UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

Searches with top quarks and W bosons at CMS

BOOST 2024

Genova, Italy, 31/7/2024

Alberto Orso Maria Iorio, for the CMS collaboration

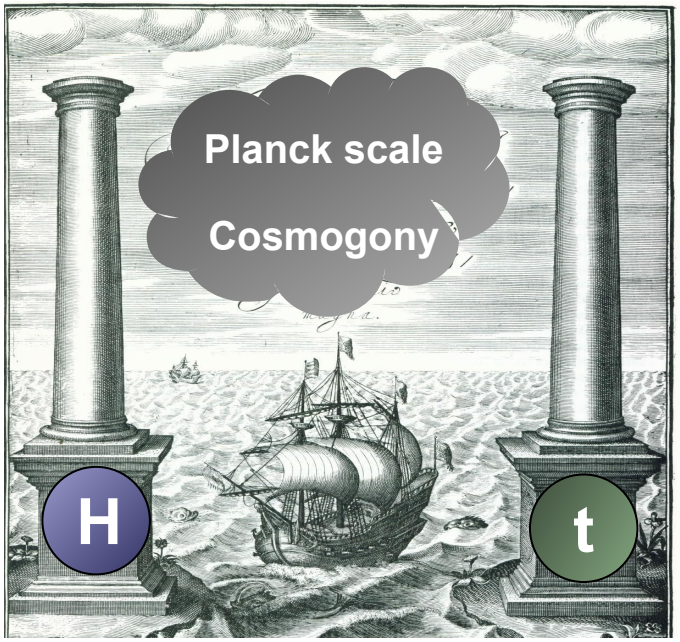
Particle physics after the Higgs: Non plus ultra?

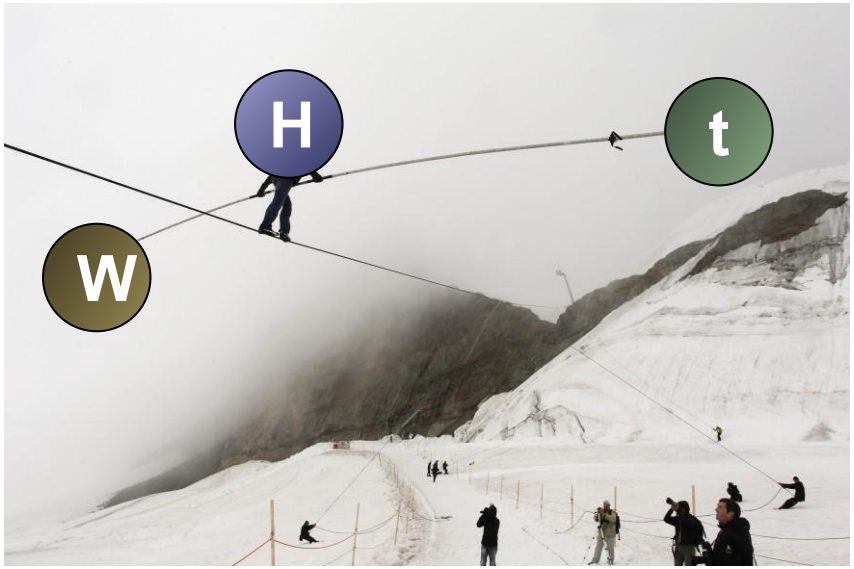
Going beyond: missing pieces

→ The inclusion of gravity

→ Dark matter, Dark energy

→ Matter-antimatter asymmetry





The SM "effective field theory vibe"

→ Origin of EWK symmetry breaking

→ Why does the Higgs stay so light

→ Why so many free parameters?

Particle physics after the Higgs: Non plus ultra?

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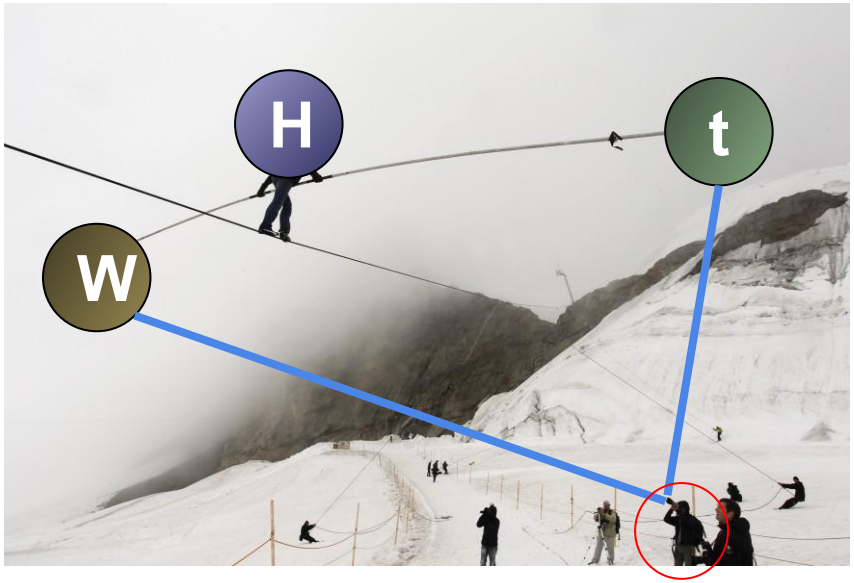
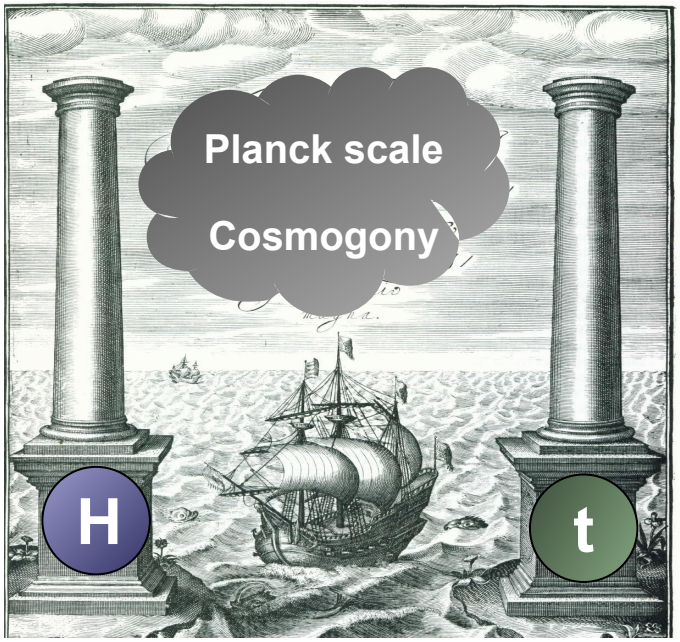




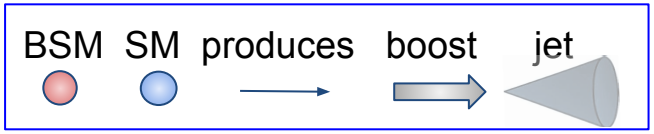
W, Top, and Higgs-associated new physics channels are good candidates to explore the new physics avenues!

Find higgs related searches in this session: ***https://agenda.infn.it/event/37093/sessions/29979/#20240731***

Us in this talk!

New physics entering the game

1) **Resonances** with **two-prong decay cascades to sm** at unexplored masses:



- We lack **energy or sensitivity** ⇒ searched for but yet out of reach

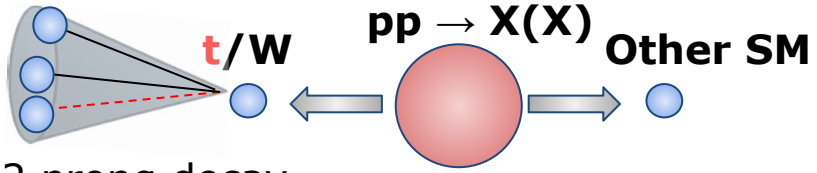
- Many "traditional signature" searches:

Vector Like quarks, excited quarks, new bosons

EXO-23-006 B2G-20-014 B2G-19-001

CMS-PAS-B2G-22-005 CMS-PAS-B2G-21-005

PLB 820 (2021) 136535 JHEP 05 (2024) 046



3/2 prong decay

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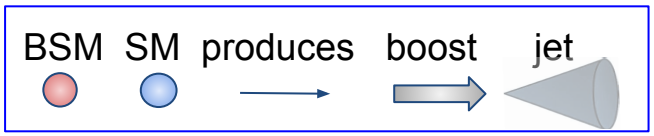

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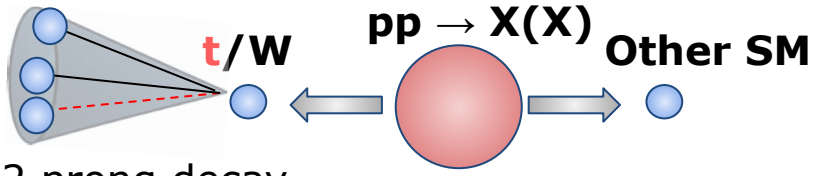


3/2 prong decay

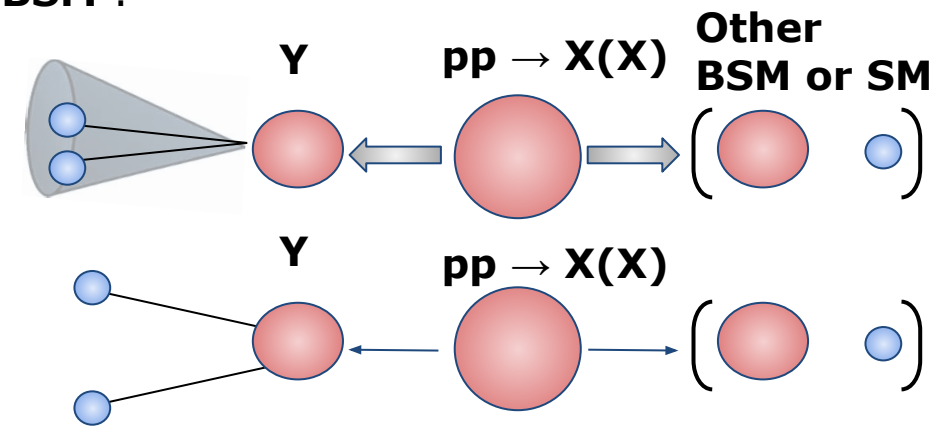
2) **Resonances** with **intermediate decays to BSM** :

- **Signature not yet fully explored:**

- Y might give one unusual jet structure

- Y mass might escape SM windows

- Entirely new channels, or **non-minimal ways to expand** on existing searches!



