Exotics Searches and Long-Lived Particles

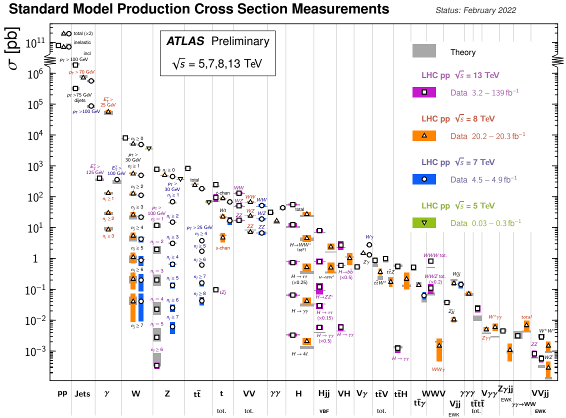
Sara Alderweireldt

on behalf of the ATLAS and CMS collaborations

La Thuile 2023

March 6th-10th, 2023

Beyond the Standard Model



Measured many SM parameters

- over a wide range of magnitude in cross section
- at multiple CoM energies

Despite great success of the SM still need to look beyond

- $g-2$
- flavour sector
- …

Multiple avenues for searches at the LHC

Leptoquarks

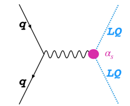
Resonances

Vector-Like Fermions

Long-Lived Particles
Unconventional Signatures

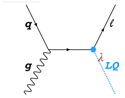
Supersymmetry
Dark Matter → ***Aran's talk*** Fri, 17:20

BSM Higgs → ***Gabriel's talk*** Fri, 16:30



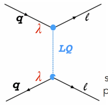
Pair production

QCD driven process
cross section depends on the mass



Single production

cross section ∝ λ^2
sensitive to higher m_{LQ} for sufficiently high λ



Off-shell production

cross section ∝ λ^4
non-resonant
sensitive to very high masses
possible interference with SM

Leptoquarks

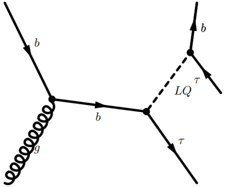
Leptoquarks offer a connection between quark/lepton sectors through Yukawa interaction (λ)

- pair-, single-, or non-resonant production
- two scalar LQs or one vector LQ
- several free parameters → grid scans (λ, β)
  - mass, charge, ...
  - β: BF into charged lepton ($\beta = 1$) or neutrino ($\beta = 0$)
  - κ: coupling to colour: nominal Yang-Mills ($\kappa = 0$) or minimal ($\kappa = 1$)

- ATLAS: LQ → $b\tau\tau$ (hh/lh)
- ATLAS: LQLQ → $b\tau b\tau$ NEW
- ATLAS: LQLQ → $t\nu b\ell$ / $t\ell b\nu$
- ATLAS: LQLQ → $t\ell t\ell$
- CMS: LQ / LQLQ → $b\tau b\tau$ / $b\tau\tau$ / $\tau\tau$
- CMS: hadronic $\tau + \not{E}_T$ NEW

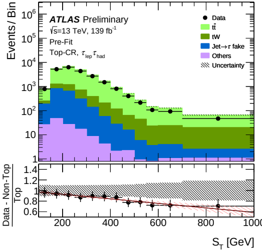
Scalar Leptoquarks

$\tau LQ^{\tilde{S}_1} \rightarrow b\tau_{had}\tau_{had}$ / $b\tau_{lep}\tau_{had}$

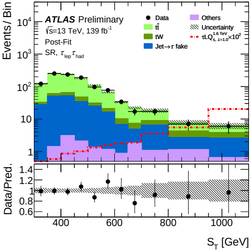


- Singly- and pair-produced scalar LQ → tau + b-hadron
  - range of LQ→$b\tau$ Yukawa coupling strength λ
- $\geq$1 b-jet, 2 τ, opposite-sign leptons, high b-jet p_T, high S_T selection
  - had−had and lep−had τ decays
  - signal/background discrimination in S_T
  - top background correction in function of S_T
- limited by statistics & top background modelling systematics
- m(LQ) excluded up to 0.89 (1.28) TeV for $\lambda = 1.0$ (2.5) for singly-produced LQ

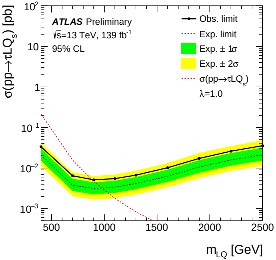
Top CR *before* correction



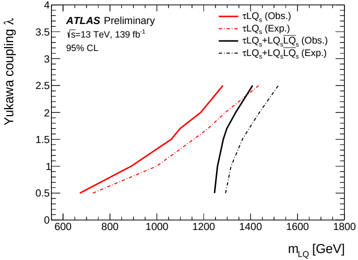
Signal at high $S_T = \sum_{\text{bjet},\ell,\tau} p_T$



Interpretation for scalar LQ & LQ+LQLQ



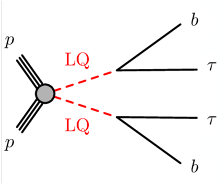
$m_{LQ} - \lambda$ plane 2D exclusion



Pair-produced Leptoquarks

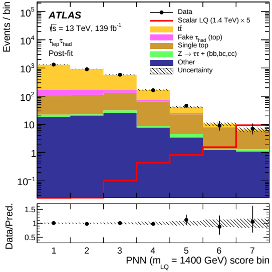
arXiv:2303.01294 NEW

$LQ_3^{d(u)} LQ_3^{d(u)} \rightarrow b\tau b\tau$

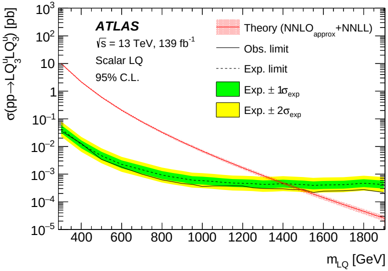


- Pair-produced scalar or vector LQ → tau + b-hadron (3rd gen)
  - interactions within the same family
- ≥2 jet (≥1 b-jet), 2 τ, opposite-sign leptons, high S_T selection
  - had–had and lep–had τ decays
  - top background correction in function of S_T
- PNN multivariate discriminant, parametrised in LQ mass
  - using multiplicity, kinematic, and angular features
- m(LQ) excluded up to 1.49 TeV (scalar) and 1.69/1.96 TeV (min/YM vector)

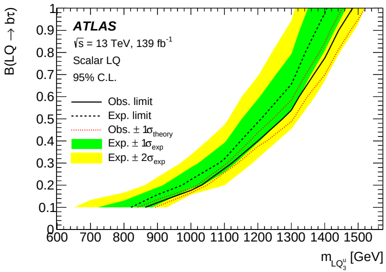
PNN discriminant ($\tau_l \tau_h$)



Interpretation for **scalar**/vector(YM/min) LQ



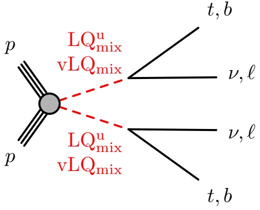
Interpretation in β, B(LQ→$b\tau$)



Pair-produced Leptoquarks → 1 lepton

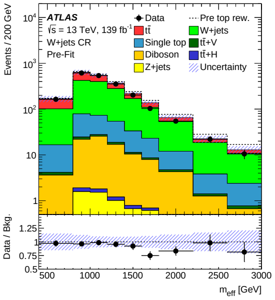
arXiv:2210.04517

$\mathrm{LQ}^{d(u)}_{\mathrm{mix}}\mathrm{LQ}^{d(u)}_{\mathrm{mix}} \to t\nu b\ell / t\ell b\nu$

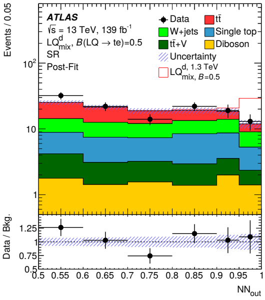


- Scalar or vector LQ → 3rd gen quark + 1st/2nd gen lepton
- ≥4 jet, ≥1 b-jet, =1 lepton, $E_T^{miss} > 250$ GeV selection
  - top background correction in function of m_{eff}
- Dedicated NN (NeuroBayes) trained separately for scalar/vector LQ channels
  - signal/background selection in NN, then simultaneous fit over all regions
- limited by statistics, top modelling systematics, and JES uncertainties
- m(LQ) excluded up to 1.46 TeV (scalar) and 1.71/1.98 TeV (min/YM vector)

