Exotic Searches at ATLAS

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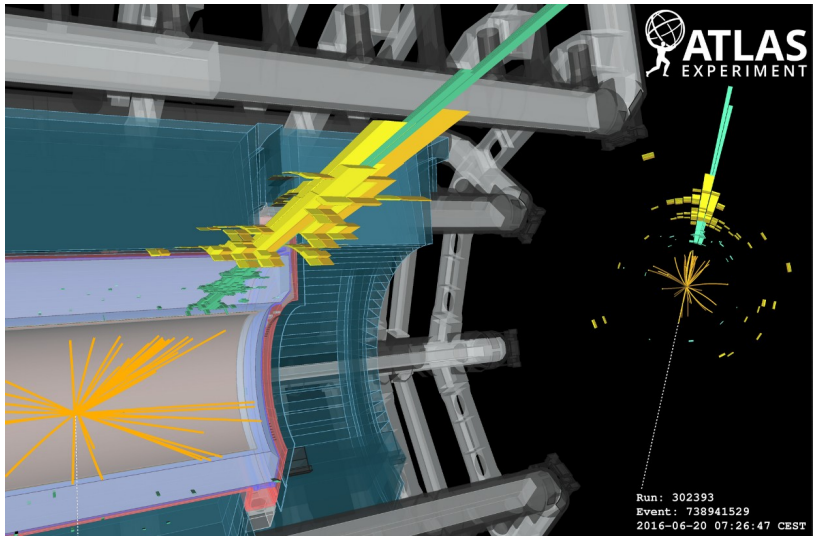
On behalf of the ATLAS Collaboration

International Conference on Neutrinos and Dark Matter
(NuDM 2024)
Cairo, Egypt

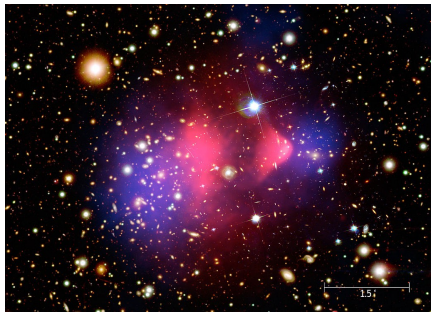


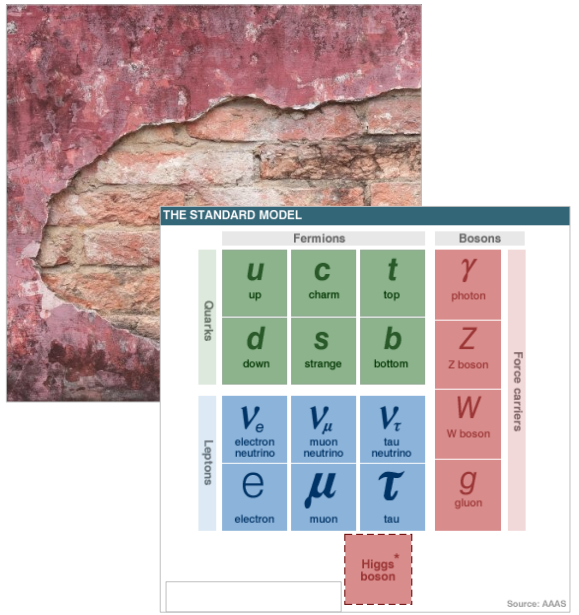
ATLAS EXPERIMENT

TRIUMF

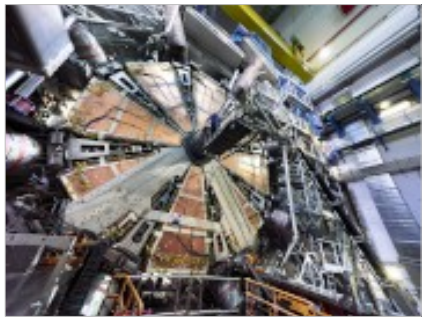
Standard Model & Beyond (?)

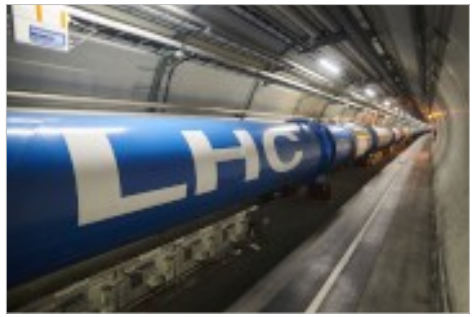
- The Standard Model (SM), a very successful theory
  - describing particles, forces & interactions
  - Higgs mechanism for mass generation
- Several pressing questions remain
  - nature of dark matter in the universe
  - hierarchy problem
  - neutrino masses
  - matter-antimatter asymmetry, etc.
- Many theories beyond the SM attempting to address these questions
  - predict existence of new particles and interactions
- ATLAS experiment at the LHC energy frontier
  - multipurpose detector & essential tool
  - precise SM measurements
  - extensive search program to hunt for BSM physics





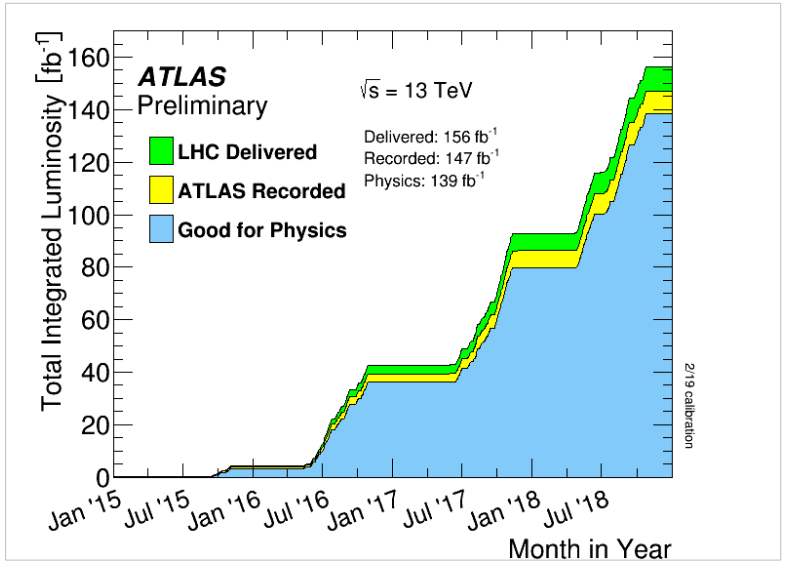
Anything else ?

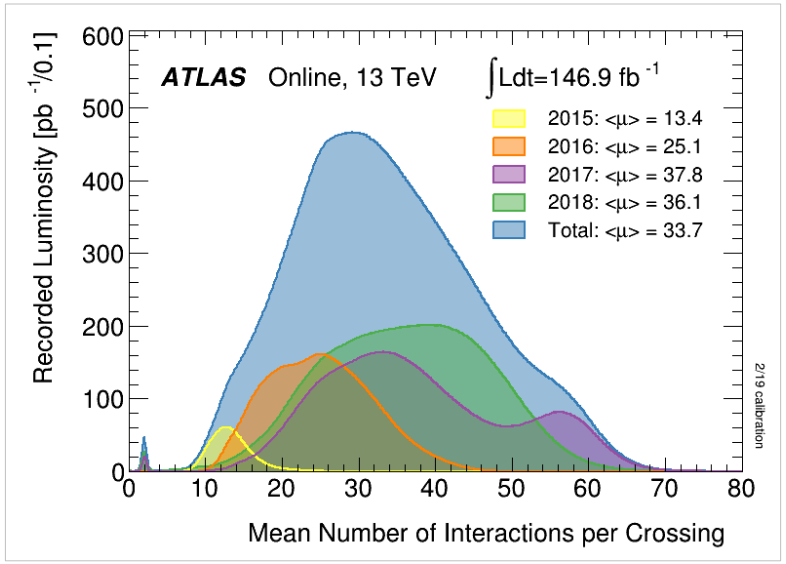




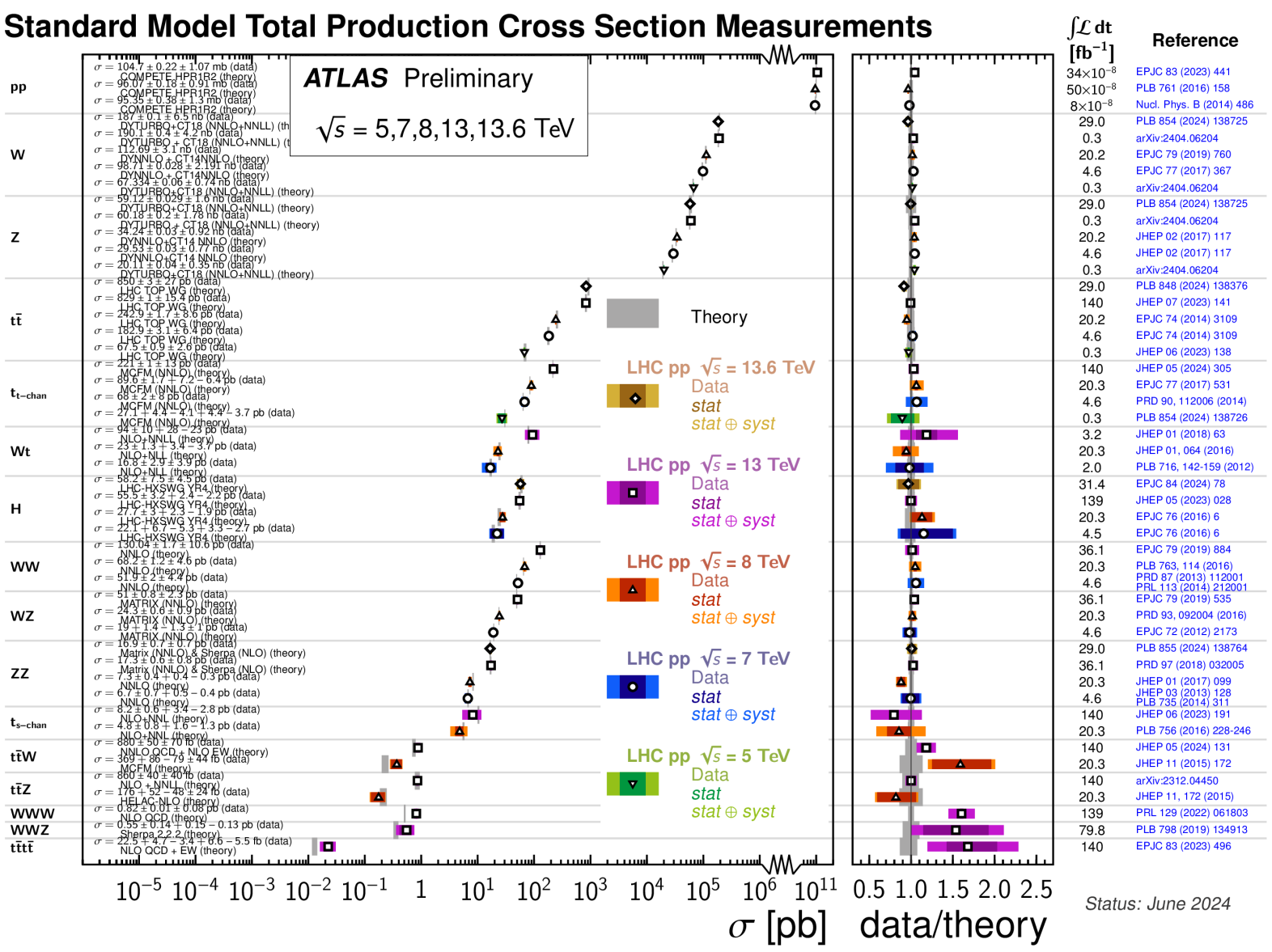
ATLAS Results Presented

- Highlights of recent measurements and searches
  - using ~140 fb^{-1} of p-p collisions at 13 TeV
  - full Run 2 dataset (2015-2018)
- Brief overview of SM measurements & Higgs couplings
- High-level view of BSM searches & limits
  - heavy particles and new resonances
  - long-lived particles
- Highlights from selected searches to match conference themes
  - heavy neutrinos
  - dark matter
  - dark sector mediators
- All ATLAS public results are nicely organized at:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

