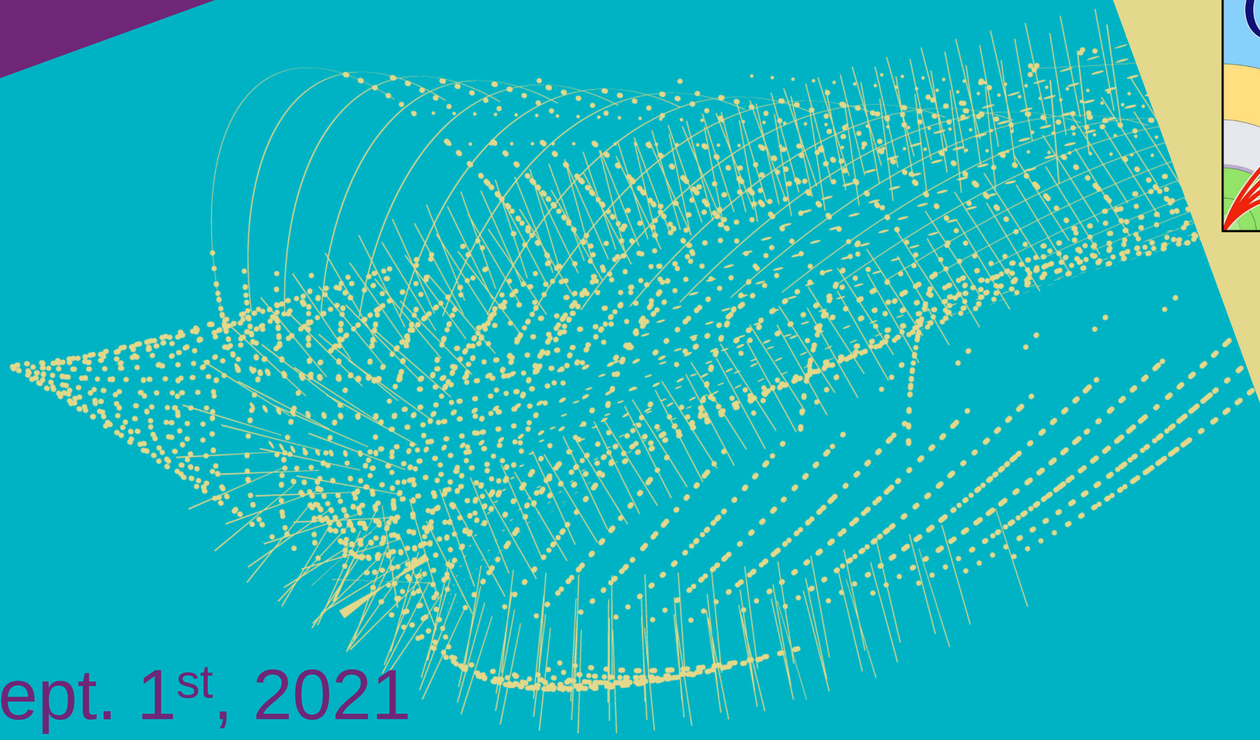
Nikhef

Radboud University

NWO

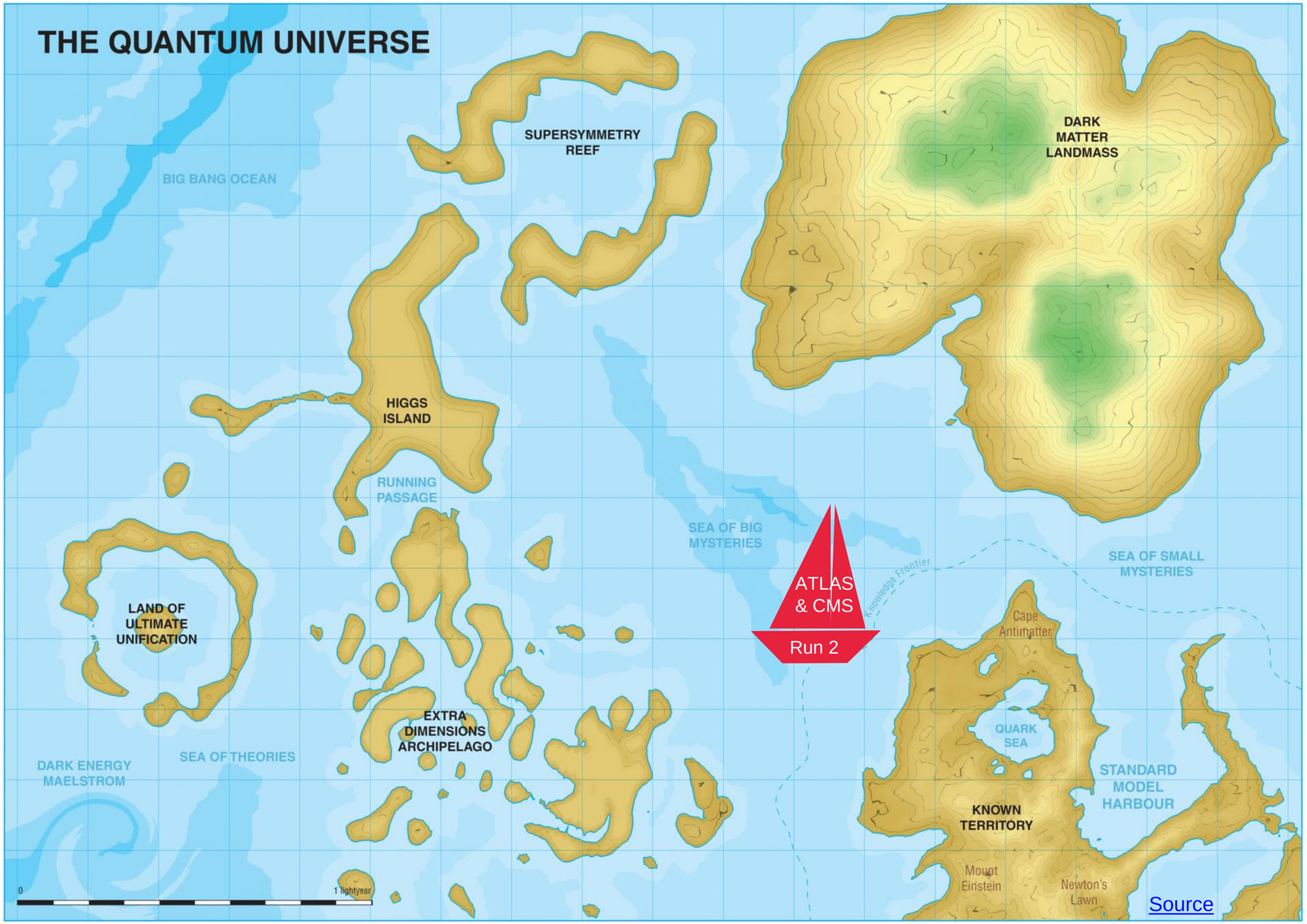


Corfu2021 SM and Beyond - Sept. 1st, 2021

EXOTICS AND BSM IN ATLAS AND CMS

Ann-Kathrin Perrevoort
on behalf of ATLAS & CMS
(ann-kathrin.perrevoort@cern.ch)

- The Standard Model (SM) leaves many questions unanswered
- Plethora of beyond SM models (BSM)
- Only few observational hints



Exotics and BSM Searches in ATLAS and CMS

Public results webpages
ATLAS Exotics HDBS
CMS Exotics Preliminary B2G

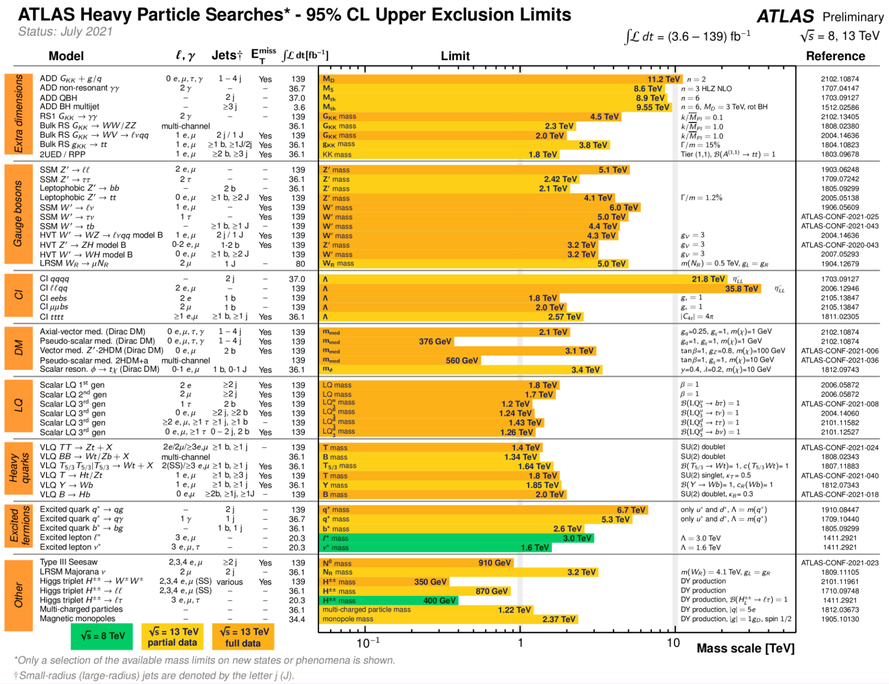
- ATLAS and CMS have a rich and very active exotics search program
- $\sim 140\,\mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13\,\mathrm{TeV}$ recorded in Run 2 (2015-2018)

