EXOTICS AND BSM IN ATLAS AND CMS

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on behalf of ATLAS & CMS

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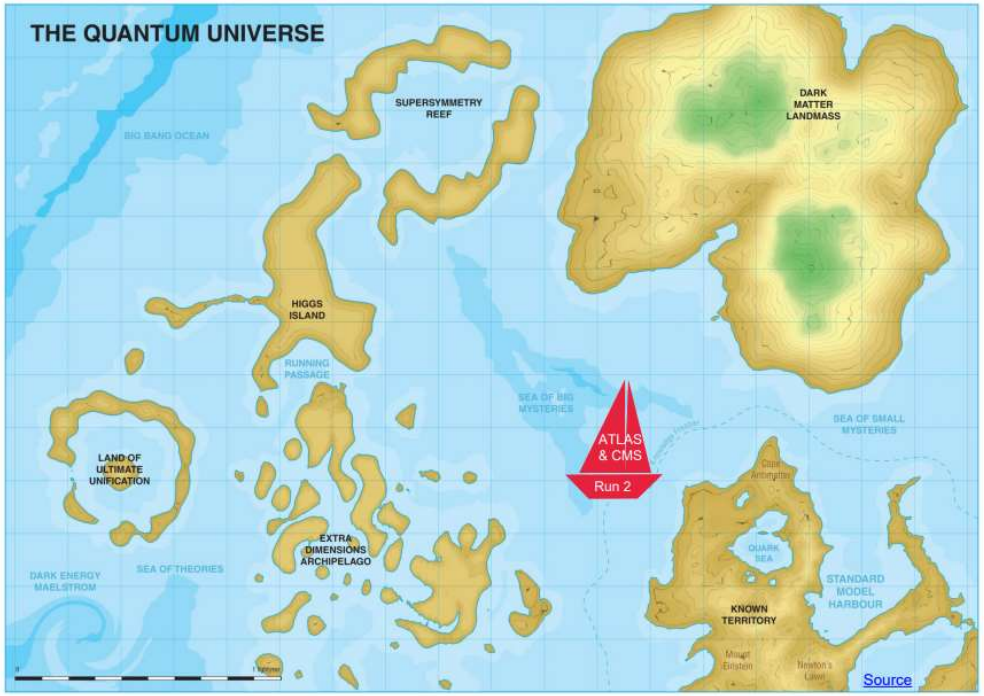
BSM Searches

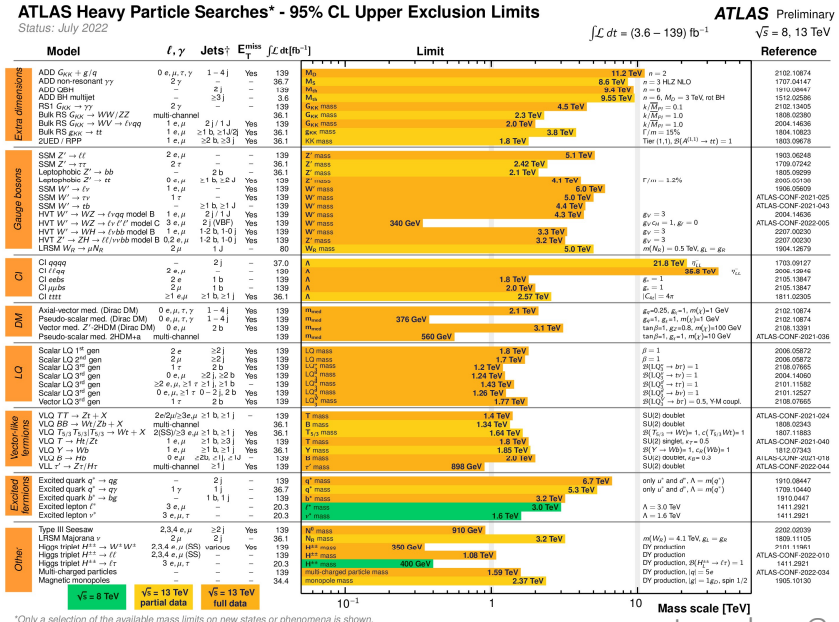
- The Standard Model (SM) leaves many questions unanswered
- Plethora of beyond SM models (BSM)
- Only few observational hints
- Run 3 will present more opportunities

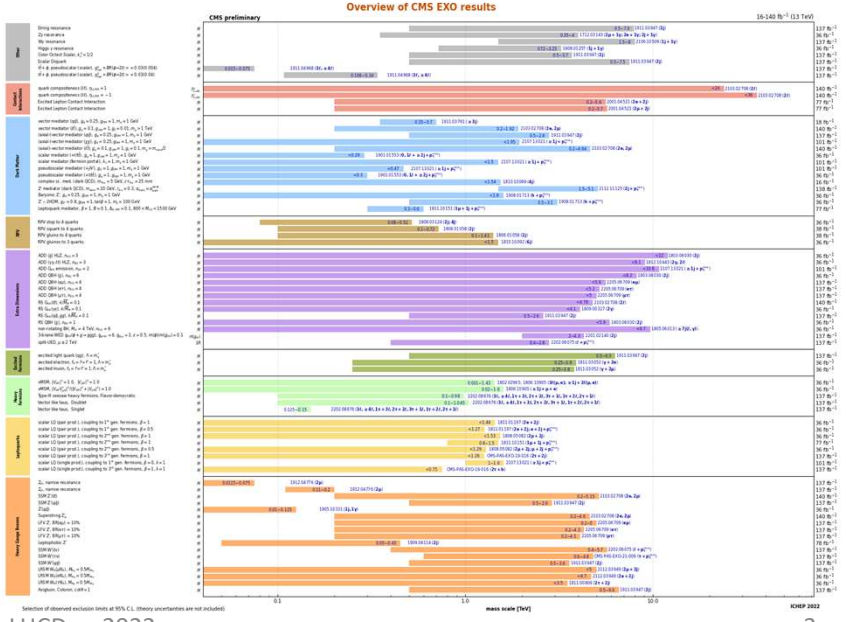


Exotics and BSM Searches in ATLAS and CMS

ATLAS and CMS have a rich and very active exotics 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 ~140fb^{-1} of pp collision data at $\sqrt{s}$ = 13TeV recorded in Run 3 has started!
- Pushing mass limits and precision

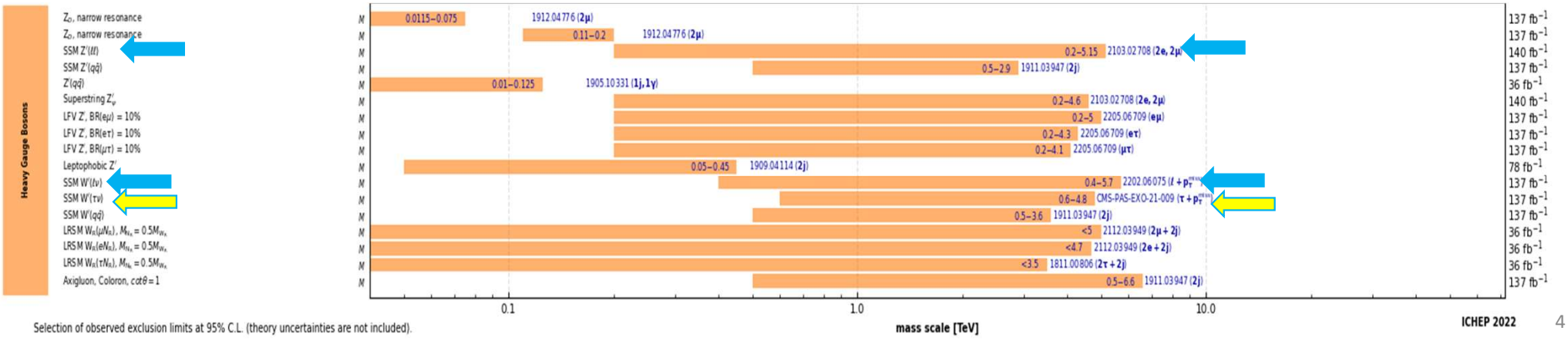




New Gauge Bosons

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

Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e,μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e,μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\ell'\ell'$ model C	3 e,μ	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H = 1, g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e,μ	1-2 b, 1-0 j	Yes	139	W' mass	3.3 TeV	$g_V = 3$	2207.00230
	HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B	0,2 e,μ	1-2 b, 1-0 j	Yes	139	Z' mass	3.2 TeV	$g_V = 3$	2207.00230
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

ICHEP 2022

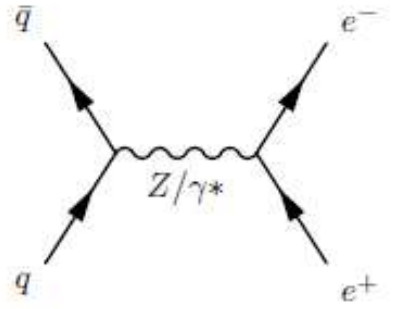
Heavy Gauge Bosons: Z' Dilepton Resonance Search

EXOT-2018-08/
CMS-EXO-19-019

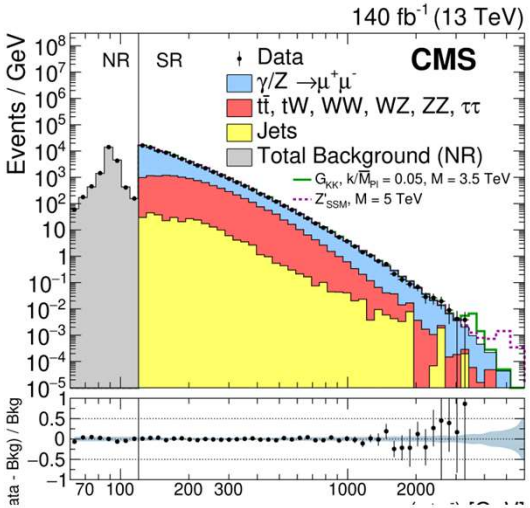
Search Channel

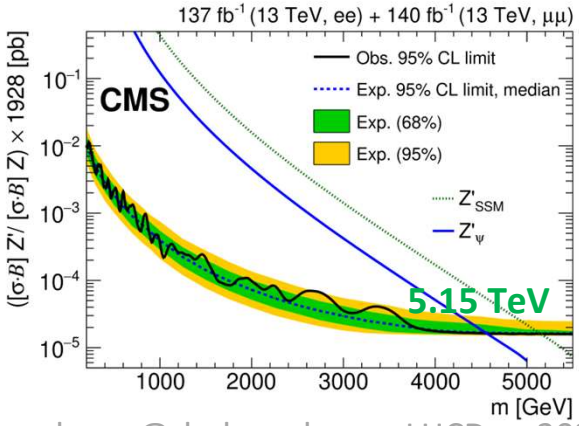
Decays to 2 electrons or 2 muons

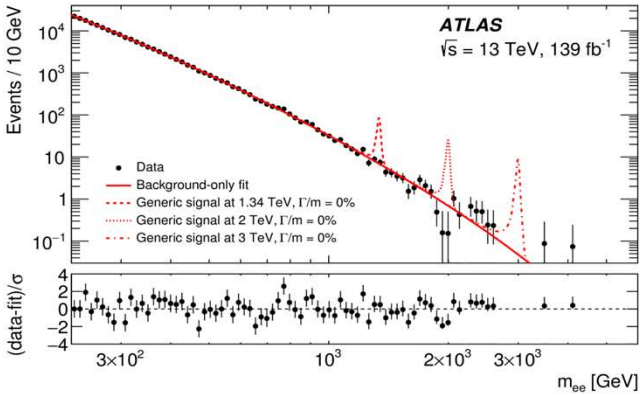
+ very clean signatures
+ good to search for other new physics: Z', Extra Dimensions



