A basic guide to Vector-like Quarks

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Outline

1. Introduction

2. Gauge-invariant description of arbitrary vector-like quarks

3. The importance of mixing

4. Phenomenology:

   - Indirect effects and constraints
   - Direct searches (decay and single production)

What is a vector-like quark?

- A spin 1/2 fermion
- with same SM quantum numbers for L and R chiralities
- color triplet (fundamental rep of $SU(3)_C$)

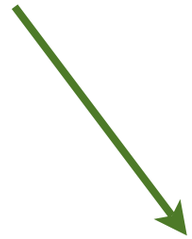
Why are they interesting?

- Appear in popular models: GUT, Xdims, composite top, ... (often associated with extended fermion multiplets and/or with EWSB and hierarchy problem) Wulzer's talk
- Anomaly cancellation
- One of a few logical possibilities
- Decoupling

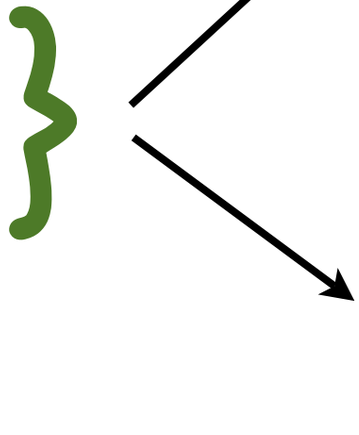
One of a few logical possibilities

- Spin 0, 1/2, 1, …

- With/without mixing



Richer phenomenology!



Leptons (color singlets)

Quarks (color triplets)

Decoupling

Unlike chiral fermions, vector-like fermions can have a gauge-invariant mass term

$$M\bar{Q}Q$$

not arising from electroweak symmetry breaking.

No effects when $M \to \infty$

:) Safer

:(Could be out of reach

Effective (model-independent) description

del Aguila, Bowick, Fishbane, Meshkov, Ramond, London, Langacker, Lavoura, Branco, Wagner, Tait, Barger, Berger, Frampton, Sher, Aguilar-Saavedra, Santiago, Pannizzi, Moreau, Wulzer, MPV, ...

- Use the full SU(3)xSU(2)xU(1) gauge invariance
- Write arbitrary quarks in terms of irreps (multiplets)
- Write most general symmetric Lagrangian (in convenient basis)
- Focus on the relevant part for processes of interest

Simple, sensible and physical parametrization in terms of couplings and masses

Easy to connect with explicit models -> subspaces of parameter space

In the following, mild requirements:

1. Mixing allowed (decay, single production, ...)
(quarks without mixing in Moreau' s talk)

2. Assume Higgs doublet(s)

3. Renormalizable couplings
(Higher order interactions in Greljo, Kamenik, Kopp '13, check talk)

del Aguila, Bowick '83

del Aguila, MPV, Santiago '00

Singlets

$$\mathbf{1}_{2/3} = T$$

$$\mathbf{1}_{-1/3} = B$$

Doublets

$$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$$

$$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$$

$$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$$

Triplets

$$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$$

$$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$$

Notation:

$\text{Isospin}_{\text{Hypercharge}}$

$T \to +2/3$
$B \to -1/3$
$X \to +5/3$
$Y \to -4/3$

} Electric charge

Lagrangian = SM + terms with extra quarks:

- Diagonal kinetic and mass terms
- Gauge interactions determined by quantum numbers
- Yukawa interactions:

SM-extra

$$\lambda_q \; \phi \, \bar{Q}_R \, q_L$$
$$\lambda_t \; \phi \, \bar{Q}_L \, t_R$$
$$\lambda_b \; \phi \, \bar{Q}_L \, b_R$$

singlets: λ_q

doublets: λ_t or/and λ_b

triplets: λ_q

extra-extra

$$\tilde{\lambda} \; \phi \, \bar{Q}_R \, Q'_L$$

the couplings $\lambda_{q,t,b}$, $\tilde{\lambda}$
are matrices in flavour space

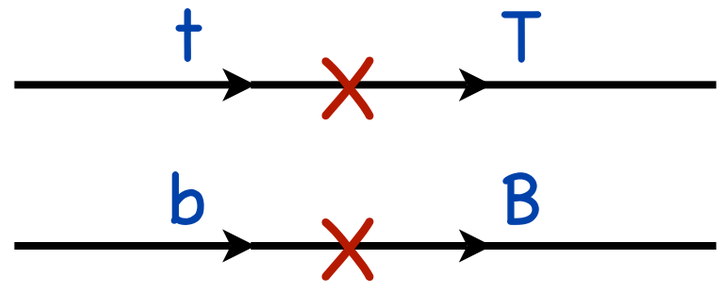
Mixing

Upon EWSB, the Yukawa couplings give rise to non-diagonal mass matrices for u,c,t,T^a and u,c,t,B^a

Diagonalize to go to mass-eigenstate base

Non diagonal interactions with
- Z and W bosons
- Higgs

- light-light (modified)
- heavy-heavy (modified/new)
- light-heavy (new)



➡ Most effects associated with mixing angles

➡ Correlations

Example: doublet $\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$ coupled to third family

(X is called $T^{5/3}$ in certain models)

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2 parameters

M , λ_t

trade for →

Physical parameters:

Heavy mass m_T (or m_X)

Mixing angle $s_R = \sin\theta_R \sim \lambda_t \dfrac{v}{m_T}$

I'm ignoring a possible phase

heavy-light couplings

$X_L t_L W \to -s_L$

$X_R t_R W \to -s_R$

$T_L b_L W \to s_L$

$T_L t_L Z \to 2 s_L c_L$

$T_R t_R Z \to -s_R c_R$

$T_L t_R H \to s_R c_R$

$T_R t_L H \to \dfrac{m_t}{m_T} s_R c_R$

light-light couplings

$t_L b_L W \to c_L$

$t_L t_L Z \to c_L^2 - s_L^2$

$t_R t_R Z \to -s_R^2$

$ttH \to c_R^2$

s_L further suppressed and not independent:

$$\tan\theta_L = \frac{m_t}{m_T} \tan\theta_R$$

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Correlations!

