Searches for New Physics at the LHC

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DESYTH workshop "Synergies Towards the Future Standard Model" 23 September 2025 - Hamburg, Germany





QUANTUM UNIVERSE

DESY THEORY WORKSHOP

SYNERGIES TOWARDS
THE FUTURE STANDARD MODEL

HELMHOLTZ

23 - 26 September 2025 DESY Hamburg, Germany

DESY.

The Standard Model of Particle Physics

... and beyond?

No gravity!

No verified theory of quantum gravity

No neutrino masses!

Are they Dirac or Majorana particles?

No naturalness!

Higgs field parameters seem highly fine-tuned

No dark matter!

But needed to explain astrophysical observations

No dark energy!

The universe is in accelerated expansion invisible source of energy?

Not enough matterantimatter asymmetry!

To explain dominance of matter today

Why 3 fermion generations?

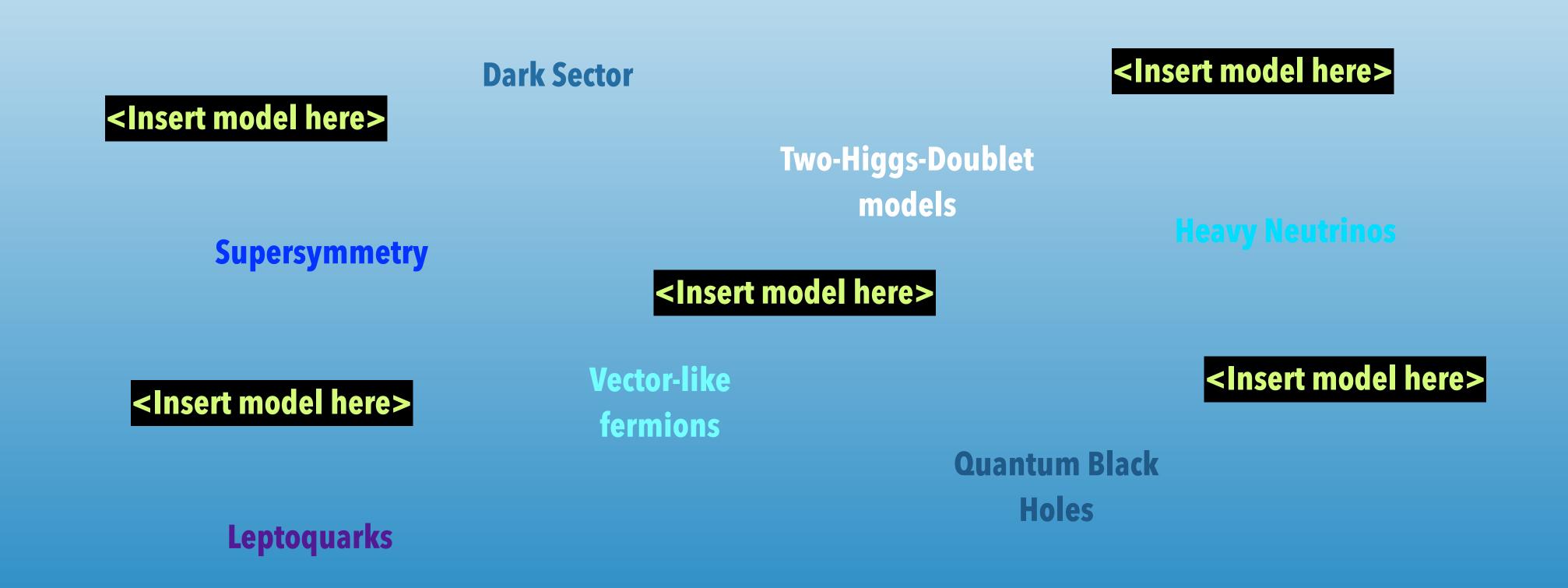
Underlying symmetry connecting quark and lepton sectors?

Why hierarchical Yukawa coupling?

Why is the top quark so heavy?

Exploring all extensions of the SM

• The sea of beyond the SM theories is vast and difficult to cover in 30 min





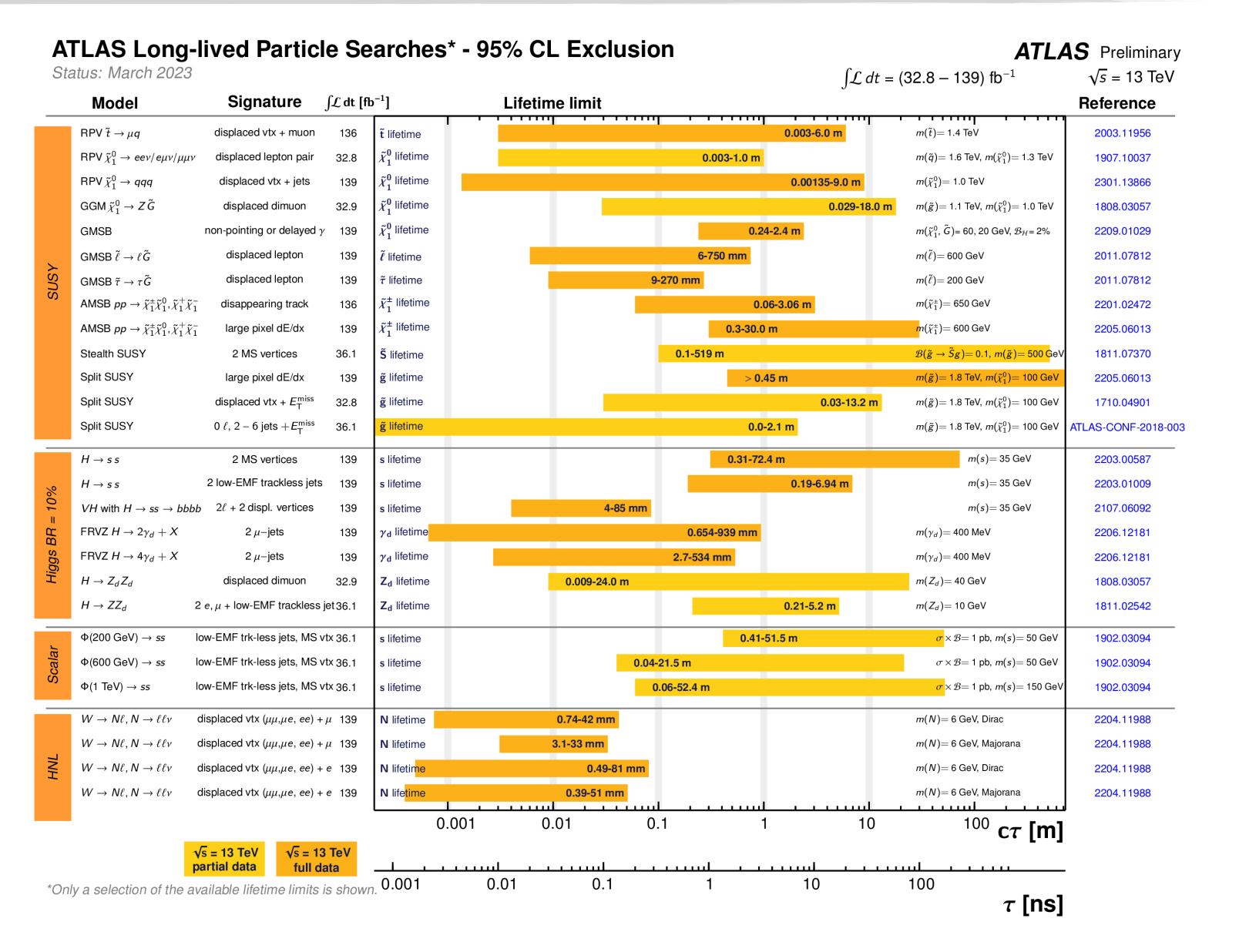
ATLAS Heavy Status: March 2023	Particle	Searc	ches	s* - 9	5% CL Up	oper Exc	lusion	Limits	[f dt = 13	ATL 6 - 139) fb $^{-1}$	4S Preliminary $\sqrt{s} = 13 \text{ TeV}$
Model	ℓ , γ	Jets†	E _T miss	∫£ dt[fb	⁻¹]	Lim	nit		J2 01 - (C	5.0 100) ID	Reference
ADD $G_{KK}+g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \to \gamma\gamma$ Bulk RS $G_{KK} \to WW/ZZ$ Bulk RS $g_{KK} \to tt$ 2UED / RPP	$egin{array}{ccc} 0 & e, \mu, au, \gamma \ & 2 & \gamma \ & - \ & 2 & \gamma \ & & & & 1 & e, \mu \ & & & 1 & e, \mu \ \end{array}$	_ 2 j ≥3 j _		139 36.7 139 3.6 139 36.1 36.1	M _D M _S M _{th} M _{th} M _{th} G _{KK} mass G _{KK} mass g _{KK} mass KK mass			4.5 TeV 2.3 TeV 3.8 TeV	8.6 TeV 9.4 TeV 9.55 TeV	$N = 2$ $N = 3 \text{ HLZ NLO}$ $N = 6$ $N = 6$, $N = 3 \text{ TeV}$, rot BH $N = \frac{1}{2} 1$	2102.10874 1707.04147 1910.08447 1512.02586 2102.13405 1808.02380 1804.10823 1803.09678
SSM $Z' \to \ell\ell$ SSM $Z' \to \tau\tau$ Leptophobic $Z' \to bb$ Leptophobic $Z' \to tt$ SSM $W' \to \ell\nu$ SSM $W' \to \tau\nu$ SSM $W' \to tb$ HVT $W' \to WZ$ model B HVT $W' \to WZ \to \ell\nu \ell'\ell'$ HVT $Z' \to WW$ model B LRSM $W_R \to \mu N_R$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} - \\ - \\ 2 \text{ b} \\ \geq 1 \text{ b}, \geq 2 \text{ J} \\ - \\ - \\ \geq 1 \text{ b}, \geq 1 \text{ J} \\ 2 \text{ j (VBF)} \\ 2 \text{ j / 1 J} \\ 1 \text{ J} \end{array}$	Yes Yes	139 36.1 36.1 139 139 139 139 139 139	Z' mass Z' mass Z' mass Z' mass W' mass	340 GeV		2.42 TeV 2.1 TeV 4.1 Te 5.1 4.4 Te 4.3 Te 3.9 TeV	6.0 TeV 0 TeV TeV eV	$\Gamma/m = 1.2\%$ $g_V = 3$ $g_V c_H = 1, g_f = 0$ $g_V = 3$ $m(N_R) = 0.5$ TeV, $g_L = g_R$	1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 ATLAS-CONF-2021-025 ATLAS-CONF-2021-043 2004.14636 2207.03925 2004.14636 1904.12679
CI qqqq CI ℓℓqq CI eebs CI μμbs CI tttt	- 2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1 j	- - - - Yes	37.0 139 139 139 36.1	Λ Λ Λ			1.8 TeV 2.0 TeV 2.57 TeV		21.8 TeV η_{LL}^- 35.8 TeV $\eta_{LL}^ g_*=1$ $g_*=1$ $ C_{4t} =4\pi$	1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
Axial-vector med. (Dirac DM Pseudo-scalar med. (Dirac Vector med. Z'-2HDM (Dirac Pseudo-scalar med. 2HDM	DM) $0 e, \mu, \tau, \gamma$ ac DM) $0 e, \mu$	2 b	- Yes Yes	139 139 139 139	$\begin{aligned} & m_{med} \\ & m_{med} \\ & m_{Z'} \\ & m_a \end{aligned}$	376 GeV	800 GeV	3.8 TeV 3.0 TeV	'	g_q =0.25, g_χ =1, $m(\chi)$ =10 TeV g_q =1, g_χ =1, $m(\chi)$ =1 GeV $\tan \beta$ =1, g_Z =0.8, $m(\chi)$ =100 GeV $\tan \beta$ =1, g_χ =1, $m(\chi)$ =10 GeV	ATL-PHYS-PUB-2022-030 2102.10874 2108.13391 ATLAS-CONF-2021-036
Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Vector LQ mix gen Vector LQ 3 rd gen	0 e, μ, ≥1	$\geq 2j$ $\geq 2j$ $2b$ $\geq 2j, \geq 2b$ $\tau \geq 1j, \geq 1b$ $\tau 0 - 2j, 2b$ $\geq 1b$	- Yes	139 139 139 139 139 139 139	LQ mass		1.24 T	3 TeV		$\begin{split} \beta &= 1 \\ \beta &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^u \to b\tau) &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^u \to t\nu) &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^d \to t\tau) &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^d \to b\nu) &= 1 \\ \mathcal{B}(\tilde{U}_1 \to t\mu) &= 1, \text{ Y-M coupl.} \\ \mathcal{B}(\mathrm{LQ}_3^V \to b\tau) &= 1, \text{ Y-M coupl.} \end{split}$	2006.05872 2006.05872 2303.01294 2004.14060 2101.11582 2101.12527 ATLAS-CONF-2022-052 2303.01294
VLQ $TT \rightarrow Zt + X$ VLQ $BB \rightarrow Wt/Zb + X$ VLQ $T_{5/3}T_{5/3} T_{5/3} \rightarrow Wt$ VLQ $T \rightarrow Ht/Zt$ VLQ $Y \rightarrow Wb$ VLQ $B \rightarrow Hb$ VLL $\tau' \rightarrow Z\tau/H\tau$	multi-chann + X 2(SS)/ \geq 3 e 1 e, μ 1 e, μ	$\mu \geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 1 \text{ b, } \geq 3 \text{ j}$ $\geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 2 \text{ b, } \geq 1 \text{ j, } \geq 1$	Yes Yes Yes	139 36.1 36.1 139 36.1 139	T mass B mass T _{5/3} mass T mass Y mass B mass τ' mass		1.34	6 TeV TeV .64 TeV 1.8 TeV 1.85 TeV 2.0 TeV		SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$ SU(2) singlet, $\kappa_T = 0.5$ $\mathcal{B}(Y \to Wb) = 1$, $c_R(Wb) = 1$ SU(2) doublet, $\kappa_B = 0.3$ SU(2) doublet	2210.15413 1808.02343 1807.11883 ATLAS-CONF-2021-040 1812.07343 ATLAS-CONF-2021-018 2303.05441
Excited quark $q^* o qg$ Excited quark $q^* o q\gamma$ Excited quark $b^* o bg$ Excited lepton τ^*	- 1 γ - 2 τ	2 j 1 j 1 b, 1 j ≥2 j	- - -	139 36.7 139 139	q* massq* massb* massτ* mass			3.2 TeV	6.7 TeV .3 TeV TeV	only u^* and d^* , $\Lambda=m(q^*)$ only u^* and d^* , $\Lambda=m(q^*)$ $\Lambda=4.6~{\sf TeV}$	1910.08447 1709.10440 1910.08447 2303.09444
Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \to W^{\pm}W$ Higgs triplet $H^{\pm\pm} \to \ell\ell$ Multi-charged particles Magnetic monopoles	2,3,4 e, μ 2 μ 2 ± 2,3,4 e, μ (S 2,3,4 e, μ (S	2 j S) various	Yes - Yes - -	139 36.1 139 139 139 34.4	N ⁰ mass N _R mass H ^{±±} mass H ^{±±} mass multi-charged particle monopole mass	350 GeV	910 GeV 1.08 TeV 1.	3.2 TeV 59 TeV 2.37 TeV		$m(W_R)=4.1~{ m TeV},g_L=g_R$ DY production DY production DY production, $ q =5e$ DY production, $ g =1g_D$, spin $1/2$	2202.02039 1809.11105 2101.11961 2211.07505 ATLAS-CONF-2022-034 1905.10130
	√s = 13 TeV partial data	$\sqrt{s} = 13$ full da			10 ⁻¹		1		10	Mass scale [TeV]	I

^{*}Only a selection of the available mass limits on new states or phenomena is shown.

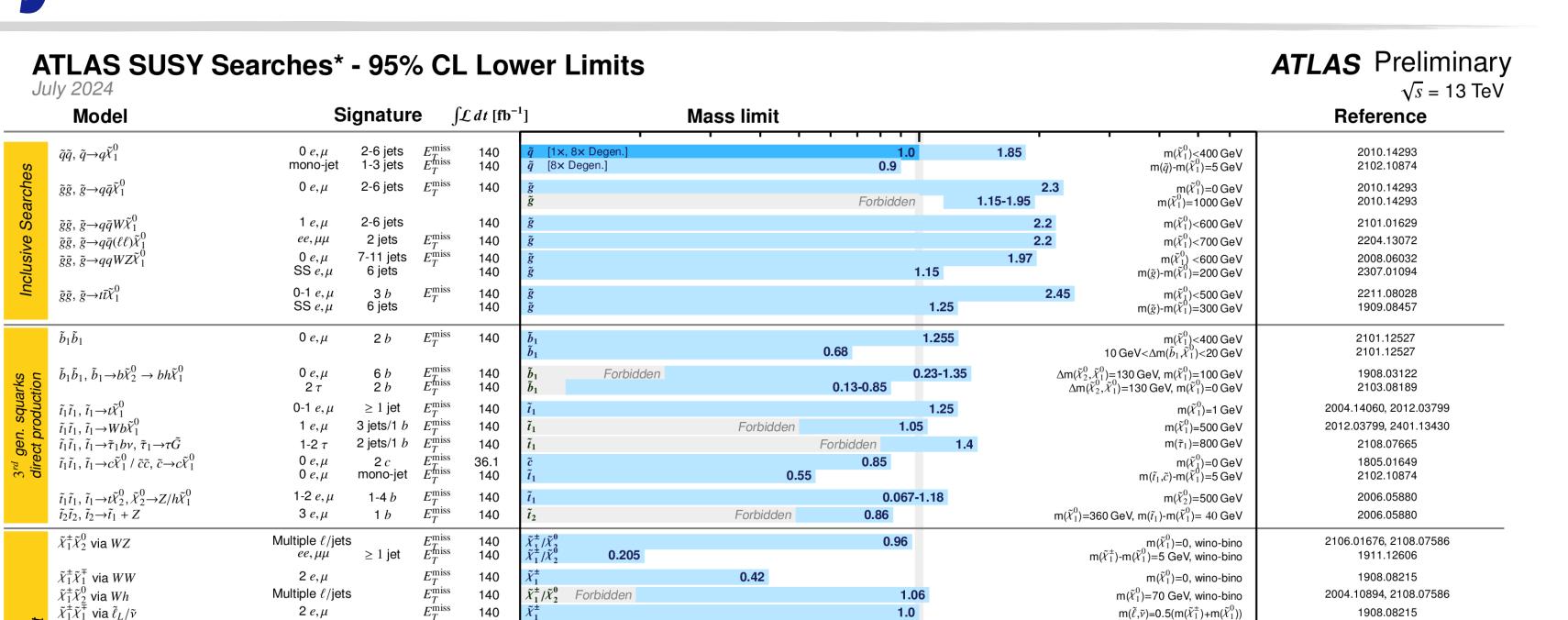
[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Summary: ATLAS LLP Searches









140 0.5 2τ 2402.00603 $\tilde{\tau}\tilde{\tau}, \tilde{\tau}{\rightarrow}\tau\tilde{\chi}_1^0$ $m(\tilde{\chi}_1^0)=0$ 140 140 $2e,\mu$ 1908.08215 $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\,\tilde{\ell}{
ightarrow}\ell\tilde{\chi}_1^0$ 0.7 $m(\tilde{\chi}_1^0)=0$ ≥ 1 jet 0.26 $ee, \mu\mu$ $\mathsf{m}(\tilde{\ell})$ - $\mathsf{m}(\tilde{\chi}_1^0)$ =10 GeV 1911.12606 $\begin{array}{ccc} \geq 3 \ b & E_{T \text{niss}}^{\text{miss}} \\ \text{0 jets} & E_{T \text{niss}}^{\text{miss}} \\ \geq 2 \ \text{large jets} & E_{T}^{\text{miss}} \end{array}$ $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$ $0e, \mu$ $BR(\tilde{\chi}_{1}^{0} \rightarrow h\tilde{G})=1$ 2401.14922 140 0.55 $BR(\tilde{\chi}_1^0 \to Z\tilde{G})=1$ $4e, \mu$ 2103.11684 $0 e, \mu$ 140 0.45-0.93 $\mathsf{BR}(\tilde{\chi}_1^0 \to Z\tilde{G}) = 1$ 2108.07586 140 ≥ 2 jets 0.77 $BR(\tilde{\chi}_1^0 \to Z\tilde{G}) = BR(\tilde{\chi}_1^0 \to h\tilde{G}) = 0.5$ 2204.13072 Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ 1 jet 0.66 Disapp. trk 140 Pure Wino 2201.02472 0.21 Pure higgsino 2201.02472 Stable \tilde{g} R-hadron pixel dE/dx 2.05 2205.06013 140 140 \tilde{g} [$\tau(\tilde{g})$ =10 ns] pixel dE/dx $m(\tilde{\chi}_1^0)=100 \text{ GeV}$ 2205.06013 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ 140 $\tilde{\ell}\tilde{\ell},\,\tilde{\ell}{
ightarrow}\ell\tilde{G}$ Displ. lep 0.74 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ ATLAS-CONF-2024-011 0.36 0.36 ATLAS-CONF-2024-011 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ pixel dE/dx 140 $\tau(\tilde{\ell}) = 10 \text{ ns}$ 2205.06013 $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$ 0.625 $3e, \mu$ $\widetilde{\mathcal{X}}_1^{\mp}/\widetilde{\mathcal{X}}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] 1.05 Pure Wino 2011.10543 0 jets 0.95 $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$ $4e, \mu$ 140 1.55 $[\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$ $m(\tilde{\chi}_1^0)=200 \text{ GeV}$ 2103.11684 ≥8 jets 140 2.34 Large $\lambda_{112}^{"}$ 2401.16333 $\tilde{g}\tilde{g}, \, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \, \tilde{\chi}_1^0 \rightarrow qqq$ $[m(\tilde{\chi}_1^0)=50 \text{ GeV}, 1250 \text{ GeV}]$ $\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$ Multiple $[\lambda_{222}^{\prime\prime}=2e-4, 1e-2]$ 1.05 36.1 0.55 ATLAS-CONF-2018-003 $m(\tilde{\chi}_1^0)$ =200 GeV, bino-like $\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow bbs$ 140 Forbidden 0.95 $m(\tilde{\chi}_1^{\pm})=500 \text{ GeV}$ 2010.01015 $\tilde{t}_1\tilde{t}_1, \, \tilde{t}_1 {\rightarrow} bs$ 2 jets + 2 b 0.61 1710.07171 BR($\tilde{t}_1 \rightarrow be/b\mu$)>20% $\tilde{t}_1\tilde{t}_1,\,\tilde{t}_1{\rightarrow}q\ell$ 2406.18367 [1e-10< λ'_{2k} <1e-8, 3e-10< λ'_{2k} <3e-9] DV 136 BR($\tilde{t}_1 \rightarrow q\mu$)=100%, $\cos \theta_t$ =1 1 μ 1.6 2003.11956