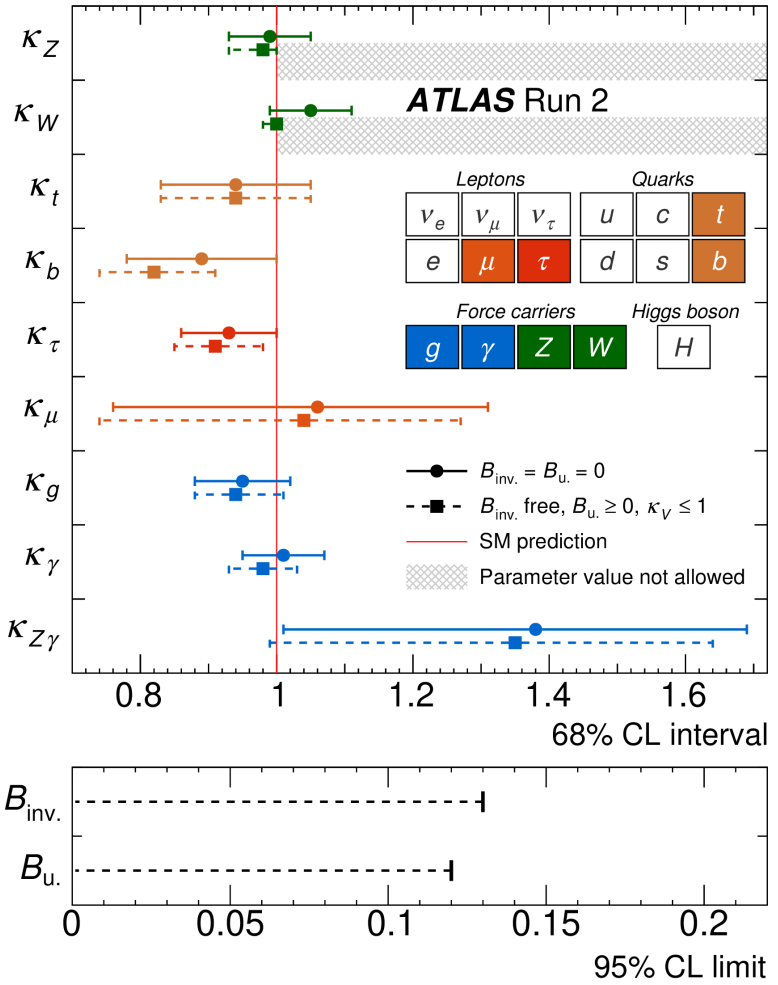




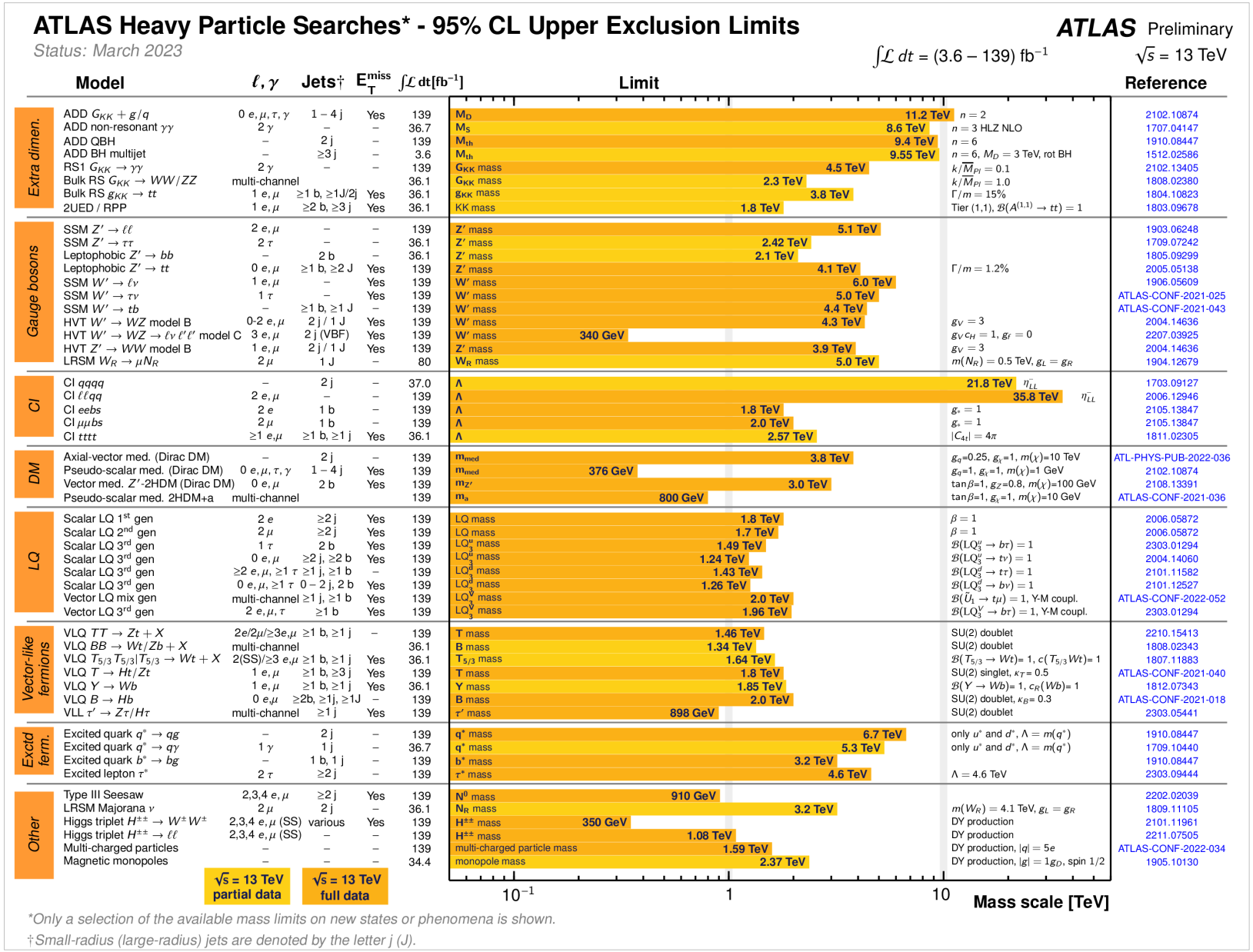
SM & Higgs Measurements



Higgs coupling-strength modifiers

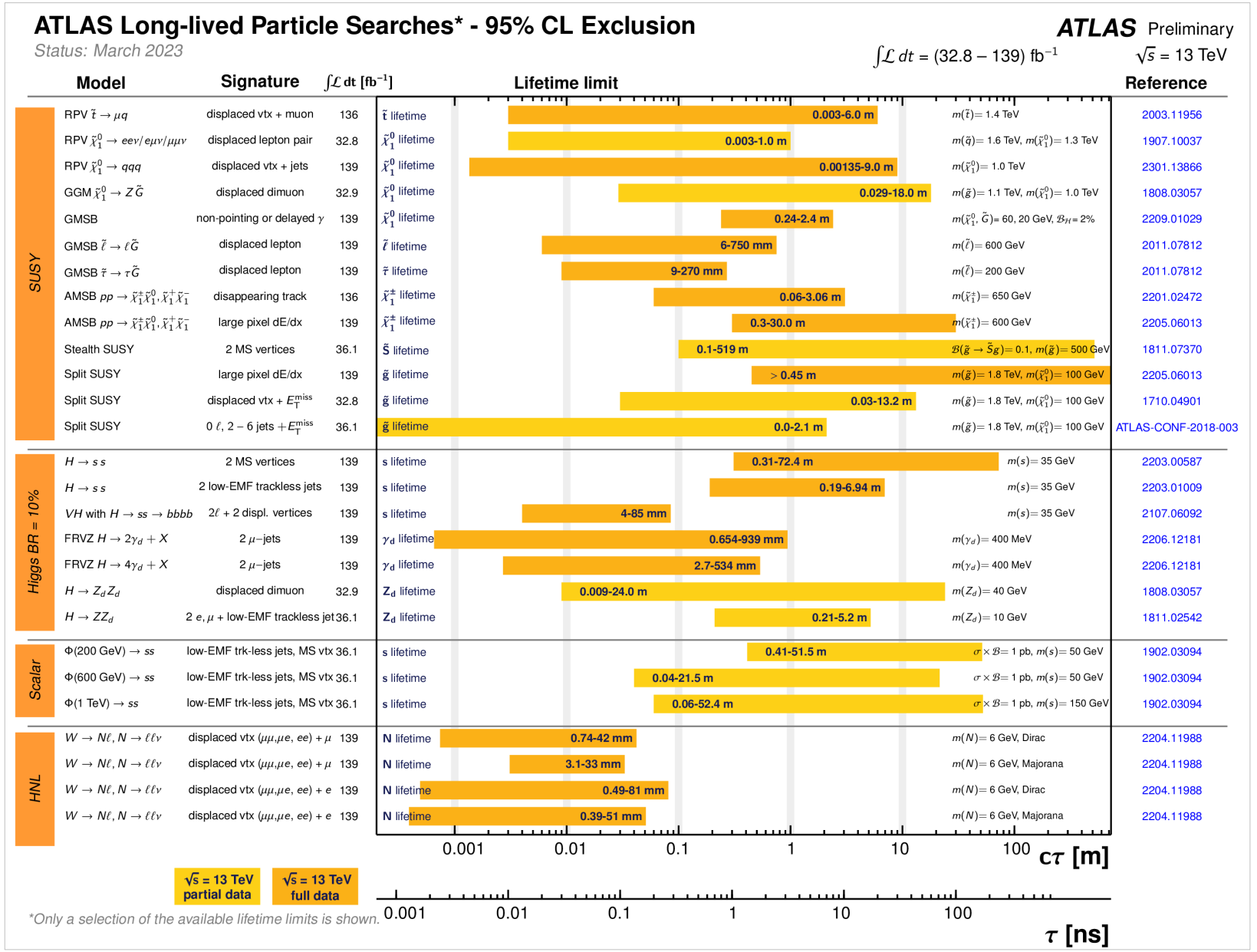


Heavy Particles & Resonances Searches



- Wide range of models and signatures covered
  - new gauge bosons
  - extra dimensions
  - contact interactions
  - leptoquarks
  - dark matter
  - excited fermions
  - vector-like fermions
  - Other (Higgs triplet, etc.)