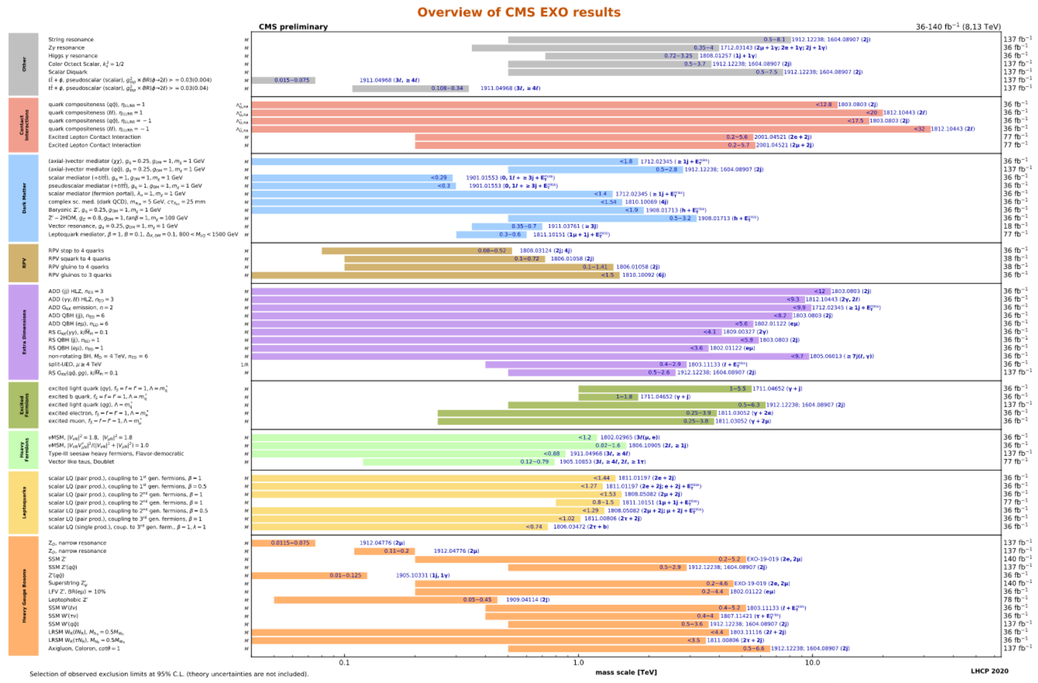
➢ Pushing mass limits and precision

- Many full Run 2 results already public and more coming

SUSY: P.Matorras-Cuevas, Sep.5 9:30
Dark matter: A.Albert, Sep.7 19:00

- This talk: selection of results with focus on recent, full Run 2 analyses

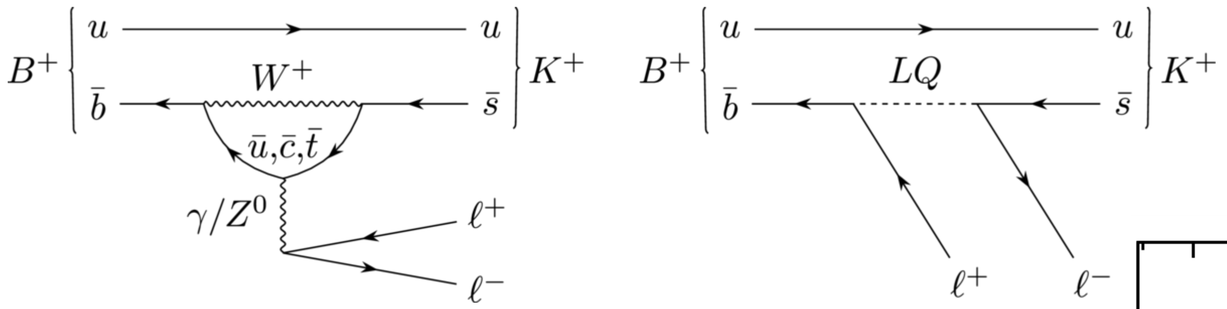


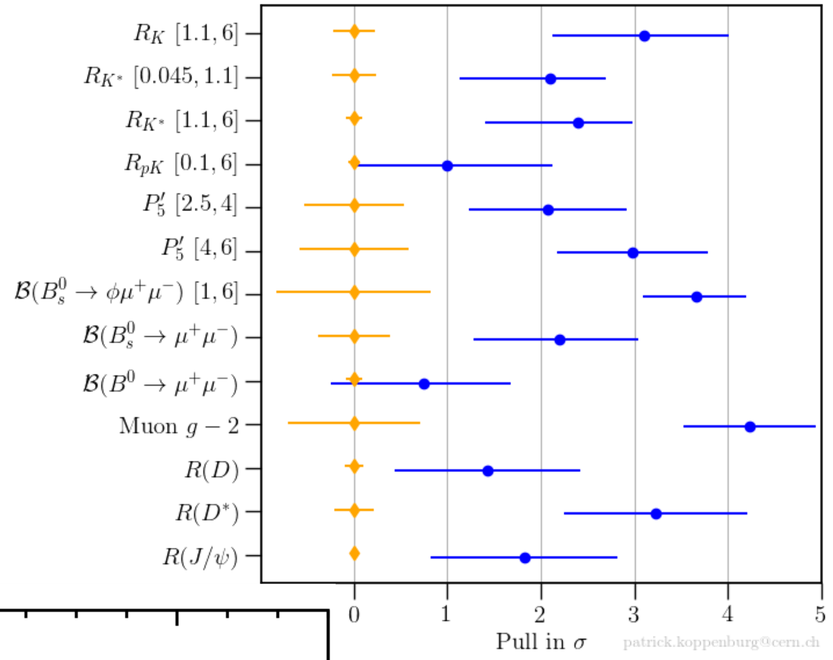


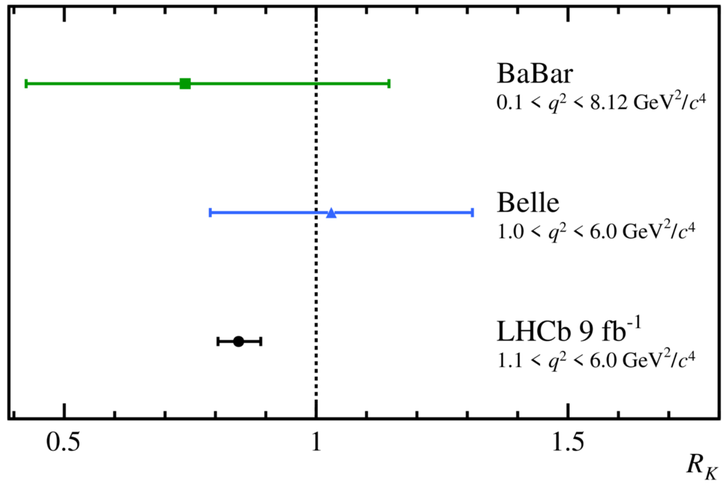
Lepton-Flavour Universality

P.Koppenburg et al. (2016), Scholarpedia, 11(6):32643
LHCb-PAPER-2021-004

- B anomalies:
  Several observations point at violation of lepton flavour universality (LFU) in $b \to s\ell\ell$ transitions, ex $R(K)$

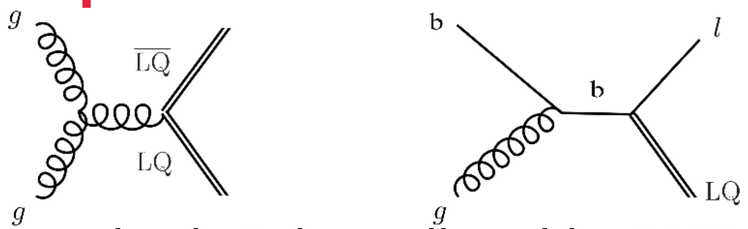






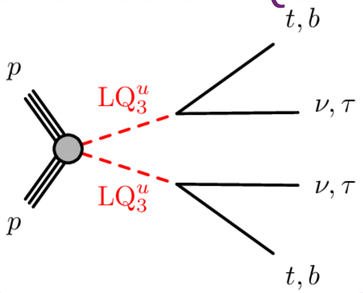
- Related to several Exotics searches:
- Leptoquarks
- Heavy vector particles W' and Z'
- $b \to s\ell\ell$ contact interaction
- Tests of other symmetries in the lepton sector:
- Dilepton ratios
- Lepton Flavour Violation

Leptoquarks

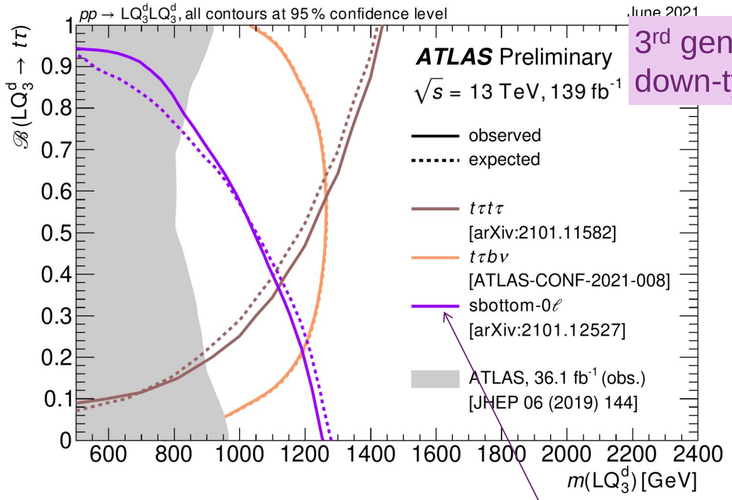


- Leptoquarks (LQs) predicted in GUTs and composite Higgs models
- LQs produced in pairs in gg fusion and $q\bar{q}$ annihilation or singly in association with a lepton

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

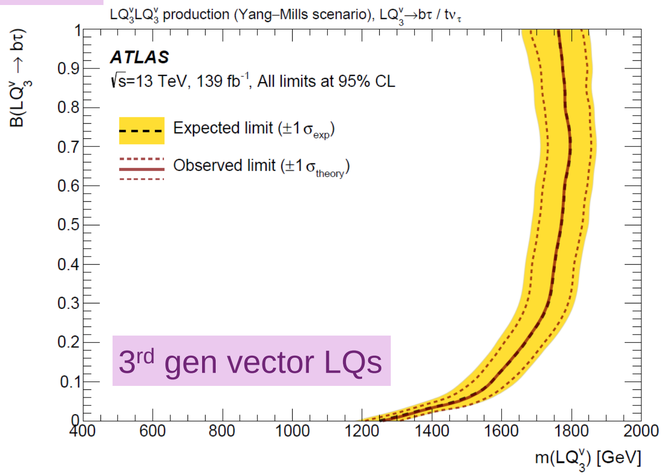


[ATL-PHYS-PUB-2021-017](#)
[CMS-EXO-19-015](#)
[CMS-EXO-20-004](#)
[ATLAS EXOT-2019-13](#)
[ATLAS SUSY-2019-18 (arXiv)](#)

