Dark Sector Searches at CMS

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ON BEHALF OF THE CMS COLLABORATION

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COMPACT MUON SOLENOID (CMS)

SM interactions are understood pretty well

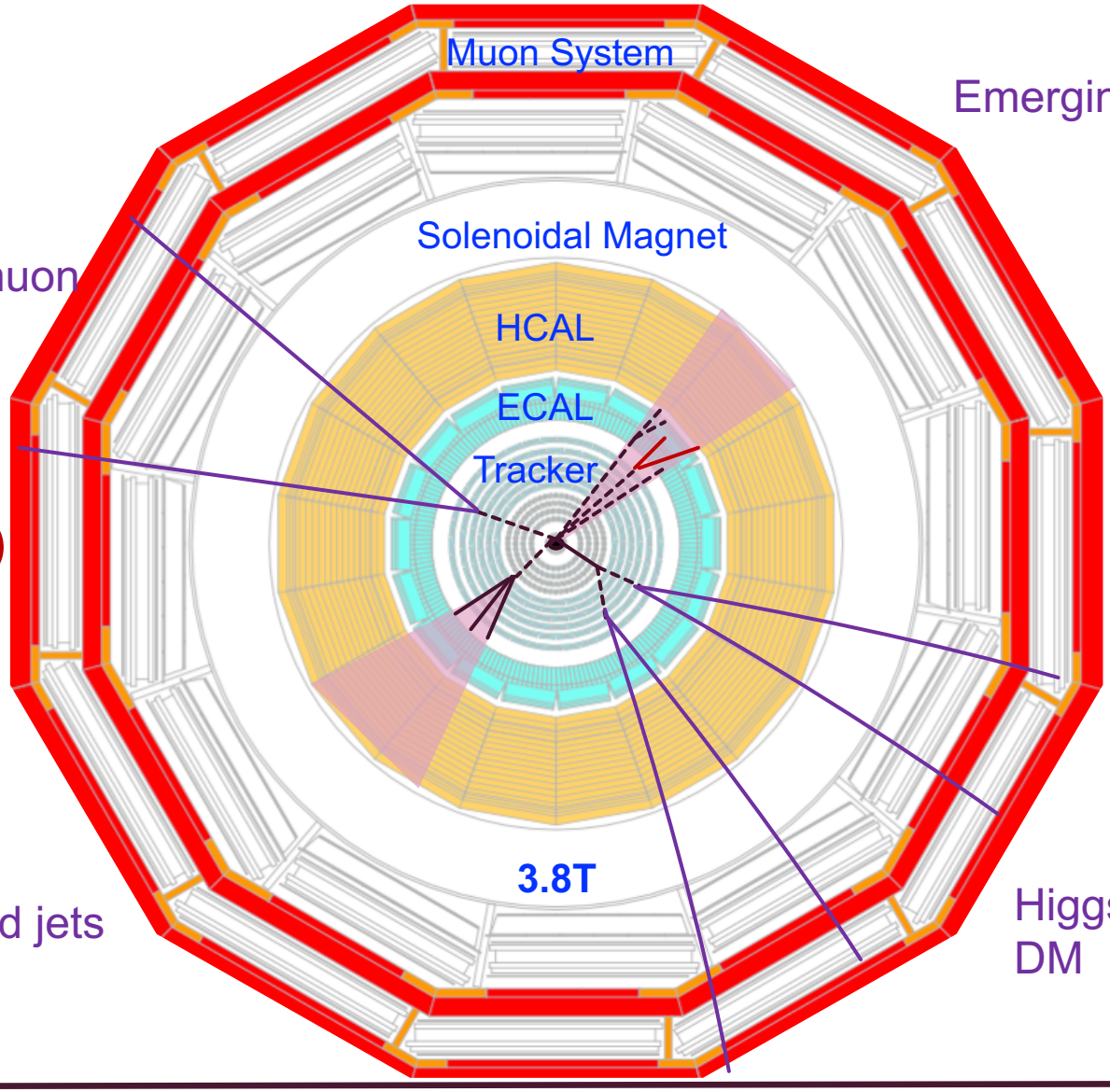
New physics signature

- Astrophysical observations indicate the existence of dark matter
- No observation in laboratory
- Several models with various type of interactions

- Dark sector interactions can give non-prompt signatures we should be looking for

- Challenging!
  - Analyses often require complex trigger strategies
  - Final states may require dedicated reconstruction techniques
  - Unconventional ways

Dark sector signatures & challenges



Emerging Jets

Displaced muon pairs

Limited phase space

Small couplings

Decays via heavy particle

Displaced jets

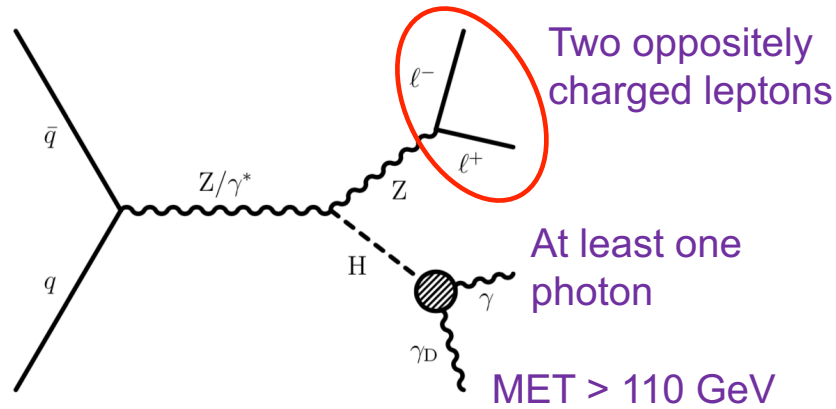
Higgs mediated DM

Dark Photons in ZH decays

CMS PAS EXO-19-007

- Search for a scalar boson produced in association with a Z boson and decaying to an invisible particle together with an isolated photon

