How to discover Vector-Like quarks at LHC?

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Outline

- What are Vector-Like Quarks (VLQs)?
- Why do we like them?
- Phenomenology
  - Simplified models and interpretations
  - Next-to simplest models

What are Vector-Like Quarks (VLQs)?

- Fermionic states that are not chiral
  - Left and right handed chiralities transform under the same way under the SM symmetries.
  - E.g.: For a top-like (T) and a bottom-like (B) quark we can allow a bare mass term as

$$\mathcal{L}_{\mathrm{VLQ}} = i\bar{B}\not{D}B - m_B\bar{B}B + i\bar{T}\not{D}T - m_T\bar{T}T +$$

  - In addition, If we want them to interact with the SM, they should **mix** with the SM quarks
    - electroweak interactions of a VLQ with the SM quarks may happen
      => by means of a model dependent coupling

$$\begin{aligned}\mathcal{L}_{\mathrm{VLQ}} = \quad & -h\left[\bar{B}\left(\hat{\kappa}_L^B P_L + \hat{\kappa}_R^B P_R\right)q_d + \bar{T}\left(\hat{\kappa}_L^T P_L + \hat{\kappa}_R^T P_R\right)q_u + \mathrm{h.c.}\right] \\ & + \frac{g}{2c_W}\left[\bar{B}\not{Z}\left(\tilde{\kappa}_L^B P_L + \tilde{\kappa}_R^B P_R\right)q_d + \bar{T}\not{Z}\left(\tilde{\kappa}_L^T P_L + \tilde{\kappa}_R^T P_R\right)q_u + \mathrm{h.c.}\right] \\ & + \frac{\sqrt{2}g}{2}\left[\bar{Y}\not{W}\left(\kappa_L^Y P_L + \kappa_R^Y P_R\right)q_d + \bar{B}\not{W}\left(\kappa_L^B P_L + \kappa_R^B P_R\right)q_u + \mathrm{h.c.}\right]\end{aligned}$$

[1] Notation of: G.Cacciapaglia, A.Deandrea, N.Gaur, D.Harada, Y.Okada, L.Panizzi'15

Why do we like them?

- Those are common objects from non-supersymmetric extensions of the SM, for conseptually different reasons, for example
  - **Compact Extra Dimensions:** The SM mass hierarchy is diluted in a ED
    - VLQs appear as excitations of the SM particles in this WED
  - **Composite models:** The gauge symmetry of the SM is extended to accomodate the Higgs boson as a Pseudo Nambu-Golstobe Boson (PNGB)

    PNGB Higgs = naturally light = mass hierarchy problem does not exist
    - the content of the fermions and gauge bosons of the theory is also extended
      - As the new objects must obey the SM symmetry, new fermions should be vector-like

In both cases, if we consider phenomenology constraints,
==> VLQ's should/could be around the LHC corner

Composite models:

Coupling and scale $g_\rho \quad f$ → Mass of the lightest resonance $m_\rho \simeq g_\rho f$

$v^2/f^2 \lesssim 0.4$ (EWPT) → $m_\rho \simeq$ TeV

ED:

Compactification scale (+ ED curvature) → Mass of the lightests excitation

↓

To solve the mass Hierarchy problem → $m_\rho \simeq$ TeV

How do they appear in our 4 dimensions?

In multiplets of the strong symmetry = as Quark Partners

In a minimal composite scenario = only one SU(2) Higgs = the global symmetry is SO(5):

- In the minimal spinorial representations of SO(5), we can write a list of the possible candidates :

Name	charge	Lagrangian	Candidates	SM
Y	4/3	$c_L \bar{Y}_L \not{W} b_L$	Y	Triplet
$X_{5/3}$	5/3	$c_{Rt} \bar{X}^R_{5/3} \not{W} t_R + c_{Lt} \bar{X}^L_{5/3} \not{W} t_L$	$X_{5/3}$	Doublet
T'	2/3	$c_{Rt} \bar{T'}_R \not{Z} t_R + c_{Lt} \bar{T'}_L \not{Z} t_R$ $+c_{Lb} \bar{T'}_L \not{W} b_L$ $+c_{Rh} h \bar{T'}_R t_L + c_{Lh} h \bar{T'}_L t_L$	$X_{2/3}$	Doublet
			$\tilde{T}$	Singlet
			T	Doublet
B'	-1/3	$c_{Rt} \bar{B'}_R \not{W} t_R + c_{Lt} \bar{B'}_L \not{W} t_R$ $+c_{Lb} \bar{B'}_L \not{Z} b_L$ $+c_{Rh} \bar{B'}_R b_L$	B	Doublet
			$\tilde{B}$	Singlet

- Exotic charge partners
- Some of the states are predicted to be degenarated depending of the specific reprerentation

Nomenclature: Q' it stands generically to any flavour

[1] Notation of: Andrea De Simone, Oleksii Matsedonskyi, Riccardo Rattazzi, Andrea Wulzer'12

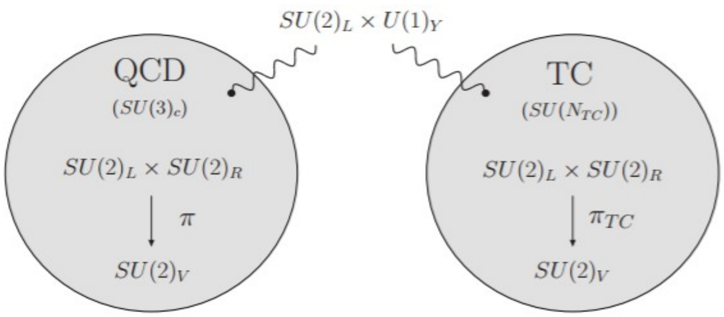
Going a bit deeper in composite models

PGB Higgs = naturally light = mass hierarchy problem does not exist

- The Higgs mass is protected by an approximate global symmetry and is only generated via quantum effects.
  - As the Higgs field is a composite state from the strong symmetry it shall not couple to the elementary part of the SM (gauge bosons and fermions)

How should the PGB Higgs boson couples to SM to break EW symmetry?

Introducing a linear mixing between the composite particles and the SM particles [1]!



➔ There is a fixed relation between the VLQ mass and the Higgs boson coupling to quarks

The partners is the 3th generation of fermions are the most likelly to be the lightest

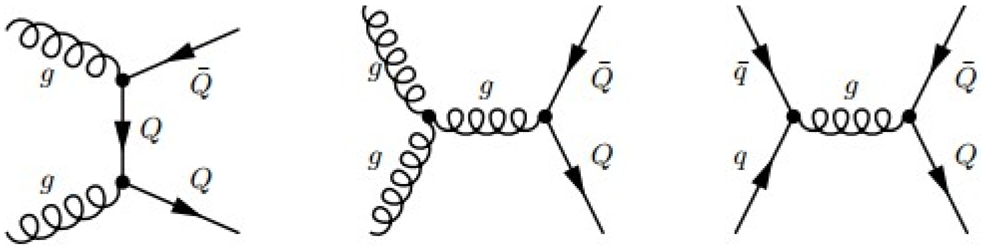
[1] David B. Kaplan, Howard Georgi, Savas Dimopoulos'83
Figure: Roberto Contino TASI lectures

How do they appear at colliders?

