Searches in CMS for new physics in final states with jets

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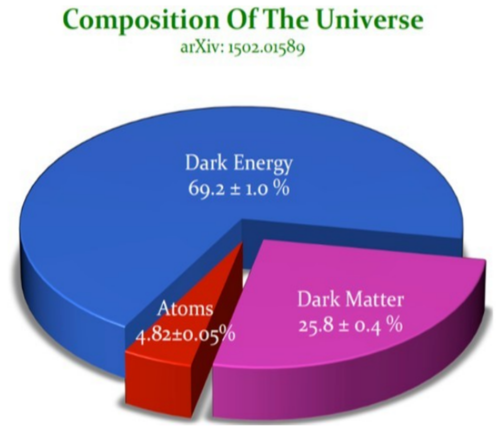
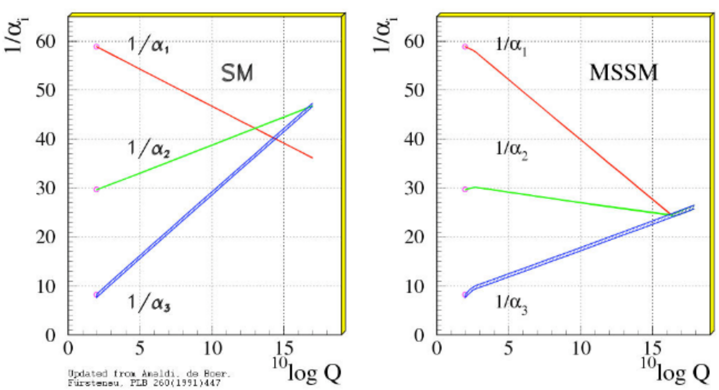
Motivation

- The Standard Model (SM) of particle physics is incomplete:
  - Why is there an imbalance of matter and antimatter in the universe?
  - How does gravity fit into our model?
  - Why do quarks and leptons come in three generations? Are they elementary particles?
  - Why are gauge couplings so different, are they unified at a higher scale? Are there more forces in nature?
  - What is 95% of the Universe made of?





- Many models of physics that extend the SM often require new particles that couple to quarks and/or gluons and decay to jets.

Jet resonance searches in CMS

There is a variety of recent resonance searches in CMS, with jets in final states using data from Run II (2016-2018) with an integrated luminosity of 138 fb^{-1}: CMS EXO public results

A **selection of recent Full Run II results** will be discussed in this talk:

- Search for **VBF production of SS muons through Majorana neutrinos or the Weinberg operator** (**CMS-EXO-21-003**)
- Search for high-mass resonances decaying to **a jet and a Lorentz-boosted resonance** (**CMS-EXO-20-007**)
- Search for **resonant and nonresonant** production of **pairs of dijet** resonances (**CMS-EXO-21-010**)
- Search for **LQs decaying to tau and b** (**CMS-EXO-19-016**)

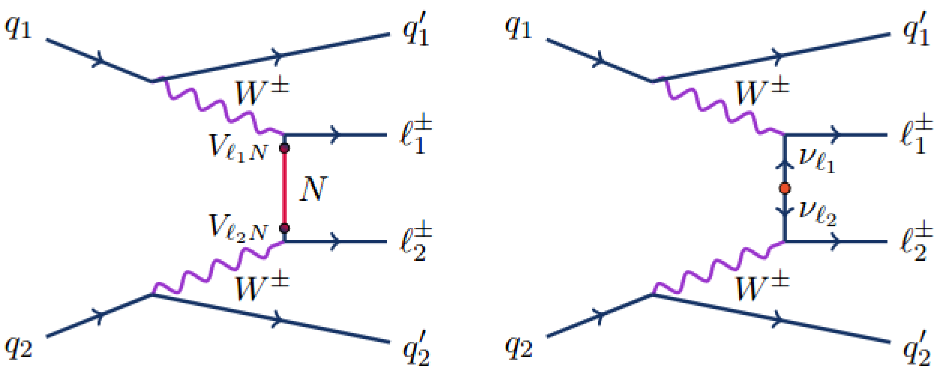
There is a dedicated talk on displaced jet analyses by Celia Fernandez Madrazo.

Search for VBF → μ±μ± through Majorana N or the Weinberg operator

CMS-EXO-21-003

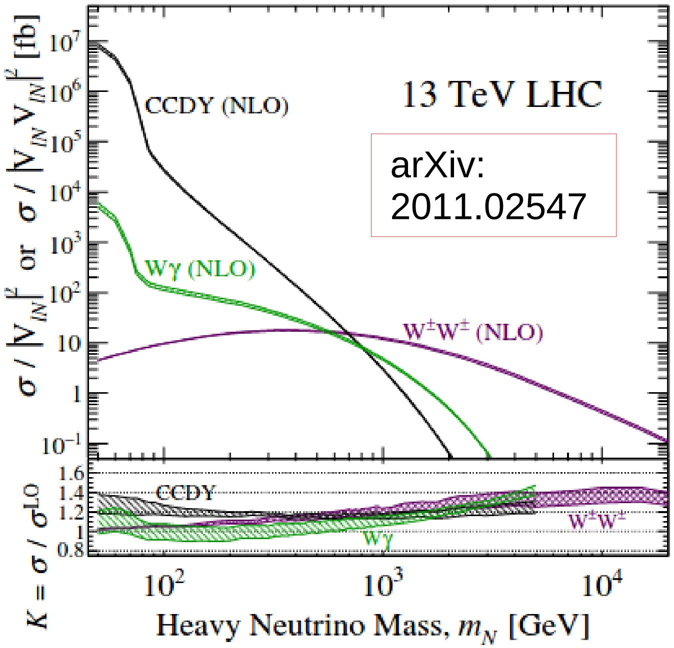
Experimental Signature:

- Two SS μ's and two jets.
- The cross section of VBF t-channel process decreases more slowly with increasing m_N compared with the traditional N hunting strategy (*s*-channel production $q\bar{q}$ annihilation).



Backgrounds:

- <u>Main</u>: WZ and non-prompt leptons estimated using CRs.
- <u>Others</u>: WW, ZZ, tZq, ttW, ttZ, and VVV



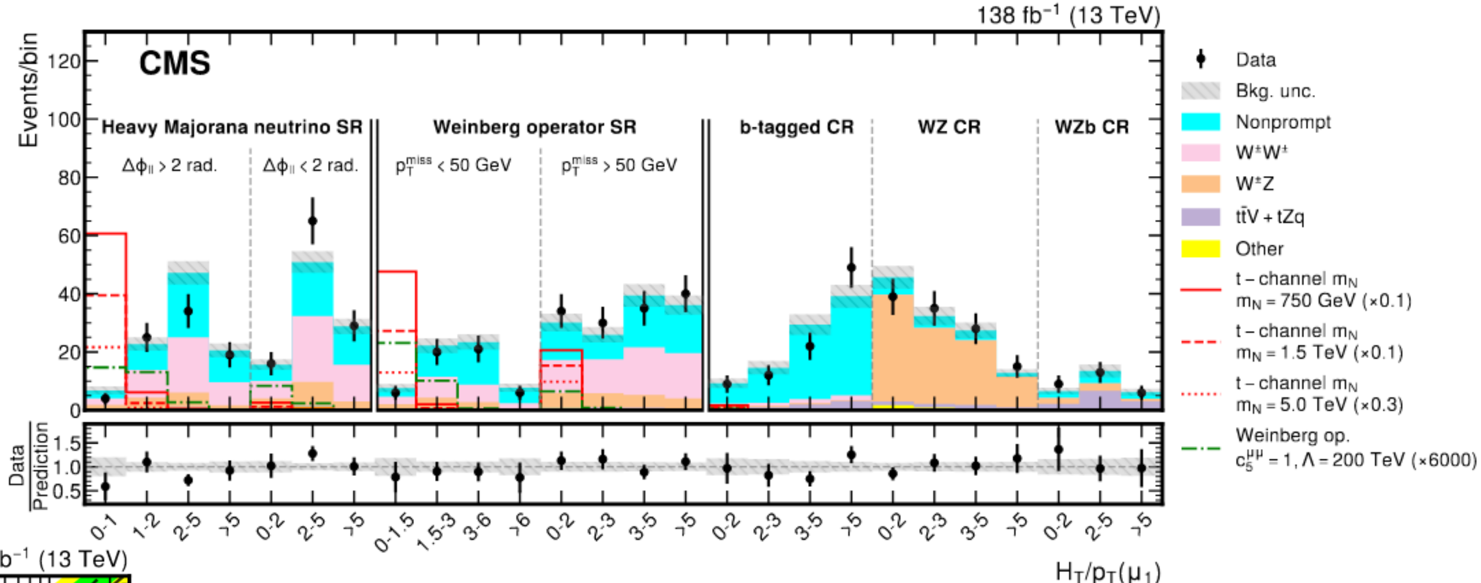
Signal Models:

