Search for Dark Matter with mono-X Signatures in CMS

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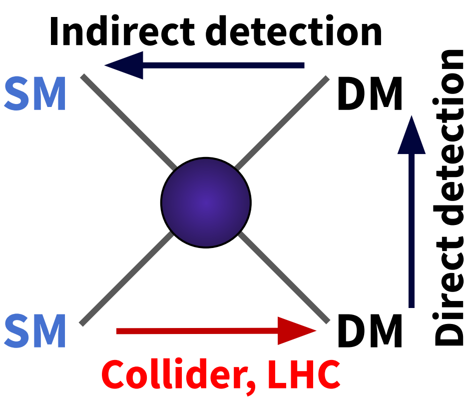
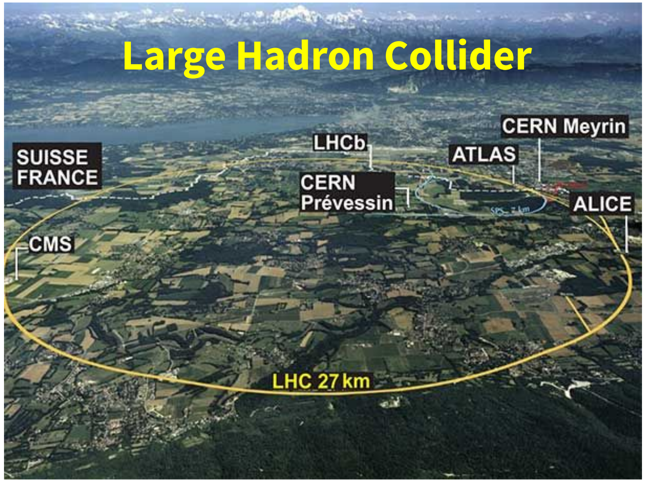
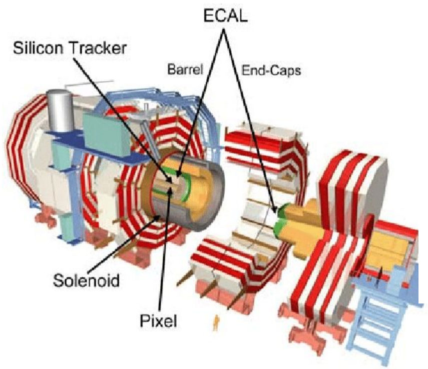
Dark Matter Search at the LHC and CMS

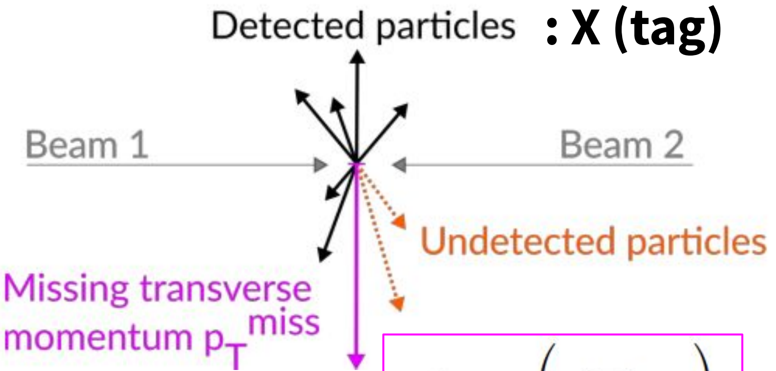
- **Dark matter (DM)** is well-established in the cosmos
  - Is it Weakly Interacting Massive Particle (WIMP)? : M~10 MeV-100 TeV
- **LHC** is world's most powerful discovery machine!
  - Run 2 : from 2015 - 2018 at $\sqrt{s}$ = 13 TeV, ~140 fb^{-1} collected ✔
  - Run 3 : started 2022 - 2025 at $\sqrt{s}$ = 13.6 TeV, ~70 fb^{-1} (now)
- **CMS** is a multi-purpose detector that records pp collisions from the LHC





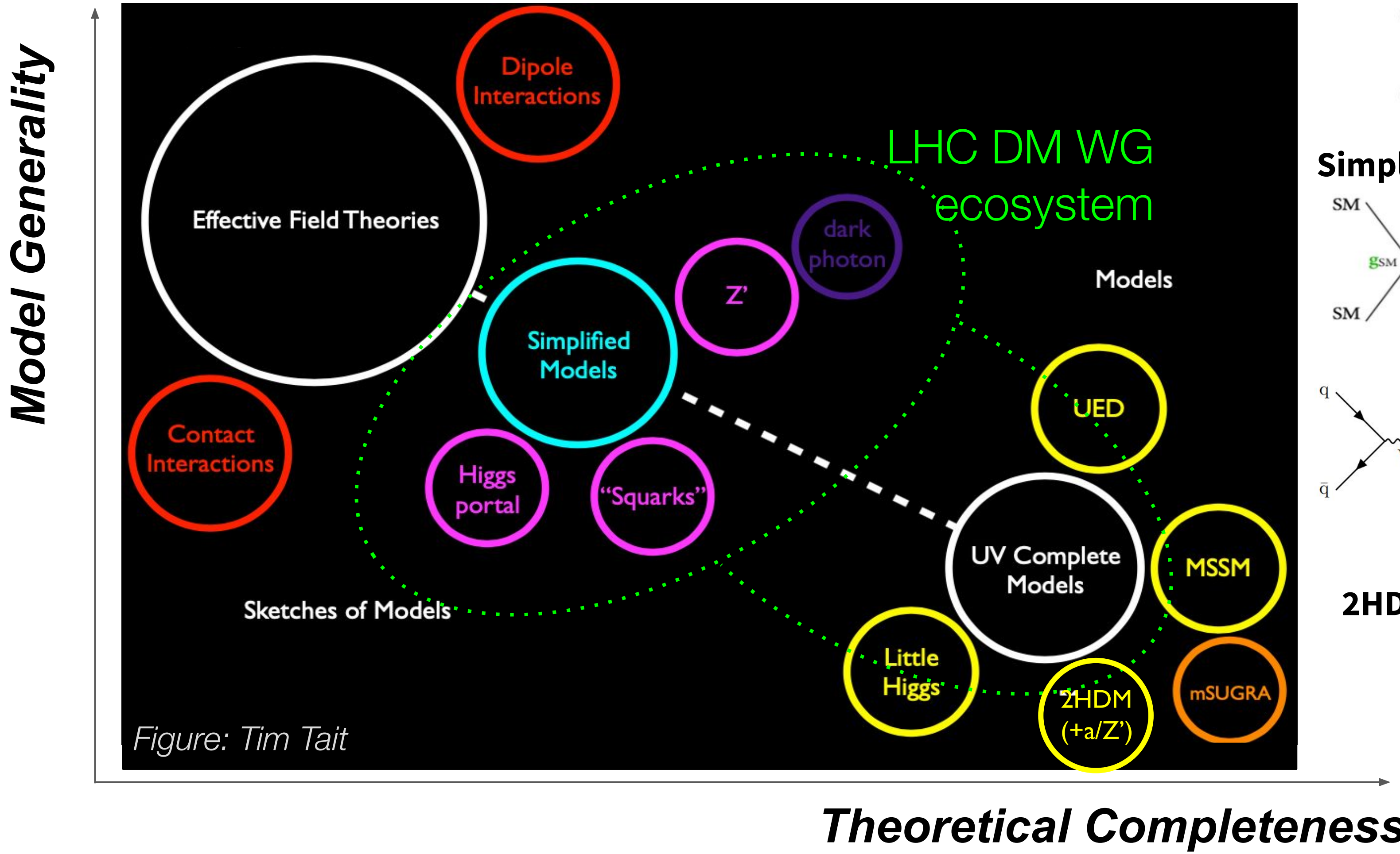
Compact Muon Solenoid

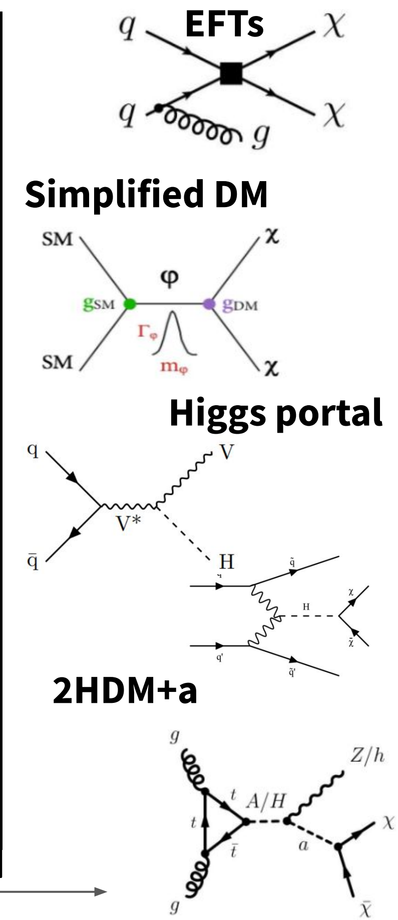




$$\vec{p}_T^{\,miss} = -\left(\sum_{i \in particles} \vec{p}_i \right)_T$$

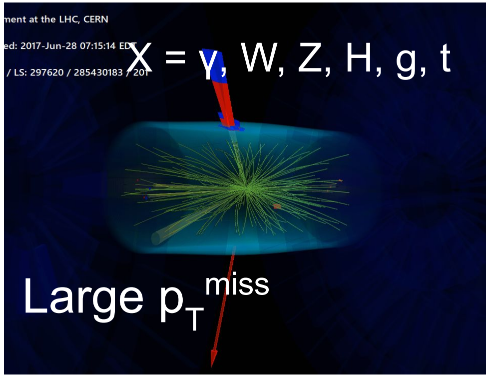
Theoretical Framework





Mono-X class of searches (CMS)

Signature X		DM Model	CMS publication	Luminosity [fb^{-1}] ($\sqrt{s}$)	
Jet, V (→qq)	+ p_T^{miss}	(1, 2, 3, 4)	*JHEP 11 (2021) 153*	137 (13 TeV)	✔
Z (→ll)	+ p_T^{miss}	(1, 4, 6)	*EPJ. C 81 (2021) 13*	137 (13 TeV)	✔
VBF	+ p_T^{miss}	(2)	*PRD 105 (2022) 092007*	19.7 (8 TeV)+140 (13 TeV)	✔
WW	+ p_T^{miss}	(8)	PAS-EXO-21-012	137 (13 TeV)	✔
Displaced μμ	+ p_T^{miss}	(9)	arXiv:2305.11649	137 (13 TeV) **most recent**	✔
Higgs	+ p_T^{miss}	(6, 7)	*JHEP 03 (2020) 025*	35.9 (13 TeV)	
γ	+ p_T^{miss}	(1, 4)	*JHEP 02 (2019) 074*	35.9 (13 TeV)	
tt, t/tW	+ p_T^{miss}	(1)	*JHEP 03 (2019) 141*	35.9 (13 TeV)	

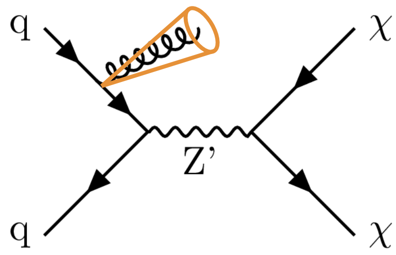


A broad spectrum of DM models and visible 'X'

1. **Simplified DM** (Spin-1,0 mediated) , Phys. Dark Univ. 27 (2020) 100371
2. **Higgs portal DM** , Phys. Lett. B 707 (2012) 570 , Phys. Rev. D 82 (2010) 055026
3. **Fermion portal DM** , JHEP 11 (2013) 171
4. **ADD** , Phys. Lett. B 429 (1998) 263
5. **Non-thermal DM**, Phys. Rev. D 93, 055007
6. **2HDM (+a/Z')** , JHEP 05, 138 (2017) , Phys. Dark Univ. 27, 100351 (2020)
7. **Baryonic Z'** , Phys. Dark Univ. 26 (2019) 100371
8. **Dark Higgs** , JHEP 4 (2017) 143
9. **Inelastic DM** , Phys. Rev.D 64, 043502 , Phys. Rev. D 93.063523 and so on …

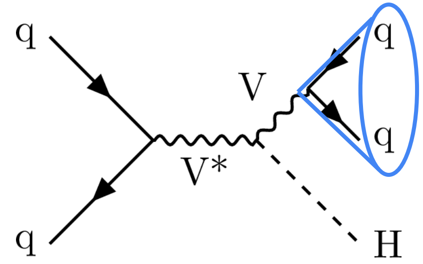
Mono-jet + mono-V(qq) search

- Signal : Jets + p_T^{miss} ⇒ Mono-jet, Mono-V categories and combined
- Selection :



Narrow jets from ISR

Jet p_T (AK4) > 250 GeV, |η| < 2.4

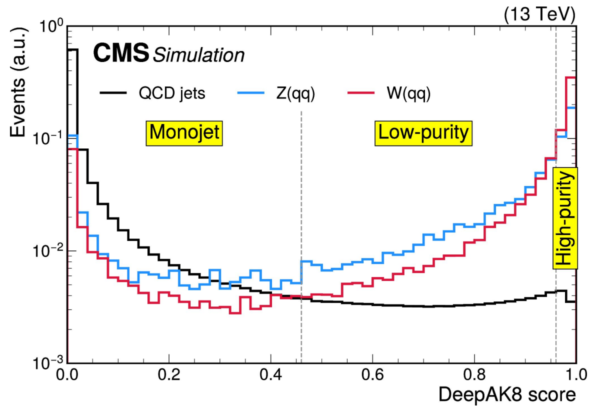


Fat jets from V→ qq

Jet p_T (AK8) > 100 (150) GeV, |η| < 2.4

M_{jj} window 65-120 GeV

- Use DNN ID to distinguish V(qq) from ISR jets
- p_T^{miss} Trigger (offline p_T^{miss} > 250 GeV)
- Veto events with leptons, photons, b-jets



- Dominant backgrounds : $Z(\nu\nu)/W(l\nu)$+jets, γ+jets
  Constrained in data-driven control regions (CR)