Partners of the 3rd generation in a minimal particle content

Decays: V + b-jet / V + top, where (V = W , Z or H) ==> A lot of things to tag!

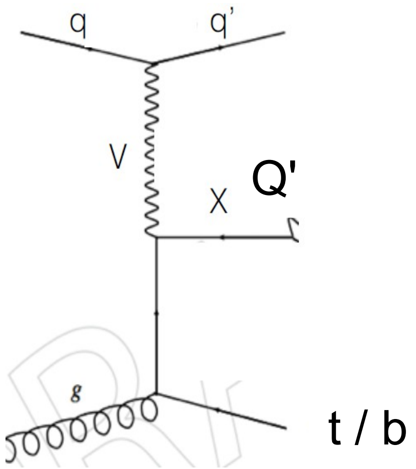
Pair production: it hapens by only QCD will be always present, the production rate is model-independent



EW single production: Model dependent prod. rate

In typical cases for the EW coupling strenght Ssingle > Sdouble for mQ' >~ 1 TeV

Leading signal process topology is 2->3 [1]



[1] D.Barducci, A.Belyaev, M.Buchkremer, G.Cacciapaglia, A.Deandrea, S. De Curtis , J.Marrouche, S.Moretti, L.Panizzi'14, O.Matsedonskyi, G.Panico, A.Wulzer'14, J.Aguilar-Saavedra, R.Benbrik, S.Heinemeyer,M.Perez-Victoria'13 ...

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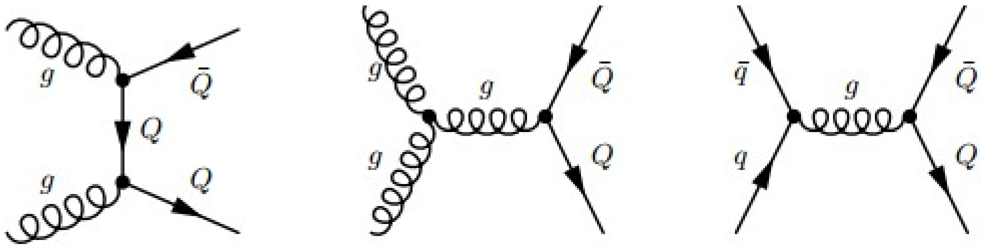

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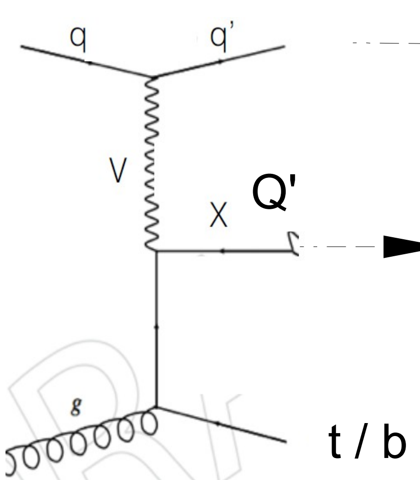
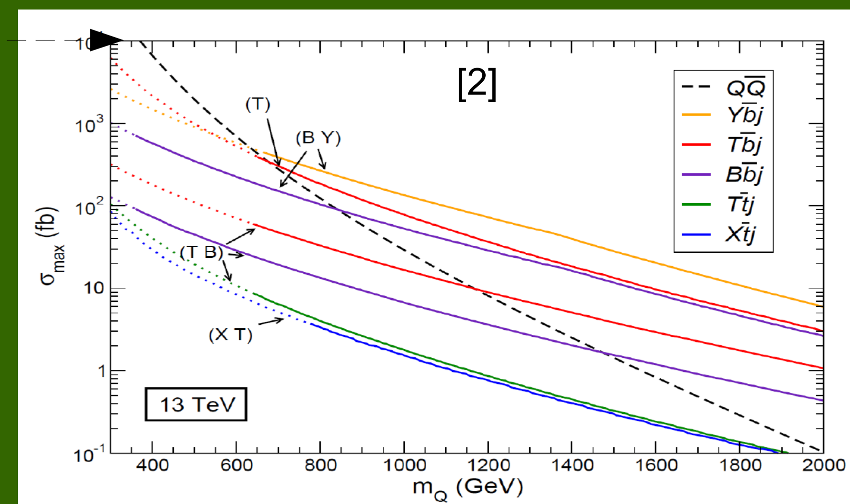
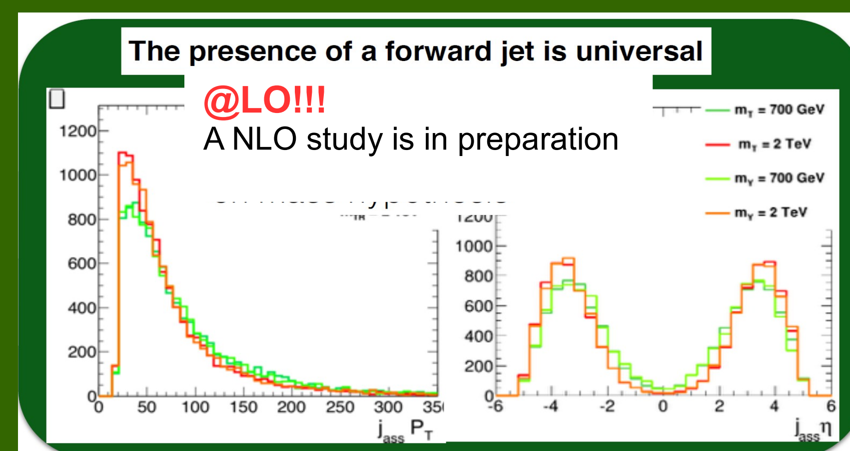


Its chirality influence pheno, specially if we have boosted t's
(see backup and the talk of LLeres)

Pheno:





See S. Beauceron talk for more on 3th gen. Q' phenomenology

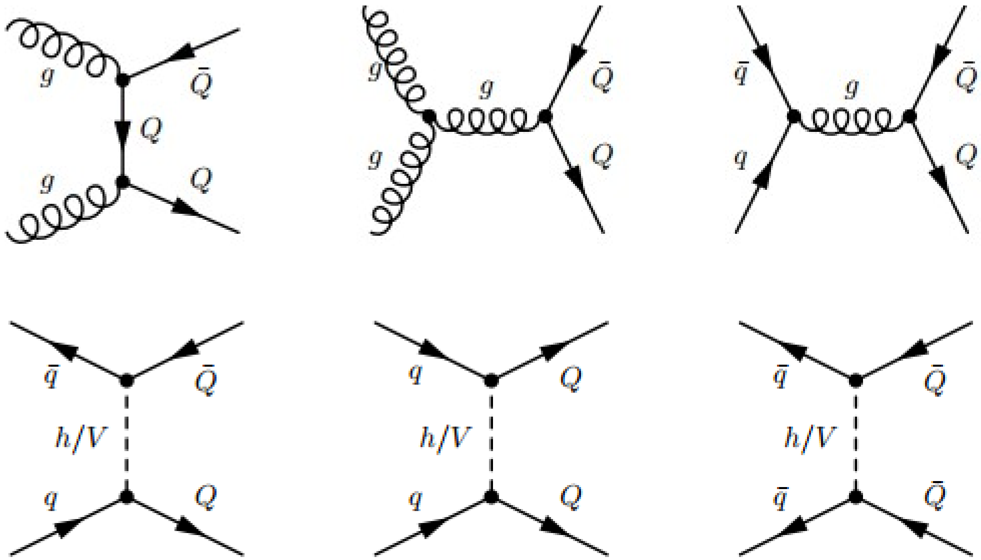
[1] D.Barducci, A.Belyaev, M.Buchkremer, G.Cacciapaglia, A.Deandrea, S. De Curtis , J.Marrouche, S.Moretti, L.Panizzi'14, O.Matsedonskyi, G.Panico, A.Wulzer'14, [2] J.Aguilar-Saavedra, R.Benbrik, S.Heinemeyer,M.Perez-Victoria'13 ...