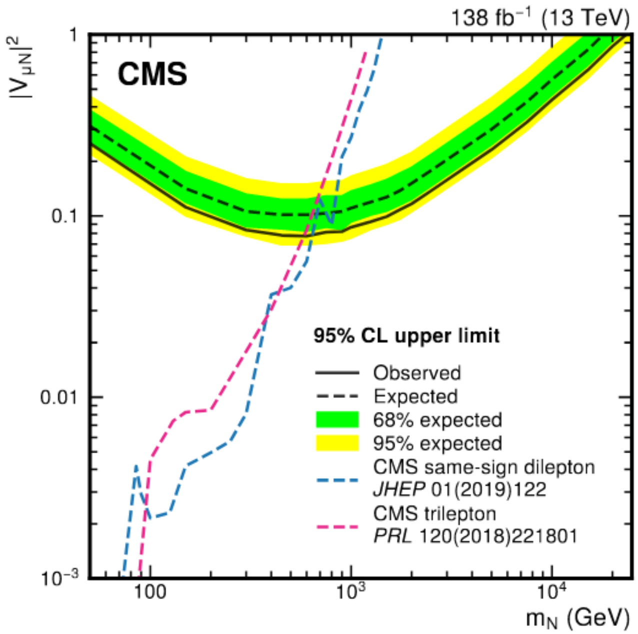
- VBF HMN at Seesaw type I
- Weinberg operator Dim.5
  - Wilson coefficient $C_5^{\ell\ell'} \sim |m_{\mu\mu}|$

Results on VBF → N → μμ through Majorana N or the Weinberg operator

CMS-EXO-21-003

- Discriminating variable for both analyses is **$H_T/p_{T(\mu1)}$**.





- **The first search for Majorana N at several TeV**: reaching very high m_N up to 23 TeV.
- **A first probe of the Weinberg operator at the LHC**: upper limit on effective $|m_{\mu\mu}|$: obs (exp) 10.8 (12.8) GeV.

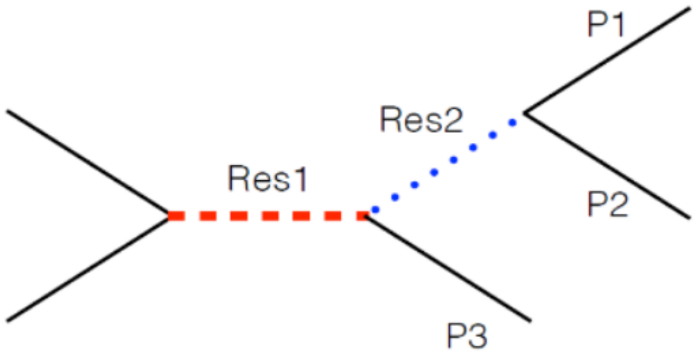
Di-tri-jets Search

CMS-EXO-20-007

Experimental Signature:

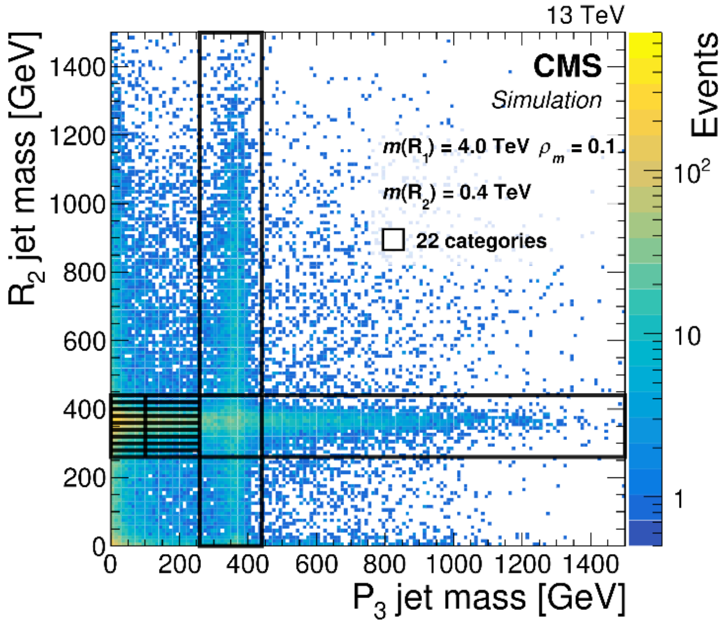
Two large-radius (wide) resolved jets, one coming from R2 (R2-jet) and one coming from the third parton (P3-jet):

- pp → R1 → R2+P3 → (P1+P2) +P3
- P1, P2, P3 are gluons



Main backgrounds:

Multijet QCD production estimated with a data-driven method, using several parametric functional forms. Discrimination between signal and QCD background, by exploiting jet substructure information and kinematics of the decay.



Signal Models:

Warped extra dimensions where R1 is a KK gluon (GKK), R2 is a radion (φ)

- GKK → φg → ggg (trijet)

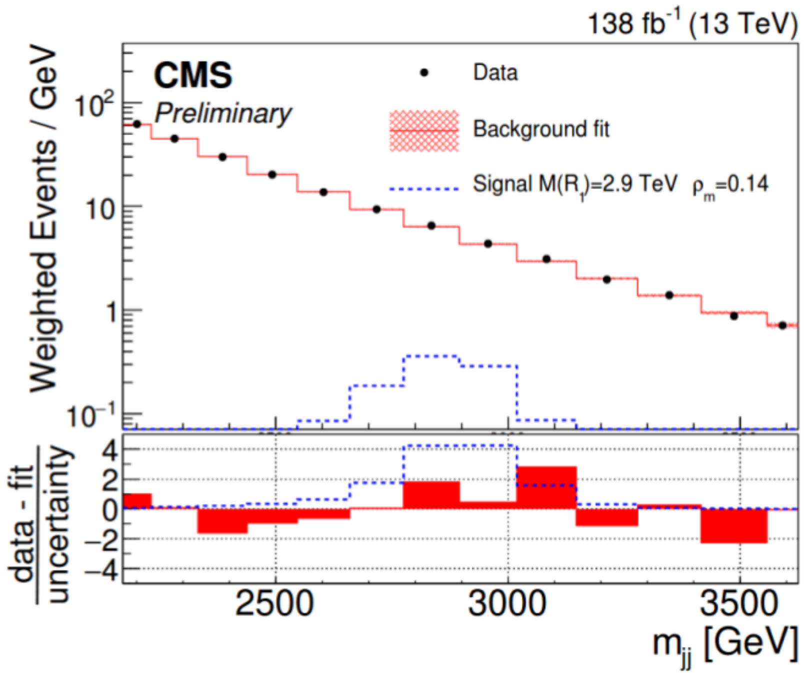
Search largely model independent.

