Highlights of BSM searches in ATLAS & CMS (including EFT interpretations & Dark Matter results)

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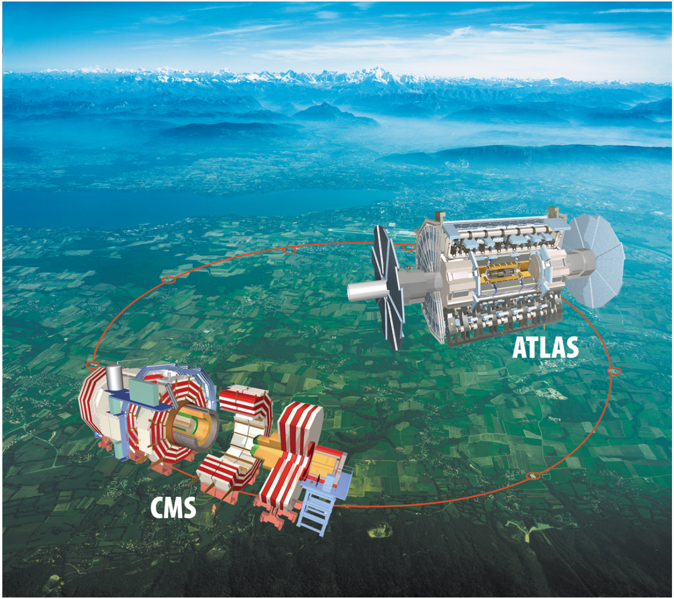
On Behalf of The ATLAS & CMS Experiments

Physics of the Two Infinities
Kyoto 2023

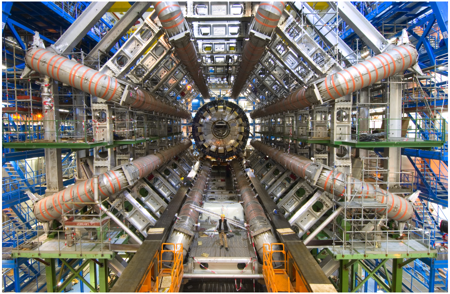
March 30th, 2023

Introduction - ATLAS & CMS



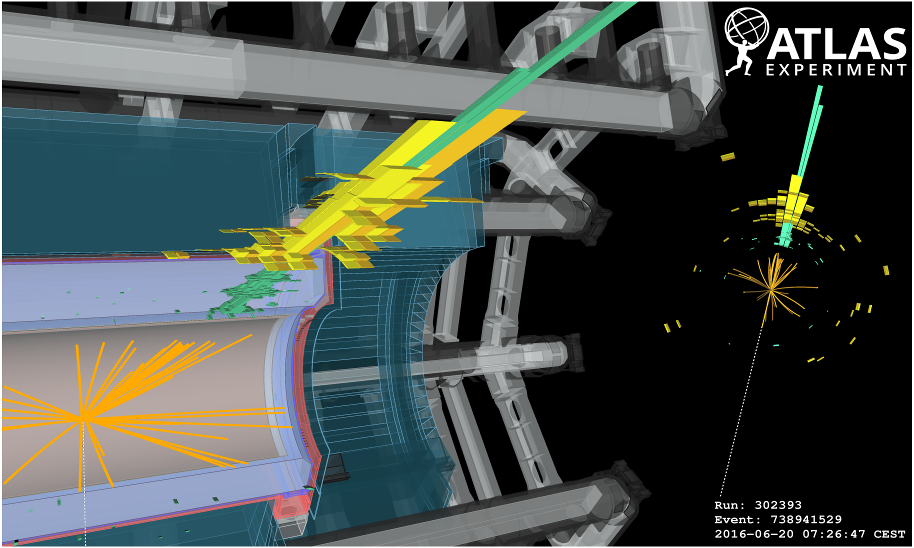
Introduction - ATLAS & CMS

ATLAS & CMS two large general purpose detectors on the 27 km Large Hadron Collider (LHC) ring, situated around two seperate proton-proton collision points.



- General Purpose - Can measure large range of phenomena.
- Similar but different design - allows essential independent replication of results.
- Both forward-backwards symmetrical cylindrical design around collision point.
- Nearly full coverage in solid angle with exception of particles travelling close to parallel to the beam.
- proton-proton collisions up to 13.6 TeV, highest energy collisions on Earth.