How do they appear at colliders?

Narrow Width Partners of the 1st /2nd generation in a minimal particle content

Decays: V + jet where (V = W , Z or H) ==> boosted bosons to tag

Pair production: Besides the model-independent QCD, there is a model dependent EW production [1]



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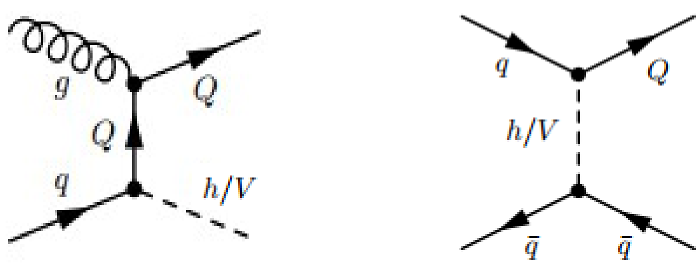

[1] See for example: G.Cacciapaglia, A.Deandrea, N.Gaur, D.Harada, Y.Okada, L.Panizzi'15.

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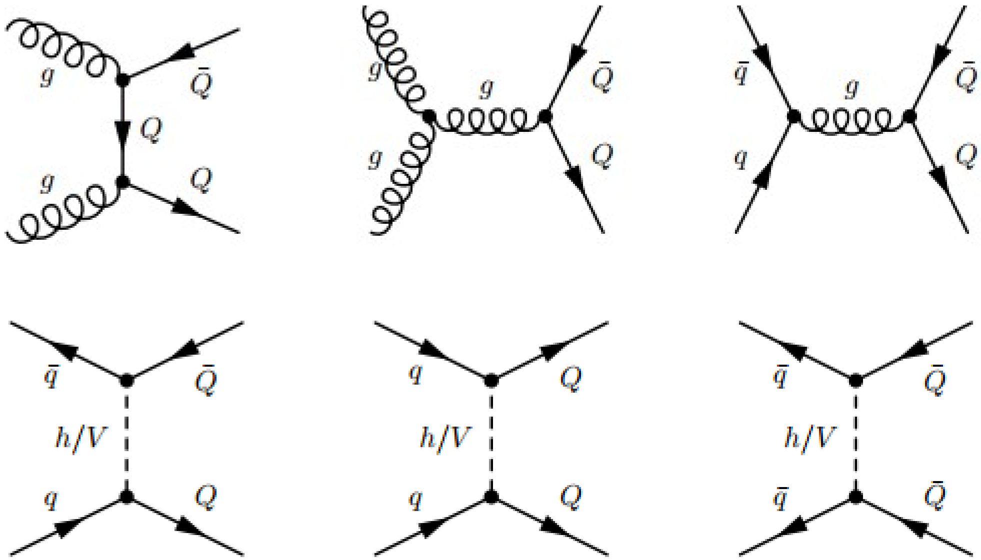

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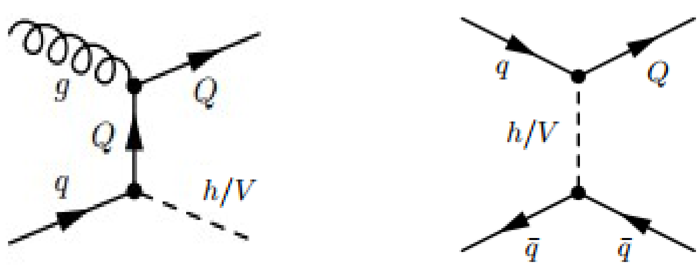
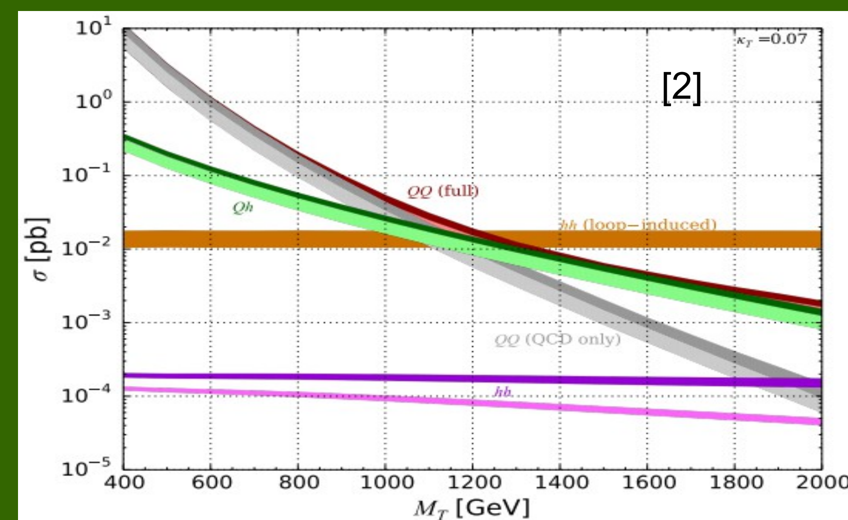
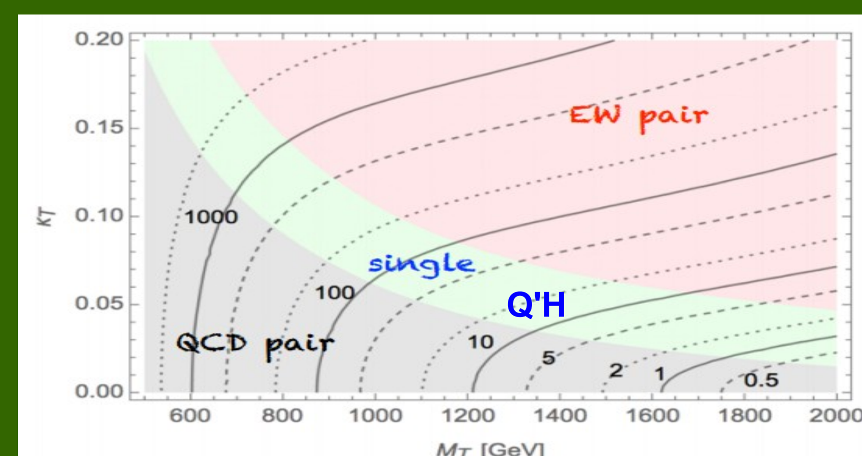


Pheno: Expl. if a 1th gen. coupling only to H
Which channel is dominant is tricky to say...