- Dark photon couples to the Higgs boson through a charged dark sector



Also look at: Higgs boson rare and exotic decays at CMS by Fengwangdong Zhang

Variable	Selection	Reject
Leptons	2 leptons, $p_T > 25/20$ GeV	WZ, ZZ, VVV
Photons	$\geq$1 photon, $E_T^\gamma > 25$ GeV	All but $Z\gamma$
$\lvert m_{\ell\ell} - m_Z \rvert$	< 15 GeV	WW, top-quark
Anti b tagging	Applied medium working point	Top-quark, VVV
Jet counting	≤ 2	Top-quark, VVV
$\Delta\phi_{\vec{\ell\ell},\vec{p}_T^{miss}+\vec{E}_T^\gamma}$	$>$2.5 radians	$Z\gamma$
$\lvert p_T^{\vec{p}_T^{miss}+\vec{E}_T^\gamma} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell}$	$<$0.4	$Z\gamma$
$\Delta\phi_{jet,p_T^{miss}}$	$>$0.5	$Z\gamma$
$p_T^{\ell\ell}$	> 60 GeV	$Z\gamma$
$m_{\ell\ell\gamma}$	> 100 GeV	$Z\gamma$
p_T^{miss}	> 110 GeV	$Z\gamma$
m_T	< 350 GeV	WW, top-quark

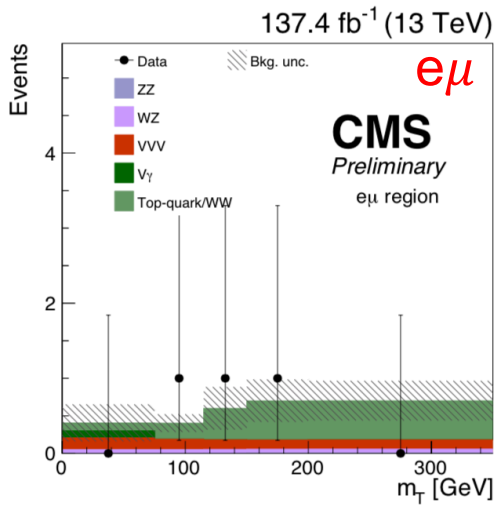
Selections and major background processes rejected by different variables used

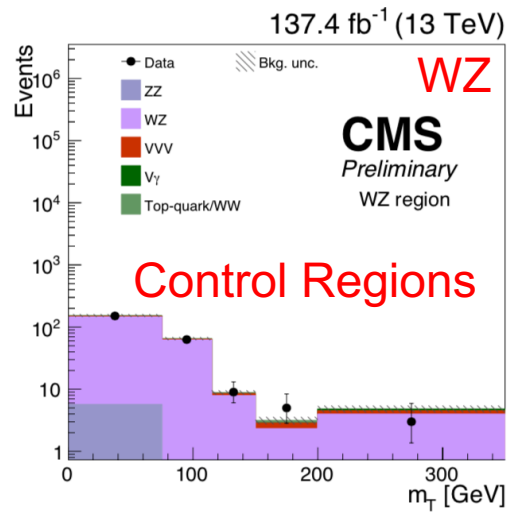
Variable of interest: m_T (MET, photon): $m_T \equiv \sqrt{2 p_T^{miss} E_T^\gamma [1 - \cos(\Delta\phi_{\vec{p}_T^{miss},\vec{E}_T^\gamma})]}$

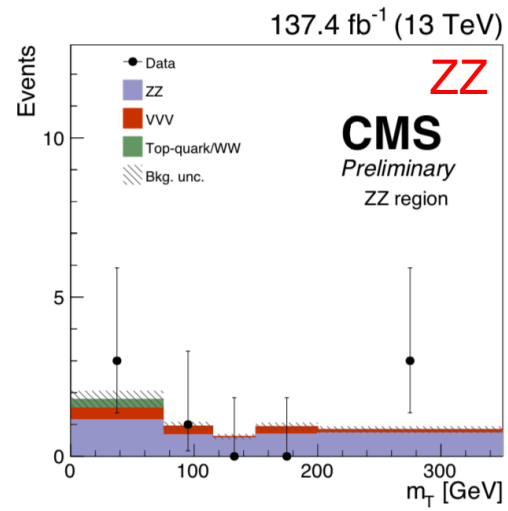
- Jacobian peak structure with end-point at $m_T \sim m_H$, flat or lower values for background