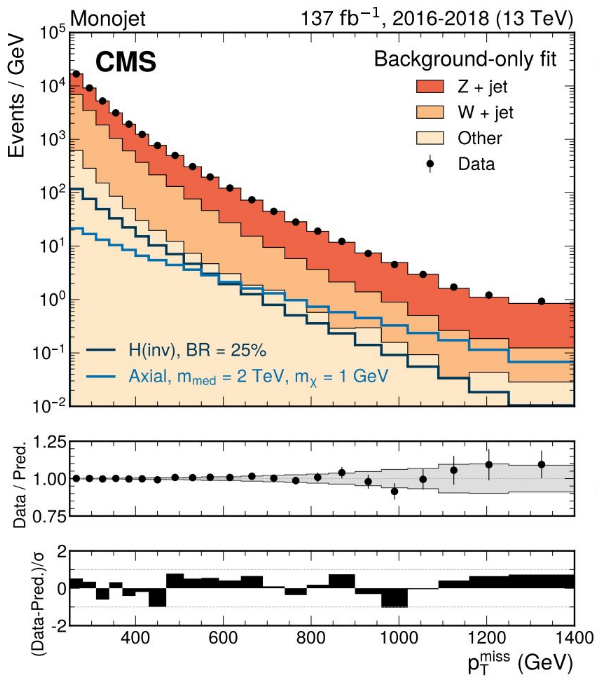
Background estimation

- Challenge: Estimate boson p_T in $Z(\nu\nu)$, $W(l\nu)$

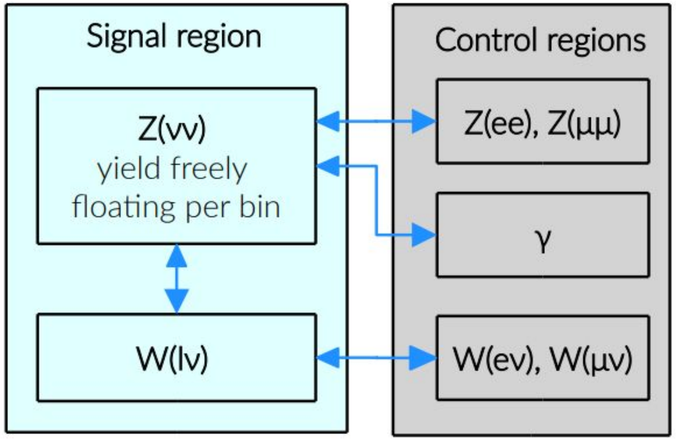
ee, $\mu\mu$,γ , e, μ

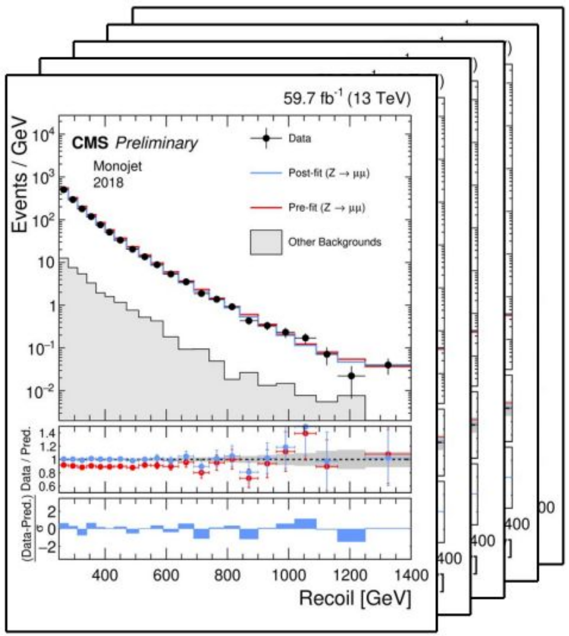
Monojet Signal Region (SR)

5 control regions (CR) per SR



Maximum-likelihood fit



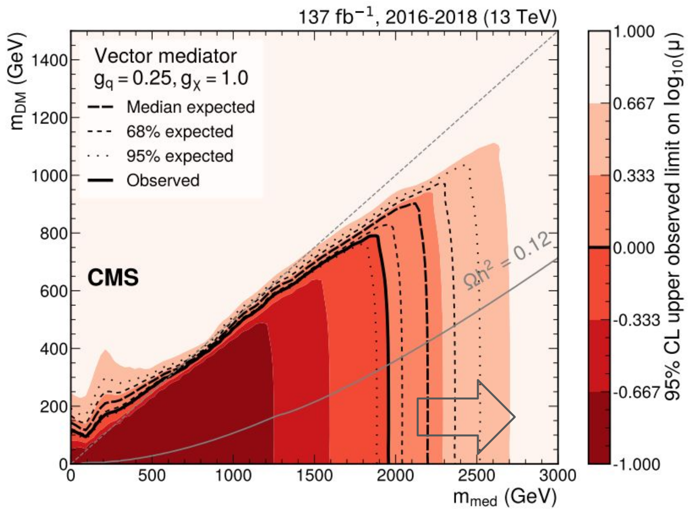


Transfer factors from MC

Normalization and shape from data
→ Common uncertainties cancel
especially theory, jet/p_T^{miss} calibration

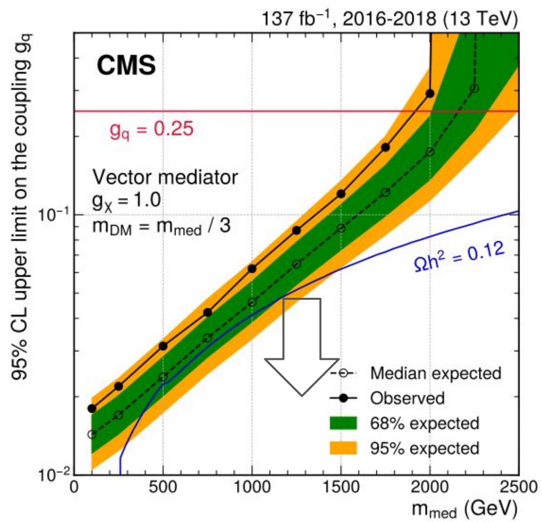
Mono-jet/V results

m_{med} vs m_{DM}



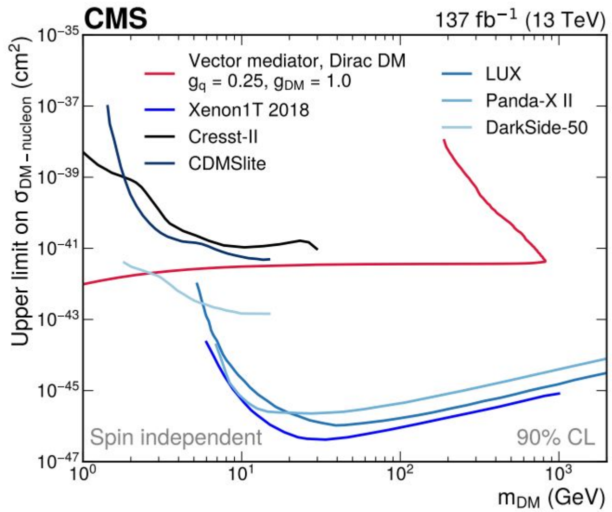
can probe up to m_{med} ~ 2 TeV

m_{med} vs g_q



probe down to g_q ~ 0.02

m_{DM} vs σ_{DM-N}

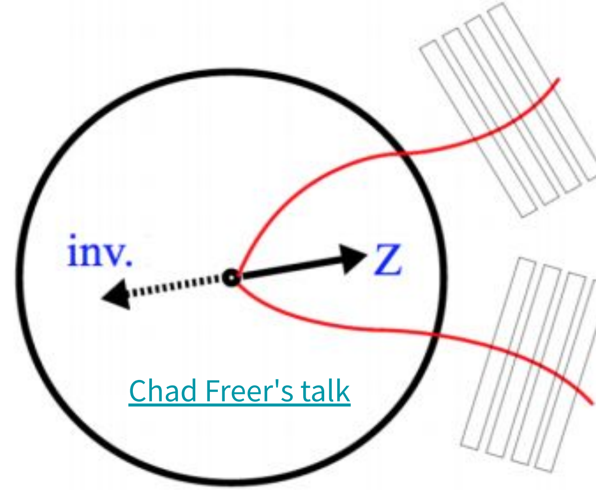


Best sensitivity at low masses

- Monojet dominates in low-g_q regime if DM coupling sizable (depends on parameters)
- Higgs portal : VH mode ⇒ Constraint on BR(h → invisible) < 27.8% (in backup)

Mono-Z(ll) search

- Signal : Events with OSSF dilepton (ee, μμ) + p_T^{miss}
- Selection :
- Single/Double lepton Triggers (ee 23,12, μμ 17,8 GeV)
- offline $p_T^{lep} > 25$ (20) GeV, $p_T^{miss} > 100$ (80) GeV
- $|M_{ll} - M_Z| < 15$ GeV, $p_T^{ll} > 60$ GeV, $\Delta R_{ll} < 1.8$
- $n_j < 2$, b-jet, tau veto $\Delta\phi(j, p_T^{miss}) > 0.5$,
- Kinematic cuts : $|p_T^{miss} - p_T^{ll}|/p_T^{ll} < 0.4$, $\Delta\phi(Z, p_T^{miss}) > 2.6$

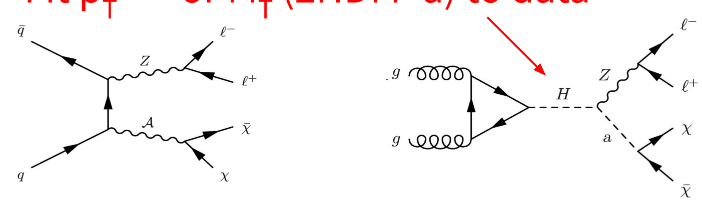


- SM Background Control Region (CR):
  - 3-lepton CR : WZ→lνll
  - 4-lepton CR : ZZ→ llll
  - eμ CR : OSOF events
  - DY CR : low p_T^{miss} sideband (80-100)

$$m_T = \sqrt{2 p_{\ell\ell}^T p_T^{miss}[1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})]}$$

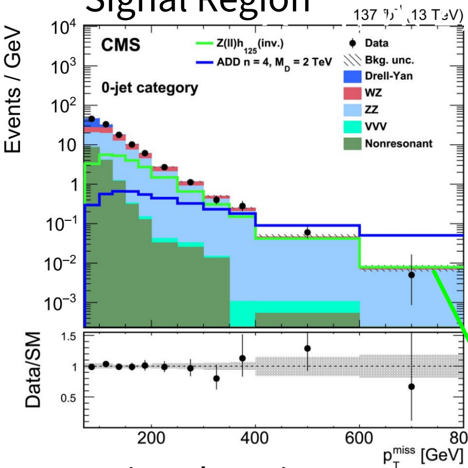
Non-resonant signal in high p_T^{miss} or M_T tail

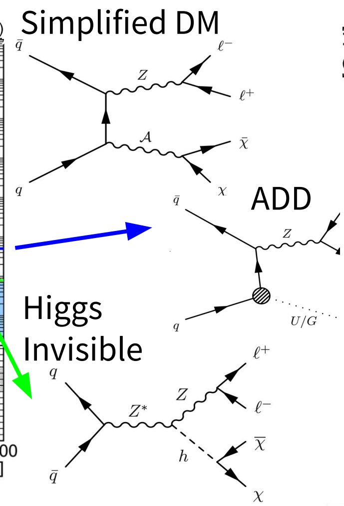
Fit p_T^{miss} or M_T (2HDM+a) to data

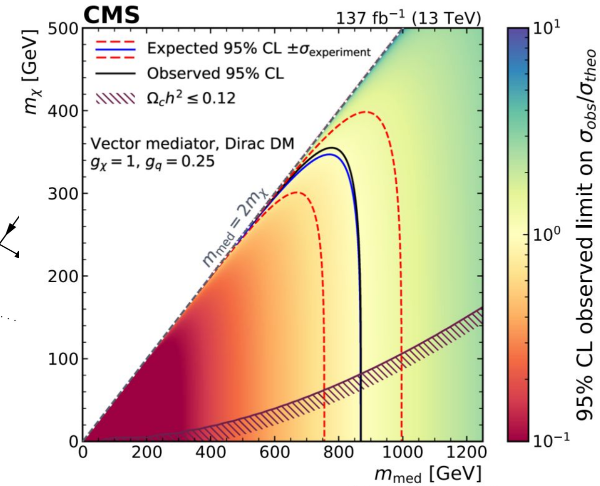


Mono-Z(ll) results

Signal Region







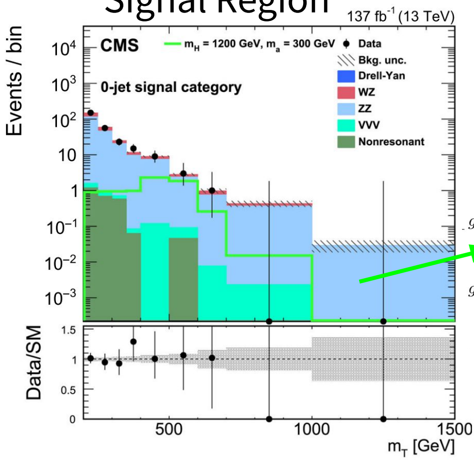
m_{med} vs m_{DM}

⇒ Simplified DM (Vector)
exclude m_{med} up to ~ 870 GeV

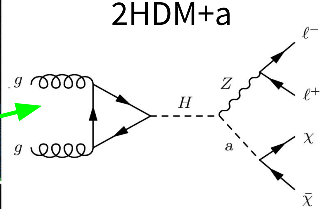
⇒ ADD
exclude M_D ~ 2.8 TeV (backup)

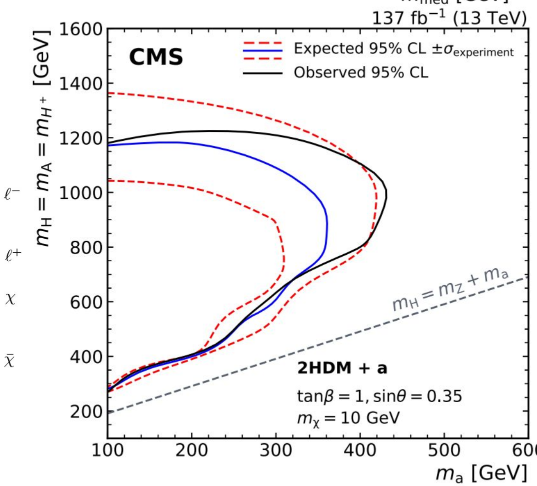
⇒ Zh(Invisible) model
BR(h → invisible) < 29 % (backup)

