



Progress and Status of Dark Sector Explorations at the LHC

Jakob Salfeld-Nebgen

Summarizing work of the LHC Experiments

Outline

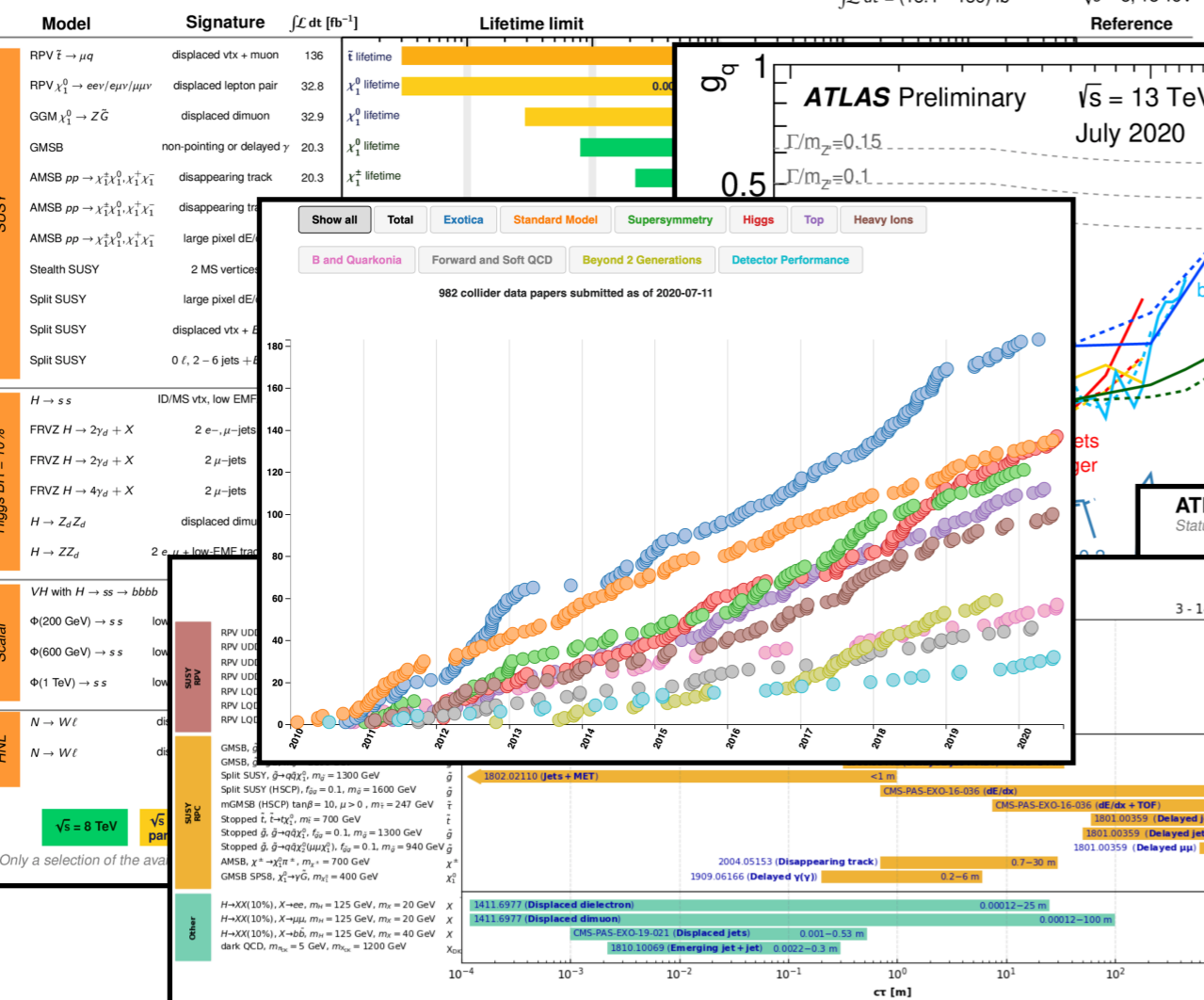
- **Dark Photons and Vector Portals**
- **Dark Photons and Dark Higgs**
- **Higgs(125) Portal and Scalar Portals**
- **Axion Like Particles**
- **Heavy neutral leptons**
- **Experimental/Technical challenges**

***Probably non-inclusive coverage, try to mention most portals and give examples, comments and pointers with roughly equal coverage for the experiments**

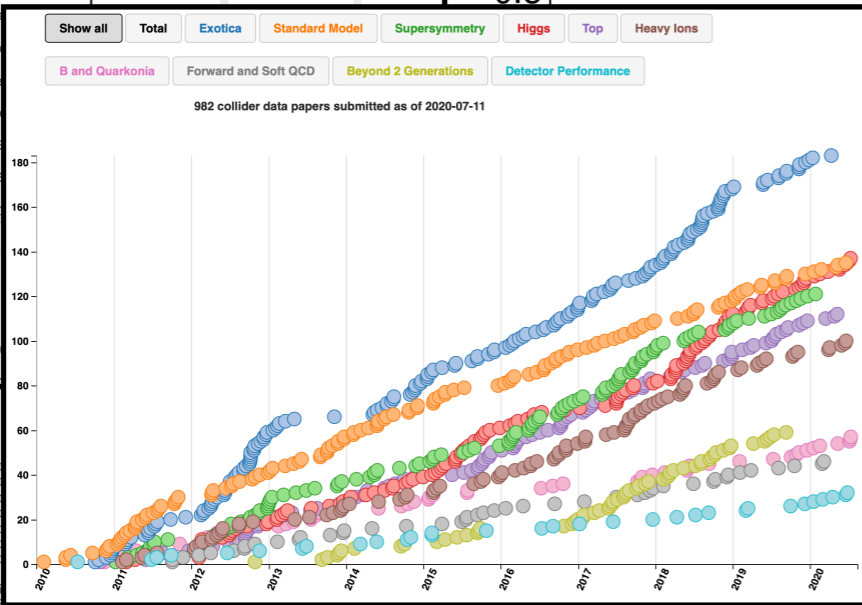
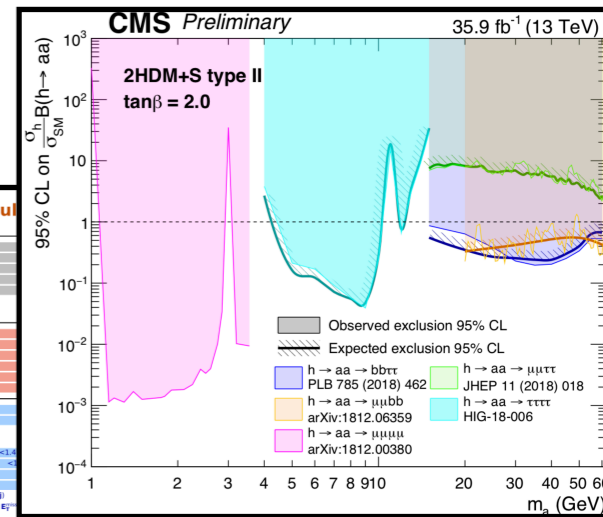
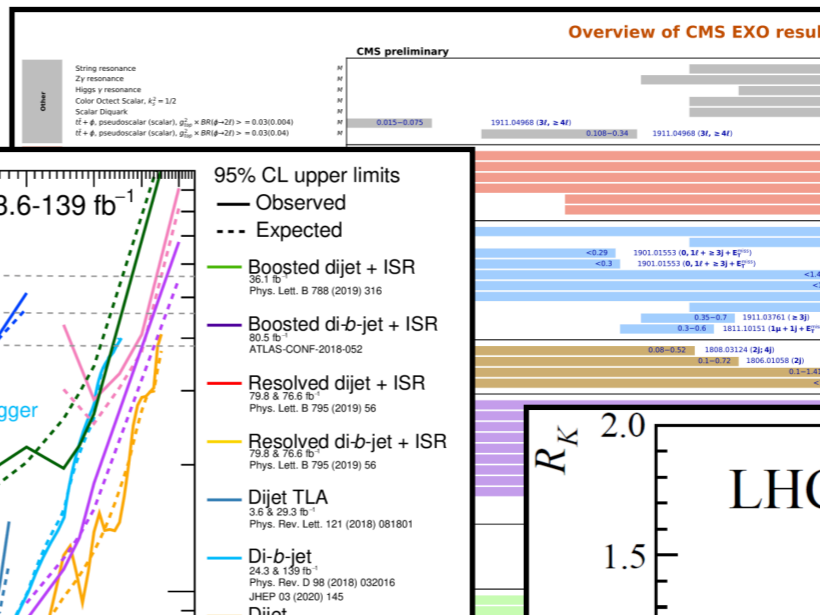
LHC BSM Land

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

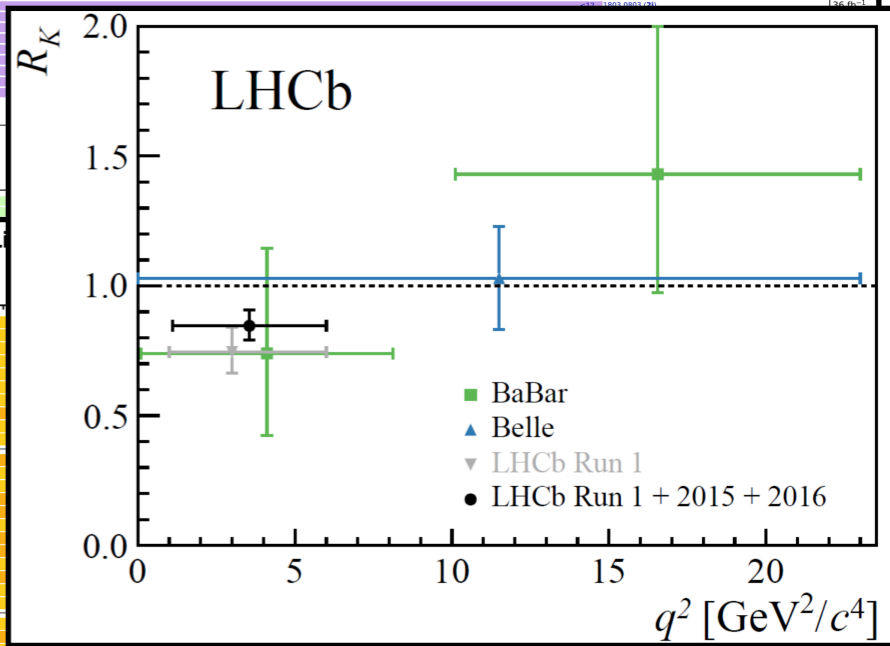
Status: May 2020



ATLAS Preliminary
 $\int \mathcal{L} dt = (18.4 - 136) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13 \text{ TeV}$
 Reference



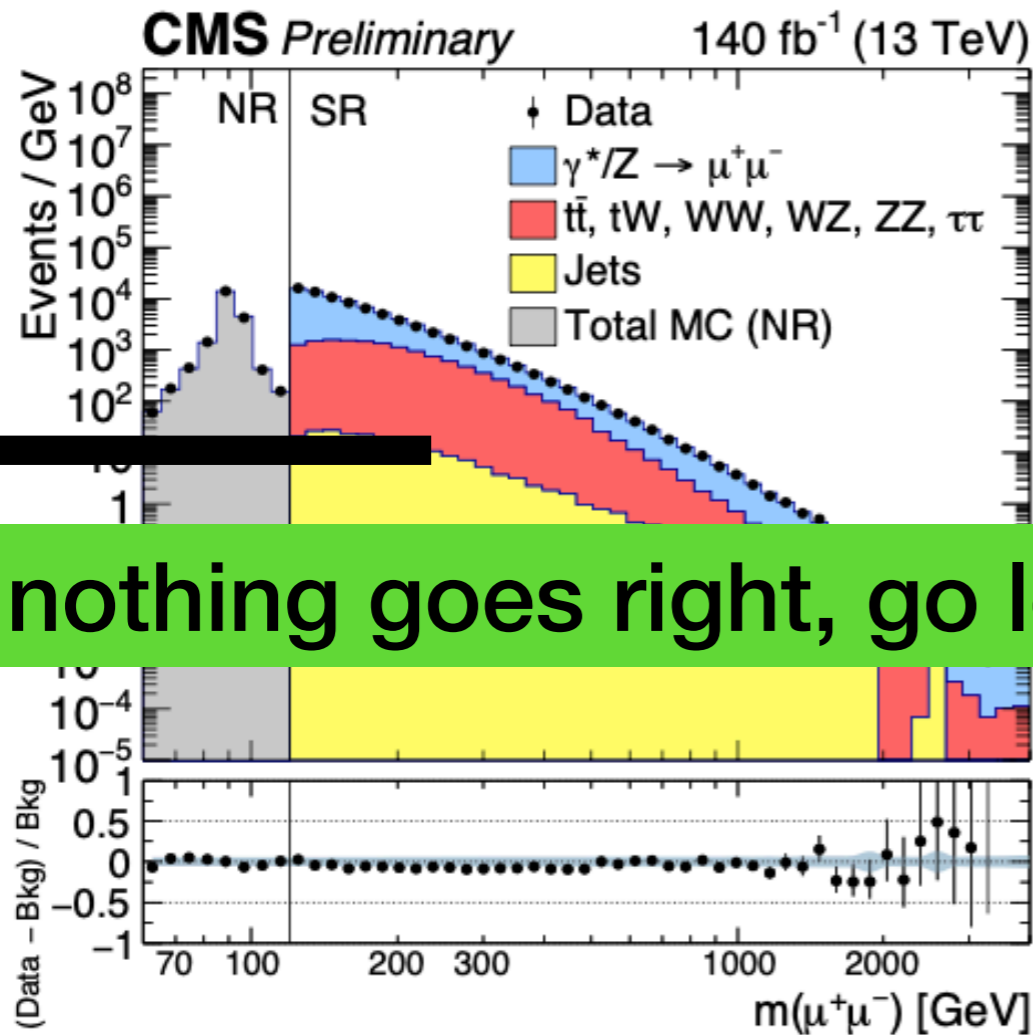
Model	Jets	Emiss	$\int \mathcal{L} dt$ [fb $^{-1}$]	Limit
1-4j	Yes	36.1	36.1	$M_{\tilde{g}}$
2j	-	37.0	37.0	$M_{\tilde{u}_L}$
$\geq 2j$	-	3.2	3.2	$M_{\tilde{u}_R}$
$\geq 3j$	-	3.6	3.6	$M_{\tilde{d}_R}$
-	-	36.7	36.7	G_{KK} mass
2j/1J	Yes	139	139	G_{KK} mass
1b, $\geq 1J/2j$	Yes	36.1	36.1	G_{KK} mass
$\geq 2b, \geq 3j$	Yes	36.1	36.1	KK mass
3fb $^{-1}$ (13 TeV)	-	-	-	Z' mass
132 fb $^{-1}$ (13 TeV)	-	139	139	Z' mass
137 fb $^{-1}$ (13 TeV)	-	36.1	36.1	Z' mass
137 fb $^{-1}$ (13 TeV)	-	139	139	W' mass
36 fb $^{-1}$ (13 TeV)	-	36.1	36.1	W' mass
13 fb $^{-1}$ (13 TeV)	-	139	139	W' mass
39 fb $^{-1}$ (13 TeV)	-	36.1	36.1	V' mass
39 fb $^{-1}$ (13 TeV)	-	139	139	V' mass
140 fb $^{-1}$ (13 TeV)	-	36.1	36.1	W_{μ} mass
77 fb $^{-1}$ (13 TeV)	-	80	80	W_{μ} mass
20 fb $^{-1}$ (8 TeV)	-	37.0	37.0	A
132 fb $^{-1}$ (13 TeV)	-	139	139	A
132 fb $^{-1}$ (13 TeV)	-	36.1	36.1	A
1-4j	Yes	36.1	36.1	$m_{H_{SM}}$
1-4j	Yes	36.1	36.1	$m_{H_{NSM}}$
1J, $\leq 1j$	Yes	3.2	3.2	$M_{\tilde{g}}$
1b, 0-1J	Yes	36.1	36.1	$M_{\tilde{g}}$
$\geq 2j$	Yes	36.1	36.1	LO mass
$\geq 2j$	Yes	36.1	36.1	LQ mass
2b	-	36.1	36.1	LQ mass
2b	-	36.1	36.1	LQ mass



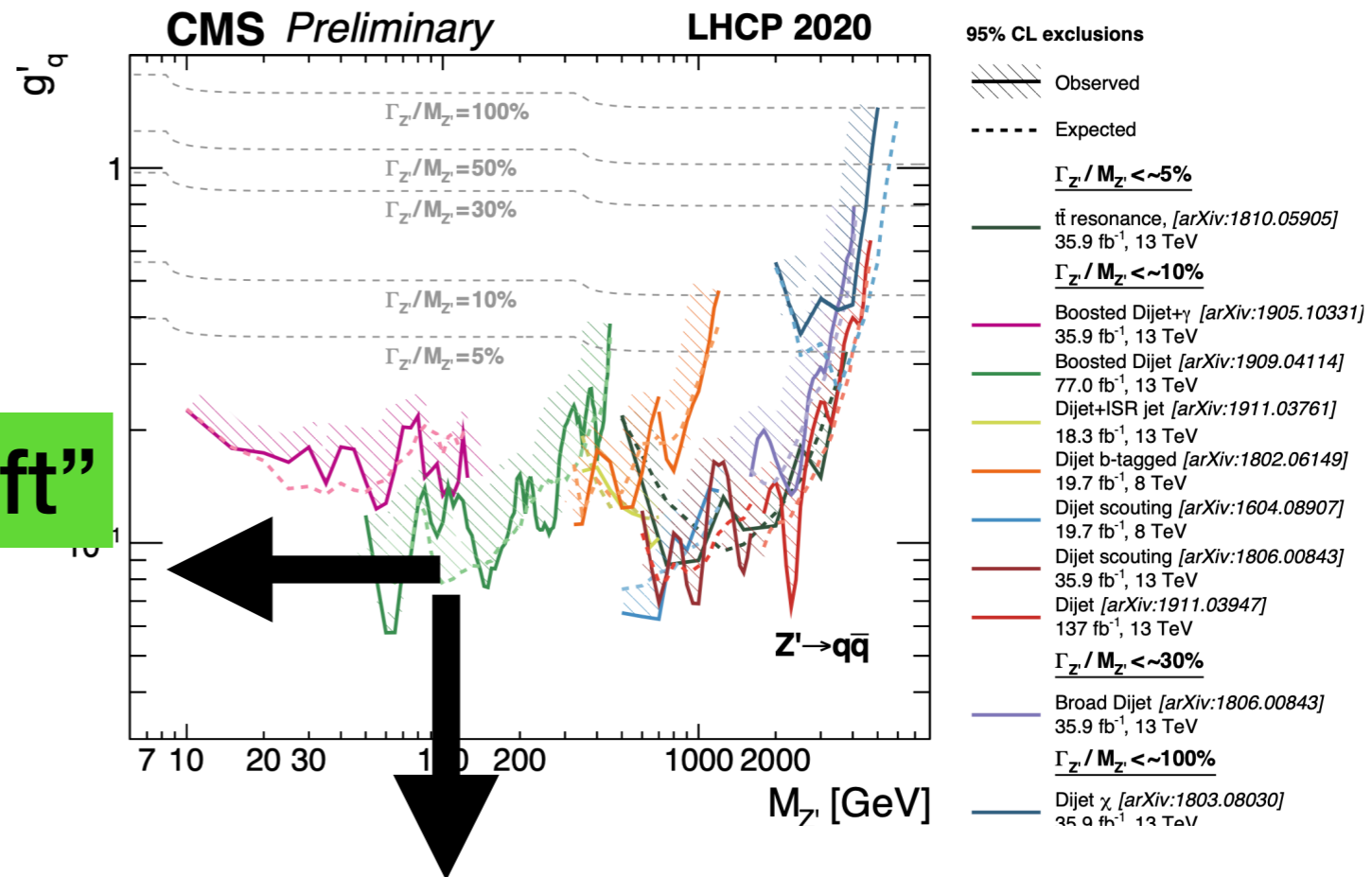
- So far in over 2k published LHC results, no significant deviations from the Standard Model Expectations. Except for LHCb $b \rightarrow sll$ (based on ≤ 2016 data)
- However, for many searches full Run-2 dataset still to be fully exploited
- The LHC is planned to provide ~ 20 times more data in the next ~ 15 years
 - LHCb may gain a factor 10 in the next 5 years

