

# High $p_t$ searches at ATLAS and CMS

New Frontiers in Lepton Flavour,  
Pisa May 2023

Prof. Adrian Bevan on behalf of the ATLAS & CMS  
collaborations

# Outline

- Motivation
- The Large Hadron Collider (LHC)
- GPDs: ATLAS and CMS
- Indirect searches:
  - Higgs couplings to fermions
  - CP violation searches
- Direct searches:
- Summary

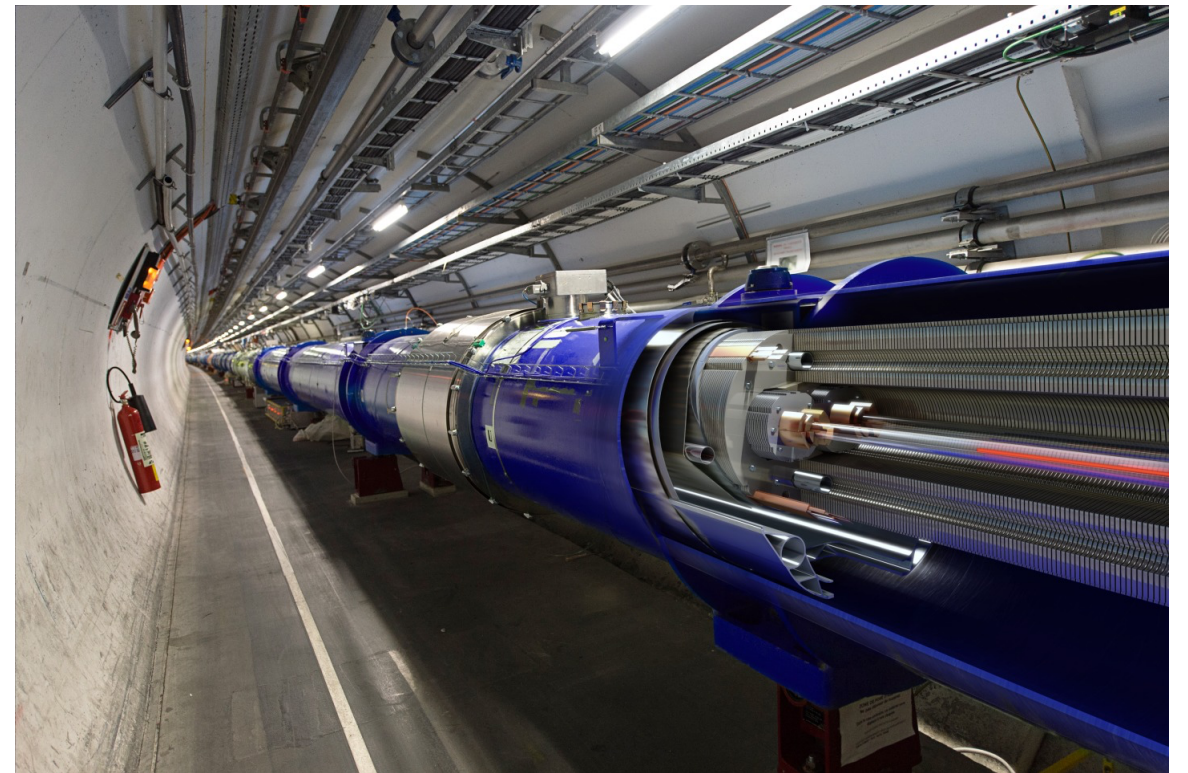
See links for listings of:  
[ATLAS Results](#)  
[CMS Results](#)

# Motivation

- Indirect searches (e.g. CP violation) at high  $p_t$  complement low energy CP studies and give new routes to answering fundamental questions in particle physics
- High  $p_t$  searches offer direct means to observe physics beyond the Standard Model (SM)
- Theory motivations can date back decades: e.g:
  - Higgs Yukawa couplings to fermions linked to the CKM matrix via diagonalisation of the mass matrix
  - New types of CP violation searches target understanding the origins of the matter-antimatter asymmetry of the universe
  - Access to high energy via the LHC and HL-LHC upgrade allow for direct searches for new types of coupling (i.e. particles)

# The Large Hadron Collider (LHC)

- pp collider at CERN on the Swiss-French border
- Superconducting magnets targeting  $\sqrt{s} = 14\text{TeV}$
- Taking data now during Run 3

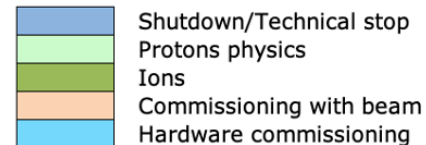
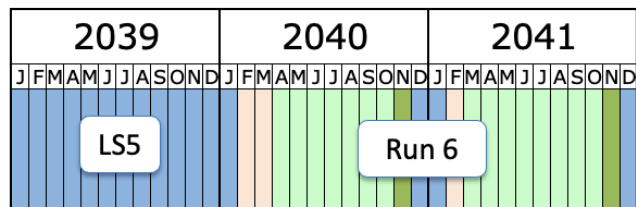
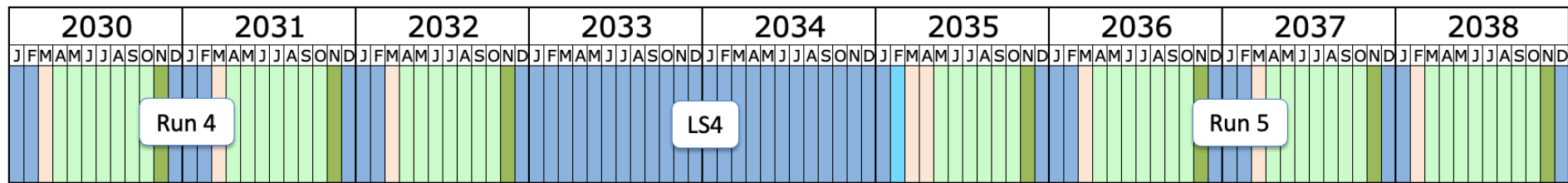
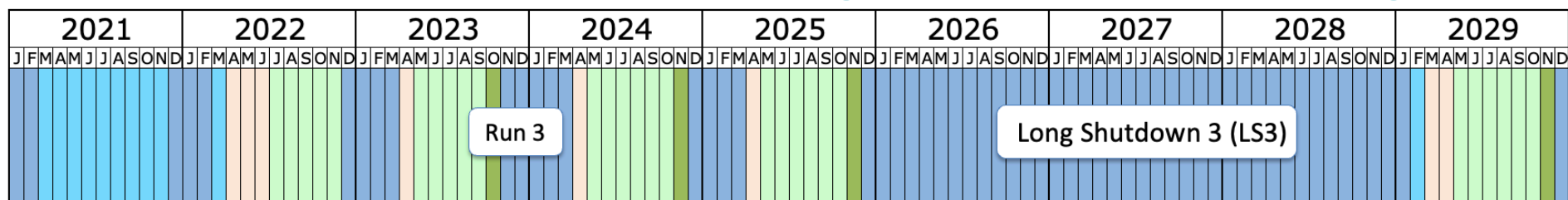




# The LHC

- Results shown use data from Run 1+2
- Run 3 in progress
- High Luminosity upgrade start up to follow long shutdown 3

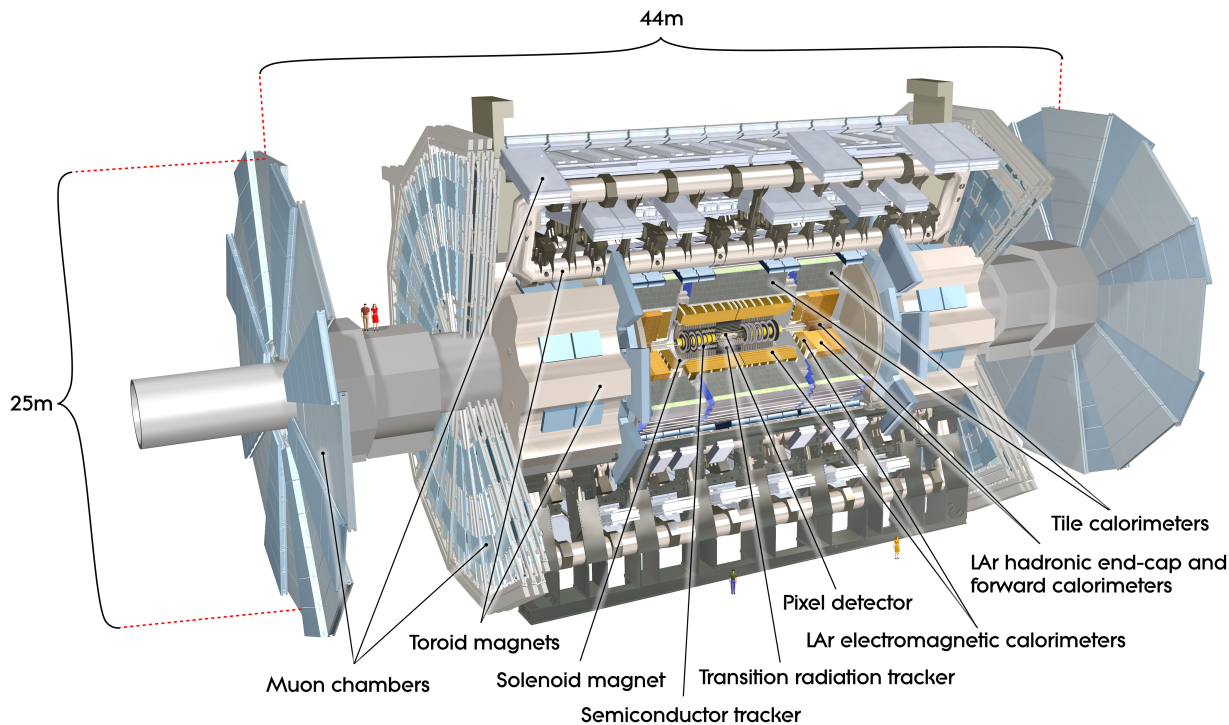
<https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm>



Last update: April 2023

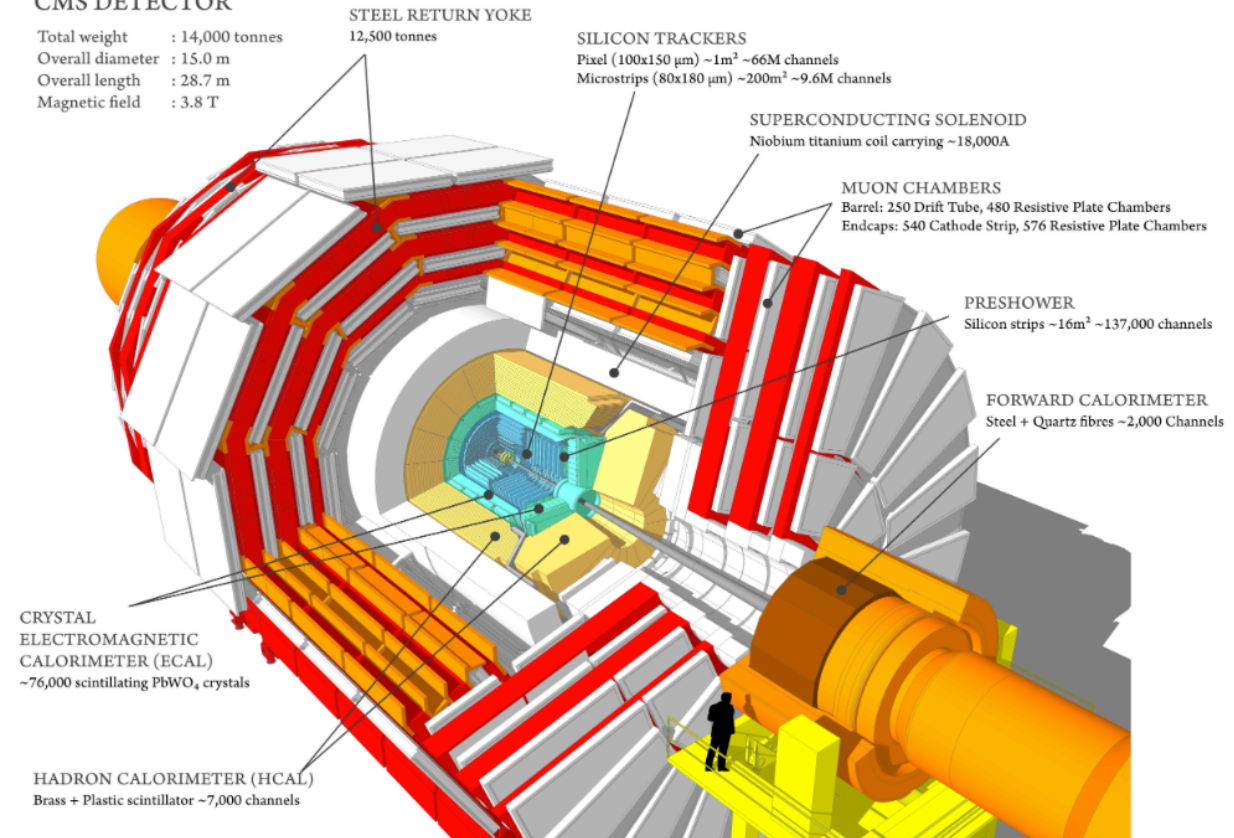
# GPDs: ATLAS and CMS

- Designed for a wide range of physics, with tracking systems, calorimeters and trigger systems;
- Magnet systems allow 4-vector reconstruction of charged particles



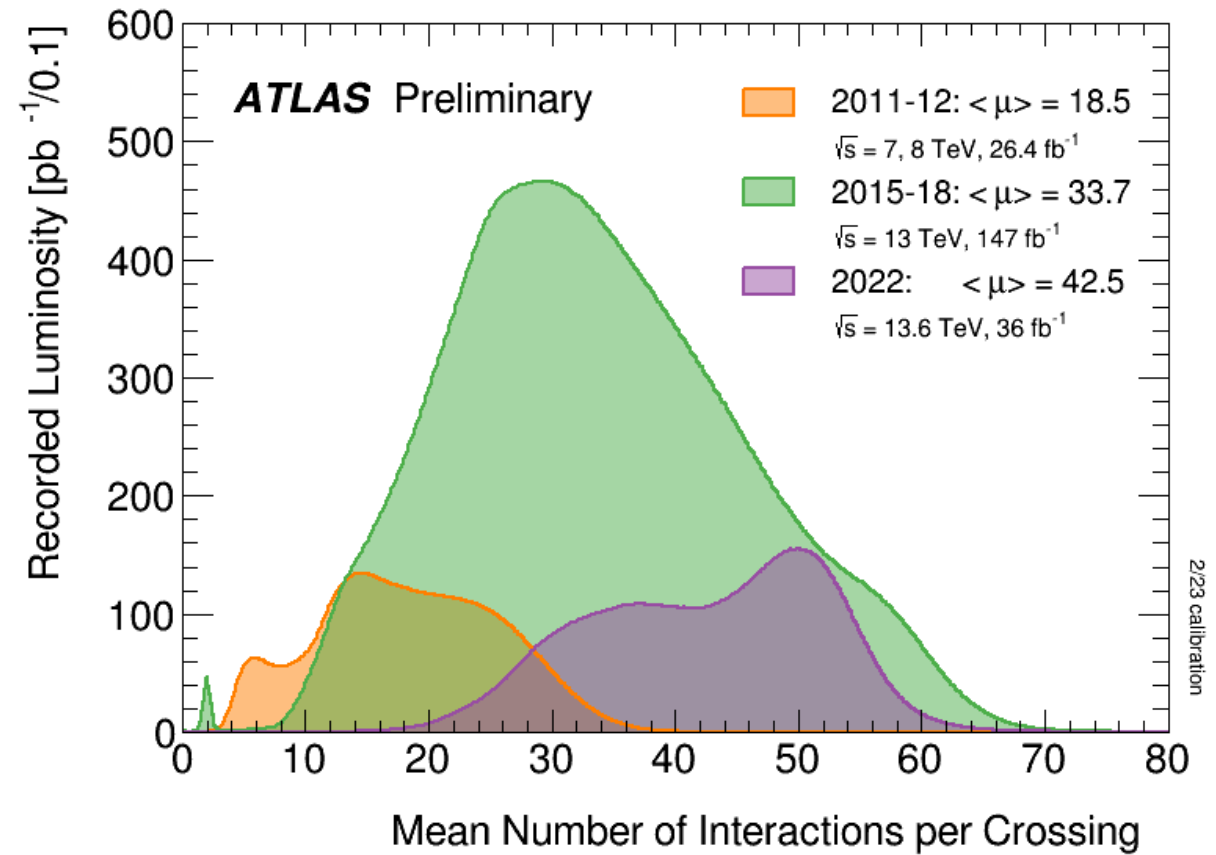
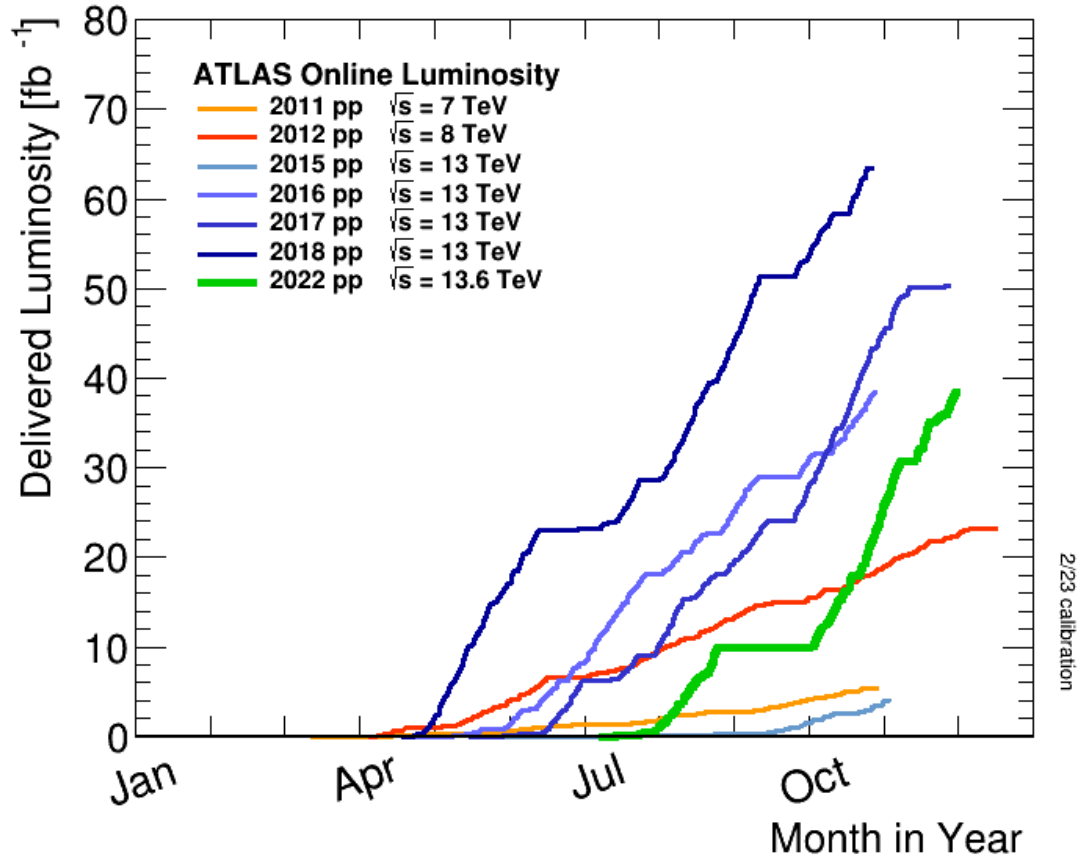
## CMS DETECTOR

Total weight : 14,000 tonnes  
 Overall diameter : 15.0 m  
 Overall length : 28.7 m  
 Magnetic field : 3.8 T



