11th Edition of the Large Hadron Collider Physics Conference

Prompt signature searches in CMS

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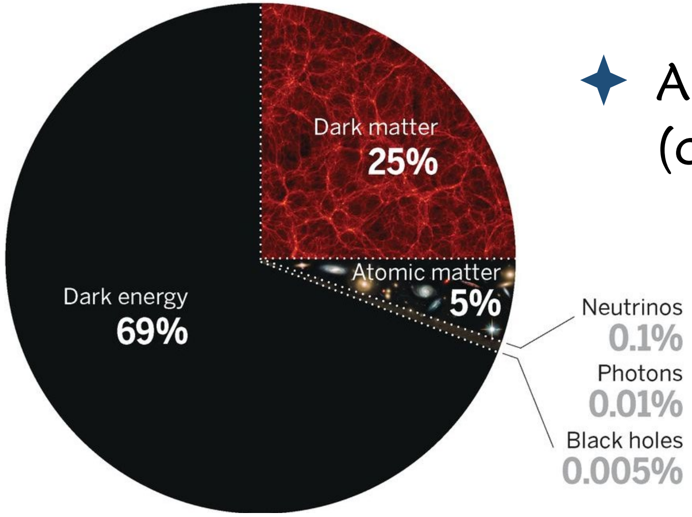
On behalf of the CMS Collaboration

Belgrade, 22 - 26 May 2023

DARK SIDE of the universe

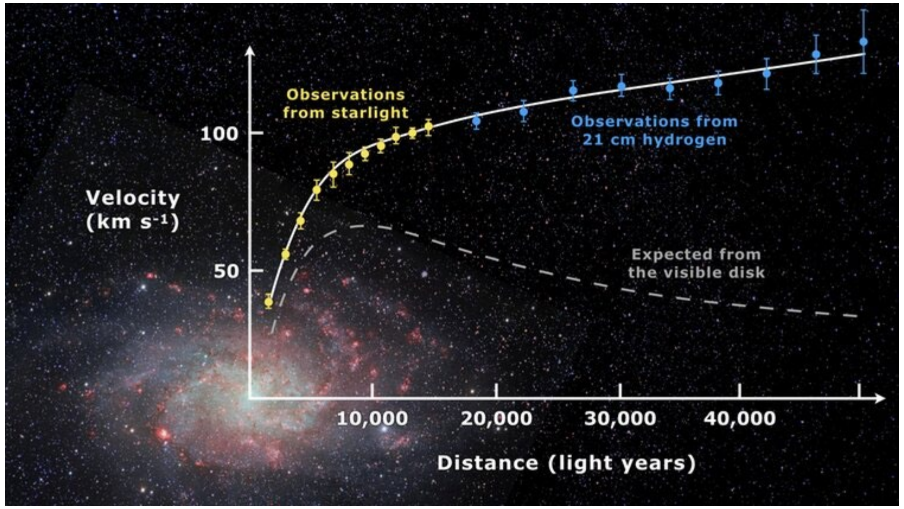
- The Standard Model is so far the most successful theory we have that describes the universe
  - Dark matter and dark energy are two loud questions waiting for a solution

BUT ONLY ~5%!



- All evidence we have on the dark matter are from the gravity (cosmology observations)

Can we find dark matter using the particle collider?



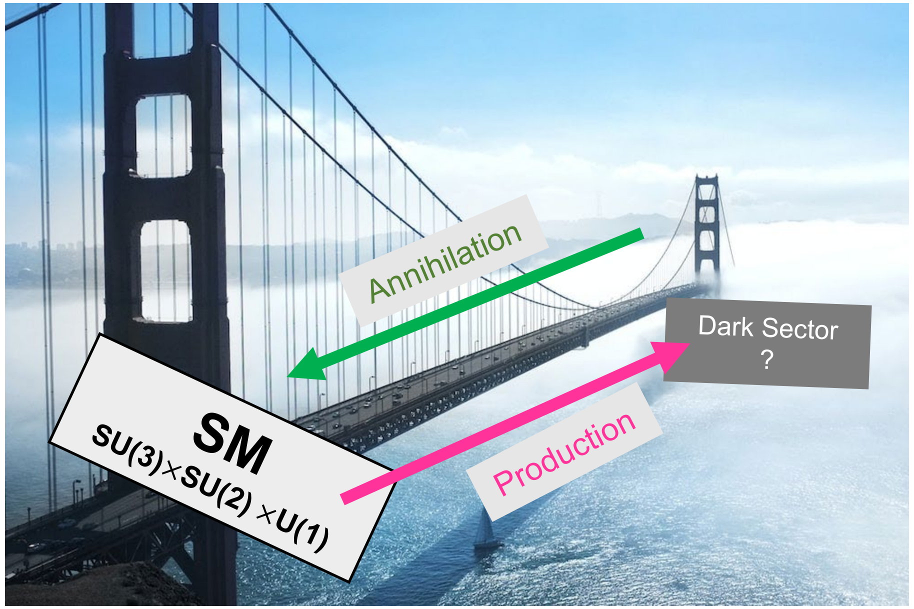
The Extended Rotation Curve and the Dark Matter Halo of M33. arXiv:astro-ph/9909252

Hubble Space Telescope image of Abell 370 galaxy cluster collisions. Credit: NASA, ESA

Using the *pp* collision @ LHC as a probe

✦ We need to have some assumptions first

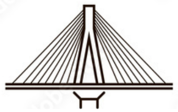
- If we want to detector dark matter using the LHC, then there must be at least some weak coupling between the SM and the dark sector



DM oriented

Simplified models
With the minimal number of free parameters

Extended Higgs sector
Generating masses of DM particles



Other more complete models

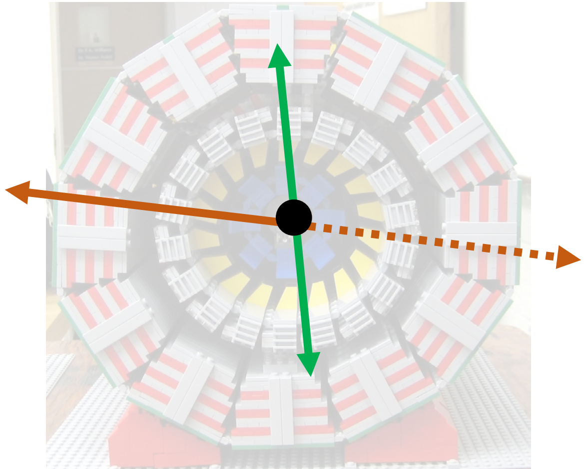
General BSM

dark photon

dark Higgs

SUSY,
extra dimensions…

- Manifest themselves as mainly two types of signatures at the CMS experiment



DM production associated with SM particles
With MET signatures, mono-X searches, semi-visible jets, dark showers …

