Searches for Exotic New Physics with ATLAS and CMS

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For the ATLAS and CMS Collaborations

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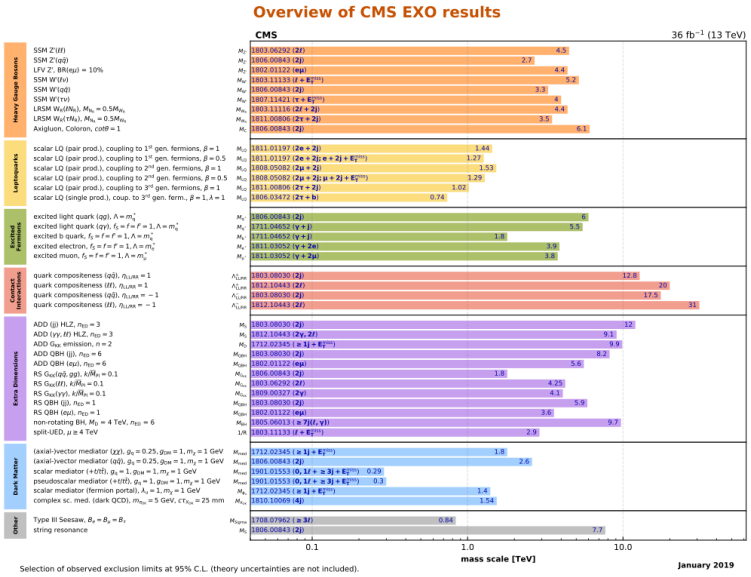
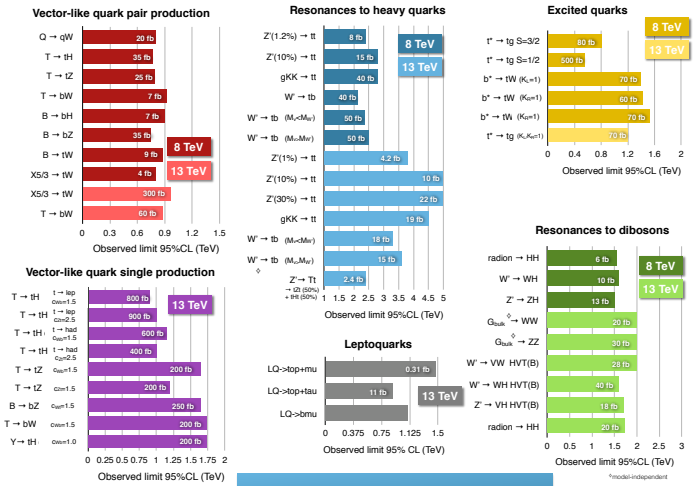
Exotics at the LHC

- ATLAS and CMS have a strong and diverse search program for BSM Physics
- In other plenary talks, we have already heard about Searches for Dark Matter, in the BSM Higgs sector, and, of course, SUSY

- Quite a bit still to talk about today
  - Bread-and-butter resonances searches: dijet, dilepton, etc.
  - Resonances with more complex, boosted signatures
  - Old classics: Leptoquarks, Seesaw, etc...
  - Novel uses of the detectors: Long-lived, highly ionizing, ...
  - And so much more
- More and more full Run 2 results are becoming available
- Embarrassment of riches: Only a small selection of results shown here





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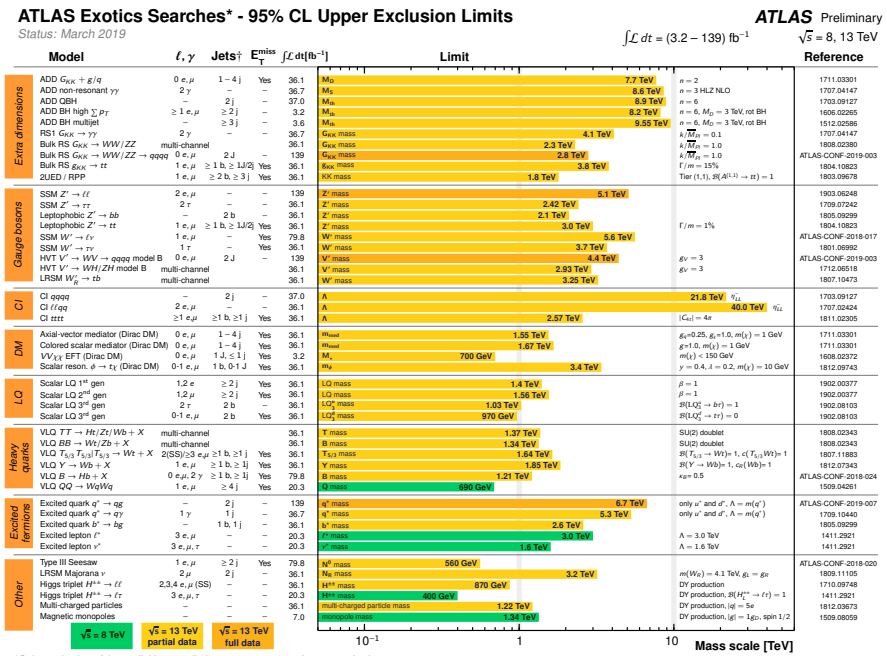
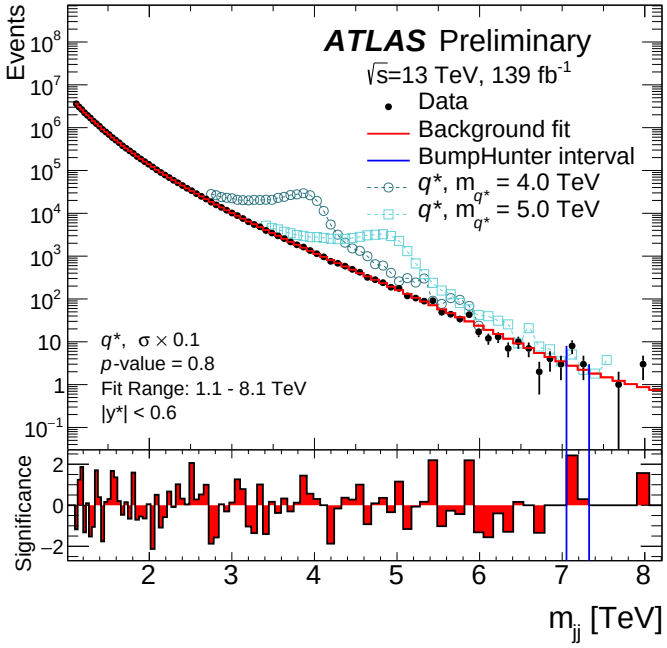
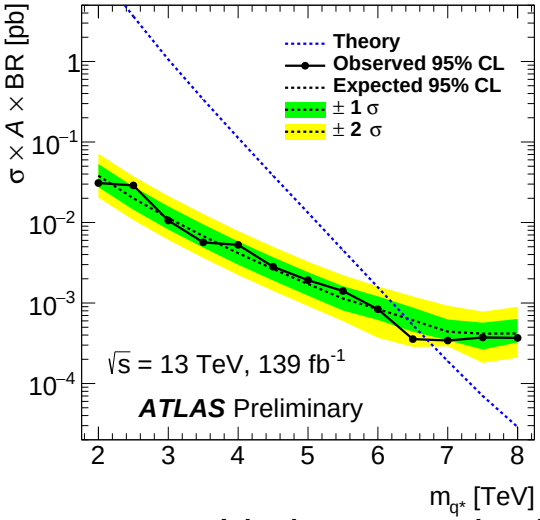
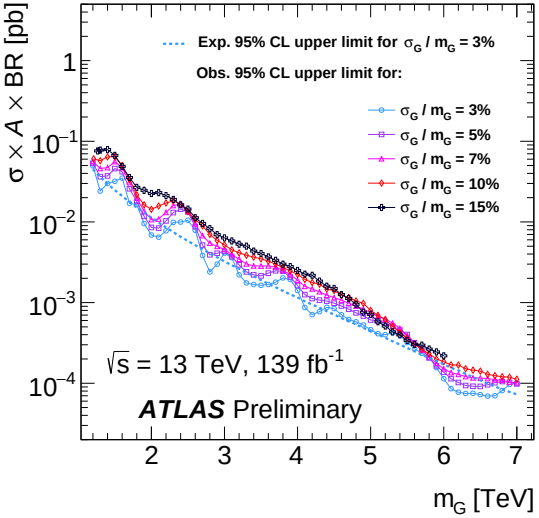


Dijet resonances

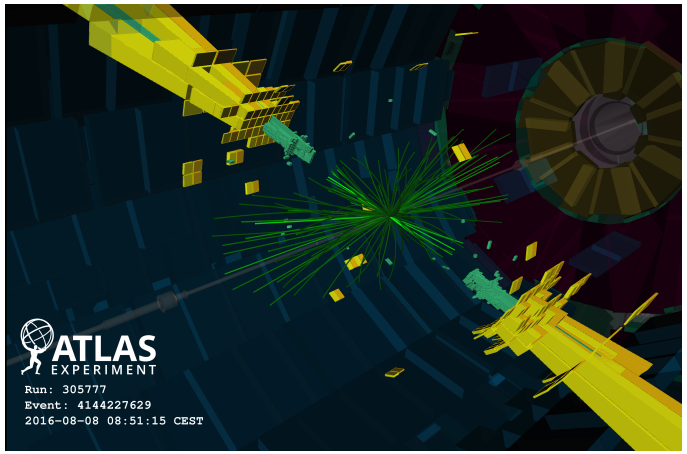


- Dijet resonances have highest mass reach of all direct resonance searches
- Bump hunt in mass spectrum of two jets with $p_T > 150\,\text{GeV}$ with $\frac{1}{2}|y_1 - y_2| < 0.6$
- Excellent mass resolution: ≈2.5% at 5 TeV
- Full Run 2 result!





Highest mass event: 8.02 TeV



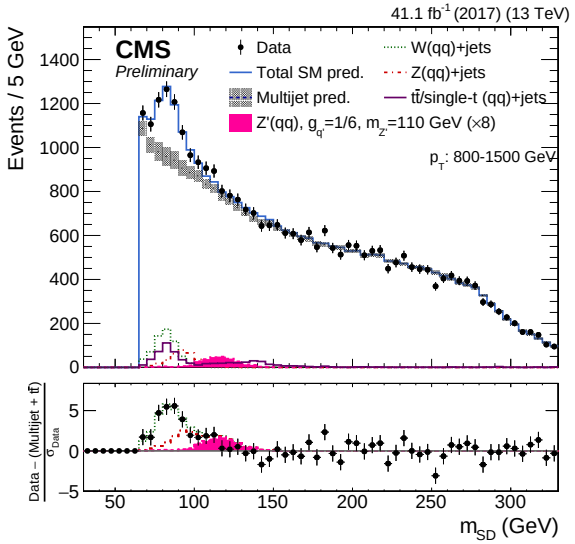
- Limits on excited quarks: $m_{q^*} > 6.7\,\text{TeV}$
- Limits on $\sigma \times \text{Acceptance} \times \text{BR}$ set for different width hypothesis up to 15%

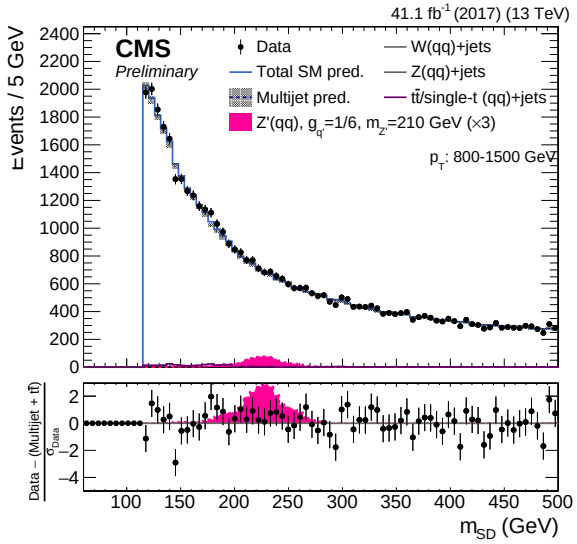
ATLAS-CONF-2019-007

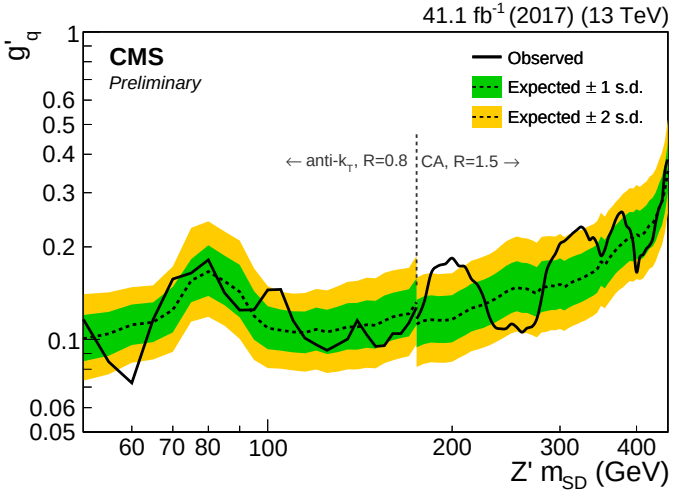
Boosted Dijet resonances

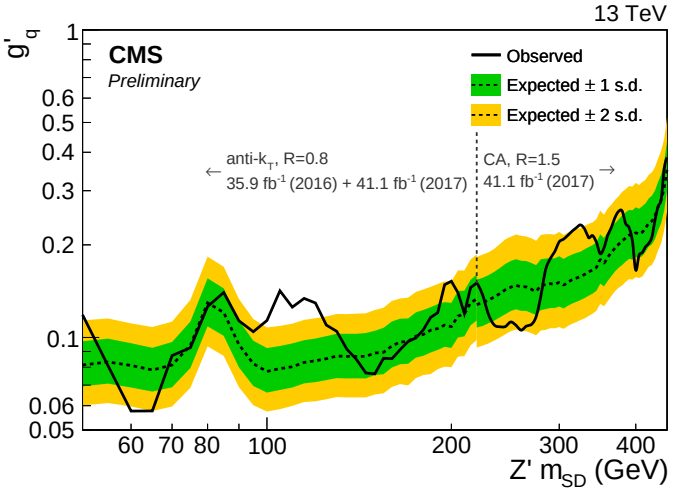
Brand New!