0.2-0.32

1-2 $e, \mu \ge 6$ jets

140

 $\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}/\tilde{\chi}_{1}^{0}, \, \tilde{\chi}_{1,2}^{0} \rightarrow tbs, \, \tilde{\chi}_{1}^{+} \rightarrow bbs$

 10^{-1} Mass scale [TeV]

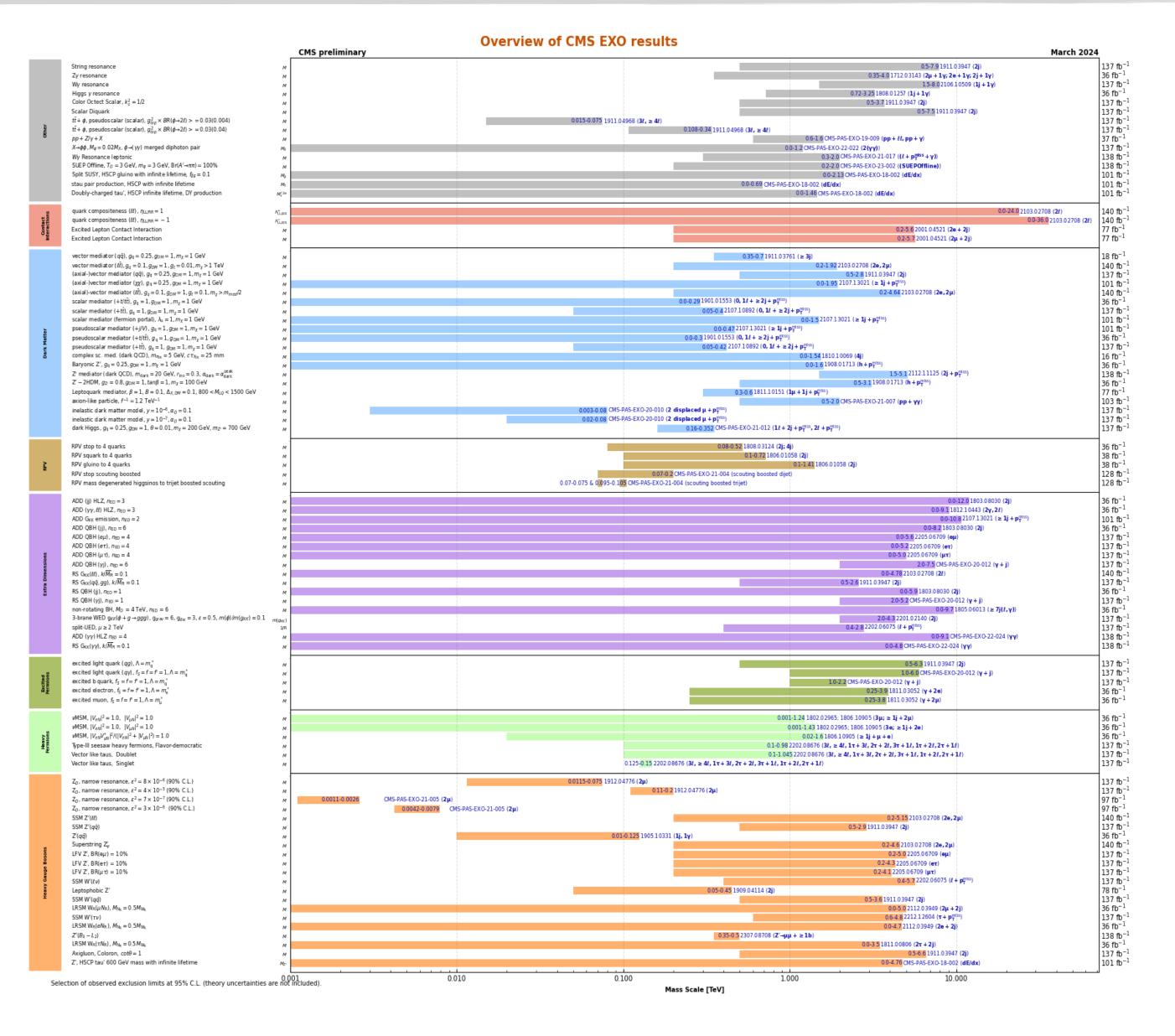
Pure higgsino

2106.09609

^{*}Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Summary: CMS EXO Searches





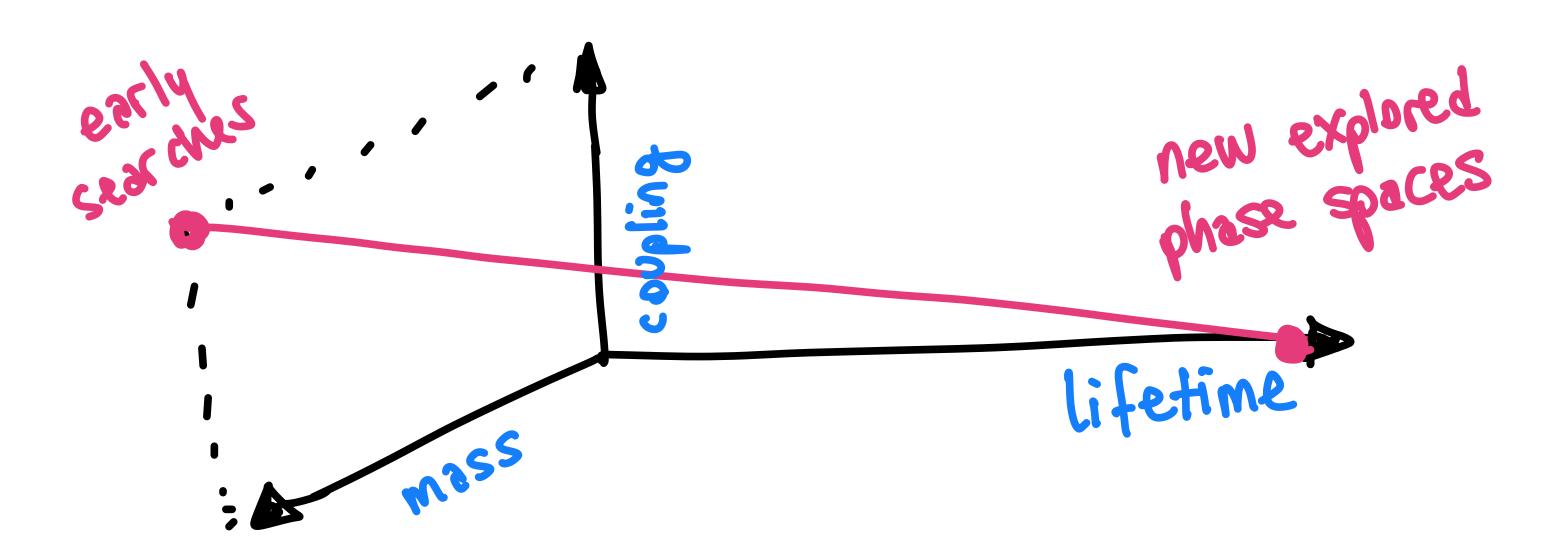
Evolution of BSM searches at the LHC

- Multiple limits (+ several 2-3 σ tensions spread across the board)
- Beginning of the LHC: low-hanging fruits (high mass, large coupling, low-background, prompt)
- We haven't observed anything so far → explore more challenging regimes!
- New Run-3 results, new corners of the phase-space, better tagger performances, new models and new signatures in the detector

Have we given up on finding BSM physics?



- Lower masses: difficult to trigger and to reconstruct; large SM background
- Lower couplings: benefit from increased luminosity
- Larger lifetimes: long-lived particle signatures in the detector



Heavy fermions & eq-coupled bosons

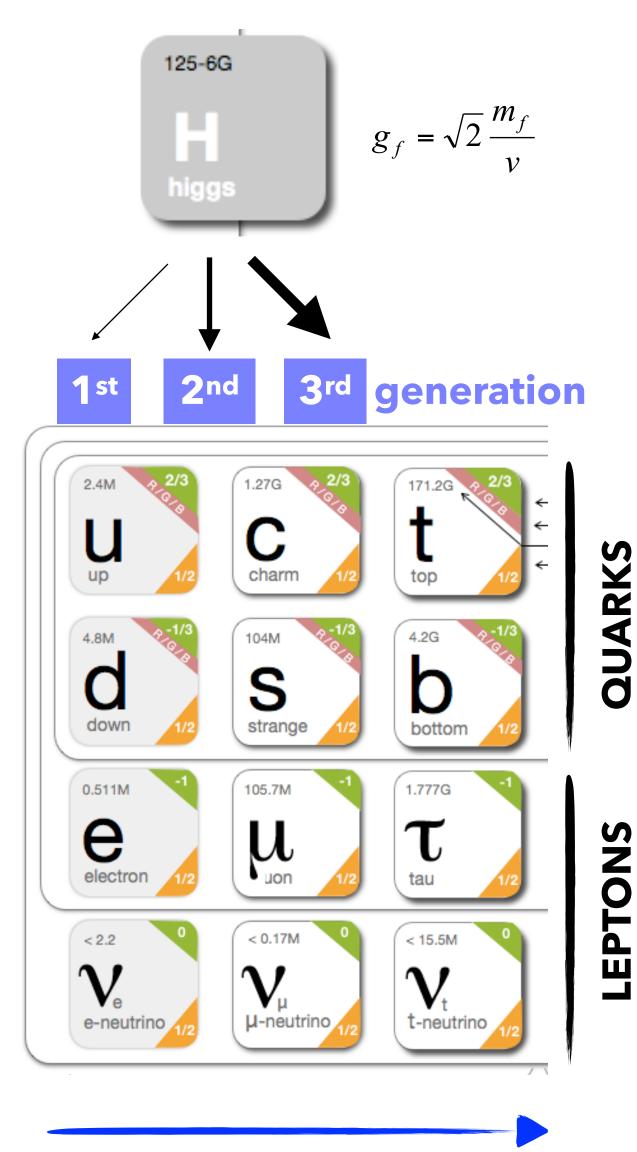
Vector-like fermions

- Hypothetical spin-½ coloured particles
- LH and RH components transform the same way under SM gauge group
- Mass not from Yukawas, evade Higgs constraints on 4th gen quarks

Leptoquarks

- Colour triplet bosons with fractional electric charge
- Carry both lepton and baryon number
- Can enable violation of lepton flavour universality

The (TH+EXP) flavour puzzle



- Why similar structure of quarks and leptons?
- Why three generations of particles?
- How do they get different masses?

Only the Higgs boson can **distinguish**between electron,
muon and tau leptons
Gives them different

masses

But... what is the underlying mechanism to do so and assign arbitrary Yukawa coupling?

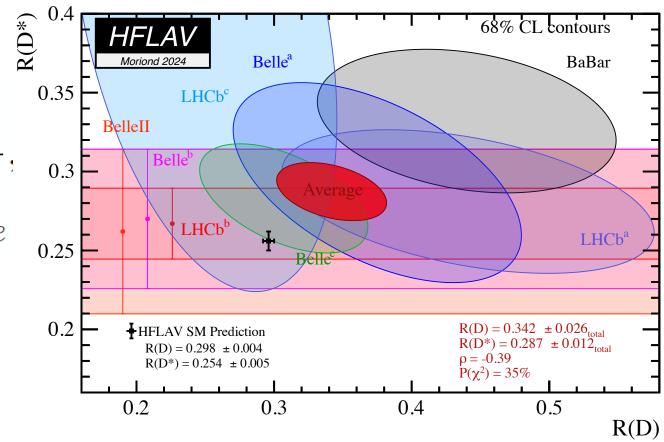
 Hints for lepton flavour universality violation observed in charged and neutral current processes in B-physics

τ vs e/ μ

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+} \tau \nu)}{\mathcal{B}(B^0 \to D^{(*)+} \ell \nu)},$$

 $\ell = \mu, e$

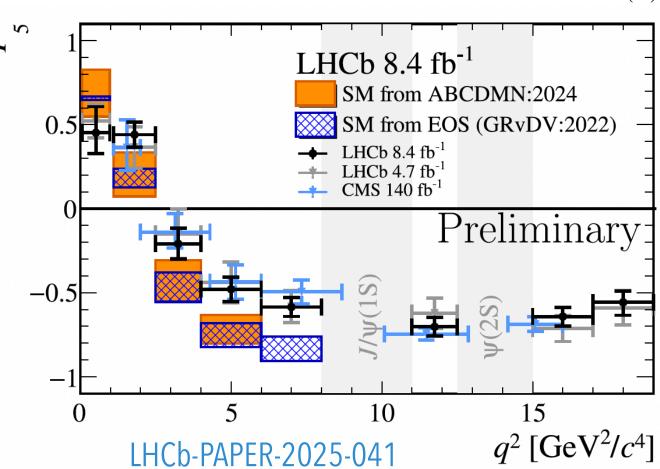
3.8 σ excess in R_D and R_{D*} combination



tensions in angular
observables and
BRs of b→sµ+µ-

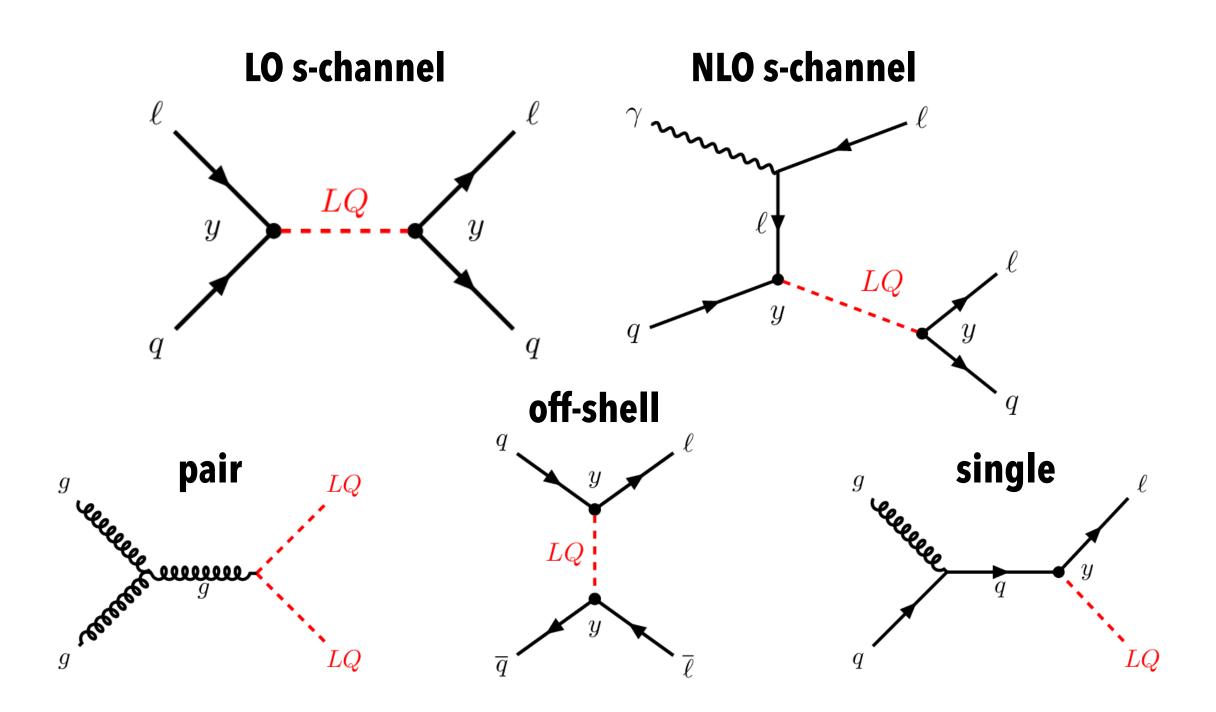
BSM physics behind flavour anomalies?
Possible R(D(*)) explanation:

leptoquarks

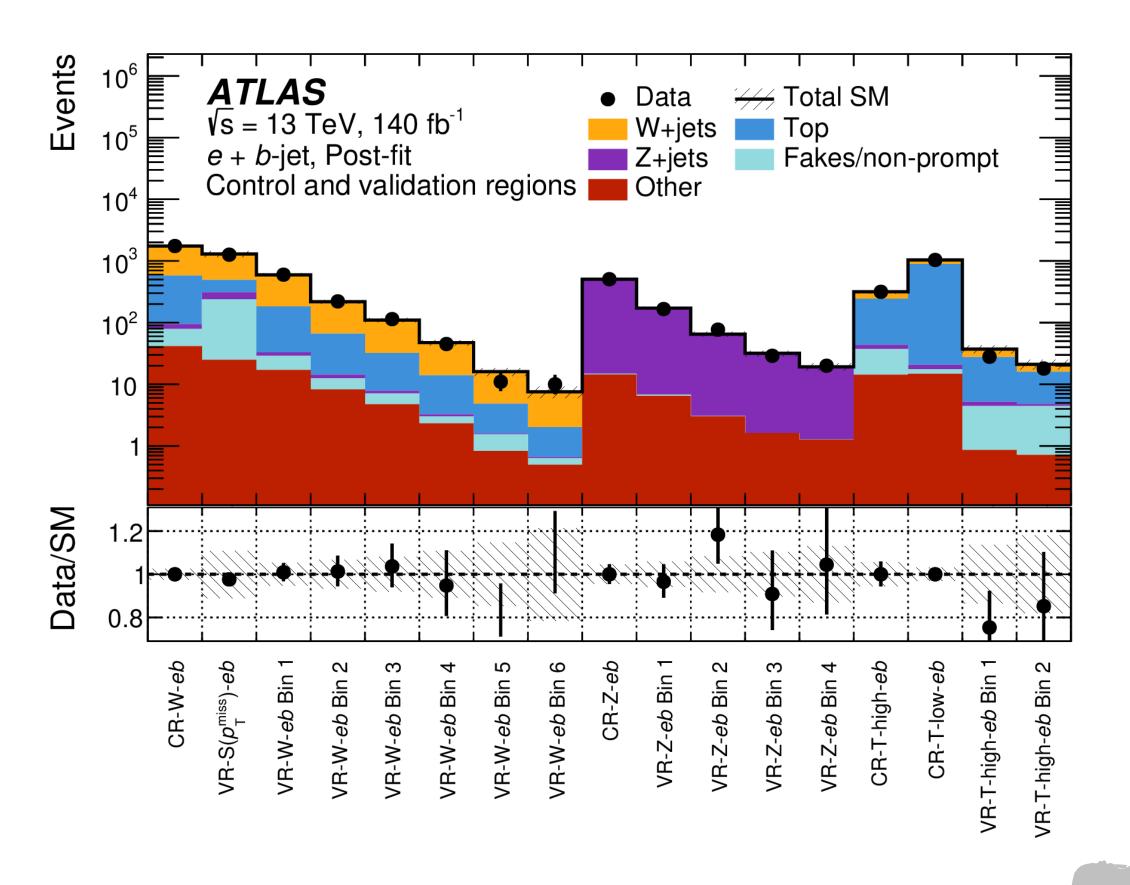




- First ATLAS search for resonant, s-channel prod. of LQs via lepton PDFs, LQ decay to 1 lepton + 1 jet
- "NLO" contributions via photon PDF motivate also targeting
 2-lepton (+jet) final states
 - Common to t-channel and single LQ production as well