CMS-PAS-B2G-23-004 JHEP 09 (2022) 088

EXO-23-006

New physics: Vector-Like Quarks

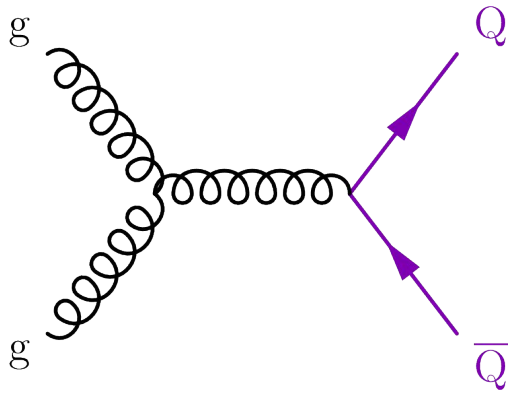
Vector-like ⇒ both left and right handed components behave the same under SU(2)

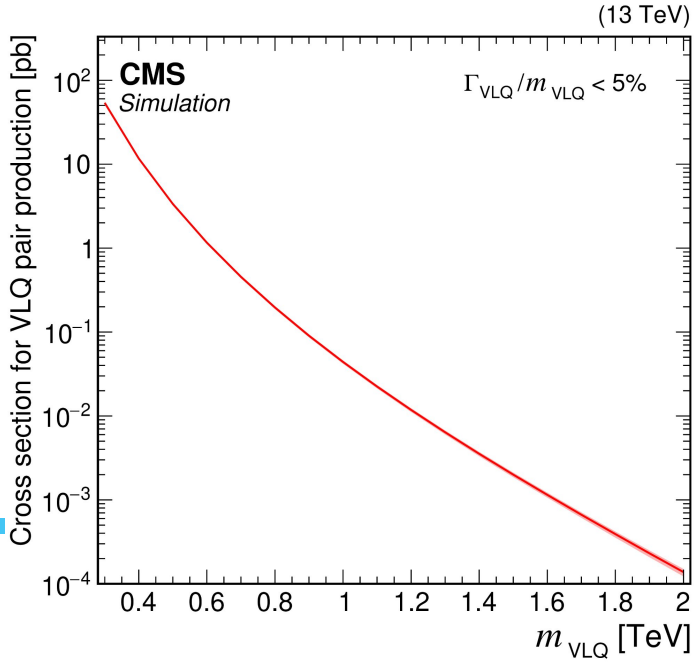
Particle content

SU(2) Multiplets	
Singlets	T,B
Doublets	(T,B) (X,T) (Y,B)
Triplets	(X,T,B) (T,B,Y)

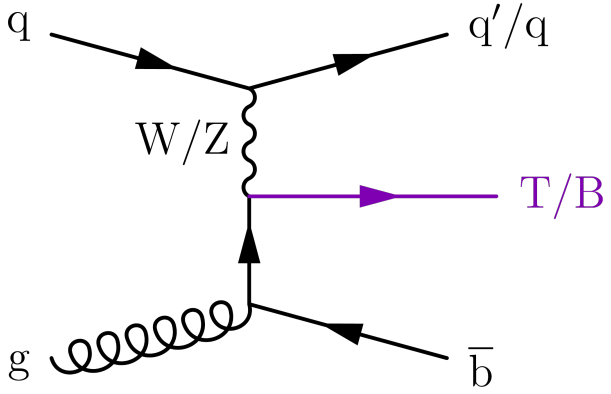
Quark Type	Charge
X	+5/3
T	+2/3
B	-1/3
Y	-4/3

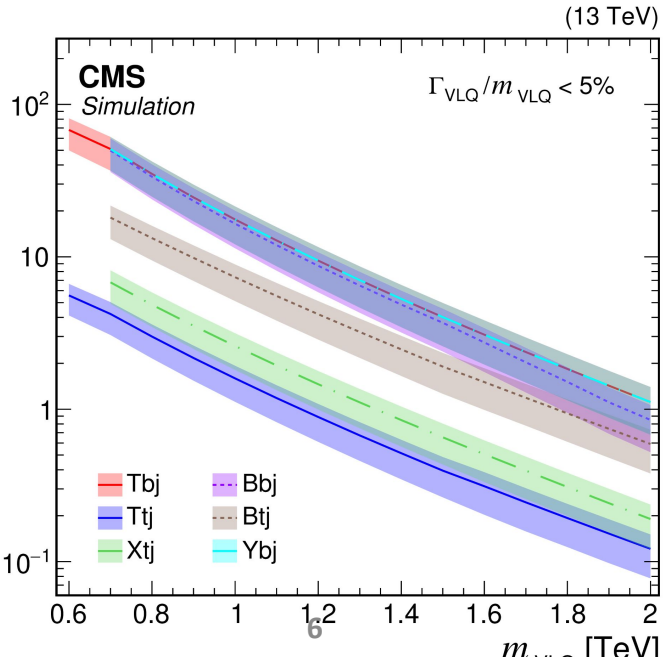
Pair production





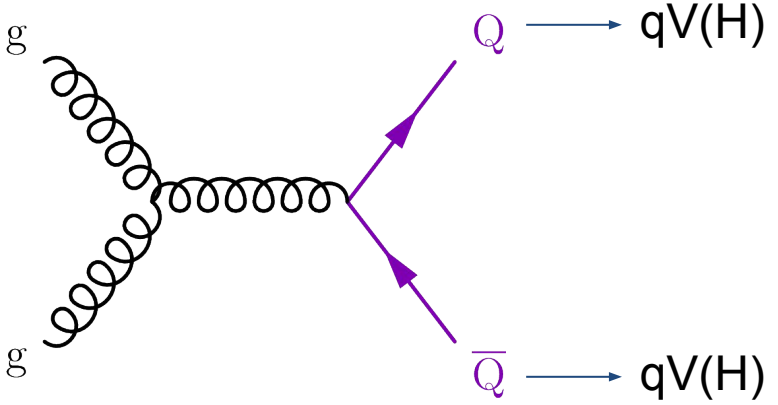
Single production





EXO-23-006

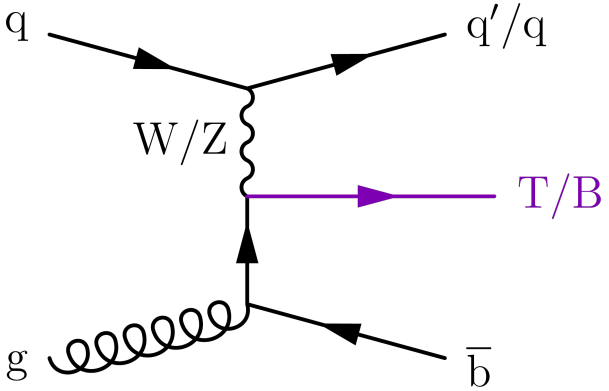
Vector-Like Quarks decays and widths



Quark	SM Decays
B	bH,bZ,tW
T	tH,tZ,bW
$X^{5/3}$	tW^+
$Y^{-4/3}$	bW^-

- **Combinatorics** of decays
  - ⇩
  - rich phenomenology
- Branching fractions are **model dependent**
  - ⇩
  - Different mix of final states!

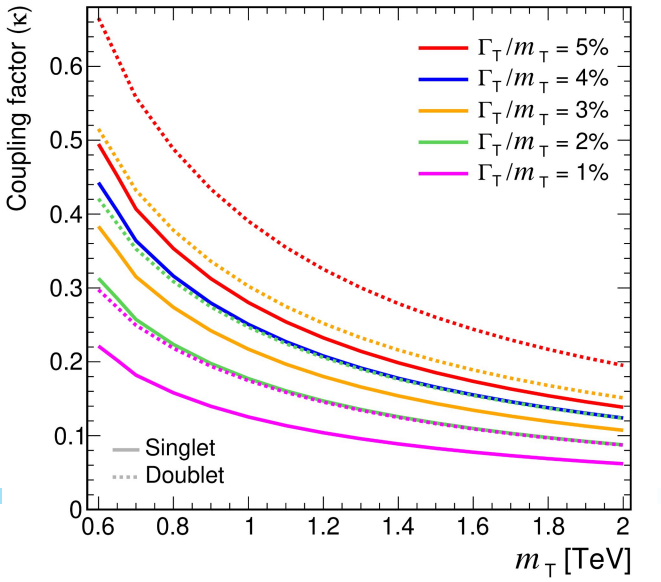
Variable total width → different final state distributions → different sensitivity



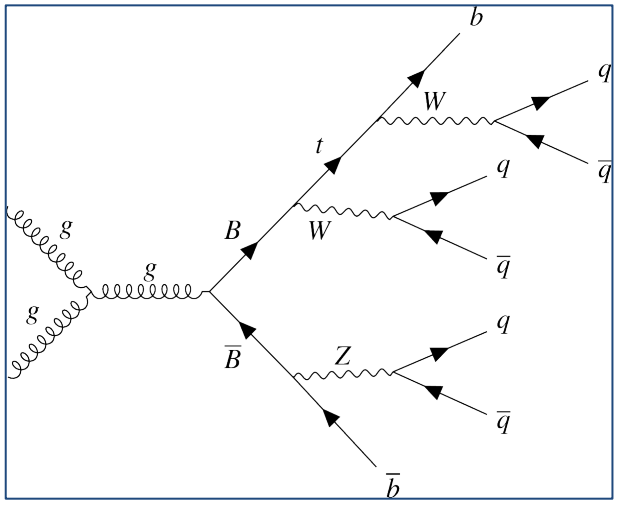
$$C_1 C_2 \hat{\sigma}(m_Q, \Gamma_Q)$$

Once the decays fixed:

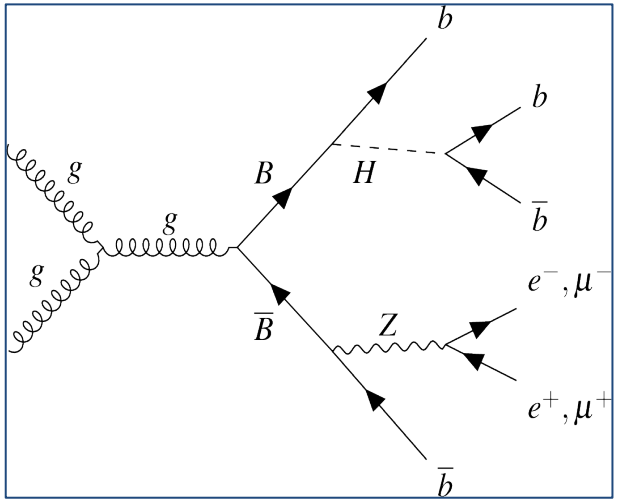
Total width and coupling strength are related



Pair-wise VLQ production: BB



$$\chi^2_{\text{mod}} = \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m}_{\text{VLQ}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}} + \frac{(m_1 - \overline{m}_1)^2}{\sigma^2_{m_1}} + \frac{(m_2 - \overline{m}_2)^2}{\sigma^2_{m_2}}$$



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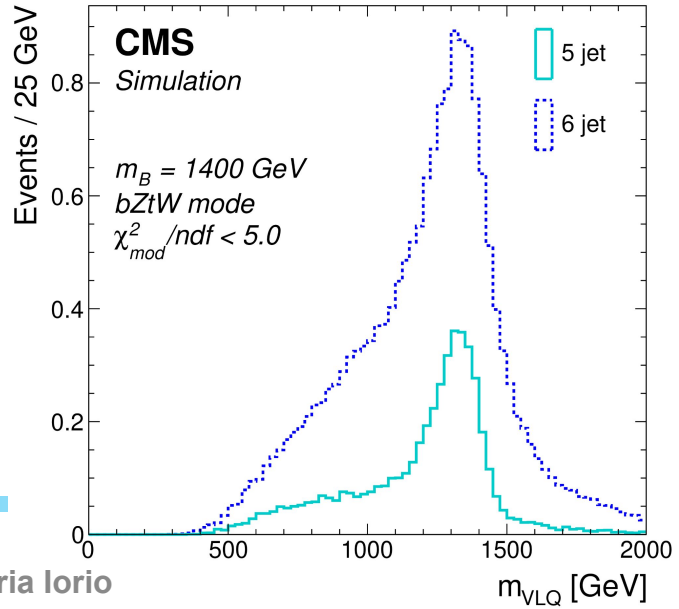
- **Decays considered per B :**

B → tW → 1b-quark + 4 light quarks
B → bH → 3b-quarks
B → bZ → 1b+bb/qq
B → bZ → 1b+μ+μ-/e+e- (at most one of these decays)

- **Selection:**

- 2-6 jets, Anti-Kt algorithm with R=0.4
- 2 to 4 of them b-tagged
- 2 opposite sign muons in the final state

- **Chi2 variables** constructed to identify best combination of jets

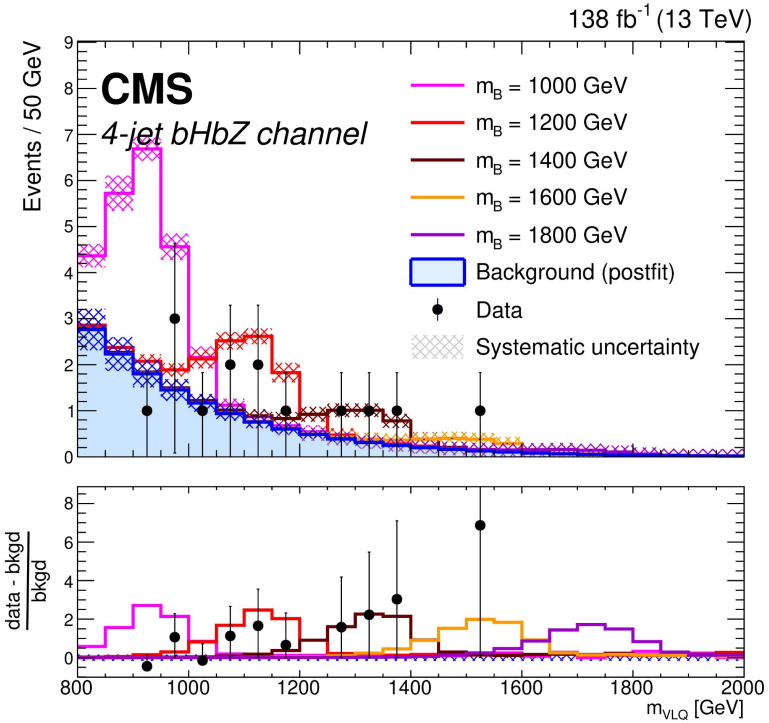


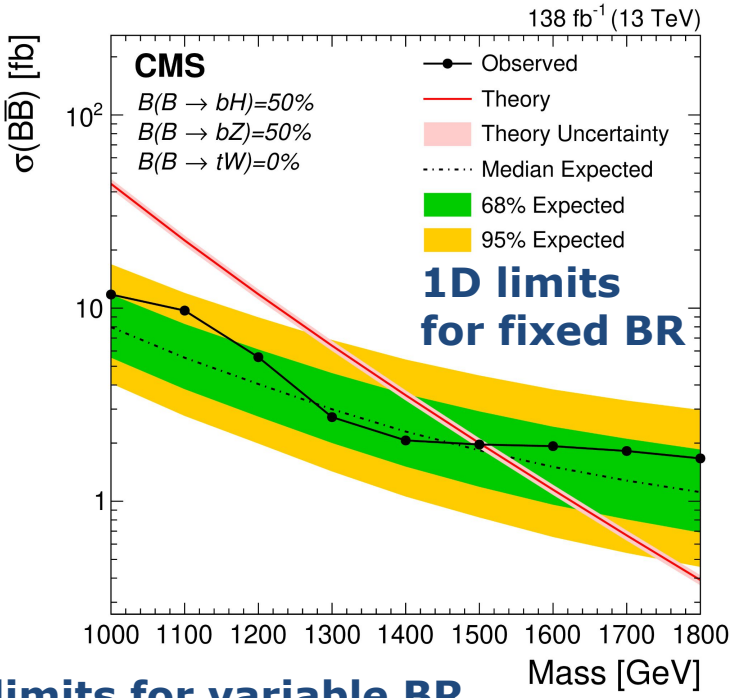
Results on VLQ BB pairs

- **Simultaneous fit** to mVLQ all regions

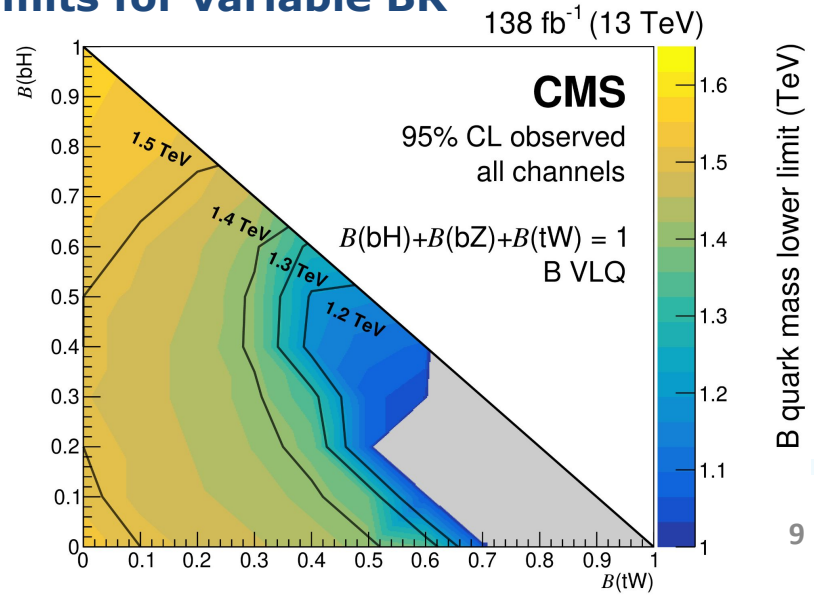
- **Main background : QCD Multijet**

- Shape extracted from non-b-tagged region
- Extrapolated to high mVLQ region
- Ratio of tagged-to-untagged extracted from high-chi2 region



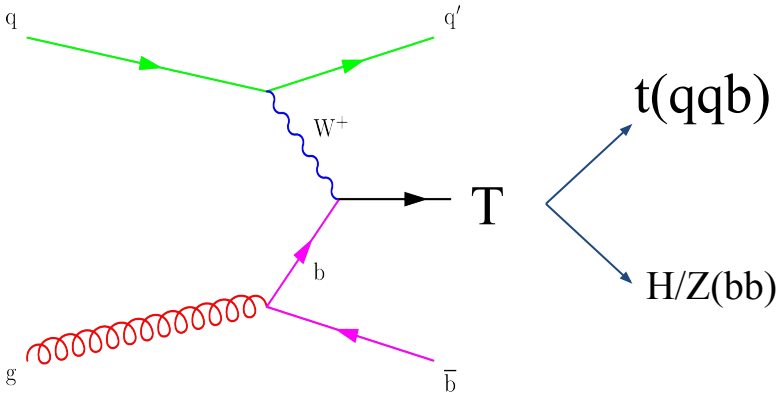


2D limits for variable BR



B2G-19-001

Single VLQ T → tH/tZ all-hadronic



Fully-hadronic resolved channels:

- Different degrees of "tightness" for the b-jets:

  Loose (L), Medium (M), or Tight (T).