Search for deviations in invariant mass







Functional form fitted to invariant-mass

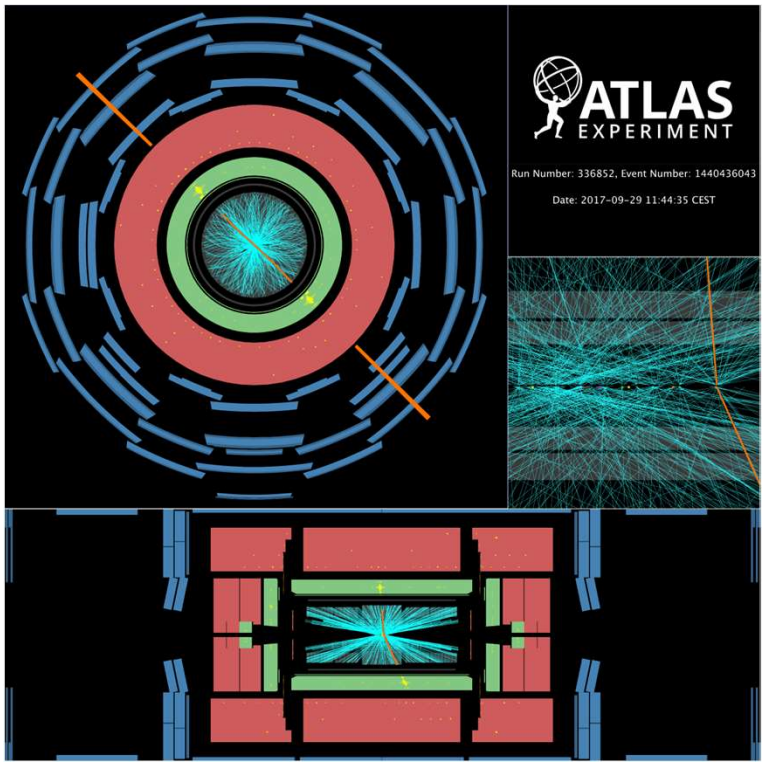
A **generic signal shape**

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

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_{ψ}	4.1	4.3	4.0	4.0	4.5	4.5
Z'_{χ}	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

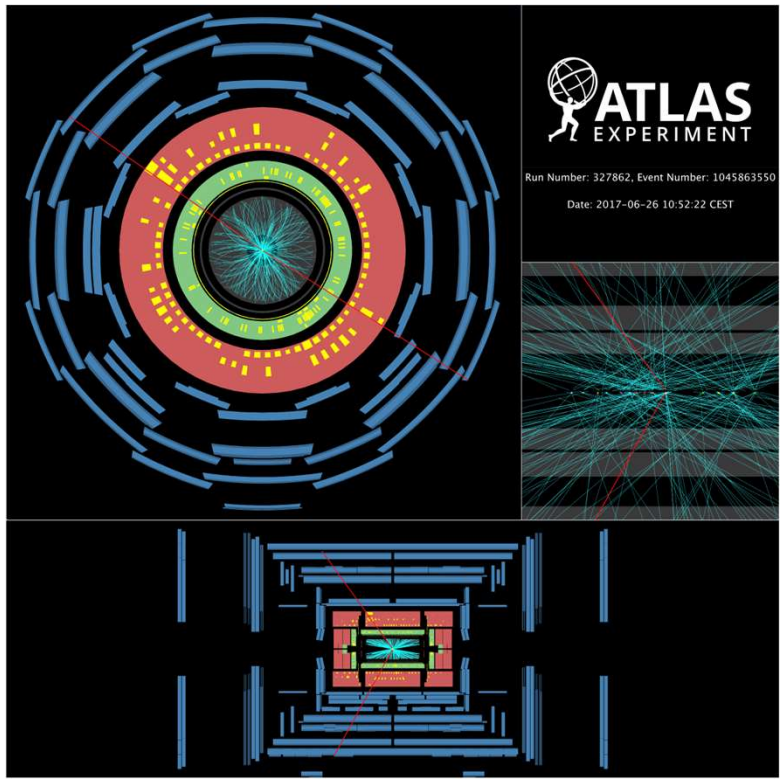
Highest invariant mass (2015—2018)

m_{ee} = 4.06 TeV



E_T = 2.01 TeV, E_T = 1.92 TeV

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



p_T = 1.82 TeV, p_T = 1.04 TeV,

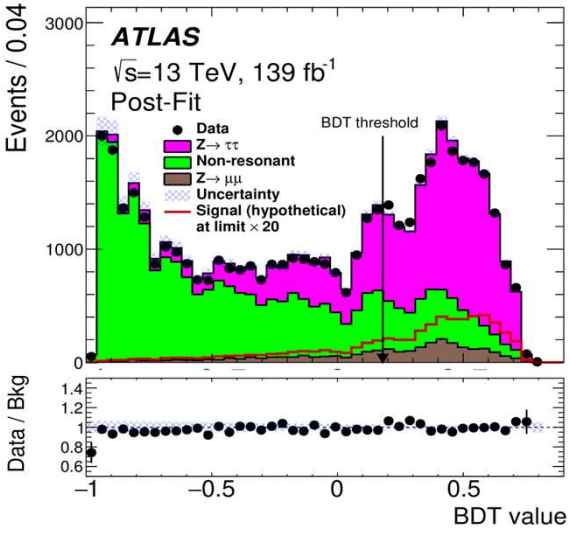
Lepton Flavor Violating Z decay

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

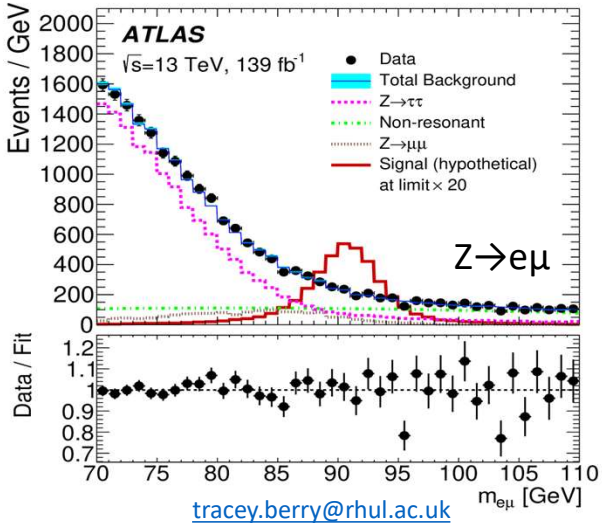
- Lepton flavour is an accidental symmetry in the SM
- Often violated in BSM theories
- LHC is a Z machine: ~ 8 billion Z's in ATLAS in Run 2

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

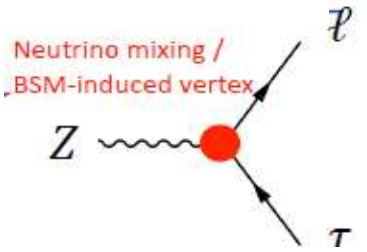
- Search for peak around Z mass
- BDT to suppress backgrounds



- 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



$Z \rightarrow e\tau/\mu\tau$



- Neutrino oscillations show that LFV indeed occurs in nature

Upper 95% CL limits	ATLAS	LEP
B(Z —> e τ)	8.1 × 10-6	9.8 × 10-6 [OPAL]
B(Z —> μ τ)	9.5 × 10-6	12 × 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/

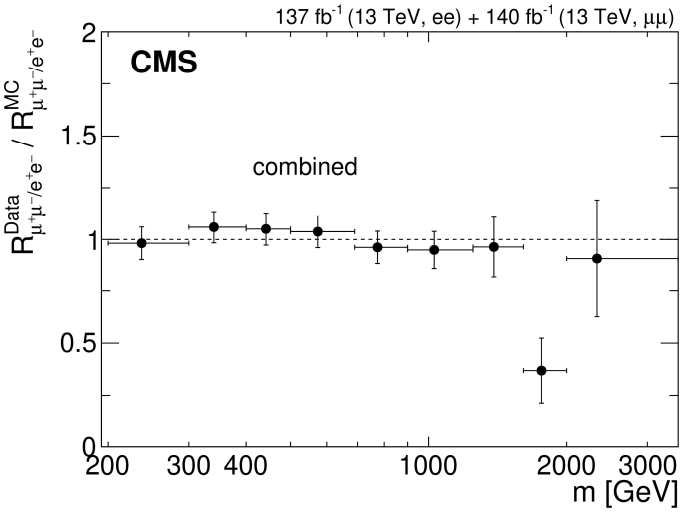
- Resonant and non-resonant di-lepton final states with high mass in many SM extensions (ex. Z', LQs)
- BSM physics can cause R to deviate from unity

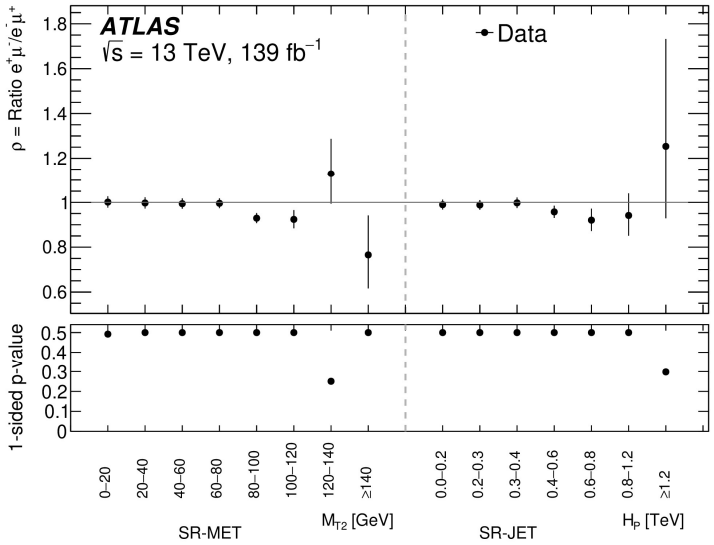
$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(qq\to\mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(qq\to e^+e^-)/dm_{\ell\ell}}$$

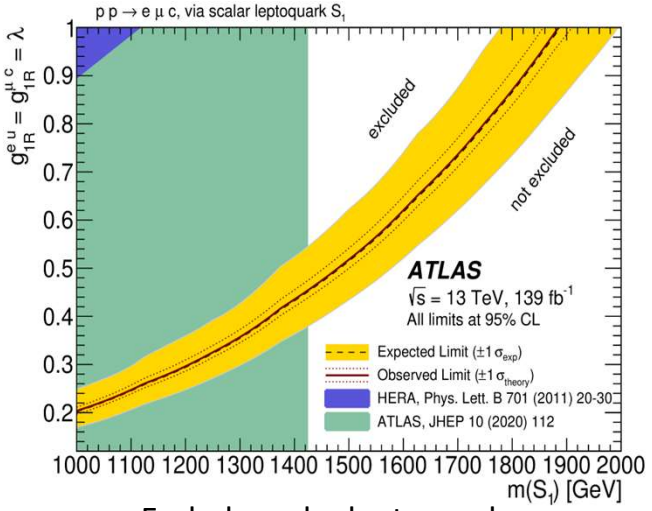
- Measure ratio of $e^+\mu^-$ to $e^-\mu^+$ pairs

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

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







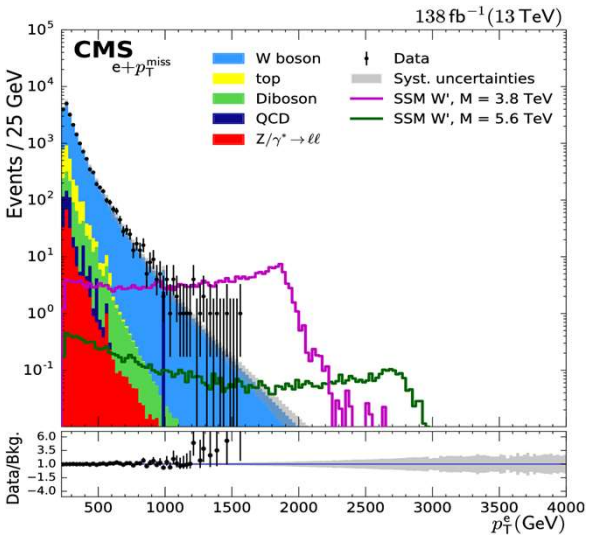
Exclude scalar leptoquarks masses below 1880 GeV

