Exotics Searches (Non-SUSY)

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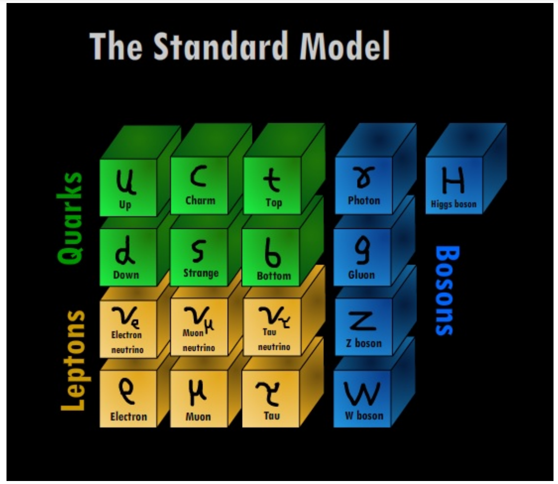
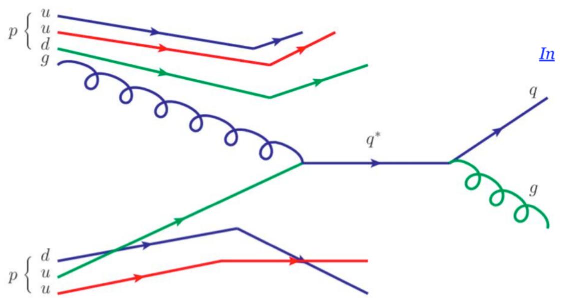
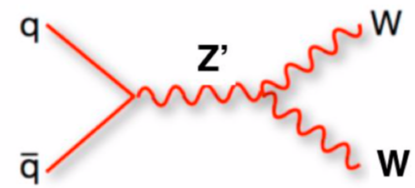
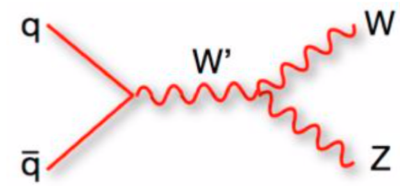
Why Exotics?

- **There remain questions unanswered by the SM**
  - **Why 3 generations of quarks & leptons?**
  - **Hierarchy problem**
  - **Dark matter/energy**
  - **…**
- **Many extensions to SM aim to solve these problems, which generally predict new resonances**
  - **Compositeness, Extra dimensions, SUSY, …**
  - **q*, l*, G*, Z'/W', …**



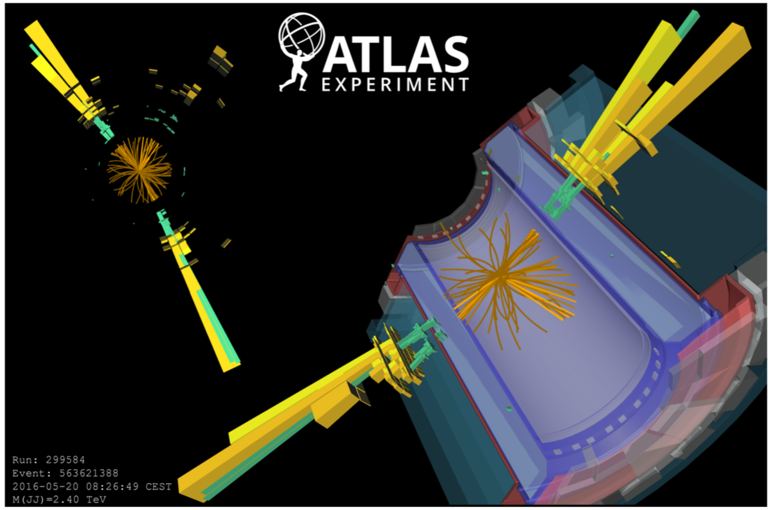




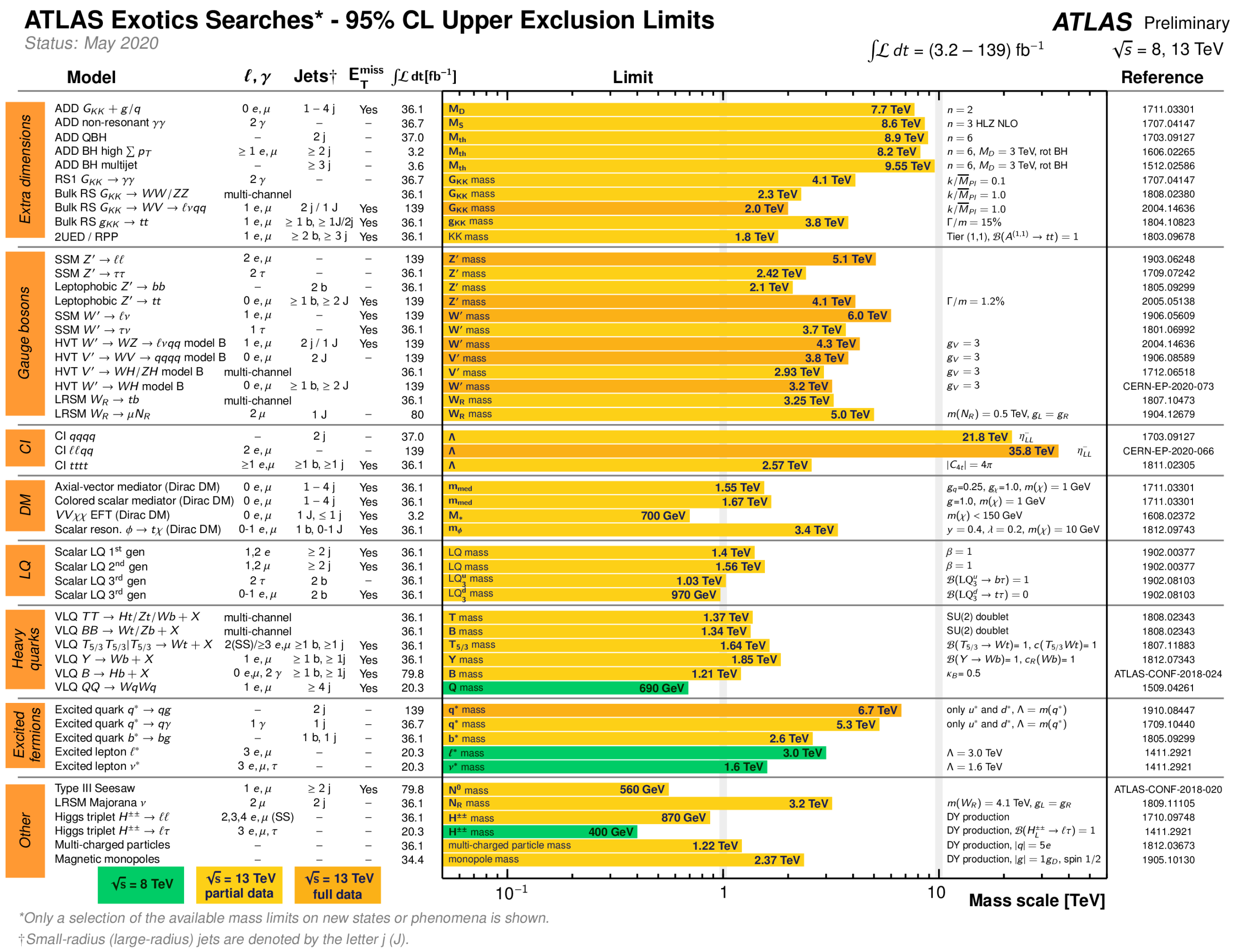


Exotics Search at LHC

- Searches using all possible final states by ATLAS & CMS
  - Mostly hunt high mass bumps
  - Explore unconventional signatures
- Be as model-independent as possible
  - Interpret with benchmark models
- New techniques are explored in different ways
  - Combined performances
  - Machine learning



Exotics Search at LHC



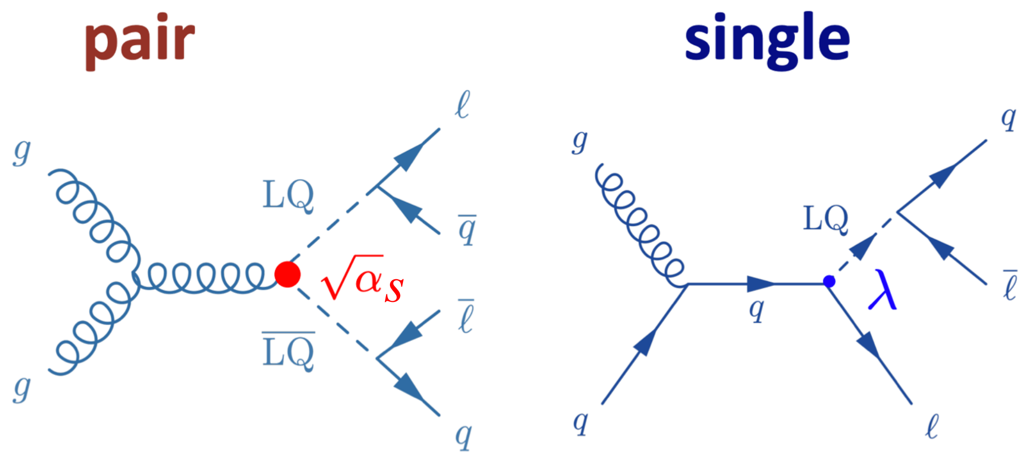
Unable to cover all the analyses. Only show the latest results

Keep balance between different topics and final states

Only a quick glance of Dark Matter results, more of which can be found in the dedicated DM plenary talk and parallel talks

Leptoquarks (LQ)

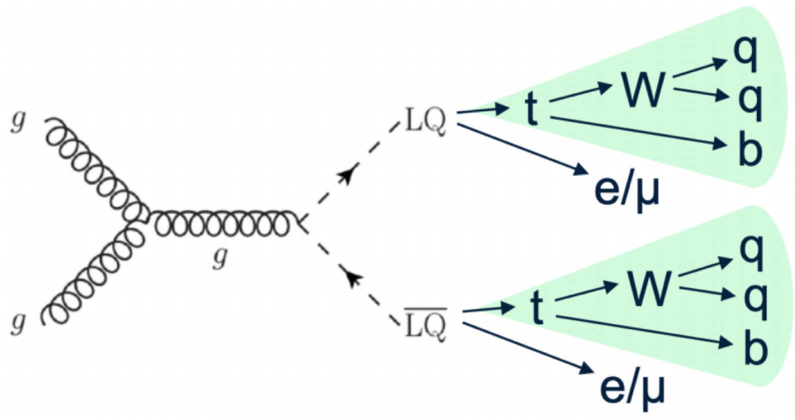
- Hypothesized in many BSM models(GUTS, RPV, SUSY, …)
- Carry both lepton and baryon numbers; Couple to lepton and quark at the same interaction vertex
- Raise interests due to B anomalies observed in various experiments
  - LQ possibly contribute to LFU anomalies at tree level