DM mediator resonances decay into SM particles
Low mass resonances searches
…

Recent CMS results

I. **Search for dark matter particles produced in W^+W^- events with transverse momentum imbalance (darkHiggs + MET)**

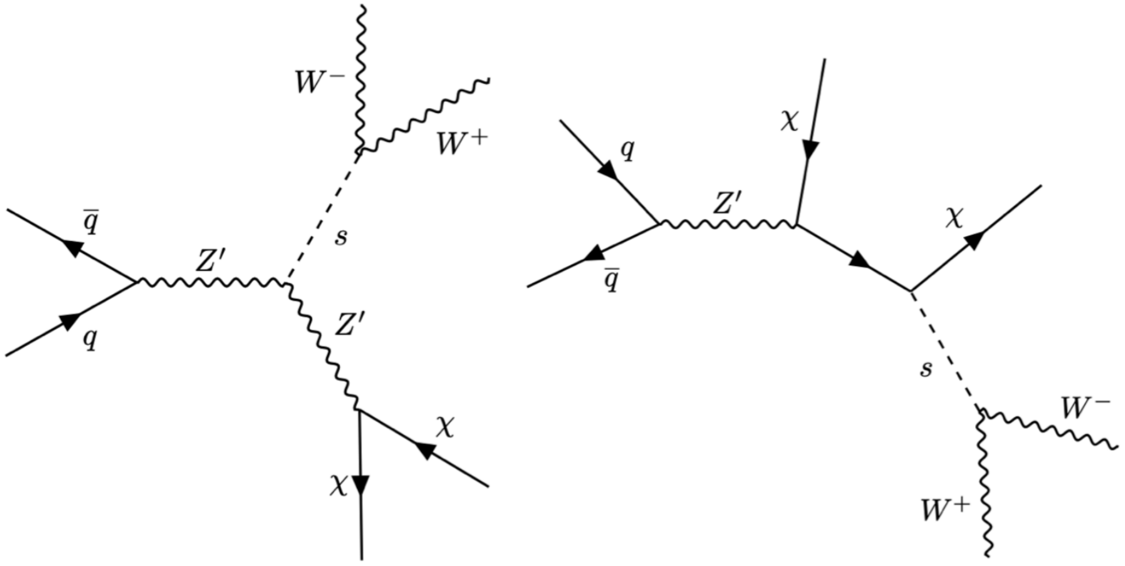
CMS PAS EXO-21-012

II. Search for prompt production of a GeV scale resonance decaying to a pair of muons

III. Other prompt searches

darkHiggs (WW) + MET

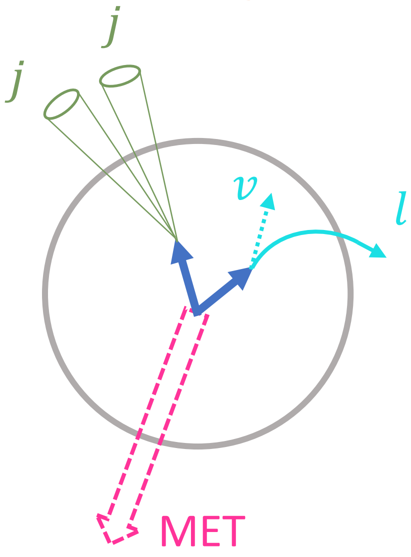
- Focus on the darkHiggs model [arXiv:1701.08780]
  - χ mass through dark Higgs (s) Yukawa coupling
  - two mediators: Z', s
  - free parameters: $m_s, m_\chi, m_{Z'}, g_\chi, g_q$

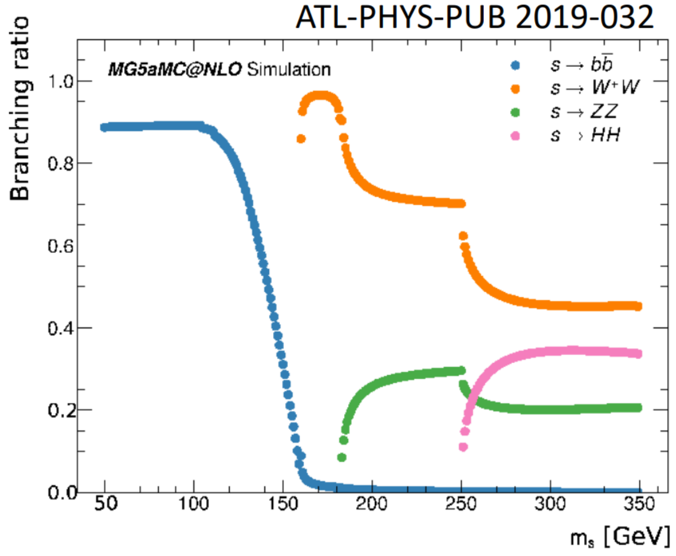


- First effort by CMS on $s \to WW$
  - WW becomes the dominating decay mode when $m_s > 160$ GeV (WW on shell)
  - Two final states are considered:

$s \to WW \to l\nu l\nu$ (di-leptonic)

$s \to WW \to l\nu jj$ (semi-leptonic, resolved)

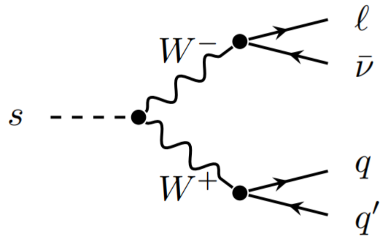




darkHiggs (WW) + MET (semi-leptonic)

✦ Signal signatures: 1 lepton, 2 jets, MET

- Triggering on muons (> 24 GeV) and electrons (> 25 GeV)
- Full Run-2 data (137 fb^{-1})



✦ Signal region selection

- Selection optimized for semi-leptonic *WW*
- Removing W-jets with b-veto to reduce top background
- High efficiency with good background reduction. Further optimized by the BDT

	Process	Estimation	CR/Validation
~17% SR	Top	MC + normalization freely floating, constrained by CR	Invert b-veto
~74% SR	W+jets	MC + normalization freely floating, constrained by CR	$m_{jj} < 65$ || $m_{jj} > 105$ GeV
~4% SR	Non-prompt	Fully data-driven estimation	Same lepton charge $m_T(l + \text{MET}) < 30$ && MET < 30 GeV

SR selection

nLeptons ≥ 1
nJet Clean ≥ 2 ($p_T > 30$ GeV, tight ID, loosePU if $p_T < 50$)
p_T^{l1} > trigger threshold
Veto 2nd loose leptons if $p_T^{l2} > 10$ GeV
$65 < m^{jj} < 105$ GeV
W candidate jets $\|\eta\| < 2.4$
b-veto DeepCSV LooseWP (excluding W candidate jets)
$\Delta\phi$(ljj, PuppiMET) > 2
$\Delta\phi$(jj,l) < 1.8, ΔR(jj,l) < 3
m_T(l + PuppiMET) > 80 GeV
PuppiMET > 60 GeV
$p_T^{ljj} > 60$ GeV

darkHiggs (WW) + MET (semi-leptonic)

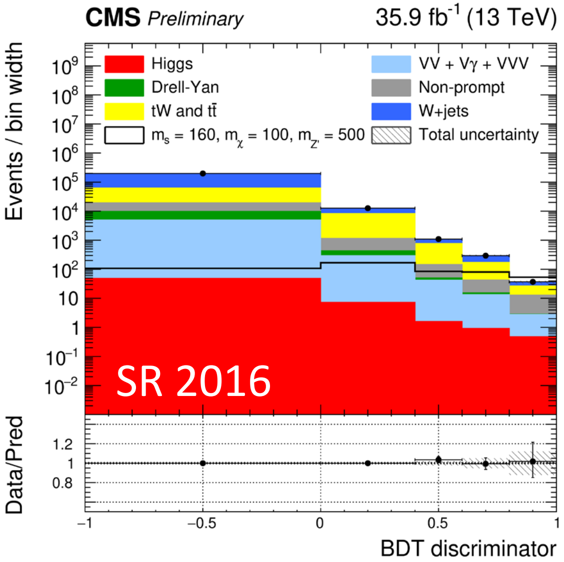
✦ BDT training

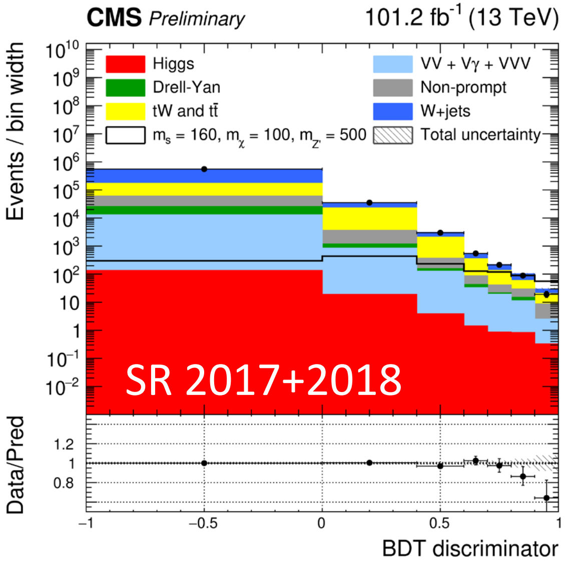
- Using 2017 sample (25%)
- Bkg: W+jets, top
- Signal: $m_{Z'} \geq 800$ GeV
- 13 variables selected based on ROCs
- Kolmogorov-Smirnov 2 sample test to avoid overtraining

99% bkg reduction (last 5 bins)

40-60% signal (last 5 bins)

