



# EXOTICS AND BSM IN ATLAS AND CMS



Dr Tracey Berry  
on behalf of ATLAS & CMS



# BSM Searches



- The Standard Model (SM) leaves many questions unanswered
- Plethora of beyond SM models (BSM)
- Only few observational hints
- Run 3 will present more opportunities





# Exotics and BSM Searches in ATLAS and CMS

ATLAS and CMS have a rich and very active program of searches

- Public results webpages [ATLAS Exotics HDBS](#) [CMS Exotics Preliminary B2G](#)
- ... only a select few here highlighted to show breadth, focus on full Run 2 results, more coming
- Run 2 (2015-2018) collected  $\sim 140\text{fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 13\text{TeV}$  recorded in Run 3 has started!
- Pushing mass limits and precision

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits  
Status: July 2022

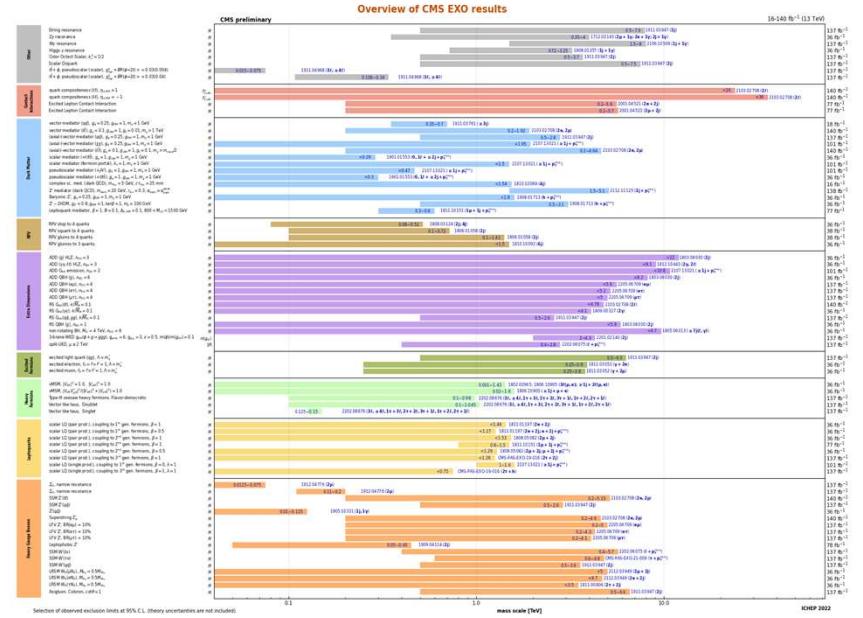
ATLAS Preliminary  
 $\sqrt{s} = 8, 13\text{TeV}$

$\int \mathcal{L} dt = (3.6 - 139)\text{fb}^{-1}$

Model	$L, \gamma$	Jets <sup>†</sup>	$E^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
<b>Extra dimensions</b>	ADD $G_{\mu\nu} + g/g$	0, $e, \mu, \tau, \gamma$	1-4	Yes	112 TeV	2102.10874
ADD non-resonant $\gamma\gamma$	0, $e, \mu, \tau, \gamma$	2	Yes	36.7	8.6 TeV	1910.05841
ADD BH multijet	0, $e, \mu, \tau, \gamma$	2	Yes	3.6	3.6 TeV	1512.05560
RS1 $G_{\mu\nu} + \gamma\gamma$	0, $e, \mu, \tau, \gamma$	2	Yes	139	2.3 TeV	2102.13405
Bulk RS $G_{\mu\nu} + WW/ZZ$	0, $e, \mu, \tau, \gamma$	2/1/1	Yes	36.1	3.3 TeV	1904.04835
Bulk RS $G_{\mu\nu} + WW \rightarrow \nu\nu$	0, $e, \mu, \tau, \gamma$	2/1, 1/0	Yes	36.1	2.0 TeV	1904.04835
Bulk RS $G_{\mu\nu} + \tau\tau$	0, $e, \mu, \tau, \gamma$	2/2 b, 3/3	Yes	36.1	1.8 TeV	1803.09678
<b>Gauge bosons</b>	SSM $Z' \rightarrow \tau\tau$	0, $e, \mu, \tau, \gamma$	2	Yes	2.9 TeV	1903.02448
SSM $Z' \rightarrow \nu\nu$	0, $e, \mu, \tau, \gamma$	2	Yes	36.1	2.42 TeV	1700.02462
Leptophobic $Z' \rightarrow bb$	0, $e, \mu, \tau, \gamma$	2 b	Yes	36.1	2.1 TeV	1805.00299
Leptophobic $Z' \rightarrow ee$	0, $e, \mu, \tau, \gamma$	2 e	Yes	139	4.1 TeV	2000.05166
SSM $W' \rightarrow \nu\nu$	0, $e, \mu, \tau, \gamma$	2	Yes	139	6.0 TeV	1906.05069
SSM $W' \rightarrow ee$	0, $e, \mu, \tau, \gamma$	2 e	Yes	139	5.0 TeV	1906.05069
SSM $W' \rightarrow \tau\tau$	0, $e, \mu, \tau, \gamma$	2	Yes	139	4.4 TeV	1906.05069
HVT $W' \rightarrow WZ \rightarrow \nu\nu$ model B	0, $e, \mu, \tau, \gamma$	2/1/1	Yes	139	4.2 TeV	2004.14026
HVT $W' \rightarrow WZ \rightarrow \nu\nu$ model C	0, $e, \mu, \tau, \gamma$	2/1/1	Yes	139	3.3 TeV	2004.14026
HVT $W' \rightarrow WW \rightarrow \nu\nu$ model B	0, $e, \mu, \tau, \gamma$	1/2 b, 1/0	Yes	139	3.2 TeV	2007.00200
HVT $Z' \rightarrow ZH \rightarrow \nu\nu$ model B	0, $e, \mu, \tau, \gamma$	1/2 b, 1/0	Yes	139	3.2 TeV	2007.00200
LISM $W_{\mu\nu} \rightarrow \mu N_{\mu}$	0, $e, \mu, \tau, \gamma$	1/3	Yes	37.0	5.0 TeV	1904.12679
<b>CI</b>	CI $q\bar{q}$	0, $e, \mu, \tau, \gamma$	2/1	Yes	21.5 TeV	1702.09197
CI $l\bar{l}q$	0, $e, \mu, \tau, \gamma$	2, 1	Yes	139	8.3 TeV	2006.15946
CI $l\bar{l}e$	0, $e, \mu, \tau, \gamma$	2, 1 b	Yes	139	8.1 TeV	2105.18847
CI $l\bar{l}\nu$	0, $e, \mu, \tau, \gamma$	2, 1 b	Yes	139	2.0 TeV	2105.18847
CI $l\bar{l}\tau$	0, $e, \mu, \tau, \gamma$	2/1 b, 2/1	Yes	36.1	1.1 TeV	1811.05592
<b>DM</b>	Axial-vector med. (Dirac DM)	0, $e, \mu, \tau, \gamma$	1-4	Yes	139	2102.10874
Pseudo-scalar med. (Dirac DM)	0, $e, \mu, \tau, \gamma$	1-4	Yes	139	376 GeV	2102.10874
Vector med. Z' (Dirac DM)	0, $e, \mu, \tau, \gamma$	2 b	Yes	139	3.1 TeV	2106.13591
Pseudo-scalar med. 2HDMa	0, $e, \mu, \tau, \gamma$	2 b	Yes	139	569 GeV	2102.10874
<b>LO</b>	Scalar $LQ^{\pm}$ gen	0, $e, \mu, \tau, \gamma$	2 e, 2	Yes	1.3 TeV	2006.05872
Scalar $LQ^0$ gen	0, $e, \mu, \tau, \gamma$	2 e, 2	Yes	139	1.7 TeV	2006.05872
Scalar $LQ^{\pm}$ gen	0, $e, \mu, \tau, \gamma$	1 e, 2 b	Yes	139	1.2 TeV	2108.07665
Scalar $LQ^0$ gen	0, $e, \mu, \tau, \gamma$	2 e, 2	Yes	139	1.24 TeV	2004.14000
Scalar $LQ^{\pm}$ gen	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 e, 1 b, 1 b	Yes	139	1.42 TeV	2101.11582
Scalar $LQ^0$ gen	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 e, 1 b, 1 b	Yes	139	1.26 TeV	2101.11582
Vector $LQ^{\pm}$ gen	0, $e, \mu, \tau, \gamma$	2 e, 2	Yes	139	1.7 TeV	2106.05872
<b>Vectorlike</b>	$VLQ \rightarrow T + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	1.3 TeV	2102.10874
$VLQ \rightarrow W + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	139	1.34 TeV	1909.02443
$VLQ \rightarrow Z + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	139	1.64 TeV	1807.11883
$VLQ \rightarrow H + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	139	1.8 TeV	2102.10874
$VLQ \rightarrow W + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	139	1.6 TeV	2102.10874
$VLQ \rightarrow Z + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	139	1.6 TeV	2102.10874
$VLQ \rightarrow H + X$	0, $e, \mu, \tau, \gamma$	2 e, 2, 1 b, 1 b, 1 b	Yes	139	1.6 TeV	2102.10874
<b>Excited</b>	Excited quark $q^* \rightarrow qg$	0, $e, \mu, \tau, \gamma$	2	Yes	6.7 TeV	1910.06447
Excited quark $q^* \rightarrow q\gamma$	0, $e, \mu, \tau, \gamma$	1, 1	Yes	36.7	3.2 TeV	1709.10440
Excited quark $q^* \rightarrow qe$	0, $e, \mu, \tau, \gamma$	1, 1 b, 1	Yes	139	3.3 TeV	1910.06447
Excited lepton $l^* \rightarrow l\gamma$	0, $e, \mu, \tau, \gamma$	3, 1 e, 1	Yes	20.3	1.6 TeV	1411.2921
Excited lepton $l^* \rightarrow l\nu$	0, $e, \mu, \tau, \gamma$	3, 1 e, 1	Yes	20.3	1.6 TeV	1411.2921
<b>Other</b>	Type III Seesaw	0, $e, \mu, \tau, \gamma$	2 e, 2	Yes	910 GeV	2002.00309
LISM Majorana $\nu$	0, $e, \mu, \tau, \gamma$	2 e, 2	Yes	36.1	1.9 TeV	1809.11025
Higgs triplet $H^{\pm} \rightarrow W^{\pm}\nu$	0, $e, \mu, \tau, \gamma$	2.3, 4 e, $\mu$ (SS)	various	Yes	150 GeV	2101.11863
Higgs triplet $H^{\pm} \rightarrow \tau\nu$	0, $e, \mu, \tau, \gamma$	2.3, 4 e, $\mu$ (SS)	various	Yes	400 GeV	2101.11863
Higgs triplet $H^{\pm} \rightarrow e\nu$	0, $e, \mu, \tau, \gamma$	2.3, 4 e, $\mu$ (SS)	various	Yes	200 GeV	2101.11863
Multi-charged particles	0, $e, \mu, \tau, \gamma$	2, 2	Yes	139	1.59 TeV	2102.10874
Magnetic monopoles	0, $e, \mu, \tau, \gamma$	2, 2	Yes	34.4	2.27 TeV	1905.10730

\*Only a selection of the available mass limits on new states or phenomena is shown.  
<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (l).

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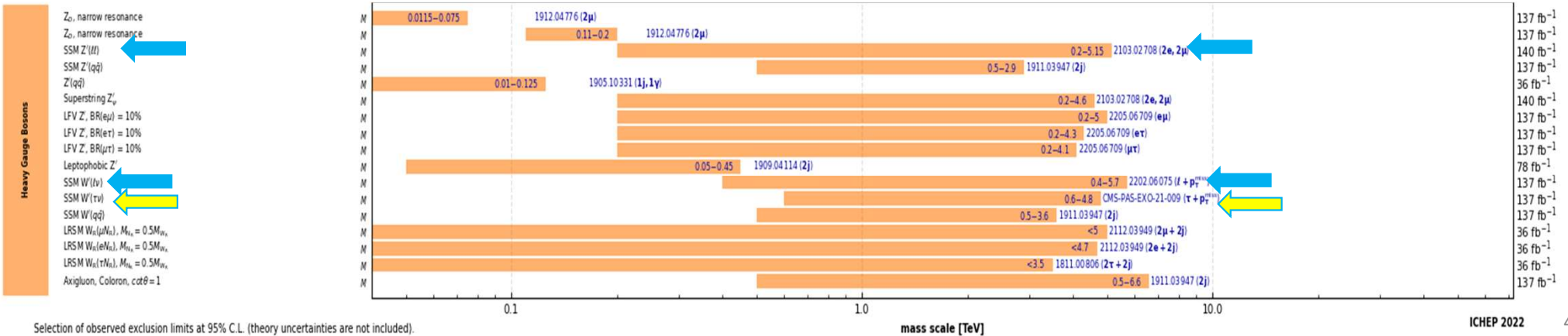
Selection of obtained exclusion limits at 95% CL (theory uncertainties are not included)

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# New Gauge Bosons

Heavy charged and neutral gauge bosons ( $W'$  and  $Z'$ ) in theories with extended gauge sectors (technicolour, Little Higgs, composite Higgs)