Signal Region



2HDM+a



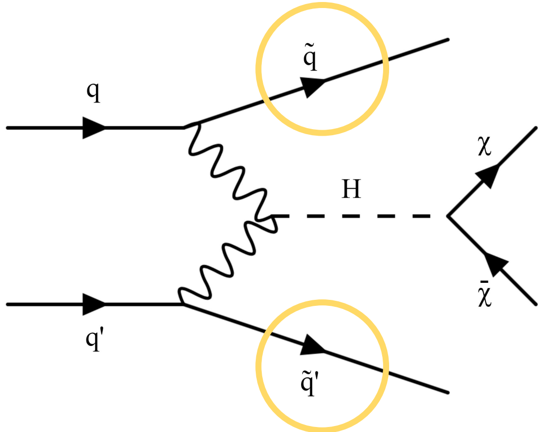


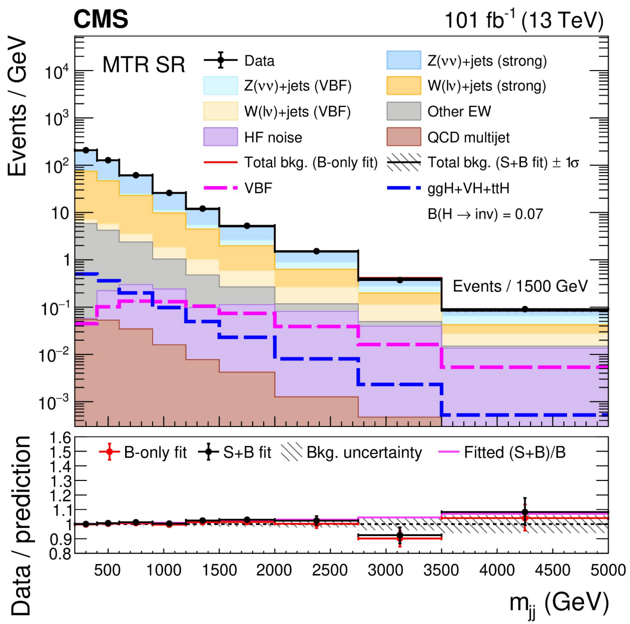
m_a vs m_H

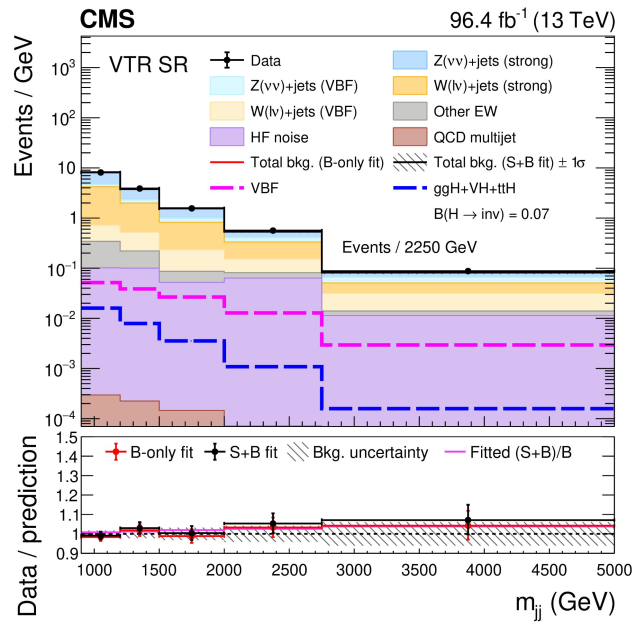
⇒ 2HDM+a model
Maximal exclusion m_a = 400 GeV
m_H = 1.2 TeV

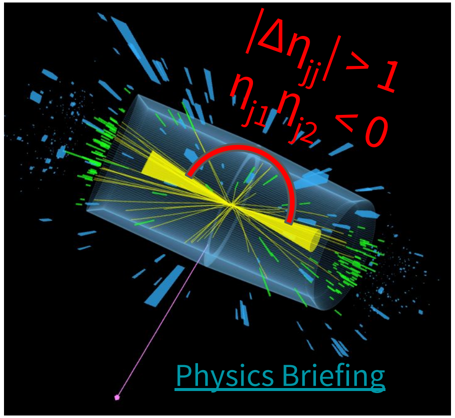
Mono-VBF search (Higgs portal)

- Signal : 2 high p_T forward ($3 \leq |\eta| \leq 5$), energetic jets + p_T^{miss}
- 2 categories : **MTR (VTR)** = MET (VBF) Triggered Region
  - $p_T^{miss} > 250$ (160 - 250) GeV, min[$\Delta\phi(p_T^{jet}, p_T^{miss})$] > 0.5 (1.8)
  - $m_{jj} > 200$ (900) GeV, $|\Delta\phi_{jj}| < 1.5$ (1.8)
- Dominant backgrounds : $Z(\nu\nu)/W(l\nu)$+jets, γ+jets ⇒ 5 CR



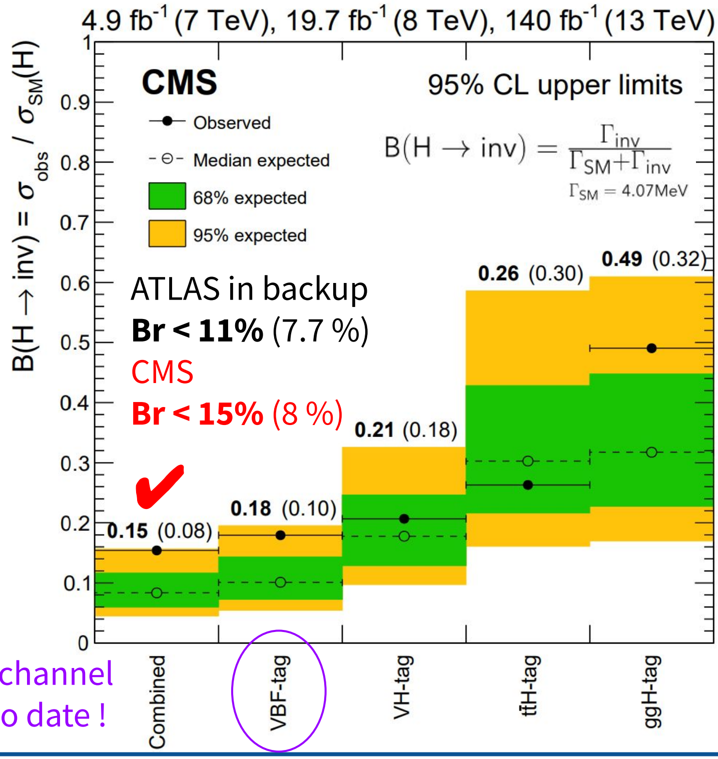




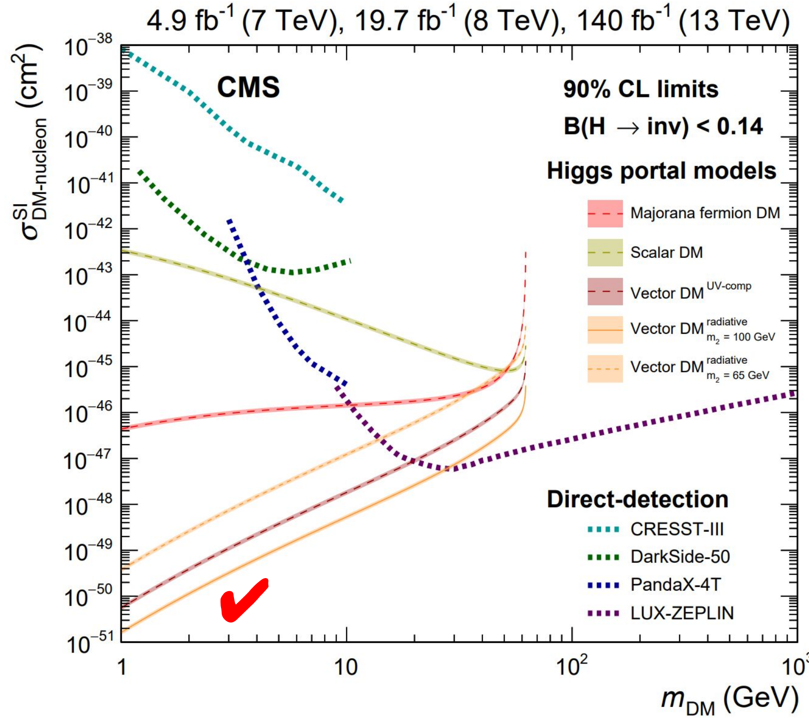


Higgs portal Interpretations

- SM exp. BR(h→inv) ~ 0.1% (given by ZZ* → 4ν) ⇒ Enhanced decay in models (**$m_{DM} < m_H/2$**)
- Combination of previous results since Run 1 (7 TeV, 8 TeV)+ 2 (13 TeV).
- BR(H→inv) limits translated to $\sigma_{WIMP\text{-}N}$ limit to compare with direct detection experiments.
- **Higgs boson** not only provides mass, it could also serve as **a portal into darkness** !



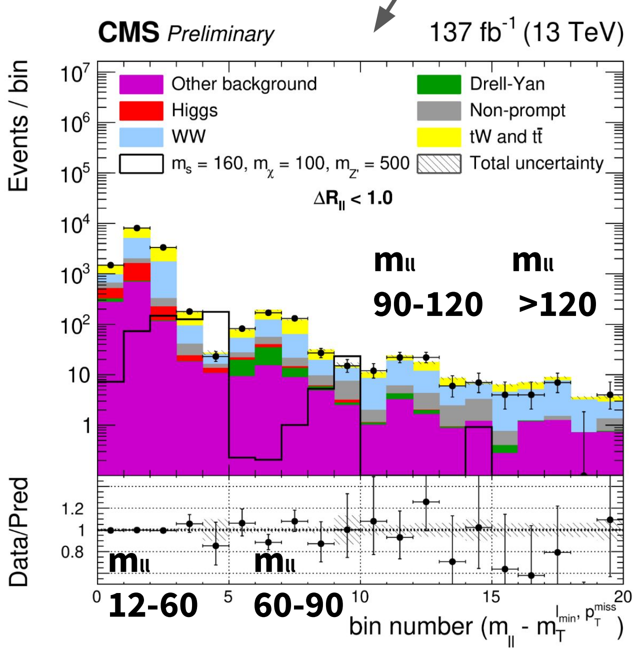
VBF-tag
Best single channel sensitivity to date !

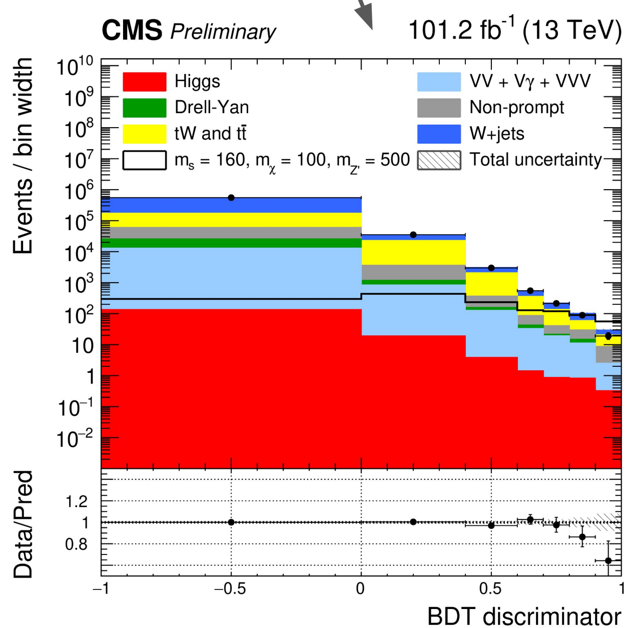


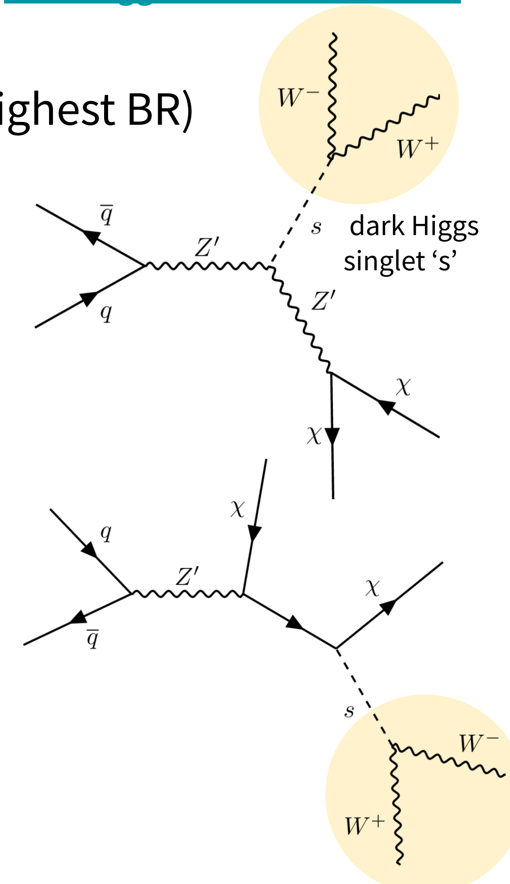
Mono-WW search

- Search for Dark matter and dark higgs in **WW** +$\mathbf{p_T^{miss}}$
- Final states : di-leptonic (μe, eμ) , semi-leptonic(1 lep+ ≧ 2jets)
- m_χ : 100 – 300 GeV, $m_{Z'}$: 200–2500 GeV, m_s : 160 –400 GeV (WW highest BR)
- Discriminators :
  m_T of subleading lepton and p_T^{miss}(di-lep), BDT (semi-lep)

[dark Higgs model 1701.08780](https://arxiv.org/abs/1701.08780)