[1] See for example: G.Cacciapaglia, A.Deandrea, N.Gaur, D.Harada, Y.Okada, L.Panizzi'15.
[2] Giacomo Cacciapaglia, Haiying Cai, A.C., Aldo Deandrea, Thomas Flacke, Benjamin Fuks3, Devdatta Majumder and Hua-Sheng Shao

How do they appear at colliders?

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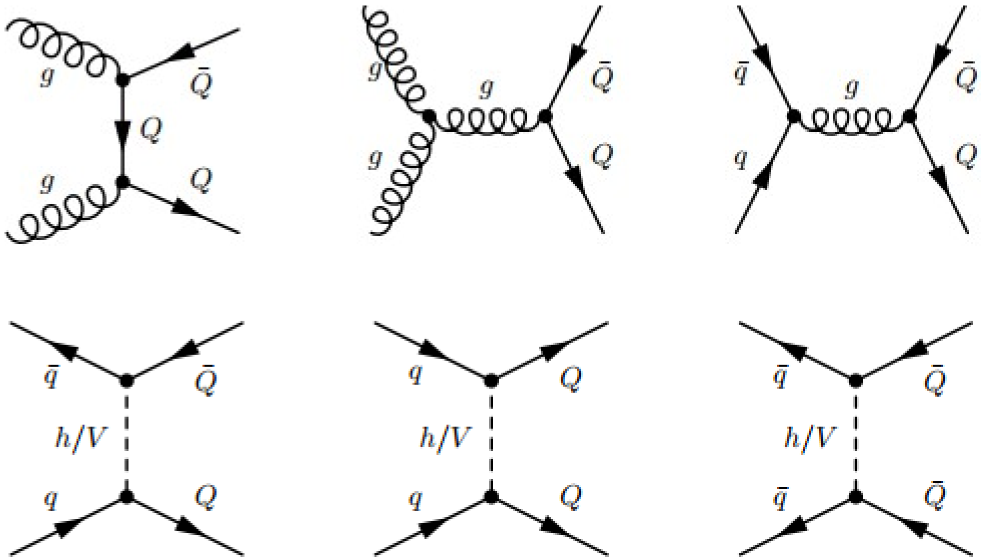
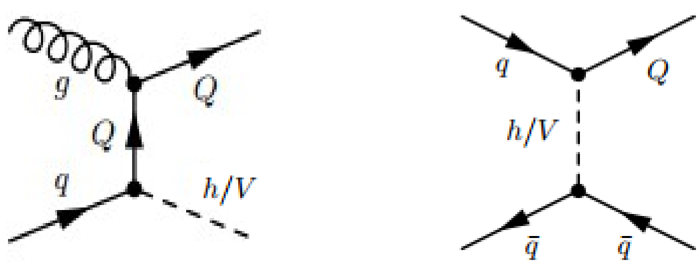
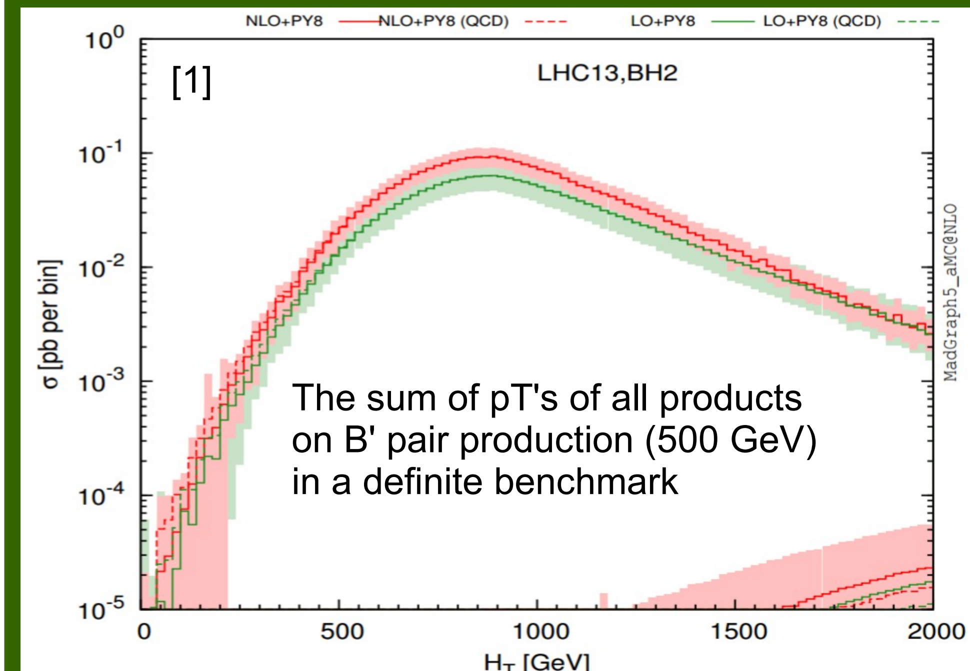


EW single production: Model dependent prod. rate



Pheno: Expl. if a 2th gen. coupling only to H

The computations at NLO QCD +PS are essencial for reliable predictions



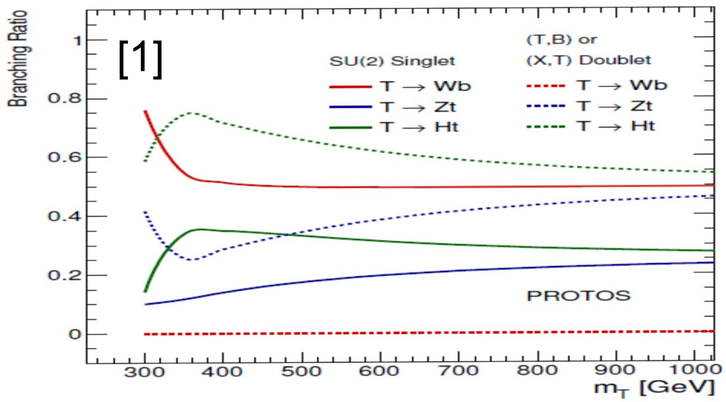
[1] Benjamin Fuksand Hua-Sheng Shao'16

How do they appear at colliders? Branching ratios

Quark partners generation, in a minimal particle content

The Branching Fractions of Q' in SM particles is benchmark deppendent, three aproaches are usually taken:

Explicit calculations on specific representations



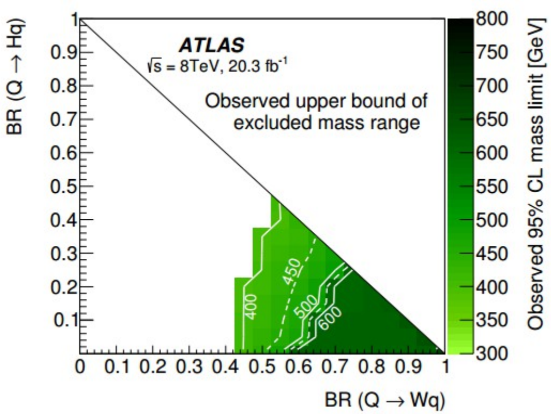
ATLAS 3rd generation results

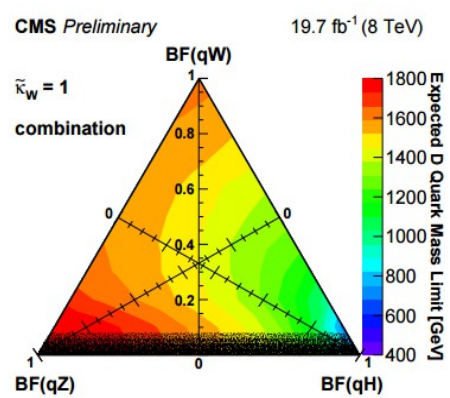
Assimptotic limits on specific quark representations based in the Equivalence Theorem [2]

BR	Wt	Wb	Zt	Zb	ht	hb	Chirality
T23 singlet	0	1/2	1/4	0	1/4	0	L
T23 doublet	0	0	1/2	0	1/2	0	R
X53 doublet	1	0	0	0	0	0	L/R
B13 singlet	1/4	0	0	1/2	0	1/2	L
B13 doublet	1	0	0	0	0	0	R
Y43 triplet	0	1	0	0	0	0	L/R

CMS 3rd generation results

Model independent limits in terms of BRs [3]





1st /2nd generation results

- If there are more than one quark multiplet and they mix with each other, the branching fractions are not constrained to be ~ the equivalence theorem result!

[1] J.Aguilar-Saavedra, R.Benbrik, S.Heinemeyer,M.Perez-Victoria'13
[2] Benjamin W. Lee, C. Quigg, H.B. Thacker'77
[3] Examples of scans from: ATLAS: 1509.04261 | CMS: B2G-12-016

How to interpret VLQ searches at colliders?

Quark partners, in a minimal particle content

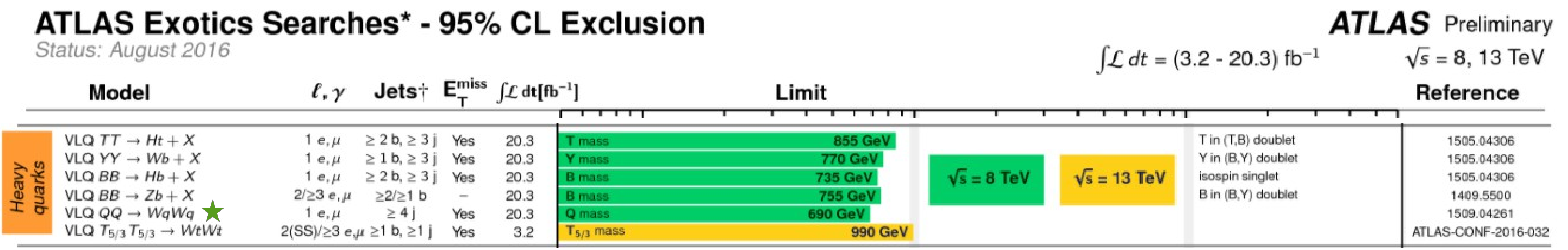
We start to have a lot of parameters, before to start to scan them one could think:
When/why to be model independent really matters for physics results?

- For precise quotes of absolute VLQ mass bounds (in benchmarks)
- Once more than one VLQ final state / production mode overlap in a given search (common for light generations)
- Combinations of searches

When we are model independent a clean visualization of summary of results is difficult
=> When we look for summary of the experimental results in terms of masses-only we should take then with a grain of salt

Summary of ATLAS and CMS bounds
Quark partners, in a minimal particle content

Limits in pair production in usual benchmarks are in the ballpark of ~900 GeV, most of the limits are for partners of the 3th generation of quarks. The only theory dependency is in the Q' BRs

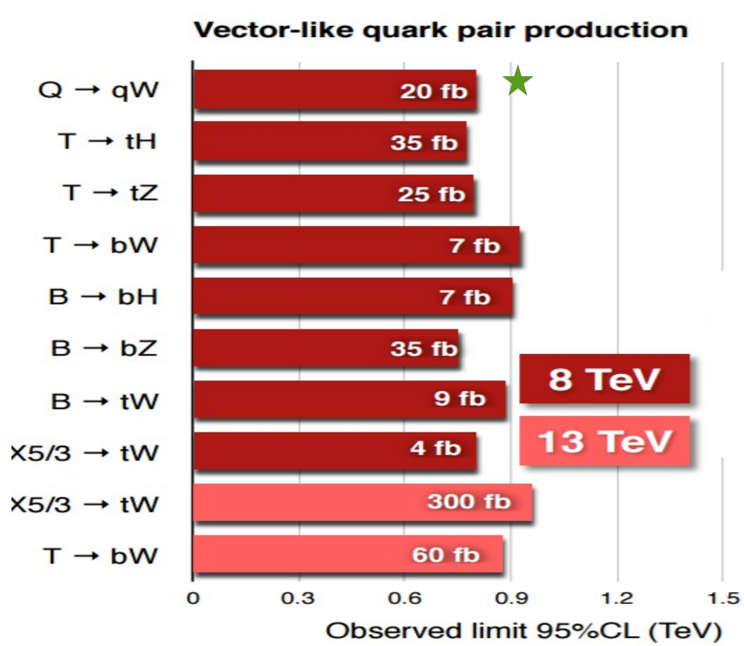


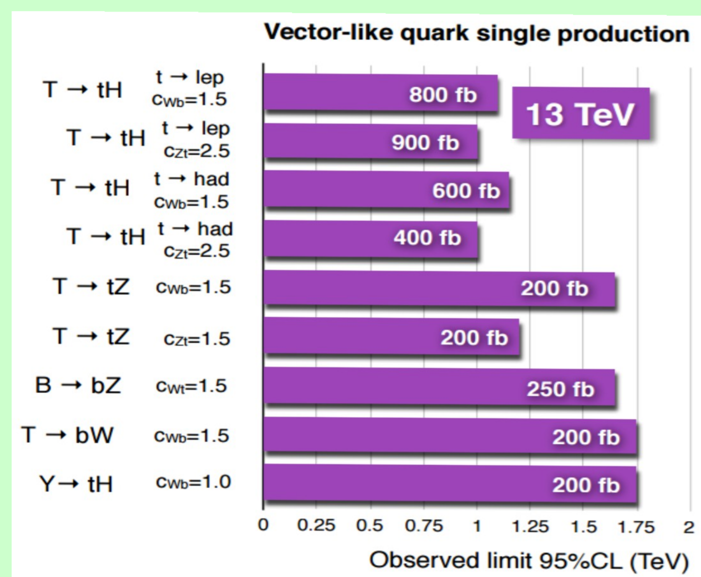
ATLAS Exotics Searches* - 95% CL Exclusion
Status: August 2016

ATLAS Preliminary
$\int \mathcal{L}\, dt = (3.2 - 20.3)$ fb^{-1} $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$ ★	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \to WtWt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032

CMS





Limits in VLQ mass are coupling-deppendent, they are is an indicative of points where the signal is a narrow resonance.