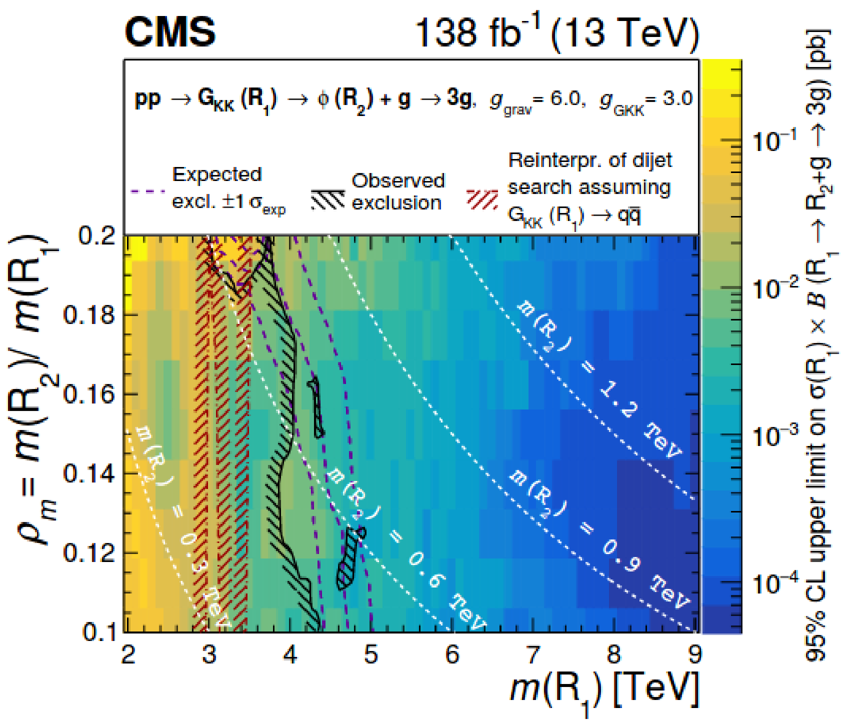
22 SRs defined in the m(R2)/m(P3) plane.

Results on Di-tri-jets

CMS-EXO-20-007

- **Maximum likelihood fit in the dijet mass performed in the SRs.**

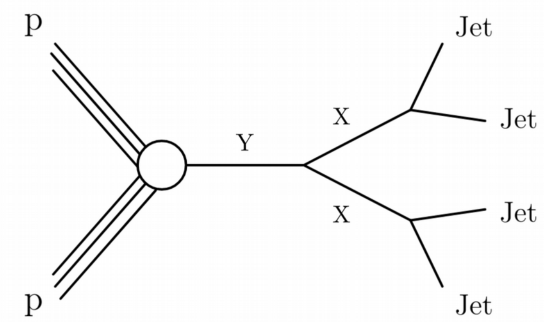


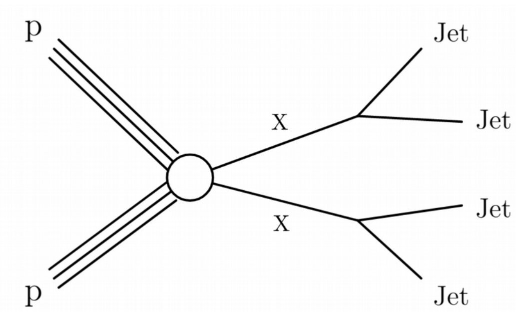


- **Excess: 1.8 σ global (3.2 σ local) → look into it in Run III.**
- By exploring a novel experimental signature, **we extend significantly the experimental exclusion of this benchmark model** of new physics at the LHC.

Paired Dijet Search

CMS-EXO-21-010





Experimental Signature:
Four or two resolved jets paired to same mass resonances.

Main backgrounds:
Multijet QCD production estimated with a data-driven method, using several parametric functional forms.

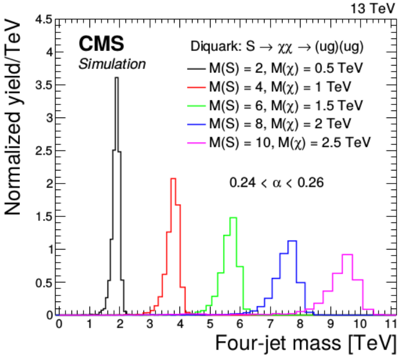
Signal Models:
Two modes of pair production of dijet resonances:

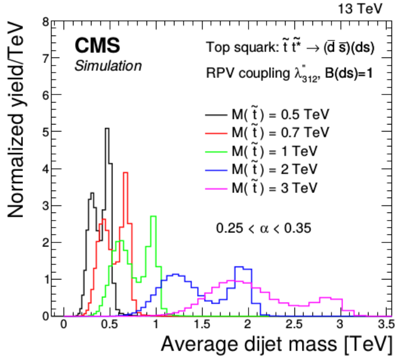
- **Resonant** → Benchmark model: Diquark decaying to vector-like quarks which decay to an up quark and gluon.

$$\mathrm{uu} \to \mathrm{S} \to \chi\chi \to (\mathrm{ug})(\mathrm{ug})$$

- **Non-resonant** → Benchmark model: R-parity violating stop pairs decaying to a d and s quark.

$$\mathrm{pp} \to \widetilde{\mathrm{t}}\widetilde{\mathrm{t}}^{*} \to (\overline{\mathrm{d}}\overline{\mathrm{s}})(\mathrm{ds})$$

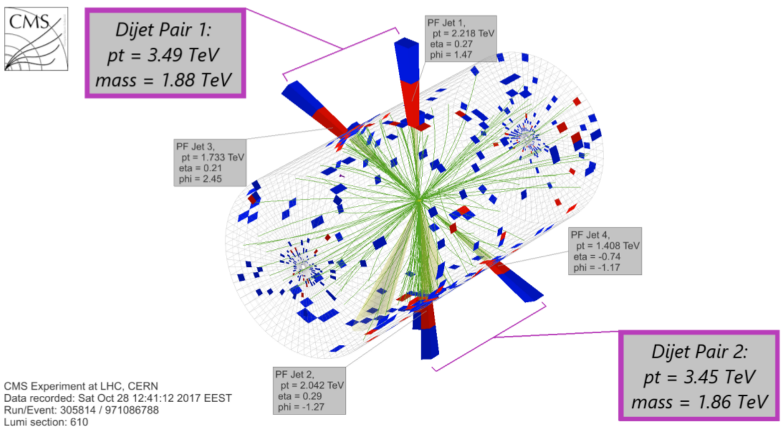


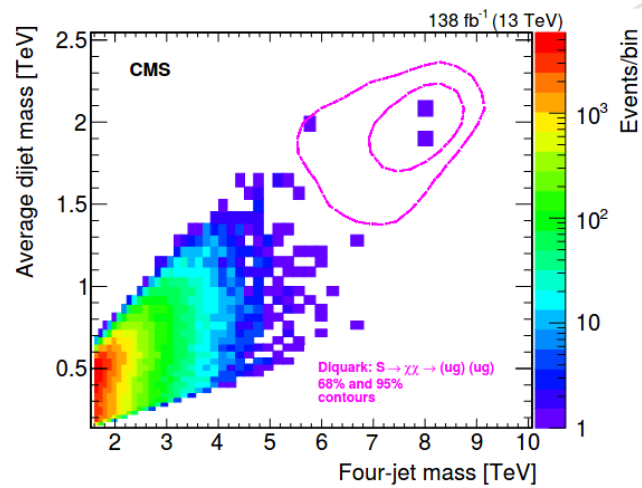


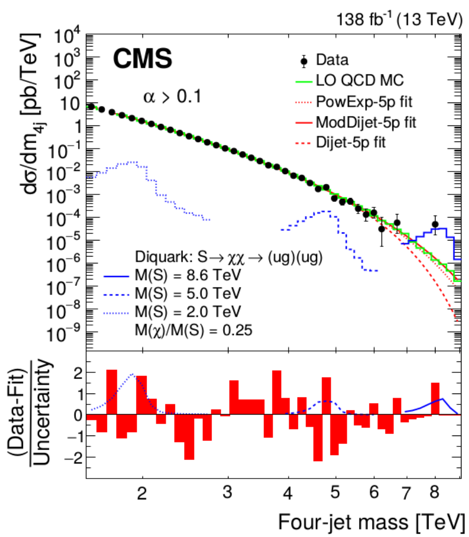
Search largely model independent.