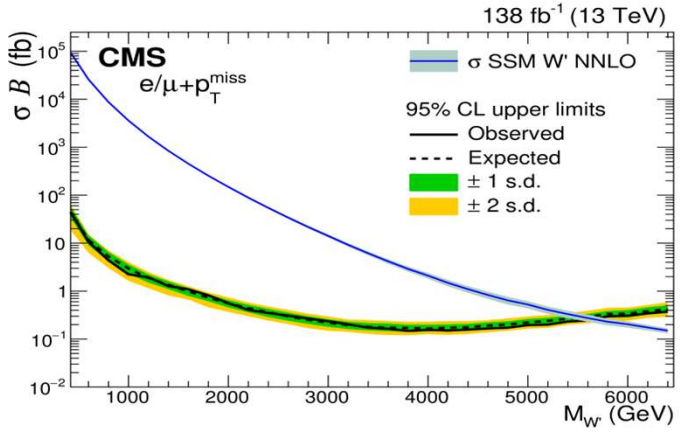
Heavy Gauge Bosons: W’

ATLAS-EXOT-2018-30
CMS-PAS-EXO-19-017
ATLAS-CONF-021-025

$W' \to \ell\nu$ decays

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

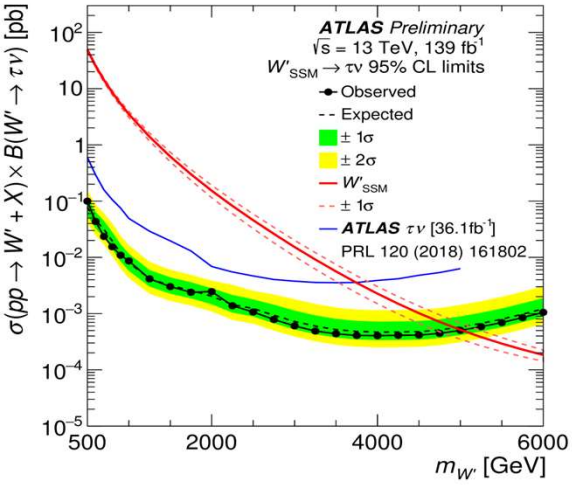




Several models probed:
SSM, split-UED, RPV-SUSY, EFT

W' boson mass less than 5.7 TeV is excluded at 95% C.L.

$W' \to \tau\nu$ decays



W′→τν production cross section
W′ bosons masses up to 5.0 TeV excluded at the 95% C.L.

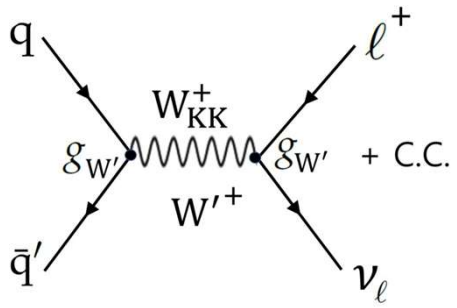
Other BSM searches: W’

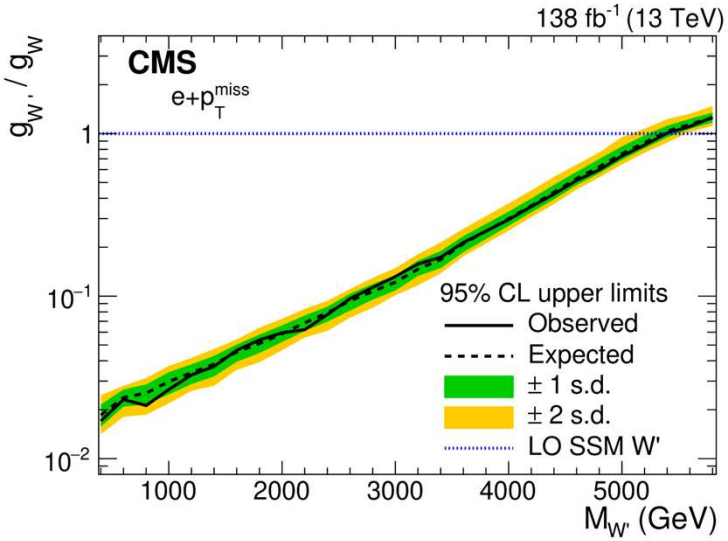
CMS-PAS-EXO-19-017

$W' \rightarrow tb$ decays

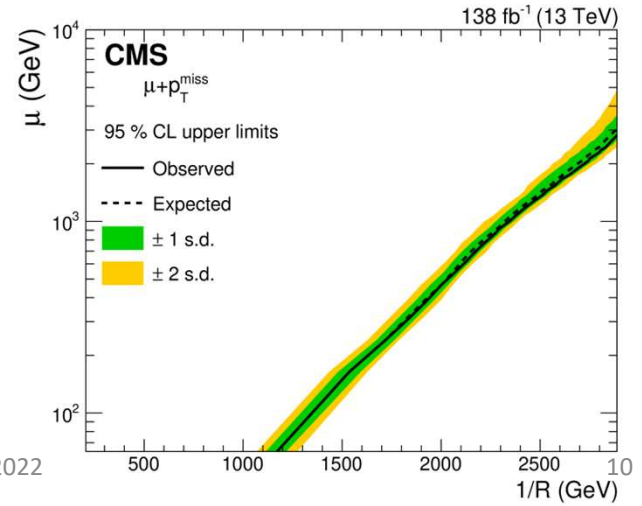
ATLAS-CONF-2021-043

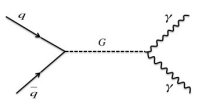
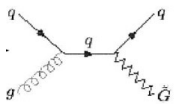
- Set limits on other models: e.g. Extra-dimensions: split UED, RPV SUSY
- First LHC results on a SM precision test :
  determination of the oblique electroweak $g_{W'}$ parameter
- Extend existing constraints on composite Higgs scenarios using results with those from the direct W' resonance search
-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



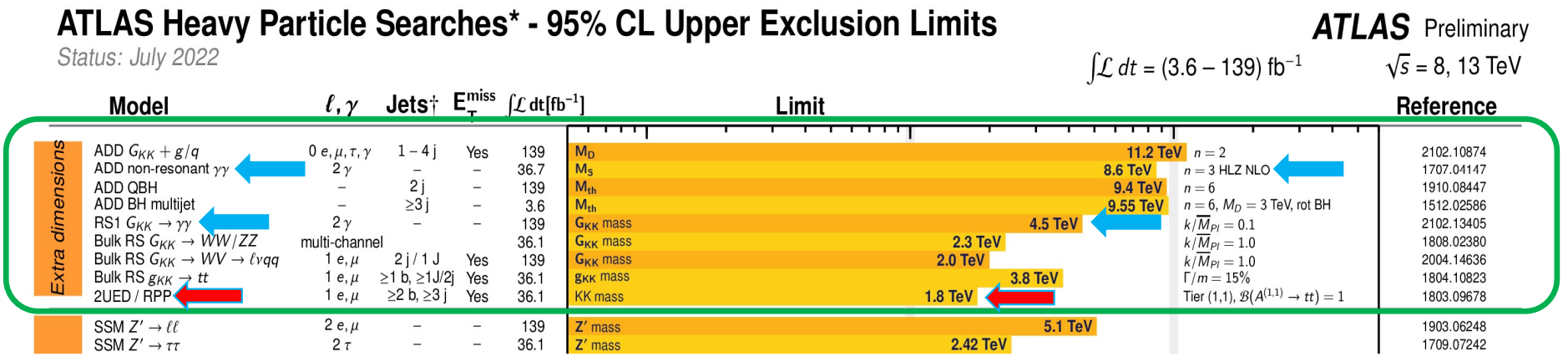


Exclusion limits in the 2D plane (1/R, μ) for the split-UED interpretation for the n=2 case



Extra Dimensions

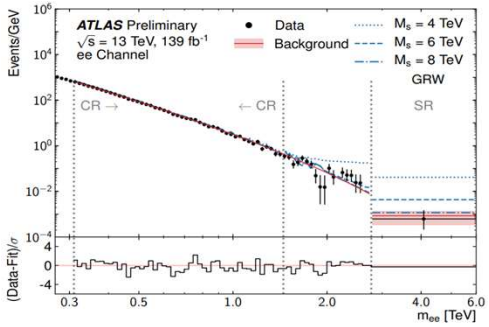


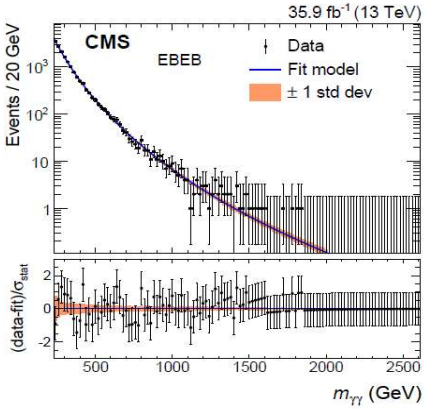
ADD model Searches

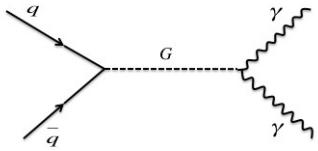
ATL-PHYS-PUB-2021-021/
[CMS-EXO-19-019](CMS-EXO-19-019)
[CMS-EXO-17-017](CMS-EXO-17-017)