Reasonable values for the couplings are c ~ 1 [1] (VLQ coupling ~ gW)

★ 1st /2nd generation

See S. Beauceron talk for a summary of the single prod searches (ATLAS+CMS)
[1] Notation of: Andrea De Simone, Oleksii Matsedonskyi, Riccardo Rattazzi, Andrea Wulzer'12

Did we exhausted the possibilities for the discovery channels?

In realistic scenarios problably not

Additional scalars:

- In QCD-like models (as composite) we usually can have additional scalar 'meson' eta (1 or 8 of color), that can be:

1) lighter than the VLQs (most likelly)
   - If this object can decay to SM particles the tipycal decay modes will be:
     => eta → W+W- / Zh / hh / gg / (gamma)^2 / ttbar ...
     => eta+/- → WZ/ Wh / tb ...

2) heavier than the VLQs: add as decay modes TT / Tt / Bb
   => This object can also be an spin-2 object (bulk KK graviton)

Additional vectors:

1) Composite vectors are likelly to be heavier than the VLQs:
   => Typical decay modes can involve VLQs
   => Z' : TT / Tt / Bb / BB
   => W' : Tb / Bt / TB

2) If there are new symmetry groups we may have new gauge bosons, those can be lighter than the VLQs,
   => Z' : WW / Zh / tt
   => W' : tb / WZ
   Those are disfavoured by Electroweak Prescision Tests, however those could be evaded if additional scalars are in the theory [1]

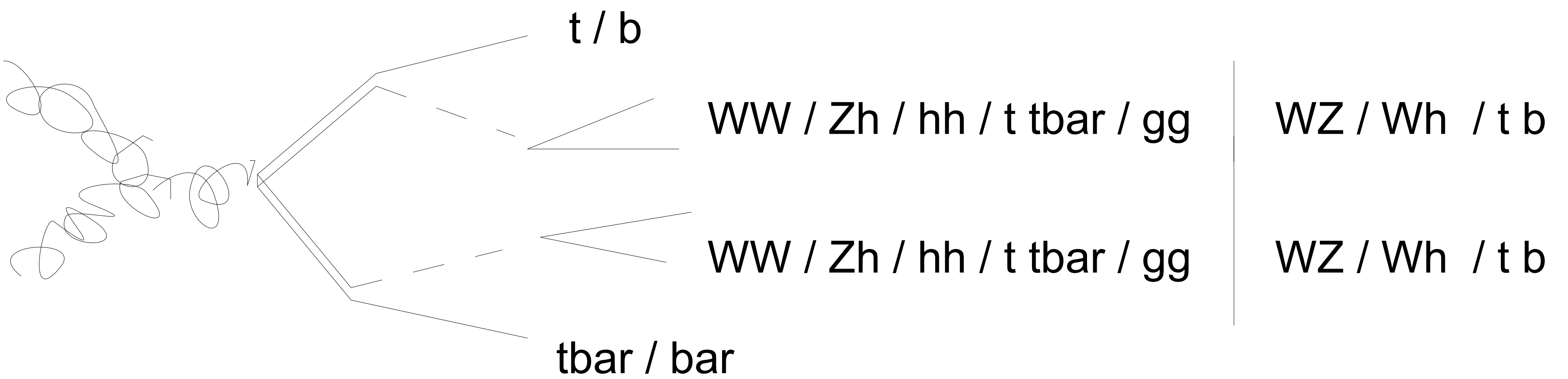
If the additional particle is heavier than the lightest VLQ we will have **exotic VLQ production**, otherwise **exotic VLQ decays** should be cosidered

[1] See for example:

How to exaust the possibilities for the discovery channels?

VLQ exotic decays – eta / W' / Z'

- If the VLQ can decay to other BSM particles it is more likelly to this to be a discovery channel **if the BRs are 100% in the new state**.
  - **This is only possible if the VLQ is generated in pairs**
    => High final state multiplicity (specially bosons)



If the single production mode is allowed to Q' it means it couples to W/Z/H and therefore its BR is shared with the SM objects.

=> The balance between where the exotic decay moders or SM ('conventional') decay modes is highly model dependent, but can be calculated in specific cases

There is no clear direct lower bound in the VLQ mass (less Q' BR to the SM)
Present searches might catch the signal, but for a precise lower mass bound for the VLQ they should be recasted [1]

[1] Work in progress: Giacomo Cacciapaglia, A.C., Aldo Deandrea, Mickaël Lespinasse

How to exaust the possibilities for the discovery channels?

Exotic production and decays with the 3th generation of quarks

Several signals, with many top's, b's and heavy bosons in the final states to get lost with

As a first try to maximize the coverage to those channels given the finite (wo)man-power to perform analyses or recasts I try to categorize by the number of t's, b's, V's and g (gamma)'s.
The physics cases are divided as comming from light or heavy new particles (wrt the lightest VLQ)

		tt	tb	tt V	tt VV	tt 4g	4 t	6 t	tb V	bb VV	bb 4V	tb VV	bbV	tt 4V
VLQ + one new particle	heavier Z'	X			X				X	X		X		
	lighter Z'	X									X			
	heavy W'		X	X	X				X					
	light W'		X									X		
	heavy eta /G*	X			X					X	X			
	ligh eta	X			X	X	X	X	X			X	X	X
Pair prod.	TT / YY				X					X				

...

This isn't a propose to the contruction more generic searches, but to group efforts from trigger to basic selections. Mass selections and signal extraction are for sure signal deppendent, but come in later stage.

Moreover, It is also good to know if other signal might be in your control region
(even if comes from different motivations)

The anologous to BSM objects coupling to the light generations is straightfoward

See other attempt of final states classification in chapter 6 of 1605.02684 (LH BSM 2015 proceedings)

Did we exausted the possibilities for the discovery channels?

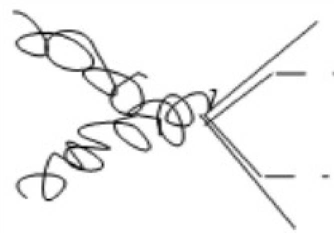
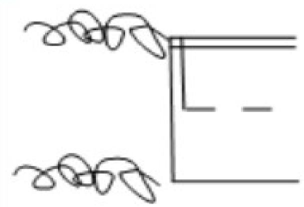
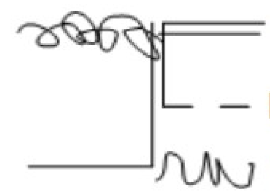
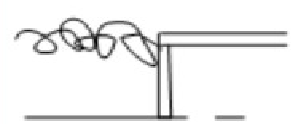
It is still possible that not

VLQs can couple to the Dark sector

If the VLQ couples with an object that could be DM, so it needs to have an intrinsic parity (DM should be produced always in pairs)

VLQs will not decay directly to W/Z/h

In the simplest vesions for the dark sector (only one DM candidate) there are no much process types possible == mostly overlap with SUSY-like Squarks/neutralino processes

Decays	Double prod.	Single prod.	+ V associated
Q' > t DM (Top partner)	 t tbar + MET		 t + V + MET
Q' > j DM Q' > b DM	jj + MET bb + MET	j + MET b + MET 	j + V + MET b + V + MET

