Non-minimal vector-like quark models

J. A. Aguilar Saavedra

Instituto de Física Téorica, Madrid

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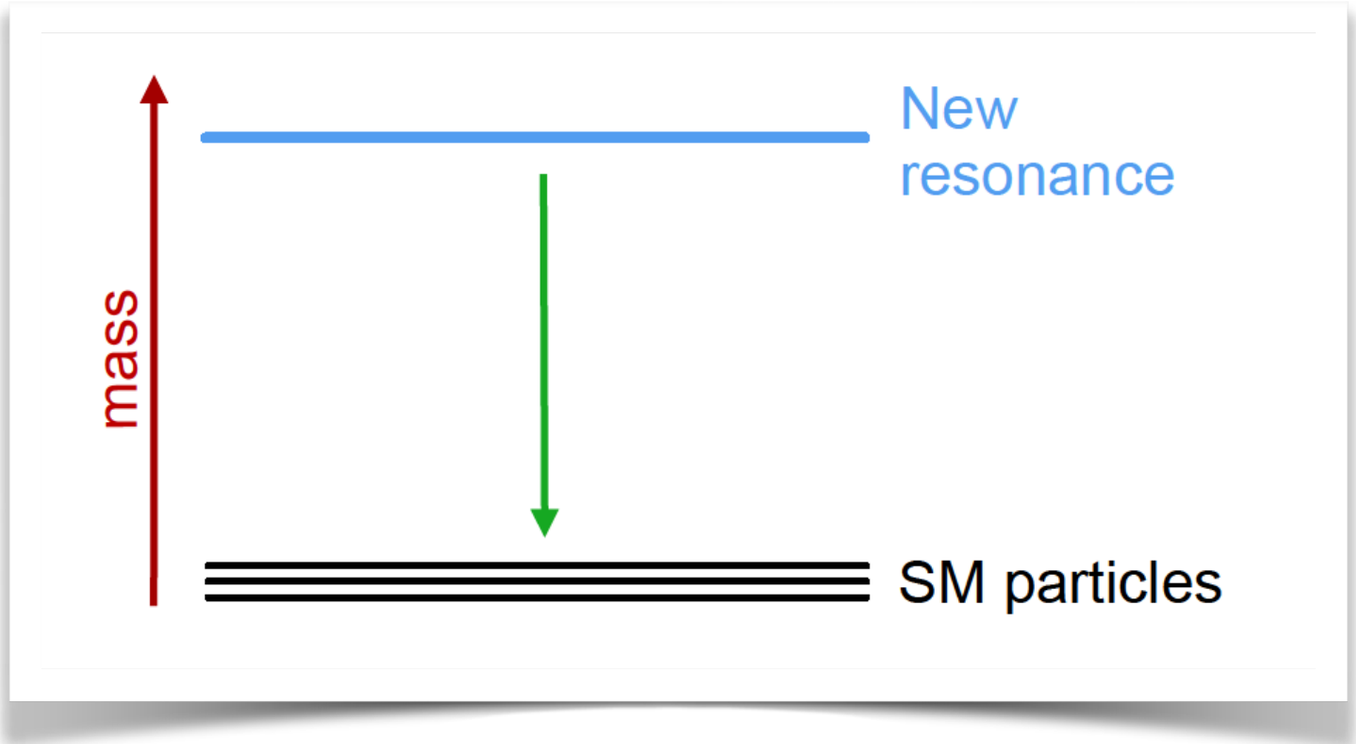
The philosophy

Beyond simplified models

Actual models are <u>not</u> simple. Simplification: ignore part of the spectrum of the model:

simplified models

This is equivalent to concentrating on some region of parameter space.

