VLQs coupling determination at the LHC and future hadron colliders

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Vector-like Quarks

VLQs are new colored states whose left- and right-handed component transform in the same way under the SM gauge group

$$\mathcal{L} \sim g\, j^{\mu,+} W_\mu^+ + h.c.$$

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \quad j_R^\mu = 0$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu (1-\gamma^5) f'$$

V-A interaction

$$j_{L,R}^\mu = \bar{f}_{L,R} \gamma^\mu f'_{L,R}$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu f'$$

Vector interaction

For VLQs a gauge invariant mass term is allowed

$$\mathcal{L}_{\text{mass}} = m_{VLQ}\, \bar{Q}_L Q_R + h.c.$$

Vector-like Quarks

They appear in many NP models that try to address the SM hierarchy problem

- **Composite Higgs**
- **Little Higgs**
- **Extra dimensions**
- **Non minimal SUSY**
- ....

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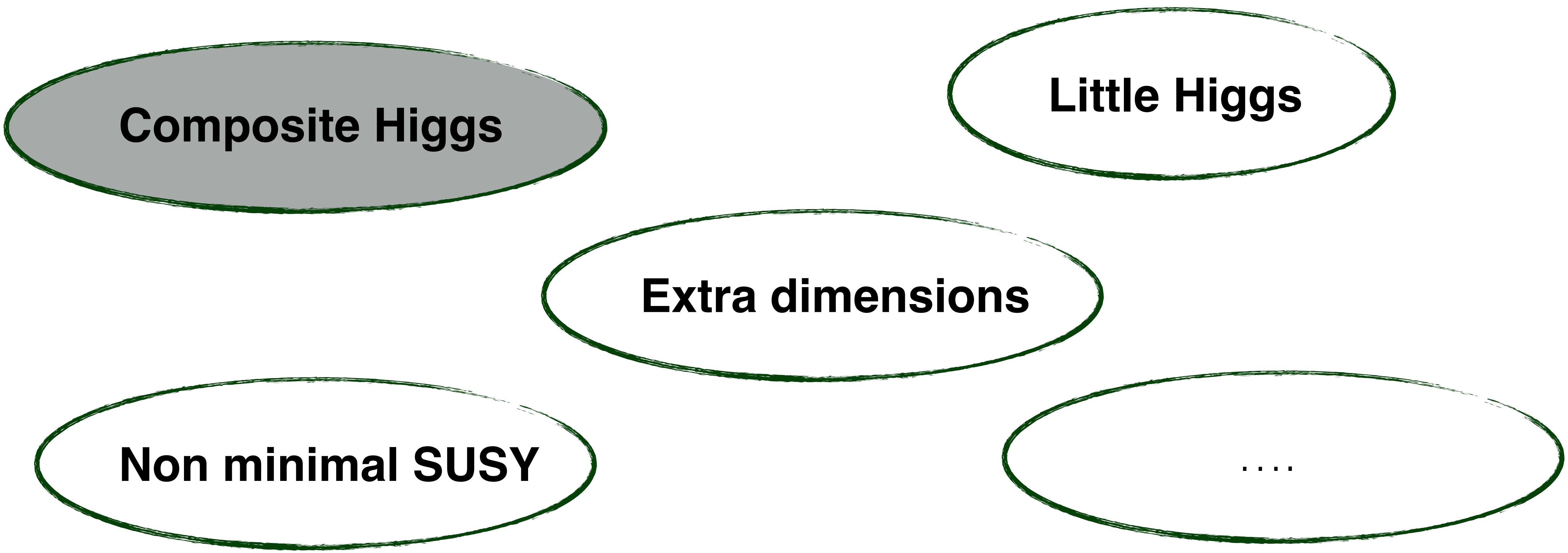

In CHMs they control the level of fine tuning of the theory
They are thus expected to be found around the TeV scale

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They are thus expected to be found around the TeV scale