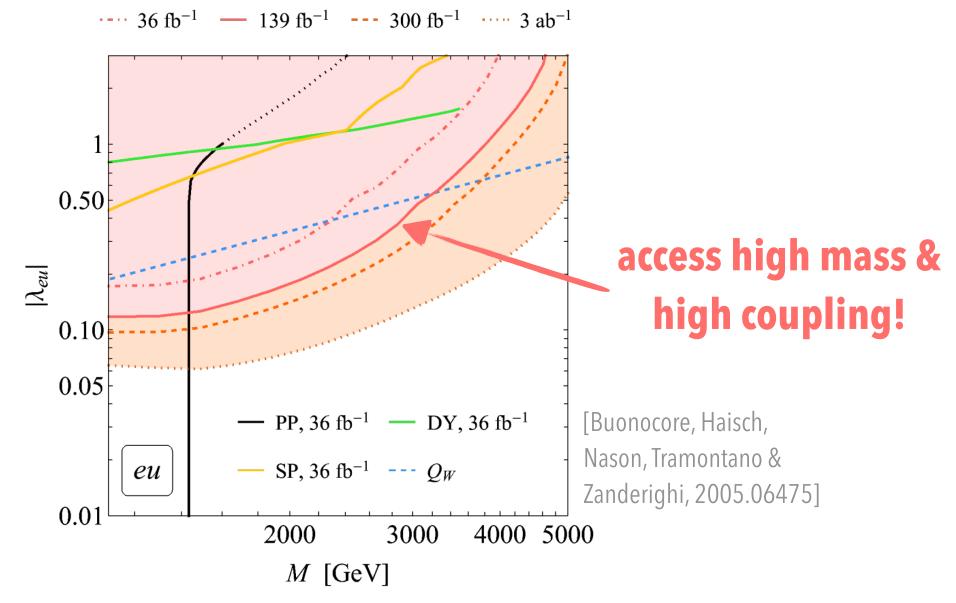


- Final states: e+light-jet, μ +light-jet, e+b-jet, μ +b-jet
- Using Run 2 (140 fb⁻¹) + partial Run 3 (55 fb⁻¹) datasets
- Fit m_{li} distributions
- tt, W+jets and Z+jets normalisation factors free-floating

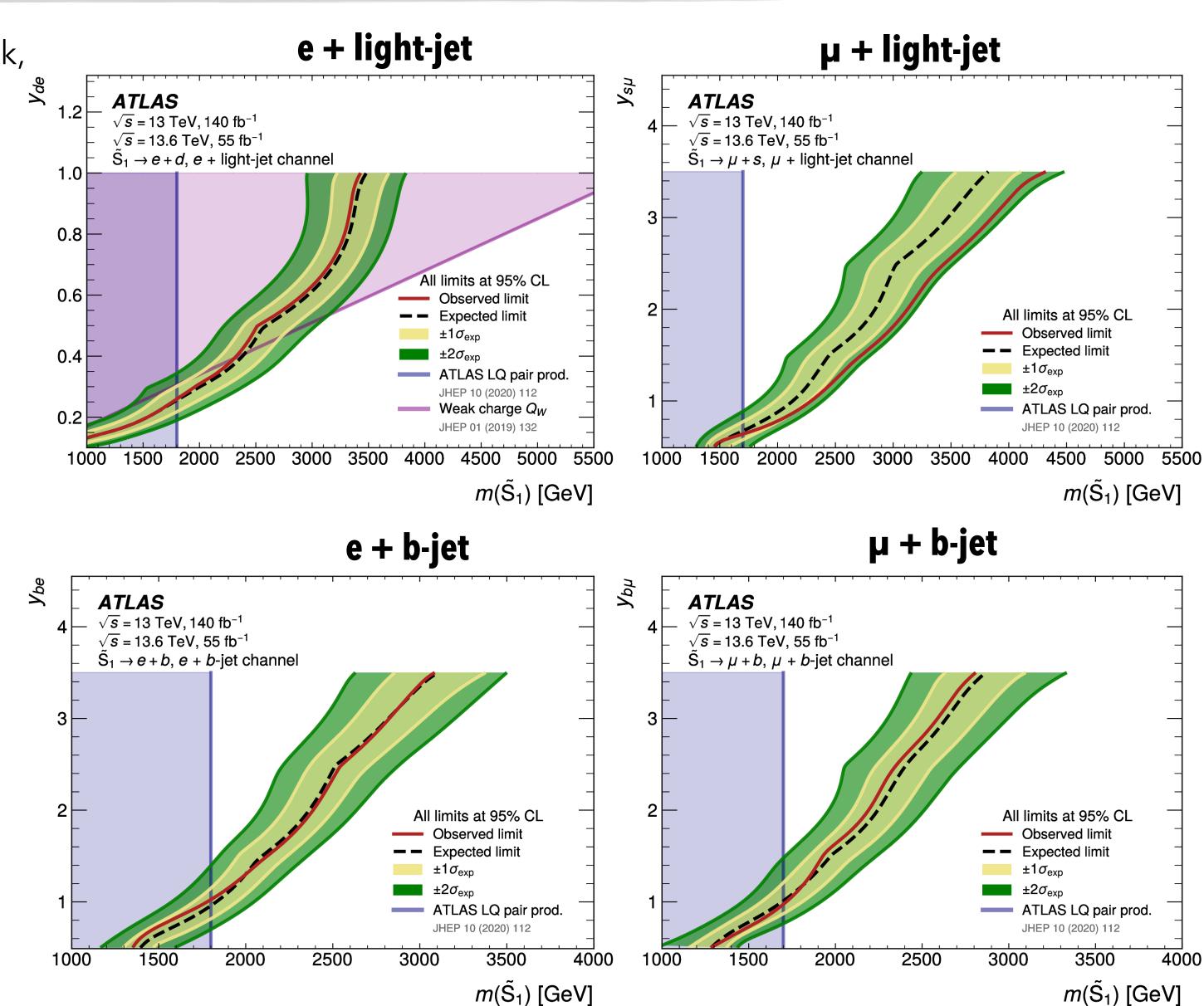




Provided Results interpreted within minimal \tilde{S}_1 -model framework, where only a single LQ coupling is non-zero

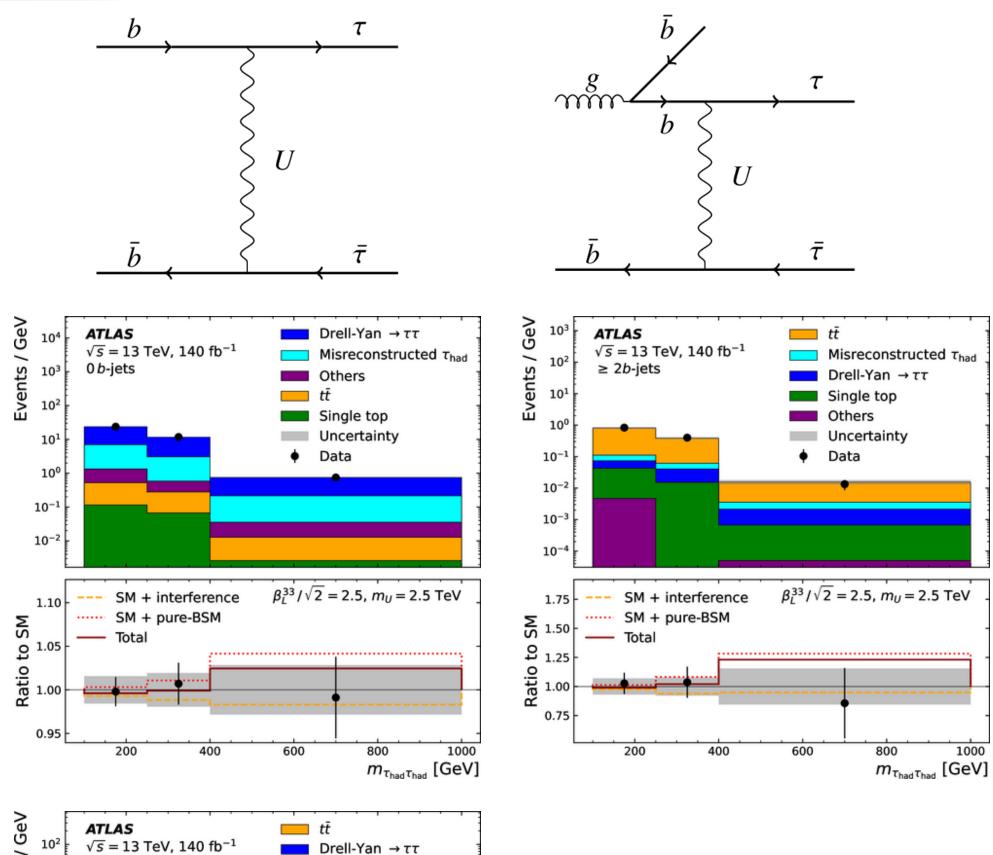


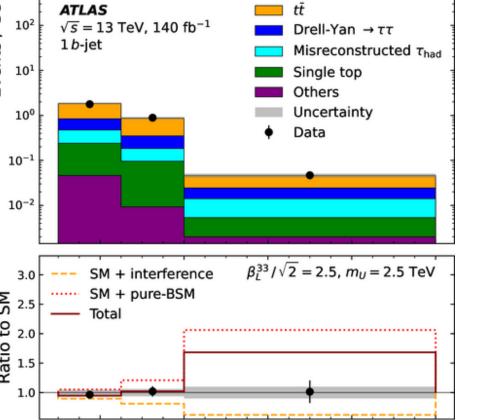
- Stringent exclusion limits on LQ masses when combining Run 2 and partial Run 3 data:
 - $m(\tilde{S}_1)$ below **3.4 TeV** (y=1.0) and **3.1 TeV** (y=3.5) excluded for e+ light-jet and e+ b-jet, respectively
 - $m(\tilde{S}_1)$ below **4.3 TeV** (y=3.5) and **2.8 TeV** (y=3.5) excluded for μ + light-jet and μ + b-jet, respectively





- Using full Run 2 dataset (140 fb⁻¹)
- Consider only the **high-mass** region ($m_{\ell\ell} > 100$ GeV) and opposite-sign $\tau_{had}\tau_{had}$ channel as signal region
 - Other channels (e τ_{had} , $\mu\tau_{had}$, e μ , same-sign $\ell\tau_{had}$) used for validation of SM background processes
- Detector-level analysis binned in (0, 1, ≥2) b-jets
- Discriminating variable: $m_{vis}(\tau\tau)$
- ullet Background processes with misreconstructed/fake $au_{
 m had}$ estimated using data-driven techniques, others from MC simulation
- Non-negligible **destructive** interference between signal and SM $Z \rightarrow \tau\tau$ estimated and included
 - **Dominates** over pure-BSM term at **low m_{\tau\tau}**





 $m_{ au_{\mathsf{had}} au_{\mathsf{had}}}$ [GeV]

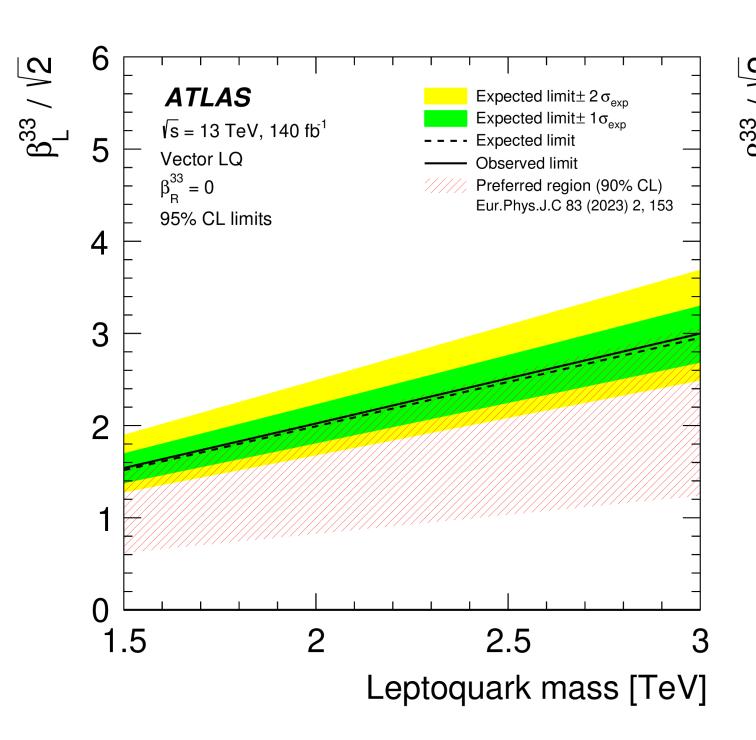
Interference scales as eta^2/m_U^2 Pure BSM as eta^4/m_U^4

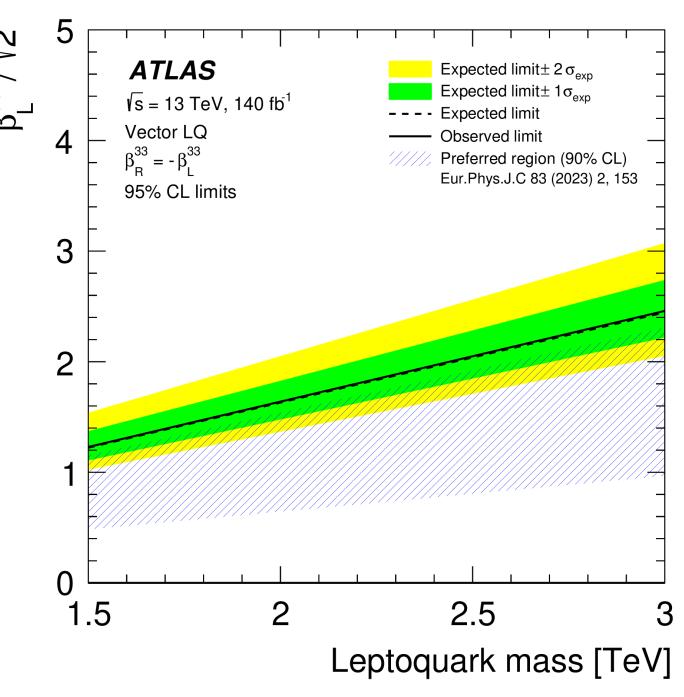


- LQ and Z' interpretation of data results
 - Also in this paper: EFT interpretation, τ anomalous magnetic moment measurement, unfolded differential measurement of $\tau\tau$ cross section
- Normalisation of tt and DY free-floating
- Vector LQ scenarios considered:

-
$$\beta_L^{33} = 1$$
, $\beta_R^{33} = 1$, $\beta_L^{33} = -\beta_R^{33}$, $\beta_L^{23} = 1$

First LQ result combining both
 interference and pure-BSM terms





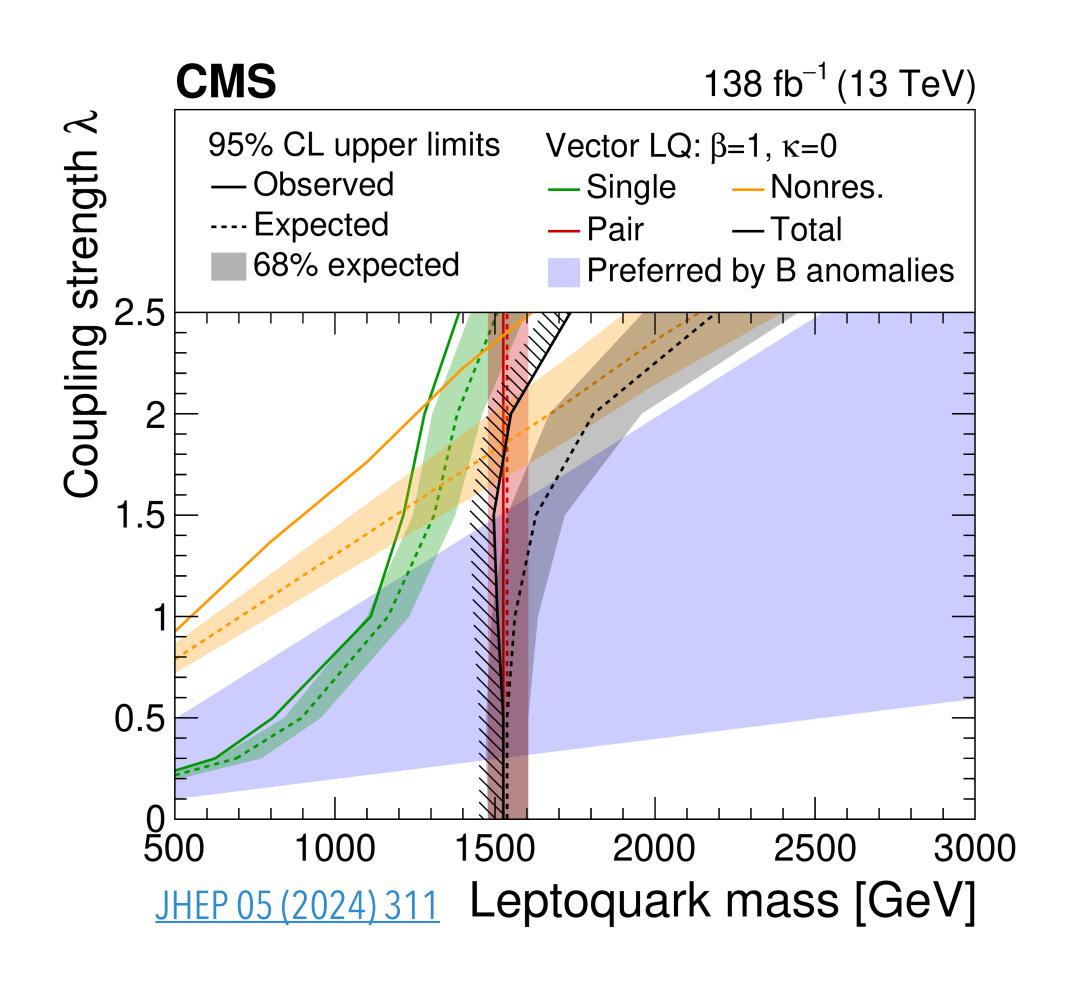
Off-shell LQ: comparison

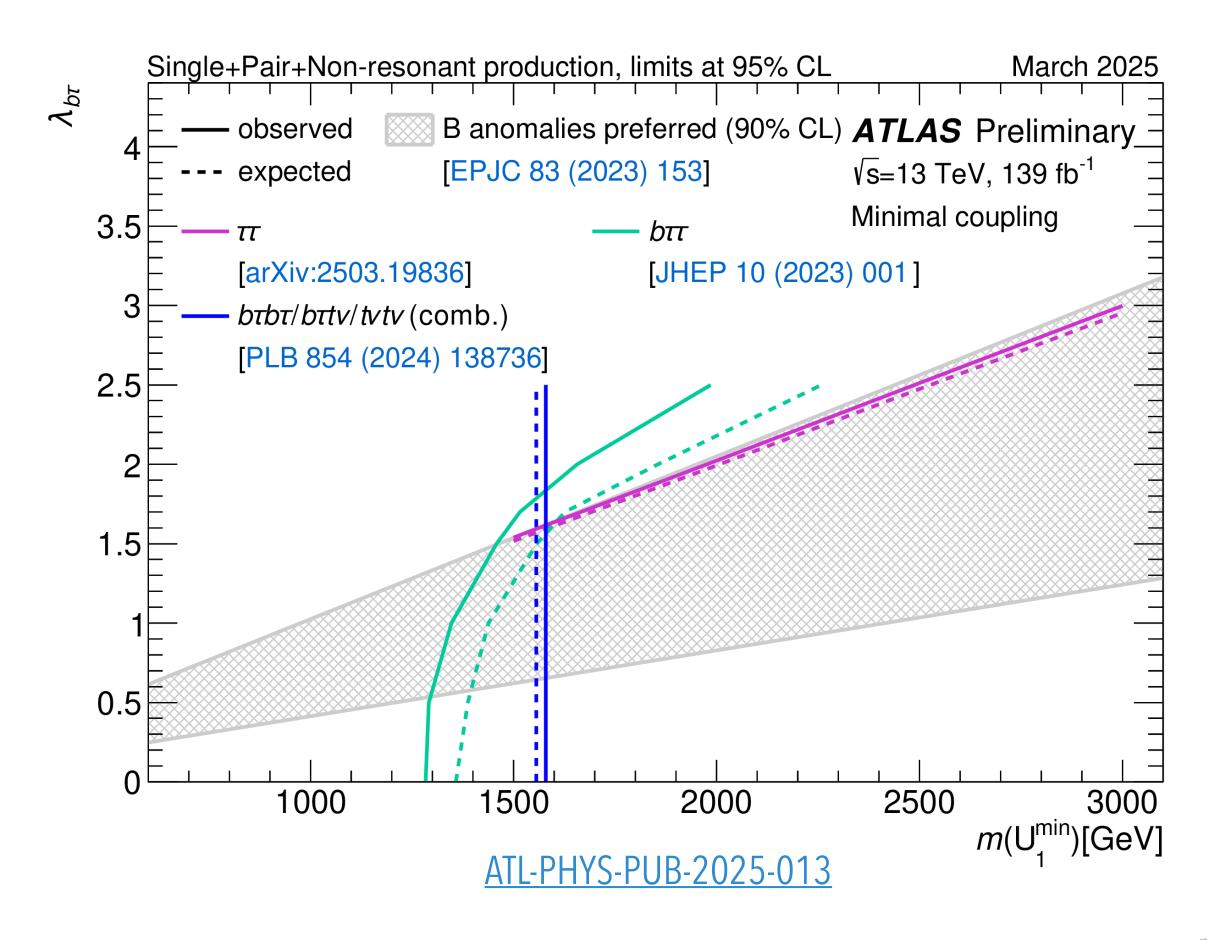






• We are becoming sensitive to the region of phase space (λ vs m_{LQ}) preferred by the B-anomalies