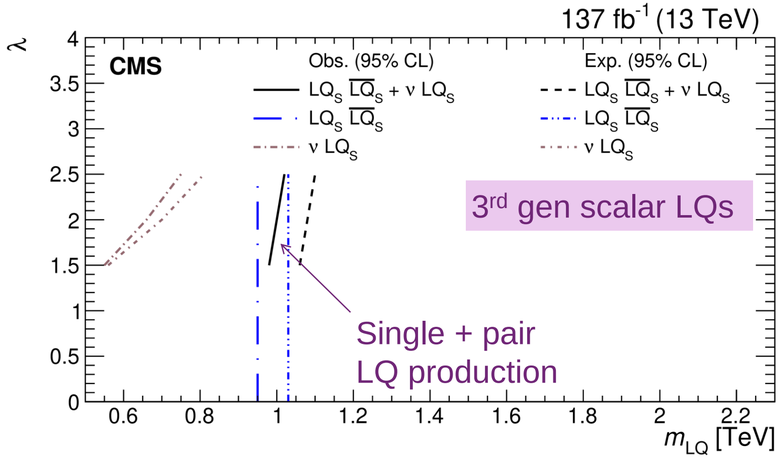


3rd gen scalar down-type LQs

Re-interpretation of SUSY results

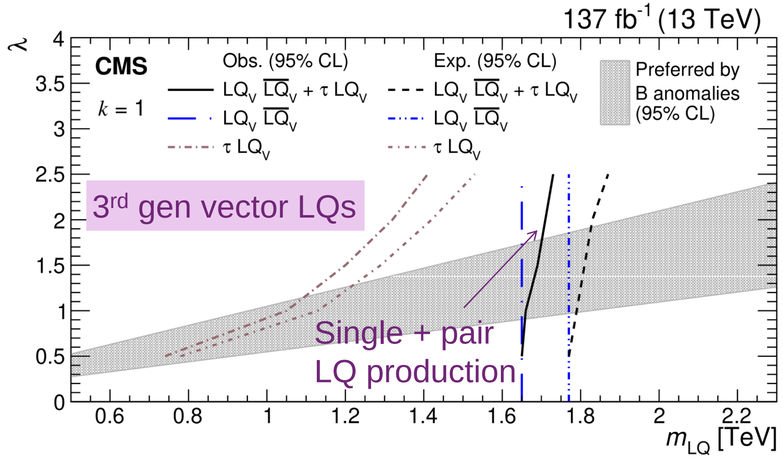


3rd gen vector LQs



3rd gen scalar LQs

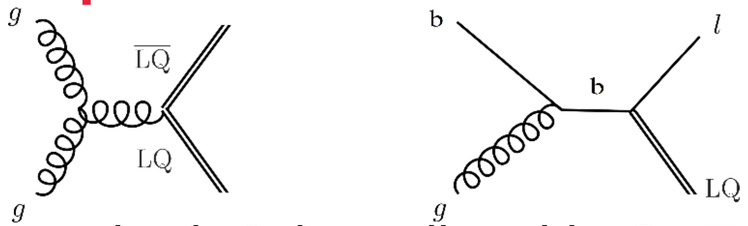
Single + pair LQ production



3rd gen vector LQs

Single + pair LQ production

Leptoquarks



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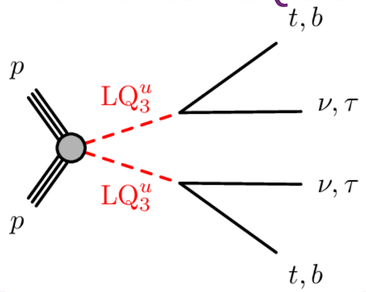
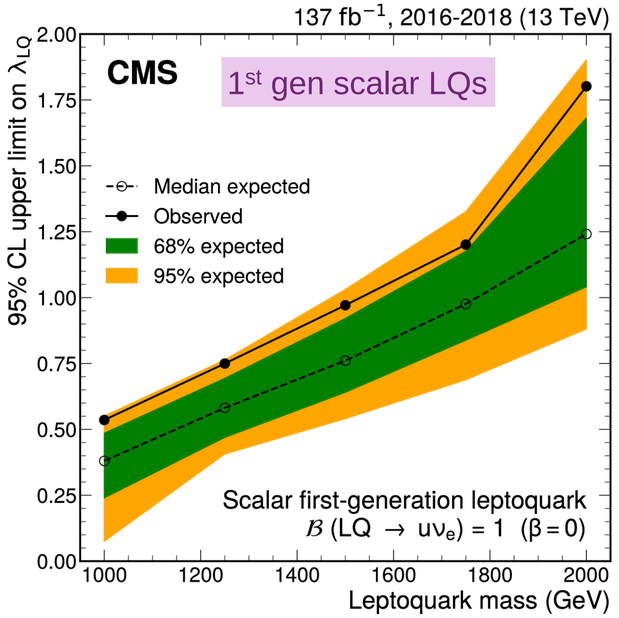
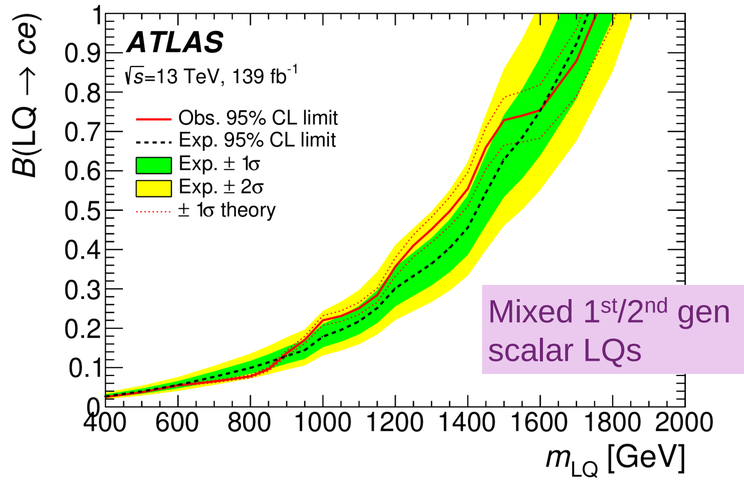
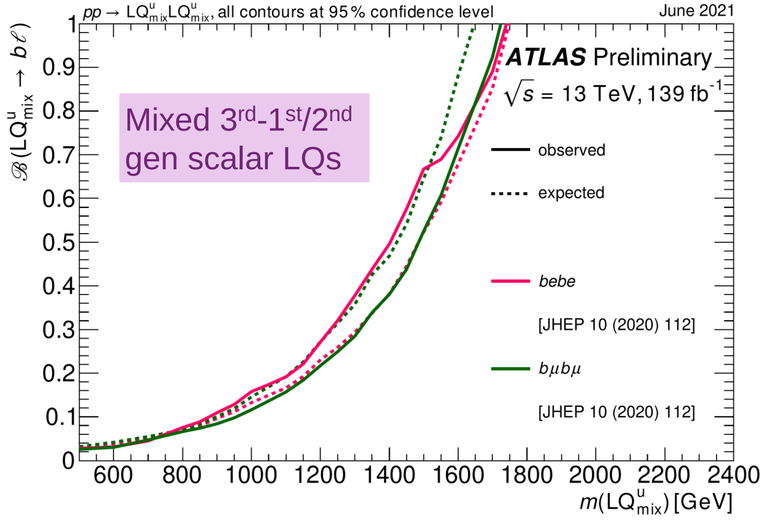


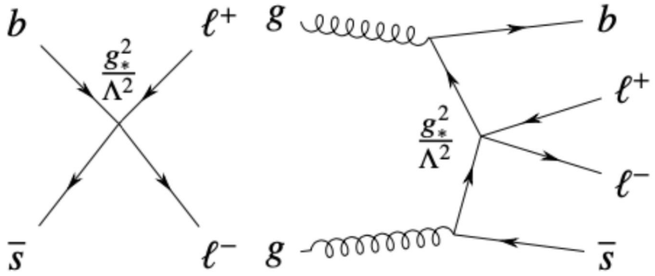
[ATL-PHYS-PUB-2021-017](#)
[CMS-EXO-19-015](#)
[CMS-EXO-20-004](#)
[ATLAS EXOT-2019-13](#)
[ATLAS SUSY-2019-18 (arXiv)](#)







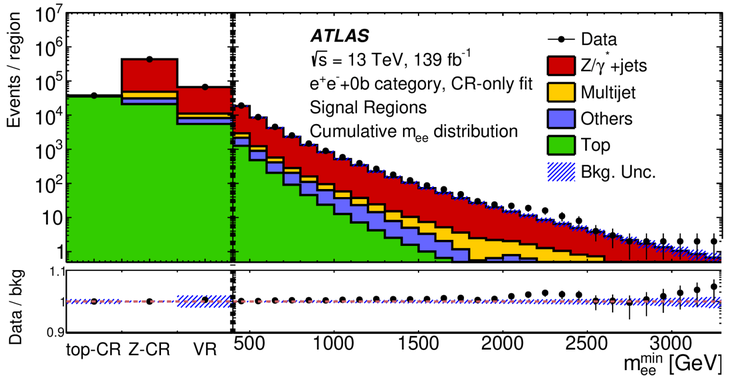
$bs\ell\ell$ Contact Interaction

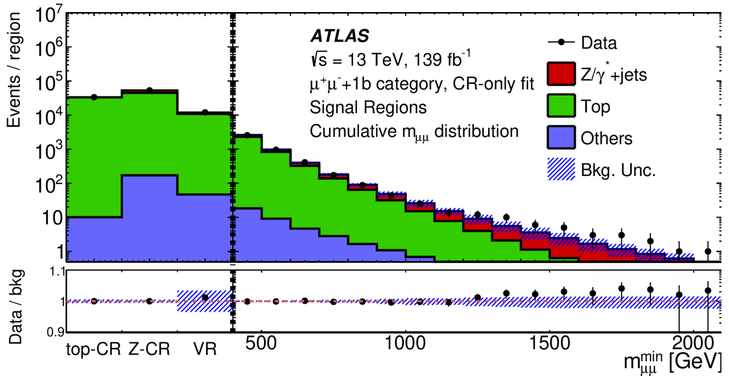


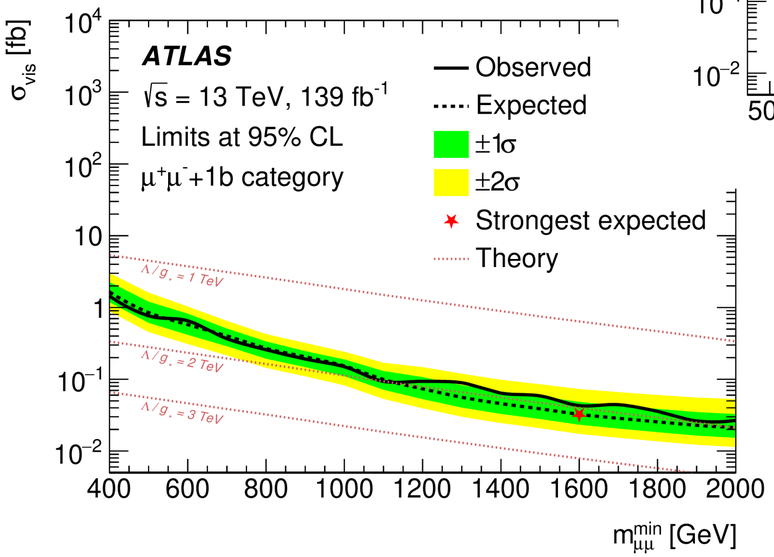
ATLAS EXOT-2018-16

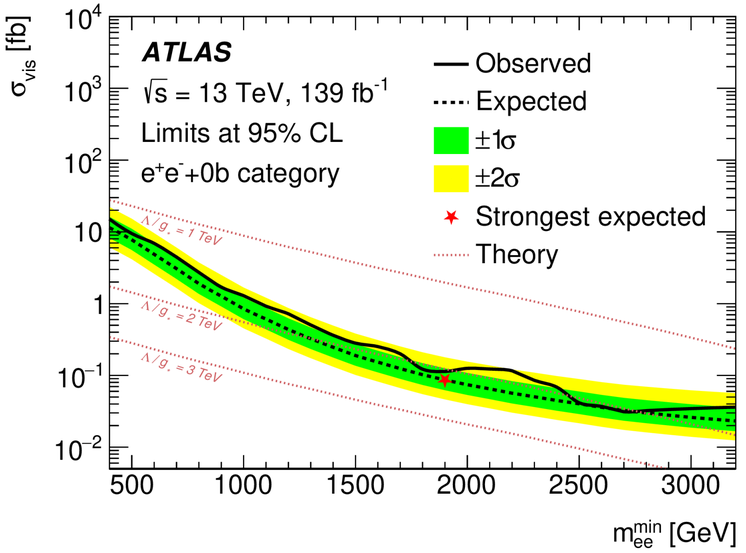
- Probing $bs\ell\ell$ contact interaction at high mass
- Final states with e^+e^- or $\mu^+\mu^-$ and potentially a b- or light quark

Fitting cumulative $m_{\ell\ell}$ distributions





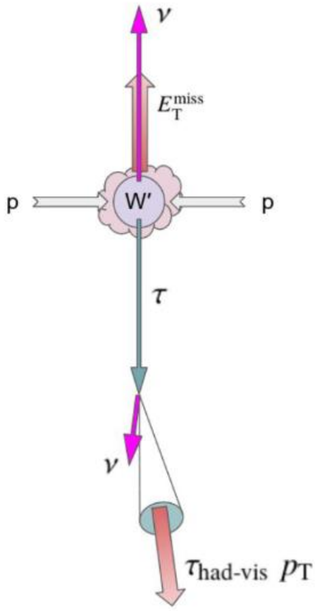


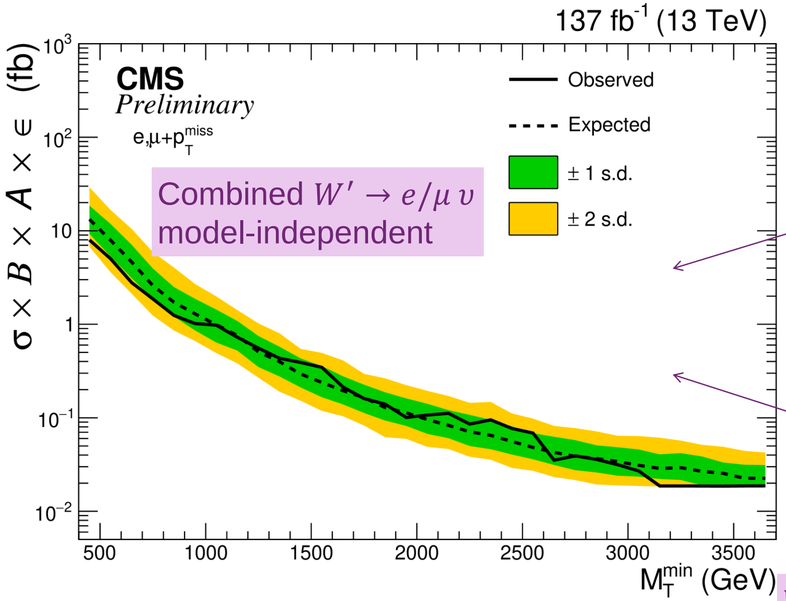


Heavy Gauge Bosons

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

- $W' \to \ell\nu$ decays
- In the transverse plane: lepton back-to-back to missing transverse momentum
- Probed in $m_{\mathrm{T}}(\ell, p_{\mathrm{T}}^{\mathrm{miss}})$ distributions
- Results for simplified Heavy Vector Triplet models (ex. Sequential Standard Model) as well as model-independent



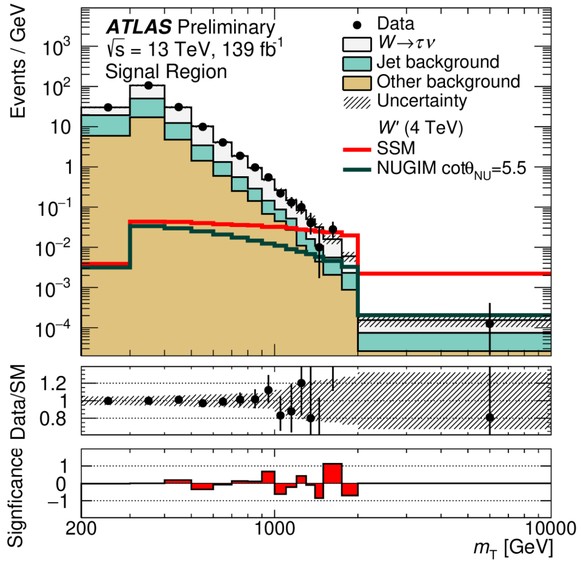


Combined $W' \to e/\mu\,\upsilon$ model-independent

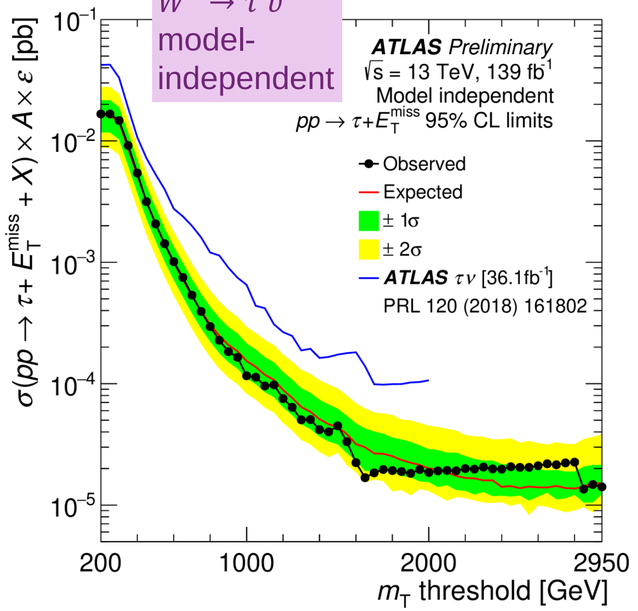
[CMS-PAS-EXO-19-017](#)
[ATLAS-CONF-2021-025](#)