Long-lived Particles Searches



- Weak coupling to the SM leads to LLPs
- Unconventional detector signatures
- A number of experimental challenges
  - trigger requirements
  - decays far from primary vertex
  - unusual shower shapes in calorimeter
  - timing information

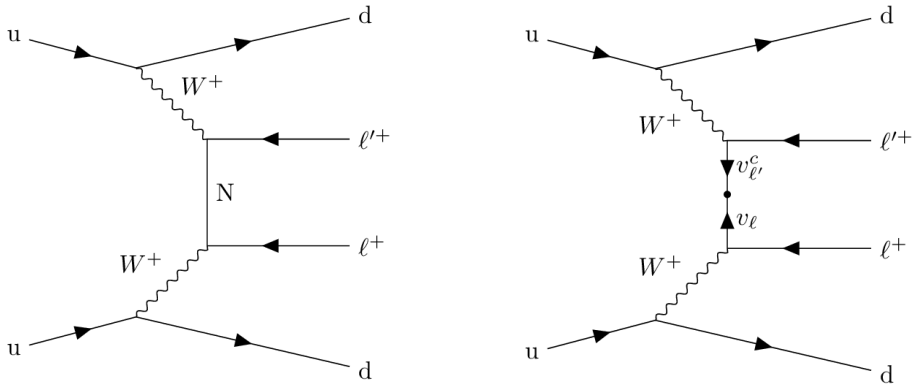
(two analyses shown at the end in "extra material" slides)

Heavy Majorana Search (I)

Phys. Lett. B 856 (2024) 138865

- In same-sign WW scattering
  - signature: same-sign *ee* or *eμ* pair
  - two jets with large invariant mass and large rapidity separation
  - complements previous search in *μμ* channel

    EPJC 83 (2023) 824
- Phenomenological Type-I Seesaw model
  - heavy Majorana neutrino couples to SM through mass mixing matrix $V_{\ell N}$
  - No tau flavour mixing considered for simplicity
- EFT where *m_N generated with dim-5 Weinberg operator and effective Majorana masses* $|m_{ee}|$ and $|m_{e\mu}|$
- Dominant SM backgrounds:
  - electroweak same-sign WW, and WZ

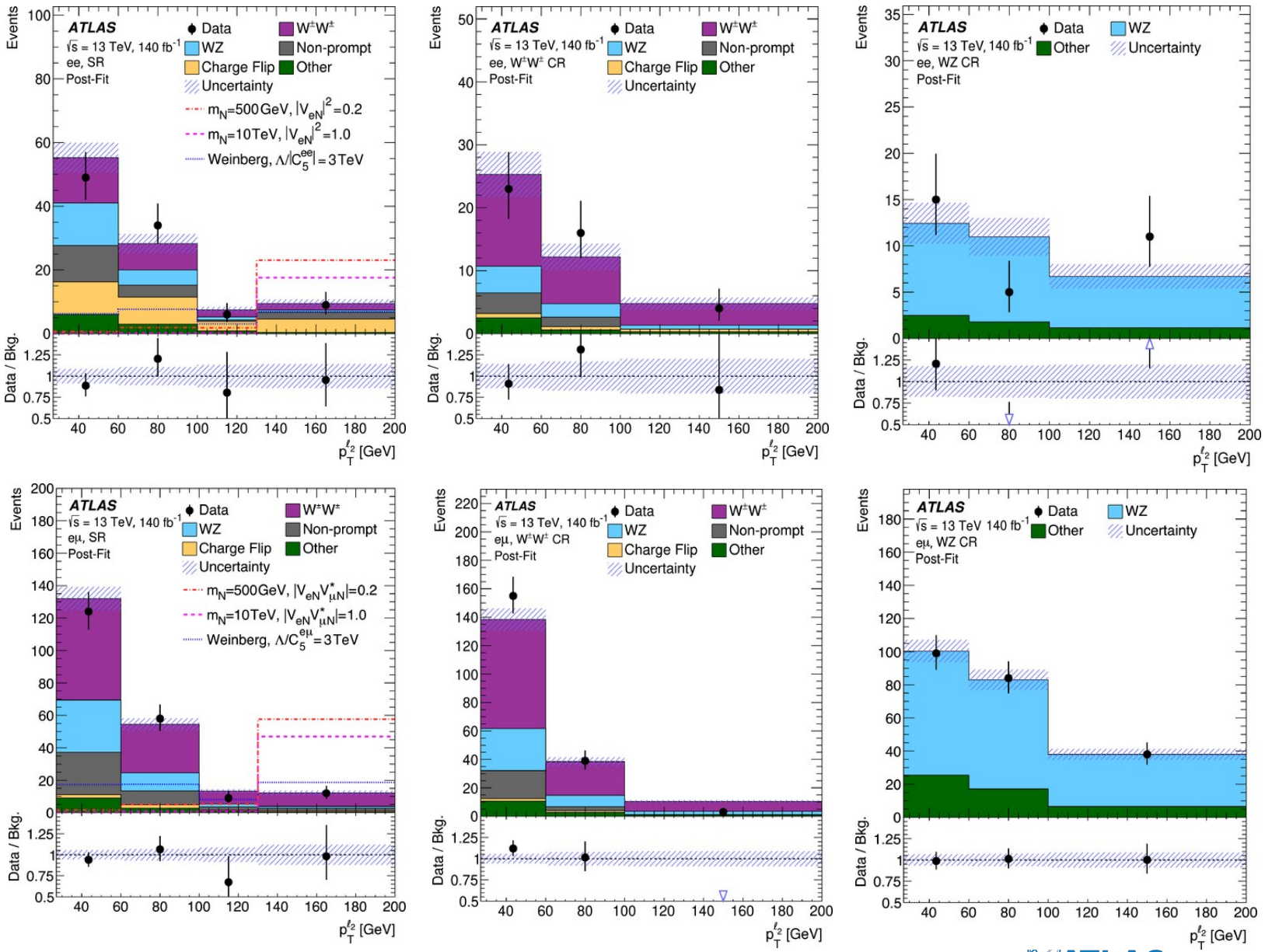


Channel	Variable	SR	$W^\pm W^\pm$ CR	WZ CR
$ee/e\mu$	N_ℓ	=2		=3
	$\lvert\Delta y_{jj}\rvert$	> 2		
	m_{jj}	> 500 GeV		
	$m_{\ell\ell\ell}$	–	–	> 106 GeV
ee	$\lvert m_{\ell\ell} - m_Z\rvert$	> 15 GeV		–
	$\lvert\eta_\ell\rvert$	<2		
	$m_{\ell\ell}$	> 20 GeV		
	$p_{\mathrm{T}}^{\ell_1}$	–	< 250	–
	$p_{\mathrm{T}}^{j_1}$	> 30 GeV	> 45 GeV	> 30 GeV
	$p_{\mathrm{T}}^{j_2}$	> 25 GeV	> 30 GeV	> 25 GeV
	$\mathcal{S}$	< 4.5	> 4.5	–
$e\mu$	$p_{\mathrm{T}}^{j_1}$	> 30 GeV	> 45 GeV	> 45 GeV
	$p_{\mathrm{T}}^{j_2}$	> 25 GeV	> 30 GeV	> 30 GeV
	$\lvert\Delta\phi_{e\mu}\rvert$	> 2.0	< 2.0	–

Heavy Majorana Search (II)

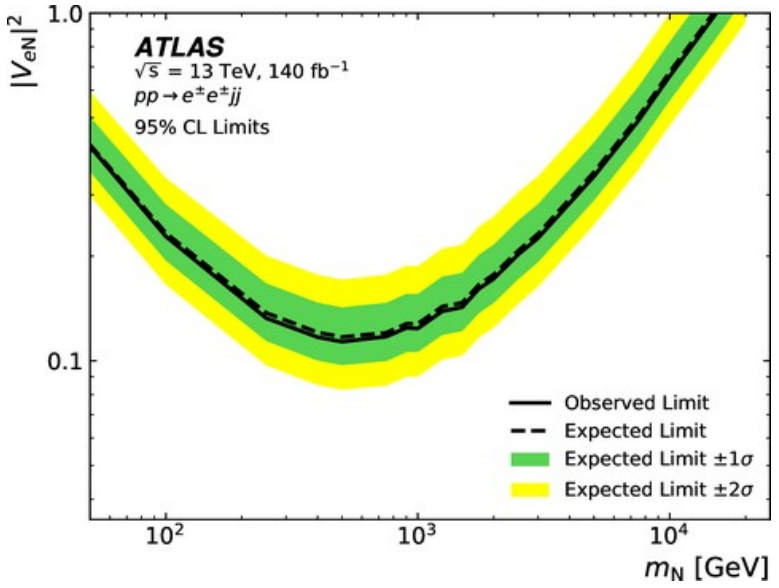
- Signal region optimized for Type-I Seesaw model with $m_N > 1$ TeV.
- Simultaneous fit in signal and control regions (background-only hypothesis)
- Good agreement between SM background prediction and data yields in the signal region:

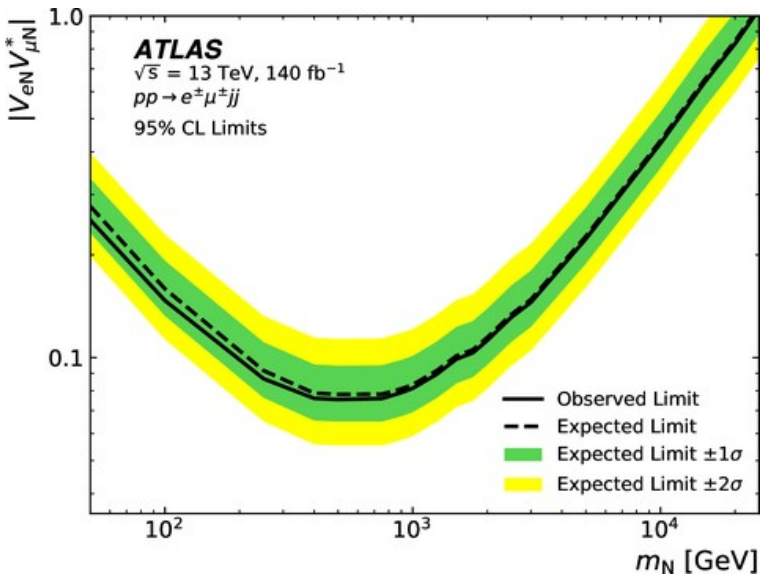
Channel	ee	$e\mu$
Same-sign WW	26.8 ± 7.3	109 ± 13
WZ	20.0 ± 5.6	46 ± 11
Non-prompt	17.7 ± 2.8	38.4 ± 5.0
Charge flip	25.8 ± 7.4	5.48 ± 0.82
Other	10.3 ± 5.3	13.1 ± 6.4
Total SM	101 ± 8	212 ± 11
Data	98	203