Leptoquark: tl tl

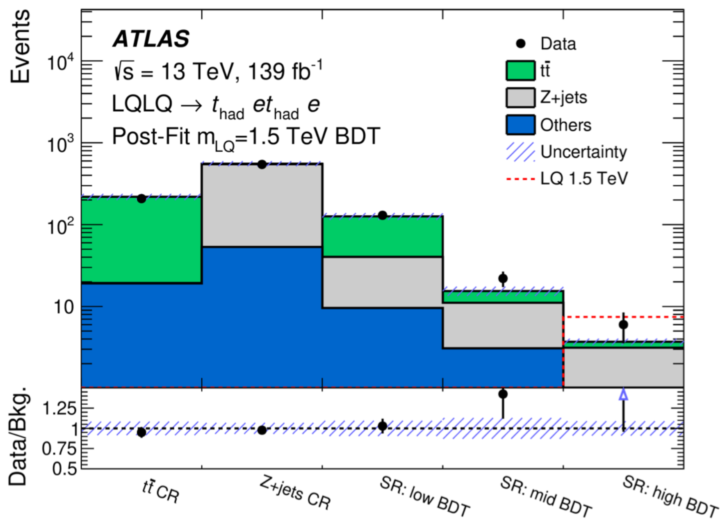
arxiv.org/abs/2010.02098

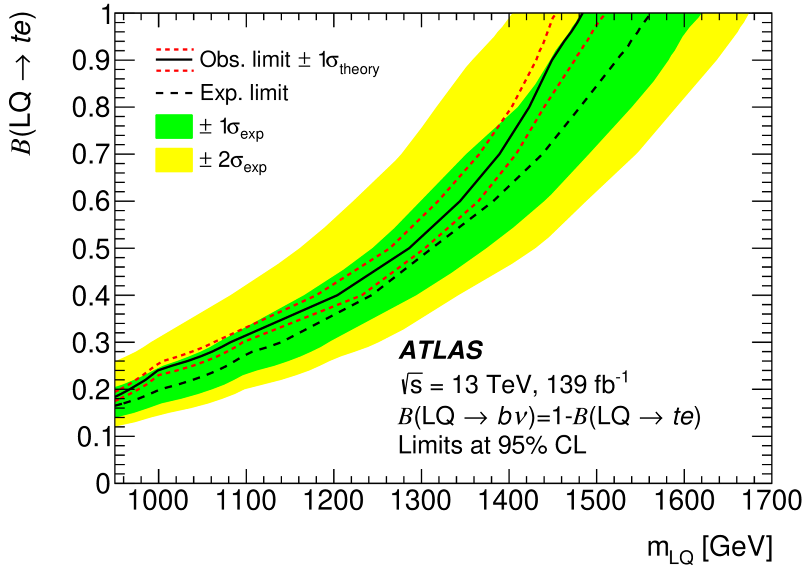
- **Investigate cross-generational couplings**
  - **Signature: te te or tμ tμ**
  - **Large jet used for top quark decay (m_{LQ} > 1TeV)**



- **BDT is exploited for LQ signal, tt, Z+jets**
  - **Use kinematic and jet substructure variables**

- **Limits on m_{LQ}: 1.48(1.47) TeV for e(μ) channel**

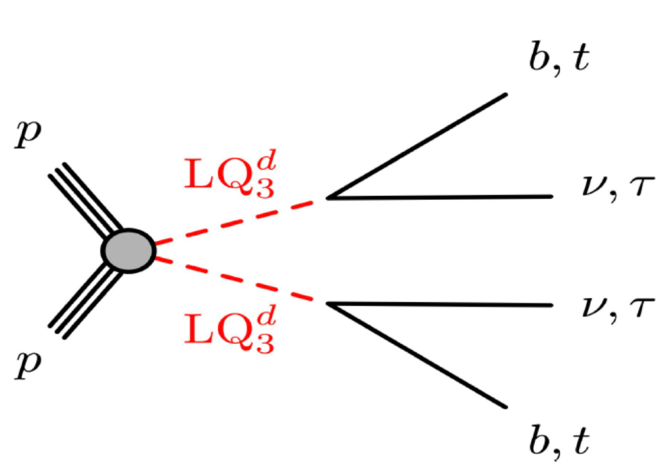


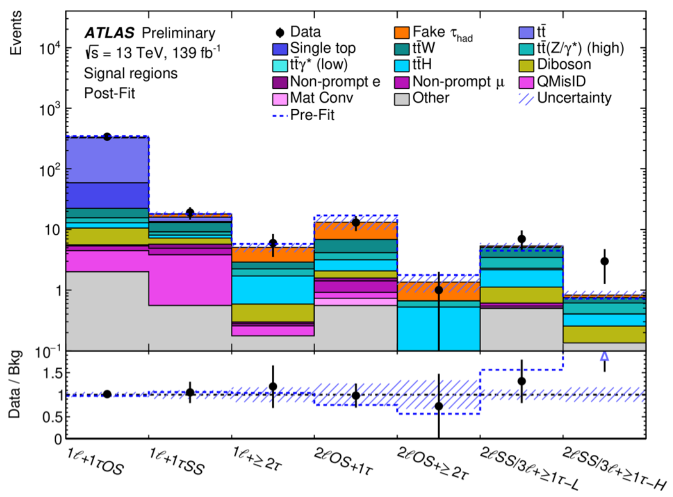


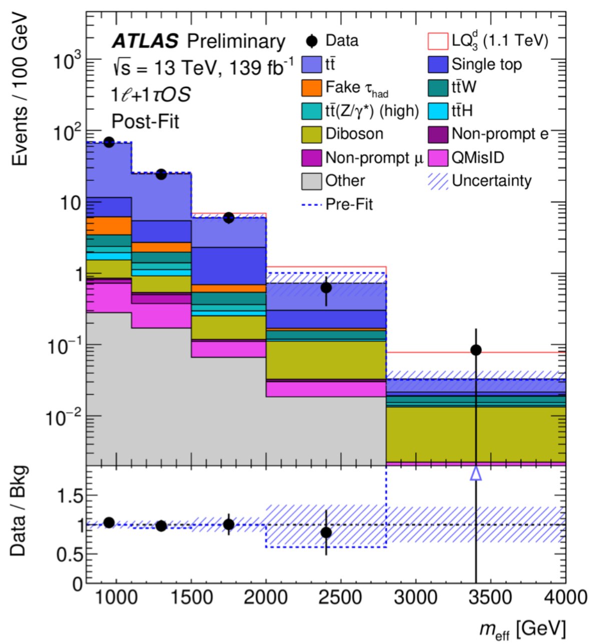
Leptoquark: tτ tτ

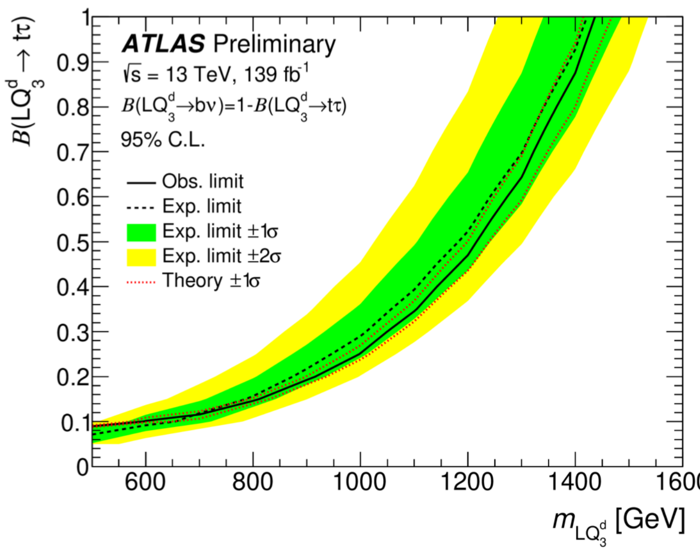
ATLAS-CONF-2020-029

- Assumption of no cross-generational couplings
- 1e/μ+ ≥ 1 τ_{had}, or ≥ two l's(e/μ)
- Various signal regions are defined based on multiplicity and flavor of leptons
- Completely limited by statistics.
  - Main sensitivity is from $1l + 1\ \tau_{had}$ channel
- Limits on m_{LQ}: 1.43 TeV for exclusive tτ decay