ATLAS results on $W' \to e/\mu\,\upsilon$: [ATLAS EXOT-2018-30](#)

Several models are probed: SSM, split-UED, RPV-SUSY, EFT



$W' \to \tau\,\upsilon$ model-independent

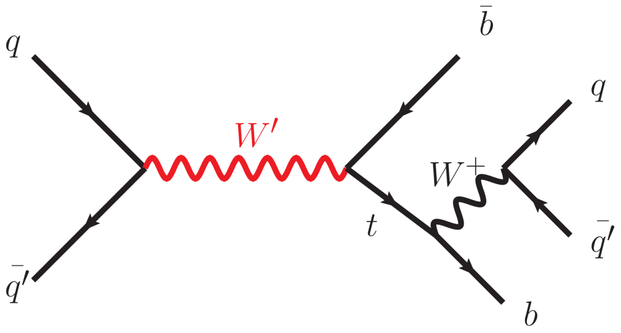


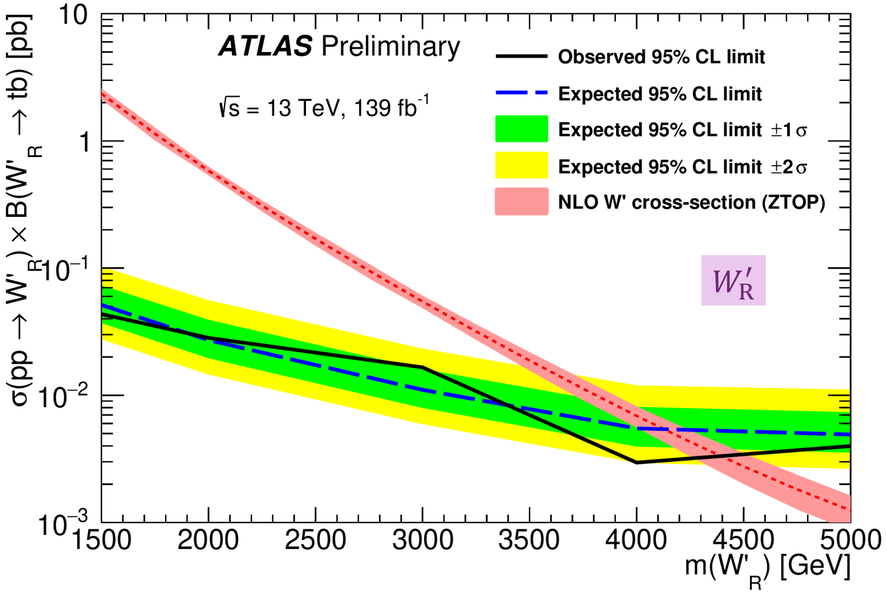
Heavy Gauge Bosons

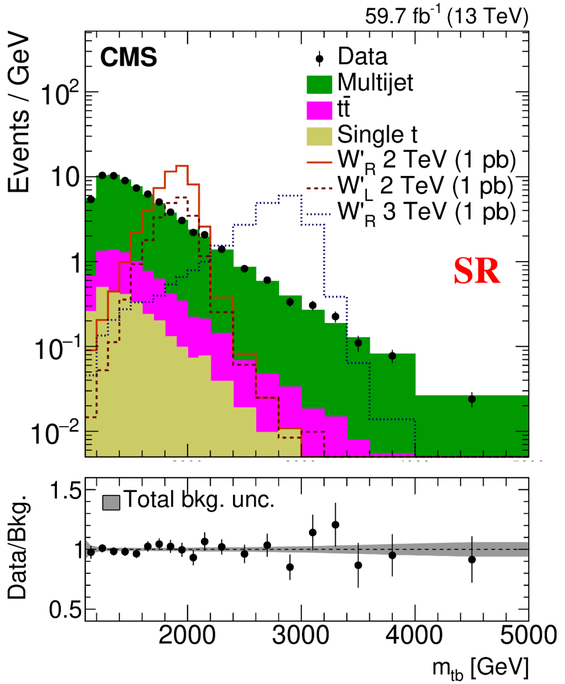
ATLAS-CONF-2021-043
CMS-B2G-20-005

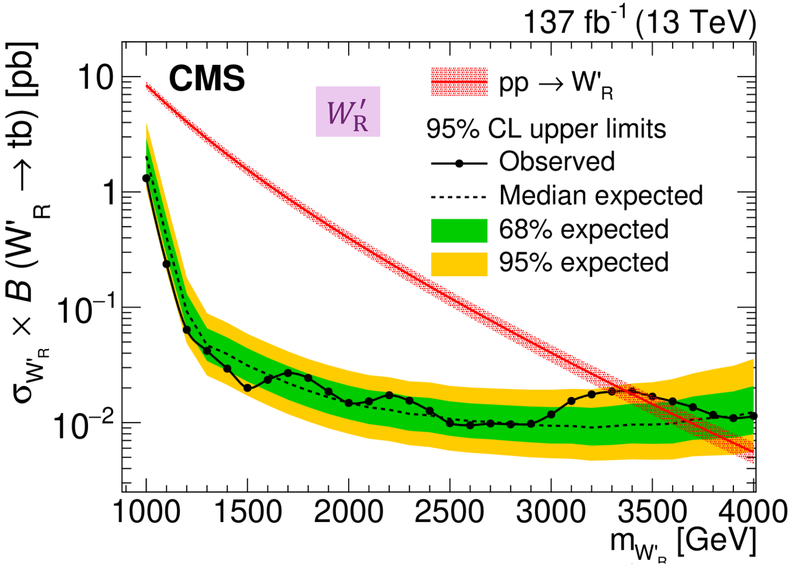
$W' \to tb$ decays

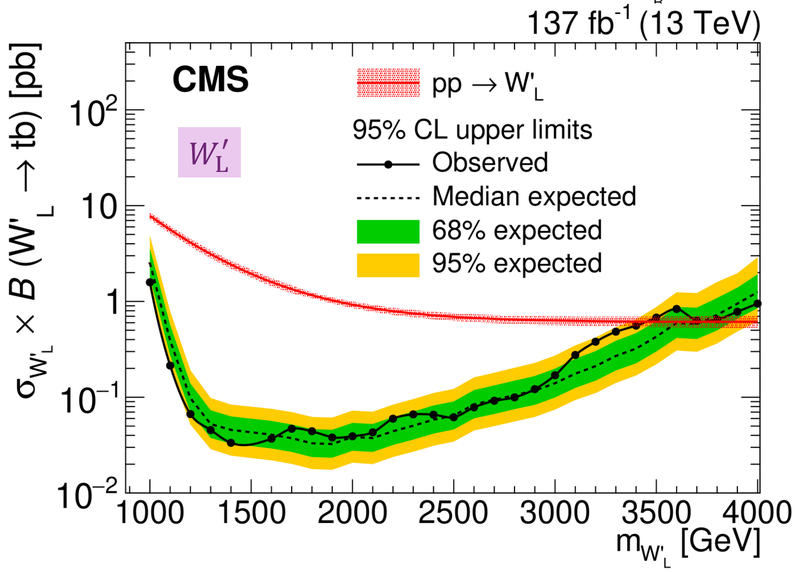
- Searches in all-hadronic final state
- Machine learning techniques exploiting jet substructure in top- and b-tagging
- W' with right- and left-handed chirality
- Search for excess in m_{tb}





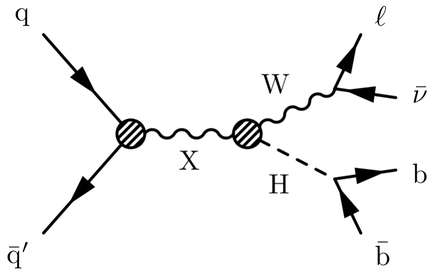






Heavy Gauge Bosons

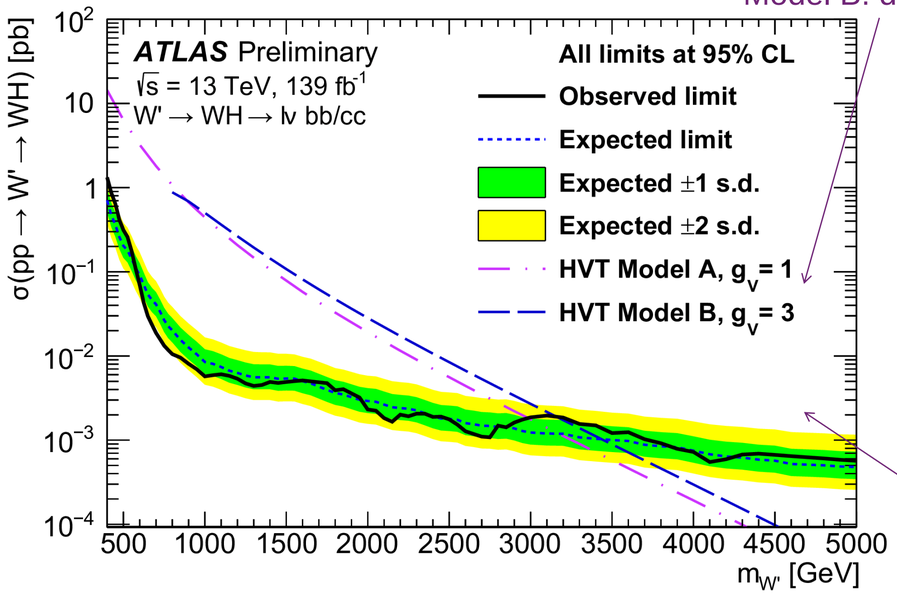
CMS-PAS-B2G-19-002
ATLAS-CONF-2021-026

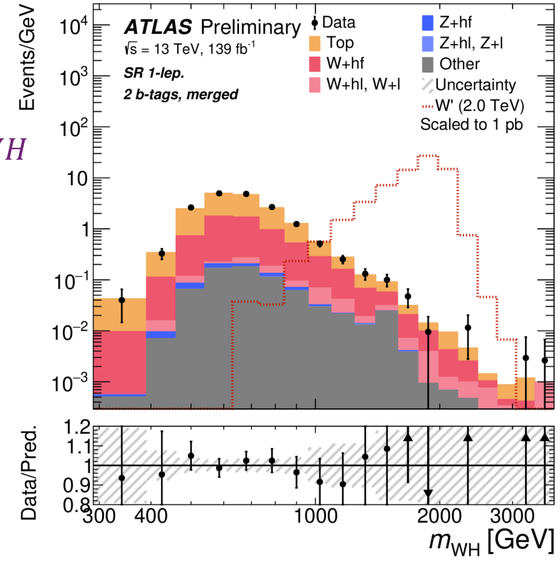


$W' \to WH$

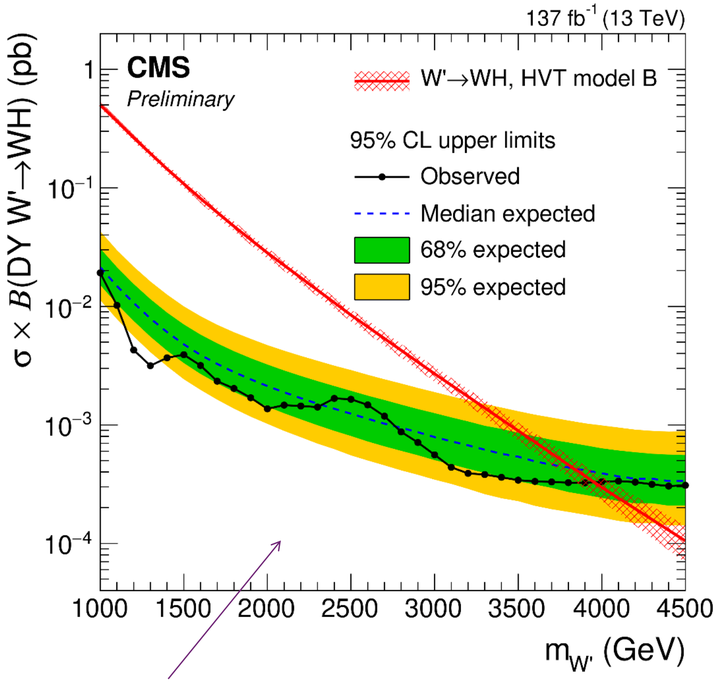
- Search for resonance in semi-leptonic channel $W' \to WH \to \ell\nu b\bar{b}$ (high $\mathcal{B}(H \to b\bar{b})$)
- Collimated decay products → large-R jets, substructure

Heavy Vector Triplet (HVT)
- Model A: SSM, $V' \to ff$
- Model B: dominant $V' \to VH$