This has motivated an intense experimental activity

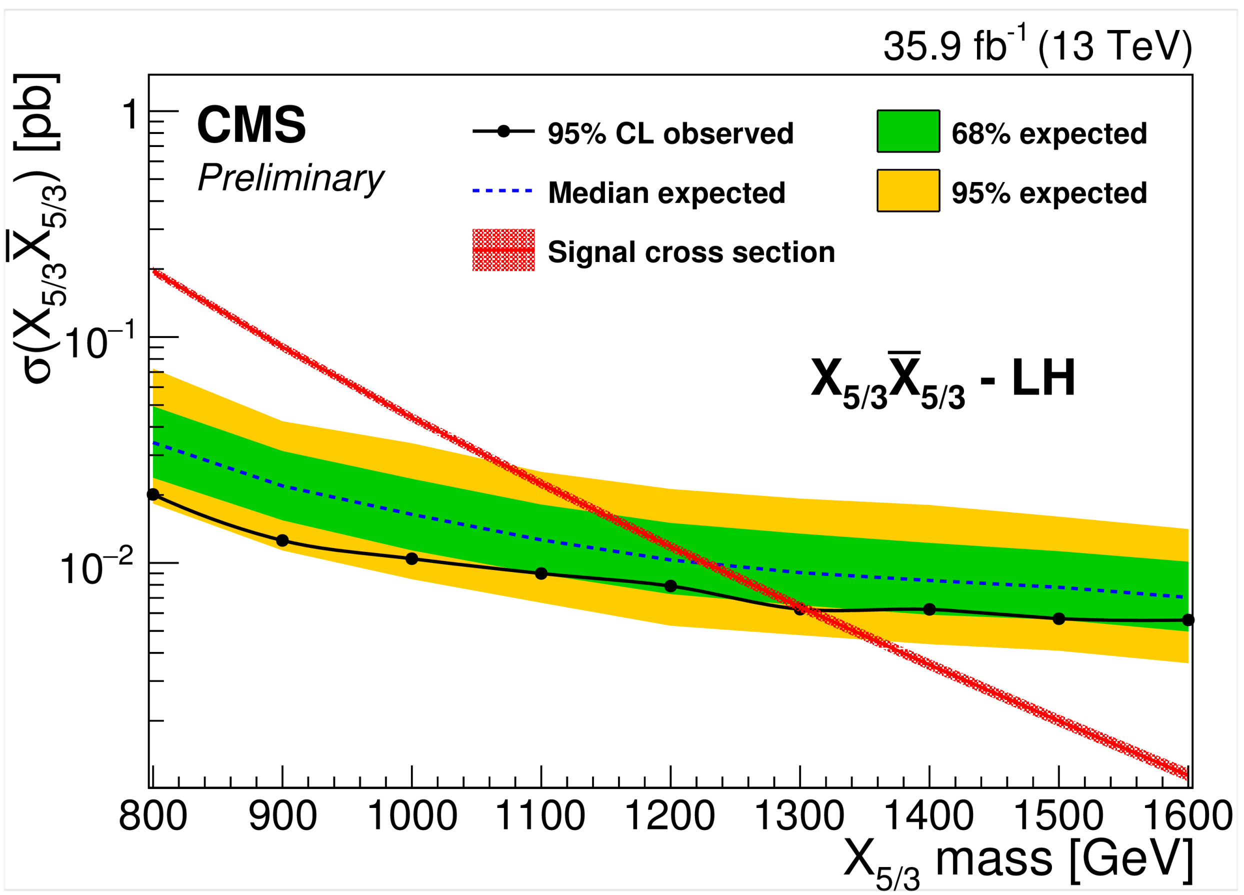
Vector-like Quarks searches at the LHC

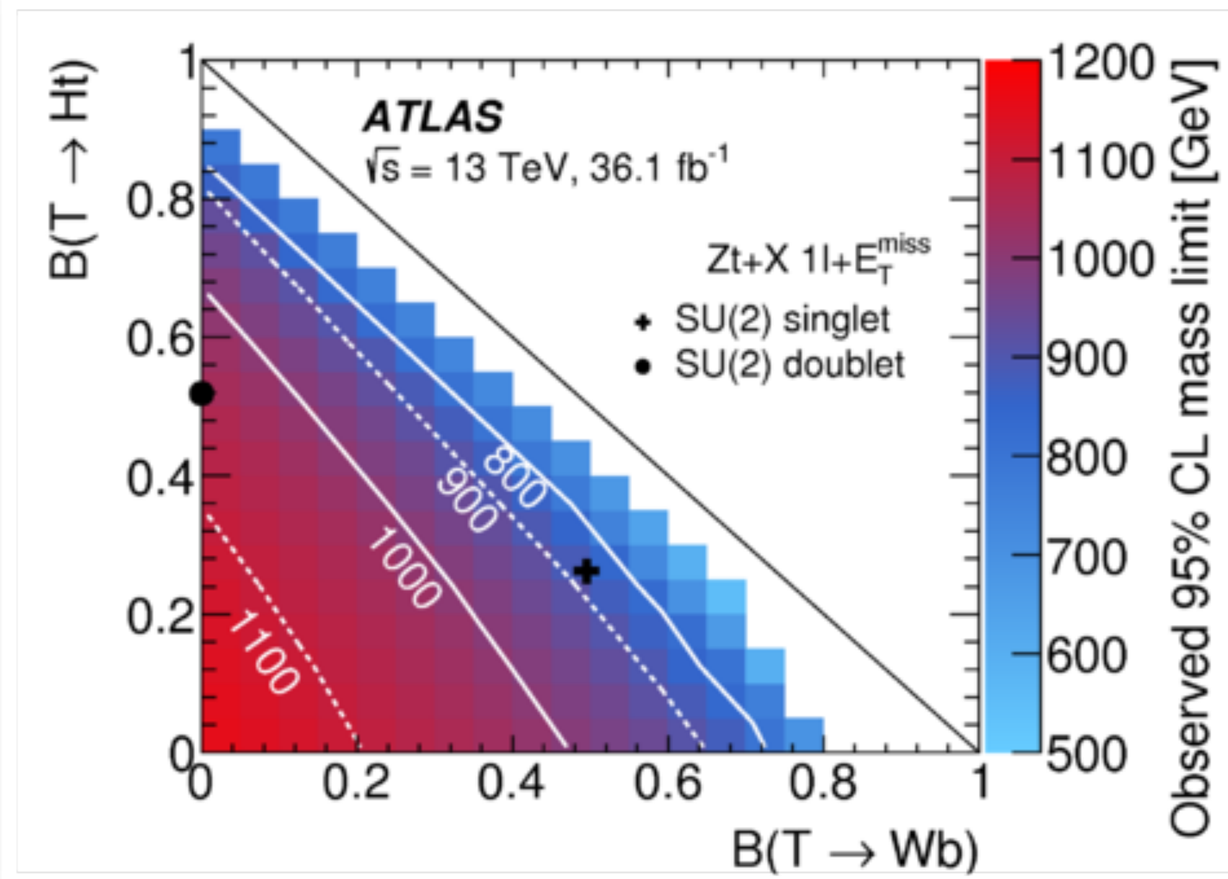
Assuming mixing with only the 3rd generation of SM quarks

$$T \to W^+b, Zt, Ht \qquad B \to W^-t, Zb, Hb$$

$$X \to W^+t \qquad Y \to W^-b$$

All these channels are covered by LHC searches





Vector-like Quarks properties

In the minimal scenario they interact with the SM through Yukawa terms

D4 interactions can only be written for singlets, doublet and triplets of $SU(2)_L$

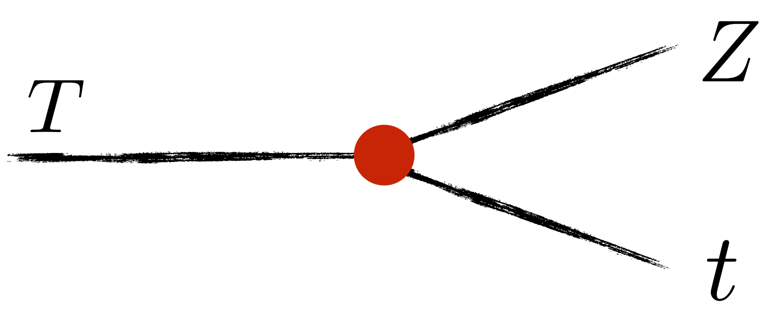
$SU(2)_L$	$U(1)_Y$	ψ	L_y
1	2/3	T	$\bar{q}_L H^c t_R$
	-1/3	B	$\bar{q}_L H b_R$
2	7/6	(X,T)	$\bar{\psi}_L H t_R$
	1/6	(T,B)	$\bar{\psi}_L H^c t_R$, $\bar{\psi}_L H b_R$
	-5/6	(B,Y)	$\bar{\psi}_L H^c b_R$
3	2/3	(X,T,B)	$\bar{q}_L \tau^a H^c \psi_R^a$
	-1/3	(T,B,Y)	$\bar{q}_L \tau^a H \psi_R^a$