Variable	Definition
p_T^{jj}	p_T of the vectorial sum of the W candidate jets
$p_T^{\ell jj}$	p_T of the vectorial sum of the visible particles
p_T^{miss}	Size of the missing transverse momentum vector
$\Delta\eta_{\ell,jj}$ and $\Delta\phi_{\ell,jj}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and the di-jet system
$\Delta\eta_{j,j}$ and $\Delta\phi_{j,j}$	$\Delta\eta$ and $\Delta\phi$ between the W candidate jets
$\Delta\eta_{\ell,p_T^{miss}}$ and $\Delta\phi_{\ell,p_T^{miss}}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and $\vec{p}_T^{miss}$
$\Delta\phi_{\ell jj,p_T^{miss}}$	$\Delta\phi$ between the vectorial sum of the visible particles and $\vec{p}_T^{miss}$
$min(p_T^{\ell}, p_T^{j2})/p_T^{miss}$	Minimum of the lepton p_T and the trailing jet p_T, divided by p_T^{miss}
$max(p_T^{\ell}, p_T^{j2})/p_T^{miss}$	Maximum of the lepton p_T and the leading jet p_T, divided by p_T^{miss}
$max(p_T^{\ell}, p_T^{j1})/m_{\ell jj p_T^{miss}}$	Maximum of the lepton p_T and the leading jet p_T, divided by the invariant mass of the vectorial sum of the visible particles and the p_T^{miss} where the missing energy is considered to be massless



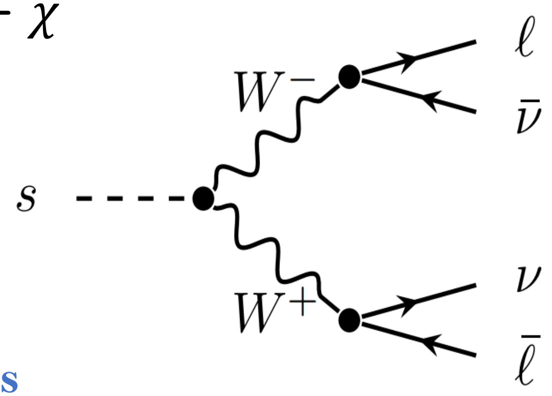


✦ Uncertainties

- MC statistics in significant bins
- Top p_T reweighting and W+jet NLO scale factors
- Experimental: lumi; trigger eff; lepton RECO, energy scale; b-tagging; MET unclustered…
- Theory: PDF; QCD scale…

darkHiggs (WW) + MET (di-leptonic)

- Signal signatures: 2 different flavor leptons ($e\mu$), MET from neutrinos + χ
  - Triggering on muons (>8 GeV) and electrons (>12 GeV) with di-lepton triggers
  - Full Run-2 data (137 fb^{-1})



Selection
nLeptons ≥ 2, Different flavour, opposite signed
$p_T^{\ell_1}$ / $p_T^{\ell_2}$ > 25 / 20 GeV
Vetoed additional loose leptons with $p_T^{\ell_3}$ > 10 GeV
$p_T^{\ell\ell}$ > 30 GeV
$m_{\ell\ell}$ > 12 GeV
p_T^{miss} > 20 GeV
min(proj. p_T^{miss}, proj. Trk p_T^{miss}) > 20 GeV
$m_T(\ell\ell + p_T^{miss})$ > 50 GeV
$\Delta R(\ell\ell)$ < 2.5
bVeto DeepCSV LooseWP (pTj > 20 GeV, Tight ID, loose pu Id if pTj < 50 GeV)

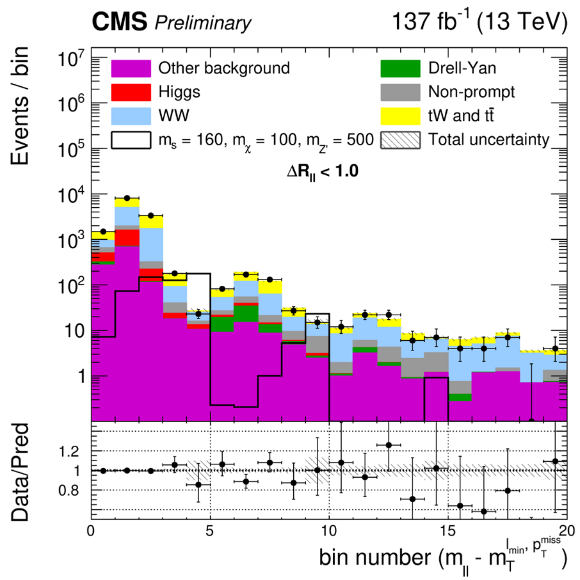
- Signal region selection
  - Reduce background from fakes
  - Suppress contributions from Drell-Yan
  - Suppress WW production
  - Suppress $t\bar{t}$ production

Process	Estimation	CR/Validation
Top	MC + normalization freely floating, constrained by CR	Invert b-veto
Non-prompt	Fully data-driven estimation	Same lepton charge
		m_T(l + MET) < 30 && MET < 30 GeV
WW	MC + normalization freely floating, constrained by CR	ΔR(l,l) > 2.5
Drell-Yan	MC + normalization freely floating, constrained by CR	m_T(ll + MET) < 50 GeV

darkHiggs (WW) + MET (di-leptonic)

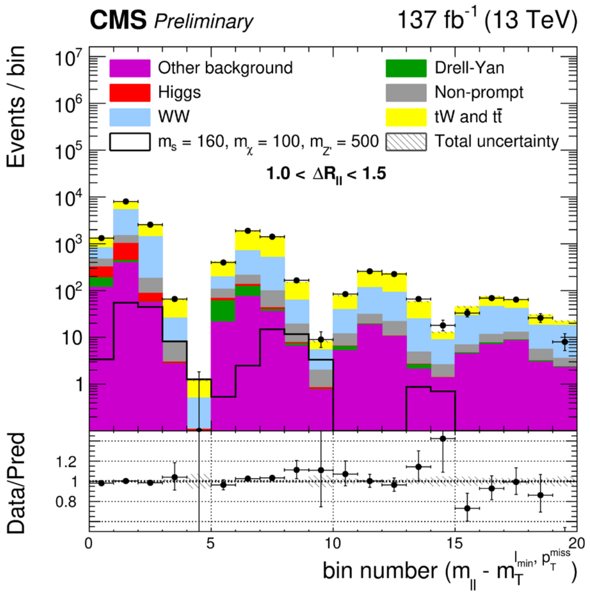
✦ Signal extraction

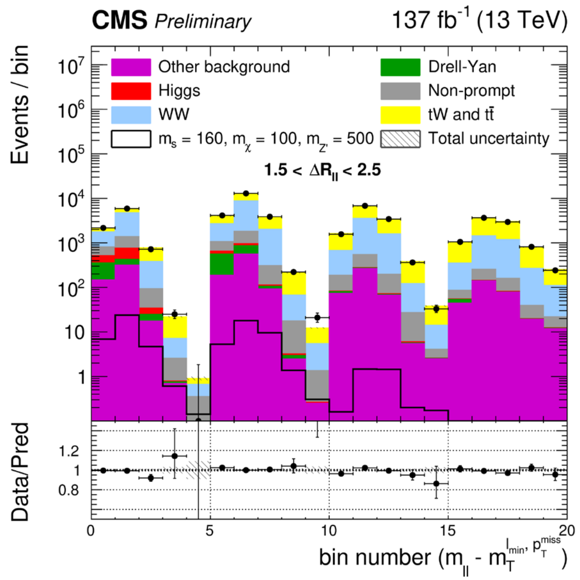
- 3-D maximum likelihood fit to $\Delta R_{ll}, m_{ll}, m_T^{l_{min}, p_T^{miss}}$ (more sensitive than variables based on lepton kinematics)
- 3 SRs on ΔR_{ll} based on how boosted the darkHiggs is: [0,1.0],[1.0,1.5] and [1.5.2.5]



✦ Uncertainties

- MC statistics in significant bins
- WW MC NNLO+NNLL scale factors,
- Top p_T reweighting
- Experimental: lumi; trigger eff; lepton RECO, energy scale; b-tagging; MET unclustered…
- Theory: PDF; QCD scale…





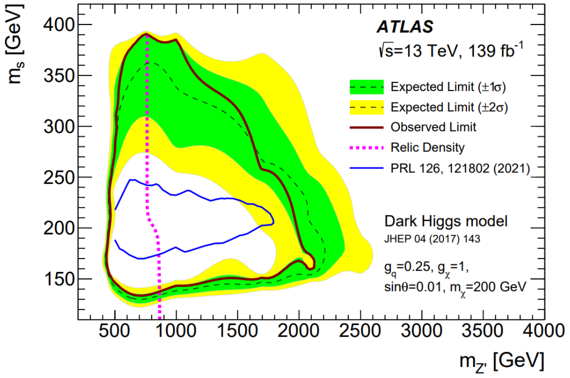
darkHiggs (WW) + MET (combination)