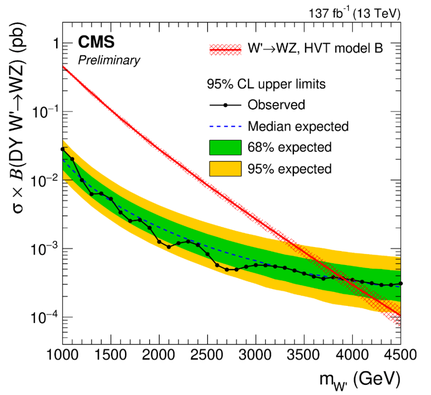




- Use resolved di-jets or a merged large-R jet
- Higgs tagging uses single or double b-tagged subjets



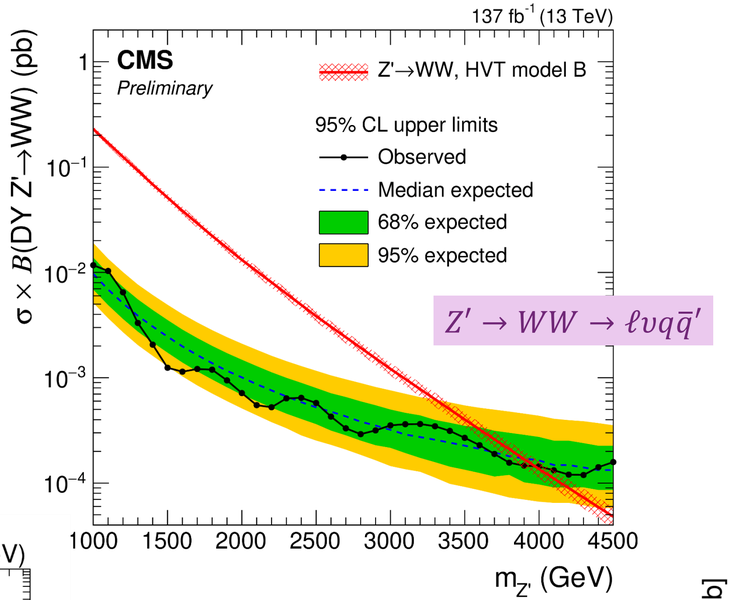
- Merged large-R jets
- Higgs tagging with double b-tagger
- Similar bounds on $W' \to WZ$, $Z' \to WW$

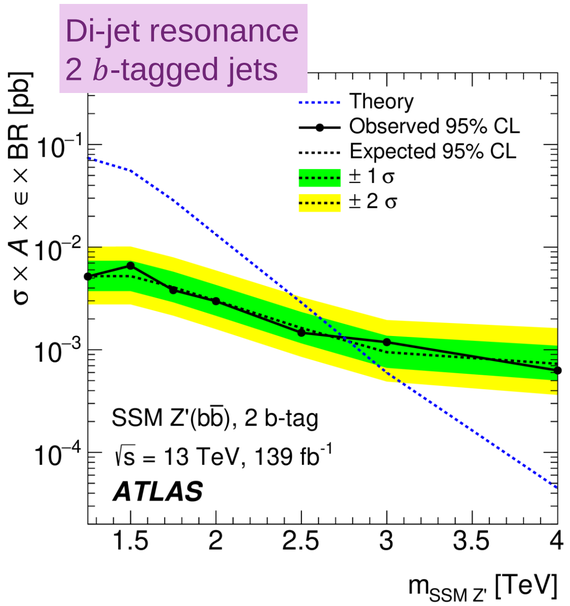


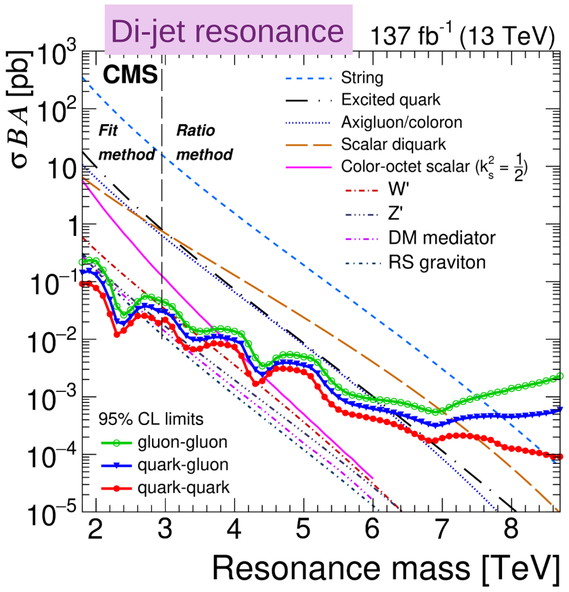
Heavy Gauge Bosons

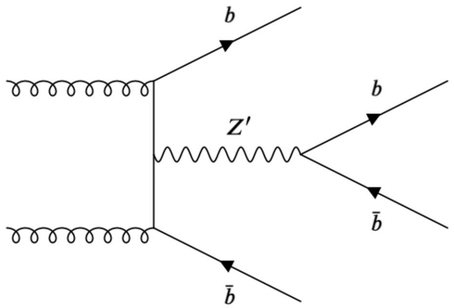
- Neutral gauge bosons Z'
- Decays to WW, $b\bar{b}$, di-leptons and di-jets studied

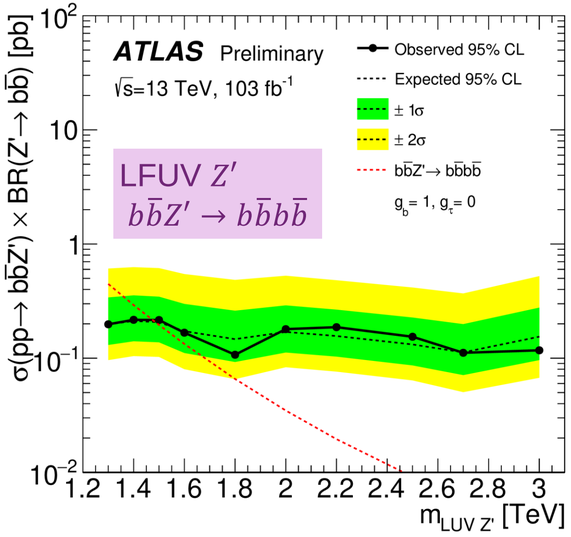
[ATLAS EXOT-2018-09](#)
[CMS-PAS-B2G-19-002](#)
[CMS-EXO-19-012](#)
[ATLAS EXOT-2019-03](#)









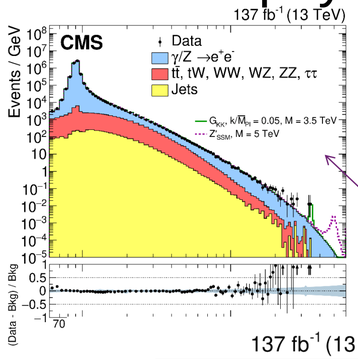


Di-lepton Ratios

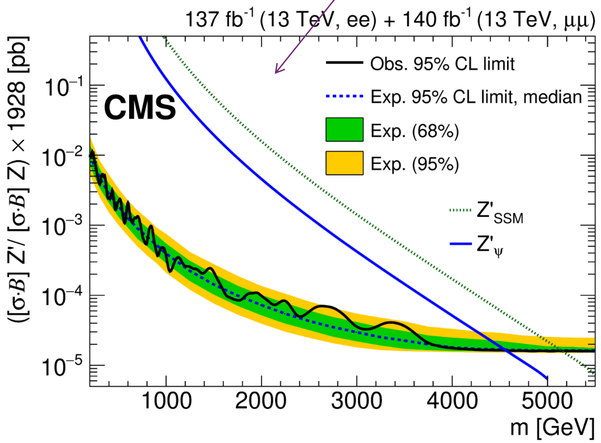
CMS-EXO-19-019
ATLAS-CONF-2021-045

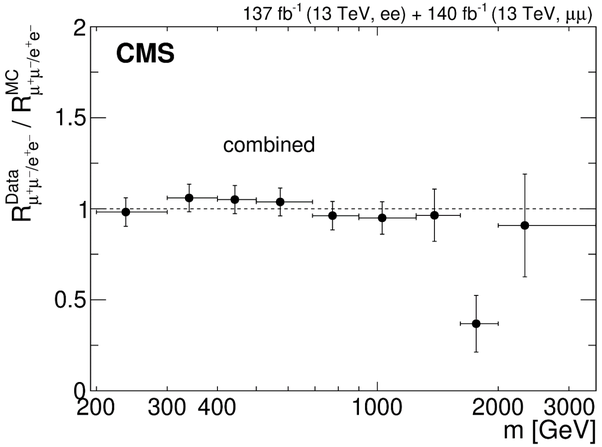
- Resonant and non-resonant di-lepton final states with high mass in many SM extensions (ex. Z', LQs)
- BSM physics can cause R to deviate from unity

$$R_{\mu^+\mu^-/e^+e^-} = \frac{\mathrm{d}\sigma(q\bar{q}\to\mu^+\mu^-)/\mathrm{d}m_{\ell\ell}}{\mathrm{d}\sigma(q\bar{q}\to e^+e^-)/\mathrm{d}m_{\ell\ell}}$$



Di-lepton resonance

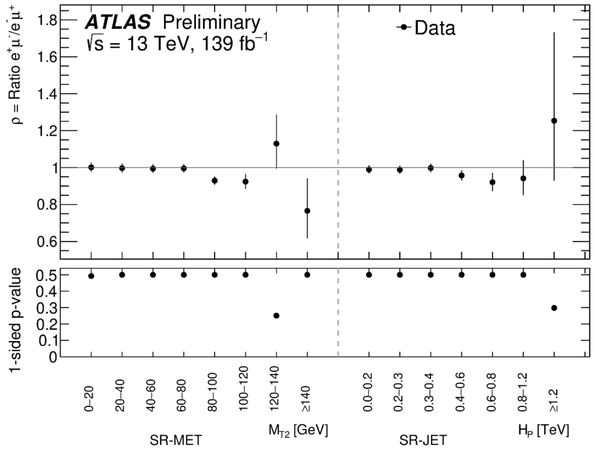


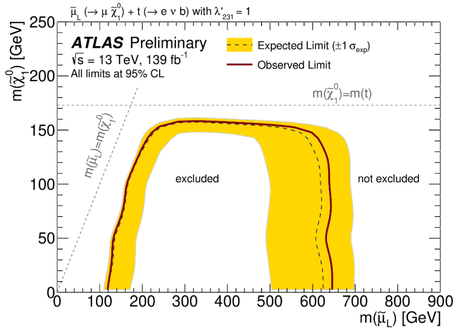


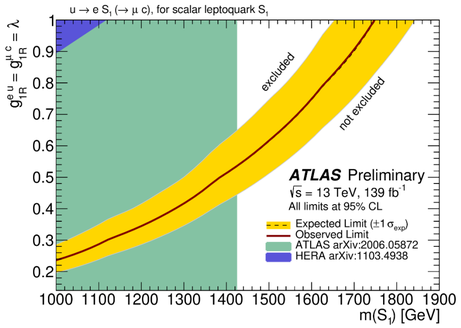
- Measure ratio of $e^+\mu^-$ to $e^-\mu^+$ pairs

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

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

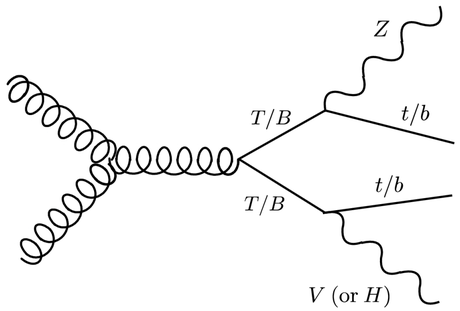






Vector-Like Quarks

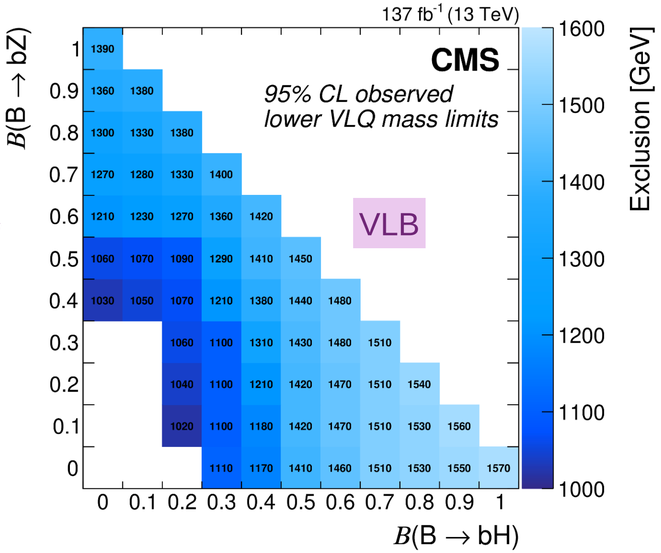
ATLAS-CONF-2021-024
[CMS-B2G-19-005](CMS-B2G-19-005)