Gauge bosons	Decays				Masses				References
	Decay	$2e, \mu$	$2\tau$	Other	$Z'$ mass	$W'$ mass	$Z'$ mass	$W'$ mass	
SSM $Z' \rightarrow \ell\ell$	←	-	-	139	5.1 TeV				1903.06248
SSM $Z' \rightarrow \tau\tau$		-	-	36.1	2.42 TeV				1709.07242
Leptophobic $Z' \rightarrow bb$		-	$2b$	36.1	2.1 TeV				1805.09299
Leptophobic $Z' \rightarrow tt$		$0e, \mu$	$\geq 1b, \geq 2J$	Yes 139	4.1 TeV				2005.05138
SSM $W' \rightarrow \ell\nu$	←	$1e, \mu$	-	Yes 139	6.0 TeV				1906.05609
SSM $W' \rightarrow \tau\nu$	←	$1\tau$	-	Yes 139	5.0 TeV				ATLAS-CONF-2021-025
SSM $W' \rightarrow tb$	←	-	$\geq 1b, \geq 1J$	-	4.4 TeV				ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B		$1e, \mu$	$2j / 1J$	Yes 139	4.3 TeV				2004.14636
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C		$3e, \mu$	$2j$ (VBF)	Yes 139	340 GeV				ATLAS-CONF-2022-005
HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B		$1e, \mu$	$1-2b, 1-0j$	Yes 139	3.3 TeV				2207.00230
HVT $Z' \rightarrow ZH \rightarrow \ell\ell\nu\nu bb$ model B		$0, 2e, \mu$	$1-2b, 1-0j$	Yes 139	3.2 TeV				2207.00230
LRSM $W_R \rightarrow \mu N_R$		$2\mu$	$1J$	-	5.0 TeV				1904.12679

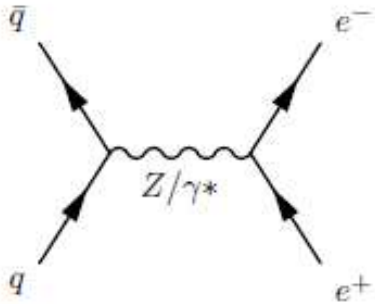




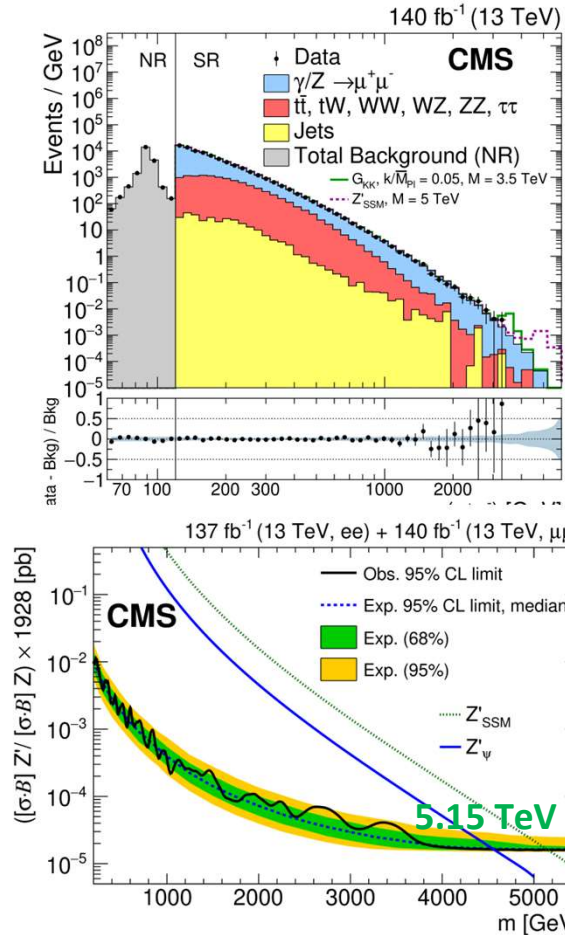
# Heavy Gauge Bosons: $Z'$ Dilepton Resonance Search

## Search Channel

- Decays to 2 electrons or 2 muons
- + very clean signatures
- + good to search for other new physics:  $Z'$ , Extra Dimensions

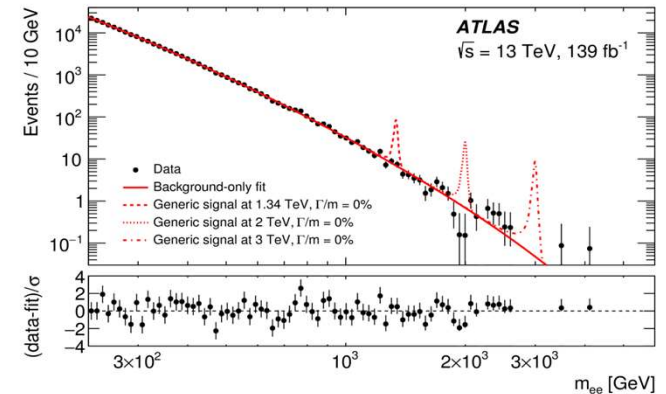


Search for deviations  
in **invariant mass**



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**Functional form fitted to invariant-mass**  
**A generic signal shape**

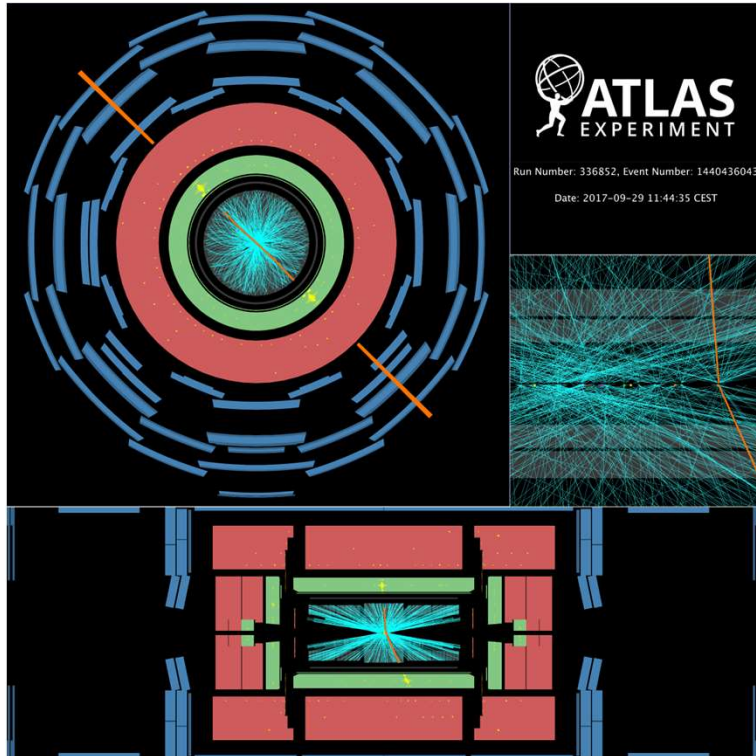
Limits applied to spin-0, spin-1 and spin-2 signal hypotheses

Model	Lower limits on $m_{Z'}$ [TeV]					
	$ee$		$\mu\mu$		$ll$	
	obs	exp	obs	exp	obs	exp
$Z'_{\psi}$	4.1	4.3	4.0	4.0	4.5	4.5
$Z'_{\chi}$	4.6	4.6	4.2	4.2	4.8	4.8
$Z'_{SSM}$	4.9	4.9	4.5	4.5	5.1	5.1

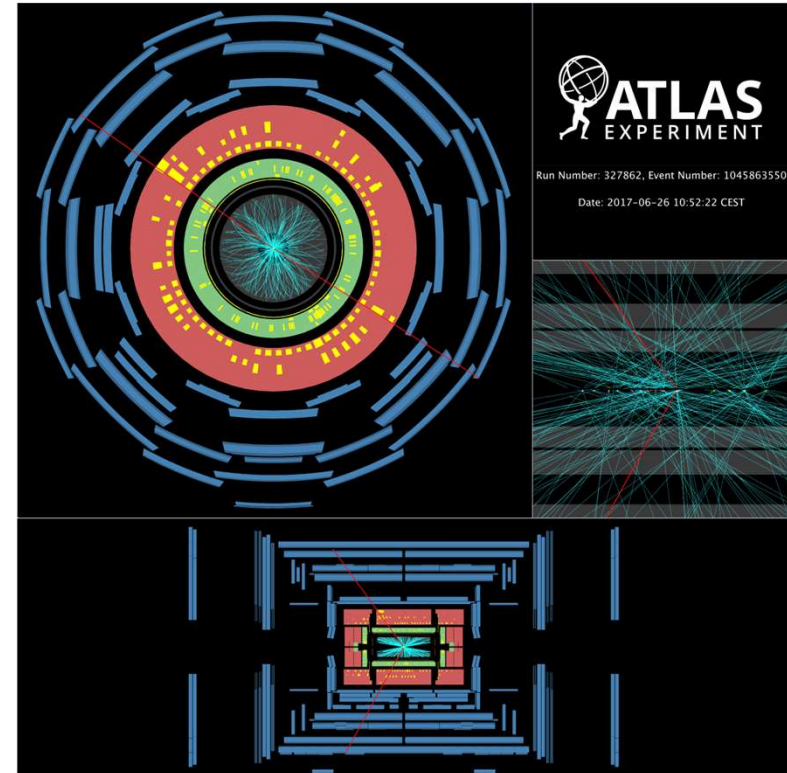
# Highest invariant mass (2015—2018)

$m_{ee} = 4.06 \text{ TeV}$

$m_{\mu\mu} = 2.75 \text{ TeV}$



$E_T = 2.01 \text{ TeV}, E_T = 1.92 \text{ TeV}$



$p_T = 1.82 \text{ TeV}, p_T = 1.04 \text{ TeV},$

# Lepton Flavor Violating Z decay

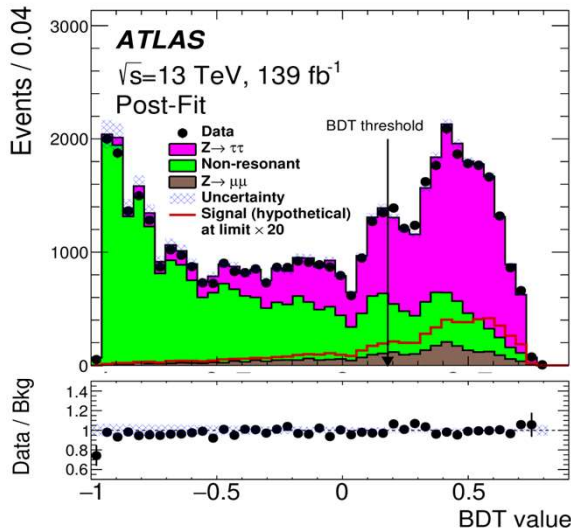
EXOT-2018-35/  
EXOT-2020-28/  
EXOT-2018-36/



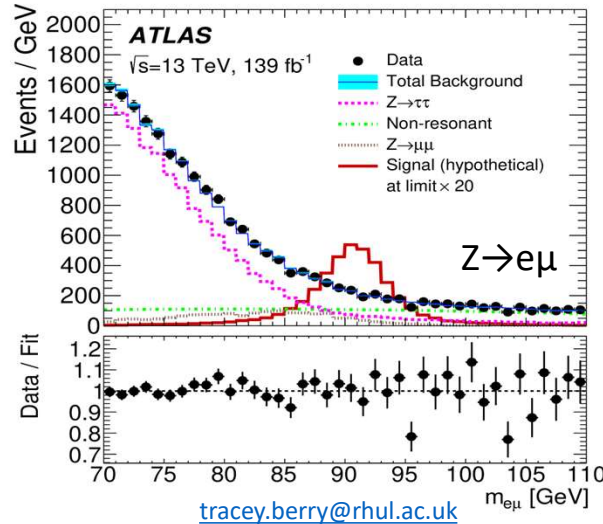
- Lepton flavour is an accidental symmetry in the SM
- Often violated in BSM theories
- LHC is a Z machine: ~ 8 billion Z's in ATLAS in Run 2

$$Z \rightarrow e^\pm \mu^\mp$$

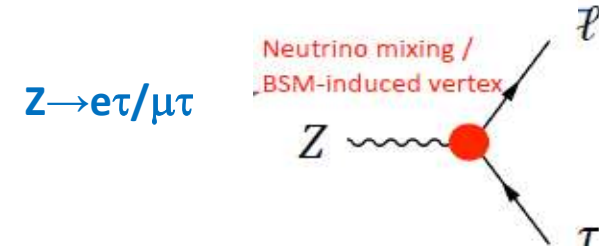
- Search for peak around Z mass
- BDT to suppress backgrounds



- No excess is observed
- Upper limit on Branching Fraction ( $Z \rightarrow e\mu$ )  $< 2.62 \times 10^{-7}$  @95% C.L.
- Most stringent limit to date



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- Neutrino oscillations show that LFV indeed occurs in nature

Upper 95% CL limits	ATLAS	LEP
$B(Z \rightarrow e \tau)$	$8.1 \times 10^{-6}$	$9.8 \times 10^{-6}$ [OPAL]
$B(Z \rightarrow \mu \tau)$	$9.5 \times 10^{-6}$	$12 \times 10^{-6}$ [DELPHI]

- NN used in analysis
- Set current most stringent upper limits on BR  $Z \rightarrow \ell \tau$ , previous limits by LEP ==> thanks to improved tau ID and lumi
- Primarily limited by statistics