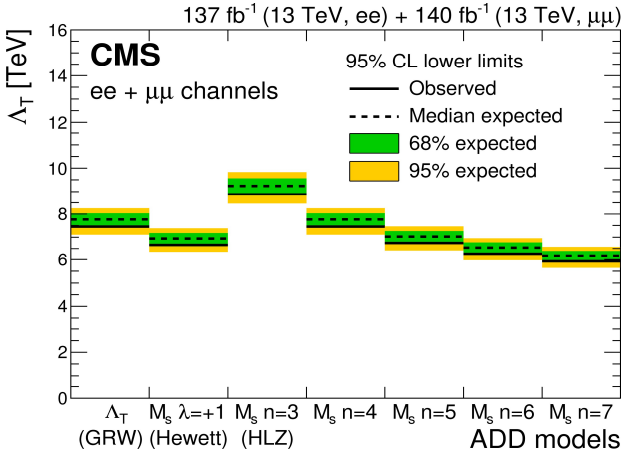
Searches for large extra dimensions

- 2 high pt electrons and muons

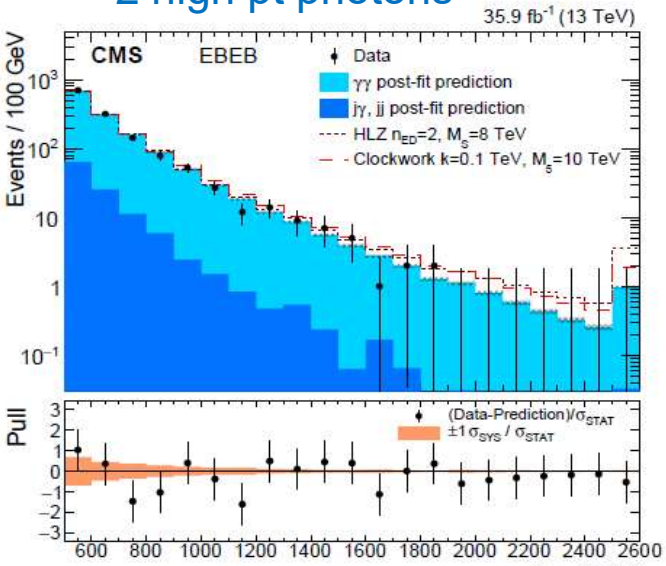








- 2 high pt photons

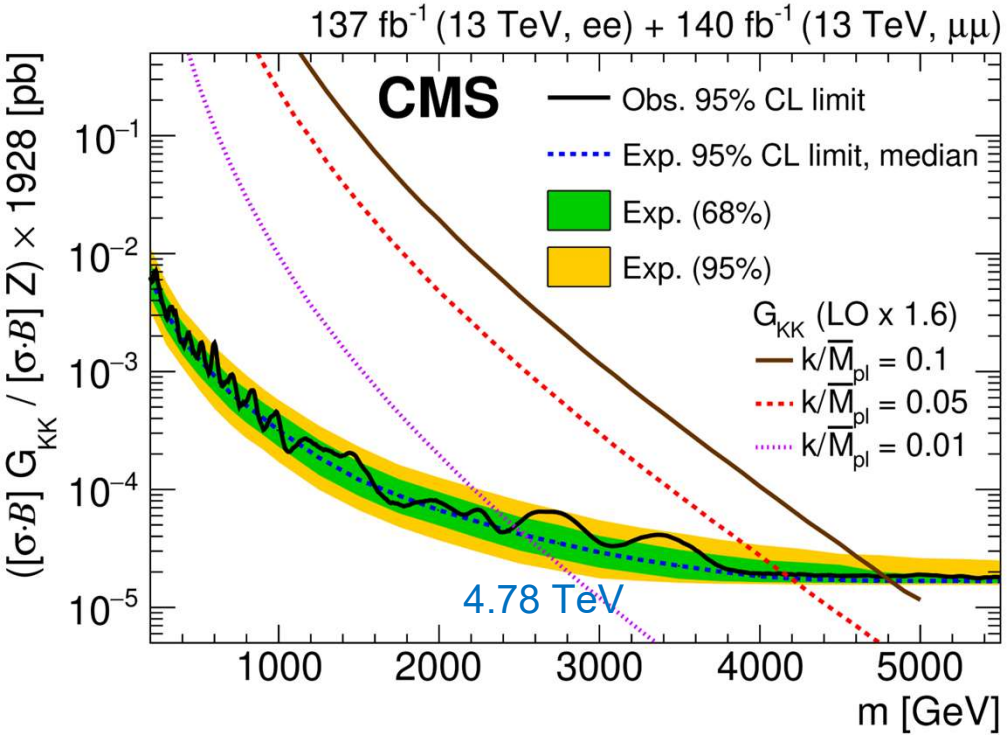


Signal	GRW	Hewett		HLZ					
		negative	positive	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Expected	$7.1^{+0.7}_{-0.5}$	$5.5^{+0.1}_{-0.3}$	$6.3^{+0.6}_{-0.4}$	$8.4^{+1.3}_{-1.1}$	$8.4^{+0.8}_{-0.6}$	$7.1^{+0.7}_{-0.5}$	$6.4^{+0.6}_{-0.5}$	$6.0^{+0.6}_{-0.4}$	$5.6^{+0.6}_{-0.4}$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

Extra Dimensions – RS Model

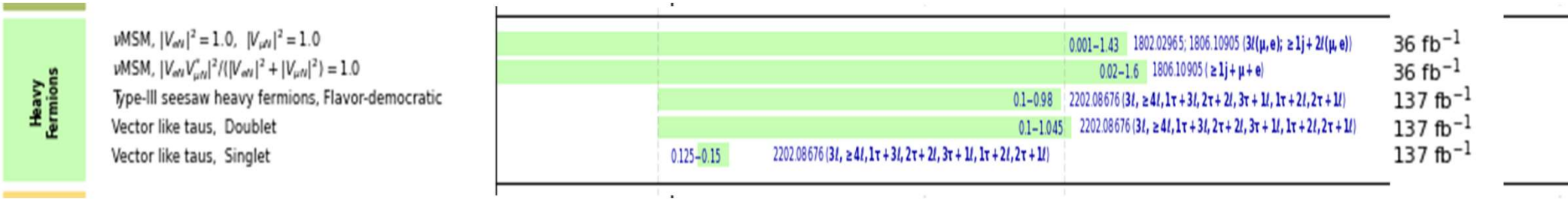
CMS-EXO-19-019

ATL-PHYS-PUB-2021-021/



Vector-like fermions/quarks

See Dylan's talk



Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}/T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb) = 1$, $c_R(Wb) = 1$	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	ATLAS-CONF-2022-044

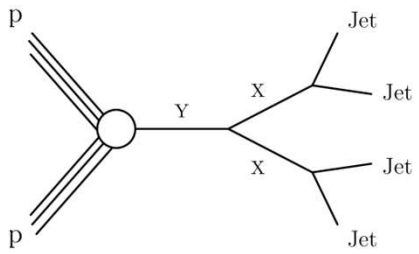
Search for resonant and nonresonant production of pairs of dijet resonances

See Dylan's talk

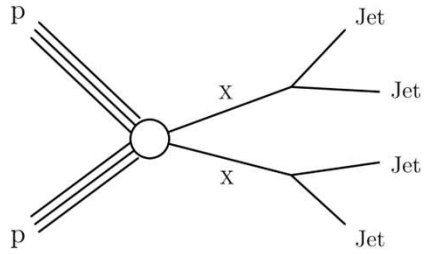
CMS-EXO-21-010

- 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

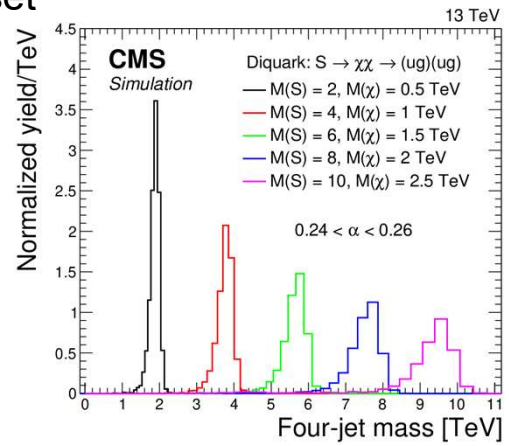
Resonant production



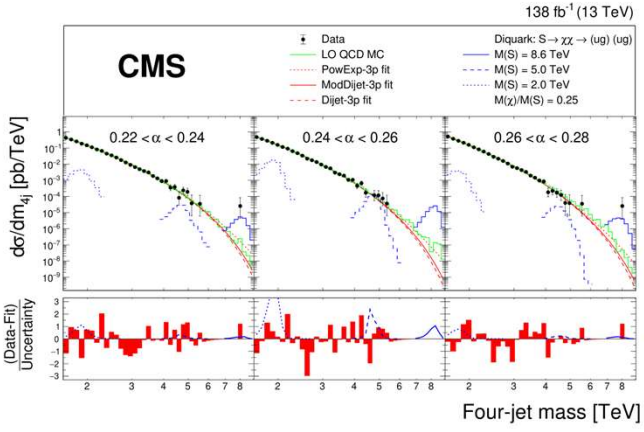
Nonresonant production



- Model-independent limits, at 95% C.L, on production cross section of four-jet and dijet resonances set

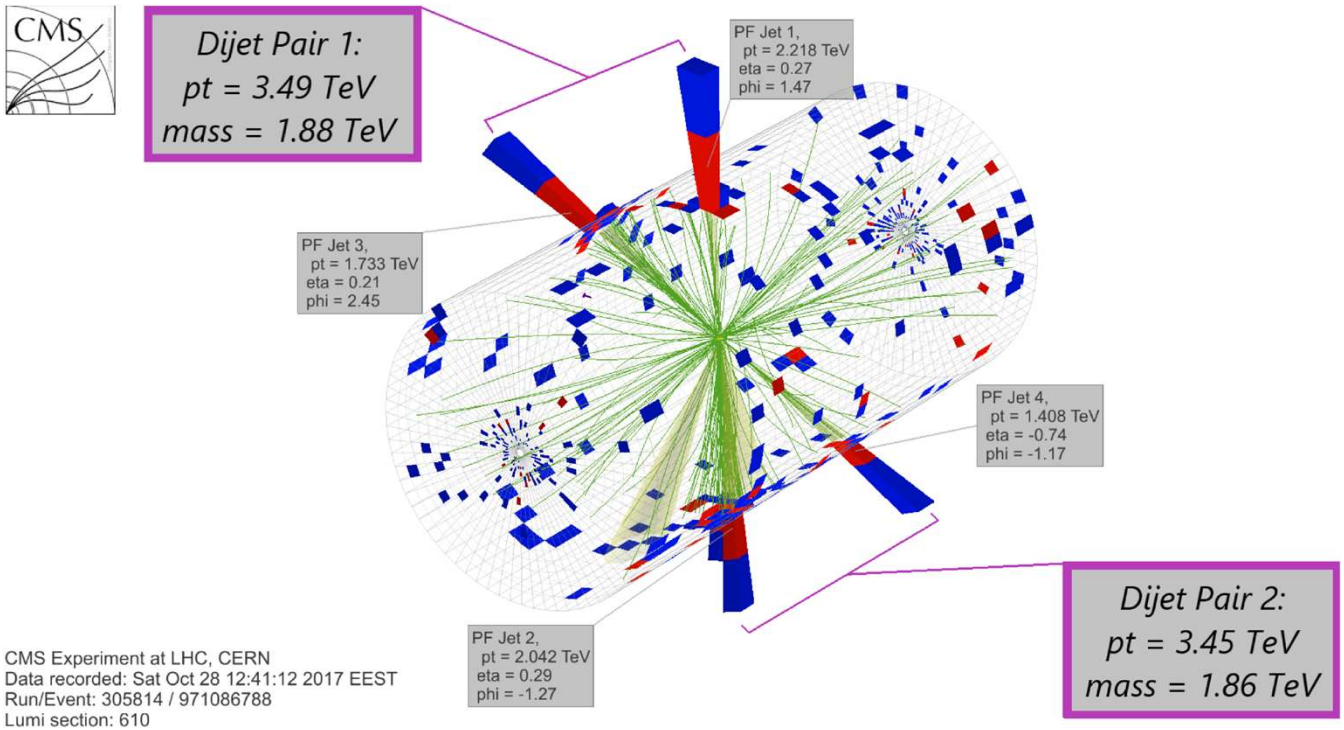


- First LHC limits on a signal model of diquarks that decay into pairs of **vector-like quarks**,
- excluding diquark masses below 7.6 TeV



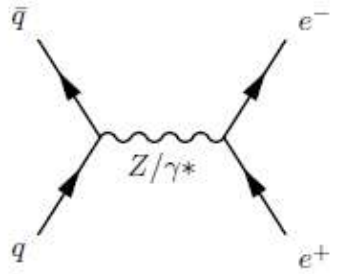
- Nonresonant search excludes pair production of **top squarks**

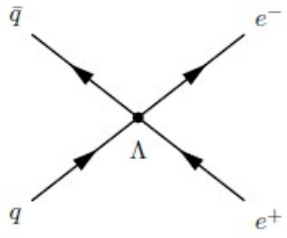
Highest four-jet mass of 8.0 TeV



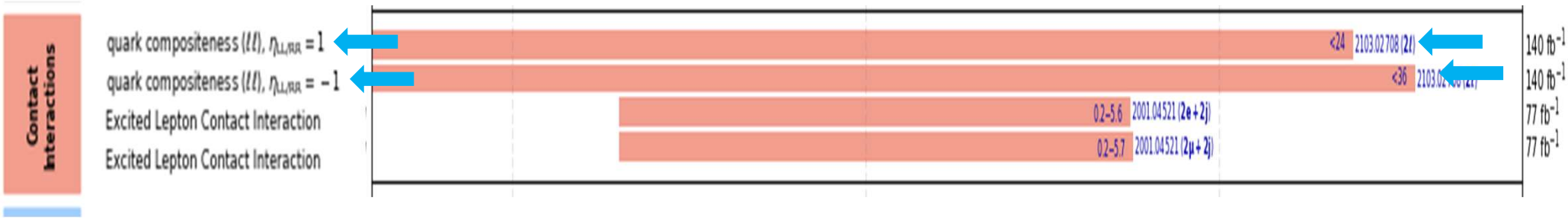
Contact Interactions

A contact interaction (CI) could be caused by
- Quark-lepton compositeness or
- Any new interaction with a massive mediator





CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	139	Λ	35.8 TeV η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ	1.8 TeV $g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ	2.0 TeV $g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV $\lvert C_{4t}\rvert = 4\pi$	1811.02305