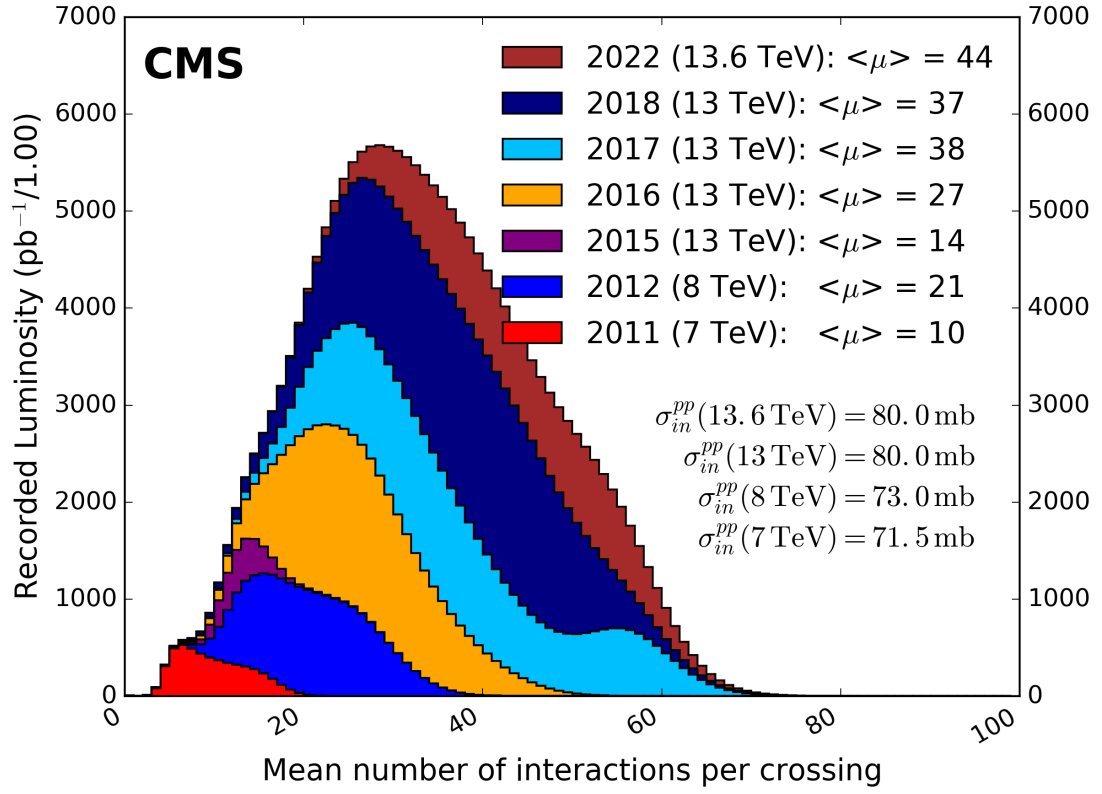
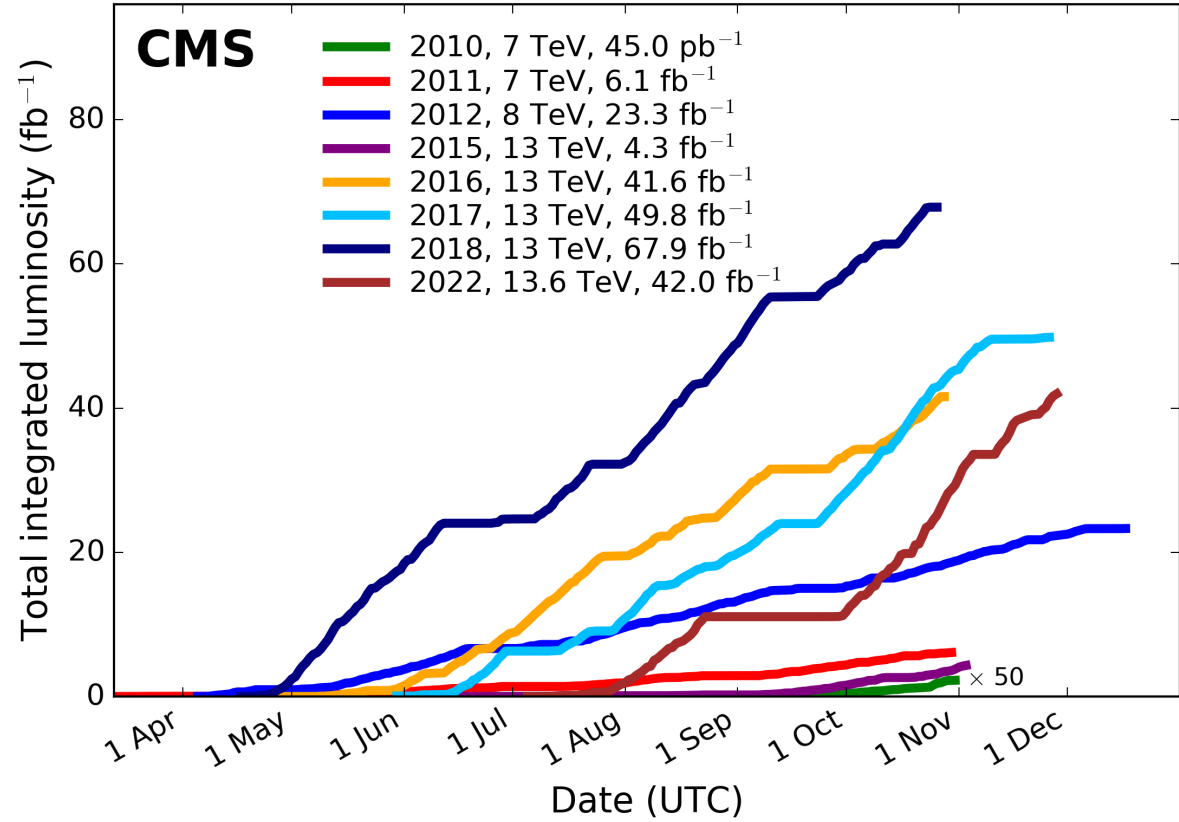
# GPDs: ATLAS and CMS

- Run 3 data taking performance similar to run 2



# GPDs: ATLAS and CMS

- Run 3 data taking performance similar to run 2





# Indirect searches

Higgs couplings and two example of high  $p_t$  CP violation searches

Other high  $p_t$  searches, including study of b CP asymmetries using semi-leptonic top decays exist; but not covered here.

# Couplings to fermions

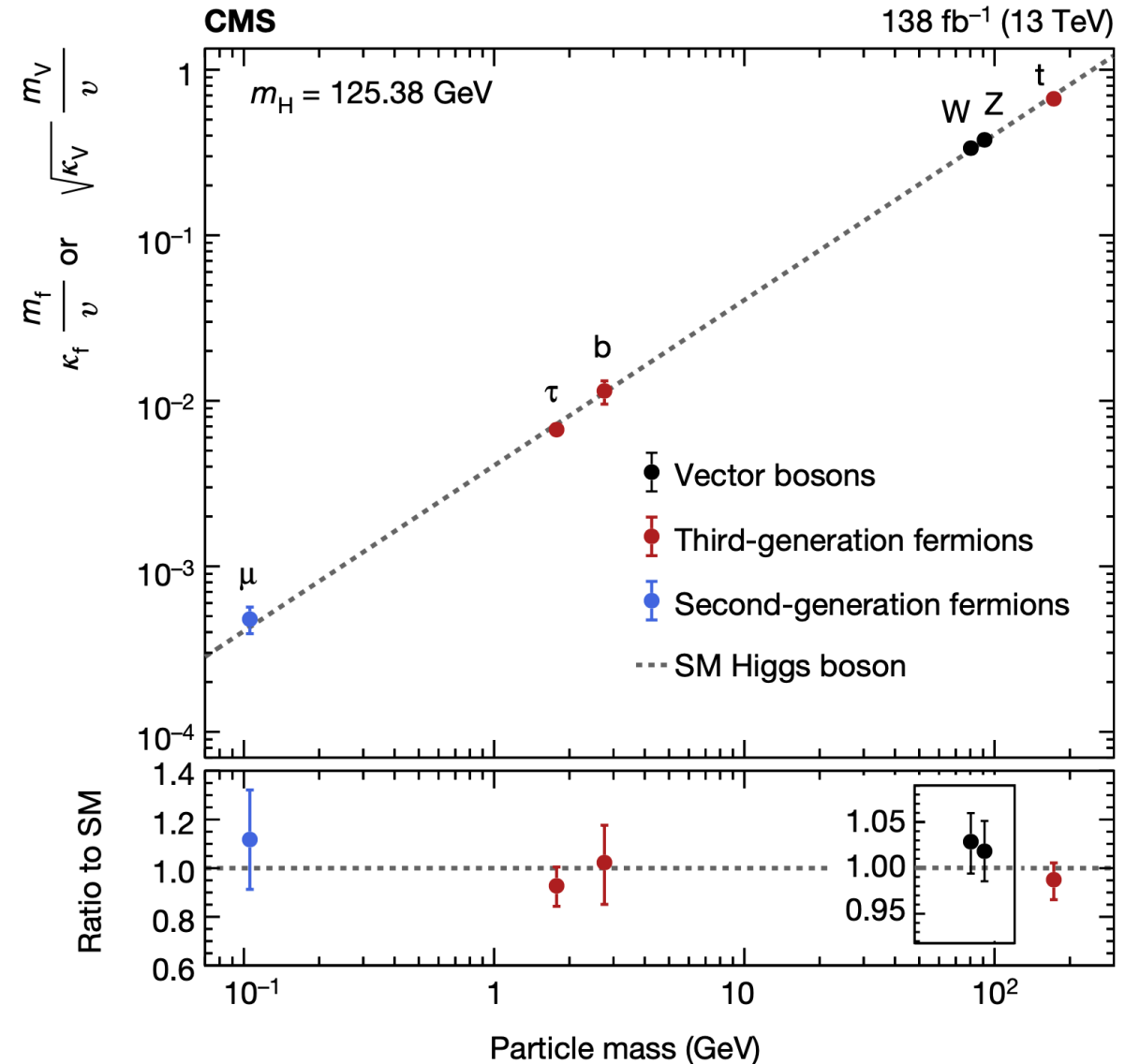
- The CKM matrix is derived from fermion mass diagonalisation in the SM

$$U' M' U'^{\dagger} = D' = \text{diag} \left( \frac{m_d}{m_b}, \frac{m_s}{m_b}, 1 \right)$$

$$U M U^{\dagger} = D = \text{diag} \left( \frac{m_{\mu}}{m_t}, \frac{m_c}{m_t}, 1 \right),$$

$$V_{CKM} = U U'^{\dagger}$$

- Couplings deviating from the SM would have implications for the CKM picture



# Couplings to fermions

- The CKM matrix is derived from fermion mass diagonalisation in the SM

$$U' M' U'^{\dagger} = D' = \text{diag}(m_u, m_c, m_t)$$

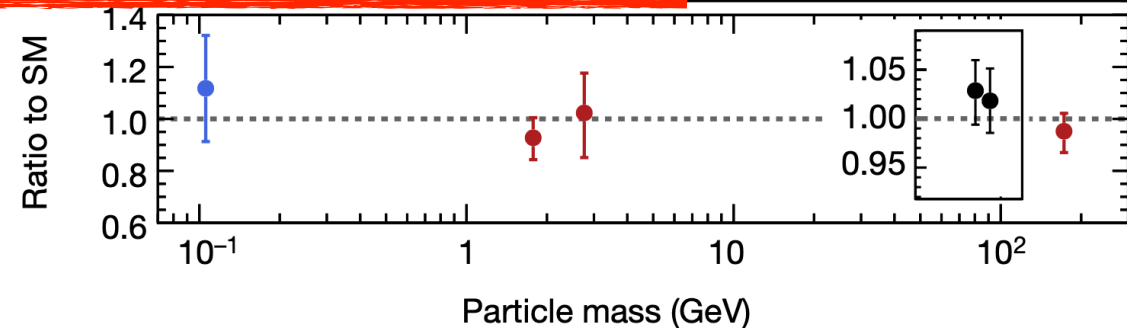
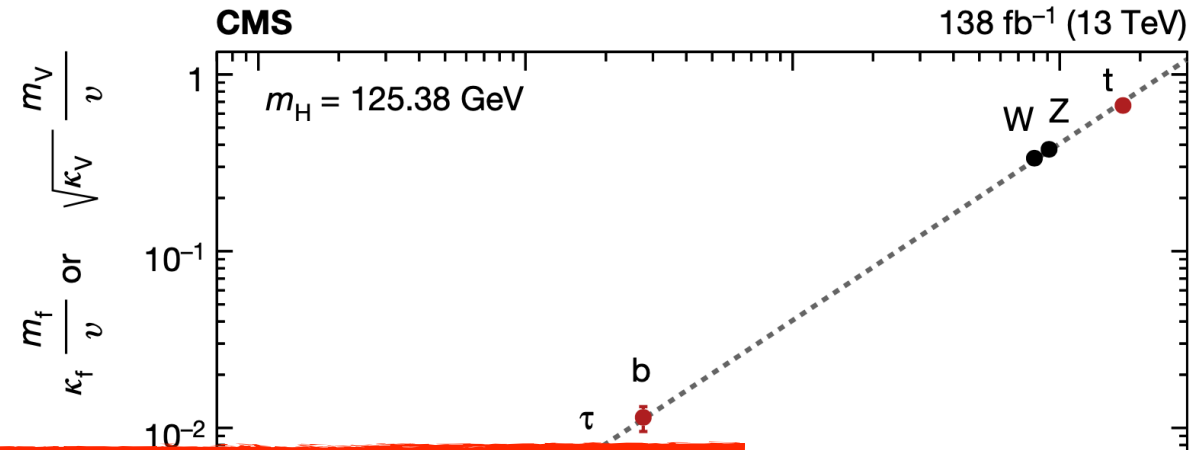
$$U M U^{\dagger} = D = \text{diag}(m_d, m_s, m_b)$$

$$V_{CKM} = U U'^{\dagger}$$

- Couplings deviating from the SM would have implications for the CKM picture

Similar picture from ATLAS results

10 years after the Higgs discovery the couplings are consistent with the SM



For ATLAS results see: [ATLAS Collaboration, Nature 607, pages 52–59 \(2022\)](#)

# CP violation

- In the 1980's new CP violation tests were being explored
- An important paper stood out among others

## NOTES ON THE OBSERVABILITY OF *CP* VIOLATIONS IN B DECAYS

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Received 16 June 1981

We describe a general method of exposing *CP* violations in on-shell transitions of B mesons. Such *CP* asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large *CP* asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing *CP* tests with a high statistics B meson factory like the  $Z^0$  (and a toponium) resonance.

[Nuclear Physics B193 \(1981\) 85-108](#)

- CKM, superweak and Higgs multiplet theories could all give rise to sources of CP violation.
  - What description was correct?
  - How do we test that?
- Superweak ruled out by  $\epsilon'$
- B Factory consistent with CKM picture.
- What about Higgs multiplets?



# CP violation: ttH and tH searches

- SM Higgs is CP even
- Presence of a CP odd component in t-H coupling would constitute CP violation (and more than one Higgs)

$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v} \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t) \psi_t H$$

- $\kappa_t, \bar{\kappa}_t$  are CP even / odd couplings
- $\psi$ 's are Dirac spinors
- $v$  is the Higgs VEV

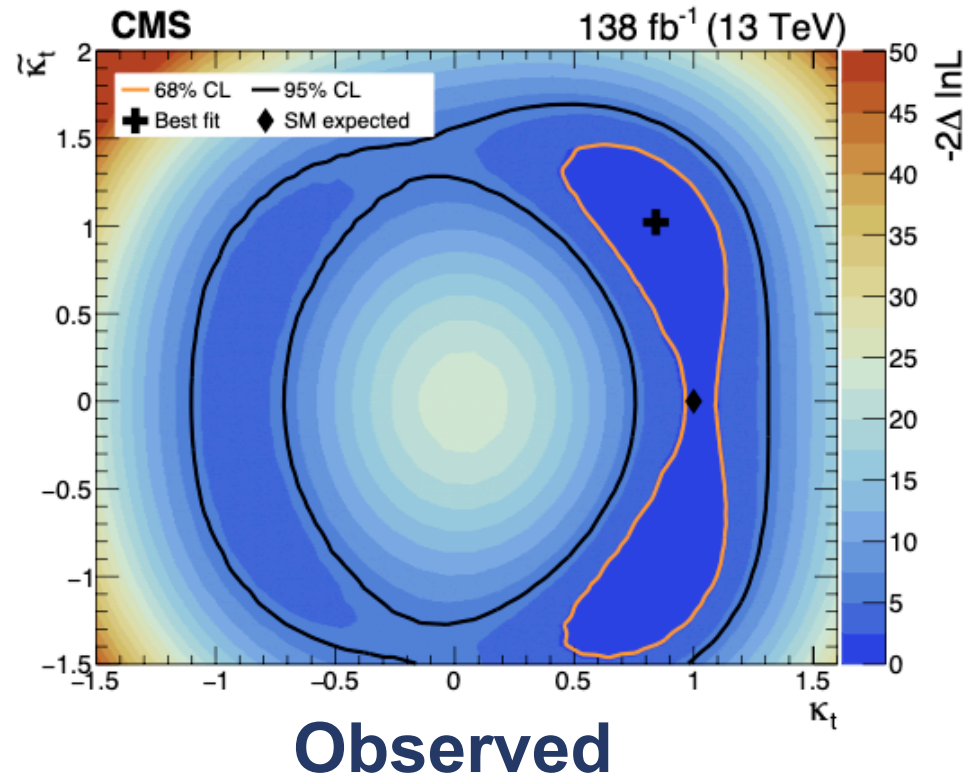
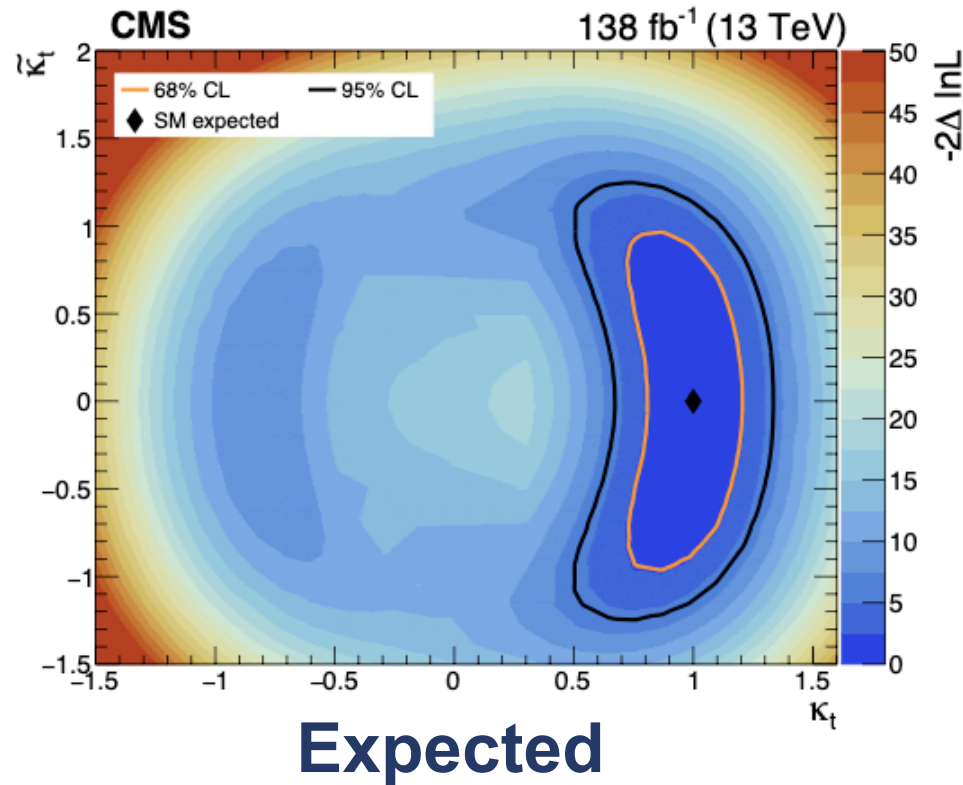
- Introduce a mixing angle  $\alpha$ :  $\cos \alpha$  /  $\sin \alpha$  describe CP even/odd terms
- $\alpha = 0^\circ, 180^\circ$  for a purely CP even state
- $\alpha = 90^\circ$  for a purely CP odd state
- otherwise the state is mixed

# CP violation searches e.g ttH and tHq, tHW

- Trigger on multi (1, 2, 3) lepton final states
- Reconstruct Higgs via WW, ZZ or  $\tau^+\tau^-$  in leptonic or hadronic decay modes
- Multivariate discriminator for background suppression
- Reducible backgrounds:
  - mainly from  $t\bar{t}$  events
  - $t\bar{t}\gamma$  leads to photon conversion background
  - leptonic charge flipping from events with both tops decaying semileptonically (issue for electron mode)
- Irreducible backgrounds from rare processes also considered
- Additional discriminator for CP-odd/even determination