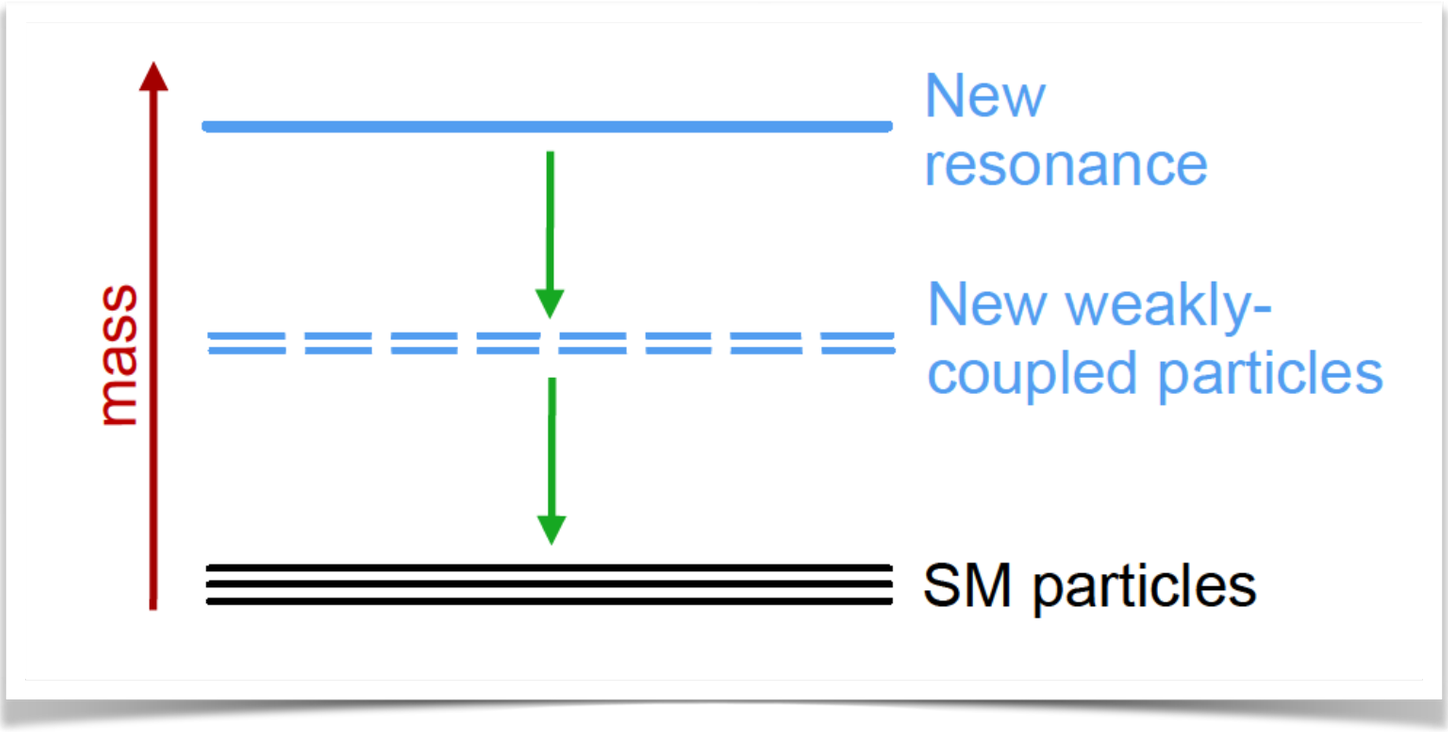


produce a new resonance that decays into SM particles

It is well known that simplified models are not consistent by themselves. And they don't necessarily describe the *correct* phenomenology.

Beyond simplified models

Next-to-simplfied models: two relevant new physics scales



produce a new resonance that decays into new particles and finally into SM particles

It may well happen that the lightest new particles are difficult to see [e.g. if they couple weakly] but can be produced in the decay of heavier ones.

This is a crucial point, otherwise we can just search for the lightest particles in simplified frameworks, as usual.

The phenomenology is more complex, with two new scales for new physics. The signals are mostly uncovered, and often elusive.

Next-to simplified models for Vector-like quarks

Vector-like quarks: simplified models

There are 7 simplified models in which one VLQ multiplet is added to the SM. Assumptions:

del Águila et al. hep-ph/0007316

- Interaction with SM particles is renormalisable.
- Decay into SM-only final states is allowed: there are interactions with only one heavy quark.

	charge 2/3	charge -1/3	
Singlets	$T_{L,R}$	$B_{L,R}$	
Doublets	$\begin{pmatrix} X \\ T \end{pmatrix}_{L,R}$ (charge 5/3)	$\begin{pmatrix} T \\ B \end{pmatrix}_{L,R}$	$\begin{pmatrix} B \\ Y \end{pmatrix}_{L,R}$ (charge -4/3)
Triplets	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}_{L,R}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}_{L,R}$	

Vector-like quarks: simplified models

These heavy multiplets interact with the SM particles through a Yukawa coupling, e.g. $(\bar{t}^0_L \ \bar{b}^0_L)\,\tilde{\Phi}\,T^0_R$ [zero superscript for weak interaction states]

→ When new electroweak eigenstates $T^0_{L,R}$ are added to the SM, the resulting mass eigenstates $u_{L,R},\ c_{L,R},\ t_{L,R},\ T_{L,R}$ are linear combinations of all of them.