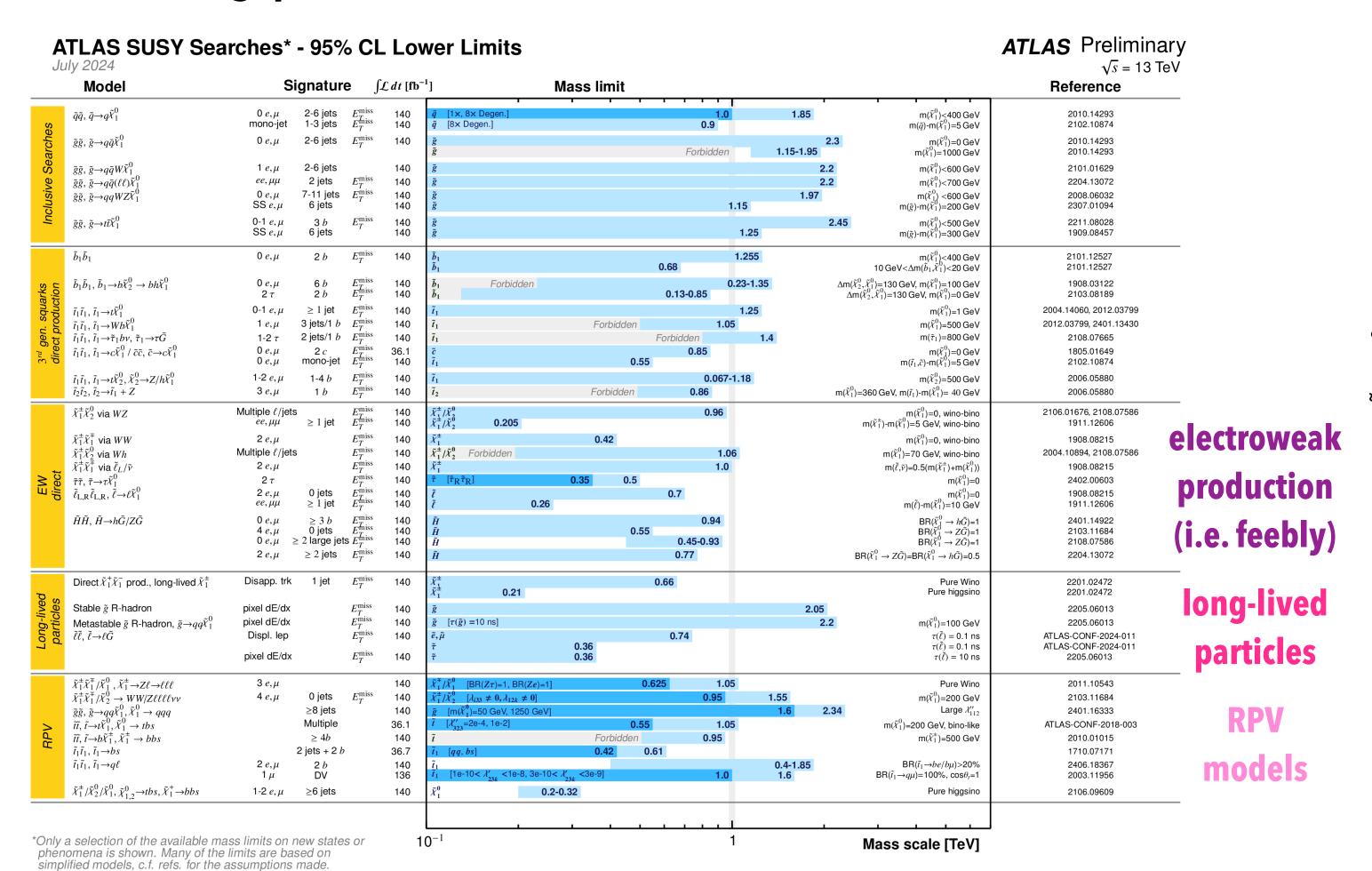
Supersymmetry

- A superpartner for every SM particle
- Fermion superpartners of the Higgs and weak gauge bosons can be WIMP dark matter
- Gauge couplings unify at a single GUT scale
- Elegant solution to the hierarchy problem

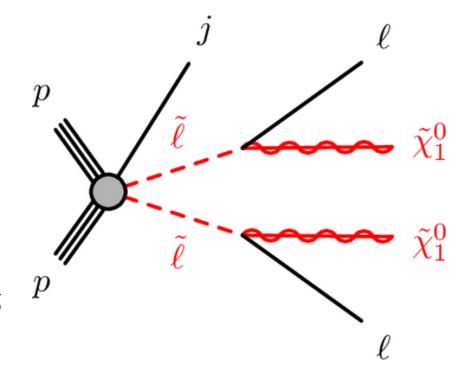
- R-parity-conserving (RPC): superpartners are pair-produced and Lightest Supersymmetric Particle (LSP) is stable \rightarrow E_T^{miss} in the final state
- **R-parity-violating (RPV):** the LSP is allowed to decay into SM particles, voiding the E_T^{miss} signature

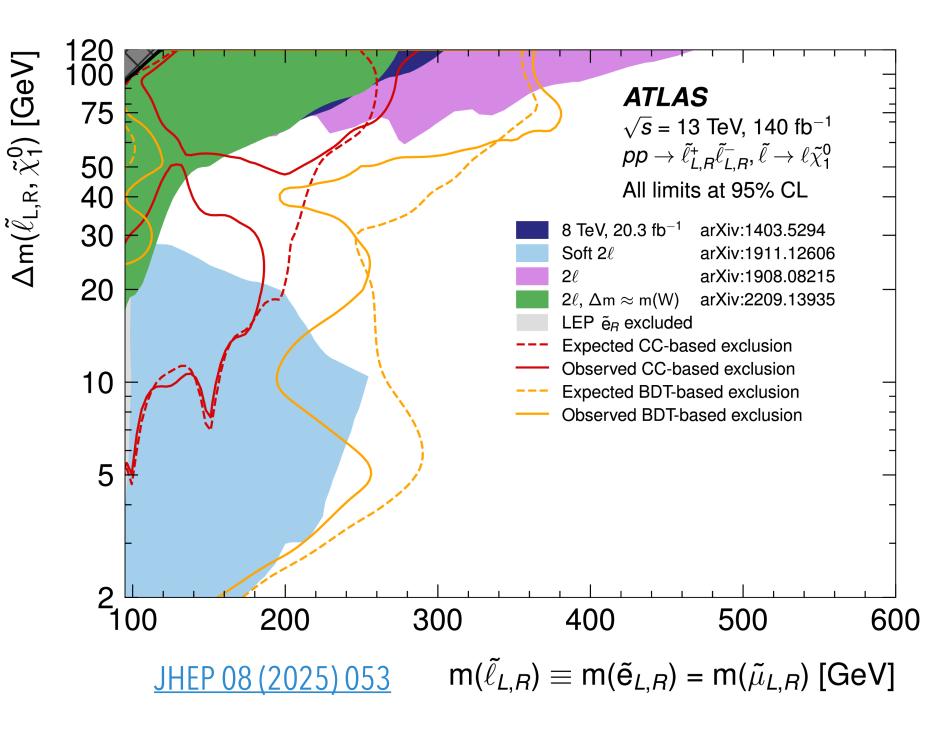
Supersymmetric: where to search?

- Stringent constraints set on many of the minimal / 'vanilla' SUSY models/particles
- Cover the uncovered (and usually more difficult!) phase space
 - Fill the gaps!



If the slepton-neutralino mass difference is **small**, searches become complicated because of **soft final-state particles**





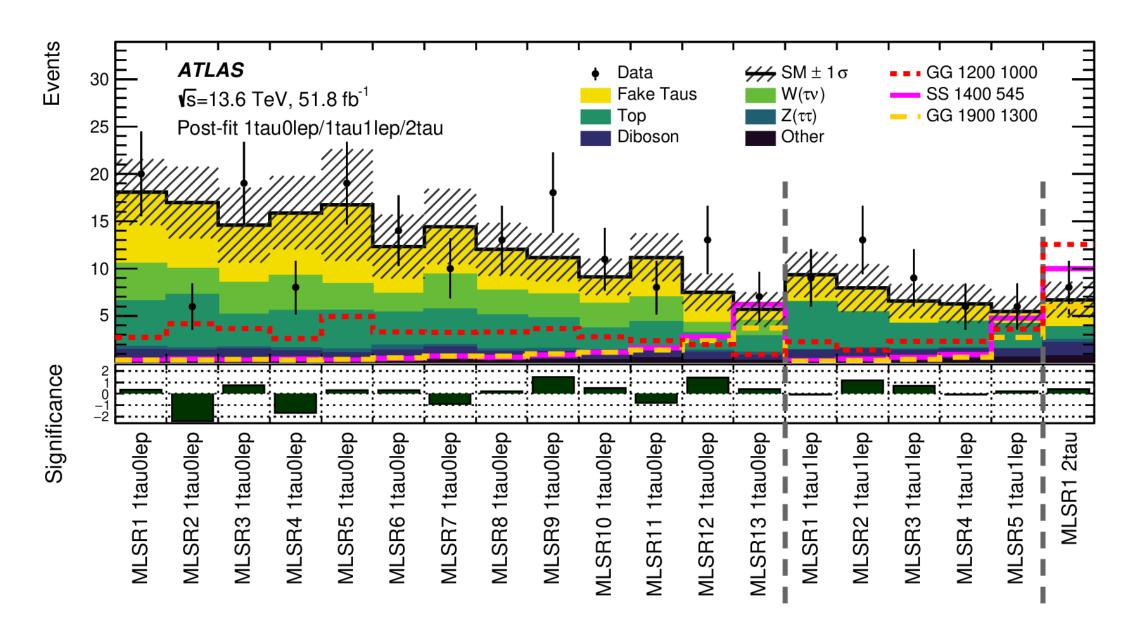
RPC squarks & gluinos: τ+E_Tmiss

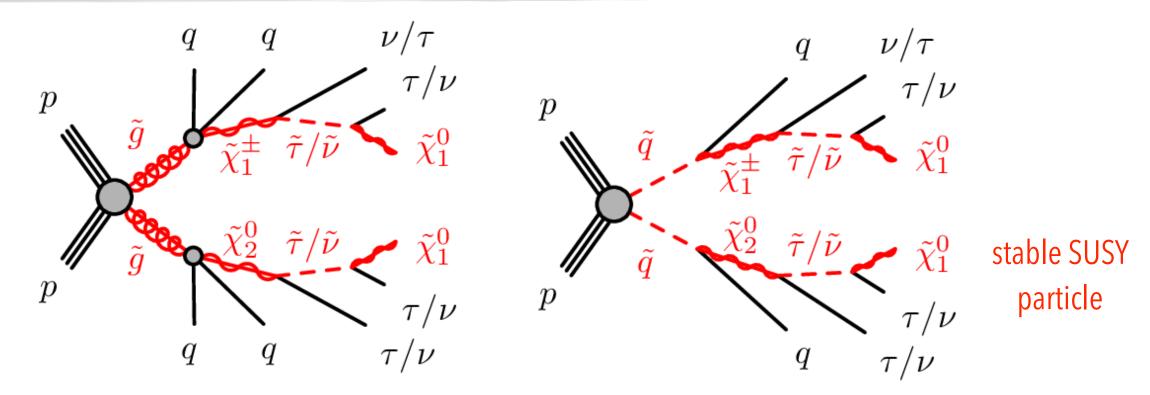
ATLAS

- Search for strongly pair produced squarks and gluinos decaying to τ , jets and E_{T}^{miss}
- Common cascade decay in MSSM
- Using Run 2 (140 fb $^{-1}$) + partial Run 3 (51.8 fb $^{-1}$) datasets
- Events selected with E_Tmiss triggers

Machine-Learning based:

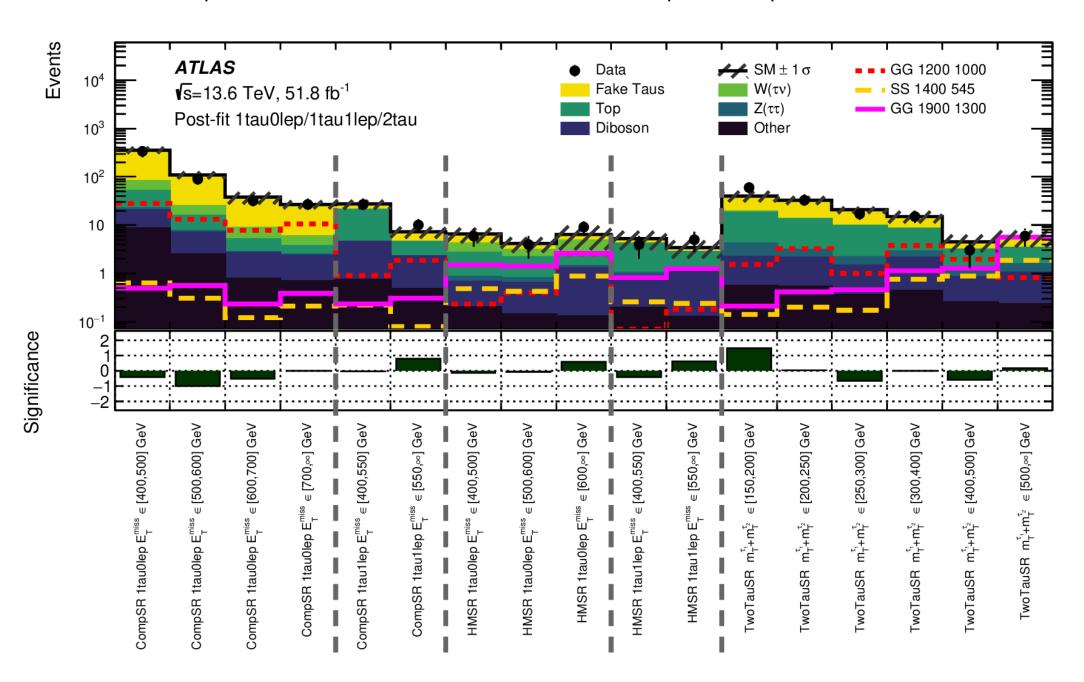
- Regions defined with multiclass-classifier
- Channels: $1\tau 0\ell$, $1\tau 1\ell$, $2\tau 0\ell$





Cut-and-count based:

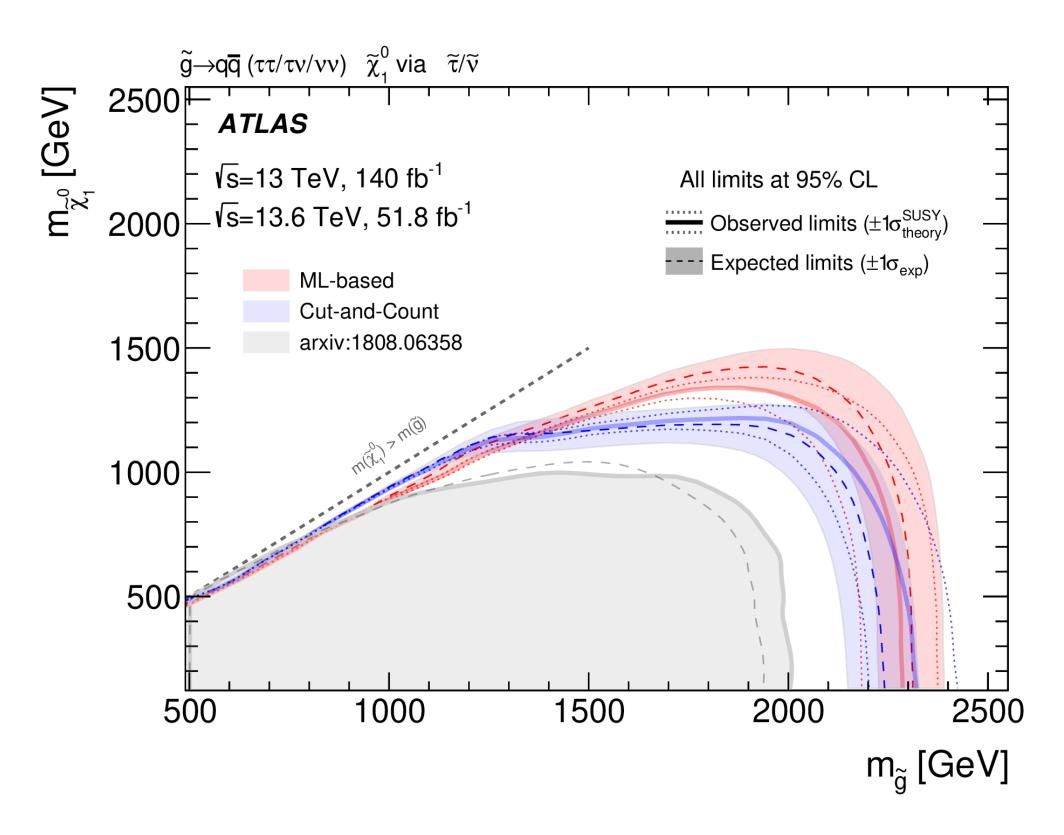
- 1τ compressed, 1τ high mass, 2τ high-mass
- E_{T}^{miss} fitted in 1τ SRs and $m_{T}^{\tau 1} + m_{T}^{\tau 2}$ in 2τ SRs

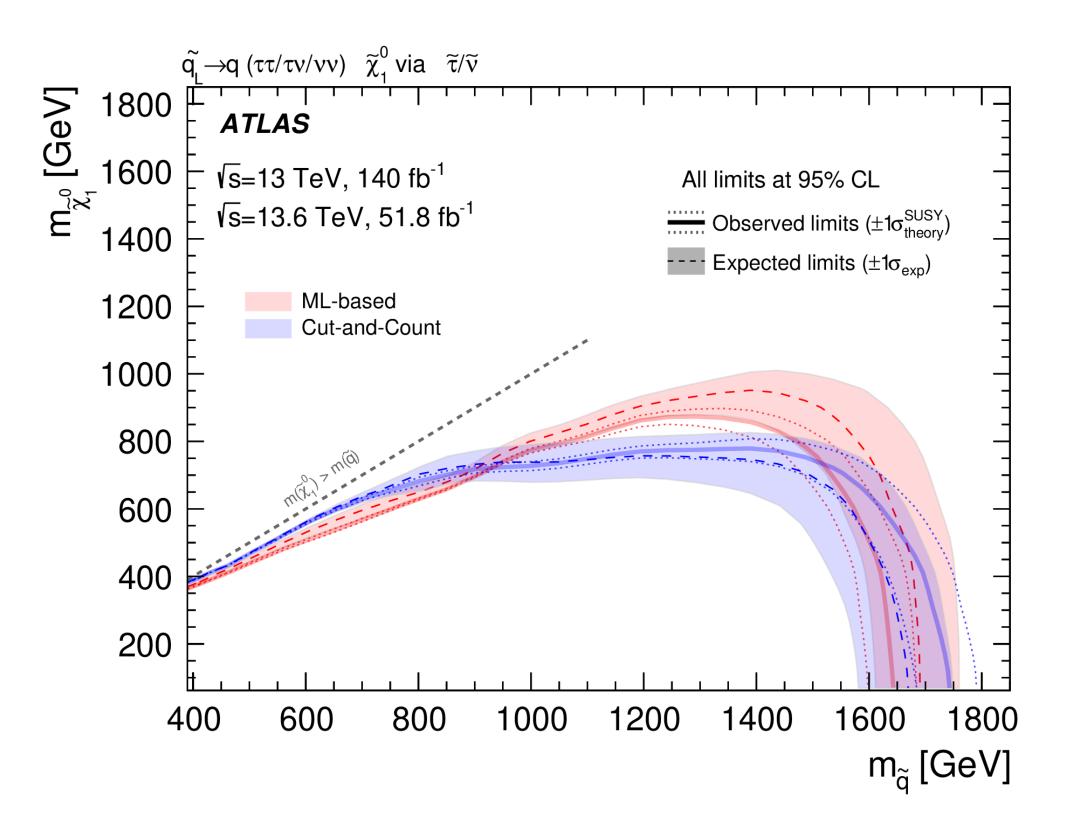


RPC squarks & gluinos: τ+E_Tmiss



- For gluino pair production models, gluino masses excluded below 2.25 GeV, and LSP masses excluded below 1.35 TeV for gluino masses around 2 TeV
- For squark pair production models, squark masses excluded up to 1.7 TeV, and LSP masses up to 0.85 TeV
- The cut-and-count-based approach slightly better in **compressed** region thanks to dedicated optimised region





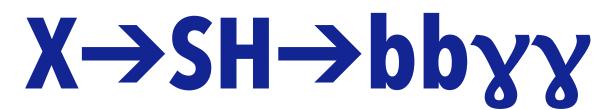
BSM (in) Higgs

Two-Higgs-doublet-model (2HDM)

- Extension of the electroweak Higgs sector by another scalar doublet
- Pheno contains a charged Higgs, a pseudoscalar and two neutral scalars, flavour-changing neutral currents, and more possibilities for CP violation and baryogenesis