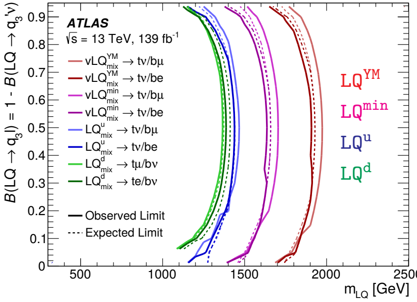
W+jets CR m_{eff}



SR NN output score



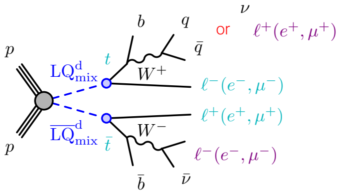
$m_{\mathrm{LQ}} - \beta$ plane 2D exclusion



Pair-produced Leptoquarks → multilepton

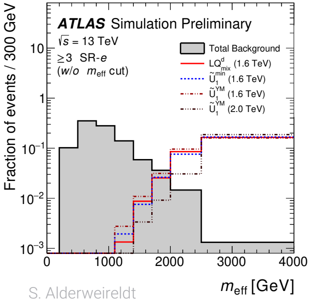
ATLAS-CONF-2022-052

$LQ^{d}_{mix}LQ^{d}_{mix} \to t\ell t\ell$

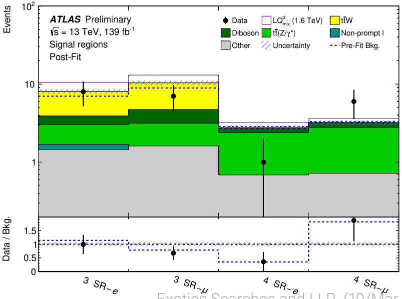


- Pair-produced scalar/vector LQ → top + multi-lep (2ℓSS; 3ℓ, 4ℓ)
- ≥2 jet (≥1 b-jet), ≥ 2ℓ selection
  - signal/background discrimination in $m_{\text{eff}} = \sum_{\text{jet},\ell} p_T + E\!\!\!/_T$ and high $m_{\ell\ell}^{\text{min}}$
- limited by statistics, lepton ID systematics
- m(LQ) excluded up to 1.6 TeV (scalar) and 1.7/2.0 TeV (min/YM vector)

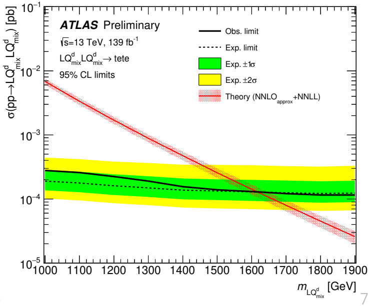
sig/bkg discrimination in m_{eff}

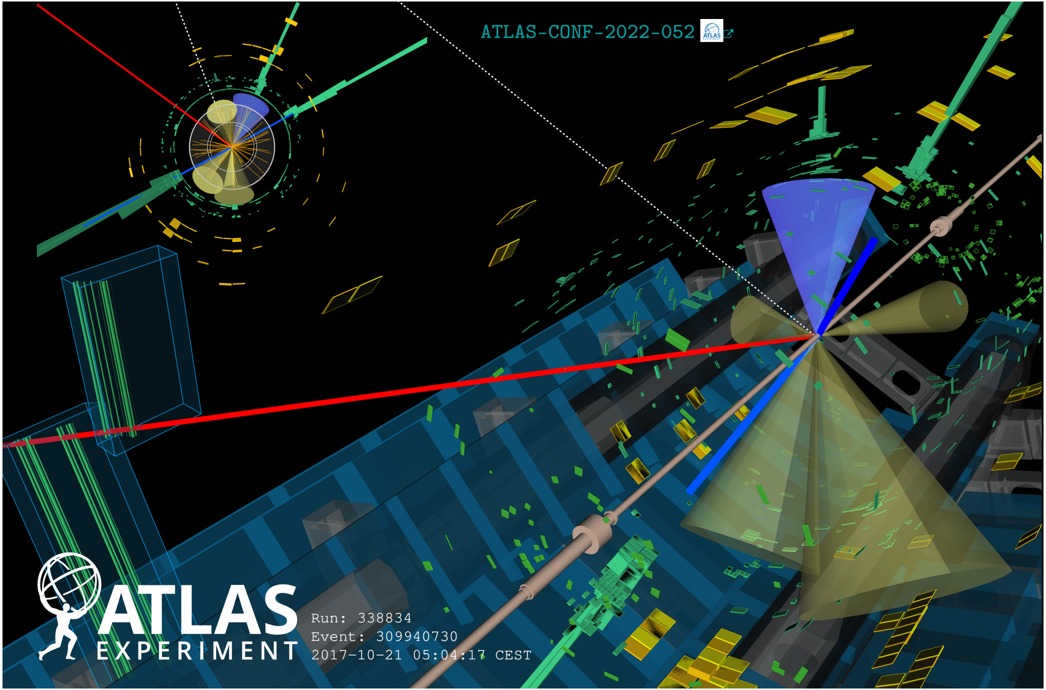


4 SRs with ≥ 3ℓ



Interpretation for **scalar**/vector(min/YM) LQ




ATLAS-CONF-2022-052
ATLAS
EXPERIMENT
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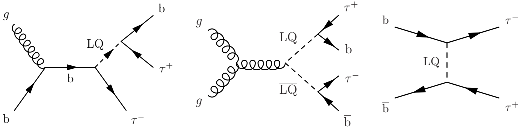
2017-10-21 05:04:17 CEST

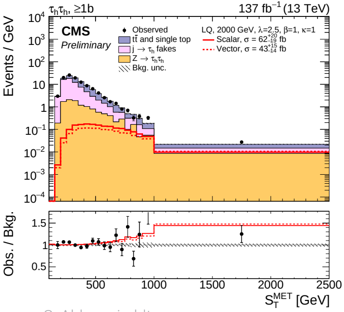
3rd gen Leptoquarks

$LQ_3 \rightarrow b\tau b\tau$ / $b\tau\tau$ / $\tau\tau$

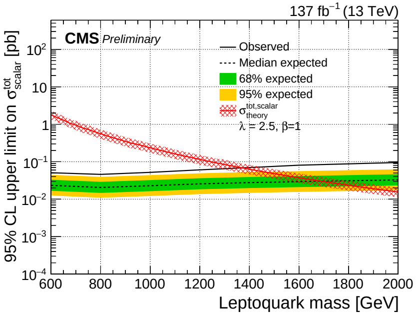


- Single-, pair-, and non-resonant LQ production & scalar and vector LQ interpretation
- $\geq$1 b-jet, $\geq$1 τ (*hh,lh,ll*) selection
  - categorise by tau-decay channel
- Novel non-resonant production $\rightarrow$ τ pair channel
  - exploit angular separation χ between taus
- m(LQ) excluded up to 1.25 TeV (scalar) and up to 1.53/1.86 TeV (min/YM vector), for $\lambda = 1$
  - excess at higher mass/λ, most prominent in non-resonant production

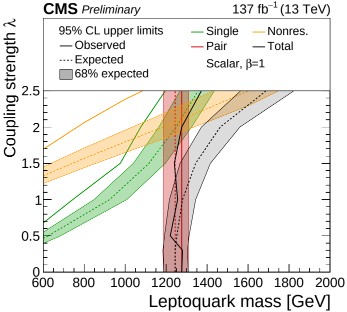
$\geq 1b\tau_h\tau_h$ SR S_T



Scalar LQ interpretation ($\lambda = 2.5$)