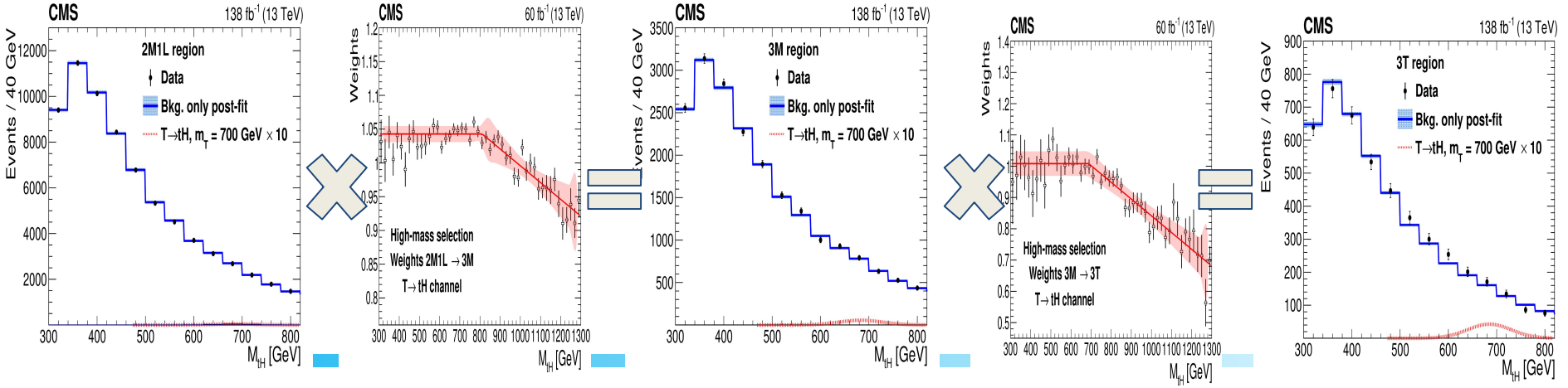
Main signal region:

- 3 T b-jets, 2 other jets
- 2 b-jets around the H/Z mass (chi2 criterion)
- Remaining 3 around the top quark mass

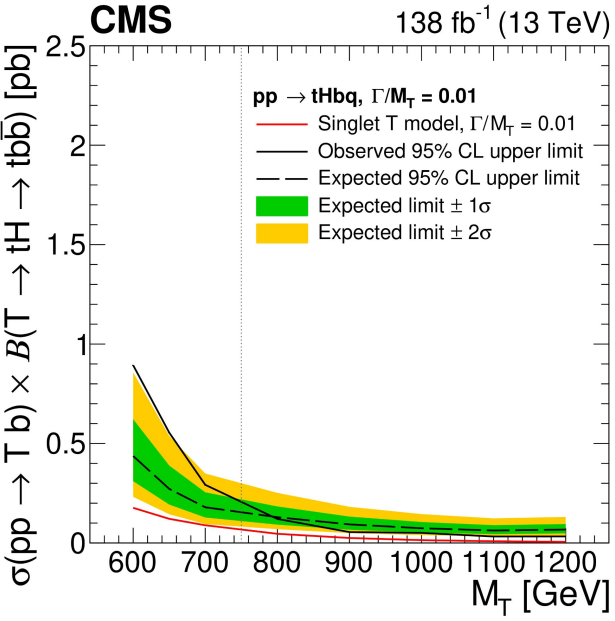
QCD Shape extraction from data:

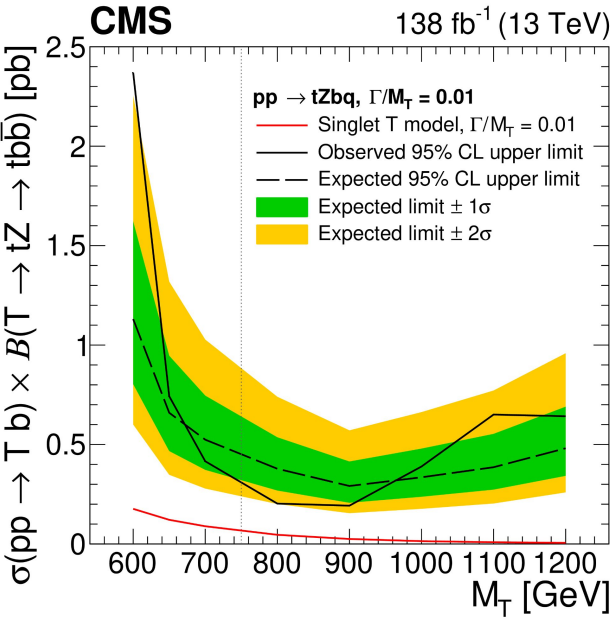
Distribution of 5-jet mass distribution is reweighted with transfer functions:

(2M1L b-jets x transfer function 1 = 3M b-jets) x transfer function 2 = 3T [signal region]



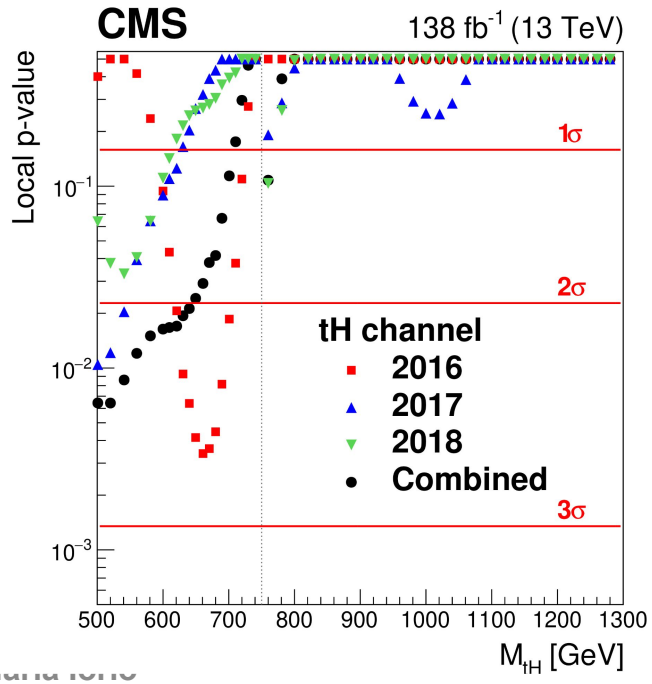
Single VLQ T results





Analysis considering decays tZ/tH:

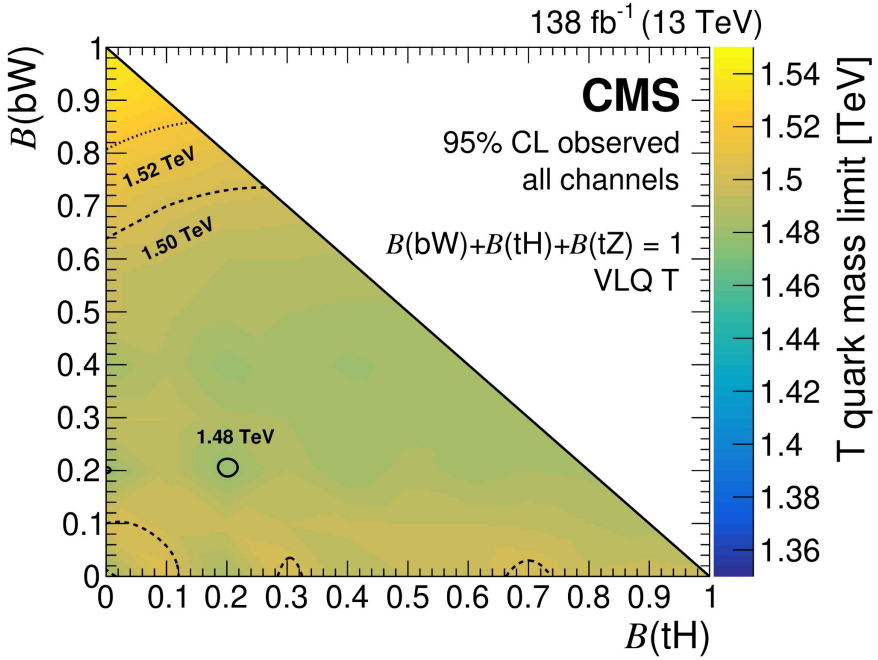
- Separately and together with equal BR hypothesis.
- Mild excess driven by 2016 data.
- When analyses performed separately, tH events can be mis-identified in the tZ channel → excess appears in tZ as well.



EXO-23-006

Overview of CMS VLQ searches

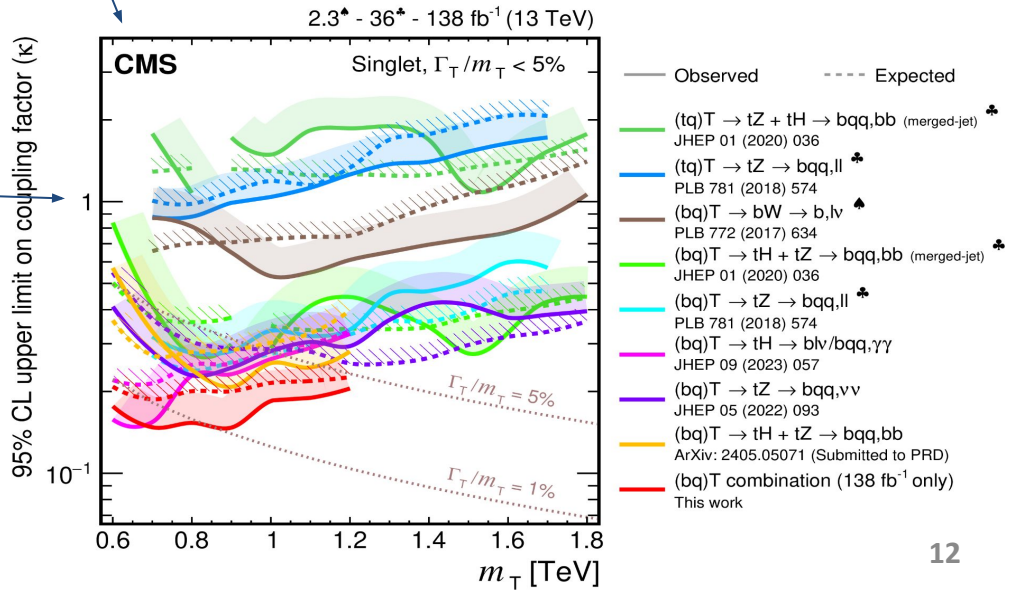
Production mode	Decay mode	Channel
$T\bar{T}$	bW, tH, tZ	0ℓ, 1ℓ, OS 2ℓ, SS 2ℓ, 3ℓ
$B\bar{B}$	tW, bH, bZ	0ℓ, 1ℓ, OS 2ℓ, SS 2ℓ, 3ℓ
$X_{5/3}\bar{X}_{5/3}$	tW	1ℓ, SS 2ℓ
$Y_{4/3}\bar{Y}_{4/3}$	bW	1ℓ
T	tZ	bqq $\ell\ell$, bqq bb, bqq $\nu\nu$
	tH	bqq $\gamma\gamma$, bqq bb
	bW	b $\ell\nu$
B	bH	b bb
	tW	bqq $\ell\nu$, b$\ell\nu$ qq, bqq qq
$X_{5/3}$	tW	bqq $\ell\nu$, b$\ell\nu$ qq, bqq qq
$Y_{4/3}$	bW	b $\ell\nu$