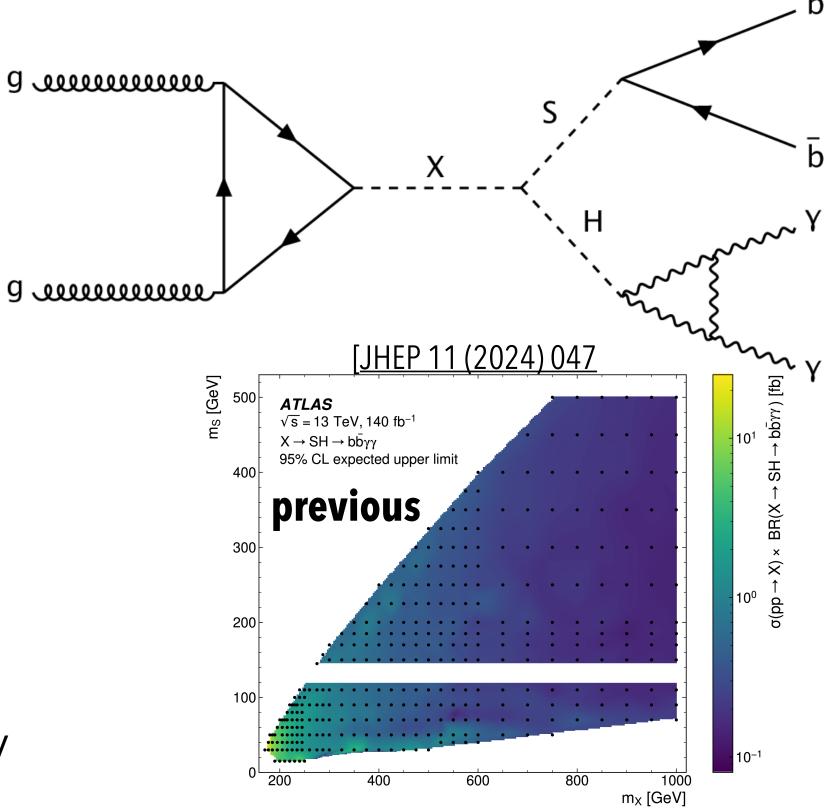
Exotic Higgs decays

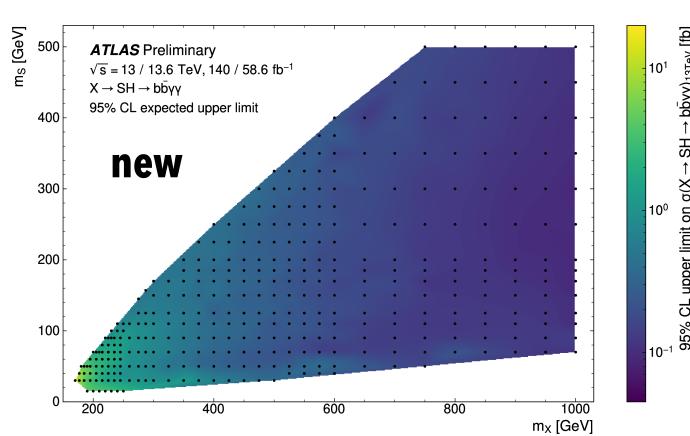
- Higgs boson decays are particularly sensitive to new physics due to the small total width
- Models predicting new light scalar(s) can lead to exotic Higgs decays, e.g.: $H \rightarrow a_1a_2 \rightarrow 4b$ or $H \rightarrow a_1a_2 \rightarrow a_1a_1a_1 \rightarrow 6b$

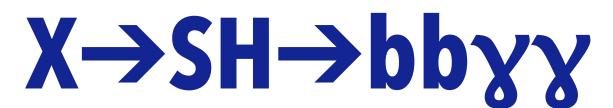




- Search for the resonant production of a heavy scalar X decaying into a SM Higgs boson and a lighter scalar S through
 X→SH→bbyy
- Using Run 2 (140 fb⁻¹) + partial Run 3 (58.6 fb⁻¹) datasets
- Main backgrounds: continuum di- γ non-resonant production and Higgs processes with H $\rightarrow \gamma \gamma$
- Main updates wrt. previous results:
 - Changing from DL1r to GN2 b-tagger
 - myy requirement changed from 120-130 GeV to 122.5-127.5 GeV
- Two SRs based on the number of b-jets, using PNNs
- Expected limits on $\sigma_{13\,\text{TeV}}$ are 15% to 73% lower than previous result (largest improvements on low-mass region)
- Inclusion of early Run 3 dataset improves sensitivity by 9-30%

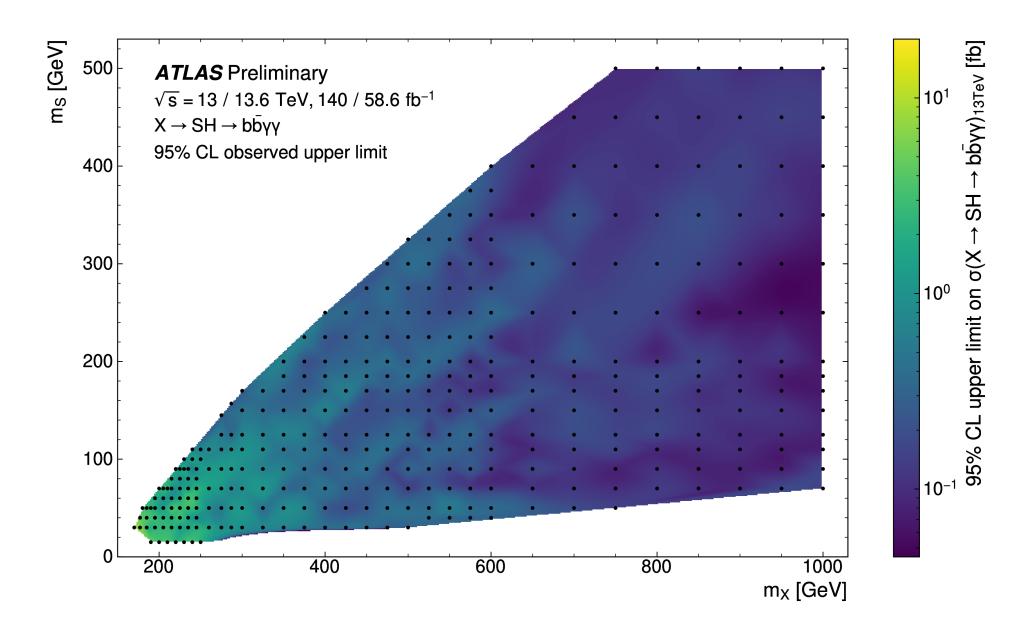


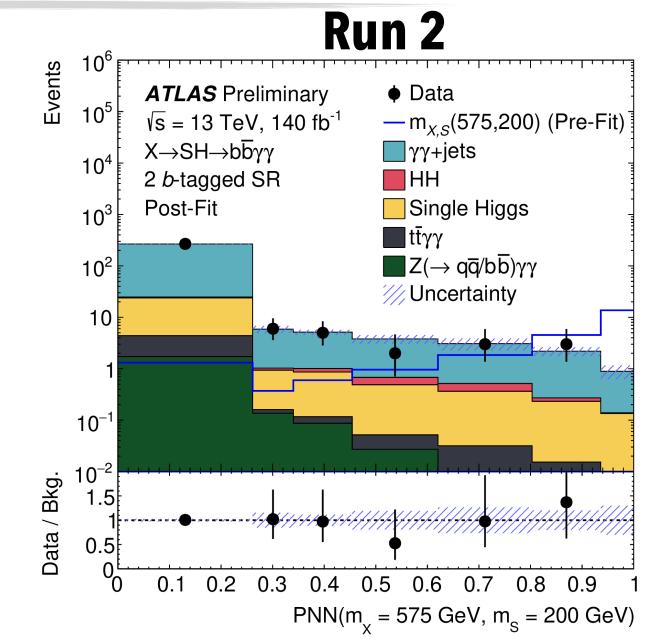


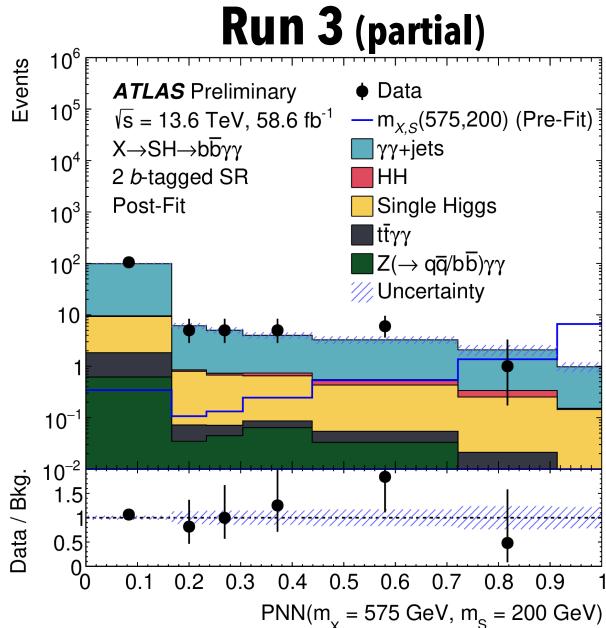




- Largest deviation from the B-only hypothesis from previous results:
 - ATLAS [JHEP 11 (2024) 047]: $(m_X, m_S) = (575, 200)$ GeV with a local (global) significance of 3.5 (2.0) σ
 - CMS [JHEP 05 (2024) 316]: $(m_X, m_S) = (650, 90)$ GeV with a local (global) significance of 3.8 (2.8) σ
- No similar deviation as previous ATLAS result, neither in Run 2 nor Run 2 + Run 3







Dark Sector

Dark Higgs model

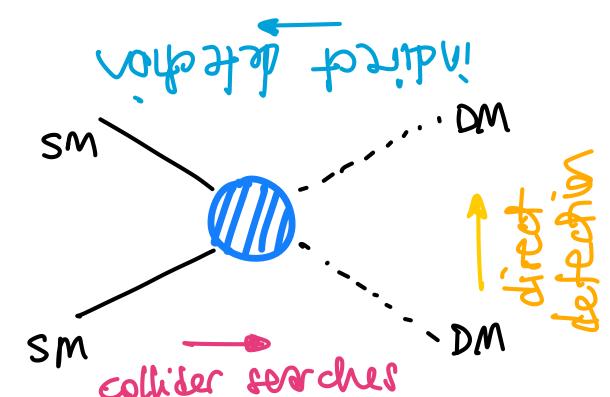
- Naturally satisfies observed relic density
- Massive dark matter (DM) and Z' from dark sector Higgs mechanism

Dark Photon

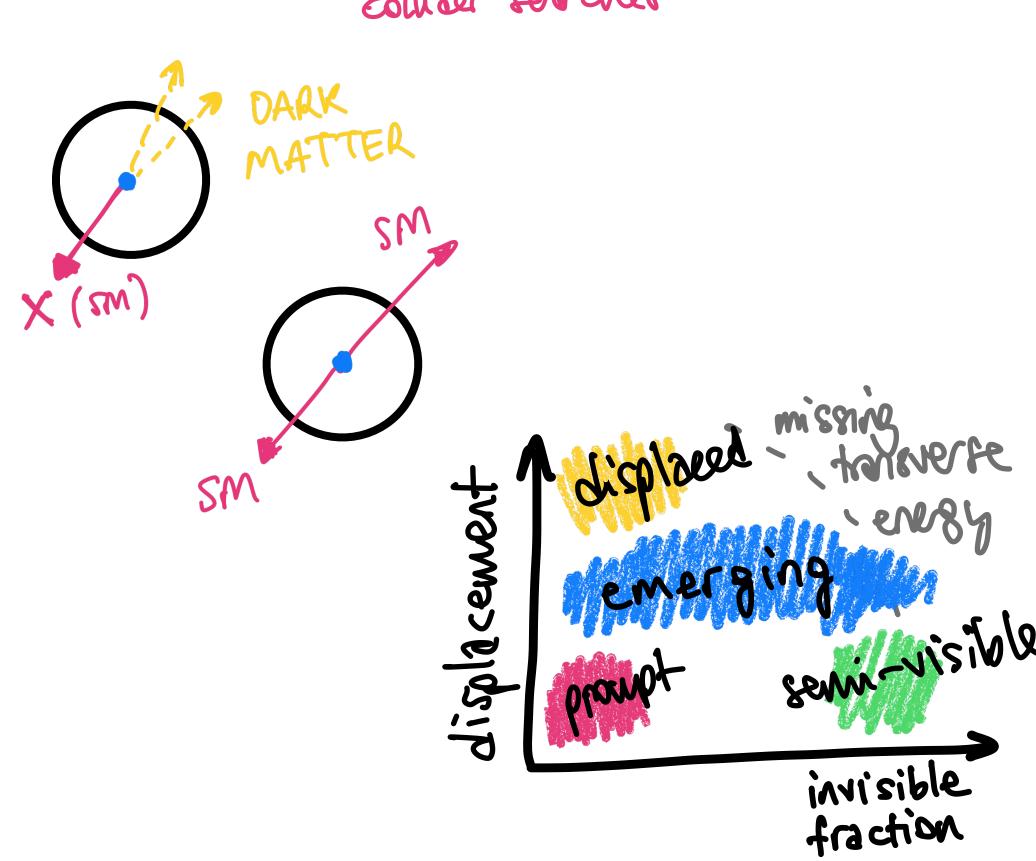
- Z_D, mediator of a broken dark U(1) gauge theory that kinetically mixes with SM hypercharge
- If the dark U(1) is broken by a hidden-sector Higgs mechanism, then mixing between dark and SM Higgs bosons also allows the exotic decay $h \rightarrow Z_D Z_D$

How to search for DM at colliders

- Three main approaches to detect DM:
 - DM-nucleus scattering (direct detection)
 - Annihilation (indirect detection)
 - Pair production at colliders



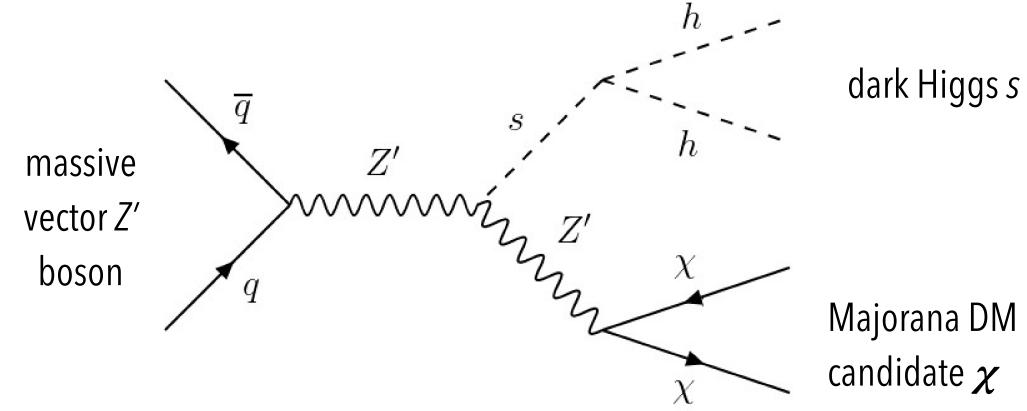
- Semi-visible final state searches: visible object(s) X
 + DM candidates E_T^{miss}
- Visible final state searches: mediator → SM
 particles (target evidence of the mediator itself, with mild dependency on the mass of the DM particle)
- Unconventional signatures: strongly interacting dark sector → Dark QCD
 - Production of dark quarks → leading to dark hadron shower = SM hadrons + stable dark hadrons (invisible DM candidate)

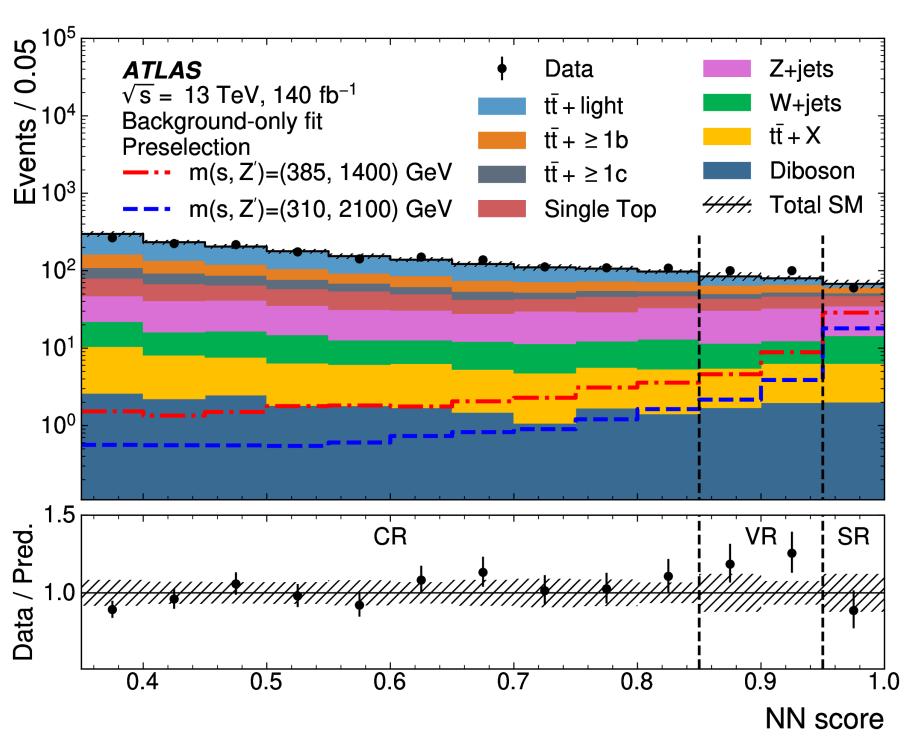


Dark Higgs, multi-b + p_Tmiss

ATLAS

- First search for resonant hh + E_Tmiss at the LHC
- Resonant topology, 4b back-to-back with p_Tmiss
 - Selections made on p_Tmiss-based variables
 - Pair b-jets to form Higgs candidates
 - Define control, validation and signal regions with NN score
- Perform fit and statistical interpretation on fully reconstructable dark Higgs mass (m_{hh} distribution)
- Normalisation factors for tt+≥1b, tt+light and Z+jets are free-floating

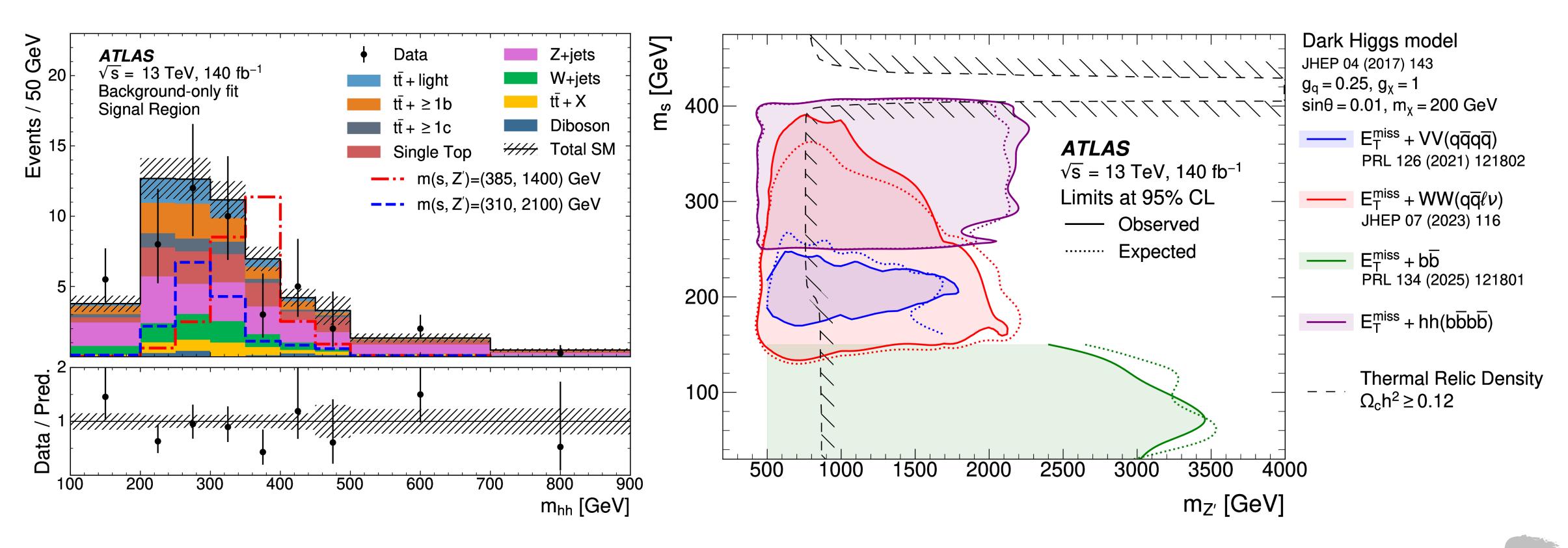




Dark Higgs, multi-b + p_Tmiss

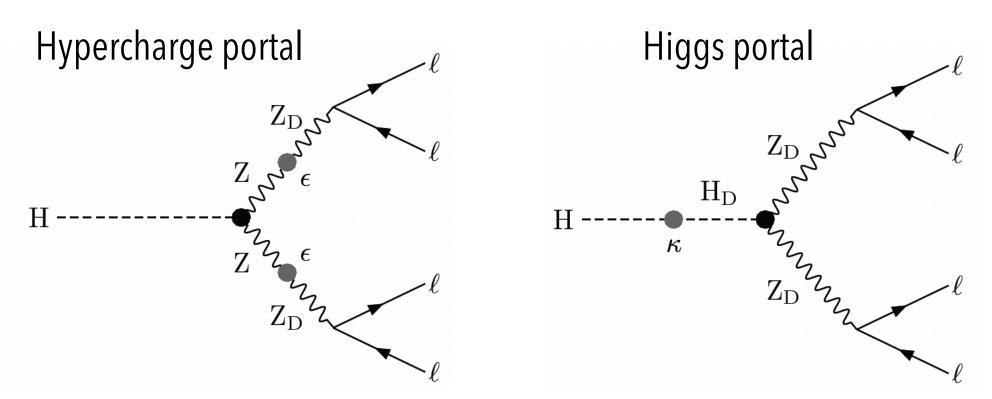


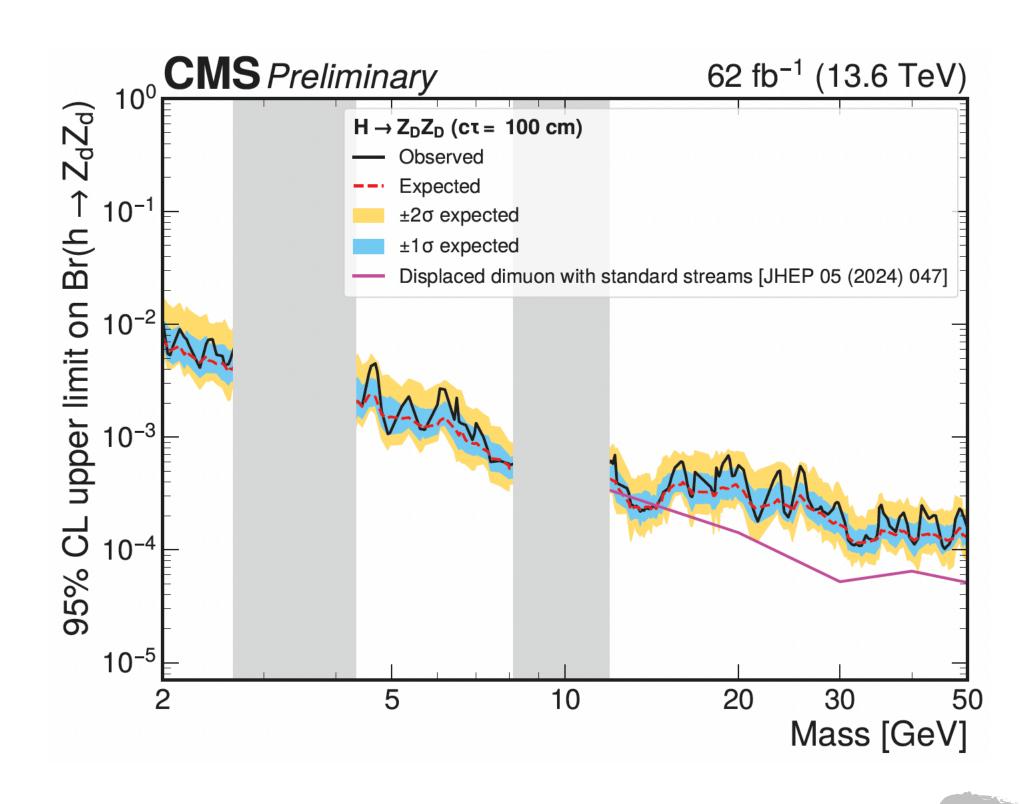
- \bullet Upper limits are derived on BSM particle masses for 250 < m_s < 400 GeV, excluding Z' masses up to 2.3 TeV
- Significantly extends existing constraints in this mass region from previous analyses
- Complement other lower-mass dark Higgs boson searches, searches for extended Higgs sectors and other collider DM searches