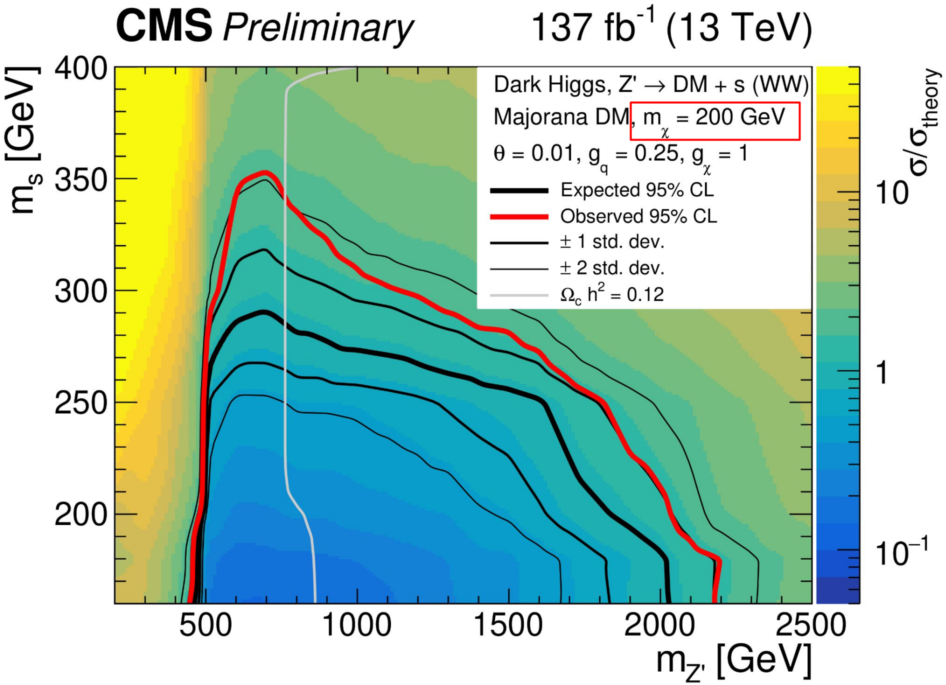


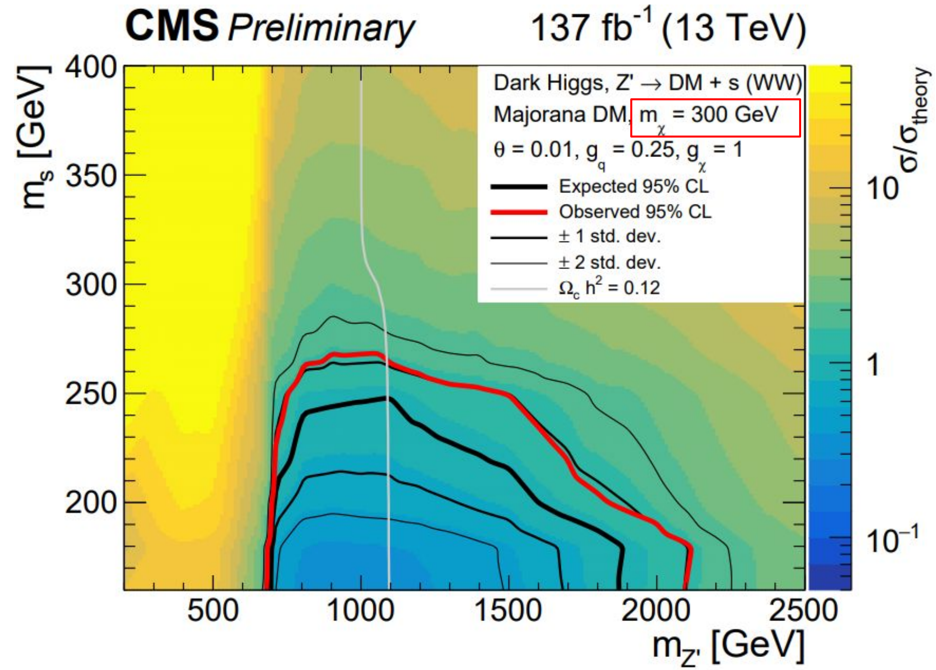
First dark Higgs attempt at CMS

Mono-WW results

- Results from the combined channel (di-leptonic + semi-leptonic decays)
- Most stringent limit for m_{DM} = 200 GeV :
  - m_s < 350 GeV exclude at $m_{Z'}$ = 700 GeV
  - $m_{Z'}$ < 2200 GeV excludes at m_s = 160 GeV

Z' coupling :	$g_q = 0.25$
	$g_\chi = 1$
Higgs mixing :	$\sin\theta = 0.01$

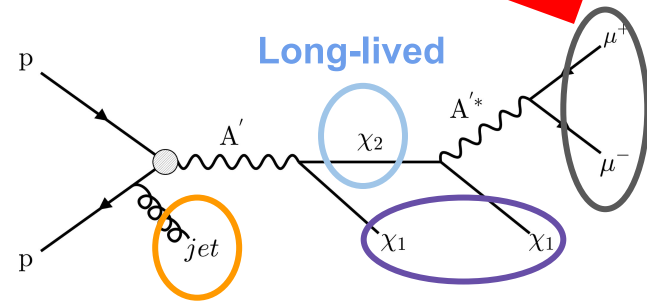




Mono-displaced μμ search

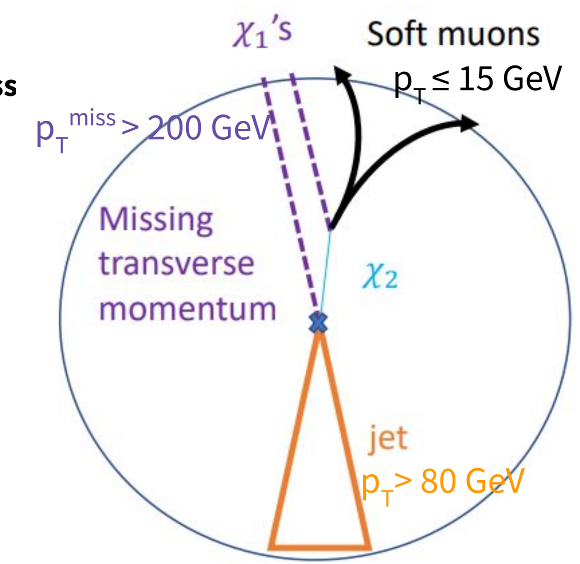
NEW

- First dedicated collider search for **inelastic DM** !
- Signature :
  Dark photon A' produced, recoiling against ISR jet.
  A' promptly decays to two DM states χ_1 and χ_2 with near mass-degeneracy (→ χ_2 is LLP)
- Macroscopic χ_2 lifetime makes a **displaced dimuon vertex**
- Small DM mass splitting (Δ) ⇒ a **soft μ collimated with p_T^{miss}**
- **Advantage of low background**



5 Parameters:
$\mathbf{m_1(\chi_1)}$= 3–80 GeV, **Δ**≡m_2-m_1= {0.1, 0.4} m_1 , $\mathbf{m_{A'} = 3m_1}$
$\mathbf{c\tau(\chi_2)}$ = 1–1000 mm, $\boldsymbol{\alpha_D} = \alpha_{EM}$, 0.1

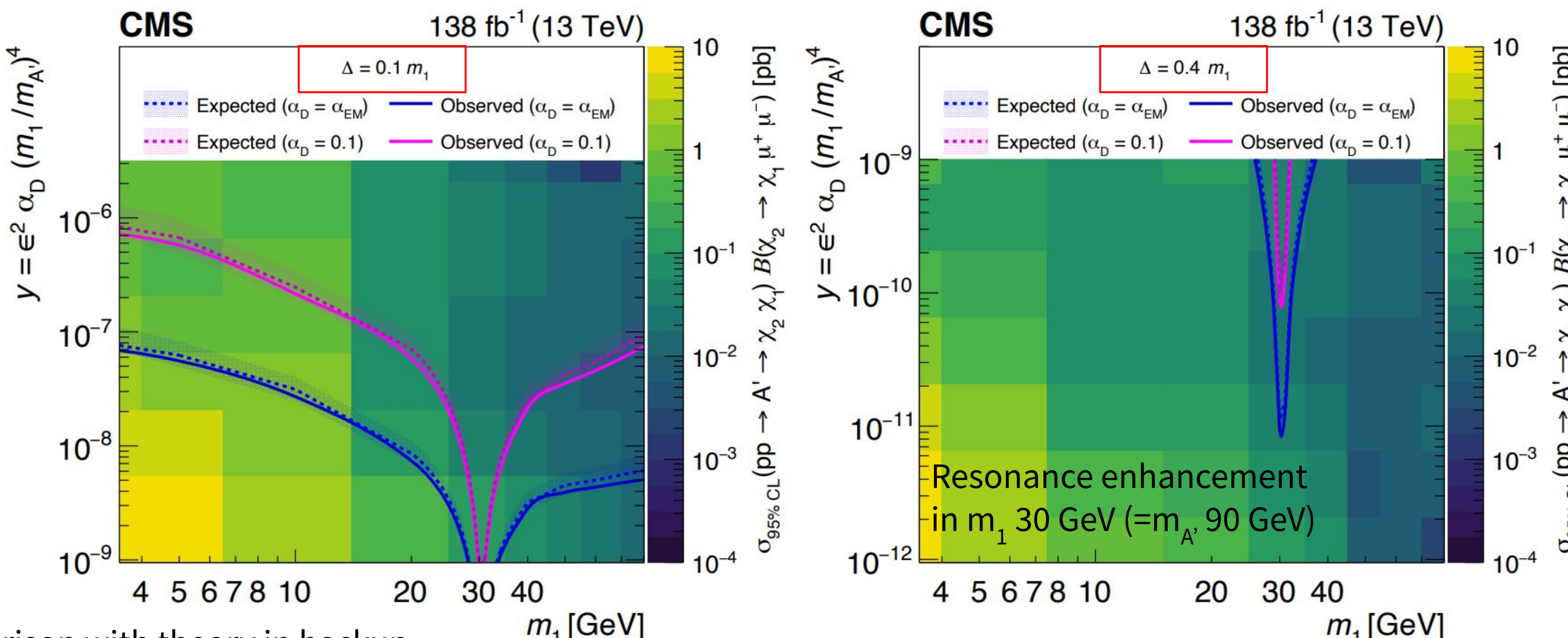
- Kinetic mixing ϵ between γ/Z and A' introduces SM portal
- Discriminator : Muon vertex displacement, dxy



CMS transverse cross-section from Andre Frankenthal

Mono-displaced μμ results

- Upper limits are set on the the $\sigma(pp \to A' \to \chi_2\chi_1) \times BR(\chi_2 \to \chi_1\mu\mu)$.
- Higher experimental sensitivity to lower mass splitting (Δ) scenarios.
- $\alpha_D = \alpha_{EM}$ scenario more sensitive, but $\alpha_D = 0.1$ scenario more cosmologically relevant.



Comparison with theory in backup

Conclusion

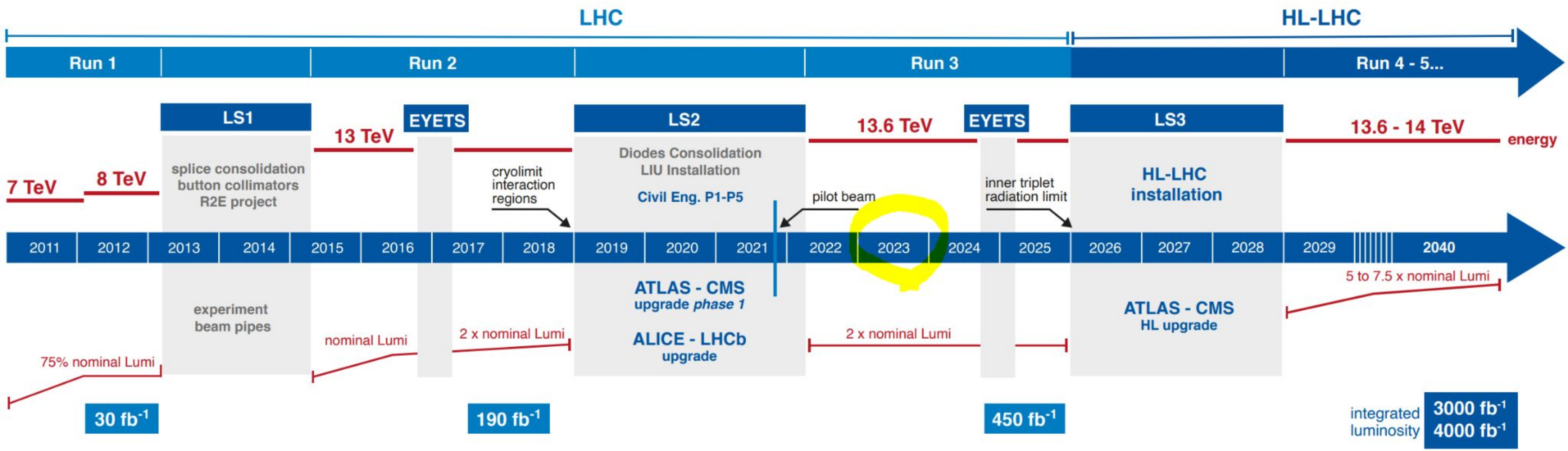
- **Mono-X Dark matter searches** are core physics program in CMS.
- Wide range of probes for different types of SM-DM interactions.
  - DM + jet, Z, H, photon, top, diboson, displaced muons ..
- Presented results for CMS, all of which use the **full Run2 results**.
- Strongest constraints from full data set typically in TeV range.
- Still plenty of additional parameter space for small couplings, etc.
- All DM public results in here ⇒ ATLAS , CMS

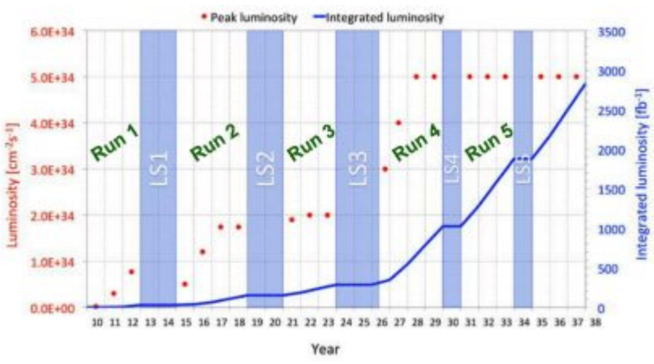
- Partial Run-2 results to be updated to full Run-2.

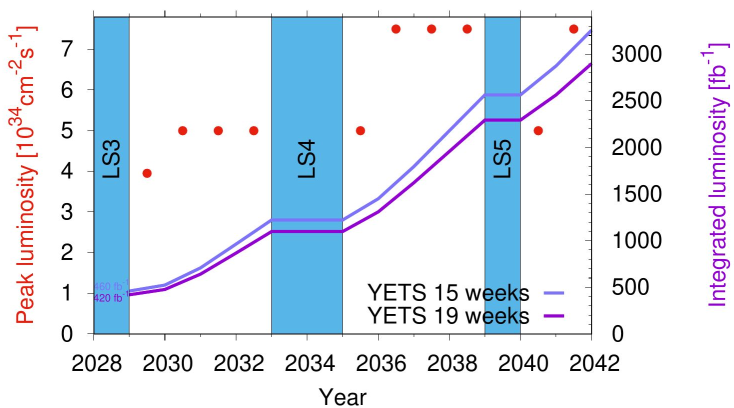
  ⇒ Stay tuned for this and the upcoming Run-3 !

Thank you for your attention!