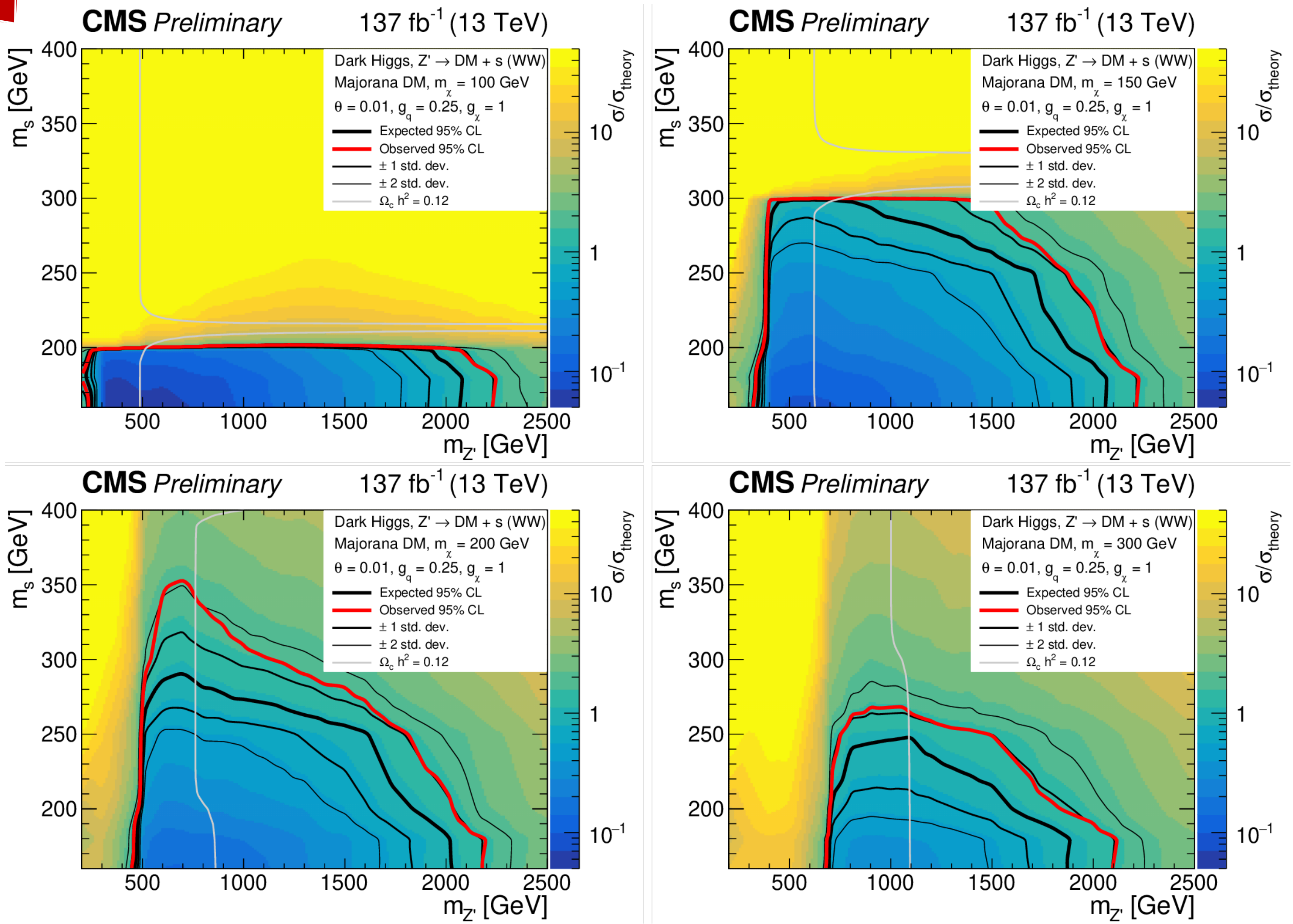
[CMS PAS EXO-21-012](#)

Target JHEP

- ✓ Extended coverage of the dark matter mass -> [100, 300] GeV
- ✓ No significant deviation is seen. Most stringent limit for m_χ=200 GeV compared to ATLAS previous results[1]

- **m_s < 350 GeV excluded @ $m_{Z'}$ = 700 GeV**
- **$m_{Z'}$ < 2200 GeV excluded @ m_s = 160 GeV**





[1] arXiv:2211.07175

Recent CMS results

I. Search for dark matter particles produced in W^+W^- events with transverse momentum imbalance (darkHiggs + MET)

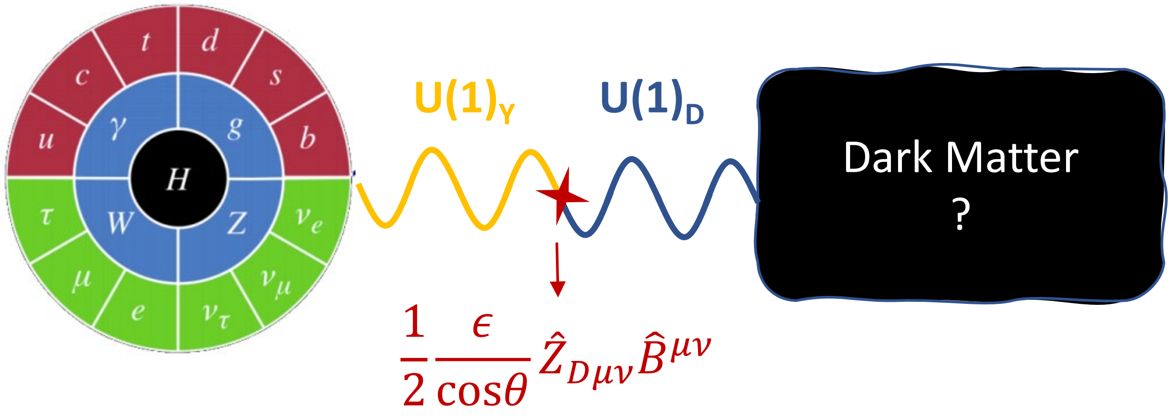
II. Search for prompt production of a GeV scale resonance decaying to a pair of muons

CMS PAS EXO-21-005

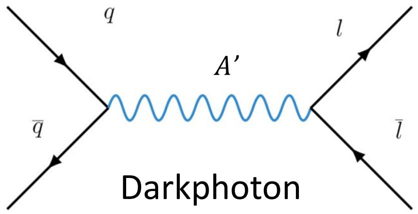
III. Other prompt searches

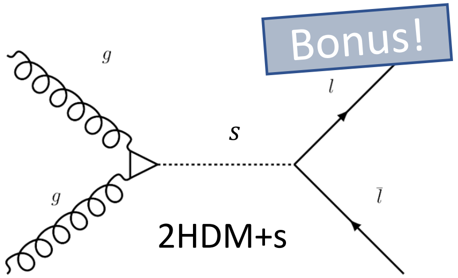
Prompt low mass di-muon with scouting

✦ Mainly targeting light mediators (short-lived)



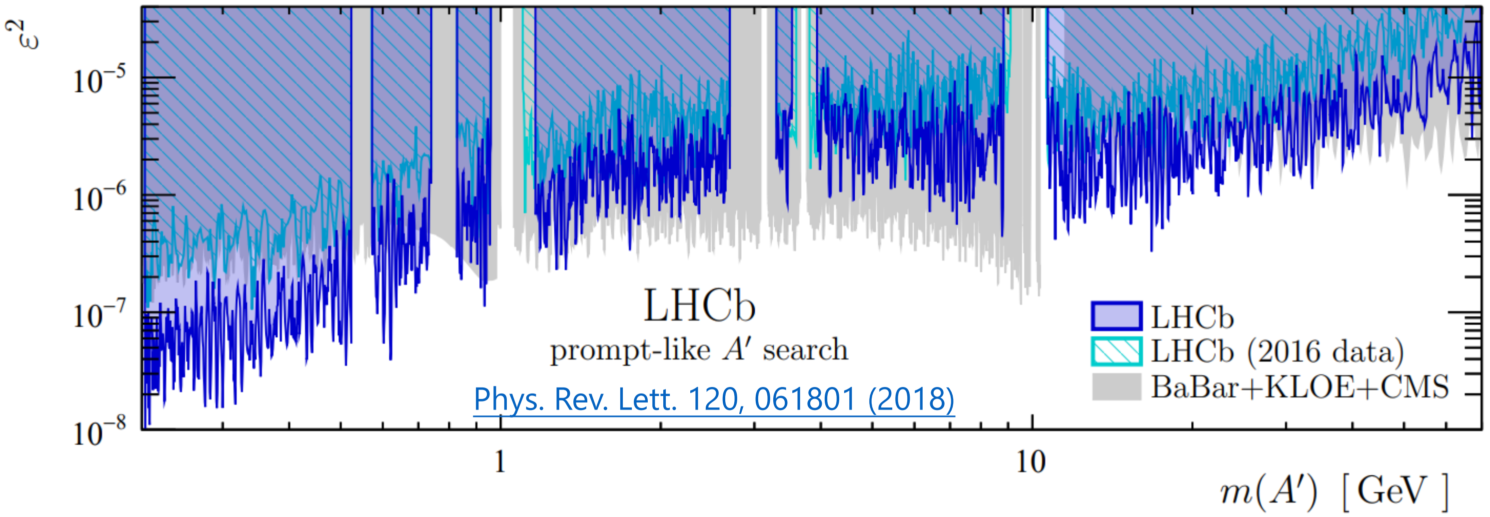
- Kinetic mixing between SM and the dark sector, controlled by mixing parameter ϵ (A')
- Portals allow SM particles to couple with the dark matter
- If the mixing is sizeable, these mediators would be short-lived





