Vector Like Dorks(listed below)

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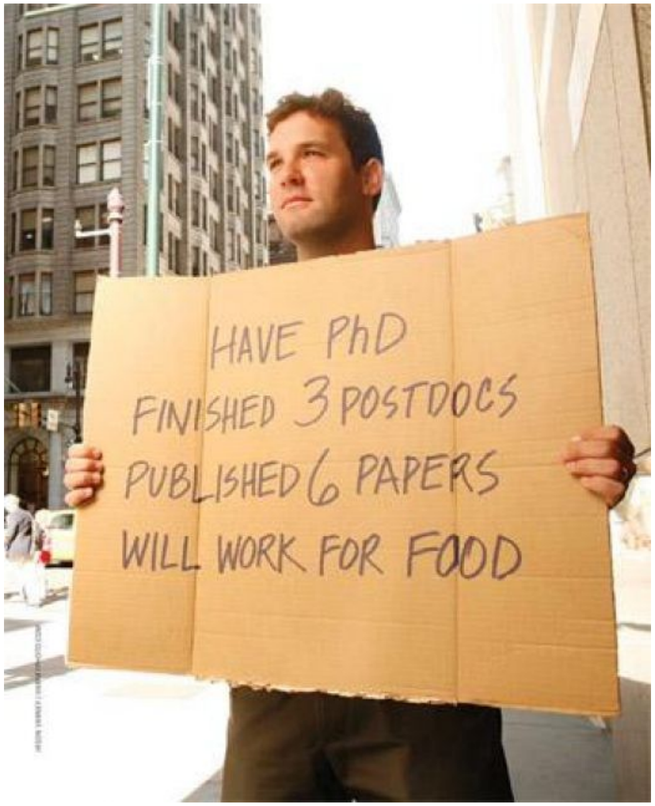
The question (outline)

Precision measurements tell us that **if new heavy quarks are discovered** (i.e., beyond the usual 3 generations), they cannot be \`just' another fourth generation but **must be \`vector-like' quarks (VLQ)** instead.

- What measurements force us into this VL nature expectation?
- What are VLQs and by what mechanisms may such states actually be discovered?
- Most recent search results in colliders
- The future of VLQ searches
- Can VLQ discovery be somehow cleverly evaded by other new physics?

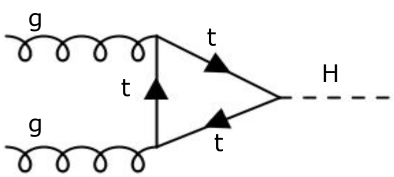
Motivation


HAVE PhD
FINISHED 3 POSTDOCS
PUBLISHED 6 PAPERS
WILL WORK FOR FOOD


No VLQ
No VLQ yet

Why not a 4th generation of quarks?

- Higgs is produced by gluon-gluon fusion through a fermion loop
- Heavy fermions **do not decouple** → "generation counter"



$$\sim m_Q \underbrace{Y_Q}_{\sim m_Q} \int dx dy \left(\frac{1-4xy}{m_Q^2 - m_H^2 xy} \right) \xrightarrow{m_Q \gg m_H} \frac{1}{3}$$

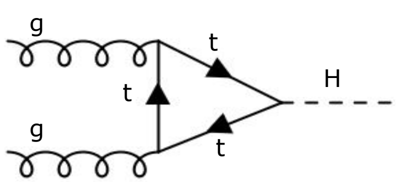
- Chiral 4th generation ruled out by experiment
  - Adding a heavy quark doublet would increase the rate of **gg→H by ~9x**

$$\left(\frac{1/3+1/3+1/3}{1/3} \right)^2 = 9$$

  - Additional constraints from EW fits (oblique parameters)
  - Even invisible Z decays

Escape Y~m?

- If $m_Q \sim Y_Q v + M_Q$ and for large masses $m_Q \sim M_Q$



$$\sim m_Q Y_Q \int dx\,dy \left(\frac{1-4xy}{m_Q^2 - m_H^2 xy}\right) \xrightarrow{m_Q \sim M_Q \gg m_H} \frac{Y_Q}{M_Q} \approx 0$$

- If the quark masses are not entirely due to EW SSB, then a "4th" generation is possible!

Challenge for a 4th generation

- Can we introduce extra heavy quarks to the SM without proportionally strong Yukawa couplings?
  - LH fermions are SU(2) doublets, but RH fermions are SU(2) singlets
  - One cannot form gauge-invariant mass terms! SSB is needed!

$$\cancel{\begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} M u_R}$$

- **But...**
  - **Color triplet** -> has QCD color charge (like quarks)
  - **Spin ½** -> fermion (like quarks)
  - **Equal left- and right-handed transformations under SU(2)**

$$\begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} M \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

✅ → **Vector-like nature!**

What can VLQs solve?

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ in SM, but 2.3σ tension with unitarity from measurements $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.09984 \pm 0.0007$
  - Extra quarks would lead to a larger overall mixing matrix
- Possible in Randall-Sundrum warped extra dimensional models (KK modes) - related to hierarchy problem
- Possible in GUT scenarios (e.g. part of SU(6), E6)
- Spontaneous CPV from vacuum of extended scalar sector (coupling of vector-like quark to complex scalar singlet + mixing → generates complex CKM matrix), solves strong CP problem

Vector-Like Quarks

Possible Vector Like Quarks?

	Singlets		Doublets			Triplets	
Multiplet	T	B	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{3}$
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$7/6$	$-5/6$	$2/3$	$-1/3$

Electric charge: T: 2/3; B: -1/3; X: 5/3; Y: -4/3

VLQ roadmap (2304.10561v3)
CMS ICHEP 2024

Mass generation

"**Color triplet** **spin ½** fermions with **equal left- and right- handed SU(2) chiral transformation**"

$$\mathcal{L}_{\text{mass}} = -\bar{Q}_L M_Q Q_R + h.c. + \text{Yukawa!}$$

(Taking singlets)

$$\mathscr{L}_{\text{mass}} = -\begin{pmatrix} \overline{u}_L^0 & \overline{\mathrm{T}}_L^0 \end{pmatrix} \mathcal{M}_u \begin{pmatrix} u_R^0 \\ \mathrm{T}_R^0 \end{pmatrix} - \begin{pmatrix} \overline{d}_L^0 & \overline{\mathrm{B}}_L^0 \end{pmatrix} \mathcal{M}_d \begin{pmatrix} d_R^0 \\ \mathrm{B}_R^0 \end{pmatrix} + \text{h.c.}$$

$$\mathcal{M}_q = \begin{array}{c} \left(\begin{array}{c:c} m_q & \overline{m}_q \\ \hdashline \overline{M}_q & M_q \end{array}\right) \begin{array}{l} \}\, 3 \\ \}\, n_q \end{array} \\ \quad\ \ 3 \qquad n_q \end{array} \qquad \text{where } m_q = \frac{v}{\sqrt{2}} Y_q \text{ and } \overline{m}_q = \frac{v}{\sqrt{2}} \overline{Y}_q$$

SM Yukawa

New Yukawa to RH fields

New mass terms due to T and B

VLQ roadmap (2304.10561v3)

VLQ interactions

- Mixing matrix is non-unitary in general, so is the CKM matrix, that is determined by the upper left 3*3 block.