Left- and right- handed chiral component rotate in a different way

$$\frac{\tan\theta^R}{\tan\theta^L} = \frac{m_q^{SM}}{m_{VLQ}} \quad \text{for} \quad SU(2)_L = 1, 3 \qquad\qquad \frac{\tan\theta^L}{\tan\theta^R} = \frac{m_q^{SM}}{m_{VLQ}} \quad \text{for} \quad SU(2)_L = 2$$

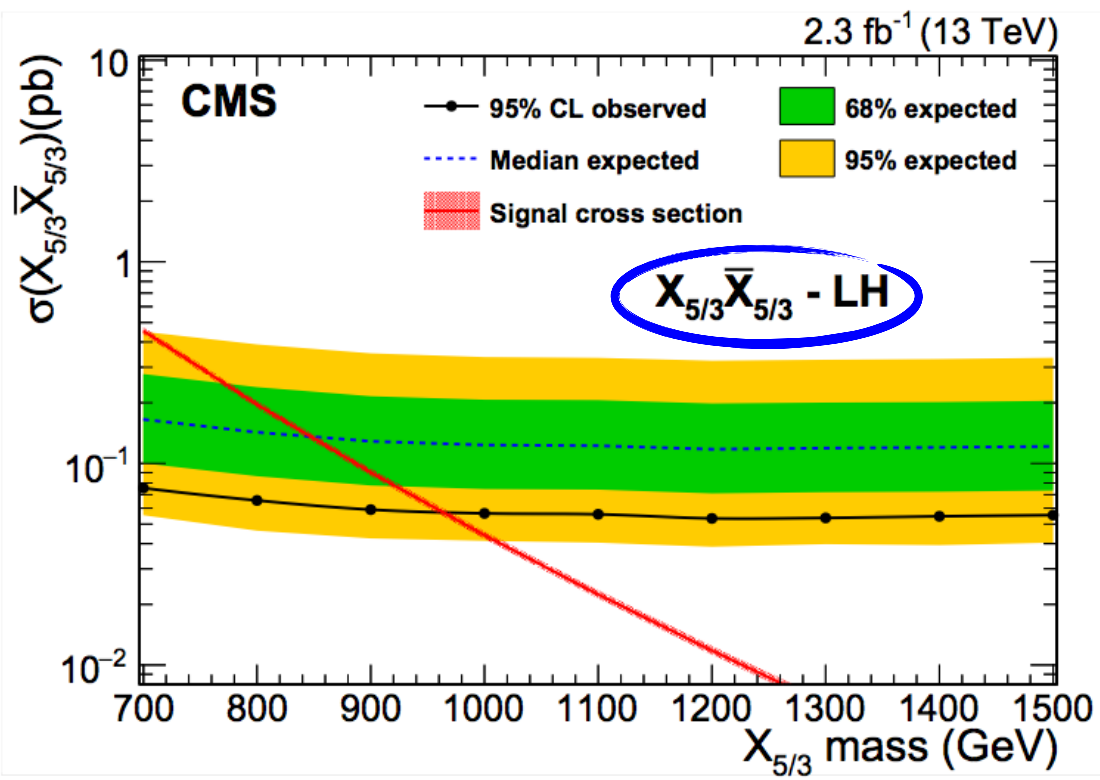
$m_{VLQ} \gg m_q^{SM}$: one of the two chiral-coupling is always suppressed

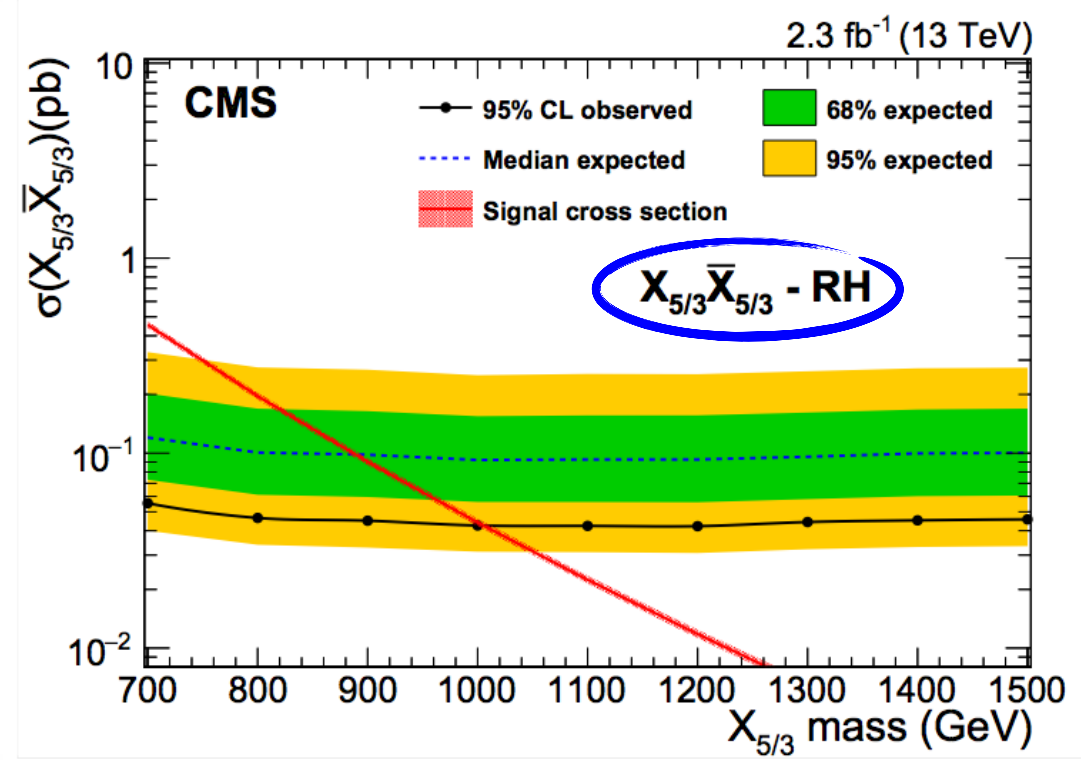
Vector-like Quarks properties



- The coupling is almost pure **Left** or **Right**
- Final state gauge bosons and quarks have a non zero polarization