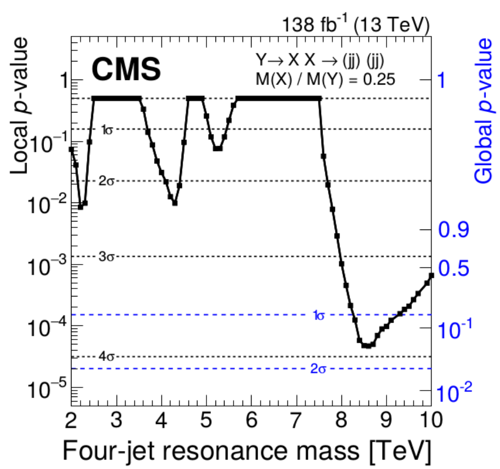
Results of resonant search

CMS-EXO-20-010









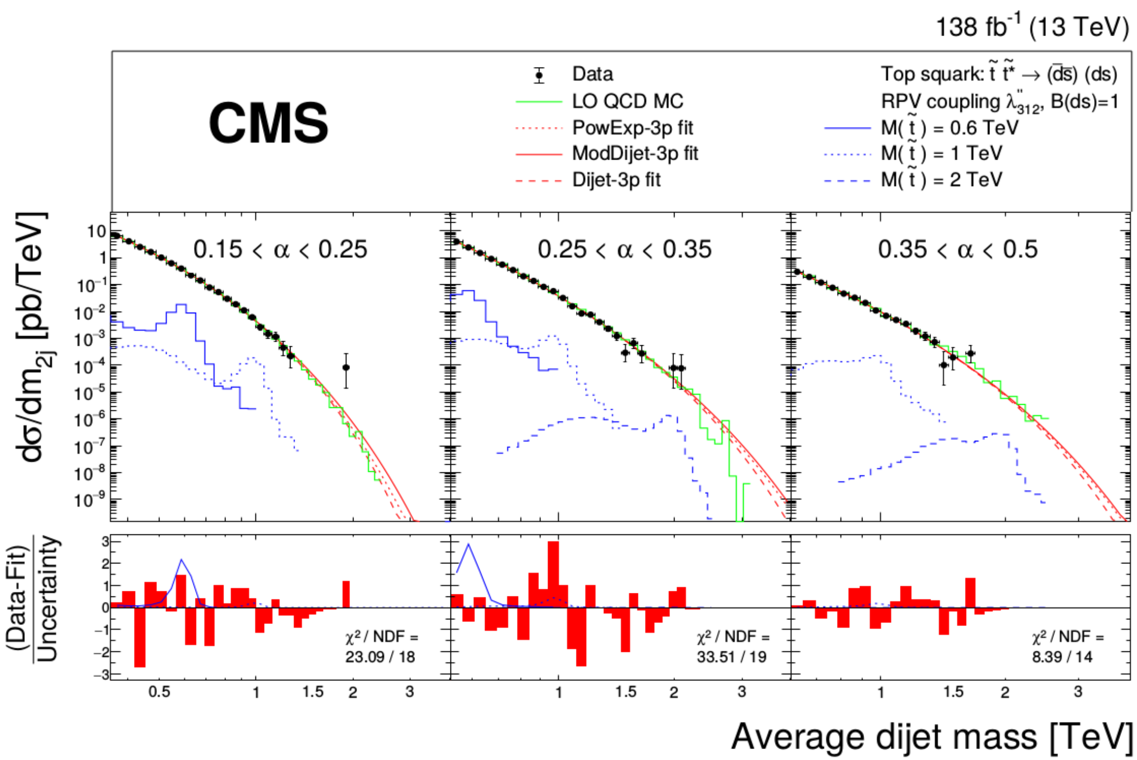
- **Maximum likelihood fit in the four jet mass performed in the SRs.**
- **Excess: 1.6 σ global (3.9 σ local) → look into it in Run III.**

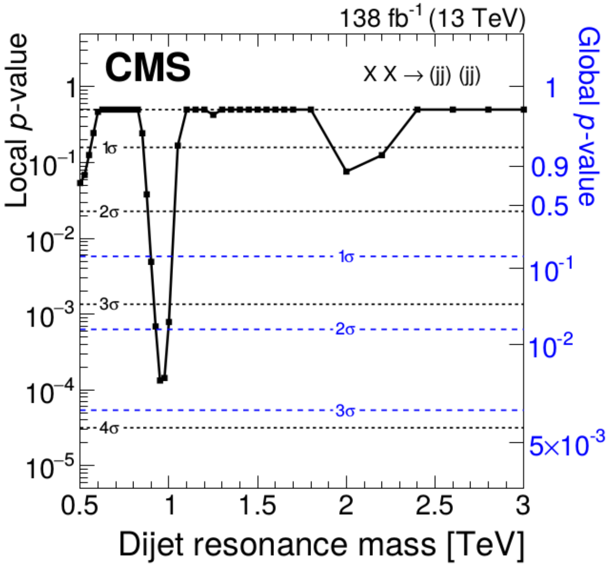
- These are the **first LHC limits on resonant pair production of dijet resonances via high mass intermediate states.**

Results of nonresonant search

CMS-EXO-20-010

- **Maximum likelihood fit in the average dijet mass performed in the SRs.**





- **Excess: 2.5 σ global (3.6 σ local) → look into it in Run III.**
- **Results significantly extend the previous limits.**

Search for LQs → τb

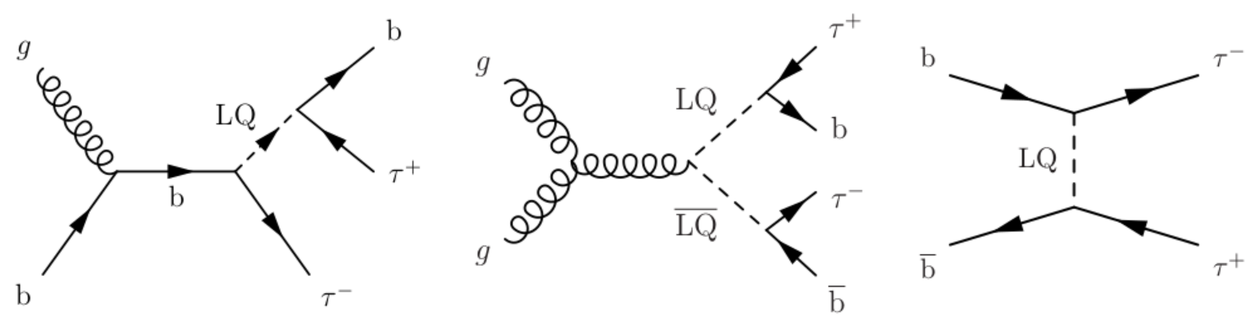
...motivated by B-anomalies

New at ICHEP 2022

CMS-EXO-19-016

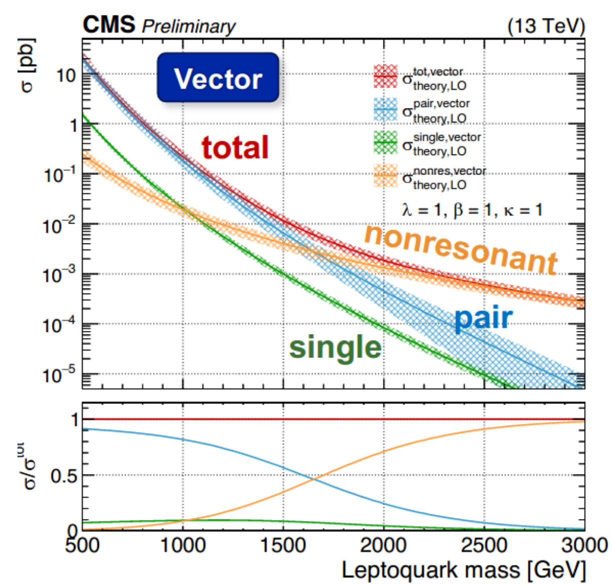
Experimental Signature:
2 τ's and 1 or 2 b tag jets