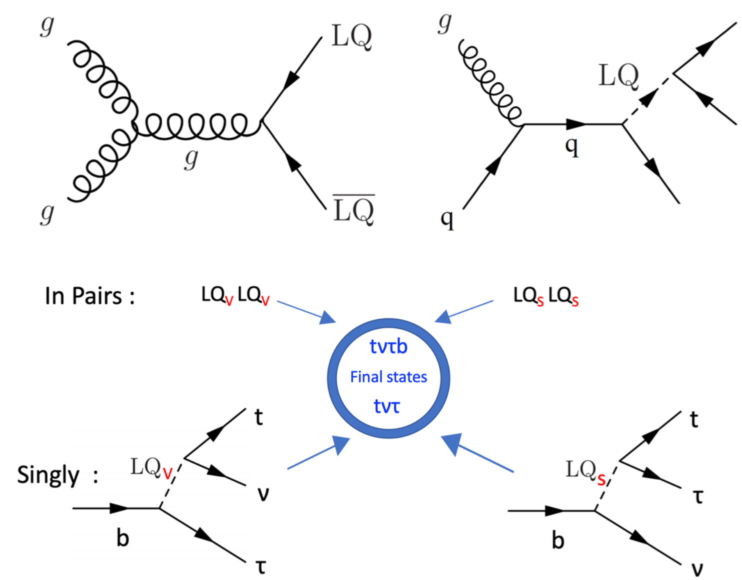


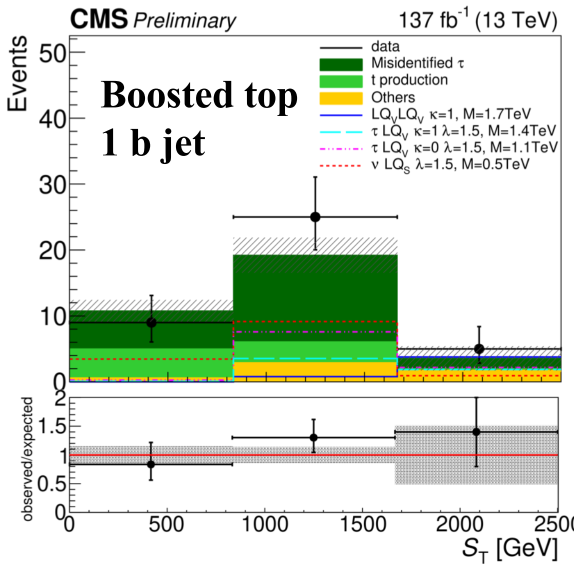


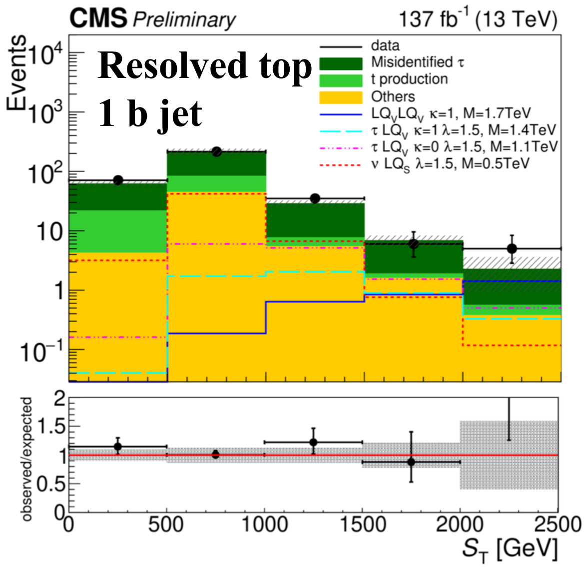


Leptoquark: singly and pairly produced

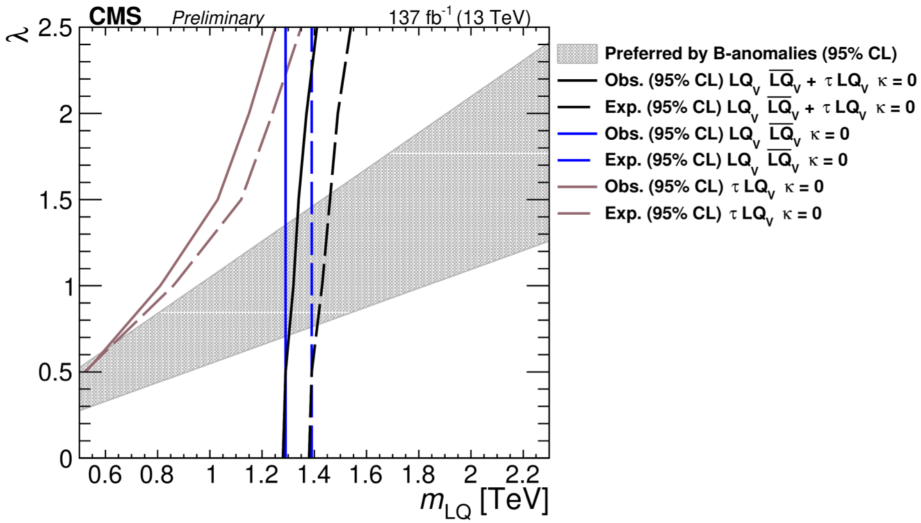
CMS-PAS-EXO-19-015





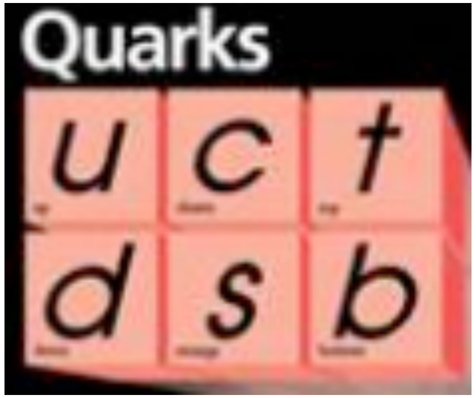


- **LQ LQ-> tτbν; LQ-> tτν**
- **Both t and τ decay hadronically, high MET**
  - **Boosted top case, previously not examined**
- **The range of lower limits on the LQ mass depends on λ (LQ-lepton-quark coupling) and the leptoquark spin**
  - **Most stringent to date**
  - **Also probe the parameter space preferred by the B anomalies**

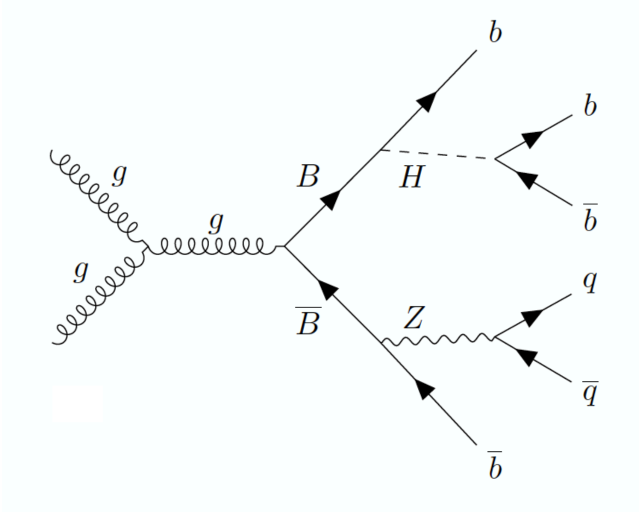


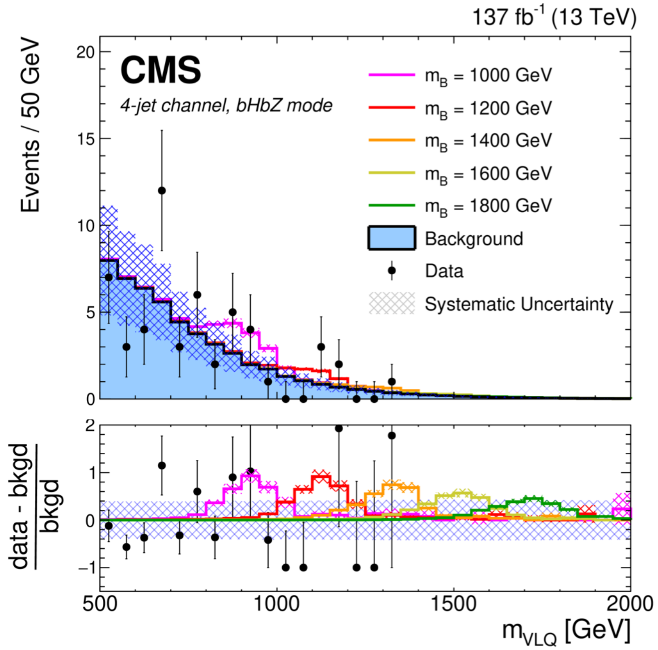
Vector-like Quarks

arxiv.org/abs/2008.09835



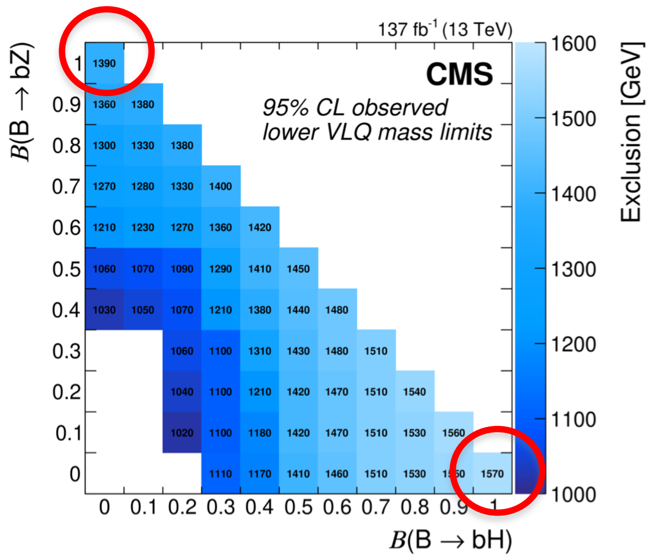
?
T
B





- **Predicted by Composite Higgs and Little Higgs models to address hierarchy problem**
- **B->bH or bZ: Fully hadronic final states**
  - **Boosted H or Z are considered; events categorized by jet multiplicity: 4, 5, 6**
- **Challenge: jet combinations to reconstruct B quark**

Lower mass limits: 1.57 TeV for pure bH decay; 1.39 TeV for pure bZ decay

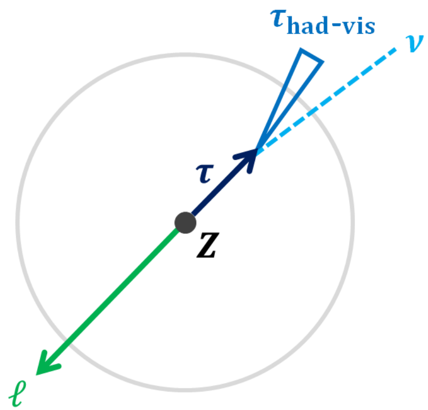


LFV Z->eτ or μτ

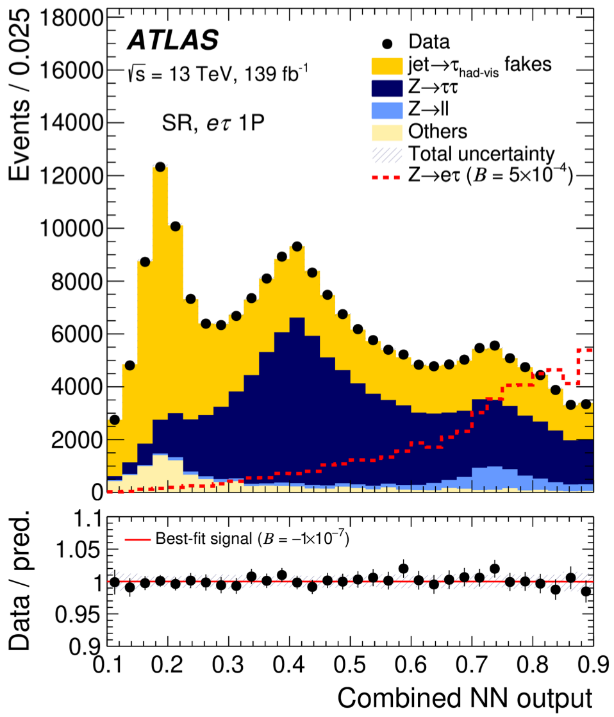
arxiv.org/abs/2010.02566

- Neutrino oscillation indicates LFV, motivating search for LFV in charged lepton interactions
- Search for Z -> hadronic τ + light lepton(e/μ)
  - Main bkgds: Z-> ττ, Z->ll, τ faked by jet
- NN used for better discrimination against bkgd
  - Fit NN in SR and CR to extract signal and constrain uncertainties

❑Supersede the best limits set by LEP more than two decades ago! Mainly limited by statistics



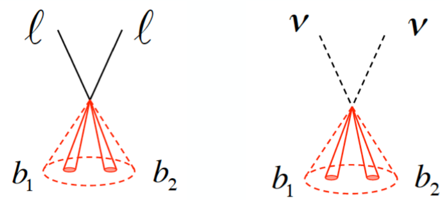
Experiment, polarisation assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
ATLAS Run 2, unpolarised τ	8.1 (8.1)	9.9 (6.3)
ATLAS Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
ATLAS Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
ATLAS Run 1, unpolarised τ [17]		17 (26)
ATLAS Run 1+Run 2 combination, τ		9.5 (6.1)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

