Exotic Searches at the LHC

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On behalf of the ATLAS and CMS collaborations

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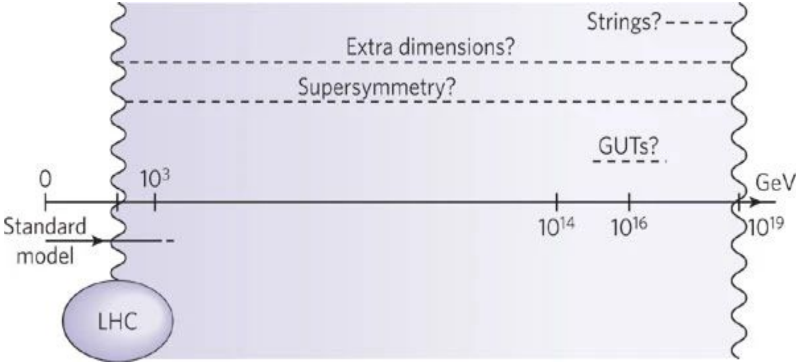
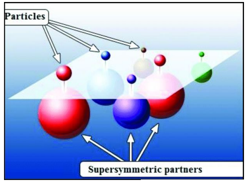
La Thuile 2022

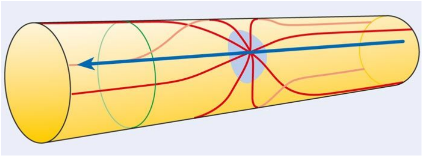
XXXV Les Rencontres de Physique de la Vallée d'Aoste

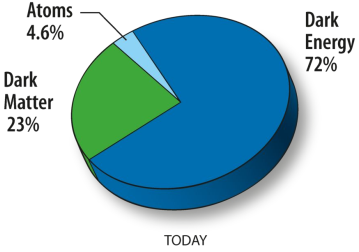
Testing BSM Physics at the LHC

- LHC is world's most powerful discovery machine
  - Hope to find hints of BSM physics in direct searches and measurements as well
- Program driven by BSM and experimental results
  - Explaining unresolved mysteries in SM
    - Hierarchy problem, Unification, Dark matter, neutrino mass, Matter-antimatter asymmetry …
  - Strong hints from measurements
    - μ g-2, B-anomalies, direct detection of DM, cosmological constraints, neutrino oscillation …
- Program driven by signatures in detector
  - Trigger and reconstruction algorithm are important
  - Improving techniques (ML) to explore more exotic world
    - Allow us to test new signature, more sensitivity



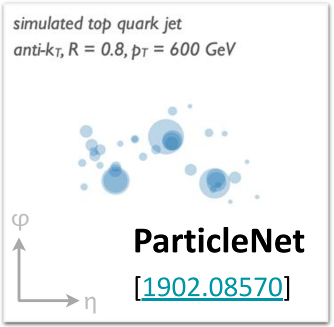


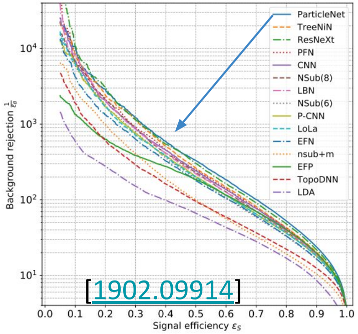




Overview of Exotic searches at LHC

- The O(100) list of BSMs being covered with full Run-2
  - Only a small subset of recent results will be showing.
  - **Search for new bosons/interactions**
    - New heavy resonances (Spin-0,1,2)
    - Leptoquarks (Spin-0/1)
  - **Search for new fermions**
    - Vector-like quarks
    - Heavy Leptons
  - **Search for Flavor anomalies (Z/Z' →eμ)**
- Analysis techniques with a dedicated role for ML
  - Improvement on Jet Tagging; Boosted decay products
  - Better background estimates





ATLAS EXOT public results link

CMS EXO public results link

CMS B2G public results link

Search for X →lν (l=e, μ)

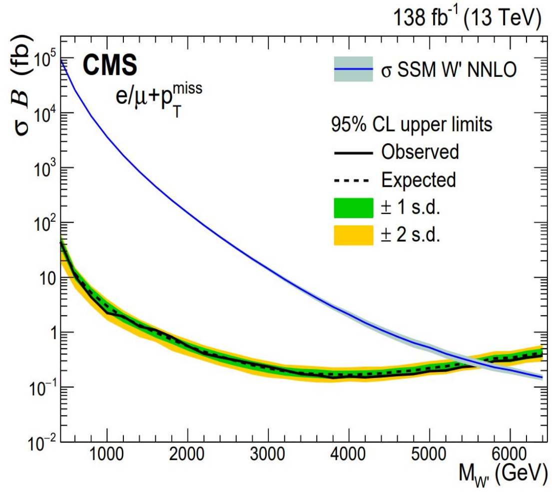
CMS-EXO-19-017 2202.06075
(13 TeV: ATLAS 1906.05609, CMS 1803.11133)

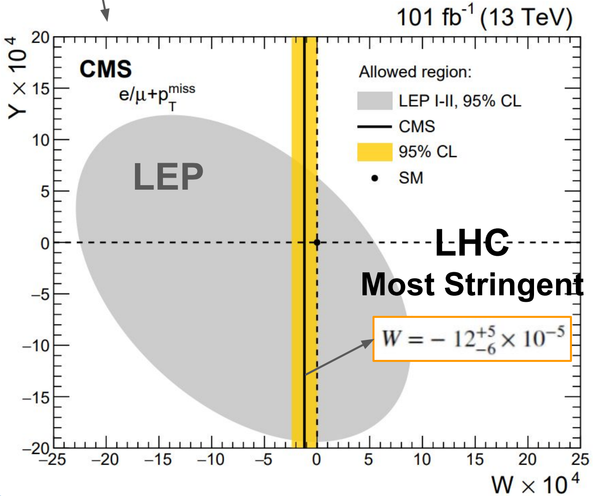
- Golden channel : Search for heavy charged W' with l+p_T^{miss}
  - Bump hunt search in M_T with various BSMs : SSM, split-UED model, RPV SUSY
  - Indirect search in effective field theory (EFT)
    - NP can induce effect on SM predictions
    - Parameterizing in the framework of **EFT**
  - Set new constraints on composite Higgs model parameter (m*-g*) with 3 different ways
  - **First results** on ***W* parameter** and **compositeness parameters** using pp→lν data

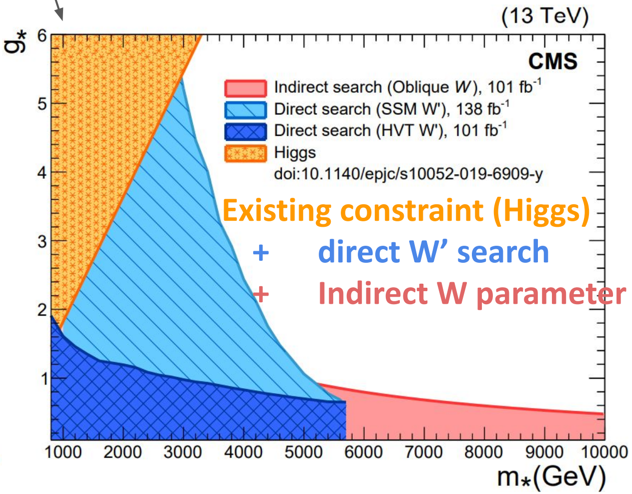
2 operators can be tested in lν

$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2, \quad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$