Channels:
$\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$ and μμ, eμ



Backgrounds:
Main: Z→ ττ, $t\bar{t}$ (constrained by μμ and eμ channel respectively), j→ τ_h fake (estimated by the Fake Factor method) Others: diboson, single top

Signal Models:
- Scalar & vector LQ signals
- Production modes: LQ pair, nonres, single
- coupling strength λ = 1-2.5
- For vector LQ:
  κ = 1,0: (non) minimal coupling



See also Olena Karacheban's talk

Results on LQs → τb

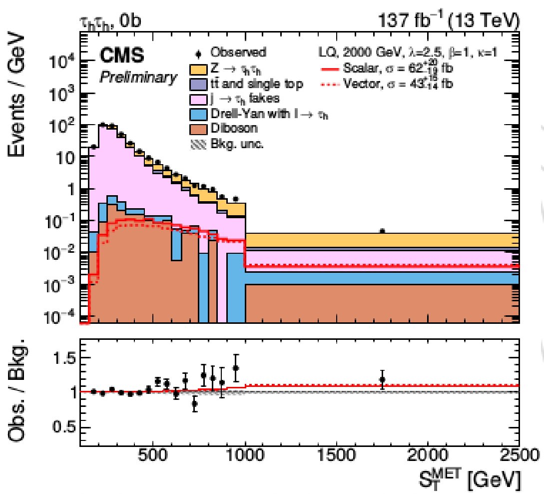
New at ICHEP 2022

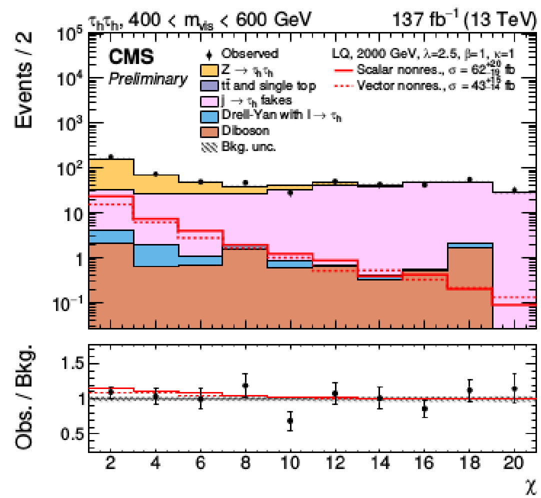
CMS-EXO-19-016

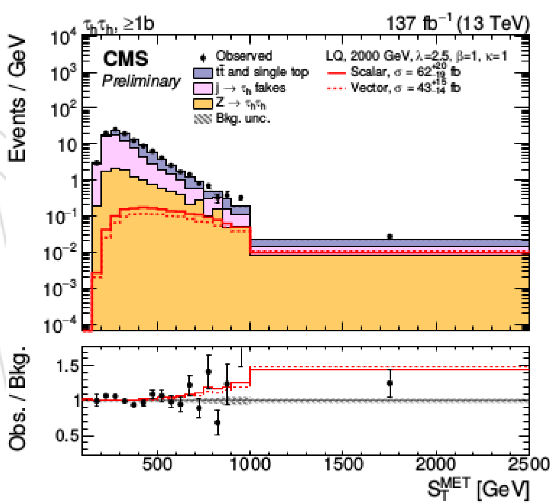
Event categories: ≥ 1 jet (0 or 1 b tag) and 0 jet (3 m_{vis} bins)

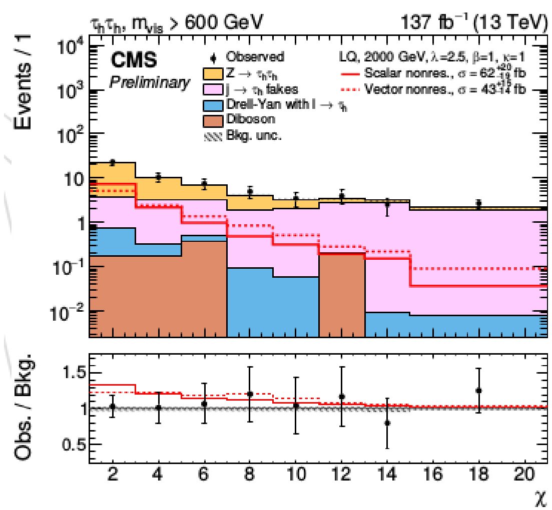
$$S_T^{MET} \equiv p_T^1 + p_T^2 + p_T^{j_1} + p_T^{miss}$$

$$\chi = e^{\Delta\eta}$$

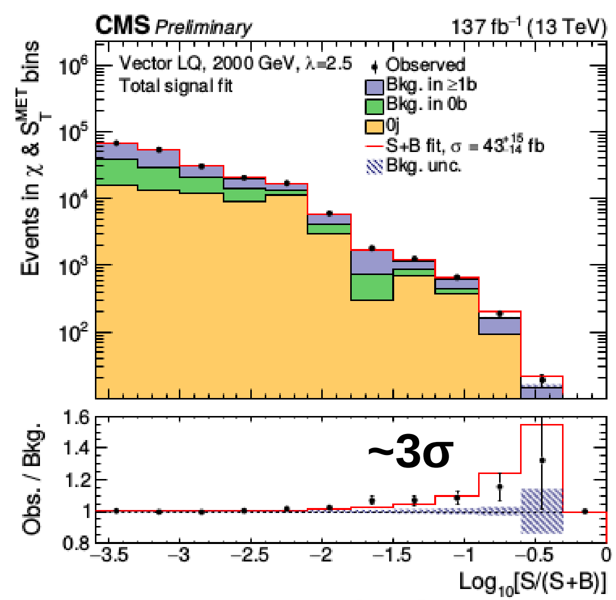








- Simultaneous maximum likelihood fit of LQ signals in χ and S_T^{MET}.
- Reorder bins by S/(S+B) from fit with total signal.