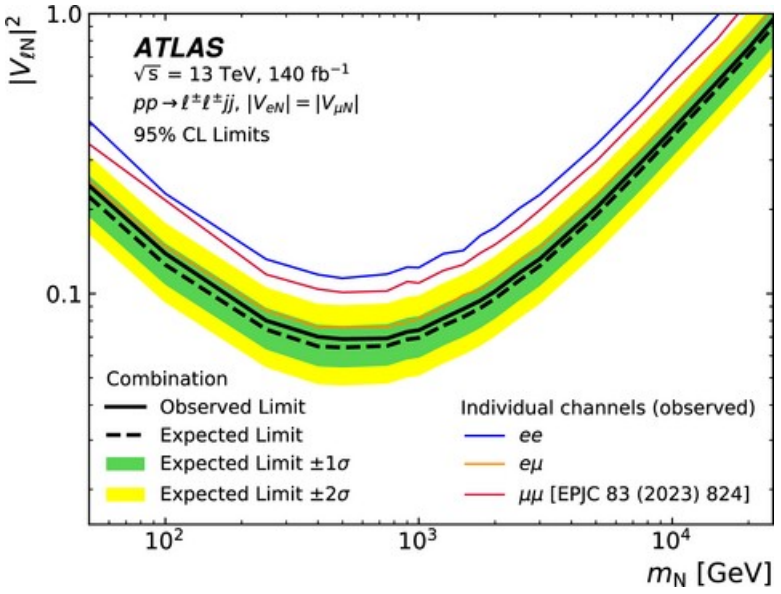


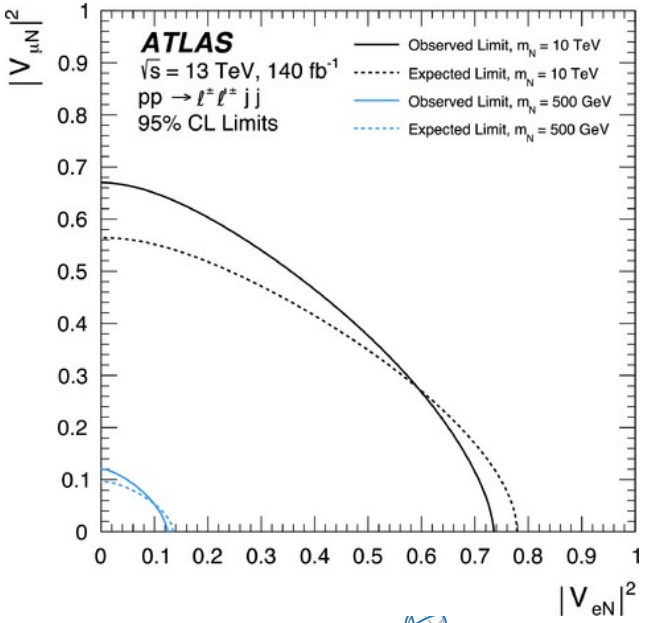
Heavy Majorana Search (III)

- Upper limit bounds obtained separately for each channel for masses between 50 GeV and 25 TeV.
- Combined limit on $|V_{\ell N}|^2$ assuming $|Ve_N|^2=|V\mu_N|^2$
  - More stringent limits than previous result in $\mu\mu$ channel
- $|Ve_N|^2=|V\mu_N|^2$ *relaxed for 2-D exclusion plot (bottom right plot)*
- Constraints on effective Majorana masses are obtained using dim-5 Weinberg operator with 95% CL upper limits for the observed (expected):
  - 24 GeV (24 Gev) for $|m_{ee}|$
  - 12 GeV (14 GeV) for $|m_{e\mu}|$





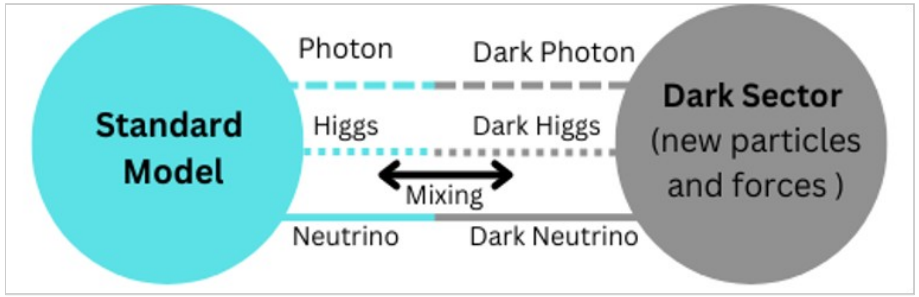


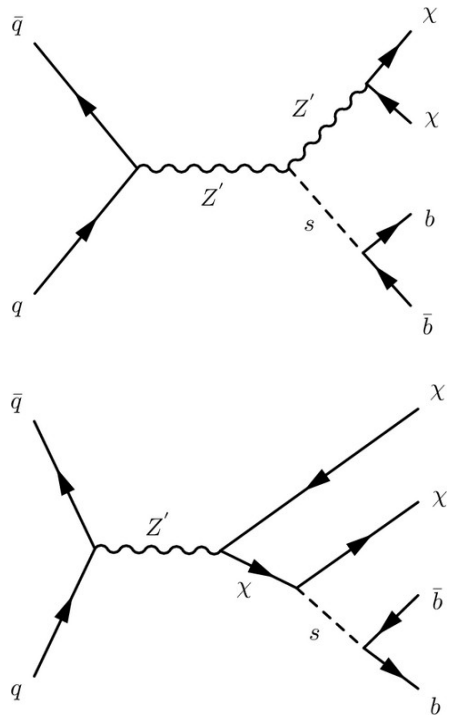


Dark Scalar $s \to b\bar{b}$ (I)

CERN-EP-2024-170

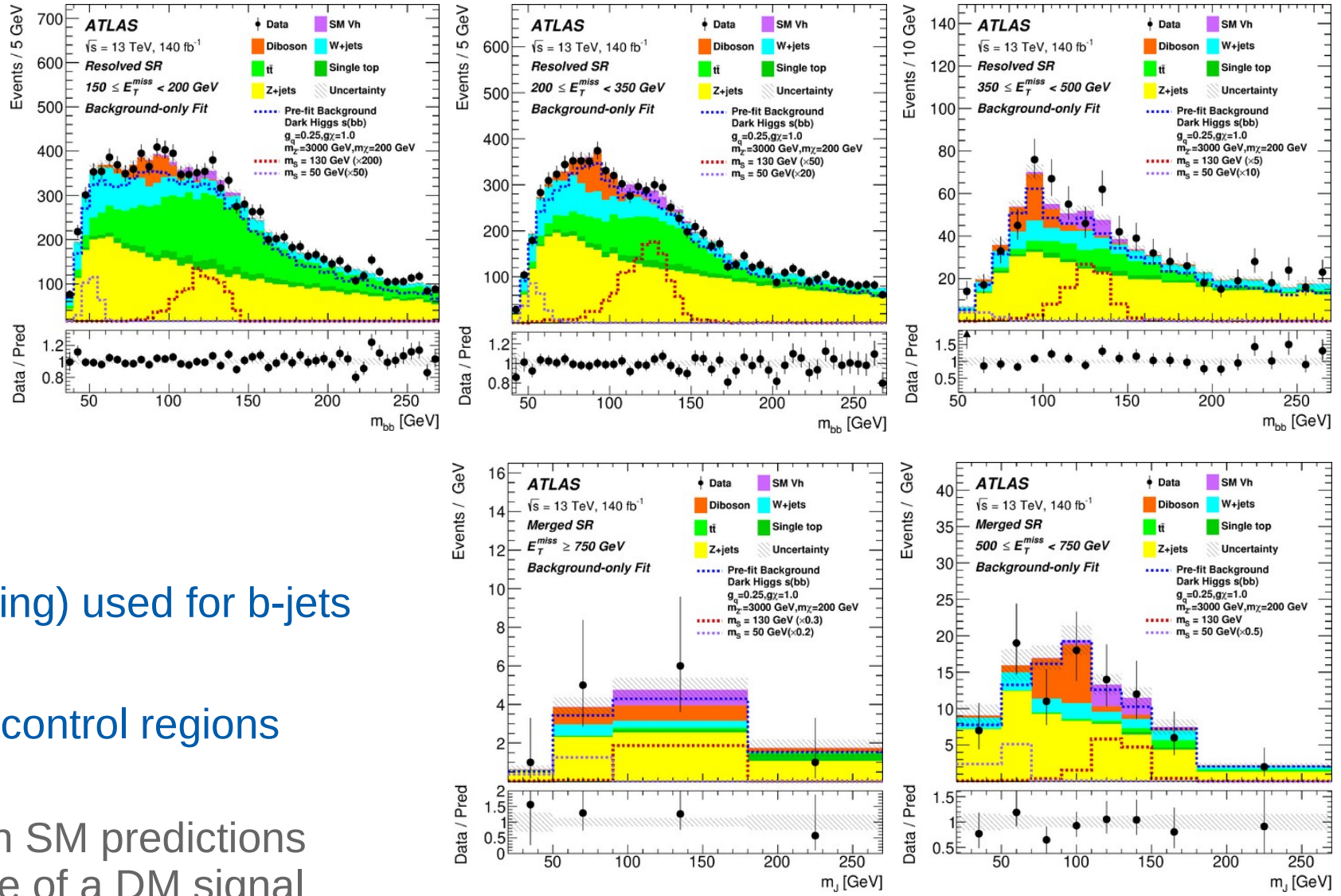
- Dark Higgs model for DM particles (χ) mass generation and Yukawa interactions with new scalar *(s)*
  - satisfies DM relic density when *s* lighter than χ
  - annihilation $\chi\chi \to ss$ can be dominant
- Searching for DM produced in association with a pair of b-quarks
  - signature: large missing E_T + resonant b-quark pair
  - never probed previously for $m_{bb} < 150$ GeV
- Three phase space scenarios explored
  - ($m_{Z'}$,m_s) plane covering 30-150 GeV in m_s and $m_{Z'}$ up to 4 TeV, with m_χ=200 GeV (avoid $\chi \to ss$ decays)
  - ($m_{Z'}$,m_s) plane with m_χ=900 GeV to enable match with relic density
  - ($m_{Z'}$,m_χ) plane with m_s=70 GeV (highest sensitivity)





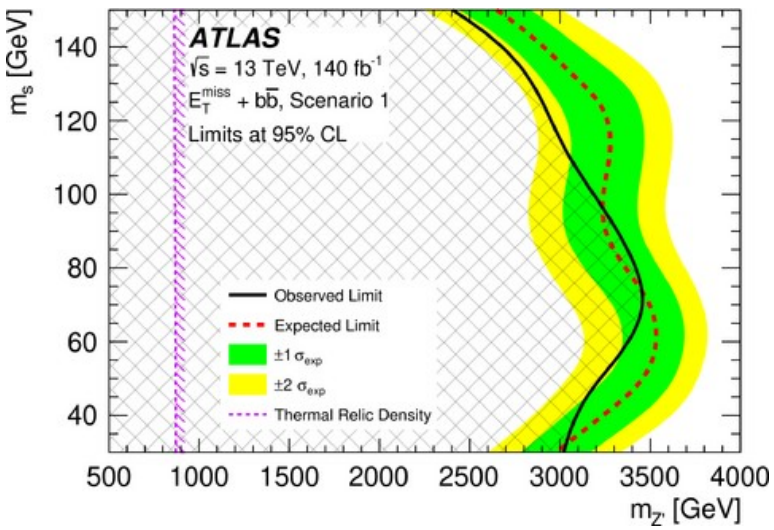
Dark Scalar $s \to b\bar{b}$ (II)