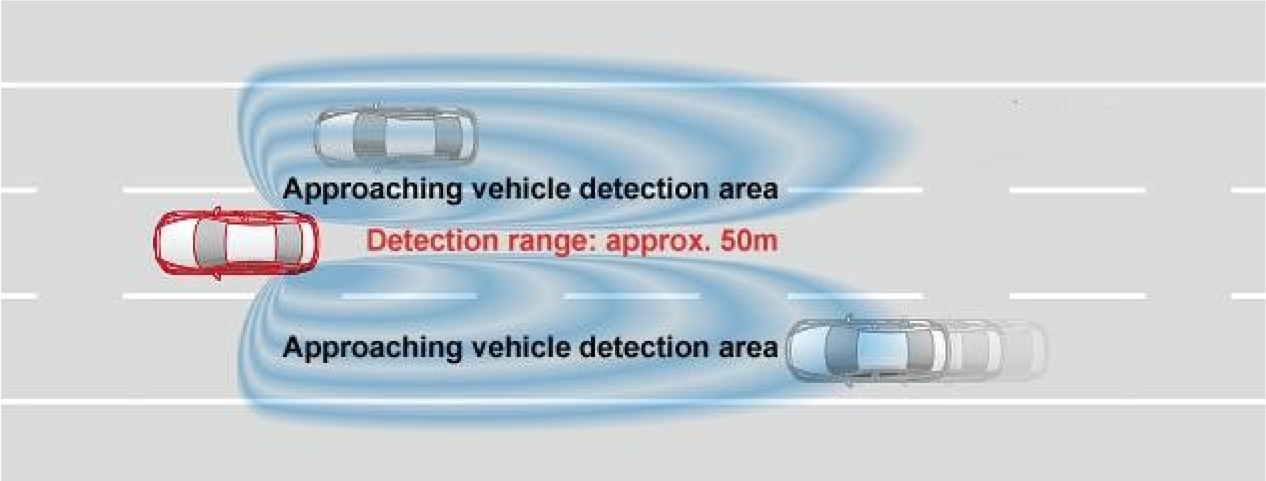
In the case of more complex dark sectors longer cascades can be considered

What can we gain from dedicated searches, how do they compare with SUSY/DM classic searches? Experiments and pheno studies [2] should be able to answer

[1] S.Kraml, U.Laa, L.Panizzi, H.Prager'16 C-R.Chen, H-C.Cheng, I.Low'15, A.Anandakrishnan, J.Collins, M.Farina, E.Kuflik, M.Perelstein'15 …

Conclusions

- Searches for VLQ are good candidates to discover new physics in strong coupled theories
  - Minimally, we look for the lightest quark partner suposing it decays to SM particles
    - Both ATLAS and CMS are looking for those objects, with a slight emphasis to the hyphotesis they only couple to the 3th generation
      - Once we discover the lightest VLQ the whole quark multiplet should be considered in the interpretation of the discovery
  - In realistic scenarios the non-SM particle content may be extended to scalars and vectors and new channels could be the most important
    - Some channels are already bein probed (direct or indirectly)



When going towards HL-LHC data we need to be sure not be leaving any opportunity unseen!

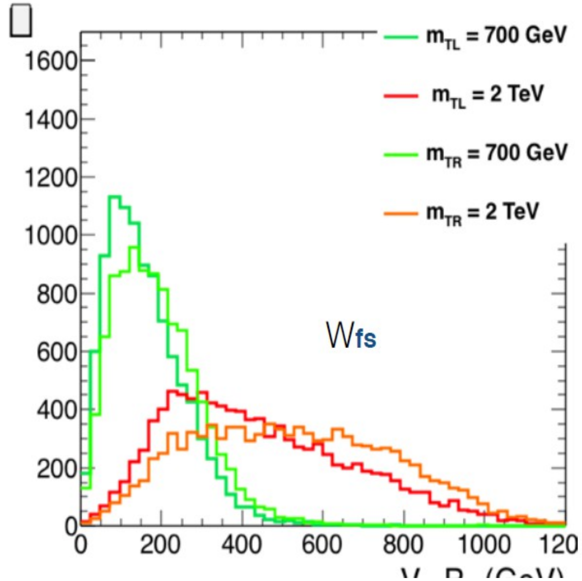

Thank you for the attention!

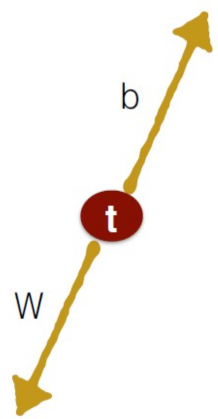
Channels: Single production (thrird generation)
Where chirality matters

Testing chirality ($T_{2/3}$) in $j(ht_{fs})t_{ass}$ / $j(Zt_{fs})t_{ass}$

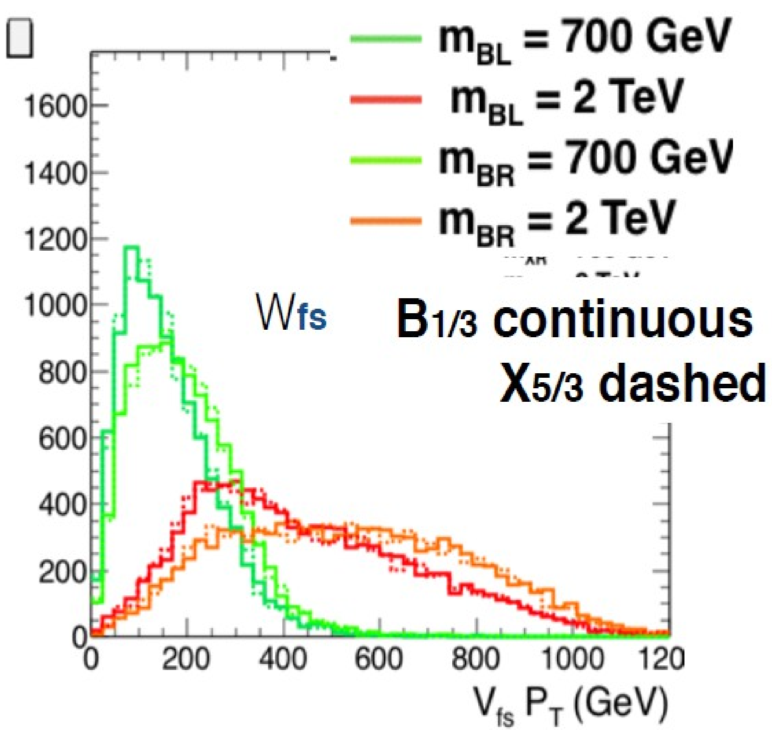
Spin correlations affect boosted top decay products

=> Chirality of the boosted top, depending on coupling changes final states distributions