- Search for a (relatively) low mass lepto-phobic Z'
- ISR jet used to tag and trigger the events
- Z' will be boosted: Identify candidates with jet substructure techniques
- Anti-k_T jets with R=0.8 for resonances up to 220 GeV
  CA jets with R=1.5 up to 450 GeV
- Limits set on Z' couplings to quarks for 2017 data
- Combined with 2016 data in low mass region
- Excess observed in 2016 not confirmed in 2017







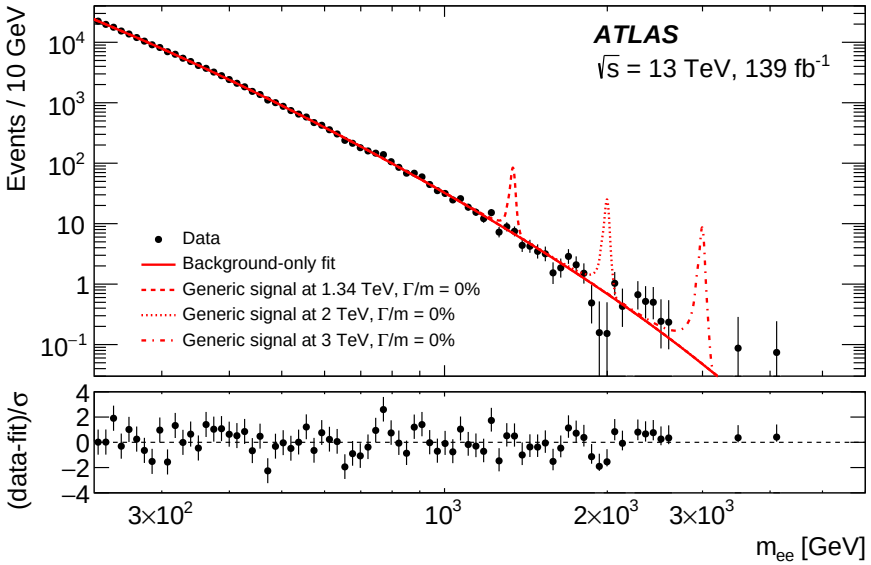


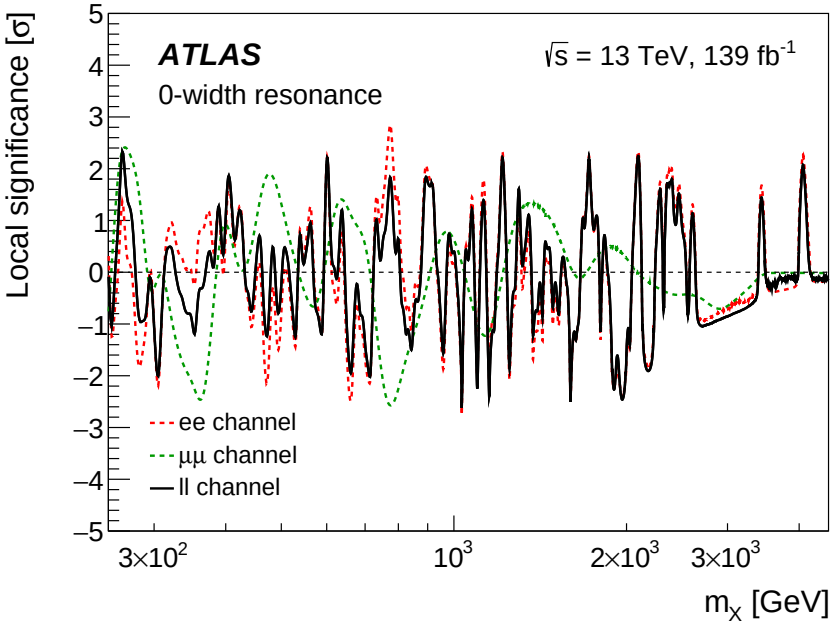
CMS-PAS-EXO-18-012

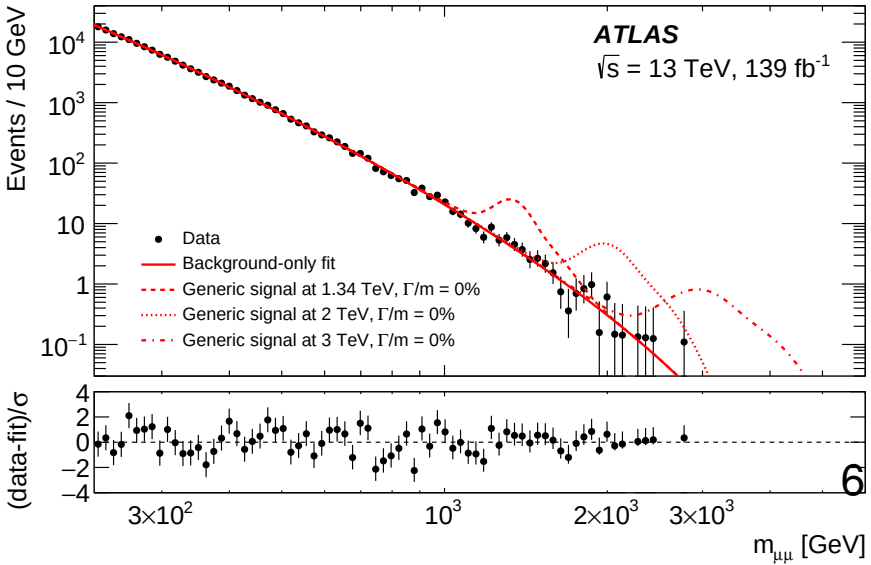
Dilepton Resonances

- New heavy dilepton resonances predicted in a multitude of New Physics models
- Searches designed to be as model-independent as possible

- Select e/μ with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $\eta < |2.4|$
- Signal model: Breit–Wigner + resolution function, restricted to $m_{\ell\ell} > m_X - 2\Delta_X$ to reduce off-shell effects
- Signal yield extracted from fit of signal and background model to the mass spectrum
- No significant deviation from SM expectation





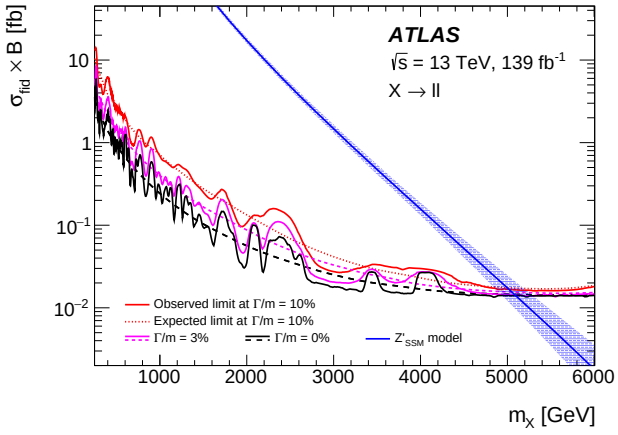


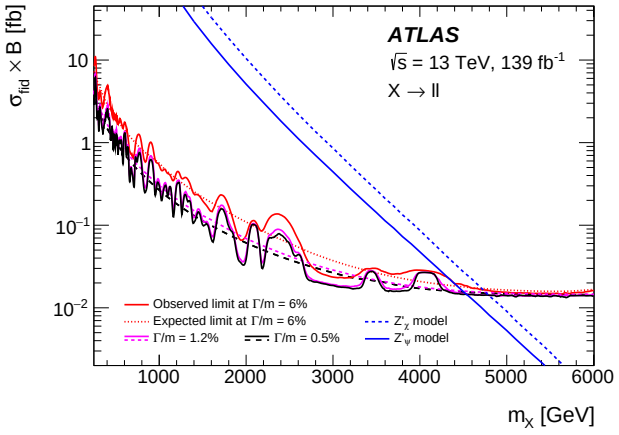
arxiv:1903.06248 Submitted to PLB

Dilepton Resonances

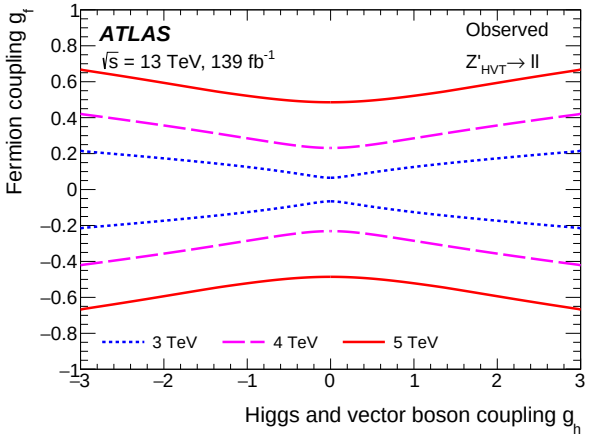
arxiv:1903.06248, Submitted to PLB

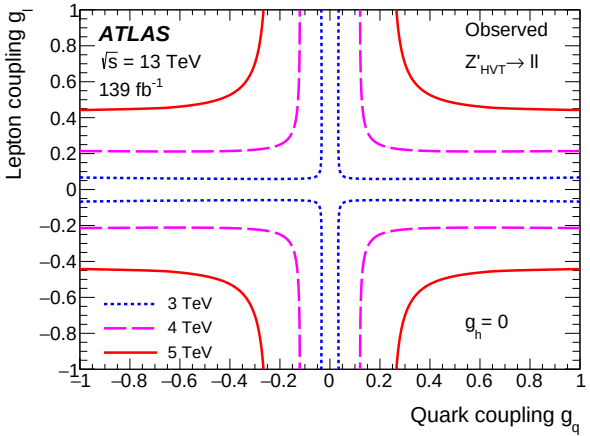
- Limits on fiducial cross section $\times$ BR for different signal widths
- Limit for SSM Z' reaches 5.1 TeV
- Limits also applicable for Spin 0 and Spin 2 resonances





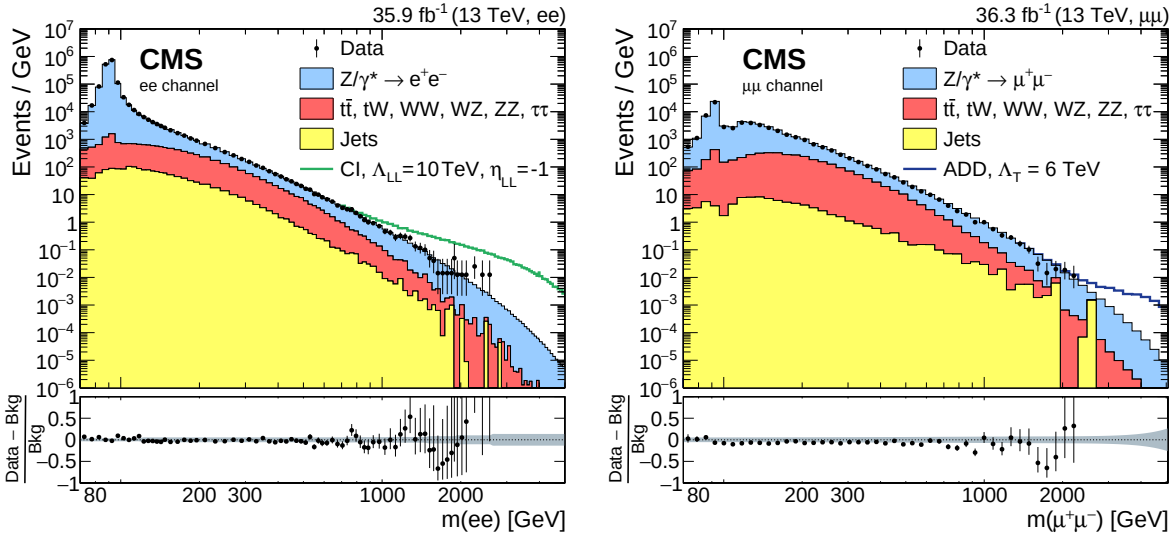
- Results interpreted in a Heavy Vector Triplet (HVT) model, Z' coexists $\approx$ mass-degenerate with $W'^{\pm}$
- Constrains on couplings to lepton, quark, and Higgs- and Vector-boson fields