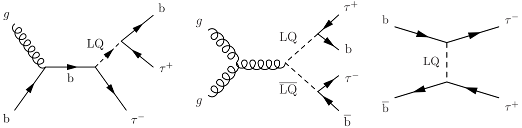
$m_{LQ} - \lambda$ plane 2D exclusion



3rd gen Leptoquarks

$LQ_3 \rightarrow b\tau b\tau$ / $b\tau\tau$ / $\tau\tau$

CMS-PAS-EXO-19-016



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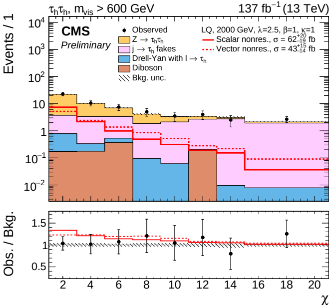
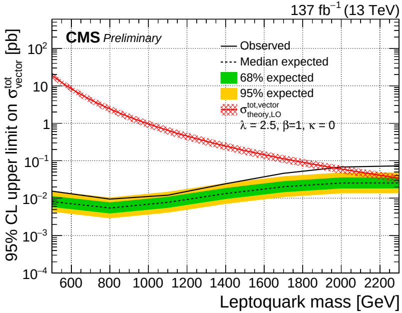
  - excess at higher mass/λ, most prominent in non-resonant production

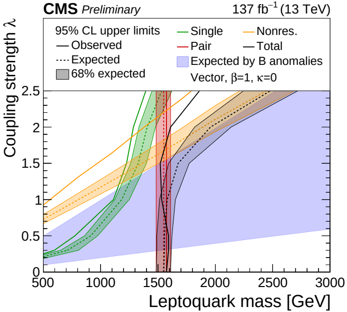
$\tau\tau$ SR angular separation



Vector LQ interpretation ($\lambda = 2.5, \kappa = 0$)



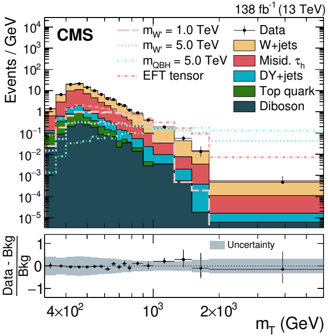
$m_{LQ} - \lambda$ plane 2D exclusion ($\kappa = 0, \beta = 1$)



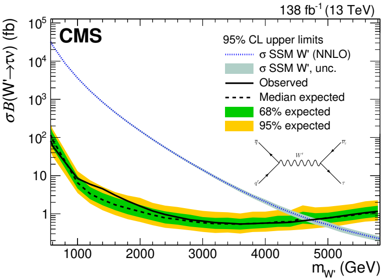
Hadronic $\tau + \not{E}_T$

(Submitted to JHEP) arXiv:2212.12604 NEW

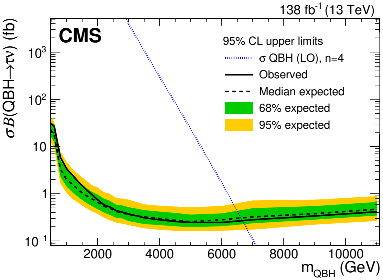
- $\tau_h + \not{E}_T$ selection
  - Search for BSM physics in $m_T(\tau, \not{E}_T)$ variable
- Multiple interpretations
  - heavy charged W' boson → exclusion up to 4.8 TeV
  - quantum black hole → exclusion up to 6.6 TeV
  - t-channel (non-resonant) LQ production
    → exclusion up to 0.2/0.5/5.9 TeV (LH/LH+RH/democratic, $\lambda = 1$)
  - 2D interpretation ifo. coupling strengths
  - model-independent and EFT limits



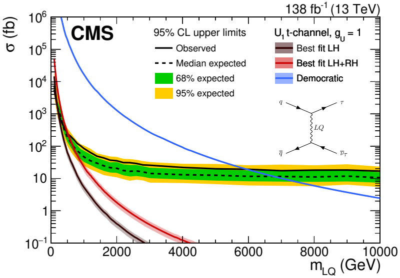
Heavy charged boson



Quantum black hole

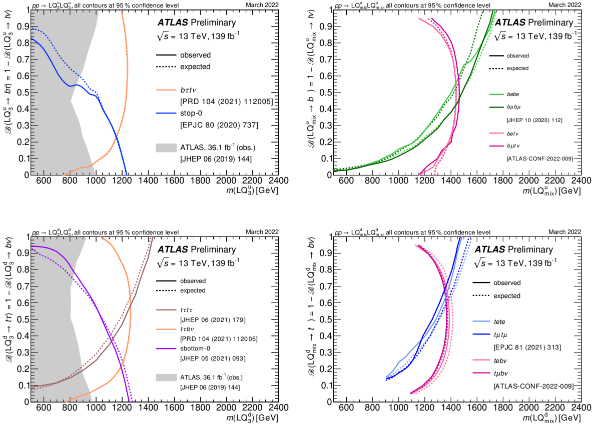


Non-resonant LQ production ($\lambda = 1$)

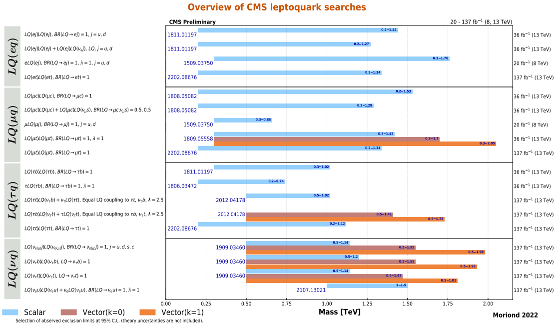


Leptoquark Summary Plots

ATL-PHYS-PUB-2022-012



CMS summary plots



Vector-Like Fermions

Vector-Like Fermions are a BSM extension which
- allows to avoid Higgs Yukawa constraints & the hierarchy problem
  → composite models, . . .
- has non-chiral new particles → same L/R charges/isospin

- triplet/double/singlet vector-like quarks (VLQ): T, B, X, Y
- doublet/singlet vector-like leptons (VLL): charged E, neutral N

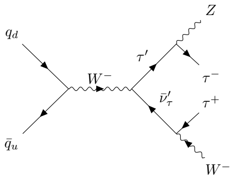
- branching fractions depend on representation
- often assume decays to 3rd generation

- ATLAS 3rd gen VLL NEW
- ATLAS VLQ TT/BB → 2/3ℓ
- ATLAS VLQ TT/BB → 1ℓ+$E\!\!\!/_T$
- ATLAS VLQ mono-top (backup)

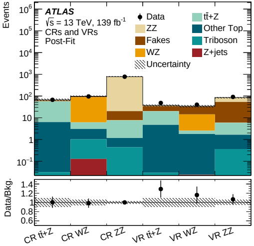
3rd generation Vector-Like Leptons

arxiv:2303.05441 NEW

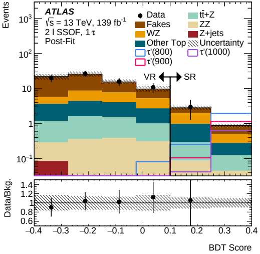
- Consider SU(2) doublet $L' = (\nu'_\tau, \tau')$ VLL → 3rd gen SM leptons
- Multi-lepton $2\ell, 3\ell, \geq 4\ell$ ($\geq 0\tau_h$) selection
- BDT discrimination: 7 SRs for different lepton multiplicities
  - 7 training regions, 34 kinematic & topological features
  - multiple VLL τ' signals in training
- limited by statistics
- m(VLL) excluded up to 900 GeV
  - similar to CMS-PAS-EXO-21-002



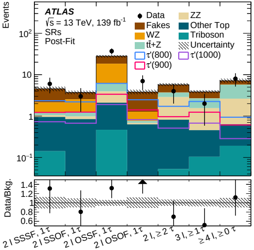
Background estimation & validation

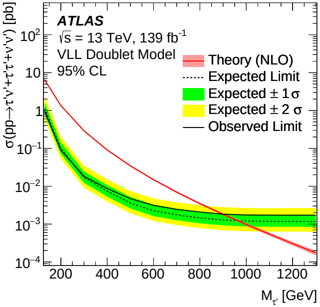


BDT discrimination



7 signal regions by lepton multiplicity





Vector-Like Quark pair production (TT/BB)