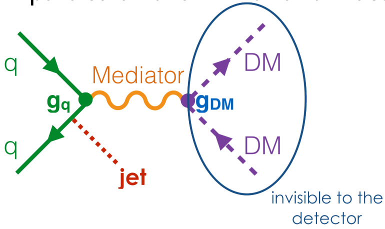
Introduction - Beyond Standard Model (BSM) Strategy

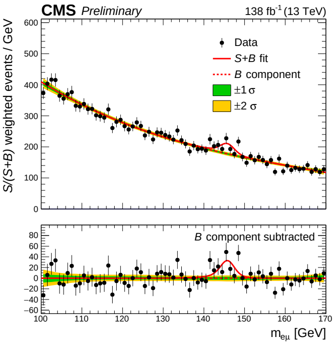


Introduction - Beyond Standard Model (BSM) Strategy

Most analyses assume new particles will not interact with the detector - Require indirect methods to detect, common examples:

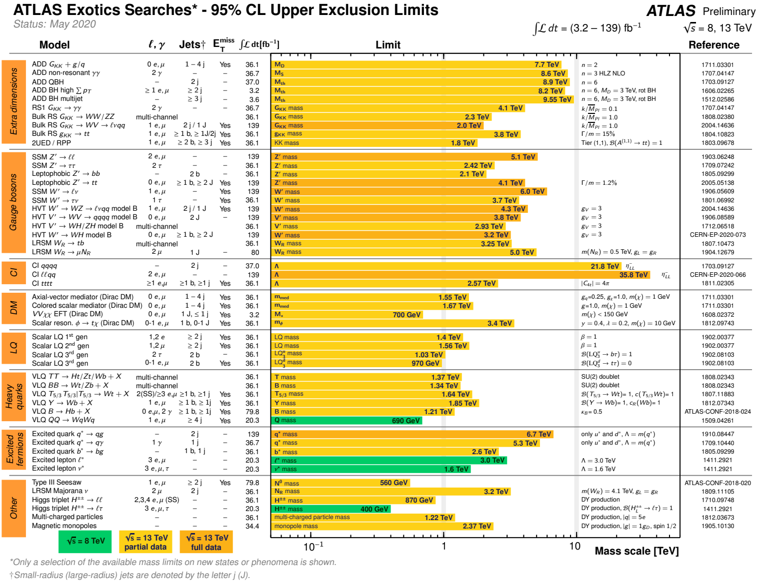
- Measure missing momentum from recoiling SM particles.
- Measure properties of SM particles potentially from a BSM particle decaying, in particular their invariant mass.



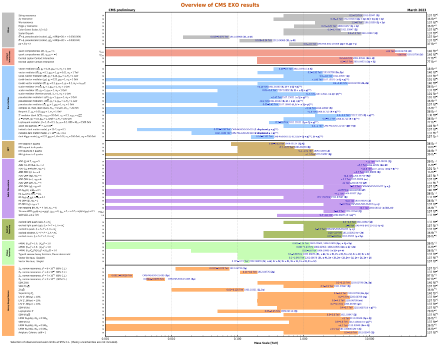


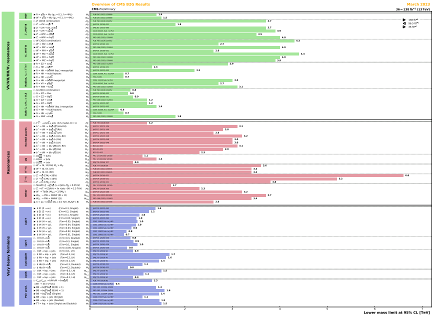
- Comparison of measured data to simulations used to search for & set limits on BSM.
- Following talk exclusively about BSM, important to note a lot of very important SM work done at ATLAS & CMS as well.

Introduction - ATLAS Summary



Introduction - CMS Summary



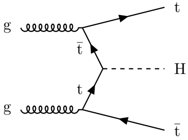


Dark Matter (DM) Searches - Contents

- We do not know the composition of most of the mass in the universe, dark matter.
- Many BSM models attempt to explain dark matter & introduce new interactions between DM & SM, allowing the potential to detect dark matter at colliders.
- Combination with astrophysical, cosmological, lab based & other measurements can help to produce stronger limits & guide each other.

- (Invisible $H \to DM$) + $t\bar{t}$ [arXiv:2211.05426]
- (Invisible $H \to DM$) + $(t\bar{t}/V)$ [arXiv:2303.01214]
- Invisible H Combination [arXiv:2301.10731]
- (Dark $H \to W^+W^-$) + DM [arXiv:2211.07175]
- $(a \to DM) + t + W$ [arXiv:2211.13138]
- (Dark $H \to b\bar{b}$) + DM [ATL-PHYS-PUB-2022-045]
- $(H \to \tau^+\tau^-) + DM$ [ATLAS-CONF-2022-069]
- (Dark $H \to W^+W^-$) + DM [CMS-PAS-EXO-21-012]

