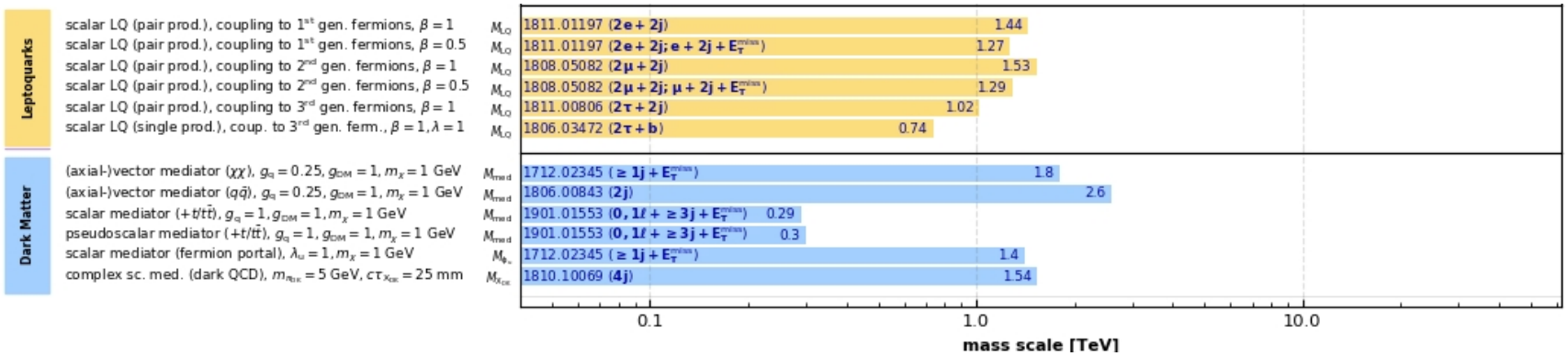


Outlook

Latest CMS results in the search for Dark Matter particles have been presented. More searches coming in the next months:

- More data (full Run-2, 130 fb^{-1})
- More channels

All CMS public results can be found here:
`https://cms-results.web.cern.ch/cms-results/public-results/publications/`



Keep posted!

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2. Search for dark matter in events with a leptoquark and missing transverse momentum in proton-proton collisions at 13 TeV, CMS PAS EXO-17-015
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4. Search for boosted quark-antiquark resonances produced in association with a photon at 13 TeV, CMS PAS EXO-17-027
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11. Search for new physics in dijet angular distributions using proton-proton collisions at 13 TeV and constraints on dark matter and other models, CMS Collaboration, The European Physical Journal C 78, 789 (2018)
12. Search for new physics in events with a leptonically decaying Z boson and a large transverse momentum imbalance in proton–proton collisions at 13 TeV, CMS Collaboration, The European Physical Journal C 4, 291 (2018)
13. Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at 13 TeV, CMS Collaboration, Phys. Rev. D 97, 092005 (2018)

BACK-UP

Mono-Higgs - combination (EXO-18-011)

H(bb)

- Trigger on E_T^{miss}, cut > 200 GeV
- 1 AK8 jet with 1 b-subjet (Z'-2HDM) or 1 CA15 jet (baryonic Z')
- MVA double b-tagging algorithm
- M_{jet} around M_H

H($\gamma\gamma$)

- Trigger on diphoton, $p_T^{\gamma_1} > 30$ GeV, $p_T^{\gamma_2} > 20$ GeV
- $M_{\gamma\gamma} > 95$ GeV
- $\Delta\phi(\vec{p}_T^{\gamma\gamma}, \vec{p}_T^{miss}) > 2.1$
- Max 2 jets with $p_T > 30$ GeV

H($\tau\tau$)

- $\tau_h\tau_h$: double τ_h trigger
- $e(\mu)\tau_h$: single $e(\mu)$ trigger
- $E_T^{miss} > 105$ GeV, $p_{T,\text{vis.}}^{\tau\tau} > 65$ GeV
- $M_{\tau\tau,\text{vis.}} < M_H$

Boosted single top (EXO-16-051)