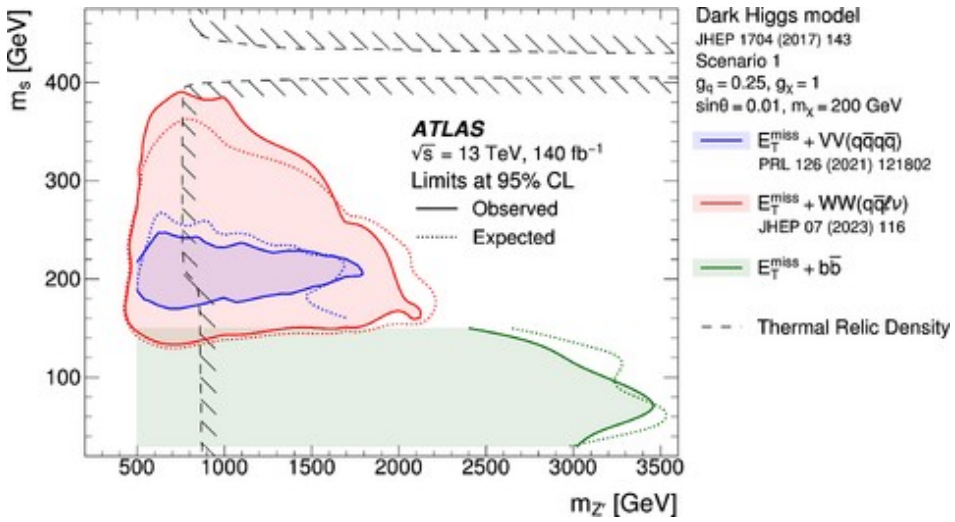
- Dominant SM background sources:
  - Z + jets
  - W + jets
  - $t\bar{t}$
  - *dibosons*
- Signal region split into five missing E_T regions to constrain background effectively
- Merged jet topology (reclustering) used for b-jets in the highly boosted regime
- Simultaneous fit in signal and control regions (background-only hypothesis)
  - Data are in agreement with SM predictions with no significant evidence of a DM signal

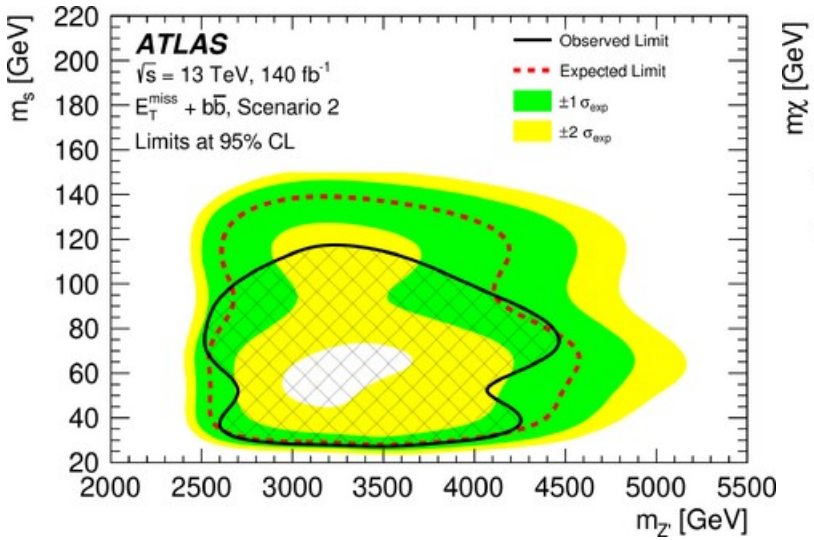


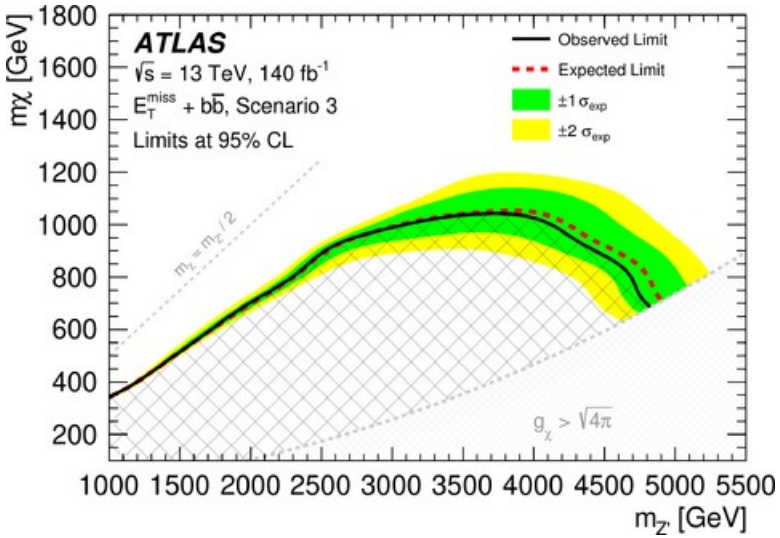
Dark Scalar $s \to b\bar{b}$ (III)

- 95% CL exclusions obtained for the three scenarios
- New search significantly extends existing limits for m_S<150 GeV
- Z' mediator mass excluded up to 3.5 TeV for considered benchmark model
  - up to 4.8 TeV (relic density inspired model)





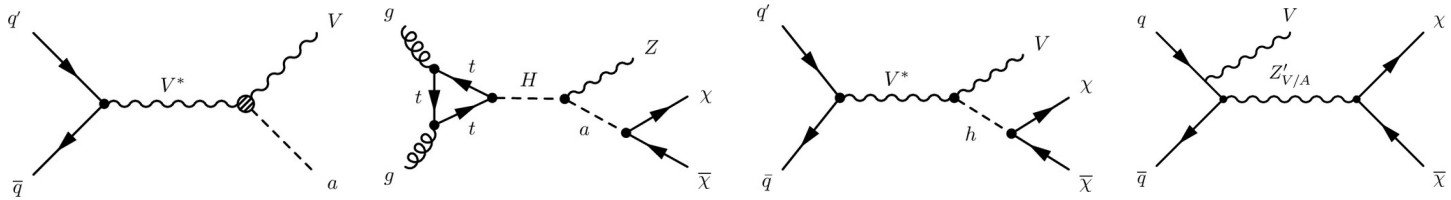




Dark matter search with *W* or *Z* (hadronic) (I)

CERN-EP-2024-128

- DM associated with W or Z production
- Four models considered
  - Axion-like particle (ALP)
  - Invisible Higgs decay
  - 2HDM with pseudo-scalar mediator
  - Simplified DM model for WIMPs with *Z'* (vector or axial-vector)
- Signature: W or Z and missing E_T
  - W or Z hadronic decays
  - Resolved or Merged jets topology (high boost)
- Dominant SM background sources:
  - $Z \to \nu\nu$ + jets ; $W \to \ell\nu$ + jets
  - $t\bar{t}$ and dibosons

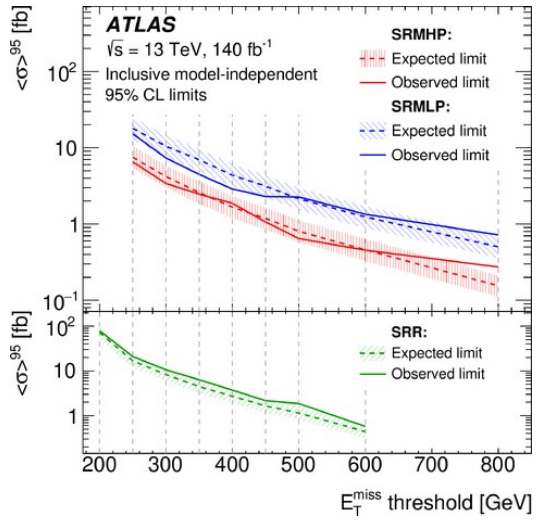


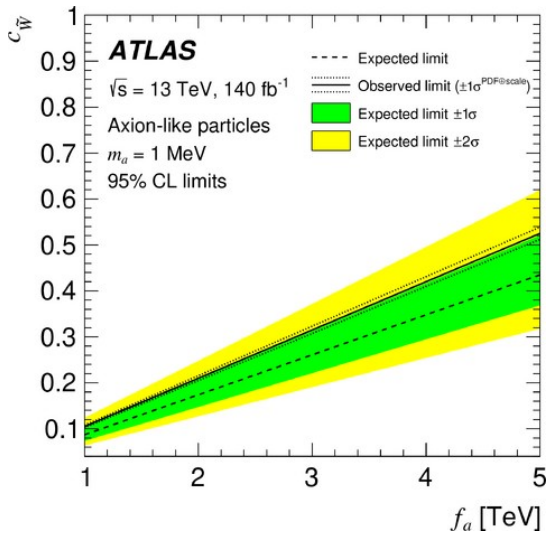
	Merged					Resolved				
Preselection	Data cleaning Primary vertex with at least two tracks with $p_T > 500$ MeV No τ-leptons $p_{T,\ell}^{miss} > 30$ GeV $\min_i(\Delta\phi(\boldsymbol{E}_{T,\ell}^{miss}, j_i)) > 20°$ $\Delta\phi(\boldsymbol{E}_{T,\ell}^{miss}, \boldsymbol{p}_{T,\ell}^{miss}) < 90°$									
$\Delta\phi(\boldsymbol{E}_{T,\ell}^{miss}, V)$	$\Delta\phi(\boldsymbol{E}_{T,\ell}^{miss}, J_1) > 120°$					$\Delta\phi(\boldsymbol{E}_{T,\ell}^{miss}, j_1 j_2) > 120°$				
$E_{T,\ell}^{miss}$	> 250 GeV					> 200 GeV				
Jets	$\geq 1J$; $\leq 4j$ $p_T^{J_1} > 200$ GeV b-tagged track jet veto outside J_1					$\geq 2j$; $\leq 4j$ $p_T^{j_1} > 45$ GeV $\sum_i p_T^{j_i} \geq 120\,(150)$ GeV for $2j$ ($\geq 3j$)				
V-tag	**High purity:** mass and substructure **Low purity:** mass and inverted substructure					$\Delta\phi(j_1, j_2) < 140°$; $\Delta R(j_1, j_2) < 1.4$ $m_{j_1 j_2} \in [65, 105]$ GeV				
	SR	CR2mu	CR2el	CR1mu0b	CR1mu1b	SR	CR2mu	CR2el	CR1mu0b	CR1mu1b
Trigger	E_T^{miss}	E_T^{miss}	Electron	E_T^{miss}	E_T^{miss}	E_T^{miss}	E_T^{miss}	Electron	E_T^{miss}	E_T^{miss}
e	0	0	2	0	0	0	0	2	0	0
μ	0	2	0	1	1	0	2	0	1	1
$\mathcal{S}$	>8	-	-	-	-	>8	-	-	-	-
$m_{\ell\ell}$ [GeV]	-	$\in [66, 116]$	$\in [66, 116]$	-	-	-	$\in [66, 116]$	$\in [66, 116]$	-	-
$m_{\mu\nu}^T$ [GeV]	-	-	-	$\in [30, 100]$	$\in [30, 100]$	-	-	-	$\in [30, 100]$	$\in [30, 100]$
$n_{b \in J}$	-	-	-	0	≥ 1	-	-	-	-	-
n_b	-	-	-	-	-	-	-	-	0	≥ 1