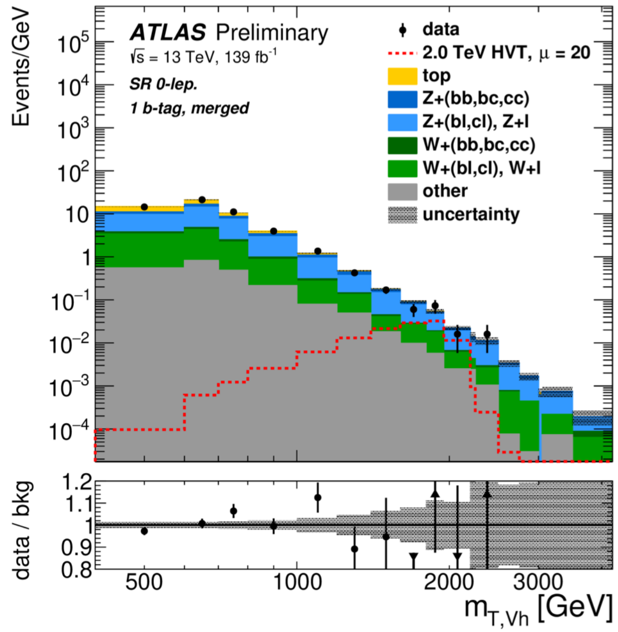


ZH resonance

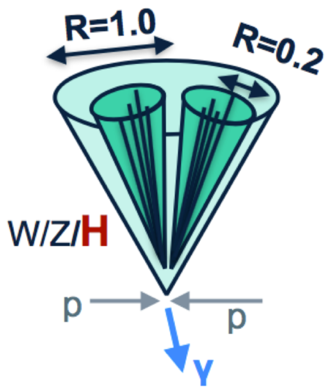
<u>ATLAS-CONF-2020-043</u>

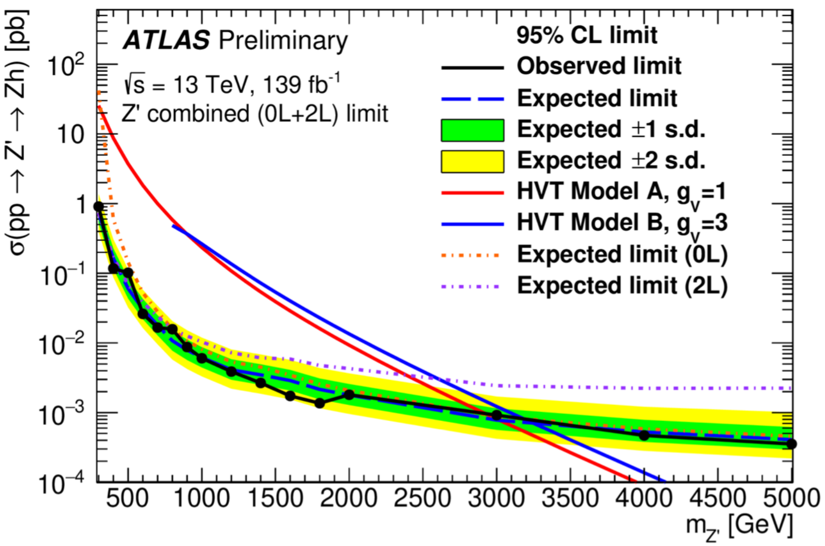
- ZH -> ll bb or ννbb
  - H->bb: resolved or merged

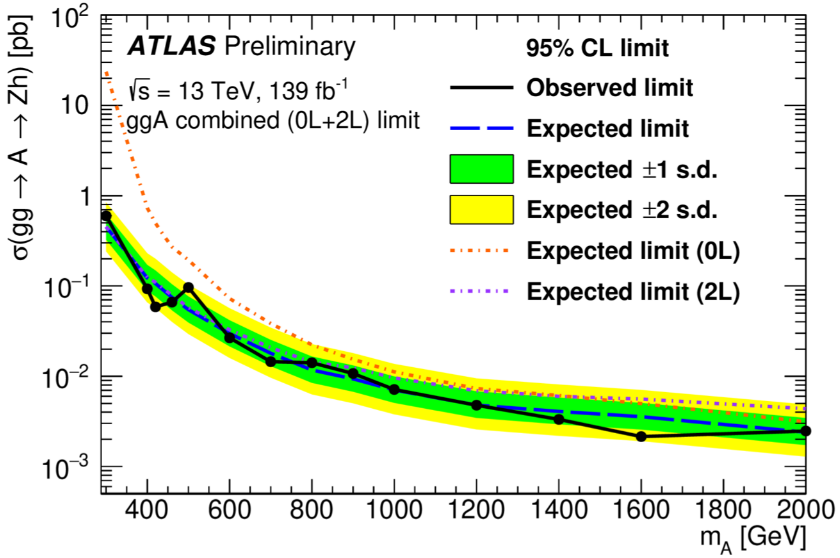




- m_T/m is used for 0-lepton/2-lepton respectively
- Many technique improvements besides more data
  - btag, l selection, jet, selection optimization, …
- Interpret for HVT Z' and CP-odd scalar A
  - Limit improves by 50% at 300 GeV and 500% at 5 TeV, compared to previous partial data result



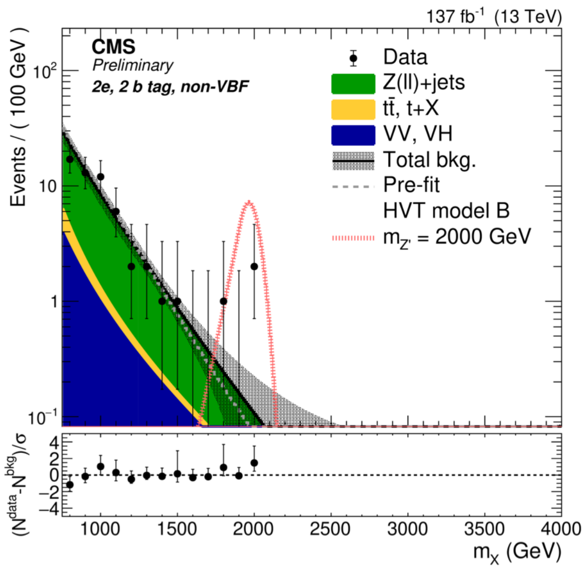


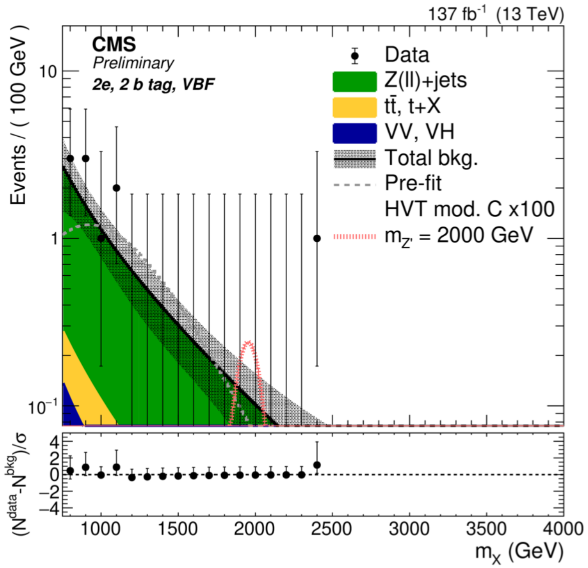


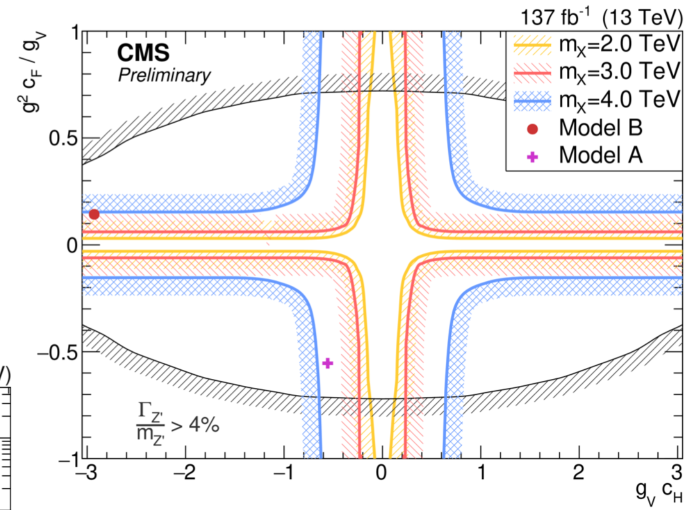
ZH resonance

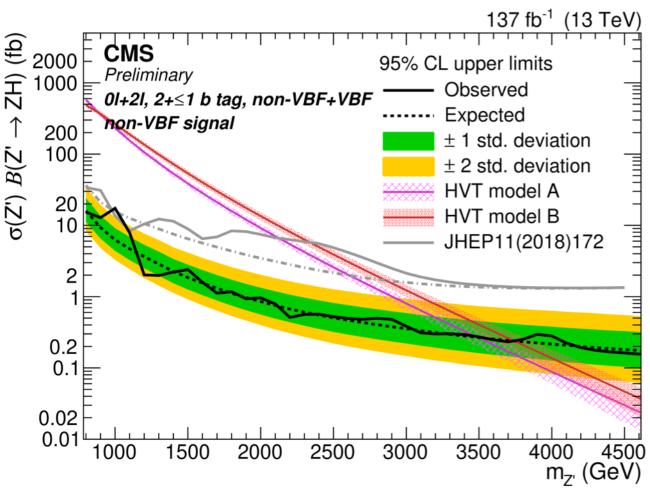
CMS-PAS-B2G-19-006

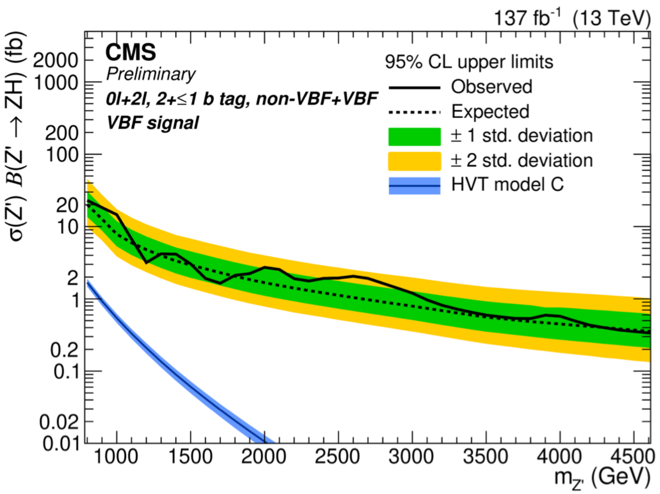
- **Dedicated categories defined to probe VBF production of heavy resonances**
  - **Exploit forward jets with large pT**