***W, Y* parameter** grows with √s



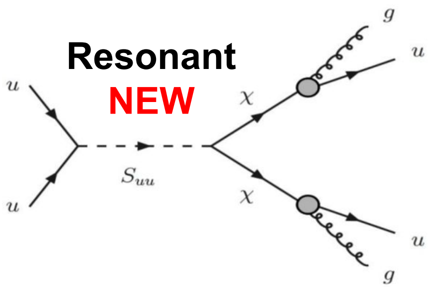


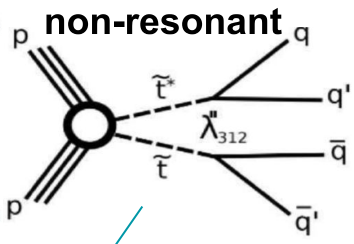


Search for Y →XX→4 j

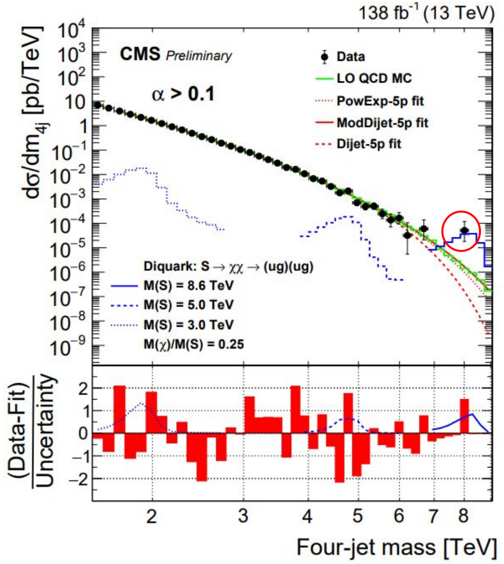
CMS-EXO-21-010

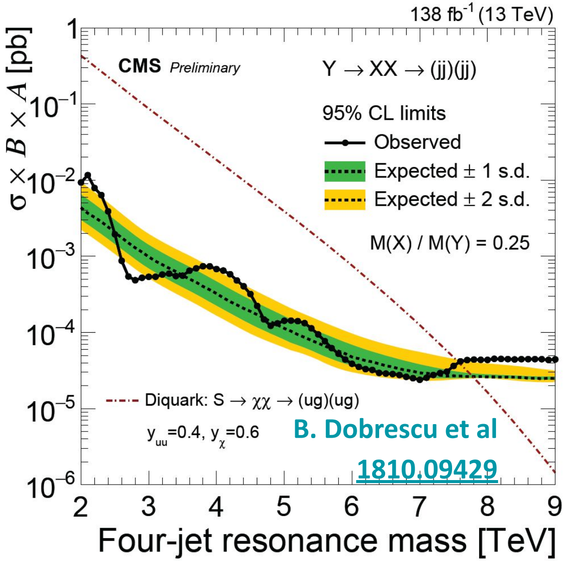
- Search for **paired-dijet resonances in 4-jet channel**
  - Both resonant (Diquark model) and non-resonant productions (RPV Stop model) are considered.
  - Optimal dijet pairing with small $M_{Asymmetry}$, ΔR^{pair}_{jj}, $\Delta\eta$
  - Background-fit in various α bins = $\langle m_{X=jj} \rangle / m_{Y=4j}$

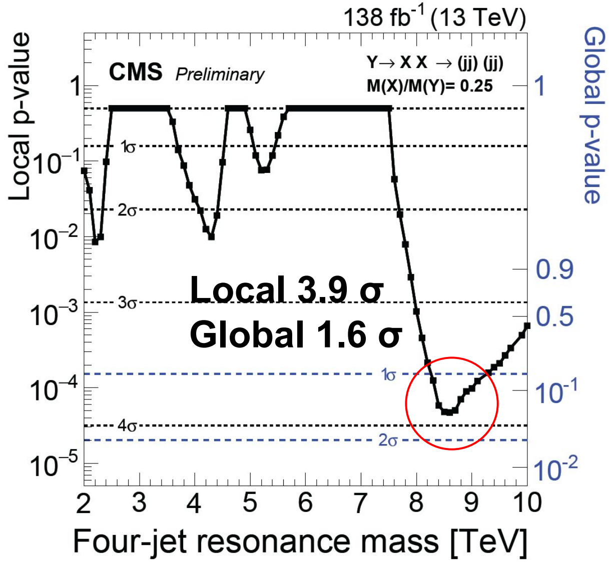




(13 TeV: ATLAS 1710.07171, CMS 1808.03124)





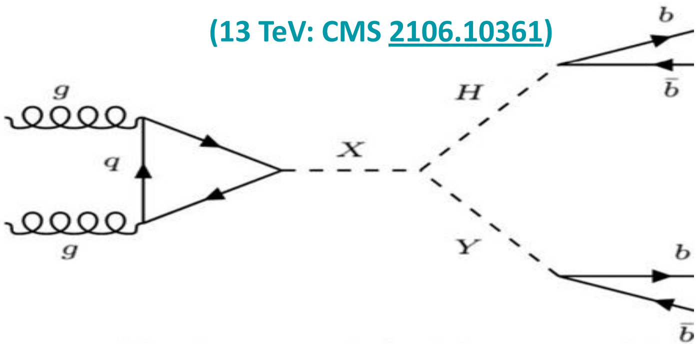


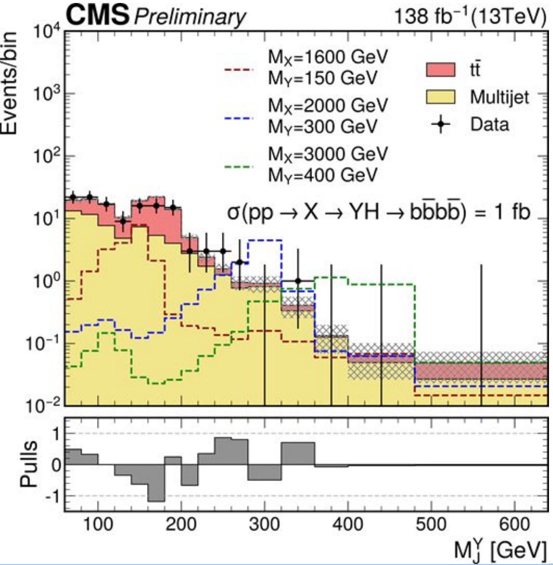
Search for X⟶ YH in 4b

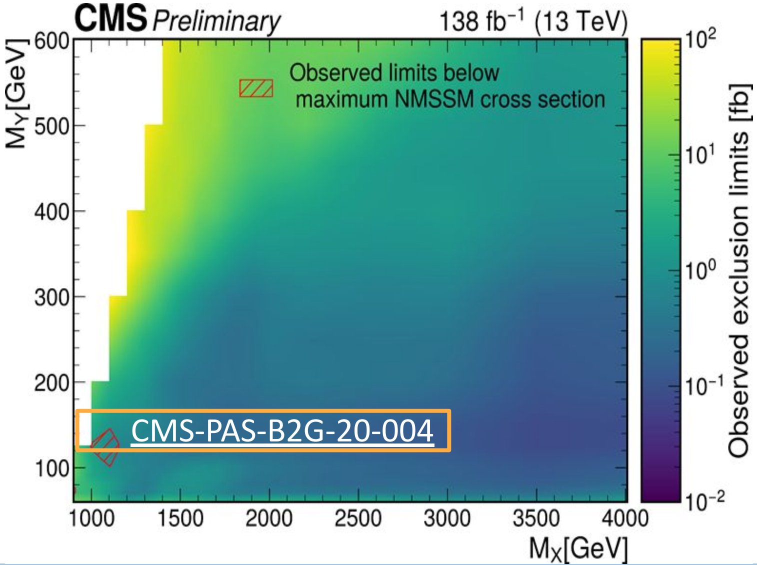
[CMS-PAS-B2G-21-003](#)