- Search for displaced multi-muon resonances
- BSM models where a Higgs boson decays to long-lived dark particles
 - The hidden sector may interact with SM either through **hypercharge portal**, or **Higgs portal** via a dark Higgs boson H_D
- Analysed 2022+2023 Run 3 dataset (62.6 fb⁻¹)
- Events classified in **four-muon** with overlapping vertex or multivertex, and **di-muon** with pointing or not pointing (to the secondary vertex) topologies
- Dedicated di-muon trigger stream (scouting) with low p_T thresholds, recorded at high rate by retaining reduced amount of information
 - Explore otherwise inaccessible phase space at low di-muon mass and non-zero displacement from the PV (masses below 10 GeV for the first time in a displaced muon analysis!)





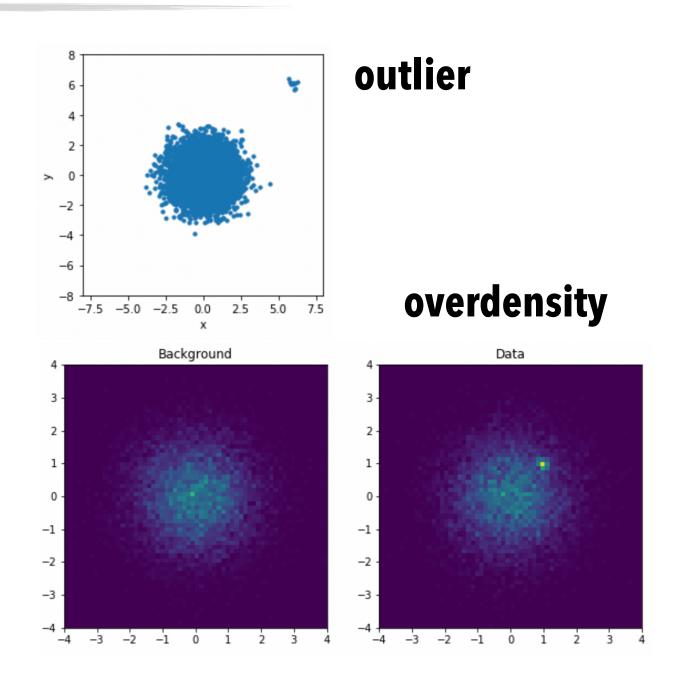
Anomaly Detection

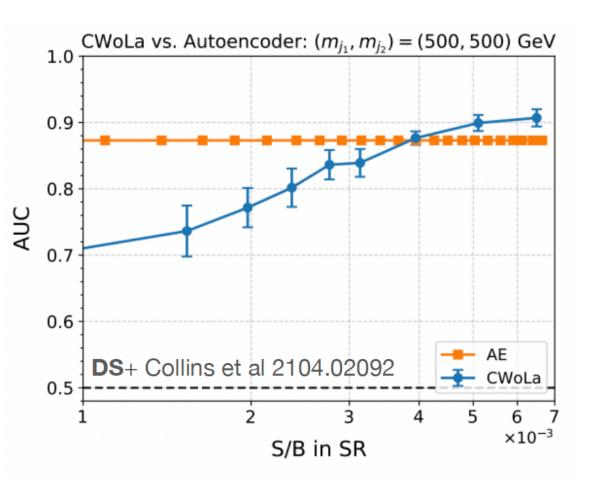
What if nature is not described by any of the available BSM models?

Be model-independent, search more broadly for signs of non-SM collisions

Are we really searching for new physics EVERYWHERE?

- Reformulate the question:
 - "Does this event look like BSM theory XYZ?", to:
 - "Does this event look like the Standard Model?"
- Use machine learning / artificial intelligence to identify anomalous objects/events
- Types of Anomalies: Outliers vs Overdensities
 - Outlier detection: detect very rare signals, but not guaranteed to be optimal
 - **Overdensity detection:** probably optimal for any unknown signal in the limit of infinite data, but performance suffers especially as signal strength decreases
 - Many proposals: CWoLa, ANODE, SALAD, CATHODE, CURTAINS, FETA, R-ANODE, ...
- Search for **resonant** (bump-hunt) or **non-resonant** anomalies
 - Most of current LHC anomaly detection results focused on resonant searches
 - Will focus on a recent ATLAS non-resonant outlier anomaly detection search





<u>David Shih, Anomaly Detection</u> <u>Topical Meeting, Sept 2025</u>



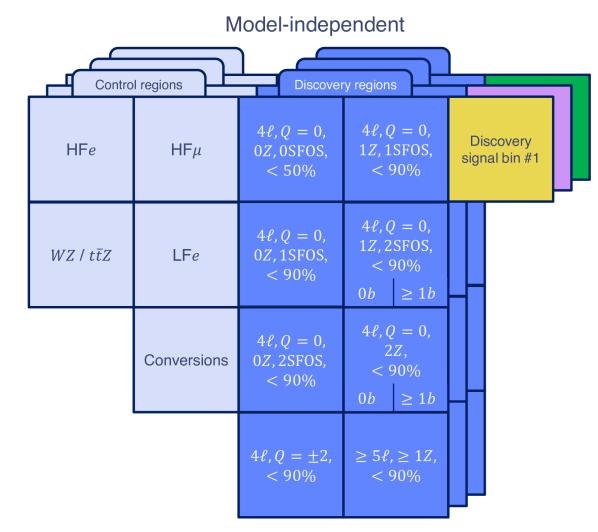
- Divide the \geq 4 lepton phase space into 4 ℓ Q=0, $Q=\pm 2$, and $\geq 5\ell$ topologies
- Use **normalising flows** as density estimators, to explicitly learn the background probability from the MC, and use it as a discriminating feature to detect outliers (anomaly score)
- Optimise two different analyses strategies exploiting the same anomaly score discriminant

- Model independent:

- Define the 50%, 90%, 99% and 99.9% background rejection points as bins
- Use the <90% bins as control regions, and >90% bins (where available) as signal bins when certain conditions satisfied, otherwise 50% bin
- Fit each discovery signal bin at a time with CRs and low-anomaly score regions to derive discovery significances and model independent limits

Model dependent:

- Use the whole anomaly score distribution as a signal region
- Further split the regions according to lepton flavour and presence of b-jets
- Fit all regions simultaneously to probe benchmark models



Each layer fitted separately.

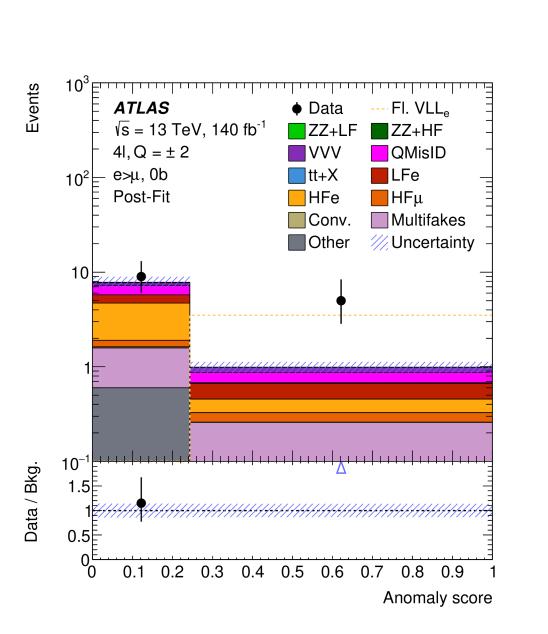
Model-dependent

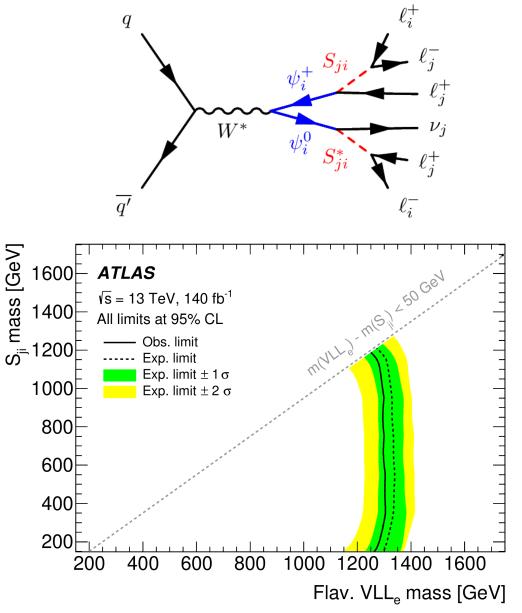
Contro	l regions	Benchm	ark regions
HFe	$HF\mu$	$4\ell, Q = 0,$ 0Z, 0SFOS	$4\ell, Q = 0,$ $1Z, 1SFOS$
WZ / tŧZ	LFe	4ℓ , $Q = 0$, $0Z$, 1SFOS	4ℓ , $Q = 0$, $1Z$, 2SFOS
	Conversions	$4\ell, Q = 0,$ 0Z, 2SFOS	$4\ell, Q = 0,$ $2Z$
		$4\ell, Q = \pm 2$	$\geq 5\ell$

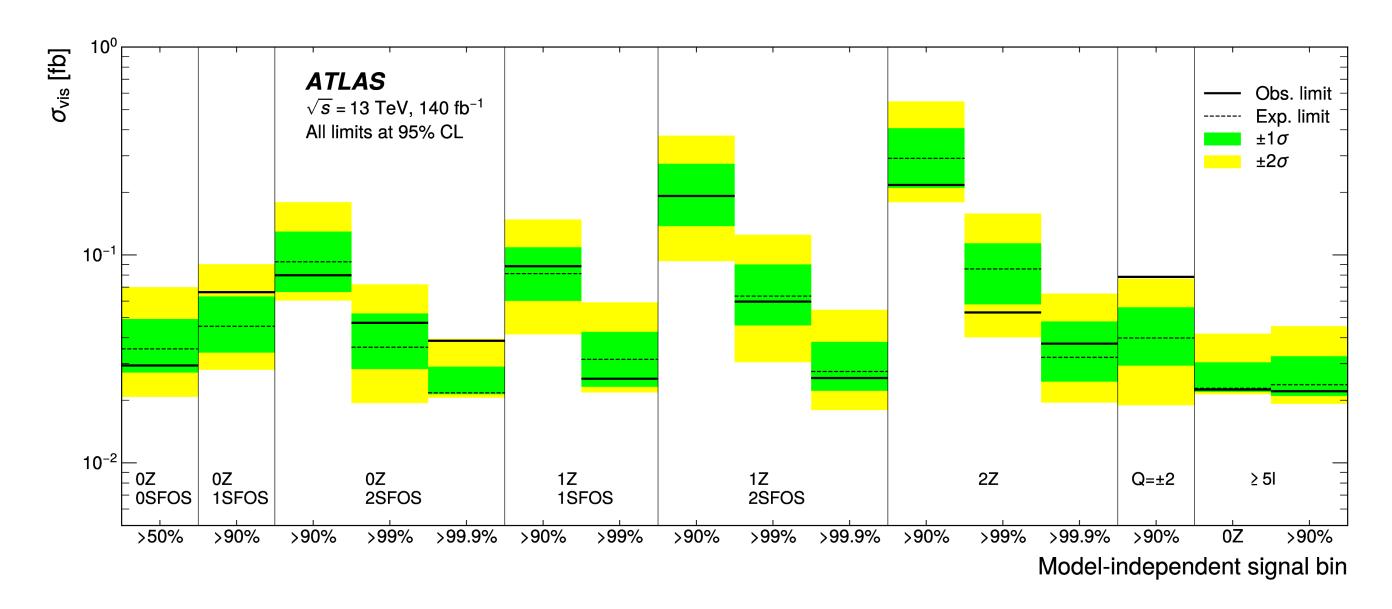
Regions further split by non-Z lepton flavour and presence of *b*-jets.

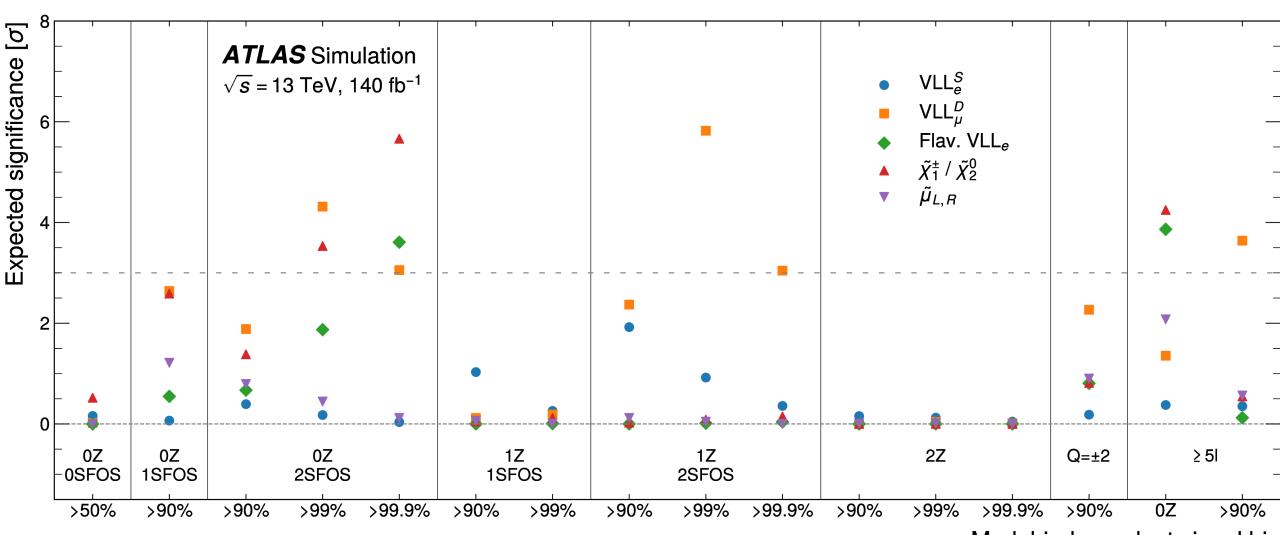


- No significant excess with respect to the SM prediction
- Competitive limits on benchmark models + model-independent limits
- LHC first exclusion limit set on the flavourful VLL model excluding up to ~1.3 (1.25) TeV for Fl. VLL e (μ)









 VLL_e^S with a mass of 200 GeV, VLL_{μ}^D with a mass of 600 GeV, flavourful VLL_e with a mass of 1200 GeV and a scalar S mass of 550 GeV, wino-like chargino with a mass of 1300 GeV and a neutralino mass of 800 GeV, and smuon with a mass of 350 GeV and a neutralino mass of 250 GeV.

Model-independent signal bin

Conclusions

- What we search for has evolved
 - Investigate **new models** (more complete, less vanilla)
 - New LQ production modes, RPV SUSY, Dark Sector ...

 Many interesting signatures to explore
 - **Search for the anomalous:** anomaly detection searches with machine learning in the rise
- We continue in discovery-mode
 - High priority to follow up with Run 3 dataset on **excesses** observed with Run 2 dataset (+ reanalysing Run 2)
 - Without disregarding **legacy** searches
- Run 3 dataset only shyly used in recent searches
 - It takes time to understand thoroughly new dataset
 - New results with partial Run 3 dataset gaining momentum!

- How we search for BSM has evolved
 - Explore uncovered phase spaces
 - Improve object reconstruction
 - **LLPs** targeted, multiple signatures in detectors
- Expect a total of Run 2 + Run 3 dataset of 500 fb-1
 - Continue being creative and engage in brainstorming with theorists about opportunities at the LHC
 - First edition of the <u>new SEARCH conference</u> series in October 2025
 - First <u>LHC BSM WG assembly meeting</u> in November 2025

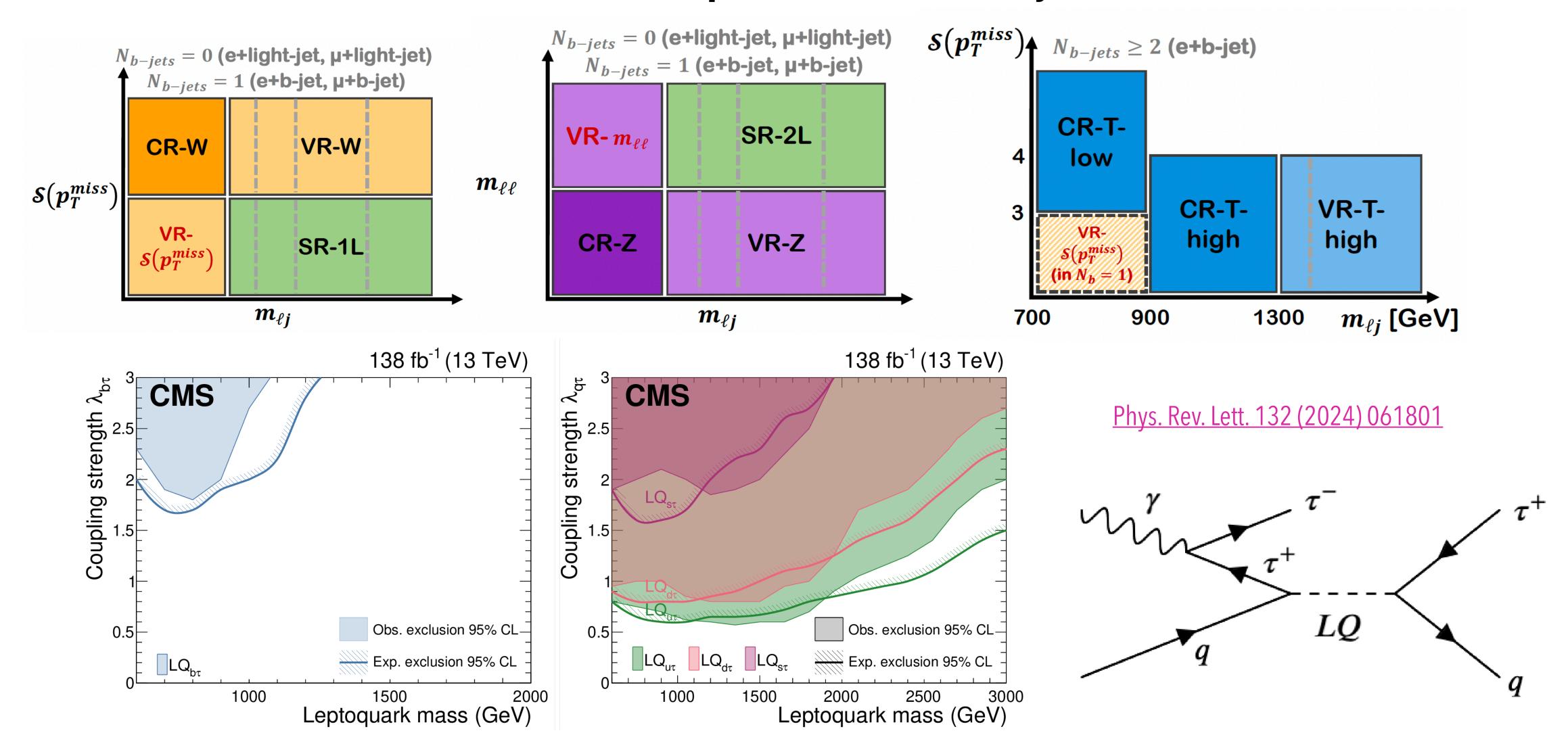
For more details on current LHC tensions and other exciting results, please see **Johannes' talk on Wednesday**!