A difference in the kinematic of the decay product is expected





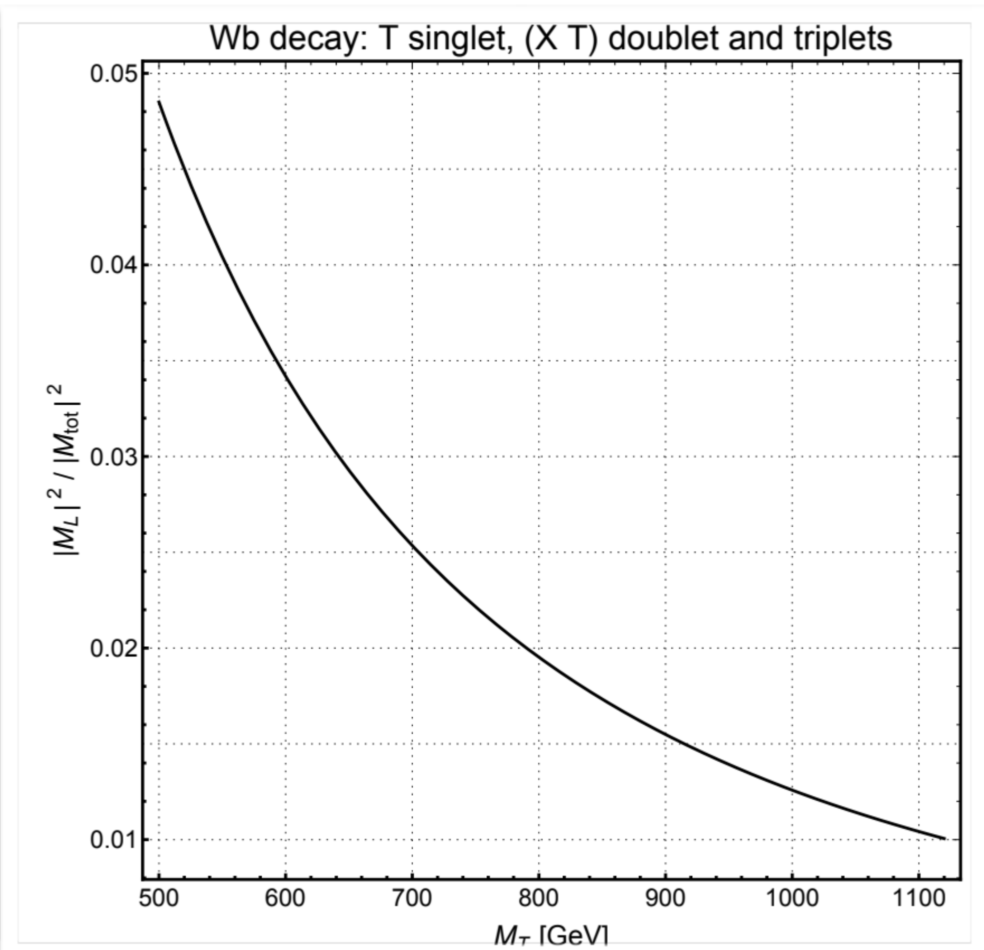
Slightly difference reach between the two hypotheses

Gauge boson polarization

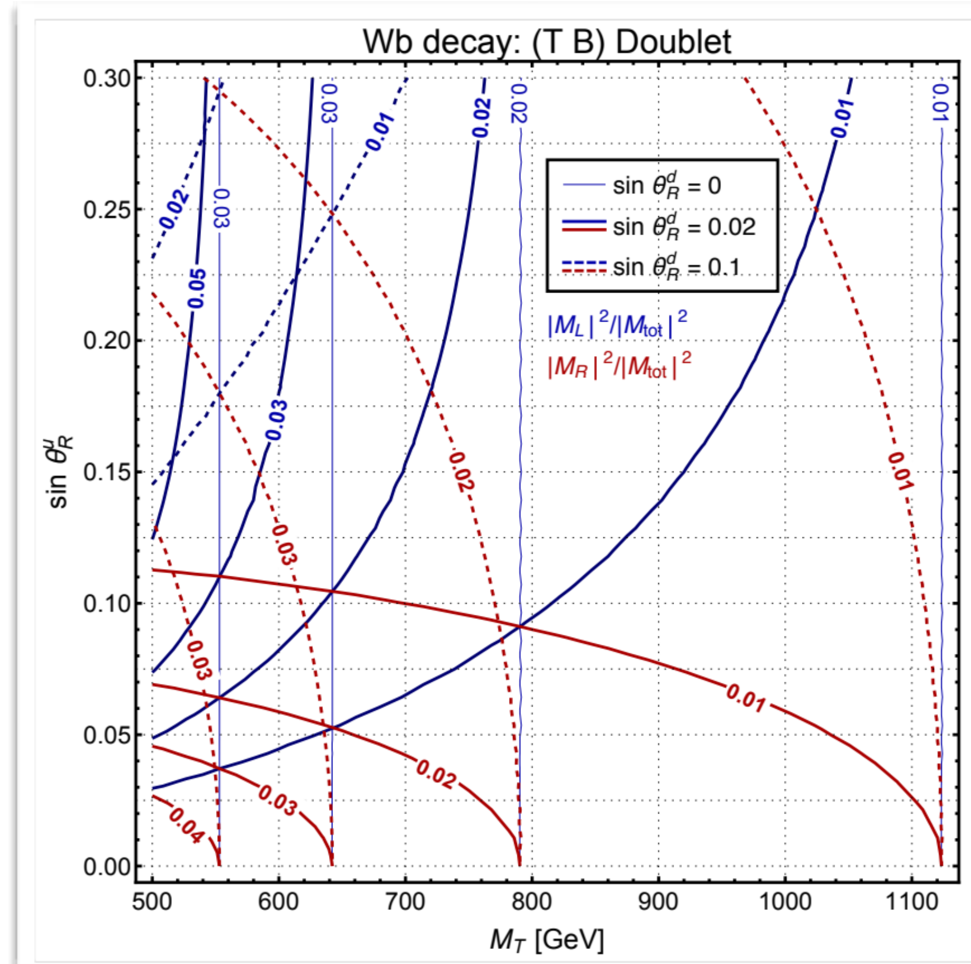
- Gauge bosons tend to have a dominant longitudinal component
- No kinematic difference in the two coupling hypotheses