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# Di-lepton Ratios

CMS-EXO-19-019

EXOT-2018-29/

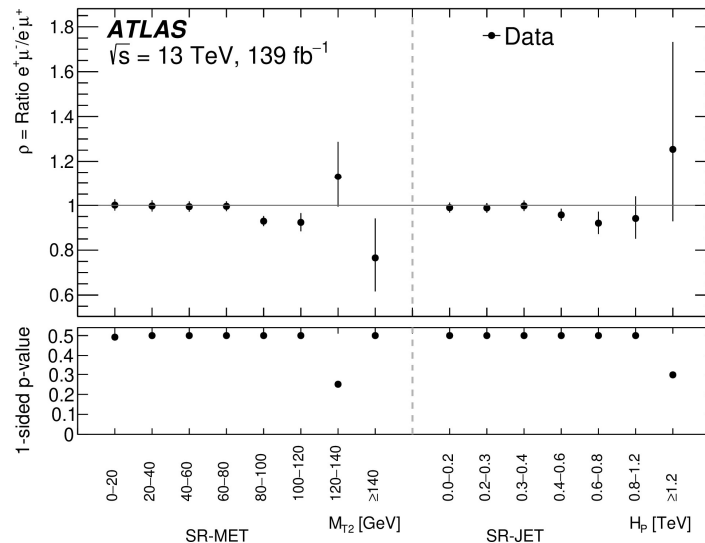
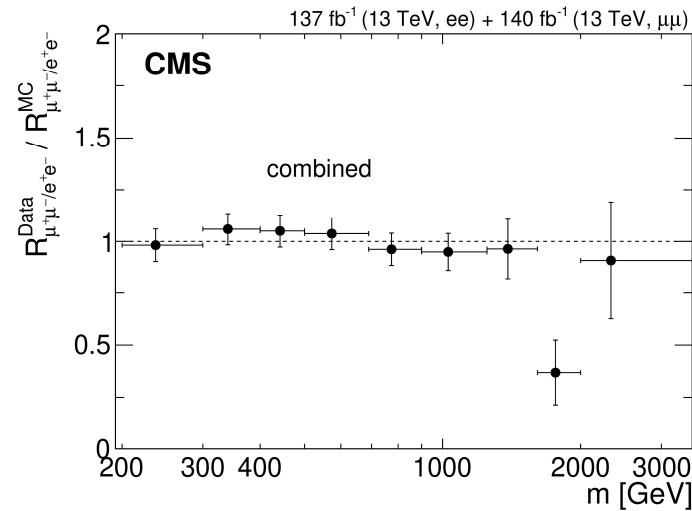
- Resonant and non-resonant di-lepton final states with high mass in many SM extensions (ex.  $Z'$ , LQs)
- BSM physics can cause  $R$  to deviate from unity

- Measure ratio of  $e+\mu^-$  to  $e-\mu^+$  pairs

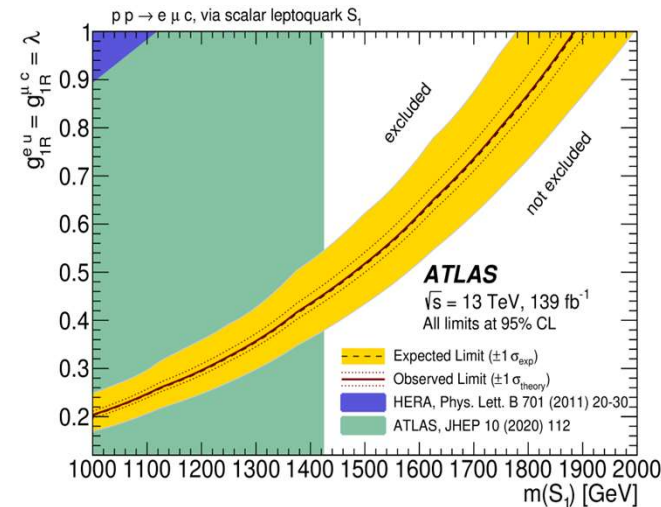
$$\rho = \frac{\sigma(pp \rightarrow e+\mu^- + X)}{\sigma(pp \rightarrow e-\mu^+ + X)}$$

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(qq \rightarrow \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(qq \rightarrow e^+e^-)/dm_{\ell\ell}}$$

- $\rho < 1$  at LHC (ex.  $W^+ \rightarrow \mu^+\nu + \text{jet} \rightarrow e^-$  fake)
- $\rho > 1$  induced by BSM physics, ex. RPV-SUSY, LQs



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Exclude scalar leptoquarks masses below 1880 GeV

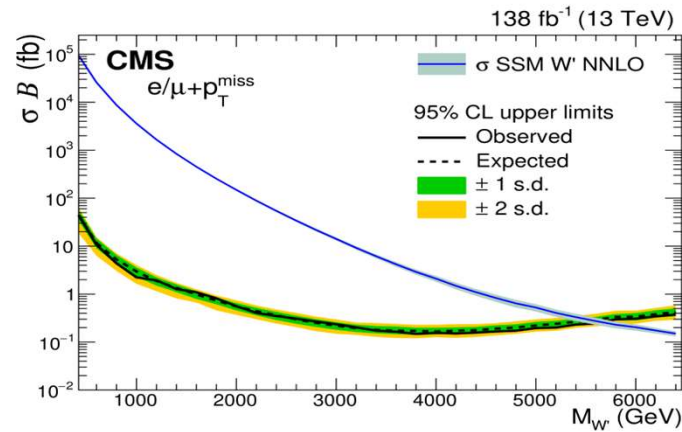
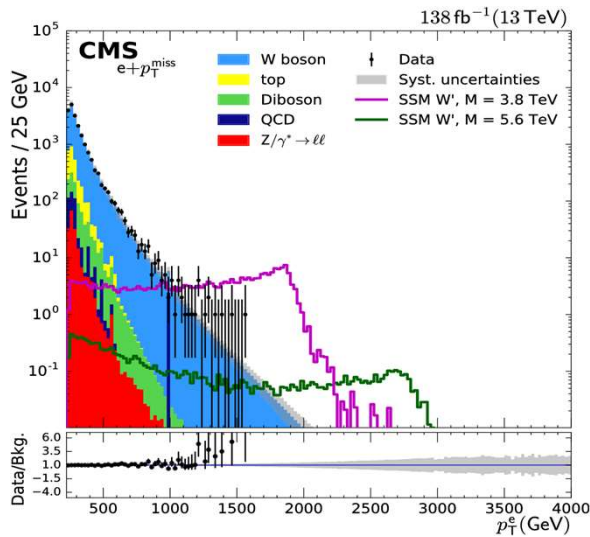


# Heavy Gauge Bosons: $W'$



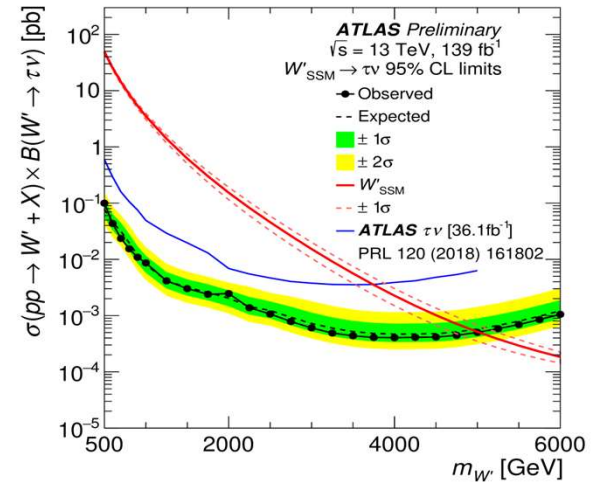
## $W' \rightarrow \ell\nu$ decays

In the transverse plane: lepton back-to-back to missing transverse momentum



Several models probed:  
 SSM, split-UED, RPV-SUSY, EFT  
 $W'$  boson mass less than 5.7  
 TeV is excluded at 95% C.L.

## $W' \rightarrow \tau\nu$ decays



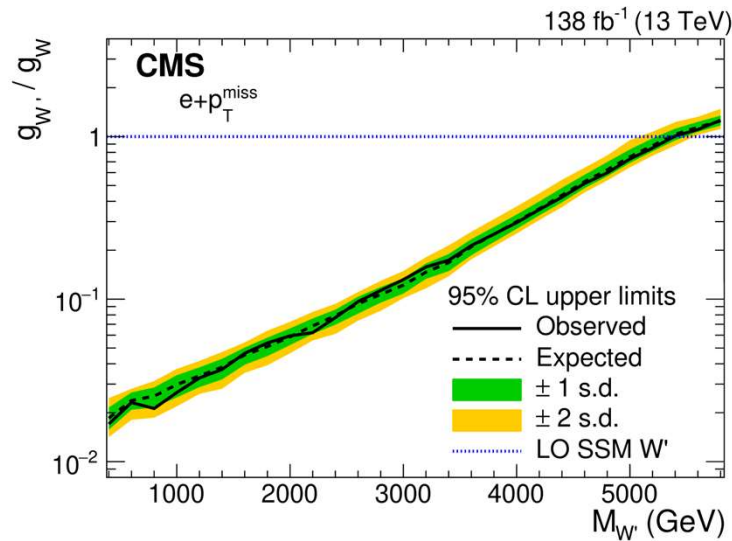
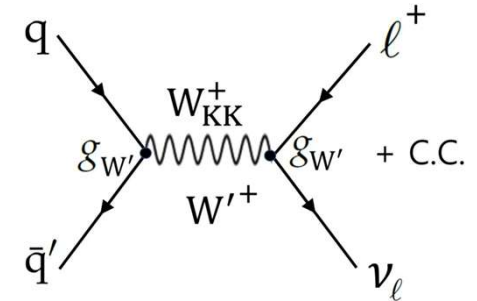
$W' \rightarrow \tau\nu$  production cross section  
 $W'$  bosons masses up to 5.0 TeV  
 excluded at the 95% C.L.



# Other BSM searches: $W'$

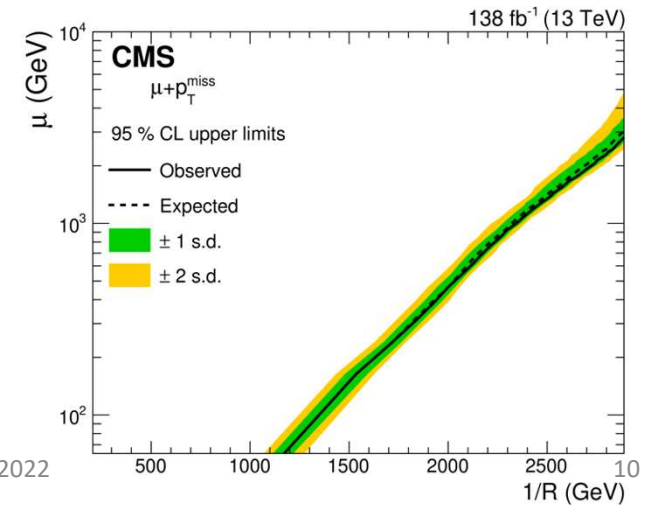


- Set limits on other models: e.g. Extra-dimensions: split UED, RPV SUSY
- First LHC results on a SM precision test :  
determination of the oblique electroweak  $g_{W'}$  parameter
- Extend existing constraints on composite Higgs scenarios using results with those from the direct  $W'$  resonance search
- First experimental exclusion on compositeness parameters using results from LHC data other than Higgs boson measurements



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Exclusion limits in the 2D plane  $(1/R, \mu)$  for the split-UED interpretation for the  $n=2$  case



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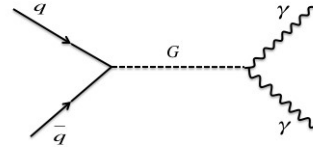


# ADD model Searches

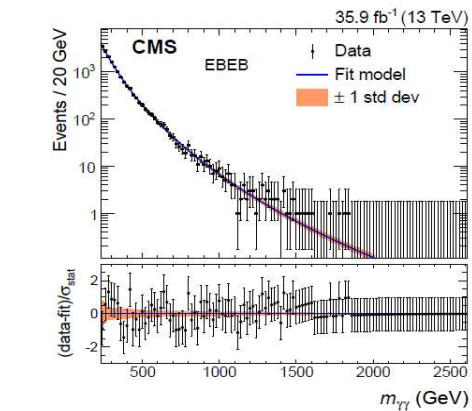
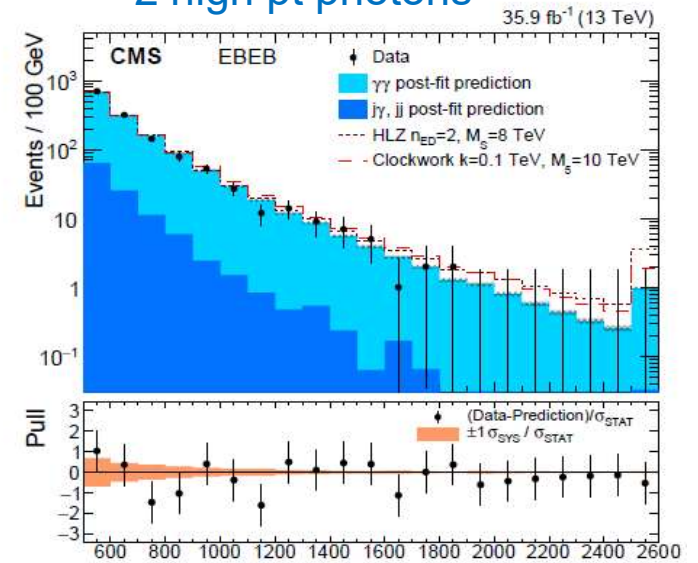
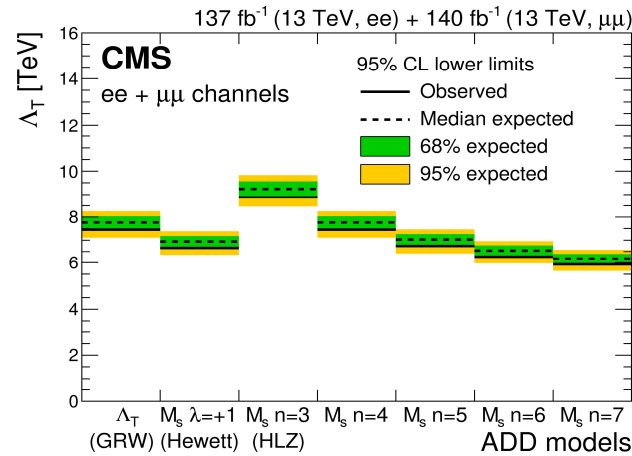
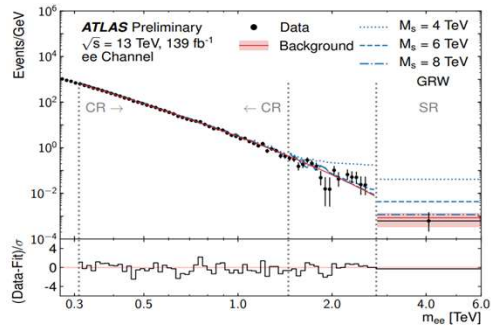