BackUp



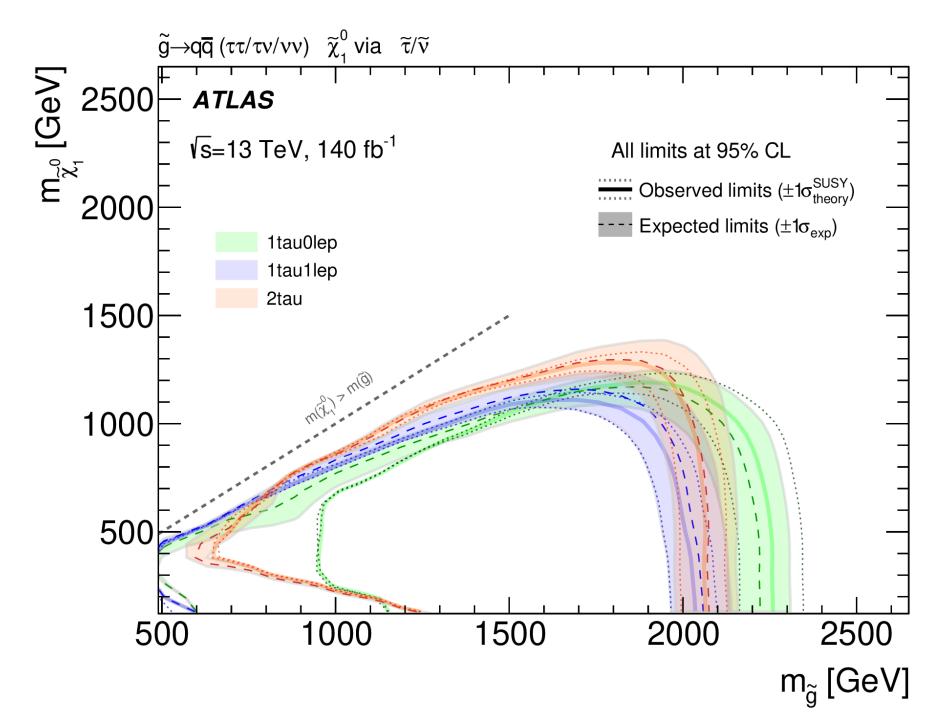
example CRs and VRs: e + b-jet

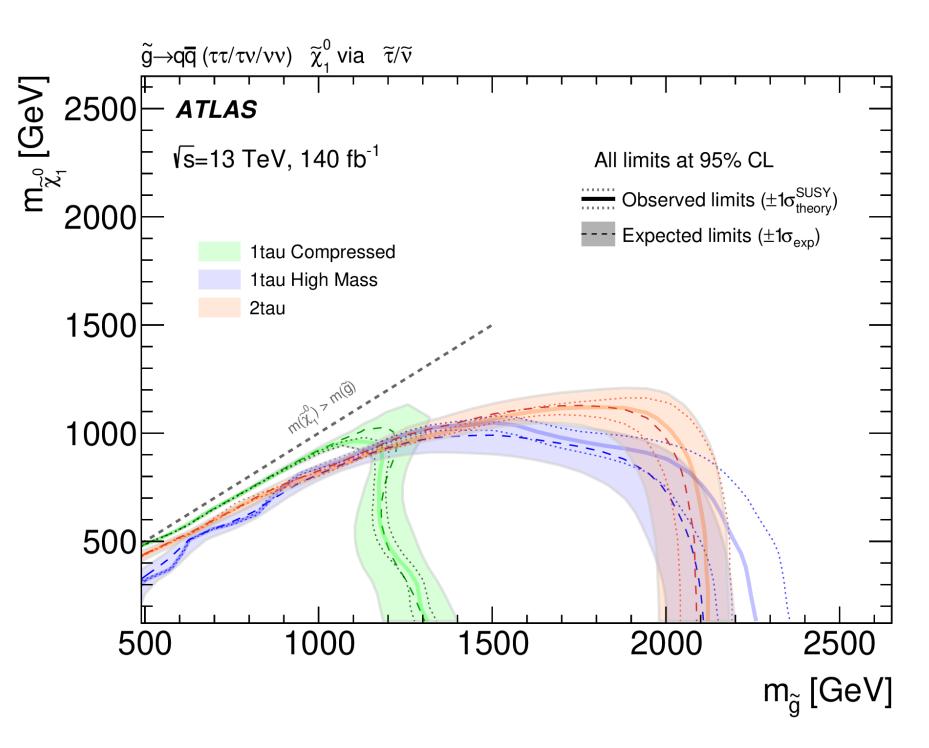


RPC squarks & gluinos: τ+E_Tmiss



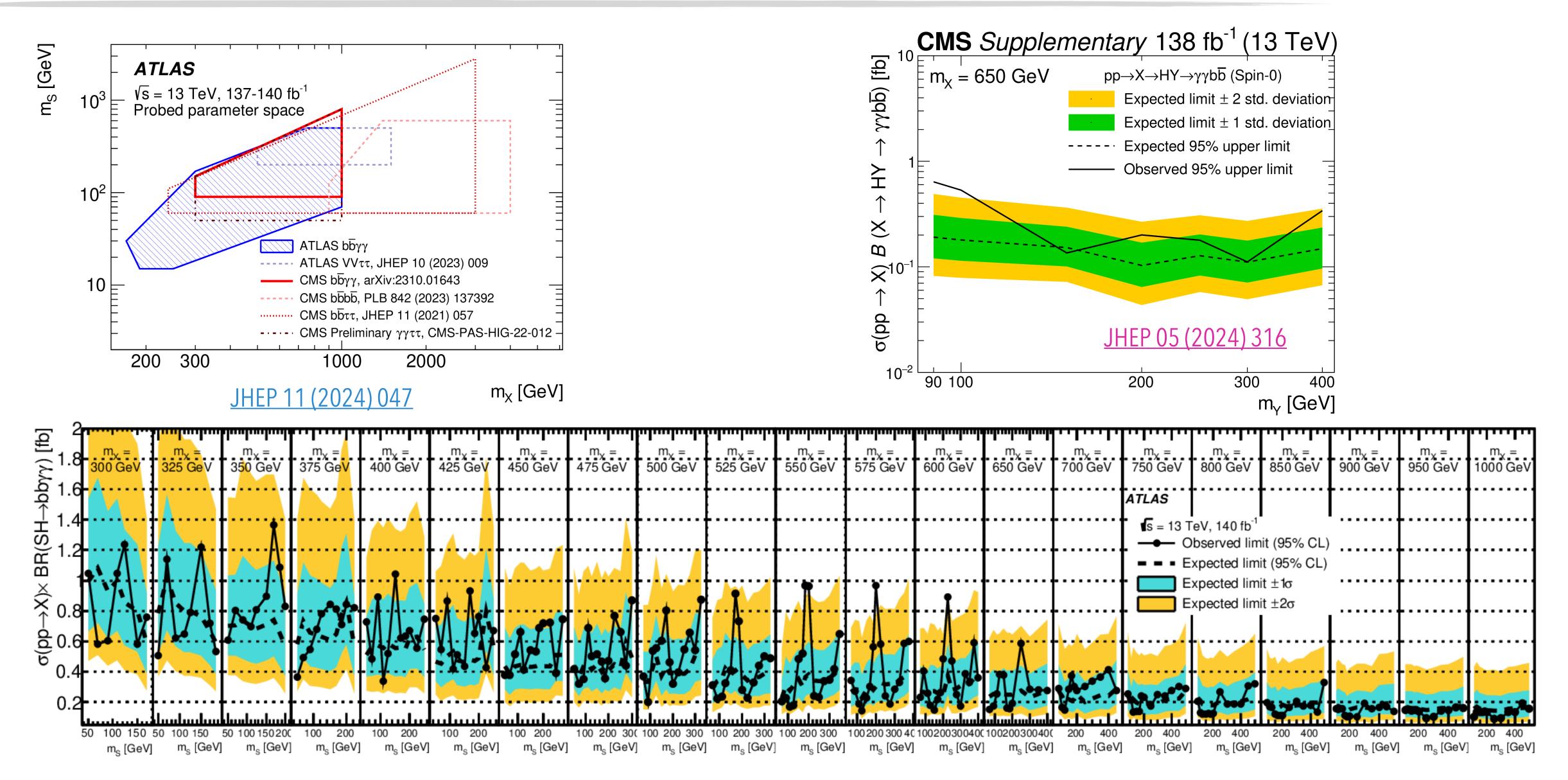
	Compre	essed SR	High M	TwoTau SR	
Channel	1tau0lep	1tau1lep	1tau0lep	1tau1lep	2таи
$N_e + N_\mu$	= 0	≥ 1	= 0	≥ 1	_
$N_{ au}$		=	1		2
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		> 4	100		> 200
$H_{\rm T}$ [GeV]		_	> 1000		> 800
$N_{ m jets}$	>	: 2	≥ 3		≥ 3
$p_{\mathrm{T}}^{\tau_1}$ [GeV]	<	45	>	45	_
$p_{\mathrm{T}}^{\tau_1}$ [GeV] $m_{\mathrm{T}}^{\tau_1}$ [GeV]	> 80	_	> 250	> 120	_
$m_{\rm T}^{\hat{\tau}_1} + m_{\rm T}^{\ell_1} \; [{\rm GeV}]$	_	> 350	_	> 350	_
$m_{\rm T}^{\tau_1} + m_{\rm T}^{\ell_1} [{\rm GeV}]$ $m_{\rm T}^{\tau_1} + m_{\rm T}^{\tau_2} [{\rm GeV}]$	_	_	_	_	> 150





$X\rightarrow SH\rightarrow bbyy$

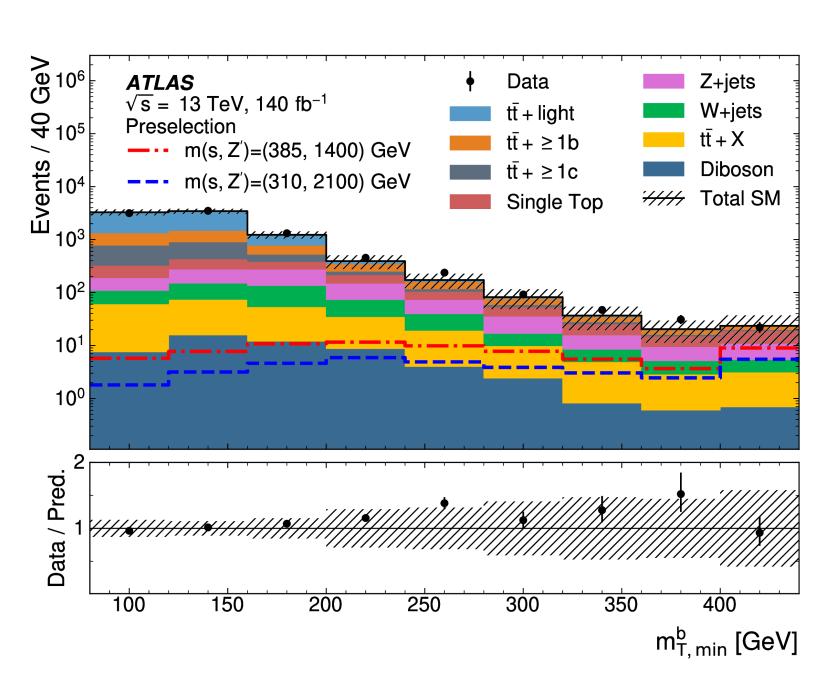


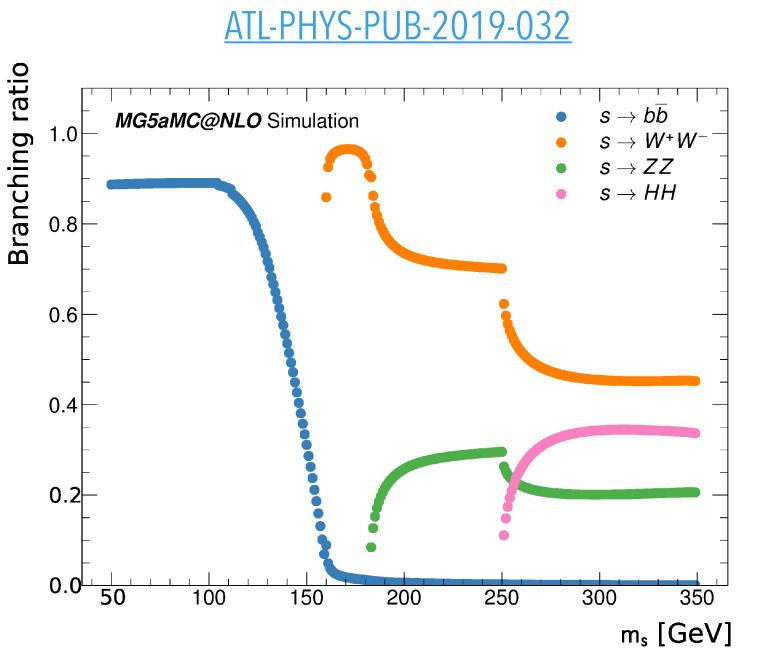


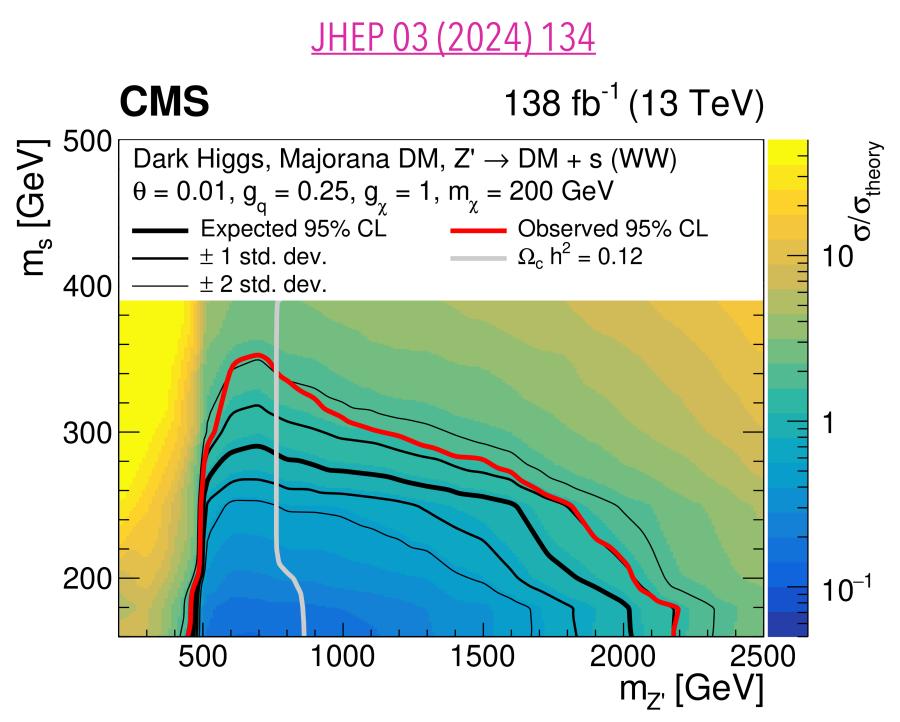
Dark Higgs, multi-b + p_Tmiss



ullet selections made on p_T^{miss}-based variables: $m_{T,min}^b$, $\Delta\phi_{min}^{4j}$ and $S(p_T^{miss})$







$$m_{\text{T,min}}^b = \min_{1 \le i \le 3} \sqrt{(p_{\text{T}}(b_i) + p_{\text{T}}^{\text{miss}})^2 - (p_{\text{x}}(b_i) + p_{\text{x}}^{\text{miss}})^2 - (p_{\text{y}}(b_i) + p_{\text{y}}^{\text{miss}})^2}$$

Dark Photon LLP to µ

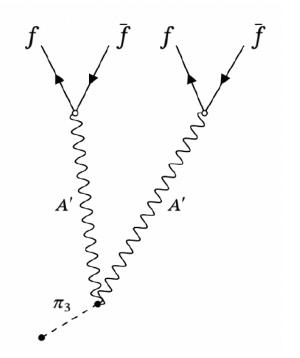


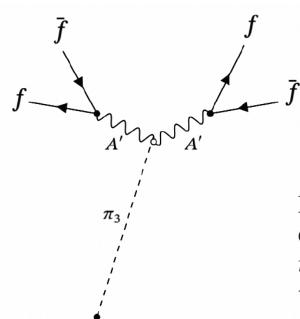
Scenario A: long-lived A'

Scenario B1: long-lived π_3

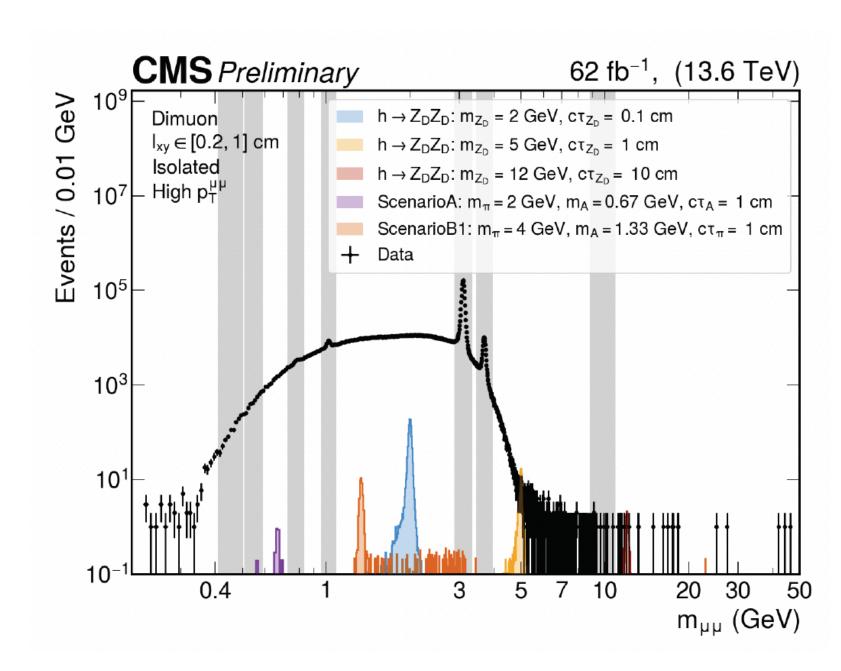
first analysis to study displaced dimuon vertices beyond 11 cm using scouting data

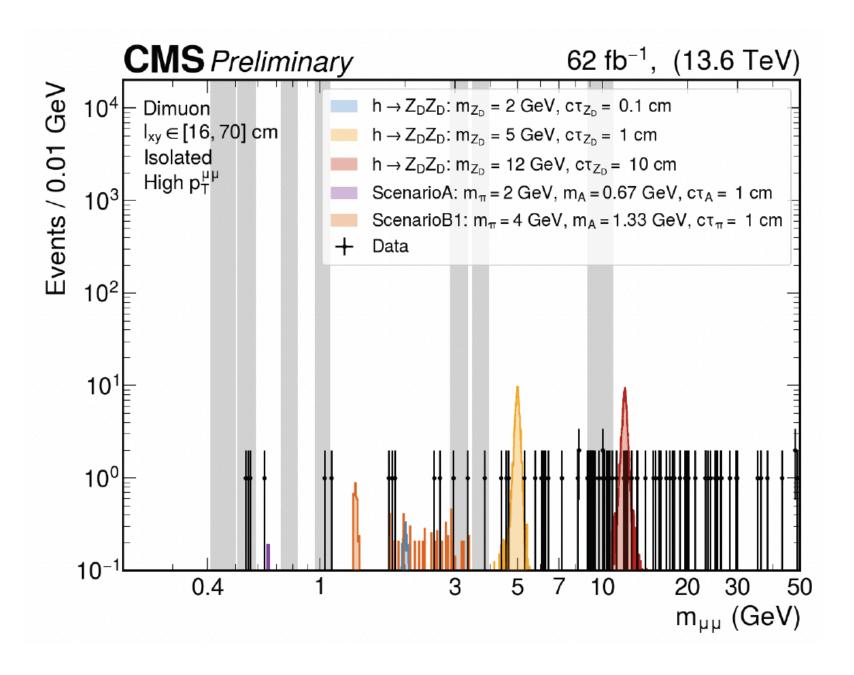
Dark Shower Scenarios:

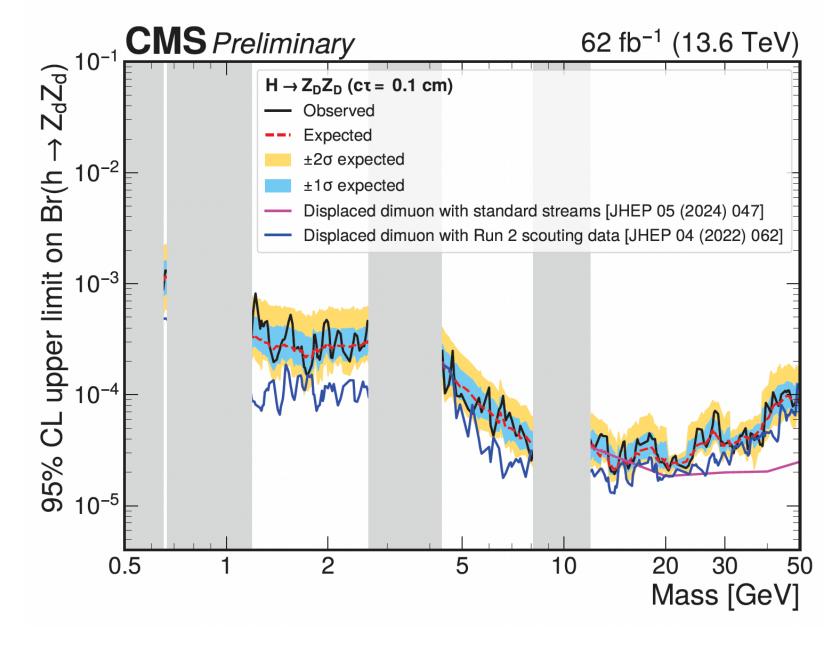




If only two muons from a SV are found, the event is categorized as a dimuon event. For dimuon events, we first define two orthogonal regions in $|\Delta\Phi(\mu\mu, SV)|$, distinguishing *pointing* and *nonpointing* topologies, with $|\Delta\Phi(\mu\mu, SV)| < 0.02$ and $0.02 < |\Delta\Phi(\mu\mu, SV)| < \pi/2$, respectively.