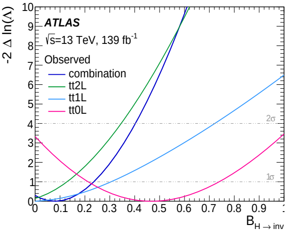
DM - Higgs Decaying to DM [1,2]

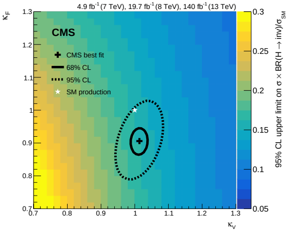


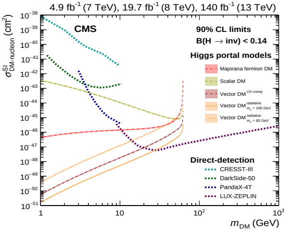
SM $\mathcal{B}_{H\to \mathrm{inv}}$ very small ($H \to ZZ^* \to 4\nu, \mathcal{B}_{H\to \mathrm{inv}} = 0.001$)

- Allows probing of BSM theories that introduce new massive particles that H can decay to.
- Many DM models allow this, in/direct coupling to H
- Many production modes of H, ttH outlined here.

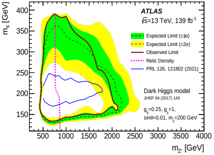
Both (ATLAS/CMS) limits in ttH of $\mathcal{B}_{H\to \mathrm{inv}} < (0.38/0.26)$ consistent with SM to within 2σ, interpreted in terms of limits on DM theories. Still lot of phase space to probe until measurement reaches SM sensitivity!

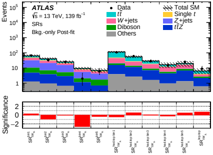


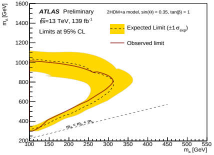


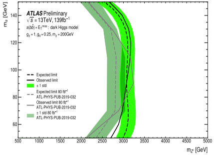


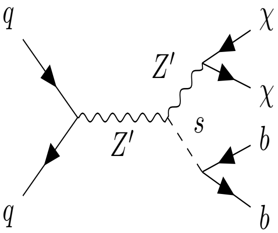
DM - Higgs Associated with DM [1,2,3,4,5]











Many BSM models predict DM can be produced alongside the Higgs or a new dark Higgs

- e.g. BSM particle emits Higgstrahlung then decays to DM.
- Huge number of potential probeable states in SM.
- Lots of opportunities to reinterpet previous analyses with new methods, Active Learning included here.

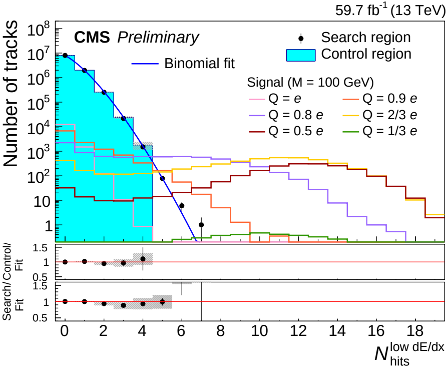
Unique Phase Spaces (UPS) - Contents

- Lots of BSM theories include phase spaces that are very unique compared to the SM.
- Some of these are less well probed than others.
- Important to cover as much phase space as possible to ensure these BSM theories can be detected.

- Fractionally charged particles [CMS-PAS-EXO-19-006]
- Doubly charged H^{++}/H^{--} [arXiv:2211.07505]
- $H \to e\mu$ (charged lepton flavour violation (CLFV)) [CMS-PAS-HIG-22-002]
- Out of time trackless jets (Long Lived Particles [LLPs]) [arXiv:2212.06695]
- Heavy LLPs [ATLAS-CONF-2022-034]
- Displaced $\mu^+\mu^- + DM$ [CMS-PAS-EXO-20-010]
- $\tilde{\mu}\tilde{\mu} \to mm$ displaced $\mu\mu + E_{\mathrm{T}}^{\mathrm{miss}}$ [ATLAS-CONF-2023-018]
- $\gamma\gamma$ Resonance + forward protons [ATLAS-CONF-2023-002]

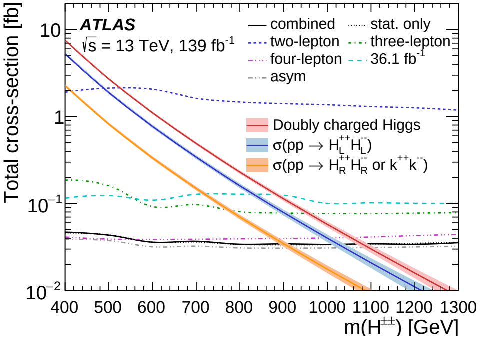
UPS - New Charges [1,2]

All fundamental SM particles charges $\pm\frac{1}{3}e, \pm\frac{2}{3}e, \pm e$. BSM could introduce fundamental particles with different charges.