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$T_L t_R H \to s_R c_R$

$T_R t_L H \to \dfrac{m_t}{m_T} s_R c_R$

Note that

➡ $|s_{L,R}| \leq 1$

➡ { s_R suppressed
  s_L very suppressed

Example: doublet $\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$ coupled to third family

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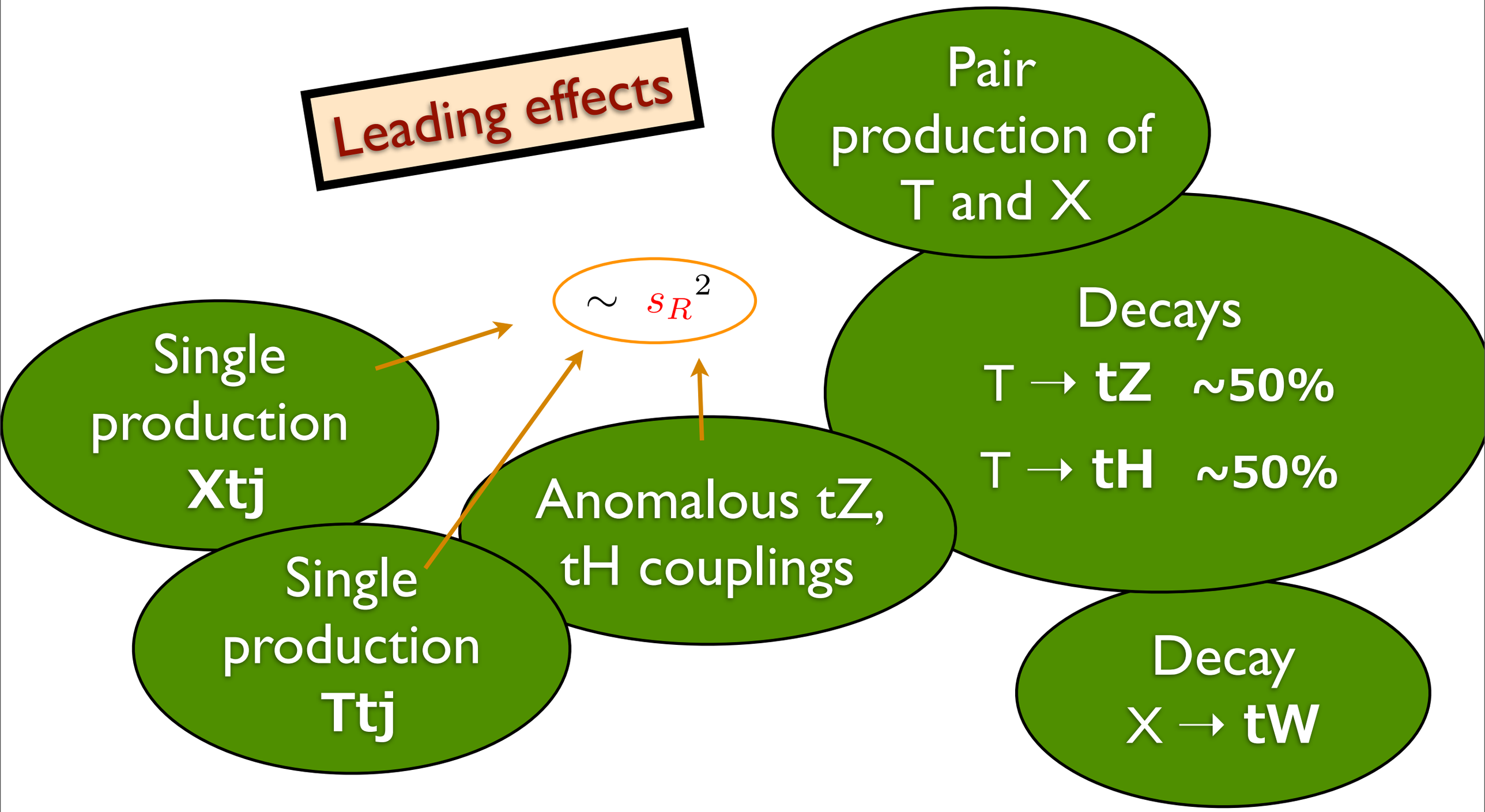


Consequences of generic mixing of general VLQ

Branco, Lavoura '86; Langacker, London '88; del Aguila, MPV, Santiago '00;
Choudhury, Tait, Wagner '01; Aguilar-Saavedra '02; Cacciapaglia et al. '12

- ✓ Mass splittings
- ✓ Light-heavy interactions ⇒ single production & decay
- ✓ Modified form of LH and RH neutral currents
- ✓ Including FCNC at tree level!
- ✓ Non-unitary CKM matrix
- ✓ RH charged currents
- ✓ New CP violating phases
- ✓ Higgs physics, oblique corrections, ...

check Nebot's talk for flavor effects

Interesting effects, but strong constraints from flavour physics.