(13 TeV: CMS [2106.10361](#))

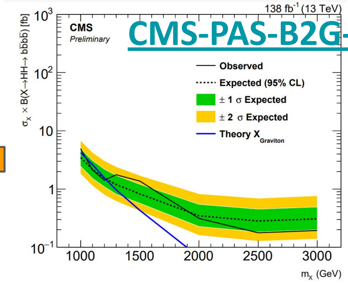
- Search for 2 new scalars (X, Y) in 4b channel
  - Motivated from NMSSM Higgs scalars model
- Using a **new jet substructure tool** ⇒ ParticleNet (ML)
  - jet as kind of "particle cloud", clustered to get info
- Signal bump in (M_X - M_Y) plane







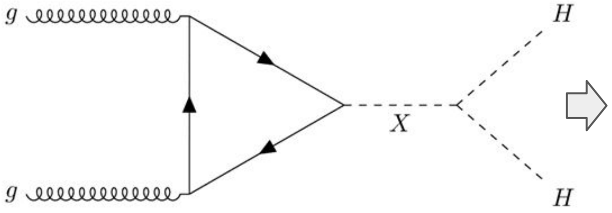
- If M_Y= M_H (125 GeV), $\sigma_X \cdot B(H \to bb)$ ~ 5e-2 fb
- **Factor 2 improved than HH⟶4b CMS result**



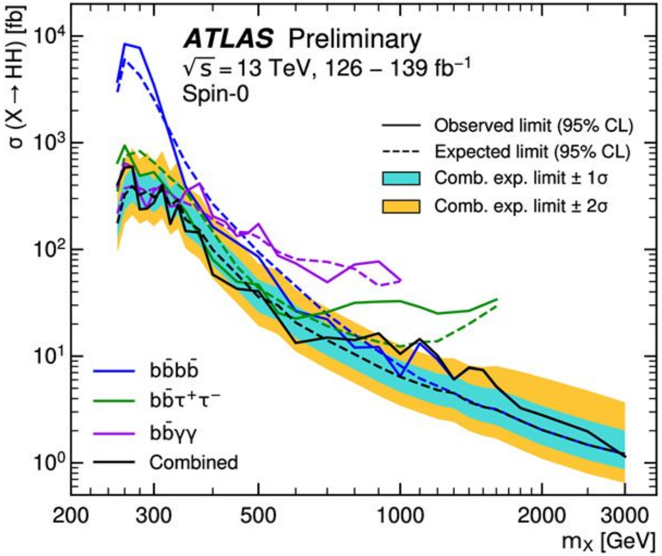
Search for X⟶ HH

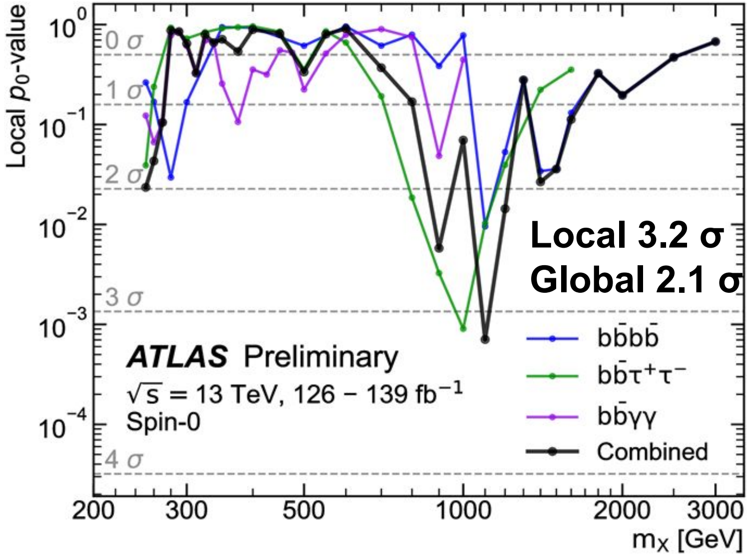
ATLAS-CONF-2021-052
(13TeV: ATLAS 1906.02025, CMS 1811.09689)

- Combination of searches for Higgs boson pairs, resonant and non-resonant
- Sensitivity of different channels in different mass ranges



bbbb
bbττ
bbγγ

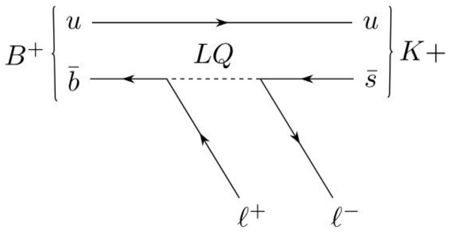




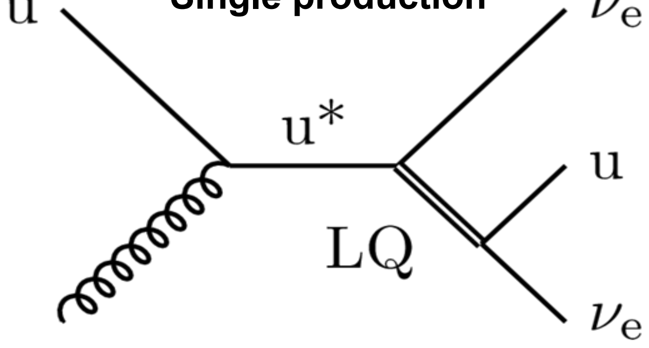
ATLAS-CONF-2021-035
ATLAS-CONF-2021-030
ATLAS-CONF-2021-016

Leptoquarks (LQ)

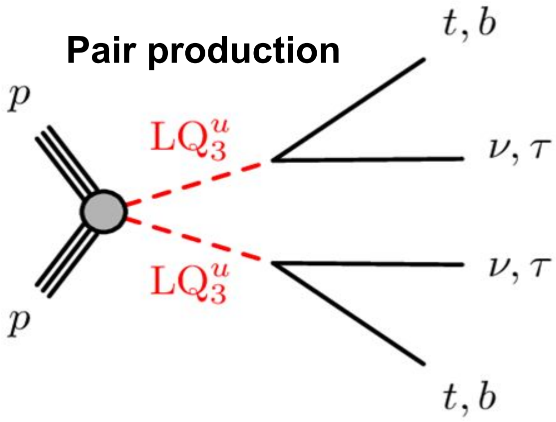
- Leptoquarks (LQs) can couple to both leptons and quarks
  - Both scalar and vector bosons are possible
- Carry fractional electric charge
- Processes can violate lepton flavor universality (LFU)
  - Possible explanation for B anomalies:
    - strongly couple to 3rd generation SM fermions
- Predicted in GUTs and composite Higgs models