But... LHC Metamorphosis (personal view)

- Energy Frontier -> Intensity Frontier + "Lifetime" Frontier

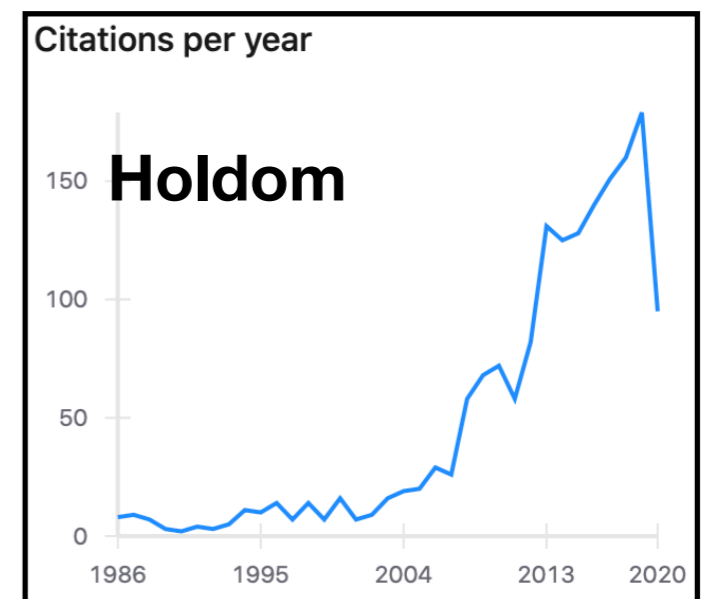
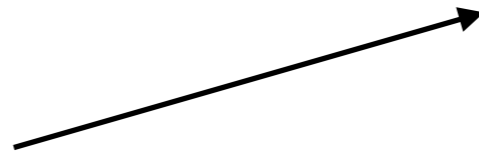


"If nothing goes right, go left"



- Low mass collider searches for feebly interacting particles have been proposed since a long time, e.g. Strassler/Zurek`06, Holdom`86, Fayet`81

► **Light U(1)_D model gaining traction**



LHCb Vector Portals

- LHCb scans 0.2-~70 GeV dimuon mass range to search for new resonances inclusively

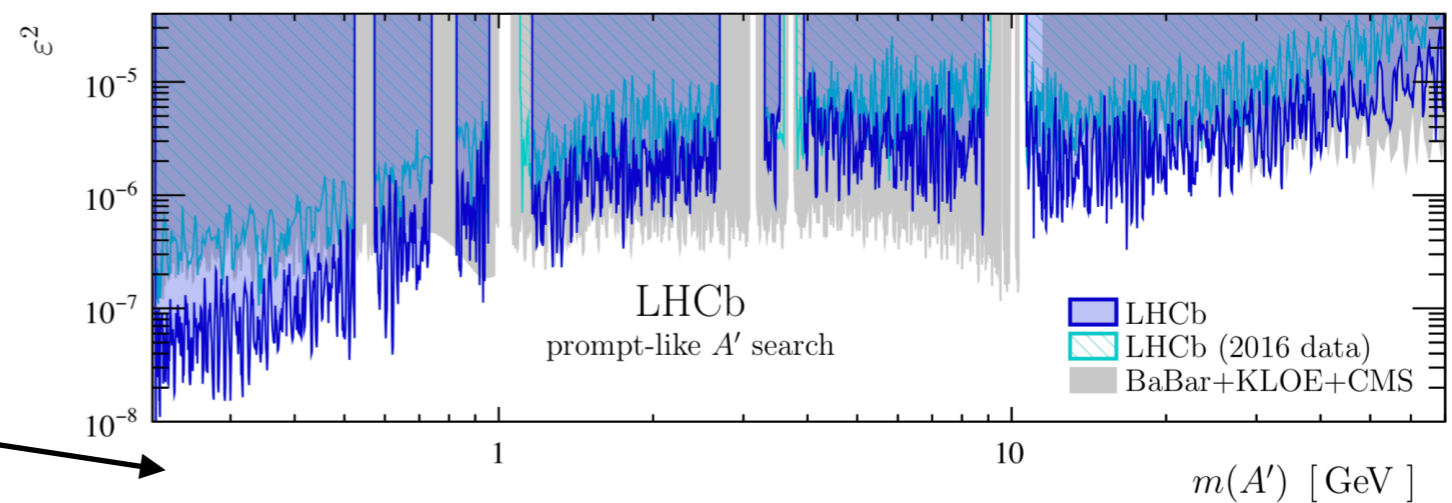
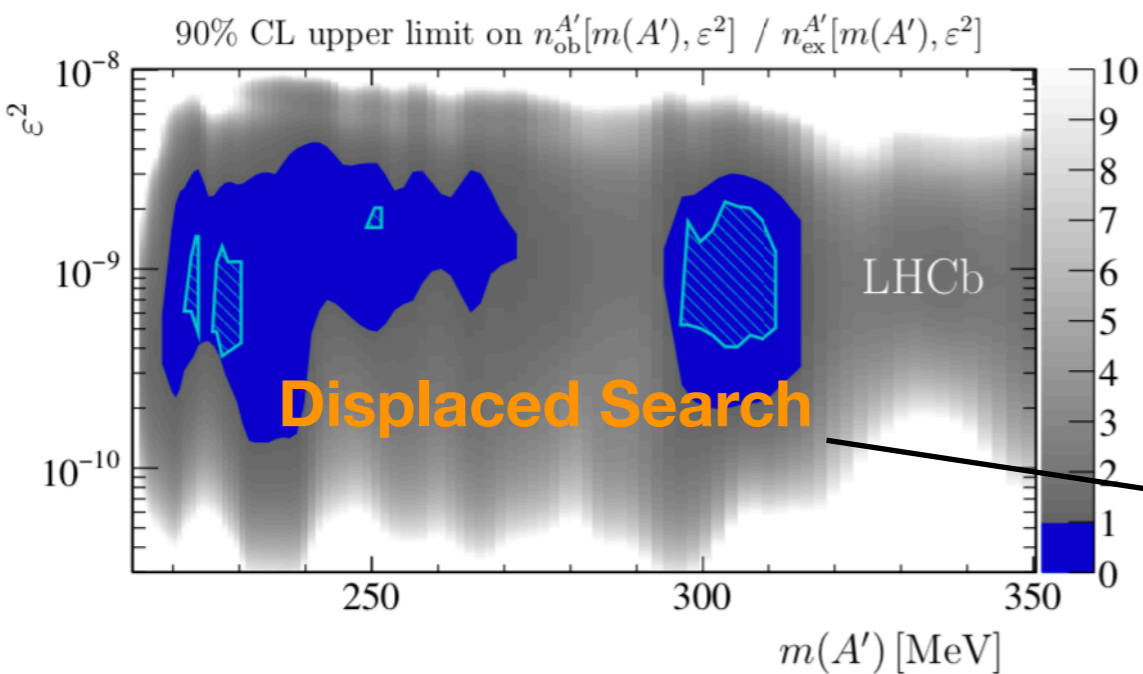
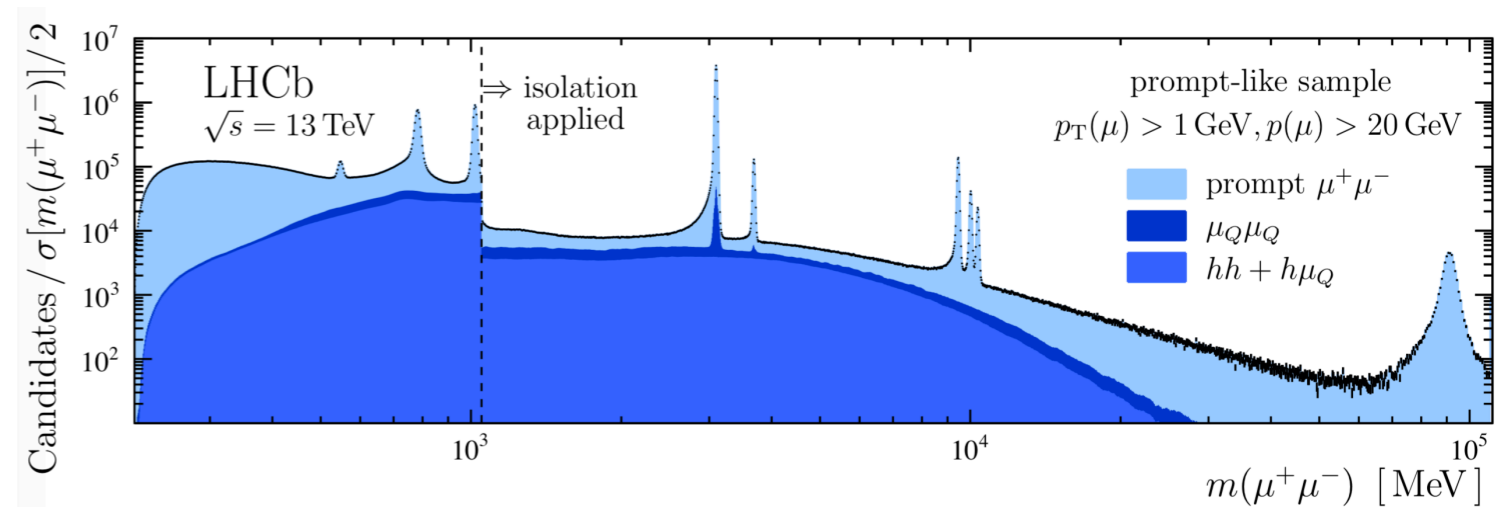
- ▶ Run-1 3 fb⁻¹, m(A) 5.5-15 GeV: [1805.09820](#)
- ▶ Run-2 1.6 fb⁻¹, m(A) 0.2-70 GeV: [1710.02867](#)
- ▶ Run-2 5.5 fb⁻¹, m(A) 0.2-70 GeV: [1910.06926](#)

$$\mathcal{L} \supset -\frac{\epsilon}{2 \cos \theta_W} B_{\mu\nu} F'^{\mu\nu}, \quad \text{vector portal}$$

Via kinetic mixing

- Main production:**

- ▶ m(A) < 1 GeV: Meson decays, m(A) > 1 GeV: Drell-Yan
- ▶ Sizeable displacement of 0.01-1 cm with sensitivity < 1 GeV



Dimuon Resonance Searches

- Additional vector portal interpretations via coupling relations

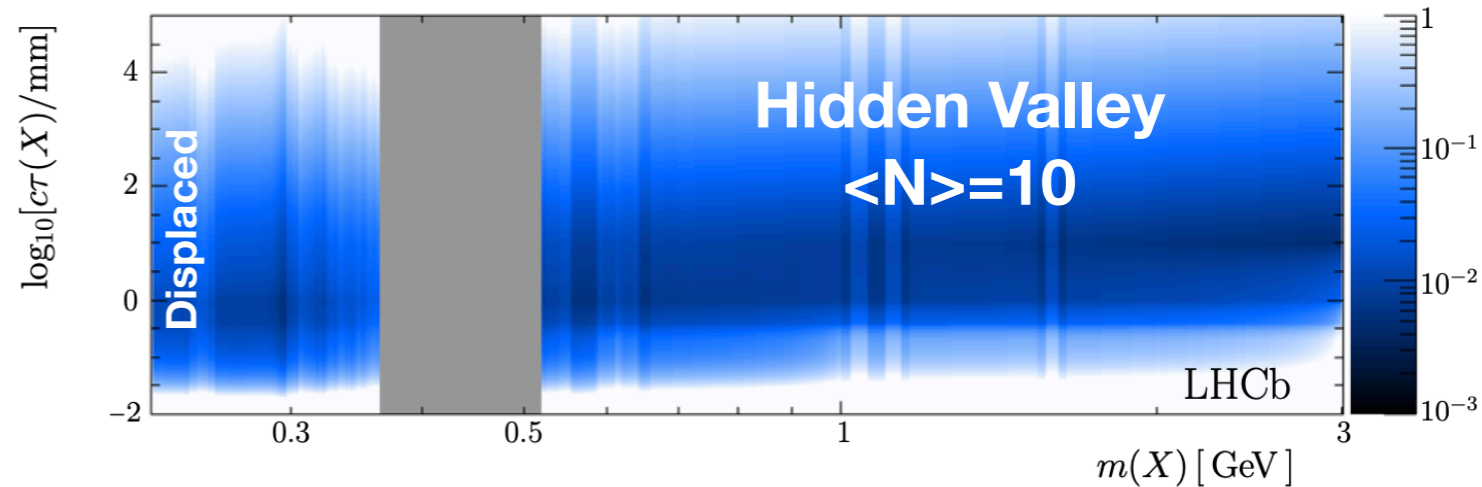
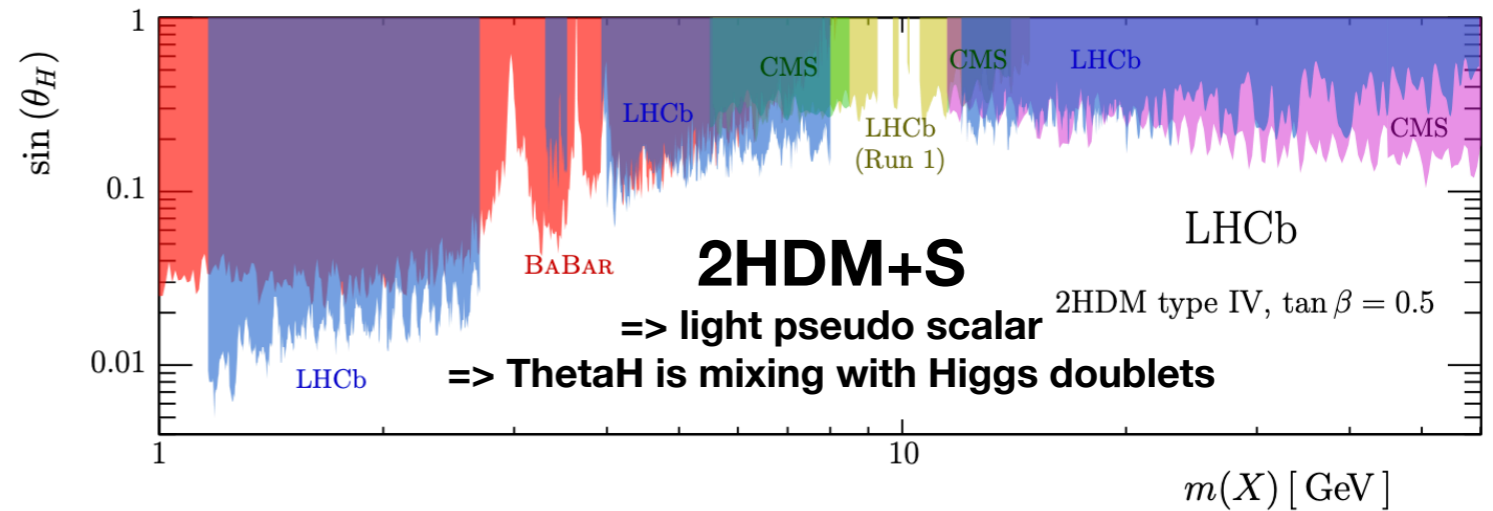
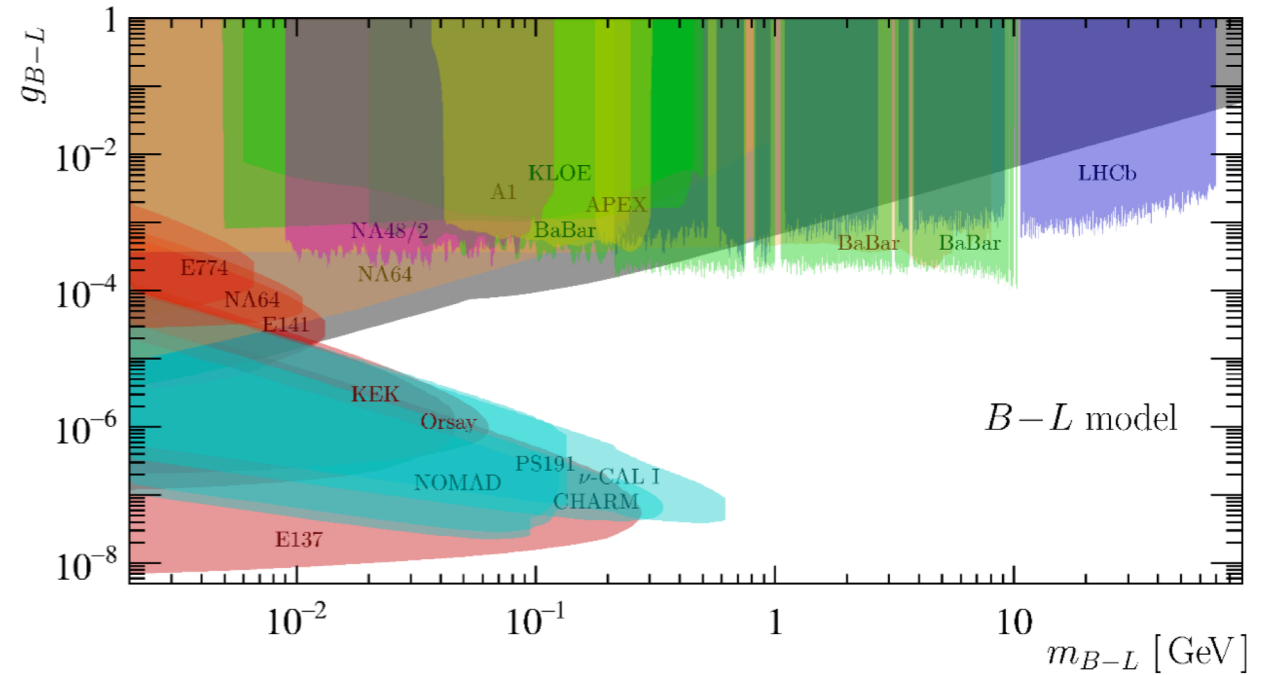
► [1801.04847](#)

- Additional model independent LHCb search performed

► [2007.03923](#)