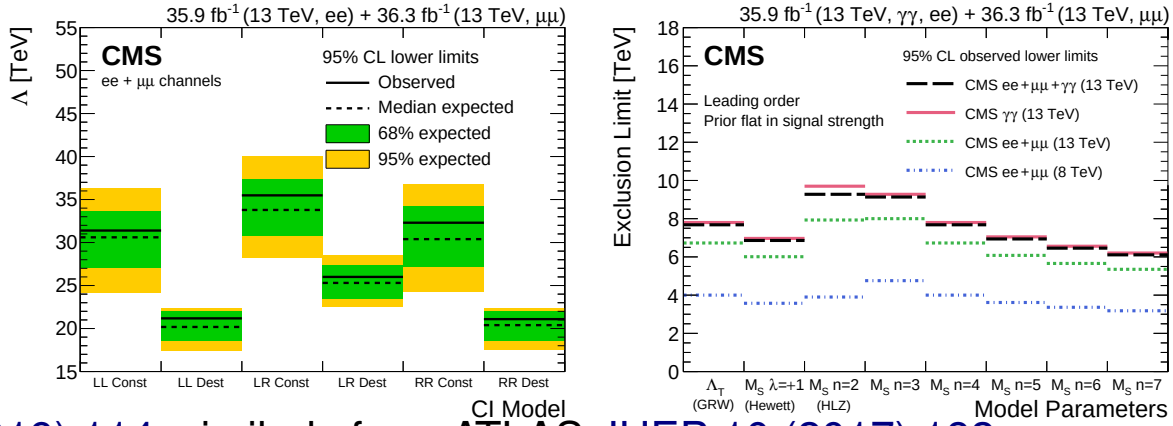


Dilepton Non-Resonant

- Recent CMS result on non-resonant interpretation of this final state on 2016 data
- Similar event selection, but backgrounds evaluated directly from MC



- Limits on energy scale of a four-fermion contact interaction range from 20-32 TeV
- Combined with a diphoton search, limits in different parameter conventions in the ADD model of Large Extra Dimensions range from 6.1 TeV to 9.3 TeV

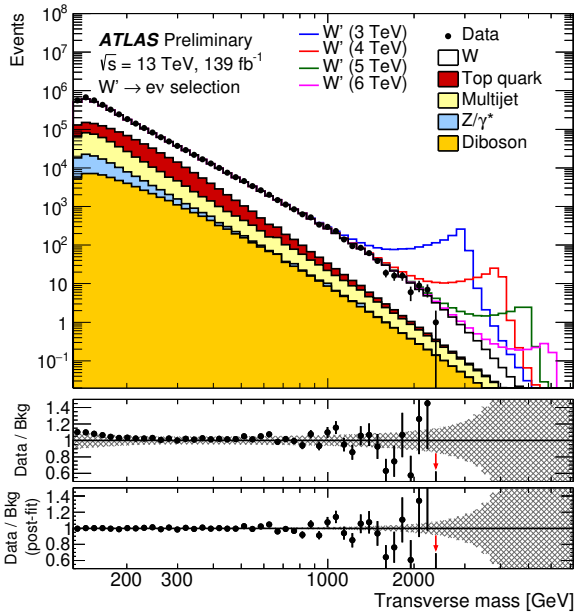


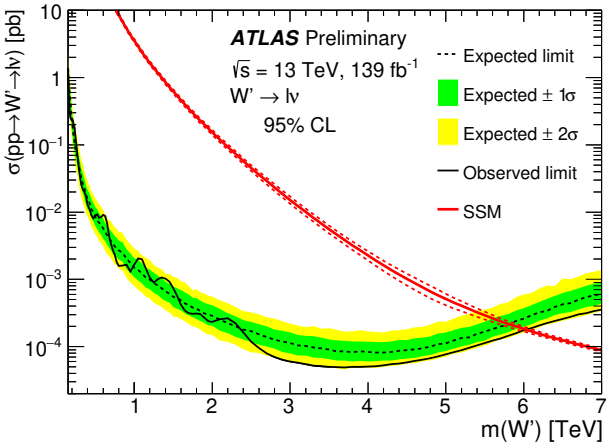
JHEP 04 (2019) 114, similarly from ATLAS JHEP 10 (2017) 182

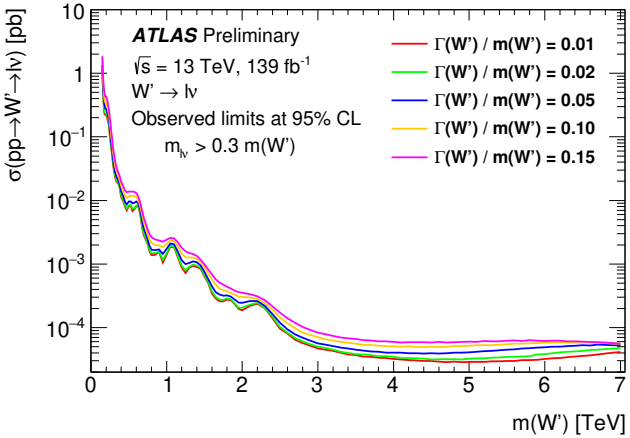
Search for W' in leptonic final states

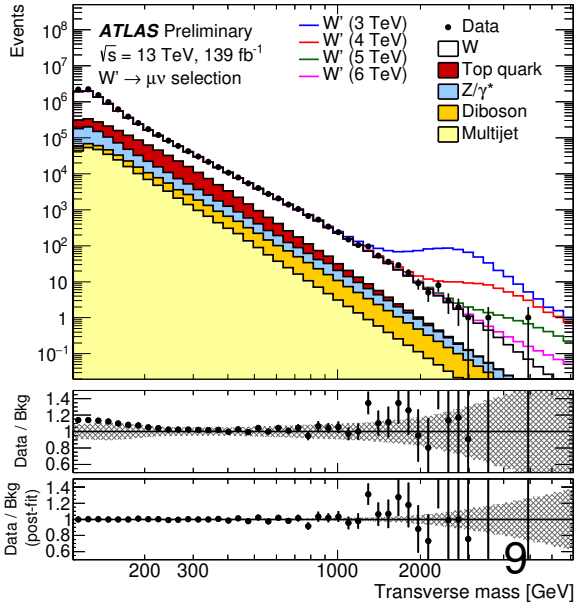
Brand New!

- Select events with a single high p_{T} lepton and large $E_{\mathrm{T}}^{\mathrm{miss}}$
- Search for heavy resonances in the $\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ transverse mass M_{T} spectrum
- Increased sensitivity with full Run 2 lumi and upgrades to reconstruction and detector alignment
- SSM W'' excluded up to 6 TeV!
- Model independent limits set on the fiducial cross section for $m_{\ell\nu} > 0.3 \cdot m(W')$ for different width hypotheses



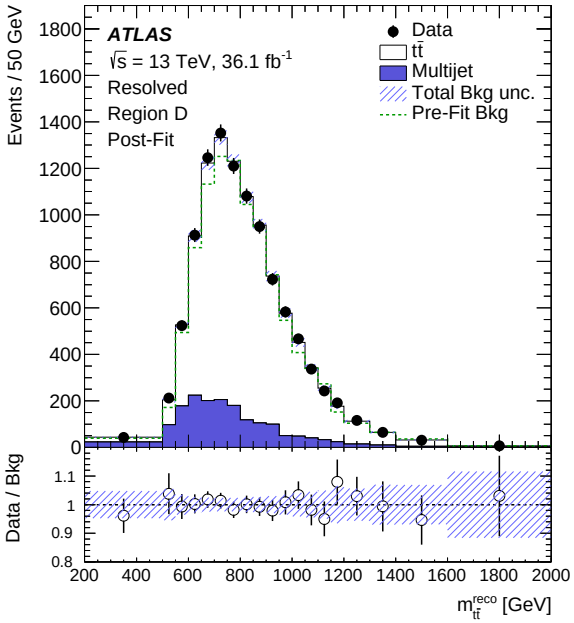


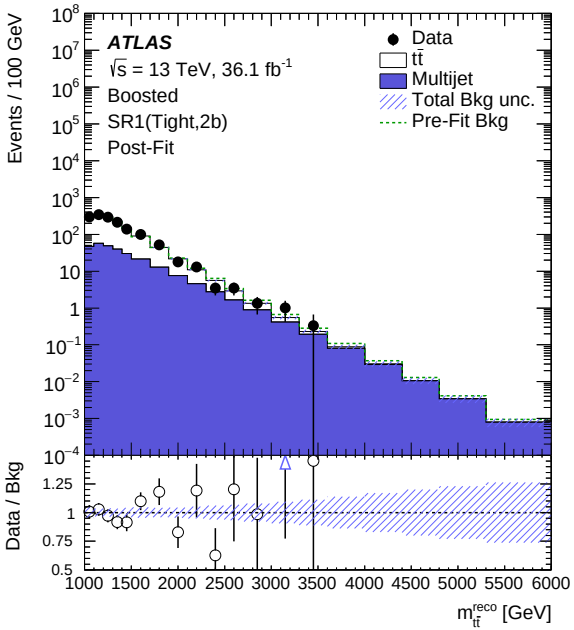




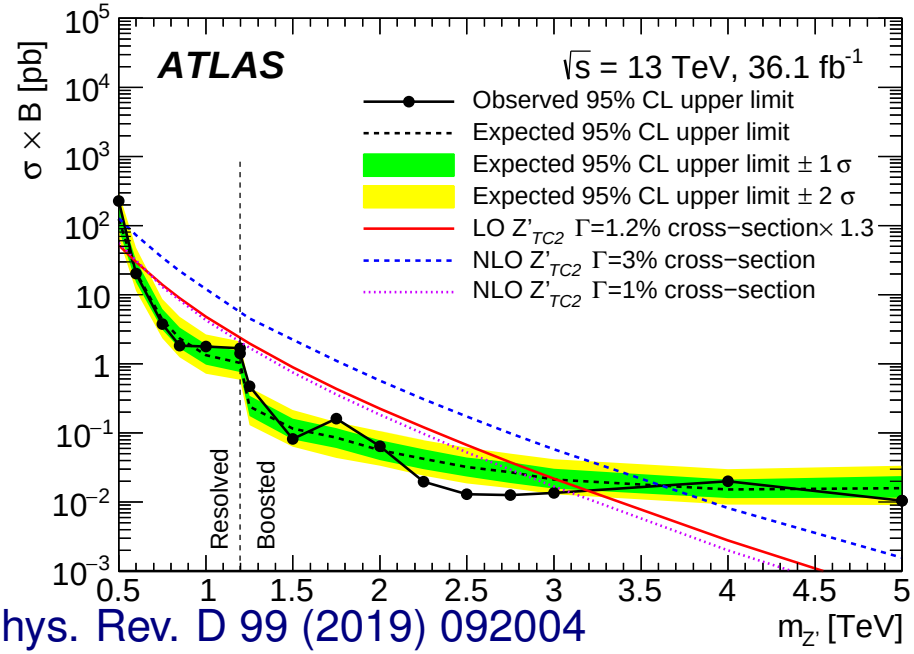
ATLAS EXOT-2018-30

$t\bar{t}$ resonances





- Search for heavy spin-1 and spin-2 resonances decaying to top pairs in the all-hadronic final states
- Decay products mostly resolved up to ≈1.2 TeV, increasingly merged for higher masses
- $t\bar{t}$ estimated from MC, QCD from data
- Top-color assisted Techicolor Z'_{TC2} excluded up to 3.6 TeV for 3% width
- Limit is 3.4 TeV for g_{KK} with 30% width

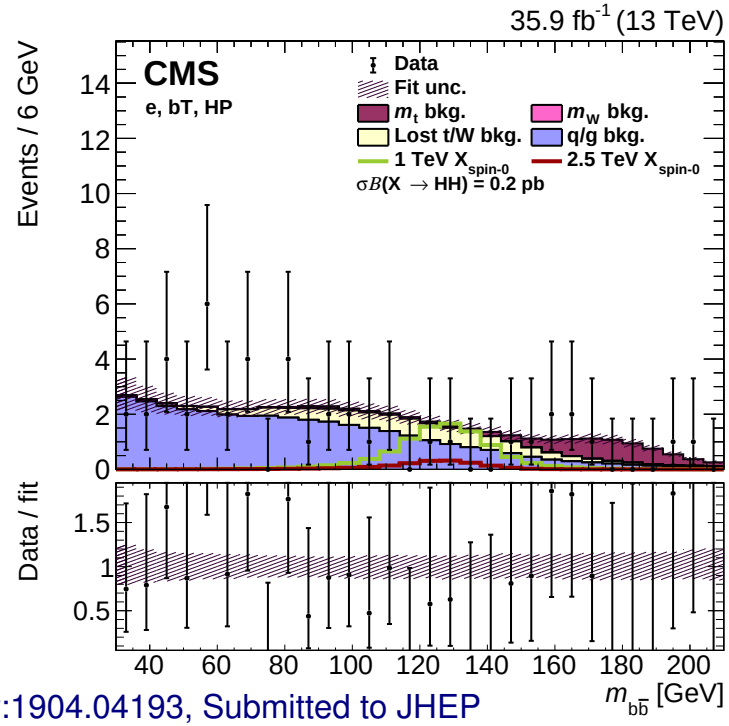


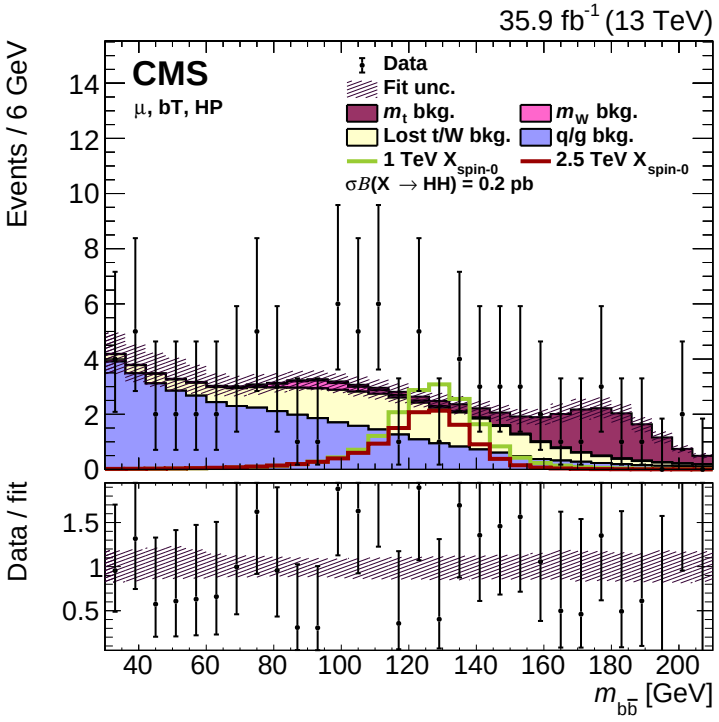
Phys. Rev. D 99 (2019) 092004

Similary from CMS with all decay modes JHEP 04 (2019) 031

Resonant Di-Higgs Search

- Di-Higgs resonances present in models with extended Higgs sector but also warped extra dimensions
  $\rightarrow$ new spin=0 or spin-2 resonance are possible
- Consider events with $H \rightarrow b\bar{b}$ and $H \rightarrow WW$, with one W decaying leptonically and the other hadroncially
- Both Higgs boson will be boosted $\rightarrow$ Require one merged $b\bar{b}$ jet and one $q\bar{q}'$ jet with a closeby lepton
- 12 event categories by number and quality of b-tags in the $b\bar{b}$ and likelihood of the $q\bar{q}'$ jet to contain exactly two subjets