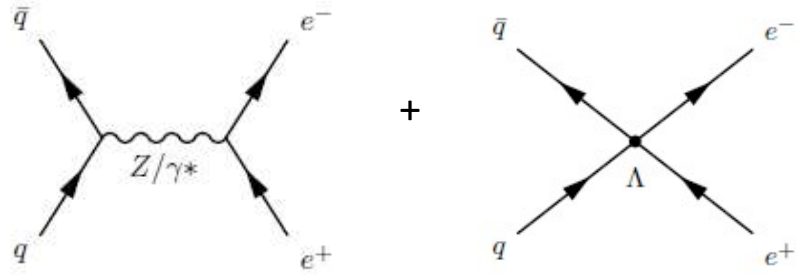


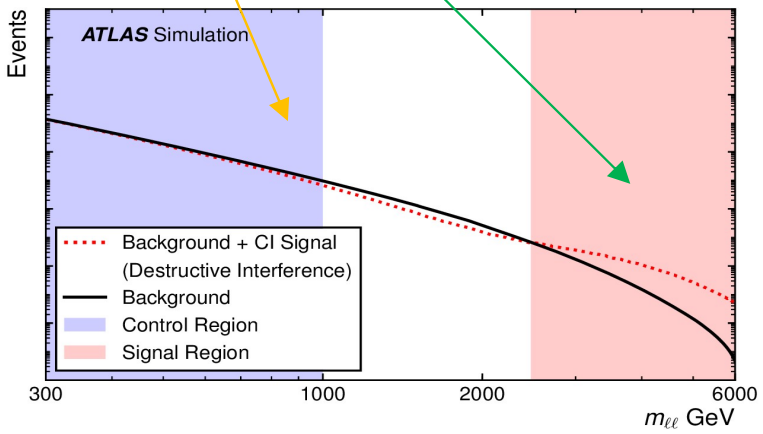
Contact Interactions: ee, μμ

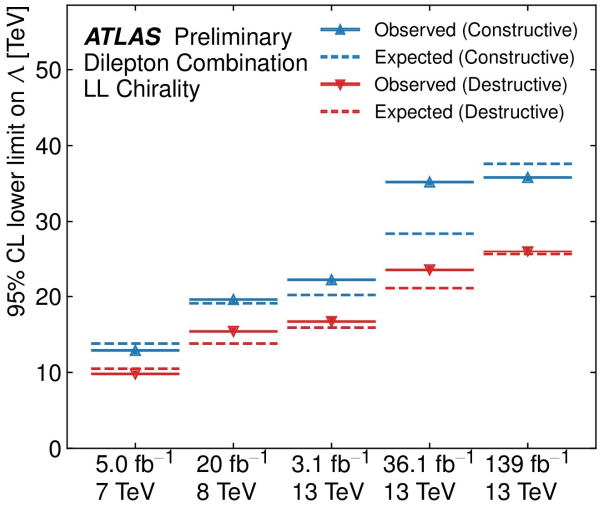
EXOT-2019-16/
CMS-EXO-19-019

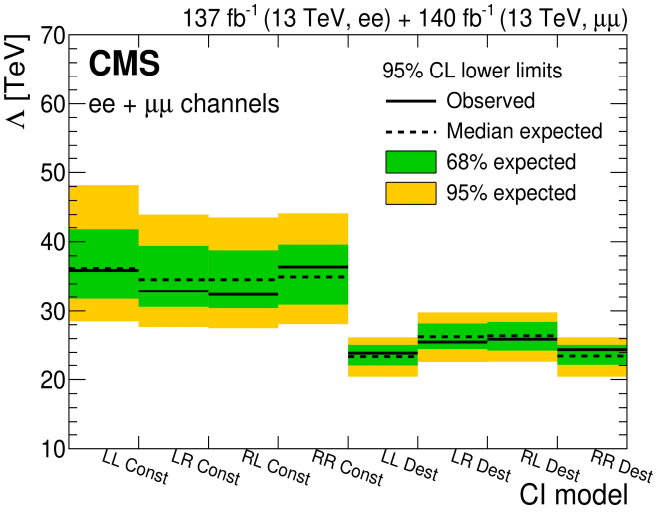
Search in invariant mass only

First non-resonant search
to use data-driven background estimation
- Fit in the low mass control region
- Extrapolate to high mass



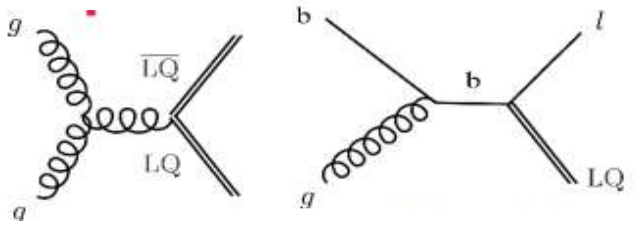


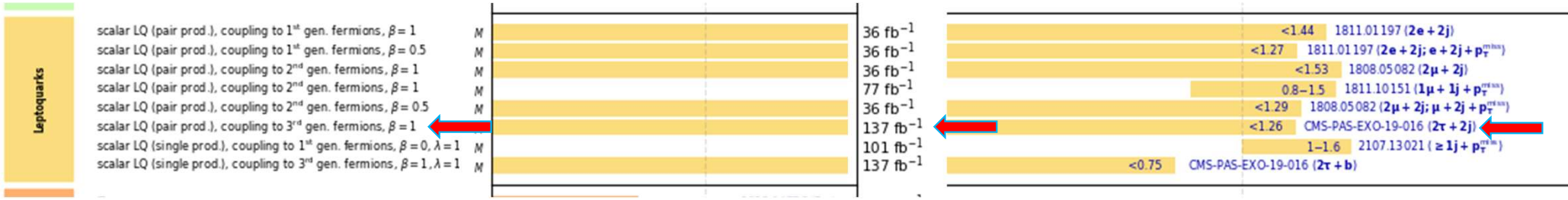




Leptoquarks

- 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 1st, 2nd , 3rd and mixed generations final states
- Scalar and vector LQs are investigated



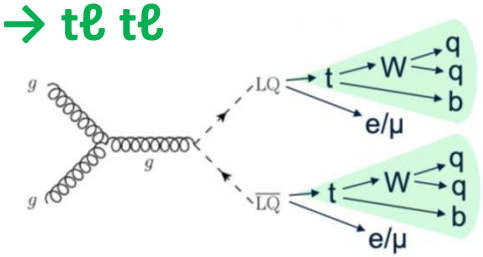


Leptoquarks

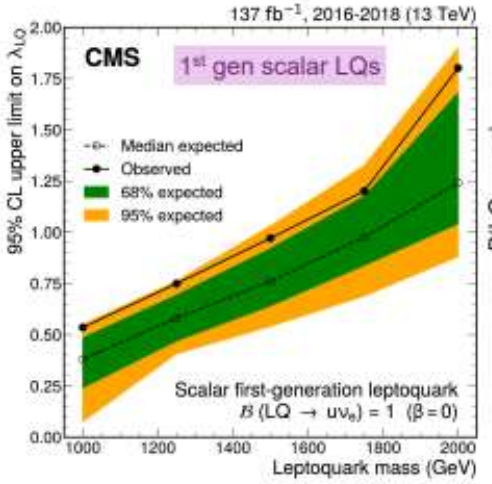
ATL-PHYS-PUB-2021-017
CMS-EXO-19-015
CMS-EXO-20-004
ATLAS EXOT-2019-13
ATLAS-CONF-2020-029

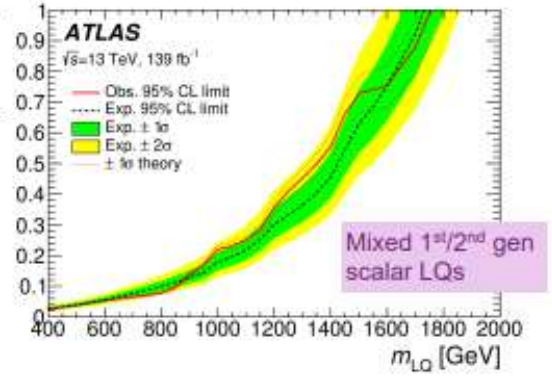
- Searches for 1st, 2nd , 3rd and mixed generations final states
- Scalar LQs are investigated
- Decays into a quark and lepton

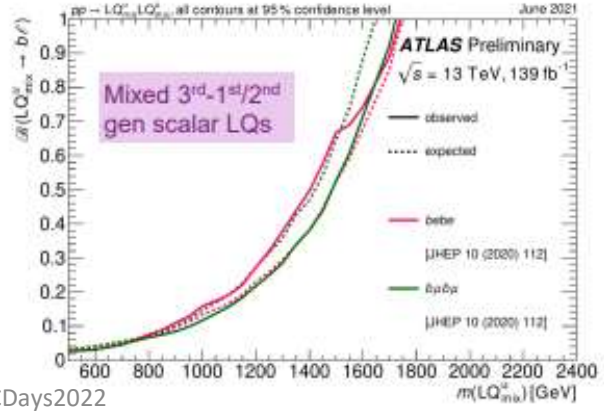
LQ → tℓ tℓ



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



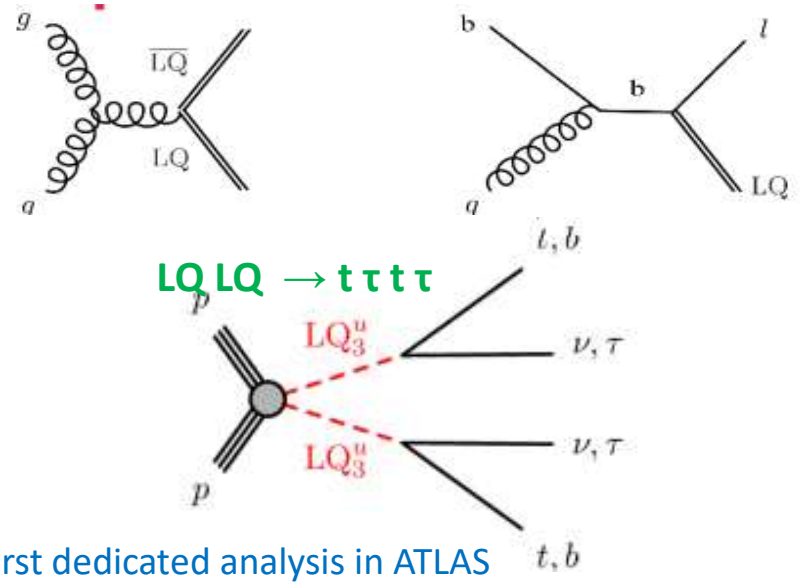


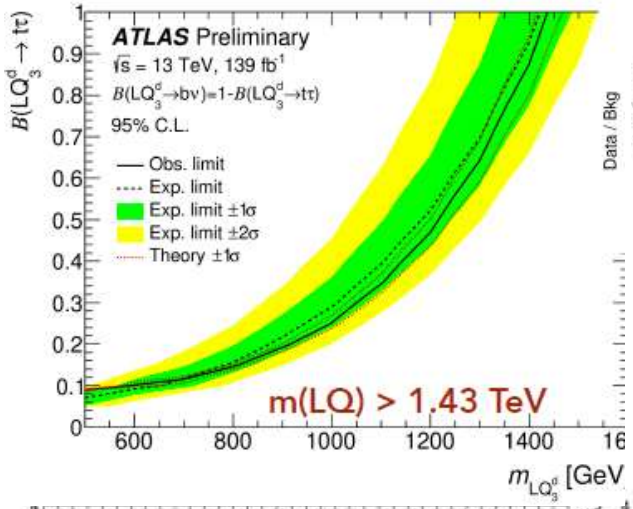


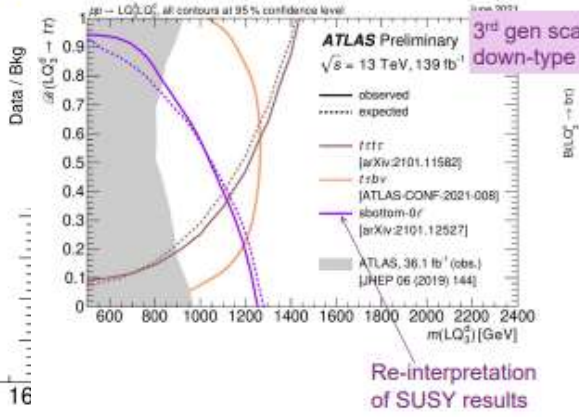
Leptoquarks

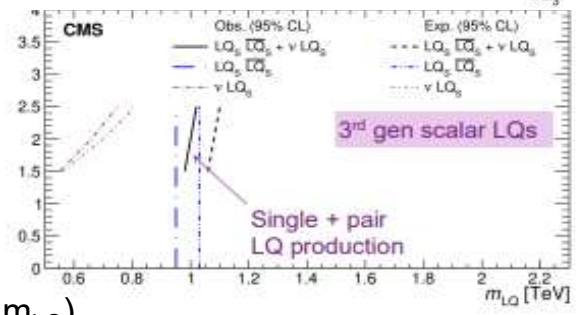
ATL-PHYS-PUB-2021-017
CMS-EXO-19-015
CMS-EXO-20-004
ATLAS-EXOT-2019-13
ATLAS SUSY-2019-18 (arXiv)