# CP violation searches e.g ttH and tHq, tHW

- 138 /fb of data used
- Result obtained compatible with the SM
- No significant CP odd component found

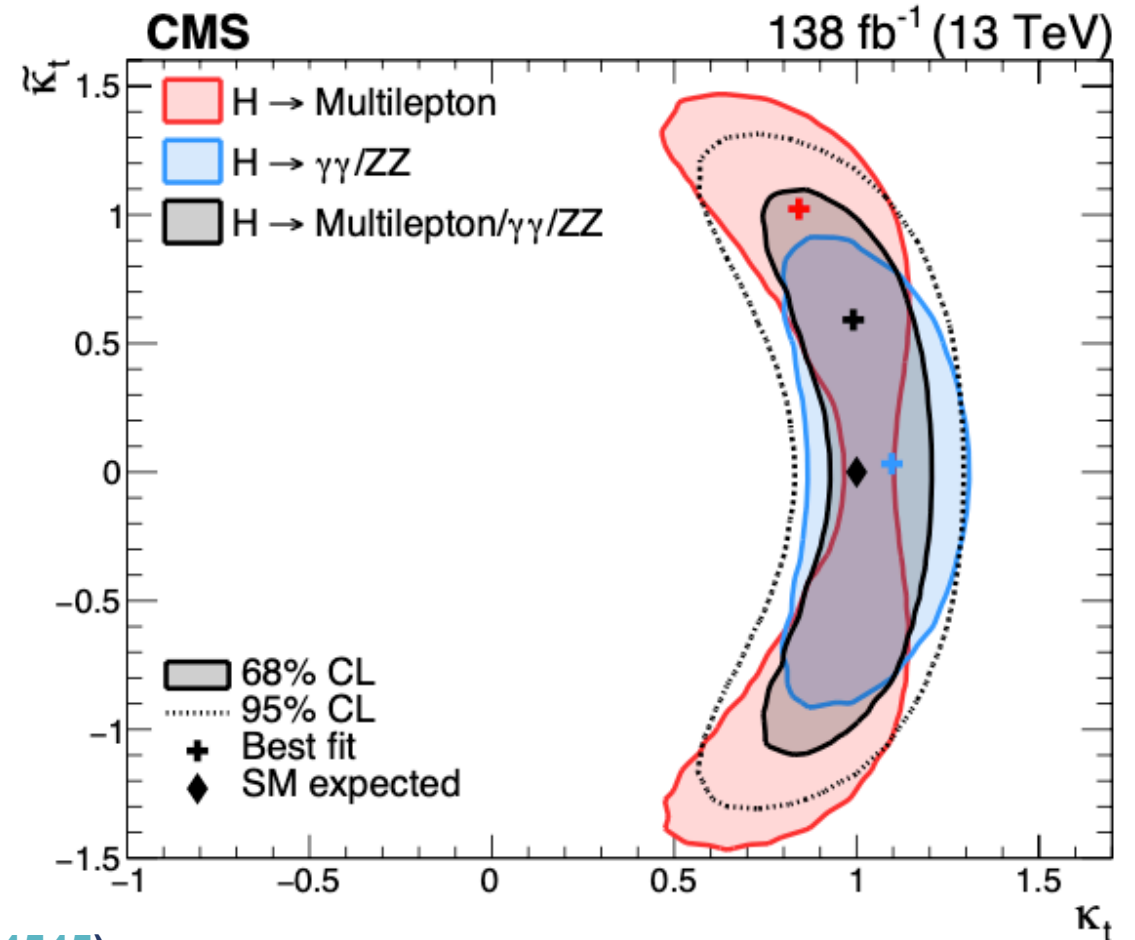


# CP violation searches e.g ttH and tHq, tHW

- Likewise combination (with previous CMS results) is compatible with the SM

Parameter	68% CL	95% CL
$\kappa_t$	(0.96, 1.16)	(0.86, 1.26)
$\tilde{\kappa}_t$	(-0.86, 0.85)	(-1.07, 1.07)

- Validates a way to disentangle CP even and odd t-H couplings for future CP violation searches



(also see ATLAS result detailed in <https://arxiv.org/abs/2004.04545>)



# CP violation searches e.g $H \rightarrow \tau^+ \tau^-$

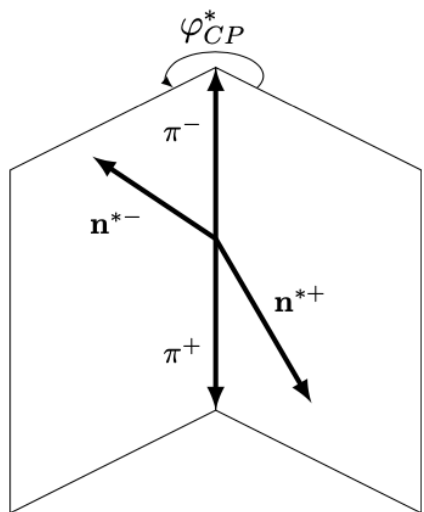
- Same motivation as for the previous example, this time looking for CP violation in the  $\tau$ -H coupling

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v} \kappa_\tau (\cos \phi_\tau \bar{\tau} \tau + \sin \phi_\tau \bar{\tau} i \gamma_5 \tau) H$$

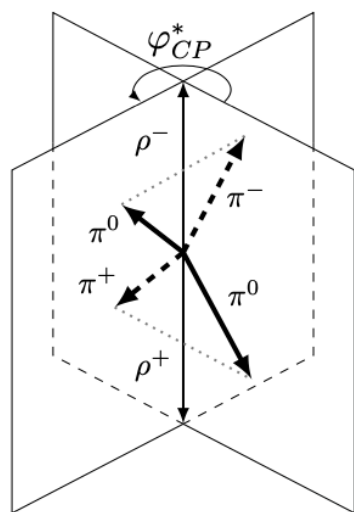
- $\phi_\tau$  is the mixing angle
  - $\cos \phi_\tau, \sin \phi_\tau$  are CP even/odd terms
  - $v$  is the Higgs VEV
  - $\kappa_\tau$  coupling strength
- $\alpha = 0^\circ$  for a purely CP even state
  - $\alpha = \pm 90^\circ$  for a purely CP odd state
  - otherwise the state is mixed

# CP violation searches e.g $H \rightarrow \tau^+ \tau^-$

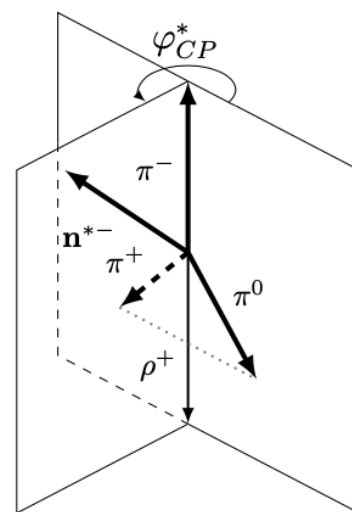
- Reconstruct acoplanarity  $\phi_{CP}^*$ , defined for different final states as



(a)  $H \rightarrow \tau^+ \tau^- \rightarrow \pi^+ \pi^- + 2\nu$



(b)  $H \rightarrow \tau^+ \tau^- \rightarrow \pi^+ \pi^0 \nu \pi^- \pi^0 \nu$



(c)  $H \rightarrow \tau^+ \tau^- \rightarrow \pi^+ \pi^0 \nu \pi^- \nu$

- Sensitive to  $\phi_\tau$  via rate as:

$$d\Gamma_{H \rightarrow \tau^+ \tau^-} \approx 1 - b(E_+)b(E_-) \frac{\pi^2}{16} \cos(\varphi_{CP}^* - 2\phi_\tau)$$

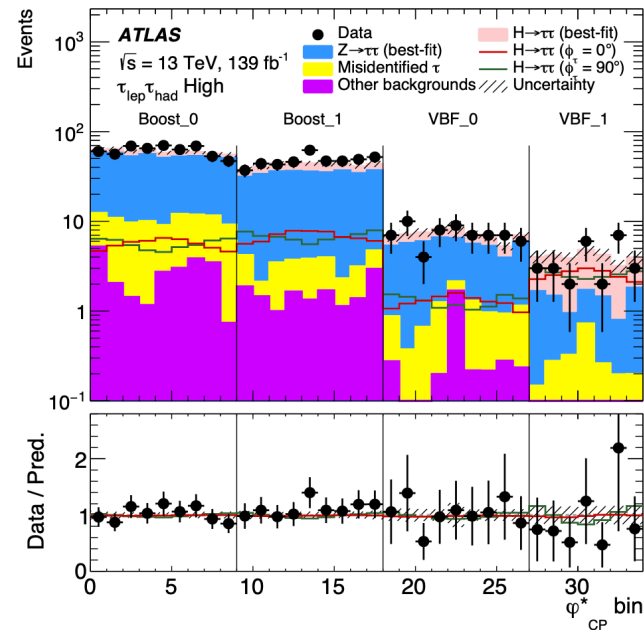
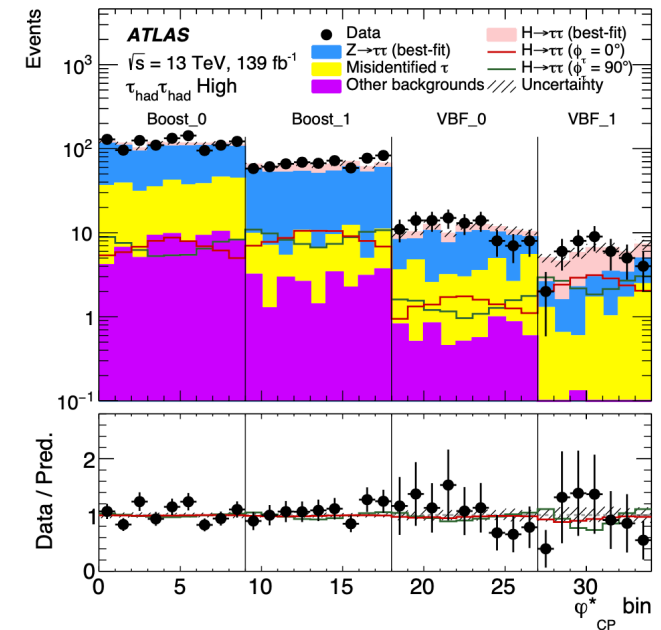
- Use leptonic and hadronic final states of the  $\tau^\pm$  in lephad and hadhad final states
- Boost into the Zero Momentum Frame of the visible decay
- Use momentum vectors and impact parameter  $n^{*\pm}$  to define the planes
- $\phi_{CP}^* = 180^\circ$  for CP even
- $\phi_{CP}^* = 0^\circ, 360^\circ$  for CP odd

- $E_\pm$  is the  $\tau^\pm$  energy
- $b(E_\pm)$  is a spectral function describing the spin analysing power

# CP violation searches e.g $H \rightarrow \tau^+ \tau^-$

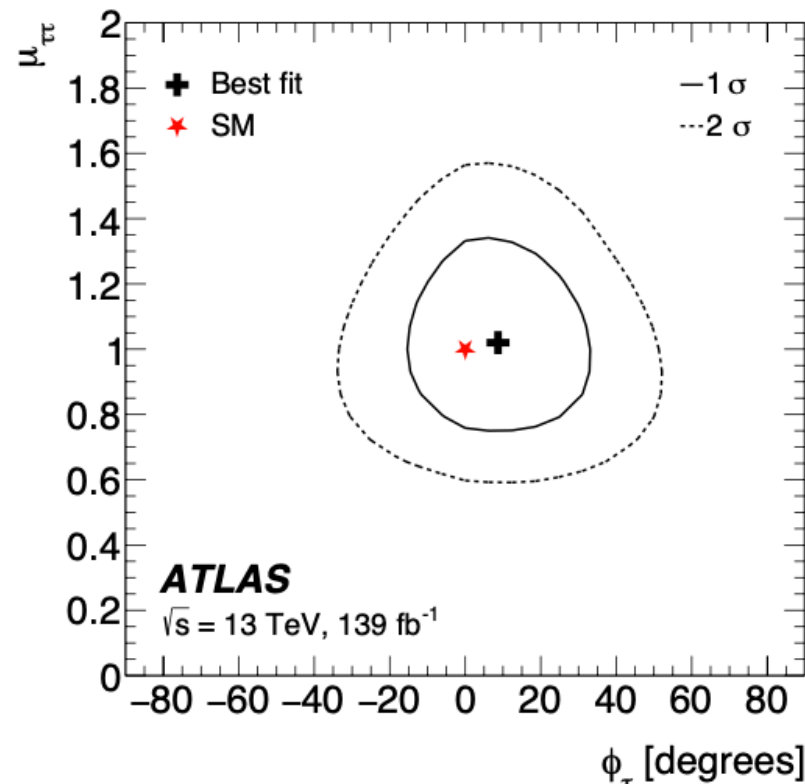
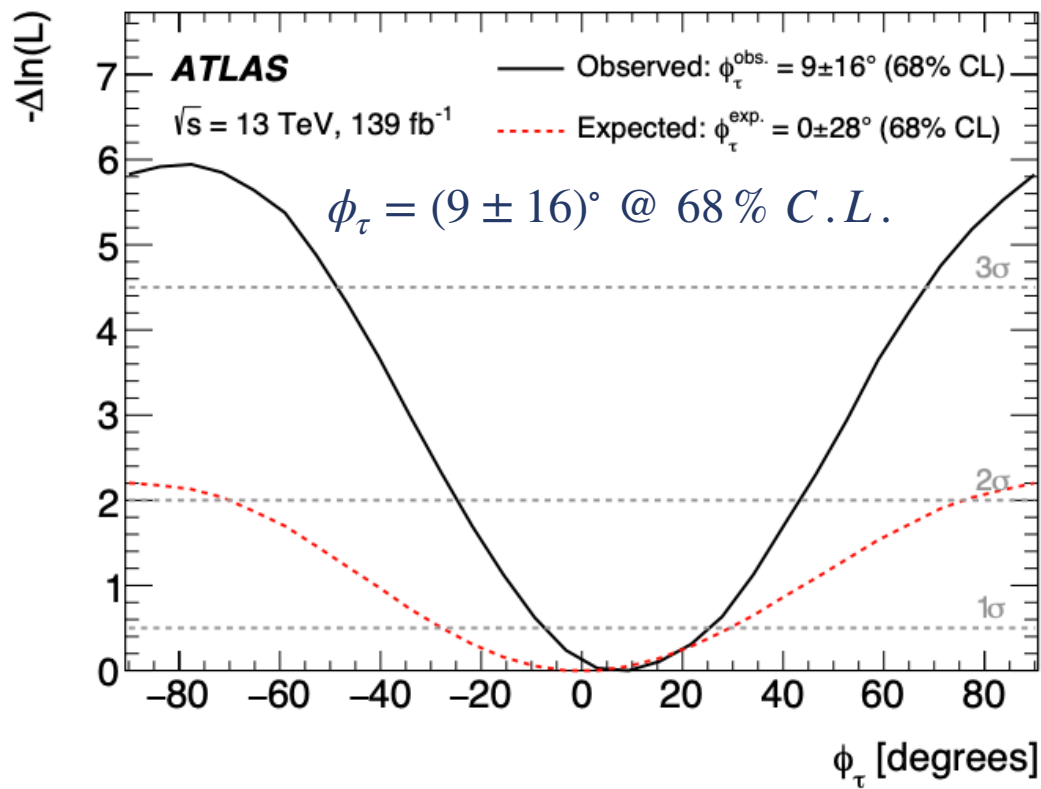
- Define 4 signal regions for VBF and boost categories of event with common selection criteria (resolved vs boosted jets)
- and additional criteria for the lephad and hadhad final selections

VBF		Boost	
$p_T^{j_2} > 30 \text{ GeV}$ $m_{jj} > 400 \text{ GeV}$ $ \Delta\eta_{jj}  > 3.0$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central $\tau$ -leptons		Not VBF $p_T^{\tau\tau} > 100 \text{ GeV}$	
Signal region ( $110 < m_{\tau\tau}^{\text{MMC}} < 150 \text{ GeV}$ )			
VBF_1	VBF_0	Boost_1	Boost_0
BDT(VBF) > 0	BDT(VBF) < 0	$\Delta R_{\tau\tau} < 1.5$ and $p_T^{\tau\tau} > 140 \text{ GeV}$	$\Delta R_{\tau\tau} > 1.5$ or $p_T^{\tau\tau} < 140 \text{ GeV}$
Z $\rightarrow \tau\tau$ control regions ( $60 < m_{\tau\tau}^{\text{MMC}} < 110 \text{ GeV}$ )			
VBF_1 Z CR	VBF_0 Z CR	Boost_1 Z CR	Boost_0 Z CR


 (a)  $\tau_{\text{lep}}\tau_{\text{had}}$  High SR

 (b)  $\tau_{\text{had}}\tau_{\text{had}}$  High SR

# CP violation searches e.g $H \rightarrow \tau^+ \tau^-$

- Signal strength and mixing phase compatible with SM
  - i.e. Signal strength ( $\mu_{\tau\tau}$ ) and  $\phi_\tau$  SM-like
  - CP odd scenario is disfavoured at  $3.4 \sigma$

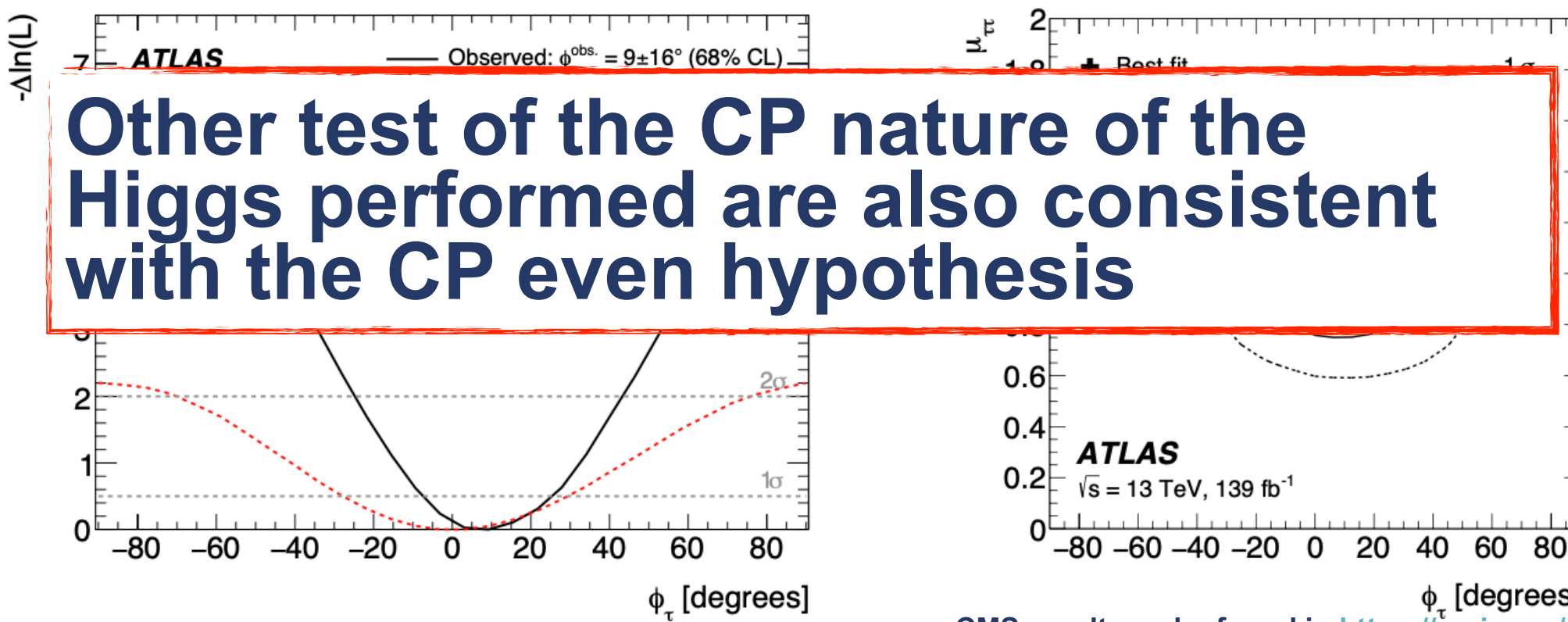


CMS result can be found in <https://arxiv.org/abs/2110.04836>



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# Direct searches

Searching directly for new particles in the data that don't fit the Standard Model(\*)