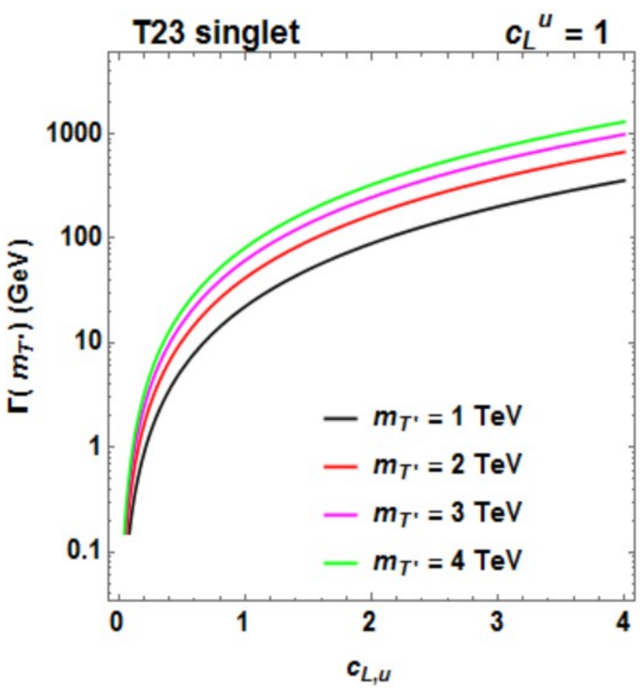


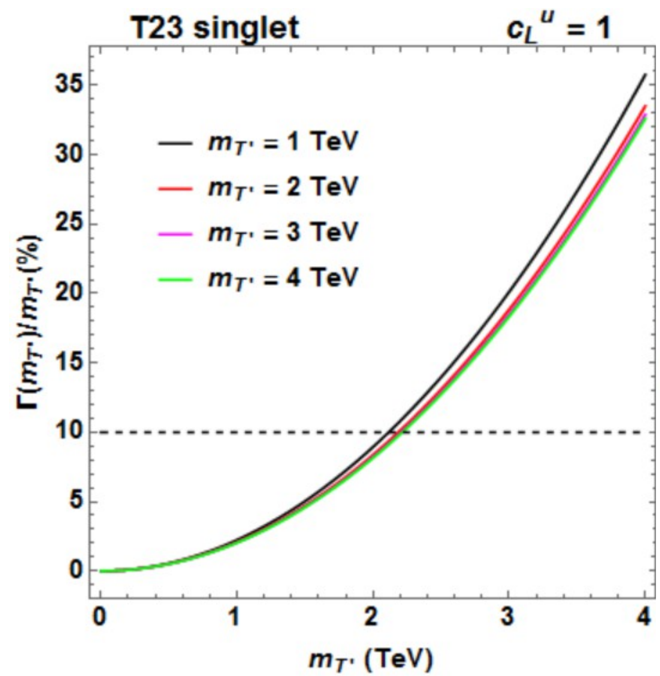


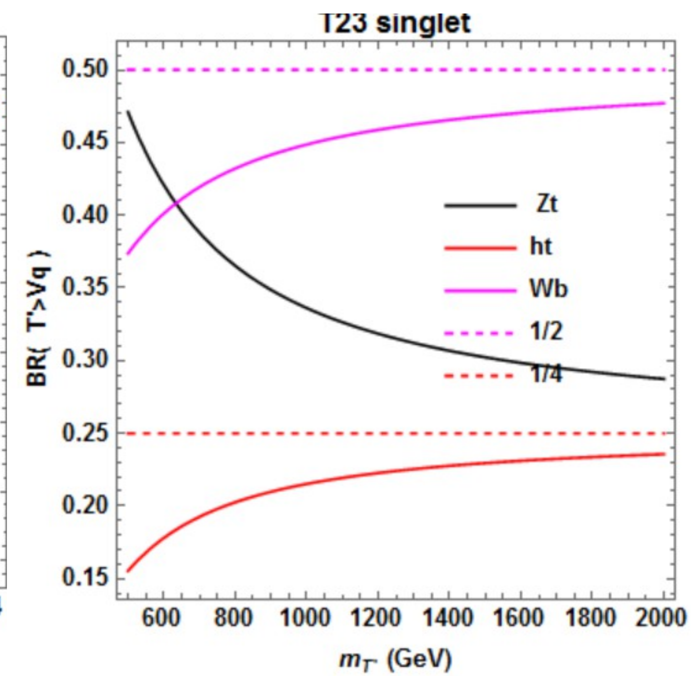
Charge does not change kinematics of final states, while chirality manifest only in the decay products of boosted tops.



How do they appear at colliders?
Total width – LO textbook calculation







The partial width for the decay into a gauge boson V and a SM quark q is given by

$$\Gamma_V = \frac{g_w^2}{32\pi}\frac{p(M_X, m_q, m_V)}{M_X^2}\left[(c_L^2 + c_R^2)\left(\frac{M_X^2 + m_q^2}{2} + \frac{(M_X^2 - m_q^2)^2}{2m_V^2} - m_V^2\right) - 6\, c_L\, c_R\, M_X m_q\right], \quad \text{(B.1)}$$

where M_X, m_q and m_V are the masses of the heavy resonance X, of the SM quark and of the gauge boson respectively. For shortness we denote by $c_{L,R}$ the V-mediated couplings of the X resonance to the Left- and Right-Handed components of q (these couplings are denoted by $c_{L,R}^{Vq}$ in the main text). The $p(M_X, m_q, m_V)$ function denotes the size of the spatial momentum of the final particles in the heavy-resonance rest frame and is given by

$$p(M_X, m_1, m_2) = \frac{\sqrt{[M_X^2 - (m_1 + m_2)^2]\,[M_X^2 - (m_1 - m_2)^2]}}{2M_X}. \quad \text{(B.2)}$$

The partial width for the decay into the Higgs and a SM quark q is given by

$$\Gamma_h = \frac{1}{8\pi}\frac{p(M_X, m_q, m_h)}{M_X^2}\left[(c_L^2 + c_R^2)\frac{M_X^2 + m_q^2 - m_h^2}{2} + c_L\, c_R\, M_X m_q\right], \quad \text{(B.3)}$$

where m_h denotes the Higgs mass.

Singlet T2/3:
cZ = cH = cW/2

The c's could go up to 4pi [1]

[1] Notation of: Andrea De Simone, Oleksii Matsedonskyi, Riccardo Rattazzi, Andrea Wulzer'12
[2] text from: Oleksii Matsedonskyi, Giuliano Panico, Andrea Wulzer'14

Coupling parametrizations

Slide stolen from Giacomo Cacciapaglia

Parameterisations

Physics-wise, the two are totally equivalent!
Feel free to make your choice!

Choice 1:

$$\hat{\kappa} = \kappa_H \frac{M_Q}{v_{\mathrm{SM}}} \qquad \tilde{\kappa} = \kappa_Z \qquad \kappa = \kappa_W$$

- kappa's are mixing angles
- PRO: easier to impose low energy constraints
- CON: for large VLQ masses, mixing suppressed

Choice 2:

$$\hat{\kappa} = c_H \qquad \tilde{\kappa} = c_Z \frac{v_{\mathrm{SM}}}{M_Q} \qquad \kappa = c_W \frac{v_{\mathrm{SM}}}{M_Q}$$

- kappa's are Yukawa couplings
- PRO: easier to match to UV theory
- CON: difficult to choose realistic range for C's