$T \to Zt$ decay

$$|M|^2_L = \frac{g^2}{2} \sin^2\theta^u_L (m^2_T - m^2_W)$$
$$|M|^2_R = 0$$
$$|M|^2_0 = \frac{g^2}{4} \frac{m^2_T}{m^2_W} \sin^2\theta^u_L \, (m^2_T - m^2_W)$$



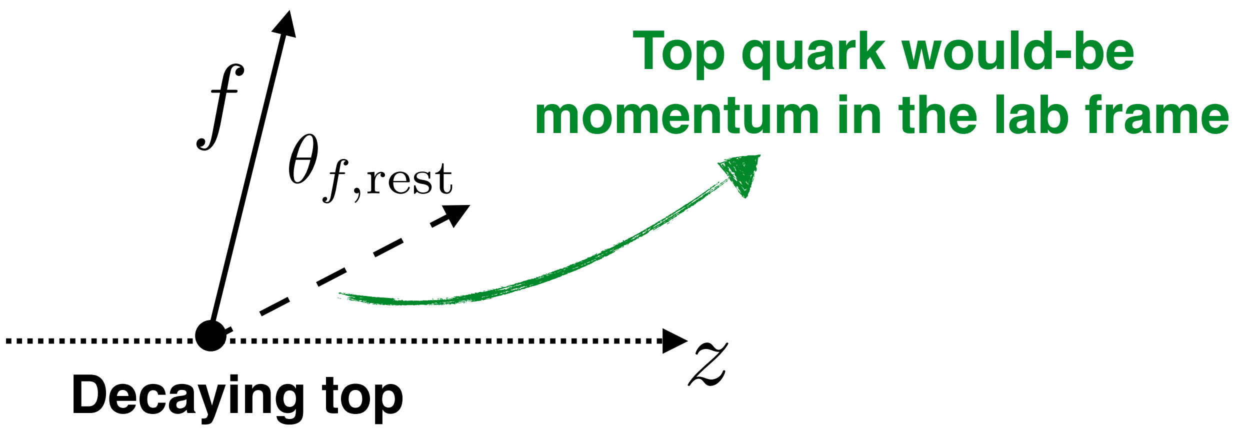
$\mathcal{O}(1\%)$ transverse component



Top quark polarization

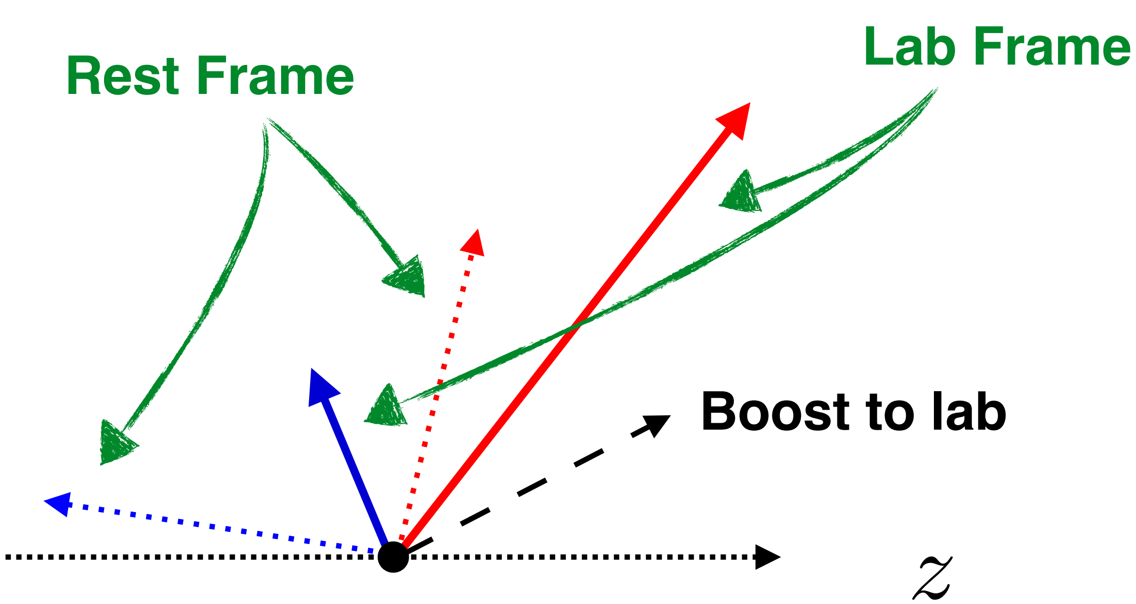
Top quark decay product carry information on its polarization

Top quark rest frame



$$\frac{1}{\Gamma_l}\frac{\mathrm{d}\Gamma_l}{\mathrm{d}\cos\theta_{f,\mathrm{rest}}} = \frac{1}{2}(1 + \kappa_f P_t \cos\theta_{f,\mathrm{rest}})$$