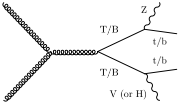
arXiv:2210.15413
arXiv:2212.05263

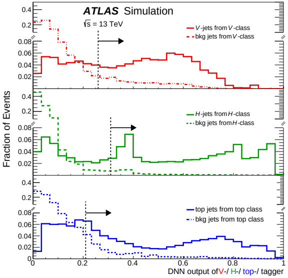
$2/\geq 3$ leptons

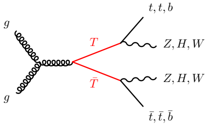
- high p_T Z
  $\rightarrow \geq 1$ b-jet + OSSF ℓ + extra ℓ
- DNN for large-R jet tagging (W/Z/H/top)
  - multi-class boosted object tagger: `MCBOT`
  - 19 fit categories based on DNN tags and lepton & b multiplicity
  - binned likelihood fit

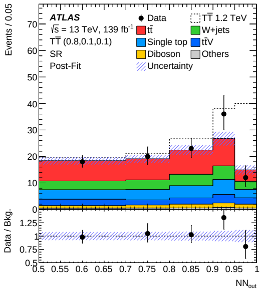
1 leptons + E_T^{miss}

- Zt/Ht/Wb / Zb/Hb/Wt
  $\rightarrow \geq 4$ jets (≥ 1 b-jet) + 1 ℓ + E_T^{miss}
- 7 NNs (NeuroBayes) trained for different TT/BB BF mixes
  - preselection in $m_{T,W}$ & $m_{T,2}$ (CR/SR)
  - top background reweighting ifo. N_j / m_{eff}
  - 13 input features
  - binned likelihood fit







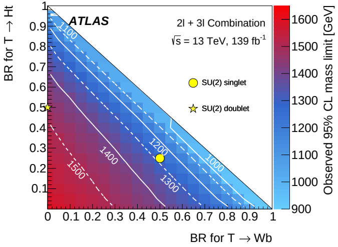


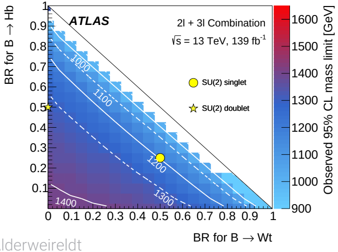
Vector-Like Quark pair production (TT/BB)

arXiv:2210.15413
arXiv:2212.05263

$2/\geq 3$ leptons

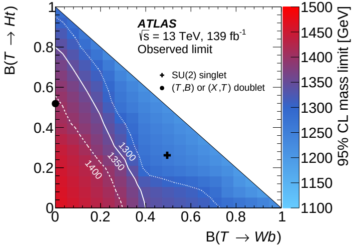
- Singlet/doublet/pure interpretations
  - 2/3ℓ combination
- Zt+X sensitivity bottom-left in mass/BF plane

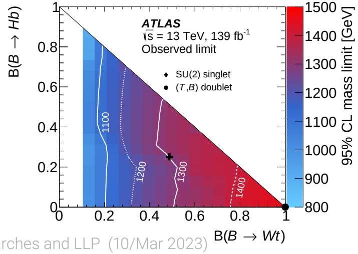




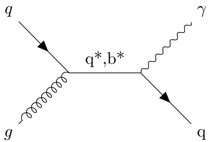
1 leptons + $\not{E}_T$

- Singlet/doublet/pure interpretations
- largest sensitivity for T→Zt (bottom-left) and B→Wt (bottom-right in mass/BF plane)





Resonance searches

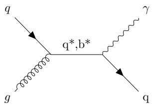


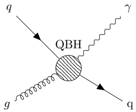
- heavy resonances in γ+jet
- di-lepton resonances
- low-mass $\mu\mu$ NEW
- 3/4 body masses in leptons+jets (backup)

Heavy resonances in γ+jet

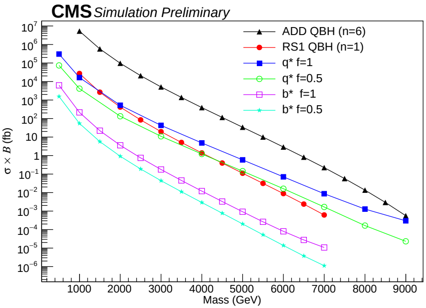
CMS-PAS-EXO-20-012

- Resonance search in $m_{\gamma+\text{jet}}$ spectrum
  - interpretation for models with excited quarks (q^*/b^*) and quantum black holes (ADD/RS)
  - $q \leftrightarrow q^*$ via contact interaction at Λ scale $\gg \sqrt{s}$, or via gauge mediation $< \sqrt{s}$
- γ + jets selection
  - recluster wide jets (ΔR=1.1) including FSR to improve $m_{\gamma+\text{jet}}$ resolution (1-1.3%)
  - select back-to-back $\Delta R(\gamma,\text{jet}) > 1$
- Smooth parametrised fit over $m_{\gamma+\text{jet}}$
- Resonance masses excluded up to 6.0 / 2.2 / 7.5 / 5.2 TeV for q^* / b^* / ADD QBH / RS QBH

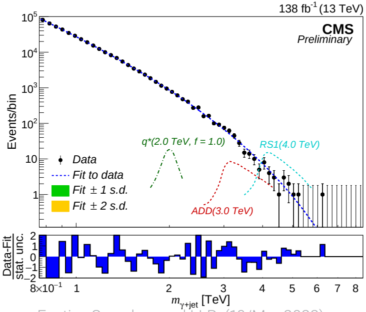


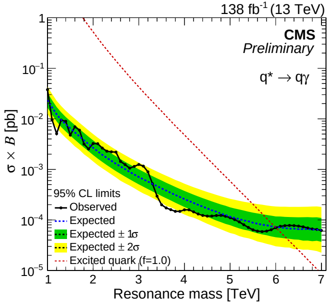


cross-section: QBH > q* > b*



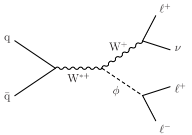
Fit of $m_{\gamma+\text{jet}}$ spectrum

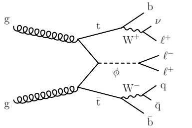




Di-lepton resonances from decays of (pseudo-)scalar bosons

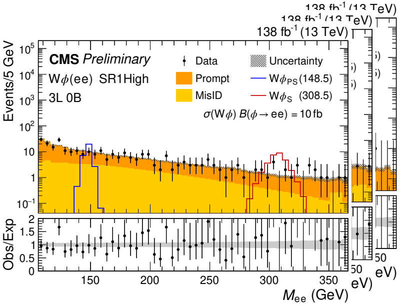
CMS-PAS-EXO-21-018



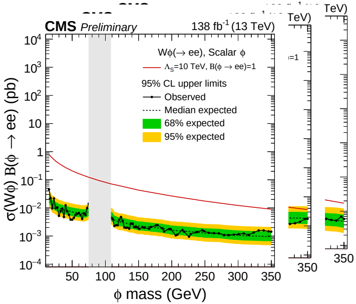


- Search for new, light, neutral, spin-0 boson ϕ, in associated production with W/Z/tt
  - consider scalar, pseudo-scalar, and higgs-like couplings
  - di-lepton decays with lepton number & charge conservation → 3/4ℓ final states
- 7 distinct orthogonal channels of different τ/light lepton multiplicities
  - categorise in N_j, N_b, N_{OSSF} & define inv/transv. masses
  - further selection on S_T, $p_{T,3}$, m_ℓ, q_ℓ
- 12+12+13 ($ee/\mu\mu/\tau\tau$) = 37 SRs for 24 signal models

37 $m_{\ell\ell}$ mass spectra

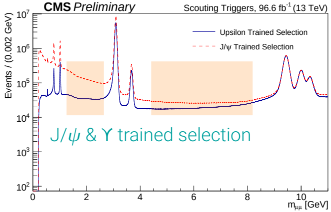


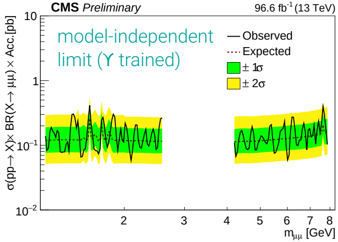
Interpretation for (pseudo)scalar/higgs-like ϕ in W/Z/ttϕ