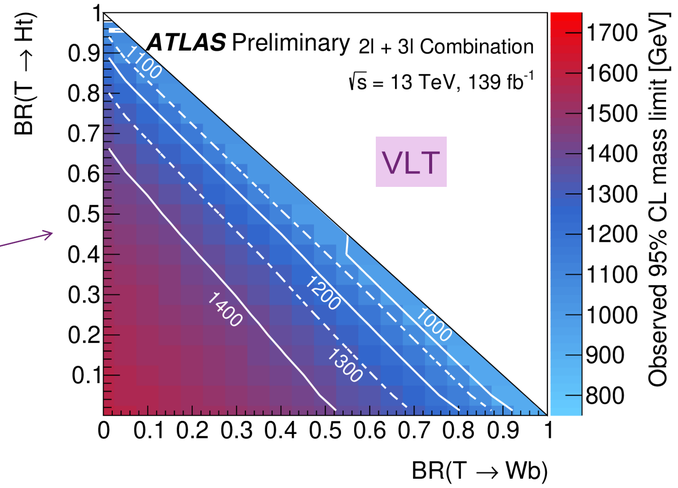
- Vector-like Quarks (VLQ) appear in many BSM models: Little Higgs, SUSY, extra dimensions, …
- Solving the fine tuning problem
- Vector-like top T and bottom B, as well as X, Y VLQs arranged in singlets, doublets and triplets

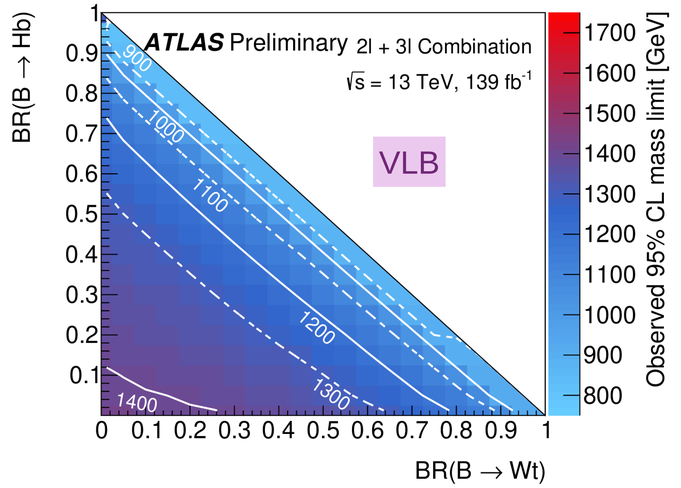
- Pair production in strong interactions

- Targeting $B \to Zb/Hb$
- Fully hadronic final state with $Z \to q\bar{q}$ and $H \to b\bar{b}$
- Boosted H/Z decay $\to$ 4, 5, 6 jets



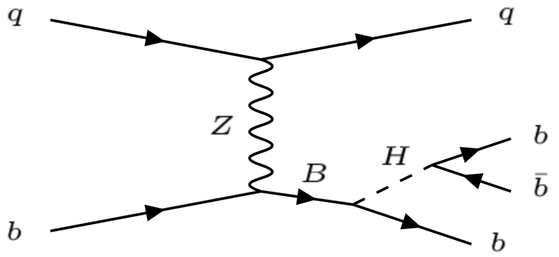
- Targeting $T \to Wb/Zt/Ht$ and $B \to Wt/Zb/Hb$
- Require boosted $Z \to \ell\ell$
- 2ℓ or 3ℓ, b-jets (≥1), large-R jets
- Deep neural net to classify jets originating from Z, W, H, top



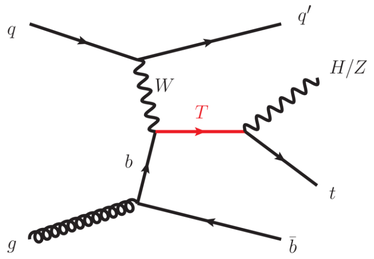


Vector-Like Quarks

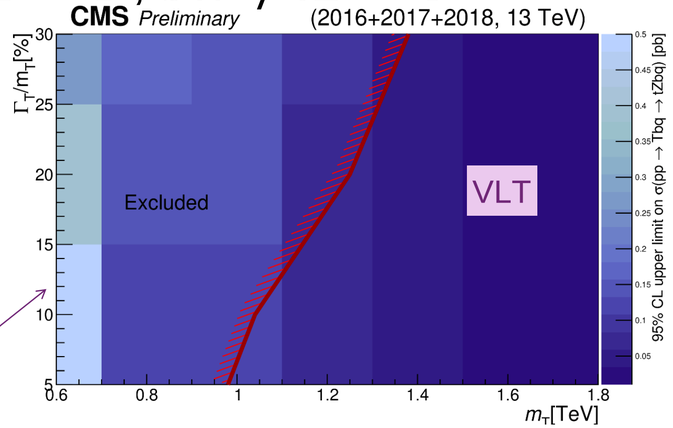
[ATLAS-CONF-2021-018](#)
[ATLAS-CONF-2021-040](#)
[CMS-B2G-19-004](#)
[CMS-PAS-B2G-20-002](#)



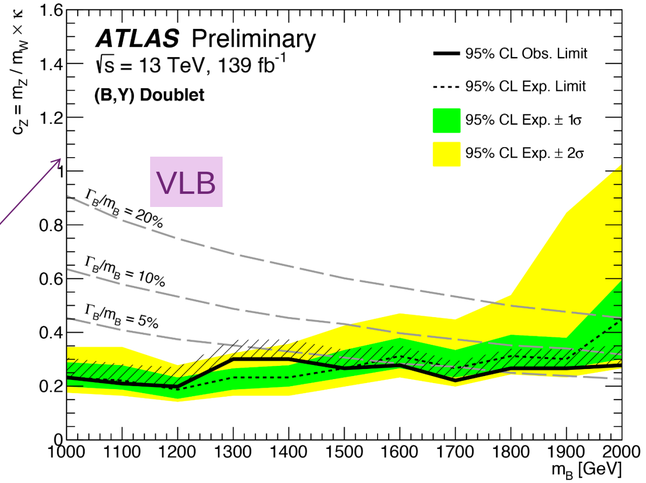
- Single VLQ production via exchange of EW gauge boson: $tW\ /\ bZ \rightarrow B$, $bW\ /\ tZ \rightarrow T$



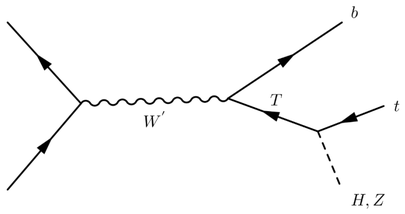
- Targeting $T \rightarrow tZ$ with $Z \rightarrow \nu\bar{\nu}$
- Top-tagging: resolved, partially resolved and boosted
- Kinematic endpoint $m_{\mathrm{T}}(t, Z \rightarrow \nu\bar{\nu})$



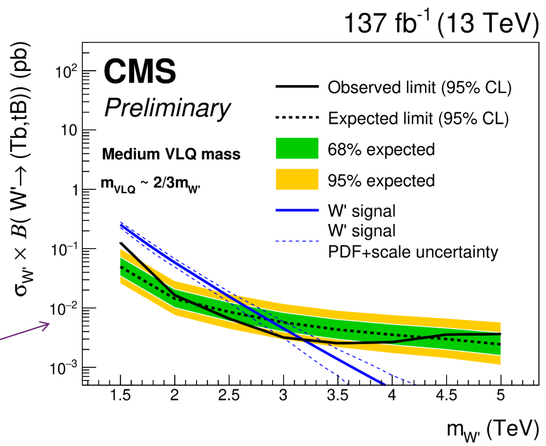
- Targeting $B \rightarrow Hb$ with $H \rightarrow b\bar{b}$
- Forward jet from production
- b-tagged small-R jet
- H reconstructed as single large-R jet with ≥2 matched b-jets
- Search for resonance m_B

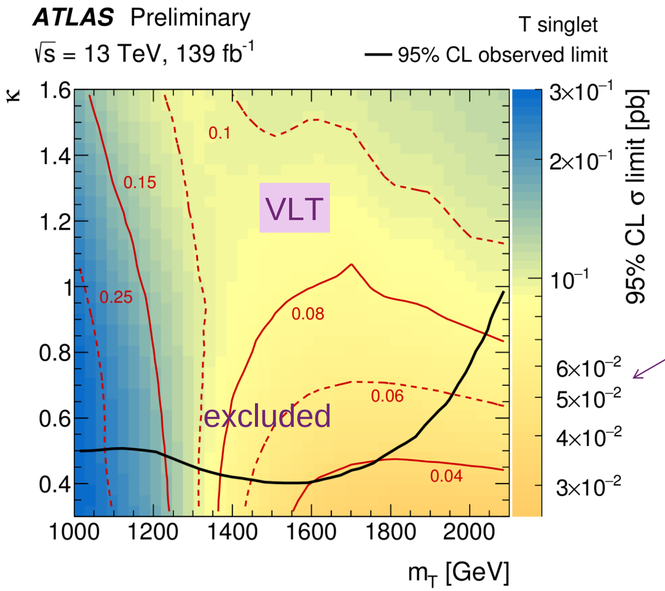


- Production in heavy gauge boson decays: $W' \rightarrow tB\ /\ bT$



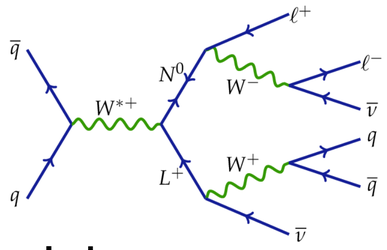
- All-hadronic final state with b, t and $H\ /\ Z$
- Exploiting jet substructure

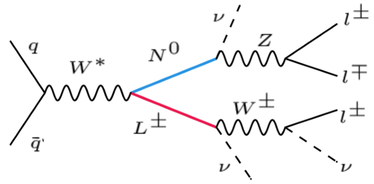


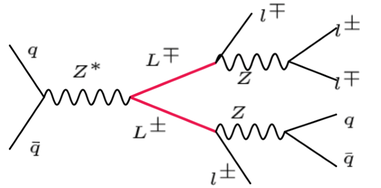


- Targeting $T \rightarrow tZ\ /\ tH$ with $Z \rightarrow q\bar{q}$ or $H \rightarrow b\bar{b}$
- Final states with single-ℓ and multiple jets/b-jets

Type-III Seesaw

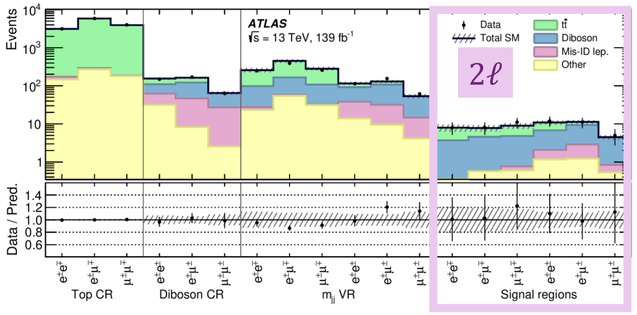


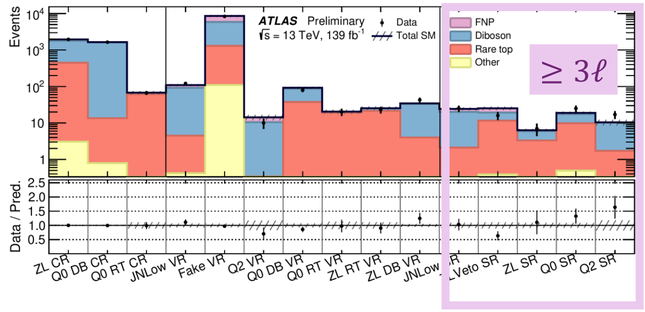




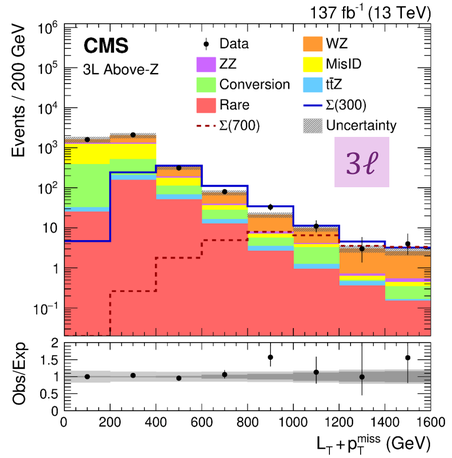
[ATLAS EXOT-2018-33](#)
[ATLAS-CONF-2021-023](#)
[CMS-EXO-19-002](#)