Dark Photons in ZH decays

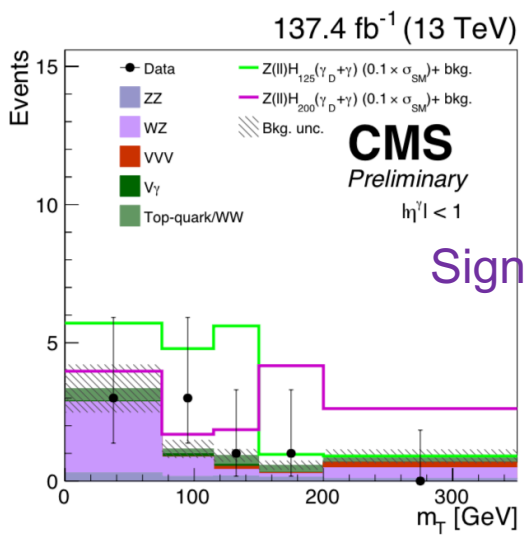
CMS PAS EXO-19-007

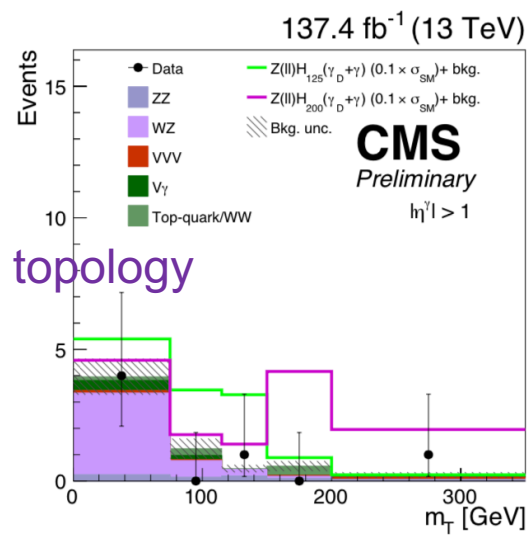






m_T distributions





Signal topology

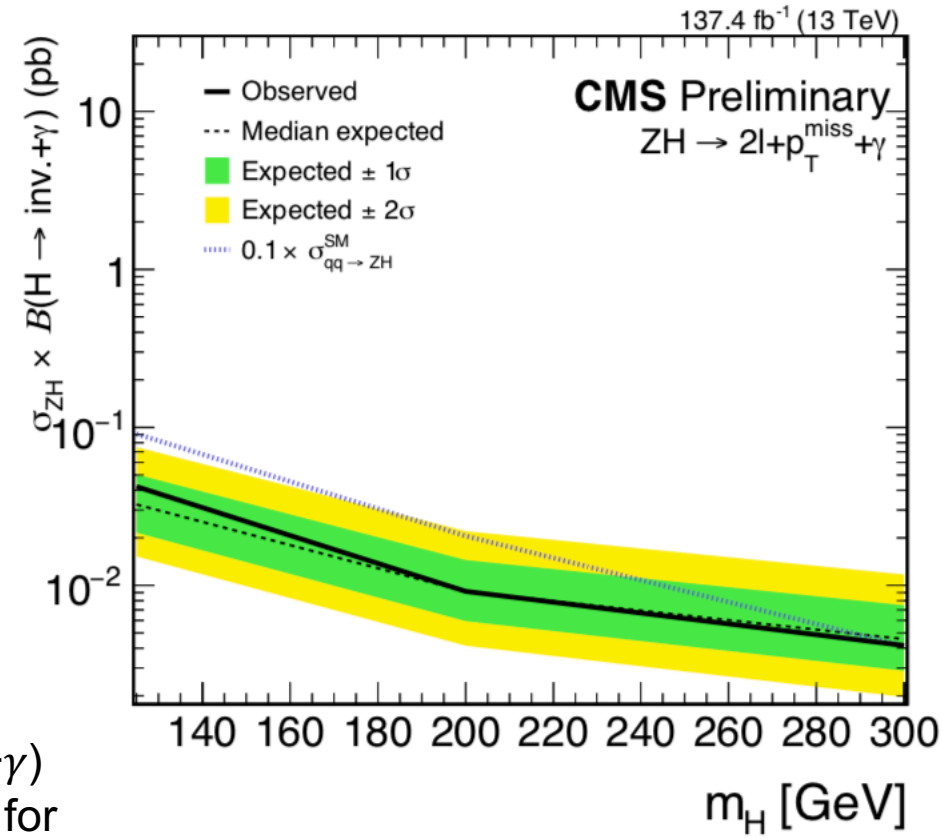
Dark Photons in ZH decays

CMS PAS EXO-19-007

Process	Yields
Data	14
Nonresonant bkg.	2.4 ± 1.1
WZ	8.1 ± 2.0
ZZ	1.5 ± 0.3
$Z\gamma$	0.7 ± 0.7
Other bkg.	0.6 ± 0.3
Total bkg.	13.3 ± 3.8
ZH_{125} (BR=10%)	17.9 ± 1.2 (1.42 ± 0.09 %)
ZH_{200} (BR=10%)	12.3 ± 0.8 (4.32 ± 0.28 %)
ZH_{300} (BR=10%)	3.9 ± 0.2 (6.80 ± 0.34 %)

Observed yields, bkg estimates and signal predictions in the signal region

Signal predictions for BR(H→invisible+γ) = 10% assuming SM ZH cross section for given H mass



The observed and expected 95% CL upper limits at m_H = 125 GeV assuming SM production rate on BR(H→invisible+γ) are **4.6% and 3.6%,** respectively