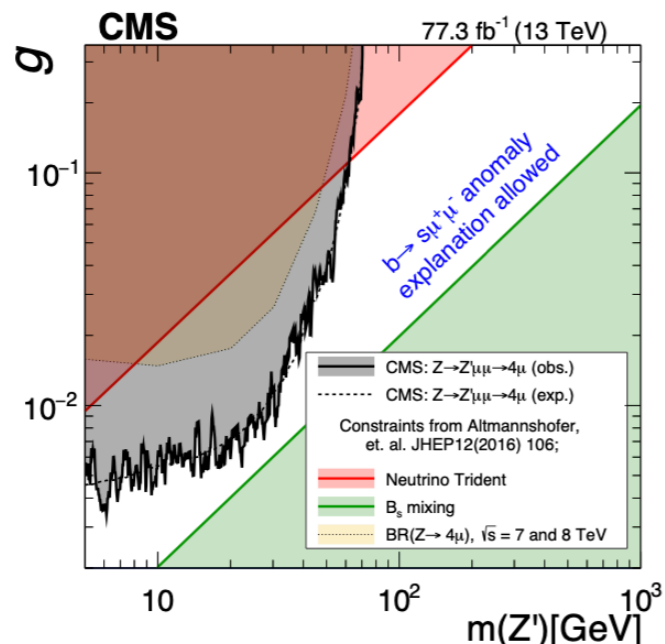
► Includes Hidden Valley and 2HDM+S interpretations

☆ [1708.05389](#), [1802.02156](#)



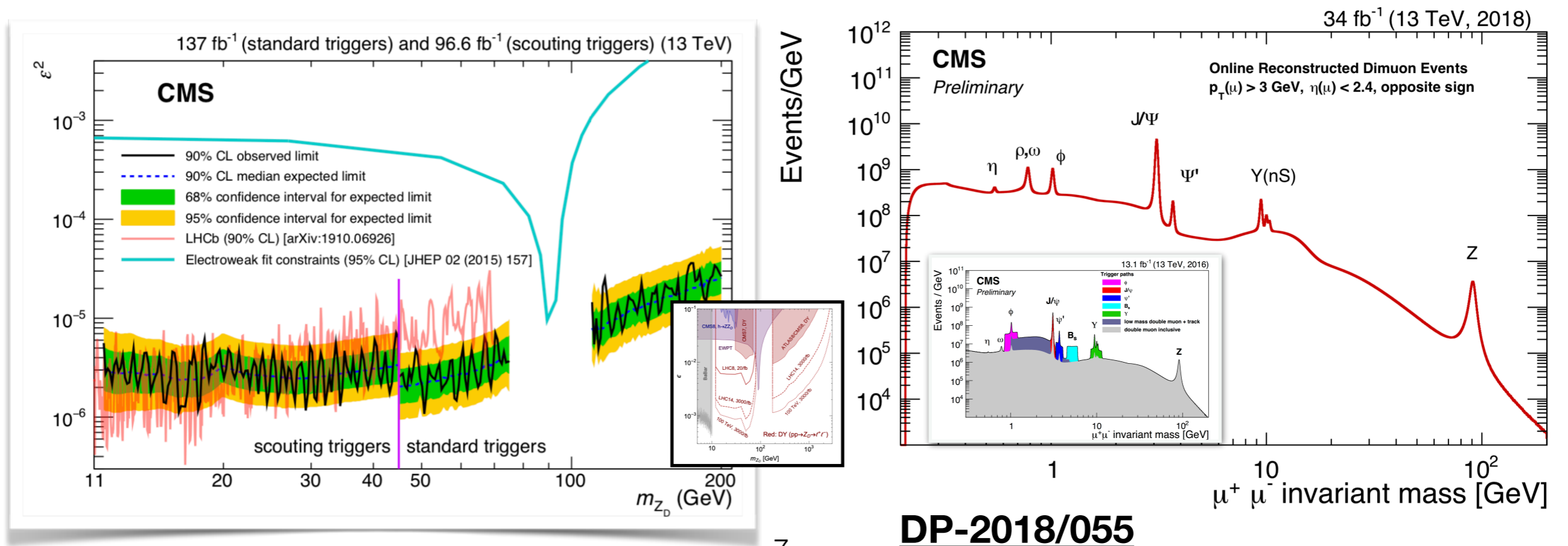
CMS search for $L_{\mu-L\tau}$ gauge boson in $Z \rightarrow 4\mu$

[1808.03684](#)



CMS Portal Search via Muons

- CMS search came out in 2019 covering $m(A)$ -range 11.5 - 200 GeV range (low mass searches still to be done)
 - ▶ [arxiv:1912.04776](https://arxiv.org/abs/1912.04776), 137 fb⁻¹ for 45-200 GeV, 97 fb⁻¹ for 11.5-45 GeV (scouting)
- Dedicated data recorded using dimuon *scouting stream* fully started in 2015, fully commissioned in 2017 - roughly 100 fb⁻¹
 - ▶ Hardware L1 trigger constraints, at HLT (Software) inclusive selection
 - ▶ Includes displaced dimuon decays up to ~10cm



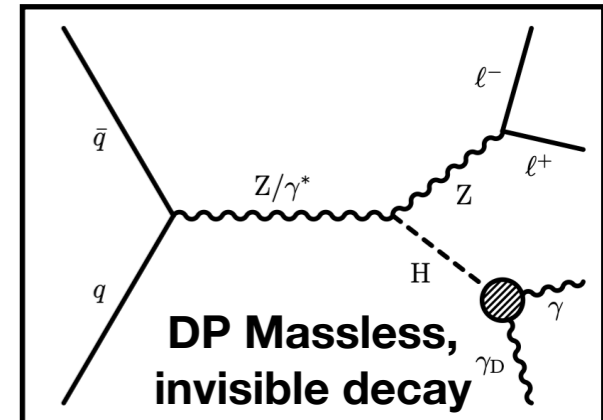
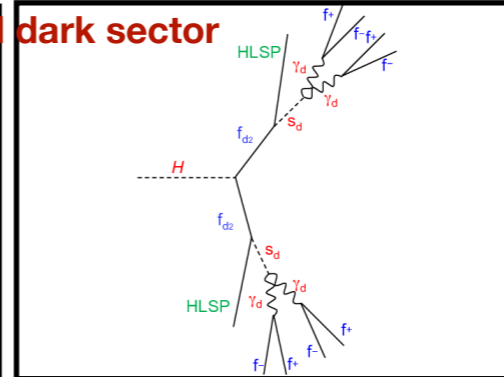
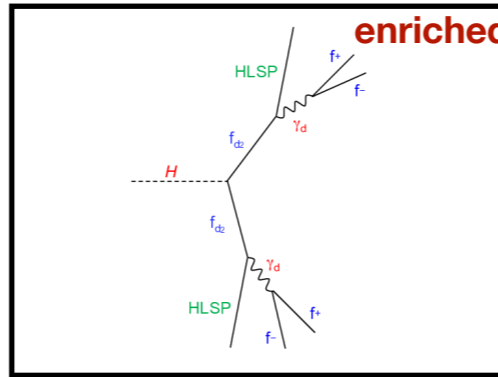
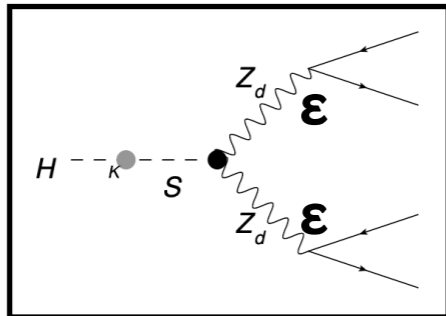
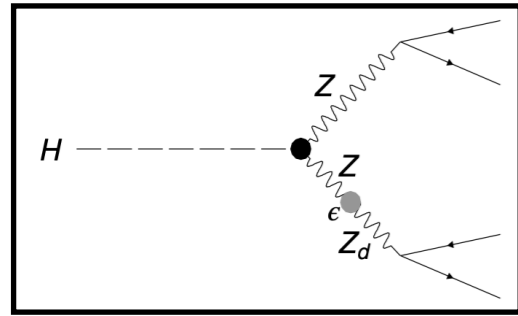
Dark Higgs and Dark Photons

- Search for $H(125) \rightarrow Z_d Z_d$, ZZ_d [1802.03388](#) or more exotic via dark fermions [1909.01246](#)

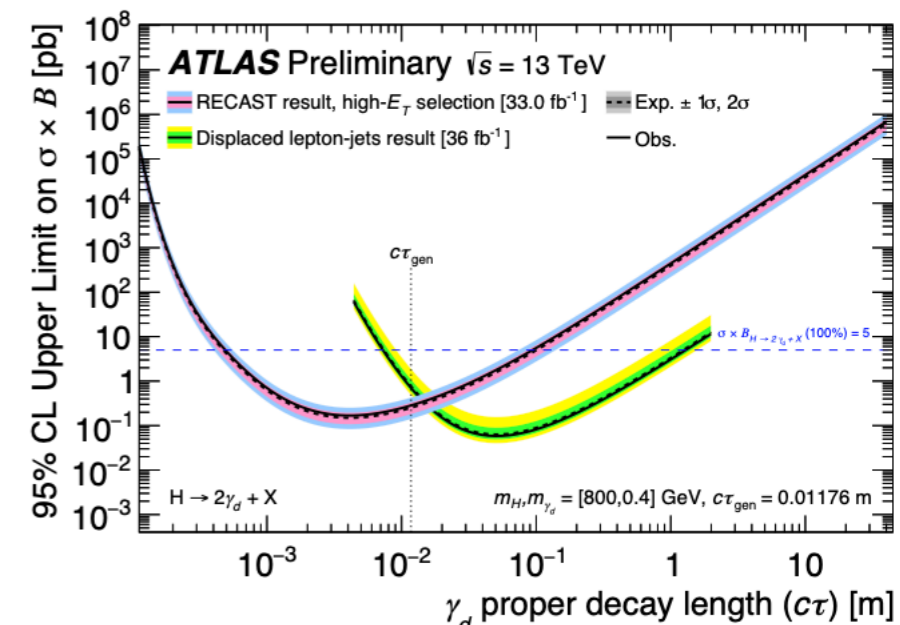
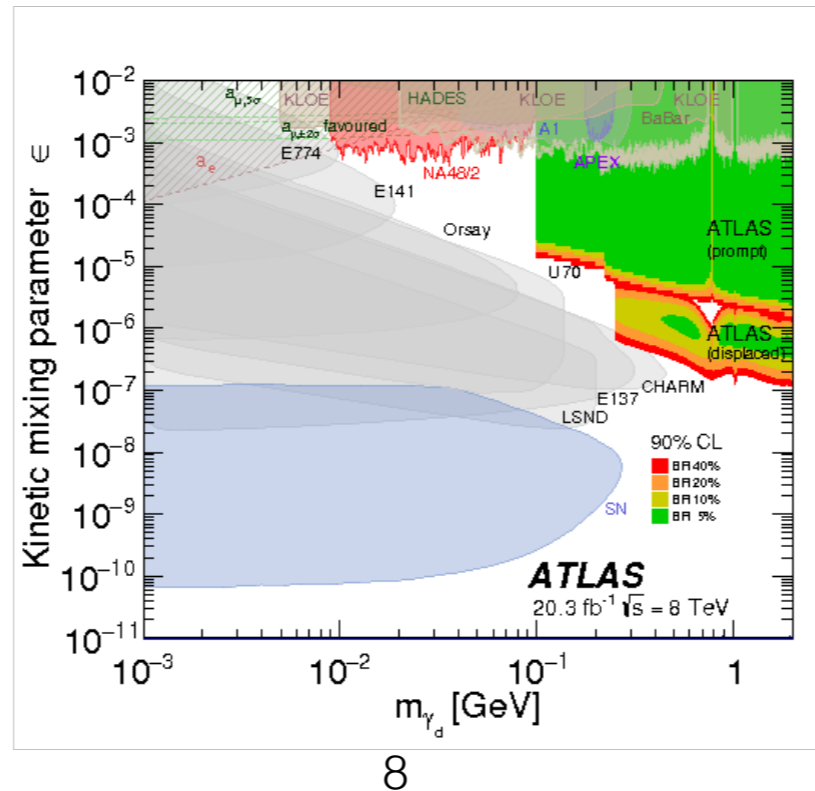
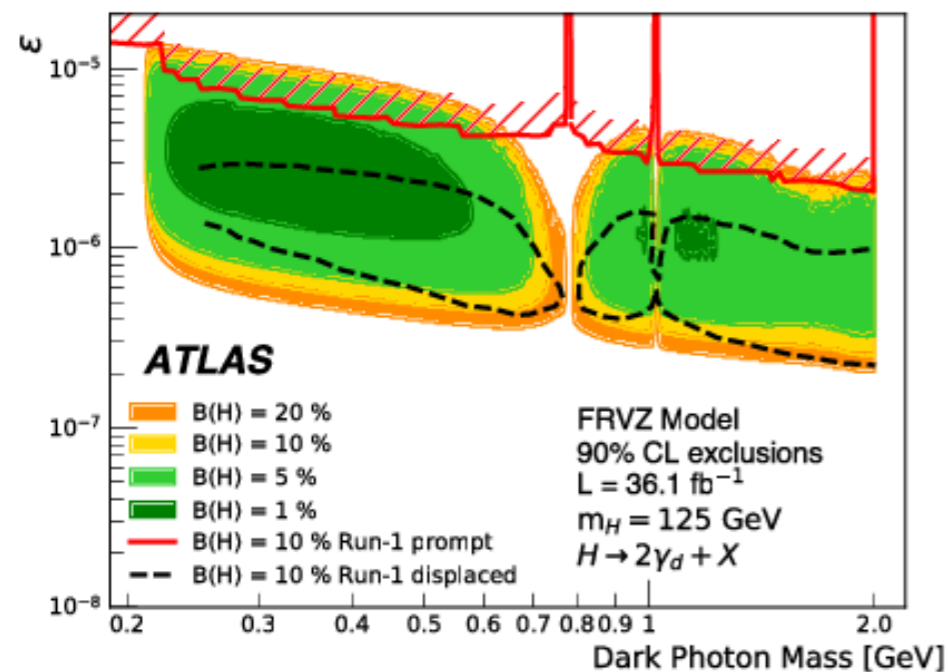
$$\mathcal{L} \supset \kappa |S|^2 |H|^2$$

CMS Search
[1908.02699](#)

► **Vector portal + Higgs portal**



- Also *displaced* hadronic DP decays (dark photon jets) considered by ATLAS, and *displaced* lepton jets, if mixing is very small, maybe the only way to find it

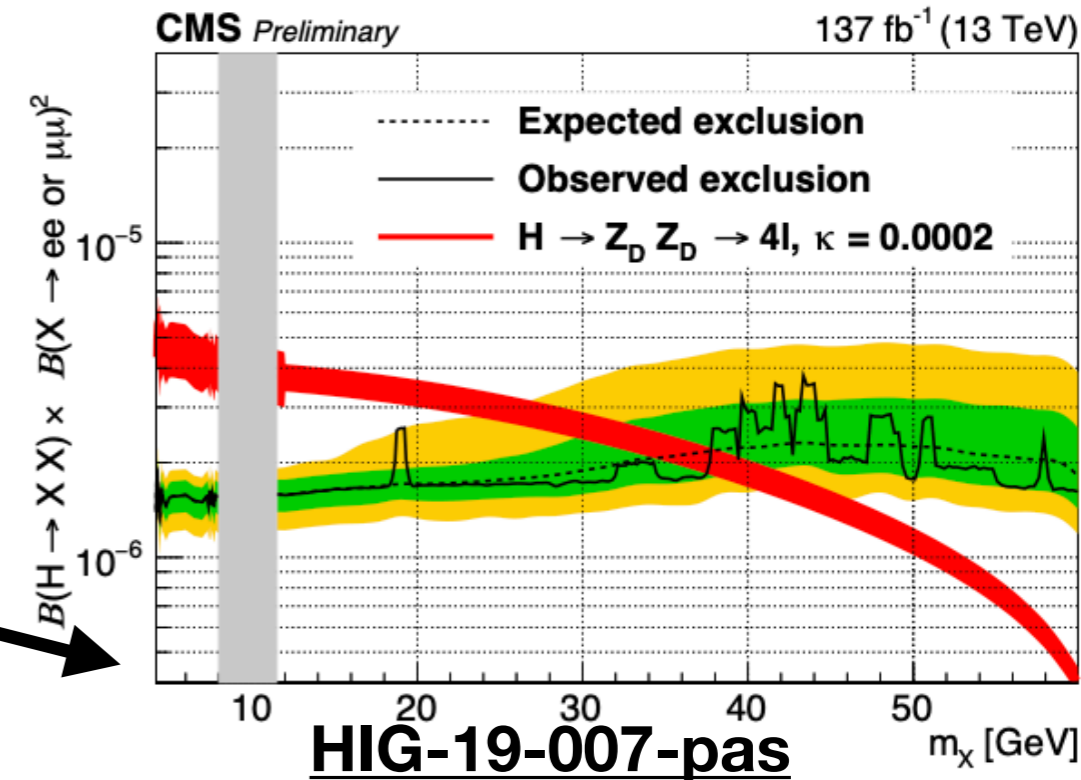
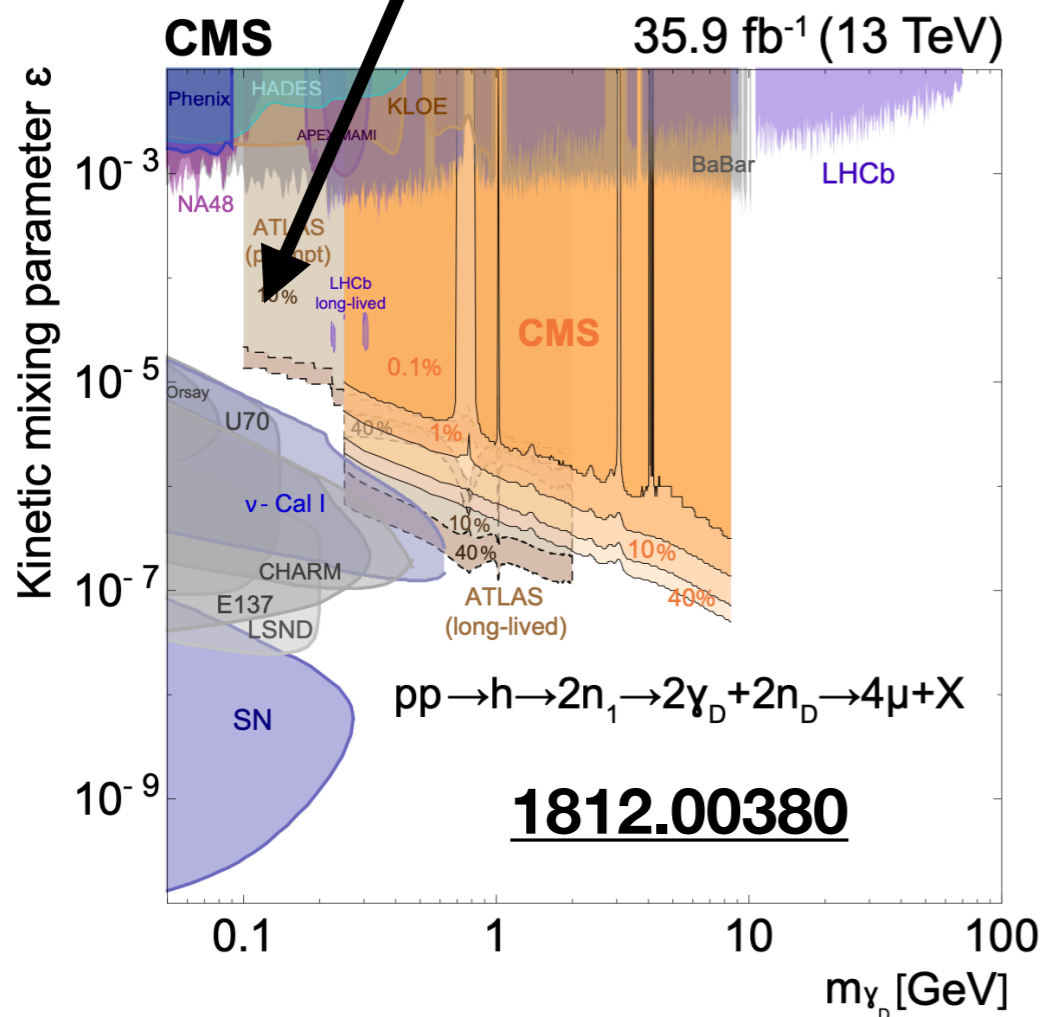