It is *expected* that the the coupling to VLQ multiplets is largest for 3rd SM generation, because of *naturality* arguments JAAS 1306.4432

The decay modes [are expected to] take place to 3rd generation quarks

$T \to W^+ b$	Br ~ 0.5	$B \to W^- t$	Br ~ 0.5	$X \to W^+ t$	Br = 1
$T \to Z\, t$	Br ~ 0.25	$B \to Z\, b$	Br ~ 0.25	$Y \to W^- b$	Br = 1
$T \to h^0\, t$	Br ~ 0.25	$B \to h^0\, b$	Br ~ 0.25	h^0 = 125 GeV Higgs	

→ Signals of pair production JAAS 0907.3155
Signals and effects of single production JAAS et al. 1306.0572

Vector-like quarks: next-to-simplified models

Minimal additions of extra particles do not enlarge the table of 7 multiplets but can change the production or decay of the VLQ.

- Production: e.g. new resonances R decaying into VLQ

  Vignaroli 1404.5558
  Araque et al. 1507.05628

  The signals are not very different from the standard ones, but there is an extra enhancement.

  Exception: the signals are quite different if the VLQ are very boosted

$$M_R \gg m_Q \sim 1 \text{ TeV}$$

  but in that case they may have little relevance due to the small cross section.

- Decay: new weakly-interacting particles lighter than the VLQ, e.g. new scalars.

  JAAS, López-Fogliani, Muñoz 1705.02526
  Chala 1705.03013
  Benbrik et al. 1907.05929
  JAAS et al. 1911.10202

Next-to-simplified models: Example 1

VLQ doublet (*T*, *B*) + extra scalar doublet

The model in 1705.02526 is a full-fledged SUSY model but the remaining particles can be ignored here

Parameters

Simplified model	Next-to-simplfied model
Quark masses m_T, m_B	Scalar masses $M_{H1}{}^0$, $M_A{}^0$, $M_{H}{}^{\pm}$
Quark mixing θ_u, θ_d [small]	tan β ; α [~ alignment]

New decay modes

$T \rightarrow H^+ b$ $\quad$ $B \rightarrow H^- t$

$T \rightarrow H_l{}^0 t$ $\quad$ $B \rightarrow H_l{}^0 b$

$T \rightarrow A^0 t$ $\quad$ $B \rightarrow A^0 b$

depending on tan β

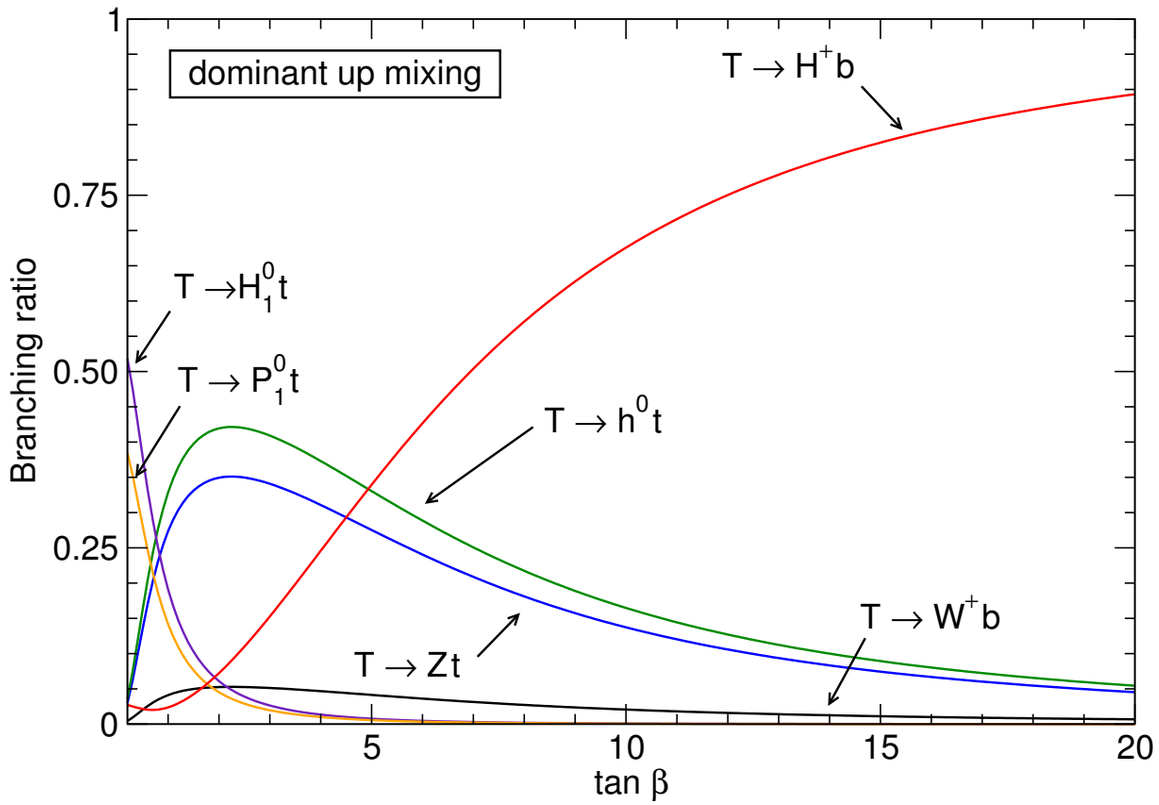
with $H^+ \rightarrow tb$; $\quad H_l{}^0 \rightarrow bb$ / tt ; $\quad A^0 \rightarrow bb$ / tt