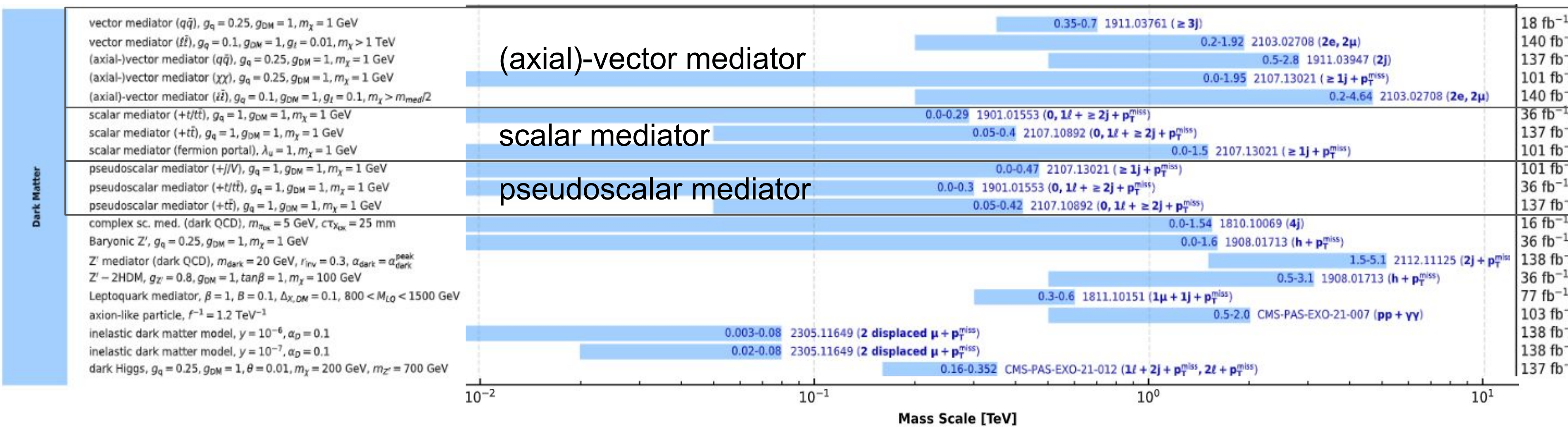
Backup (LHC schednule)







CMS DM summary plot

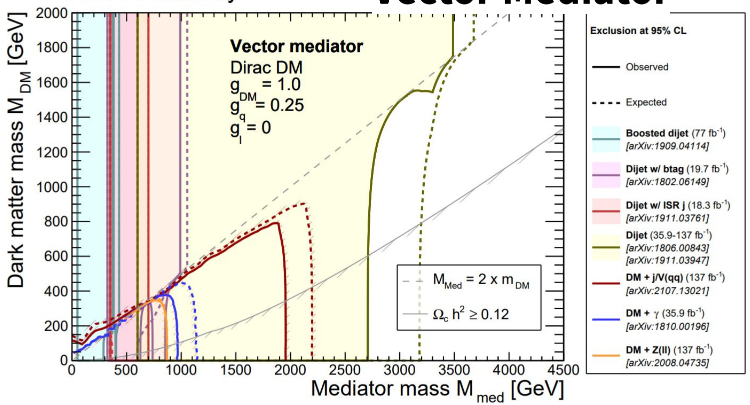


CMS DM summary plots

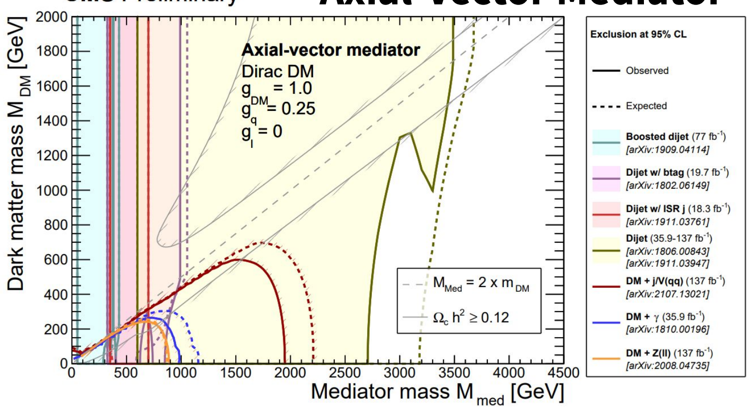
m_{med} vs m_{DM}

[SummaryPlotsEXO13TeV]

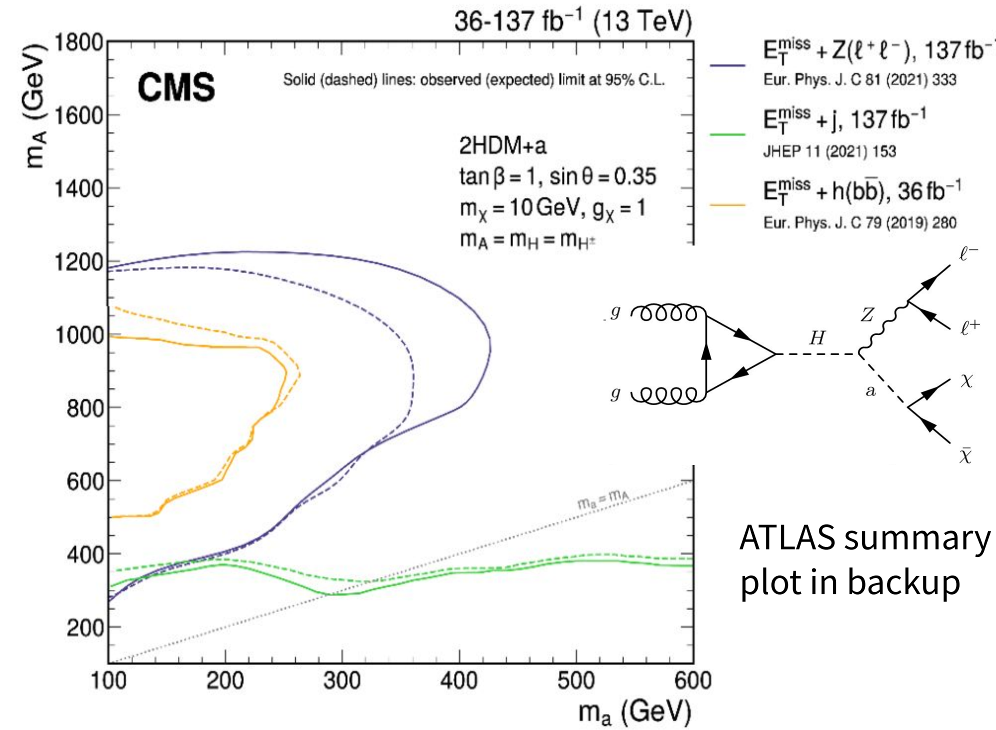
CMS Preliminary **Vector Mediator**



CMS Preliminary **Axial-Vector Mediator**

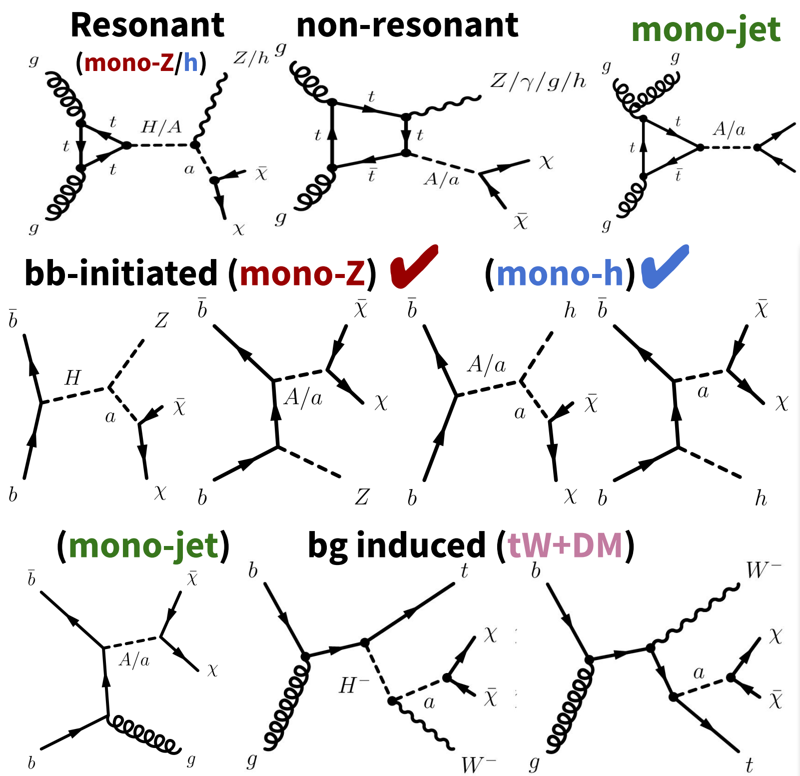


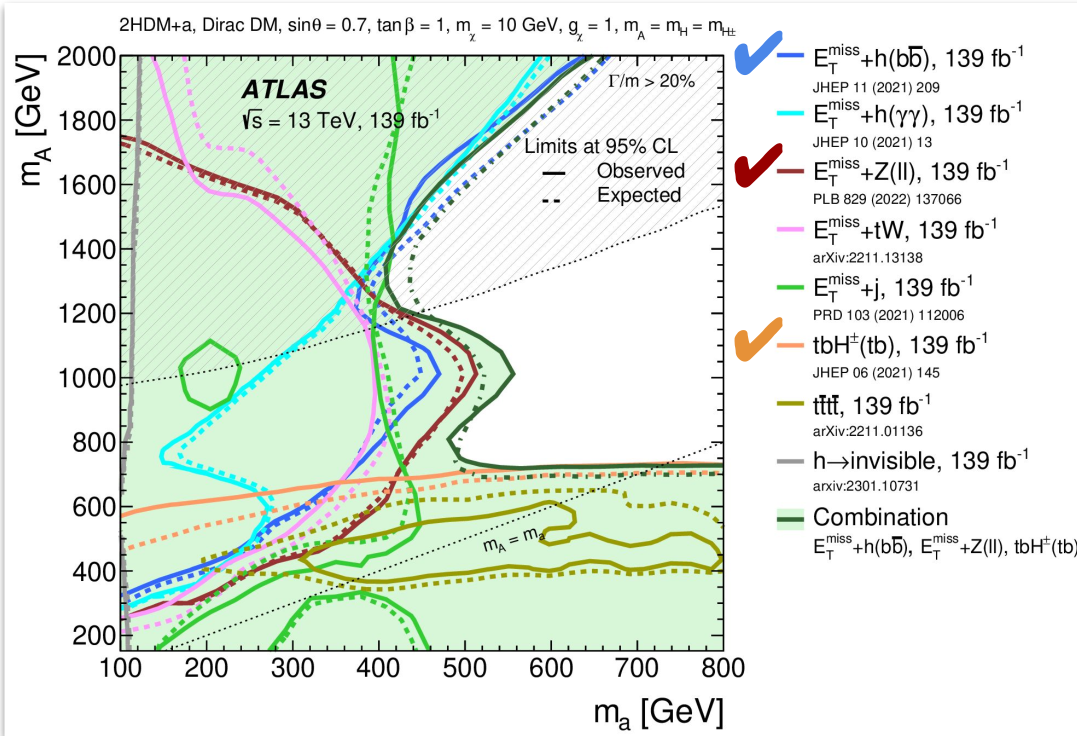
2HDM+a
m_a vs m_A



ATLAS summary plot in backup

2HDM+a DM Searches (ATLAS)

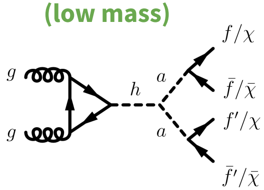




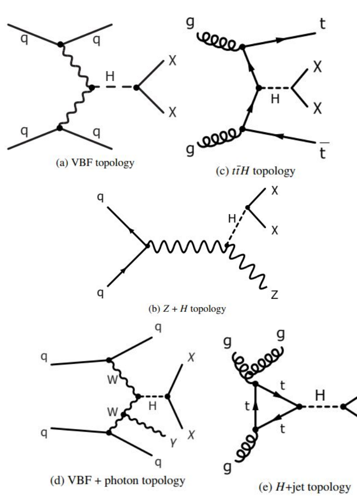
Higgs not only provides mass, it could also serve as a portal into darkness !

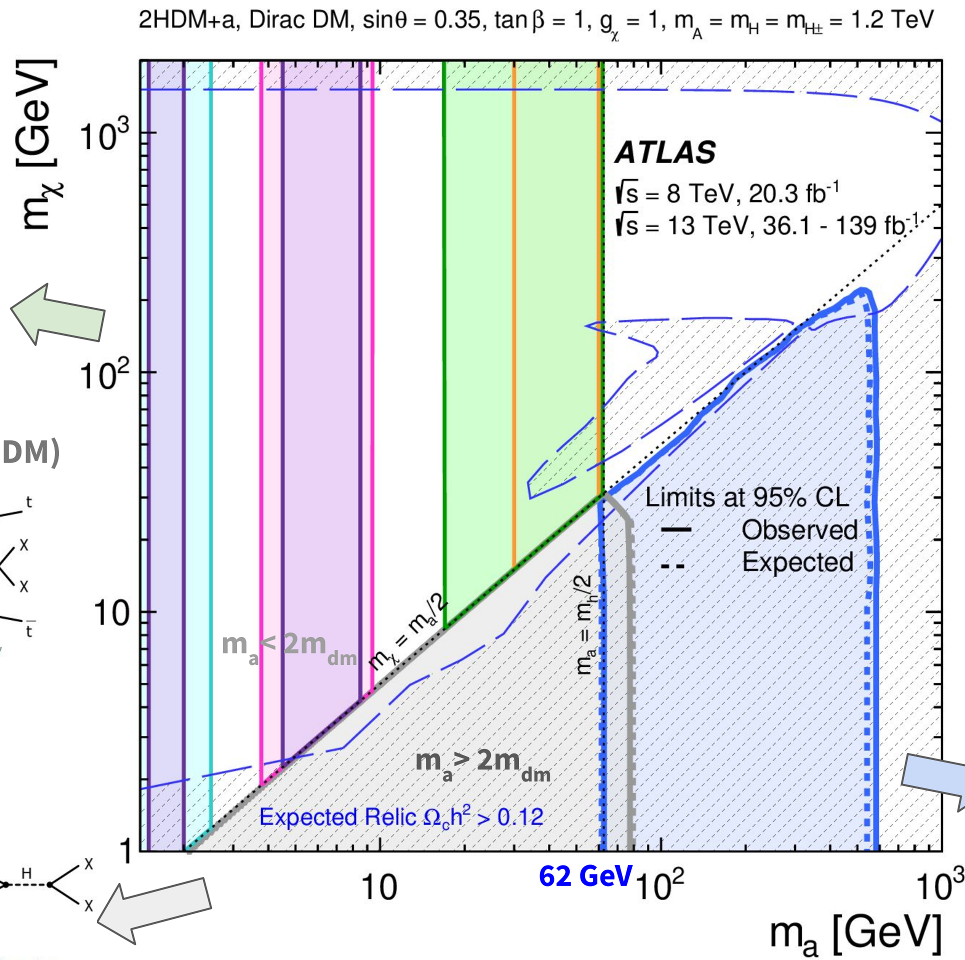
2HDM+a DM Searches (ATLAS)