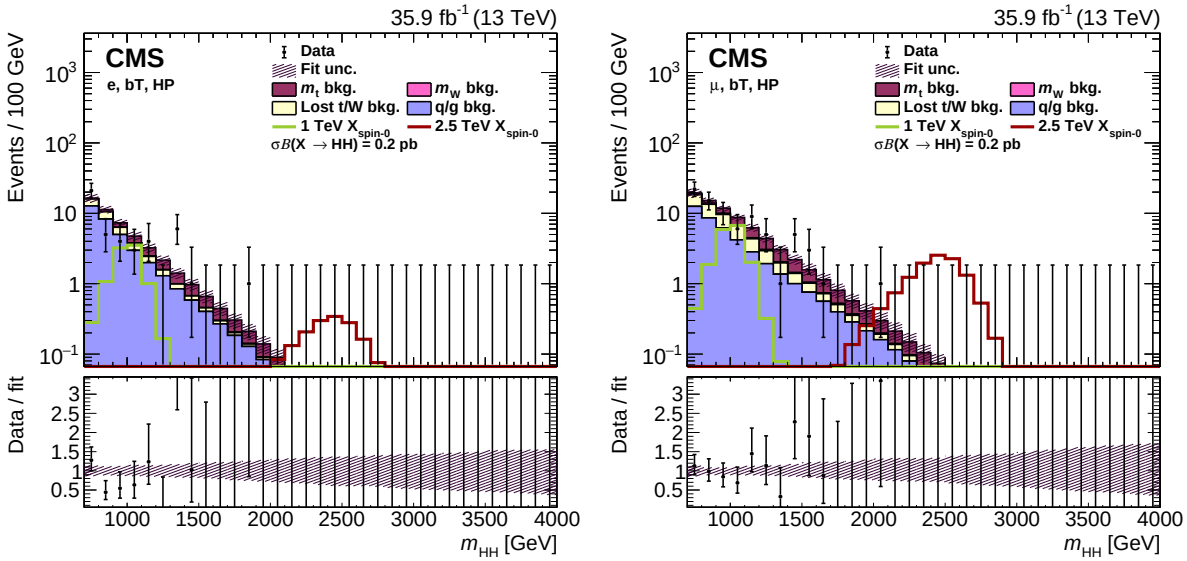




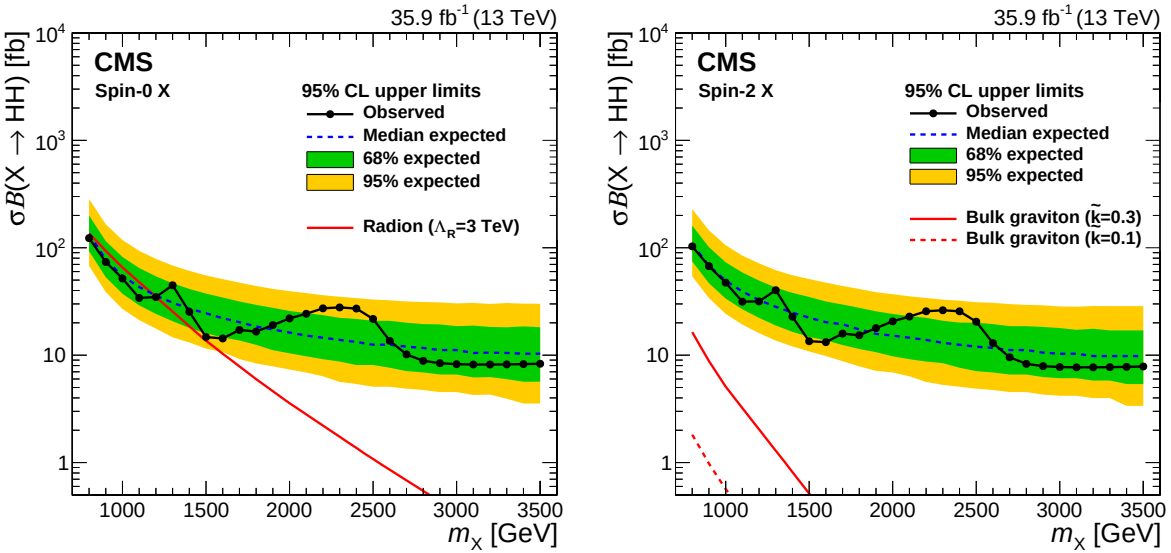
arxiv:1904.04193, Submitted to JHEP

Resonant Di-Higgs Search

- Background/Signal yields estimated from 2D-ML template fits in $m_{b\bar{b}}$ and m_{HH}



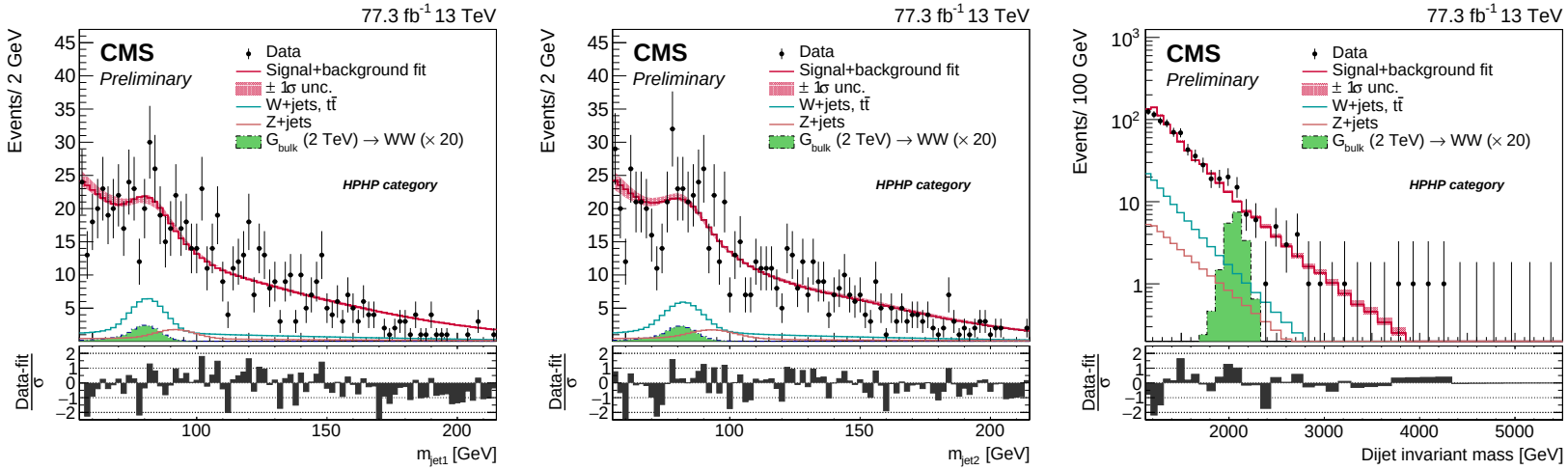
- Limits are set on the signal cross section for Spin-0 and Spin-2 resonances



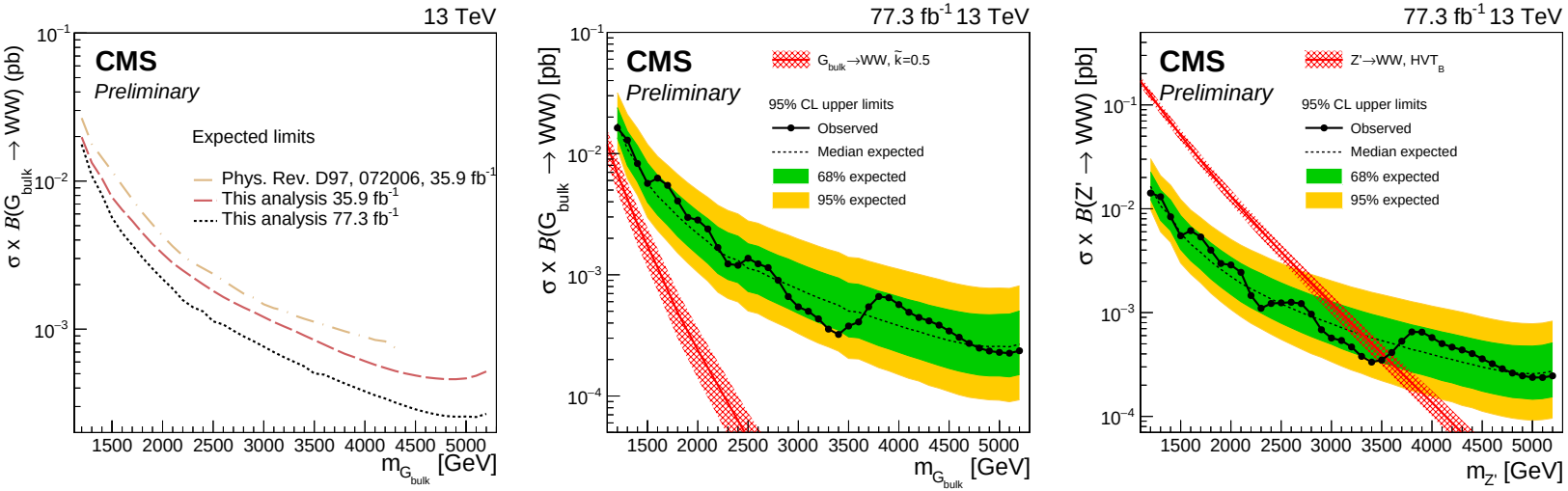
arxiv:1904.04193, Submitted to JHEP, similarly from ATLAS JHEP 04 (2019) 092

Diboson Resonances in all-hadronic final states

- Search for heavy resonances decaying to two boosted Vectorbosons by selecting V-tagged dijet events
- Multidimensional fit to m_{jj}, m_{j1}, and m_{j2} increases sensitivity



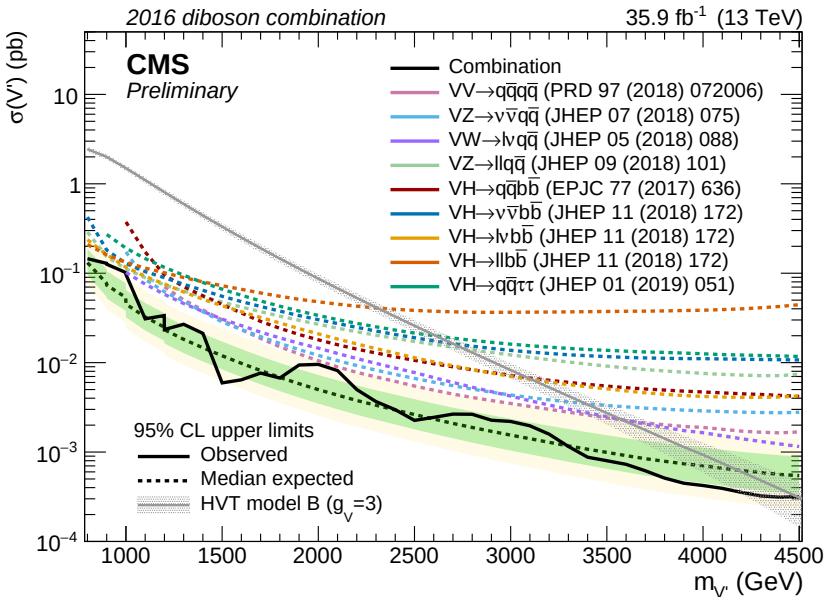
- Significant improvement over previous 1-D fit technique
- Limits set on RS Gravitons and HVT Z's