Doubly charged Higgs.

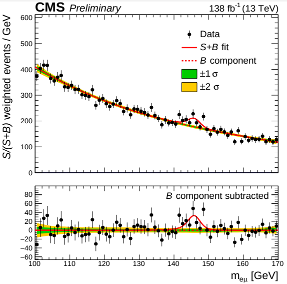
- Decay into same charge pairs.
- *e*/*mu* considered, including LFV.
- Also violates fermion flow.

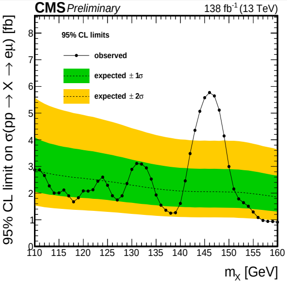


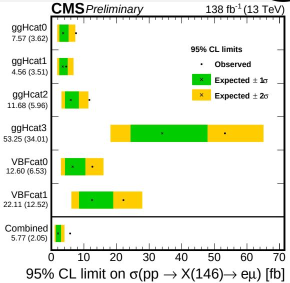
Fractionally charged particles.

- Ionise more weakly than SM, large number of low $\frac{dE}{dX}$ hits.
- Challenging, strong understanding of trigger & reconstruction.

UPS - Charged Lepton Flavour Violation [1]

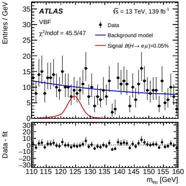






SM conserves charged l number, not fundamental symmetry like charge.

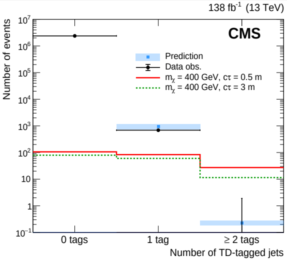
- Violated in neutral leptons (neutrino oscillation).
- Most natural BSM includes CLFV.

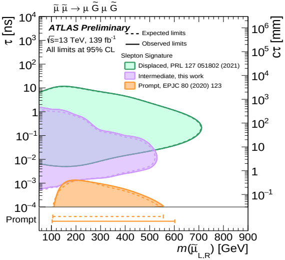


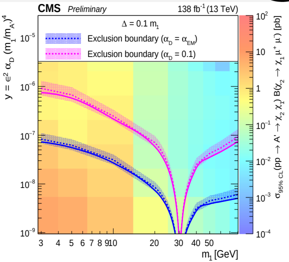
CMS search for new resonance (X) with similar production mode to H that decays $X \to e\mu$ (CLFV)

- $2.8(3.8)\sigma$ global(local) excess at m_X =146 GeV.
- Similar old ATLAS search [PhysLetB.2019.135148] sees no excess in combined, very small excess in VBF channel.

UPS - LLPs [1,2,3,4]



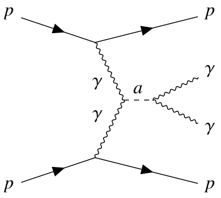




BSM that does not interact with detector may decay to particles that do.

- Traditionally consider BSM decaying instantly.
- BSM may travel measurable distances, substantially changes phase space.
- Lots of LLP phase space to cover, requires dedicated triggers and reconstruction algorithms only recently possible to reliably probe.
- Here two methods to search for LLPs, trackless out of time jets (BSM particle decays beyond tracker at a late time) & displaced muons.

UPS - Forward Protons [1]

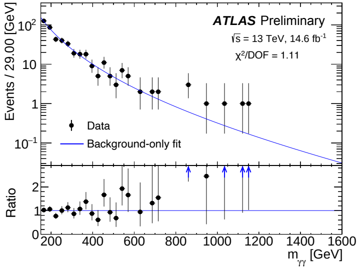


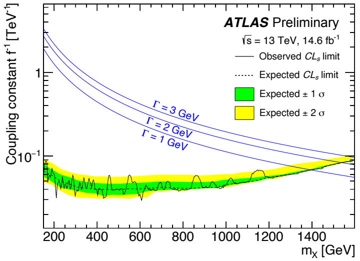
Axion-like particle (a) from collision of $\gamma\gamma$ emitted by p.

- p recoil slightly when emitting γ.
- p travel along beam pipe, missed by ATLAS.
- $m_{\gamma\gamma}$ measured to search for a.

Additional detector, AFP, >200 m away.

- Can detect slightly scattered p.
- Greatly reduces background when combined with ATLAS.
- Consistent with SM, strong limits set, g_a <0.04-0.09 TeV^{-1} assuming 100% decay BR.