$t \to cZ$, ...

Usually, mixing with only one SM family

Phenomenology: simple models

Mostly based on

Aguilar-Saavedra, Benbrik, Heinemeyer, MPV,
"A handbook of vector-like quarks," 2013

- Consider one multiplet at a time

  ✓ Robust for direct searches (unless degenerate VLQ with same charge)

  ✓ Care with indirect searches

- Mixing with 3rd generation only

  ✓ Avoid flavour problems

  ✓ Motivated by CKM, EWSB, hierarchy and (partial) top/bottom compositeness

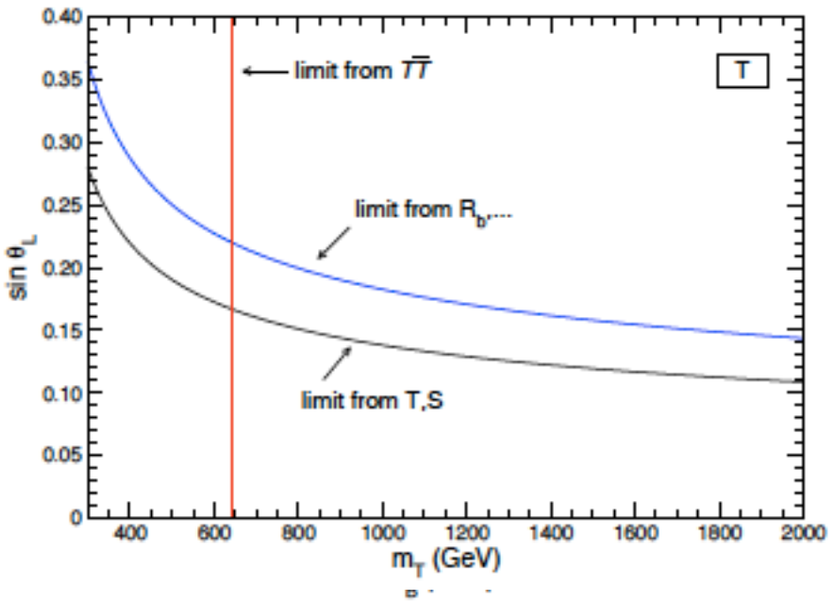
Indirect effects and constraints

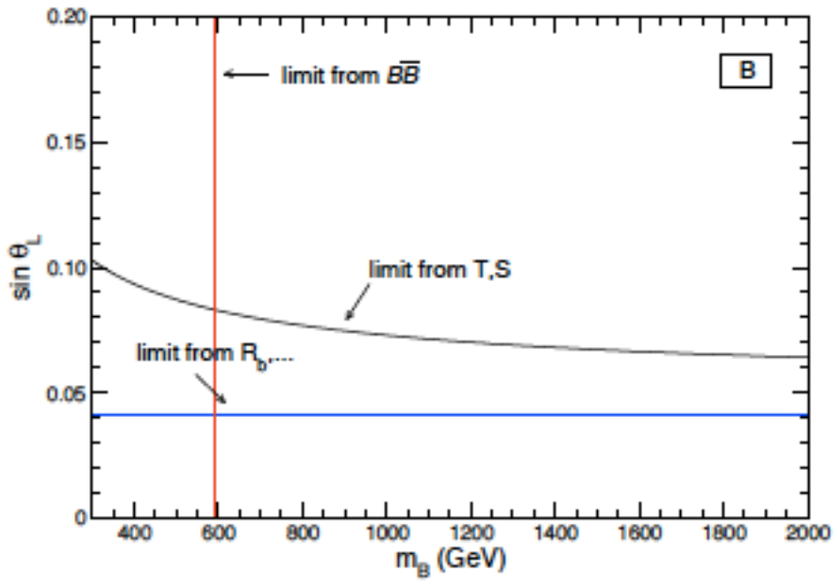
Modified t & b couplings

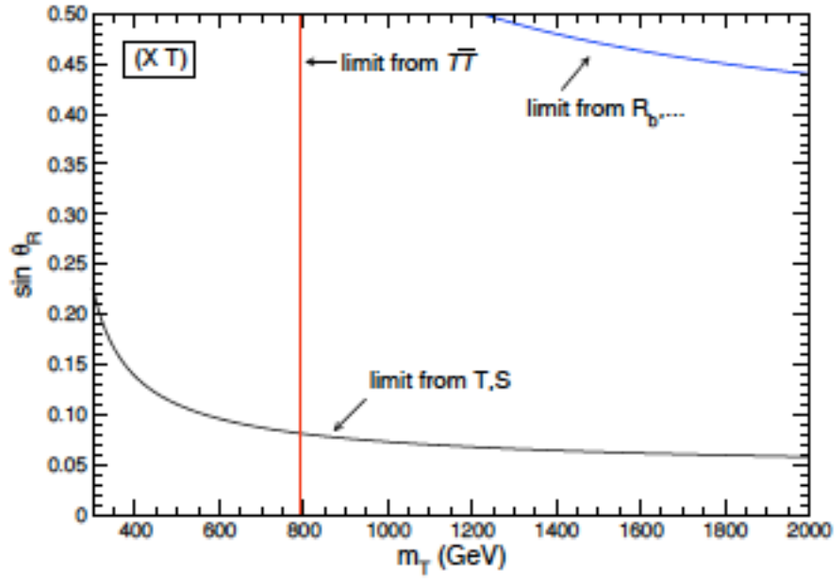
del Aguila, MPV, Santiago '00

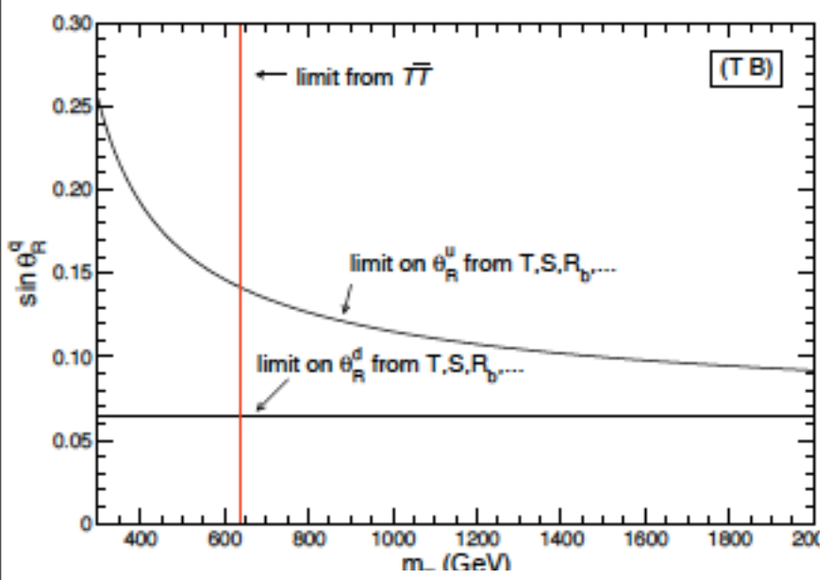
	# par	δW_{tb}^L	δW_{tb}^R	δX_t^L	δX_b^L	δX_t^R	δX_b^R	δY_t	δY_b
T	1	↓	—	↓	—	—	—	↓	—
B	1	↓	—	—	↓	—	—	—	↓
$\begin{pmatrix} T \\ B \end{pmatrix}$	2	—	↑	—	—	↑	↑	↓	↓
$\begin{pmatrix} X \\ T \end{pmatrix}$	1	—	—	—	—	↑	—	↓	—
$\begin{pmatrix} B \\ Y \end{pmatrix}$	1	—	—	—	—	—	↑	—	↓
$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	1	↑	—	↓	↑	—	—	↓	↓
$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$	1	↑	—	↑	↓	—	—	↓	↓