CMS-PAS-B2G-18-002

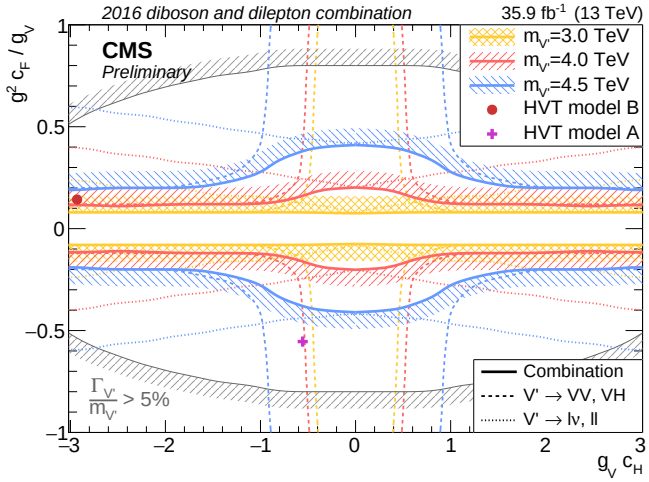
Combination of Diboson and Dilepton resonances

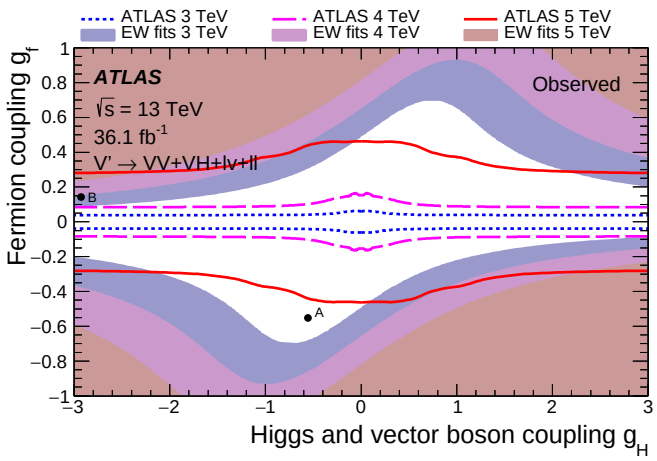
- Both CMS and ATLAS have a substantial search program for new resonances to VV/VH/Dielepton
- For maximum sensitivity, results from different final states are combined in each experiment



- Combination of $V' \to VV/VH$ sets stringent limits when decays to SM bosons dominate
- Combining further with $\ell\ell$ and $\ell\nu$ results increases sensitivity where decays to leptons are significant

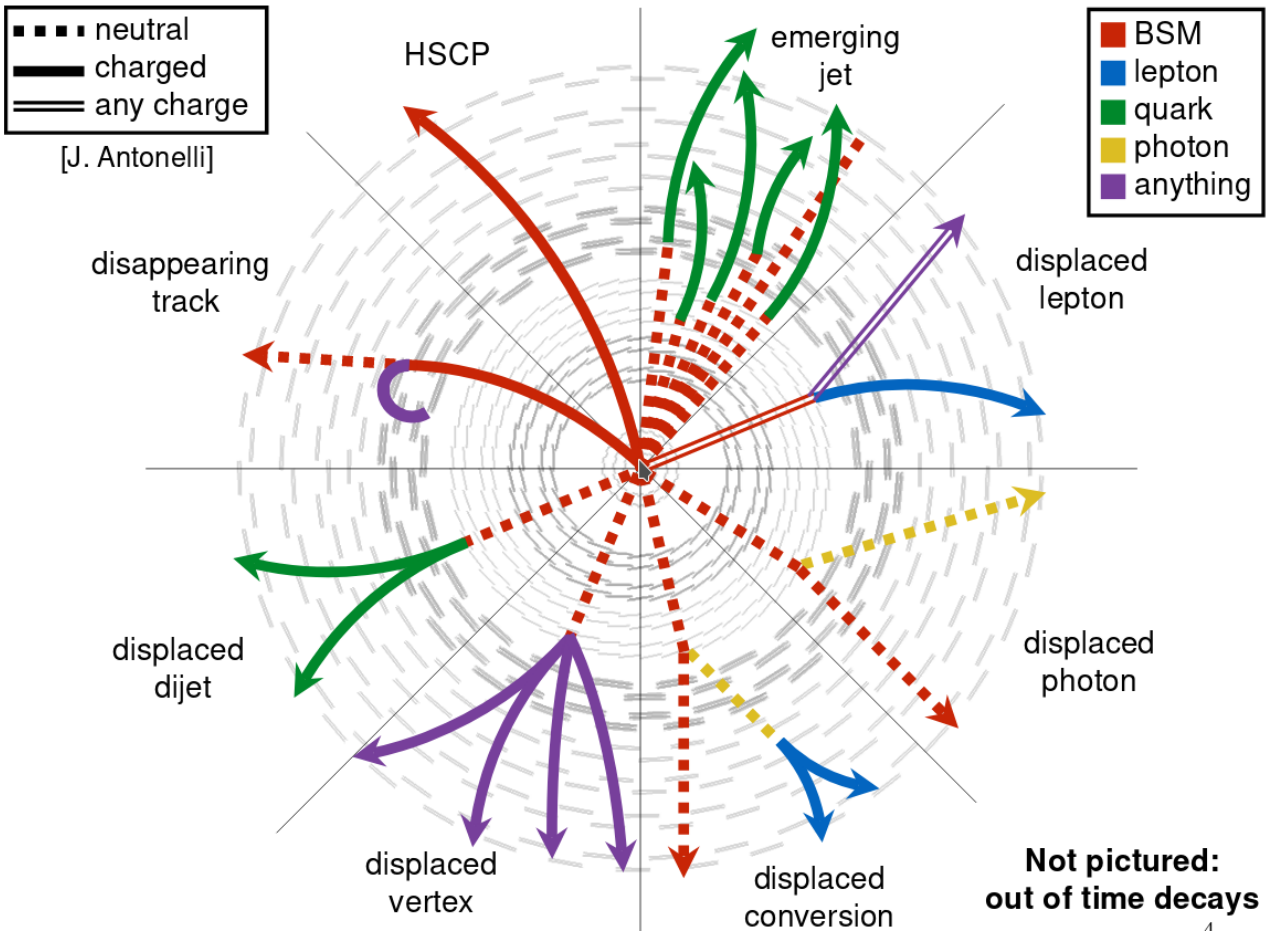
CMS-PAS-B2G-18-006, Phys. Rev. D 98 (2018) 052008





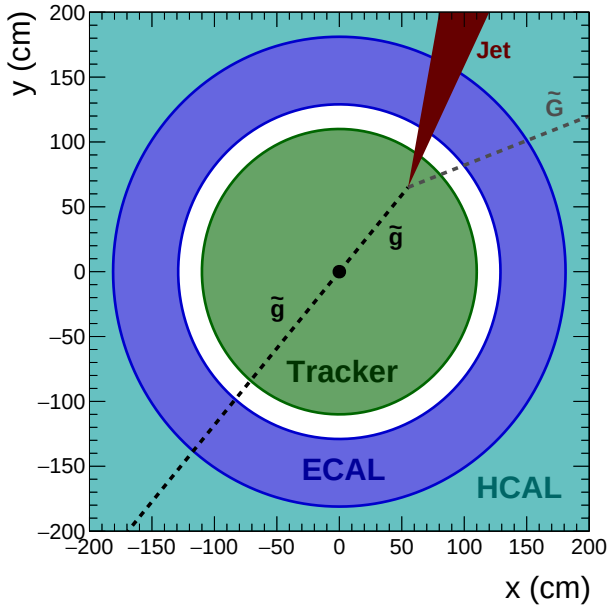
Long-lived signatures

- Traditional searches focused on prompt decays of BSM particles
- As that phase space is increasingly covered, the search program for long-lived particles is growing significantly
- Depending on the nature of the LLP and the decay length there is a multitude of interesting experimental challenges

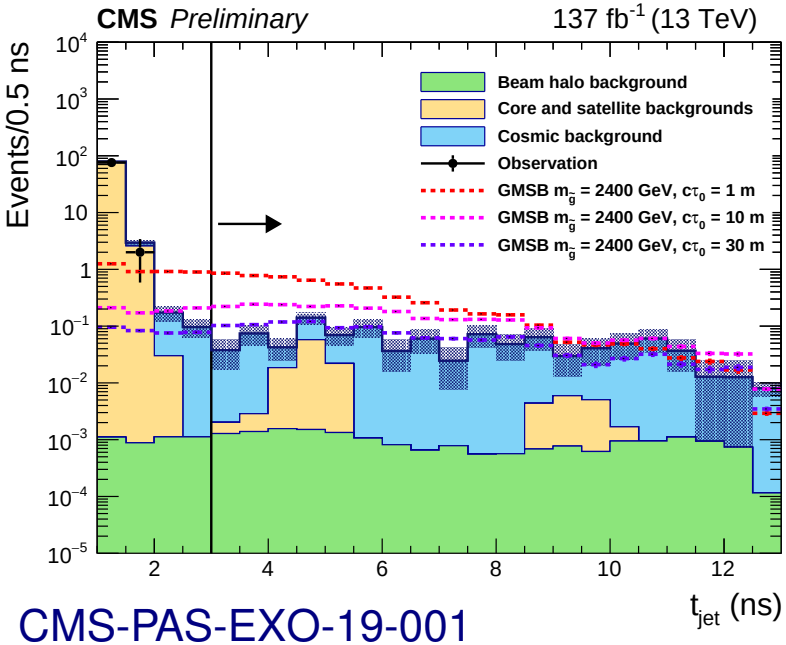


Delayed Jets

- Search for long-lived particles decaying to a jet and an invisible particle outside the tracker acceptance



- ECAL timing of the jet defined as median time of all cells associated with a jet
- Suite of calorimeter and muon system information used to reject instrumental and beam backgrounds
- Prompt jets reject by requiring few associated tracks to the jet

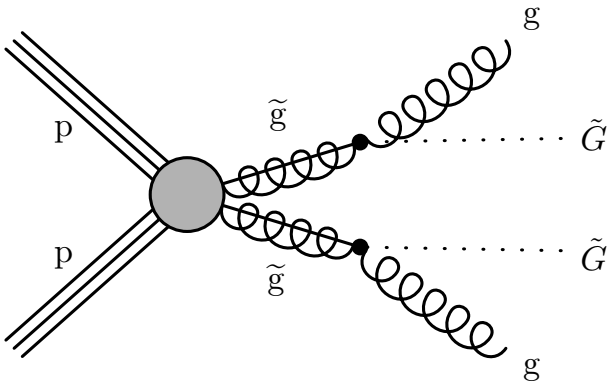


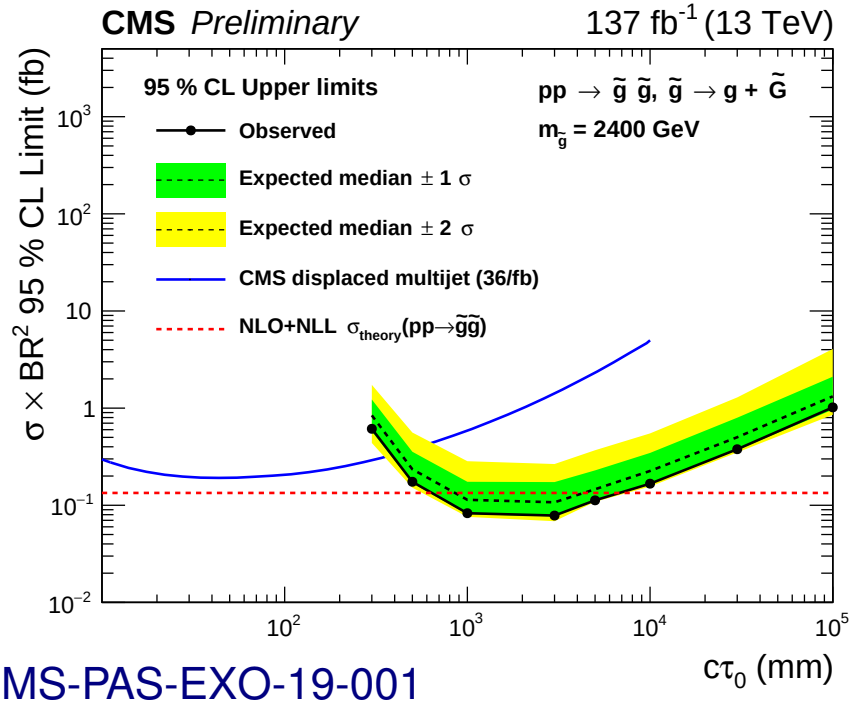
CMS-PAS-EXO-19-001

- Require 1 central delayed jet with $p_T > 30$ GeV and $E_T^{miss} > 300$ GeV
- Dominant background from cosmic muons