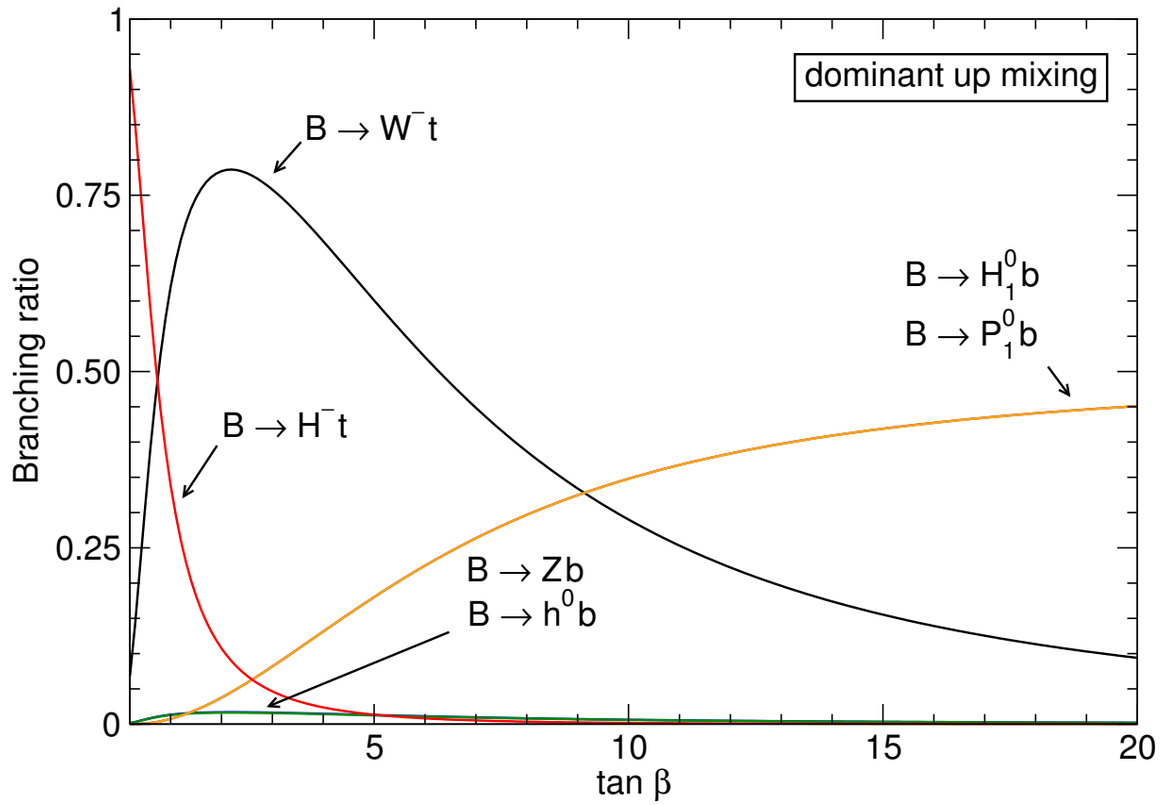
Next-to-simplified models: Example 1

VLQ doublet (T, B) + extra scalar doublet

Many possibilities depending on mixing hierarchies [details in 1705.02526]

- Most likely: $\sin\theta_d \ll \sin\theta_u$ [because $m_t \gg m_b$]
- Also assuming $m_{T,B} \gg M_{H1}{}^0, M_A{}^0, M_H{}^\pm$ [to avoid kinematical suppression]





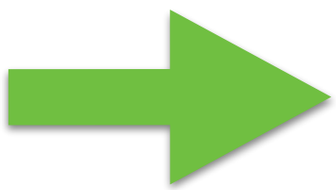
Dictionary for plots: $P_1{}^0 = A^0$ [pseudo-scalar]

Next-to-simplified models: Example 1

Example of novel final states in *TT* / *BB* production

low tan β	large tan β
$T \rightarrow H_1^0 / A^0\ t \rightarrow$ 3 tops	$T \rightarrow H^+\ b \rightarrow$ 1 top + 2 b's
$B \rightarrow H^-\ t \rightarrow$ 2 tops + 1 b	$B \rightarrow H_1^0 / A^0\ b \rightarrow$ 3 b's
TT → 6 tops	*TT* → 2 tops + 4 b's
BB → 4 tops + 2 b's	*BB* → 6 b's

... plus many other options for intermediate tan β, other mixing assumptions, ...