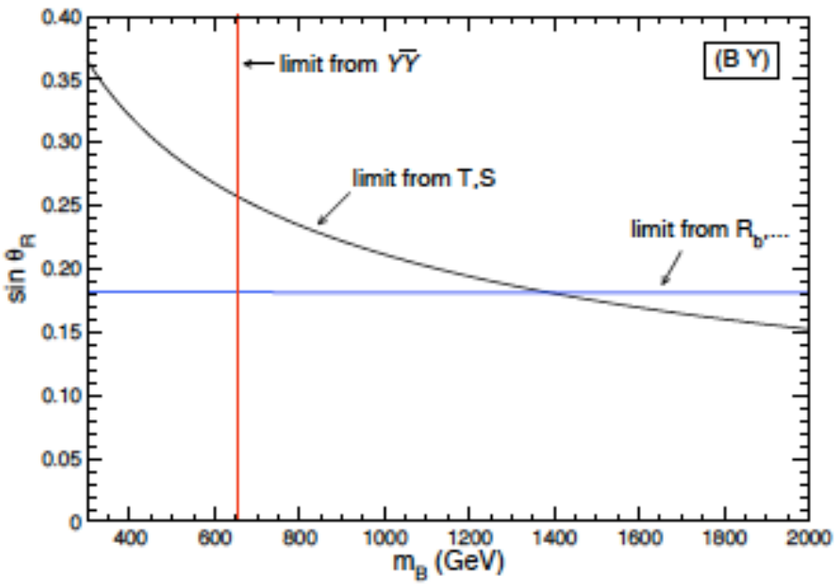
Electroweak precision limits

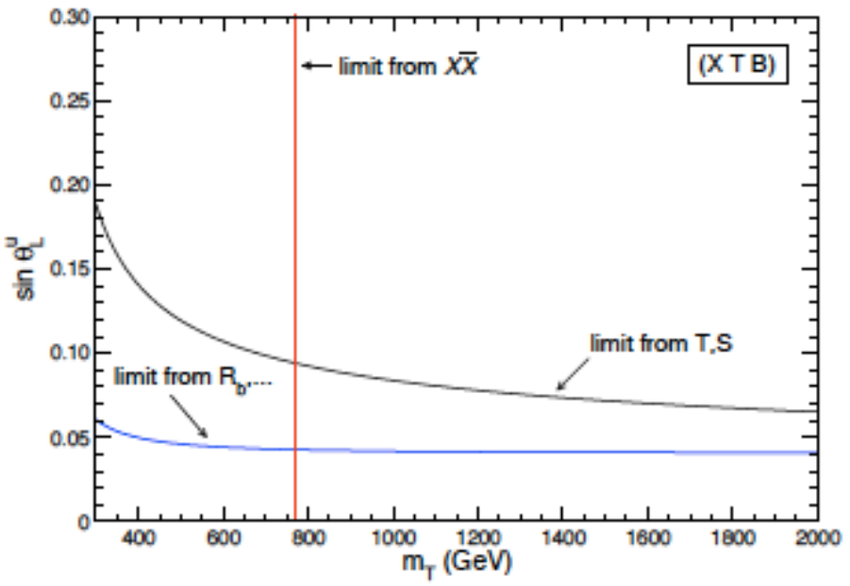


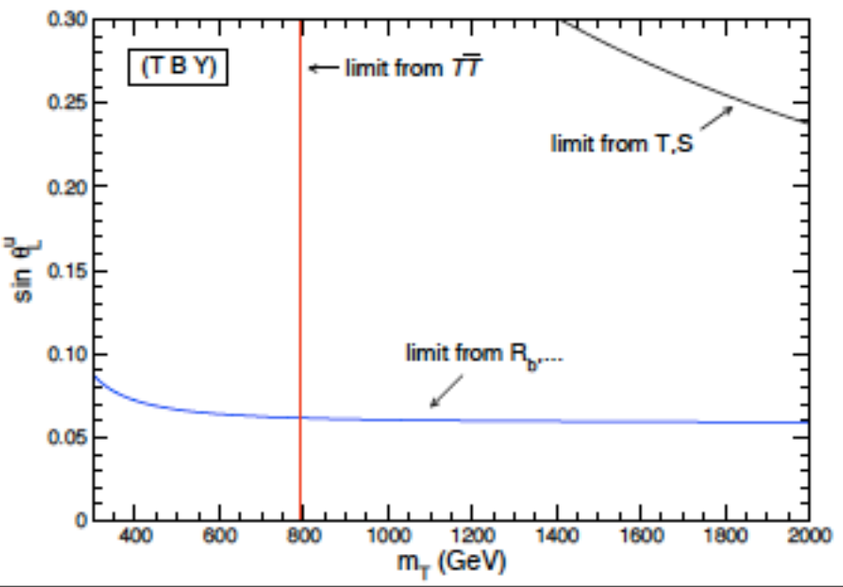