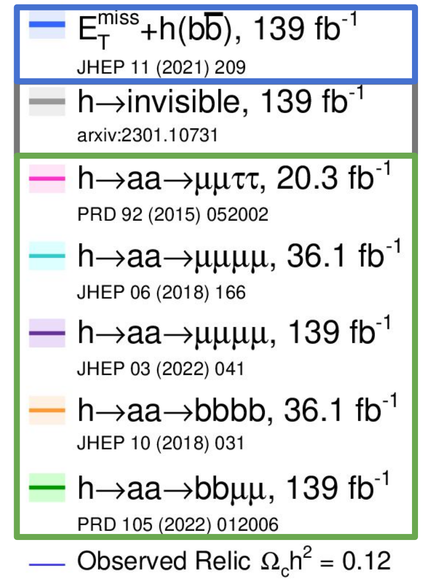
h→aa→xxyy
(low mass)



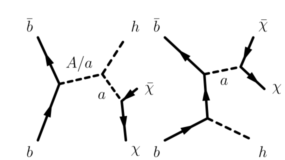
h→invisible(DM DM)





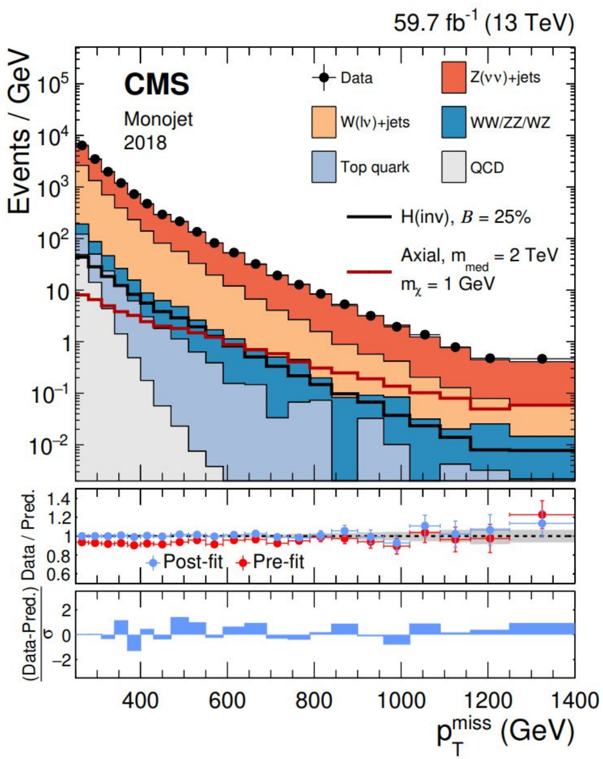


mono-h

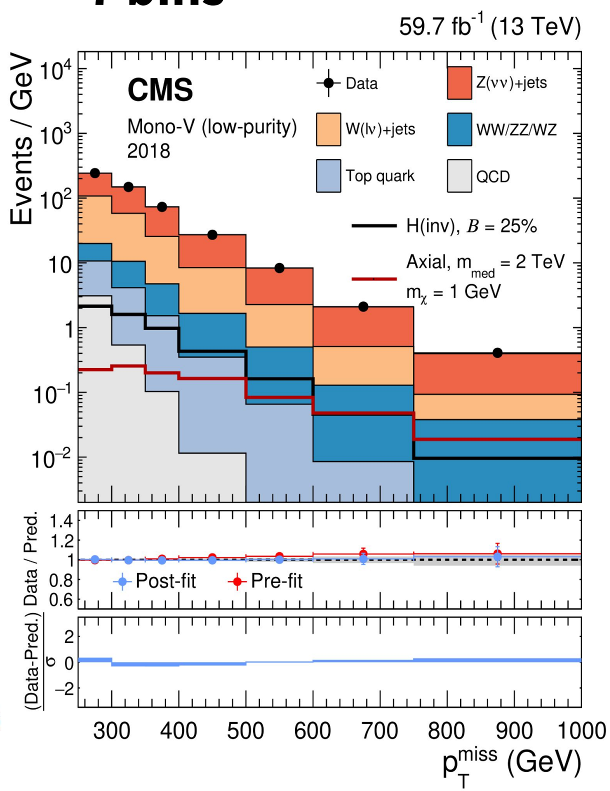


Mono-Jet/V(qq) Signal Region (SR)

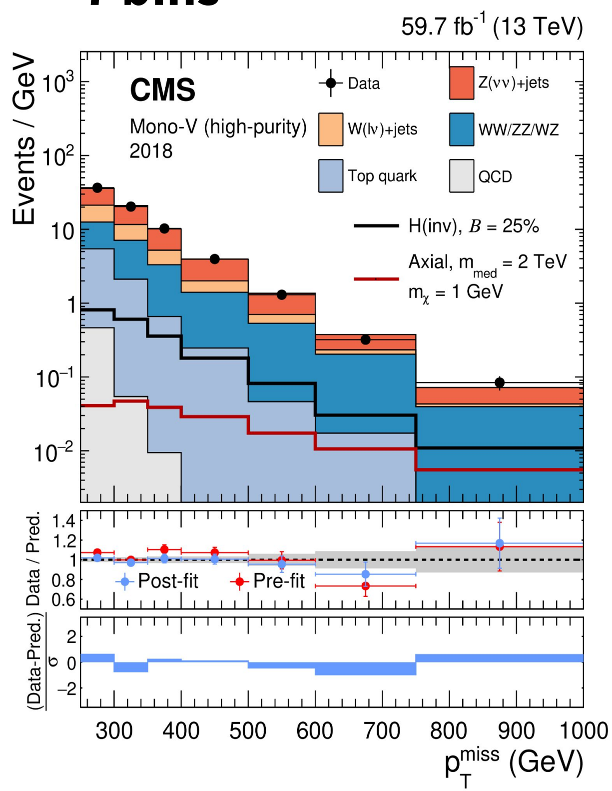
Mono-Jet
22 bins



Mono-V (low purity)
7 bins

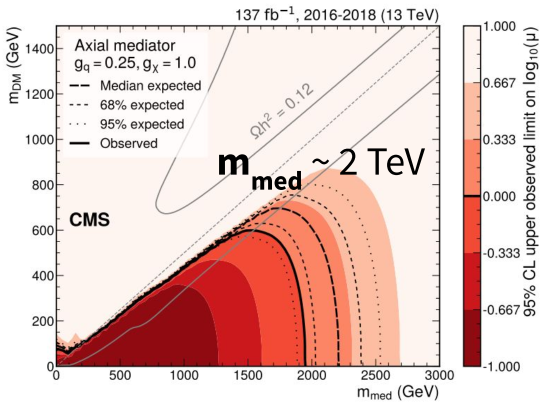


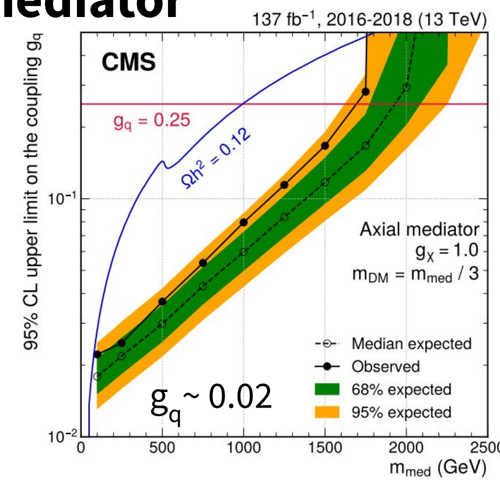
Mono-V (high purity)
7 bins



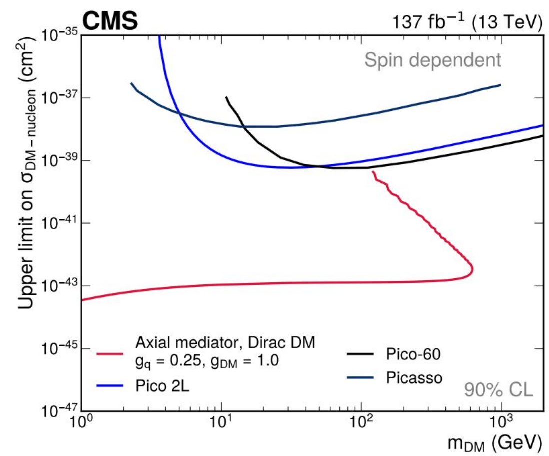
Mono-Jet/V(qq) results

Axial-vector mediator

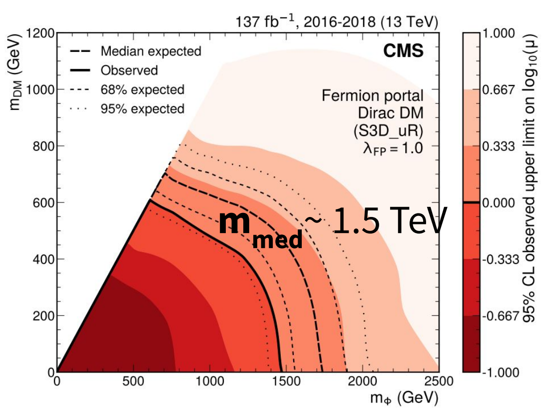




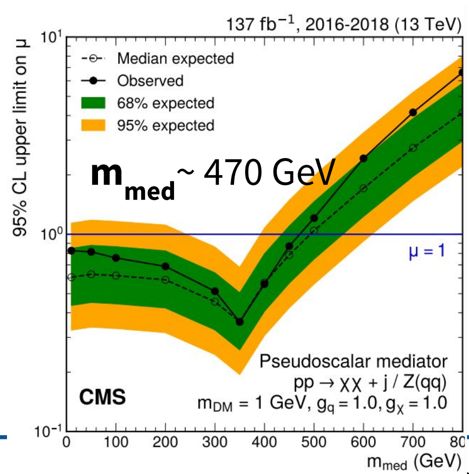
SD DM-nucleon scattering



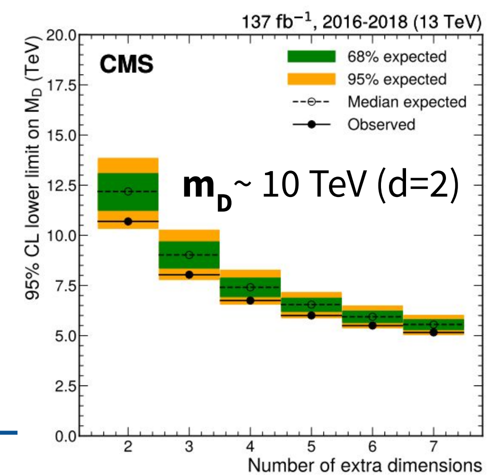
Fermion portal



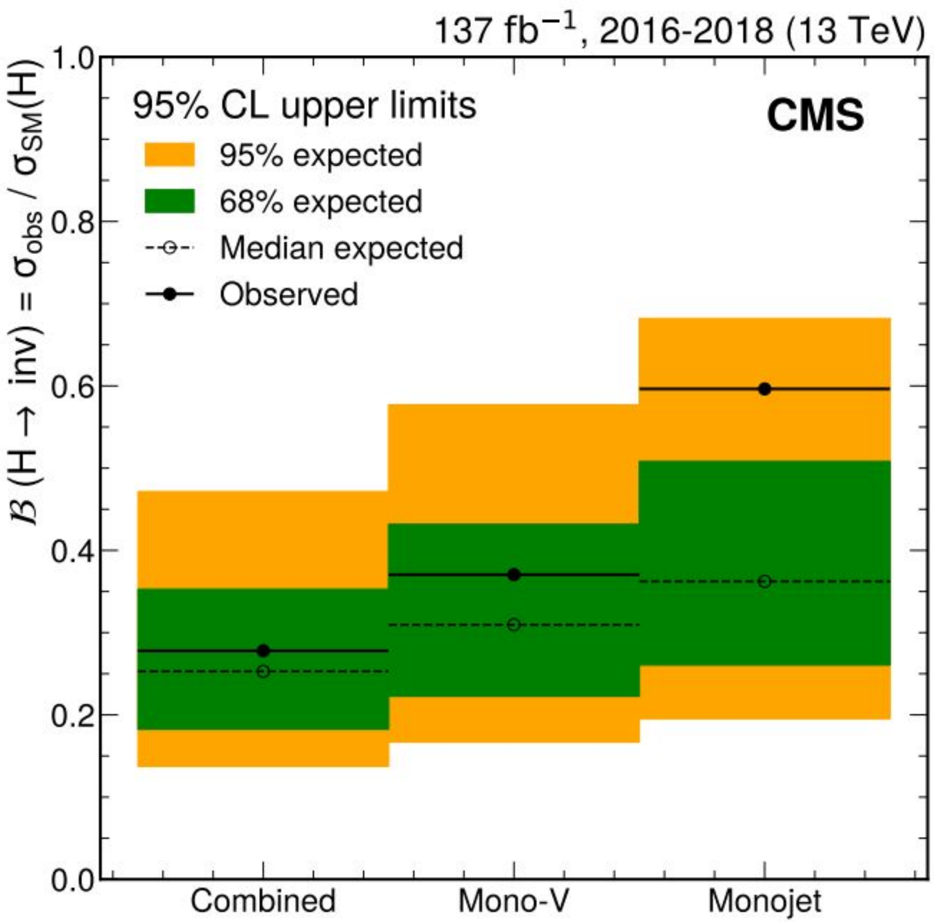
Pseudoscalar mediator



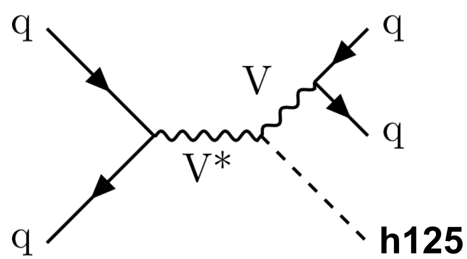
ADD

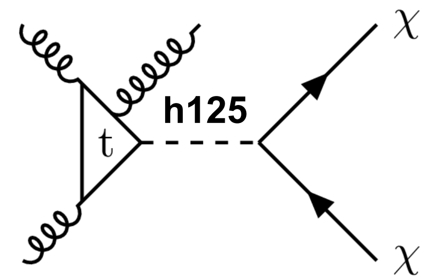


Mono-jet/V : Limit on BR(h→invisible)