  $\mathcal{V}_\chi^q$ diagonalizes the mass matrix, hence must be unitary, but not A and B!!

$$\mathcal{V}_\chi^q = \left(\begin{array}{c} A_\chi^q \\ \hdashline B_\chi^q \end{array} \right) \begin{array}{l} \}\,3 \\ \}\,n_q \end{array} ,$$

- Since only the SM model quarks is charged under SU(2), the mixing matrix need not be unitary.

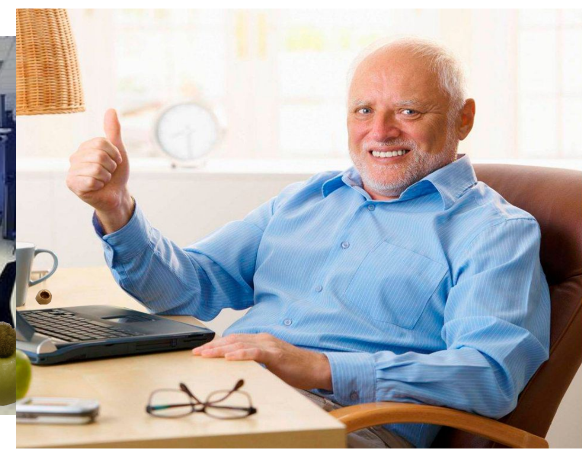
$$\boxed{V \equiv A_L^{u\,\dagger} A_L^d \,,}$$

- FCNC now exists at tree-level: for example Z-mediated interaction:

$$\mathscr{L}_Z = -\frac{g}{2\cos\theta_W}\left[(\bar{u}_L \quad \bar{T}_L)F^u\gamma^\mu \begin{pmatrix} u_L \\ T_L \end{pmatrix} - (\bar{d}_L \quad \bar{B}_L)F^d\gamma^\mu \begin{pmatrix} d_L \\ B_L \end{pmatrix} - 2\sin^2\theta_W J^\mu_{\text{em}}\right] Z_\mu, \quad F^u \equiv VV^\dagger, \quad F^d \equiv V^\dagger V$$

VLQ roadmap (2304.10561v3)

Detecting VLQs



Detecting VLQs: Decay

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- The dominant decay modes of VLQs are to third-generation SM quarks
  - Decay into 1st and 2nd gen quarks is not forbidden, it is ‘not favoured’
    - These channels do not address the hierarchy problem
  - Most experiments limit their search to Q decaying to t or b and some boson

ATLAS (2401.17165)

Detecting VLQs: Decay

- ATLAS & CMS mostly look into the decay of SU(2) singlets and doublets

		Decays
Singlet	T	$T \to bW^+, tZ, tH$
	B	$B \to tW^-, bZ, bH$
Doublet	(T, B)	$T \to tZ, tH, B \to bW^-$
	(X, T)	$X \to tW^+, T \to tZ, tH,$
	(B, Y)	$B \to bZ, bH, Y \to bW^-$

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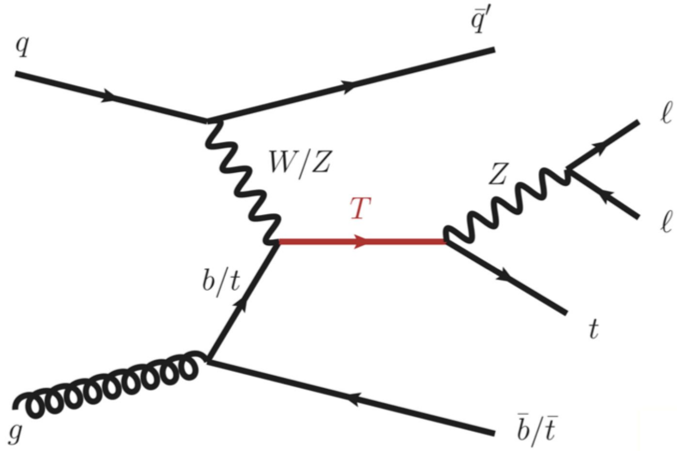
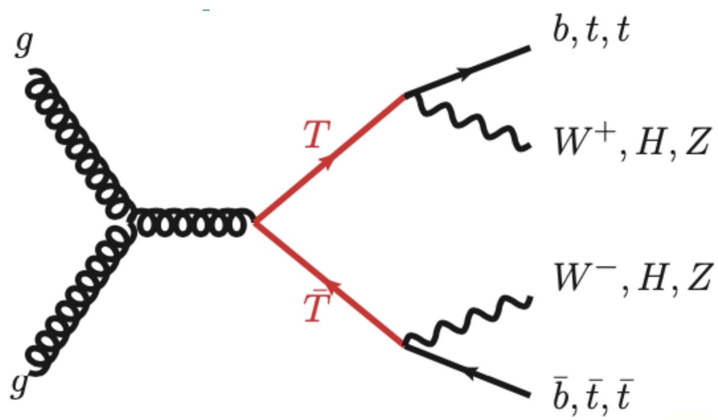
Detecting VLQs: Production

Experimental searches divided into two categories:

Single production



Pair production



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Detecting VLQs: Production

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Detecting VLQs: Production

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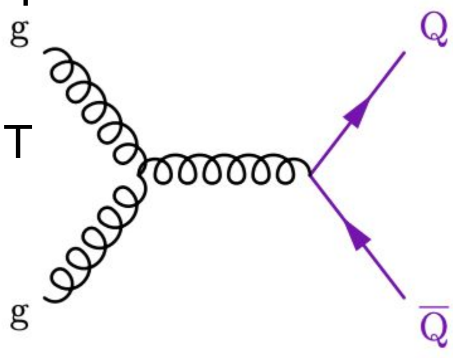
Within single and pair production there are a couple of options:

- Strong production:
  - Depends on strong coupling constant and mass of T
  - More model independent as cross section only depends on mass of T



Detecting VLQs: Production

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- Strong production:
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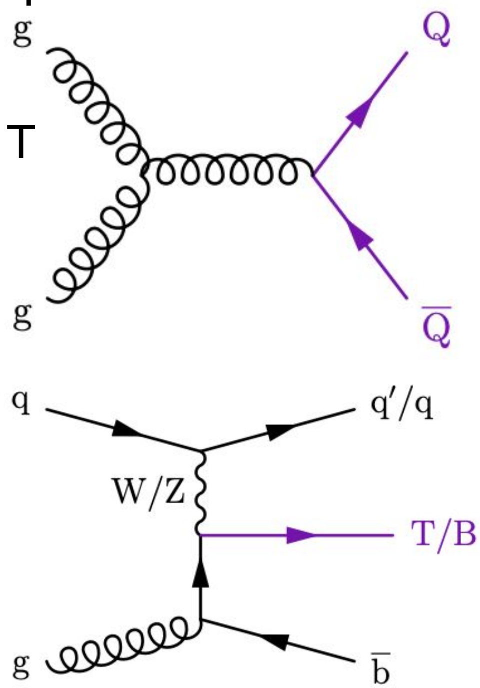
- EW production:
  - Cross section dependent on coupling to (regular) quarks; coupling strength changes with choice of VLQ mass and width
  - Relatively heavy VLQs can be investigated



Detecting VLQs: Production

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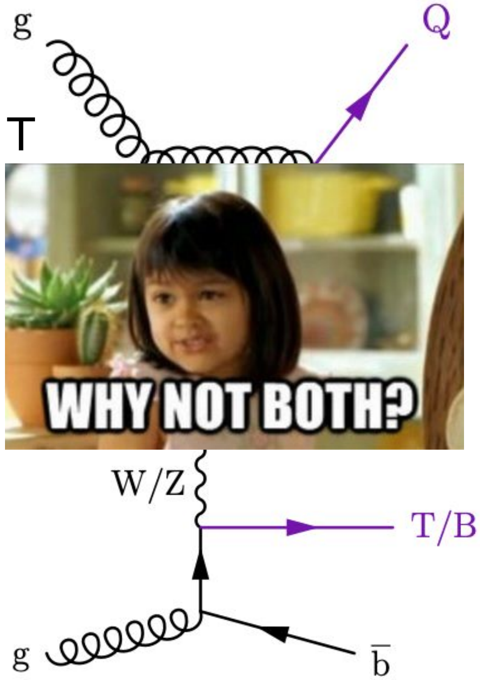

Detecting VLQs: Channels

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Production mode	Decay mode	Channel
$\mathrm{T\overline{T}}$	bW, tH, tZ	0ℓ, 1ℓ, OS 2ℓ, SS 2ℓ, 3ℓ
$\mathrm{B\overline{B}}$	tW, bH, bZ	0ℓ, 1ℓ, OS 2ℓ, SS 2ℓ, 3ℓ
$\mathrm{X_{5/3}\overline{X}_{5/3}}$	tW	1ℓ, SS 2ℓ
$\mathrm{Y_{4/3}\overline{Y}_{4/3}}$	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
$\mathrm{X_{5/3}}$	tW	bqq $\ell\nu$, b$\ell\nu$ qq, bqq qq
$\mathrm{Y_{4/3}}$	bW	b $\ell\nu$
$\mathrm{Z' \to T\overline{T}}$	bW	0ℓ
	tH, tZ	1ℓ
$\mathrm{W' \to Tb}$	tH, tZ	0ℓ
$\mathrm{W' \to Bt}$	bH, bZ	0ℓ

[CMS May 2024 (2405.17605)]

Detecting VLQs: Channels

- Way too many channels to show
- Short answer:
  VLQs have not been detected

Production mode	Decay mode	Channel
$T\overline{T}$	bW, tH, tZ	0ℓ, 1ℓ, OS 2ℓ, SS 2ℓ, 3ℓ
$B\overline{B}$	tW, bH, bZ	0ℓ, 1ℓ, OS 2ℓ, SS 2ℓ, 3ℓ
$X_{5/3}\overline{X}_{5/3}$	tW	1ℓ, SS 2ℓ
$Y_{4/3}\overline{Y}_{4/3}$	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	$b\,\ell\nu$
$Z' \to T\overline{T}$	bW	0ℓ
	tH, tZ	1ℓ
$W' \to Tb$	tH, tZ	0ℓ
$W' \to Bt$	bH, bZ	0ℓ

CMS May 2024 (2405.17605)

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Highlight some of the most recent constraints

Production mode	Decay mode	Channel
$T\overline{T}$	bW, tH, tZ	$0\ell, 1\ell$, OS 2ℓ, SS 2ℓ, 3ℓ
$B\overline{B}$	tW, bH, bZ	$0\ell, 1\ell$, OS 2ℓ, SS 2ℓ, 3ℓ
$X_{5/3}\overline{X}_{5/3}$	tW	1ℓ, SS 2ℓ
$Y_{4/3}\overline{Y}_{4/3}$	bW	1ℓ
T	tZ	$\mathrm{bqq}\,\ell\ell$, bqq bb, $\mathrm{bqq}\,\nu\nu$
	tH	$\mathrm{bqq}\,\gamma\gamma$, bqq bb
	bW	$\mathrm{b}\,\ell\nu$
B	bH	b bb
	tW	$\mathrm{bqq}\,\ell\nu$, $\mathrm{b}\ell\nu$ qq, bqq qq
$X_{5/3}$	tW	$\mathrm{bqq}\,\ell\nu$, $\mathrm{b}\ell\nu$ qq, bqq qq
$Y_{4/3}$	bW	$\mathrm{b}\,\ell\nu$
$Z' \to T\overline{T}$	bW	0ℓ
	tH, tZ	1ℓ
$W' \to Tb$	tH, tZ	0ℓ
$W' \to Bt$	bH, bZ	0ℓ