Emerging Jets

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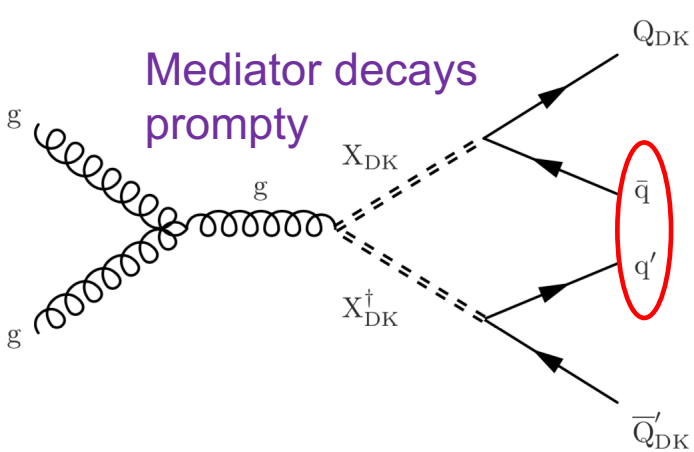
- Class of models includes new, electrically-neutral fermions called “dark quarks”
- Not charged under the forces of the SM but are charged under a new force in the dark sector (“dark QCD”) that has confining properties similar to SM QCD
- Such models naturally explain the observed mass densities of baryonic matter and dark matter
- This search consider particularly, the dark QCD model of Bai, Schwaller, Stolarski, and Weiler (BSSW) that predicts **“emerging jets”**

Mediator decays prompty



Dark quark initiate shower of dark pions: eventually SM particles produced

Two ordinary jets (SM quarks)

Lots of Hadronic activity: Trigger on H_T

Emerging Jets (EJs): Long-lived dark hadrons giving rise to displaced vertices when decaying to SM hadrons

Emerging Jets

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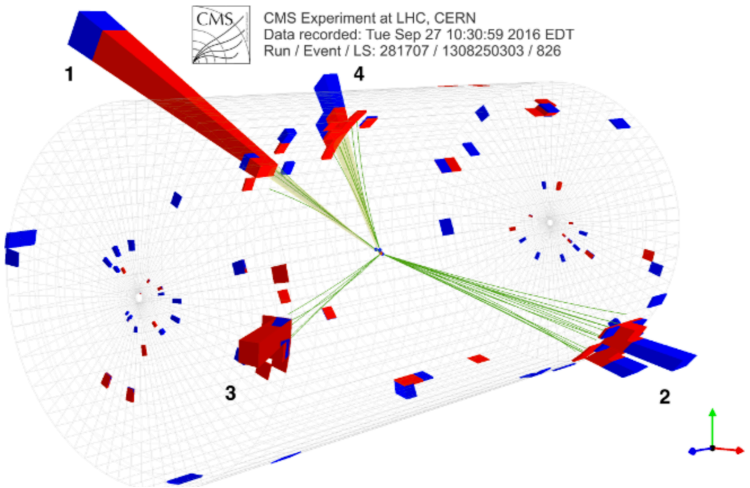
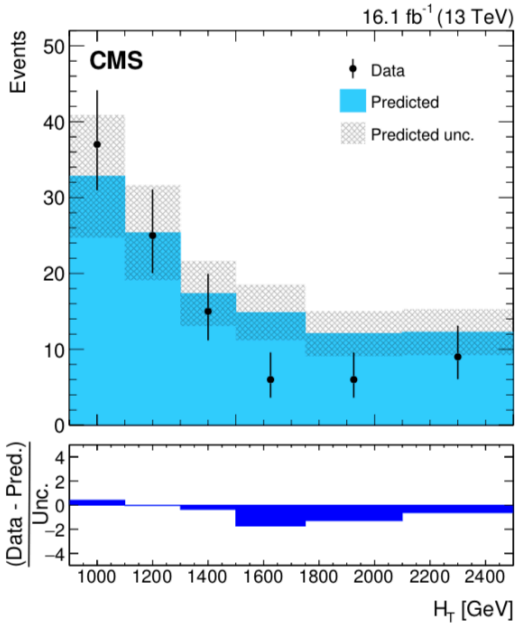
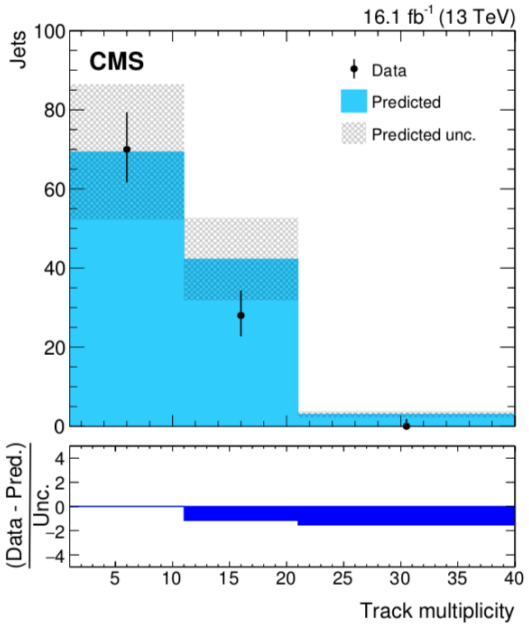
- Use of displacement and associated tracks and vertices to tag EJs
- 4 Jets: either 2-EJs or 1-EJ and large MET
- Multijets with b-jets main background: use data-driven estimates, studied as a function of track multiplicity