## Searches for large extra dimensions

- 2 high pt electrons and muons



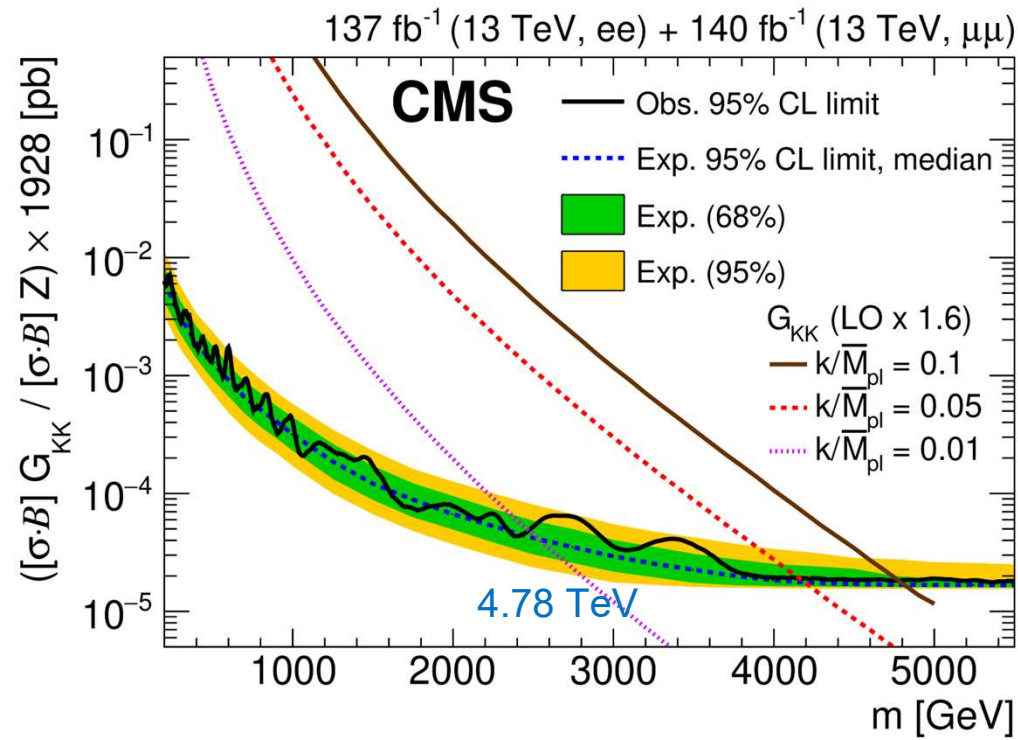
- 2 high pt photons



Signal	GRW	Hewett		HLZ					
		negative	positive	$n_{ED} = 2$	$n_{ED} = 3$	$n_{ED} = 4$	$n_{ED} = 5$	$n_{ED} = 6$	$n_{ED} = 7$
Expected	$7.1^{+0.7}_{-0.5}$	$5.5^{+0.1}_{-0.3}$	$6.3^{+0.6}_{-0.4}$	$8.4^{+1.3}_{-1.1}$	$8.4^{+0.8}_{-0.6}$	$7.1^{+0.7}_{-0.5}$	$6.4^{+0.6}_{-0.5}$	$6.0^{+0.6}_{-0.4}$	$5.6^{+0.6}_{-0.4}$
Observed	7.8	5.6	7.0	9.7	9.3	7.8	7.0	6.6	6.2



# Extra Dimensions – RS Model



# Vector-like fermions/quarks

See Dylan's talk



Heavy Fermions

$v_{MSM}, |V_{\mu\nu}|^2 = 1.0, |V_{\nu\mu}|^2 = 1.0$   
 $v_{MSM}, |V_{\mu\nu} V_{\nu\mu}'|^2 / (|V_{\mu\nu}|^2 + |V_{\nu\mu}|^2) = 1.0$   
 Type-III seesaw heavy fermions, Flavor-democratic  
 Vector like taus, Doublet  
 Vector like taus, Singlet

	0.001-1.43	1802.02965, 1806.10905 ( $3l(\mu, e); \geq 1j + 2l(\mu, e)$ )	36 fb <sup>-1</sup>
	0.02-1.6	1806.10905 ( $\geq 1j + \mu + e$ )	36 fb <sup>-1</sup>
	0.1-0.98	2202.08676 ( $3l, \geq 4l, 1\tau + 3l, 2\tau + 2l, 3\tau + 1l, 1\tau + 2l, 2\tau + 1l$ )	137 fb <sup>-1</sup>
	0.1-1.045	2202.08676 ( $3l, \geq 4l, 1\tau + 3l, 2\tau + 2l, 3\tau + 1l, 1\tau + 2l, 2\tau + 1l$ )	137 fb <sup>-1</sup>
	0.125-0.15	2202.08676 ( $3l, \geq 4l, 1\tau + 3l, 2\tau + 2l, 3\tau + 1l, 1\tau + 2l, 2\tau + 1l$ )	137 fb <sup>-1</sup>

Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu \geq 1b, \geq 1j$	-	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 $T_{5/3} T_{5/3}   T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3e, \mu \geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883
	VLQ $T \rightarrow Ht/Zt$	$1e, \mu \geq 1b, \geq 3j$	Yes	139	T mass	1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	$1e, \mu \geq 1b, \geq 1j$	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	1812.07343
	VLQ $B \rightarrow Hb$	$0e, \mu \geq 2b, \geq 1j, \geq 1J$	-	139	B mass	2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel $\geq 1j$	Yes	139	$\tau'$ mass	898 GeV	SU(2) doublet	ATLAS-CONF-2022-044



# Search for resonant and nonresonant production of pairs of dijet resonances

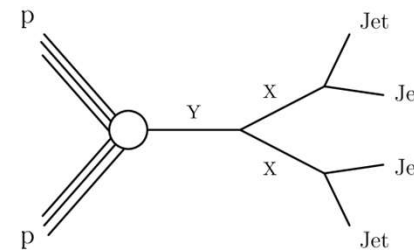


See Dylan's talk

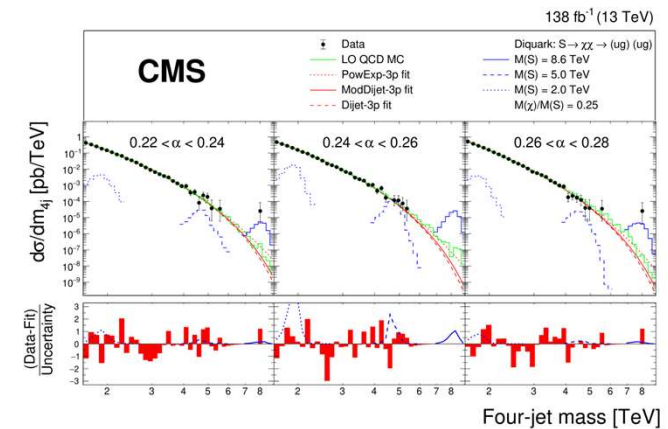
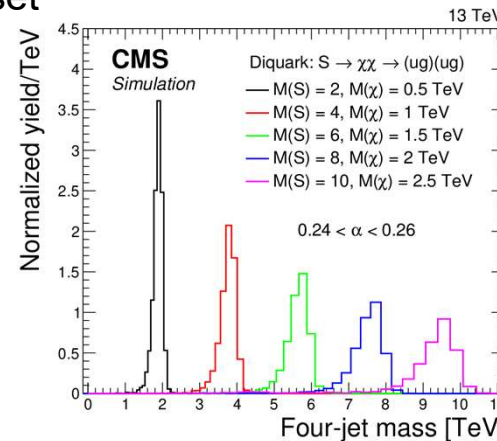
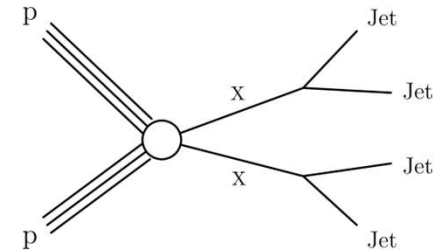
[CMS-EXO-21-010](#)

- Search for pairs of dijet resonances with same mass in final states with at least four jets
- Where 4 jet production proceeds
  - via an intermediate resonant state or
  - nonresonant production
- Model-independent limits, at 95% C.L, on production cross section of four-jet and dijet resonances set
- First LHC limits on a signal model of diquarks that decay into pairs of **vector-like quarks**,
- excluding diquark masses below 7.6 TeV
- Nonresonant search excludes pair production of **top squarks**

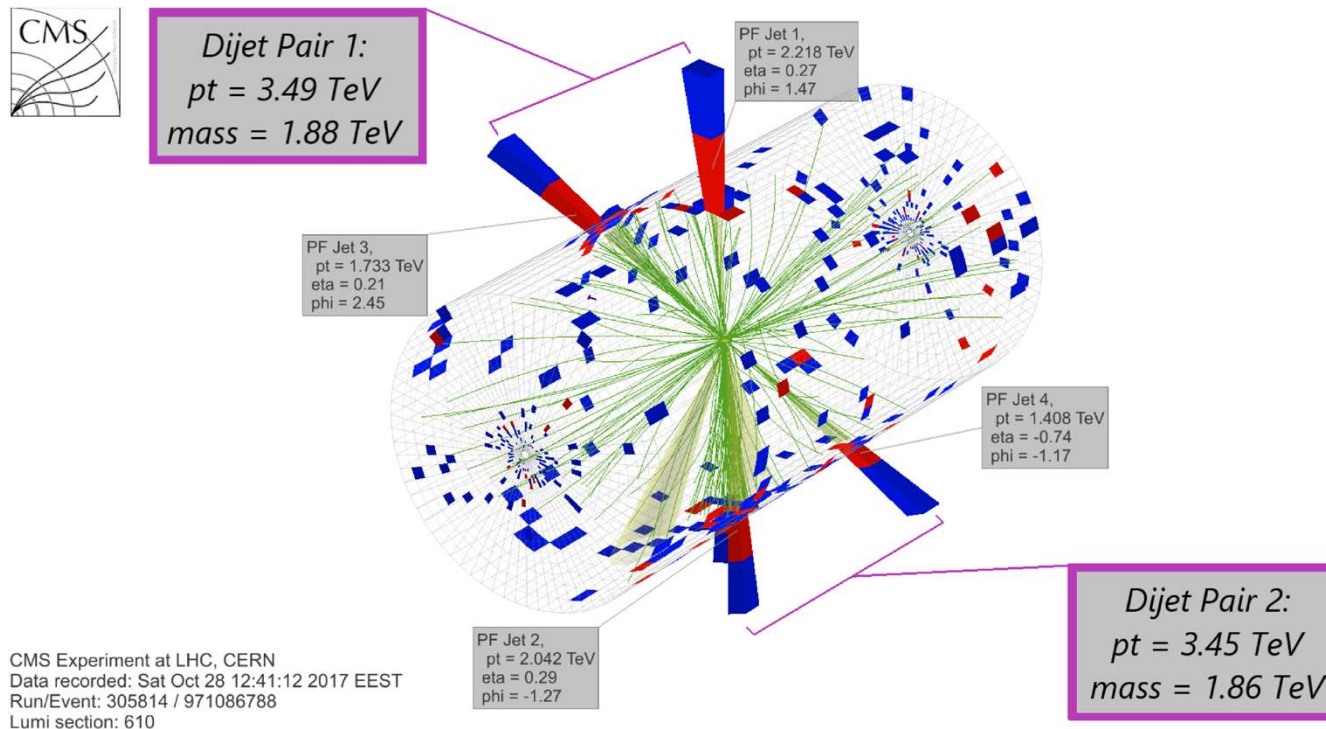
Resonant production



Nonresonant production



# Highest four-jet mass of 8.0 TeV

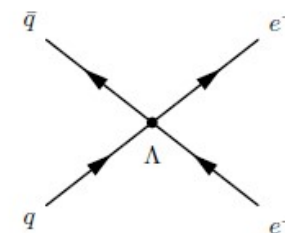
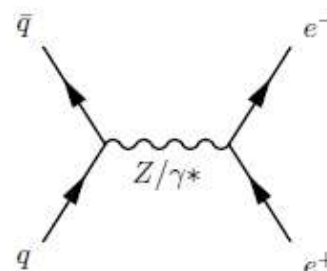


CMS Experiment at LHC, CERN  
Data recorded: Sat Oct 28 12:41:12 2017 EEST  
Run/Event: 305814 / 971086788  
Lumi section: 610

# Contact Interactions

A contact interaction (CI) could be caused by

- Quark-lepton compositeness or
- Any new interaction with a massive mediator



CI	Flavor	Number of flavors	Yes	36.1	Lambda	21.8 TeV	$\eta_{ll}^-$	1703.09127
CI qqqq	-	2j	-	37.0	Lambda	35.8 TeV	$\eta_{ll}^-$	2006.12946
CI llqq	2 e, mu	-	-	139	Lambda	1.8 TeV	$g_* = 1$	2105.13847
CI eebs	2 e	1 b	-	139	Lambda	2.0 TeV	$g_* = 1$	2105.13847
CI muubs	2 mu	1 b	-	139	Lambda	2.57 TeV	$ C_{4t}  = 4\pi$	1811.02305
CI tttt	$\geq 1$ e, mu	$\geq 1$ b, $\geq 1$ j	Yes	36.1	Lambda			

Contact Interactions	Upper Limit	Lower Limit	Reference	Upper Limit	Lower Limit	Reference
quark compositeness (ll), $\eta_{LL,RR} = 1$	$< 24$		2103.02708 (21)	$< 24$		2103.02708 (21)
quark compositeness (ll), $\eta_{LL,RR} = -1$	$< 36$		2103.02708 (21)	$< 36$		2103.02708 (21)
Excited Lepton Contact Interaction	0.2-5.6	2001.04521 (2e+2j)				
Excited Lepton Contact Interaction	0.2-5.7	2001.04521 (2mu+2j)				