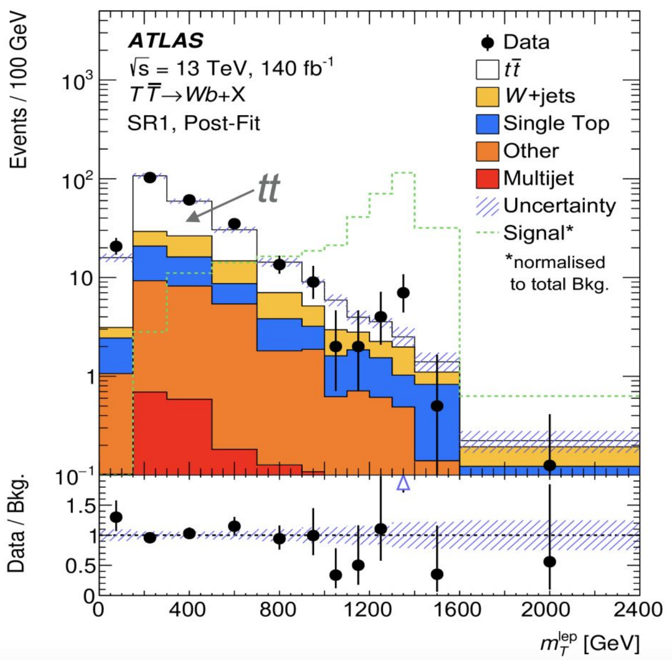
CMS May 2024 (2405.17605)

ATLAS Highlights

Detecting VLQs

ATLAS ICHEP 2024

Pair production of heavy T?



Detecting VLQs

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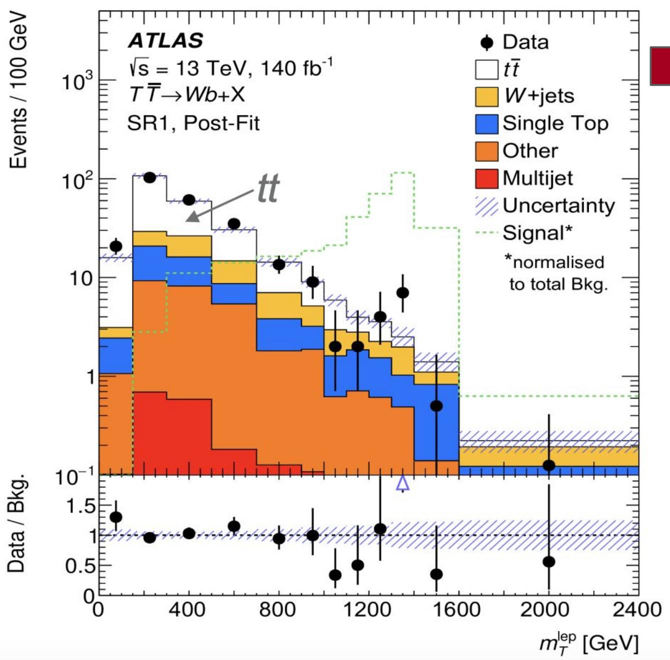
Limits on pair production of heavy T



No discovery, but can use this to place precise constraints on production σ

Detecting VLQs

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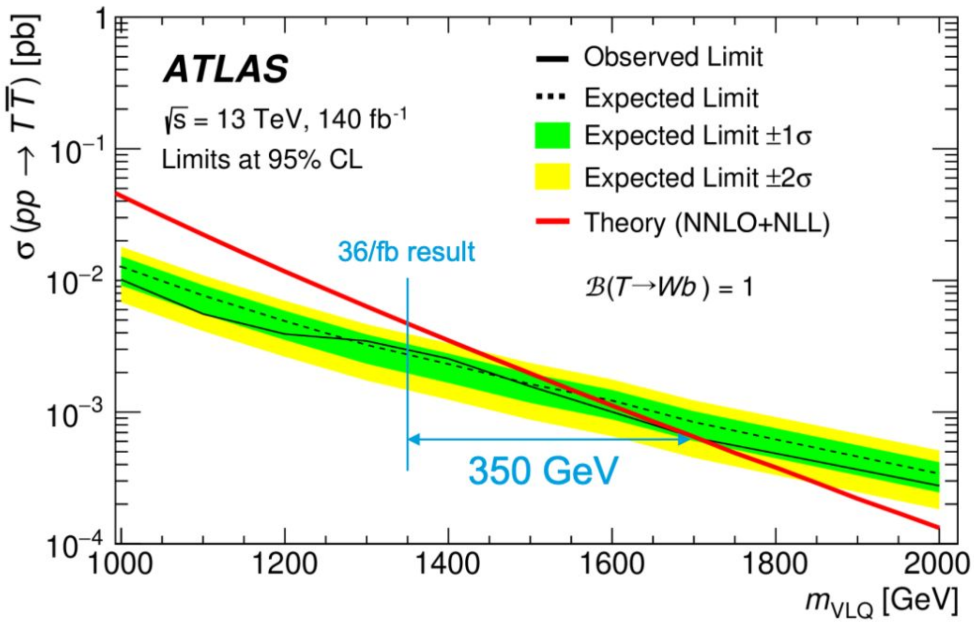
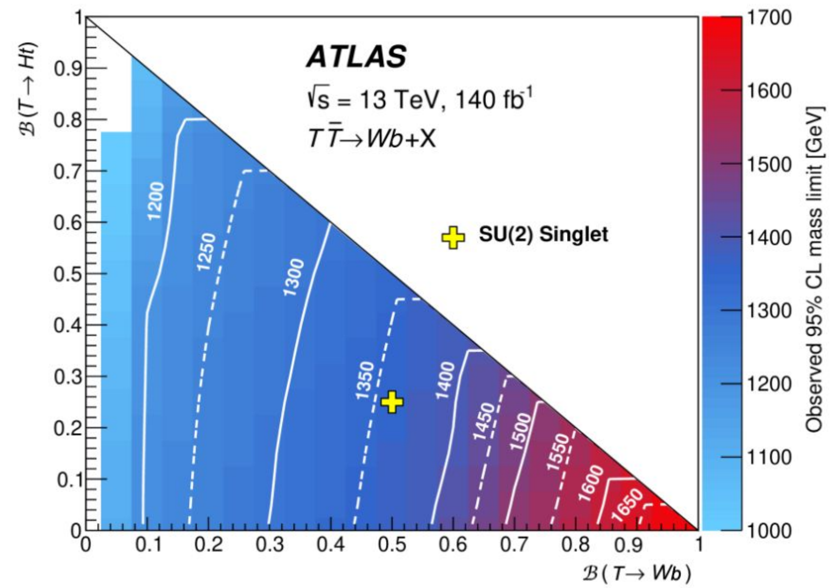
Limits on pair production of heavy T