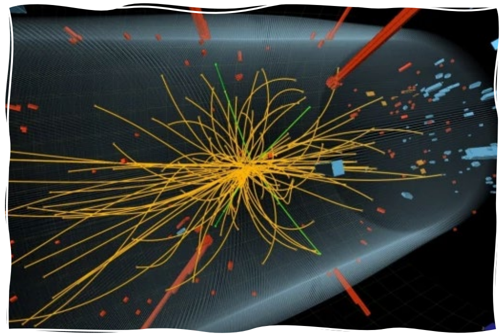
✦ A challenging search with traditional trigger strategies

- Unknown dark photon mass and coupling
- Low-pt objects, very high trigger rate with traditional triggers
- Huge data set to process, resource consuming



Prompt low mass di-muon with scouting

- CMS data scouting



40 MHz

L1 trigger

100 kHz

HLT trigger

1 kHz

Total Bandwidth

Event Rate * Size

~ 1 GB/s

Offline RECO & storage

HLT object RECO

Reduced event size

HLT object repack

1.5 kB/evt

Scouting data

~ 3 kHz

~ 5 MB/s

Traditional muon triggers
$p_T(\mu) > \sim 15$ GeV

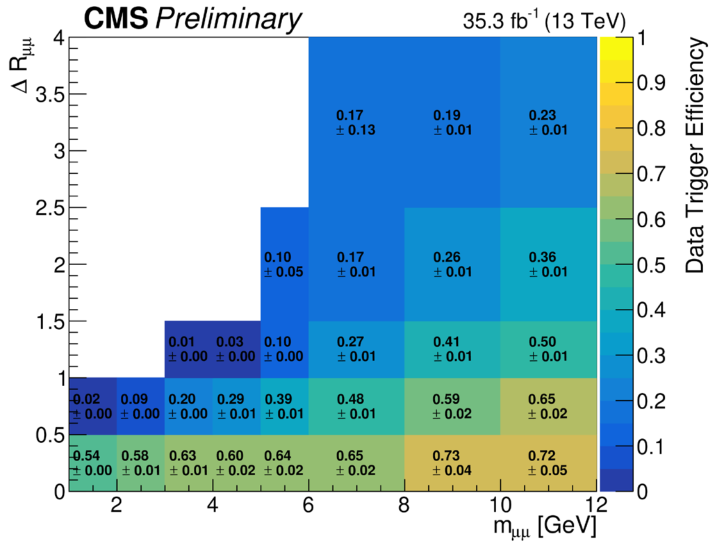
Sacrifice event content to lower trigger thresholds (more physics possibilities)

Scouting muon triggers
$p_T(\mu) > 3$ GeV
($m_{\mu\mu} \sim 200$ MeV)

Prompt low mass di-muon with scouting

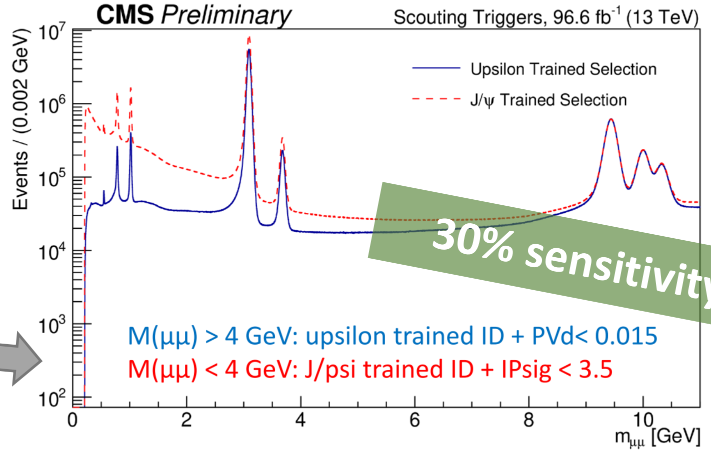
- Targeted signature: 2 muons with small primary vertex displacement
  - Triggering on double muons (>3 GeV) with the scouting method
  - 2017 + 2018 data (97 fb^{-1})
  - Benchmark model: **Hidden Abelian Higgs Model, 2HDM+s**

arXiv:0803.1243 JHEP03(2018)178

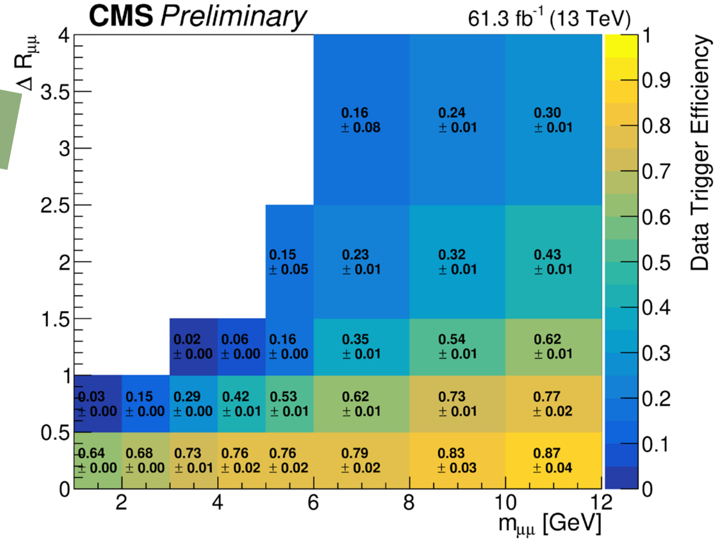


Baseline selections

> 1 opposite sign muon pair
$p_T > 4$ GeV, $\lvert\eta\rvert < 1.9$
|PV - BeamSpot| (L) < 0.2 cm
Pass two custom muon BDT IDs ($m_{\mu\mu} < 4$ GeV: J/ψ $m_{\mu\mu} > 4$ GeV: Upsilon)



30% sensitivity ↑



Add. Selection

Dark photon "inclusive"

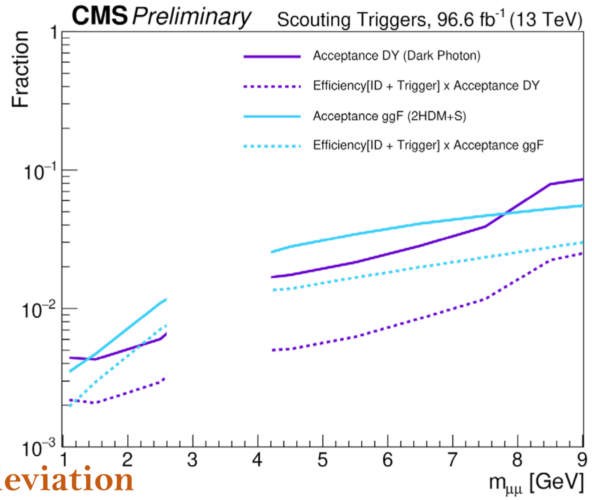
Pseudoscalar "boosted"

mass	$m_{\mu\mu} < 4$ GeV	$m_{\mu\mu} > 4$ GeV	$m_{\mu\mu} < 4$ GeV	$m_{\mu\mu} > 4$ GeV
p_T	> 4 GeV		> 5 GeV	
Vertex	sig$L$ < 3.5	L < 0.015cm	sig$L$ < 3.5	
$p_{T\mu\mu}$	-	-	> 35 GeV	> 20 GeV