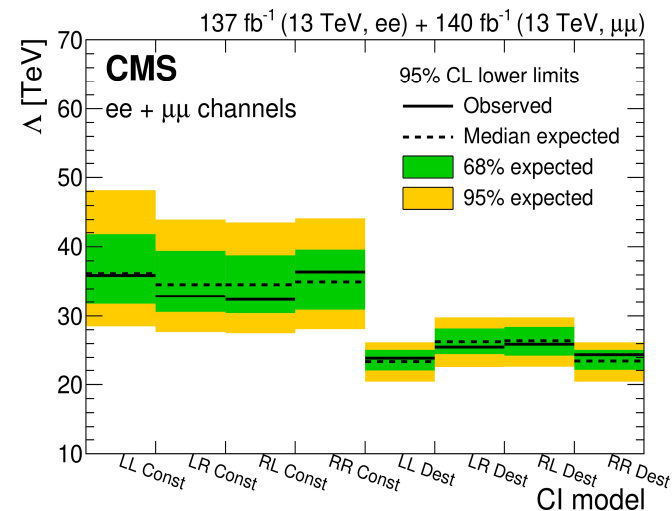
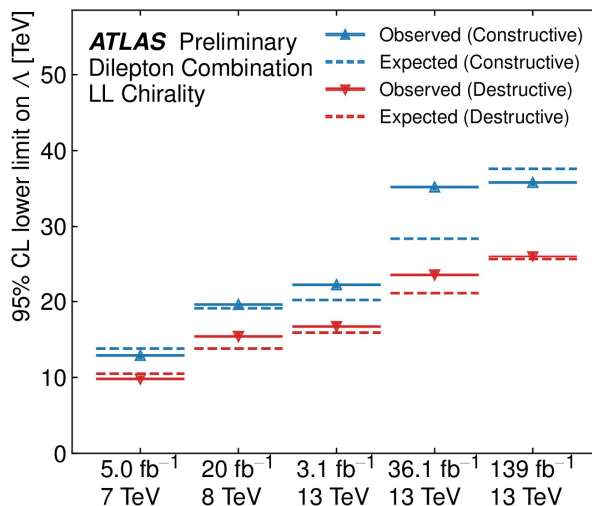
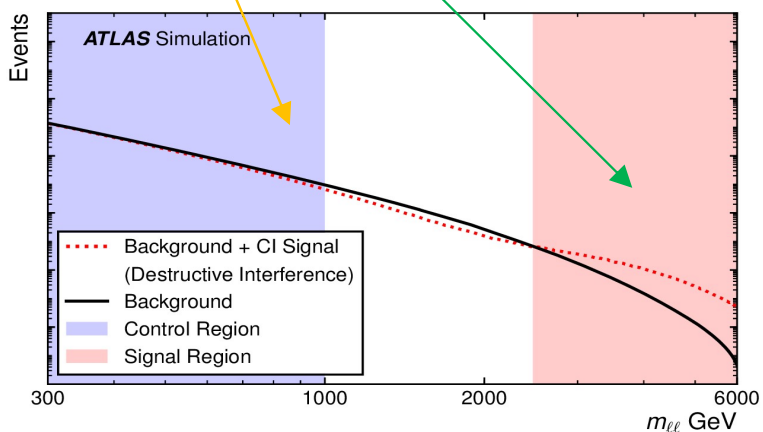
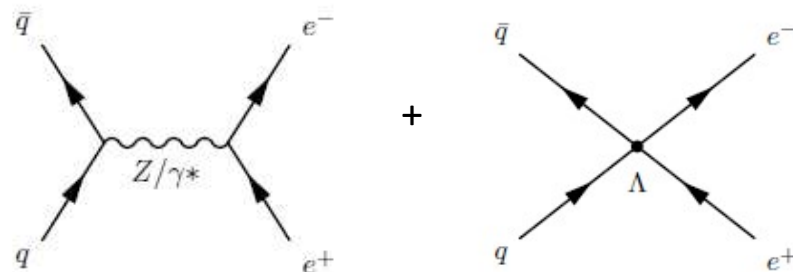
# Contact Interactions: $ee, \mu\mu$

Search in invariant mass only

*First non-resonant search*

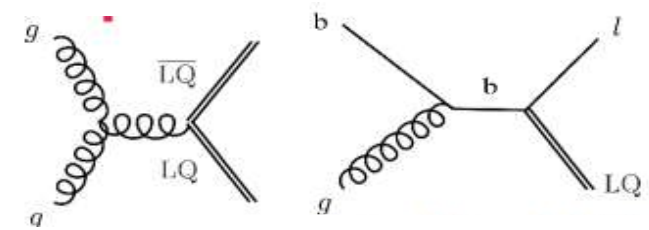
to use data-driven background estimation

- Fit in the low mass control region
- Extrapolate to high mass



# Leptoquarks

- Leptoquarks (LQs) predicted in GUTs and composite Higgs models
- LQs produced in pairs in  $gg$  fusion and  $q\bar{q}$  annihilation or singly in association with a lepton
- Decays into a quark and lepton
- Searches for 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> and mixed generations final states
- Scalar and vector LQs are investigated



LQ	Production	Decay	Yes	Count	Mass	Searches	Reference
Scalar LQ 1 <sup>st</sup> gen	$2e$	$\geq 2j$	Yes	139	LQ mass	1.8 TeV	2006.05872
Scalar LQ 2 <sup>nd</sup> gen	$2\mu$	$\geq 2j$	Yes	139	LQ mass	1.7 TeV	2006.05872
Scalar LQ 3 <sup>rd</sup> gen	$1\tau$	$2b$	Yes	139	$LQ_3^u$ mass	1.2 TeV	2108.07665
Scalar LQ 3 <sup>rd</sup> gen	$0e, \mu$	$\geq 2j, \geq 2b$	Yes	139	$LQ_3^d$ mass	1.24 TeV	2004.14060
Scalar LQ 3 <sup>rd</sup> gen	$\geq 2e, \mu, \geq 1\tau$	$\geq 1j, \geq 1b$	-	139	$LQ_3^u$ mass	1.43 TeV	2101.11582
Scalar LQ 3 <sup>rd</sup> gen	$0e, \mu, \geq 1\tau$	$0-2j, 2b$	Yes	139	$LQ_3^d$ mass	1.26 TeV	2101.12527
Vector LQ 3 <sup>rd</sup> gen	$1\tau$	$2b$	Yes	139	$LQ_3^v$ mass	1.77 TeV	2108.07665

$\beta = 1$   
 $\beta = 1$   
 $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$   
 $\mathcal{B}(LQ_3^u \rightarrow t\nu) = 1$   
 $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 1$   
 $\mathcal{B}(LQ_3^d \rightarrow b\nu) = 1$   
 $\mathcal{B}(LQ_3^v \rightarrow b\tau) = 0.5, Y-M \text{ coupl.}$

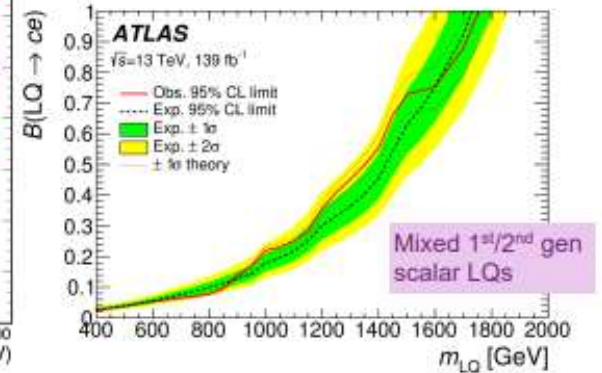
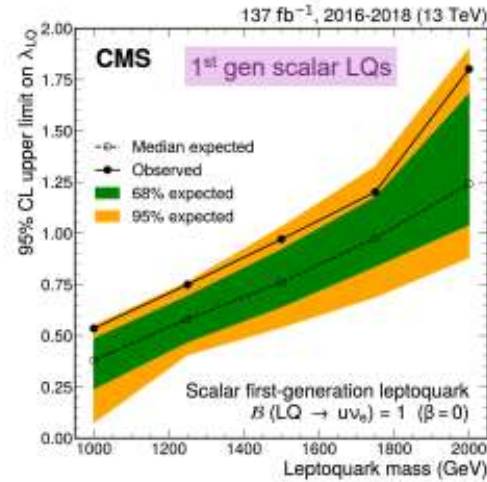
Leptoquarks	Search	Upper Limit	Reference
scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 1$	M	36 fb <sup>-1</sup>	<1.44 1811.01197 (2e + 2j)
scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 0.5$	M	36 fb <sup>-1</sup>	<1.27 1811.01197 (2e + 2j; e + 2j + p <sup>miss</sup> )
scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 1$	M	36 fb <sup>-1</sup>	<1.53 1808.05082 (2μ + 2j)
scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 1$	M	77 fb <sup>-1</sup>	0.8-1.5 1811.10151 (1μ + 1j + p <sup>miss</sup> )
scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 0.5$	M	36 fb <sup>-1</sup>	<1.29 1808.05082 (2μ + 2j; μ + 2j + p <sup>miss</sup> )
scalar LQ (pair prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1$	M	137 fb <sup>-1</sup>	<1.26 CMS-PAS-EXO-19-016 (2τ + 2j)
scalar LQ (single prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 0, \lambda = 1$	M	101 fb <sup>-1</sup>	1-1.6 2107.13021 (≥ 1j + p <sup>miss</sup> )
scalar LQ (single prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1, \lambda = 1$	M	137 fb <sup>-1</sup>	<0.75 CMS-PAS-EXO-19-016 (2τ + b)



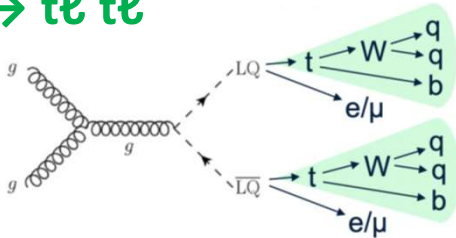
# Leptoquarks



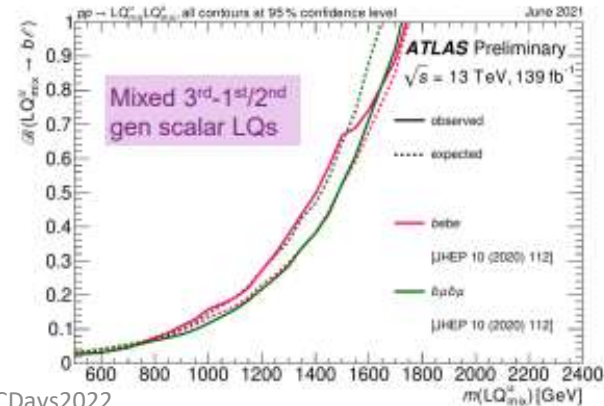
- Searches for 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> and mixed generations final states
- Scalar LQs are investigated
- Decays into a quark and lepton



LQ  $\rightarrow$  t $\ell$  t $\ell$

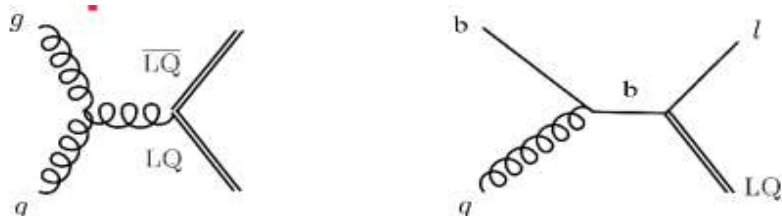


cross-generational LQ  $m(LQ) > 1.48$  TeV

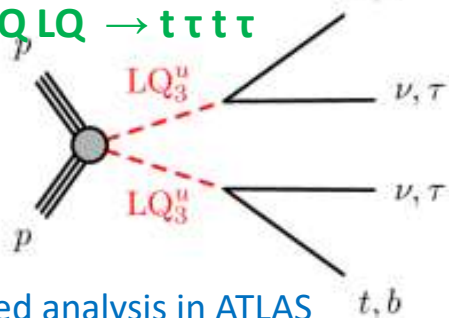


# Leptoquarks

- Searches for 3rd generation only and mixed generations final states
- Scalar and vector LQs are investigated
- Decays into a quark and lepton