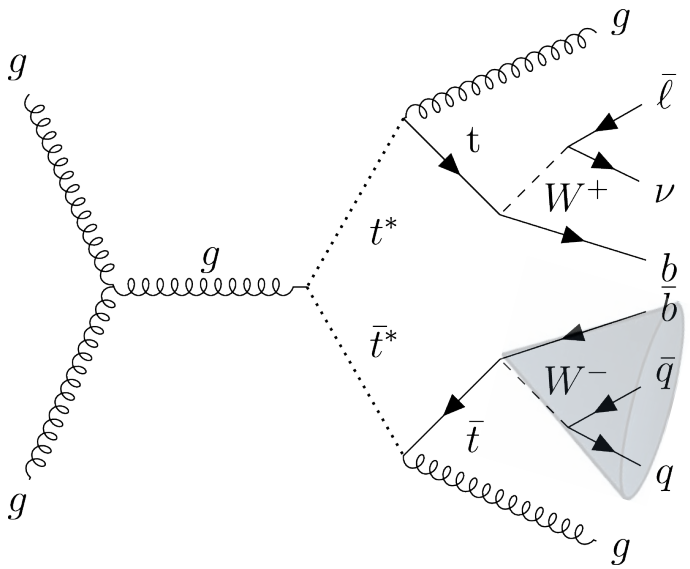
Bird's eye view of searches

- **Vector-like quarks**
  → reinterpretations in terms of the couplings

- **Exotic production** channels of VLQ presented



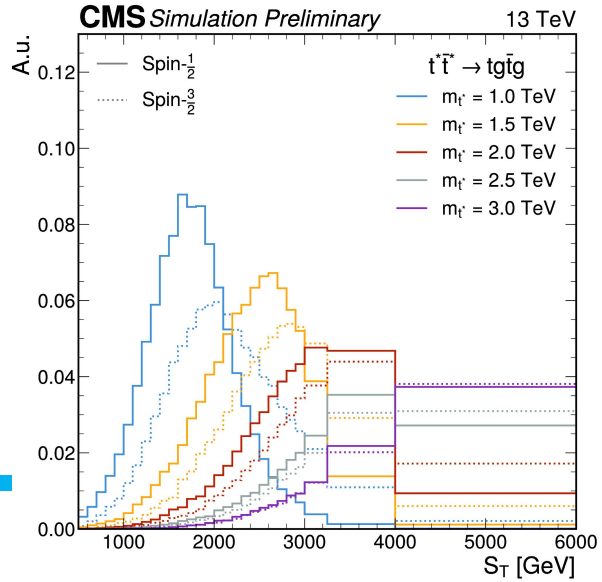
Excited quarks: t* → tg



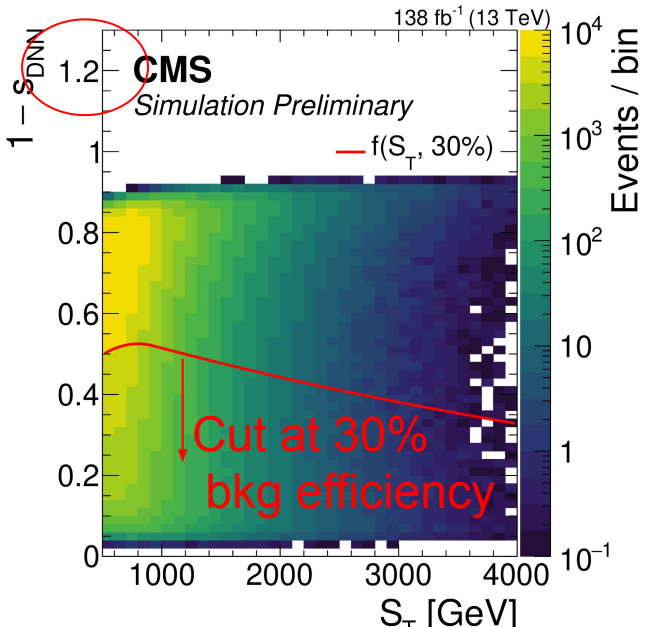
Excited top quark partners decaying to top + g

- 1 top decaying leptonically, the other hadronically
- Wide p_T range: top quark with different degrees of lorentz boost → variable radius jet - HOTVR
- The other top quark decays leptonically:
  → 1 lepton, 1 b-jet, MET 1 hadronic top quark jet.
  → 2 gluons → 2 Anti-kt jets with R=0.4

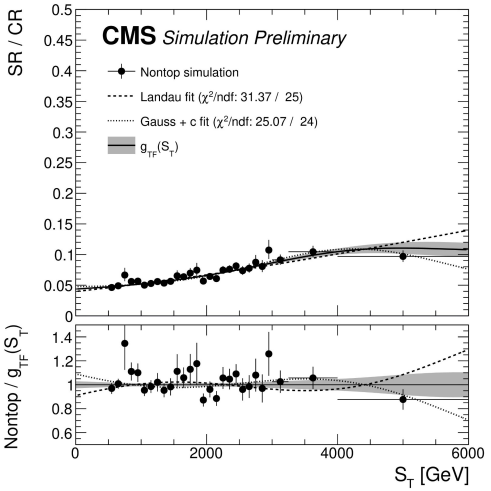
Discriminating variable: S_T = scalar sum of all p_T



Deep Neural Network: objects 4-momenta and ID



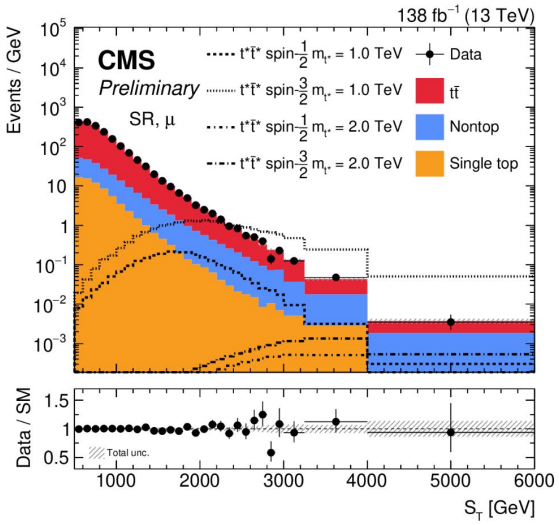
S_T: shape extraction from CR at 0 b-jet

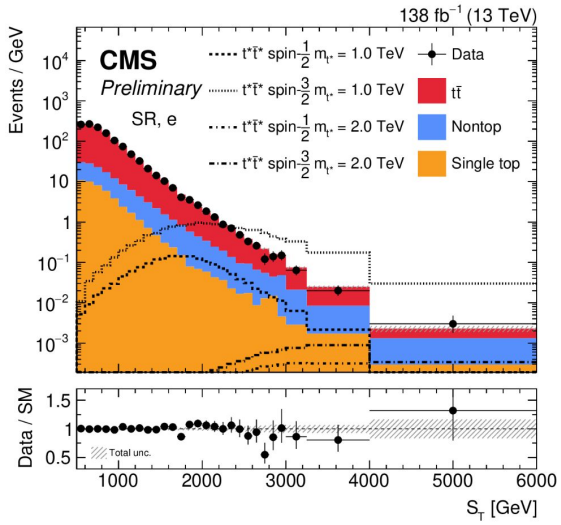


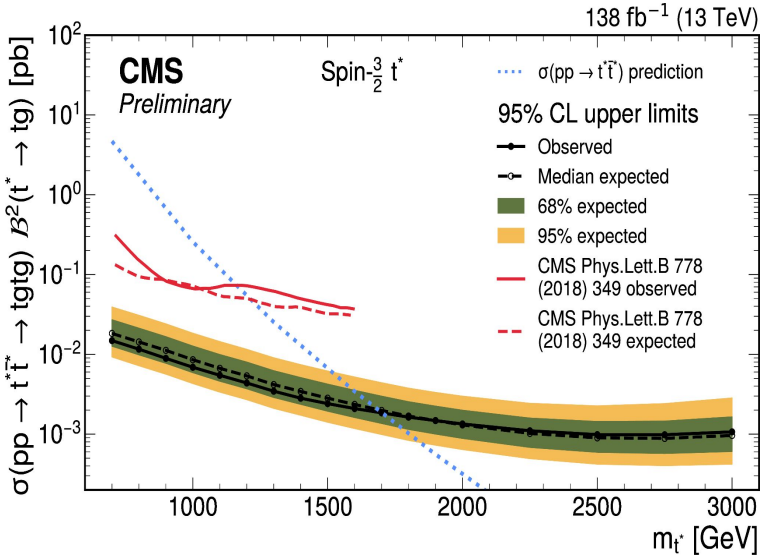
Results on t* → tg models

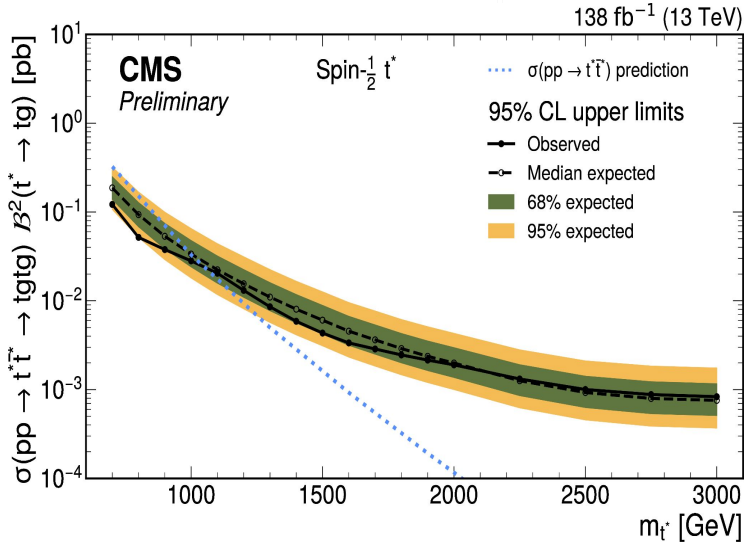
Signal extraction:

- Fit to the ST distribution in both channels
- Analysis interpreted in **different spin hypotheses for t***