Results on LQs → τb

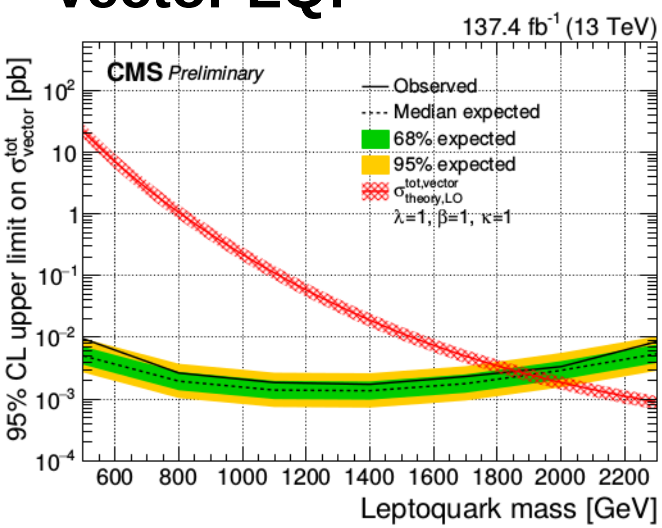
New at ICHEP 2022

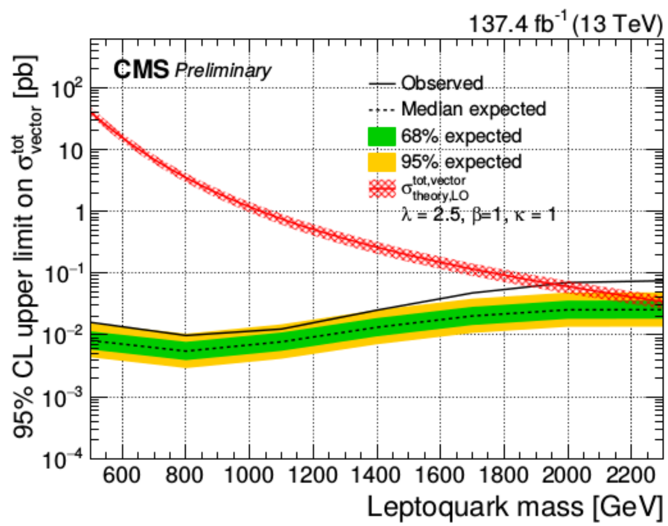
CMS-EXO-19-016

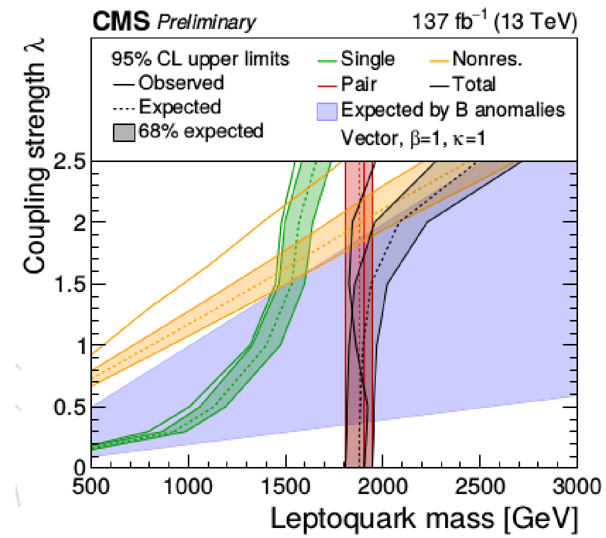
Upper limits placed on scalar / vector LQ on the three production modes:

$$\sigma^{tot} \equiv \sigma^{single} + \sigma^{pair} + \sigma^{nonres}$$

Vector LQ:







- **Upper limits are set on the third-generation scalar LQ production cross section and on coupling strength as a function of the LQ mass.**
- **We observe a ~3σ excess above m_{LQ} > 1800 GeV driven by the non-resonance mode → look into it in Run III.**

Summary

- **Hadronic final states offer great sensitivity to many models of new physics.**

- Searches for hadronic resonances in CMS were presented:
  - No significant deviations from SM so far but several excesses to keep an eye and to drive us where to look next.
  - Constraints in several benchmark models.

- Significant **improvements** due to
  - Data driven methods to estimate the background.
  - Jet sub-structure techniques.
  - Increased luminosity with full Run II datasets.
  - New final states are explored.

- **Hope that with all the improvements and advancements on reconstruction, trigger, analysis approaches and techniques, we should be able to fully exploit the Run III discovery potential and either make a discovery, or improve limits beyond luminosity scaling.**

Thank you!