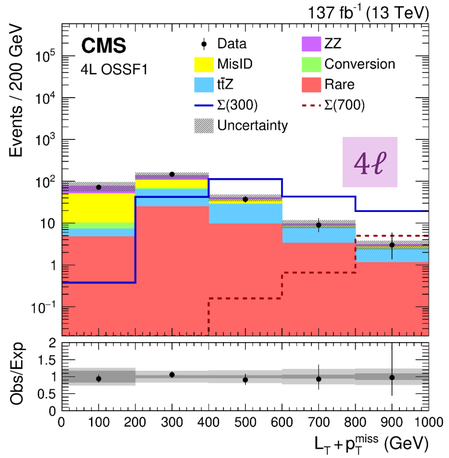
- Seesaw mechanism naturally explains smallness of neutrino masses
- Type-III seesaw predicts heavy charged ($L^{\pm}$) and neutral (N^0) leptons (all denoted as Σ)
- Decay to a SM boson and a lepton/neutrino



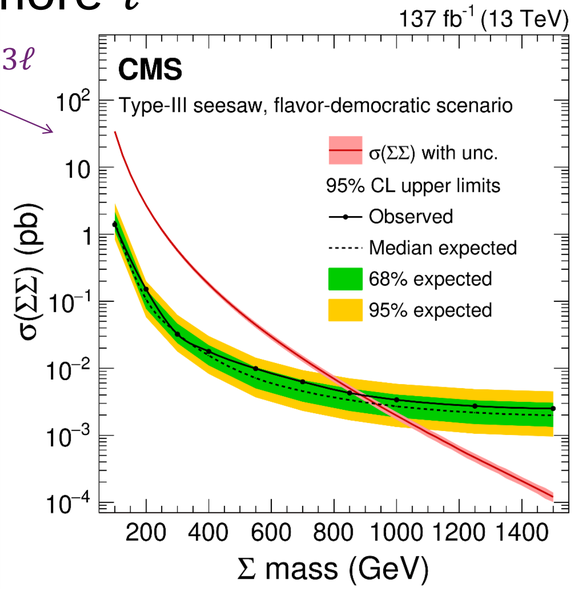


- Searches in final states with 2ℓ, 3ℓ or more ℓ plus jets and $p_{\mathrm{T}}^{\mathrm{miss}}$

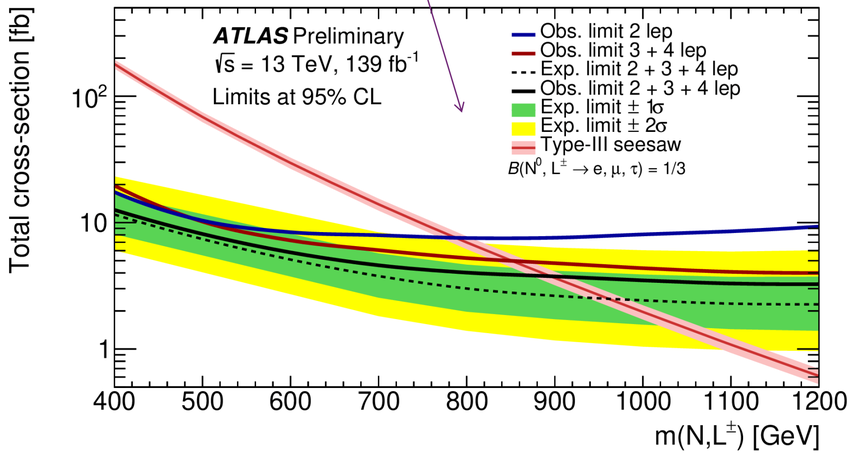




Multilepton search with $\geq 3\ell$ with and without $p_{\mathrm{T}}^{\mathrm{miss}}$

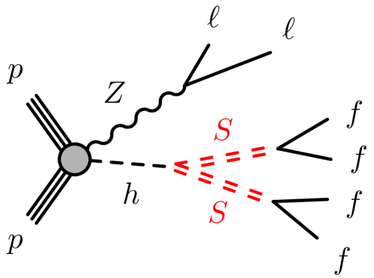


Combination of separate 2ℓ (+ 2 jets and large $p_{\mathrm{T}}^{\mathrm{miss}}$) and 3ℓ + $\geq 4\ell$ analyses



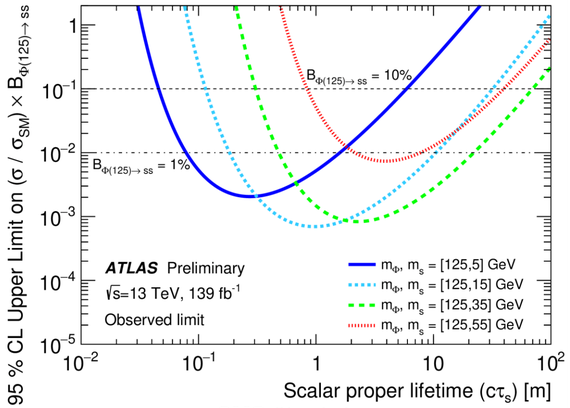
Exotic Decays of the Higgs

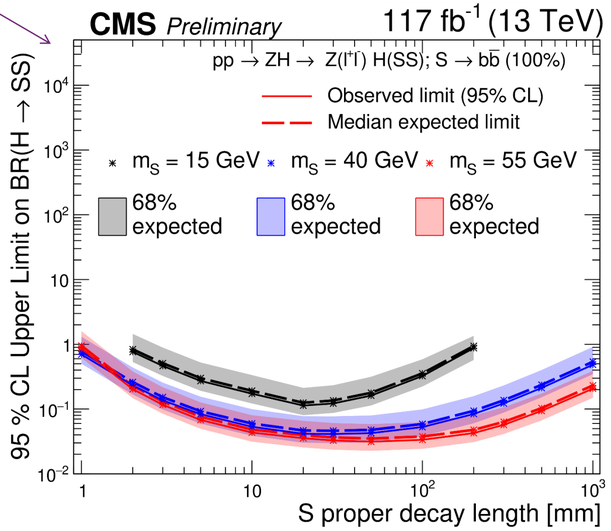
- Although H looks SM-like in all measurements so far, there is still space for BSM physics with $\mathcal{B}(H \to \text{BSM particles})$ up to ~10%
- H decays to long-lived particles (LLPs) → displaced jets/vertices or even invisible



H produced in association with $Z \to \ell\ell$
$H \to 2$ LLPs with LLP $\to b\bar{b}/d\bar{d}$ at displaced vertices

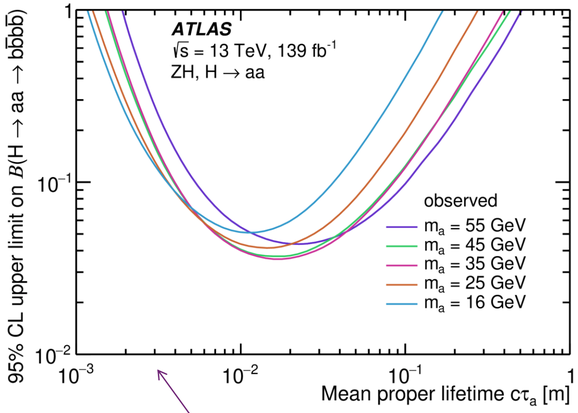
[CMS-PAS-EXO-20-003](#)
[CMS-EXO-20-015](#)
[ATLAS EXOT-2018-57](#)
[ATL-PHYS-PUB-2021-020](#)
[ATLAS-CONF-2021-032](#)

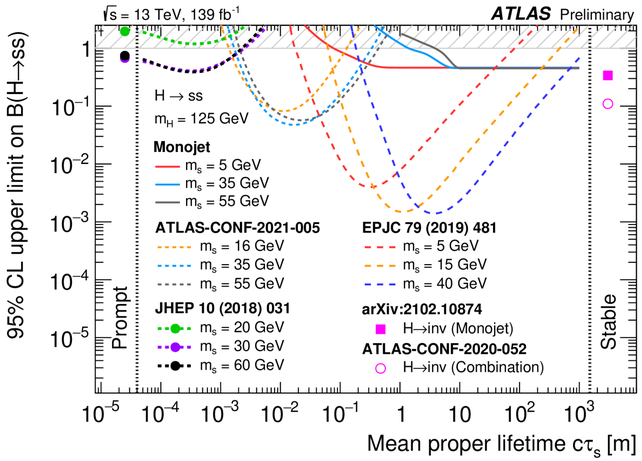


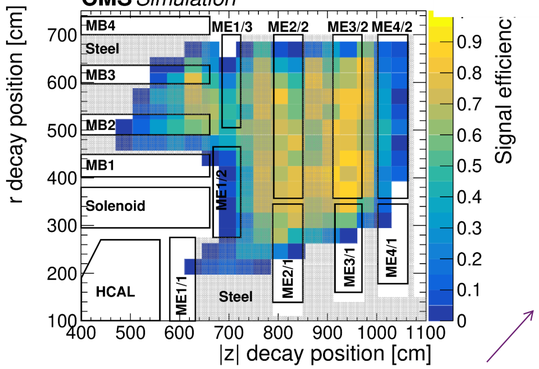


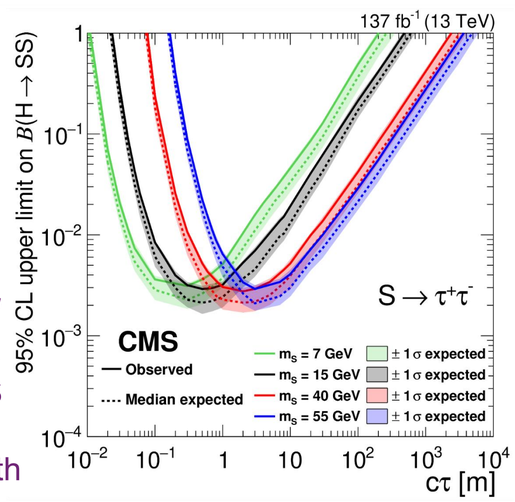
Re-interpretation of monojet + $p_{\mathrm{T}}^{\mathrm{miss}}$
$H \to 2$ LLPs which escape undetected

$H \to 2$ LLPs $\to 4$ jets with displaced vertices in the muon spectrometer









H produced in association with $Z \to \ell\ell$
$H \to 2$ LLPs $\to b\bar{b}b\bar{b}$ with displaced vertices

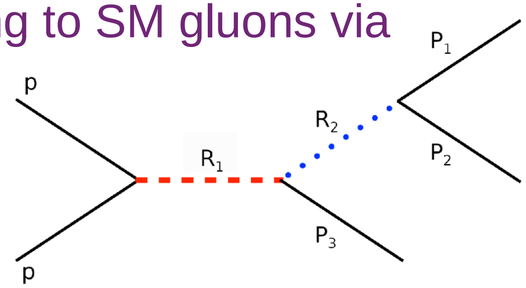
Shower from LLP decays in CMS endcap muon detectors
→ extended reach in decay length
LLP $\to b\bar{b}/d\bar{d}/\tau\tau$

Three-Body Resonances

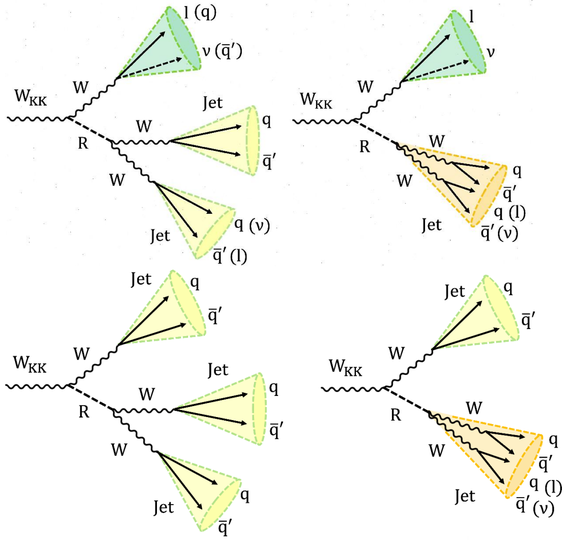
CMS-PAS-EXO-20-007
CMS-PAS-B2G-20-001
CMS-PAS-B2G-21-002