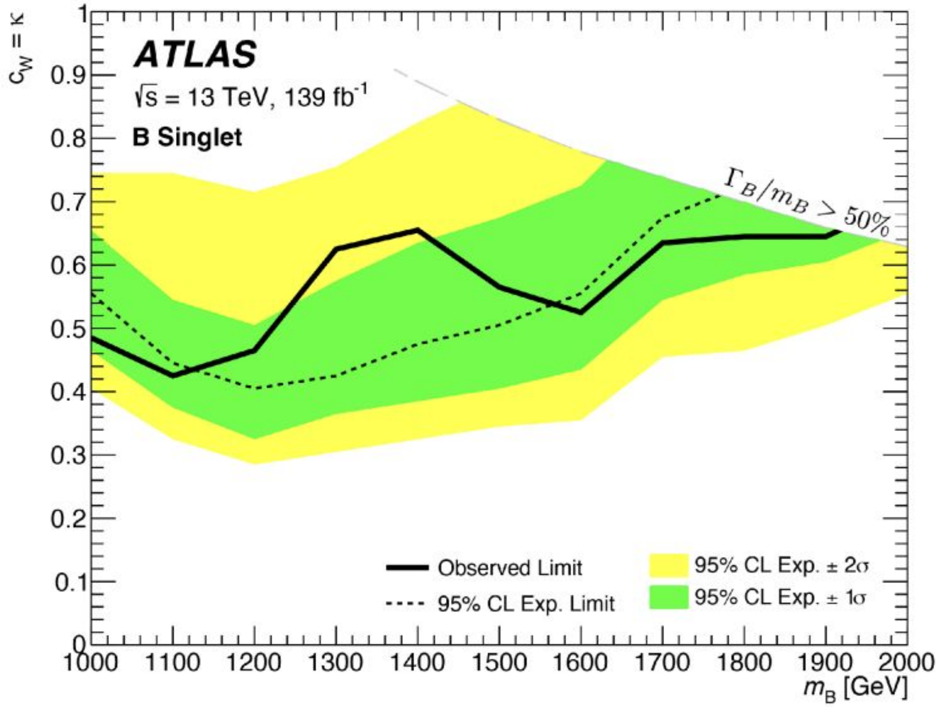




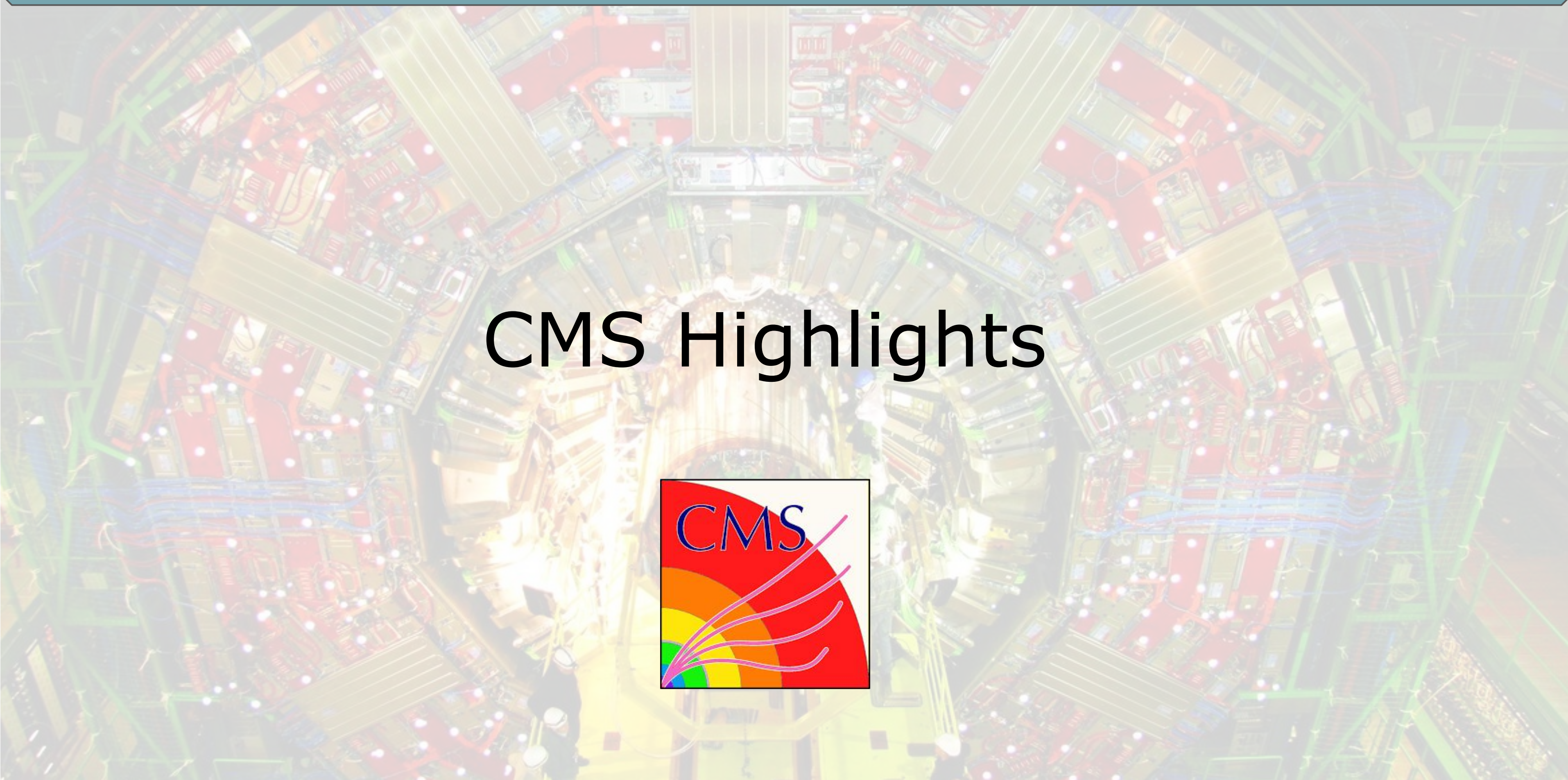
Detecting VLQs

ATLAS ICHEP 2024

Constraints on the coupling strength of the B



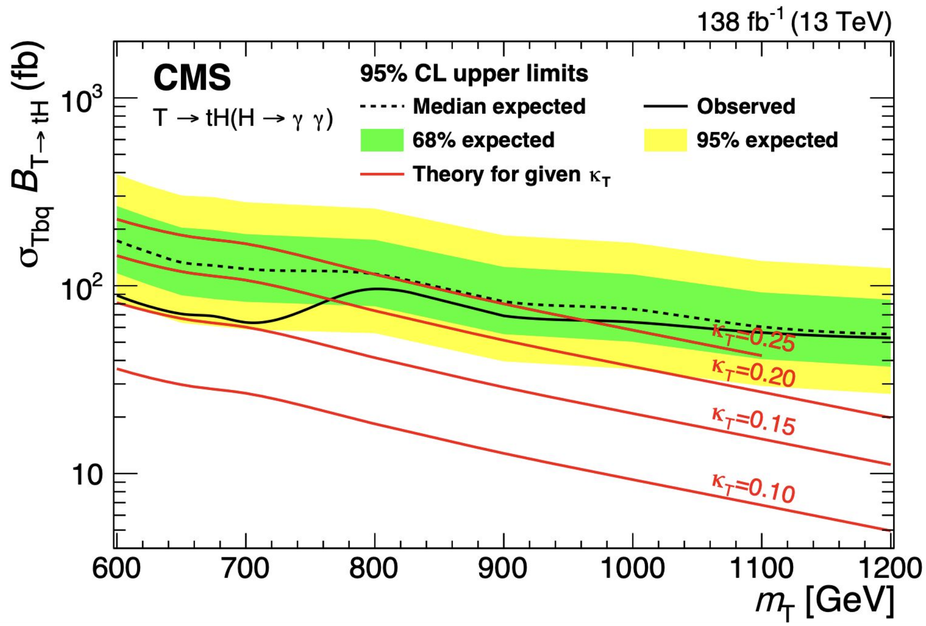
CMS Highlights



Detecting VLQs

[CMS ICHEP 2024](#)

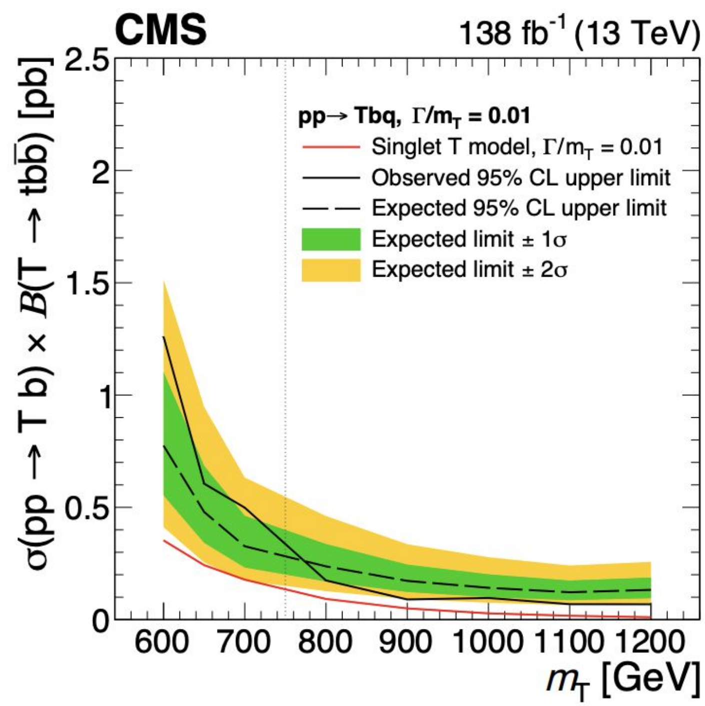