Laboratory frame

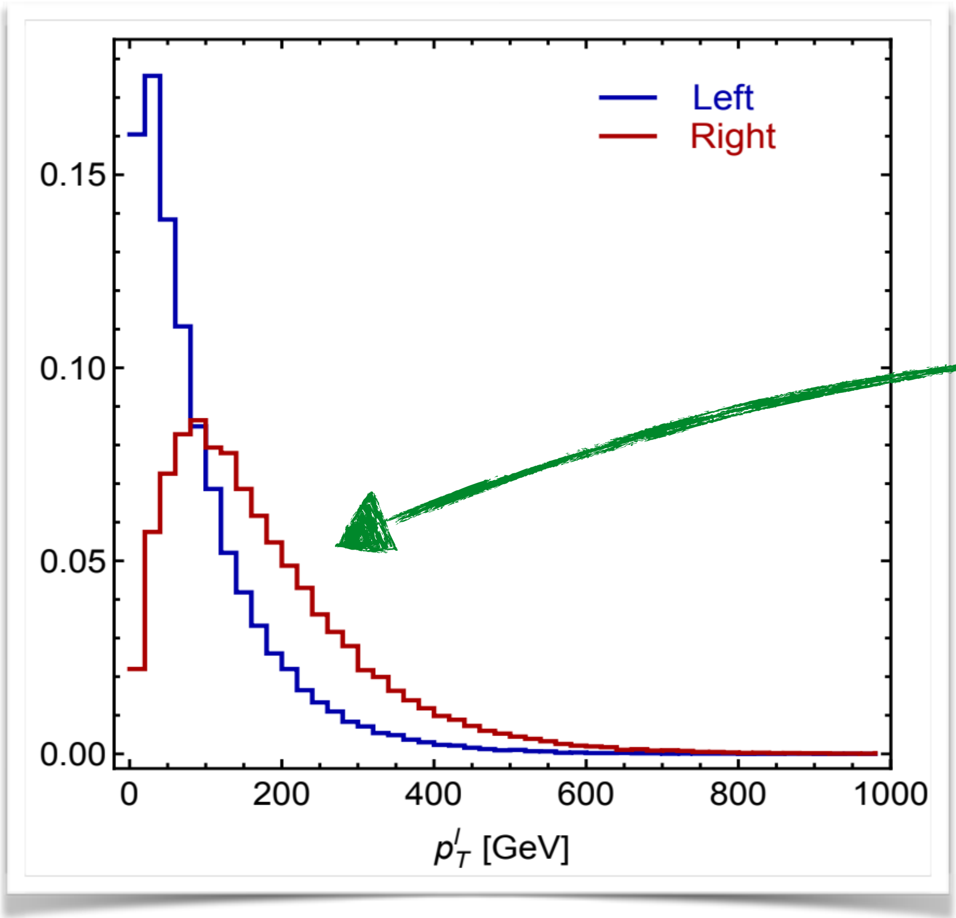


Boost to Lab. frame produces harder object for positively polarized top quarks, i.e. right-handed coupling

Easier to pass selection cuts for right-handed VLQs: higher mass reach

Top quark polarization

p_T distribution of the lepton from a polarized top from a VLQ decay



If a VLQ were to be discovered at the LHC can this difference be used to disentangle the two hypotheses?

- Assume we can subtract the SM background

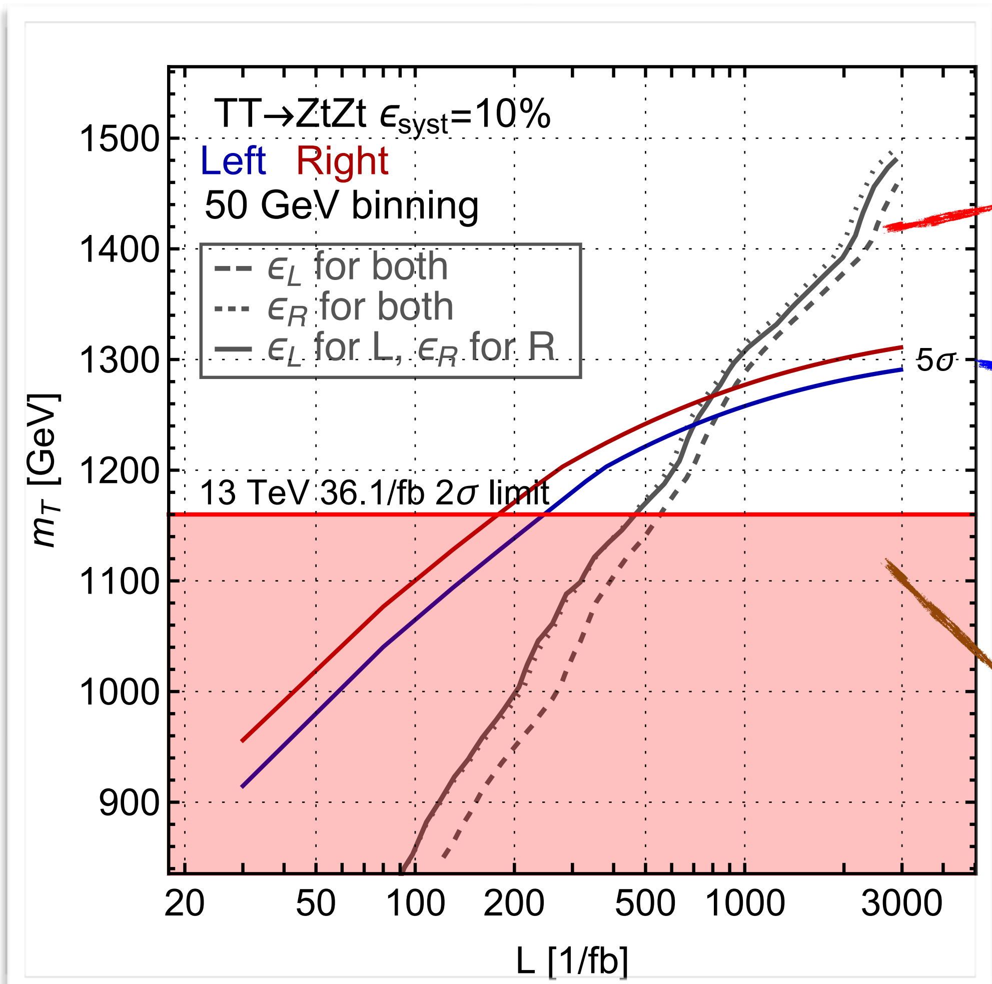
- Test the discrimination power via a χ^2

$$\chi^2 = \sum_{i=1}^{n_{\rm bins}} \frac{(L_i - R_i)^2}{\max(L_i, R_i)}$$

LHC discrimination power

Charged 2/3 VLQ decaying entirely in Zt in the single ℓ plus $E_T^{\rm miss}$ final state