The H_T and number of associated tracks of the observed data events and expected background in one of the CRs

Emerging Jets

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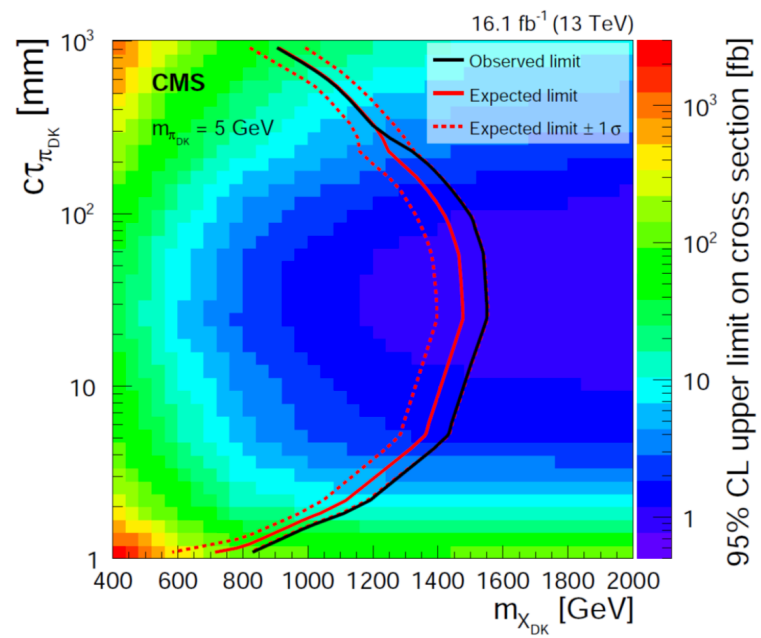
	Criteria group	PU_{dz} (<) [cm]	D_N (<)	$\langle IP_{2D} \rangle$ (>) [cm]	α_{3D} (<)
SR	EMJ-1	2.5	4	0.05	0.25
SR	EMJ-2	4.0	4	0.10	0.25
SR	EMJ-3	4.0	20	0.25	0.25
SR	EMJ-4	2.5	4	0.10	0.25
SR	EMJ-5	2.5	20	0.05	0.25
SR	EMJ-6	2.5	10	0.05	0.25
SM QCD	EMJ-7	2.5	4	0.05	0.40
SM QCD	EMJ-8	4.0	20	0.10	0.50

Requirements on the variables used in identifying emerging jets

Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

Expected and observed event yields for each selection set

- Dark pion decay lengths between 5 and 225 mm for dark mediators with masses between 400 and 1250 GeV are excluded
- First dedicated search for the pair production of a new particle that decays to a jet and an emerging jet



Dark Photons to 4 Muons

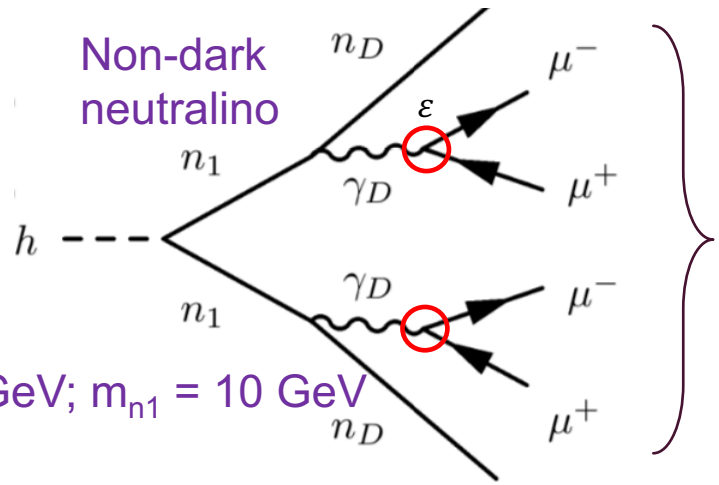
arXiv:1812.00380
CMS HIG-18-003

- Search for the pair production of a light boson that decays into a pair of muons
- Interpretations: Supersymmetry (SUSY) models with hidden sectors (dark SUSY)
  - Breaking of a new $U(1)_D$ symmetry gives rise to a massive dark photon γ_D

Dark neutralino: undetected (MET)