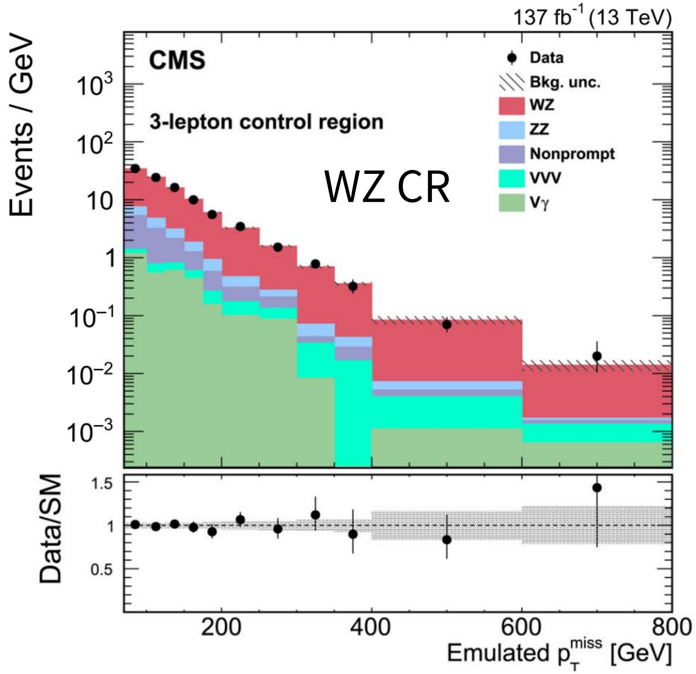
The final combined (Mono-V + Mono-jet) limit : **27.8% (25.3% expected)**

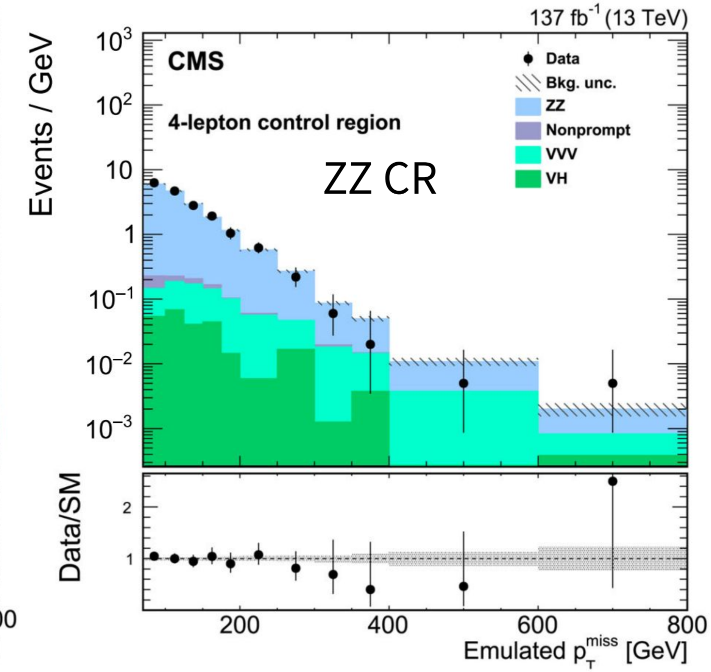


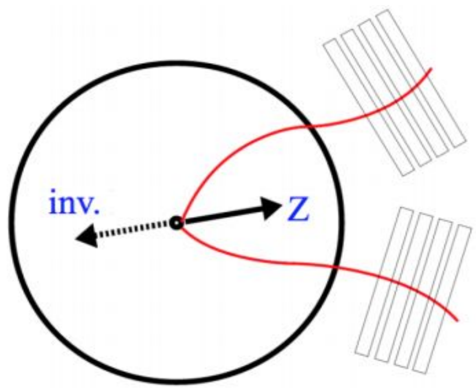


Mono-Z(ll) background estimation

- 3-lepton (WZ) and 4-lepton (ZZ) control regions to estimate 2-lepton WZ and ZZ
  - Also, eμ CR : OSOF events and DY CR : low p_T^{miss} sideband (80-100)



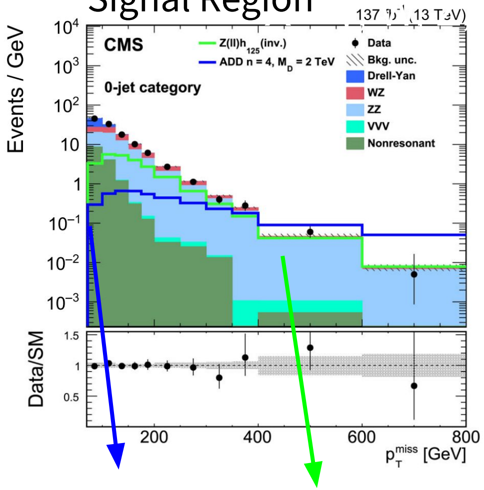




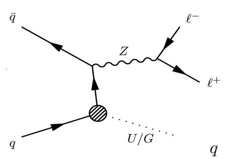
Emulated p_T^{miss} (M_T) is estimated from the vectorial sum of p_T^{miss} and additional lepton p_T

Mono-Z(ll) results; ADD, h invisible

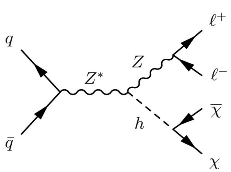
Signal Region



ADD



Higgs Invisible



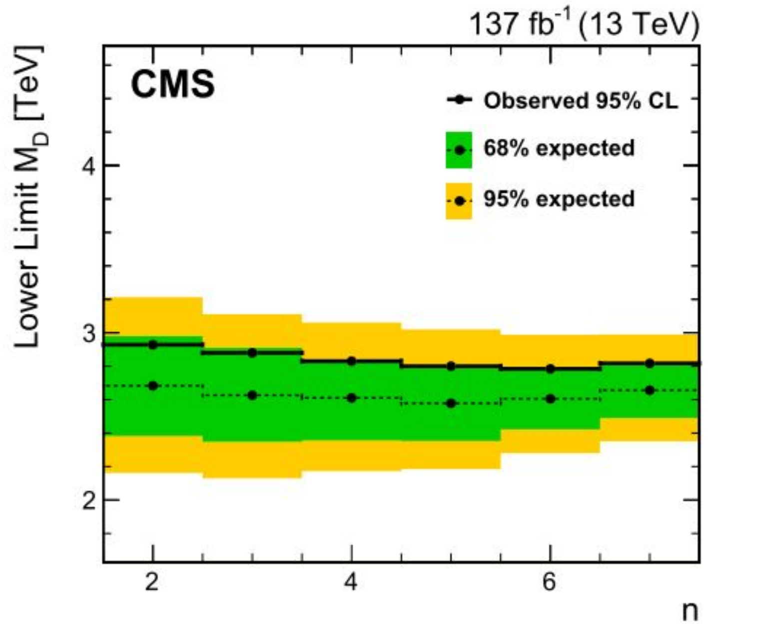


Fig. 12 The 95% CL expected and observed exclusion limits on M_D as a function of the number of extra dimensions n

⇒ ADD (the fundamental Planck scale M_D)
exclude M_D ~ 2.8 TeV (backup)

⇒ Zh(Invisible) model
Br(h → invisible) < 29 % (backup)

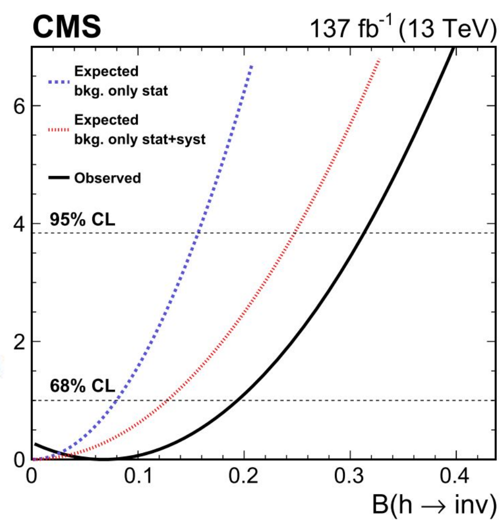


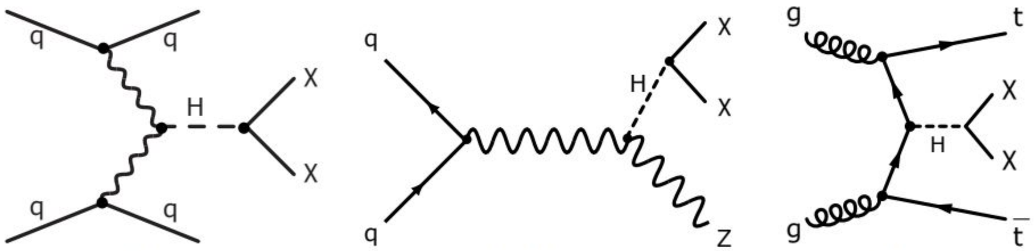
Fig. 9 The value of the negative log-likelihood, $-2\Delta\ln\mathcal{L}$, as a function of the branching fraction of the Higgs boson decaying to invisible particles

Higgs portal WIMP (CMS, ATLAS)

Analysis tag	Production mode	Integrated luminosity (fb^{-1})		
		7 TeV	8 TeV	13 TeV (Run 2)
VBF-tagged	VBF	—	19.2 [90]	140 [89][34]
VH-tagged	Z($\ell\ell$)H	4.9 [90]	19.7 [90]	140 [89][32]
	Z($b\bar{b}$)H	—	18.9 [90]	—
	V(jj)H	—	19.7 [91]	140 [89][this paper]
	Boosted VH	—	—	138 [33]
$t\bar{t}$H-tagged	$t\bar{t}$H (hadronic)	—	—	138 [this paper]
	$t\bar{t}$H (leptonic)	—	—	138 [29, 30]
ggH-tagged	ggH	—	19.7 [91]	140 [89][33]

CMS

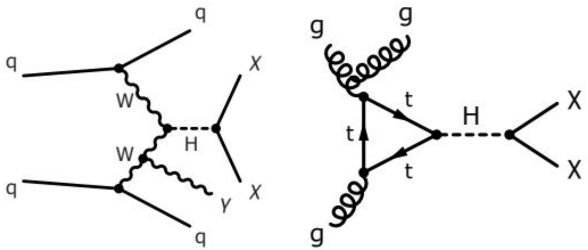
2303.01214



(a) VBF topology (b) $Z+H$ topology (c) $t\bar{t}H$ topology

ATLAS

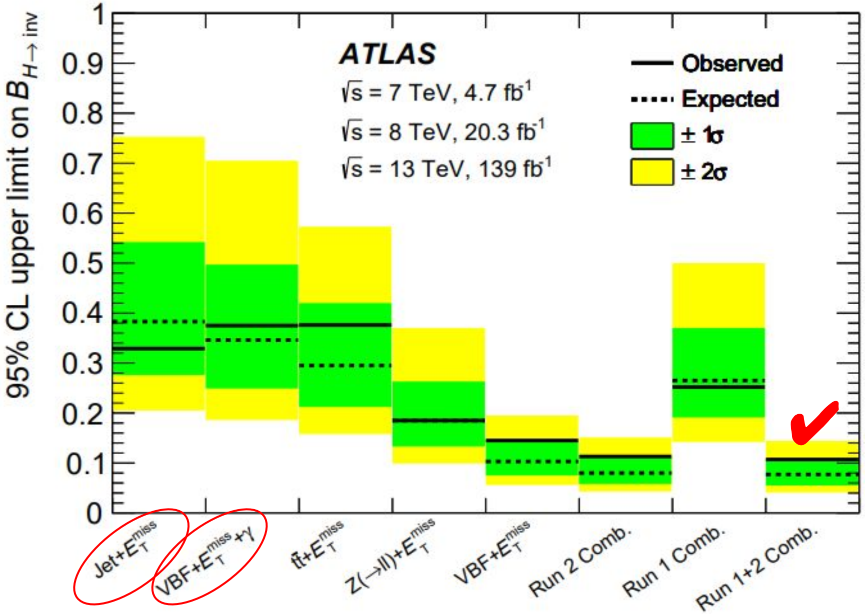
2301.10731

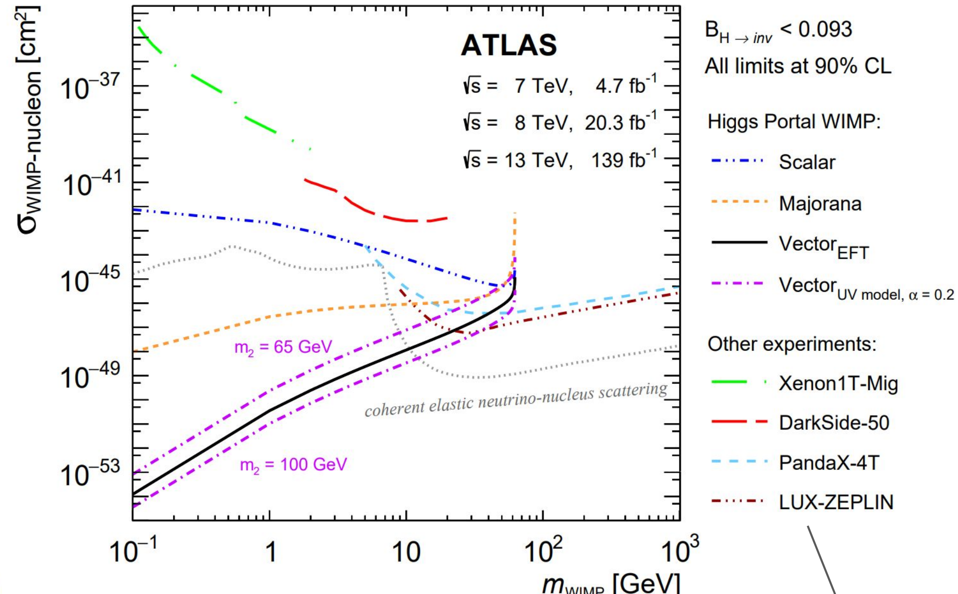


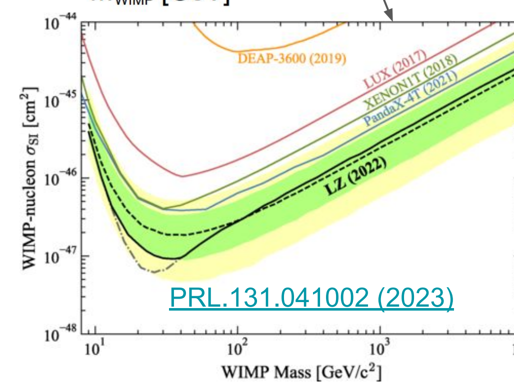
(d) VBF + photon topology (e) H+jet topology

Higgs portal WIMP (ATLAS)

Combined limit on BR(h→ invisible)







PRL.131.041002 (2023)

ATLAS : **Br < 11%** (7.7 %)
CMS : **Br < 15%** (8 %)