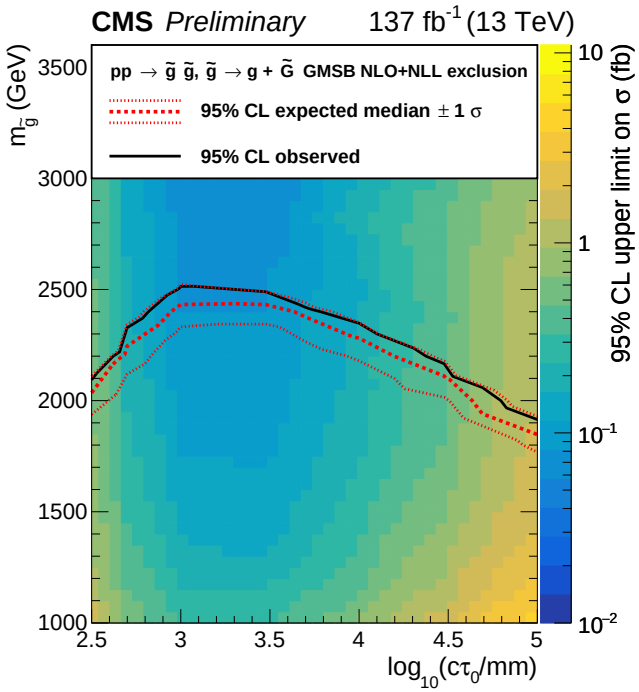
Delayed Jets

- Results interpreted in Gluino pair production in a GMSB model
- Limits set for $0.3\,\mathrm{m} < c\tau < 30\,\mathrm{m}$
- Best limit on $m_{\tilde{g}}$ is 2.5 TeV for $c\tau = 1$ m





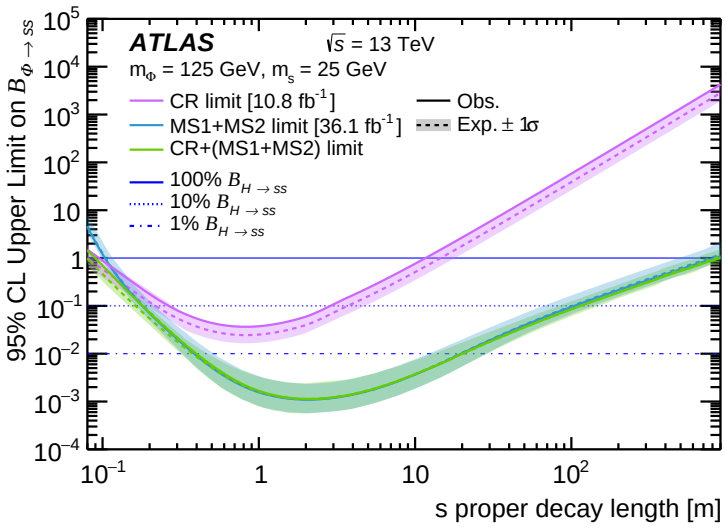
CMS-PAS-EXO-19-001

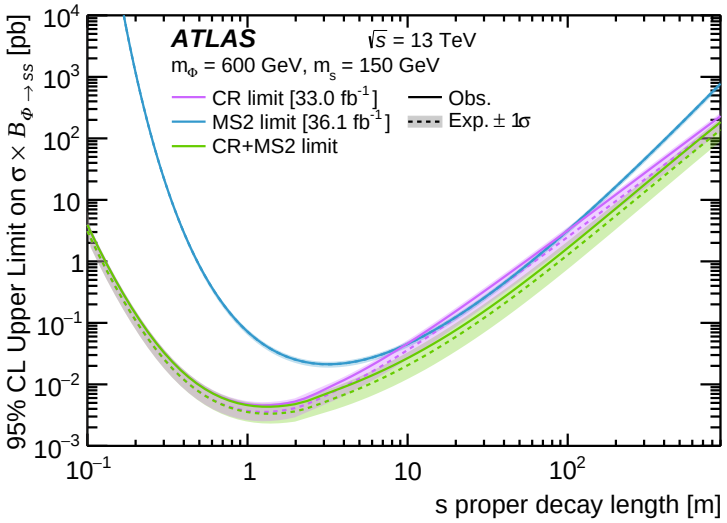


Displaced neutral particles in ATLAS

- Consider long-lived scalar particles *s* from a Hidden Sector pair-produced via mediator Φ
- Two analyses, searching for decays either in the HCAL or in the muon system

- Displaced jets in the HCAL are identified using a per-jet BDT, making use of the HCAL/ECAL energy ratio CR and other jet and track properties
- Final event selection uses a per-event BDT including signal and background-like jets and other event properties
- Dominant QCD background estimated from data
- Combine with search for vertices of decays in the muon system
- Calo-based analysis significantly extends limits for high masses of mediator Φ





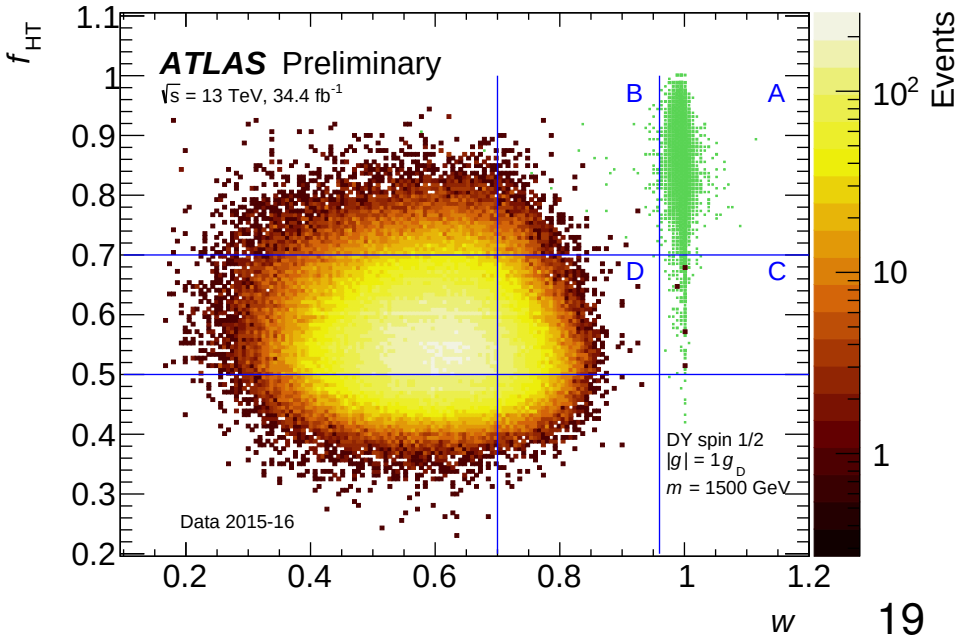
arxiv:1902.03094, Submitted to EPJC

Search for Magnetic Monopoles and HECOs

Brand New!

- Brand new ATLAS result on monopoles and high-electric charge objects
- Magnetic Monopoles present in GUTs are usually very massive ($\approx 10^{16}$ GeV), but can be in reach of the LHC in some BSM models
- Monopoles with magnetic charge $|g| = g_{\mathrm{D}}$ have a signature similar to a particle with electric charge $|z| = 68.5\,e$
- Large energy loss through ionization, monopoles (and other highly charged particles) might be stopped in the ECAL

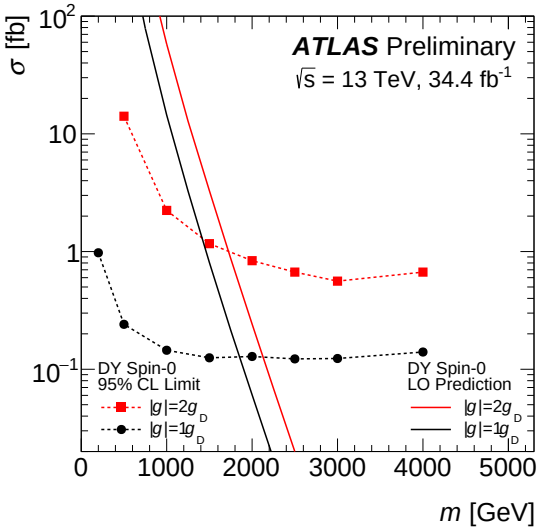
- Use high-threshold (2-6 keV) hits in the ATLAS TRT plus pencil-like ECAL clusters to identify monopole/HECO candidates
- Use fraction of HT TRT hits and fraction of energy contained in the most energetic ECAL cells in the calorimeter clusters to define signal region
- Background estimated with ABCB method

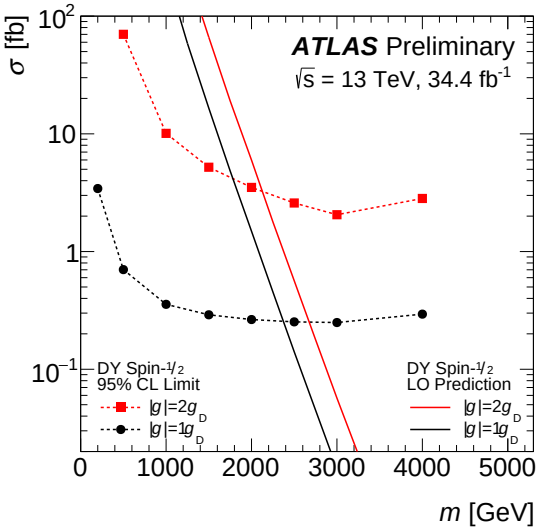


ATLAS EXOT-2017-20

Search for Magnetic and HECOs

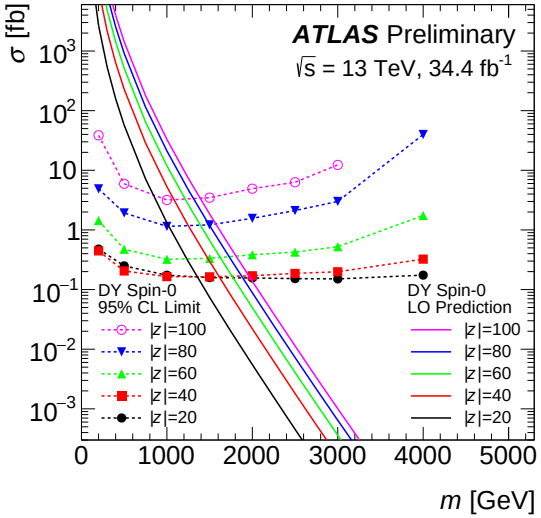
Brand New!

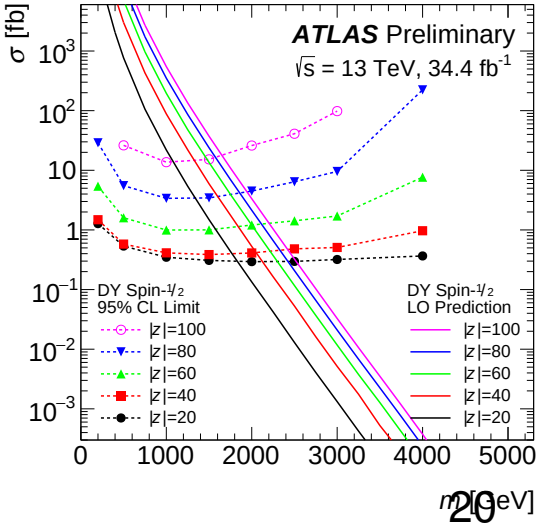




- Limits set on monopoles and HECOs in spin-0 and spin-1/2 scenarios
- Consider charges of $|g| = 1$ and 2 g_{D} and $|z| = 20 - 100$ for HECOs

- Improvements over previous ATLAS searches by a factor of 5
- For $|g| = 2g_{\mathrm{D}}$, surpasses previous limits from MoEDAL which uses induction techniques
- First LHC limits of $|z| = 80 - 100$
- More details in the talk from C. Alpigiani yesterday