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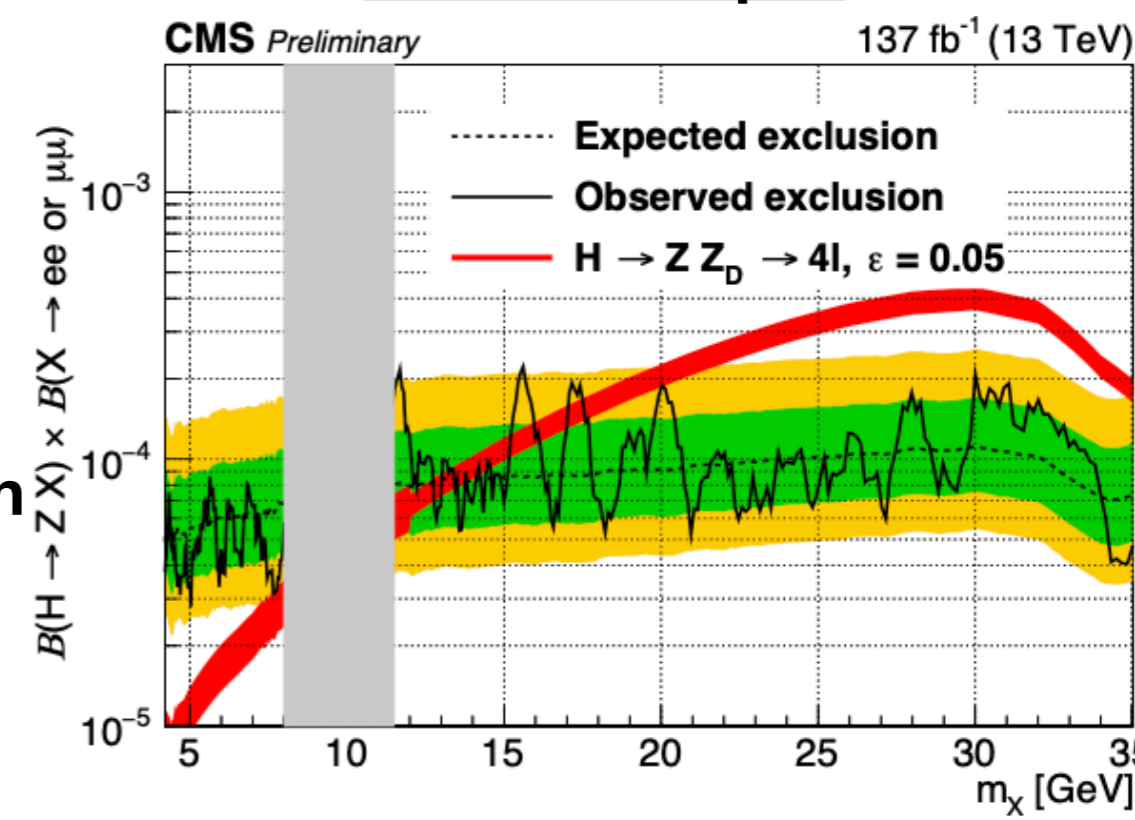
Dark Higgs and Dark Photons

- Prompt Search(2e/2mu) by CMS full Run-2 dataset
- displaced by CMS (4mu), yet to fully updated
- **What about displaced/prompt electrons**

► For $m_A < 2 \cdot m(\mu)$? difficult spectrum, hard to fit?



Also ALP interpretation available



Hadronic Vector Portal Searches

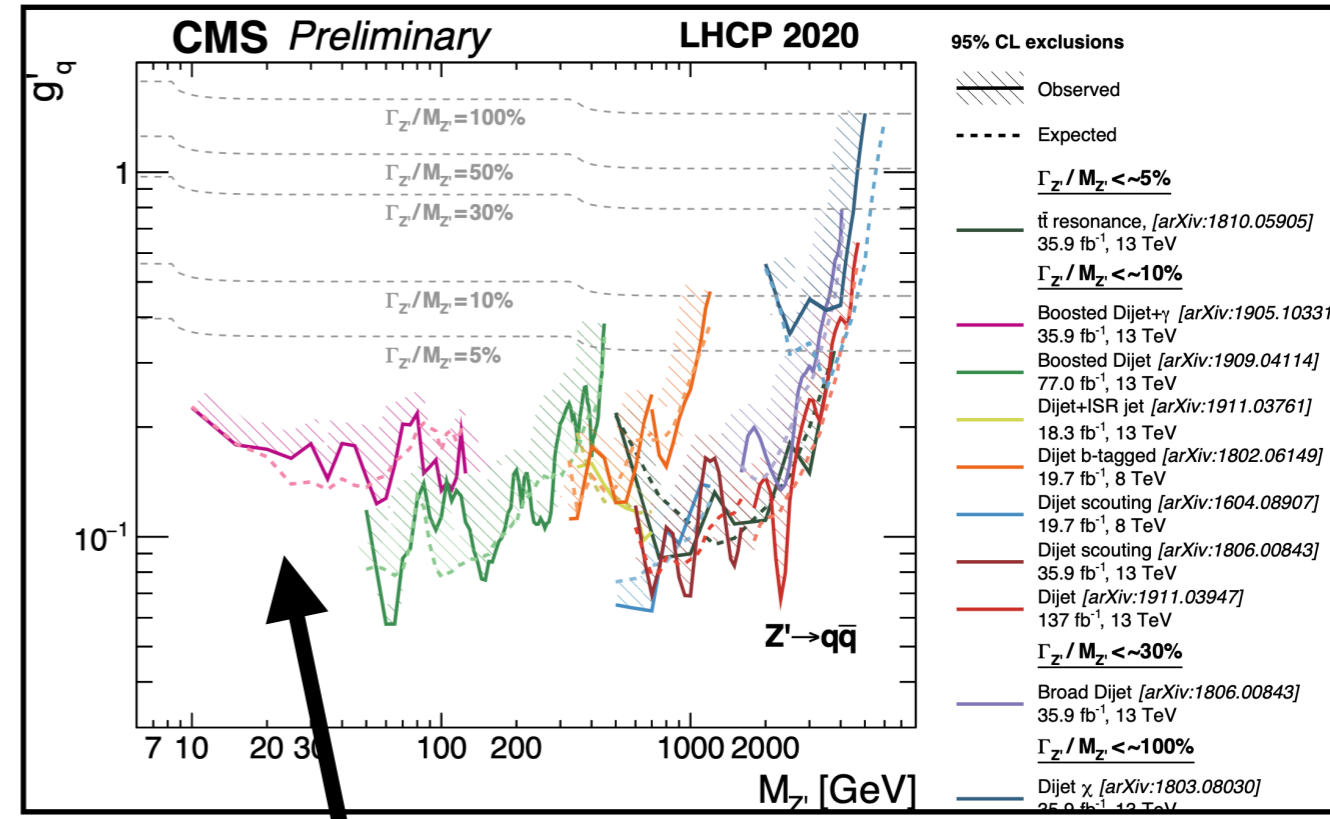
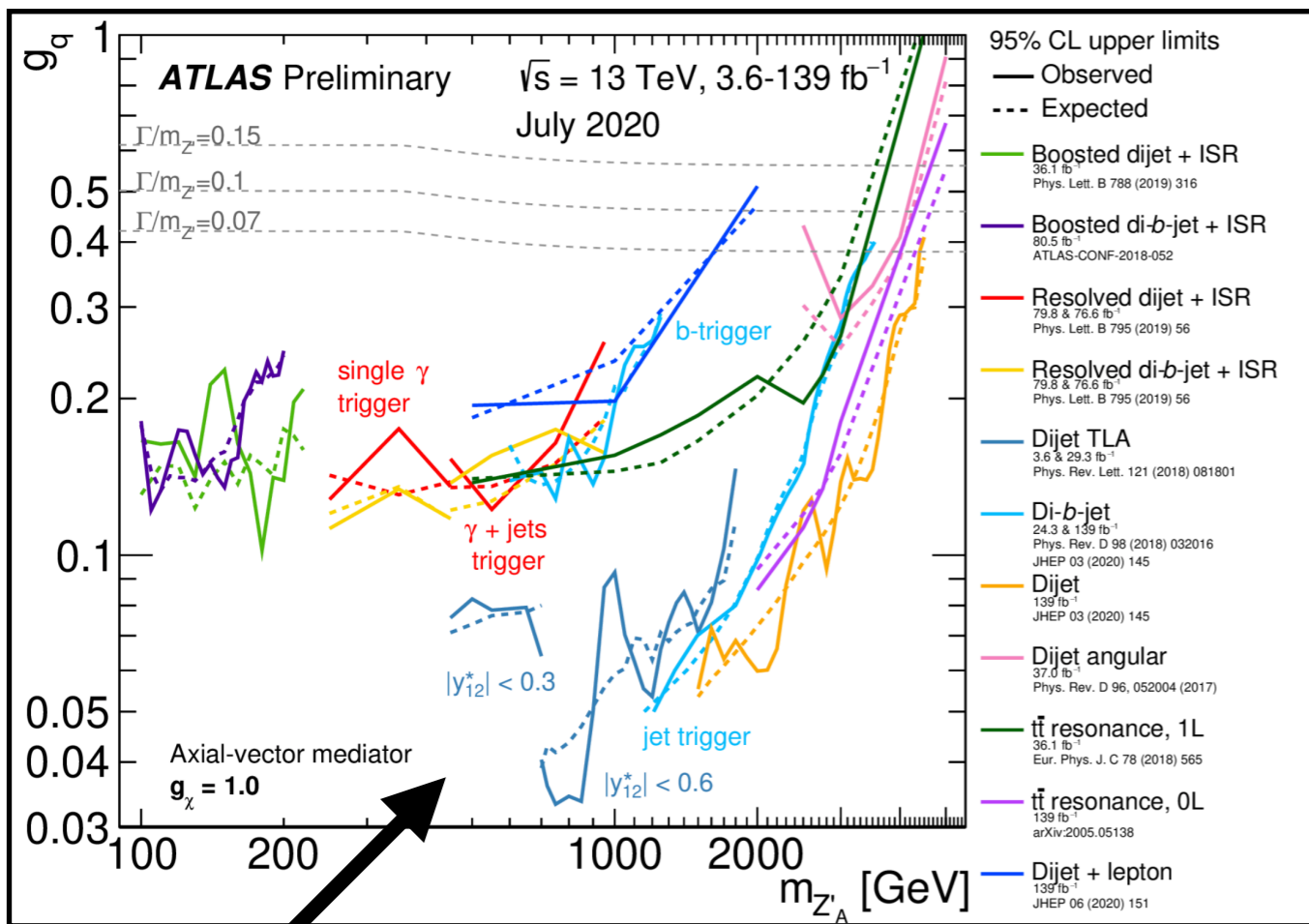
- Assuming simplified (leptophobic) Vector Portals

► <https://arxiv.org/pdf/1703.05703.pdf>

- Experimentally low mass and coupling regime probed via dedicated *trigger-level-analyses/scouting* and *jet-substructure* analysis for boosted mediators

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu \bar{\ell} \gamma^\mu \ell,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma_5 q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu \bar{\ell} \gamma^\mu \gamma_5 \ell.$$



Trigger-Level-Analysis!

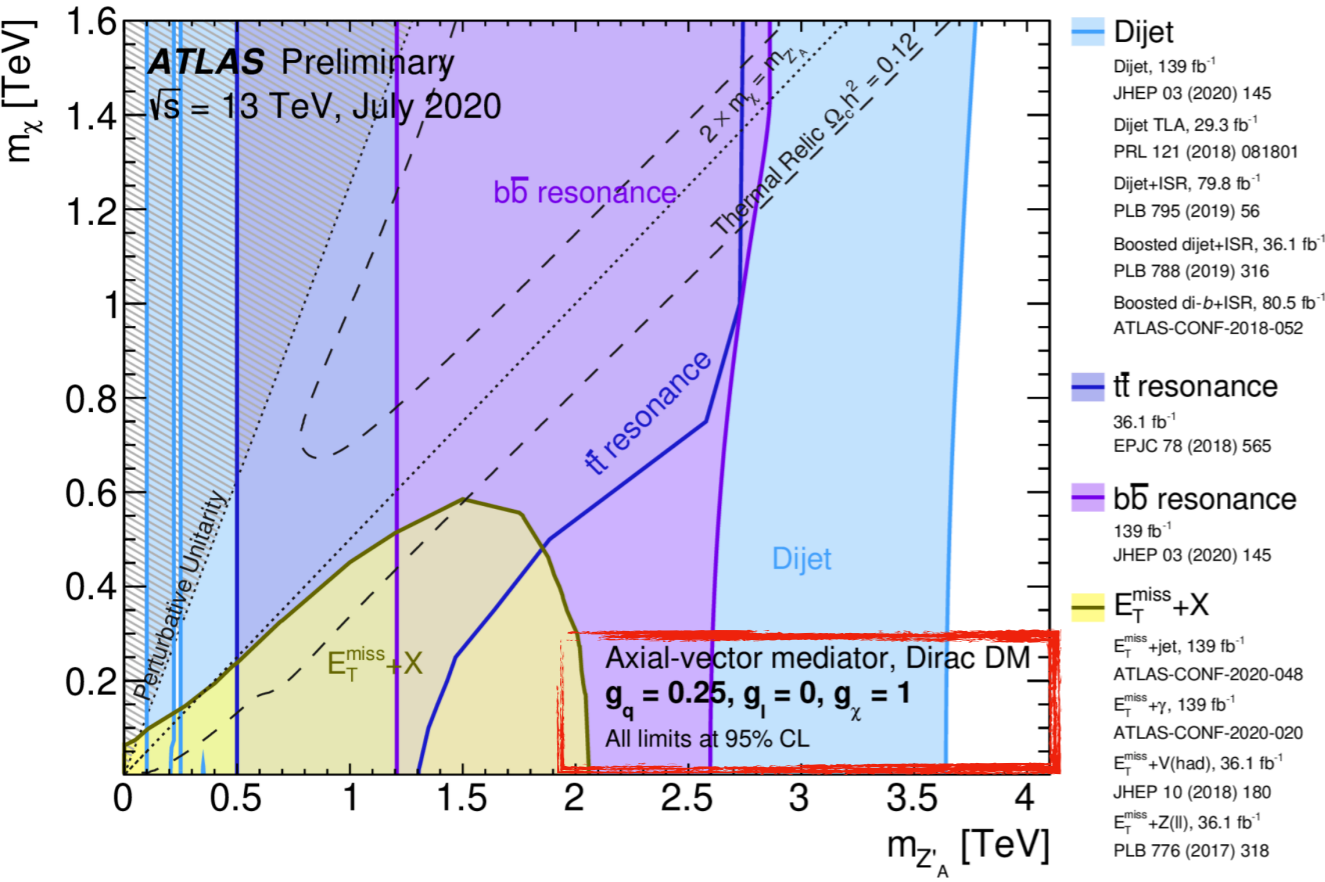
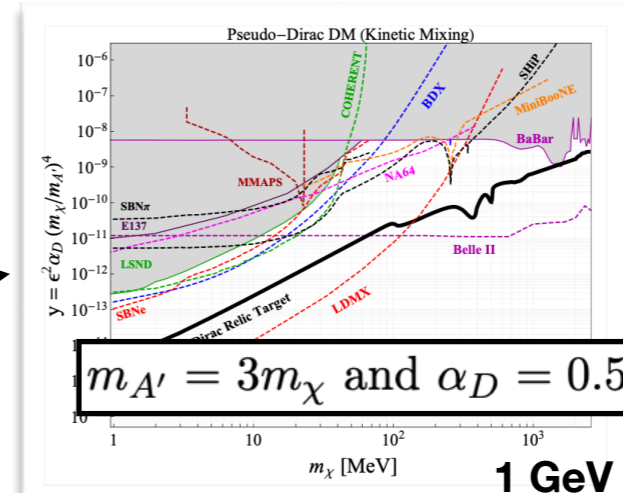
Boosted Z' , recoiling photon

Vector Portal Dark Matter

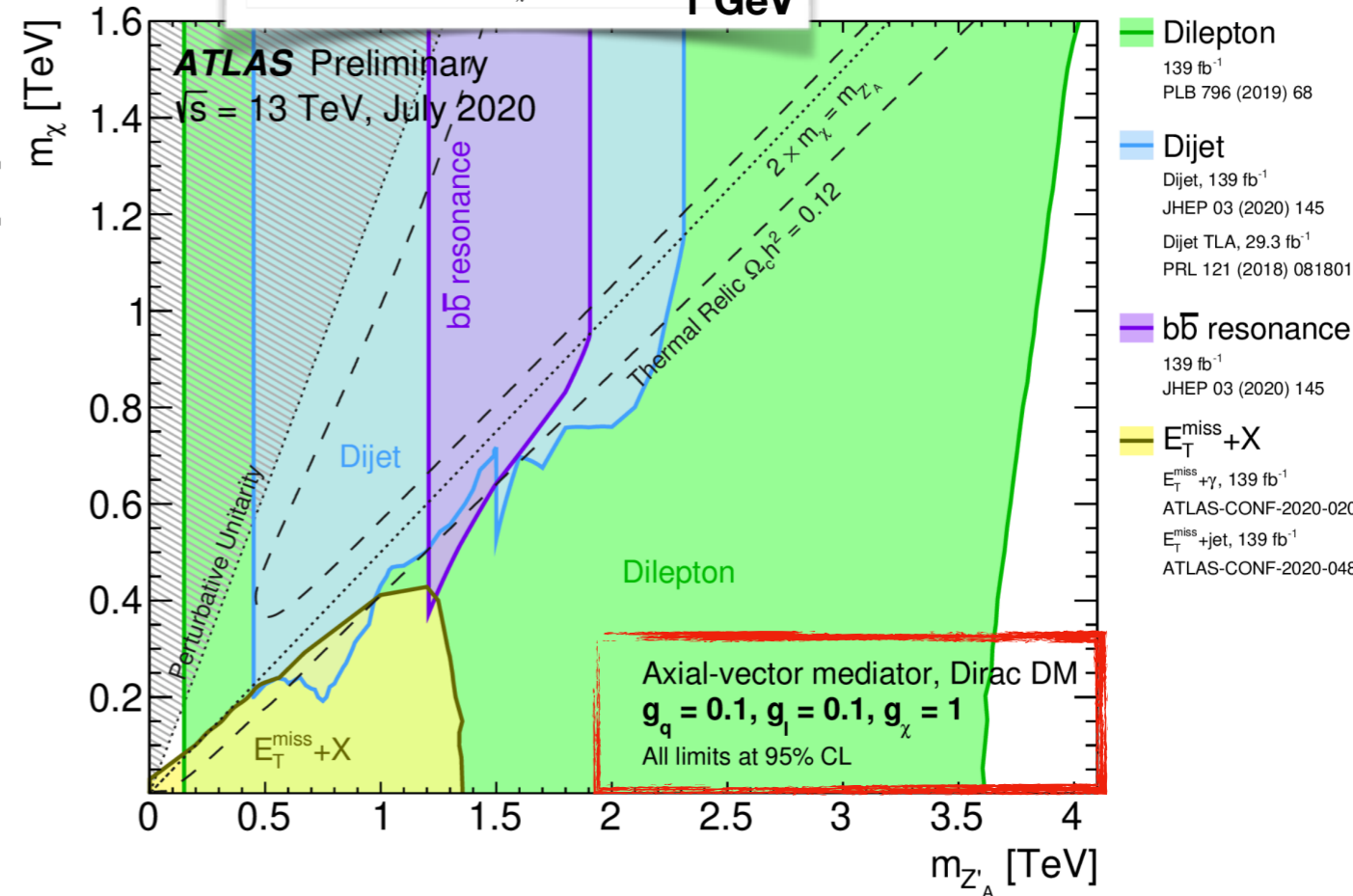
- Following recommendations of LHCDMWG, can set limits in m_χ - $m_{Z'}$ plane and compare to MET+X searches