Common feature: presence of multiple *b* quarks and *W* bosons that can be tagged.

Differences:

- multiplicity of *W* bosons
- kinematics [peaks in n-body invariant masses]

Next-to-simplified models: Example 11

VLQ doublets / singlets + extra scalar singlet

The model in 1911.10202 is a composite Higgs model with several VLQ doublets and singlets but we can focus on lightest VLQ and new scalar

New parameters

Scalar mass $M_{H1}{}^0$
Scalar mixing sin γ

New decay modes

$T \to H_1{}^0 t$ $B \to H_1{}^0 b$

induced by small mixing with SM Higgs doublet

At variance with the previous case, now the extra scalar $H_1{}^0$ decays

$H_1{}^0 \to WW$ $H_1{}^0 \to ZZ$ $H_1{}^0 \to h^0 h^0$ $H_1{}^0 \to t\,t$

TT / *BB* production → Common feature: presence of at least two *b* quarks and multiple *W*/*Z*/h^0 bosons that can be tagged.

Next-to-simplified models: other examples

Other examples:

- Composite Higgs model with singlet T and scalar singlet S Chala 1705.03013

  $T \to S\,t$ $S \to bb$ / S stable [MET]

  Signals similar to $T \to h^0\,t$ [with different mass] if S not stable
  $T \to Z\,t$ with $Z \to \nu\nu$ if S stable

- Model with singlet T and new scalar S Benbrik et al. 1907.05929

  $T \to S\,t$ $S \to \gamma\gamma$ $S \to Z\gamma$

  The model is signature-motivated, these loop decays of S are expected to be sub-dominant.