Show only a few examples of analyses in this area from ATLAS and CMS

(\*)The LHC has discovered many new particles e.g. XYZ states and pentaquarks, those are beyond the scope of this talk

Model	$\ell, \gamma$	Jets†	$E_{\tau}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$M_D$ 11.2 TeV $n=2$	2102.10874	
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV $n=3$ HLZ NLO	1707.04147	
	ADD QBH	-	$2 j$	-	139	$M_{\text{th}}$ 9.4 TeV $n=6$	1910.08447	
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV $n=6, M_D = 3 \text{ TeV, rot BH}$	1512.02586	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	139	$G_{KK}$ mass 4.5 TeV $k/\bar{M}_{pl} = 0.1$	2102.13405	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV $k/\bar{M}_{pl} = 1.0$	1808.02380	
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	$1 e, \mu$	$2 j / 1 J$	Yes	139	$G_{KK}$ mass 2.0 TeV $k/\bar{M}_{pl} = 1.0$	2004.14636	
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$g_{KK}$ mass 3.8 TeV $\Gamma/m = 15\%$	1804.10823	
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$KK$ mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678		
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z'$ mass 5.1 TeV	1903.06248	
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z'$ mass 2.42 TeV	1709.07242	
	Leptophobic $Z' \rightarrow b\bar{b}$	-	$2 b$	-	36.1	$Z'$ mass 2.1 TeV	1805.09299	
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138	
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	$W'$ mass 6.0 TeV	1906.05609	
	SSM $W' \rightarrow \tau\nu$	$1 \tau$	-	Yes	139	$W'$ mass 5.0 TeV	ATLAS-CONF-2021-025	
	SSM $W' \rightarrow t\bar{b}$	-	$\geq 1 b, \geq 1 J$	-	139	$W'$ mass 4.4 TeV	ATLAS-CONF-2021-043	
	HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	$W'$ mass 4.3 TeV $g_V = 3$	2004.14636	
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	$W'$ mass 340 GeV $g_V c_H = 1, g_F = 0$	ATLAS-CONF-2022-005	
	HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$ model B	$1 e, \mu$	$1-2 b, 1-0 j$	Yes	139	$W'$ mass 3.3 TeV $g_V = 3$	2207.00230	
HVT $Z' \rightarrow ZH \rightarrow \ell\ell/\nu\nu b\bar{b}$ model B	$0, 2 e, \mu$	$1-2 b, 1-0 j$	Yes	139	$Z'$ mass 3.2 TeV $g_V = 3$	2207.00230		
LRSM $W_R \rightarrow \mu N_R$	$2 \mu$	$1 J$	-	80	$W_R$ mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$	1904.12679		
CI	CI $qqqq$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$	1703.09127	
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	$\Lambda$ 35.8 TeV $\eta_{LL}$	2006.12946	
	CI $e\bar{e} b\bar{b}$	$2 e$	$1 b$	-	139	$\Lambda$ 1.8 TeV $g_s = 1$	2105.13847	
	CI $\mu\mu b\bar{b}$	$2 \mu$	$1 b$	-	139	$\Lambda$ 2.0 TeV $g_s = 1$	2105.13847	
	CI $t\bar{t} t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV $ C_{4t}  = 4\pi$	1811.02305	
DM	Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$m_{\text{med}}$ 2.1 TeV $g_q = 0.25, g_\tau = 1, m(\chi) = 1 \text{ GeV}$	2102.10874	
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$m_{\text{med}}$ 376 GeV $g_q = 1, g_\tau = 1, m(\chi) = 1 \text{ GeV}$	2102.10874	
	Vector med. $Z'$ -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{\text{med}}$ 3.1 TeV $\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$	2108.13391	
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	$m_{\text{med}}$ 560 GeV $\tan\beta = 1, g_\tau = 1, m(\chi) = 10 \text{ GeV}$	ATLAS-CONF-2021-036		
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$	2006.05872	
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$	2006.05872	
	Scalar LQ 3 <sup>rd</sup> gen	$1 \tau$	$2 b$	Yes	139	LQ mass 1.2 TeV $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	2108.07665	
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ mass 1.24 TeV $\mathcal{B}(LQ_3^d \rightarrow t\nu) = 1$	2004.14060	
	Scalar LQ 3 <sup>rd</sup> gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	-	-	139	LQ mass 1.43 TeV $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 1$	2101.11582	
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu, \geq 1 \tau$	$0-2 j, 2 b$	Yes	139	LQ mass 1.26 TeV $\mathcal{B}(LQ_3^d \rightarrow b\nu) = 1$	2101.12527	
	Vector LQ 3 <sup>rd</sup> gen	$1 \tau$	$2 b$	Yes	139	LQ mass 1.77 TeV $\mathcal{B}(LQ_3^d \rightarrow b\tau) = 0.5, \text{Y-M coupl.}$	2108.07665	
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	SU(2) singlet, $\kappa_T = 0.5$	1807.11883
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	SU(2) doublet, $\kappa_B = 0.3$	1812.07343
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass 2.0 TeV	SU(2) doublet	ATLAS-CONF-2021-018
VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau'$ mass 898 GeV	SU(2) doublet	ATLAS-CONF-2022-044	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	$q^*$ mass 6.7 TeV	only $u^*$ and $d^*, \Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV	only $u^*$ and $d^*, \Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow b\bar{g}$	-	$1 b, 1 j$	-	139	$b^*$ mass 3.2 TeV		1910.0447
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	1411.2921
	Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	$N^0$ mass 910 GeV	$m(W_R) = 4.1 \text{ TeV, } g_L = g_R$	2202.02039
	LRSM Majorana $\nu$	$2 \mu$	$2 j$	-	36.1	$N_R$ mass 3.2 TeV	DY production	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV	DY production, $ q  = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g  = 1g_D, \text{spin } 1/2$	1905.10130

Huge industry of searches for new particles by both experiments

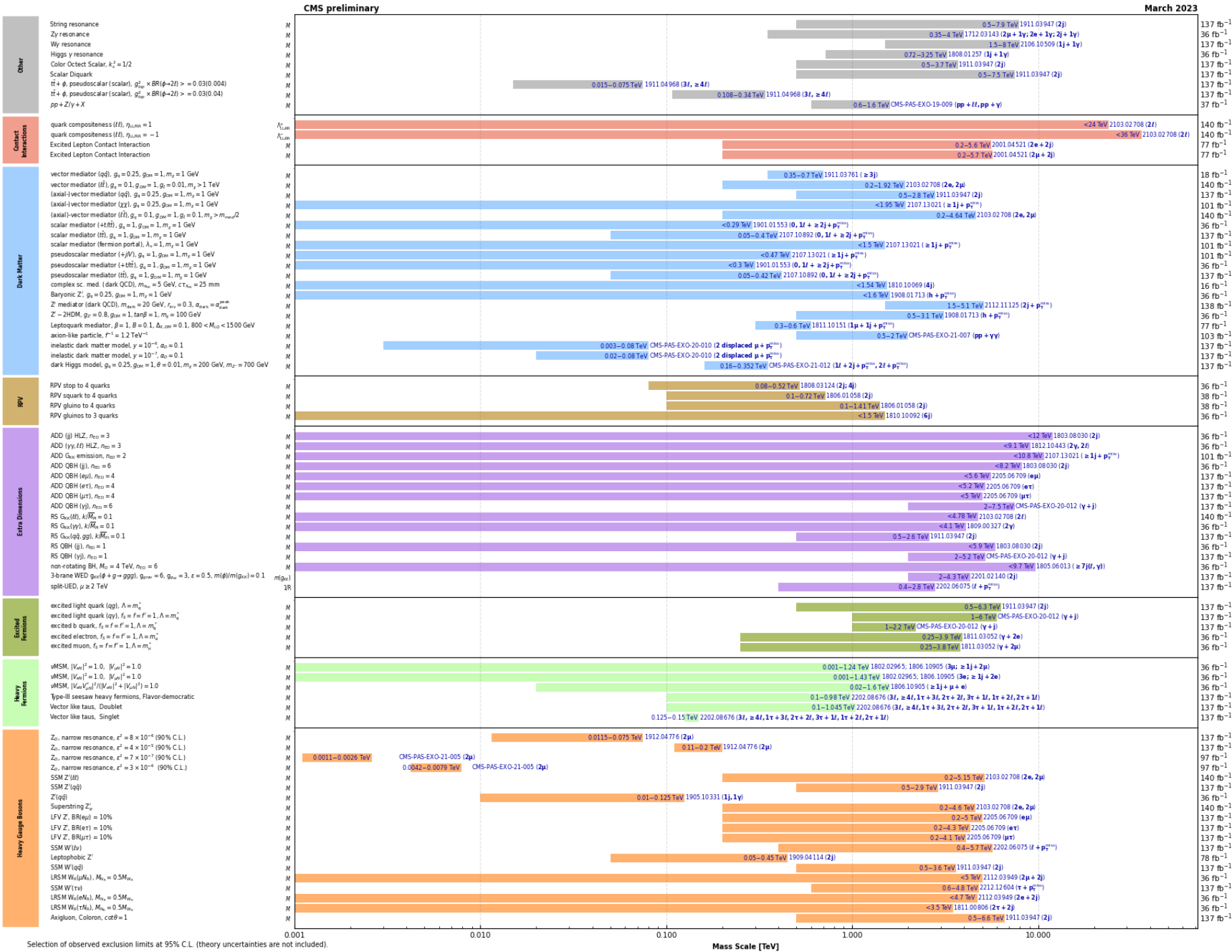
Covers exotic and SUSY searches

Using a better understanding of the detectors to push exploration into more challenging areas of analysis e.g. semi-visible jets

$\sqrt{s} = 8 \text{ TeV}$   $\sqrt{s} = 13 \text{ TeV}$  partial data  $\sqrt{s} = 13 \text{ TeV}$  full data

\*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).



# (Exotics)

Huge industry of searches for new particles by both experiments

Covers exotic and SUSY searches

Using a better understanding of the detectors to push exploration into more challenging areas of analysis e.g. semi-visible jets

# ATLAS SUSY Searches\* - 95% CL Lower Limits

March 2023

ATLAS Preliminary

$\sqrt{s} = 13$  TeV



Model	Signature	$\int \mathcal{L} dt$ [fb <sup>-1</sup> ]	Mass limit	Reference						
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{\chi}_1^0$	0 $e, \mu$ mono-jet	2-6 jets 1-3 jets	$E_T^{miss}$ $E_T^{miss}$	139 139	$\bar{q}$ [1x, 8x Degen.] $\bar{q}$ [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 5$ GeV	210.14293 2102.10674
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 $e, \mu$	2-6 jets	$E_T^{miss}$	139	$\tilde{g}$ $\tilde{g}$	Forbidden	2.3 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{\chi}_1^0) = 1000$ GeV	210.14293 210.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets	$E_T^{miss}$	139	$\tilde{g}$		2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	$E_T^{miss}$	139	$\tilde{g}$		2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	2204.13072
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0 $e, \mu$ SS $e, \mu$	7-11 jets 6 jets	$E_T^{miss}$ $E_T^{miss}$	139 139	$\tilde{g}$ $\tilde{g}$		1.97 1.15	$m(\tilde{\chi}_1^0) < 600$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	2008.06032 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 $e, \mu$ SS $e, \mu$	3 $b$ 6 jets	$E_T^{miss}$	139 139	$\tilde{g}$ $\tilde{g}$		2.45 1.25	$m(\tilde{\chi}_1^0) < 500$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	2211.08028 1909.08457
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$	2 $b$	$E_T^{miss}$	139	$\tilde{b}_1$ $\tilde{b}_1$	Forbidden	1.255 0.68	$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV < $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$	0 $e, \mu$ 2 $\tau$	6 $b$ 2 $b$	$E_T^{miss}$ $E_T^{miss}$	139 139	$\tilde{b}_1$ $\tilde{b}_1$	Forbidden	0.23-1.35 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\chi}_1^0$	0-1 $e, \mu$	$\geq 1$ jet	$E_T^{miss}$	139	$\tilde{t}_1$		1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 $e, \mu$	3 jets/1 $b$	$E_T^{miss}$	139	$\tilde{t}_1$	Forbidden	0.65	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 $\tau$	2 jets/1 $b$	$E_T^{miss}$	139	$\tilde{t}_1$	Forbidden	1.4	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 $e, \mu$ 0 $e, \mu$	2 $c$ mono-jet	$E_T^{miss}$ $E_T^{miss}$	36.1 139	$\tilde{t}_1$ $\tilde{t}_1$		0.85 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 $e, \mu$	1-4 $b$	$E_T^{miss}$	139	$\tilde{t}_1$		0.067-1.18	$m(\tilde{\chi}_1^0) = 500$ GeV	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$	1 $b$	$E_T^{miss}$	139	$\tilde{t}_2$	Forbidden	0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via WZ	Multiple $\ell$ /jets $ee, \mu\mu$	$\geq 1$ jet	$E_T^{miss}$ $E_T^{miss}$	139 139	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ $\tilde{\chi}_1^+/\tilde{\chi}_2^0$		0.96 0.205	$m(\tilde{\chi}_1^0) = 0$ , wino-bino $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^+\tilde{\chi}_1^+$ via WW	2 $e, \mu$		$E_T^{miss}$	139	$\tilde{\chi}_1^+$		0.42	$m(\tilde{\chi}_1^0) = 0$ , wino-bino	1908.08215
	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via Wh	Multiple $\ell$ /jets		$E_T^{miss}$	139	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$	Forbidden	1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^+\tilde{\chi}_1^+$ via $\tilde{L}_i/\tilde{\nu}$	2 $e, \mu$		$E_T^{miss}$	139	$\tilde{\chi}_1^+$		1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$		$E_T^{miss}$	139	$\tilde{\tau}$	$[\tilde{\tau}_L, \tilde{\tau}_{R,1}]$	0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660
	$\tilde{L}_{L,R}\tilde{L}_{L,R}, \tilde{L} \rightarrow \tilde{L}\tilde{\chi}_1^0$	2 $e, \mu$ $ee, \mu\mu$	0 jets $\geq 1$ jet	$E_T^{miss}$ $E_T^{miss}$	139 139	$\tilde{L}$ $\tilde{L}$		0.7 0.256	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{L}) - m(\tilde{\chi}_1^0) = 10$ GeV	1908.08215 1911.12606
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$ 4 $e, \mu$ 0 $e, \mu$ 2 $e, \mu$	$\geq 3$ $b$ 0 jets $\geq 2$ large jets $\geq 2$ jets	$E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$	36.1 139 139 139	$\tilde{H}$ $\tilde{H}$ $\tilde{H}$ $\tilde{H}$		0.13-0.23 0.55 0.45-0.93 0.77	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 0.5$	1806.04030 2103.11684 2108.07586 2204.13072	
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^+$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk	1 jet	$E_T^{miss}$	139	$\tilde{\chi}_1^+$ $\tilde{\chi}_1^+$		0.66 0.21	Pure Wino Pure higgsino	2201.02472 2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{miss}$	139	$\tilde{g}$		2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{miss}$	139	$\tilde{g}$	$[\tau(\tilde{g}) = 10$ ns]	2.2	$m(\tilde{\chi}_1^0) = 100$ GeV	2205.06013
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{G}$	Displ. lep		$E_T^{miss}$	139	$\tilde{t}_1$		0.7	$\tau(\tilde{t}_1) = 0.1$ ns $\tau(\tilde{t}_1) = 0.1$ ns $\tau(\tilde{t}_1) = 10$ ns	2011.07812 2011.07812 2205.06013
	pixel dE/dx		$E_T^{miss}$	139	$\tilde{\tau}$		0.34 0.36			
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 $e, \mu$		$E_T^{miss}$	139	$\tilde{\chi}_1^+/\tilde{\chi}_1^0$	[BR(Z $\tau$ )=1, BR(Z $e$ )=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\nu\nu$	4 $e, \mu$	0 jets	$E_T^{miss}$	139	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$	$[\lambda_{133} \neq 0, \lambda_{124} \neq 0]$	0.95 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\bar{q}q$	Multiple	4-5 large jets	$E_T^{miss}$	36.1	$\tilde{g}$	$[\tilde{m}(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV]	1.3 1.9	Large $\mathcal{M}_{12}$	1804.03568
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	$\geq 4b$	$E_T^{miss}$	139	$\tilde{t}_1$	$[\lambda'_{323} = 2e-4, 1e-2]$	0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like $m(\tilde{\chi}_1^0) = 500$ GeV	ATLAS-CONF-2018-003
	$\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow bbs$	Multiple	$\geq 4b$	$E_T^{miss}$	139	$\tilde{t}_1$		0.95		2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 $b$		$E_T^{miss}$	36.7	$\tilde{t}_1$	[ $qq, bs$ ]	0.42 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 $e, \mu$ 1 $\mu$	2 $b$ DV	$E_T^{miss}$	36.1 136	$\tilde{t}_1$		0.4-1.45 1.6	$BR(\tilde{t}_1 \rightarrow b\ell/h\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%$ , $\cos\theta = 1$	1710.05544 2003.11956	
$\tilde{\chi}_1^+\tilde{\chi}_2^0/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu$	$\geq 6$ jets	$E_T^{miss}$	139	$\tilde{\chi}_1^0$		0.2-0.32	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.

10<sup>-1</sup> 1 Mass scale [TeV]

Huge industry of searches for new particles by both experiments

Covers exotic and SUSY searches

Using a better understanding of the detectors to push exploration into more challenging areas of analysis e.g. semi-visible jets



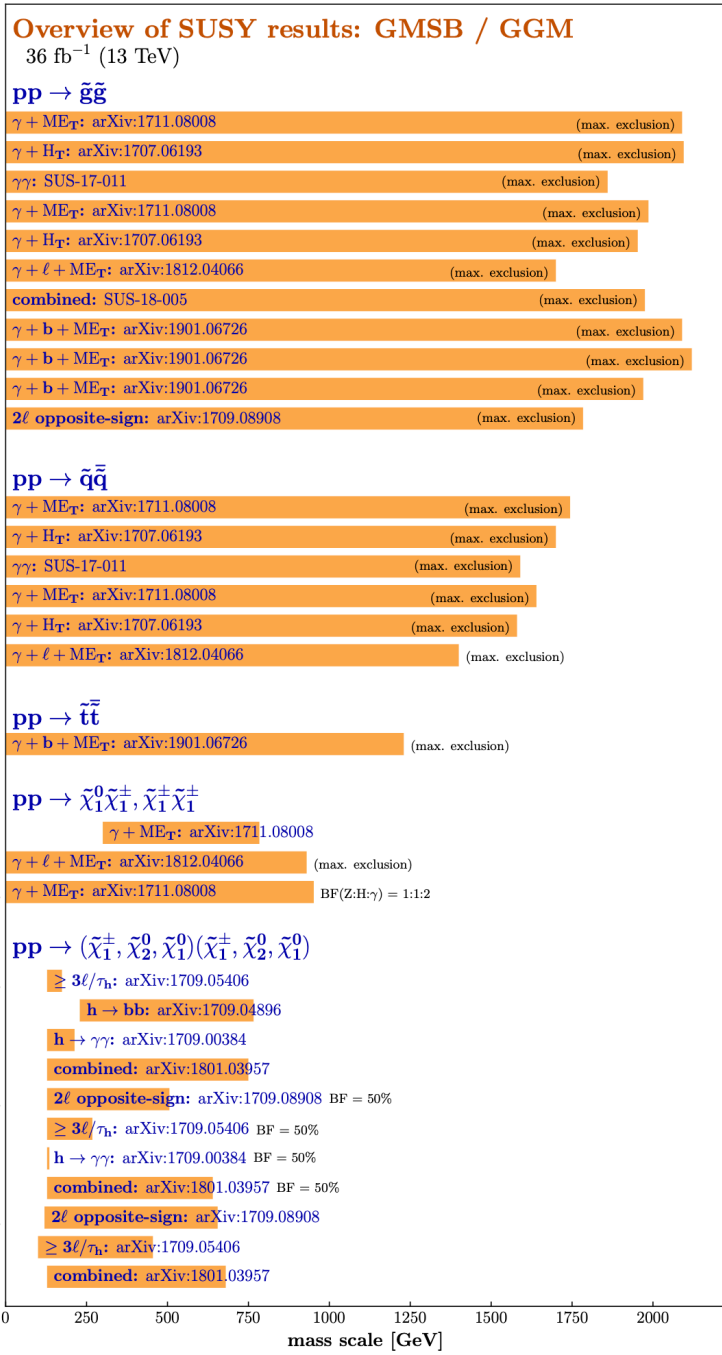


# (SUSY)

Huge industry of searches for new particles by both experiments

Covers exotic and SUSY searches

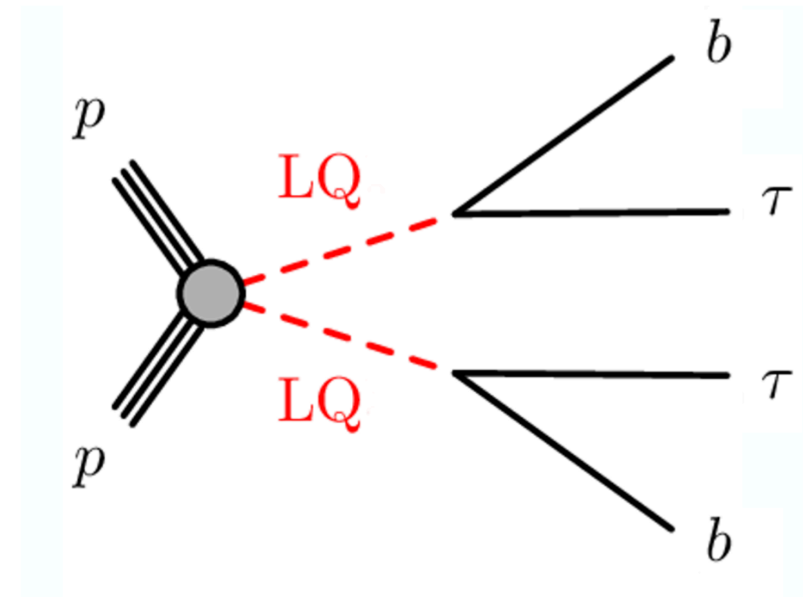
Using a better understanding of the detectors to push exploration into more challenging areas of analysis e.g. semi-visible jets



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities  $\Delta M$  and  $x$  represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to  $\Delta M$ , respectively, unless indicated otherwise.