Mono-VBF event selection

Observable	MTR	VTR
Choice of pair	leading-p_T jets	leading-m_{jj} jets
Leading (subleading) jet	$p_T > 80\ (40)$ GeV, $\lvert\eta\rvert < 4.7$	$p_T > 140\ (70)$ GeV, $\lvert\eta\rvert < 4.7$
p_T^{miss}	>250 GeV	$160 < p_T^{miss} < 250$ GeV
$\min(\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet}))$	>0.5	>1.8
$\lvert\Delta\phi_{jj}\rvert$	<1.5	<1.8
m_{jj}	>200 GeV	>900 GeV
$\lvert p_T^{miss} - \text{calo}\ p_T^{miss}\rvert / p_T^{miss}$	<0.5	
Leading/subleading jets $\lvert\eta\rvert < 2.5$	NHEF < 0.8, CHEF > 0.1	
HF noise jet candidates	0 (using the requirements from Table **??**)	
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 20$ GeV, $\lvert\eta\rvert < 2.3$	
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, DeepCSV Medium	
$\eta_{j1}\eta_{j2}$	<0	
$\lvert\Delta\eta_{jj}\rvert$	>1	
Electrons (muons)	$N_{e,\mu} = 0$ with $p_T > 10$ GeV, $\lvert\eta\rvert < 2.5\ (2.4)$	
Photons	$N_\gamma = 0$ with $p_T > 15$ GeV, $\lvert\eta\rvert < 2.5$	

Inelastic DM search

Key Parameters

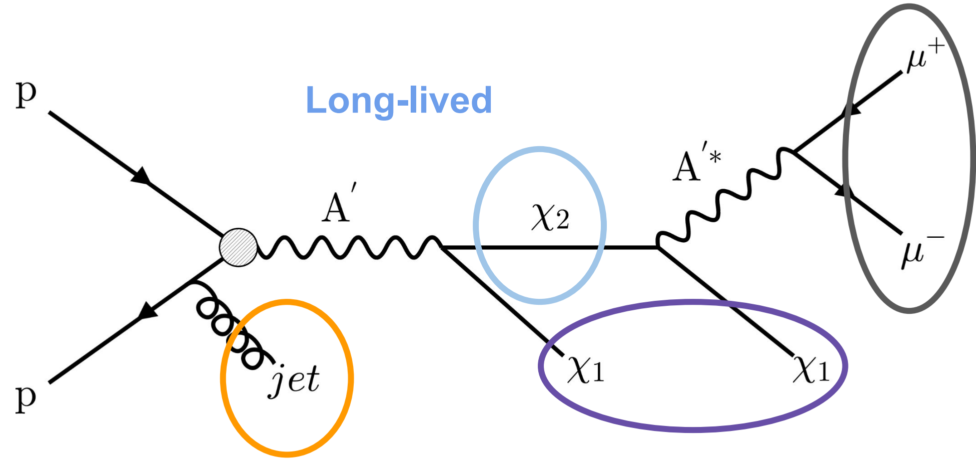
- m_1 (DM mass)
- x (mass splitting fraction)
  - $\Delta = x m_1$
  - $m_2 = m_1 + \Delta$
- $c\tau$ (χ_2 lifetime)

} **Varied in CMS search**

- α_D (dark $U(1)$ coupling) } **Fixed @ 0.1 or α_{EM}**

- $m_{A'} = 3m_1$
- ϵ (kinetic mixing parameter)

} **Fixed, or determined by other parameters**



Two important quantities to consider in exploring iDM parameter space:

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}}\right)^4 \propto \langle \sigma v \rangle$$

- Determines relic density
- Need to ensure consistency with cosmological observations

$$\Gamma_{\chi_2} = \frac{4\epsilon^2 \alpha \alpha_D \Delta^5}{15\pi m_{A'}^4}$$

- Lifetime of heavier DM particle
- Small mass splitting Δ and kinetic mixing can give χ_2 a **macroscopic lifetime**

Inelastic DM search-Event selection

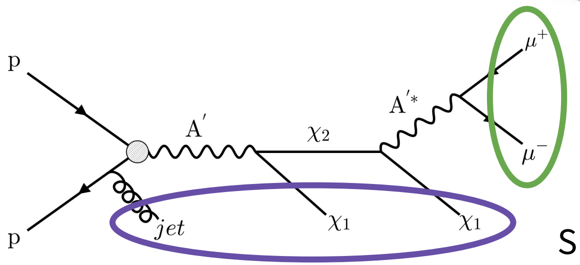
- **Jet & MET selection:**
  - Trigger on MET triggers
  - Offline MET > 200 GeV
  - 1 or 2 jets only
  - Leading jet p_T > 80 GeV, |η| < 2.4
  - Sub-leading jet p_T > 30 GeV
  - |Δϕ|(MET, leading jet) > 1.5
  - |Δϕ|(MET, sub-leading jet) > 0.75
  - No b-tagged jets

- **Dimuon selection:**
  - 2 ID'd dSA muons
  - $q_1 \, != q_2$
  - Vertex χ^2/dof < 4 (pick lowest)
  - dR(muons) < 0.9
  - 3D angle $\alpha > 2.8$ rad
  - |Δϕ|(MET, muons) < 0.5 (next slide)

displaced Stand Alone muon

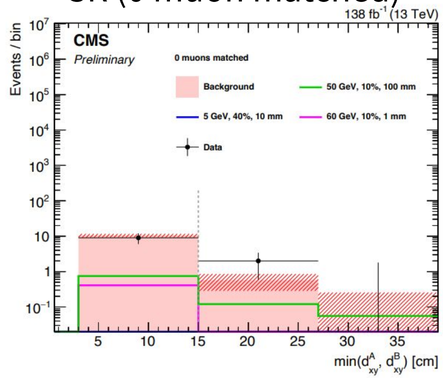
- **dSA ID:** Use only muon hits
  - Number of muon chambers > 1
  - Number of muon hits > 12
  - And > 18 if no CSC hits
  - Track χ^2/dof < 2.5
  - $\sigma(p_T) \,/\, p_T < 1.0$
  - & $p_T > 5$ GeV, $|\eta| < 2.4$

- **"PF" Loose ID:**
  - Muon is a PF muon
  - And muon is a Global Muon
  - & $p_T > 5$ GeV, $|\eta| < 2.4$

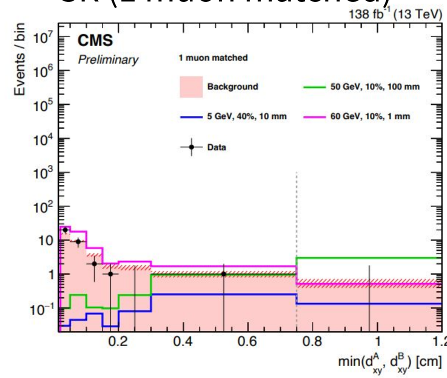


- **SR categorization:**
  - 0, 1, or 2 dSA matches with ID'd PF muons

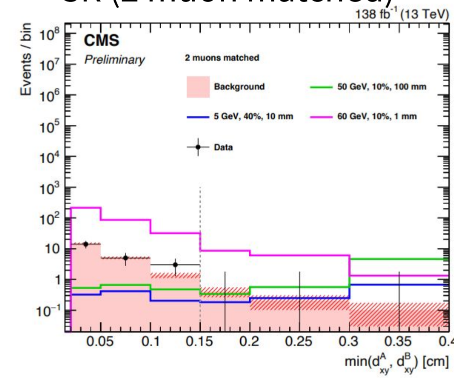
SR (0 muon matched)



SR (1 muon matched)



SR (2 muon matched)



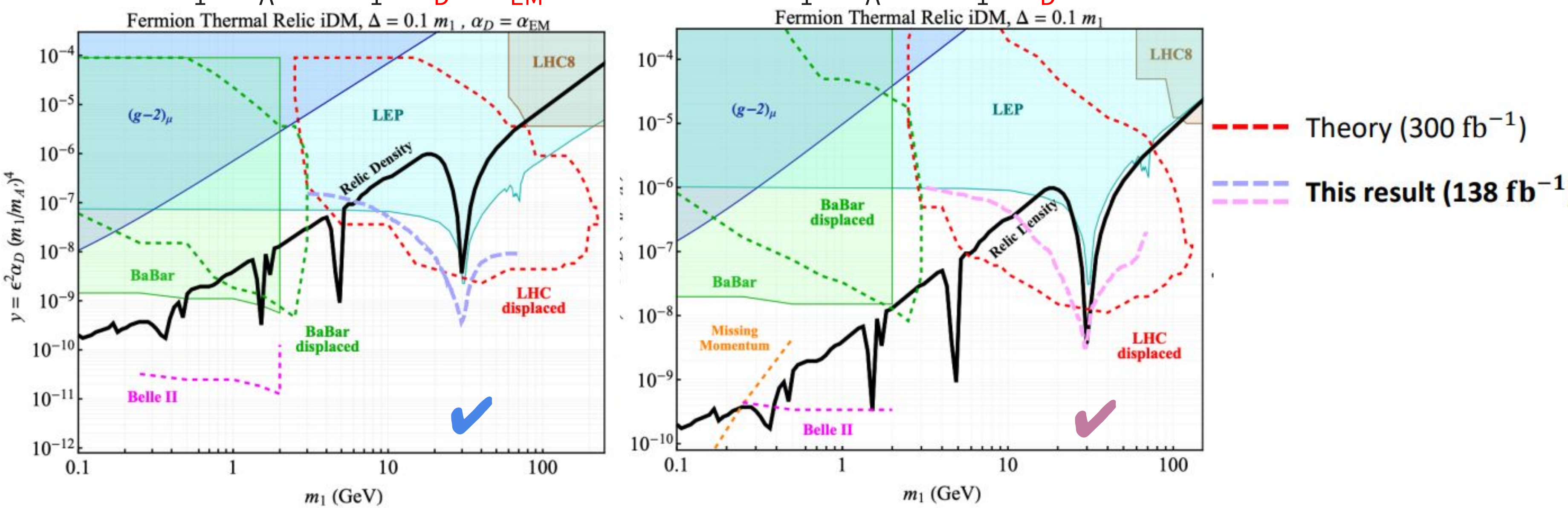
from A. Frankenthal's talk at UCLA DM 2023

Inelastic DM - Comparison with theory

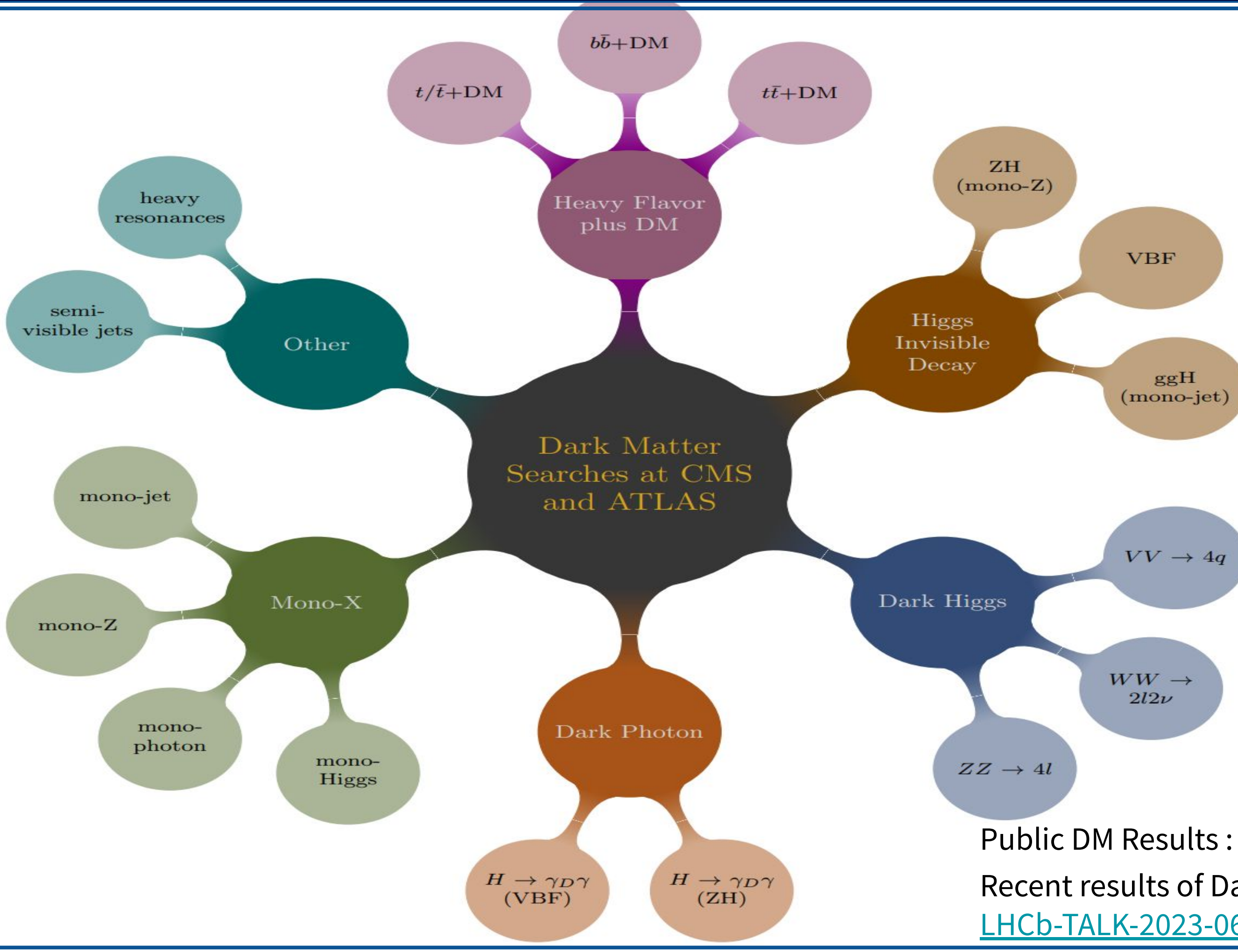
- Depending on mass splitting, can probe an unexplored and relic density-consistent range of parameter space!
- Sensitivity to <u>heavier dark matter</u> compared to direct detection experiments, lepton colliders, and fixed-target experiments
- Sensitivity better than expectation given ~ half of dataset

iDM could explain the observed thermal-relic DM abundance in the universe

$\Delta=0.1\,m_1, m_{A'} = 3m_1$, $\alpha_D = \alpha_{EM}$ $\quad$ $\Delta=0.1\,m_1, m_{A'} = 3m_1$, $\alpha_D = 0.1$



DM Searches



Public DM Results : ATLAS , CMS

Recent results of Dark Sector @ LHCb LHCb-TALK-2023-060

picture made by danyer.perez.adan@cern.ch