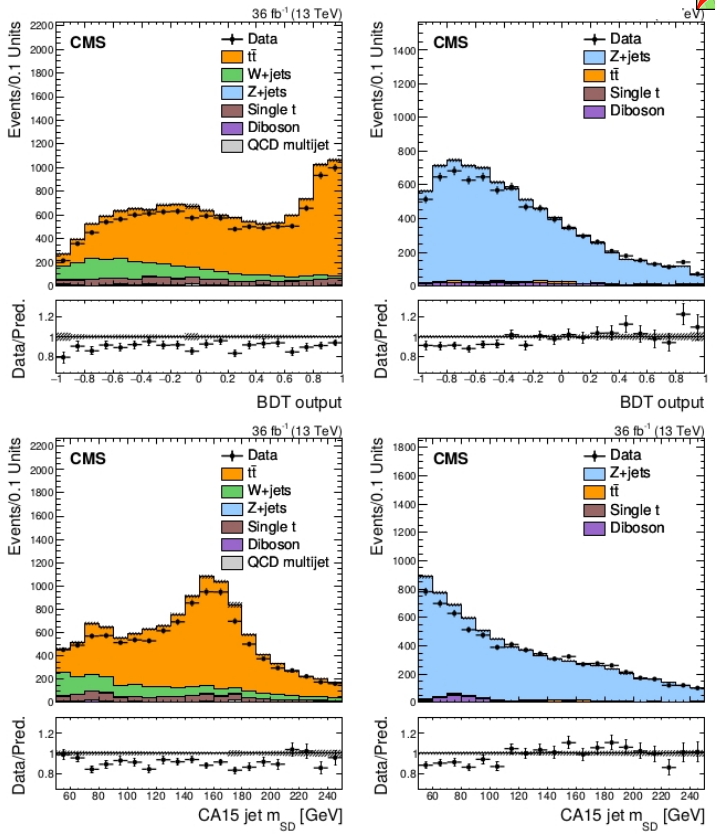
Signature: boosted top to all-hadronic + E_T^{miss}

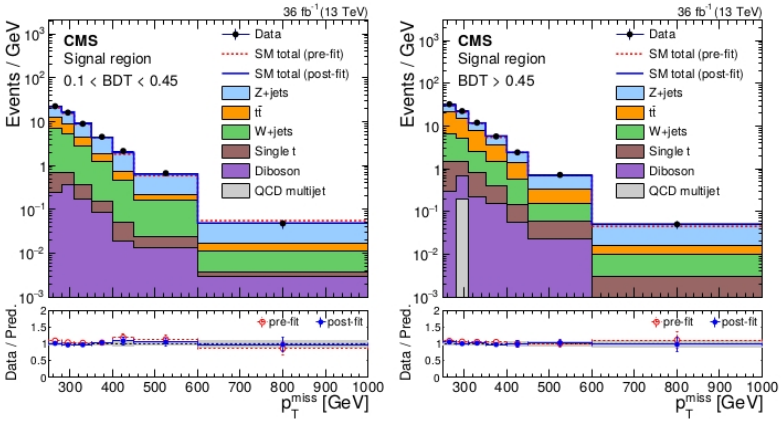
t-jet identification:

- CA15 clustered with $p_T > 250$ GeV
- Grooming with "soft drop" SD algo.
- Tagging with BDT (using τ_3/τ_2, f_{rec}, ECF ratios)

Trigger on E_T^{miss}/H_T^{miss}

- $E_T^{miss} > 250$ GeV
- $N_{\text{t-jet}} = 1$
- 2 SR: BDT$\in$[0.1,0.45] or BDT>0.45