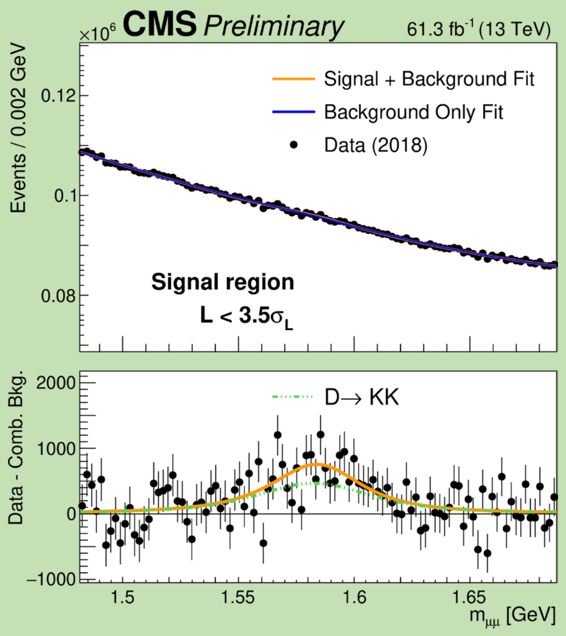
Prompt low mass di-muon with scouting

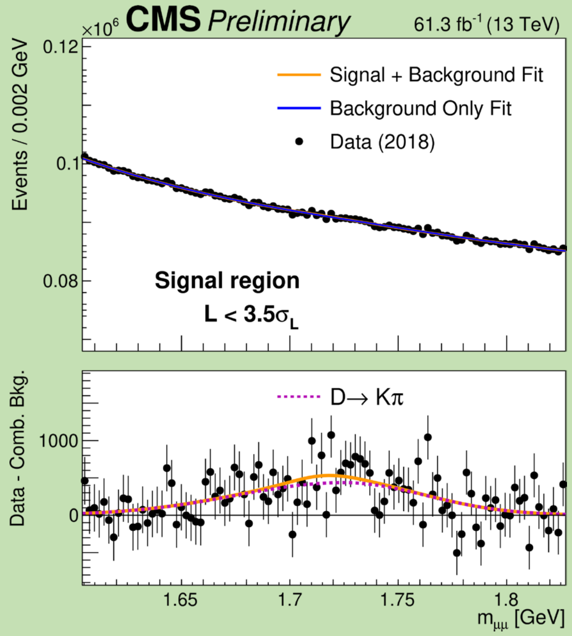
- Bump-hunt on the di-muon mass spectra
  - Signal shape: DCB+Gaus
  - Background estimation: empirical parametric functions **(corrected for the $D_0 \to KK/K\pi$ mis-identification)** with discrete profiling

Effect	$m_{\mu\mu} < 2.6$ GeV	$m_{\mu\mu} > 4.2$ GeV
Integrated luminosity	2.3–2.5%	
Mass resolution	20%	
Trigger efficiency	1–20%	
Muon ID efficiency	4–9%	12–20%
Vertex selection	—	3%
Efficiency application	8%	4%
D meson normalization TFs	20–25%	—

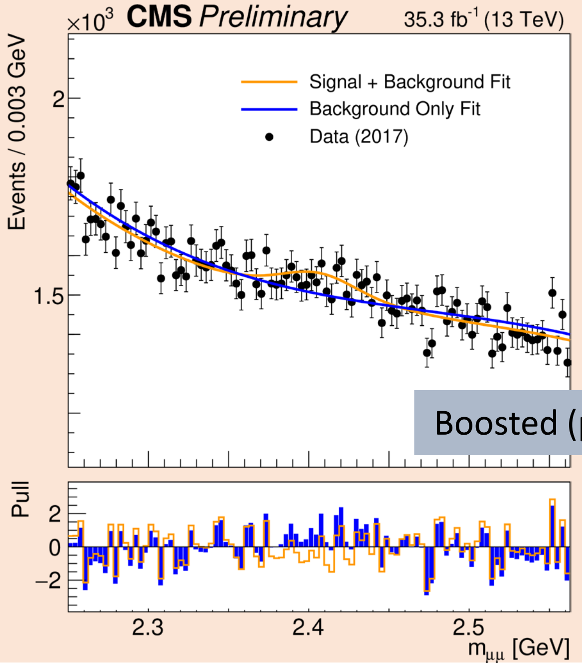


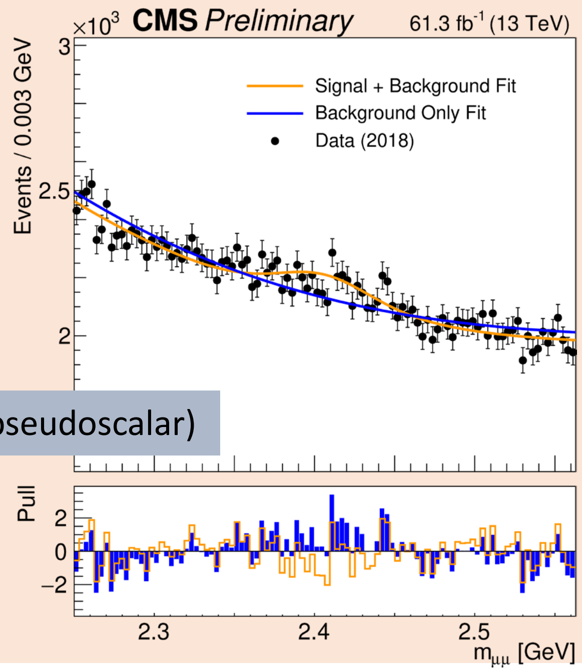
$D_0 \to KK/K\pi$ mis-identification





s+b fit for the most significant deviation





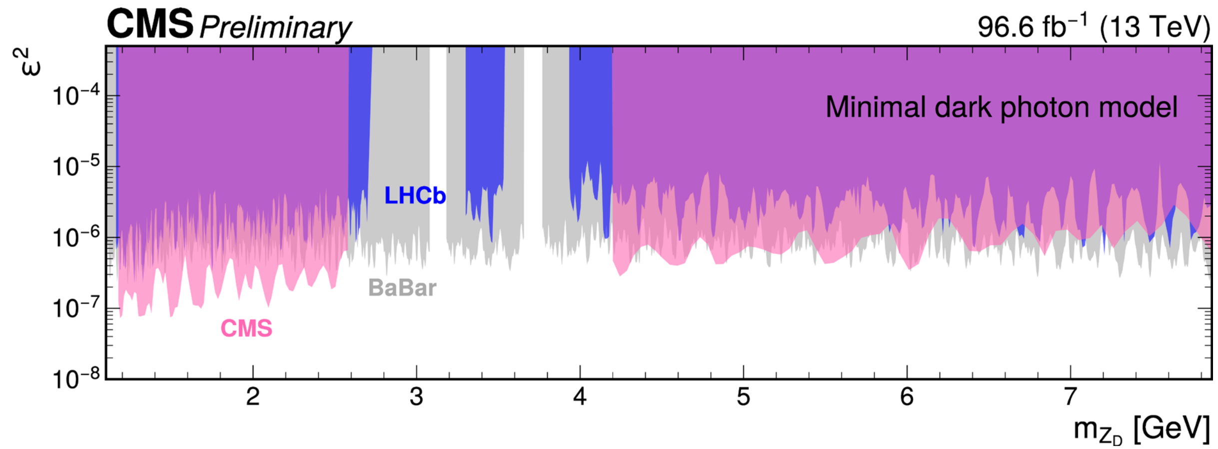
Boosted (pseudoscalar)