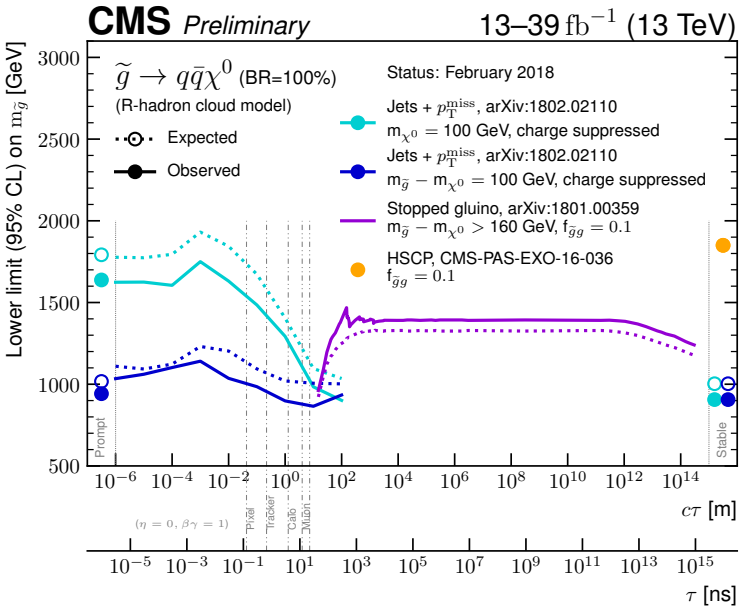


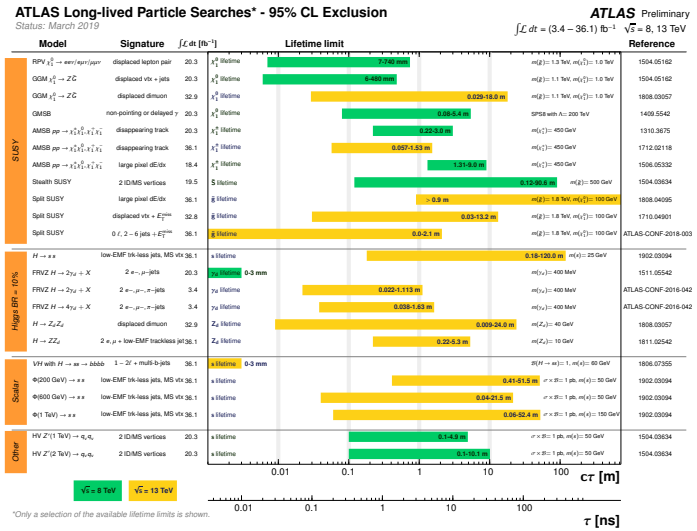


ATLAS EXOT-2017-20

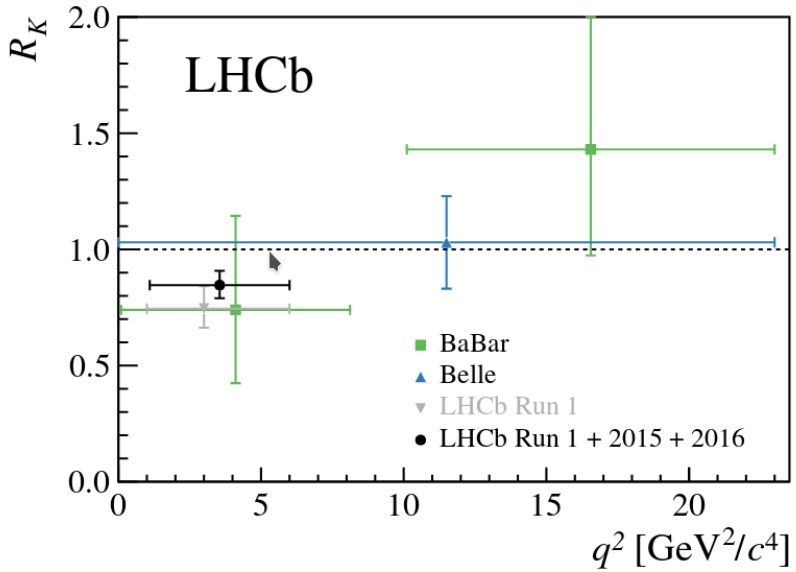
Summary LLP

- This just scratches the surface of the ATLAS/CMS search program for long-lived particles
- Several analysis techniques used to cover $c\tau$ from 10^{-6} to 10^{14} m in some models
- Range from 0.1 to 100 m covered by a variety of analyses, ensuring sensitivity to all kinds of BSM Physics





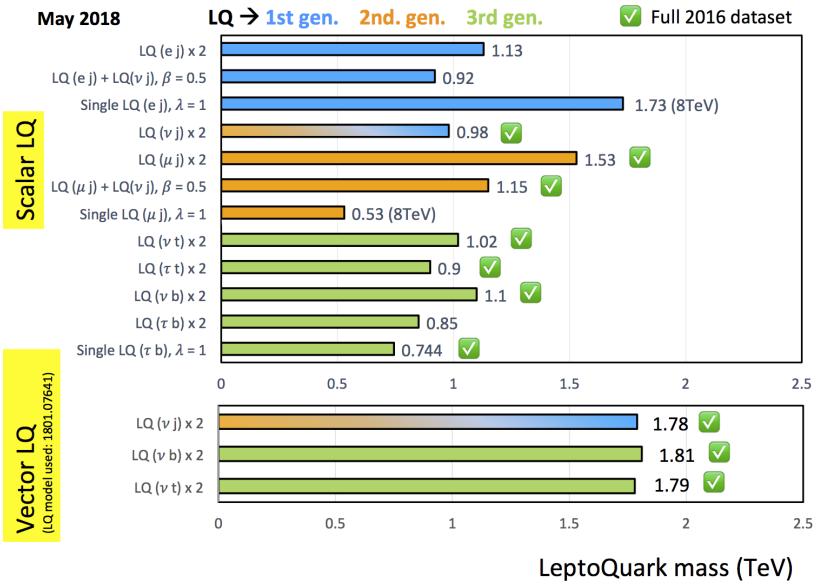
Leptoquarks



Phys. Rev. Lett. 122, 191801

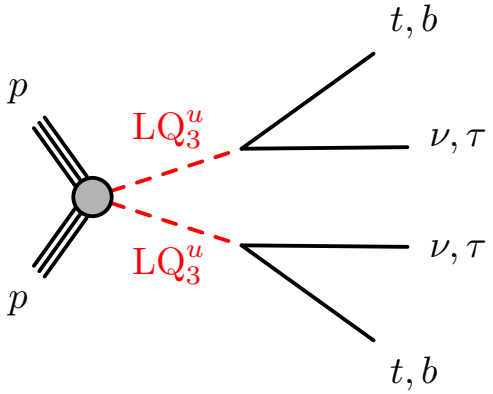
- Leptoquarks are fractionally charged bosons with both non-zero baryon and lepton number
- Appear in several BSM theories such as GUTs
- Could be candidates for explaining the flavor-nonuniversality hinted at for example by LHCb

- BRW model assumes three generations of LQs, interacting with the three generations of quarks and leptons through the coupling $\lambda_{\mathrm{LQ}\to\ell q}$, usually set to $\sqrt{4\pi\alpha}$
- For scalar LQs, the only other relevant parameter is the BR into charged lepton + quark β

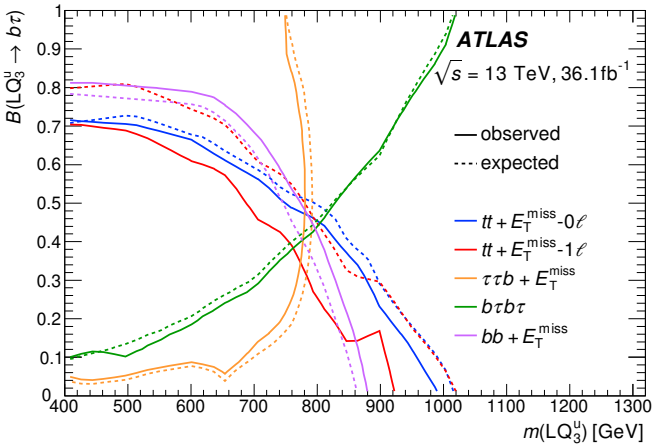


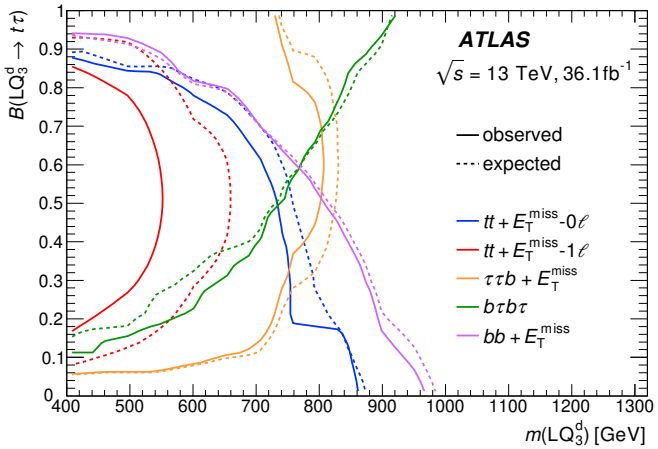
Third Generation LQs in ATLAS

- Pair production of 3rd gen. LQs results in a large variety of final states
- This analysis combines a dedicated search in the $b\tau b\tau$ channel with reinterpretation of SUSY searches in several final states containing $E_{\mathrm{T}}^{\mathrm{miss}}$



- The $b\tau b\tau$ analysis selects events with 1 or 2 b-tags and distinguishes $\tau_{had}\tau_{had}$ and $\tau_{\ell}\tau_{had}$ categories in each case
- Signal-like events are selected using BDTs based on a variety of event properties
- Limits are set separately for u-type and d-type LQs and reach from 800 GeV to $>$ 1 TeV depending on branching ratios when combining all analyses

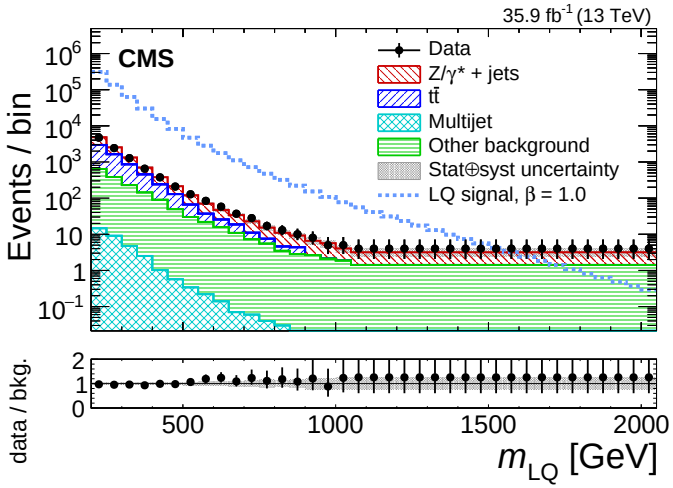


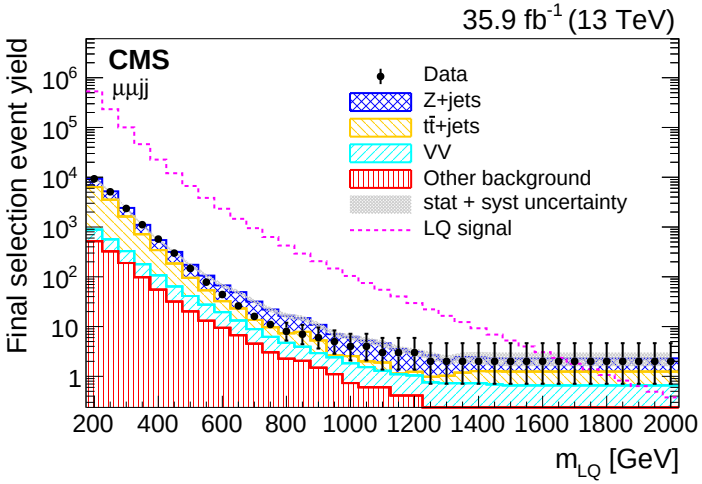


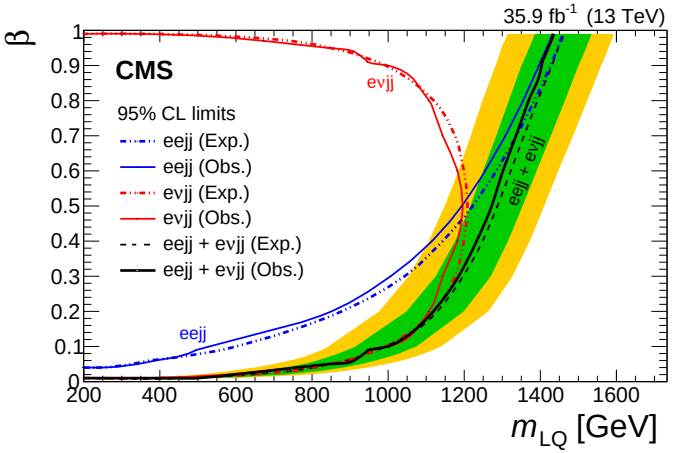
arvix:1902.08103, Submitted to JHEP

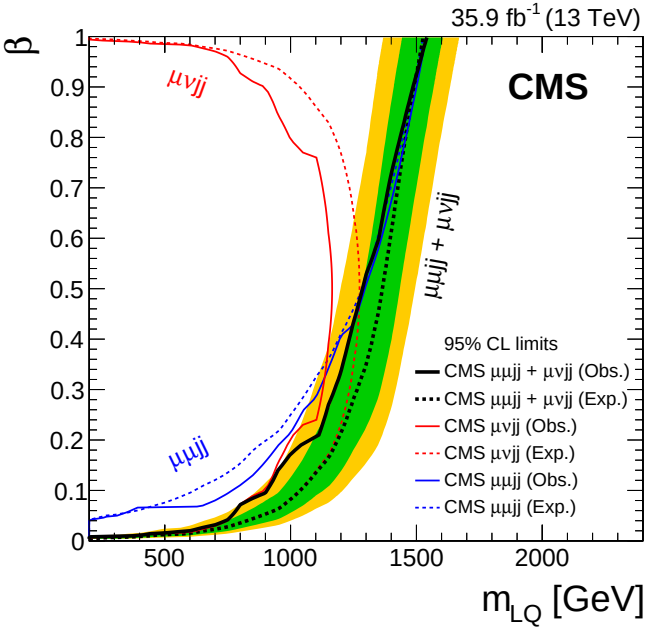
1st and 2nd Generation LQs in CMS

- Two similar analyses in CMS searching for 1st and 2nd gen. LQs in the $\ell\nu jj/\ell\ell jj$ final states
- Backgrounds are mostly Z+jets and $t\bar{t}$
- Limits up to 1.4 TeV