Constraints on production cross section



Detecting VLQs

CMS ICHEP 2024

Constraints on production cross section of single T



Detecting VLQs

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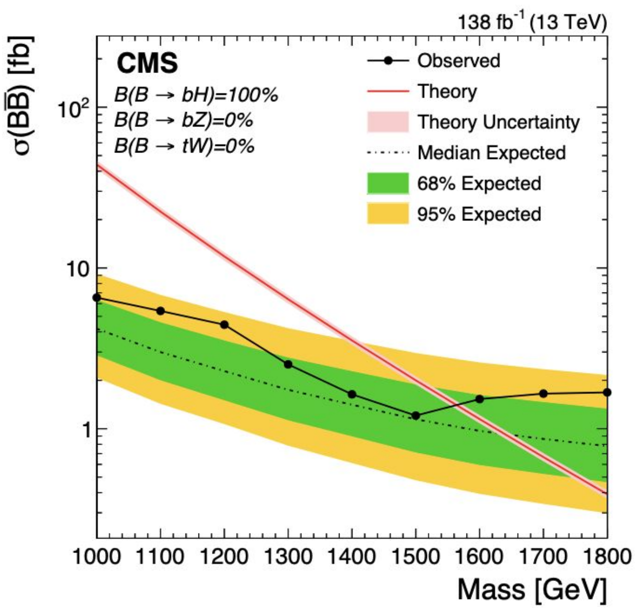
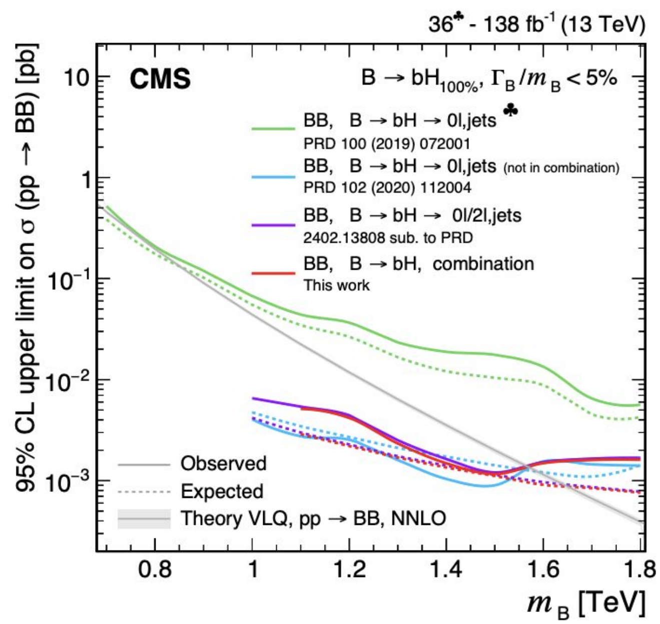
Constraints on BB pair production