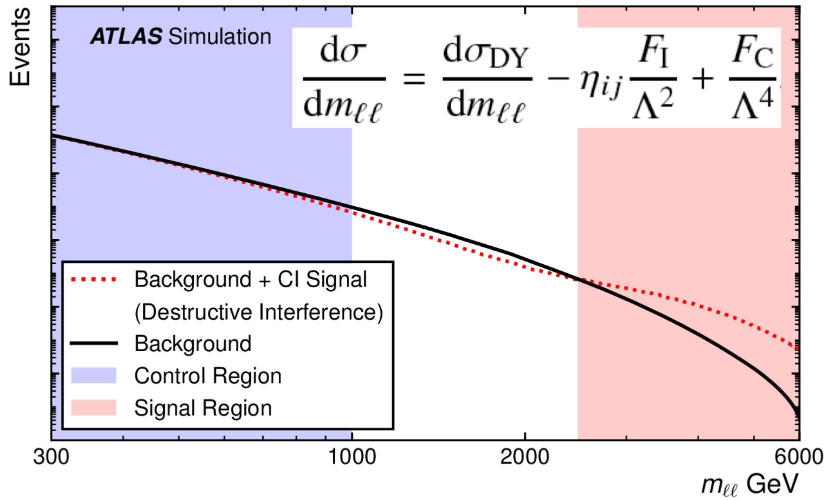




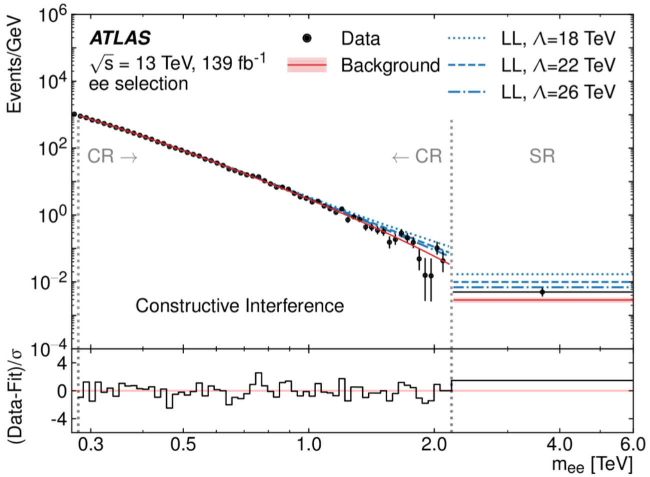


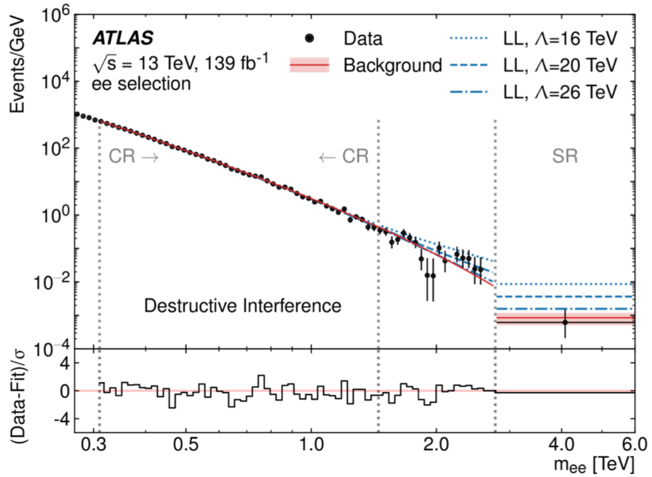
Non-resonant di-lepton (ee/μμ)

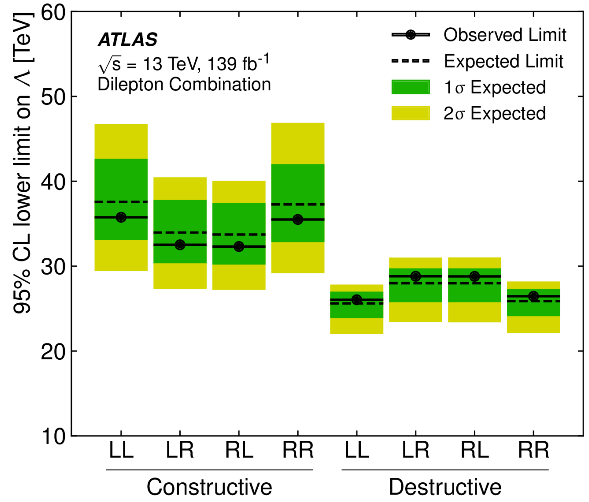
- **Probe two-quark and two-lepton Contact Interaction (CI)**
- **Functional form is fit to data for dilepton invariant mass in CR**
- **Set limits on CI scale Λ for various chiral structures**
  - **Strongest limit is from LL constructive : 35.8 TeV**



arxiv.org/abs/2006.12946

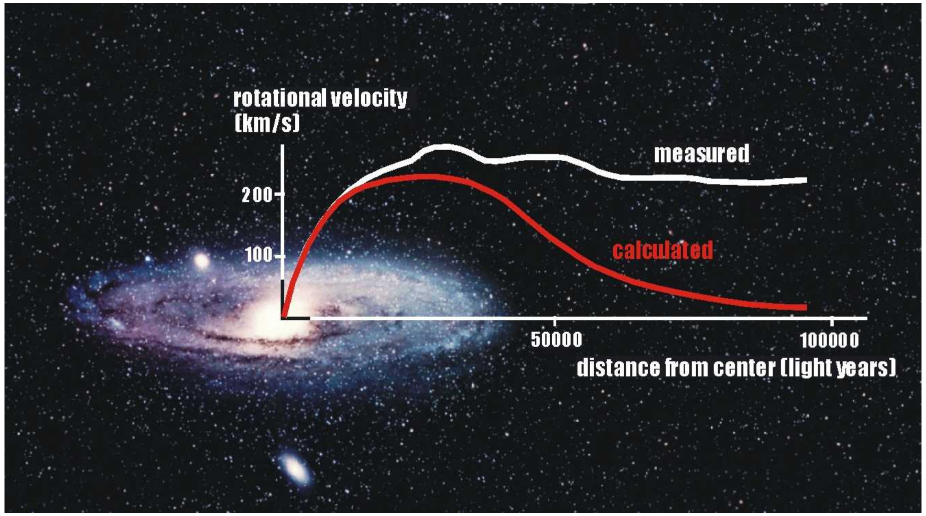




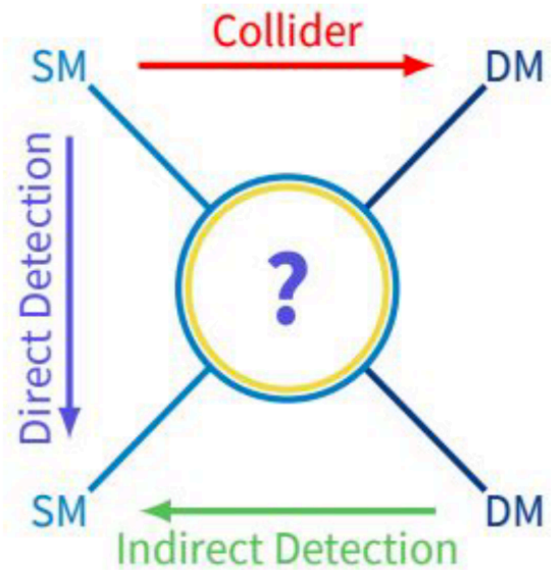


Dark Matter (DM)

- Weakly Interacting Massive Particles (WIMPs) are attractive at colliders
  - Lead to correct relic density of non-relativistic matter
  - Couple to SM particles



- Search DM at colliders
  - Rely on visible particle(s) produced in association with invisible DM

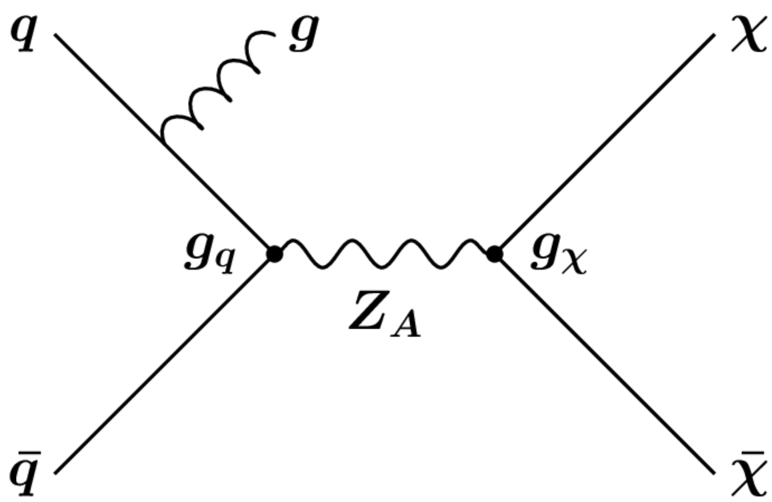


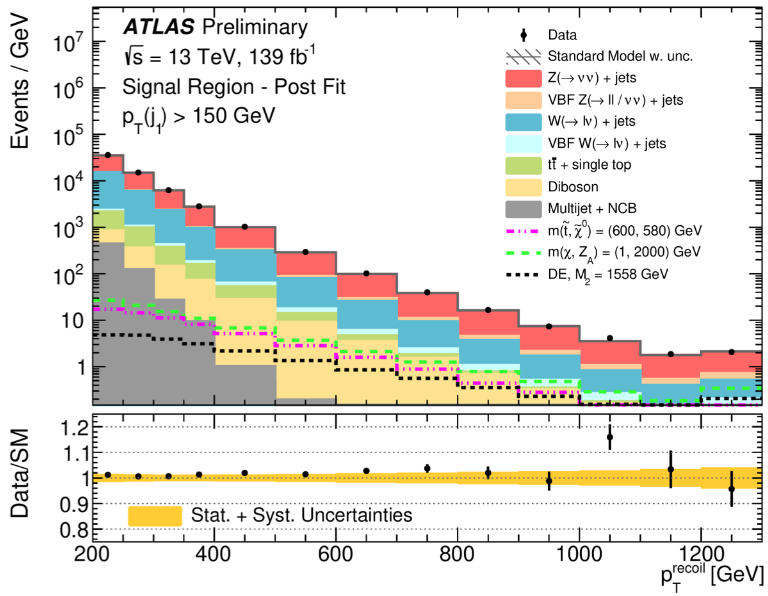
- Simplified Mono-X signatures are largely investigated at the LHC
  - ✓Mono-jet
  - ✓Mono-photon
  - ✓Mono-V
  - ✓Mono-Higgs
  - ✓……