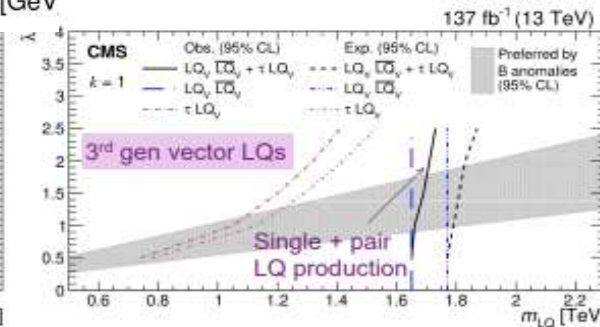
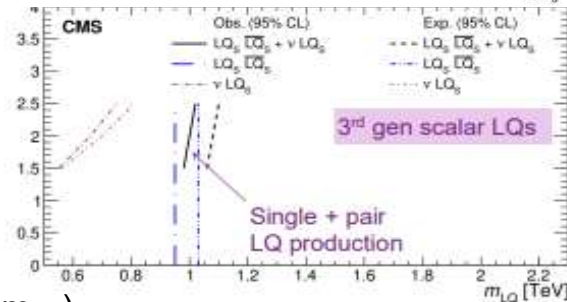
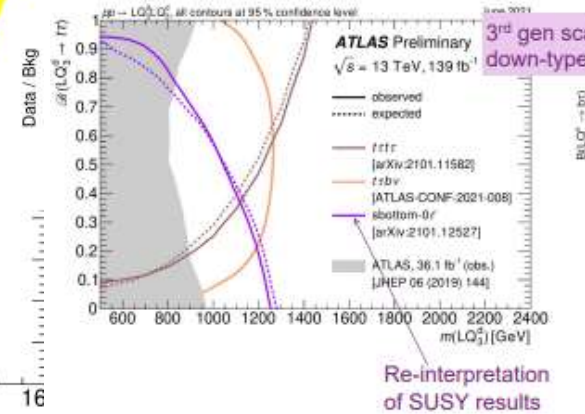
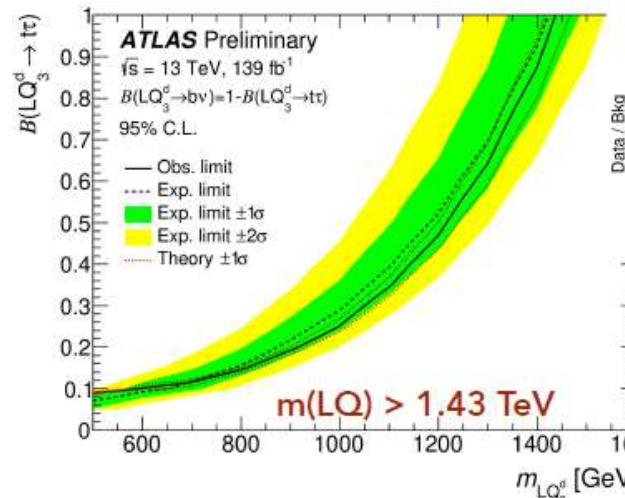


$LQ LQ \rightarrow t\tau t\tau$



- First dedicated analysis in ATLAS

Improvement of a factor of x10 in sensitivity ( $\sim 500$  GeV in  $m_{LQ}$ ) with respect to ATLAS and CMS  $36 \text{ fb}^{-1}$ )

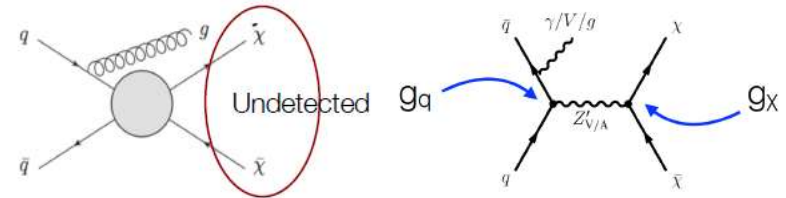


# Dark Matter

See Adelina's talk

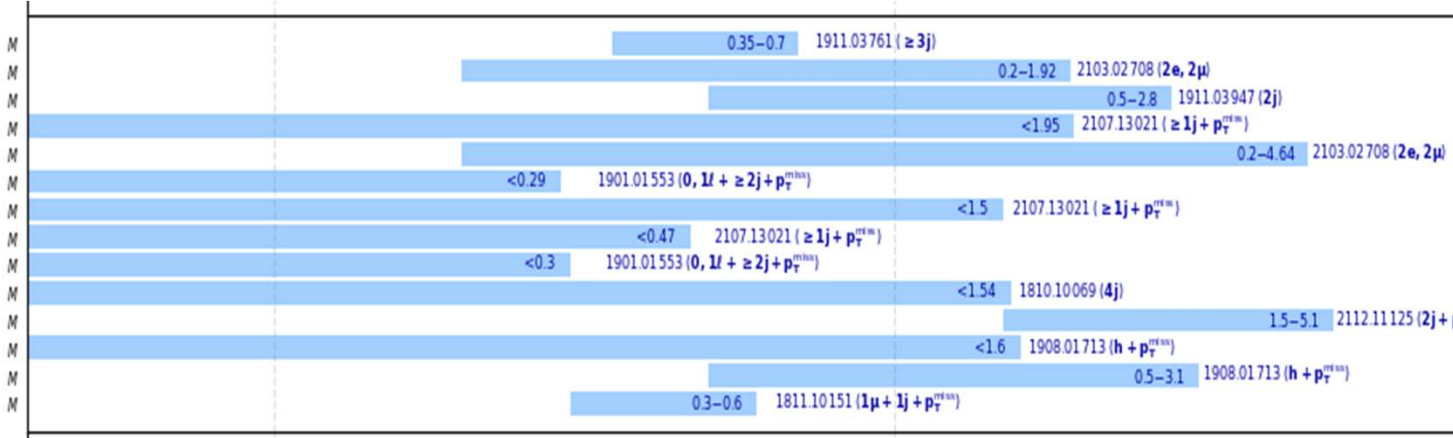


- Pair production at LHC
- DM candidates **escape** detector (weakly interacting)
- Large **missing energy** (MET) is the key variable



Dark Matter

vector mediator ( $qq$ ),  $g_q = 0.25, g_{DM} = 1, m_\chi = 1$  GeV  
 vector mediator ( $ll$ ),  $g_q = 0.1, g_{DM} = 1, g_l = 0.01, m_\chi > 1$  TeV  
 (axial-)vector mediator ( $qq$ ),  $g_q = 0.25, g_{DM} = 1, m_\chi = 1$  GeV  
 (axial-)vector mediator ( $\chi\chi$ ),  $g_q = 0.25, g_{DM} = 1, m_\chi = 1$  GeV  
 (axial-)vector mediator ( $ll$ ),  $g_q = 0.1, g_{DM} = 1, g_l = 0.1, m_\chi > m_{top}/2$   
 scalar mediator ( $+t\bar{t}$ ),  $g_q = 1, g_{DM} = 1, m_\chi = 1$  GeV  
 scalar mediator (fermion portal),  $\lambda_{ij} = 1, m_\chi = 1$  GeV  
 pseudoscalar mediator ( $+jV$ ),  $g_q = 1, g_{DM} = 1, m_\chi = 1$  GeV  
 pseudoscalar mediator ( $+t\bar{t}$ ),  $g_q = 1, g_{DM} = 1, m_\chi = 1$  GeV  
 complex sc. med. (dark QCD),  $m_{\tilde{g}} = 5$  GeV,  $c\tau_{\tilde{g}} = 25$  mm  
 $Z'$  mediator (dark QCD),  $m_{Z'} = 20$  GeV,  $r_{UV} = 0.3, a_{dark} = a_{SM}^{dark}$   
 Baryonic  $Z'$ ,  $g_q = 0.25, g_{DM} = 1, m_\chi = 1$  GeV  
 $Z' - 2HDM$ ,  $g_Z = 0.8, g_{DM} = 1, \tan\beta = 1, m_\chi = 100$  GeV  
 Leptoquark mediator,  $\beta = 1, B = 0.1, \Delta_{L, DM} = 0.1, 800 < M_{LQ} < 1500$  GeV



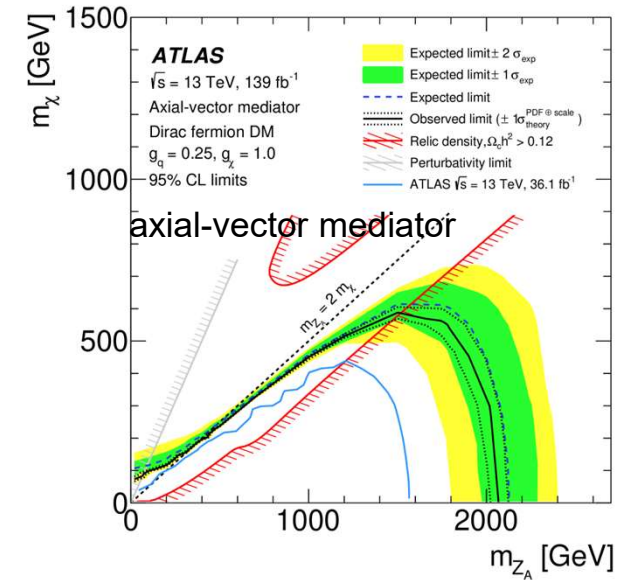
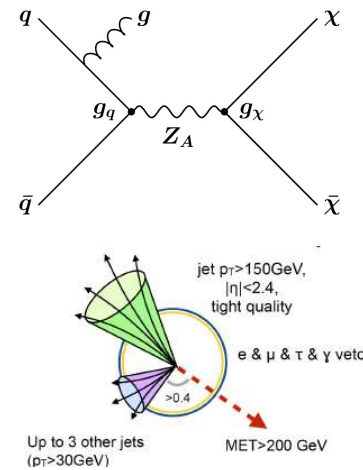
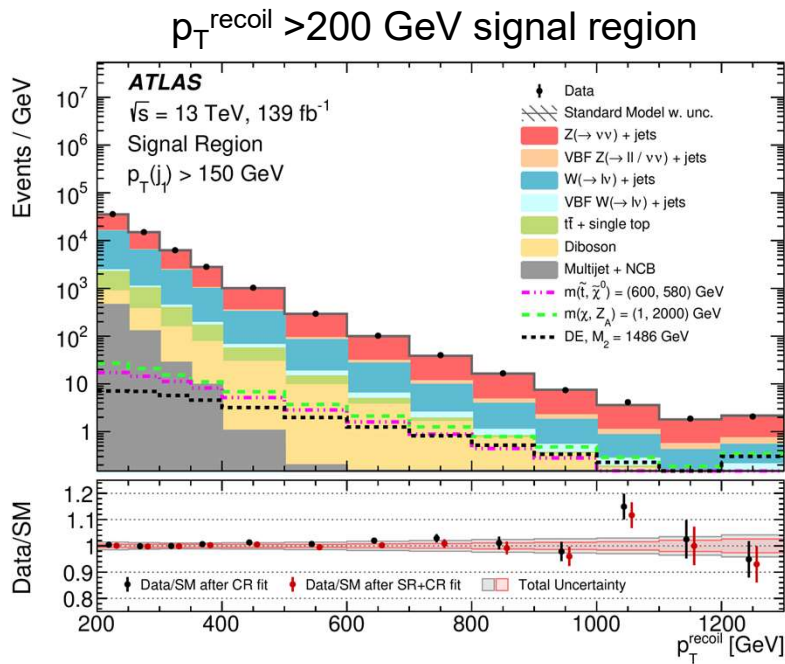
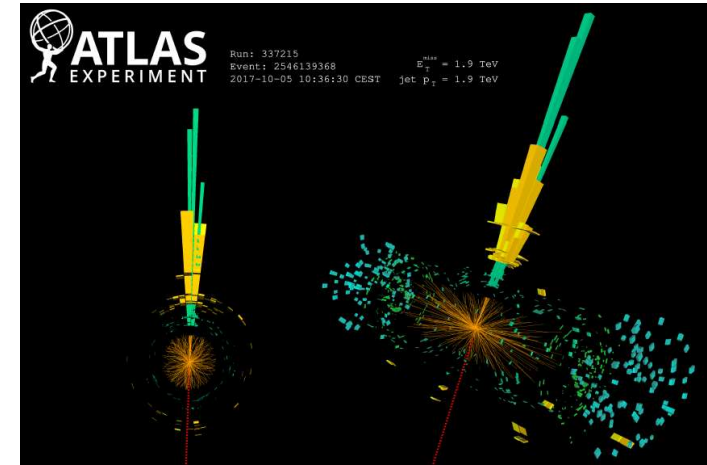
DM	Mediator	Channels	Spin	Yes	Count	Mass	Reference	Parameters	Reference
	Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$m_{med}$	2.1 TeV	$g_q=0.25, g_\chi=1, m(\chi)=1$ GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$m_{med}$	376 GeV	$g_q=1, g_\chi=1, m(\chi)=1$ GeV	2102.10874
	Vector med. $Z' - 2HDM$ (Dirac DM)	$0 e, \mu$	2 b	Yes	139	$m_{med}$	3.1 TeV	$\tan\beta=1, g_Z=0.8, m(\chi)=100$ GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	$m_{med}$	560 GeV	$\tan\beta=1, g_\chi=1, m(\chi)=10$ GeV	ATLAS-CONF-2021-036

# Mono-jet

- Most sensitive mono-X channel for ISR processes
- Search: for a Missing Energy excess.
- Dominant backgrounds: **Z(vv)+jets** and **W(lv)+jets** constrained in 1 and 2 lepton control regions



[EXOT-2018-06/](#)