▶ [1703.05703](#)

▶ Other experiments take over in low mass Dark Matter region



ATL-PHYS-PUB-2020-021



Once lepton couplings are enabled, di-lepton searches dominate sensitivity

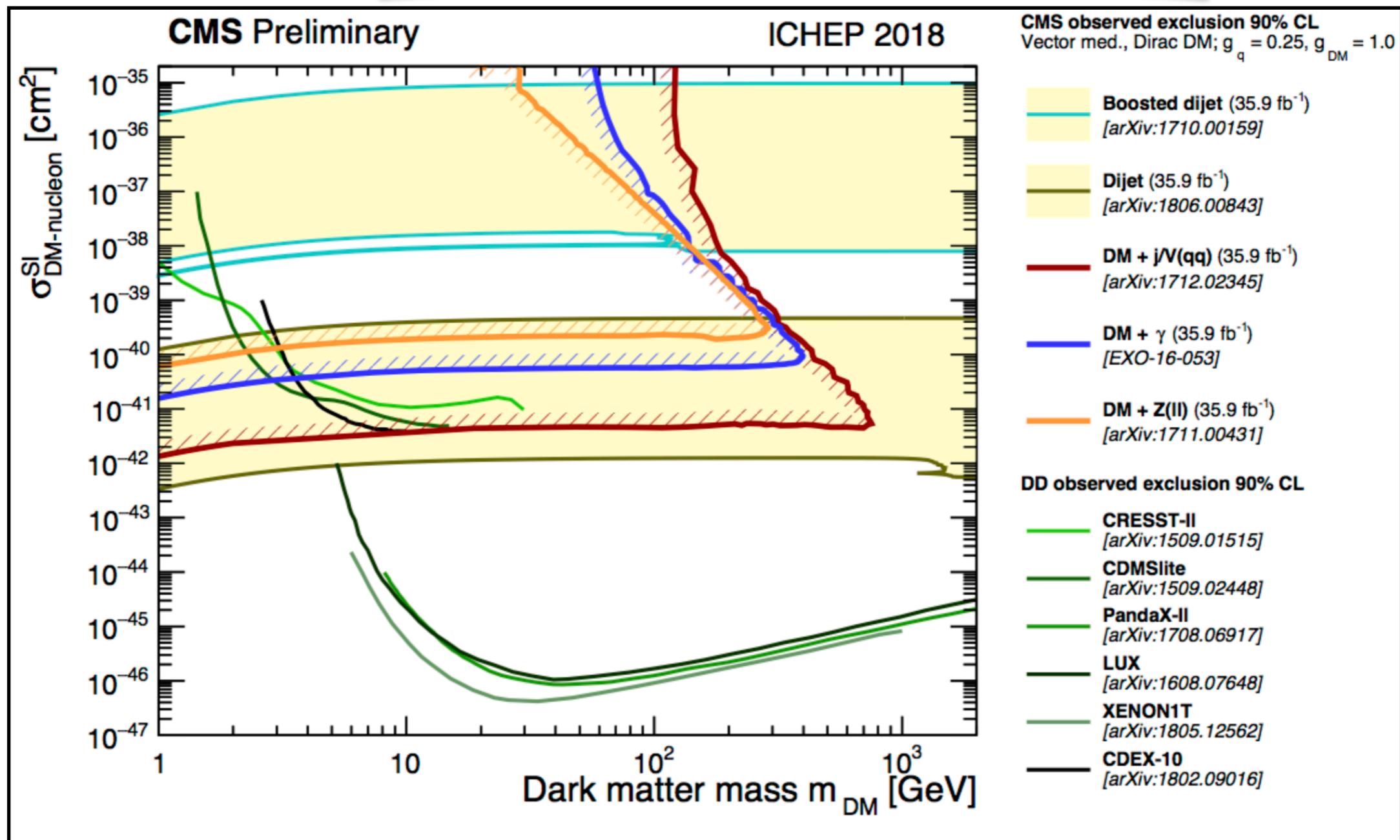
[CMS Plots Here](#)

DM-nucleon Cross Sections

- For given couplings can compare to direct detection experiments

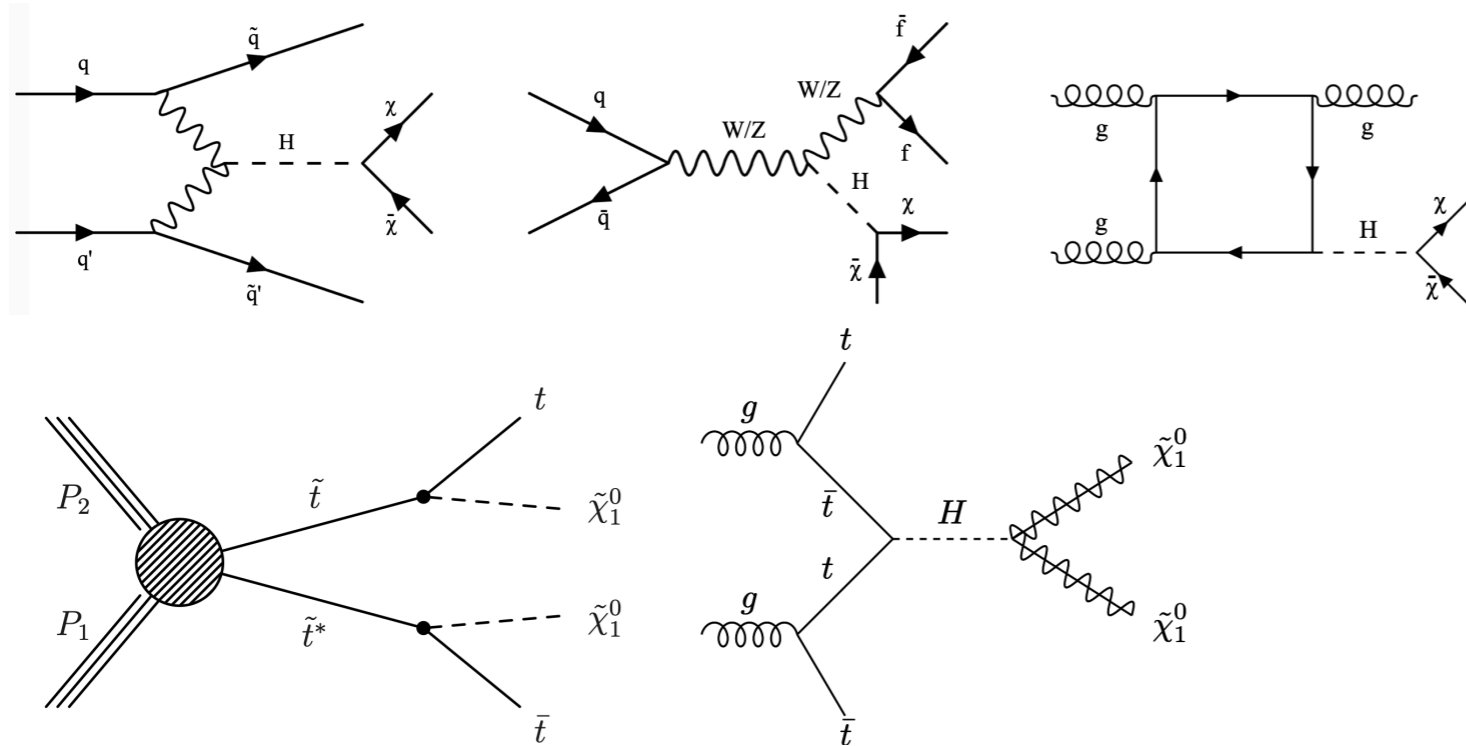
► [1603.04156](#)

$$\sigma_{\text{SI}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2$$



The Higgs Portal Dark Matter

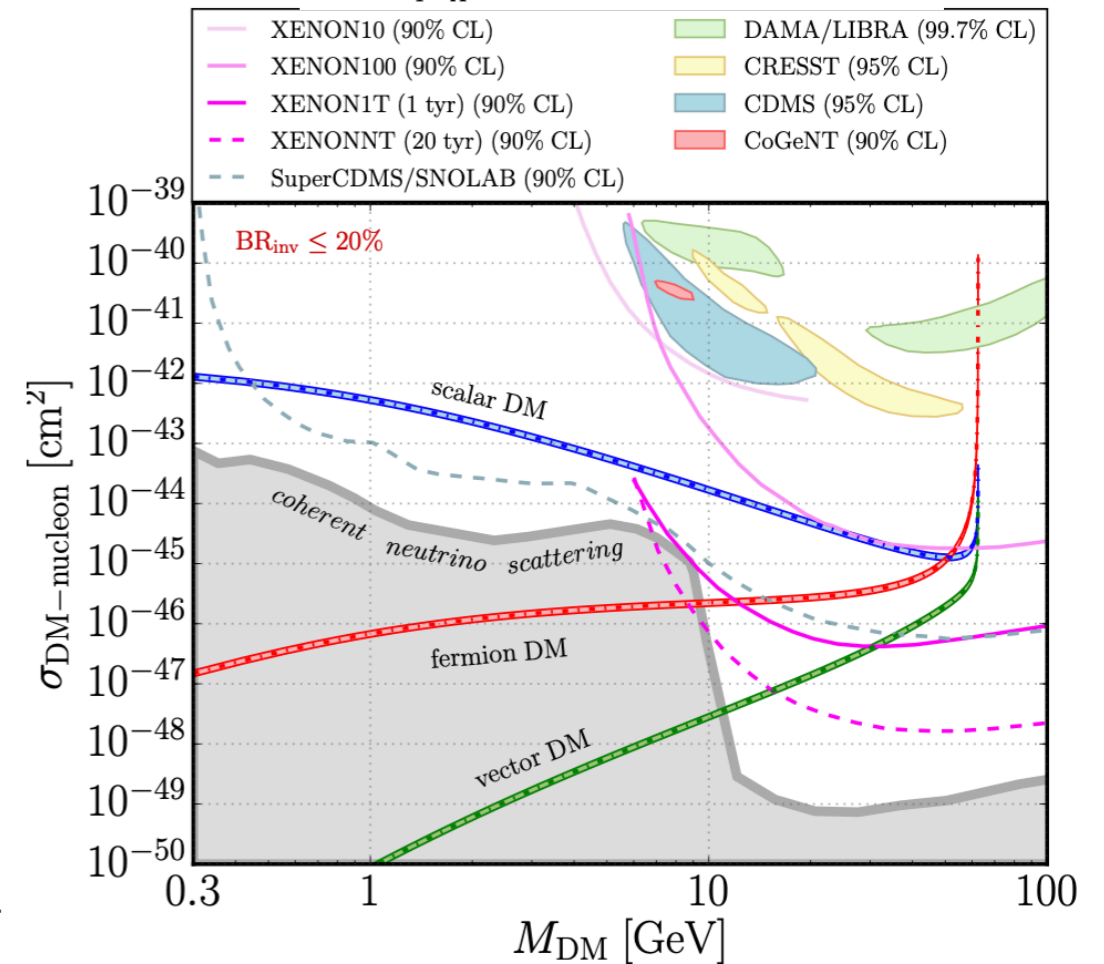
- So far discussed generally vector portal, with any mediator mass
- LHC produces Higgs(125) bosons directly under controlled environment => Higgs(125) portal of particular interest



$$\mathcal{L} \supset -\frac{1}{4} \lambda_{hSS} H^\dagger H S^2 \quad (\text{scalar DM}) \quad \text{or}$$

$$\mathcal{L} \supset +\frac{1}{4} \lambda_{hVV} H^\dagger H V_\mu V^\mu \quad (\text{vector DM}) \quad \text{or}$$

$$\mathcal{L} \supset -\frac{1}{4} \frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi} \chi \quad (\text{fermion DM}),$$



CMS combination: <https://arxiv.org/abs/1809.05937>

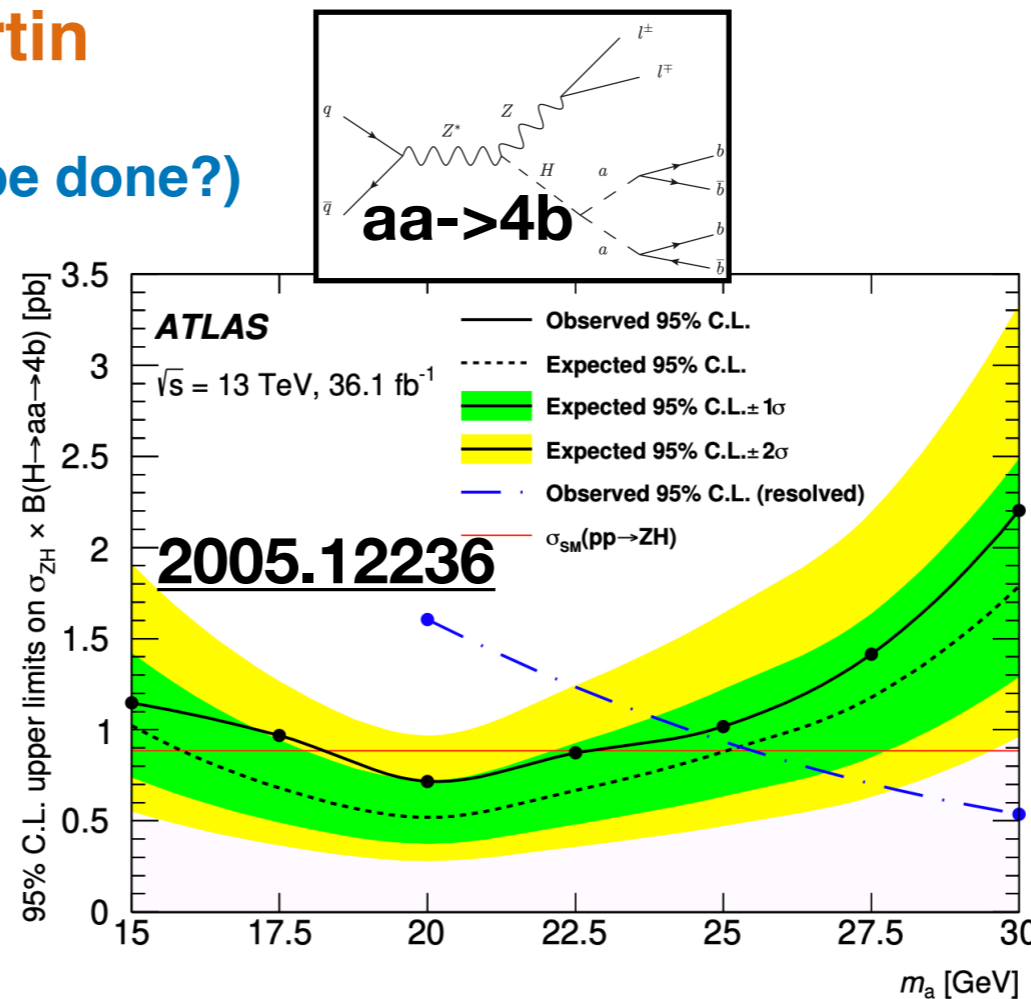
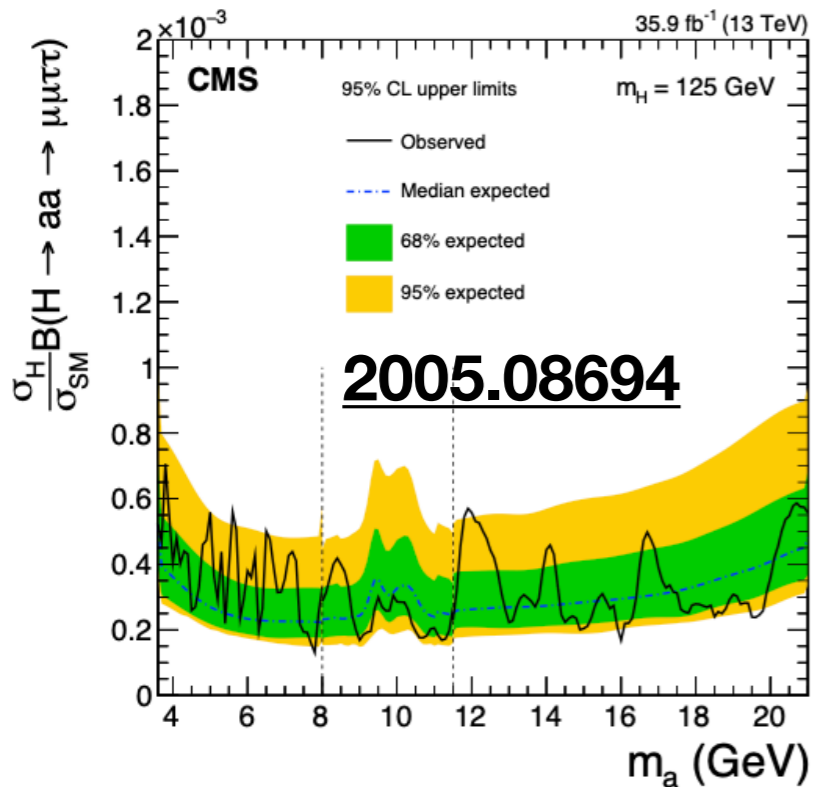
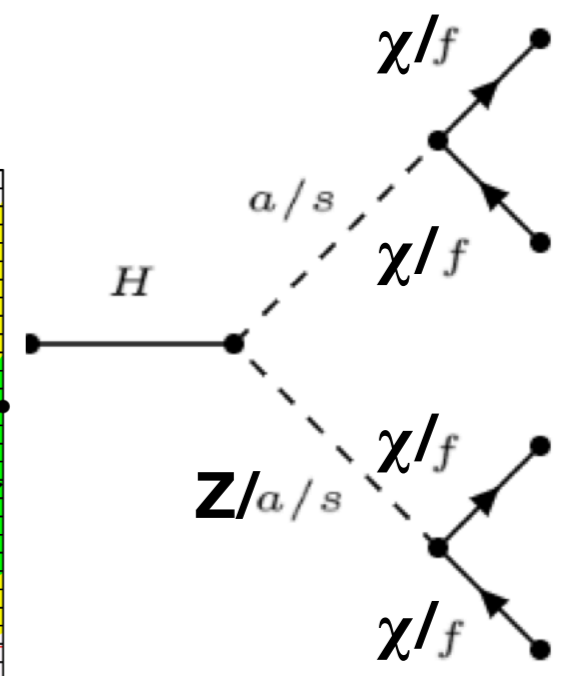
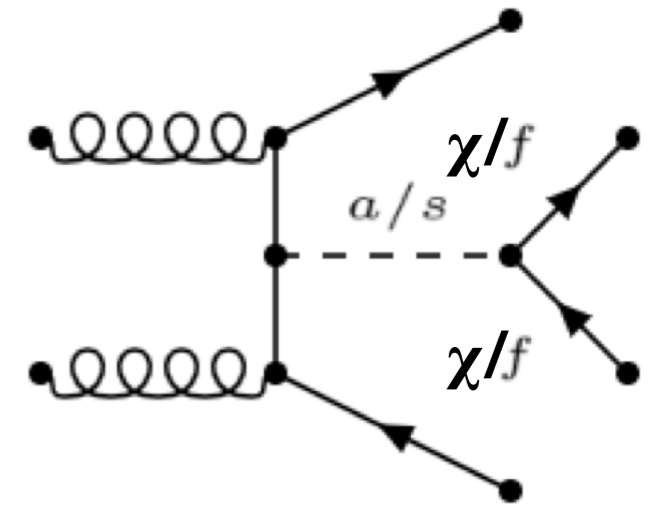
Latest ATLAS Search: ATLAS-CONF-2020-008

HL-LHC/HE-LHC BSM Higgs CERN-LPCC-2018-04

(Pseudo)Scalar Mediator Searches

- Low mass (pseudo) scalar mediators in 2-Higgs-Doublet-Models (UV completeness) gained interest

- ▶ [LHCDMWG Paper, Djouadi et al. 1903.03616](#)
- ▶ [Nice ATLAS combination/review paper: 1903.01400](#)
- ▶ Also [Kahlhoefer et al. 1701.07427](#), suggests that $m_X \sim 1$ GeV is excluded for $2 \cdot m(a) < m(H)$, check
- ▶ [Exploration paper Curtin et al 1312.4992](#)
(which analysis are left to be done?)