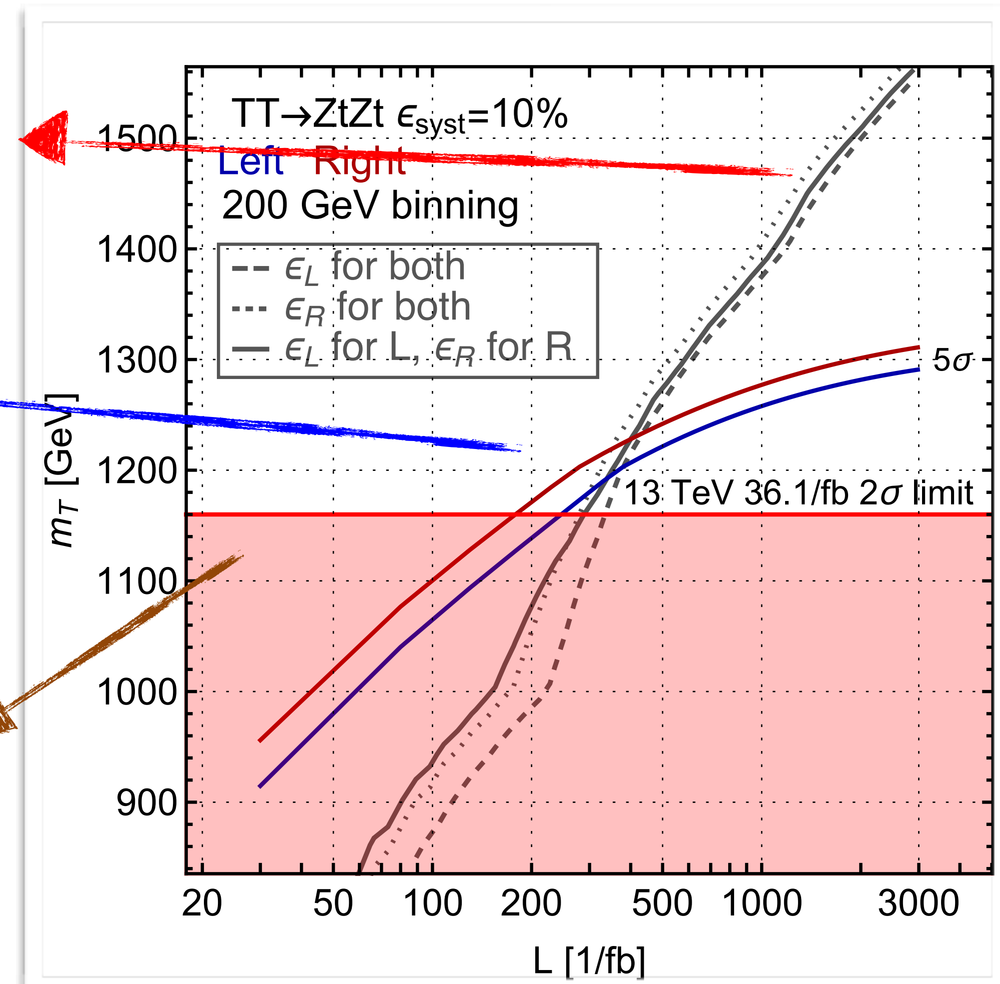
Mostly invisible Z : the lepton comes from the top decay



2σ discrimination

Discovery projection

Current 2σ limit



- The binning impacts the discrimination reach. Optimization possible
- LHC able to discriminate the hypotheses in all the discovery range accessible