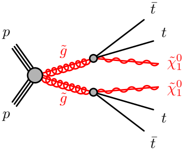


Supersymmetry (SUSY) - Contents

- SUSY often considered a natural symmetry to have.
- Introduces bosonic partner for every fermion, & fermionic partner for every boson.
- Allows very phenomenologically rich models - hence can cause effects in many different phase spaces, allows many analyses.
- Can potentially solve many issues with the SM, in particular the WIMP miracle arose from expectations of $\approx$ TeV scale SUSY, interesting to probe at LHC.

- $(HH/HZ) \to \gamma\gamma b\bar{b}$ [ATLAS-CONF-2023-009]
- $E_{\mathrm{T}}^{\mathrm{miss}} + \geq 3b$ [arXiv:2211.08028]
- Squark/gluino decay chain to multilepton [ATLAS-CONF-2023-017]
- $(e/\mu)+$ multijet [arXiv:2211.08476]
- 2(top squark) $\to$ 2(4-body decay), single lepton [arXiv:2301.08096]

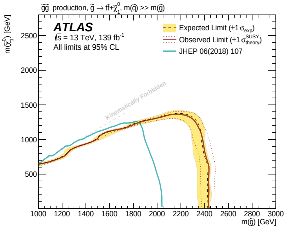
SUSY - Higgsino [1,2]

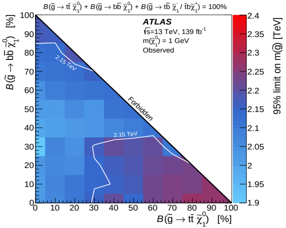


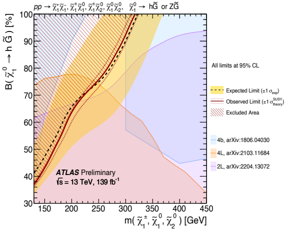
Many models motivated by natural SUSY have the lightest supersymmetric particle (LSP) be a neutralino $\tilde{\chi}_1^0$ that is almost a pure higgsino.

- LSP particularly interesting as a DM candidate.
- If DM is entirely natural LSP, LSP likely on *TeV* scale.
- Production of higgsino usually associated with multijet.

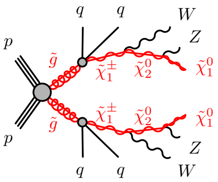
Considered here both the Higgsino being an LSP (does not decay) & Higgsino not LSP & decays to (h/Z)+$\tilde{G}$ (gravitino).







SUSY - Long Decay Chain [1]

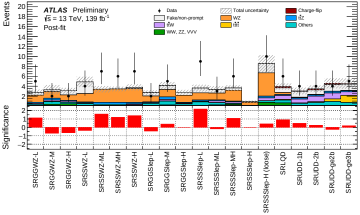


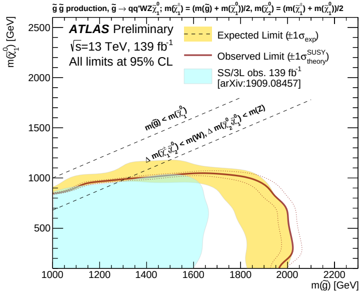
SUSY introduces many new particles.

- Allows long decay chains - complex final states.
- Ideal to be probed by multilepton.

Many Signal Regions (SR)

- Allows probing many SUSY particles at once.
- All SRs consistent with SM to within $\lesssim 2\sigma$.
- Strong limits set on many SUSY particles.



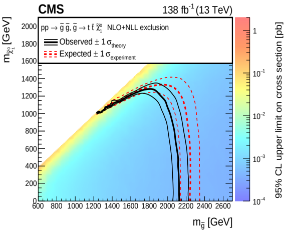


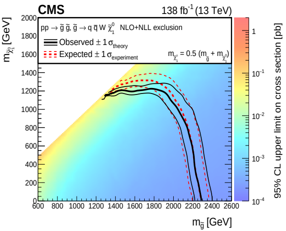
SUSY - lepton + multi heavy objects [1,2]

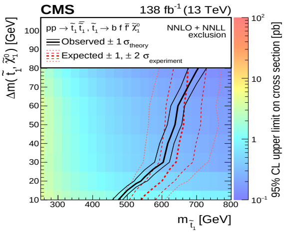
Most models of SUSY having the top squark ($\tilde{t}$) being the lightest squark.

- Cosmological observations imply $\tilde{t}$ has similar mass to the LSP.
- Suppresses two & three body decays.
- Pair produced gluinos also decay to multiple heavy objects.
- Motivates search for final state with many massive objects.
- Large multijet background, reduced by requiring a single lepton.

Consistent with SM, strong limits set on $m_{\tilde{t}}$, $m_{\tilde{g}}$ & $m_{\tilde{\chi}_1^0}$.