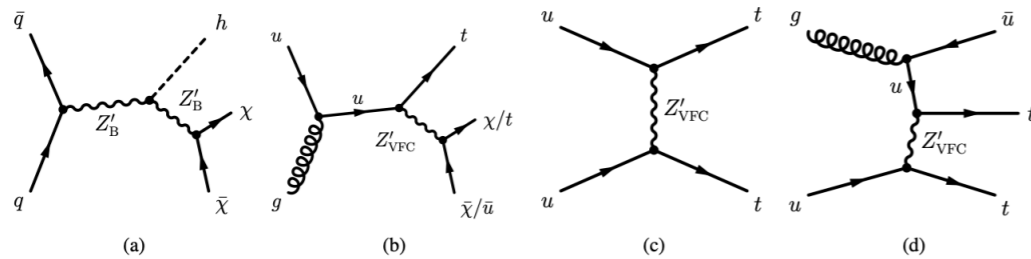
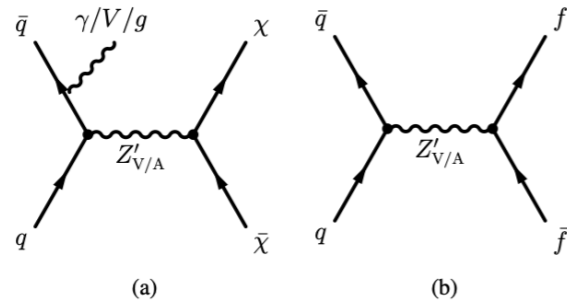


Trigger $p_T(\mu) > 24$ GeV

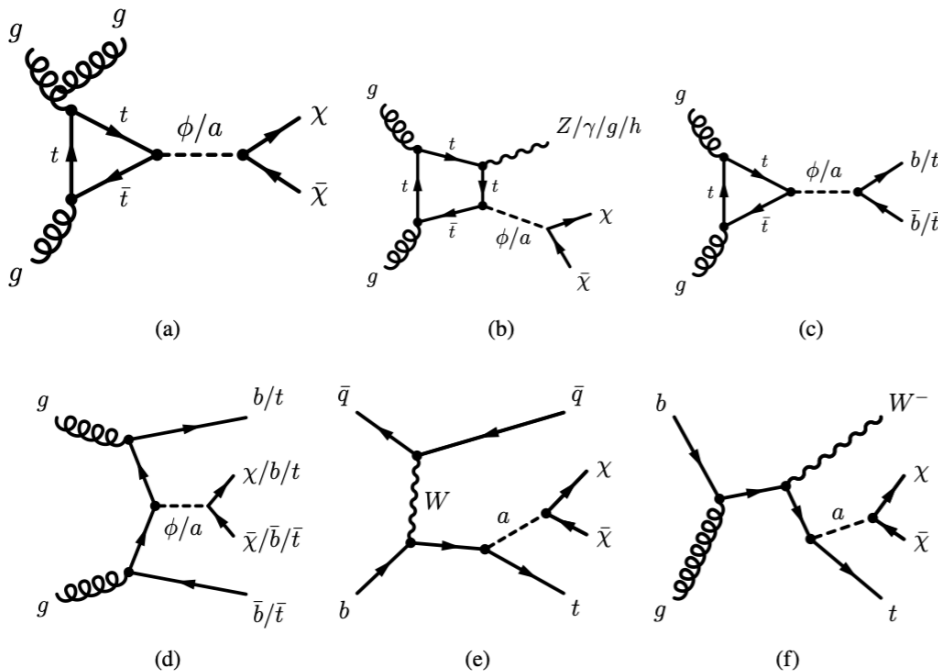
Vector and Scalar Portal

Production modes for ETmiss signatures

Vector



Scalar

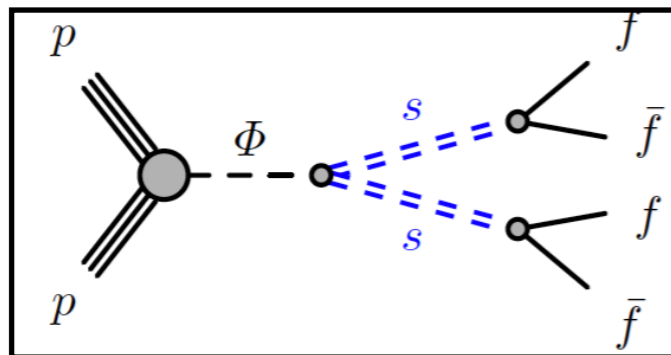


Analysis	Models targeted	Final-state signature
Jet + E_T^{miss} [26]	V/AV(*), S/PS(*), SCC _q (*), DE	1–4 jets, E_T^{miss} , 0 ℓ .
$h(\text{inv})$ [29, 186]	2HDM+a	2 jets, E_T^{miss} , m_{jj} , $\Delta\eta_{jj}$.
$\gamma + E_T^{\text{miss}}$ [21]	V/AV(*)	1 photon, 0–1 jets, E_T^{miss} , 0 ℓ .
$Z(\ell\ell) + E_T^{\text{miss}}$ [24]	V/AV, 2HDM+a	2 ℓ , E_T^{miss} , $m_{\ell\ell} \sim m_Z$.
$W/Z(qq') + E_T^{\text{miss}}$ [20]	V/AV, 2HDM+a	E_T^{miss} , W/Z candidate (resolved and boosted topologies).
$h(b\bar{b}) + E_T^{\text{miss}}$ [23]	VBC, 2HDM+Z'(*), 2HDM+a	E_T^{miss} , h candidate (resolved and boosted topologies).
$h(\gamma\gamma) + E_T^{\text{miss}}$ [22]	VBC, 2HDM+Z'(*), 2HDM+a	2 photons, $m_{\gamma\gamma} \sim m_h$, E_T^{miss} .
$t + E_T^{\text{miss}}$ [30]	VFC	E_T^{miss} , t candidate (all decay channels).
$b(\bar{b}) + E_T^{\text{miss}}$ [25]	S/PS(*), SCC _b (*), 2HDM+a	1–2 b-jets, E_T^{miss} , 0 ℓ .
$t\bar{t} + E_T^{\text{miss}}$ [25, 27]	S/PS(*), SCC _t (*), 2HDM+a, DE	0–2 ℓ , 1–2 b-jets, ≥ 1 –4 jets, E_T^{miss} , $m_{T2}^{\ell\ell}$.

► [1903.01400](https://arxiv.org/abs/1903.01400)

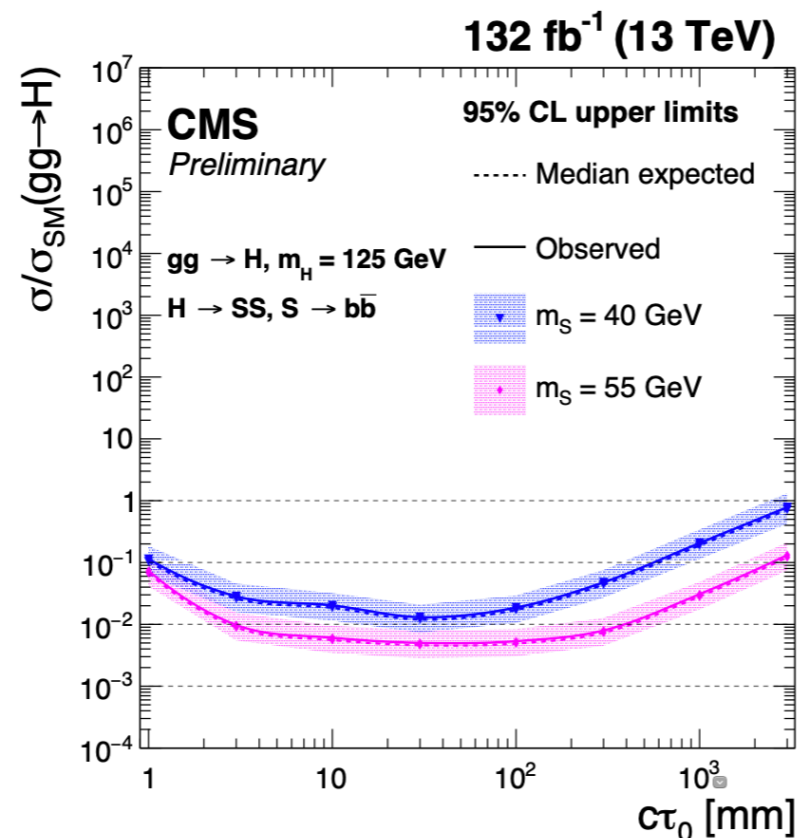
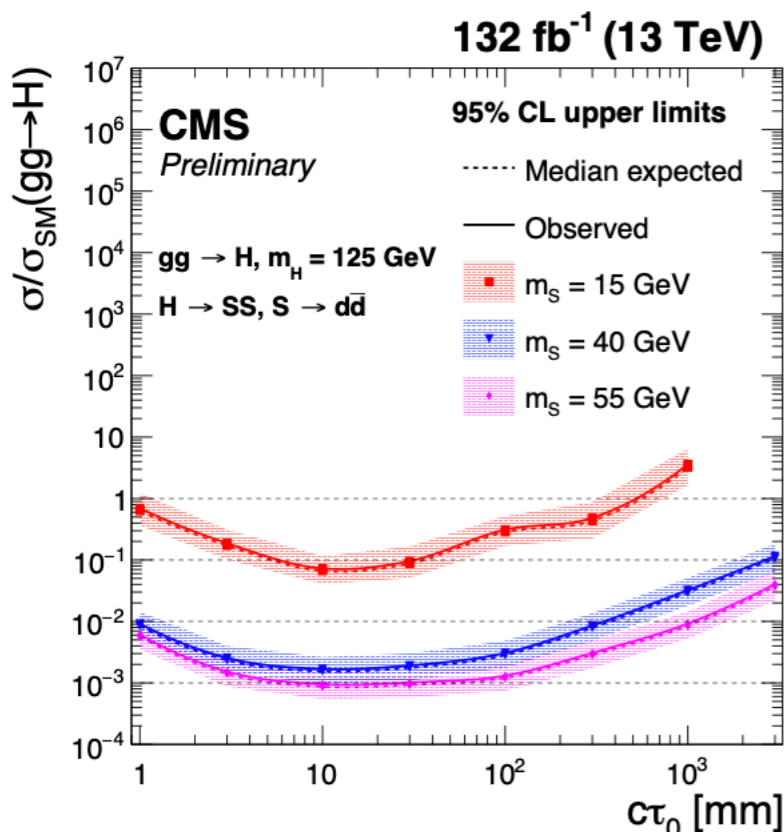
Displaced Searches

- Search for displaced jets explores sensitivity to feebly coupled scalars



Also largely displaced

CMS Search 132/fb



e.g. trackless jets

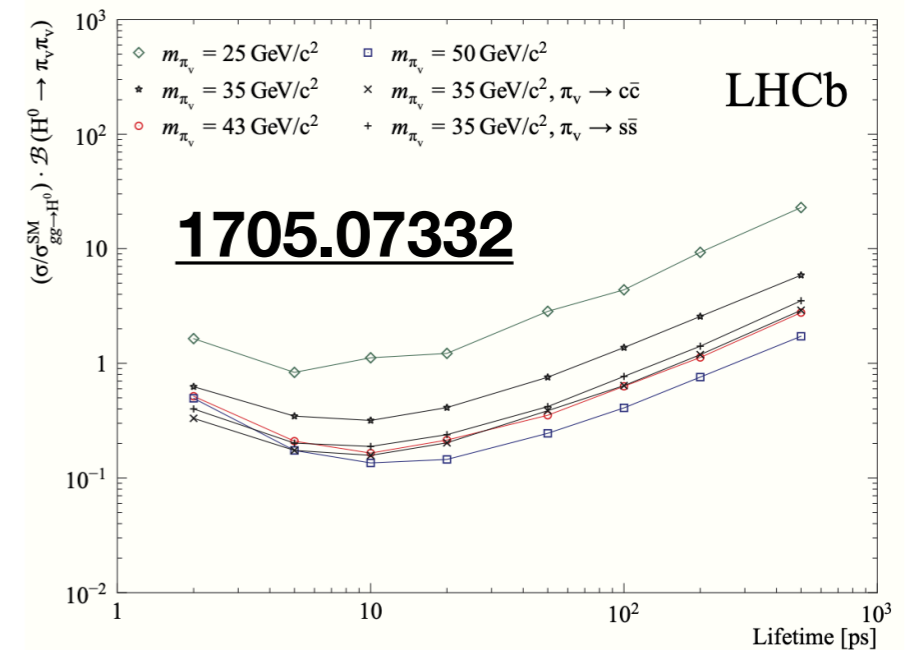
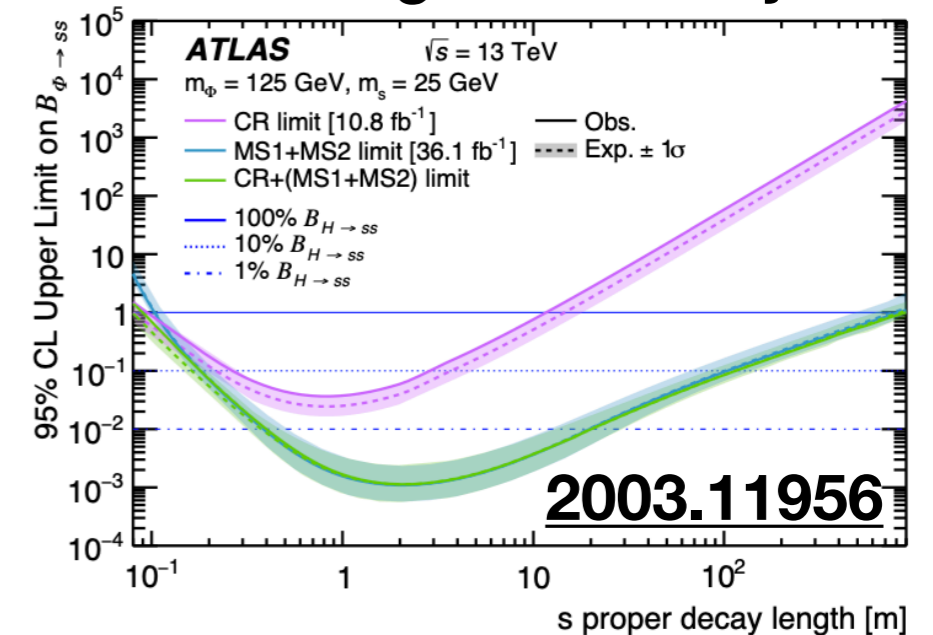


Figure 4: Observed upper limit versus lifetime for different π_ν masses and decay modes. The decay $\pi_\nu \rightarrow b\bar{b}$ is assumed, unless specified otherwise.

ATLAS Displaced Searches

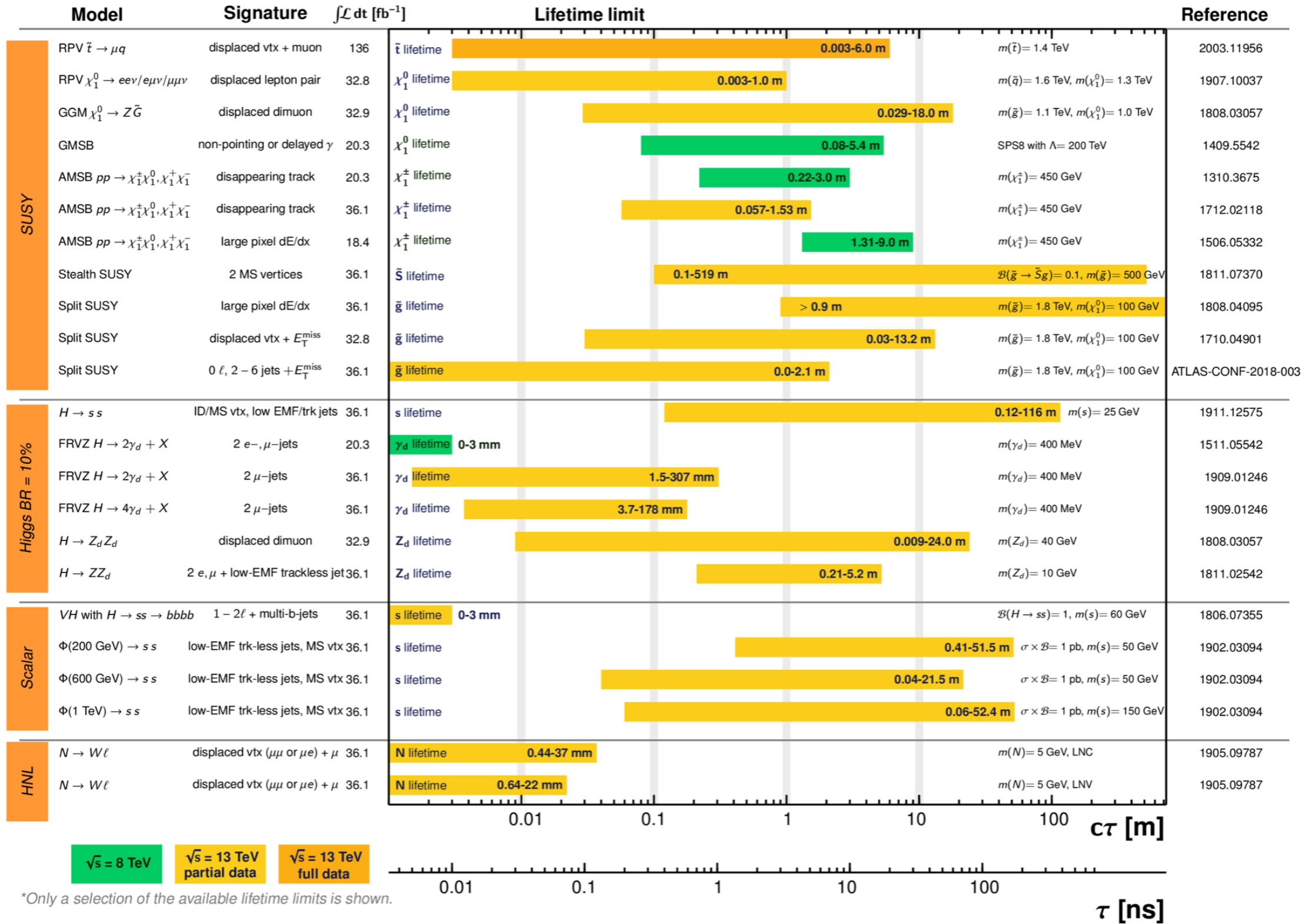
ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: May 2020