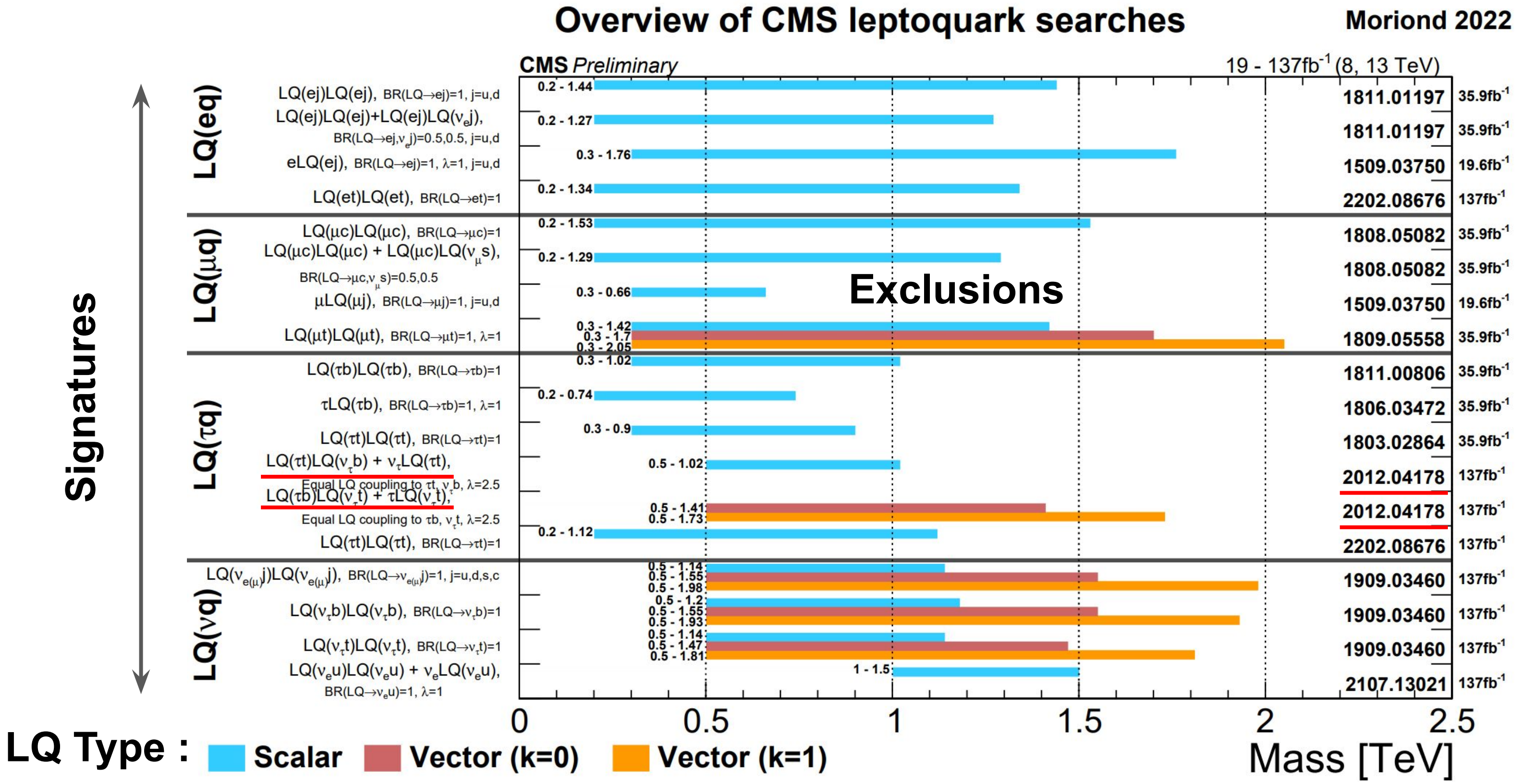
Single production



Pair production



Overview of LQ Searches



Dedicated searches for 1st, 2nd, 3rd or mixed generation

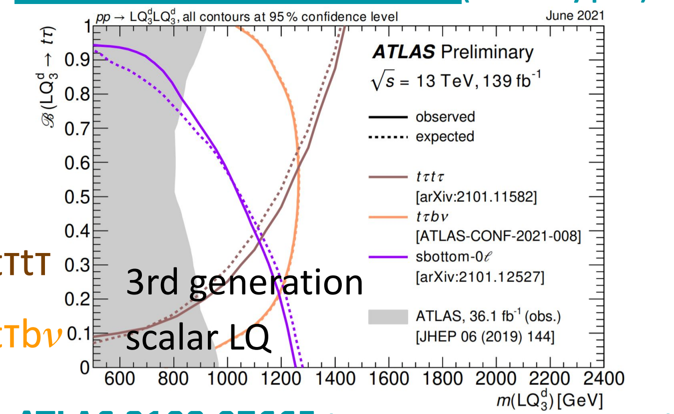
CMS LQ SummaryPlot 13TeV

ATLAS LQ SummaryPlot 13TeV

Search for 3rd generation LQ

- Search for 3rd generation scalar and vector LQs
- Both pair and single production
- LQs couple to all 3rd generation fermions
- Most stringent constraint to date on 3rd LQs.

ATLAS-PHYS-PUB-2021-017(summary plot)

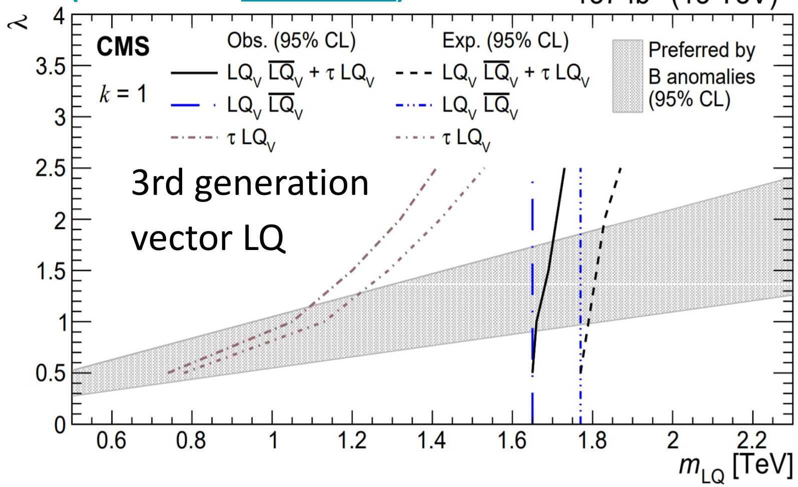


$LQ\overline{LQ} \rightarrow t\tau t\tau$

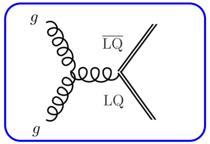
$LQ\overline{LQ} \rightarrow t\tau b\nu$

CMS-EXO-19-015 arXiv:2012.04178

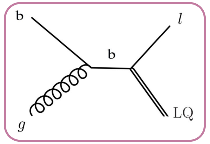
(13 TeV CMS 1805.10228)

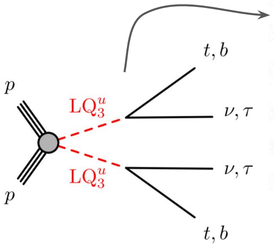


$LQ\overline{LQ} \rightarrow t\nu b\tau$

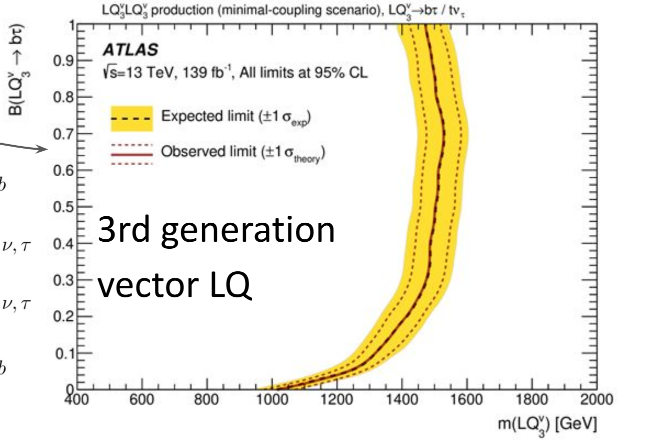


$\tau LQ \rightarrow \tau t\nu$



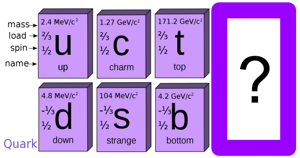


ATLAS 2108.07665 (13TeV ATLAS 1902.08103)