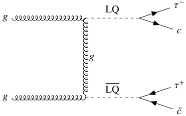




Leptoquarks (LQ) & Vector-like Quarks (VLQ) - Contents

- A simple 4th generation of quarks identical to the known 3 generations of quarks with more mass is excluded. However, a new particle similar to quarks is possible.
- Many BSM theories include leptoquarks (behave like quarks but carry lepton numbers) & vector-like quarks (behave like quarks but non-chiral).
- Leptoquarks & vector-like quarks are able to decay into SM particles allowing detection.

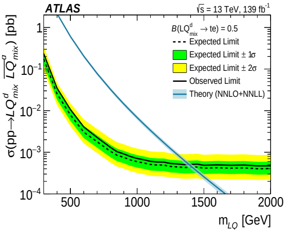
- pair scalar & vector $LQ \to (t/b) + (e/\mu)$ [arXiv:2210.04517]
- pair scalar & vector $LQ \to b + \tau$ [arXiv:2303.01294]
- pair $LQ \to j + \tau$ [arXiv:2303.09444]
- pair VLQ, at least one $VLQ \to (t/b) + (Z \to l^- l^+)$ [arXiv:2210.15413]
- pair VLQ T/B Final state $(e/\mu) + \geq 3j + \geq 1b + E_{\mathrm{T}}^{\mathrm{miss}}$ [arXiv:2212.05263]
- pair VLQ in leptonic final states [CMS-B2G-20-011]
- VLQ $T \to t + (H \to \gamma\gamma)$ [arXiv:2302.12802]
- LQ $\to \tau + b$ [CMS-PAS-EXO-21-009]
- LQ $+ \tau$ [CMS-PAS-EXO-19-016]

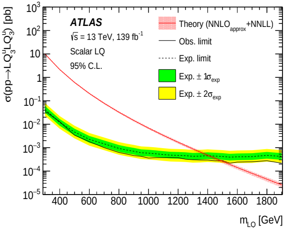


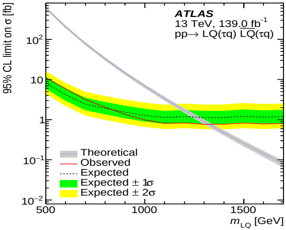
Due to leptoquark's color charge, can be created (among other ways) in pairs through s-channel interaction with g.

- Decay into both quark & lepton.
- Considered here coupling to heavy quarks & all 3 leptons.
- Many LQ models assume only couple to one fermion generation, important to check all as well as mixed generations.

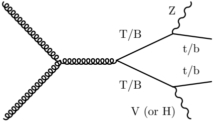
Good agreement with SM, strong limits set.





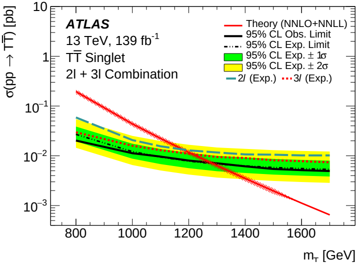


VLQ - Pair Produced VLQ [1,2]



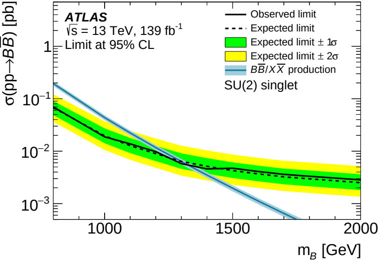
Like quarks, VLQ may be produced in pairs directly from g.

- Decay into $(W/Z/H) + q$
- Often assumed to preferentially couple to 3rd-generation

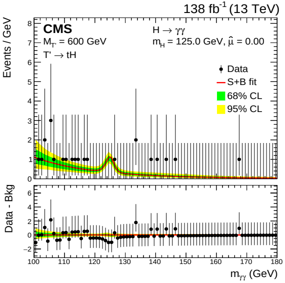


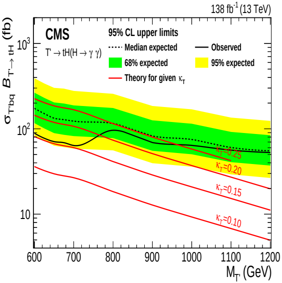
Considered cases: ≥ 1 high energy leptonically decaying $Z + (t/b)$, & high $E_T^{miss} + (e/\mu) + \geq 3j + \geq 1b$

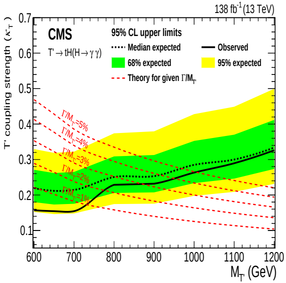
- Complementary, high E_T^{miss} catches cases were energetic Z missed due to neutrino decay.
- b tag greatly reduces background.