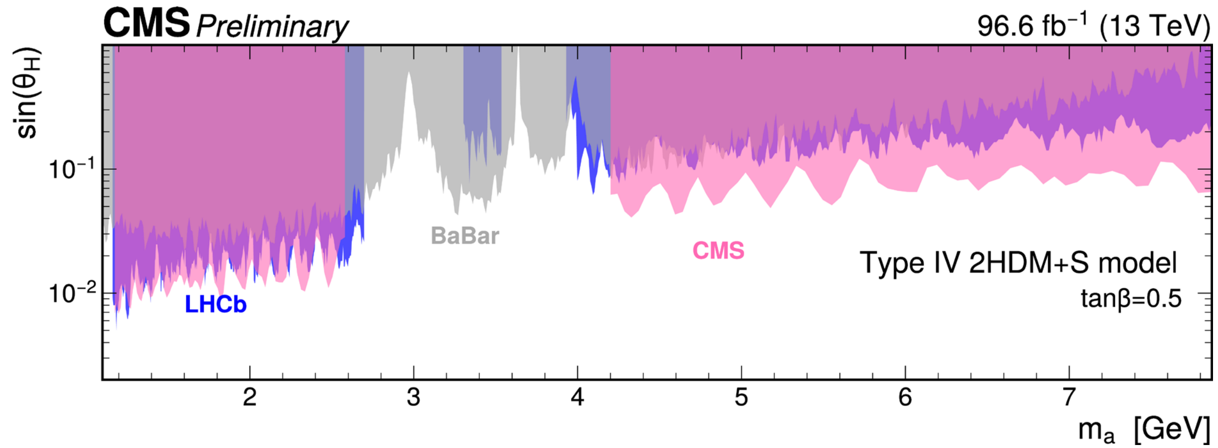
Prompt low mass di-muon with scouting

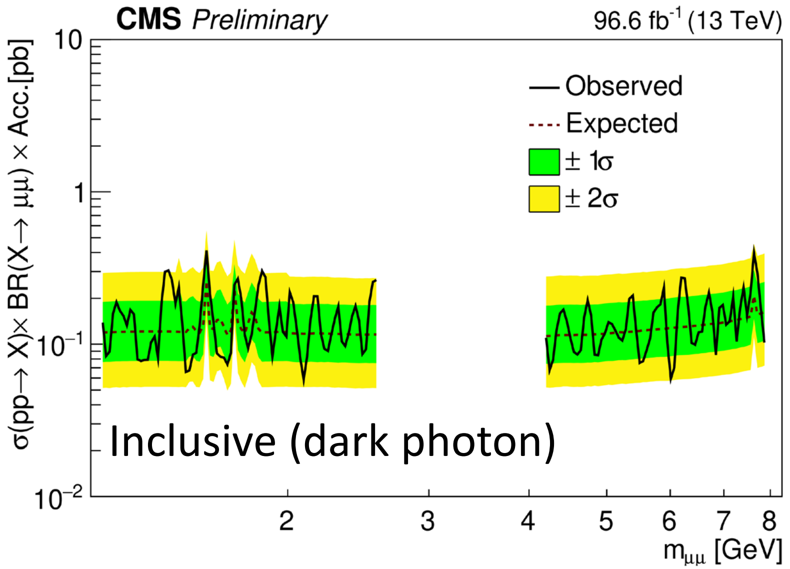
- Limits are set for $m_{\mu\mu}$ in [1.1, 2.6] and [4.2, 7.9] GeV
  - Largest excess @ 2.41 GeV in the boosted category, low mass selection

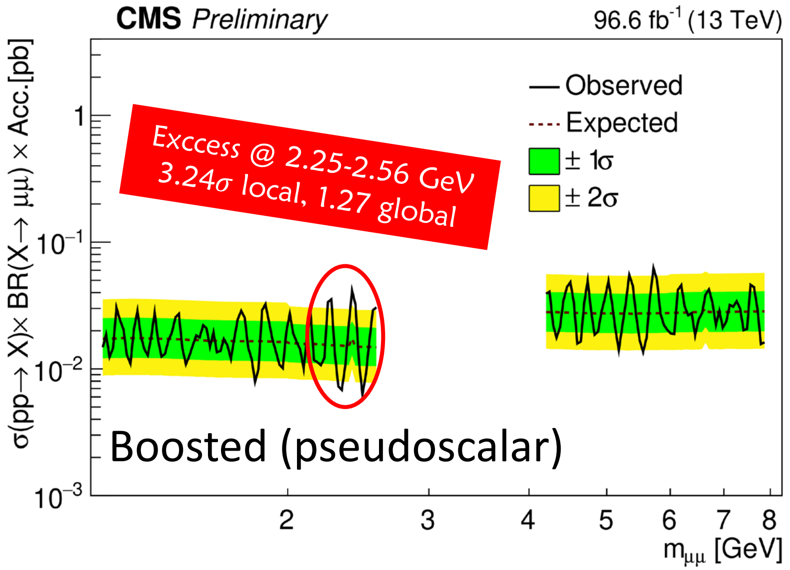
Local 3.2σ, global 1.3σ

Target JHEP









Recent CMS results

I. Search for dark matter particles produced in W^+W^- events with transverse momentum imbalance (darkHiggs + MET)

II. Search for prompt production of a GeV scale resonance decaying to a pair of muons

III. Other prompt searches (for more complete models)

CMS PAS EXO-22-008 CMS PAS EXO-22-016

Other prompt searches

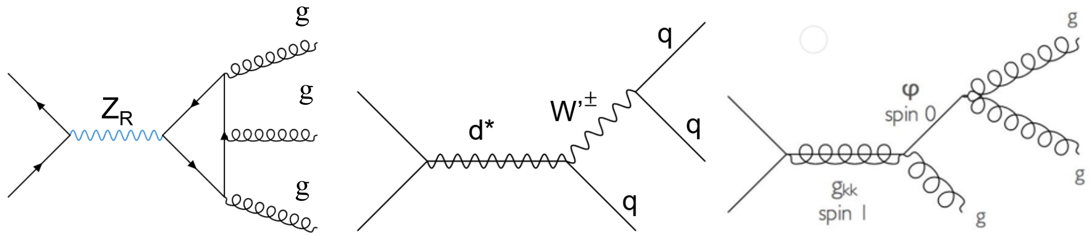
New!!

Search for resolved high-mass trijet resonances

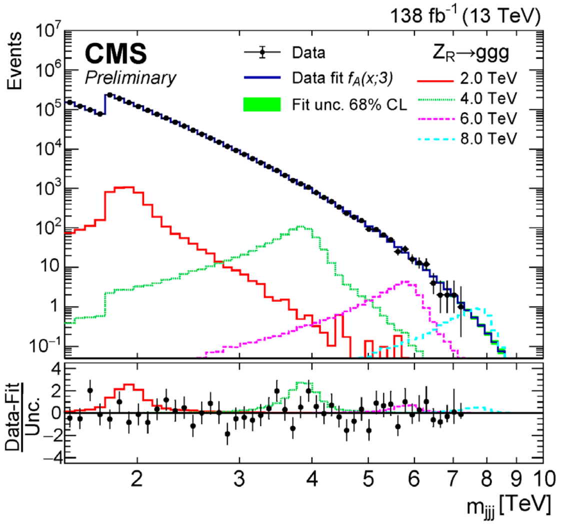
CMS-PAS-EXO-22-008

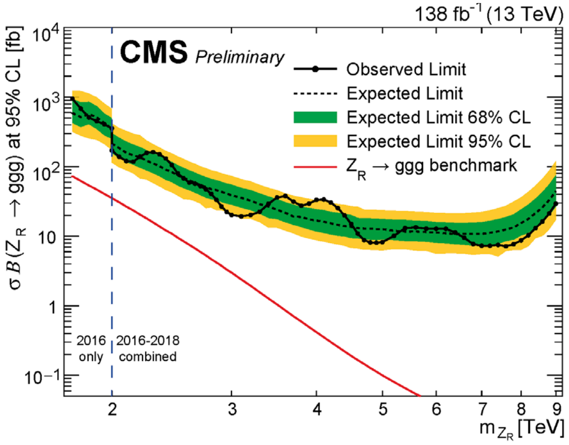
✦ **First search** for the single production of resolved trijet resonances!