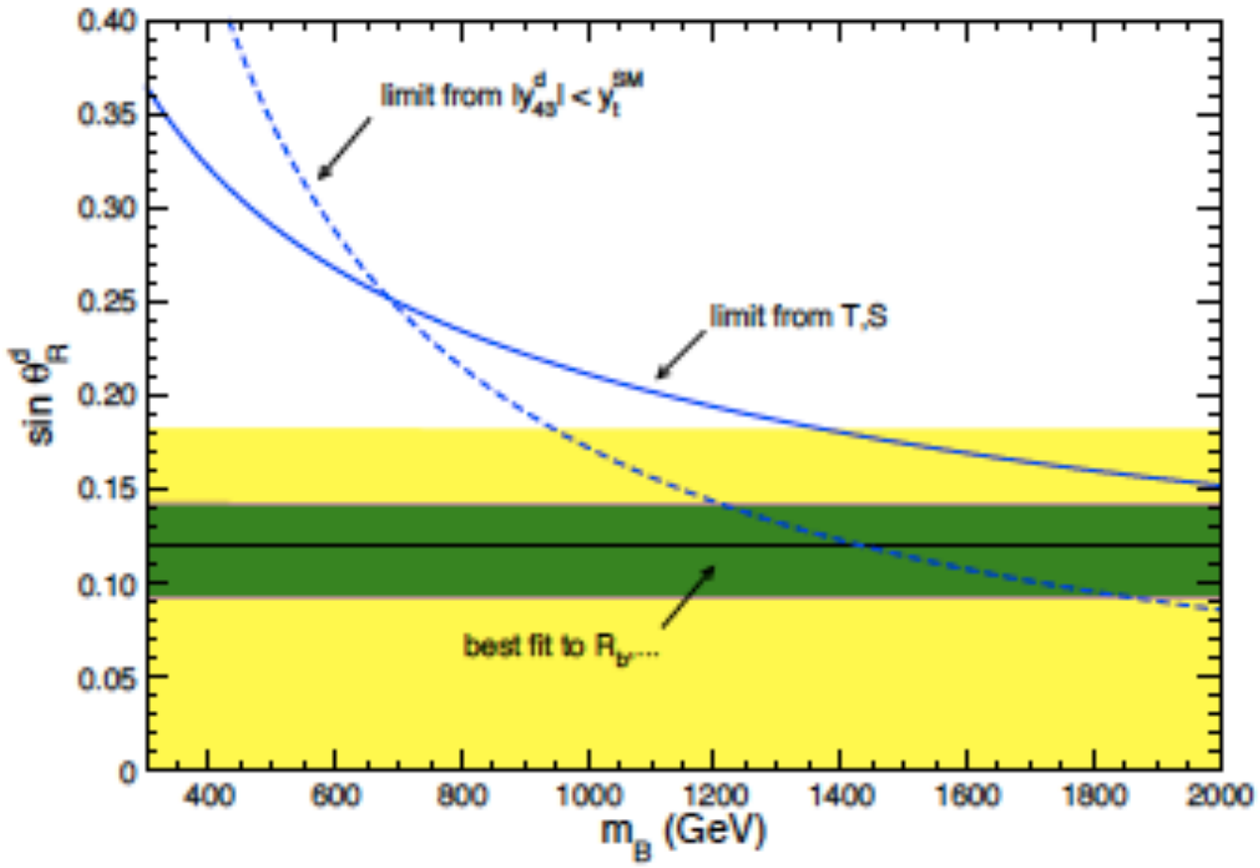
$$S,\ T$$

$$R_b,\ A_{FB}^b,\ A_b,\ R_c$$

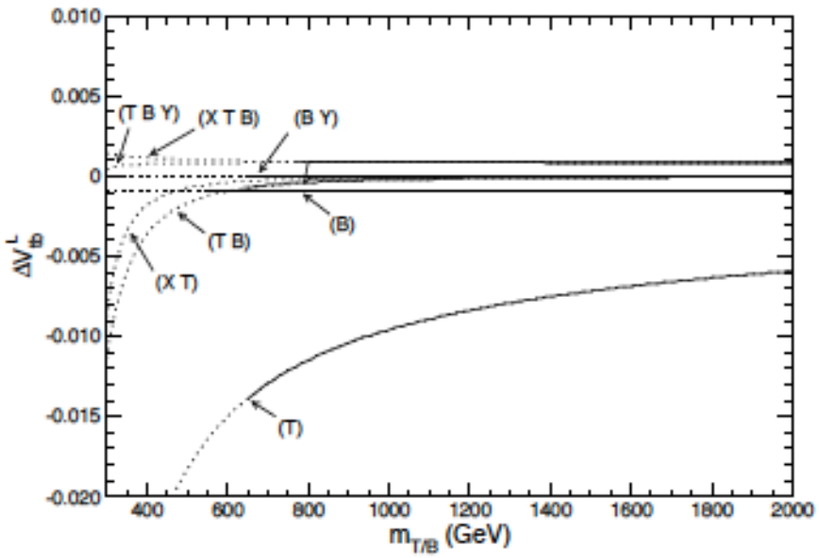
Direct limits not updated