Detecting VLQs: remarks

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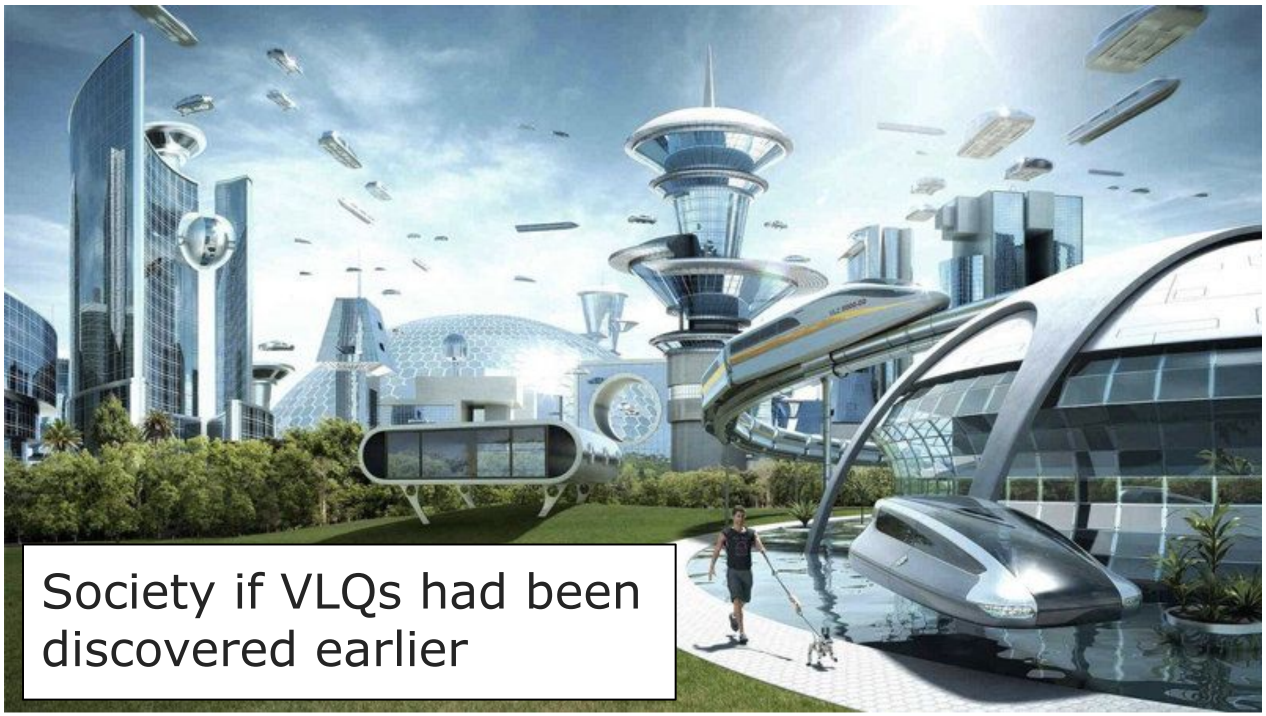
- No evidence for VLQs observed (yet?)
- Analyses techniques and strategies are steadily improving
  - Techniques can be used by other non BSM analyses in ATLAS & CMS
- Much stronger constraints wrt Run 1
  - Able to constrain up to a much higher mass and with much higher precision

Vector-Like Quarks in the future

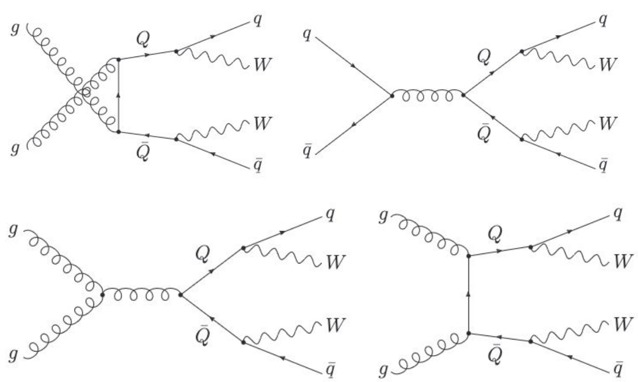


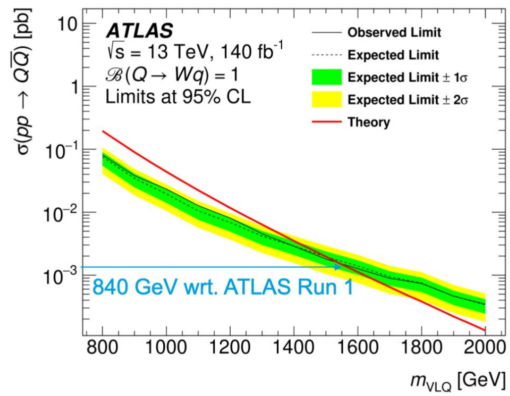
Future Search Prospects

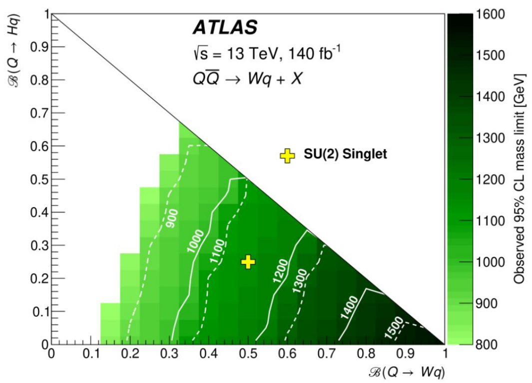
ATLAS ICHEP 2024

Pair production via strong interaction, then Q→Wq, where q is a light quark

- Most searches focused on coupling to heavy quarks
- Some models (e.g. LRMM, E6 GUTs) predict lightest VLQ coupling mostly to lightest SM quarks







Future Search Prospects

- HL-LHC
  - 3σ exclusion limits and 5σ discovery within reach for 600-1000 GeV mass (ATLAS ICHEP 2024)
- FCC-hh
  - 5σ discovery for pair produced down-type VLQs can be increased to 2980 GeV and to 2.1 TeV for up-type VLQs (Down type iso-singlet quarks at the HL-LHC and FCC-hh, Search for single production of vectorlike top partners through thth channel at the HE-LHC and FCC-hh)
- Muon collider
  - Production of TeV-mass VLQ enhanced for μμ annihilation (The Muon Smasher's Guide)