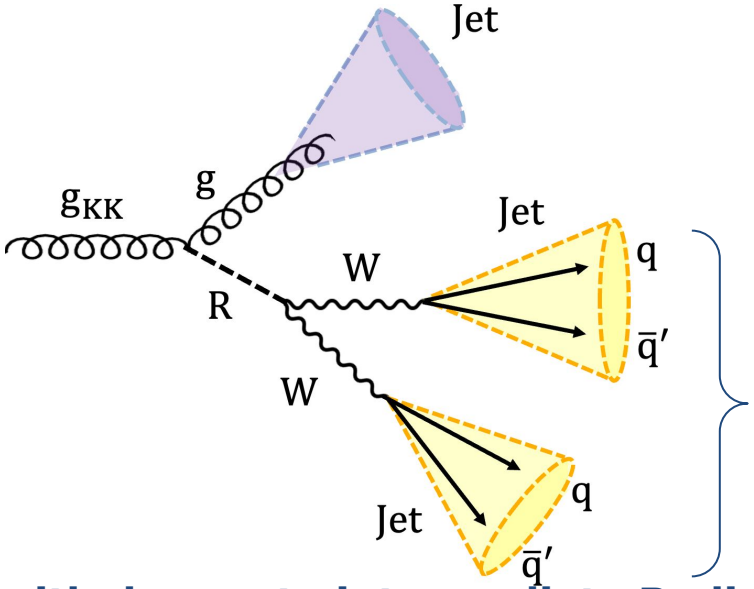


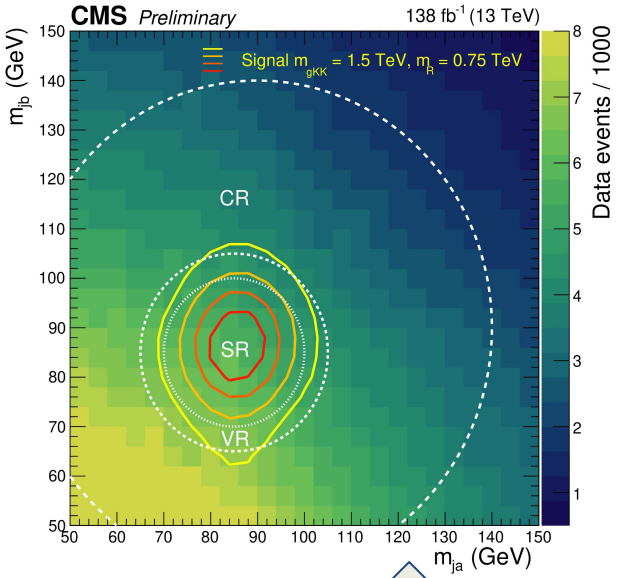




CMS-PAS-B2G-23-004

New resonances to tri-bosons



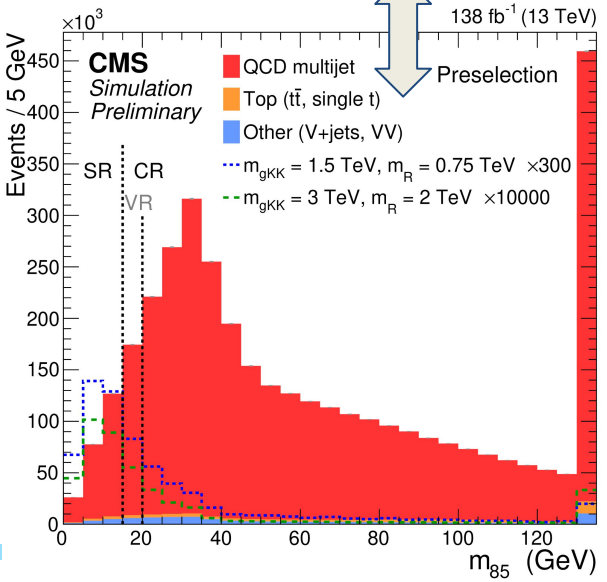


gKK with decays to intermediate Radion:
one of several possible tri-boson channels, dominant in some of the KK benchmarks (see WWW in this talk)

- **2 boosted W bosons** : Anti-Kt jets, R= 0.8, two thresholds for particle-net tagger 0.5 and 1% mis-id

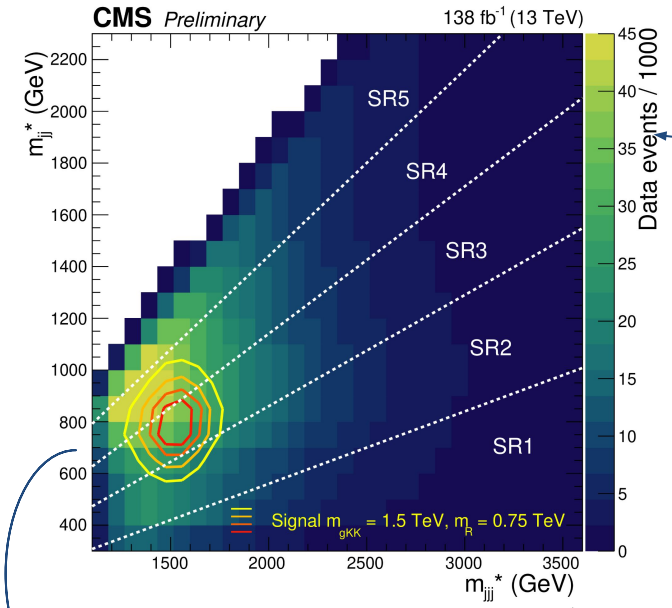
$$m_{85} \equiv \sqrt{(m_{ja} - 85\,\text{GeV})^2 + (m_{jb} - 85\,\text{GeV})^2}$$

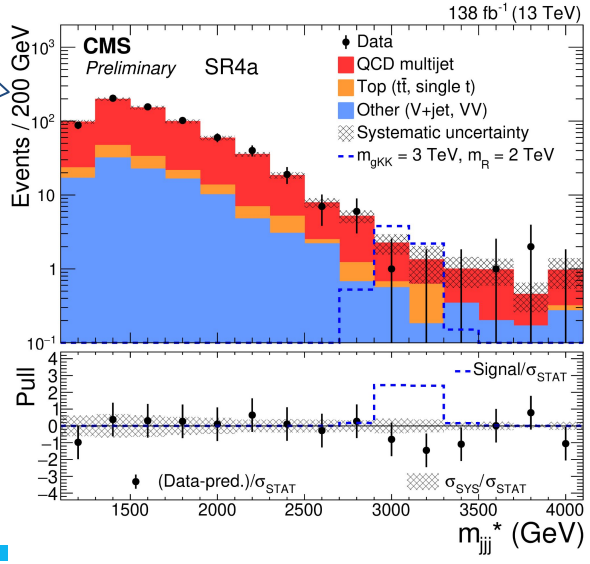
- Required m85 < 15, the rest used for control regions



CMS-PAS-B2G-23-004

Tri-bosons signal extraction

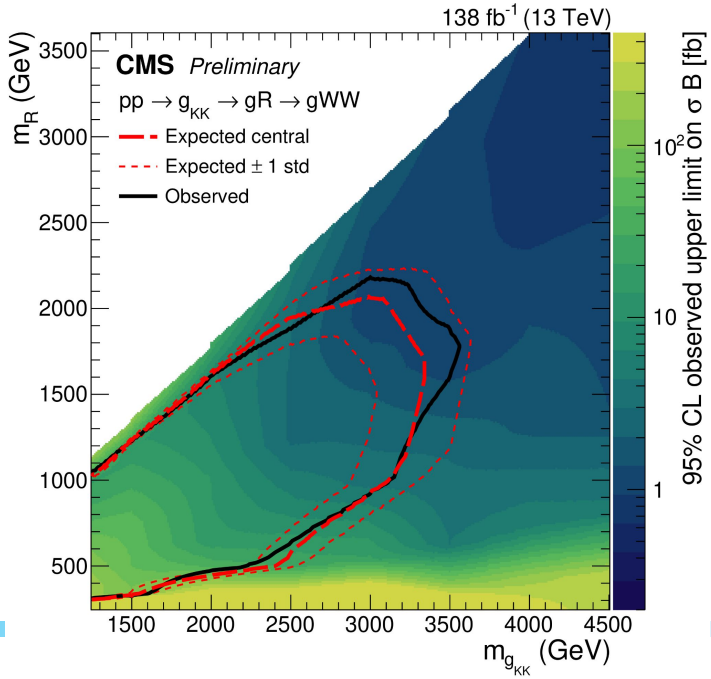




Signal regions definition:

- SR are defined as **bins in the mjj/mjjj variable.**
- SRa ⇔ both W jets particle-net mis-id at 0.5%
- SRb ⇔ 1 W at 0.5% mis-oid, the other between 1% and 0.5 mis-id thresholds.