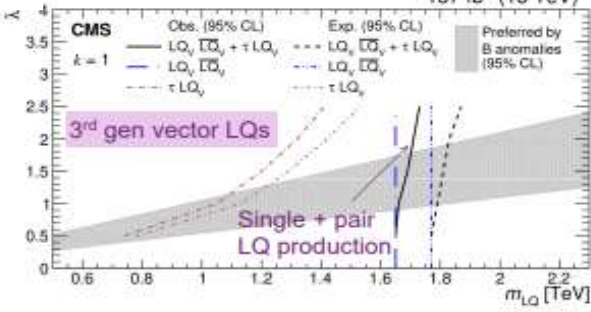
- Searches for 3rd generation only and mixed generations final states
- Scalar and vector LQs are investigated
- Decays into a quark and lepton











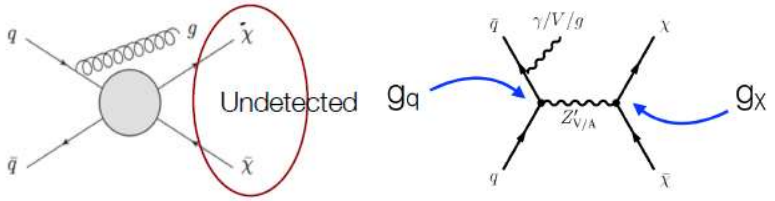
- First dedicated analysis in ATLAS

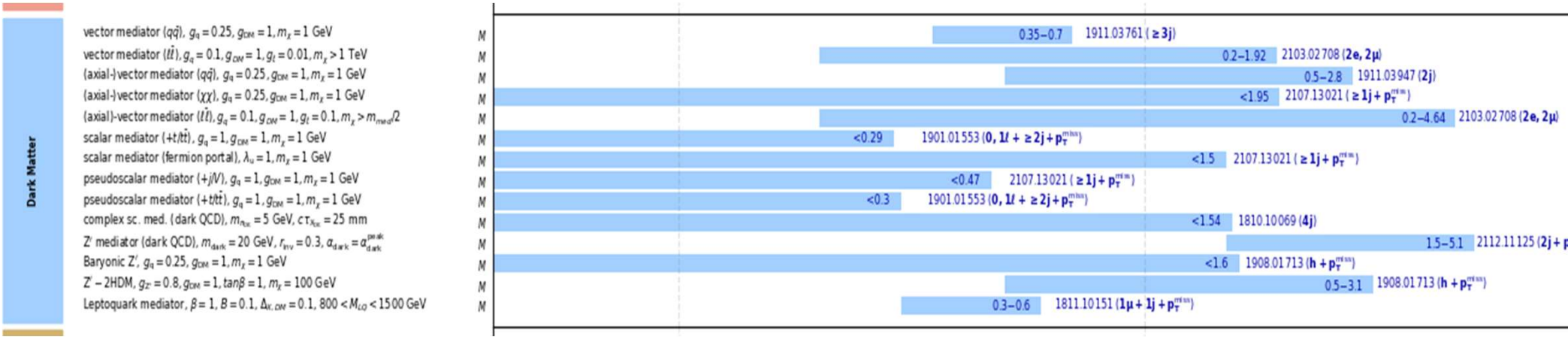
Improvement of a factor of x10 in sensitivity (~500 GeV in m_{LQ}) with respect to ATLAS and CMS 36 fb $^{-1}$)

Dark Matter

See Adelina's talk

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



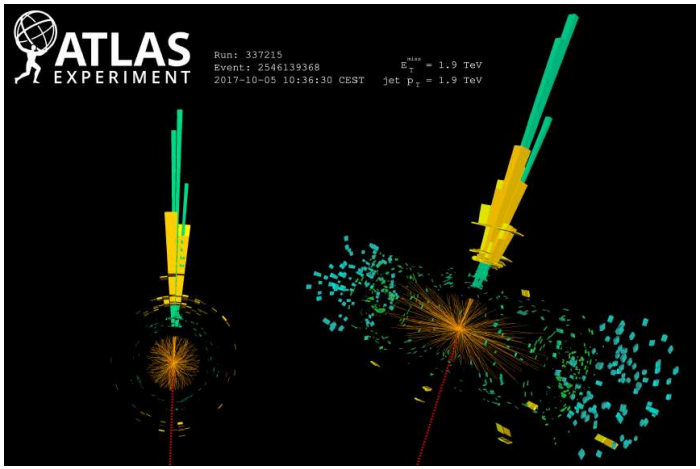


DM	Axial-vector med. (Dirac DM)	0 e,μ,τ,γ	1 – 4 j	Yes	139	m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e,μ,τ,γ	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z′-2HDM (Dirac DM)	0 e,μ	2 b	Yes	139	m_{med}	3.1 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med}	560 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036

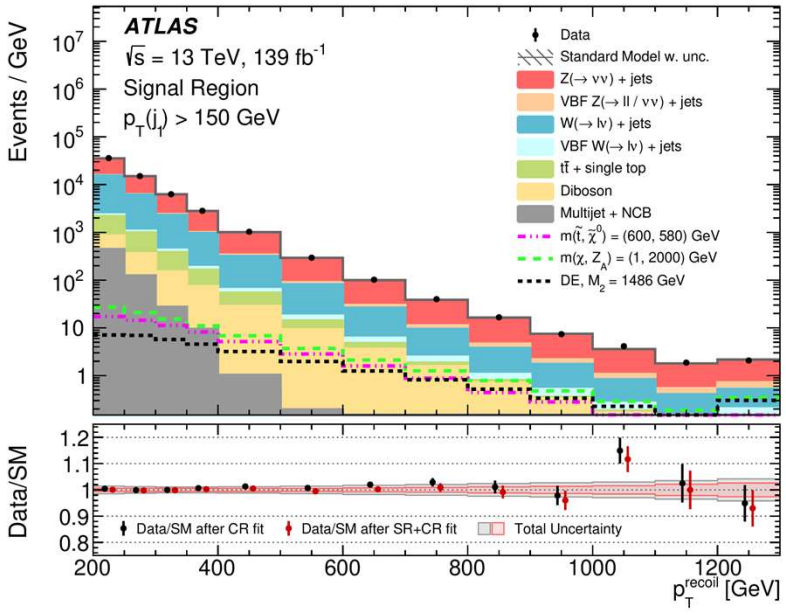
Mono-jet

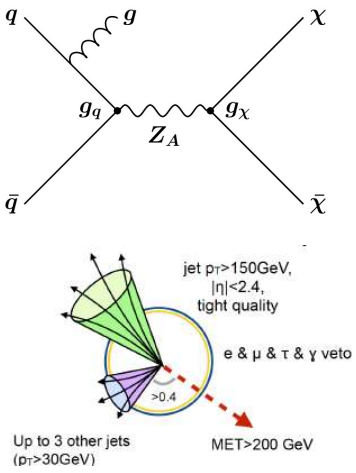
- Most sensitive mono-X channel for ISR processes
- Search: for a Missing Energy excess.
- Dominant backgrounds: **Z(νν)+jets** and **W(lν)+jets** constrained in 1 and 2 lepton control regions