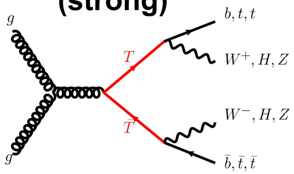


New Fermions: VLQ, heavy leptons

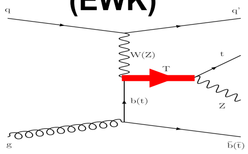
- Vector-like quarks (VLQ)
  - VLQs are colored spin ½ fermions
  - L/R-handed transform in the same way
  - Can mix with SM quarks to regulate Higgs mass



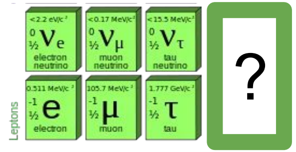
Pair production (strong)

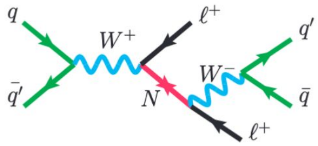


Single production (EWK)



- Heavy Neutrinos (HN)
  - Potential BSM solutions for neutrino mass :
    - Type-I Seesaw models : HN mix with SM ν
    - Type-III Seesaw models : SU(2) triplet Σ^0,Σ^+, Σ^- leptons
    - Left-Right Symmetry model (LRSM) : W_R, Z' along with 3 HN_R
    - Composite model
  - If HN is Majorana neutrino, Lepton Number Violation is possible



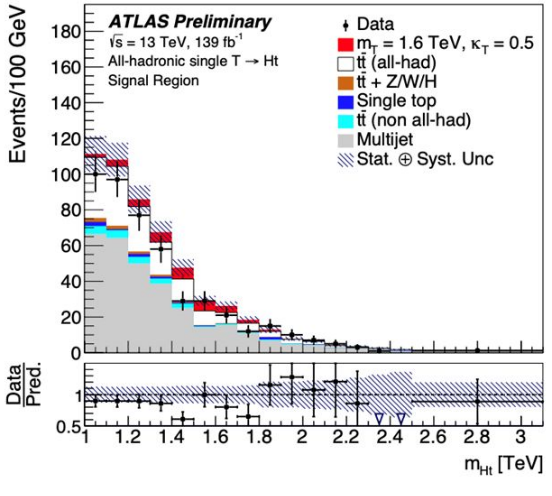


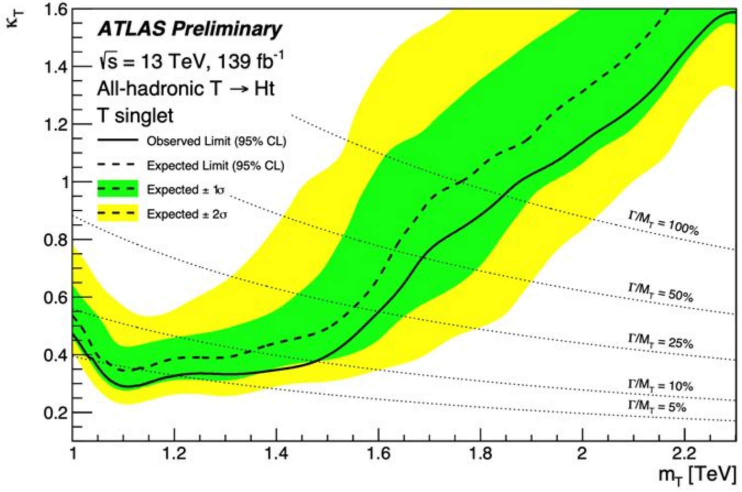
Vector-like T quark→Ht (fully hadronic)

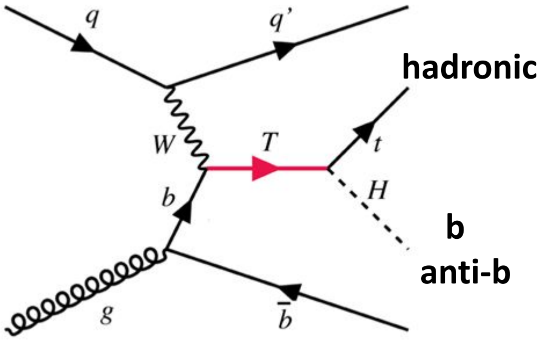
ATLAS- EXOT-2019-07 2201.07045

(13 TeV CMS 1909.04721)

- For heavy T-quark mass (>1 TeV), VLQs would mainly be produced singly if coupling is sufficiently large.
- Higgs and top are reconstructed as large-radius jets.
- tagging used to split further into search, validation and normalization regions
- Use data-driven method for multijet background





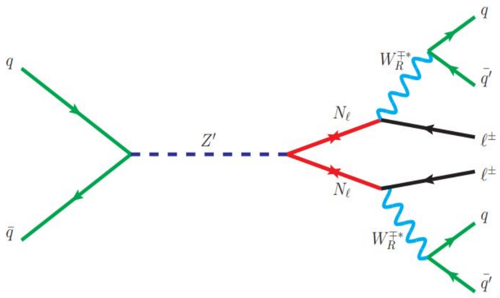


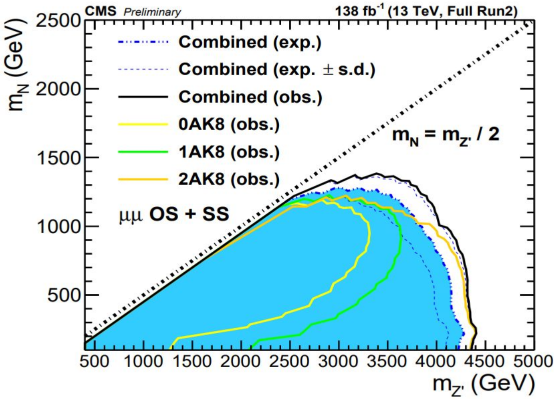
Search for heavy neutrino (HN)

- HN can be pair produced from Z' in LRSM
- First in CMS with 13 TeV (ATLAS 8 TeV)
- More complicated topology : 3 SR
  - 2 resolved (0 AK8J, 2 l) $m_N/m_{Z'}$ ~1
  - 1 resolved + 1 boosted (1 AK8J, 1-2 l)
  - 2 boosted (2 AK8J, 0-2 l) $m_N/m_{Z'}$ << 1
- Combinations of l (same-flavor)+jets

CMS-EXO-20-006

(8TeV ATLAS 1506.06020)

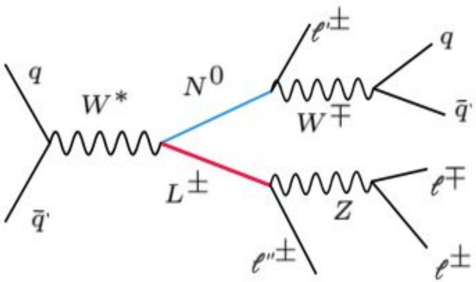


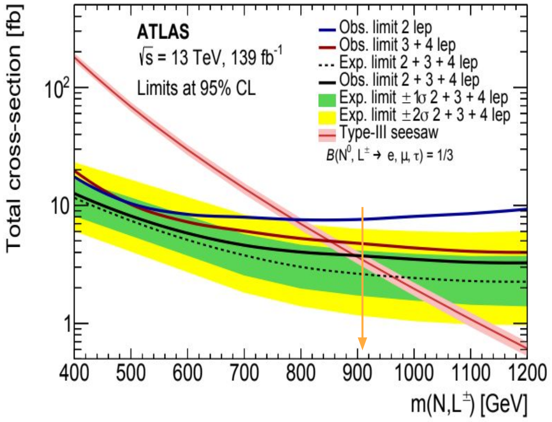


- HN and HL can be produced from virtual EW boson in Type-III seesaw model
- First combination with ll+jets channel
- A significant improvement in the sensitivity, m(N,L) < 910 GeV is excluded