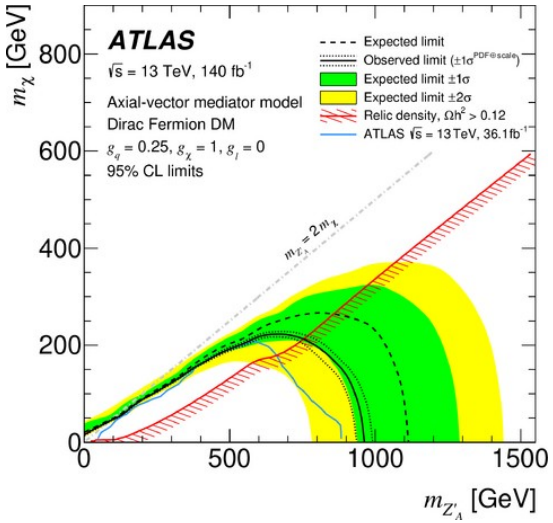
Dark matter search with *W* or *Z* (hadronic) (II)

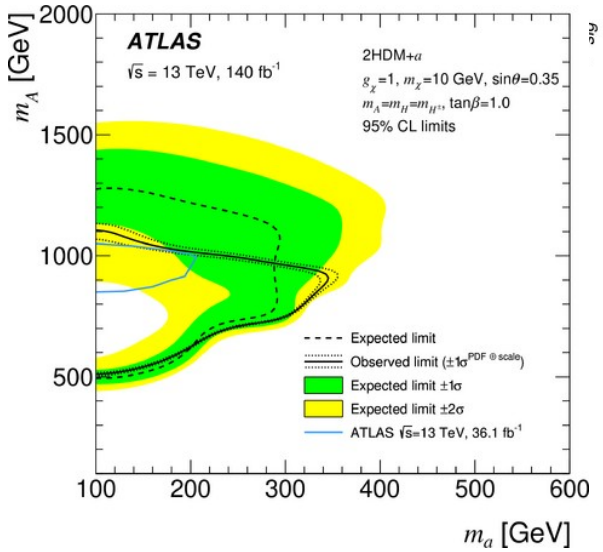
- Simultaneous likelihood fit in both signal and control regions: no excess observed
- Both model independent and model dependent exclusion limits obtained
  - 2HDM+a: using benchmark scenarios recommended by LHC DM Working group

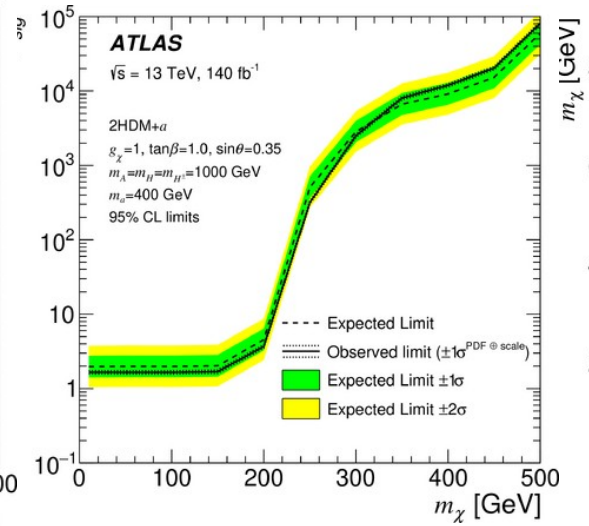
	Signal Regions		
Sample	SRMHP	SRMLP	SRR
$Z(\to \nu\nu)$ + jets	12 200 ± 500	54 100 ± 1200	180 100 ± 2500
$W(\to \ell\nu)$ + jets	6320 ± 330	25 600 ± 700	105 500 ± 2000
Diboson	3700 ± 700	5800 ± 1500	13 100 ± 3000
$t\bar{t}$	1240 ± 130	2470 ± 340	23 600 ± 1300
Other	380 ± 50	490 ± 60	3920 ± 340
$Z(\to \ell\ell)$ + jets	55 ± 6	266 ± 13	1480 ± 40
Multijet	24 ± 18	140 ± 100	1900 ± 1400
Total background	23 870 ± 160	88 880 ± 300	329 500 ± 800
Data	23 861	88 836	329 588

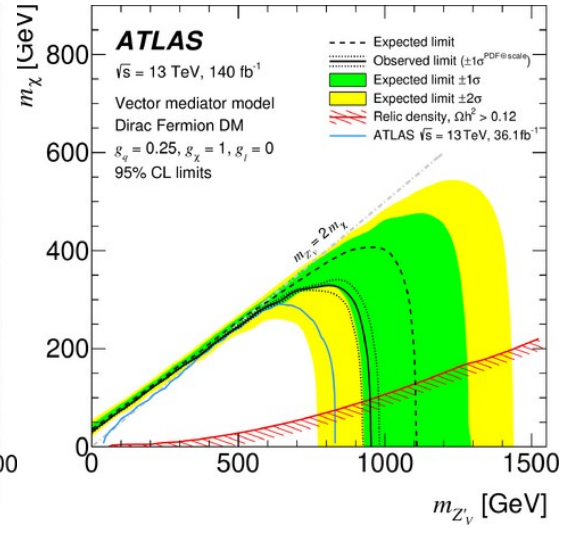












Dark Photon Search (I)

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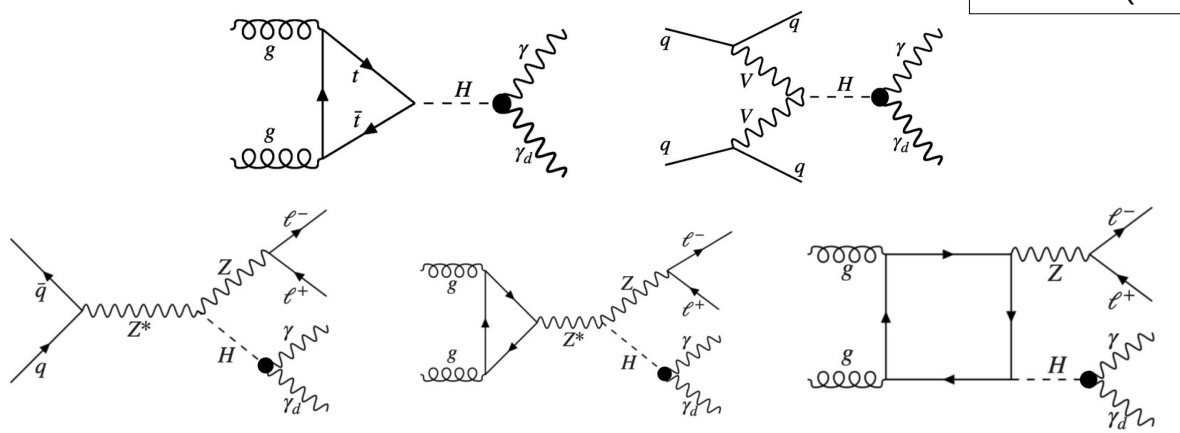
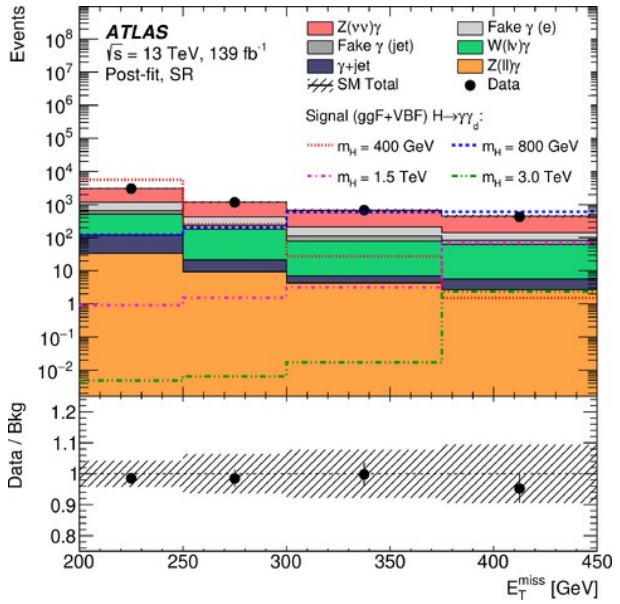
- Model extension with extra $U(1)_d$
  - massless γ_d
  - coupling through Higgs (SM or BSM)
- Three channels considered
  - ggF, VBF and *ZH*
  - different event topology
- Combination of VBF and ZH channels uses SM Higgs assumption
- Combination of ggF and VBF under H_{BSM} assumption (from 400 GeV to 3 TeV)
- Dominant SM backgrounds:
  - *Z* ($\to \nu\nu$) γ + jets ; W ($\to \ell\nu$) γ+ jets

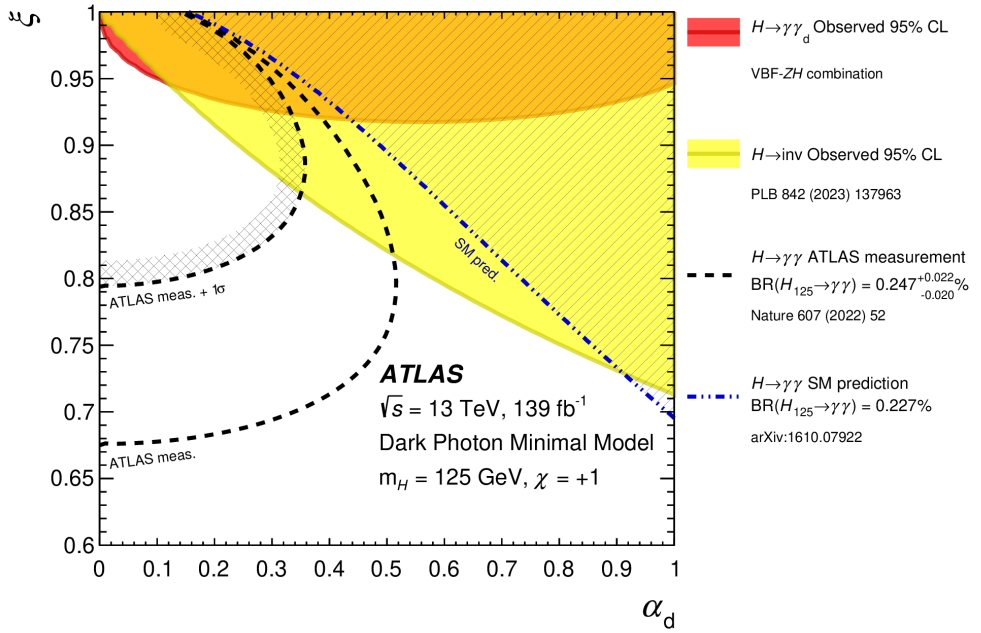


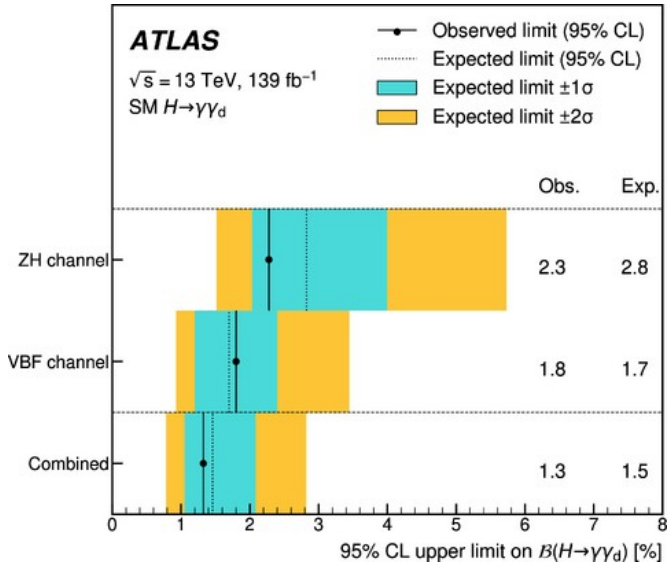
Channels	VBF	*ZH*	ggF
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_{T}^{γ} [GeV]	$\in (15, \max(110, 0.733 \times m_{\mathrm{T}}))$	> 25	> 150
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0$ (e, μ)	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0$ (e, μ, τ)
Disc. variables	m_{jj} and m_{T} in SR and 4 CRs	BDT score and 1 CR	$E_{\mathrm{T}}^{\mathrm{miss}}$
Reference			
Processes considered in the combination	VBF, ggF	*ZH*	ggF, VBF
Combination scenario	SM, BSM	SM	BSM