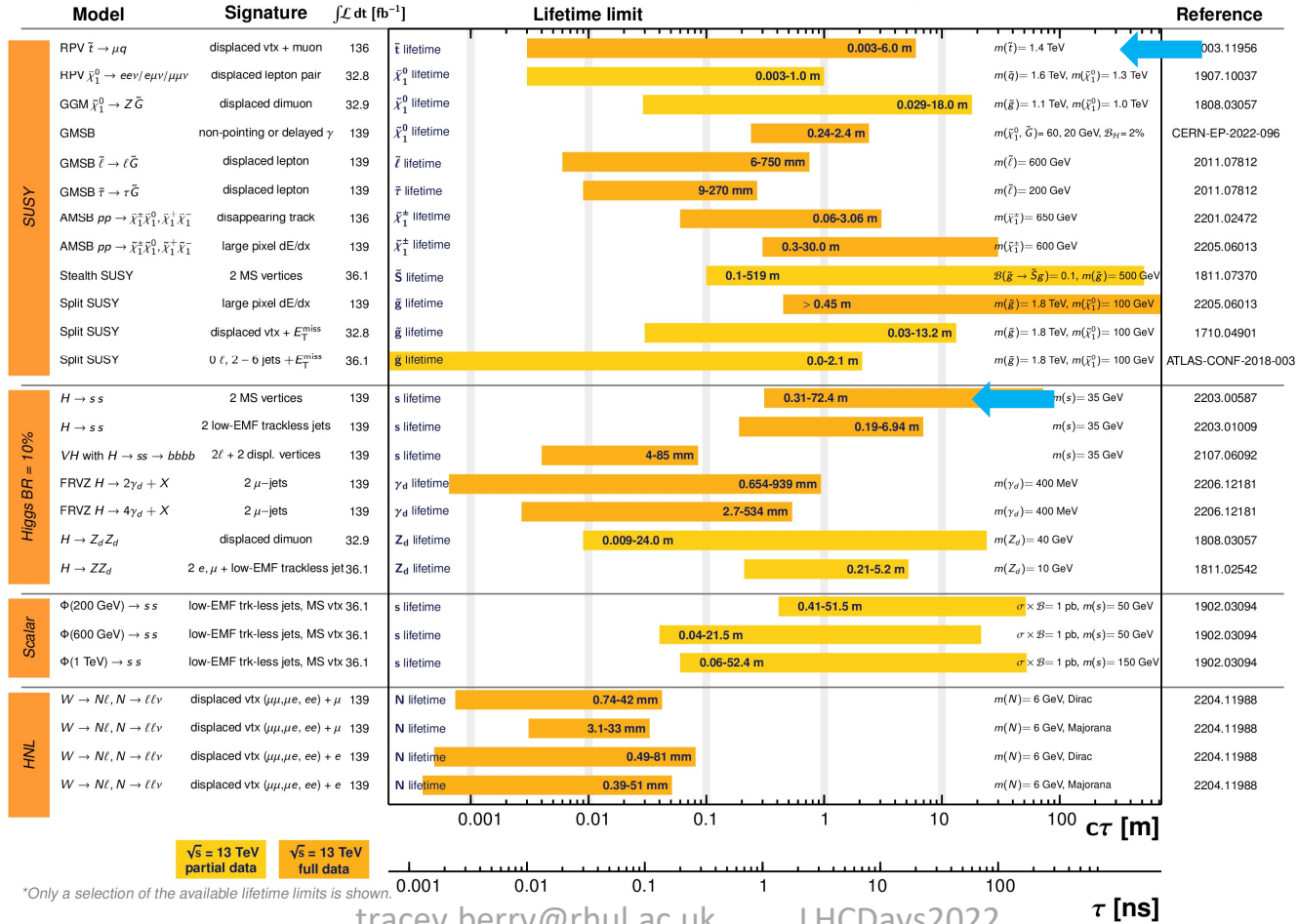




# Long-Lived Particle Searches

ATLAS Long-lived Particle Searches\* - 95% CL Exclusion  
Status: July 2022

ATLAS Preliminary  
 $\int \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 13 \text{ TeV}$





# Searches for long lived particles

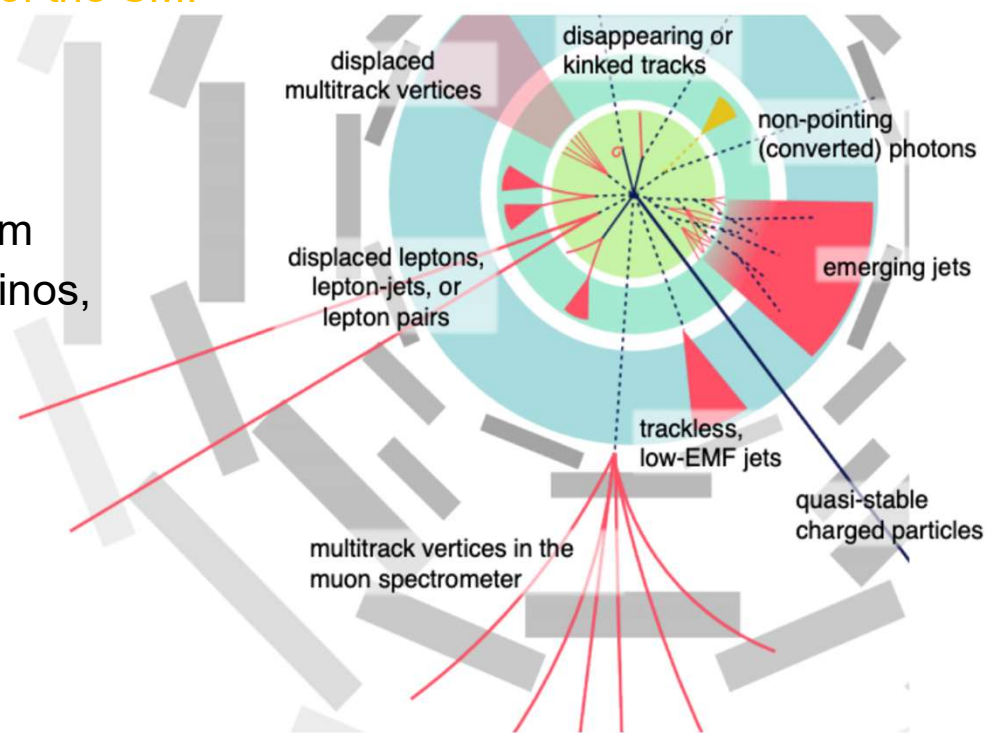
- Long-lived (LL) and unconventional exotic particles with striking signatures predicted by many extensions of the SM.

- Examples:

- Heavy, long-lived, charged particles
- Sleptons
- Particles can decay in the detector after few cm
- Neutralinos in GMSB, mass-degenerate gauginos, particles of a Hidden Sector

## Challenging experimentally

- Non-standard reconstruction
- Displacements, timing and ionization
- Dedicated triggers
- Non-standard background is a challenge
- Detector noise, cosmic rays, reconstruction failures
- Usually estimated from data

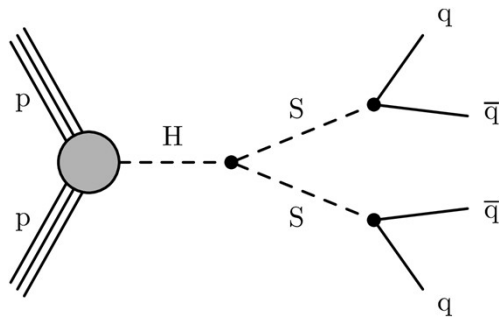
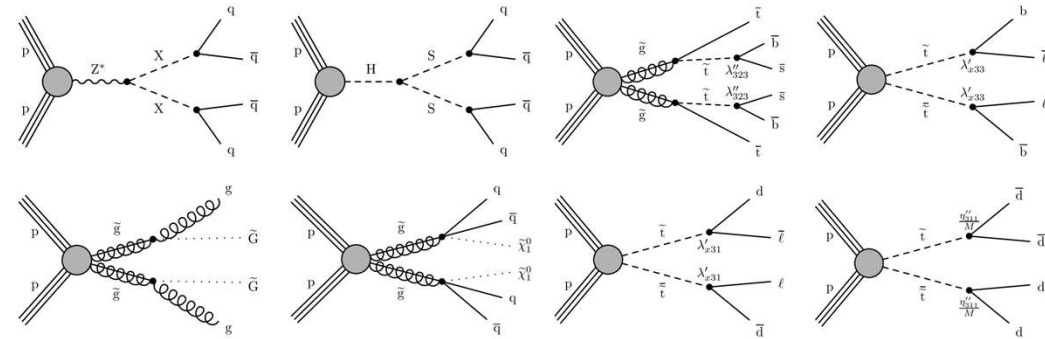


# Displaced jets

CMS-EXO-19-021

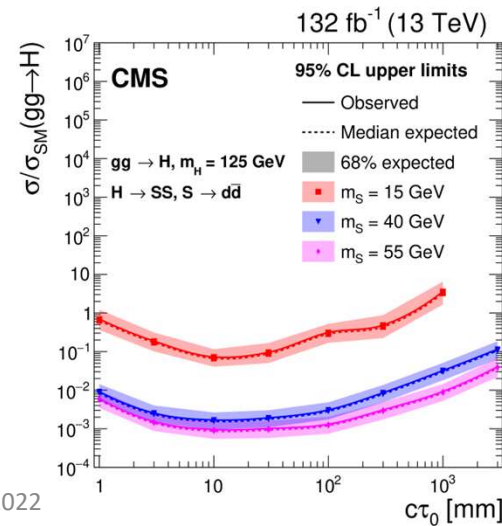


- **Distinctive topology** : pair of jets originating at a secondary vertex
- **Different signal models** targeted:
- LLP decaying to q-qbar, Exotic decays of Higgs:  $gg \rightarrow H \rightarrow 2S, S \rightarrow qq$  where  $c\tau \sim 1\text{mm to } 3\text{m}$



## Highlights:

- Dedicated displaced triggers
- Dedicated secondary vertex reconstruction
- BDT with variables like vertex track multiplicity



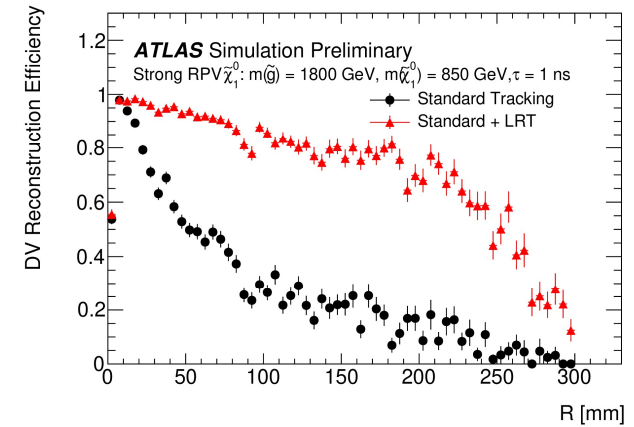
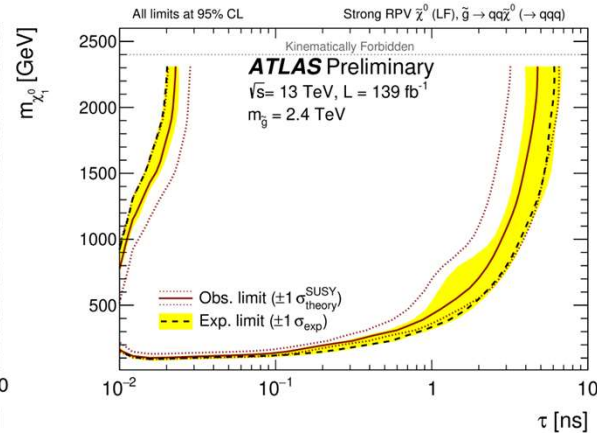
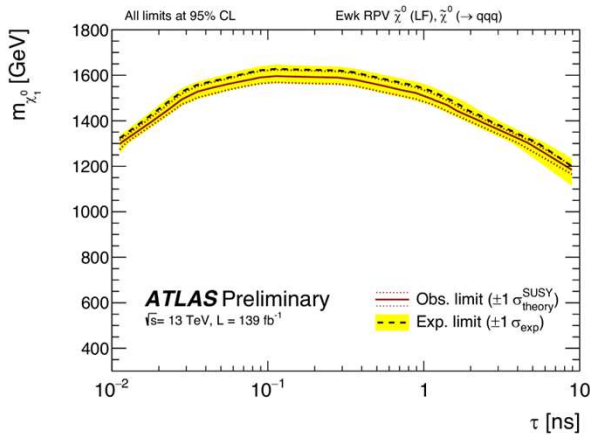
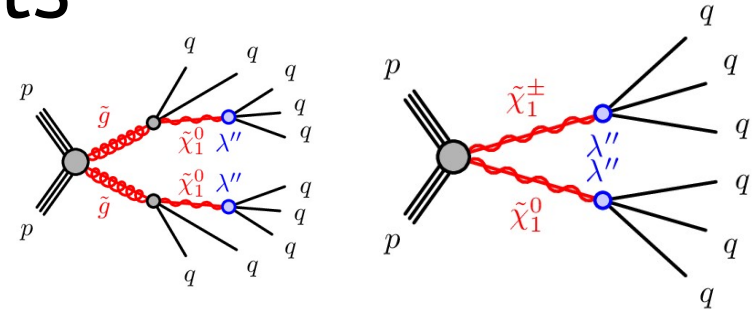
# Displaced vertex + jets

Search for long-lived particles (LLPs) decaying into hadrons  
In events with a displaced vertex (DV) and several jets

Uses dedicated reconstruction techniques that significantly  
increase the sensitivity to LLP decays

Backgrounds are instrumental, data-driven estimation

Interpretations in strong and electroweak SUSY models



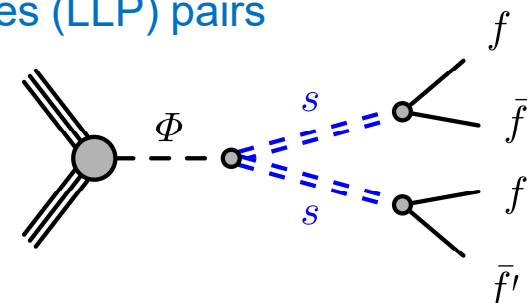
Electroweakino masses below 1.5 TeV  
are excluded for mean proper lifetimes  
in the range from 0.03 ns to 1 ns

Limits on pair-production of supersymmetric particles with long-lived  
electroweakinos that decay via a small R-parity-violating coupling

# Displaced jets in muon system (2vtx)

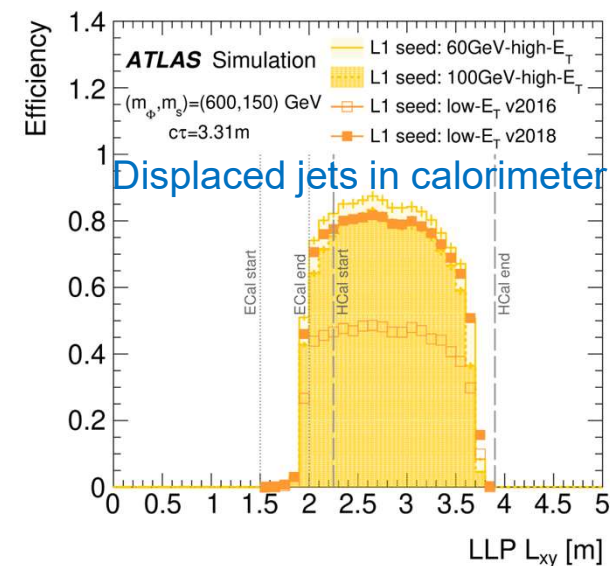
- Search for events with two displaced vertices from long-lived particles (LLP) pairs