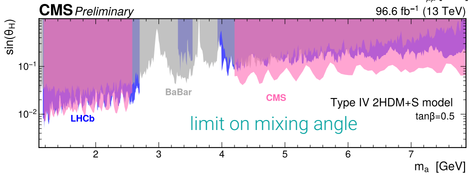


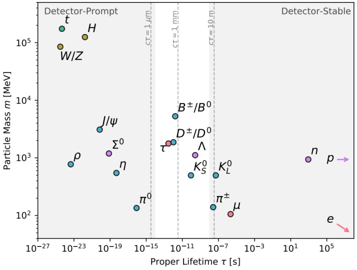
Low mass $\mu\mu$ resonances

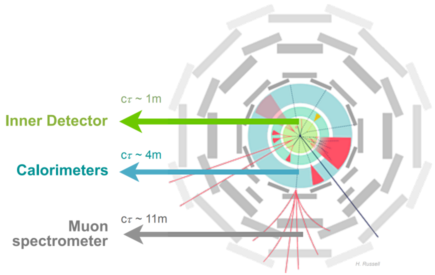
- Search performed on dedicated scouting trigger stream (2017–2018)
  - record di-muon events with transverse momenta as low as 3 GeV
  - save only partial event information to reduce the high-level trigger rate
- Search for narrow resonances in the low mass range
  - bump hunt 1.1–2.6 and 4.2–7.9 GeV range in di-muon mass
  - multivariate ID to reduce mis-ID muon contribution, and data-driven trigger & reco efficiency
  - J/ψ (Υ) training for low mass/boosted (higher mass) category
  - background est.: O(4) Bernstein combinatorial + peaking from CRs, signal: double CB + gaussian
  - largest excess 3.2(1.3)σ local (global) at $m_{\mu\mu}$ = 2.41 GeV
- Limits set on di-muon resonance production
  - interpretation in the context of a dark photon model, and a 2HDM+scalar model $\sim g-2$
- Using the same trigger: observation of $\eta \to 4\mu$, CMS-PAS-BPH-22-003











Long-Lived Particles
& Unconventional Signatures

Consider charged/neutral LLPs and more unconventional signatures
- unusual energy deposits
- displaced vertices

Also with unconventional backgrounds
- detector noise
- machine-induced background
- data-driven approaches

- ATLAS Pixel dE/dx
- ATLAS Multi-Charged Particles
- CMS Fractionally Charged Particles
- ATLAS Displaced Vertices + jets
- ATLAS Displaced Heavy Neutral Leptons
- ATLAS (Vertexed) Displaced Photons
- CMS Delayed Trackless Jets
- ATLAS Displaced 'hadronic' jets (backup)
- ATLAS Decays in the muon system (backup)

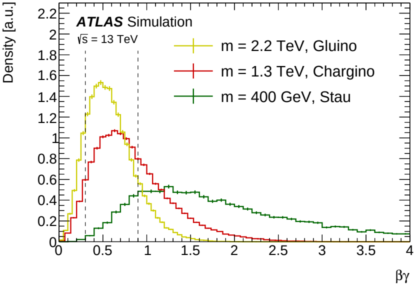
Ionisation in Trackers

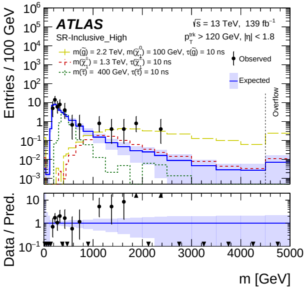
Pixel dE/dx

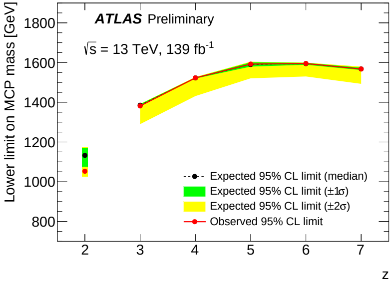
- Target massive charged LLPs
  - determine m ∼ Bethe-Bloch: m = p / $\beta\gamma$
- High E_T^{miss}, high p_T isolated track, large ionisation selection
  - calibrate dE/dx ∼ $\beta\gamma$ in low mu runs
  - fully data-driven background estimation
- Consistent with SM in all-but-one SR
  - 3.6 (3.3)σ local (global) excess ∼ 1.4 TeV
  - not confirmed to be consistent with actual slow particles in additional ToF measurements ($\beta \sim 1$)
  - could still be consistent with e.g. boosted LLPs, or MCPs [ref]

Multi-Charged Particles

- Target heavy multi-charged particles ($|q| = 2 - 7e$)
  - long-lifetime → exploit muon-like signature
  - anomalously high ionisation dE/dx in ID, TRT, and MDT
- Single/late muon + E_T^{miss} preselection
  - MDT dE/dx significance for final selection
- m(MCP) excluded between 500-1600 GeV
- Sensitivity insufficient to probe cross-sections relevant in pixel dE/dx excess context



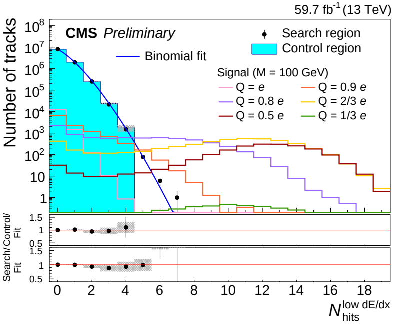


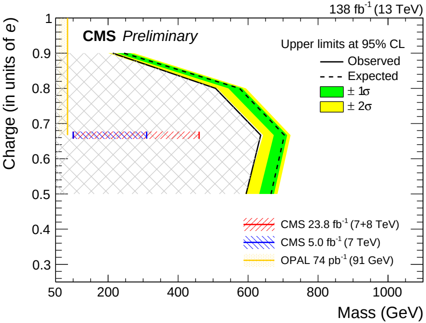


Ionisation in Trackers

Fractionally Charged particles

- Consider free-propagating particles with charges $< 1e$
  - Portal scenarios, hidden symmetries, fields weakly/non-connected to the SM
  - Previous results for $|q| = 2/3$ from 7 & 8 TeV analyses
- FCPs only ionise matter weakly $\sim$ low charge $\rightarrow$ analyse tracker dE/dx
  - count 'low' dE/dx hits: background $\ll$ signal
  - tracker layer dependent 'low' threshold
  - almost background free SRs
- FCPs excluded for masses up to 636 GeV for charges 0.5–0.9e





Displaced vertices

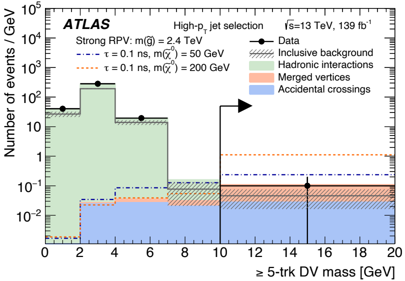
Target LLP decays inside the inner tracker

arXiv:2301.13866 NEW

arXiv:2204.11988

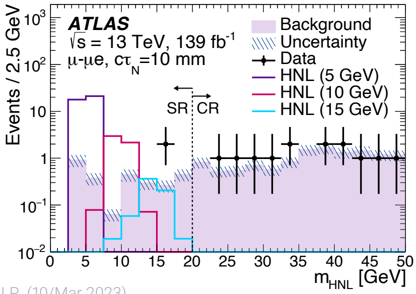
Displaced Vertex + jets

- Search for LL particles decaying into hadrons
- 2–7 high p_T jet selection + ≥1 displaced vertex with ≥5 tracks and mass>10 GeV
  - additional dedicated SR for lower p_T jets
  - rely on large-radius tracking
- Interpretation for strong and EW production SUSY models
  - limits set in broad ps–ns range



Displaced Heavy Neutral Leptons

- Displaced vertex from decay of LL HNL
- Prompt lepton + opposite-sign, displaced, di-lepton vertex selection
  - HNL mass reco through energy-momentum conservation
  - rely on large-radius tracking
- Interpretation both for LFC and LFV scenarios
  - first direct search results for two-quasi degenerate HNL models (2QDH)
  - good agreement with SM → limits set



(Vertexed) delayed displaced photons

arXiv:2209.01029
ATLAS-CONF-2022-051

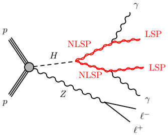
- Target photons from heavy LLP decays
  - late w.r.t. bunch crossing + non-pointing
  - exploit LAr calorimeter timing and pointing: ∼0.2ns/10mm resolution → derive pointing in z along the beam axis