# Direct searches: Leptoquark decay to $b\tau$

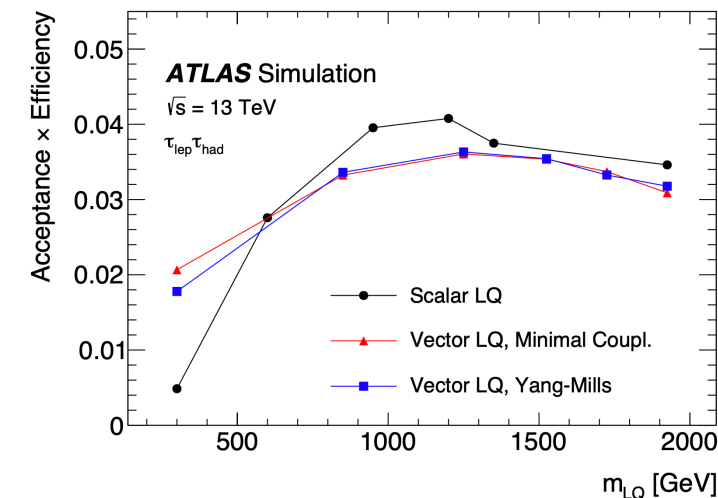
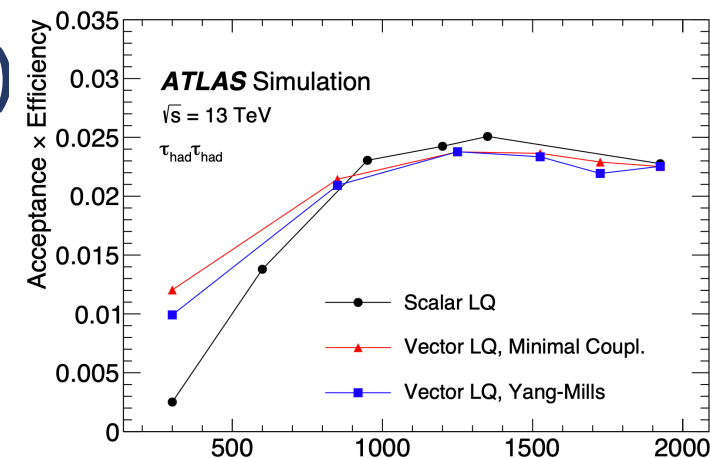
- Assumes leptoquark (LQ) pair production
- Assume decay only into the same generation
- Use  $b\tau b\tau$  selection
- $\tau$ 's are reconstructed into lep(tonic) and had(ronic) final states:
  - $\tau_{had}$  is seeded by jets
  - $\tau_{lep}$  is seeded by  $e$  and  $\mu$
- Backgrounds include  $t\bar{t}$ , single top, mis-reconstructed  $\tau$ 's, Z+jets



# Direct searches: Leptoquark decay to $b\tau$

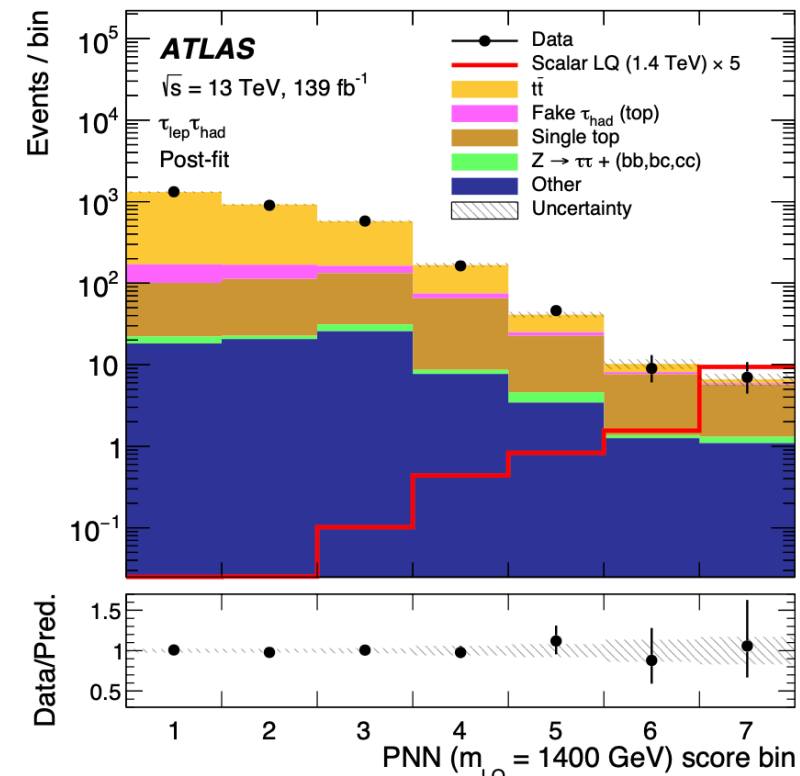
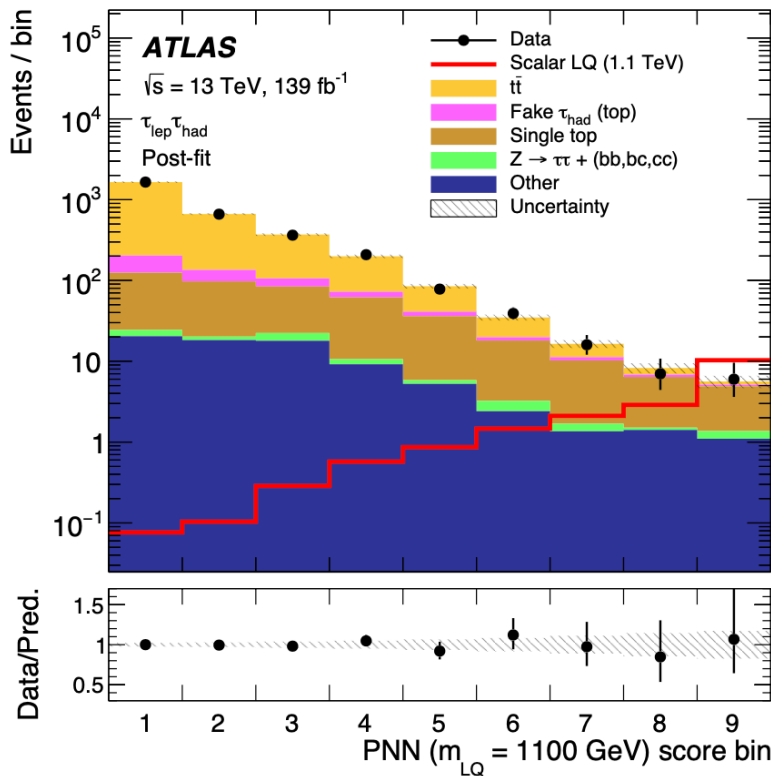
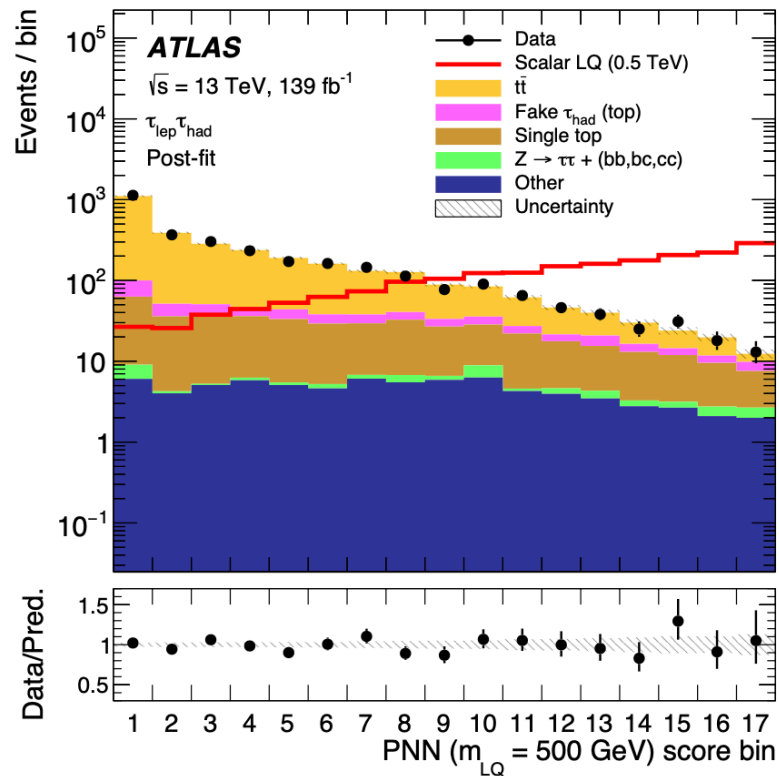
- Selection focuses on 1 prong  $\tau_{lep}$  and 1 and 3 prong  $\tau_{had}$  events
- O(%) overall efficiency (depends on model/mass)

	$\tau_{lep}\tau_{had}$ channel	$\tau_{had}\tau_{had}$ channel
$e/\mu$ selection	= 1 'signal' $e$ or $\mu$ $p_T^e > 25, 27$ GeV $p_T^\mu > 21, 27$ GeV	No 'veto' $e$ or $\mu$
$\tau_{had-vis}$ selection	= 1 $\tau_{had-vis}$ $p_T^\tau > 100$ GeV	= 2 $\tau_{had-vis}$ $p_T^\tau > 100, 140, 180$ (20) GeV
Jet selection		$\geq 2$ jets $p_T^{jet} > 45$ (20) GeV 1 or 2 $b$ -jets
Additional selection		Opposite charge $e, \mu, \tau_{had}$ and $\tau_{had}$ $m_{\tau\tau}^{MMC} \notin 40 - 150$ GeV $E_T^{miss} > 100$ GeV $s_T > 600$ GeV



# Direct searches: Leptoquark decay to $b\tau$

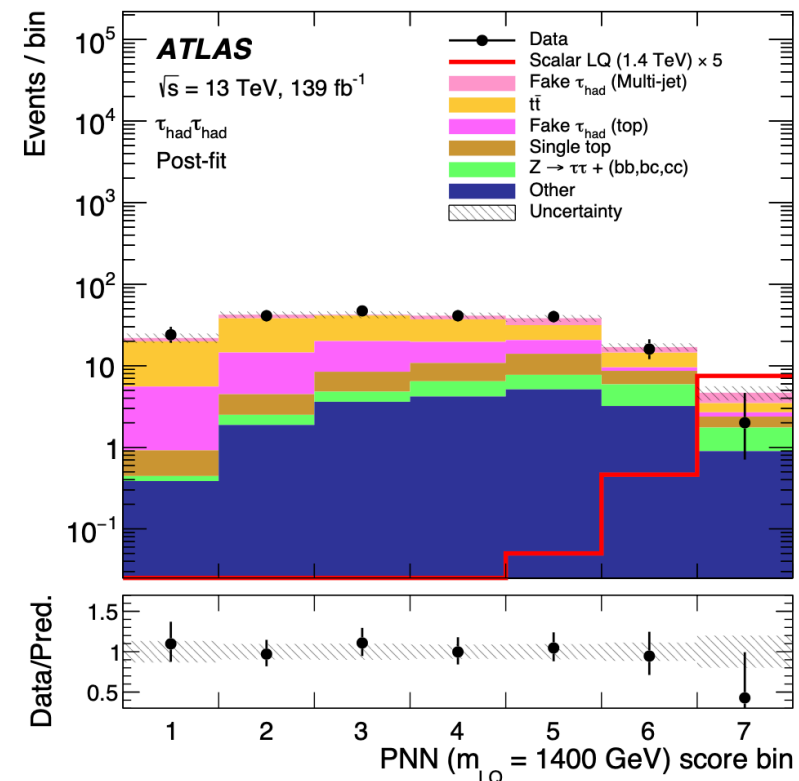
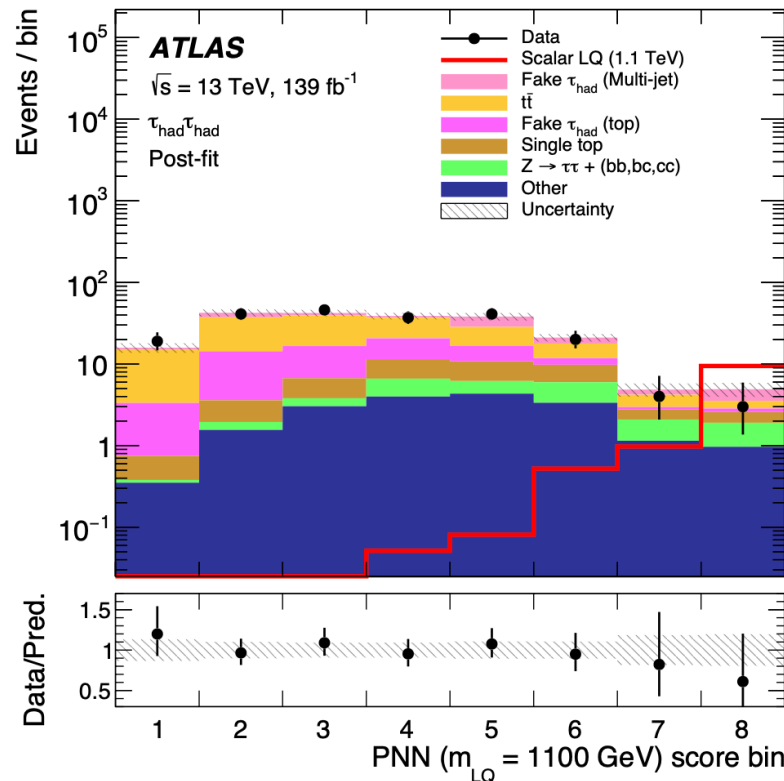
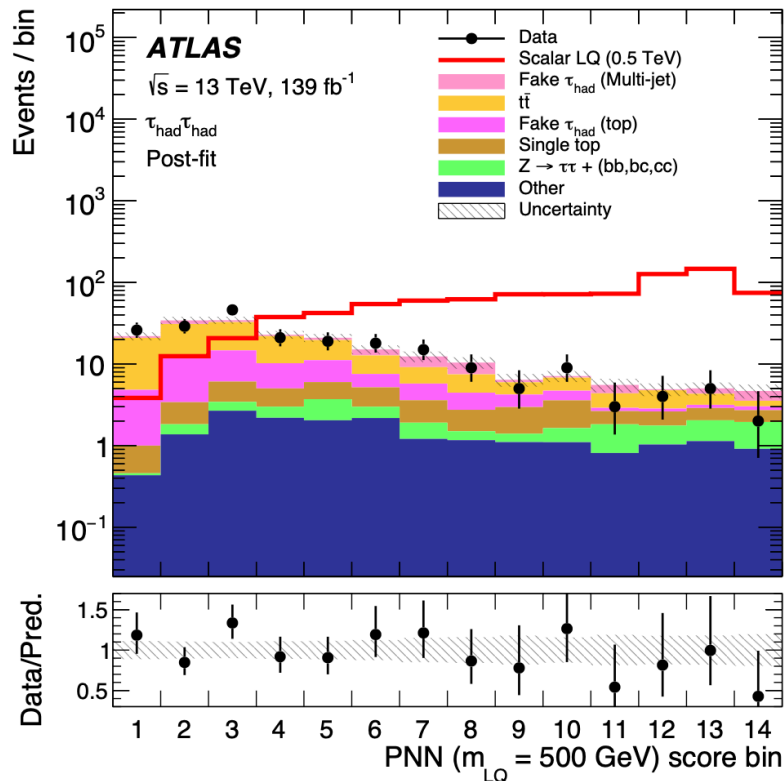
- Uses parameterised NN (with LQ mass) to extract signal from background



lephad

# Direct searches: Leptoquark decay to $b\tau$

- Uses parameterised NN (with LQ mass) to extract signal from background



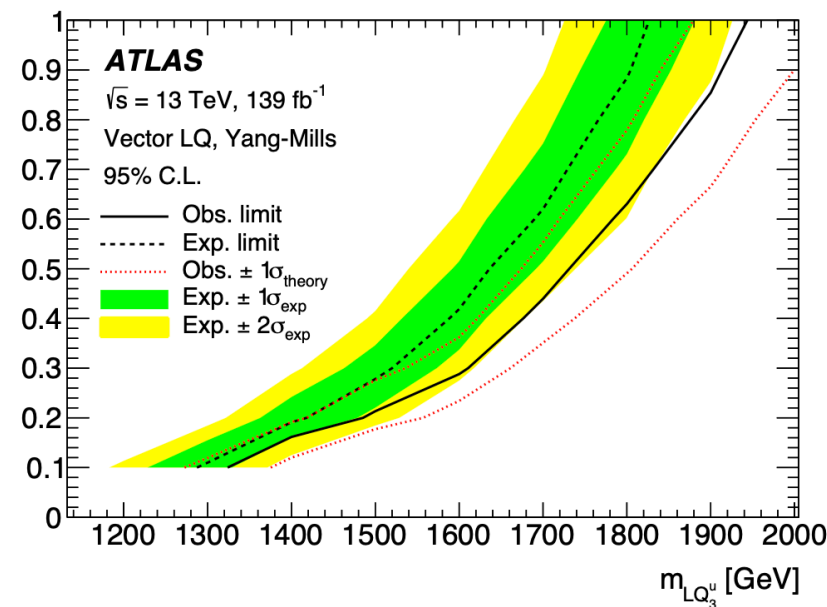
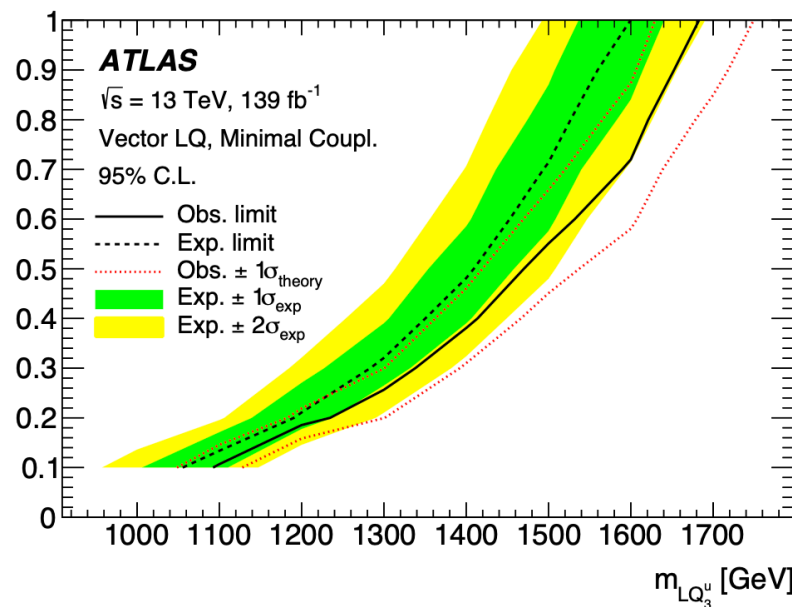
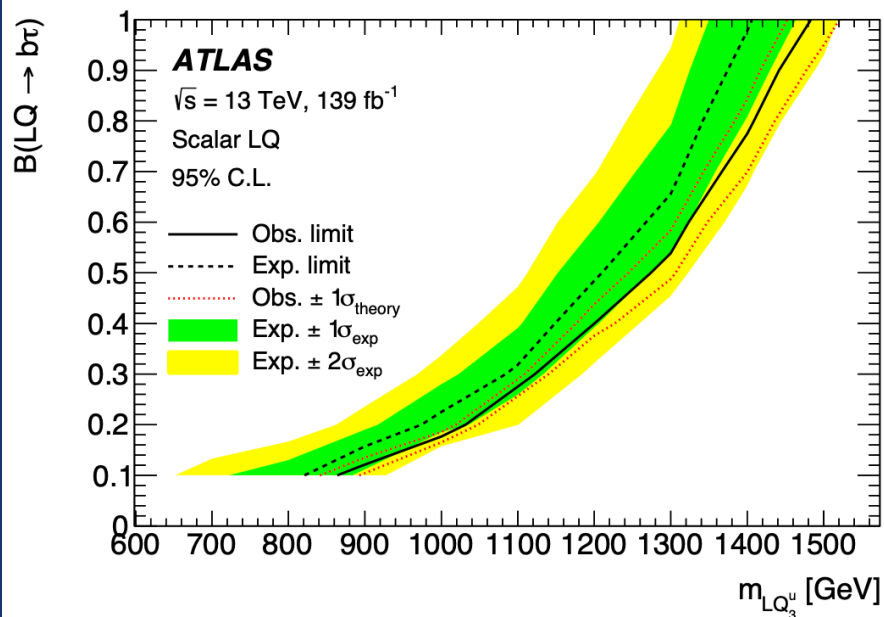
hadhad