Non-dark neutralino

Trigger: At least three muons



Couple of oppositely charged muon pairs

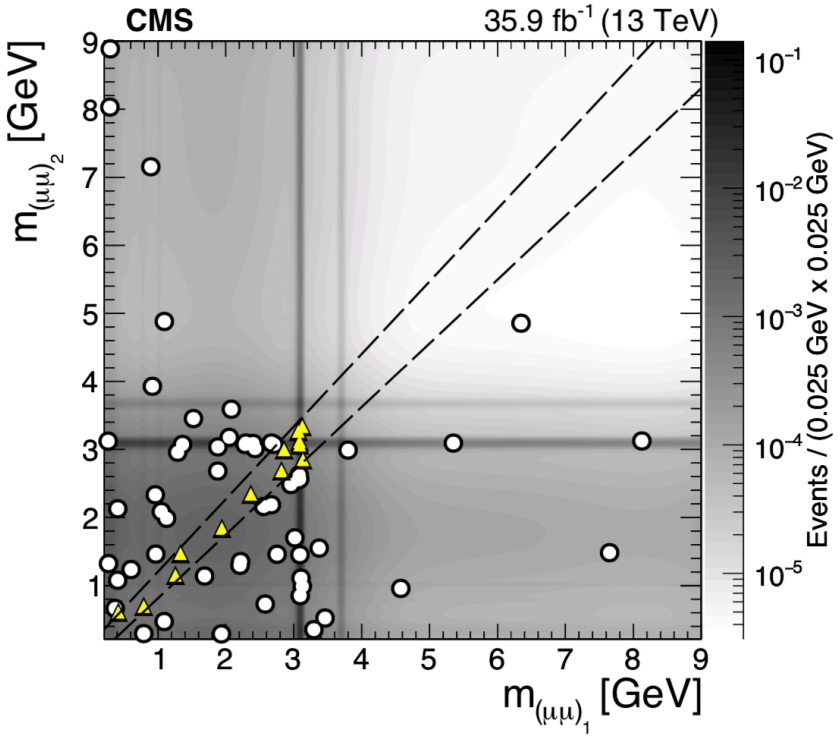
m_h = 125GeV; m_{n1} = 10 GeV

- The lifetime, and thus the displacement, of the dark photon is dependent upon kinematic mixing parameter ε and the mass of the dark photon

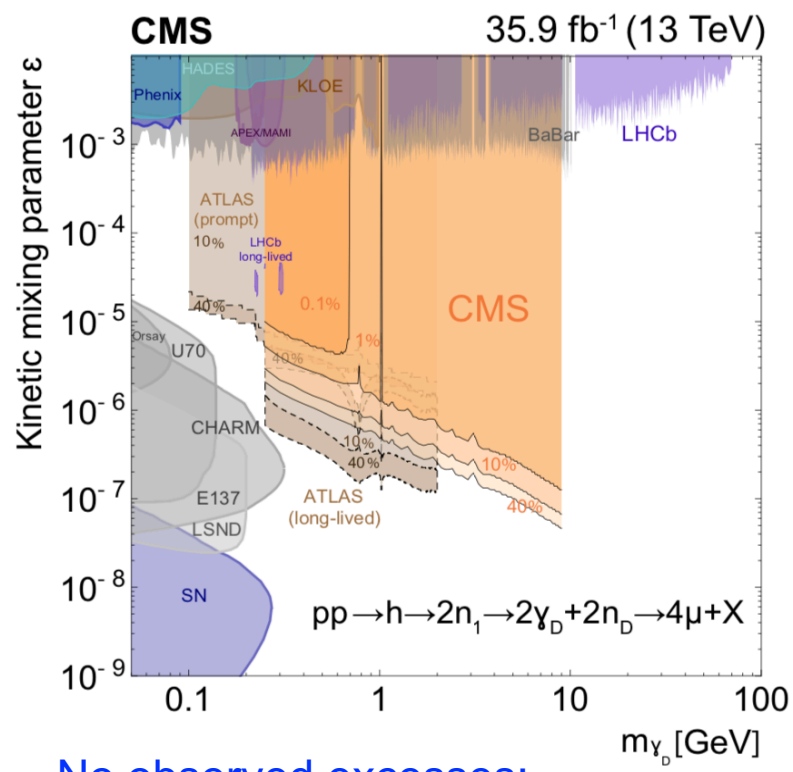
Dark Photons to 4 Muons

arXiv:1812.00380
CMS HIG-18-003

- Similar invariant mass for muon pairs
- Negligible backgrounds: bb, J/ψ pair production, Z+ J/ψ , electroweak 4μ via off-shell Zs