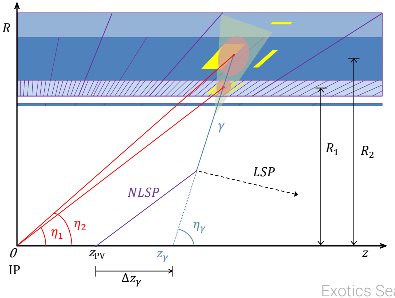
Not vertexed

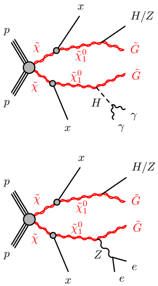
- 2γ from LL NLSPs + trigger on lepton leg
  - photons from different decays
- Shape fit of timing distribution in $1\gamma/\geq 2\gamma$ & pointing/timing categories
- Interpretation ∼ GMSB model
  - scan BF(→NLSP pair) & NLSP-LSP mass splitting

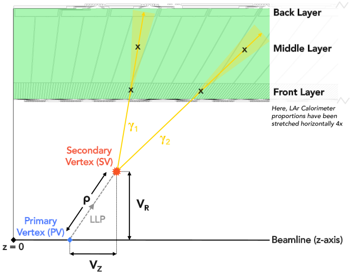
Vertexed

- 2γ / $2e$ from H/Z decays
  - photons from the same decay
- Shape fit of timing distribution in pointing/timing categories
- Interpretation ∼ GMSB model
  - for both pure NLSP→Z/H + $\tilde{G}$, w.r.t. mass/lifetime









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  - photons from different decays
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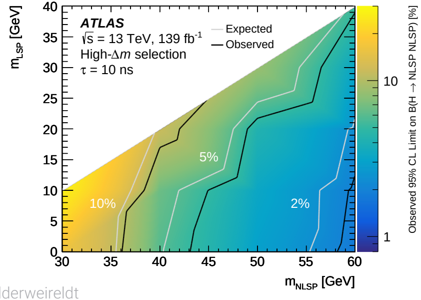
- Interpretation ~ GMSB model
  - scan BF(→NLSP pair) & NLSP-LSP mass splitting



Vertexed

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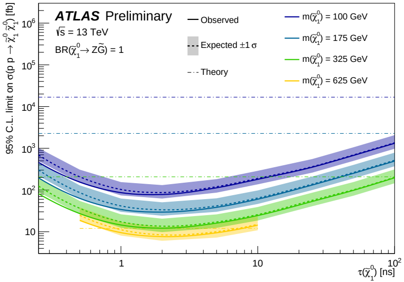
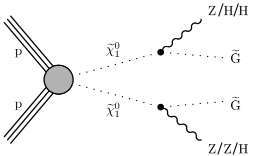
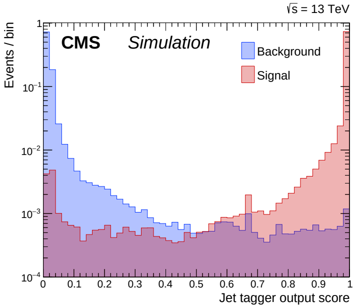
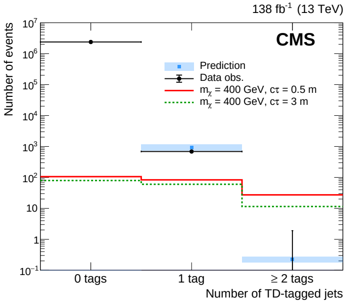


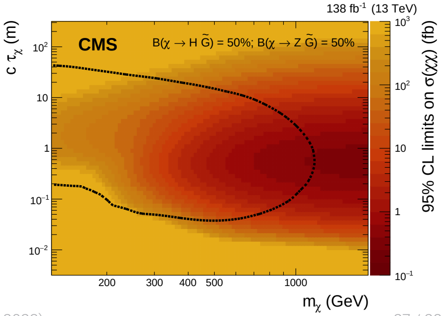
Delayed trackless jets

- Target LL decays beyond the tracker
  - GMSB model production as benchmark, varying BF(Z/H)
- Trackless Delayed jets: far decays or slower moving
- DNN based on trackless and out-of-time information
  - 22 track & ECAL features
  - jet time resolution 400-600ps
- 2D interpretation scanning $c\tau$ and m(NSLP)
  - m(NLSP) excluded up to 1.18 TeV
  - highest sensitivity around $c\tau \sim$0.5m
  - previous results based on tracks: smaller $c\tau < 0.2m$, or muon system: larger $c\tau > 1m$



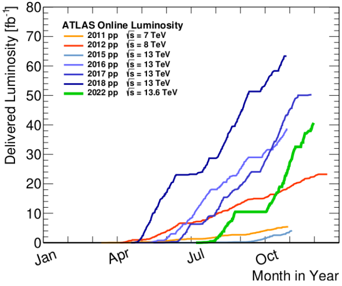


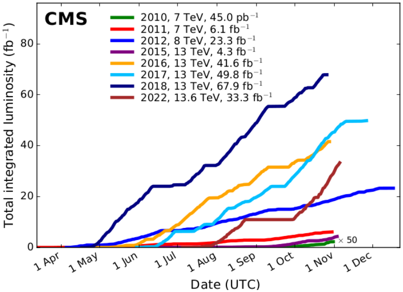




Summary & Outlook

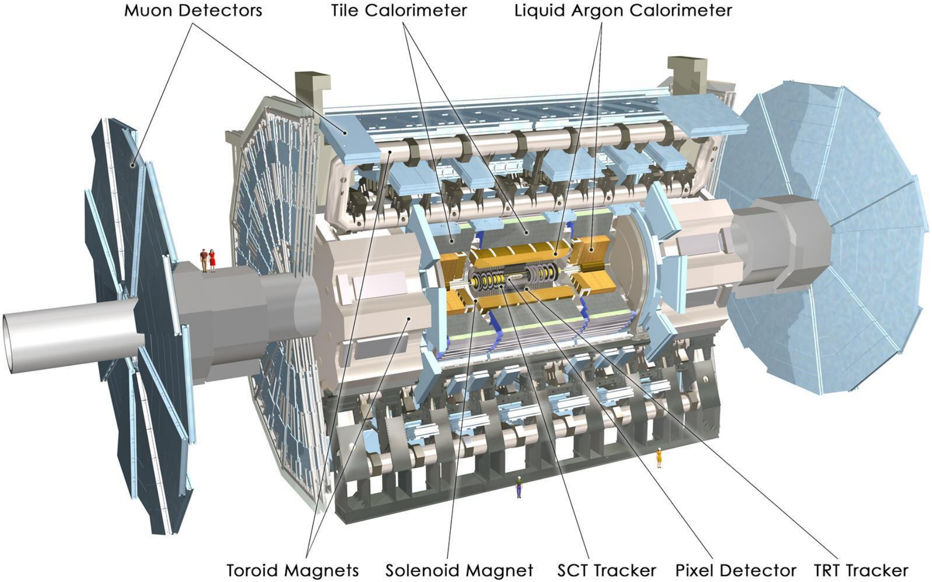
- Many new and improved results from both experiments on
  - Leptoquarks
  - Vector-Like Fermions
  - Resonance searches
  - Long-Lived Particles & Unconventional Signatures
- Various detailed summary plots available: see backup slides
- Stay tuned for more results as Run 3 data becomes available from ATLAS and CMS!