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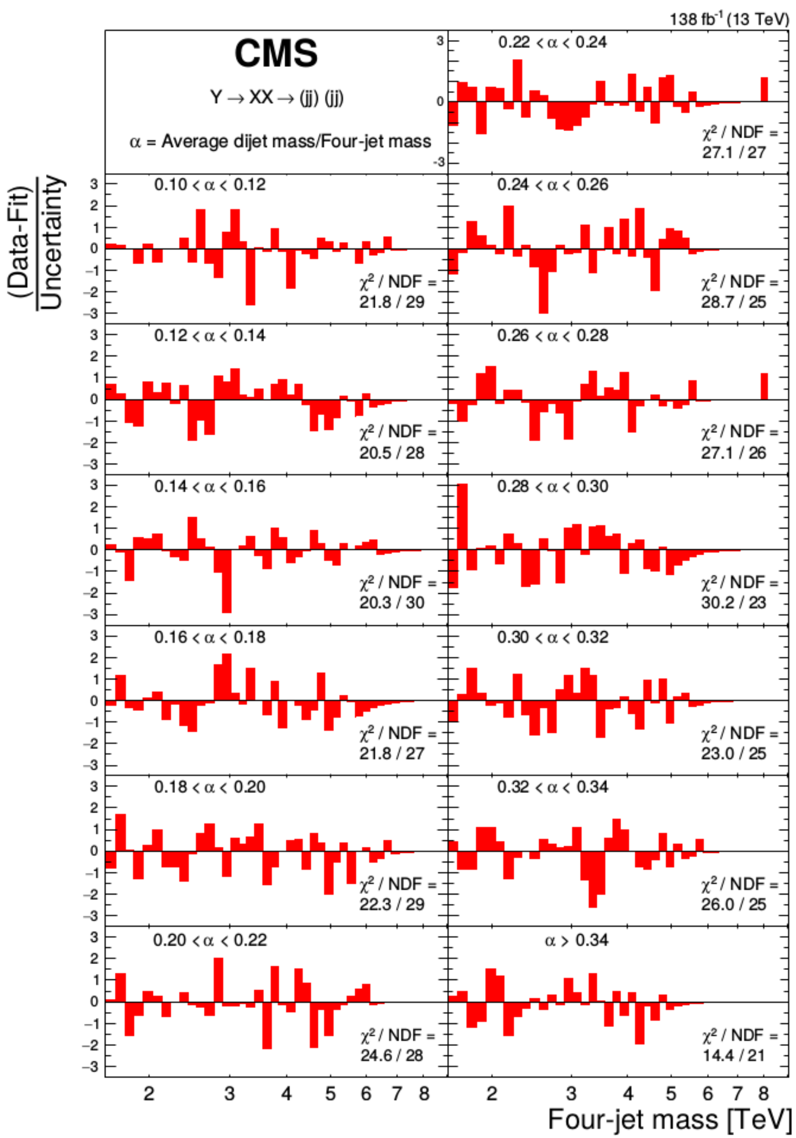
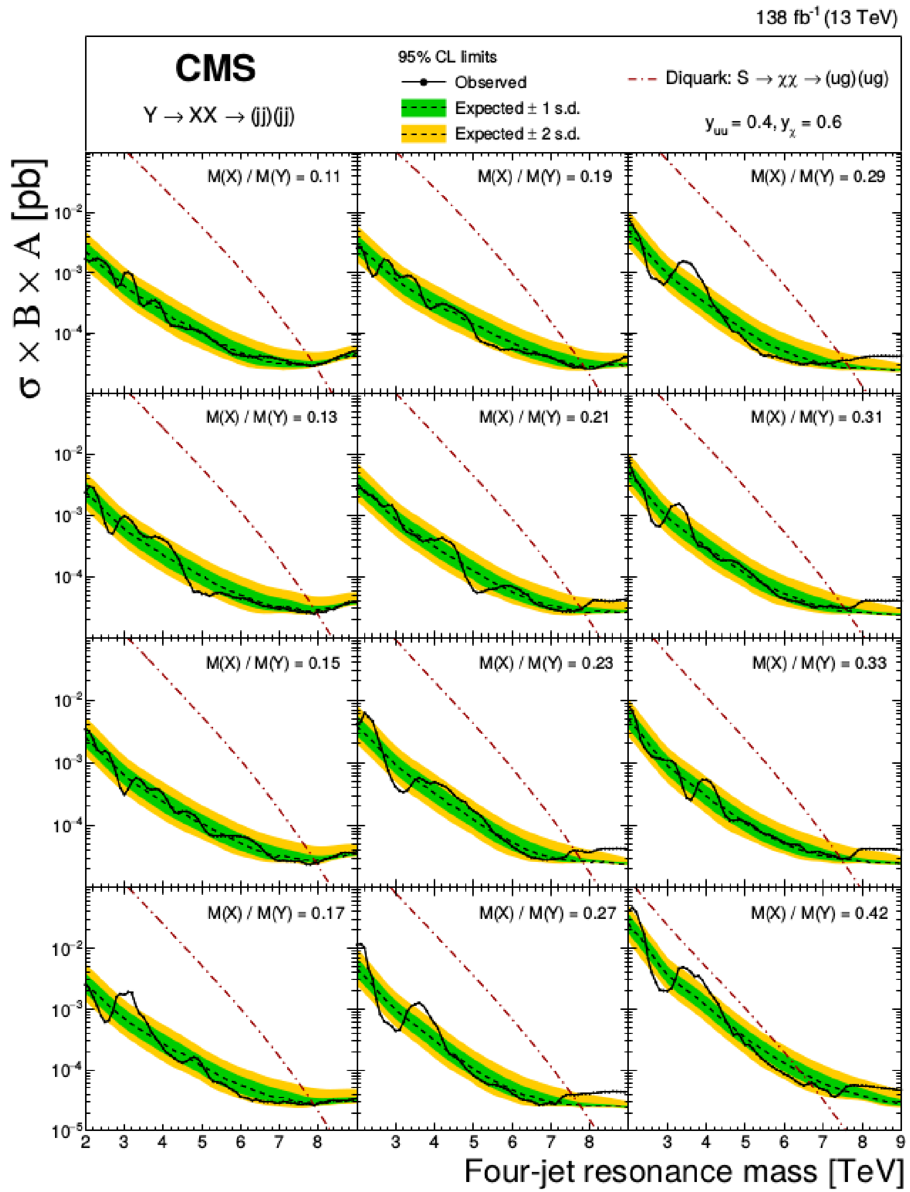
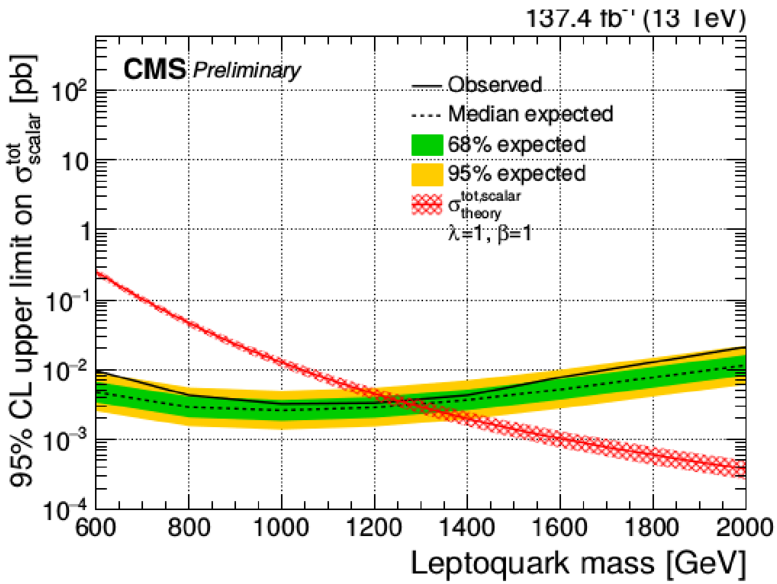
Back up