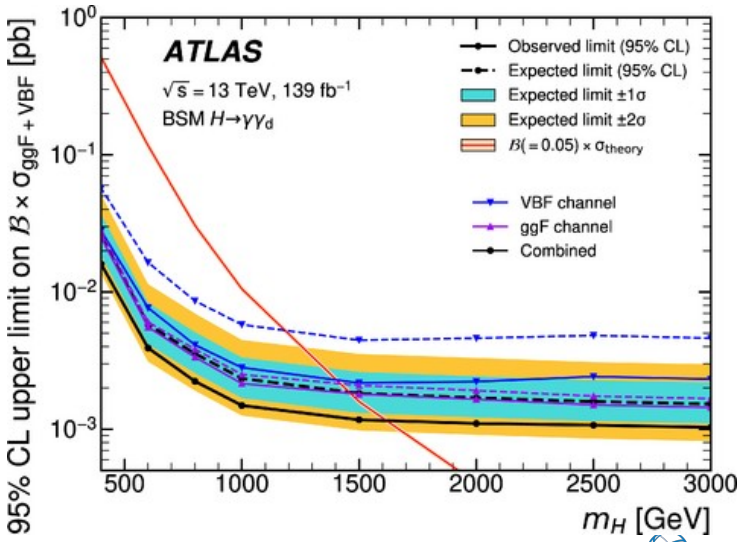
Dark Photon Search (II)

- No excess observed, Good agreement between data and background prediction.
- New 95% CL upper limits obtained from channel combinations
- $Br(H_{125} \rightarrow \gamma\gamma_d) < 1.3\%$
- H_{BSM} masses < 1.6 TeV excluded, assuming 5% branching ratio for $H_{BSM} \rightarrow \gamma\gamma_d$









Dark Mesons Search (I)

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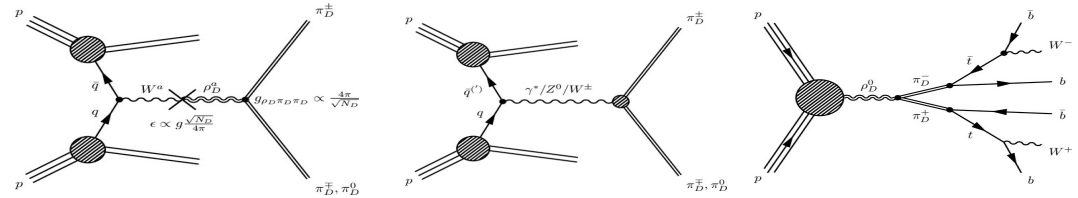
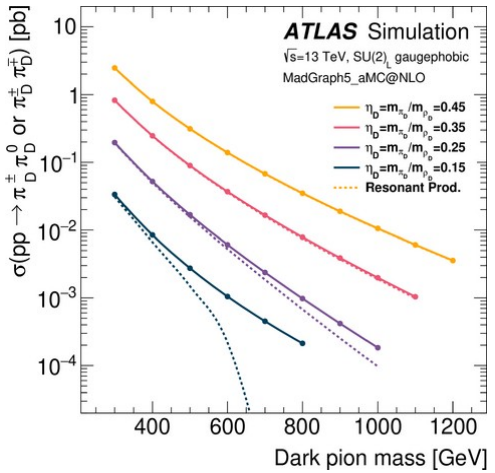
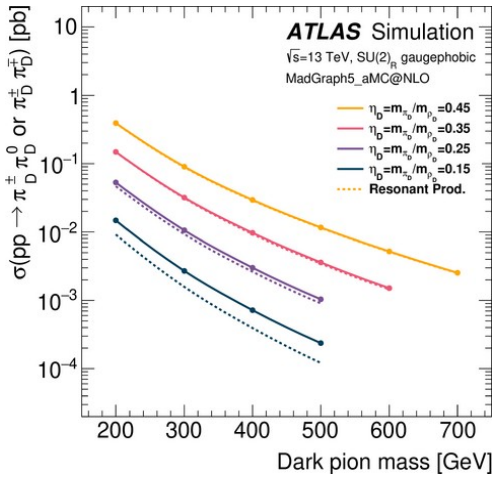
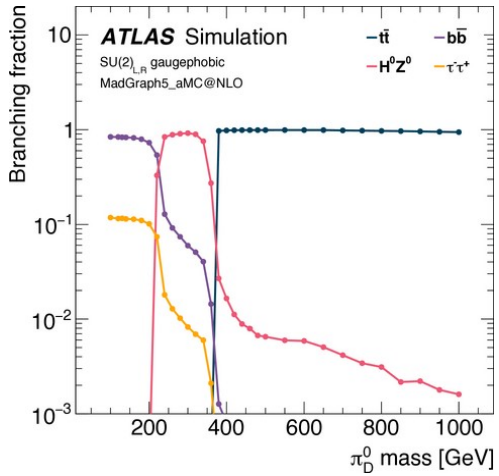
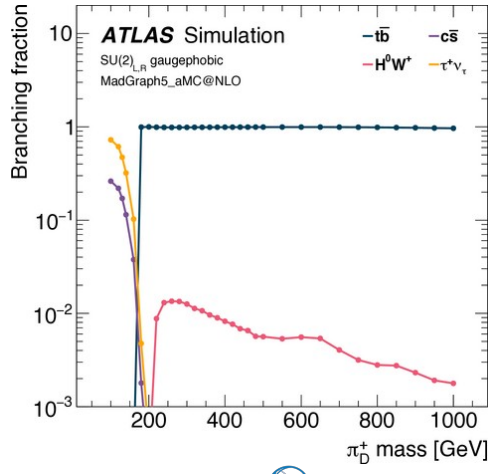
- SM extension with new strongly-coupled gauge theory with fermion representation which transforms under the electroweak group
  - QCD-like dark sector with couplings to SM
  - models contain stable dark scalar baryon which could account for observed DM
- For this search: pseudoscalar triplet of dark pions π_D , and triplet of dark rho vector mesons ρ_D
  - case where $\eta_D = m_{\pi D} / m_{\rho D} < 0.5$
  - pair production of π_D
  - gaugephobic decays: t and b at high mass, c and τ at low mass
- Two channels: all hadronic and one lepton
  - Dominant SM backgrounds: multijet and $t\bar{t}$







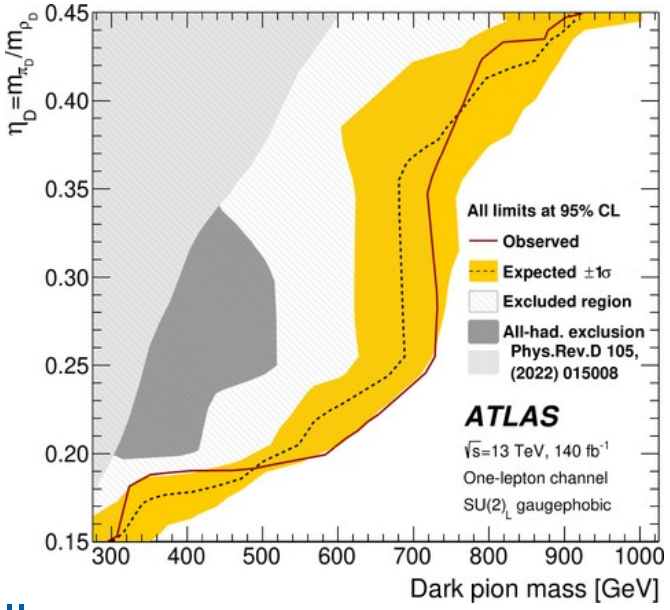


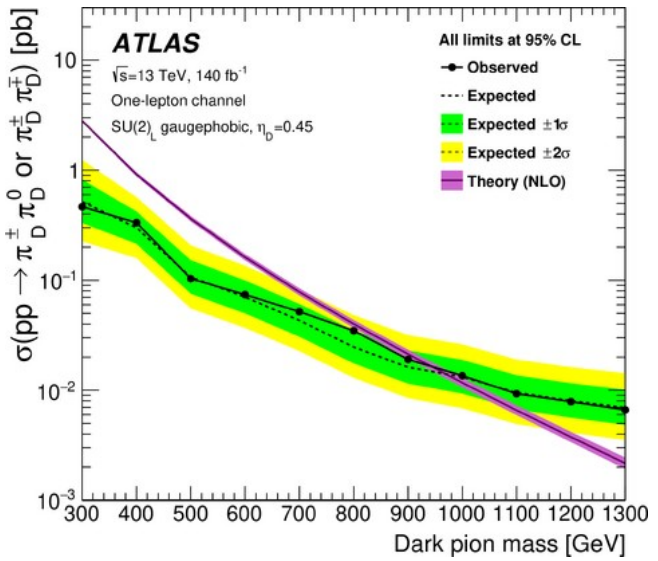


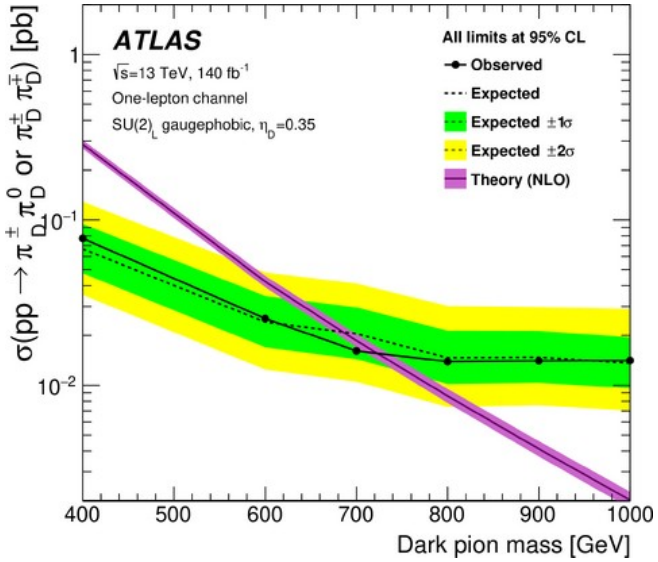
Dark Mesons Search (II)