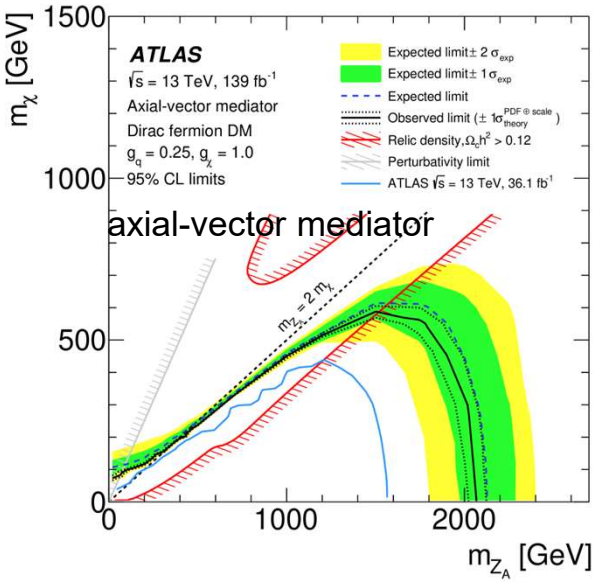
EXOT-2018-06/



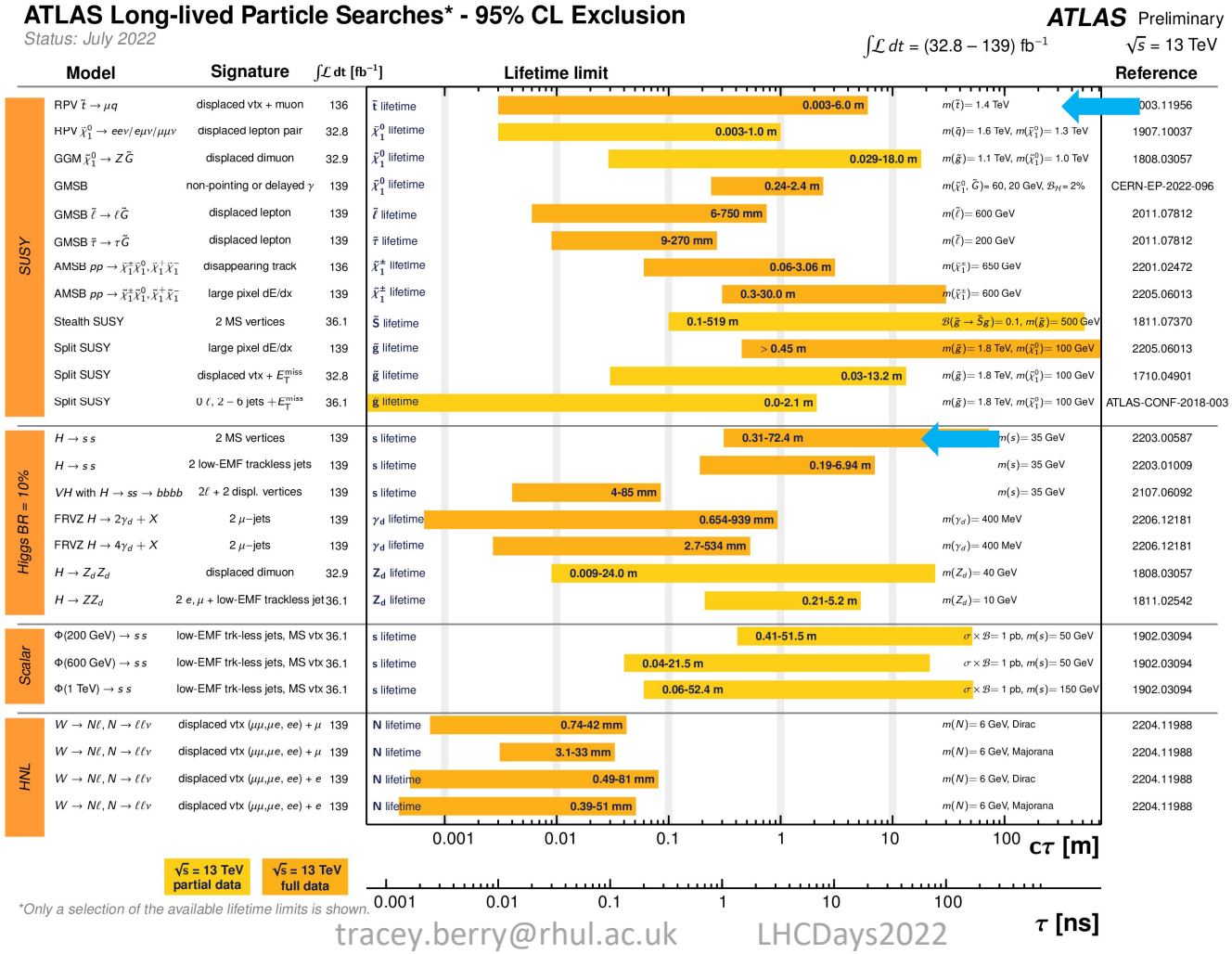
p_T^{recoil} >200 GeV signal region







Long-Lived Particle Searches



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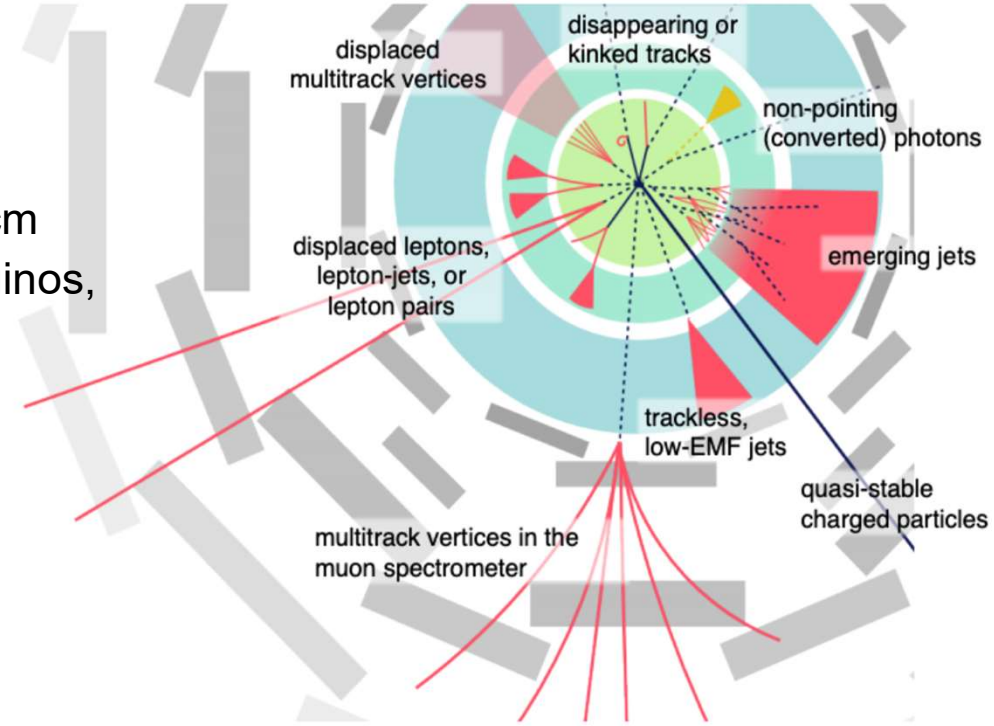
Searches for long lived particles

- 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

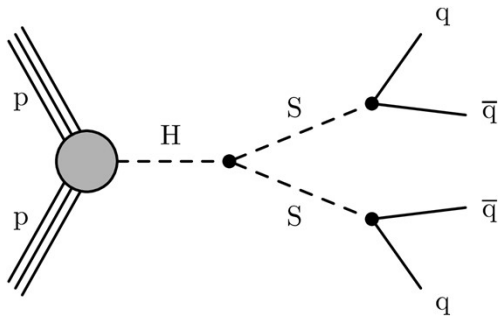
- Non-standard reconstruction
- Displacements, timing and ionization
- Dedicated triggers
- Non-standard background is a challenge
- Detector noise, cosmic rays, reconstruction failures
- Usually estimated from data

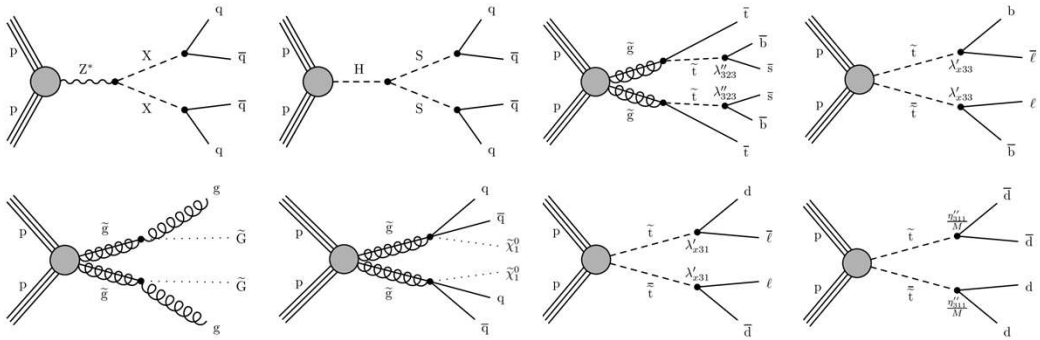


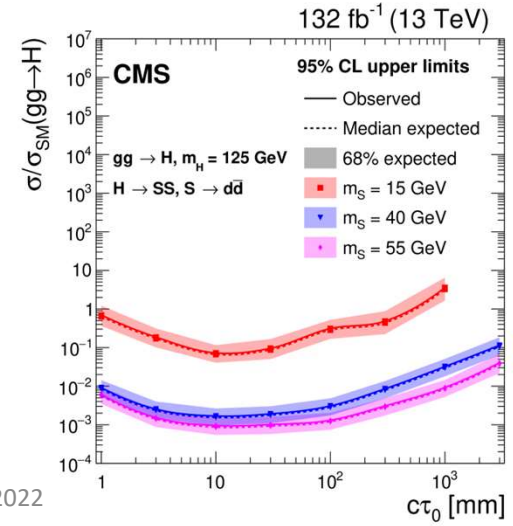
Displaced jets

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 → H → 2S, S → qq
  where cτ ~ 1mm to 3m







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

Displaced vertex + jets

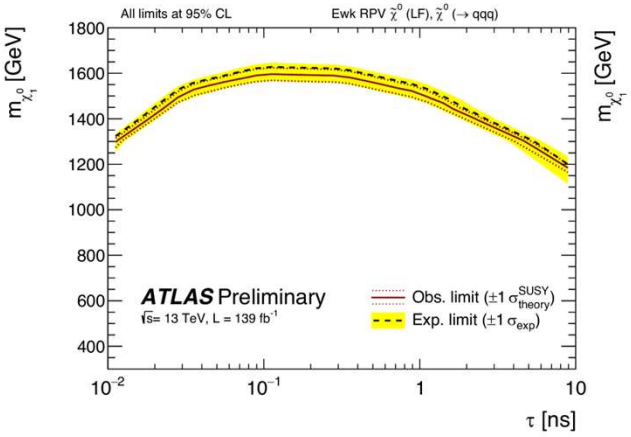
ATLAS-CONF-2022-054/

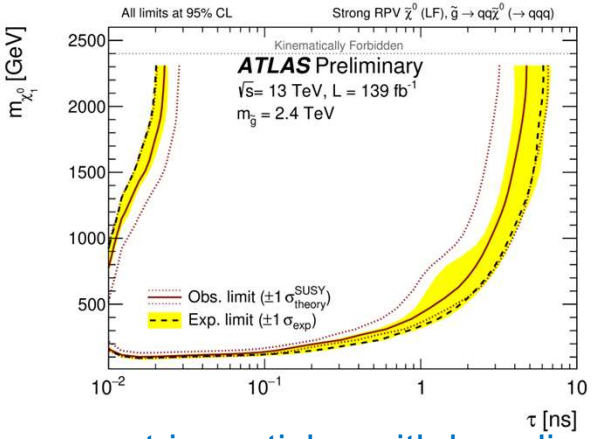
Search for long-lived particles (LLPs) decaying into hadrons
In events with a displaced vertex (DV) and several jets

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

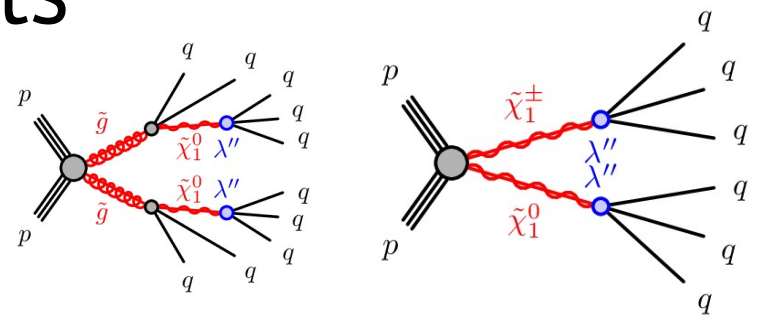
Backgrounds are instrumental, data-driven estimation

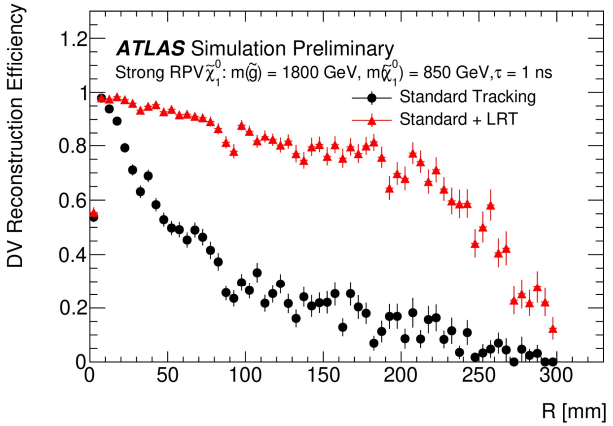
Interpretations in strong and electroweak SUSY models





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



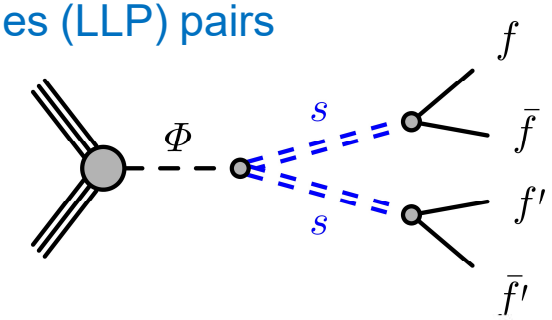


Electroweakino masses below 1.5 TeV are excluded for mean proper lifetimes in the range from 0.03 ns to 1 ns

Displaced jets in muon system (2vtx)

EXOT-2019-24/

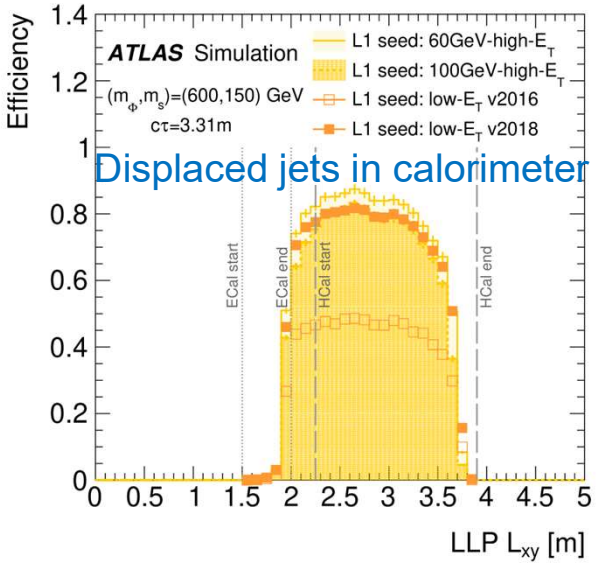
- Search for events with two displaced vertices from long-lived particles (LLP) pairs