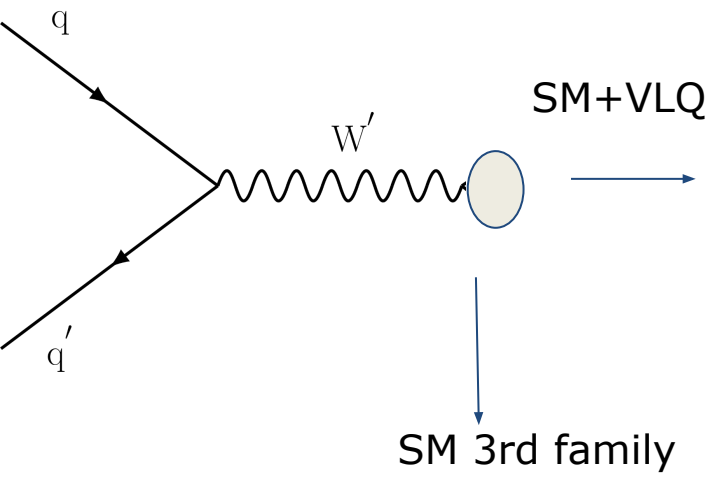
Signal extraction: fit to the mjjj in SRa and SRb



Heavy W' searches

W' → third generation

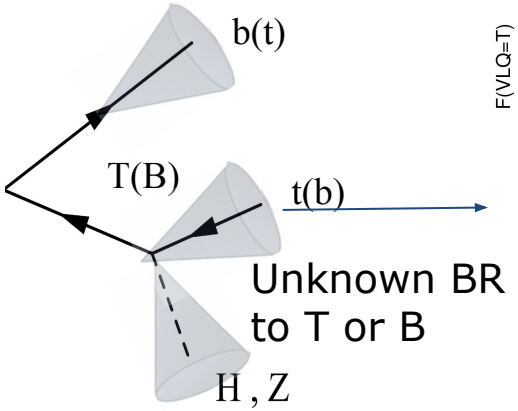
- 1 bottom quark → 1 b-jet + …

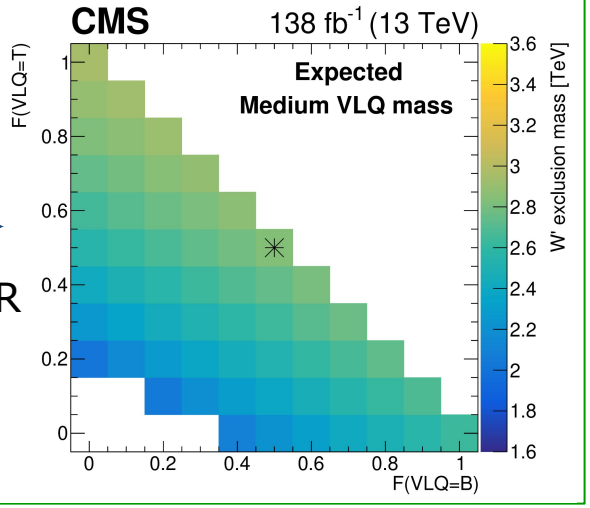


1 quark + 1VLQ

JHEP 09 (2022) 088

…+1 b-jet 2 Anti-kt: 1 top-tagged + 1 H/Z-tagged

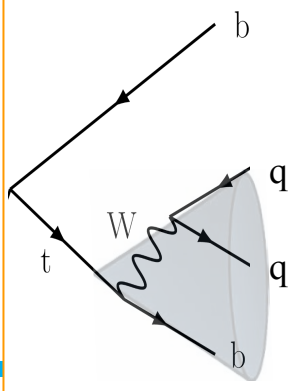


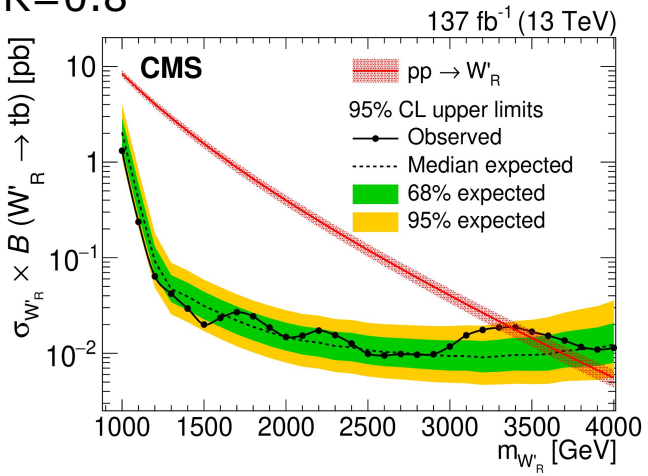


Hadronic top quark

PLB 820 (2021) 136535

…+1 Anti-kt, R=0.8

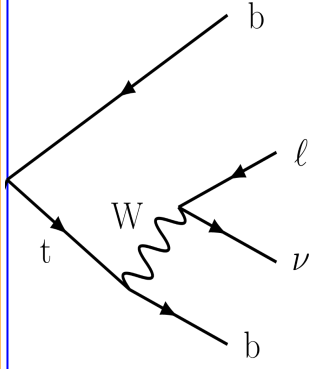


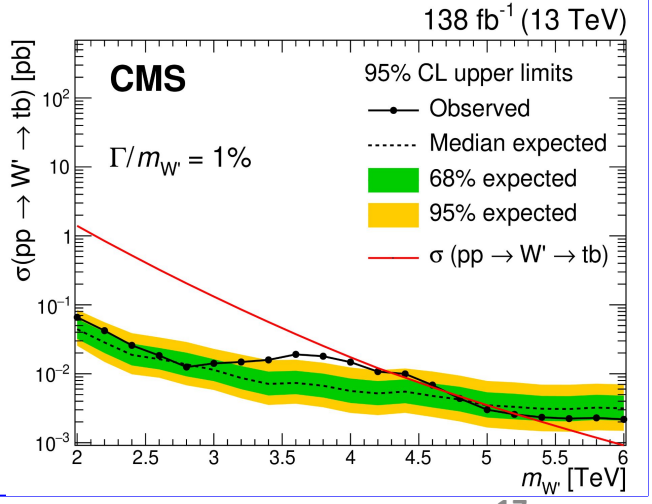


Leptonic top quark

JHEP 05 (2024) 046

…+1 b-jet + 1





Summary: new physics and heavy SM-hitters

Many **promising physics models** foreseeing the involvement of heavy SM partners **are still possible!**

The presence of **top quarks and W bosons** also makes for **complex and challenging** final states

⇒ we need to **still scour thoroughly** all "standard" signatures

⇒ we **might be missing** new physics b/c Nature prefers a **"non-minimal" scenario!**

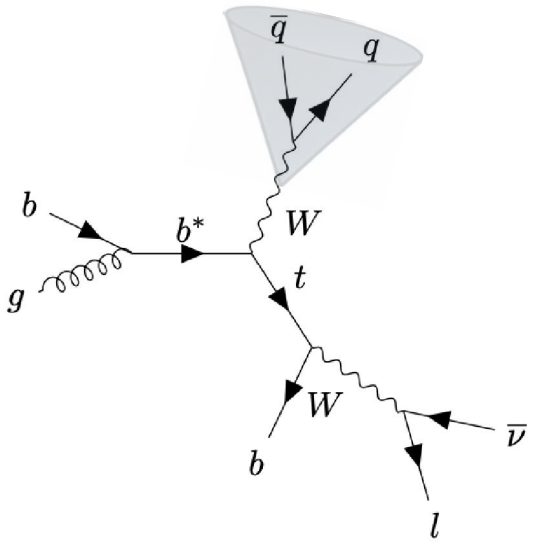
A significant effort, is ongoing to expand our signatures and improve our sensitivity and reach, **involving both technical prowess and creative thinking**.

Many interesting results yet to come!

Thanks!

Backup

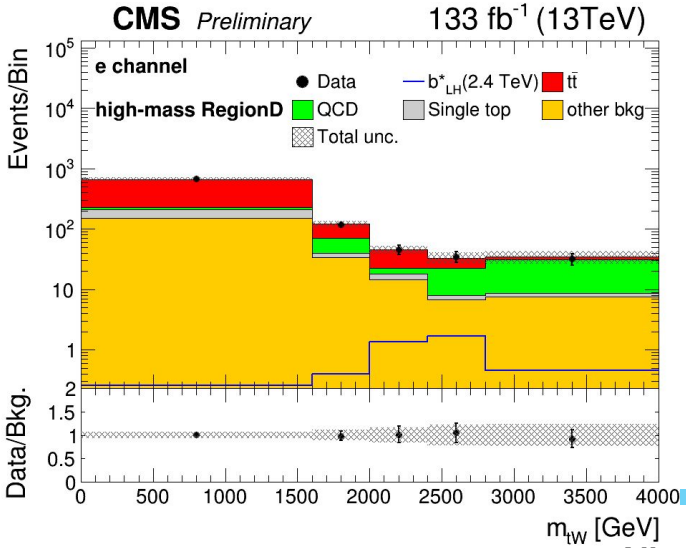
Excited quarks: b* → tW



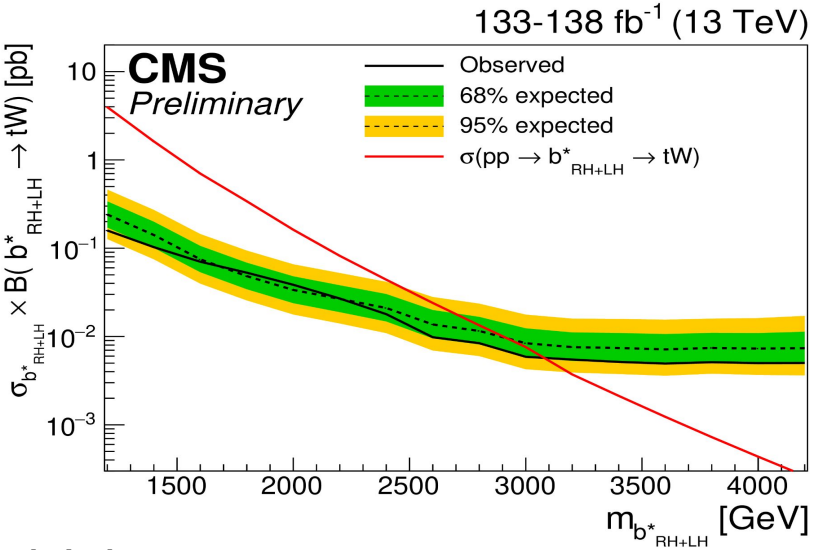
Resonant production of a b* decaying to a top and a W boson

- W boson decaying hadronically, top quark to leptons
- W-jet uses Anti-kt, R=0.8, and n-subjettines tau2/tau1 to discriminate against QCD-jets
- Background uses CR defined by inverting tau2/tau1 cuts