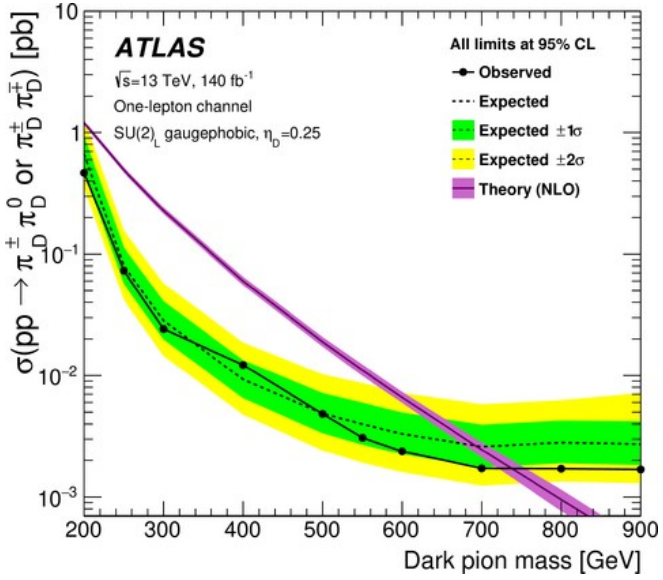
Variable	All-hadronic channel	One-lepton channel
N_{lep}(baseline)	0	1
N_{lep}(signal)	-	1
$N_{jets}(R = 0.4)$	≥ 6	≥ 5
$N_{jets}(R = 1.2)$	≥ 2	-
$N_{b\text{-jets}}$	≥ 3	≥ 3
H_T	≥ 1150 GeV	≥ 300 GeV

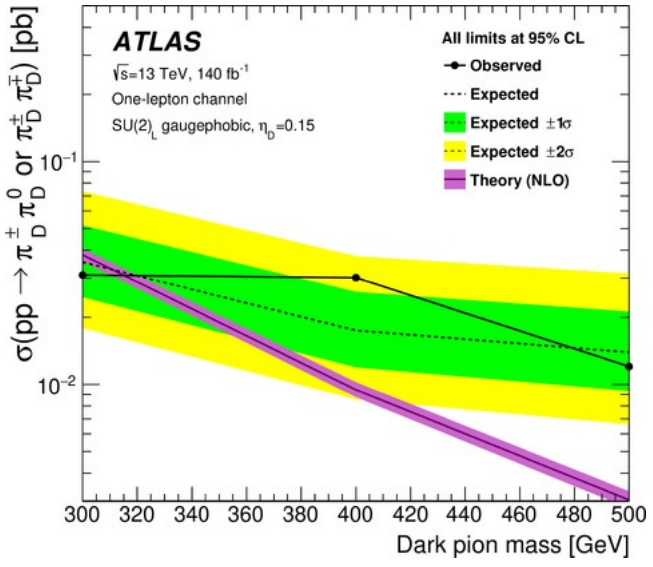
- 95% CL upper limits on dark pions pair production
- $SU(2)_R$ not sensitive due to low production cross section
- One-lepton channel covers all hadronic exclusion











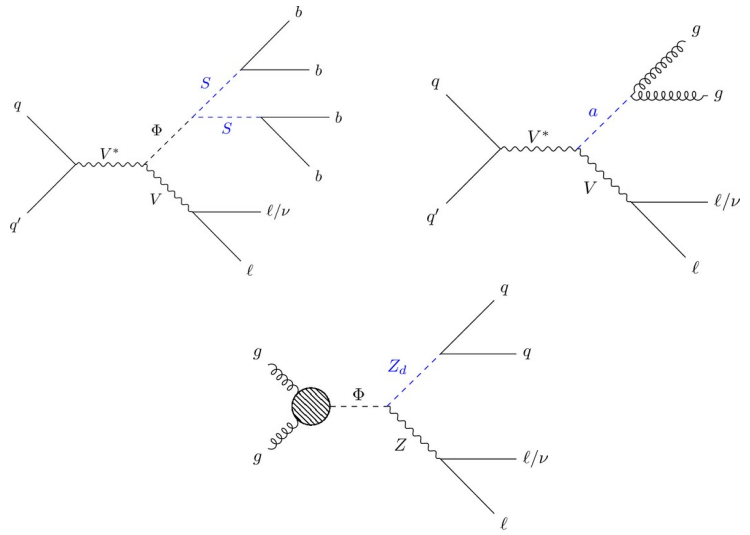
Conclusion & Future prospects

- Extensive program in ATLAS to search for BSM physics, only a small subset was highlighted
  - wide range of models
  - different analysis strategies
  - different final states and event topology
  - using the full Run 2 dataset (2015-2018)
  - no significant excess observed over background expectation
- All ATLAS exotics searches with up to date information can be found at:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- Please stay tuned...

EXTRA MATERIAL

Long-lived Particles Search I (decay in calorimeter)

- Wide class of models covered:
  - DM, SUSY, Axions
- Search conducted in three channels
- Special LLP trigger
  - ratio of calorimeter energies (EM vs HAD)



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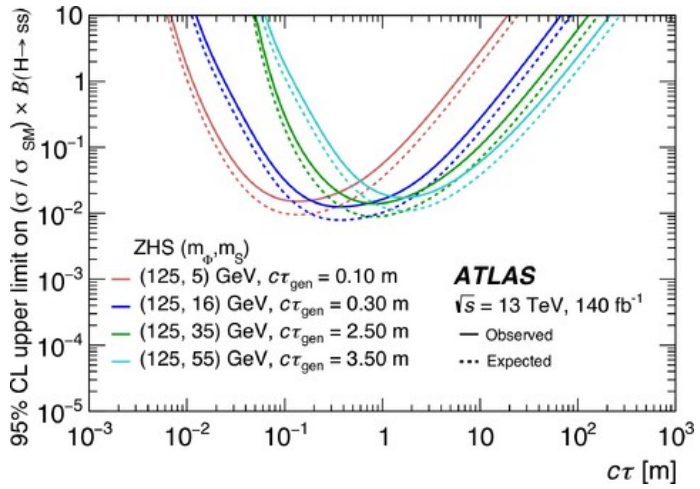

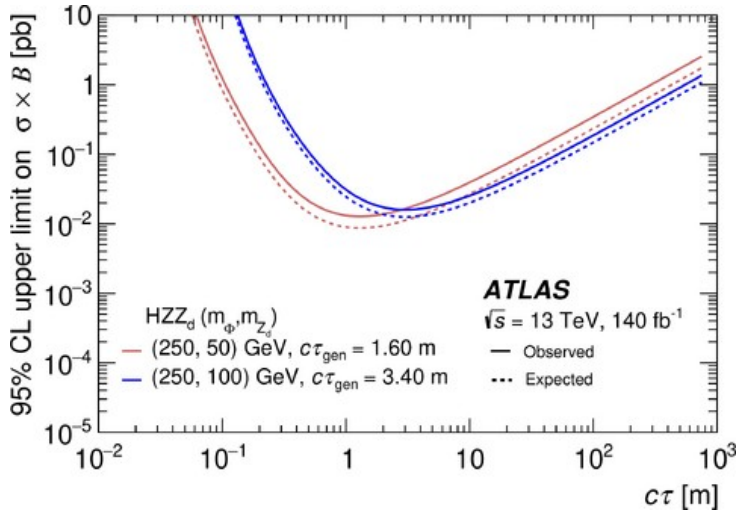

Selection	CalR+2J
Trigger	Satisfy CalRatio trigger
Number of clean jets	≥ 3
$\sum \Delta R_{\text{min}}$	> 0.5
Trigger matching	At least one signal candidate
Signal/BIB jet candidate time	-3 ns $< t <$ 15 ns
Signal/BIB jet candidate $\log_{10}(E_{\text{H}}/E_{\text{EM}})$	> -1.5
Signal jet candidate η	$\notin (1.45, 1.55)$
$\text{NN}_{\text{CalR+2J}}$	≥ 3
Region A	$\sum \Delta R_{\text{min}} \geq 0.71$ $\text{NN}_{\text{CalR+2J}} \geq 7.61$

Selection	CalR+Z low-E_{T}	CalR+Z high-E_{T}
Vector boson candidates	1 Z, 0 W	1 Z, 0 W
BDT score	$\text{BDT}^{\text{low-}E_{\text{T}}}_{\text{CalR+Z}}$ score > 0.6	$\text{BDT}^{\text{high-}E_{\text{T}}}_{\text{CalR+Z}}$ score > 0.7
$j^{\text{sig1}\ell}$ $\log_{10}(E_{\text{H}}/E_{\text{EM}})$	> 0.8	> 0.8
$j^{\text{sig1}\ell}$ p_{T}	> 80 GeV	> 70 GeV
Lepton p_{T}	> 70 GeV	> 60 GeV
Region A	$\text{BDT}^{\text{low-}E_{\text{T}}}_{\text{CalR+Z}}$ score > 0.99 $\sum \Delta R_{\text{min}} \geq 0.9$	$\text{BDT}^{\text{high-}E_{\text{T}}}_{\text{CalR+Z}}$ score > 0.985 $\sum \Delta R_{\text{min}} \geq 1$

Selection	CalR+W WALP	CalR+W low-E_{T}	CalR+W high-E_{T}
Vector boson candidates	0 Z, 1 W	0 Z, 1 W	0 Z, 1 W
BDT score	$\text{BDT}^{\text{ALP}}_{\text{CalR+W}} > 0.82$	$\text{BDT}^{\text{low-}E_{\text{T}}}_{\text{CalR+W}} > 0.92$	$\text{BDT}^{\text{high-}E_{\text{T}}}_{\text{CalR+W}} > 0.89$
$j^{\text{sig1}\ell}$ $\log_{10}(E_{\text{H}}/E_{\text{EM}})$	> 1	> 1	–
$j^{\text{sig1}\ell}$ p_{T}	> 70 GeV	> 60 GeV	> 100 GeV
Lepton p_{T}	–	> 40 GeV	> 60 GeV
$\Delta\phi$(lepton, $E_{\text{T}}^{\text{miss}}$)	< 1.5	–	–
Region A	$\text{BDT}^{\text{ALP}}_{\text{CalR+W}} \geq 0.975$ $\sum \Delta R_{\text{min}} \geq 1.1$	$\text{BDT}^{\text{low-}E_{\text{T}}}_{\text{CalR+W}} \geq 0.985$ $\sum \Delta R_{\text{min}} \geq 1.4$	$\text{BDT}^{\text{high-}E_{\text{T}}}_{\text{CalR+W}} \geq 0.99$ $\sum \Delta R_{\text{min}} \geq 1.1$

Long-lived Particles Search II (decay in inner detector)

- LLPs with masses between 5 and 55 GeV (hadronic decays)
- pair production from exotic decay of Higgs
- Axion-like particles associated with a Z or exotic top decay
- Six signal regions considered

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