- In the muon spectrometer (MS):  
reconstruct vertices of LLPs decaying to jets
- Vertices displaced between 3 m and 14 m w.r.t primary



- Observed number of events consistent with expected background
- Limits for several benchmark signals are determined

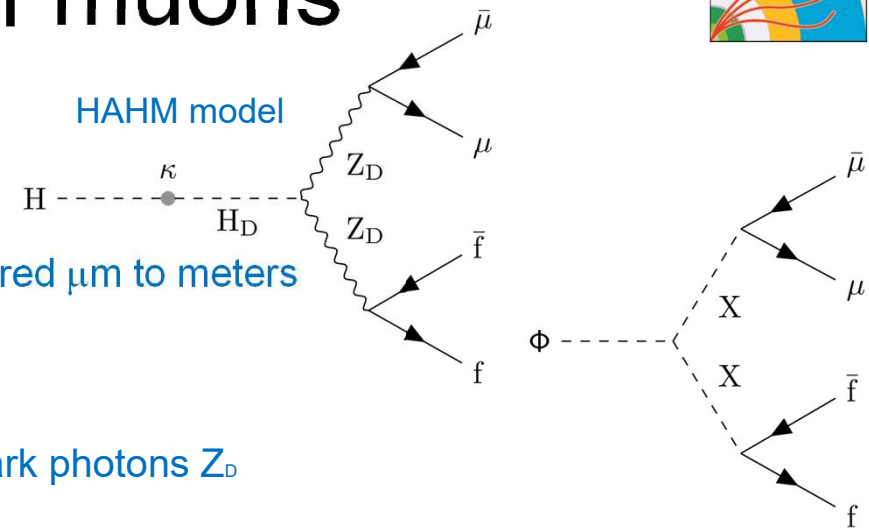
- First exclusion limits for branching fractions (BF) into neutral LLPs below 0.1%, for  $m_H = 125$  GeV
- BF above 10% are excluded at 95% C.L. for LLP proper lifetimes ranging from 4 cm to 72.4 m
- First results for LLPs decaying into  $tt^-$  in MS





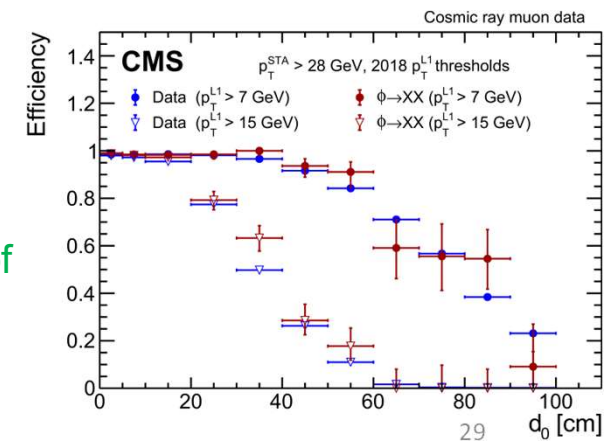
# LLPs decaying to a pair of muons

- Inclusive search for LLPs decaying to a pair of muons
- Signature: pair of oppositely charged muons originating from a common secondary vertex displaced from pp interaction point by several hundred  $\mu\text{m}$  to meters
- Results interpreted in frameworks:
  - Hidden Abelian Higgs Model (HAHM) in which Higgs boson decays to a pair of long-lived dark photons  $Z_D$
  - Simplified model LLPs produced in decays of an exotic heavy neutral scalar boson



Best limits to date on the branching fraction of the Higgs boson to dark photons for  $c\tau(Z_D)$  between 0.03 and 0.5 mm, for HAHM with  $m(Z_D) > 20 \text{ GeV}$  &&  $< m_H/2$

Best constraints on LLPs with masses larger than 10 GeV, produced in decays of an exotic scalar boson heavier than the Higgs and decaying to pair of muons

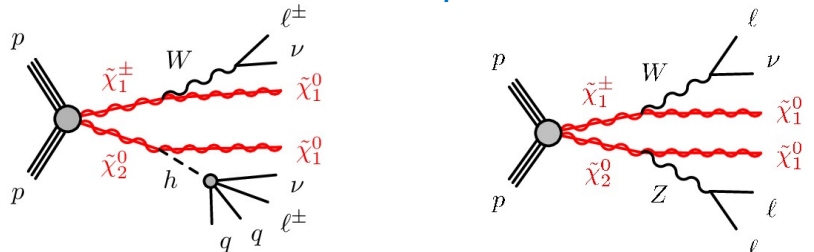




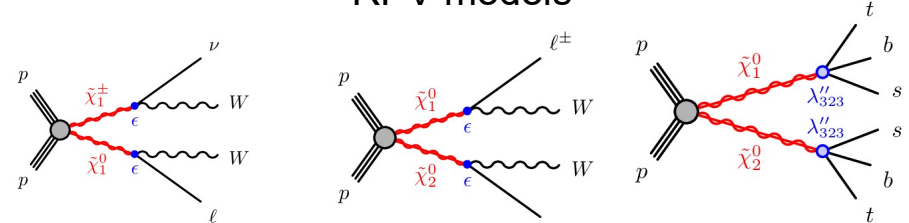
# Electroweak same-sign / 3-lepton

Search for winos and higgsinos in events with either a pair of **same-sign** leptons (e/μ) or 3 leptons  
 Interpretations in R-parity conserving (RPC) and R-parity violating (RPV) models

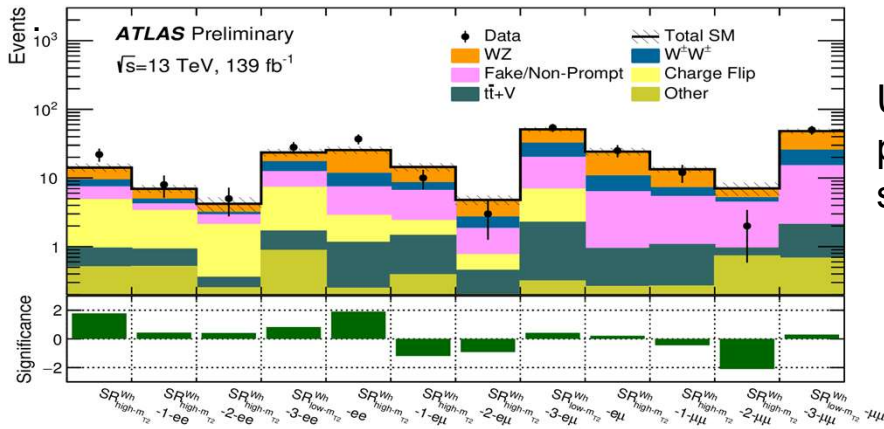
## RPC simplified models



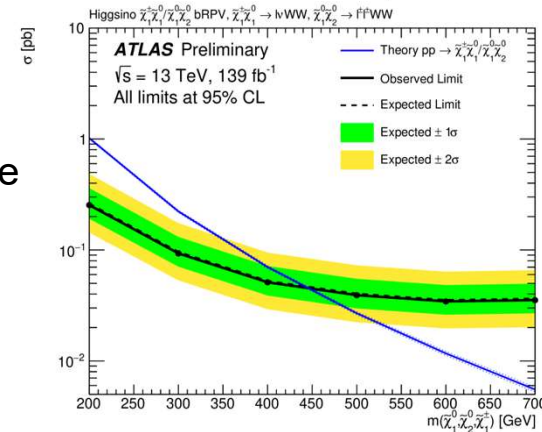
## RPV models



## Intermediate states including Wh or WZ pairs



Upper limits on the production cross sections set



Wino masses up to 525 GeV and 260 GeV are excluded respectively, for a bino of vanishing mass

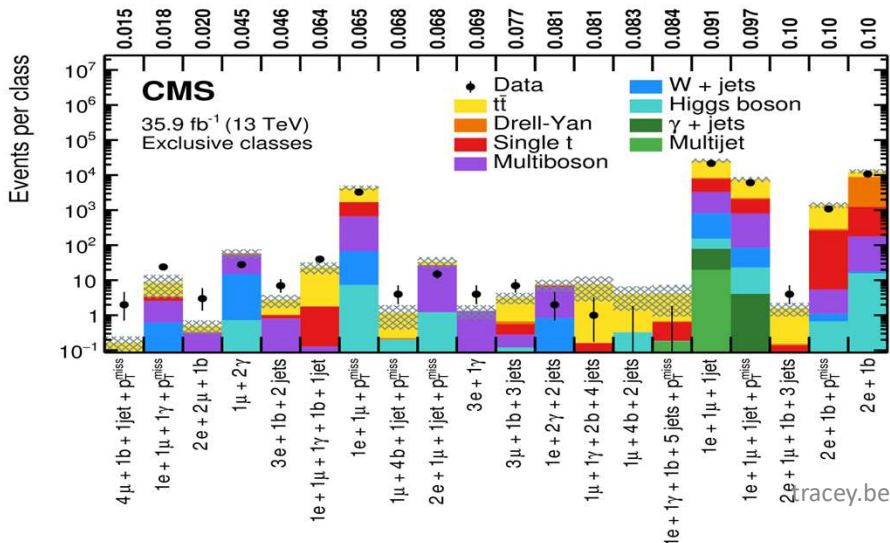
In a natural R-parity-violating model with bilinear terms Higgsino masses smaller than 440 GeV are excluded

# Multilepton General

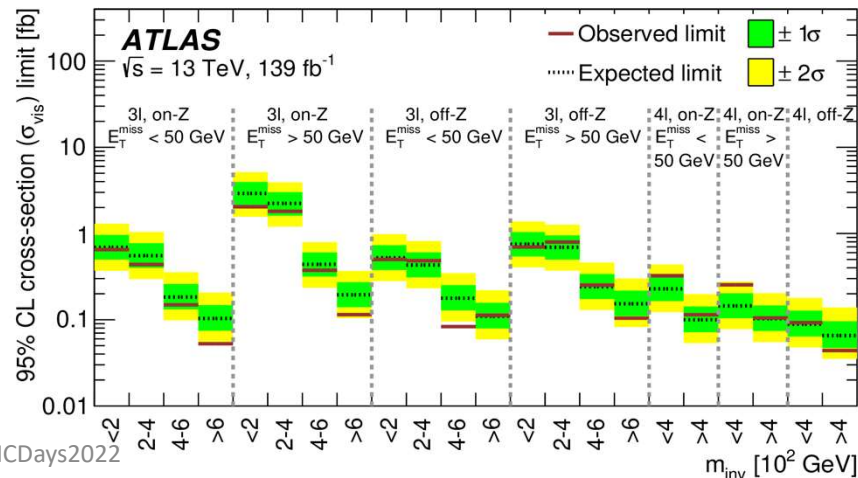
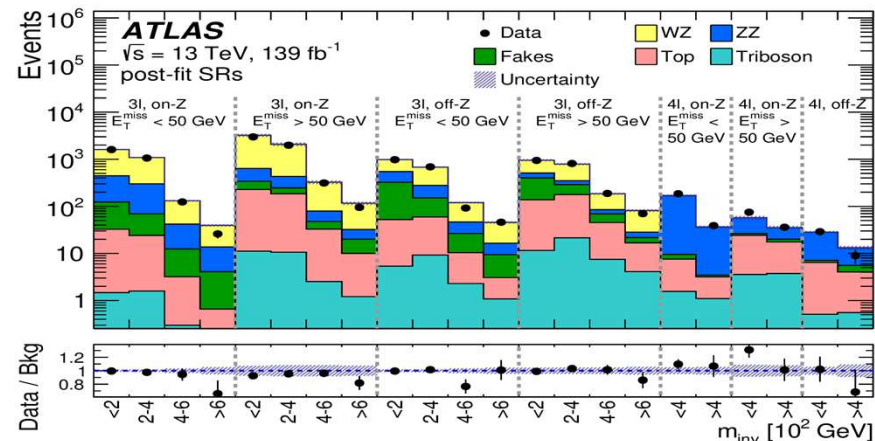
- Leaving no stone unturned
- Potential signals may be overlooked by model-specific analyses
- Identify interesting channels & search with minimal model dependence.
- Aims to be sensitive to a wide range of potential new-physics theories simultaneously

- $3\ell$  and  $4\ell$  events, where  $\ell=e,\mu$ , 22 event categories

## Model Unspecific Search in CMS (MUSiC)



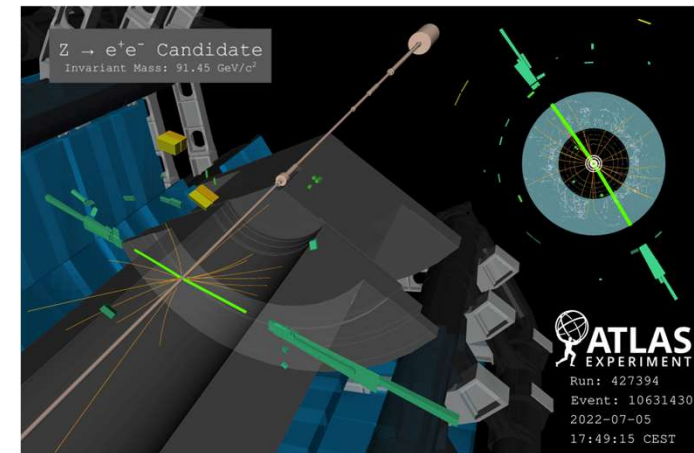
racey.berry@rhul.ac.uk



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# Conclusion

- Searching for exotics is a broad program:  
both in terms of questions asked and of final states
- Exciting and varied area to work in
- Some Run 2 results being finalised
- Looking forward to analysing Run 3 data



- Thanks for listening!

- Any Questions?