Main discriminant: mass of the tW pair



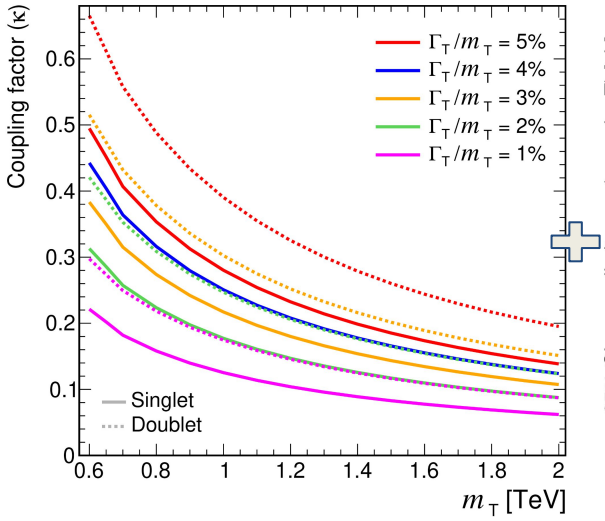
Hypotheses: LH, RH, or RH+LH

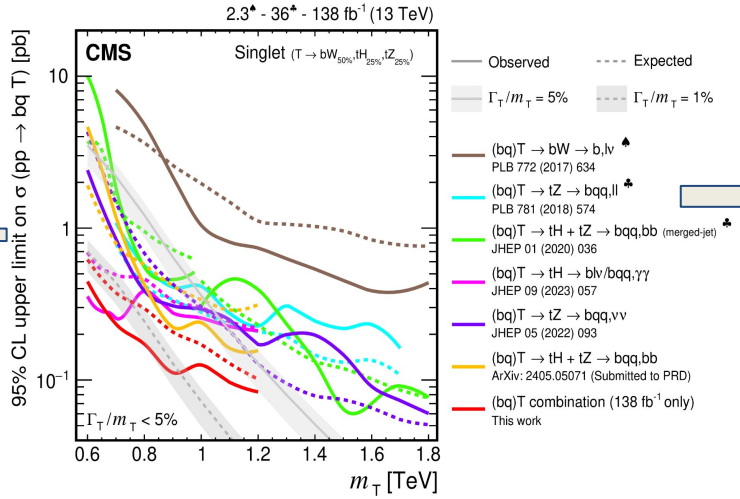


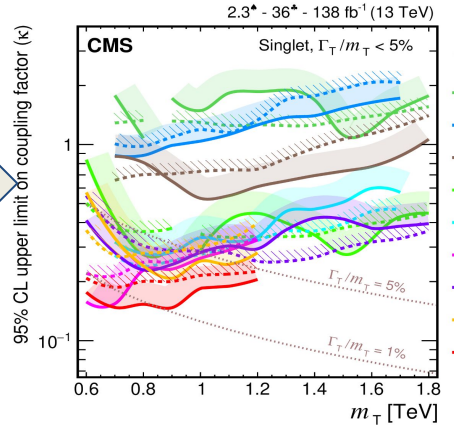
EXO-23-006

Other interesting VLQ overview plots

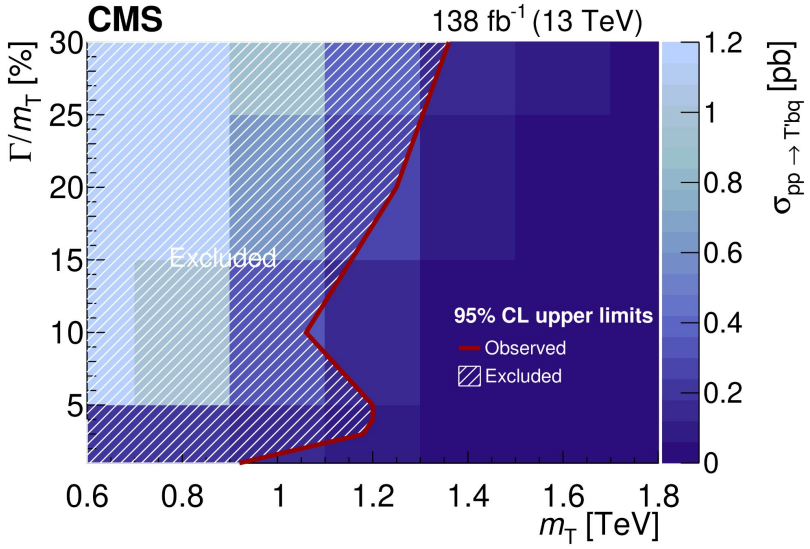
Width and couplings are related once fixed the BR



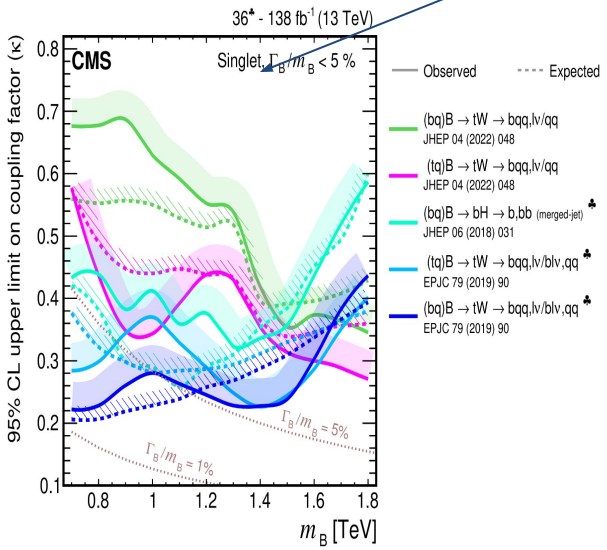


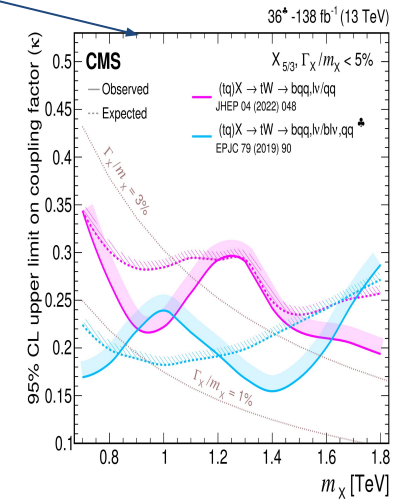


We can scan the width as well:



Similar results for **B** and **X**

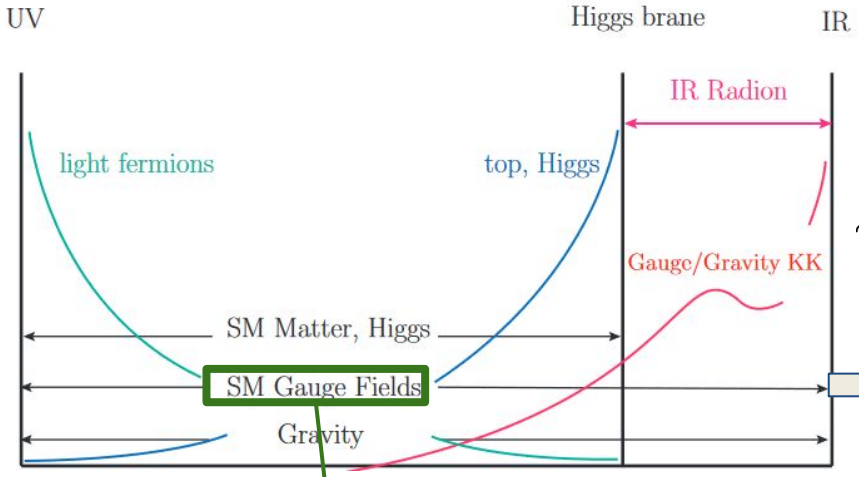




Tri-boson channels benchmarks

Warped extra dimensions:

Taken from https://arxiv.org/pdf/1612.00047



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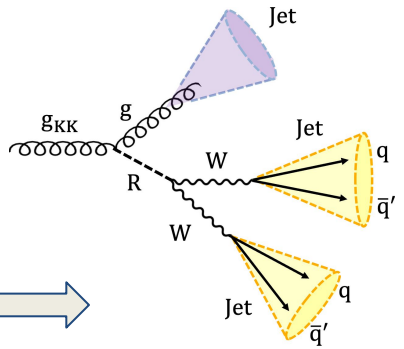
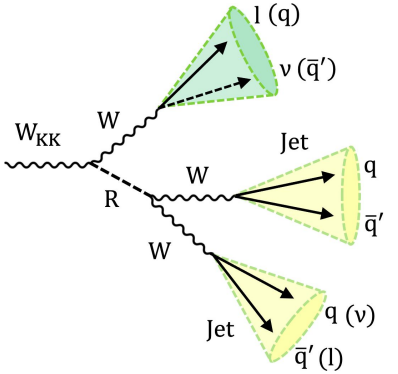


…or…

Phys. Rev. Lett. 129 (2022) 021802



See also this talk by Chen Zhou https://agenda.infn.it/event/37093/contributions/234298/

Vast phase space to explore

→ Depending on which field can extend into the bulk you can have different couplings to NP

→ Obviously gWW is dominant in scenarios with larger coupling of the g_{KK} over W_{KK}

	Process	Name	m_{KK}	m_φ	$g_{\gamma KK}$	$g_{W KK}$	g_{gKK}	g_{grav}
γ_{KK}	$\gamma_{KK} \to \gamma\varphi \to \gamma gg$ (5.1)	γ-γgg-BP1	3	1	3	6	3	3
		γ-γgg-BP2	3	1.5	2.7	6	3	4.1
g_{KK}	$g_{KK} \to g\varphi \to g\gamma\gamma$ (5.2.2)	g-$g\gamma\gamma$-BP1	3	1	2.7	6	6	2.25
		g-$g\gamma\gamma$-BP2	3	1.5	2.7	6	6	3
	$g_{KK} \to g\varphi \to ggg$ (5.2.1)	g-ggg-BP1	3	1	2.7	6	3	2.45
		g-ggg-BP2	3	1.5	2.7	6	3	4
	$g_{KK} \to g\varphi \to gV_hV_h$ (5.2.3)	g-gVV-BP1	3	1	2.65	3	6	3
		g-gVV-BP2	3	1.5	2.65	3	6	5
W/Z_{KK}	$W_{KK} \to W_l\varphi \to W_lgg$ (5.3)	W-Wgg-BP1	2.5	1	3.5	4.4	3	3.5
		W-Wgg-BP2	3	1.5	3	3.5	3	5.1

Substructure variables

Energy correlation functions:

$$N_2(\beta) = \frac{2e_3^\beta}{(e_2^\beta)^2}$$

$${}_1e_2^\beta = e_2^\beta = \sum_{1\le i<j\le n_J} z_i z_j \Delta R_{ij}^\beta$$

$$z_i \equiv \frac{p_{Ti}}{\sum_{j\in \text{jet}} p_{Tj}}$$

$${}_2e_3^\beta = \sum_{1\le i<j<k\le n_J} z_i z_j z_k \min\{\Delta R_{ij}^\beta \Delta R_{ik}^\beta, \Delta R_{ij}^\beta \Delta R_{jk}^\beta, \Delta R_{ik}^\beta \Delta R_{jk}^\beta\}$$

N-subjettiness:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$