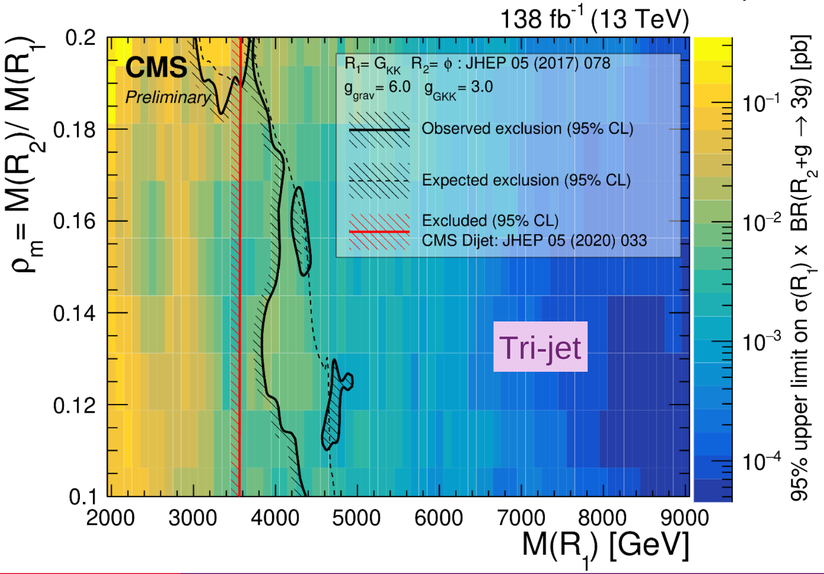
First tri-jet and tri-boson searches at the LHC

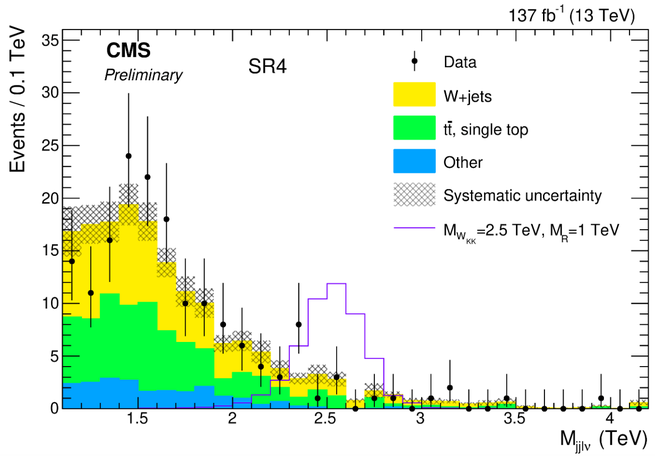
- Tri-jet:
- Kaluza-Klein (KK) gluon decaying to SM gluons via radion $G_{KK} \rightarrow \phi g \rightarrow ggg$
- Double resonance
- Jet substructure

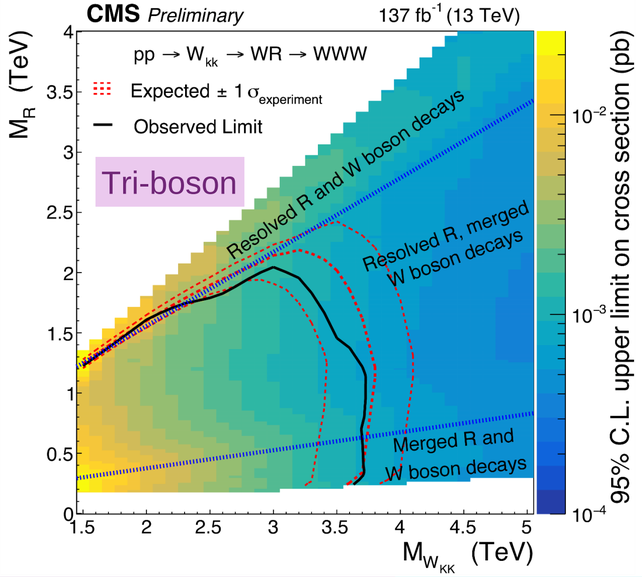


- Tri-boson:
- KK excited massive W $W_{KK} \rightarrow WR \rightarrow WWW$
- Lepton + large-R jet(s)
- All-hadronic final state





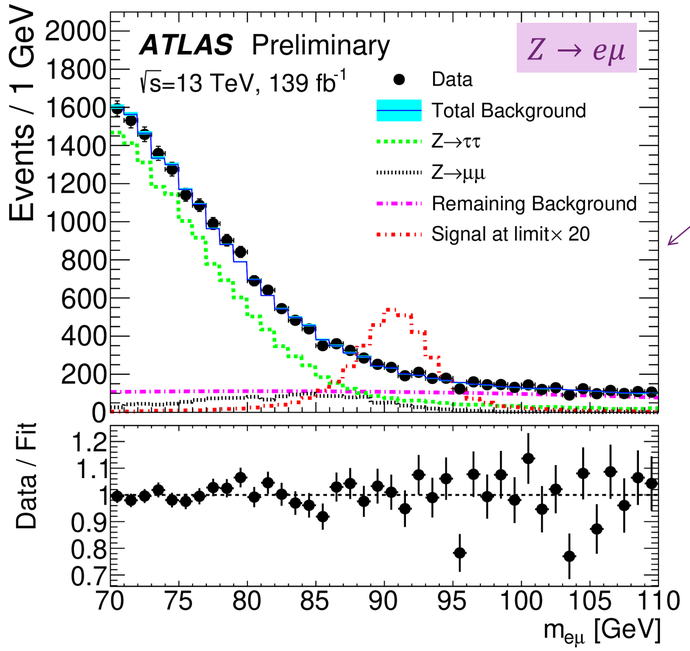




Lepton Flavour Violation in Z Decays

[ATLAS EXOT-2018-36]
[ATLAS EXOT-2020-28]
[ATLAS-CONF-2021-042]

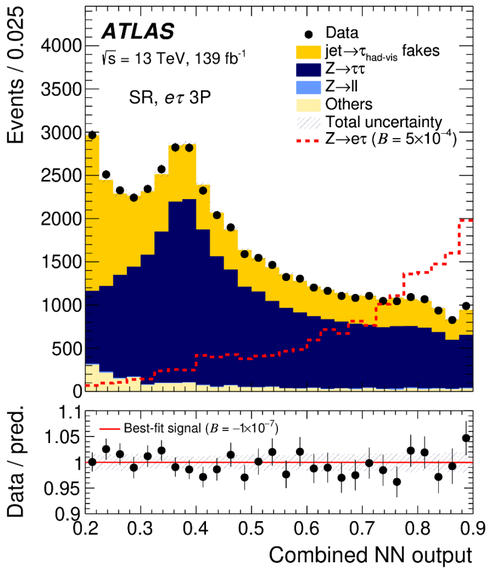
- Lepton flavour is an accidental symmetry in the SM
- Often violated in BSM theories
- LHC is a Z machine: ~8 billion Z's in ATLAS in Run 2
- Still limited by statistics

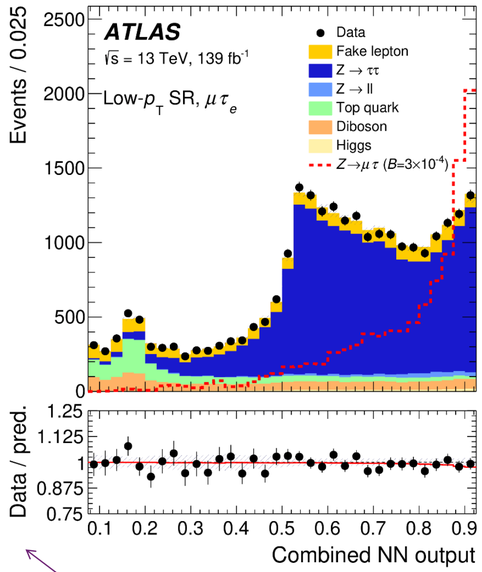


$Z \to e^{\pm}\mu^{\mp}$

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

- $\mathcal{B}(Z \to e\mu) < 3.04 \cdot 10^{-7}$ at 95% CL





Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

$Z \to \ell^{\pm}\tau^{\mp}$

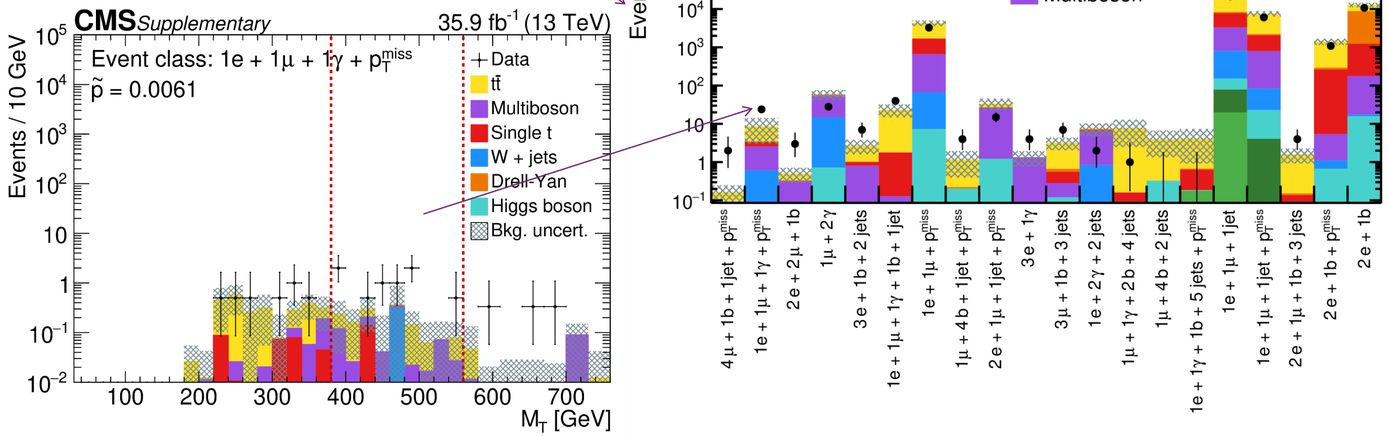
- Hadronic and leptonic τ decays
- Neural net to suppress backgrounds
- NN classifier is fitted
- Limits improved by factor ~2 wrt LEP

General Searches

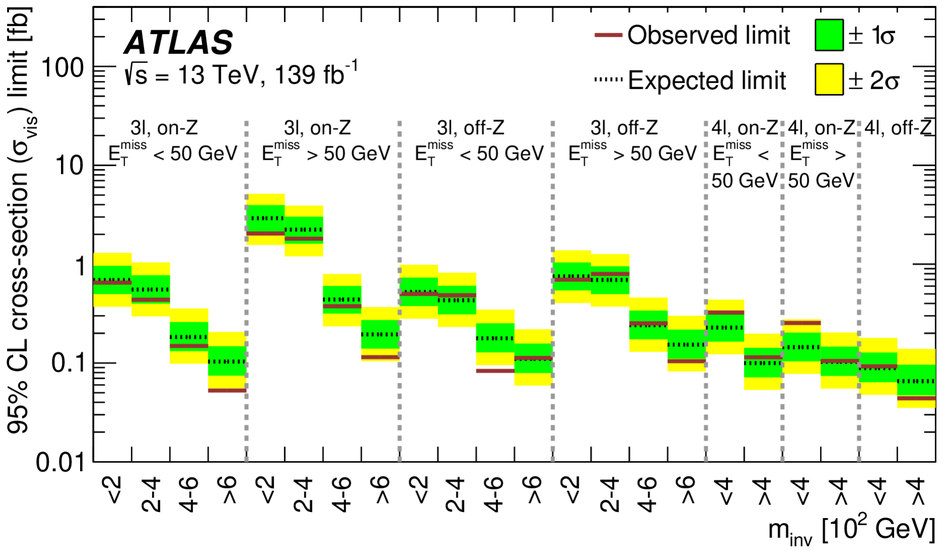
[ATLAS EXOT-2019-36](#)
[CMS-EXO-19-008](#)

- Leaving no stone unturned
- Potential signals might be overlooked by model-specific analyses
- Identify interesting channels for dedicated searches

MUSiC:
Automated search in final states with $\geq 1\ell$



General Multilepton Search:
Final states with 3ℓ and 4ℓ



Successfully evaluated against type-III Seesaw and $H^{\pm\pm}$ analyses

Model	Mass [GeV]	Best single SR	m_{inv}	$A \times \epsilon$	σ^{95}_{exp} [fb]		σ^{95}_{obs} [fb]
Type-III Seesaw	400	3ℓ, Off-Z, $E_{\text{T}}^{\text{miss}} > 50$ GeV	> 600 GeV	0.0036	41	$^{+17}_{-11}$	27
	700	3ℓ, Off-Z, $E_{\text{T}}^{\text{miss}} > 50$ GeV	> 600 GeV	0.012	12	$^{+5}_{-3}$	8.8
$H^{\pm\pm}$	300	4ℓ, Off-Z	> 400 GeV	0.37	0.18	$^{+0.08}_{-0.05}$	0.12
	500	4ℓ, Off-Z	> 400 GeV	0.40	0.16	$^{+0.07}_{-0.05}$	0.11

Exotics and BSM Searches in ATLAS and CMS

- ATLAS and CMS perform a vast Exotics search program for a multitude of models and final states

- Many full Run 2 results already public, more to come in the near future
- No observation of Exotics yet
- Limits are being pushed thanks to large dataset and advances in analysis techniques
- Analysis preservation for future re-interpretation

- Preparations for Run 3 in full swing