# Direct searches: Leptoquark decay to $b\tau$

- No signal observed: place limits on models

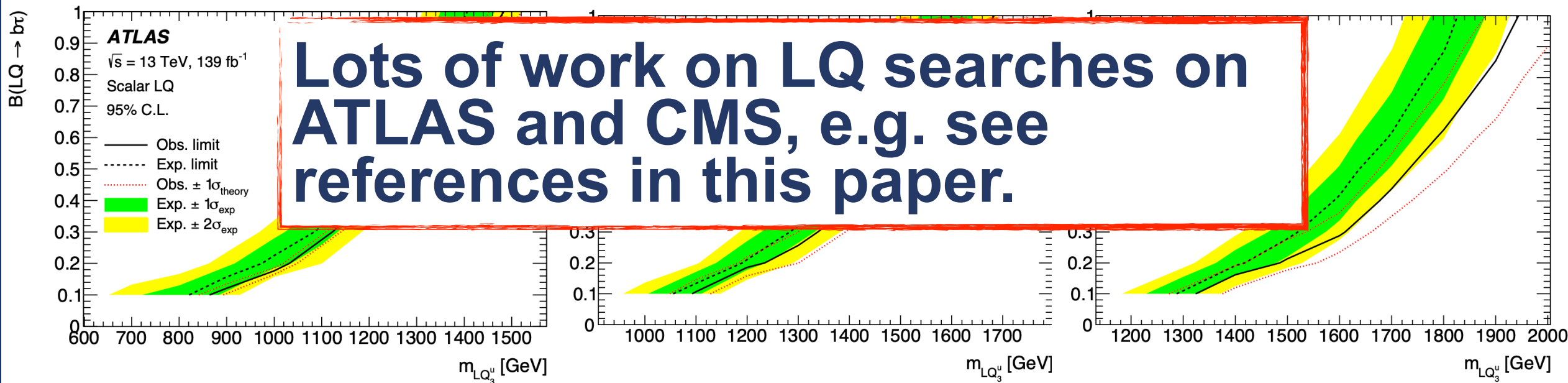
	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1490	1410
Vector LQ (minimal-coupling)	1690	1600
Vector LQ (Yang-Mills)	1960	1840



# Direct searches: Leptoquark decay to $b\tau$

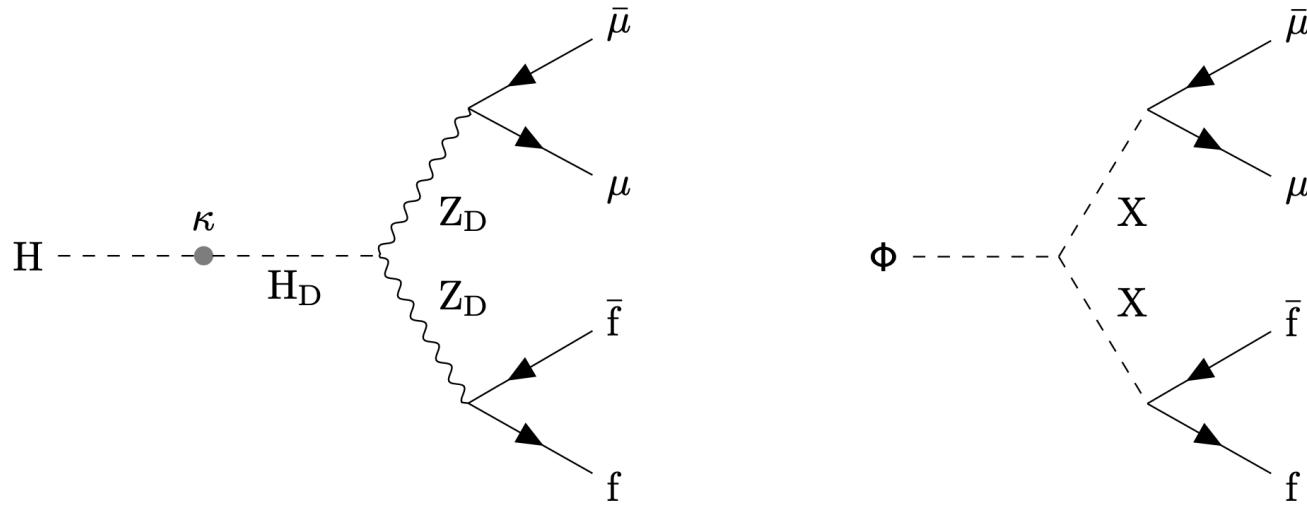
- No signal observed: place limits on models

	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1490	1410
Vector LQ (minimal-coupling)	1690	1600
Vector LQ (Yang–Mills)	1960	1840



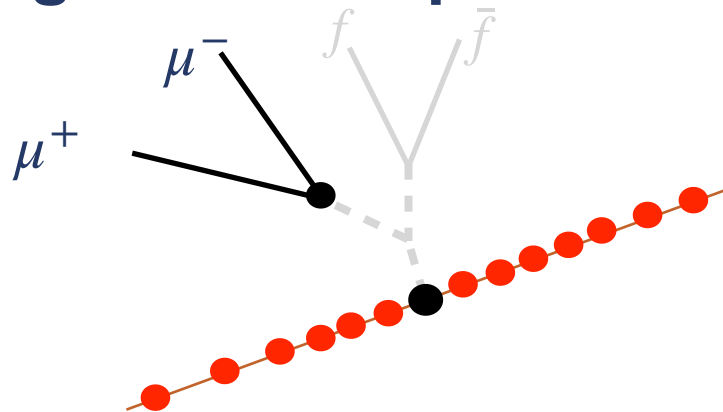
# Direct searches: Long Lived Particles (LLPs)

- Wide range of theoretical possibilities examples include:



- Higgs portal model dark photon ( $Z_D$ ) decay [left]
- Heavy scalar ( $\Phi$ ) decaying to LLPs ( $X$ ) [right]

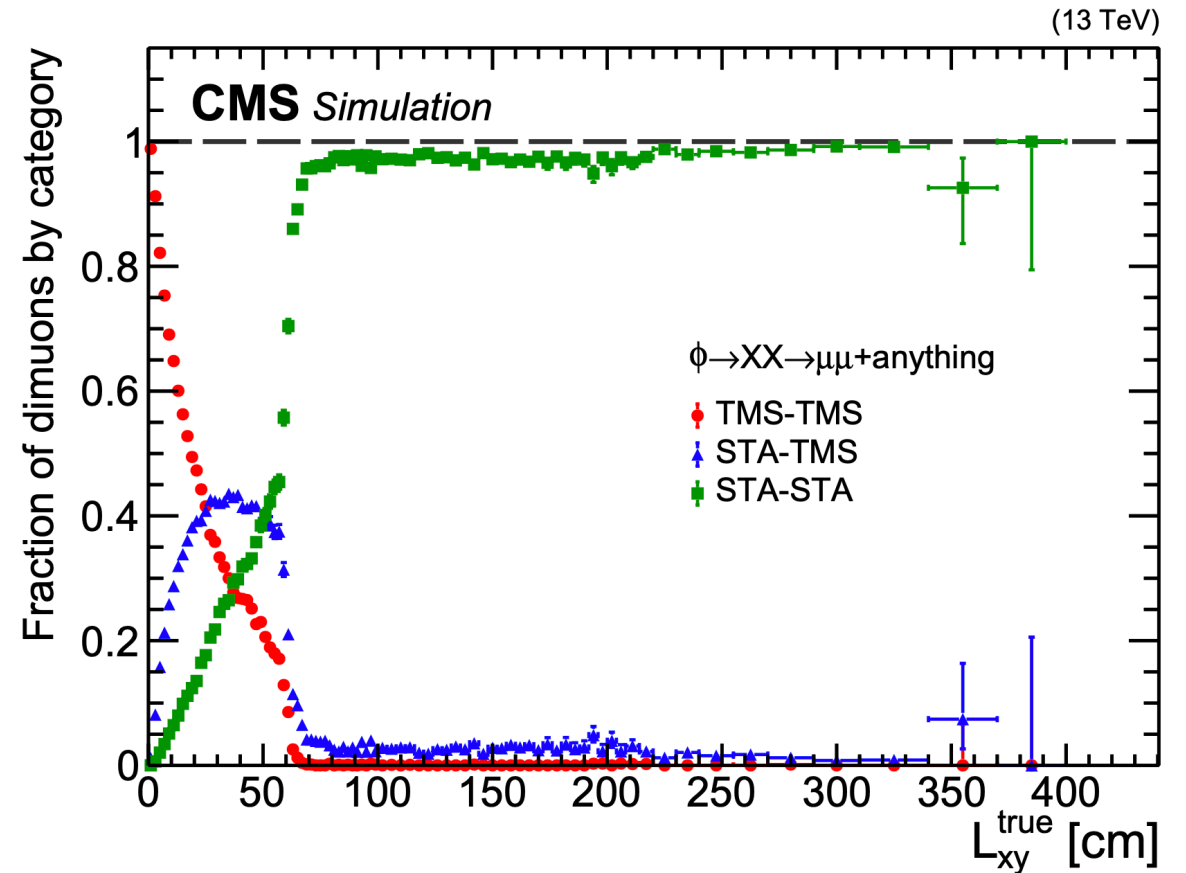
- Signature: displaced vertices from dimuons



- Select primary vertex as hardest scattering in event (based on tracks)
- Common displaced vertex fitted to a pair of tracks consistent with  $\mu^+ \mu^-$

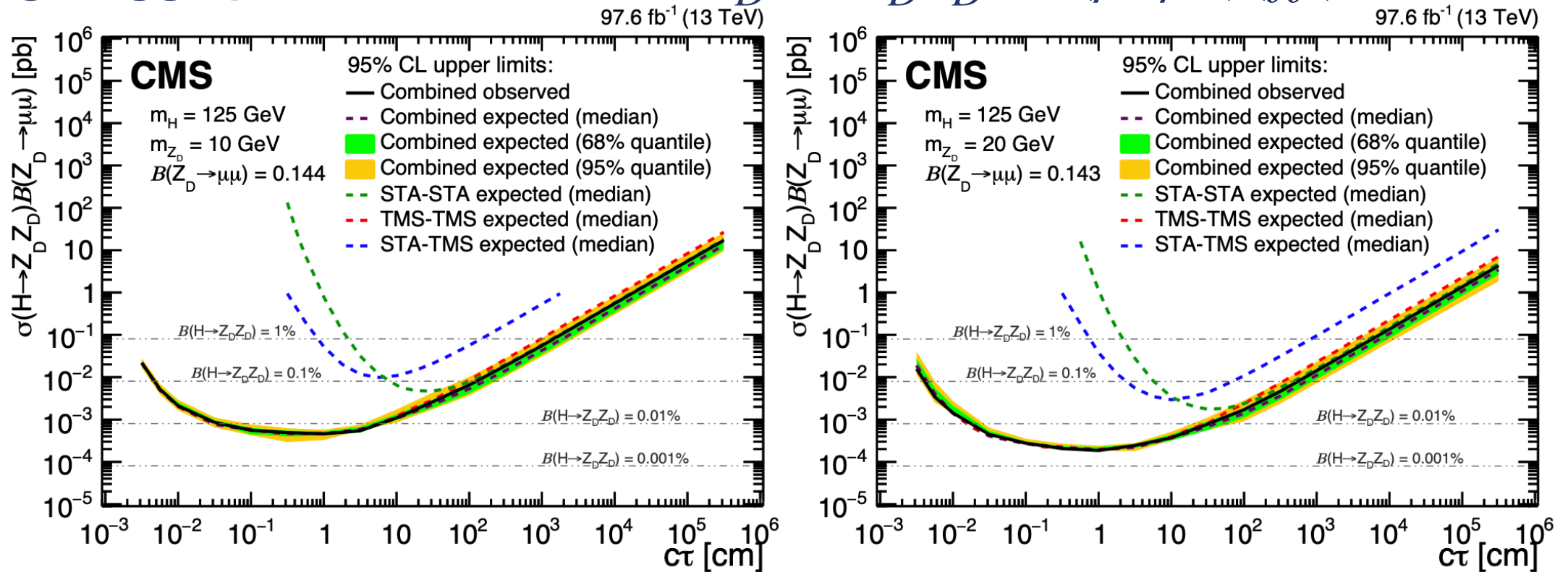
# Direct searches: Long Lived Particles (LLPs)

- TMS muons:
  - tracker + muon system
  - good momentum resolution
  - range limited by tracker radius
- STA muons:
  - muon system only
  - lower momentum resolution
  - works out to several meters
- Combinations of these muons provide coverage out to 4m in transverse decay length:  $L_{xy}$



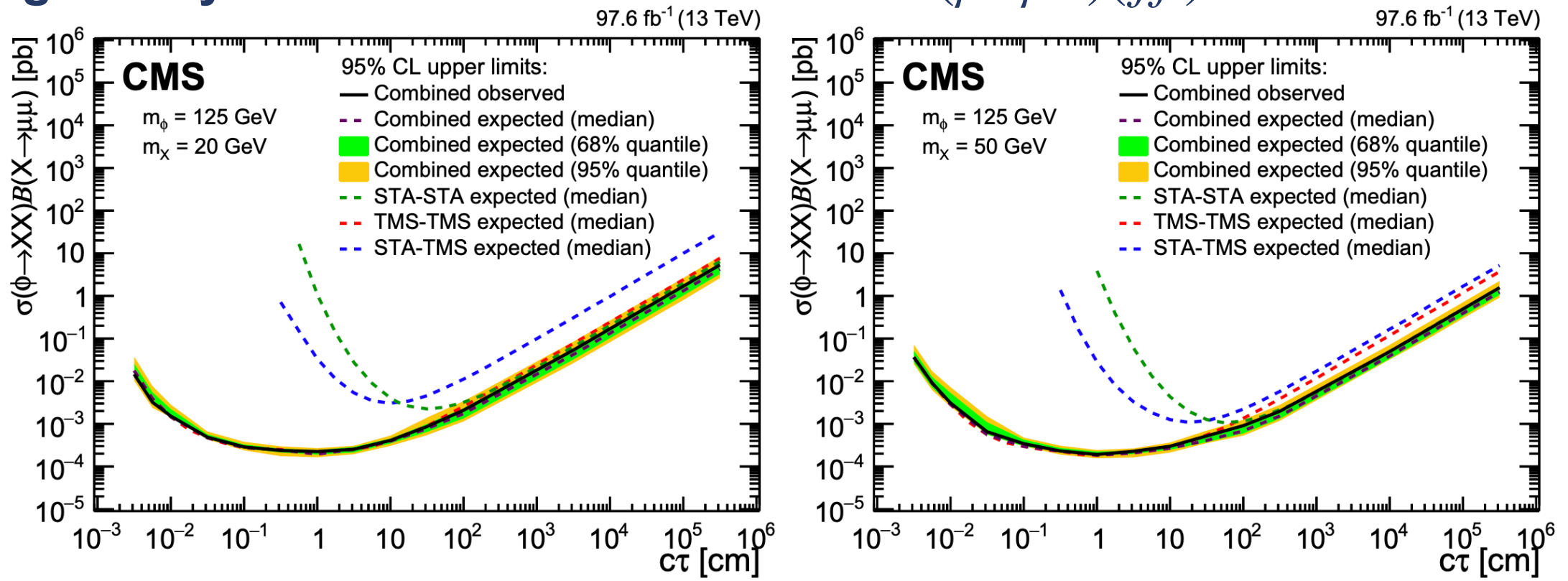
# Direct searches: Long Lived Particles (LLPs)

- No dimuon resonances found
- Limits placed for different assumed intermediate particle masses  
e.g. Higgs portal model:  $H \rightarrow H_D \rightarrow Z_D Z_D \rightarrow (\mu^+ \mu^-)(f\bar{f})$



# Direct searches: Long Lived Particles (LLPs)

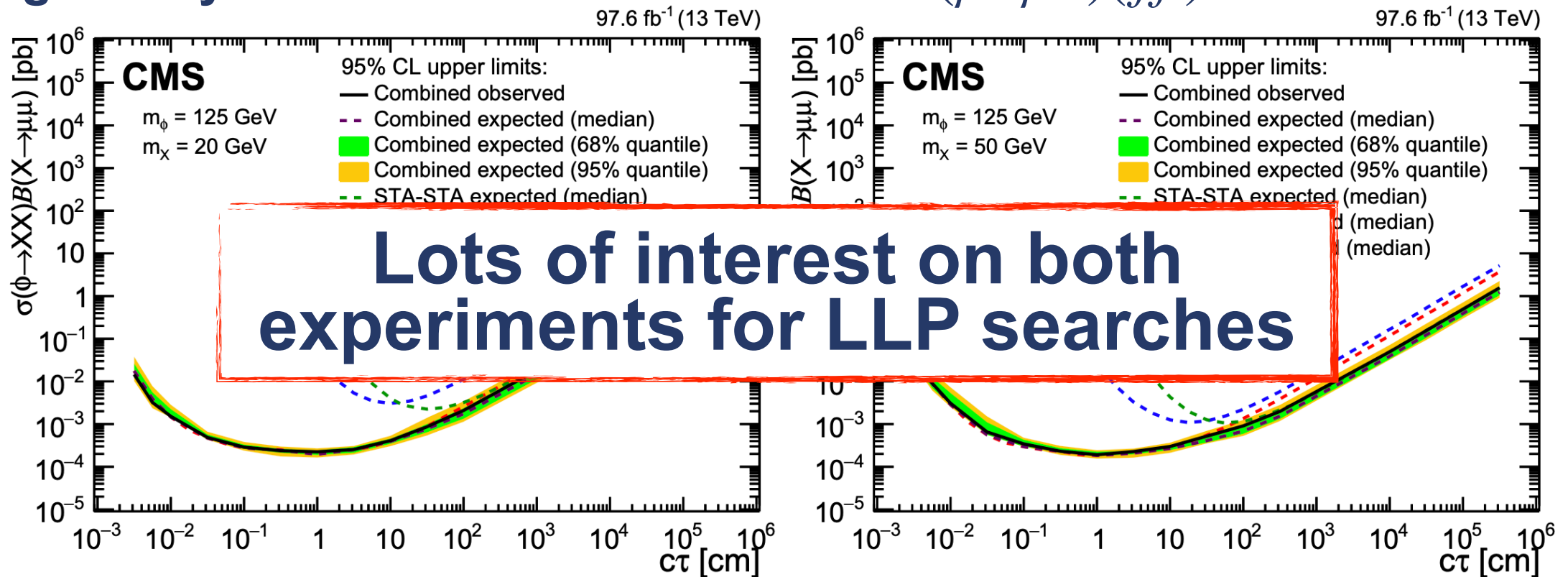
- No dimuon resonances found
- Limits placed for different assumed intermediate particle masses  
e.g. Heavy scalar scenario:  $\Phi \rightarrow XX \rightarrow (\mu^+ \mu^-)(f\bar{f})$