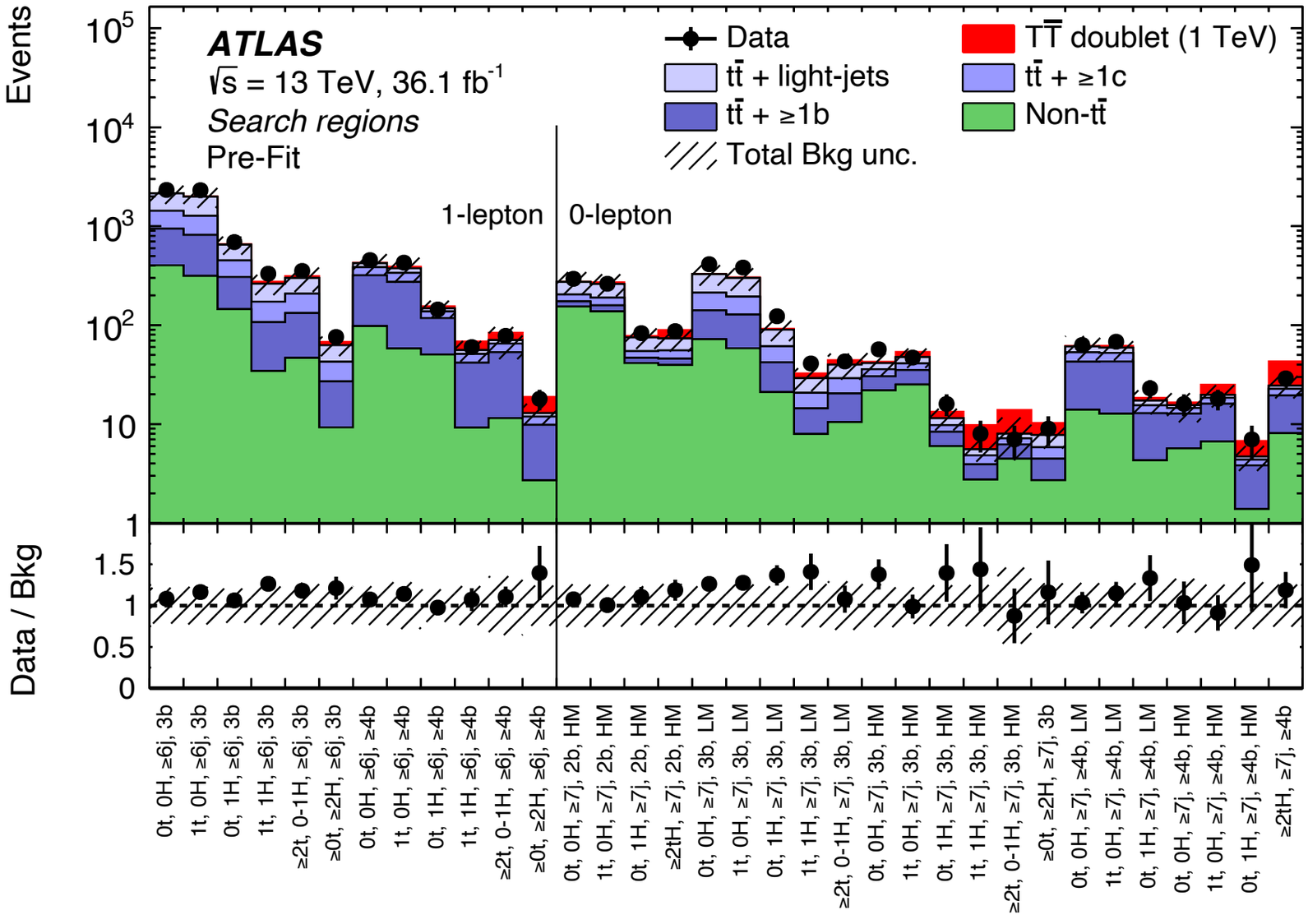
Sensitivity in searches

Example of search that is sensitive [but not optimised]

ATLAS search for events with multi-jets with several *b*-tagged jets together with one charged lepton or large MET

ATLAS 1803.09678

Many signal regions based on multiplicities of various objects



Sensitivity in searches

Examples of searches with little sensitivity to `exotic´ decay modes

ATLAS search for events with *b*-tagged jets, a charged lepton, MET and a *W* jet, with $T \rightarrow Wb$ reconstruction

ATLAS 1707.03347

looking for an excess of events where we attempt to reconstruct two heavy quarks

$T_1 = W_1 + b_1 \quad T_2 = W_2 + b_2$

and minimise $m(T_1) - m(T_2)$, has little sensitivity to the exotic decay modes

ATLAS search for events with *b*-tagged jets, a charged lepton, MET and a *W* jet, with $B \rightarrow Wt$ reconstruction

ATLAS 1806.01762

similar problem

Proposals for searches

Model-independent interpretation of standard searches

There are at least five parameters entering the interpretation:

- Heavy quark mass *M*
- Production cross section σ  mixing parameter, when mass M and flavour of initial quark is fixed
- Branching ratios to *Wb*, *Zt*, *Ht*, … [for *T* quarks]

  One can define Br(*W*) + Br(*Z*) + Br(*H*) ≡ ρ ≤ 1

Need to make hypothesis about extra modes. Most conservative / model agnostic: they are just not seen: zero efficiency for assumed event selection [This is not equivalent to having MET of course]

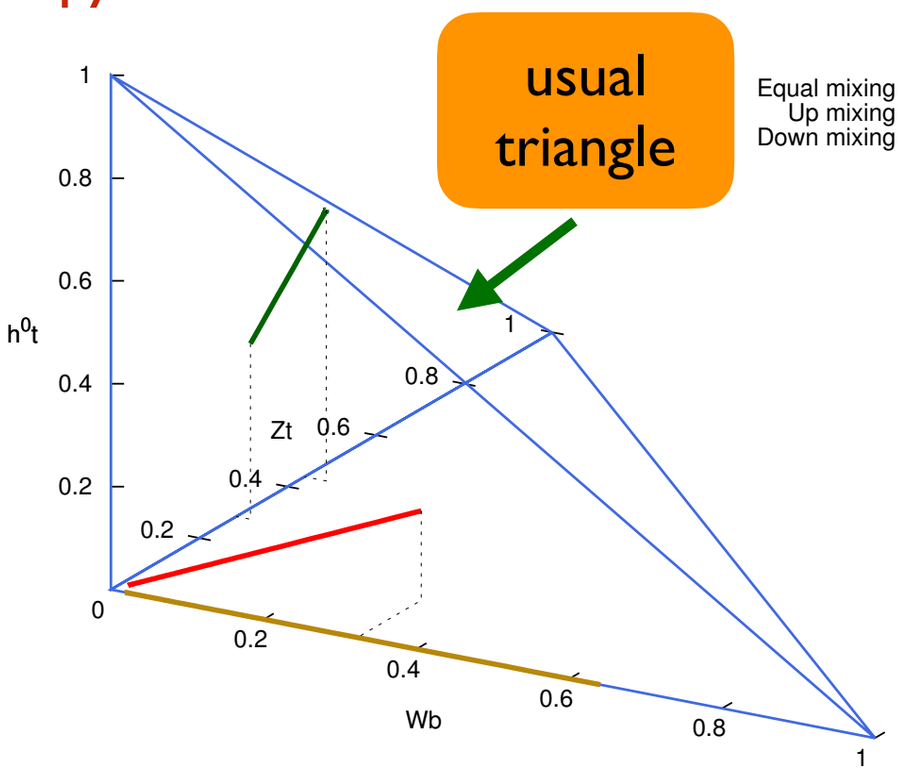
Can also go to higher dimensionality by considering specific new modes, but five dimensions is complicated enough!