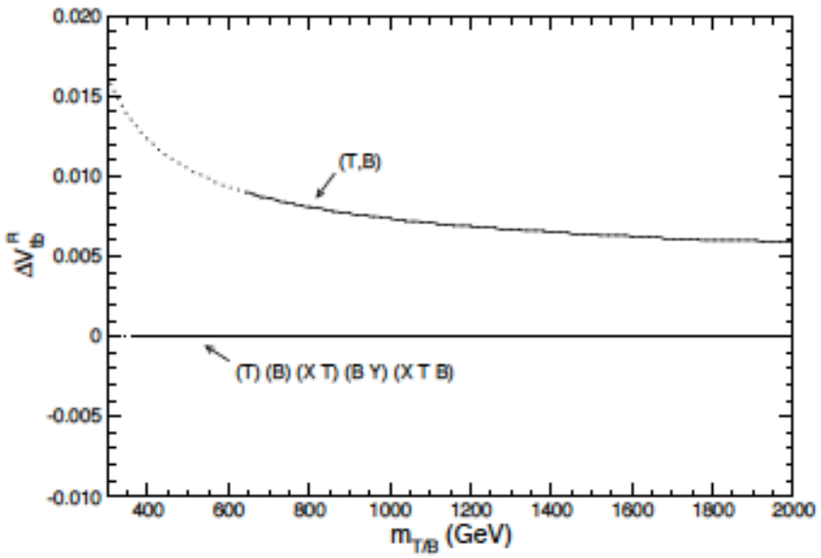
Electroweak precision limits

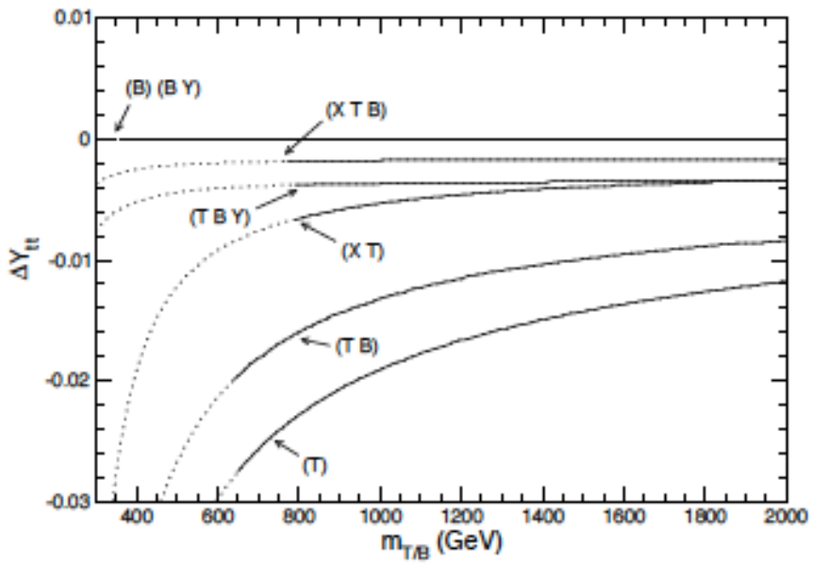
Improved fit for doublet $\begin{pmatrix} B \\ Y \end{pmatrix}$