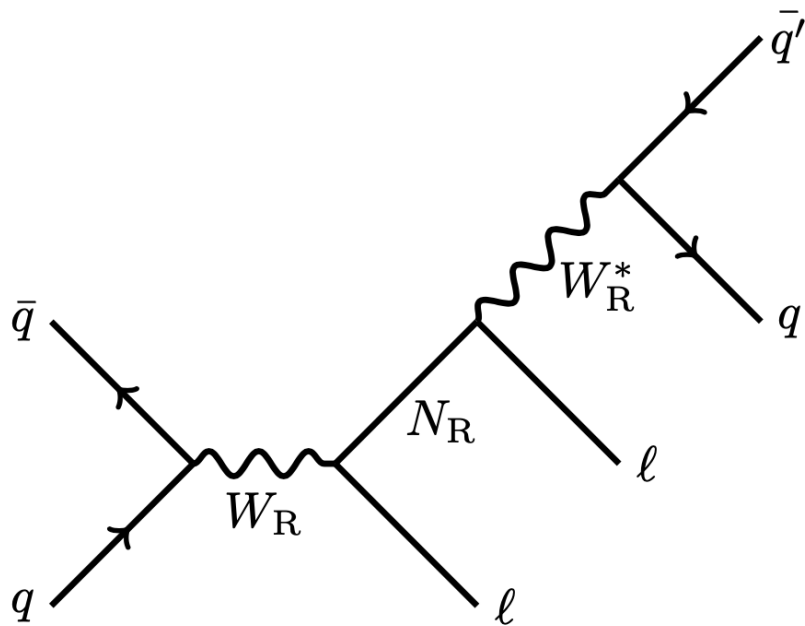
# Direct searches: Long Lived Particles (LLPs)

- No dimuon resonances found
- Limits placed for different assumed intermediate particle masses  
e.g. Heavy scalar scenario:  $\Phi \rightarrow XX \rightarrow (\mu^+ \mu^-)(f\bar{f})$

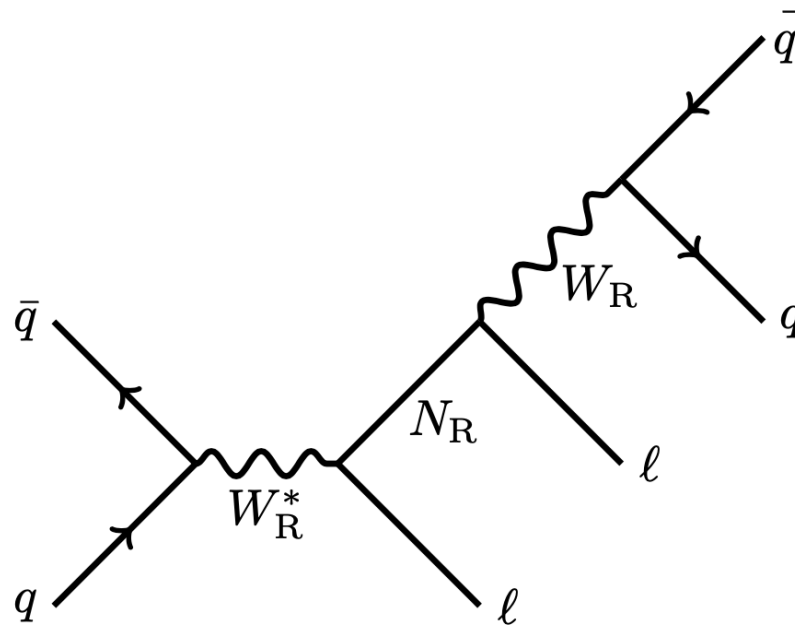


# Direct searches: Heavy neutral lepton

- Sea Saw mechanism predicts right handed neutrinos
- The Left-Right Symmetric Model extension predicts a heavy right handed neutrino  $N_R$  and partners of the  $W$  and  $Z$  boson,  $W_R$  and  $Z_R$



$$m(W_R) > m(N_R)$$



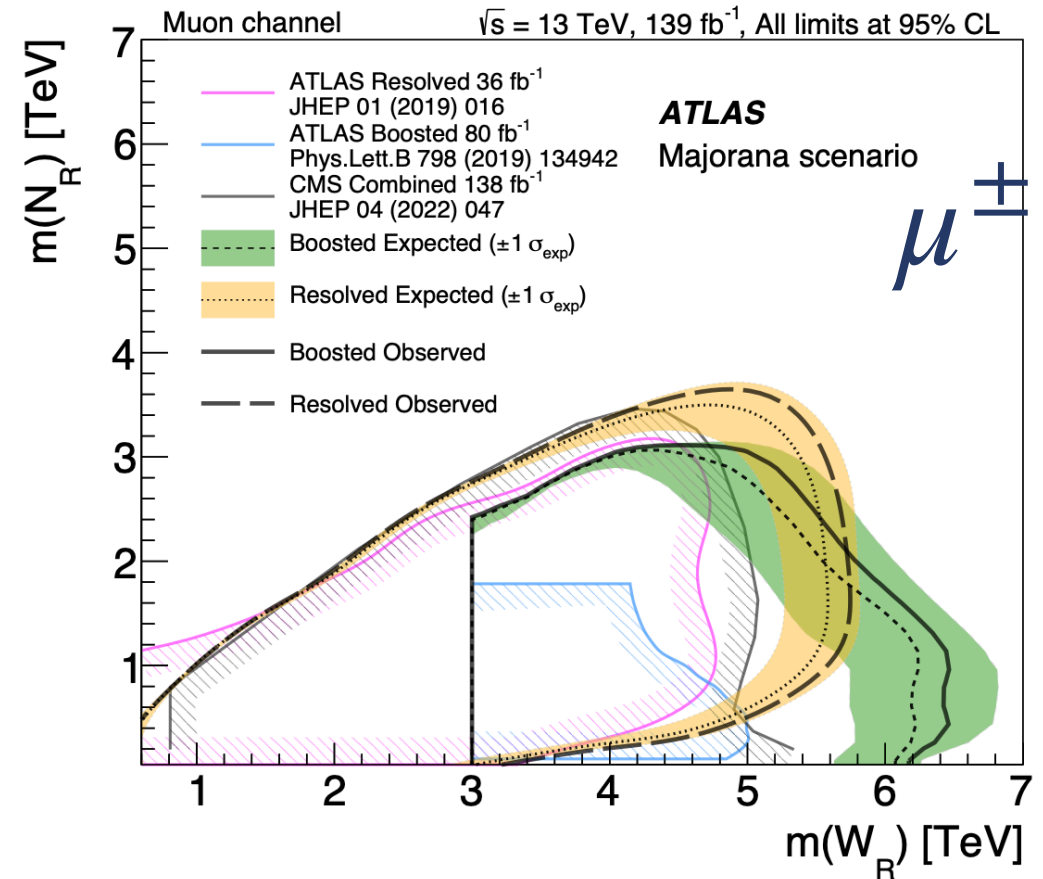
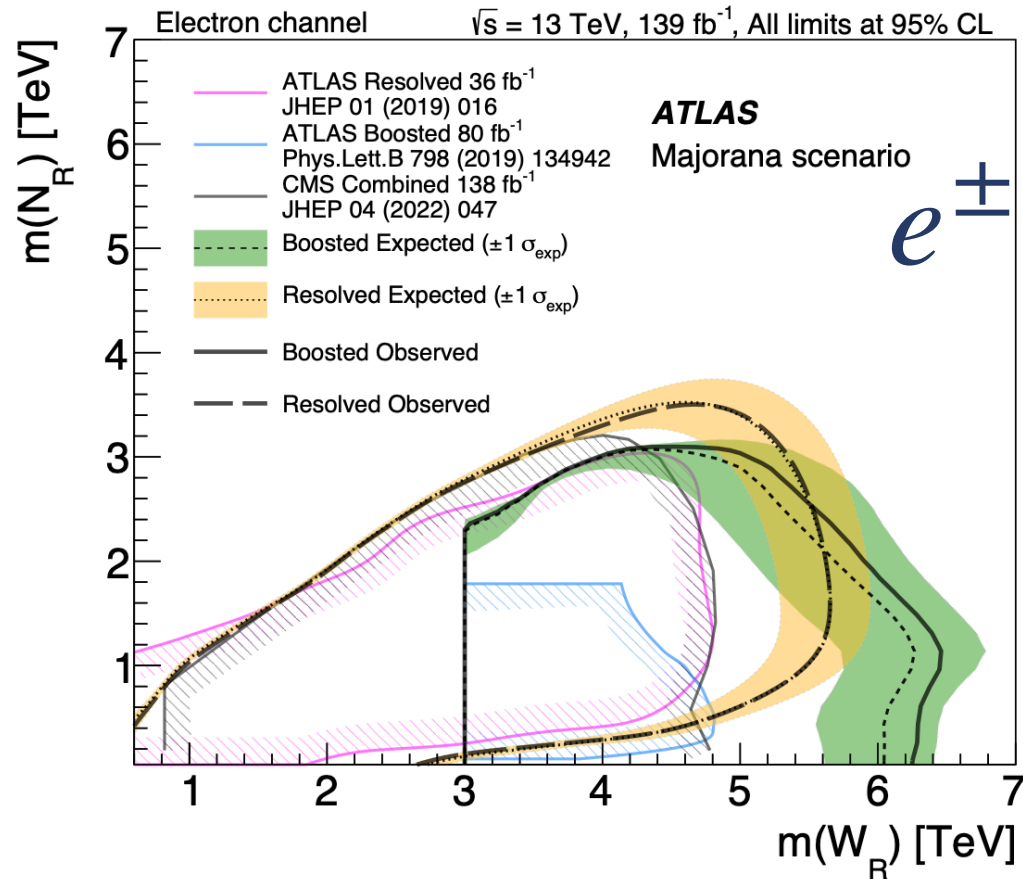
$$m(W_R) < m(N_R)$$

Lepton charge distinguishes between Dirac and Majorana neutrino structure

Analysis neglects lepton flavour mixing

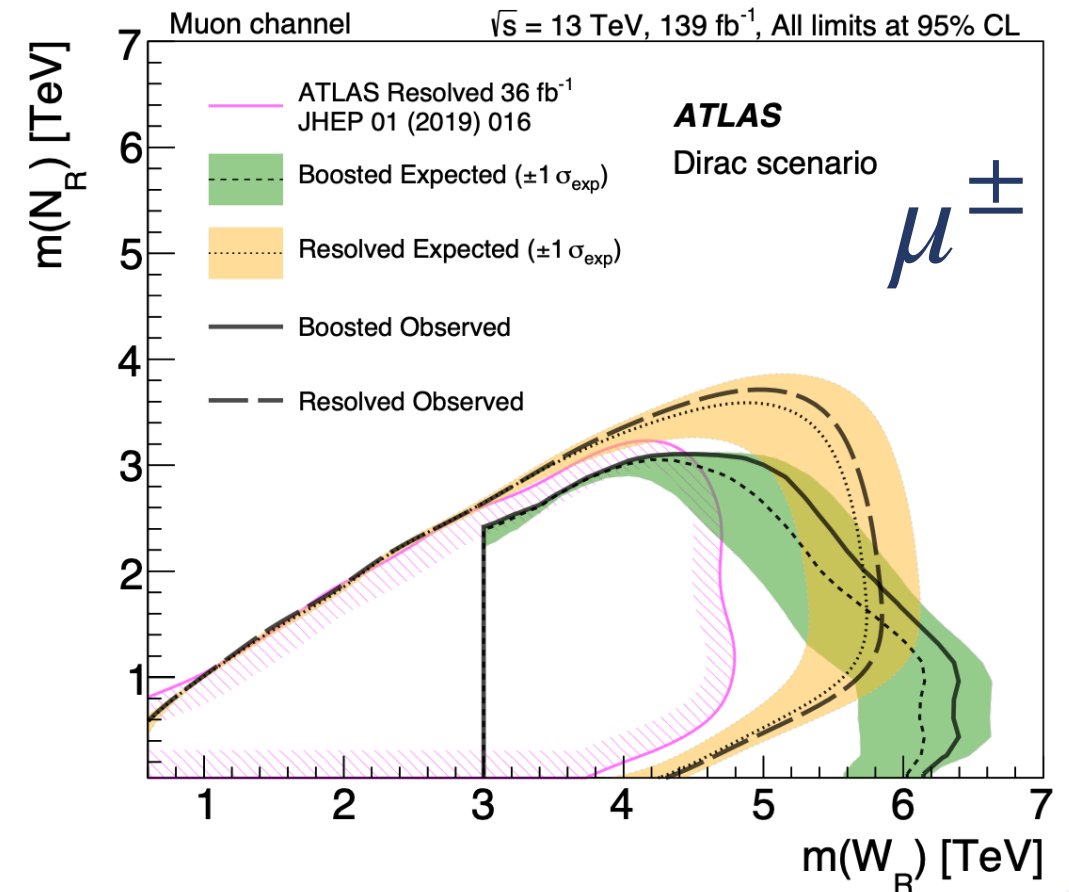
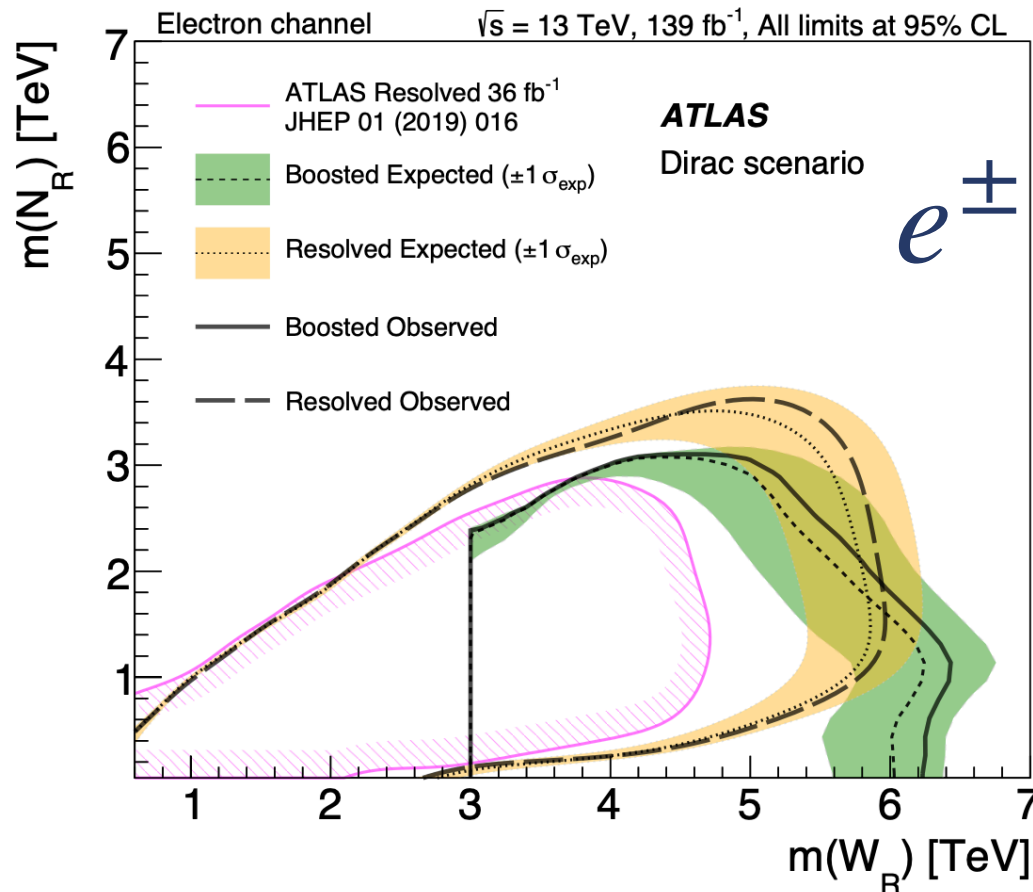
# Direct searches: Heavy neutral lepton

- No signal found
- Exclusion limits for the Majorana neutrino scenario set



# Direct searches: Heavy neutral lepton

- No signal found
- Exclusion limits for the Dirac neutrino scenario set



# Summary

- High  $p_t$  physics linked to our understanding of flavour via the Higgs
- CP violation searches using Higgs couplings complement searches performed at low energy B, D, K ( $\nu$ 's) and with top
- Searches for effects beyond the SM, either directly or indirectly using high  $p_t$  data have not paid dividend (yet)
- Run 3 has only just started, and with the High Luminosity upgrade construction underway, expect significant increases in data to continue the quest for new physics
- New ideas are constantly being tested, and the increase of data will ensure this trend continues through into the HL-LHC era



# Additional slides

# Couplings to fermions

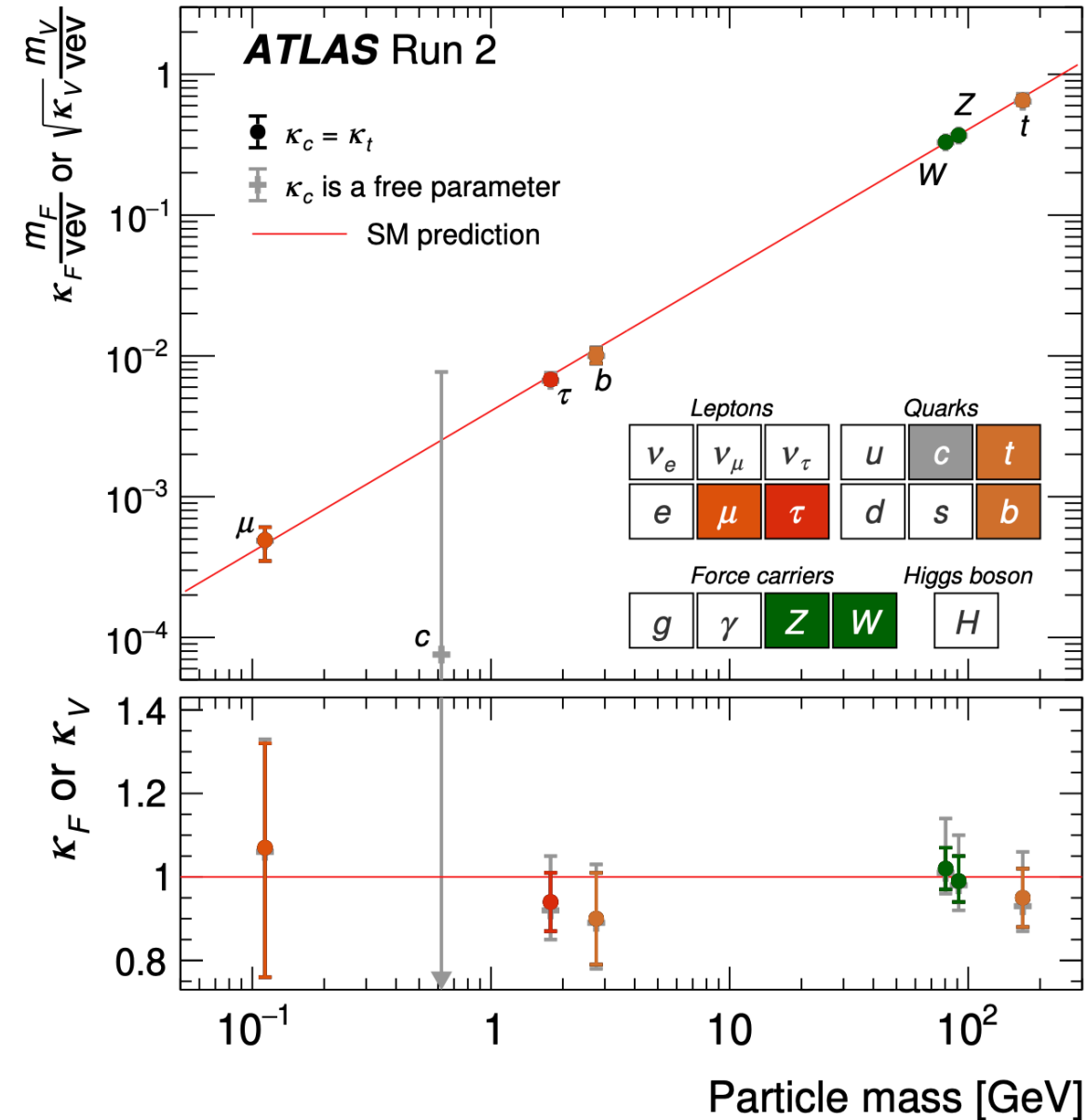
- The CKM matrix is derived from fermion mass diagonalisation in the SM

$$U' M' U'^{\dagger} = D' = \text{diag} \left( \frac{m_d}{m_b}, \frac{m_s}{m_b}, 1 \right)$$

$$U M U^{\dagger} = D = \text{diag} \left( \frac{m_{\mu}}{m_t}, \frac{m_c}{m_t}, 1 \right),$$

$$V_{CKM} = U U'^{\dagger}$$

- Couplings deviating from the SM would have implications for the CKM picture



# CP violation searches e.g ttH and tHq, tHW

- XGBoost used for CP determination
- Shape differences in  $m_{ttH}$ ,  $\Delta\eta$  and  $\Delta R$  feed into CP determination
- e.g. the 2ISS + 0th channel