Triangles: Data events in SR
Bullets: Data events outside SR



No observed excesses:
constrain γ_D masses 0.25 – 8.5 GeV

Higgs invisible

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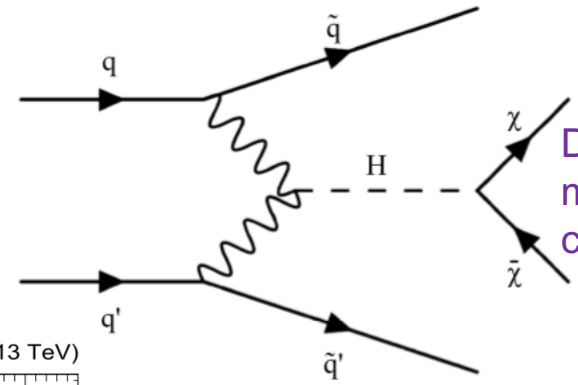
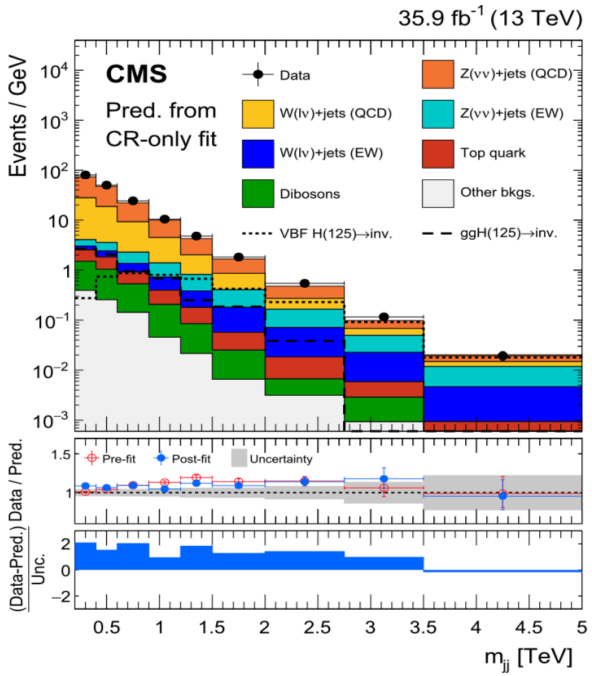
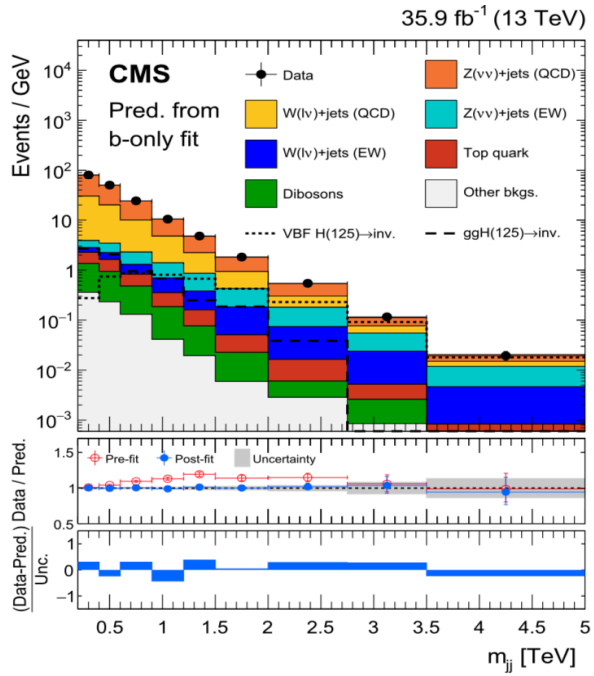
- Search for invisible decays of a Higgs boson in association with jets
- Search exploits large m_{jj} and $|\Delta\eta_{jj}|$ that characterize VBF higgs production
- Major background (95%): $Z(\nu\nu)$+jets and $W(\ell\nu)$+jets



Dark matter candidates

Higgs production via associated production & gg-fusion also considered





Observed M_{jj} distribution in signal region compared to expected backgrounds

Left: Fits in all CRs excluding SR

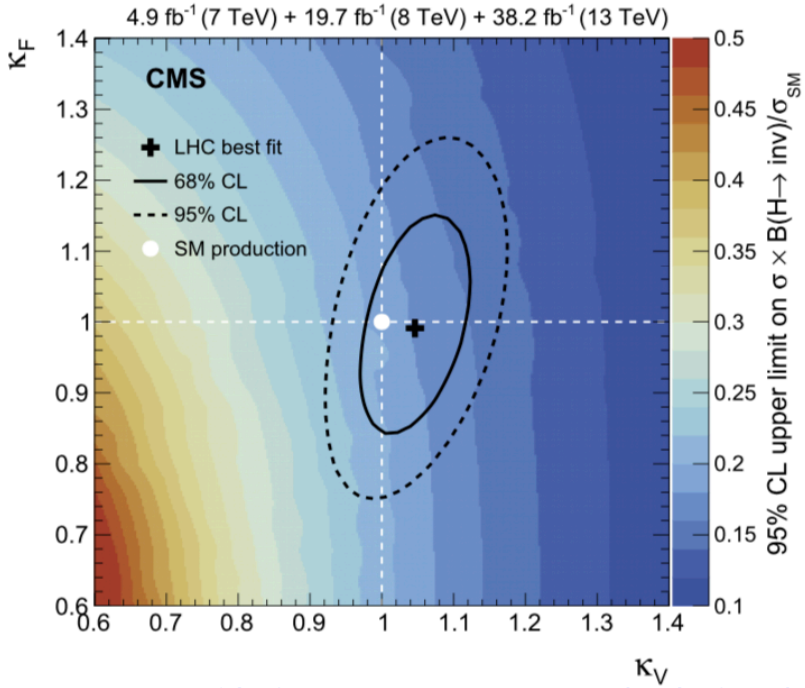
Right: Fits including SR as well

Upper limit on $B(H \rightarrow inv)$ of 0.19 (0.15) at 95% CL, assuming SM production rates for the Higgs boson and a Higgs boson mass of 125.09 GeV