ATLAS Preliminary

$$\int \mathcal{L} dt = (18.4 - 136) \text{ fb}^{-1}$$

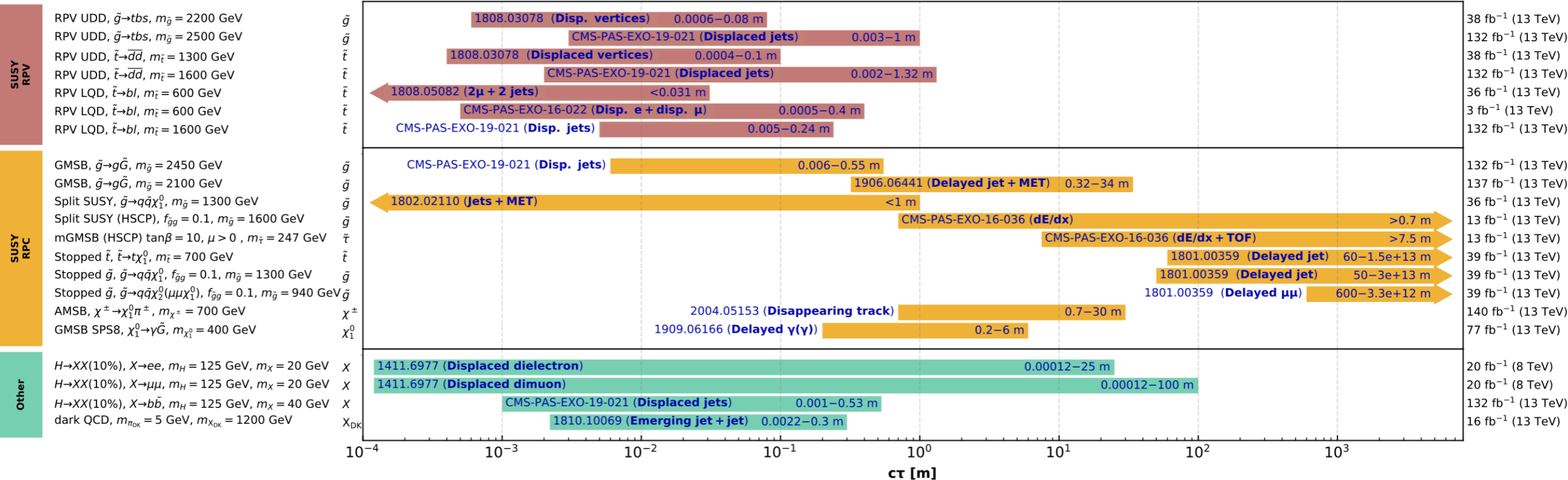
$$\sqrt{s} = 8, 13 \text{ TeV}$$



CMS Displaced Searches

Overview of CMS long-lived particle searches

CMS Preliminary 3 - 140 fb⁻¹ (8, 13 TeV)



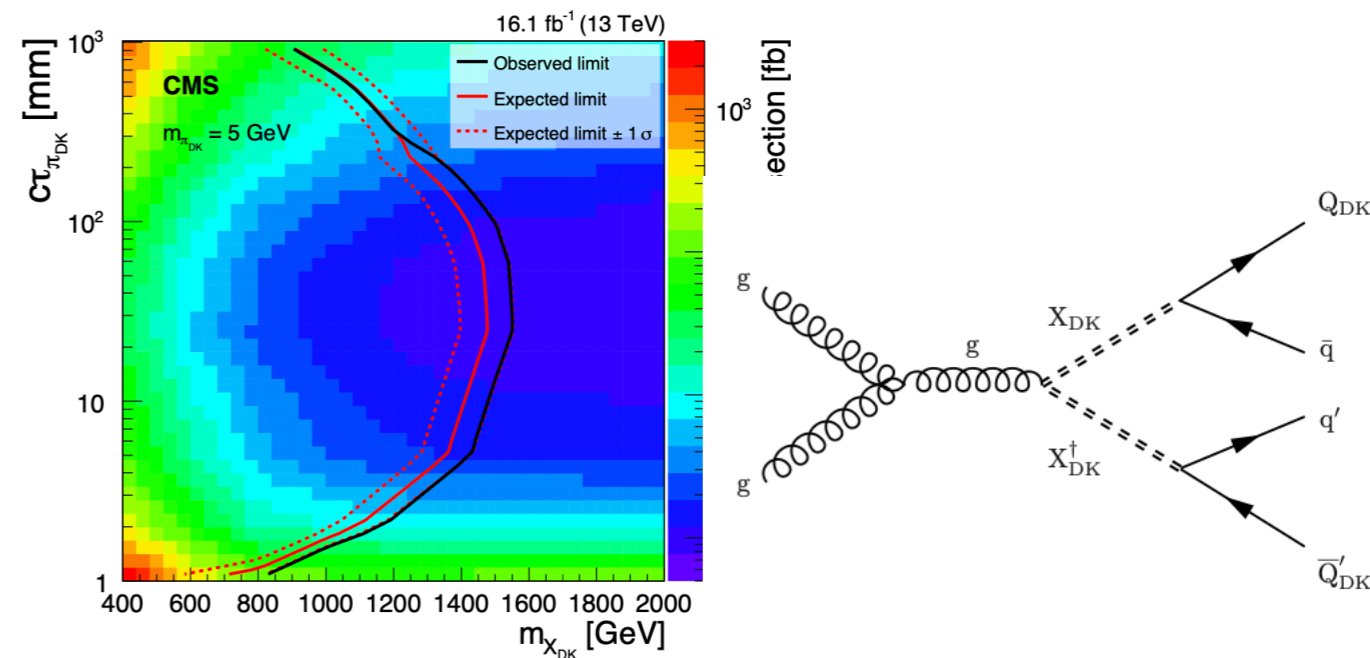
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

LHCP 2020

- **CMS search for hidden valley model (emerging jets, with dedicated jet vertex/track analysis)**

► **Recent interest also to investigate dark showers in jets**

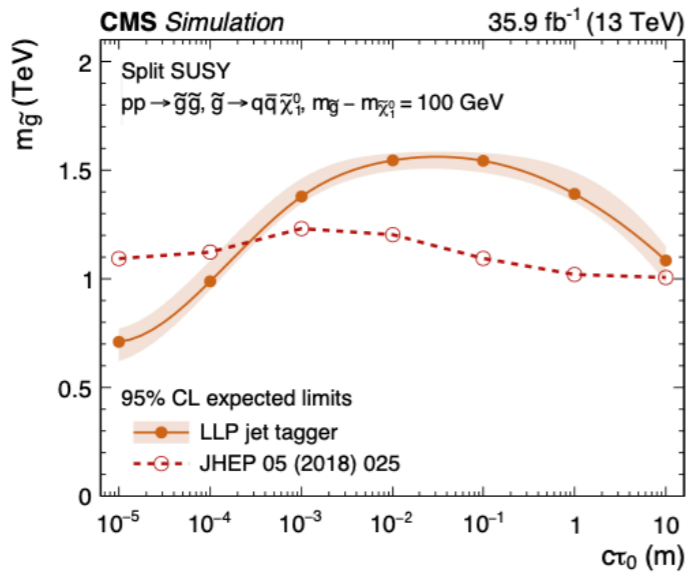
1810.10069



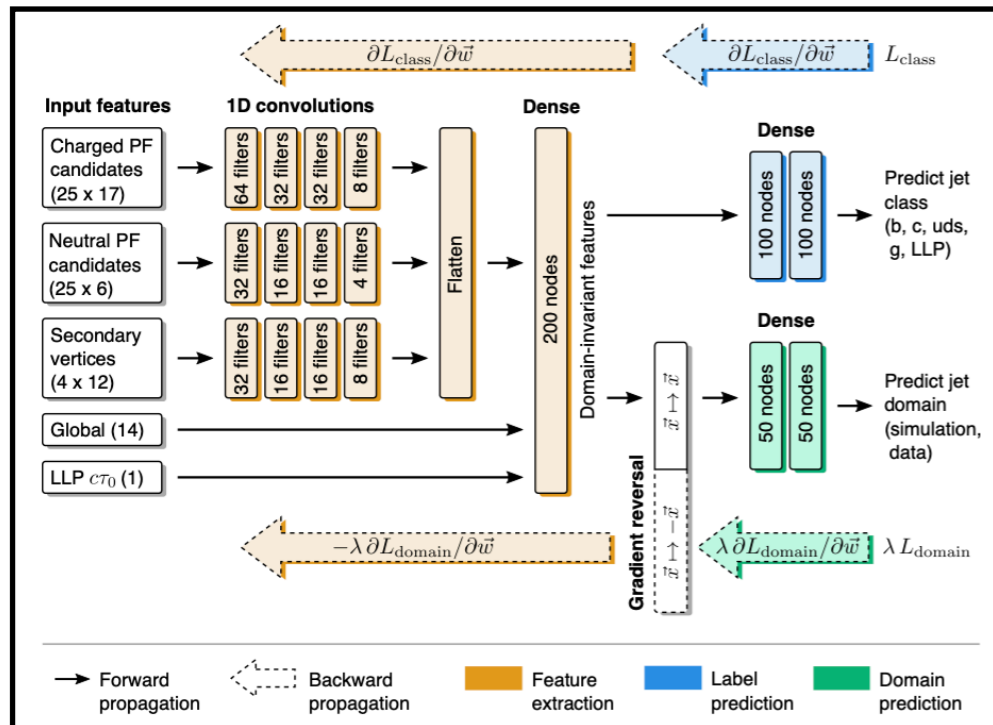
Displaced Searches, Tech. Aspects

- New venues in technical aspects for BSM searches

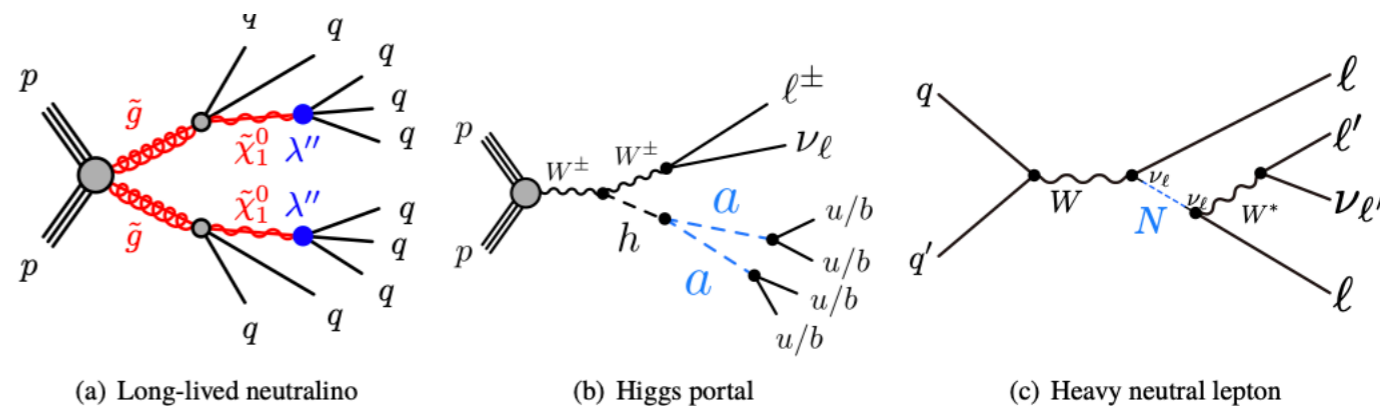
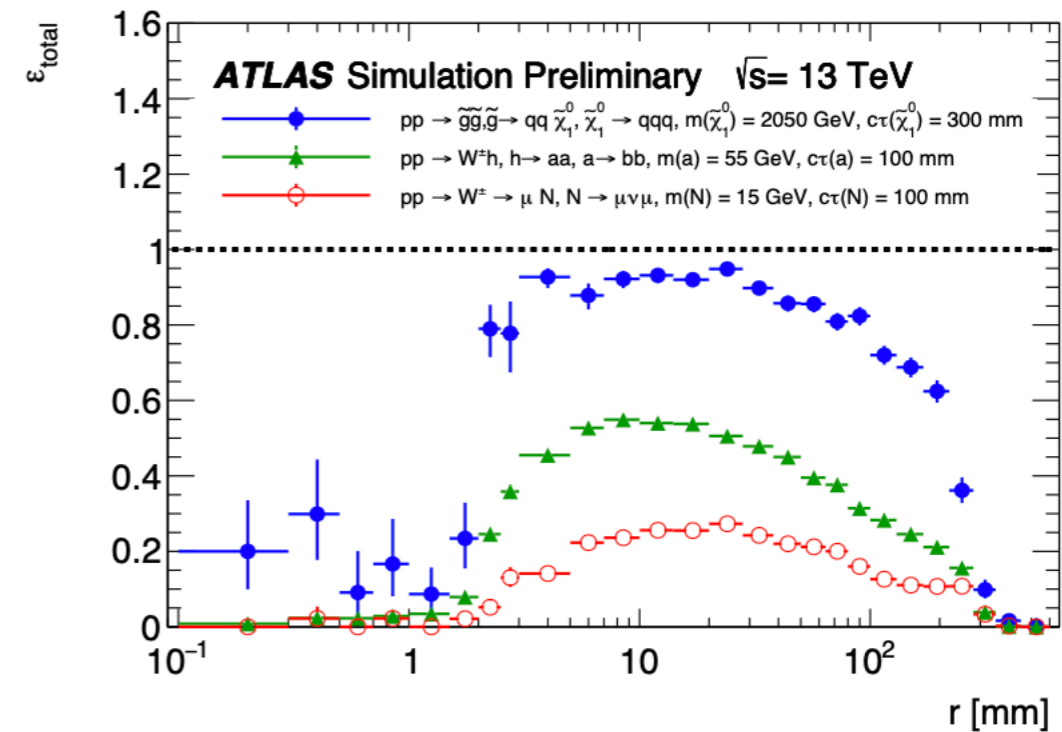
CMS developed ML algo for displaced hadronic signatures



1912.12238



ATLAS developed specific tracking and vertex algorithms for displaced signatures

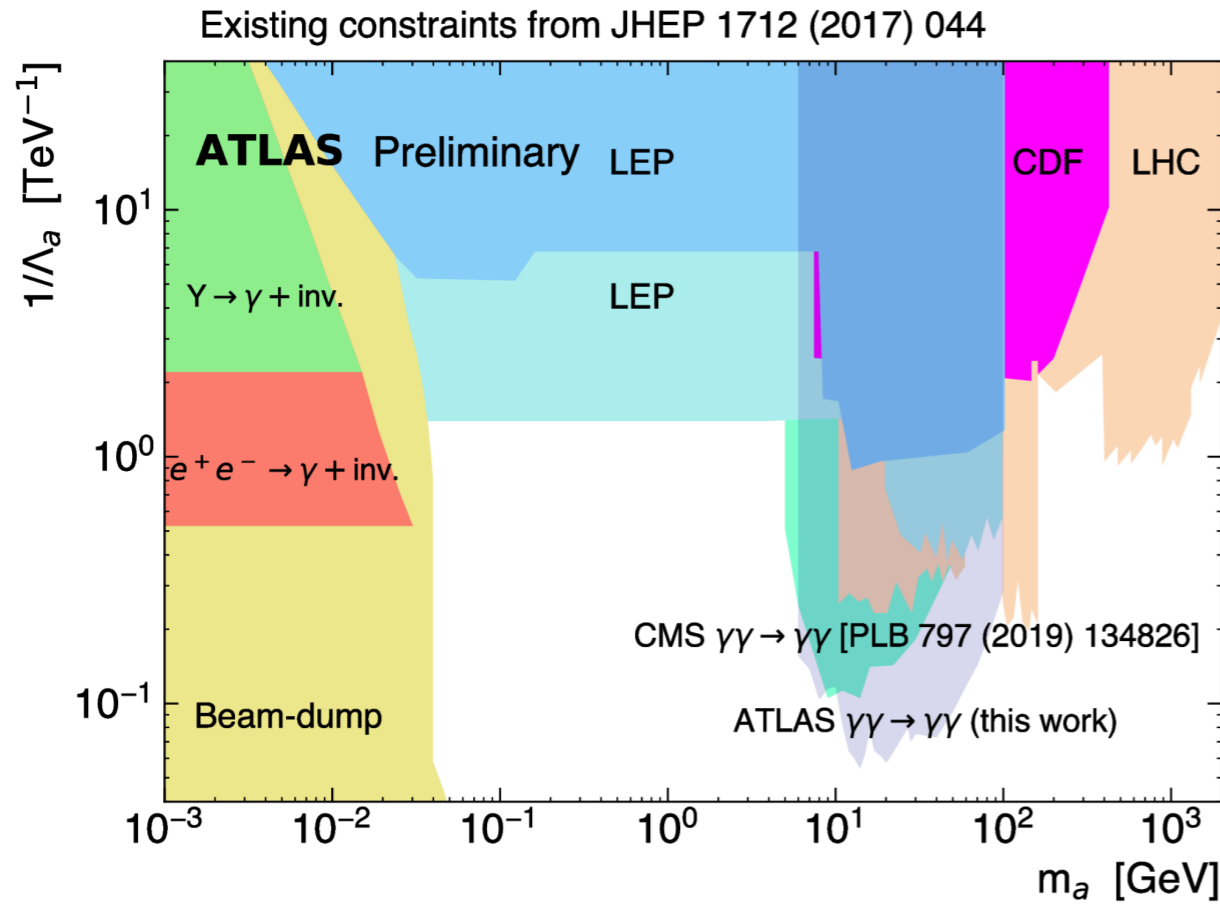


ALPs Heavy Ions Collisions

- Axion-Like-Particle Search in PbPb collisions, as proposed in e.g. Knapen et al
- Low mass diphoton searches currently not very well covered in pp collisions, for ALPs still mostly 8 TeV data used