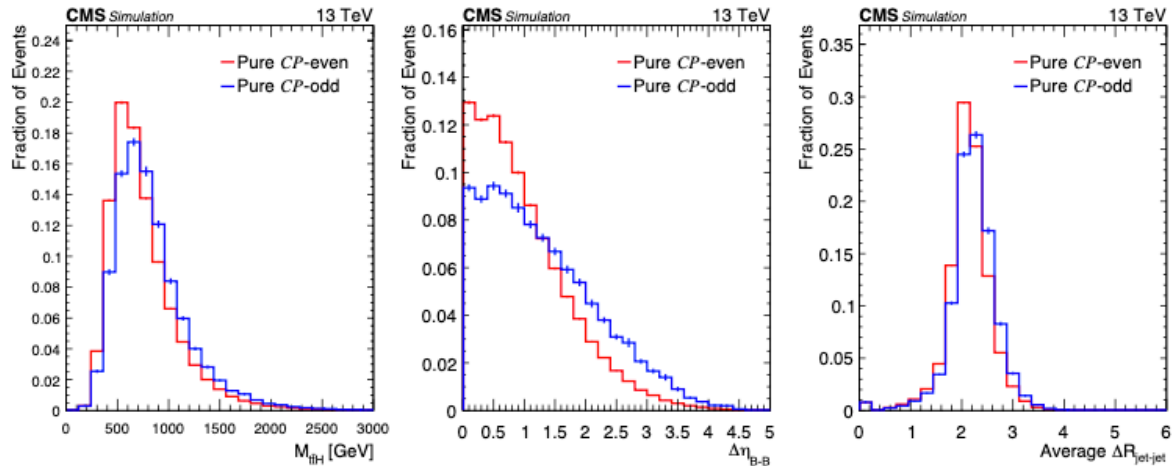


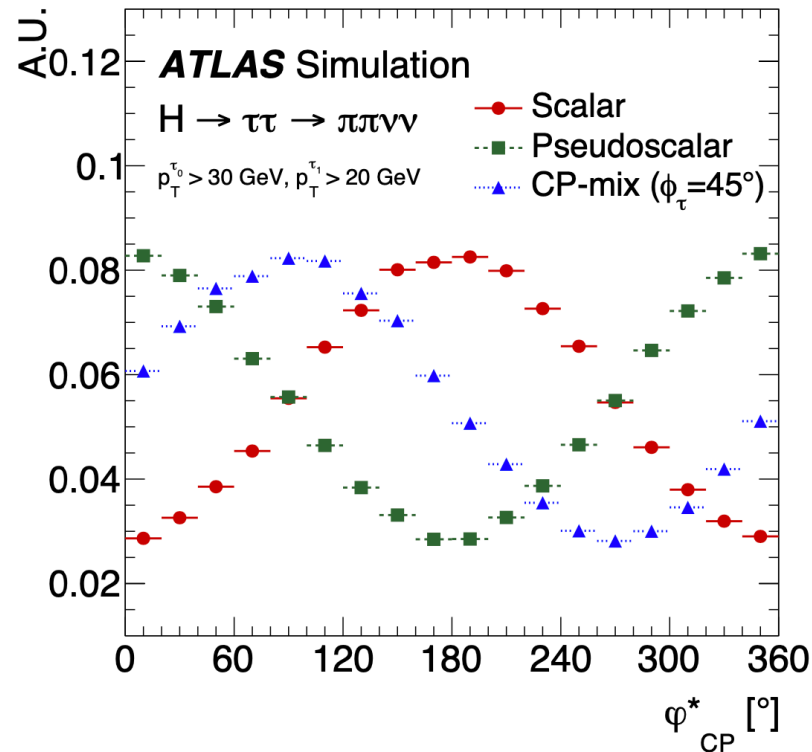
Table 4: Input features for the three BDTs. A check mark (✓) indicates the variable is used in a given final state, whereas a long dash (—) indicates the variable is not used in that final state.

Variable description	2ℓSS + 0τ <sub>h</sub>	2ℓSS + 1τ <sub>h</sub>	3ℓ + 0τ <sub>h</sub>
$p_T$ of jet 1	—	—	✓
$p_T$ of jet 2	—	—	✓
$p_T$ of lepton 1	✓	✓	✓
$p_T$ of lepton 2	✓	✓	✓
$p_T$ of lepton 3	—	—	✓
$p_T$ of $\tau$ lepton	—	✓	—
$\eta$ of lepton 1	✓	✓	—
$\eta$ of lepton 2	✓	✓	—
$\eta$ of $\tau$ lepton	—	✓	—
$\phi$ of lepton 1	✓	✓	—
$\phi$ of lepton 2	✓	✓	—
$\phi$ of $\tau$ lepton	—	✓	—
$m_T(l_1, p_T^{\text{miss}}) + p_T^{\text{miss}}$	✓	—	—
$m_T(l_2, p_T^{\text{miss}}) + p_T^{\text{miss}}$ system	✓	—	—
$\Delta R$ of lepton 1 to its closest jet	✓	✓	✓
$\Delta R$ of lepton 2 to its closest jet	✓	✓	✓
Invariant mass of the reconstructed $t\bar{t}H$ system ( $M_{t\bar{t}H} = \sum_i p_i^{\text{lep}} + \vec{p}_T^{\text{miss}} + \sum_{i \leq k} p_i^{\text{jet},*}$ )	✓	✓	✓
$\Delta\eta$ of two jets with highest b score in the laboratory frame ( $\Delta\eta_{BB}$ )	✓	✓	✓
$\Delta\eta$ of the two leptons in frame of two most-likely b jets	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the dilepton system frame	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the $\ell_1$ - $\ell_2$ system frame	—	—	✓
$\Delta\eta$ of two jets with highest b score in the $\ell_1$ - $\ell_3$ system frame	—	—	✓
$\Delta\phi$ of the two leptons in frame of two most-likely b jets	—	✓	—
$\Delta\phi$ of two jets with highest b score in the dilepton system frame	—	✓	—
Average $\Delta R$ among all jets	✓	✓	—
Jet multiplicity	✓	✓	—
$p_T^{\text{miss}}$	✓	✓	—
Azimuthal angle of $\vec{p}_T^{\text{miss}}$	✓	✓	—
Highest BDT score of jet triplet from t	✓	✓	—
Higgs jet tagger	—	✓	—
Angle of $t\bar{t}$ and H boson in $t\bar{t}H$ -system	—	✓	—
Angle between two t in $t\bar{t}$ -frame	—	✓	—
$\Delta R_{l_3-l_1} = \sqrt{(\eta_{\ell_3} - \eta_{\ell_1})^2 + (\phi_{\ell_3} - \phi_{\ell_1})^2}$	—	—	✓
$\Delta R_{l_1-l_2} = \sqrt{(\eta_{\ell_1} - \eta_{\ell_2})^2 + (\phi_{\ell_1} - \phi_{\ell_2})^2}$	—	—	✓
$\Delta R_{l_2-l_3} = \sqrt{(\eta_{\ell_2} - \eta_{\ell_3})^2 + (\phi_{\ell_2} - \phi_{\ell_3})^2}$	—	—	✓
$\eta_{\text{jet}1} - \eta_{\text{jet}2}$	—	—	✓
$p_T^{\text{jet}1} + p_T^{\text{jet}2} + p_T^{\text{jet}3} + p_T^{\text{miss}}$	—	—	✓
Total number of variables	19	25	16

\* k = 6 (4) in the 2ℓSS + 0τ<sub>h</sub> (2ℓSS + 1τ<sub>h</sub> and 3ℓ + 0τ<sub>h</sub>) final state

# CP violation searches e.g. $H \rightarrow \tau^+ \tau^-$

- cos/sin dependence is used to determine the CP content of the data: Scalar is CP even (SM-like), pseudoscalar is CP odd.



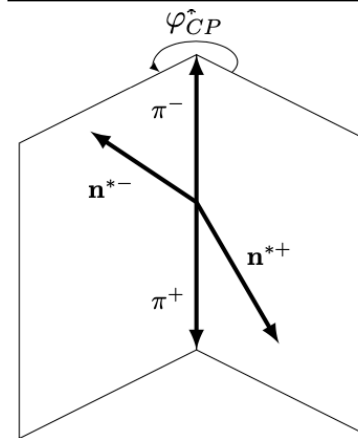
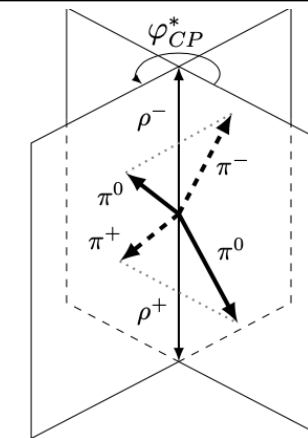
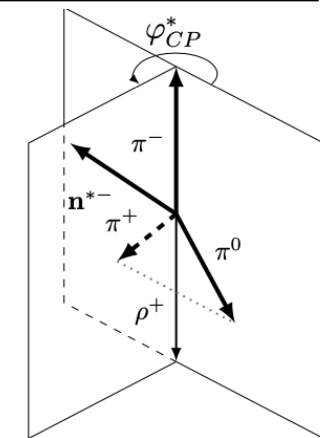
Set of nuisance parameters	Impact on $\phi_\tau [^\circ]$
Jet energy scale	3.4
Jet energy resolution	2.5
Pile-up jet tagging	0.5
Jet flavour tagging	0.2
$E_T^{\text{miss}}$	0.4
Electron	0.3
Muon	0.9
$\tau_{\text{had}}$ reconstruction	1.0
Misidentified $\tau$	0.6
$\tau_{\text{had}}$ decay mode classification	0.3
$\pi^0$ angular resolution and energy scale	0.2
Track ( $\pi^\pm$ , impact parameter)	0.7
Luminosity	0.1
Theory uncertainty in $H \rightarrow \tau\tau$ processes	1.5
Theory uncertainty in $Z \rightarrow \tau\tau$ processes	1.1
Simulated background sample statistics	1.4
Signal normalisation	1.4
Background normalisation	0.6
Total systematic uncertainty	5.2
Data sample statistics	15.6
Total	16.4

# CP violation searches e.g $H \rightarrow \tau^+ \tau^-$

- Use different reconstruction methods to account for the missing  $\nu$  when reconstructing the plane:

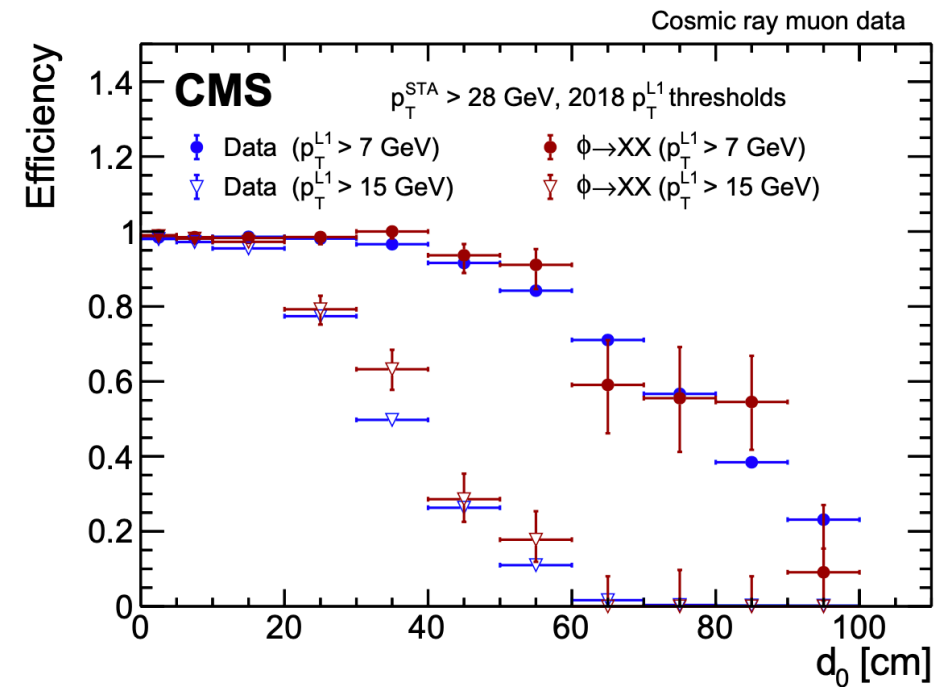
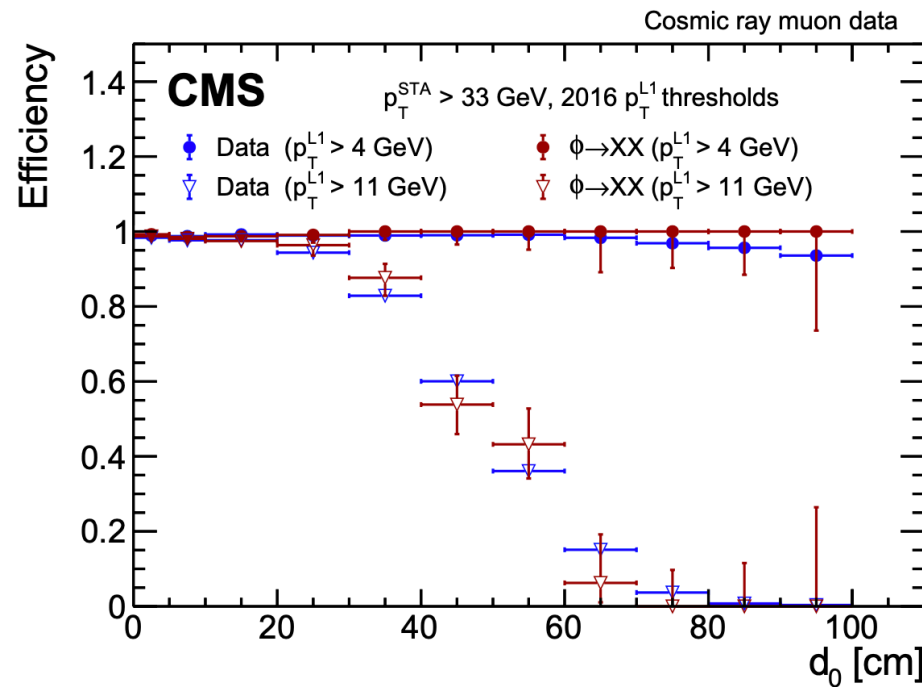
- 1 prong decays - use impact parameter (IP) vector (directional distance between the point of closest approach of the charged particle primary track and the position of the primary vertex) and charged particle momentum
- $\rho$  decay - use the two pion momenta
- $a_1$  method - use the sum of the neutral pion 4 momenta in place of the neutral pion in the  $\rho$  method
- Some channels require combination of the IP and

Decay channel	Decay mode combination	Method	Fraction in all $\tau$ -lepton-pair decays
$\tau_{\text{lep}} \tau_{\text{had}}$	$\ell$ -1p0n	IP	8.1%
	$\ell$ -1p1n	IP- $\rho$	18.3%
	$\ell$ -1pXn	IP- $\rho$	7.6%
	$\ell$ -3p0n	IP- $a_1$	6.9%
$\tau_{\text{had}} \tau_{\text{had}}$	1p0n-1p0n	IP	1.3%
	1p0n-1p1n	IP- $\rho$	6.0%
	1p1n-1p1n	$\rho$	6.7%
	1p0n-1pXn	IP- $\rho$	2.5%
	1p1n-1pXn	$\rho$	5.6%
	1p1n-3p0n	$\rho$ - $a_1$	5.1%

(a)  $H \rightarrow \tau^+ \tau^- \rightarrow \pi^+ \pi^- + 2\nu$ (b)  $H \rightarrow \tau^+ \tau^- \rightarrow \pi^+ \pi^0 \nu \pi^- \pi^0$ (c)  $H \rightarrow \tau^+ \tau^- \rightarrow \pi^+ \pi^0 \nu \pi^- \nu$

# Direct searches: Long Lived Particles (LLPs)

- Use either full tracking or muon system only for track reconstruction (TMS and STA track combinations)
- di-muon trigger efficiency strongly depends on impact parameter  $d_0$
- Cosmic rays used to validate Monte Carlo expectations - good agreement gives confidence that this type of analysis can be done





# Direct searches: Heavy neutral lepton

- Leptons and jets categorised for resolved and boosted studies

		Resolved		Boosted		
		Baseline	Fake estimation	Baseline	Leading	Fake estimation
<b>Electrons</b>	$ \eta $		(0, 1.37] or [1.52, 2.47]			
	$p_T$ (GeV)		> 25	> 25		> 200
	Quality	Tight	Loose	Medium		Tight
	Isolation	Loose	Fail Loose or Tight	Loose	HighPtCaloOnly	Loose but fail HighPtCaloOnly
		Baseline	Fake estimation	Baseline	Leading	
<b>Muons</b>	$p_T$ (GeV)		> 25	> 28	> 200	—
	$ \eta $		< 2.5		< 2.5	—
	Quality		High- $p_T$ if $p_T > 300$ GeV else Medium	Medium	Tight	—
	Isolation	FixedCutTightTrackOnly	fail FixedCutTightTrackOnly	—	Tight	—
<b>Small-<math>R</math> jet</b>	$p_T$ (GeV)		> 20			
	$ \eta $		< 2.5			
<b>Large-<math>R</math> jet</b>	$p_T$ (GeV)		—		> 200	
	$ \eta $		—		< 2	

# Direct searches: Heavy neutral lepton

- Resolved analysis targets  $\Delta m = m(W_R) - m(N_R) < 4 \text{ TeV}$  and breaks data down into same and opposite sign (SS/OS) selections

Variable	rSRSS2e	rSRSS2mu	rSROS2e	rSROS2mu
Number of electrons	2	0	2	0
Number of muons	0	2	0	2
Lepton charge	same sign		opposite sign	
Leading lepton $p_T$ [GeV]			> 40	
Dilepton mass $m_{\ell\ell}$ [GeV]			> 400	
$\Delta R_{\ell\ell}$	< 3.9		—	
Number of small- $R$ jets with $p_T > 100 \text{ GeV}$			$\geq 2$	
Number of $b$ -tagged jets			0	
Dijet mass $m_{jj}$ [GeV]			> 110	
$h_T \equiv p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$ [GeV]			> 400	

# Direct searches: Heavy neutral lepton

- Boosted analysis targets larger  $\Delta m$  where the large  $R$  jet overlaps with a high  $p_T$  lepton

Region	bSR1e (higher $\Delta m$ )	bSR2e (lower $\Delta m$ )	bSR2mu
Number of large- $R$ jets		1	
Number of electrons	1	2	0
Number of muons	0	0	2
Leading lepton $p_T$ [GeV ]		> 200	
$E_T^{\text{miss}}$ [GeV ]		< 200	—
$ \cos \theta $	> 0.7	—	—
$\Delta\phi_{J,\ell_1}$		> 2.0	
$\Delta\eta_{J,\ell_1}$	< 2.0	—	—
Dilepton $p_T$ (GeV)	—	—	> 200
Dilepton mass $m_{\ell\ell}$ [GeV ]	—	> 200	
Number of $b$ -tagged small- $R$ jets		0	