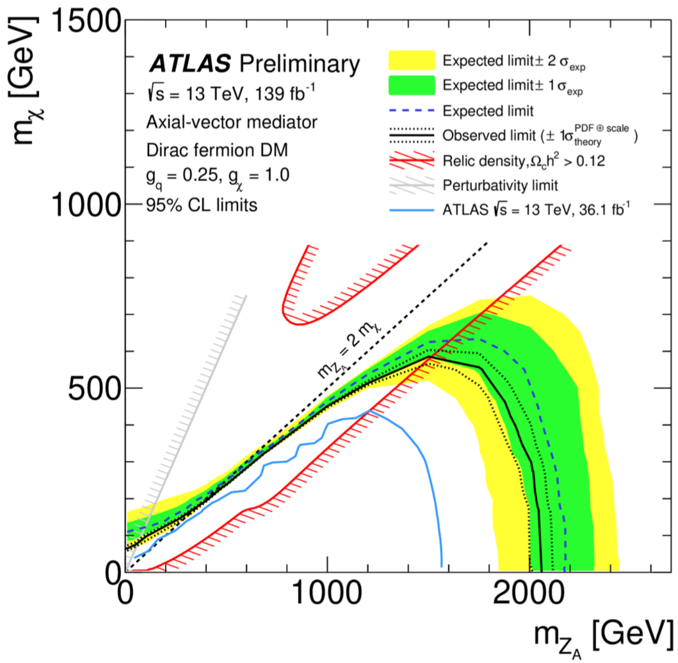
DM: Mono-jet

ATLAS-CONF-2020-048

- Mono-jet is golden channel in search for WIMP at colliders
  - $\geq$ 1 jet, high MET, no reconstructed lepton/γ
- Improved theoretical predictions for W+jets and Z+jets production: V+jets systs down by factor 2
  - NNLO in QCD and NLO in EW
- Various models are used to interpret
  - Axial-vector mediator, SUSY, dark energy inspired model, Extra dimension, Axion-like particles, etc.

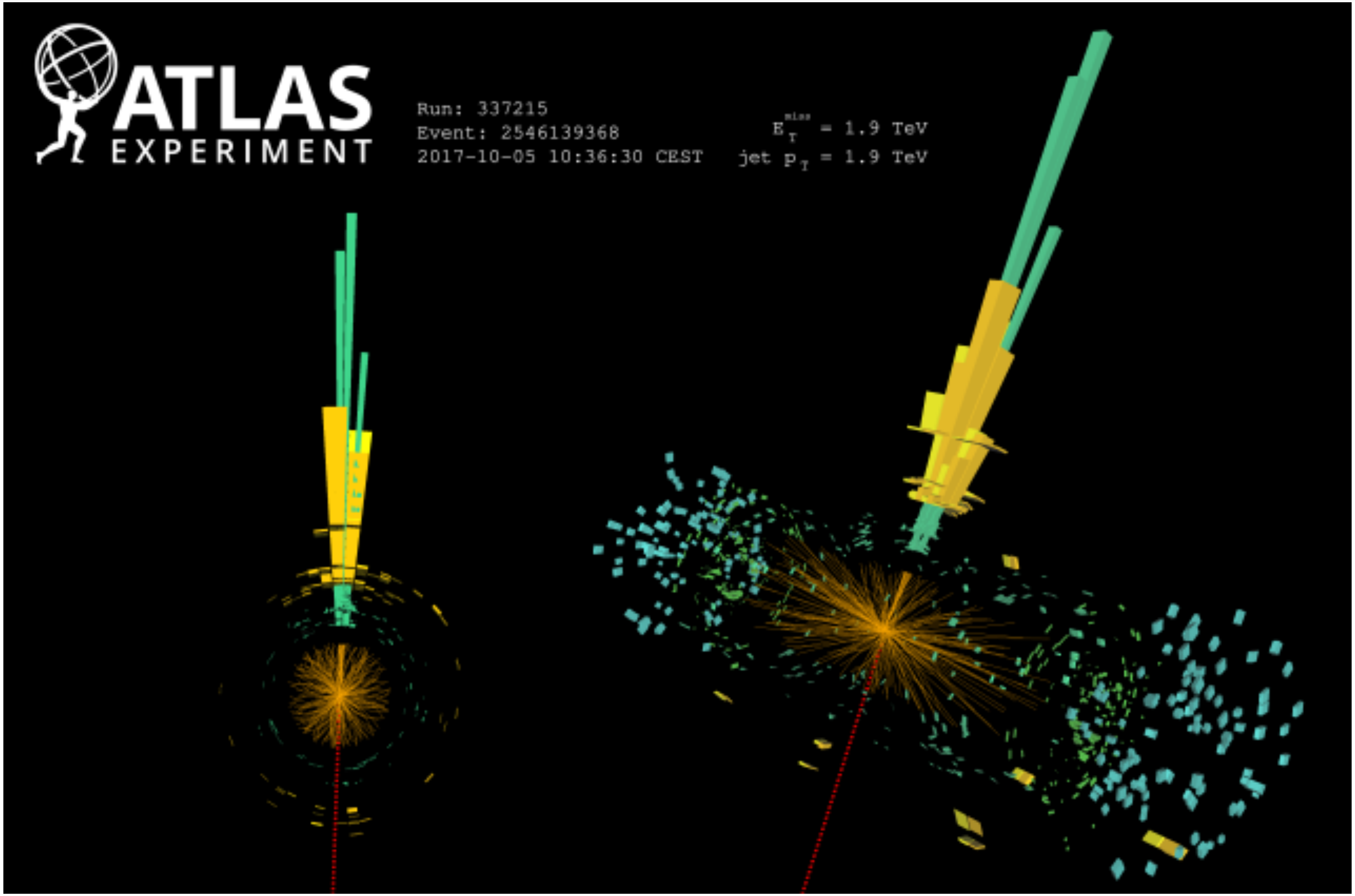






DM: Mono-jet

ATLAS-CONF-2020-048

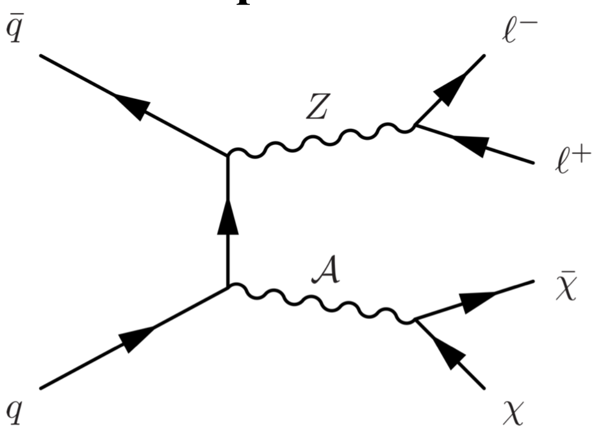


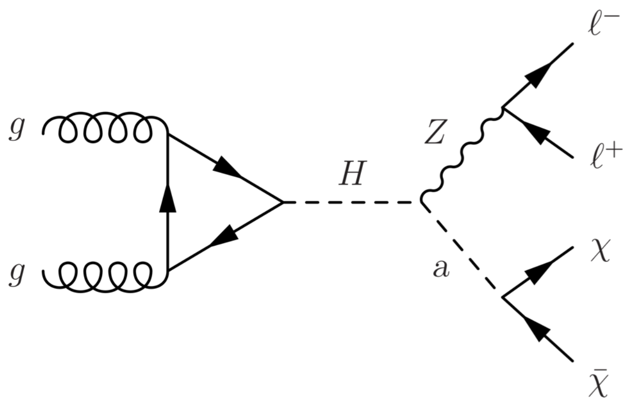
Highest-momentum (1.9 TeV) monojet recorded so far by ATLAS.

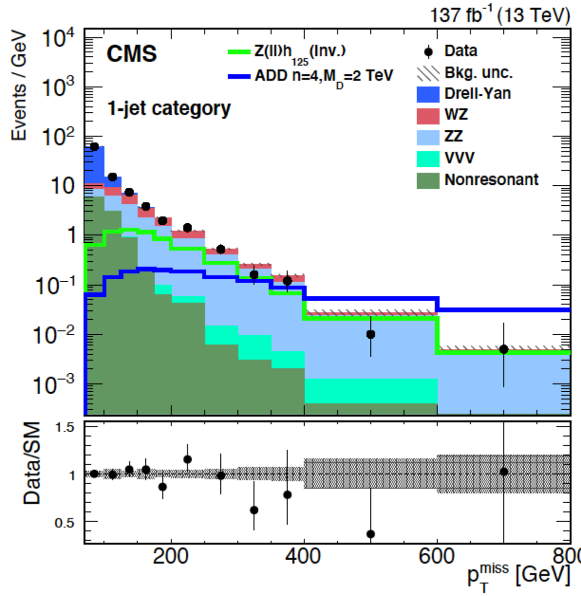
DM: Mono-Z

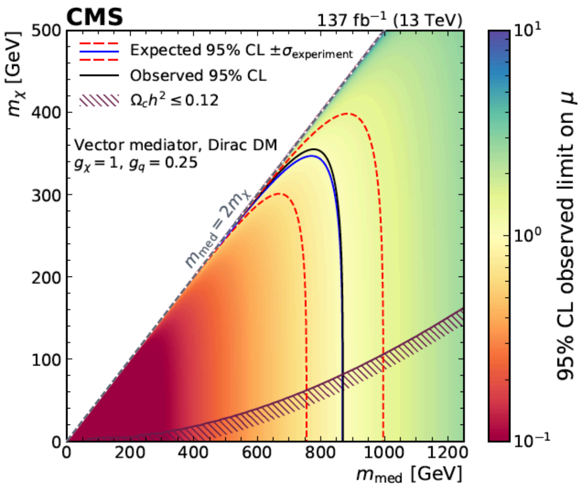
arxiv.org/abs/2008.04735

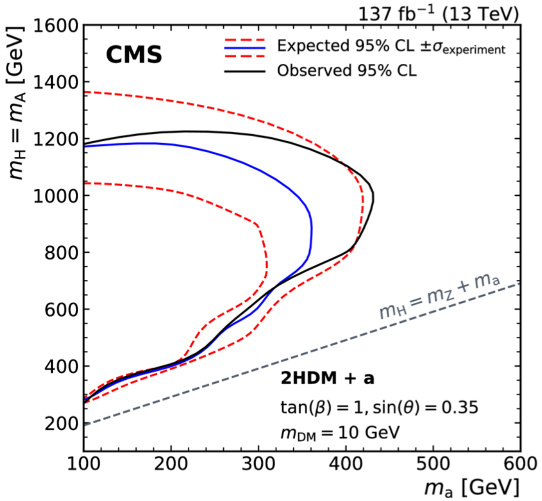
Simplified DM **2HDM+a**











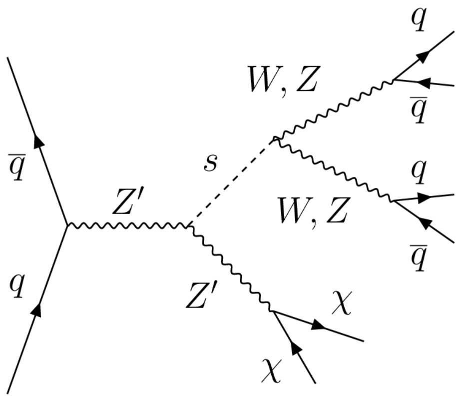
- **Z(->ee/μμ)+MET**
- **Divide into 0-jet and 1-jet categories to account for different S/B ratios**
- **Interpret with DM models and other scenarios of BSM**
  - **MET is used for all models, except for 2HDM+a for which m_T is used**