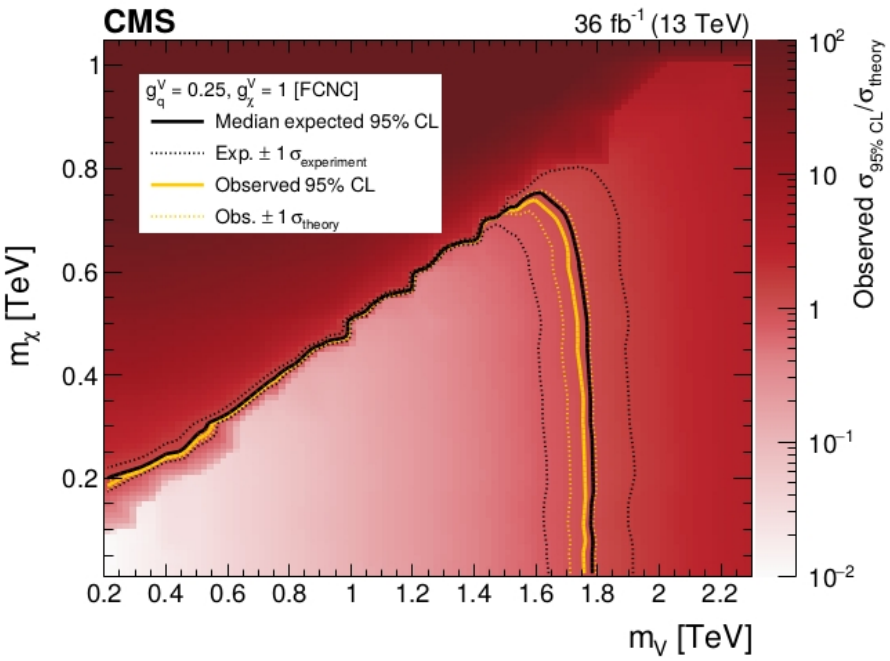




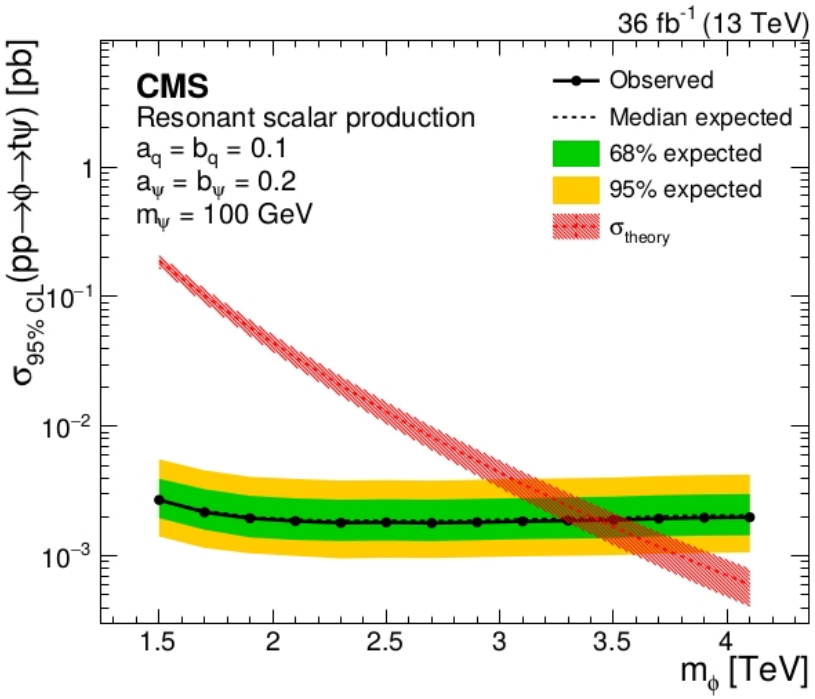
Boosted single top (EXO-16-051)

Results:

FCNC (vector couplings)