VLQ - Singly Produced VLQ [1]

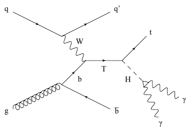






VLQ may be singly produced from $W \to (q + VLQ)$.

- T' then decays to $(W/Z/H) + q$
- Allows a fairly simple clean final state.



Consider here $T' \to tH$ where $H \to \gamma\gamma$

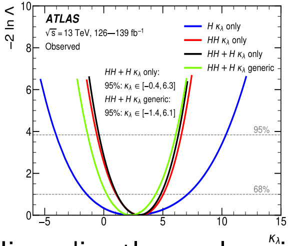
- Diphoton has excellent mass resolution.
- Allows increased sensitivity to search for peak above falling diphoton mass continuum, despite low branching ratio.

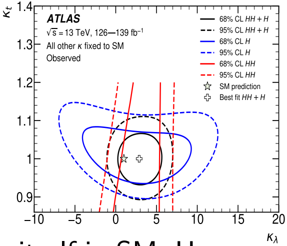
Higgs - Contents

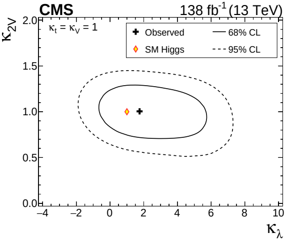
- Scalars sensitive to new particles, particularly through internal loops. Possibility of BSM to modify properties of H (e.g. branching ratios).
- H couples directly with all massive particles in SM (possible exception of neutrinos), possibly similar mechanism allowing coupling to BSM particles.
- Higgs only recently discovered, much to still investigate.
- Hence a Higgs portal to the dark sector often investigated.

- Higgs self coupling combination [arXiv:2211.01216]
- $H \to 4l$, constraining self coupling [CMS-PAS-HIG-21-009]
- Higgs combination [Nature 607, 60–68 (2022)]
- nonresonant pair $H \to bb\bar{b}\bar{b}$ [arXiv:2301.03212]
- nonresonant pair $H \to WW\gamma\gamma$ [CMS-PAS-HIG-21-014]
- HEFT pair $H \to (b\bar{b}) + (\gamma\gamma/\tau\tau)$ [ATL-PHYS-PUB-2022-019]

Higgs - Higgs Self Coupling [1,2, 3]





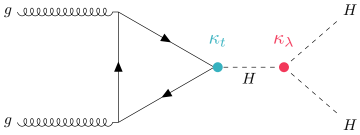


Higgs directly couples with itself in SM. However trilinear coupling small.

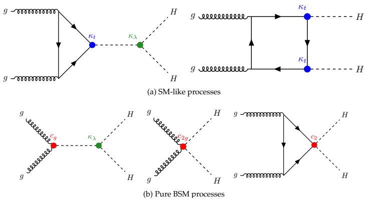
- k_λ a measure of H trilinear coupling deviation from SM, SM $k_\lambda = 1$.
- BSM can modify this coupling through internal loops.
- Important to produce stringent constraints on H self interaction.

Investigated here by searching for double H decays $(4b, 2b2\tau, 2b2\gamma)$ & $4l$.

- Complementary, important to investigate many channels.
- Observed CMS limit $-5.5 < k_\lambda < 15.1$.
- Observed ATLAS limit $-2.2 < k_\lambda < 7.7$.



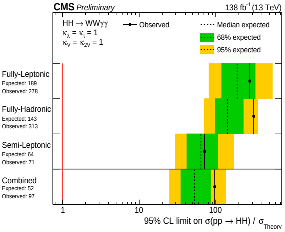
Higgs - Higgs pair production [1,2,3]

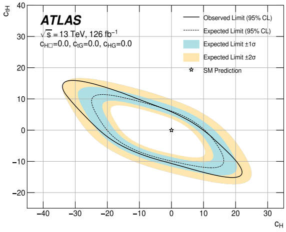


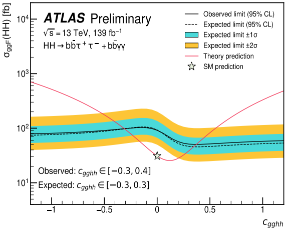
Higgs can be pair produced in SM, both through self coupling & other interactions.

- Can be reinterpreted as an effective field theory (EFT).
- Many Effective Couplings (EC) to probe.
- BSM can cause deviations to any or all of these effective couplings.

Measurements of $4b$,$2W2\gamma$,$2b2\gamma$ & $2b2\tau$ used to measure EC.