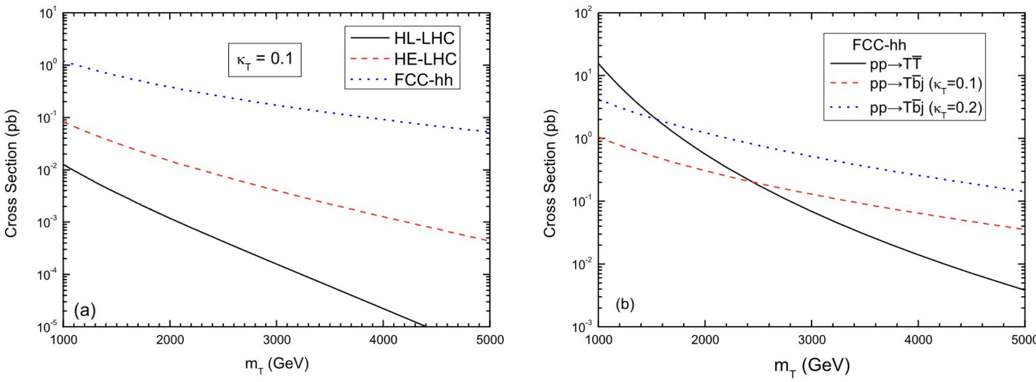
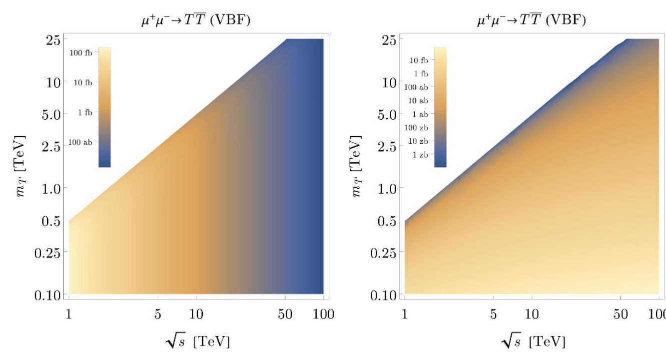
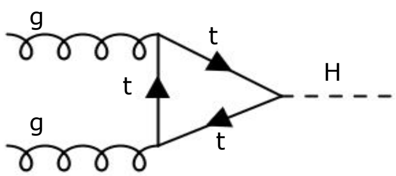


Fig. 2 **a** The dependence of the cross sections for the process $pp \to T\bar{b}j + \bar{T}bj$ on the T quark mass m_T at 14 TeV LHC, HE-LHC and FCC-hh with $\kappa_T = 0.1$; **b** the cross sections of top partners single production and pair production versus its mass at the FCC-hh



Alternative to Vector-Like Quarks

Does not quack like a VL-quack?



$$\sim m_Q Y_Q \int dx dy \left(\frac{1-4xy}{m_Q^2 - m_H^2 xy} \right)$$

- Crucially, for a 'normal' 4th generation $Y_Q \sim m_Q$
- What if the signs of Yukawa couplings are opposite (wrong)?

$$\sim Y_Q m_Q \int dx dy \left(\frac{1-4xy}{m_Q^2 - m_H^2 xy} \right) - Y_{Q'} m_{Q'} \int dx dy \left(\frac{1-4xy}{m_{Q'}^2 - m_H^2 xy} \right)$$

$$\xrightarrow{m_{Q,Q'} \gg m_H} \frac{Y_Q}{m_Q} - \frac{Y_{Q'}}{m_{Q'}} \approx 0?$$

Can it quack like that?

- In the SM field redefinitions can absorb the sign (phase) of the Yukawas → extend the scalar sector!
- In 2HDM-II the signs are controlled by mixing parameters
  - α – neutral scalar mixing, β – doublet/vev mixing angle

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i + \phi_i^0}{\sqrt{2}} \end{pmatrix}$$

$$\kappa_V^{\mathrm{II}} = \sin(\beta - \alpha),$$

$$\kappa_u^{\mathrm{II}} = \sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha),$$

$$\kappa_d^{\mathrm{II}} = \kappa_\ell^{\mathrm{II}} = \sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha).$$

$$\cos(\beta - \alpha) = \frac{r}{\tan\beta},$$

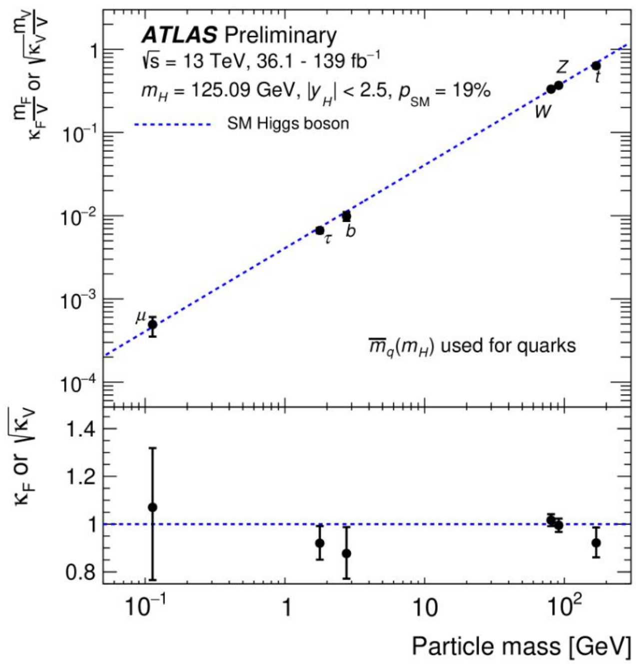
$$\kappa_V^{\mathrm{II}} \approx 1, \qquad \kappa_u^{\mathrm{II}} \approx 1, \qquad \kappa_{d,\ell}^{\mathrm{II}} \approx 1 - r.$$

- r=2 gives the wrong sign limit!

VLQ vs. Wrong Sign?

- VLQ would be "off the charts"

- If "on the charts" then *definitely* additional new physics!
  - e.g. extended scalar sector



WHAT IS THE MAIN POINT?

It’s friends we made along the way

We found the VLQs!!!!!

Bonus Harolds