Model-independent interpretation - pair production

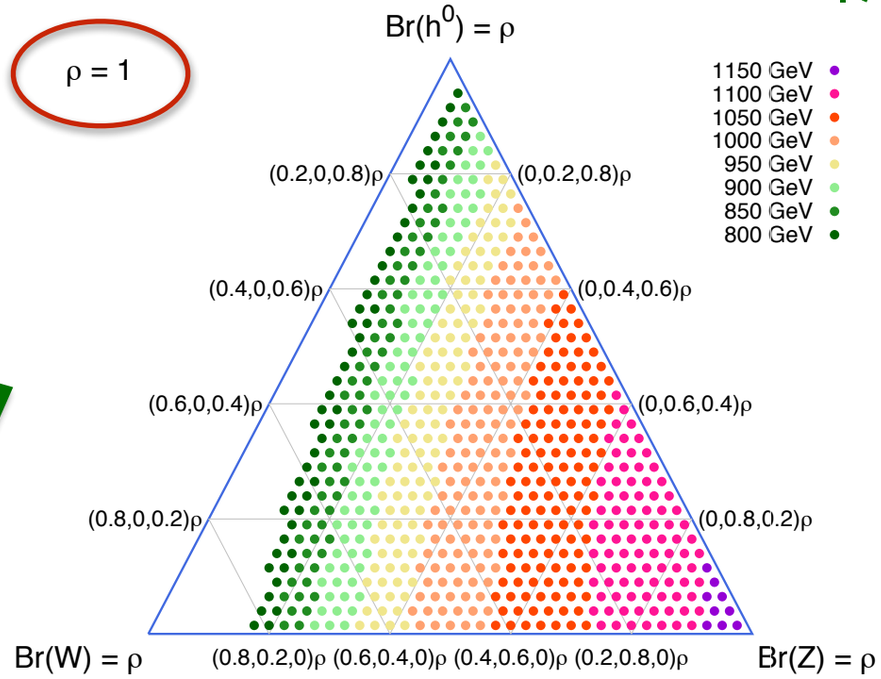
In pair production $M \Longleftrightarrow \sigma$: one fewer parameter.

JAAS, López-Fogliani, Muñoz
1705.02526

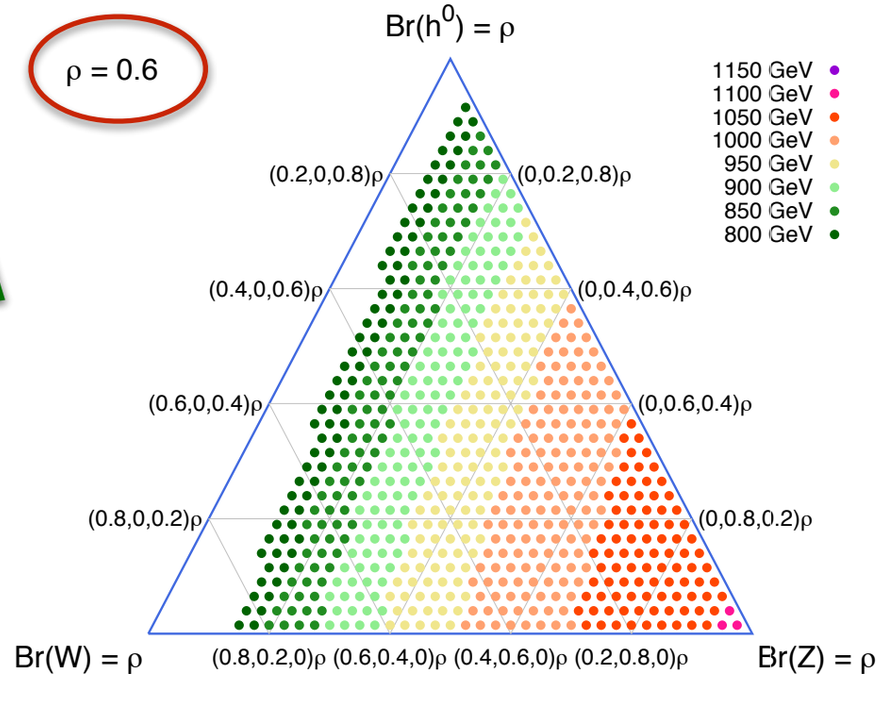
Generalisation of the triangle:
pyramid



slices of fixed ρ



slices of fixed ρ



Model-independent interpretation - single production

In single production, σ × ρ play the role of ρ: it is equivalent to have smaller cross section or to have `invisible´ modes that make Br(*W*) + Br(*Z*) + Br(*H*) ≡ ρ < 1