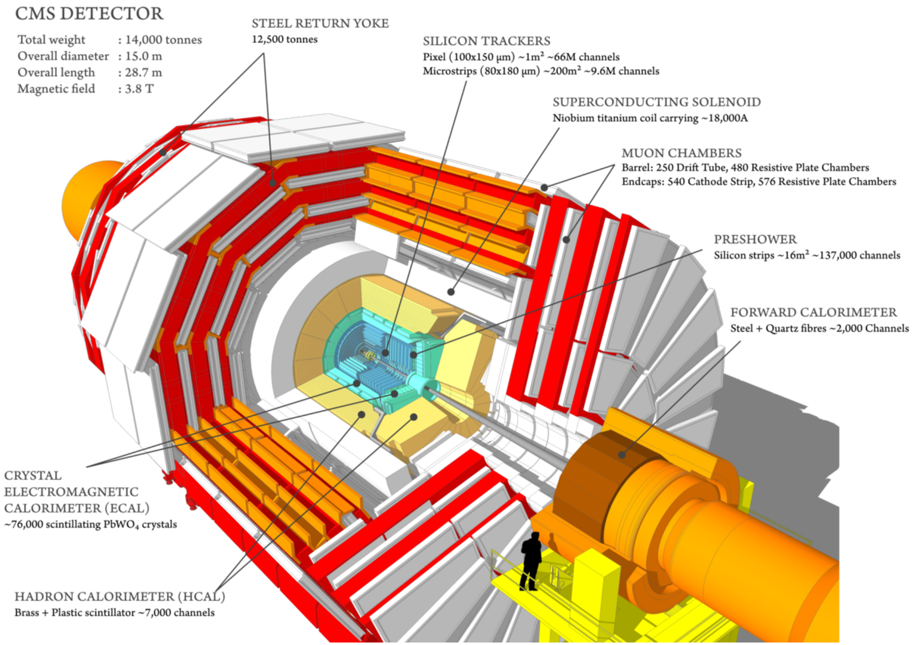




Additional material

ATLAS Detector

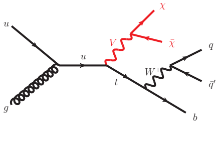
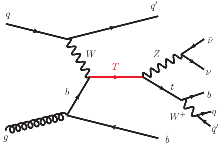


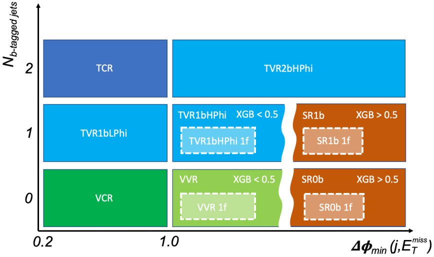

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

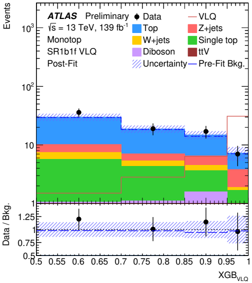
Mono-top + invisible

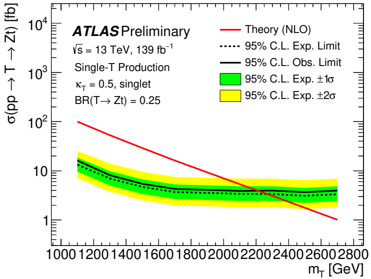
ATLAS-CONF-2022-036

- Target top-associated DM or VLQ (T)
- DNN top and b-tagging
- Top-tagged jet + lepton veto + high E_T^{miss} selection
  - categorise in Nb and min($\Delta\phi$(jet,E_T^{miss}))
- Extreme gradient BDT for sig/bkg discrimination
  - 3 versions: VLQ, resonant, and non-resonant DM
- Apply likelihood fit on yields and score
  - interpret ifo. resonanant / non-resonant DM production
  - in association with single *t* or single vector-like *T*



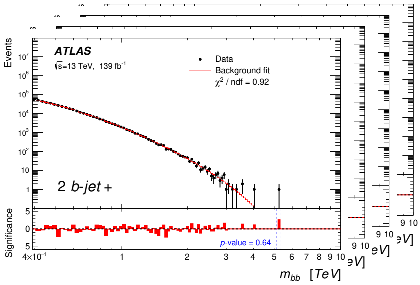




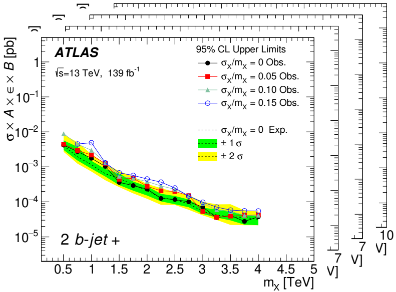
3/4 body masses in lepton+jets

- Heavy resonance search
- 2 jets (incl. b-jets), =1 lepton (e/μ) selection
- Fit 3/4-body invariant mass spectra w/ multiple interpretations
  - model-independent limits on generic resonances
    - assuming gaussian resonance peaks
  - dedicated interpretations
    - SSM W′->WZ′ with small ΔM(W′,Z′); excluded < 2.5 GeV
    - DM SM axial-vector Z′ + SM W
    - W_{KK} with phi radion → gg; excluded mphi < 1 TeV
    - composite lepton with Z′; excluded (500 GeV ℓ, <1.3 TeV Z′)

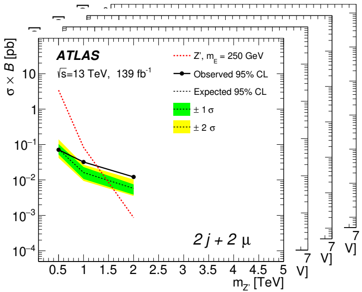
Invariant mass distributions



Model-independent results



Model-specific results



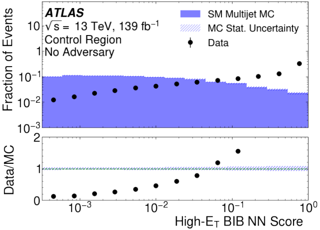
Displaced "hadronic" jets

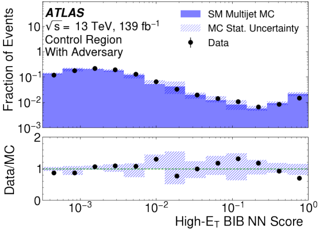
JHEP 06 (2022) 005, arXiv:2203.01009
ATLAS-CONF-2022-038

- Targetting benchmarks in hidden sector models

CalRatio

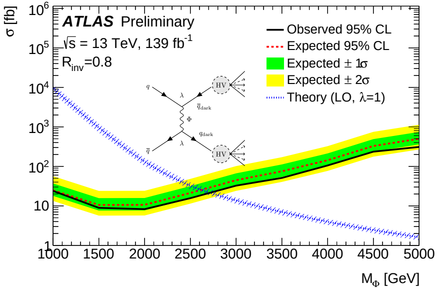
- low/high $\not\!E_T$ CalRatio selection
  - isolated calorimeter activity
  - dedicated CalRatio trigger (ratio had/EM deposits)
- Dedicated NN solutions for BIB/QCD background
  - Adversary Network to avoid using info not well-modelled in simulation
  - per-event BDT for beam-induced-background discrimination
- Limits set for
  - mediator masses 60 GeV–1 TeV, improved both above/below 200 GeV
  - LLP scalar masses 5–475 GeV





Semi-visible jets

- Semi-visible jets from partial decays back to SM particles
- Select on
  - back-to-back jet balance
  - $\not\!E_T$ aligned with high-p_T jet
- Limits set for mediator masses 1–5 TeV
  - exclusion in 2.4–2.7 TeV window
  - additional interpretation ifo. coupling strength

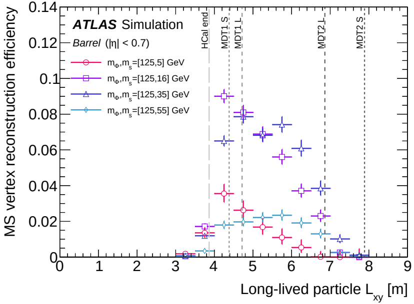


Decays in the muon system

Phys. Rev. D 106(2022)032005, arXiv:2203.00587
arXiv:2206.12181

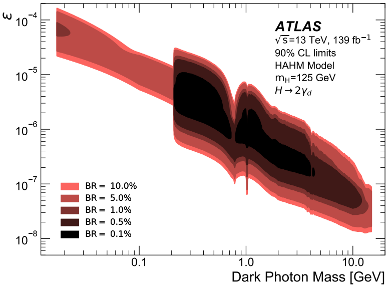
DV from neutral LLPs

- Decays to hadronic jets in the muon spectrometer
  - two displaced decays in the muon system
  - veto on ID/calo activity
  - dedicated trigger
- Interpretation for scalar portal model
  - (scalar) $\Phi(125) \to ss$ (long-lived)
  - limits set ifo. lifetime and BF($\Phi \to ss$)