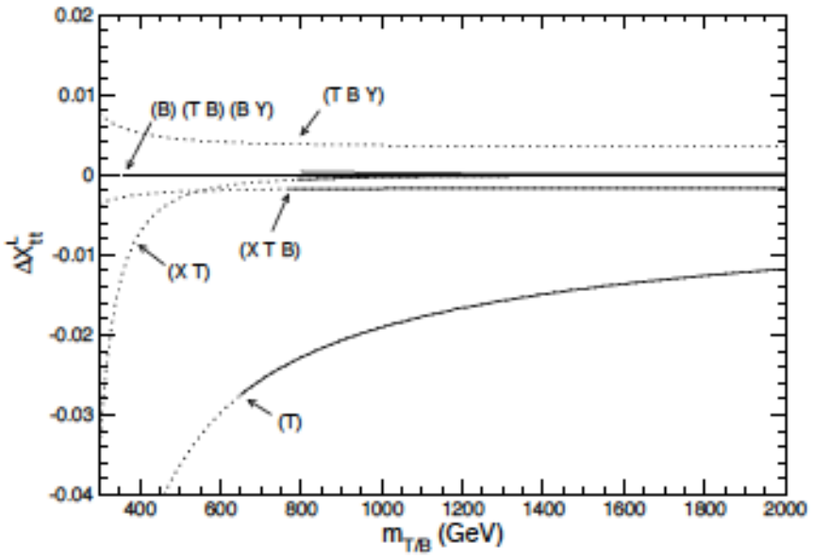


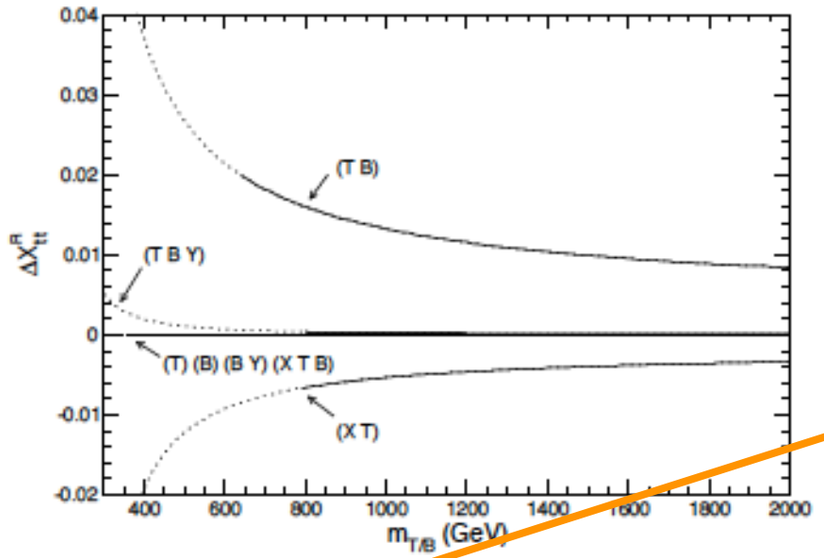
Anomalous top couplings



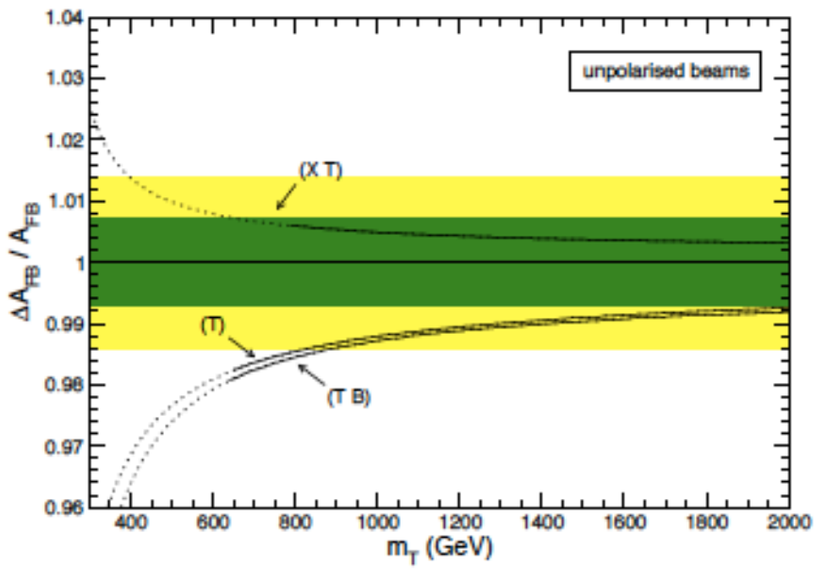


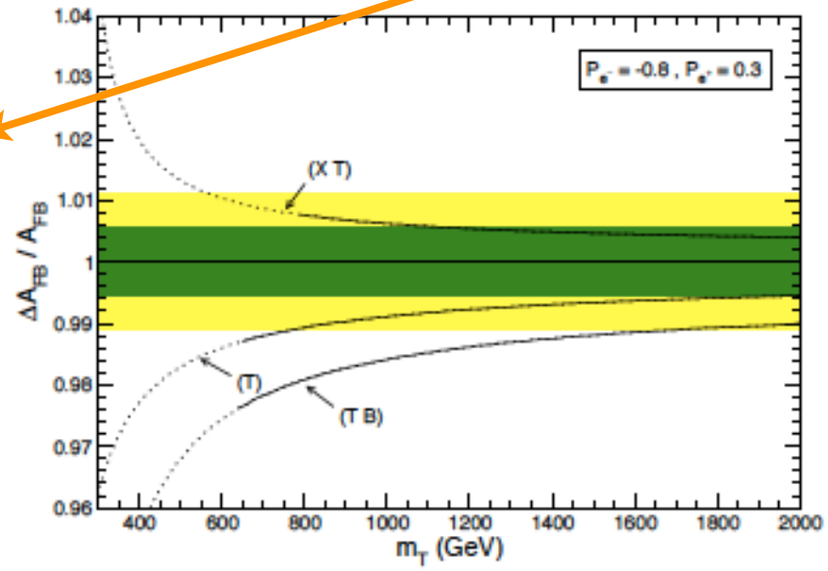


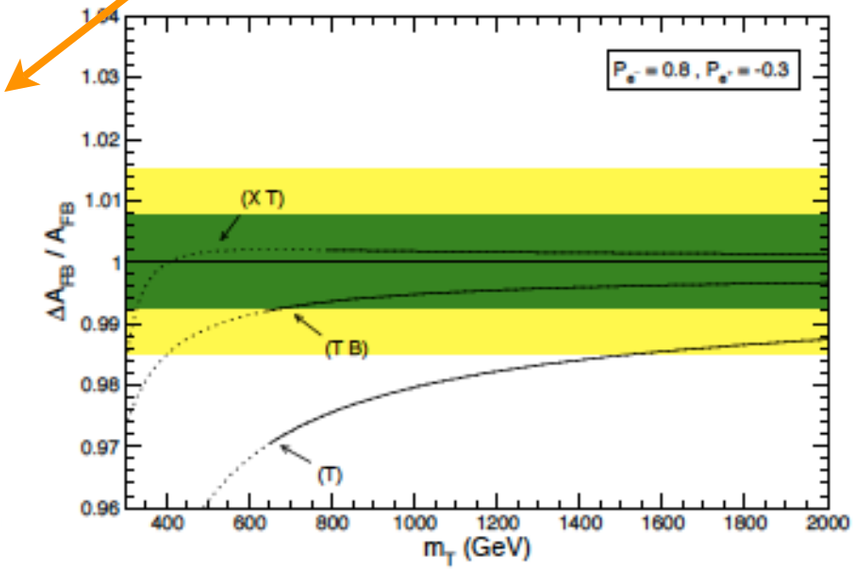




ILC







Higgs physics

$gg \to H, \qquad H \to gg, \qquad H \to \gamma\,\gamma$

- Cancellation in charge +2/3 sector between
  - T loop
  - t loop with modified top couplings

- Contribution of B loop proportional to mixing square