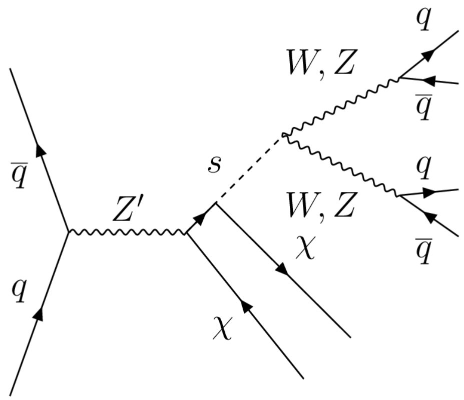
Simplified DM: highest mass limit improved by 150 GeV than previous one

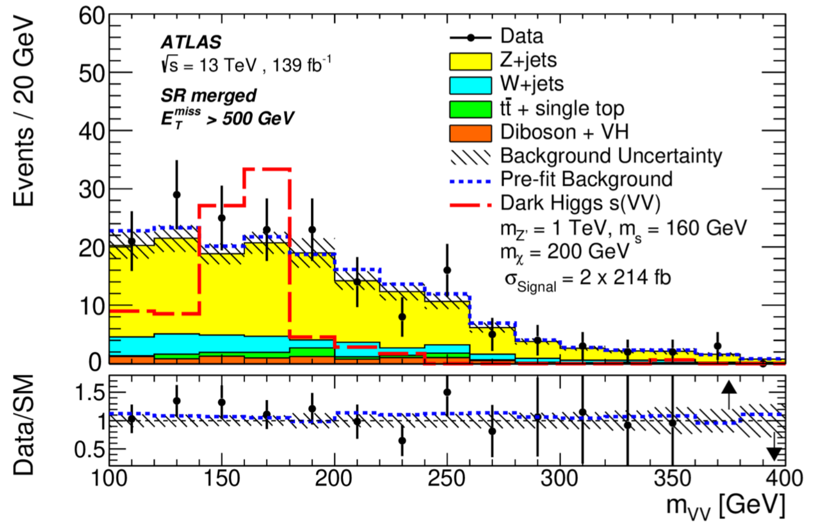
2HDM+a: best sensitivity for m_H=1 TeV, where m_a>440 GeV

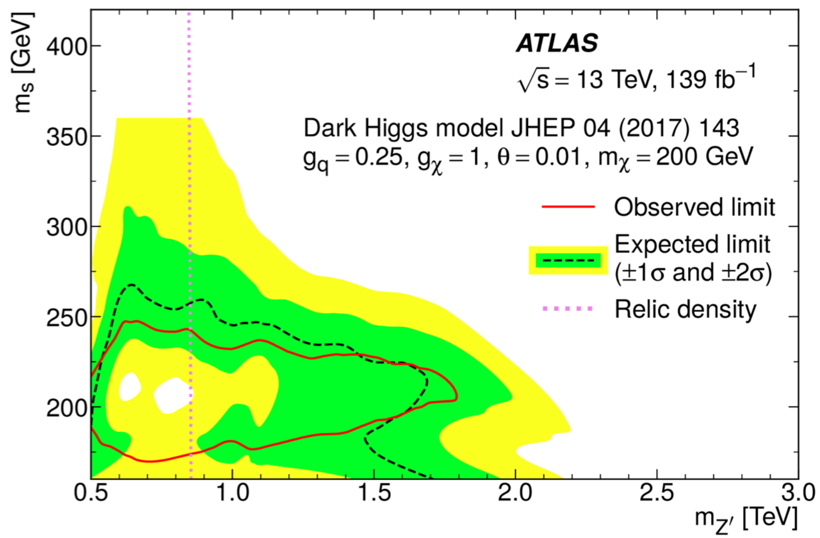
DM: VV+MET

arxiv.org/abs/2010.06548









- **Novel search in previously uncovered final states:**
  - ***sχχ* -> VV(hadronic decay) + large MET**
  - **Dominant background: V+jets**

- **Novel track-assisted reclustering (TAR) improves resolution of jet substructure observables, to better reconstruct s->V(qq)V(qq)**

- **Sensitivity dominated by merged category. Interpret with dark Higgs model**
  - **Exclude $m_{Z'}$ up to 1.8 TeV for m_s= 210 GeV**

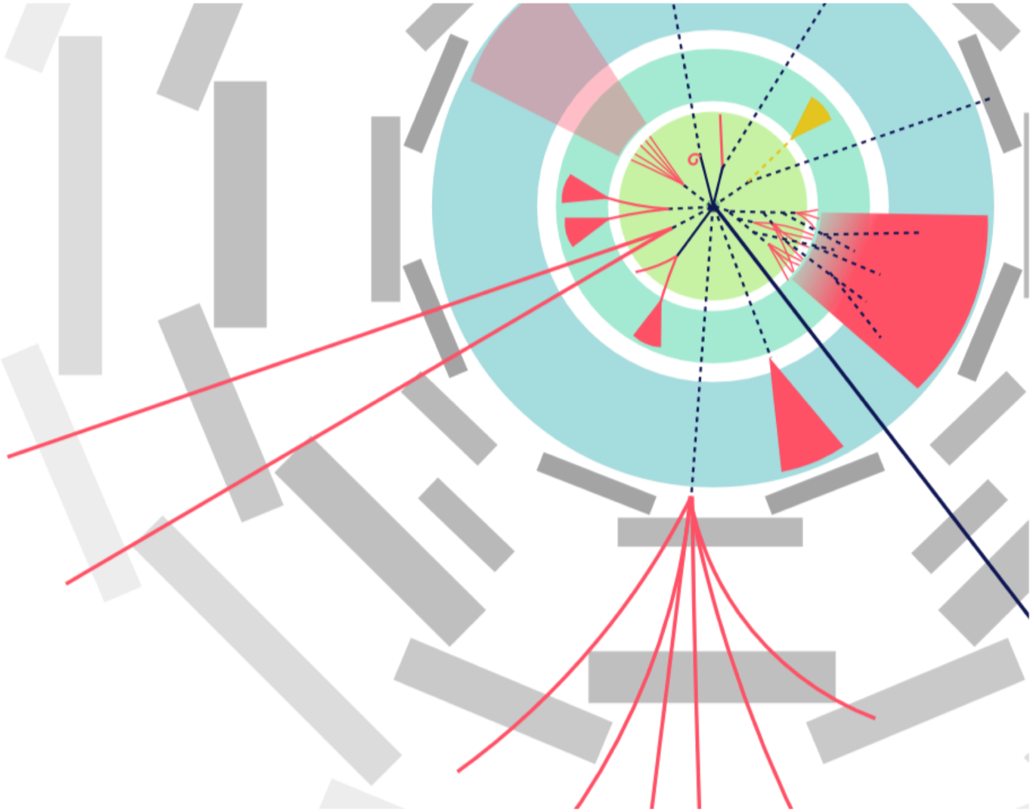
Unconventional Signatures:
Long Lived Particles(LLP)

- Most new physics analyses aim at prompt decays from signal, while there is huge phase space of possible BSM signatures

- LLP is predicted by many extensions to SM
  - Decay in the detector after a few cm

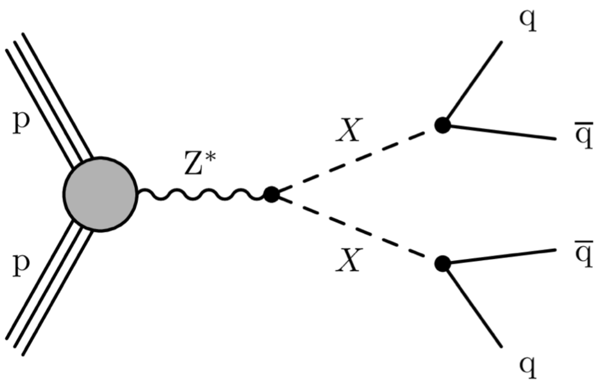
- Technical challenges:
  - Non-standard reconstruction
  - Displacements, timing and ionization
    - Dedicated triggers

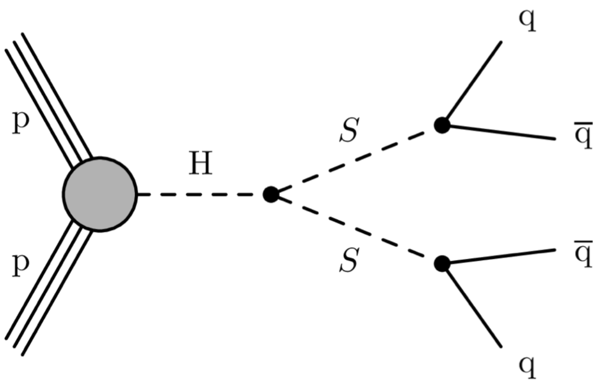
- Advantages:
  - Probe unexplored models at TeV scale
  - No irreducible SM background