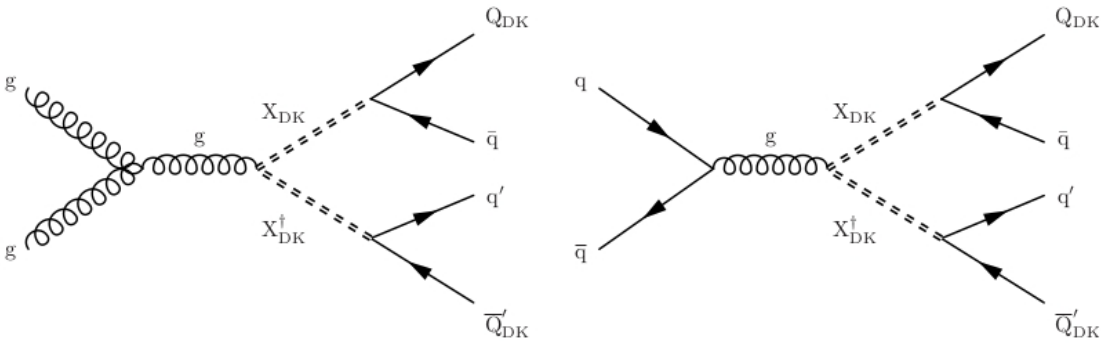


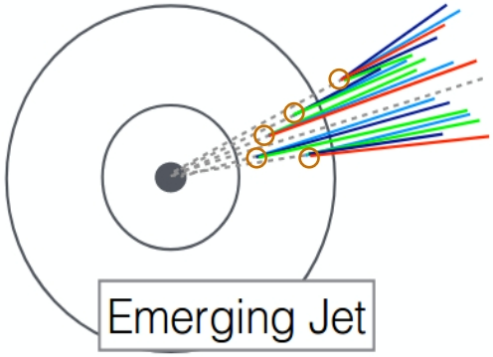
Scalar resonance



Emerging jets (EXO-18-001)

(A. E. del Valle)

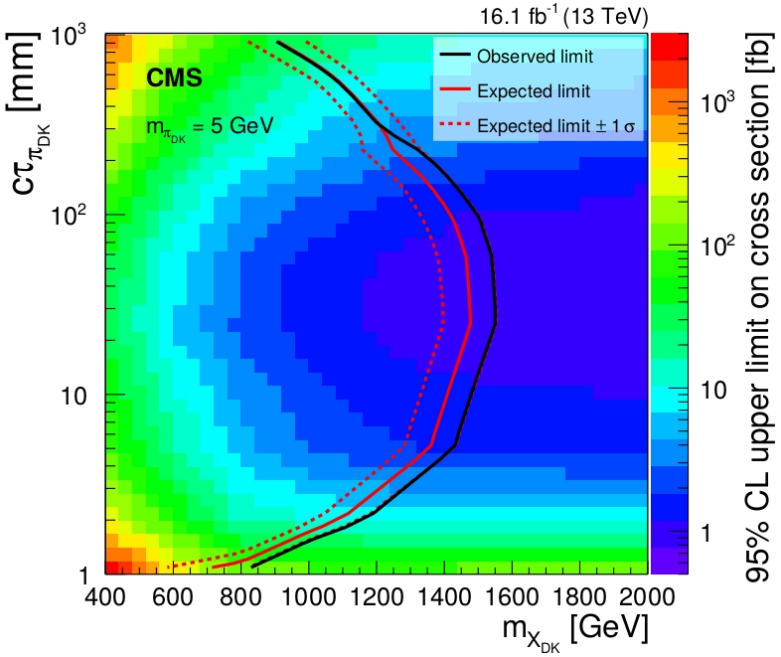




Signature: 2 jets + 2 emerging jets from dark quarks

Trigger on H_T, then $H_T > 900$ GeV. Select emerging jets requiring:

- 4 variables defined to ID emerging jets based on: large IP_{xy}, low IP_z, low fraction of p_T from prompt tracks
- 2 emerging-tagged jets OR 1 emerging + E_T^{miss}

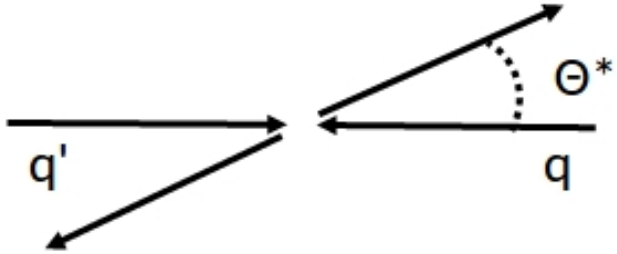


Dijet angular distributions (EXO-16-046)

Strategy

Search for an excess in the $\chi_{\text{dijet}} = e^{|y_1 - y_2|} = \frac{1+|\cos\theta*|}{1-|\cos\theta*|}$ distribution

QCD: flat, BSM: excess at low values



Trigger on H_T

- Jet $p_T > 450$ GeV or $H_T > 900$ GeV
- Bin data in M_{jj} bins to improve sensitivity
- **Unfold jet info to interpret it as info on generated-level parton**