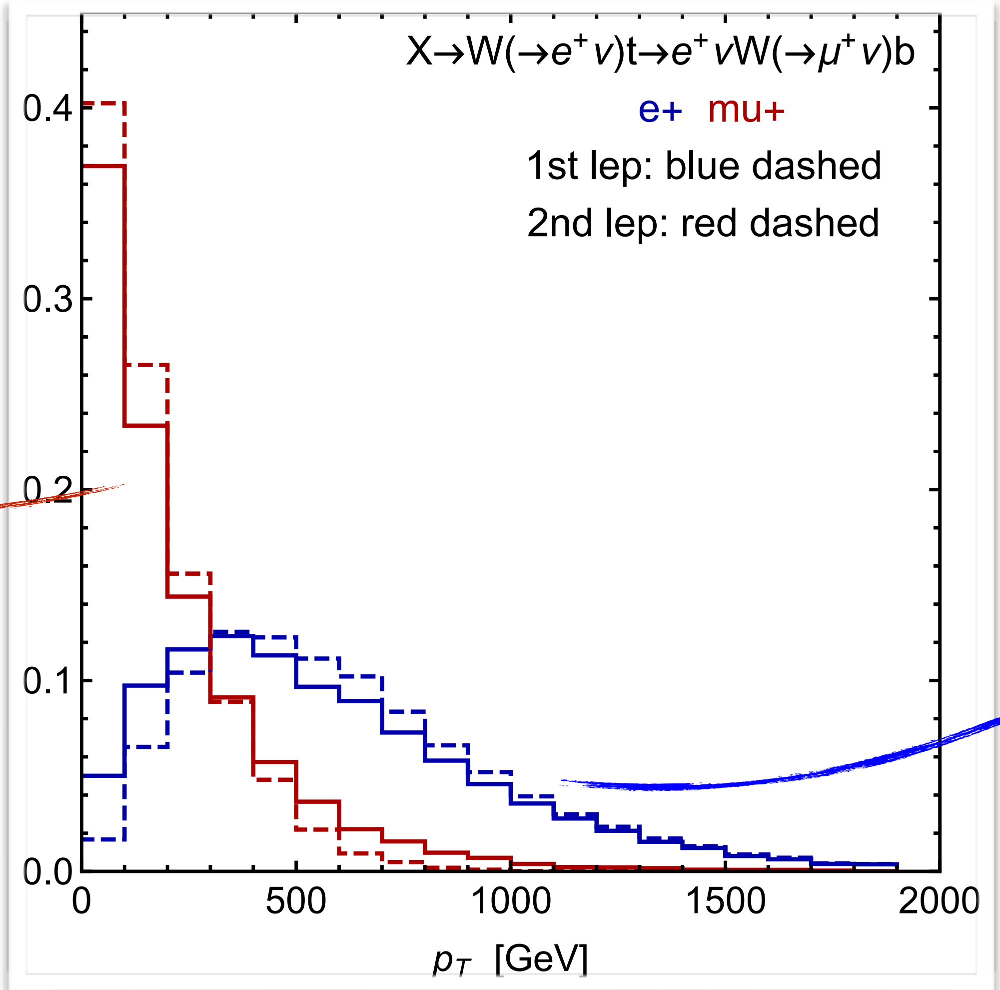
HE-LHC discrimination power

Charged 5/3 VLQ decaying entirely in Wt in the same-sing 2ℓ final state

Must pick the lepton from the top, and from not the W decay

Identification possible: the lepton from the top is always softer

Lepton from top decay

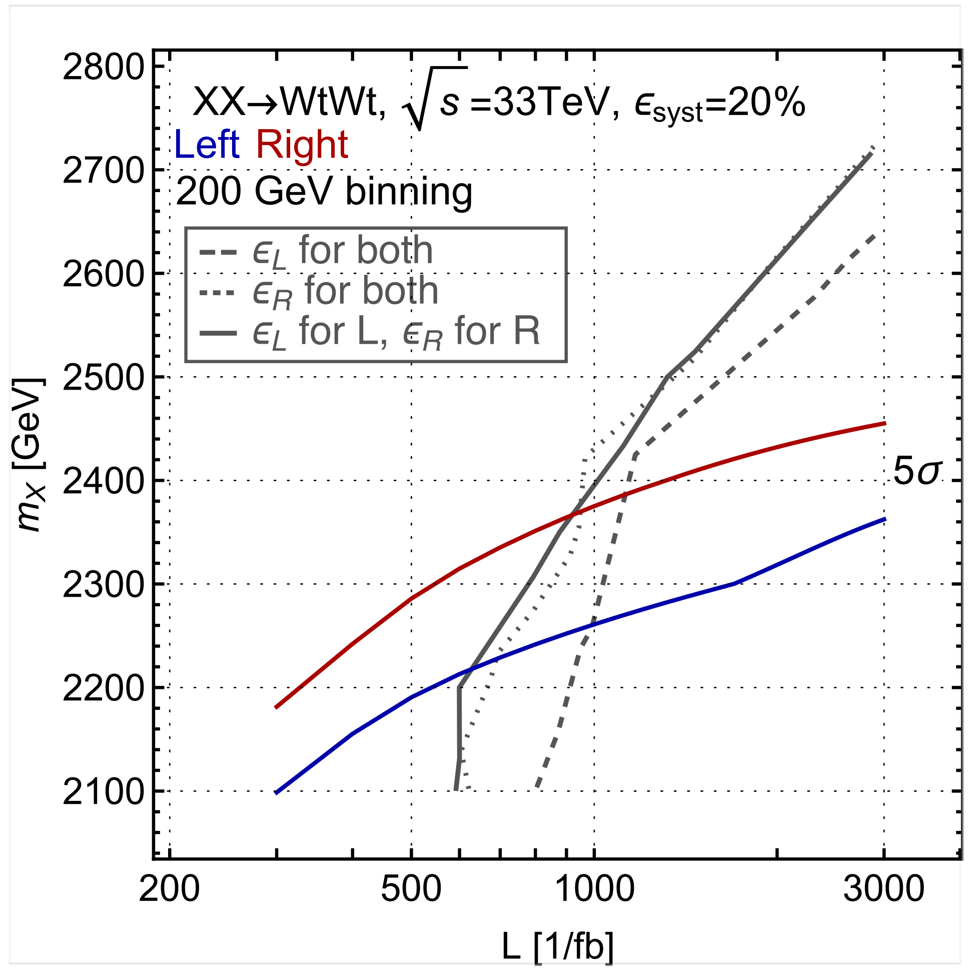


Lepton from W decay

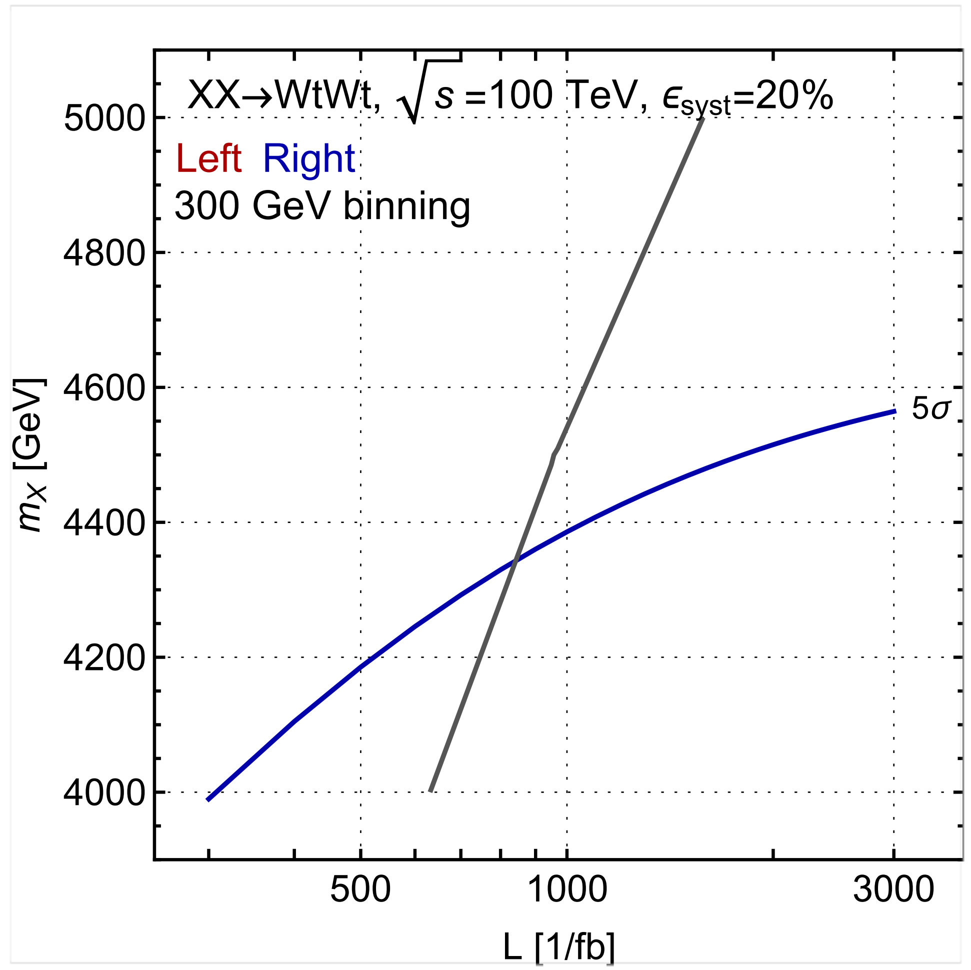
Use the sub-leading lepton distribution to perform the discrimination

HE-LHC discrimination power

LHC-33



LHC-100



High energy hadron collider prototypes are able to discriminate the coupling hypothesis in all their accessible discovery range

Conclusions

- HL-LHC and HE-LHC will increase the exclusion-discovery reach on the masses of BSM states

- Important to assess whether these machines will be able to discriminate amongst different model hypotheses should NP be found

- Polarized top quarks arising from VLQs decay can be used as a probe to discriminate the coupling structure of the VLQs with SM states

- HL-LHC and HE-LHC will be able to discriminate between left- and right-handed coupling in all their accessible discovery range

Open questions

- Focused on pair-produced VLQs: what about single production?

- What can be said if a VLQ doesn’t decay into a top quark?