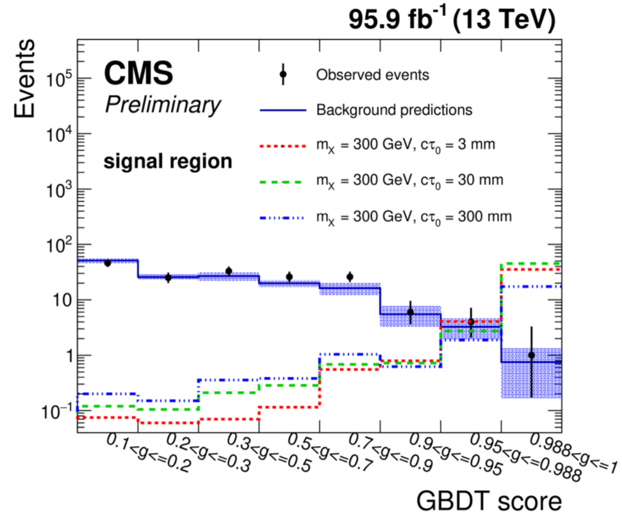


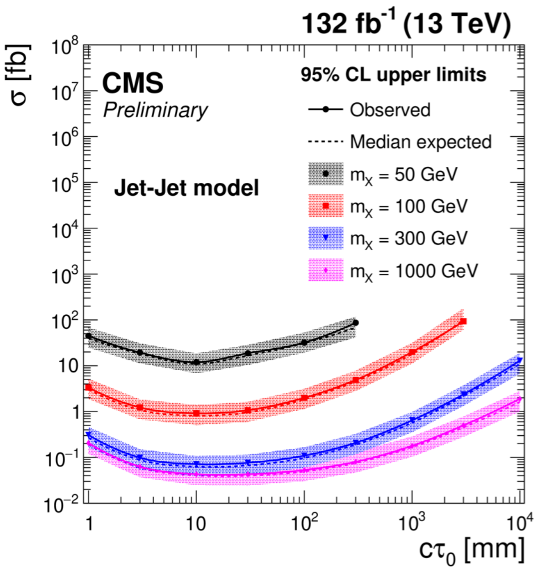
Long Lived Particles

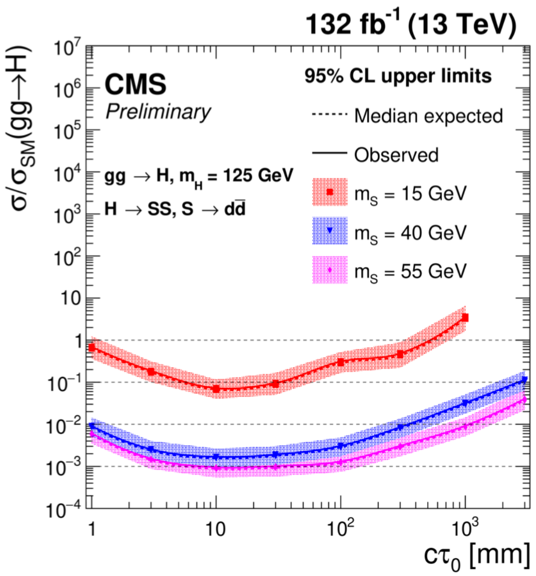
CMS-PAS-EXO-19-021











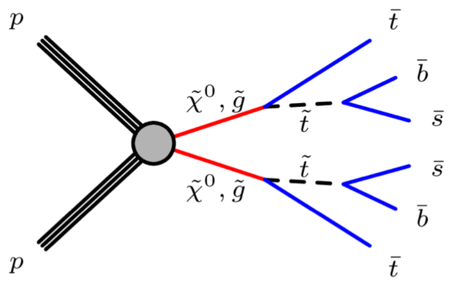
- Search for displaced tracks and displaced vertices within a dijet system
- Inclusive search, with at least one LLP having displaced vertex, as model-independent as possible
- GBDT is used for better discrimination
  - Use track and cluster information

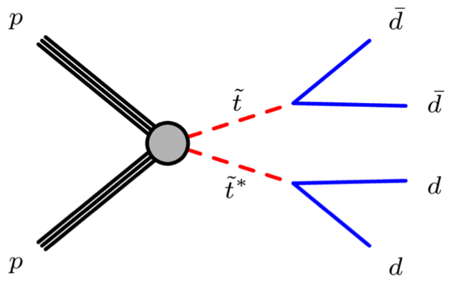
Exclude σ > 0.07fb for $c\tau_0 \in$(2mm, 250mm) & m_X > 500 GeV

Exclude σ/σ_{SM} > 0.01 for $c\tau_0 \in$(1mm, 1m) & $m_S \in$ (40GeV, 50GeV)

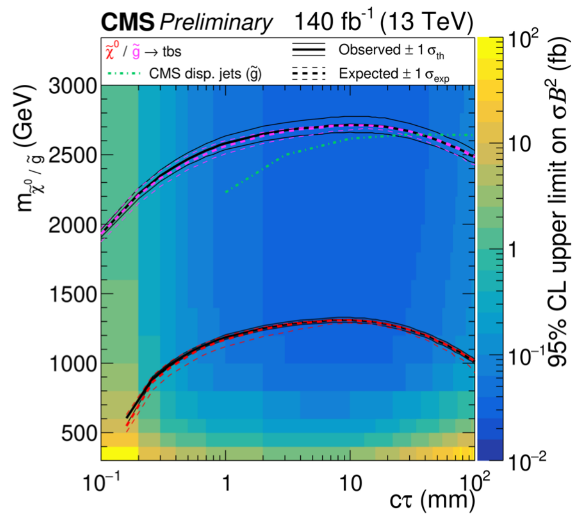
Long Lived Particles

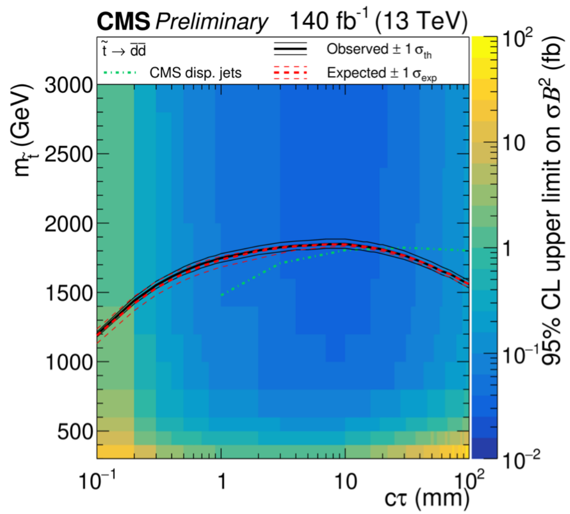
CMS-PAS-EXO-19-013





- **Target LLP with decay length between 0.1 and 100 mm that each decay into ≥ 2 quarks**
  - **Achieved high sensitivity to decay lengths < 20 mm, by requiring two reconstructed vertices inside beam pipe**





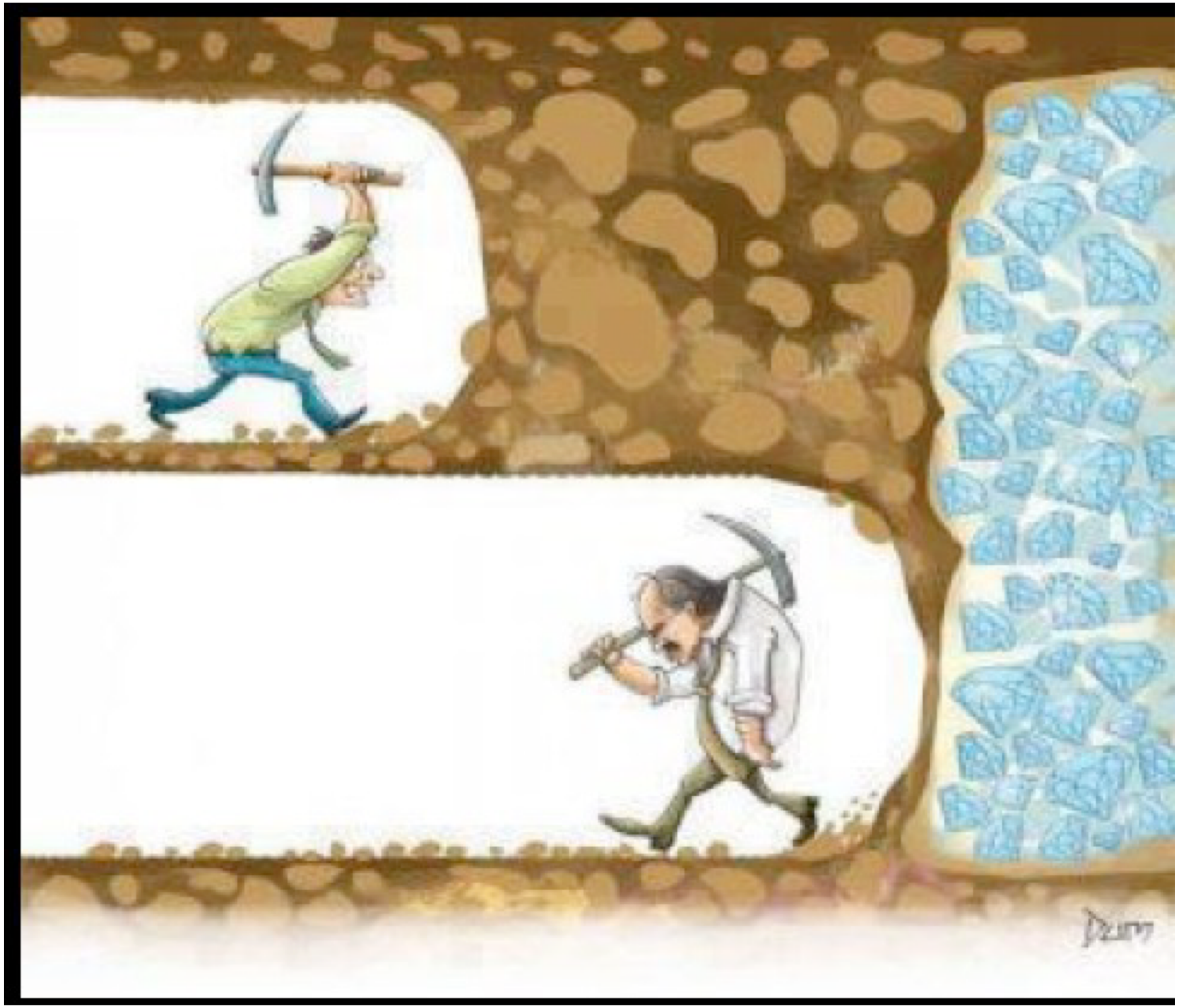
- **For Long-lived neutralinos, gluinos and top squarks, pair production is excluded for > 0.08 fb for mass (0.8, 3 TeV) and decay length (1, 25 mm)**

		Predicted multijet signal yields			
d_{VV} range	Predicted background yield	0.3 mm	1.0 mm	10 mm	Observed
0–0.4 mm	0.235 ± 0.003 (stat) ± 0.059 (syst)	0.7 ± 0.2	0.7 ± 0.1	0.20 ± 0.02	0
0.4–0.7 mm	0.096 ± 0.003 (stat) ± 0.031 (syst)	0.8 ± 0.2	1.1 ± 0.2	0.10 ± 0.01	0
0.7–40 mm	0.011 ± 0.001 (stat) ± 0.006 (syst)	0.8 ± 0.2	5.4 ± 0.9	12 ± 1	0

Summary

- Relentless efforts are made by the LHC to explore new physics in many ways, productive with excellent results covering different aspects
- Many more new Run-2 results to come
  - Better analysis techniques could yield sensitivity beyond expectation
- LLP/unconventional signatures become more important
  - 0-background searches benefit more from luminosity increasing

Keep Working



Keep Working

Thank you !