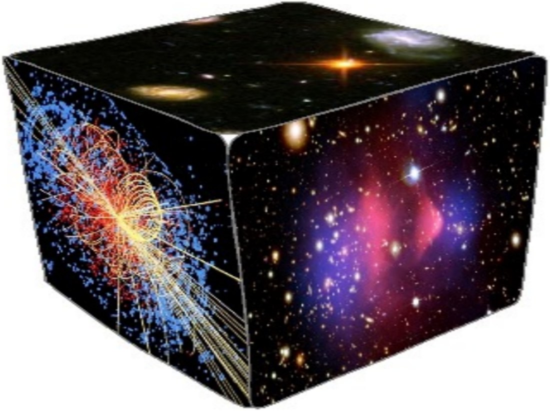




Conclusion

Extremely rich & varied BSM analyses at ATLAS & CMS. Important to fully utilise LHC & cover all phase space possible. Many strong results.

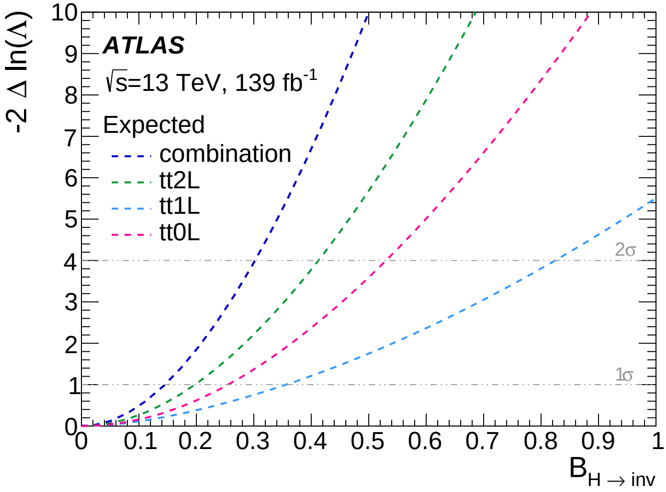
- Limits set on rare invisible decays of H, interpreted in terms of DM.
- Many DM & other BSM models probed via potential interactions with H.
- Lots of Higgs effective couplings measured, interpreted to limit BSM.
- Lots of new unique analyses covering new phase space, for instance LLPs & new charges.
- Very distant detectors (AFP & ATLAS) matching events to produce strong probes of BSM.
- Many final states probed to cover phenomenologically rich SUSY.
- Strong limits set on leptoquarks & vector-like quarks in many analyses.
- Hints of resonance at 146 GeV decaying via charged lepton flavour violation. Important to note more work needs to be done to determine if fluctuation or real, looking forward to Run-3 results to improve this measurement.



Backup Slides

DM - Higgs Decaying to DM

ATLAS, expected



DM - Higgs Decaying to DM

ATLAS

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + $E_{\text{T}}^{\text{miss}}$	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + $E_{\text{T}}^{\text{miss}}$ + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + $E_{\text{T}}^{\text{miss}}$	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + $E_{\text{T}}^{\text{miss}}$	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + $E_{\text{T}}^{\text{miss}}$	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

CMS

Channel	Best fit $\mathcal{B}(\text{H} \to \text{inv})$	$\mathcal{B}(\text{H} \to \text{inv})$
Combined	$0.08^{+0.04}_{-0.04}$	0.15 (0.08 exp)
VBF-tag	$0.09^{+0.05}_{-0.05}$	0.18 (0.10 exp)
VH-tag	$0.04^{+0.09}_{-0.09}$	0.21 (0.18 exp)
$\text{t}\bar{\text{t}}$H-tag	$-0.08^{+0.16}_{-0.16}$	0.26 (0.30 exp)
ggH-tag	$0.22^{+0.16}_{-0.16}$	0.49 (0.32 exp)

Talk on LLPs - https://cds.cern.ch/record/2852462

Search for W′ bosons decaying to a top and a bottom quark in leptonic final states at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for W′ bosons decaying to a top and a bottom quark in final states including electrons or muons is performed with the CMS detector at the LHC. The analyzed data correspond to an integrated luminosity of 138 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV. In general, good agreement with the Standard Model expectation is observed. The largest observed excess is found for a W′ boson mass hypothesis of 3.8 TeV with a relative decay width of 1%, with a local (global) significance of 2.6 (2.0) standard deviations. Upper limits on the production cross sections of W′ bosons decaying to a top and a bottom quark are set. Left- and right-handed W′ bosons with masses below 3.9 and 4.3 TeV are excluded at 95% confidence level in the approximation that the new particle has negligible decay width. Limits are also set considering decay widths of up to 30% of the W′ boson mass. These are the most stringent limits to date on W′ bosons decaying to a top and a bottom quark.

This document has been revised with respect to the version dated March 23, 2023.