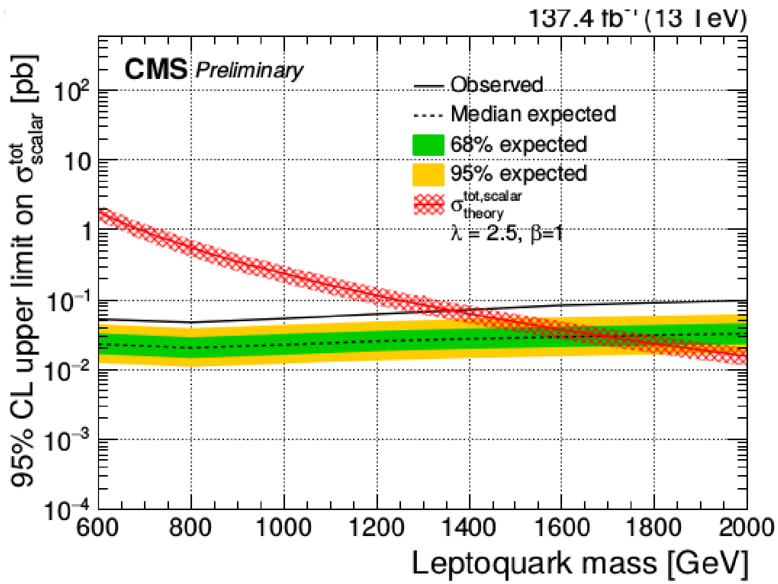
Paired Dijet Search

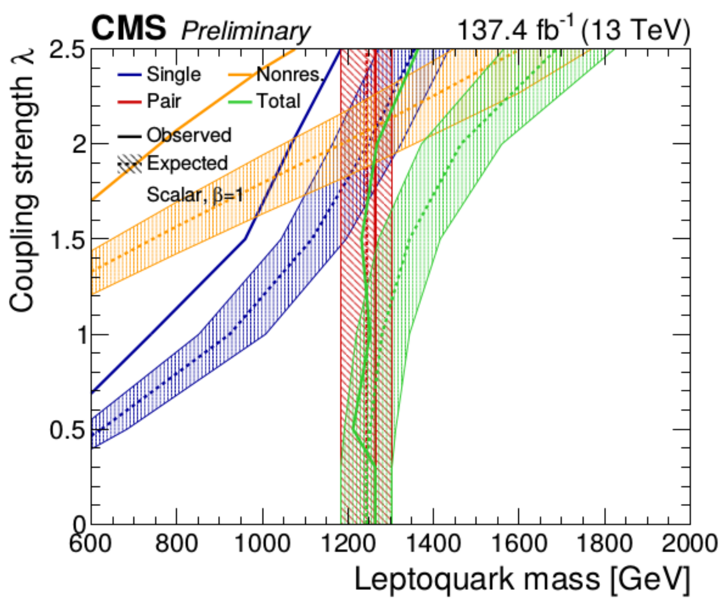




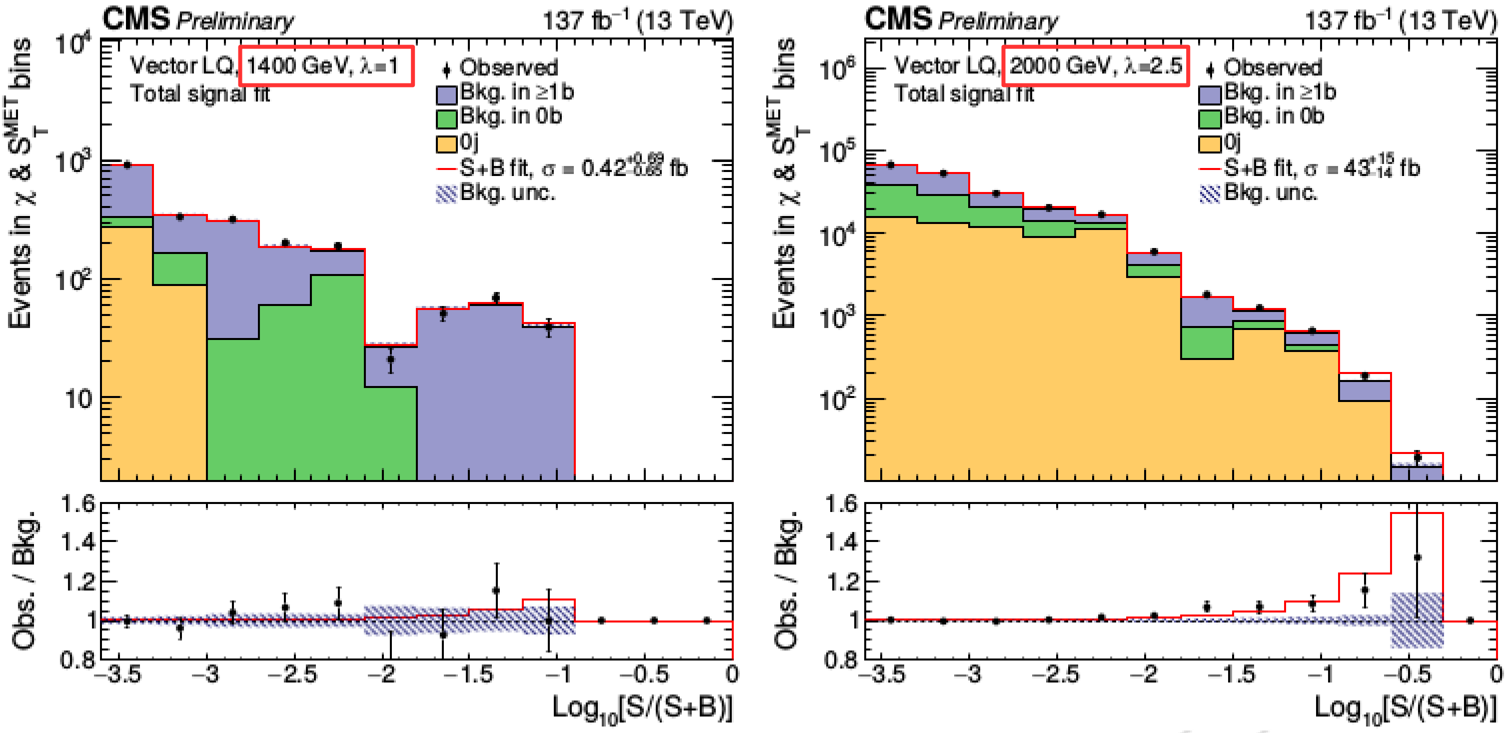
Search for LQ_3 (scalar) → bτ







Search for $LQ_3 \rightarrow b\tau$



λ: coupling strength of the LQ-lepton-quark vertex

Search for $LQ_3 \rightarrow b\tau$

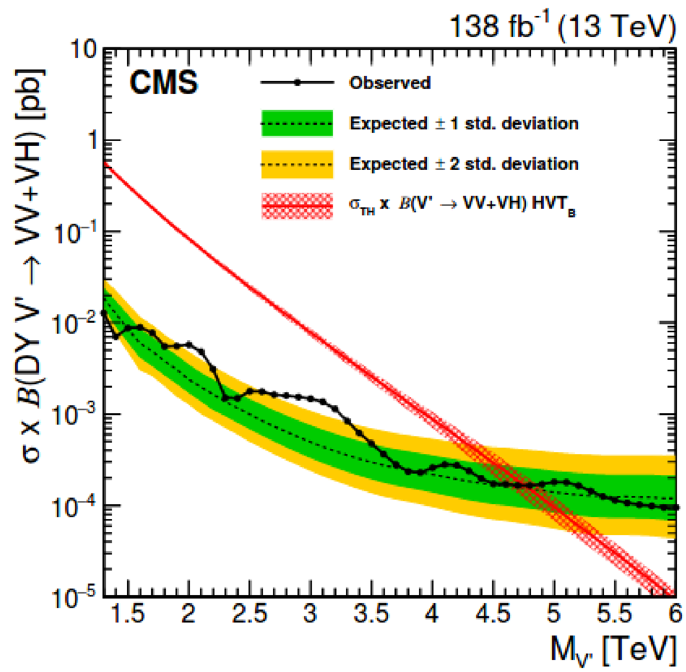
Table 2: Best-fit LQ cross sections σ for various masses and coupling strengths λ, and the corresponding significance z (given in standard deviations) for different production modes individually, as well as their combination.

Signal	$m_{LQ} = 1400\,\mathrm{GeV}$		$m_{LQ} = 2000\,\mathrm{GeV}$	
	σ [pb]	z	σ [fb]	z
Scalar				
Pair	$0.24^{+0.47}_{-0.45}$	0.5	$0.22^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.15^{+0.95}_{-0.92}$	1.3	$0.64^{+0.68}_{-0.65}$	1.0
Single, $\lambda = 2.5$	$9.1^{+5.6}_{-5.3}$	1.7	18^{+11}_{-11}	1.7
Nonres.	70^{+23}_{-22}	3.4	63^{+20}_{-19}	3.5
Total, $\lambda = 1$	$1.7^{+1.9}_{-1.8}$	0.9	$9.6^{+6.2}_{-5.9}$	1.7
Total, $\lambda = 2.5$	43^{+16}_{-15}	2.9	62^{+20}_{-19}	3.4
Vector, $\kappa = 0$				
Pair	$0.24^{+0.46}_{-0.44}$	0.0	$0.24^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.00^{+0.89}_{-0.85}$	1.2	$0.60^{+0.66}_{-0.63}$	1.0
Single, $\lambda = 2.5$	$9.1^{+6.5}_{-6.2}$	1.5	25^{+18}_{-17}	1.4
Nonres.	58^{+18}_{-17}	3.5	51^{+16}_{-15}	3.5
Total, $\lambda = 1$	$1.2^{+1.5}_{-1.4}$	0.8	$7.7^{+5.1}_{-4.8}$	1.7
Total, $\lambda = 2.5$	$12.2^{+7.1}_{-6.8}$	1.8	43^{+15}_{-14}	3.1
Vector, $\kappa = 1$				
Pair	$0.24^{+0.46}_{-0.44}$	0.0	$0.24^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.00^{+0.89}_{-0.85}$	1.2	$0.60^{+0.66}_{-0.63}$	1.0
Single, $\lambda = 2.5$	$9.1^{+6.5}_{-6.2}$	1.5	25^{+18}_{-17}	1.4
Nonres.	58^{+18}_{-17}	3.5	51^{+16}_{-15}	3.5
Total, $\lambda = 1$	$0.42^{+0.69}_{-0.66}$	0.0	$1.3^{+1.5}_{-1.4}$	0.5
Total, $\lambda = 2.5$	$12.2^{+7.1}_{-6.8}$	1.8	43^{+15}_{-14}	3.1

Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state

B2G-20-009

- The **bosons** that are **highly Lorentz-boosted** they form a single large-radius jet.
- **Novel machine learning techniques** are employed to distinguish jets from W, Z, and H boson decays from other jets.



- In a HVT model, spin-1 Z′ and W′ resonances with masses below 4.8 TeV are excluded at the 95% CL.
- These limits are the best to date.
- Limits also on graviton model, boson production through VBF etc.

Local (global) significance of 3.6 (2.3) σ for mild excesses of events at masses of 2.1 and 2.9 TeV → Look into it in Run 3