ATLAS 2202.02039

(13TeV ATLAS 2008.07949 CMS 1911.04968)





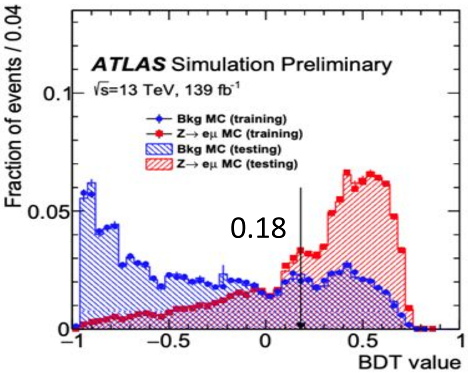
Lepton flavor anomalies test in Z→eμ

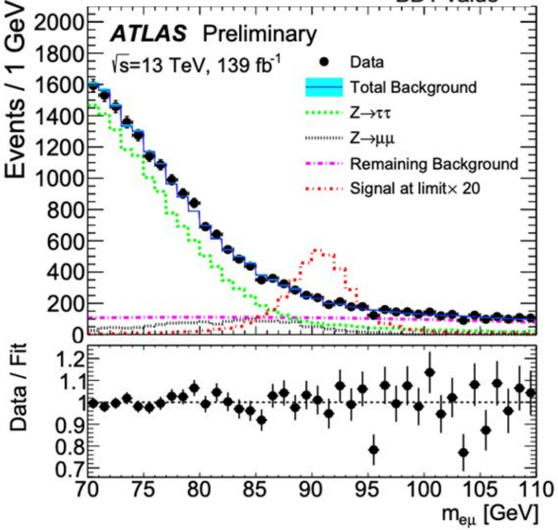
ATLAS-CONF-2021-042

- LFV has been observed in the neutrino sector
  - Charged-LFV can be **strong hints of New Physics**
  - Search for cLFV decay **Z → eμ** process
- BDT is trained in leading jet p_T, p_T^{miss} and $p_T^{e\mu}$
- Use ratio to the average of observed dielectron and dimuon events to reduce systematic uncertainties

- Stringent direct constraint **BR(Z→eμ) < 3.04 × 10^{-7}**
  - Previous LEP constraint: BR(Z → eμ) < 1.7 × 10^{-6}
  - Indirect searches μ→eee or eγ : BR(Z → eμ) < 5 × 10^{-13}
  - Also, ATLAS has the strongest limits on Z->lτ :
    BR (Z→$e\tau$) < 5.0 × 10^{-6}, BR(Z→$\mu\tau$) < 6.5 × 10^{-6}

ATLAS arXiv:2105.12491



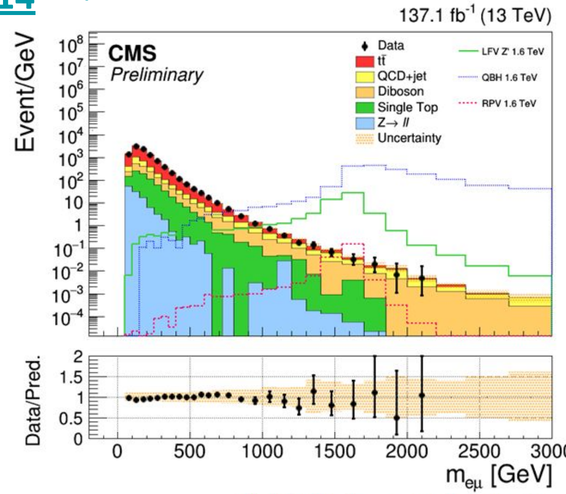


Flavor anomalies test in TeV scale

CMS-PAS-EXO-19-014

(13TeV CMS 1802.01122 , ATLAS 1807.06573)

- $X \rightarrow e\mu/e\tau/\mu\tau$ search
  - targeting X = LFV Z', QBH, stauneutrino in RPV SUSY
  - Two high p_T lepton selected and remove misidentified τ's by applying a m_T requirement
  - Use collinear mass distribution in eτ/μτ final states
  - Data-driven estimate of non-prompt/misidentified e/μ/τ coming from jets

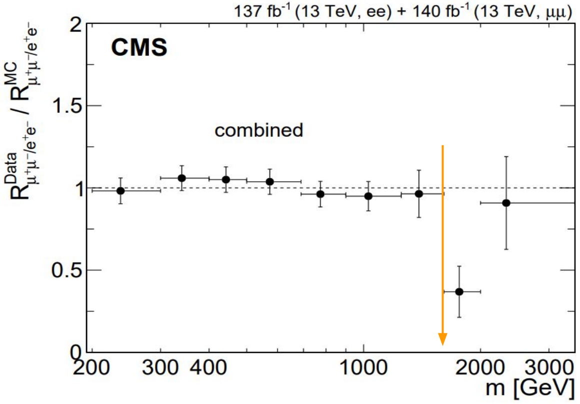


- In Z' search
  - First attempt to test LFV at TeV region
  - Using flavor ratio 'R' of dimuon differential σ to dielectron w.r.t dilepton mass.
  - The ratio is taken from unfolded mass spectra

CMS EXO-19-019

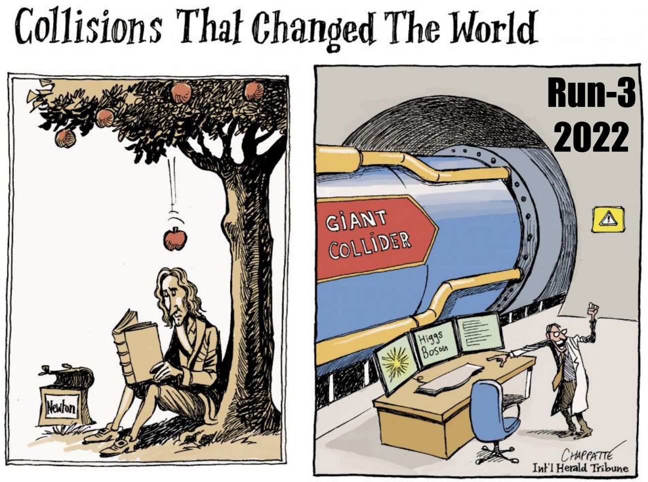
2103.02708

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \rightarrow \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \rightarrow e^+e^-)/dm_{\ell\ell}}$$