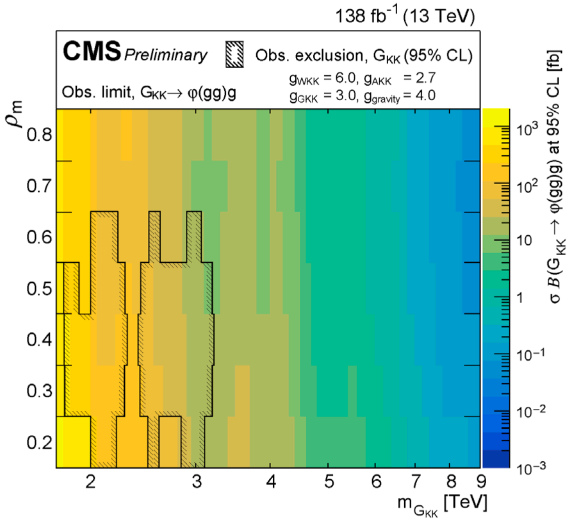
- Targeted both the **3-body decay** ($X \rightarrow jjj$) and **cascade decay** ($X \rightarrow Yj \rightarrow jjj$) in [1.75, 9.0] TeV. Extended a previous CMS search[1] for the cascade decay
- Bump-hunt on m_{jjj} with energy radiated by final state gluons recovered. Background estimated from parametric function fits to the data

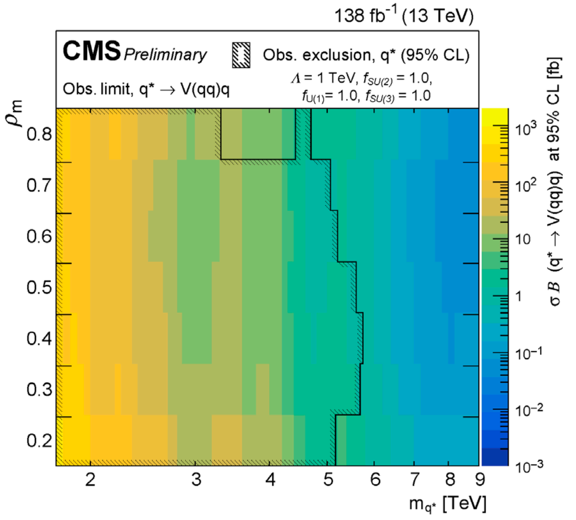


- No significant excess. Limits could be easily reinterpreted with other models predicting such new heavy resonances









More in Manos's talk

[1] Phys. Lett. B 832 (2022) 137263

Other prompt searches

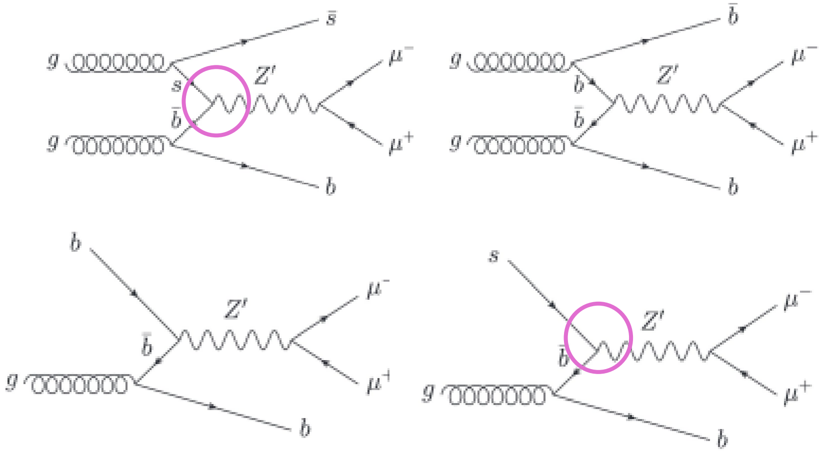
New!!

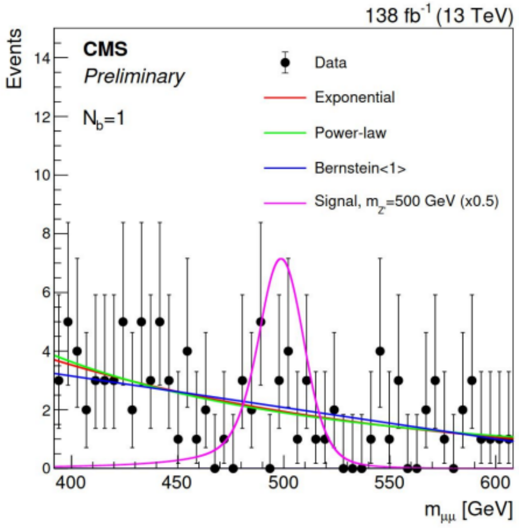
high mass dimuon resonance associated with b quark jets

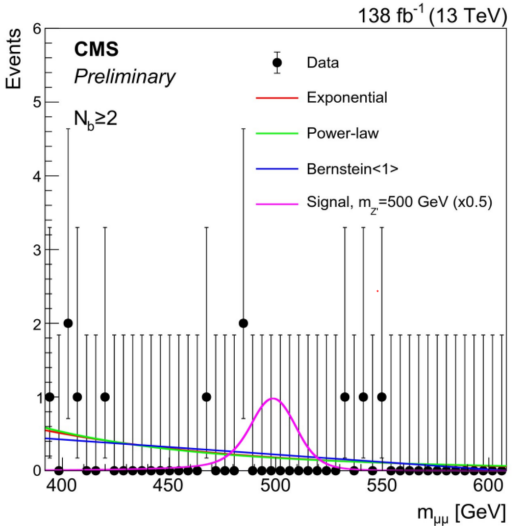
CMS-PAS-EXO-22-016

✦ Main target: new Z' (for $b \to sll$ anomalies)

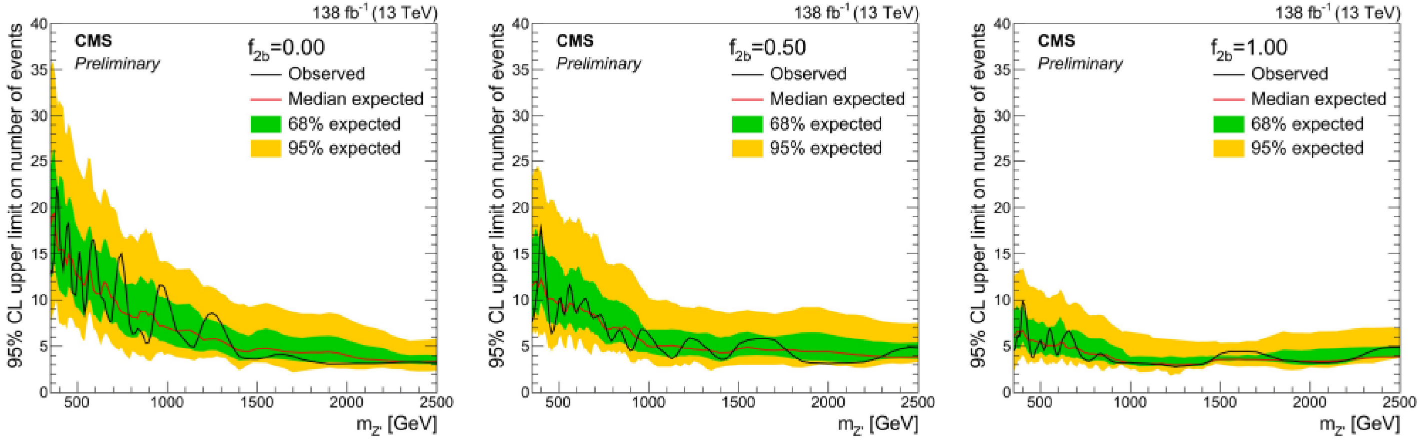
- Events categorized based on the number of b-jet (= 1 or ≥ 2).
- $t\bar{t}$ killer: background rejected with $\min(m_{\mu b}) > 175$ GeV
- Bump-hunt, SM background estimated from parametric function fits to the data
- Z' between 0.35 - 2.5 TeV are considered. Limits could be interpreted by any neutral resonance model







More in Manos's talk

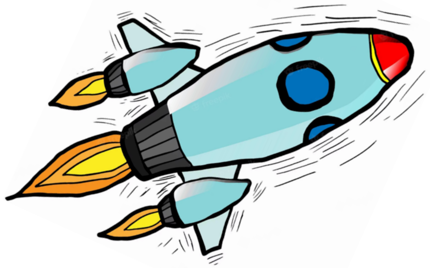


Conclusions

- ✓ Continuous efforts by the CMS on the search for dark matter, as well as other generic BSM scenarios
- ✓ Improved data taking / analysis techniques provided more stringent results
- ✓ Unfortunately, the dark particles are still playing the "hide and seek" with us

- ✓ Second year in Run-3, moving to look at new Run-3 data
- ✓ Doubled statistics allows further essential scrutinizes of excesses seen in Run-2
- ✓ New possibilities
  - New advanced taggers based on ML
  - Data parking, can we gain something from it for low-pt searches?
  - …

Let's go



DARKER