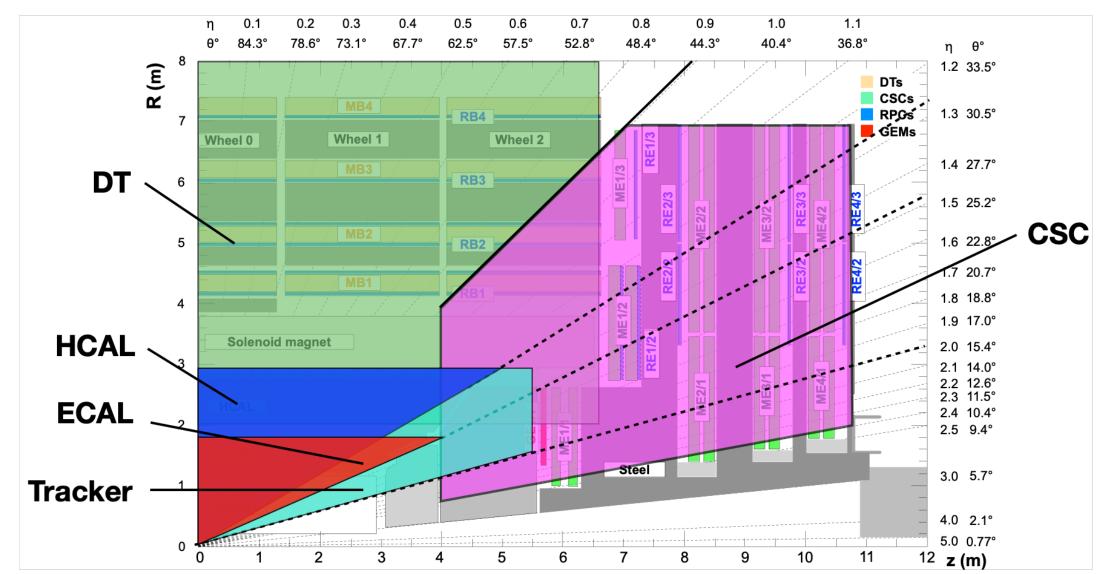
LLP triggers

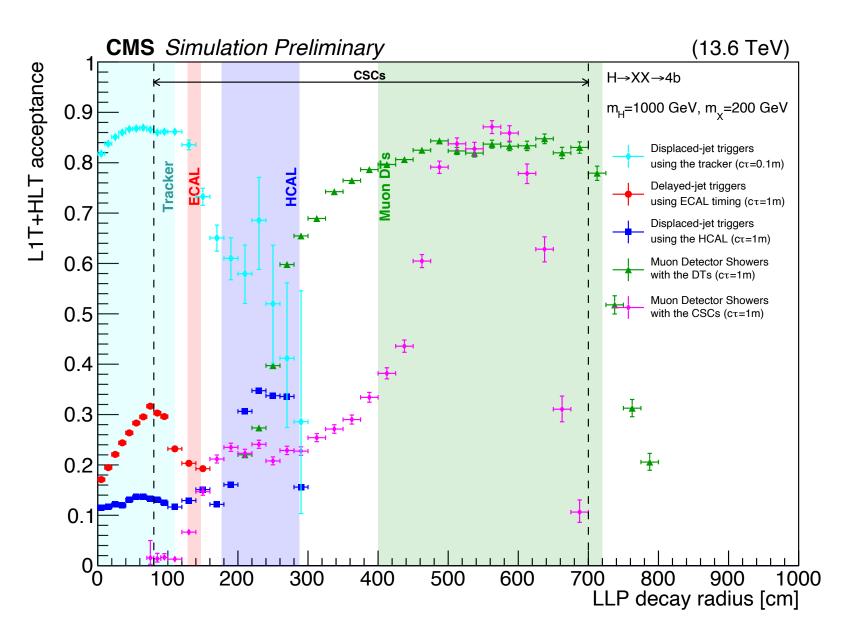


- Dedicated triggers targeting LLPs enable increased sensitivity to wide variety of signal models
- During Run 3, variety of such triggers were introduced and/or improved compared to Run 2
- Capitalise on different CMS subdetectors, hence can target different phase space in LLP searches
- The powerful complementarity of the program is shown using Twin Higgs model as a benchmark

Data	Total rate [Hz]	Pure rate [Hz]
Standard	393	311
Parking	234	182
Scouting	4200	3800
Full reconstruction: standard or parking	586	389

- Calculated from one run in 2024 data for pile-up 63.6 and instantaneous luminosity of 2.1x10³⁴
- Total rate: OR of LLP HLT trigger paths, accounting for overlaps
- Pure rate: total rate not saved by any other HLT path





LLP triggers

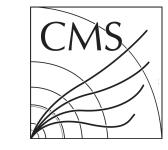
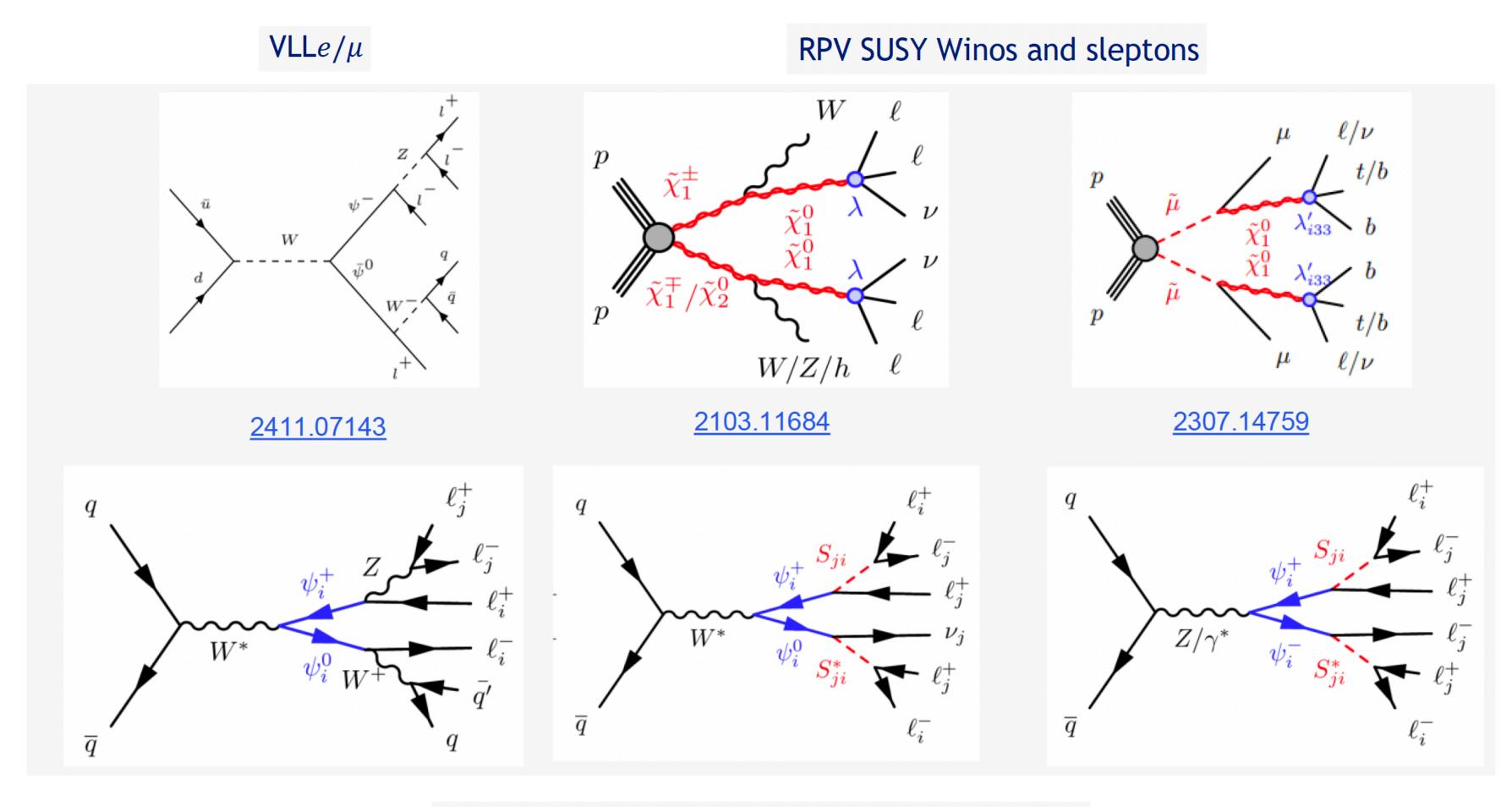


Table 2: The LLP triggers and their total rates at the HLT in Run 3, calculated from 2024 data for an instantaneous luminosity of $2.1 \times 10^{34}~\rm cm^{-2}s^{-1}$, with a mean PU of 63.6. Triggers implemented for the first time in Run 3 are indicated by a dagger (†). Rate values in parentheses correspond to the parked data rates; all others are standard data rates except for dimuon scouting. Nearly all rates shown have a statistical uncertainty of less than 1 Hz. "Disp." is used as an abbreviation for "displaced" and "req." is used as an abbreviation for "requirement". The terms used in this table are explained in the corresponding subsection within Section 6.

Triggered signature	Trigger description	HLT rate [Hz]
Disappearing track	$p_{\mathrm{T}}^{\mathrm{miss}} > 105\mathrm{GeV} + \geq 1\mathrm{isolated}\mathrm{track}(p_{\mathrm{T}} > 50\mathrm{GeV})$	4
Disp. tau	\geq 2 disp. $\tau_{\rm h}$ ($p_{\rm T}$ > 32 GeV, d_0 > 0.005 cm) [†] \geq 1 disp. $\tau_{\rm h}$ ($p_{\rm T}$ > 24 GeV) + \geq 1 μ ($p_{\rm T}$ > 24 GeV) [†] \geq 1 disp. $\tau_{\rm h}$ ($p_{\rm T}$ > 34 GeV) + \geq 1 e ($p_{\rm T}$ > 34 GeV) [†]	36
Disp. jet	\geq 2 jet ($p_{\rm T}>40$ GeV, inclusive tagging req.) + $H_{\rm T}>430$ GeV \geq 2 jet ($p_{\rm T}>40$ GeV, disp. tagging req.) + $H_{\rm T}>240$ GeV + \geq 1 L1 μ ($p_{\rm T}>6$ GeV)	53 (163)
HCAL-based disp. and delayed jet	\geq 2 jet ($p_{\rm T}$ > 40 GeV, displ. tagging req.) + $H_{\rm T}$ > 170 GeV [†] \geq 2 jet ($p_{\rm T}$ > 40 GeV, inclusive. tagging req.) + $H_{\rm T}$ > 200 GeV [†] \geq 1 jet ($p_{\rm T}$ > 60 GeV, neutral hadron energy fraction >0.7) + $H_{\rm T}$ > 200 GeV [†]	35
ECAL-based delayed jet	≥1 inclusive and trackless jet [†]	37 (77)
Delayed diphoton	\geq 2 ECAL superclusters (time $>$ 1 ns) †	15
Disp. photon + H_T	$\geq \! 1 \; \gamma \; (p_{\mathrm{T}} > 60 \mathrm{GeV}) + \mathrm{PF} H_{\mathrm{T}} > 350 \mathrm{GeV}$	12
Disp. single and dimuon	$ \geq 2 \text{ L2 } \mu (p_{\text{T}} > 10 \text{ GeV}, d_0 > 1 \text{ cm})^{\dagger} $ $ \geq 2 \text{ L3 } \mu (p_{\text{T}} > 16, 10 \text{ GeV}, d_0 > 0.01 \text{ cm})^{\dagger} $ $ \geq 2 \text{ L2 } \mu (p_{\text{T}} > 23 \text{ GeV}) $ $ \geq 1 \text{ L2 } \mu (p_{\text{T}} > 50 \text{ GeV}, d_0 > 1 \text{ cm})^{\dagger} $ $ \geq 1 \text{ L3 } \mu (p_{\text{T}} > 30 \text{ GeV}, d_0 > 0.01 \text{ cm})^{\dagger} $	165

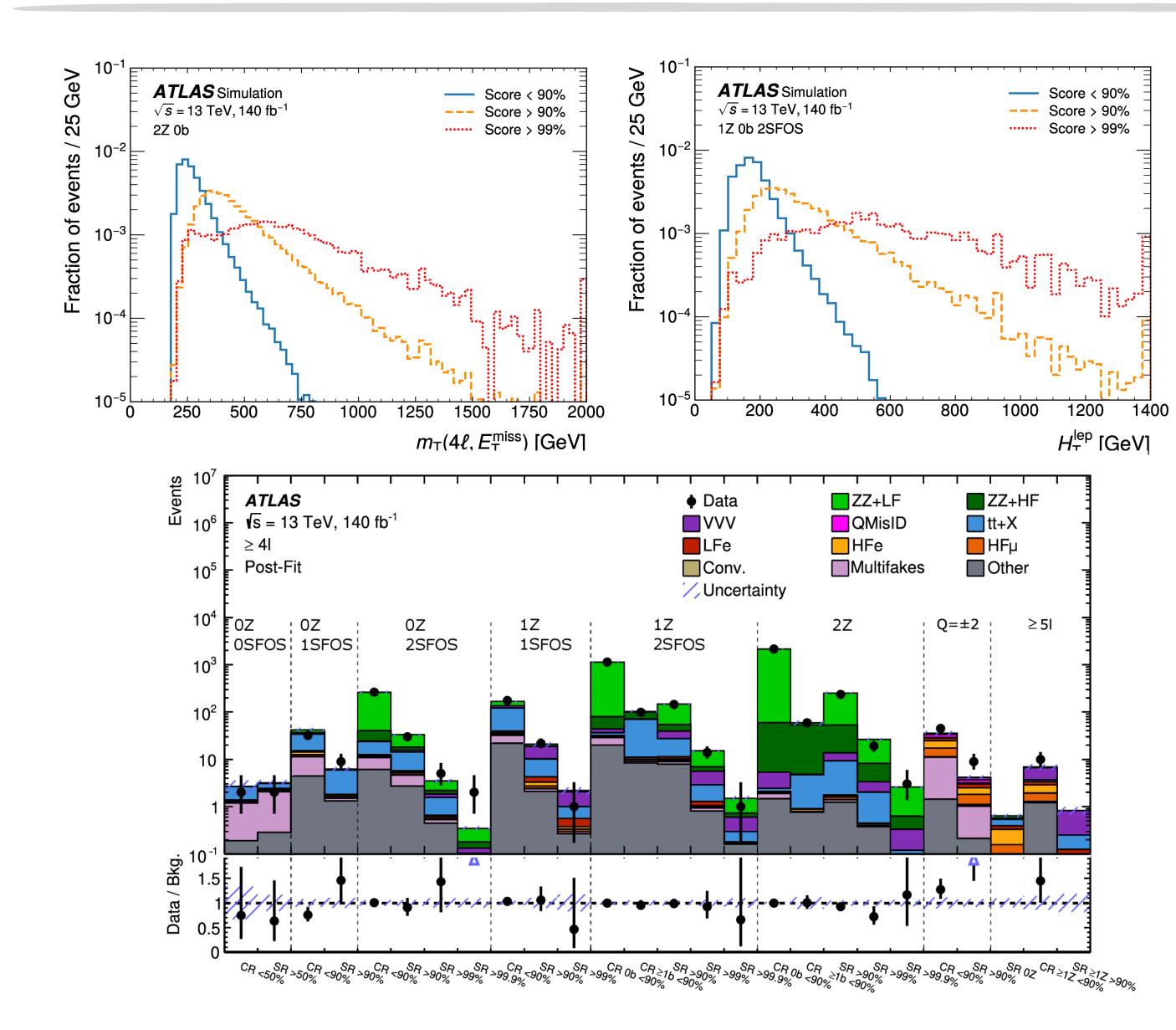
Double disp. L3 muon	\geq 2 L3 μ ($p_{\rm T} > 43{ m GeV}$)	2
Disp. L3 muon+photon	\geq 1 L3 μ ($p_{\rm T} >$ 43 GeV) + γ ($p_{\rm T} >$ 43 GeV) \geq 1 L3 μ ($p_{\rm T} >$ 38 GeV, $d_0 >$ 1 cm) + γ ($p_{\rm T} >$ 38 GeV)	5
Dimuon scouting	\geq 2 scouting μ ($p_{\rm T} > 3$ GeV)	4200
MDS in CSCs	≥1 CSC cluster (≥200/500 hits in outer/inner rings) [†] ≥2 CSC clusters (≥75 hits) [†]	14
MDS in CSCs + X	\geq 1 CSC cluster (\geq 100 hits) + \geq 1 e ($p_{\rm T} > 5{\rm GeV}$) [†] \geq 1 CSC cluster (\geq 100 hits) + \geq 1 L3 μ ($p_{\rm T} > 5{\rm GeV}$) [†] \geq 1 CSC cluster (\geq 100 hits) + \geq 1 $\tau_{\rm h}$ ($p_{\rm T} > 10{\rm GeV}$) [†] \geq 1 CSC cluster (\geq 50 hits) + \geq 1 γ ($p_{\rm T} > 20{\rm GeV}$) [†]	14
MDS in DTs	L1 $p_{\rm T}^{\rm miss} > 150{\rm GeV} + \ge 1{\rm DT}{\rm cluster}(\ge 50{\rm hits})^{\dagger}$ $\ge 1{\rm L1}{\rm CSC}{\rm cluster} + \ge 1{\rm DT}{\rm cluster}(\ge 50{\rm hits})^{\dagger}$	9
Jet No-BPTX	\geq 1 out-of-time jet ($E > 60 \text{GeV}$)	1
Muon No-BPTX	\geq 1 out-of-time L2 μ ($p_{\rm T} > 40{ m GeV}$)	7

Multilepton anomaly detection: benchmark models



VLL e/μ through flavourful scalar S $\frac{2011.12964}{4}$

Multilepton anomaly detection



Training variable	Description
	Input to $4\ell Q = 0$, $4\ell Q = \pm 2$, and $\geq 5\ell 1Z$
$H_{ m T}^{ m lep} \ H_{ m T}^{ m jets} \ E_{ m T}^{ m miss}$	Sum of transverse momenta of leptons
$H_{ m T}^{ m jets}$	Sum of transverse momenta of jets
$E_{ m T}^{ m miss}$	Missing transverse energy
$N_{ m jets}$	Number of jets
$p_{\mathrm{T}}(Z)$	Transverse momentum of lepton pair closest to Z boson
	Input to $4\ell Q = 0$ and $4\ell Q = \pm 2$
$p_{ m T}(\ell\ell)$	Transverse momentum of lepton pair second-closest to Z boson
m(Z)	Invariant mass of lepton pair closest to Z boson
$m(\ell\ell)$	Invariant mass of lepton pair second-closest to Z boson
$m^{\mathrm{high}}(3\ell)$	Largest invariant mass of lepton pair closest to Z boson and another lepton
$m^{\mathrm{low}}(3\ell)$	Smallest invariant mass of lepton pair closest to Z boson and another lepton
$m(4\ell)$	Invariant mass of four-lepton system
$m_{\mathrm{T}}(4\ell, E_{\mathrm{T}_{.}}^{\mathrm{miss}})$	Transverse mass of four leptons and $E_{\rm T}^{\rm miss}$
$m_{\mathrm{T}}(Z,E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of lepton pair closest to Z boson and $E_{\rm T}^{\rm miss}$
$m_{\mathrm{T}}(\ell\ell,E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of lepton pair second-closest to Z boson and $E_{\rm T}^{\rm miss}$
$m_{\mathrm{T}}(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}) \ \sum_{i=1}^{\mathrm{jets}} \mathrm{pcb}_i$	Sum of pseudo-continuous b-tagging score

Multilepton anomaly detection