- 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 into $t\bar{t}$ in MS



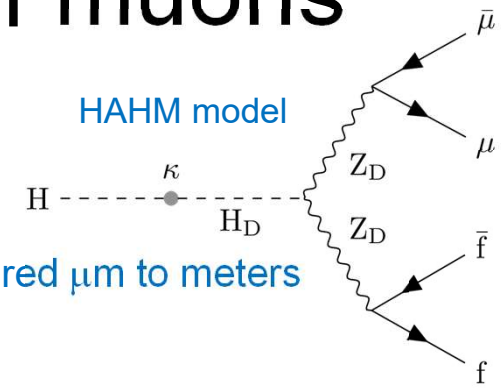
Displaced jets in calorimeter

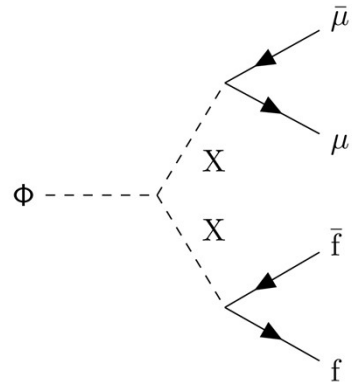
EXO-21-006/

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 μm to meters

HAHM model

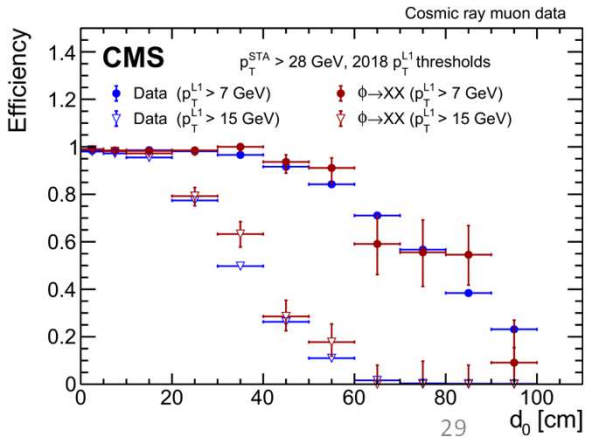




- Results interpreted in frameworks:
  - Hidden Abelian Higgs Model (HAHM)
    in which Higgs boson decays to a pair of long-lived dark photons Z_D
  - Simplified model
    LLPs produced in decays of an exotic heavy neutral scalar boson

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 $m(Z_D) > 20$ 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

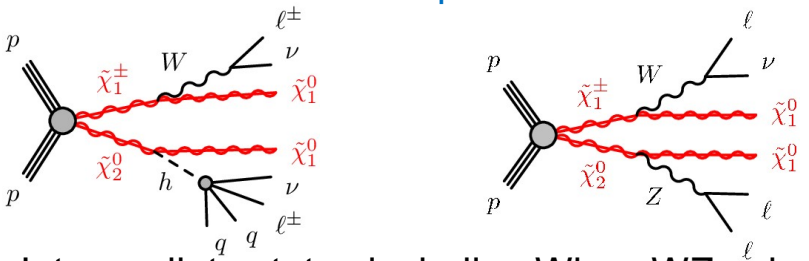


ATLAS-CONF-2022-057/

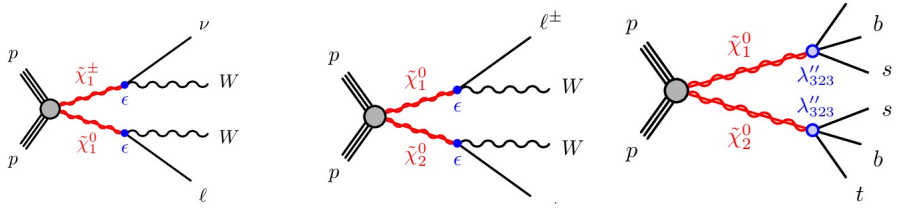
Electroweak same-sign / 3-lepton

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

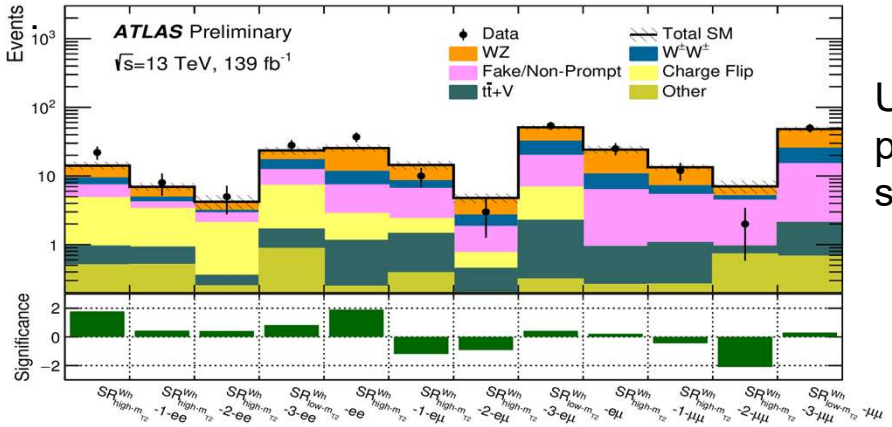
RPC simplified models



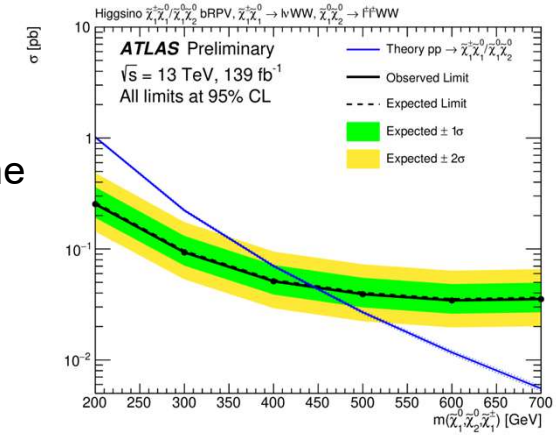
RPV models



Intermediate states including Wh or WZ pairs



Upper limits on the production cross sections set



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

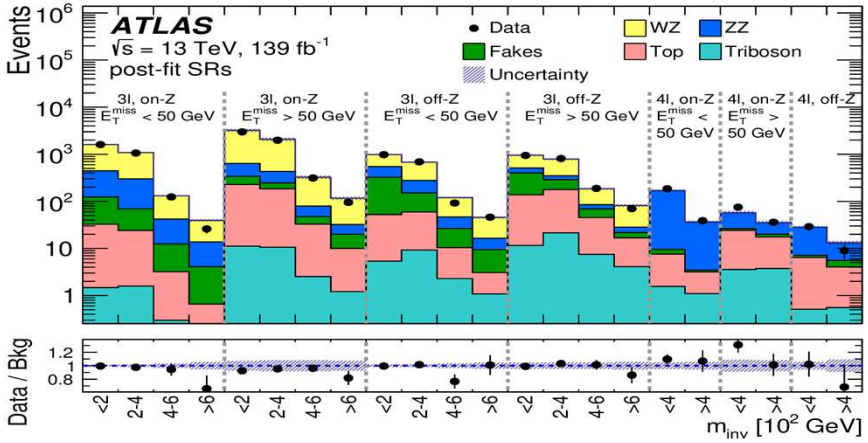
Wino masses up to 525 GeV and 260 GeV are excluded respectively, for a bino of vanishing mass

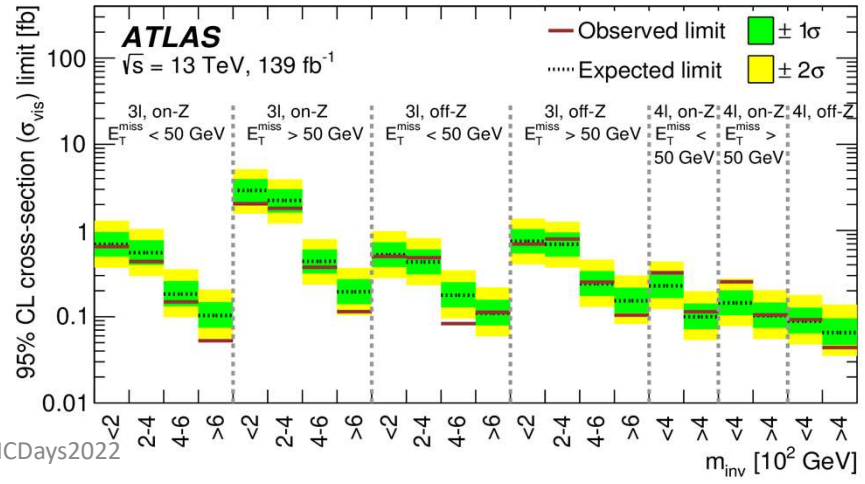
Multilepton General

ATLAS-EXOT-2019-36/
CMS-EXO-19-008/

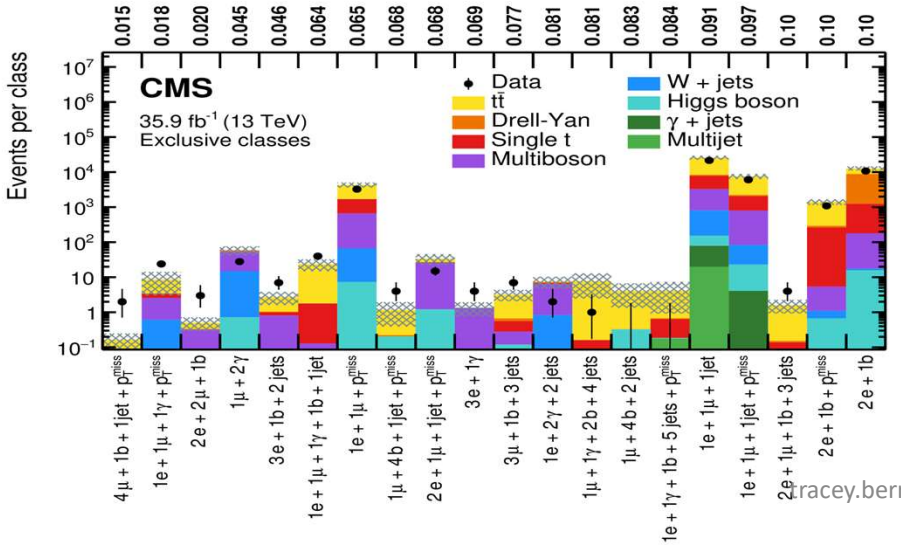
- Leaving no stone unturned
- Potential signals may be overlooked by model-specific analyses
- Identify interesting channels & search with minimal model dependance.
- Aims to be sensitive to a wide range of potential new-physics theories simultaneously

- 3ℓ and 4ℓ events, where ℓ=e,μ , 22 event categories



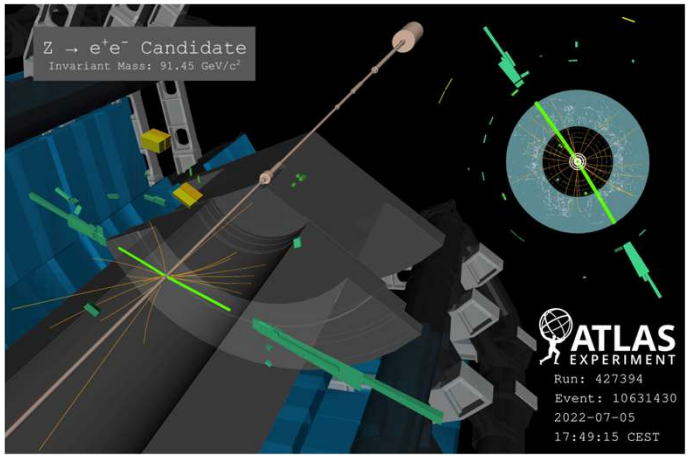


Model Unspecific Search in CMS (MUSiC)



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?