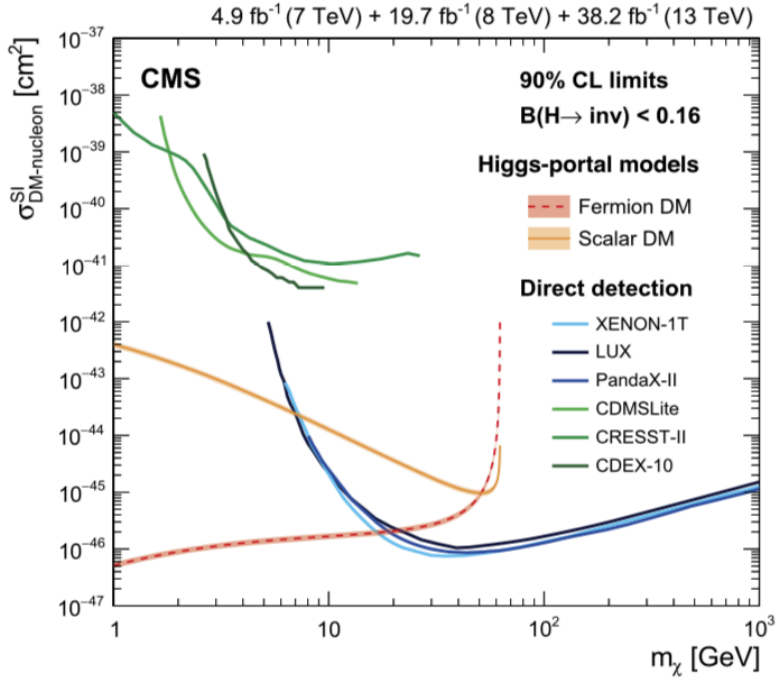
Higgs invisible

Phys. Lett. B 793 (2019) 520

Interpretations: Higgs portal models of Dark Model interactions



Observed 95% CL upper limits on (σ /σSM) *B* (H → inv), whose production xs varies as a function of coupling multipiers



Constraints on the spin-independent DM- nucleon interaction cross section

The observed 90% CL upper limit of *B*(H → inv) < 0.16 is interpreted in terms of Higgs-portal models of dark matter (DM) interactions

Limits provides the strongest constraints on fermion (scalar) DM particles with masses smaller than about 18 (7) GeV

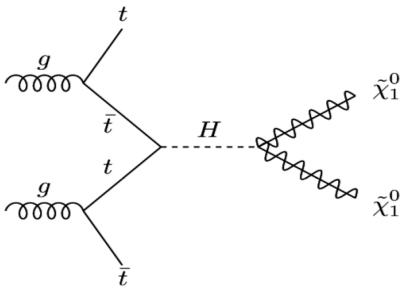
Invisible Higgs boson decays

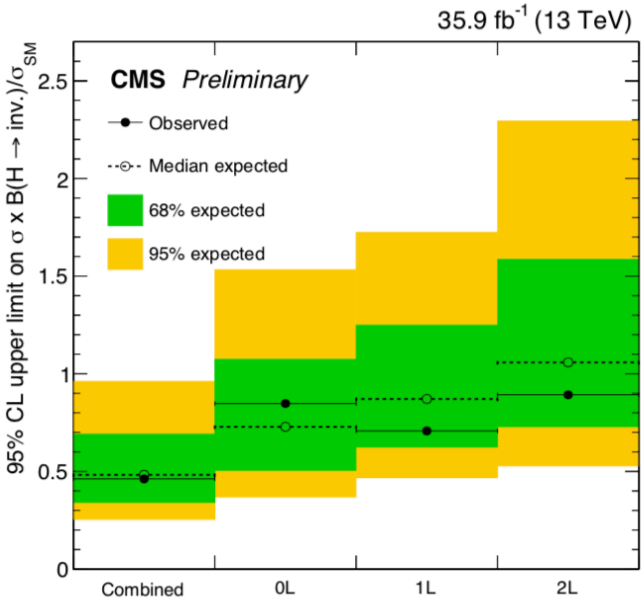
using ttH production

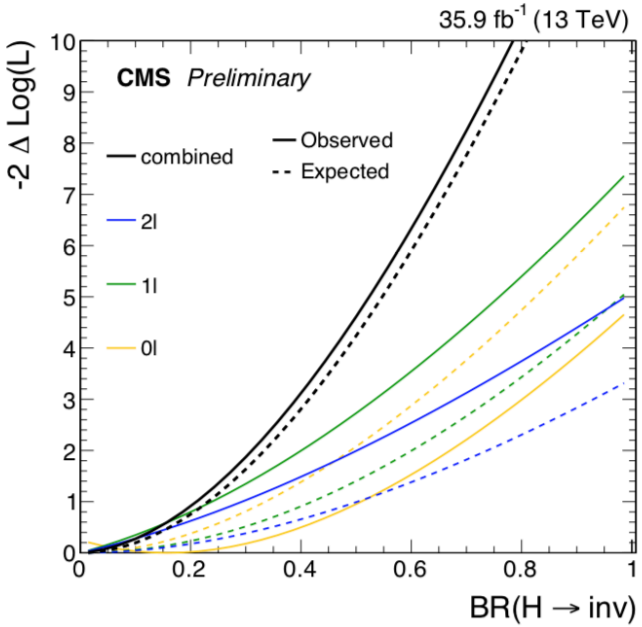
CMS PAS HIG-18-008

First upper bounds on the branching fraction of invisible Higgs boson decays (H → inv) using ttH production

The observed (expected) upper limits on B(H → inv) at the 95% CL are 0.85 (0.73), 0.71 (0.87), and 0.89 (1.06) at the 95% CL for the all-hadronic, semi-leptonic, and di-leptonic final states, respectively







Combined observed (expected) upper limit for BR(H → inv) < 0.46 (0.48) at the 95% CL for a Higgs boson mass of 125 GeV

Summary

- No excess yet
  - New ideas, brain-storming to continue
- Lots of exciting searches from CMS on-going
- Highlighted several recent results on Dark sector searches today
- Displaced vertices searches continue to attract new efforts and ideas
- A lot of room for new searches in this comparatively unexplored frontier

Stay tuned for more results!

EXTRA MATERIAL

Higgs invisible

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