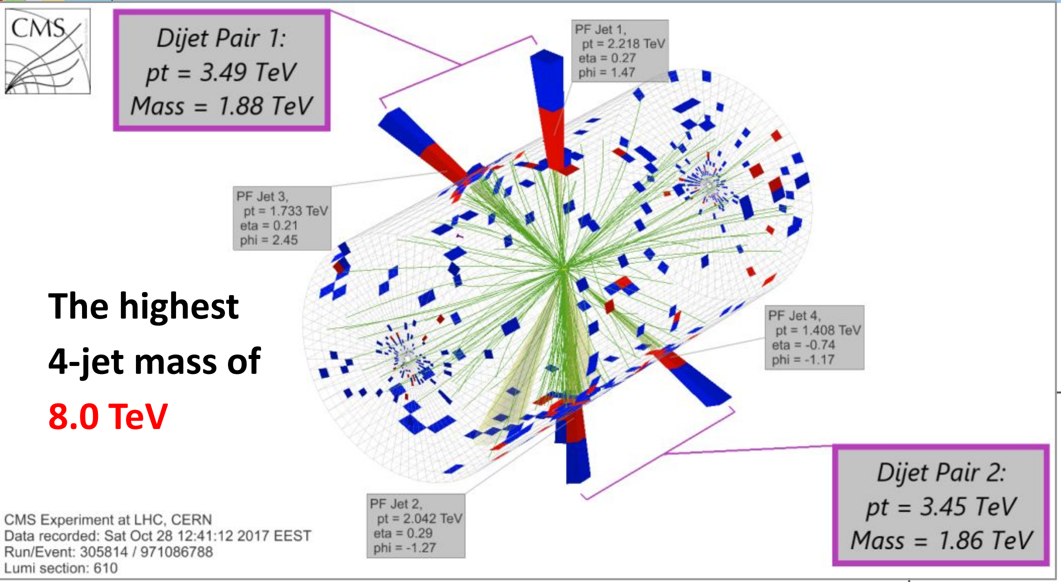
Conclude

- Large number of BSM scenarios and signatures explored with LHC Run2 data.
    - Sensitivity significantly improved with new reconstruction & analysis techniques.
    - Several new models/signatures explored for the first time !
- No clear evidence for BSM yet, but significantly extended range of model phase-space excluded.
- Still expanding on results with
    - More data and more exotic models
    - More exotic signatures in detector
    - More exotic analysis techniques
- **Stay tune for upcoming LHC Run-3 era !!**



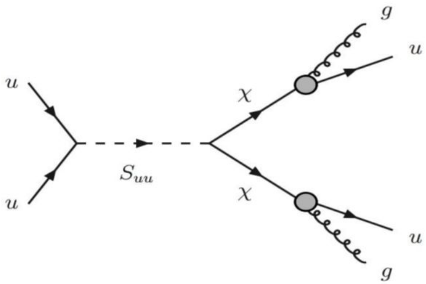
Backup

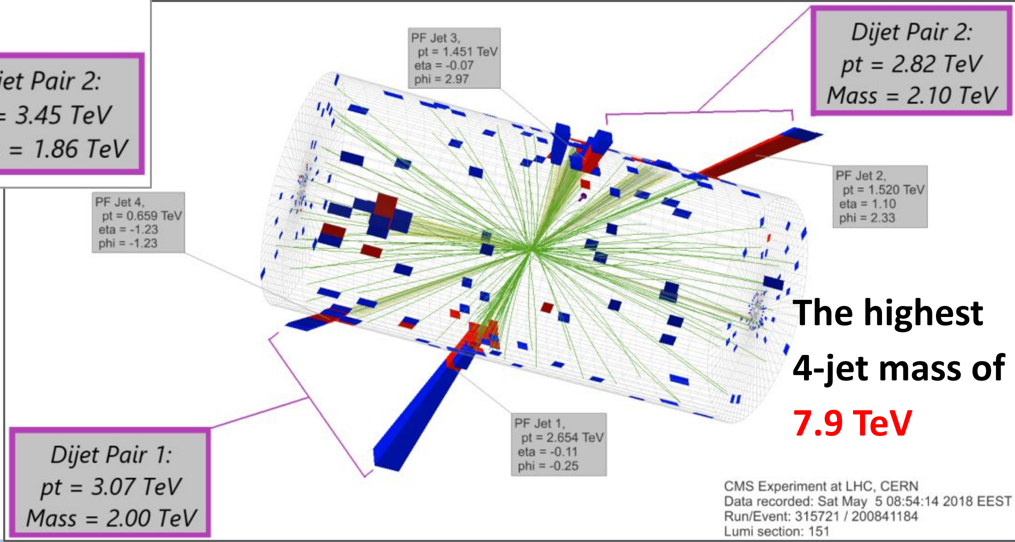
Event display for the highest 4-jet mass



The highest 4-jet mass of **8.0 TeV**

- **CMS EXO-21-010:** Search for **paired-dijet resonances in 4-jet**
- The grouping of the 4 observed jets into 2 dijet pairs (purple) dijet pair mass of ~2 TeV



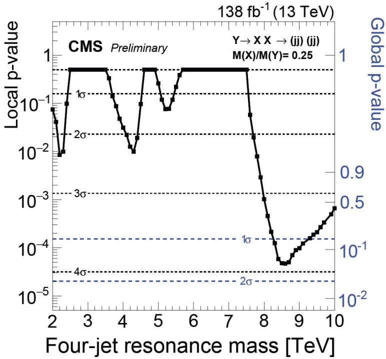


The highest 4-jet mass of **7.9 TeV**

Paired dijet resonance - Run3

CMS-EXO-21-010

- What is the expectation with Run-3? (resonant)
  - In Run III expect increase of center of mass energy from 13 TeV to 13.6 TeV and increase of luminosity from 140 to 500 fb-1
  - For center-of-mass energy at 13.6 TeV and the same luminosity expect the signal and background cross section to increase ~ 2.2 times (at 8.6 TeV), and there is no more LEE for events at ~8.6 TeV. As a result we expect an improvement in the local significance by a factor of 1.5.
  - In backup: COM = 14 TeV estimates



Run III Data	
Luminosity (fb^{-1})	Significance at 8.6 TeV (standard deviations)
30	2.8
70	4.2
140	5.9
500	11.2

Full Run II and Run III data	
Luminosity (fb^{-1})	Significance at 8.6 TeV (standard deviations)
140 (RunII)+30(RunIII)	3.2
140 (RunII)+70(RunIII)	4.5
140 (RunII)+140(RunIII)	6.1
140 (RunII)+500(RunIII)	11.3

Z' to dilepton Search - Flavor Ratio R

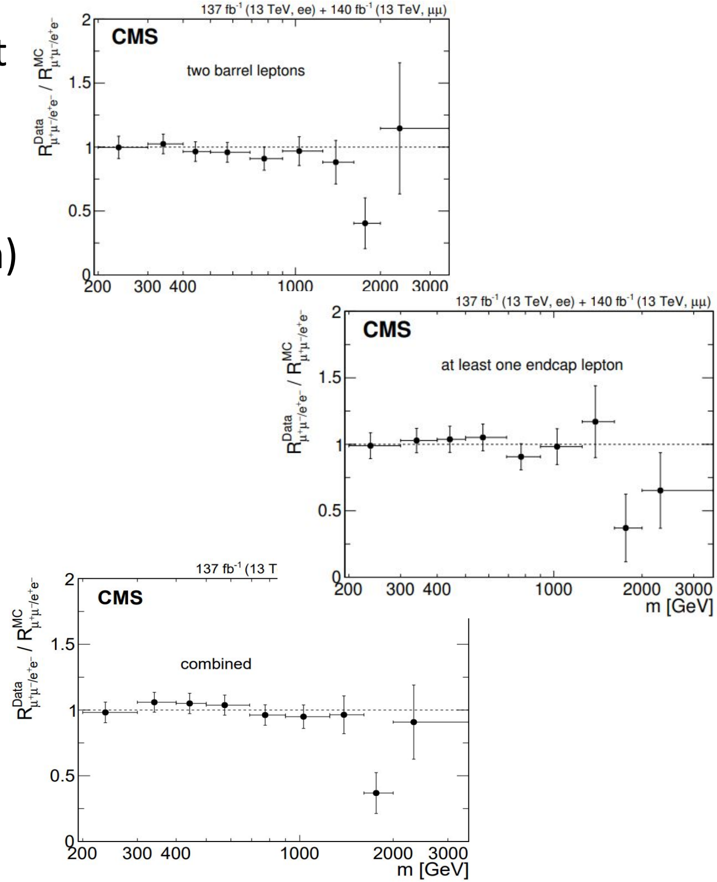
CMS EXO-19-019 [2103.02708]

- Good agreement with SM prediction up to ~ 1.5 TeV
  Above 1.5 TeV, some deviations are observed, because slight excess in the dielectron channel.