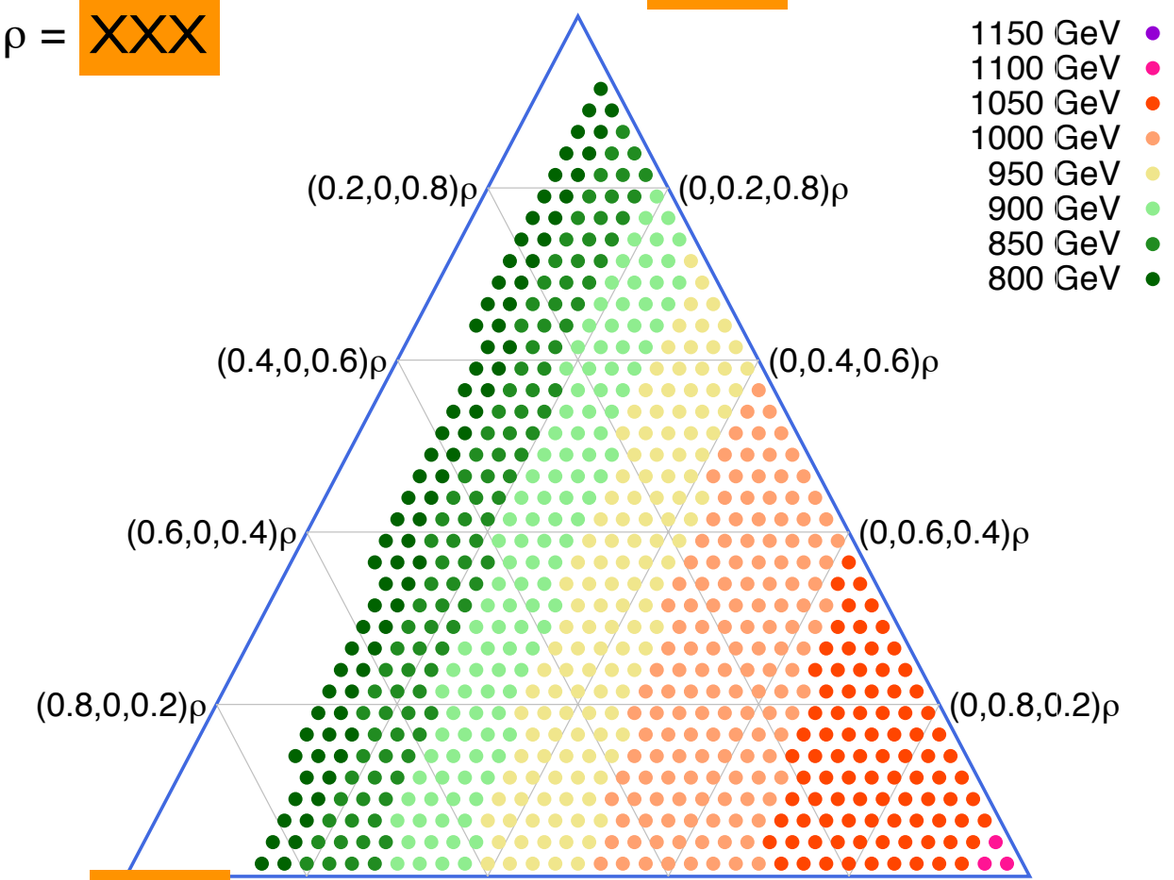
σ × ρ = const

σ × ρ = XXX

*h*⁰ dominated

σ × Br(h^0) = XXX

mass scale: colour



σ × Br(W) = XXX

σ × Br(Z) = XXX

W dominated

Z dominated

Optimised searches with ML

In VLQ pair production, both in the `standard´ and [most of] the exotic decay modes, final states have multiple *b* quarks, and $W/Z/h^0$ bosons that are likely boosted.

The same happens in single production but with smaller multiplicities

Then, my proposal for improved search strategies for VLQ is the use of:

- ☑ A generic tagger for boosted $W/Z/h^0$/... — MUST — JAAS, Joaquim, Seabra 2008.12792
- ☑ A machine learning (ML) automated tool to detect features in kinematical distributions
  [e.g. peaks in n-body invariant mass] — SOFIE — JAAS, 2111.12647

The tagging of *b* jets and large-radius jets can be used to select events that have interesting `objects´ and reduce background. A ML tool can subsequently be used to look for kinematical features.

Optimised searches with ML

The method has not yet been tested on multi-body final states. Currently, only results 2-body final states

Application to multi-bod final states under way… expected next Fall.

End