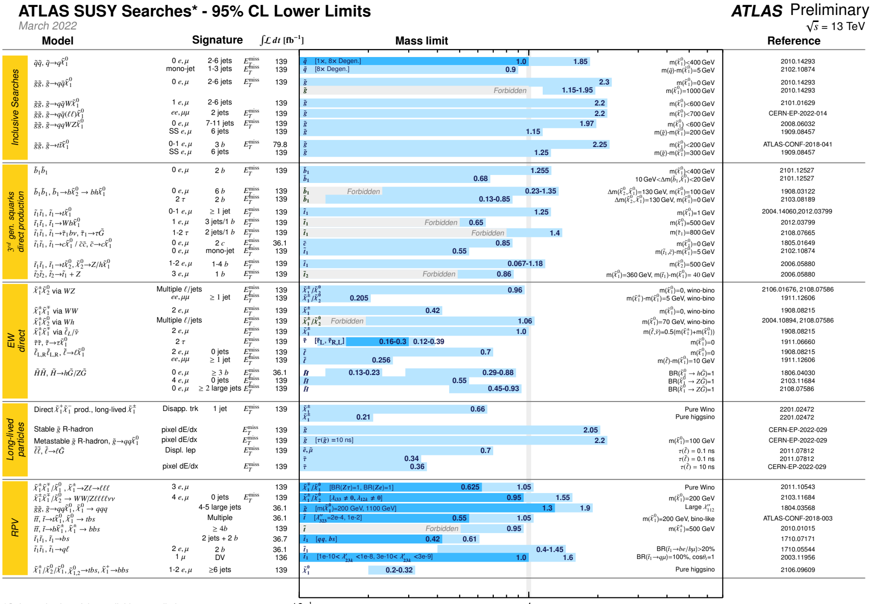


Collimated pairs of leptons/light hadrons

- Displaced collimated SM fermions in calo/MS
  - two displaced decays in the muon system
  - veto on ID activity
- Interpretation for LL dark photons
  - limits set ifo. mass and lifetime, and kinetic mixing parameter SM−hidden sector



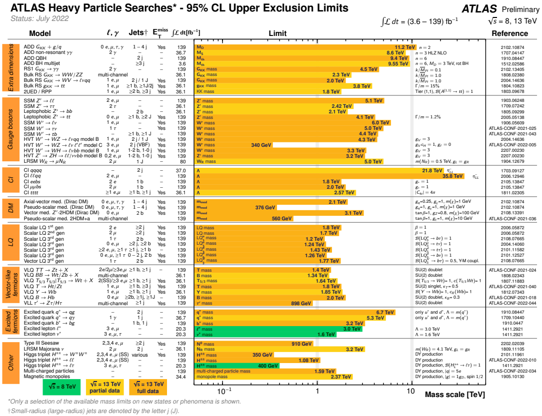
Summary Plots

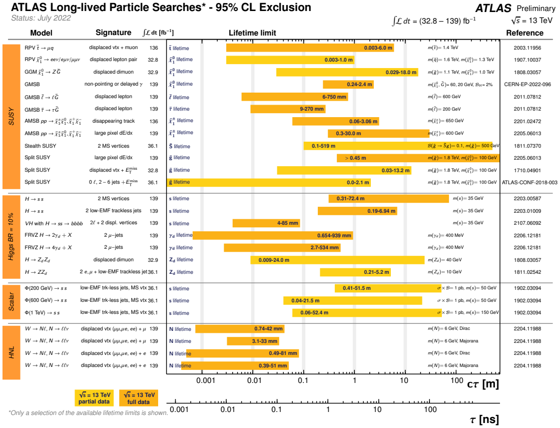


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Summary Plots

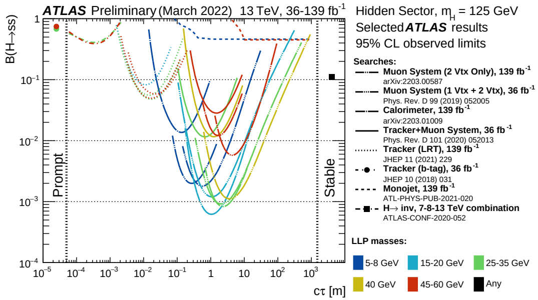
ATL-PHYS-PUB-2022-034

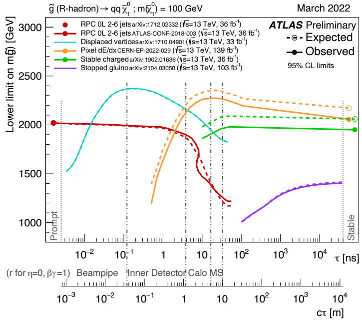


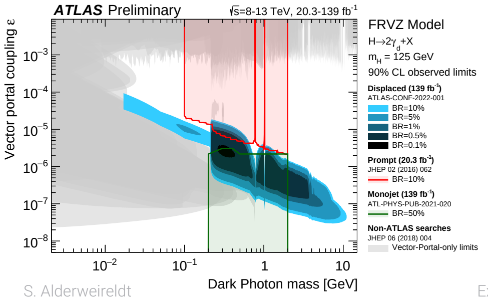


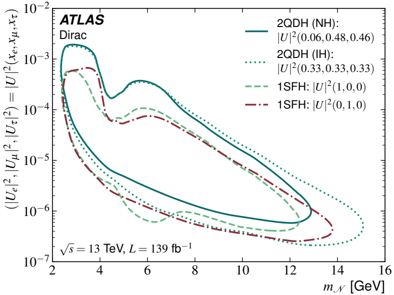
Summary Plots

ATL-PHYS-PUB-2022-007 (LLP)
ATL-PHYS-PUB-2022-013 (SUSY)
arXiv:2204.11988 (HNL)



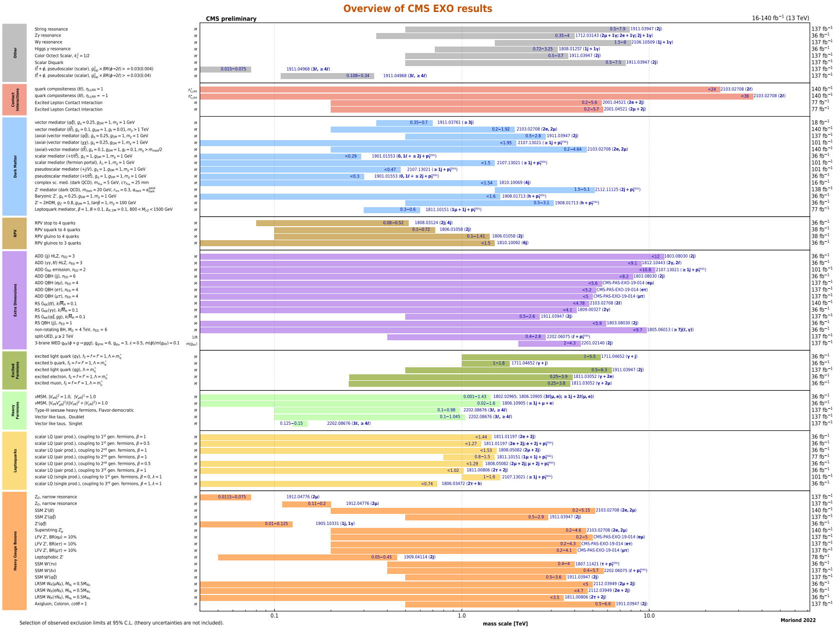






Summary Plots

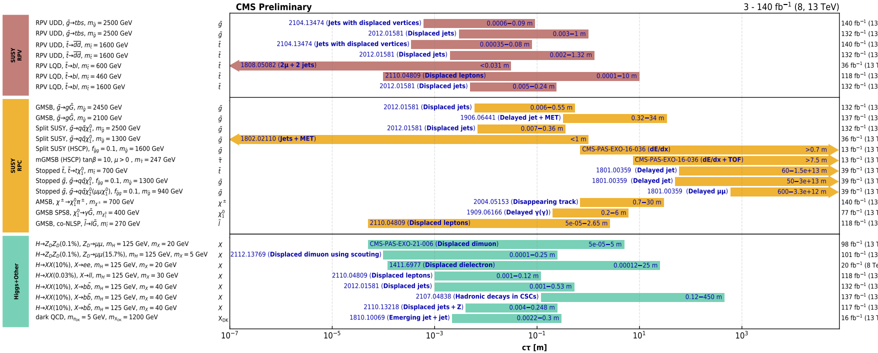
CMS EXO Summary plots



Summary Plots

CMS EXO Summary plots

Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.