Merged multi photon jet signatures to be exploited at ATLAS and CMS

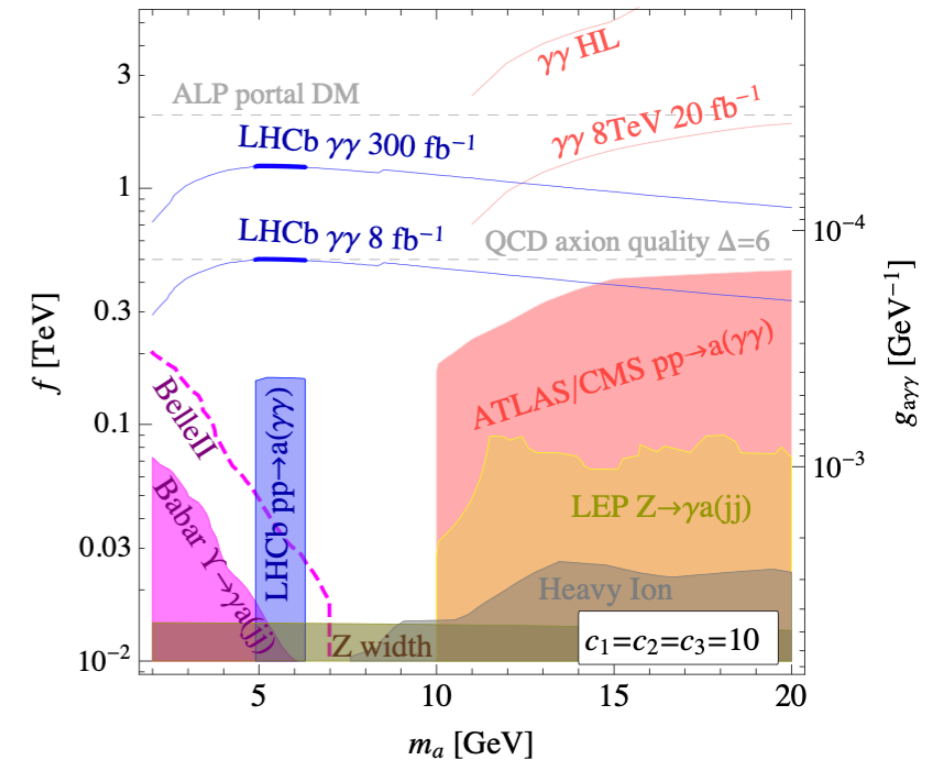
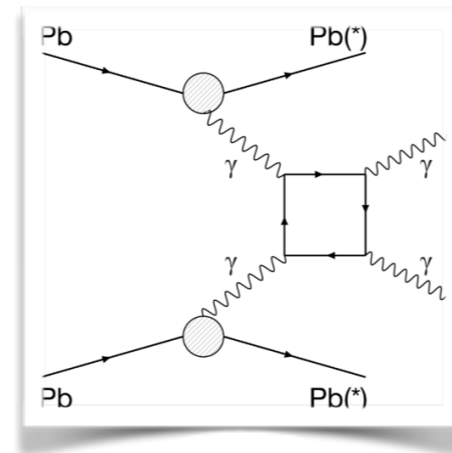
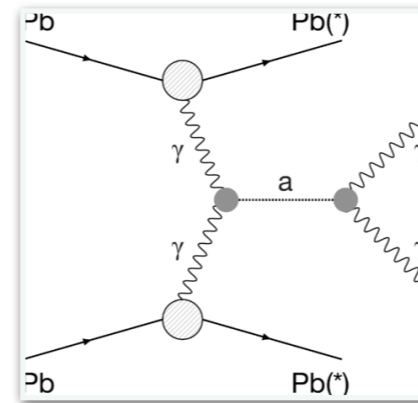
Diphoton resonance searches also at LHCb



ATLAS-CONF-2020-010

ATLAS: 2.2 nb⁻¹

CMS: 0.4 nb⁻¹



1810.09452

Dark Sector in Heavy Ion Collisions

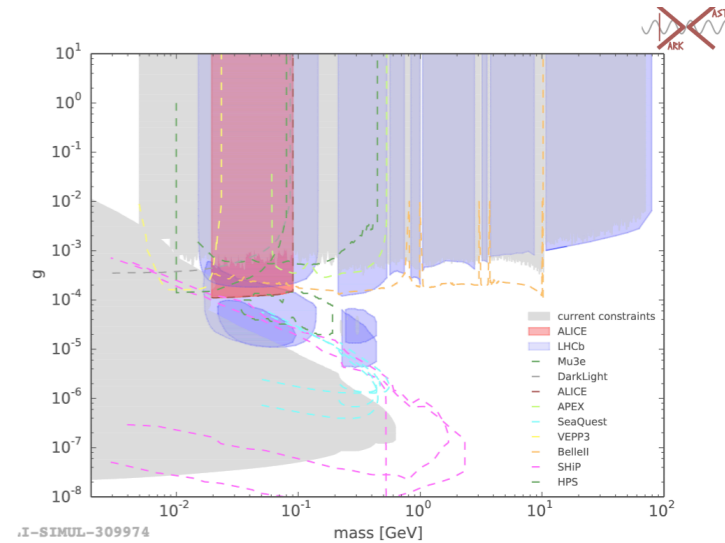
- General recent interest in BSM exploitation of Heavy Ion collisions

▶ [1812.07688](#), Recent public document and discussion

ALICE Dark Photon reach

▶ Experimental features:

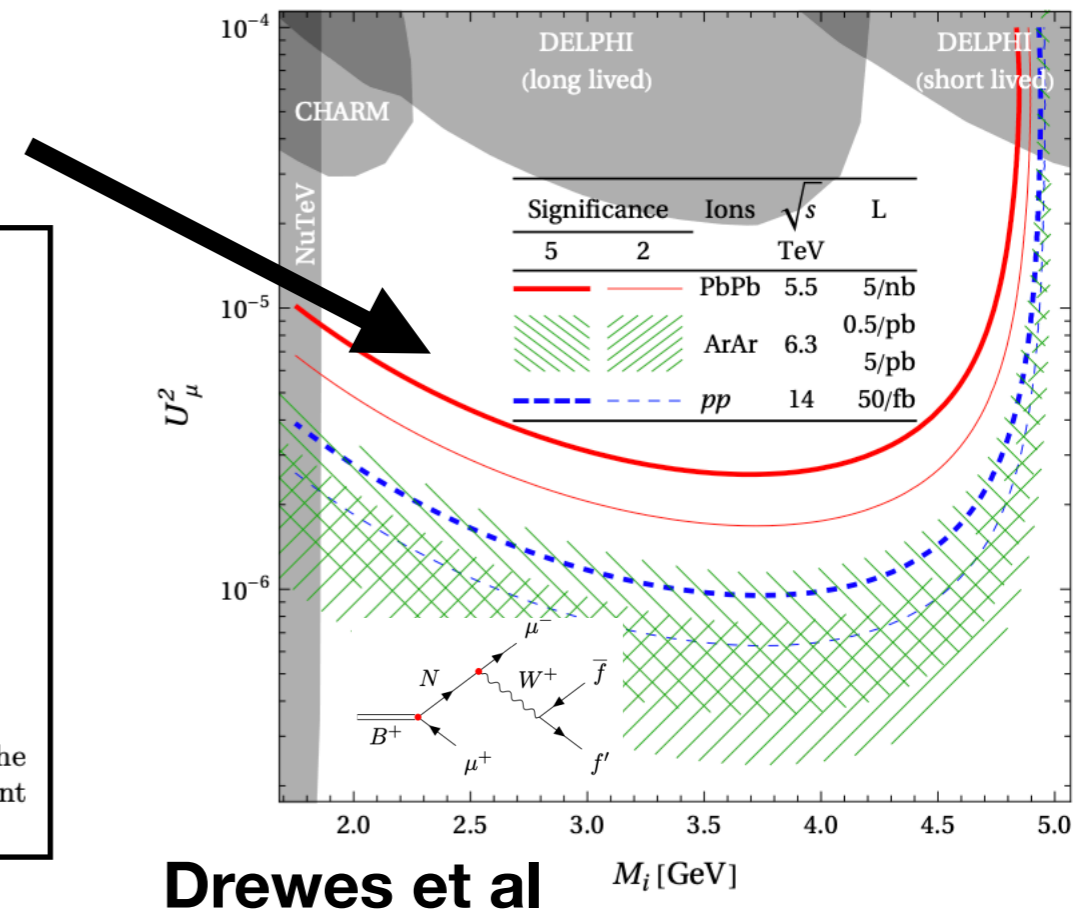
- ☆ large Z^4 cross section enhancement in ultraperipheral collisions
- ☆ ~No Pile-Up (but large number of charged tracks),
- ☆ 100x lower NN luminosities, lower centre-of-mass energy



Example : HNL search for equal running time

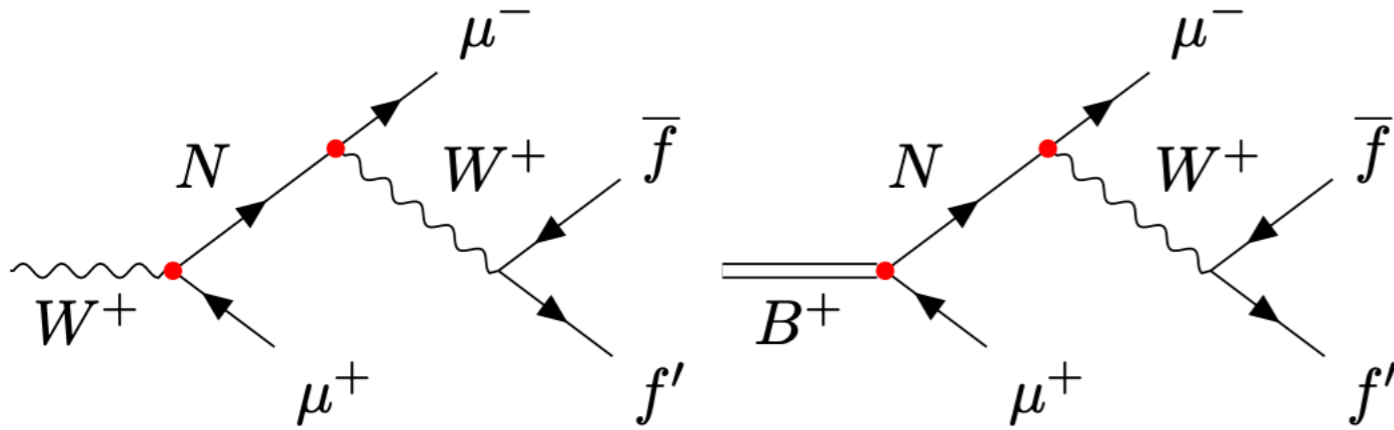
Production mode	BSM particle/interaction	Remarks
Ultraperipheral	Axion-like particles	$\gamma\gamma \rightarrow a$, $m_a \approx 0.5-100$ GeV
	Radion	$\gamma\gamma \rightarrow \phi$, $m_\phi \approx 0.5-100$ GeV
	Born-Infeld QED	via $\gamma\gamma \rightarrow \gamma\gamma$ anomalies
	Non-commutative interactions	via $\gamma\gamma \rightarrow \gamma\gamma$ anomalies
Schwinger process	Magnetic monopole	Only viable in HI collisions
Hard scattering	Dark photon	$m_{A'} \lesssim 1$ GeV, advanced particle ID
	Long-lived particles (heavy ν)	$m_{LLP} \lesssim 10$ GeV, improved vertexing
Thermal QCD	Sexaquarks	DM candidate

Table 1: Examples of new-physics particles and interactions accessible in searches with HI collisions at the LHC, listed by production mechanism. Indicative competitive mass ranges and/or the associated measurement advantages compared to the pp running mode are given.



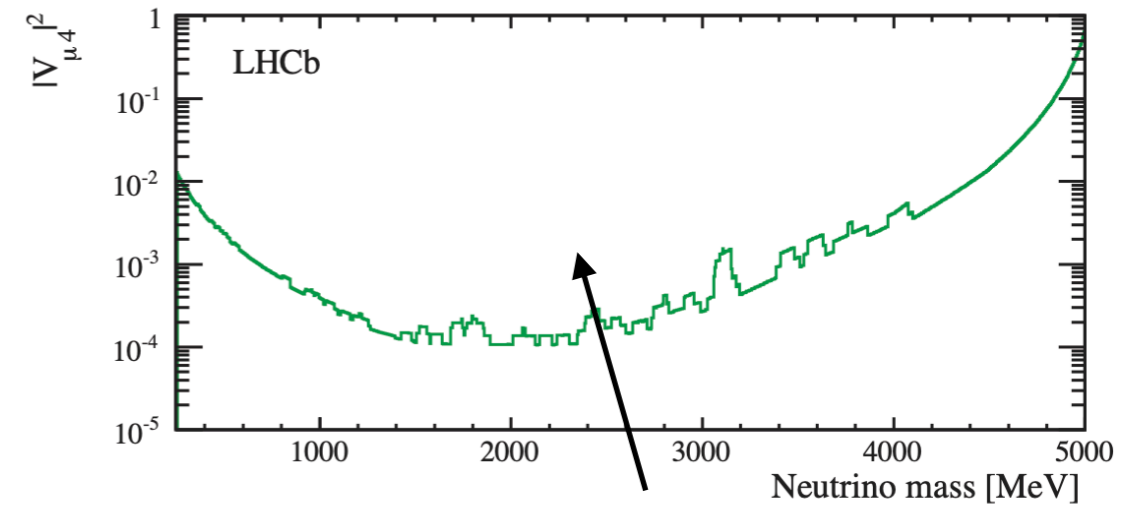
Heavy Neutral Leptons

- LHCb exploits $B \rightarrow 2\mu + \pi$, CMS on-shell W decays



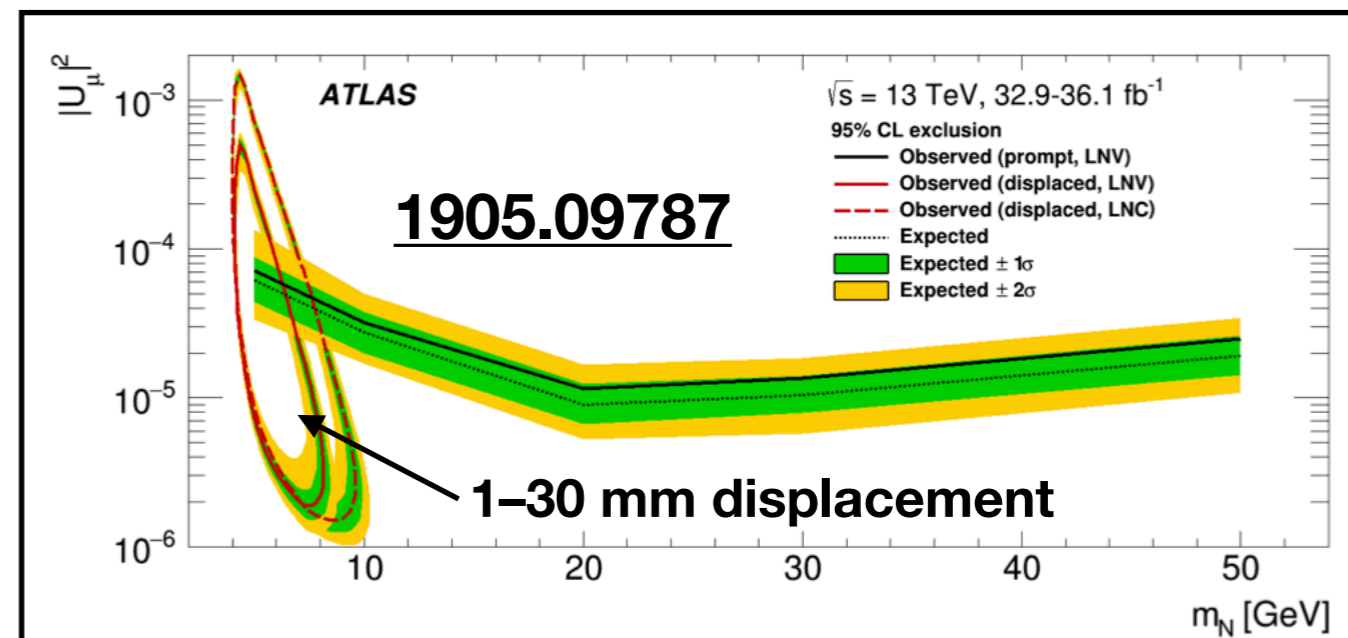
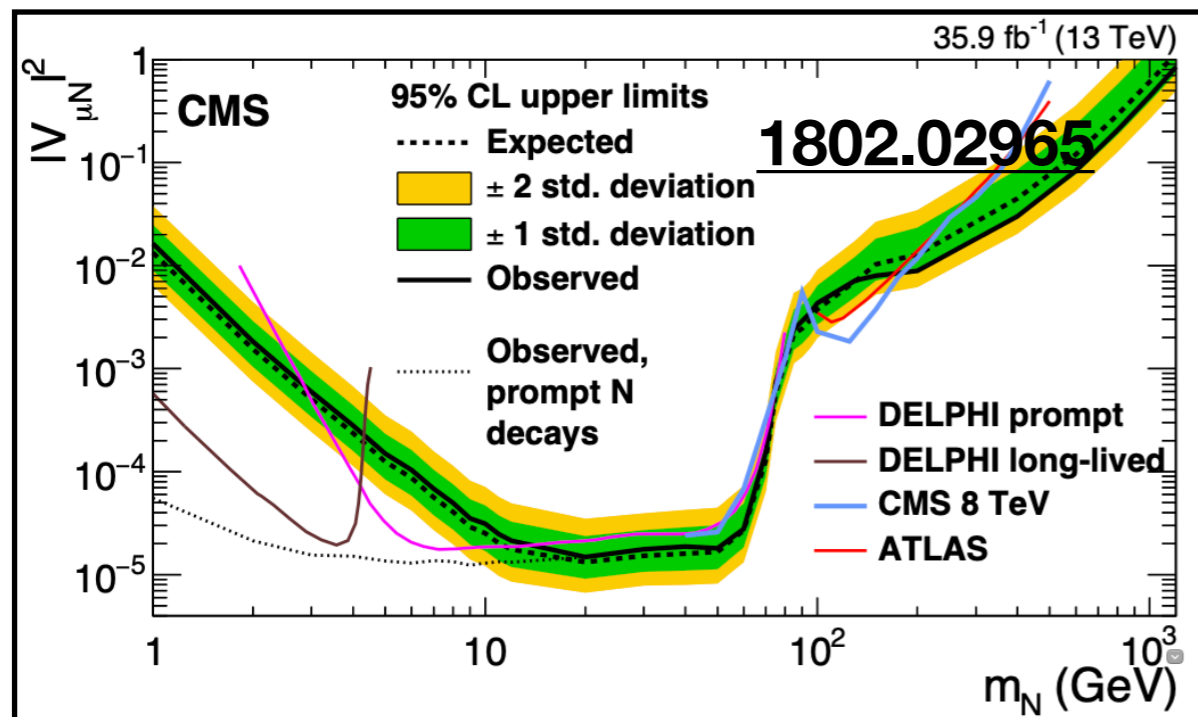
Other production modes exist

1401.5361



Discussion on limit
by Shuve, Peskin, in
1607.04258

- Also need (possible) to probe tau neutrino mixing parameter, currently (CMS only prompt search)



Summary and Progress

- **Dedicated Dark Sector searches and interpretations are increasing at the LHC experiments**
 - ▶ **Extensive benchmark and DM interpretations framework developments**
 - ▶ **Additional dedicated displaced searches recently, and more to come**
 - ▶ **More focus on dedicated searches for low mass mediators**
- **Dedicated event reconstruction techniques progressing. For low mass and low multiplicity signatures (probably others too) further development of the *Turbo/Scouting/TLA* high-rate data-taking techniques is interesting venue**
- **Full understanding of where the LHC multipurpose experiments could improve existing parameter space constraints at low mass will be useful**
 - ▶ **In particular with more inclusive triggering**
- ***A collider not discussed but of potential Dark Sector interest is the EIC at BNL***
 - ▶ **Recent [workshop](#), [BSM studies for LHeC](#) [here](#)**

Additional Material