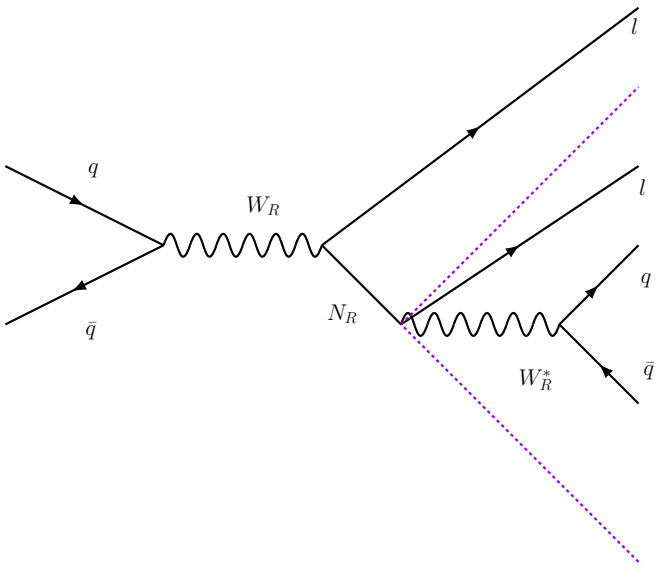


PRD 99 (2019) 052002, PRD 99 (2019) 032014 similarly from ATLAS
arxiv:1902.00377, submitted to EPJC

Heavy Neutrino

- The origin of neutrino masses is not understood with the Standard Model
- Could be explained by the seesaw mechanism, where the small ν masses are "balanced" by the existence of heavy neutrinos
- Type I and II seesaw models can be part of Left-Right symmetric models, where a heavy right-handed neutrino N_R appears alongside a heavy right-handed W_R

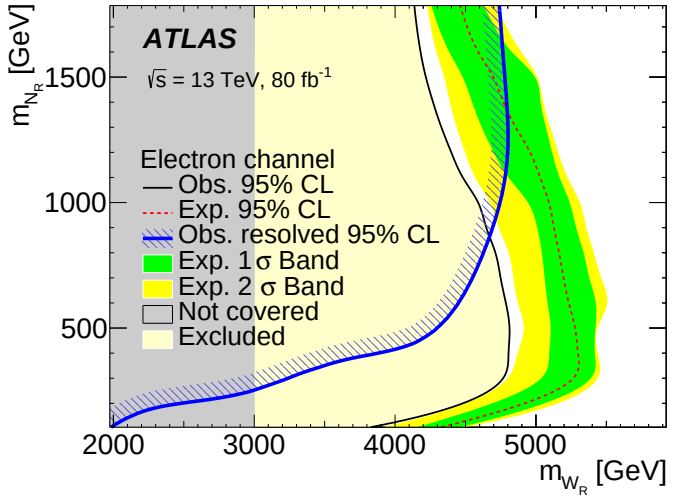
- This analysis considers the case where $m_{W_R} >> m_{N_R} \rightarrow$ decay products of N_R are boosted into a single large jet
- Select events with 2 same-flavor lepton, the leading lepton being back-to-back with a large area jet containing the second lepton

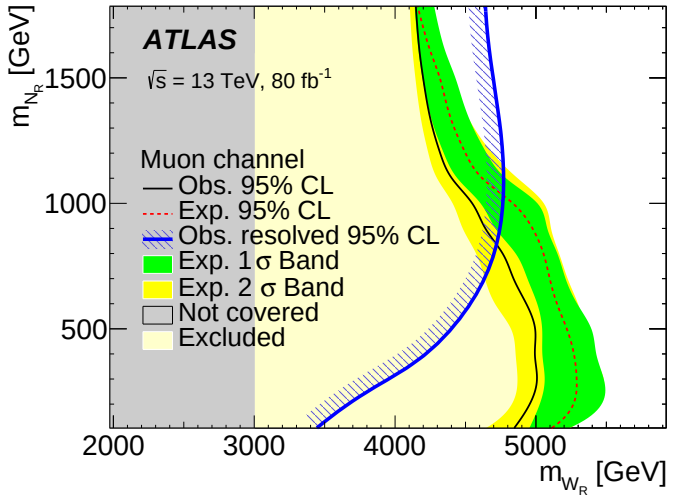


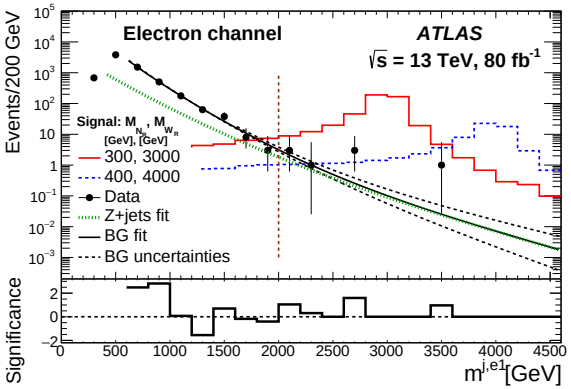
arxiv:1904.12679, Submitted to PLB

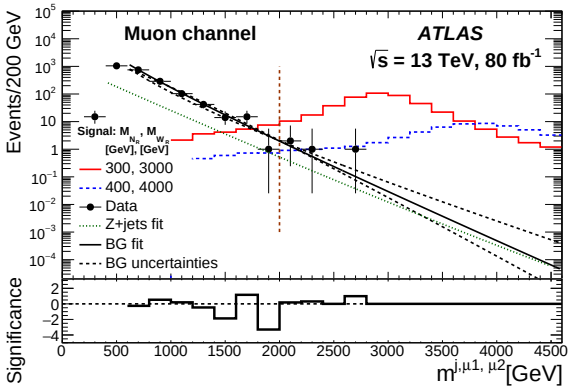
Heavy Neutrino

- W_R candidates are reconstructed from the leading lepton and the jet
- Signal peaks in the mass distribution of this signal
- Background estimated from fit to the data in the low mass region
- Limits on m_{W_R} up to 5 TeV for $m_{N_R} \approx 0.5$ TeV
- Significantly improves existing limits for low m_{N_R}



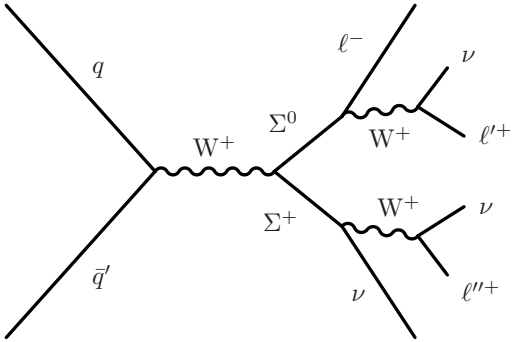




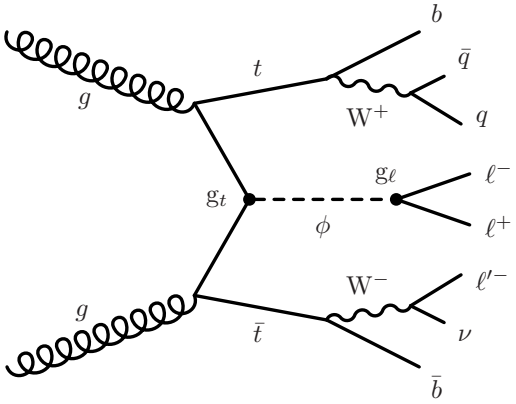


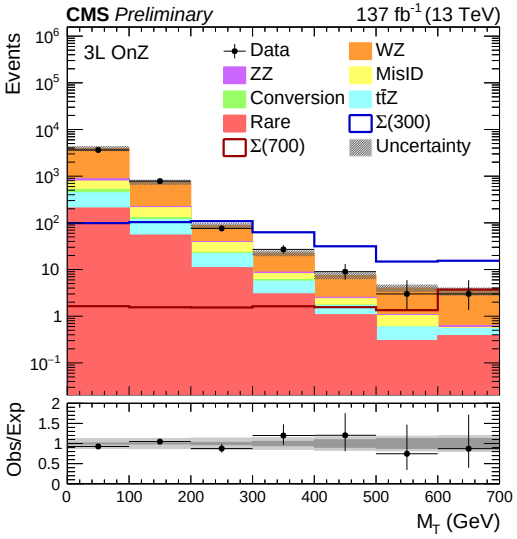
arxiv:1904.12679, Submitted to PLB

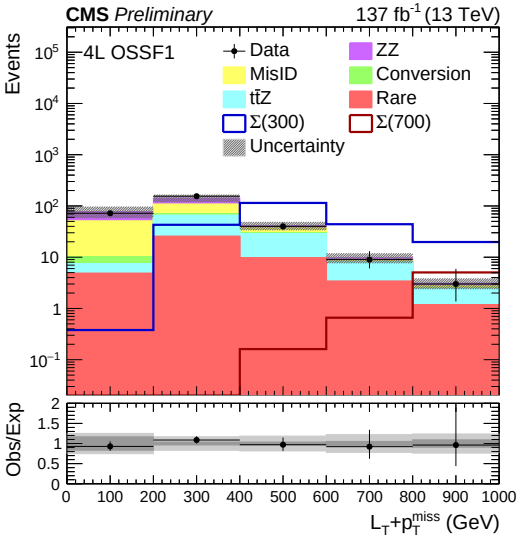
New Physics in Multileptons



- Type-III Seesaw mechanism introduces SU(2) triplet of Dirac leptons $\Sigma^{\pm,0}$
- Also considered: (pseudo-)scalar Φ decaying to leptons, produced in association with top quarks
- Search performed in full Run 2 data set, considering events with three light leptons
- Combinations of lepton charges and flavors as well as event activity variables are used to define a multitude of signal bins

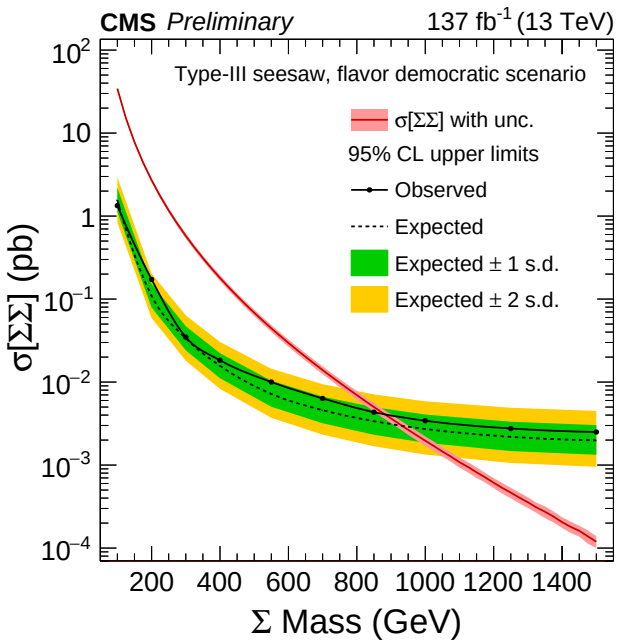




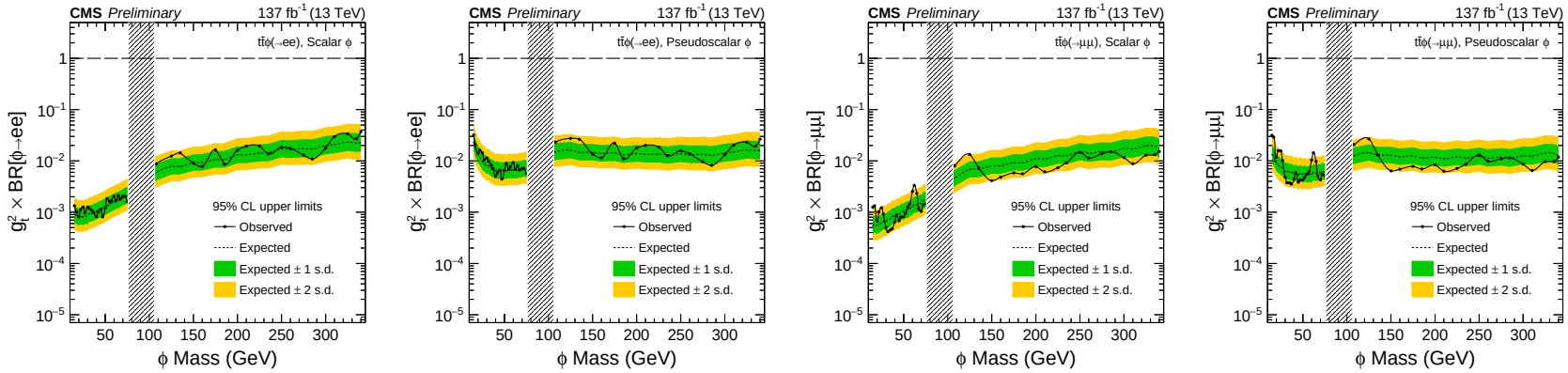


CMS-PAS-EXO-19-002

New Physics in Multileptons



- Limits on the production cross section of heavy lepton pairs in Type-III Seesaw models
- Lepton masses below 880 GeV excluded in flavor-democratic models
- Limits also set on coupling strength $\times$ BR in for (pseudo-)scalars Φ separately for decays into ee and $\mu\mu$



CMS-PAS-EXO-19-002

Summary

- Vast search program for BSM Physics in ATLAS and CMS
- Presented here was only a small selection, focusing on recent results
- So many topics not included:
  - Excited Leptons
  - Vector-like Quarks
  - And many more
- The flood of full Run 2 result should be upon us soon, expanding our knowledge about what's out there even further
- New results will appear all the time from both CMS and ATLAS

- Most parallel talks about BSM searches already happened, but let me advertise for this afternoon:
  - Search for New Resonances in Hadronic Final States with the ATLAS and CMS Detectors by F. Cirotto
  - Searches for new phenomena in leptonic final states with the ATLAS and CMS detectors by B. Li
  - Beyond the standard model physics at the HL-LHC with CMS by E. Usai