- Chi-square test (Mll > 400 GeV) is performed.
  17.9/7 for combined (two EB leptons + at least one EE lepton) case and corresponding **one-sided p-value is 0.012**

- No significant deviation from lepton flavor universality is observed.

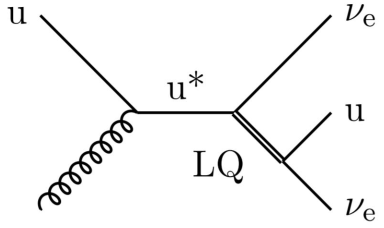
- This search will be continued with Run 3 data improving the lepton flavor ratio measurement with log-likelihood ratio : bin-by-bin correlations are handled as nuisance parameters of the likelihood ⟶ gives better estimation of the uncertainty at high mass



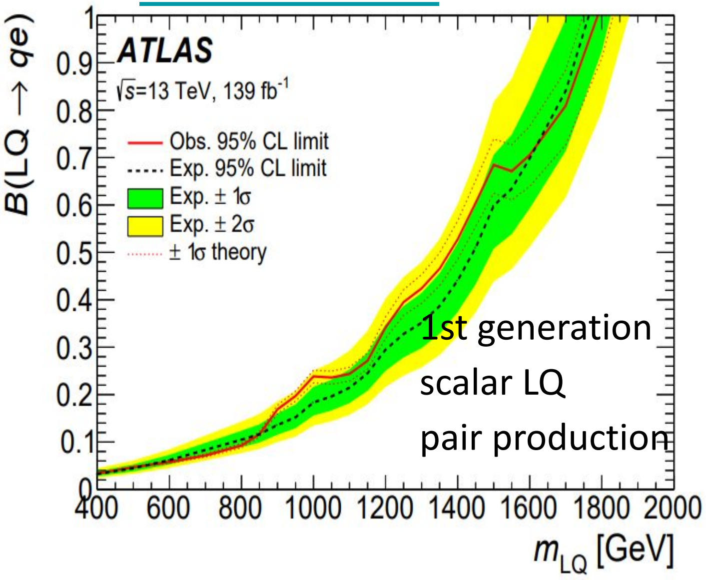
Search for 1st generation LQ

CMS-EXO-20-004 arxiv:2107.13021

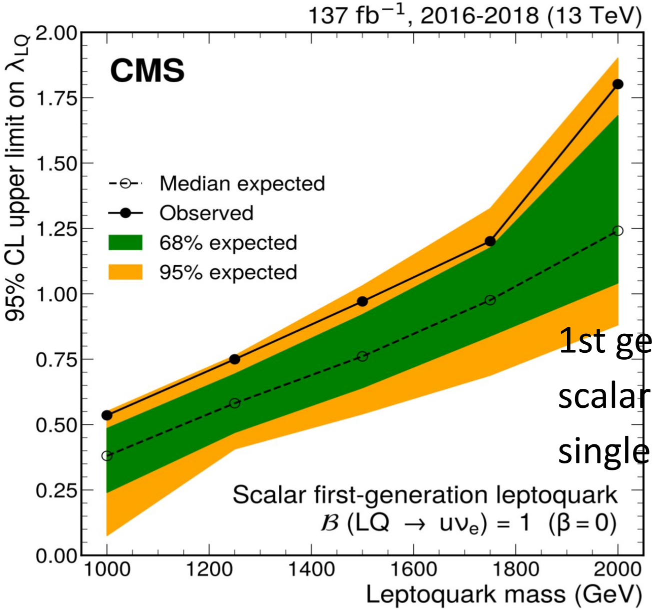
- Search for 1st scalar LQ decaying into a lepton and a jet
- Both pair production and single production
- In case of LQ couples to uν, signal mainly influencing the single production rate



ATLAS arxiv:2006.05872



1st generation scalar LQ pair production



1st generation scalar LQ single production

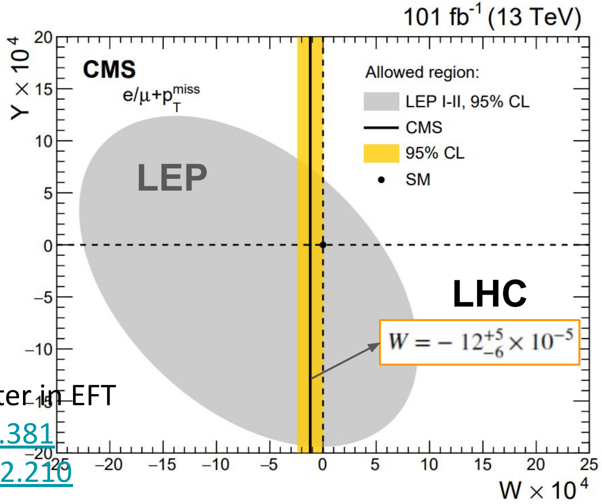
Two new approaches in lv

Effective Field Theory Approach

EFT approach quantifies potential deviations from the SM expectations through the *W* parameter

$$\left|\frac{P_W}{P_W^{(0)}}\right|^2 = \left(1 + \frac{(2t^2-1)W}{1-t^2} + \frac{t^2 Y}{1-t^2} - \frac{W\,(q^2 - m_W^2)}{m_W^2}\right)^2$$

Modified SM predictions by **reweighting method.**
Compared with data and set the W-parameter



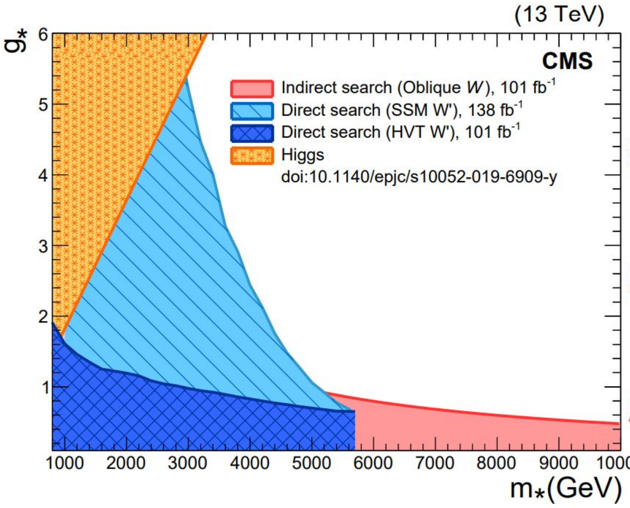
W, Y parameter in EFT
PhysRevD.46.381
PhysLettB.772.210

Composite Higgs boson models

H compositeness
JHEP06(2007)

Input for this reinterpretation comes in 3 complementary ways

1. **direct W' search** : W' boson to be a composite resonance. The gauge coupling to the new constituents is g*
2. **indirect EFT approach** : *W* parameter is used to quantify deviations from the SM.
3. **Higgs** : NP modify SM prediction of H prod/decay modification can be scaled.



$$g_{W'} = \frac{g^2}{g_*}$$

$$g_*^{\,2} = \frac{g^2 M_W^2}{W m_*^2}$$

$$\Delta\mu_H = \frac{g_*^{\,2} v^2}{m_*^2}$$