$H \to bb$

- Reduced width, enhanced BR into other final states

All together, ~ 10% effects at most when limits above apply

- Larger effects possible in presence of several multiplets with $\tilde{\lambda}$ couplings

Talk by Moreau

Direct searches

Pair Production at LHC

Dominated by QCD (depends only on mass)

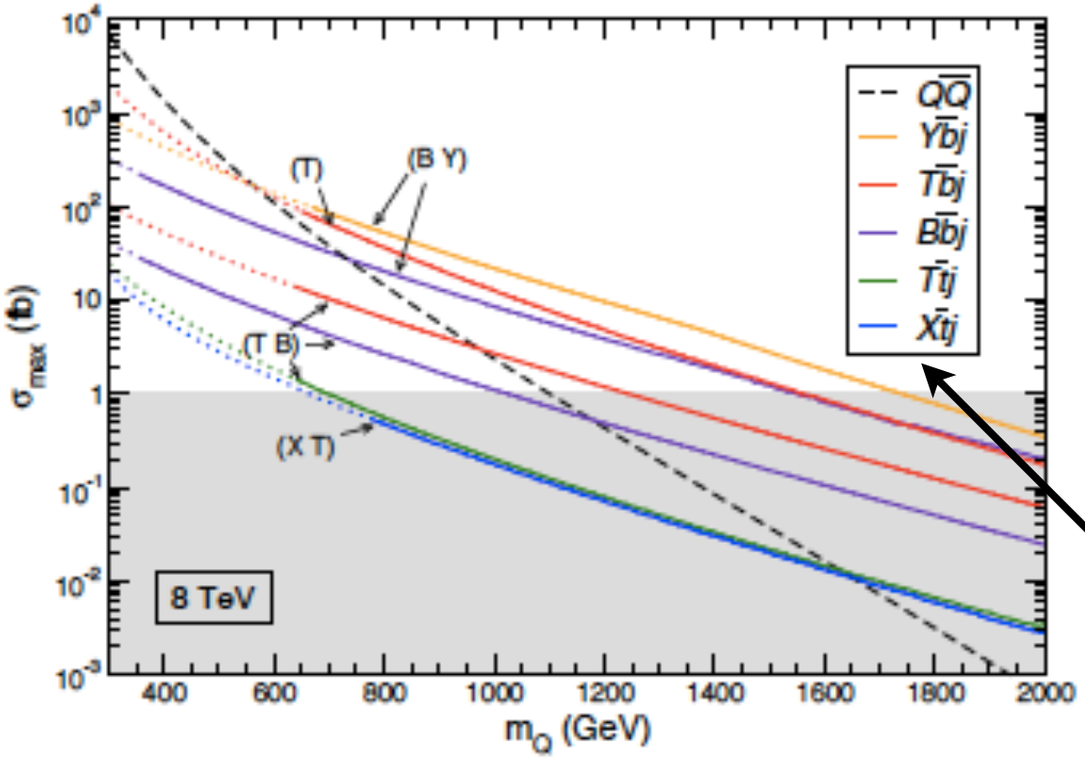
Complete analysis of pair production and decay of singlets and doublets in

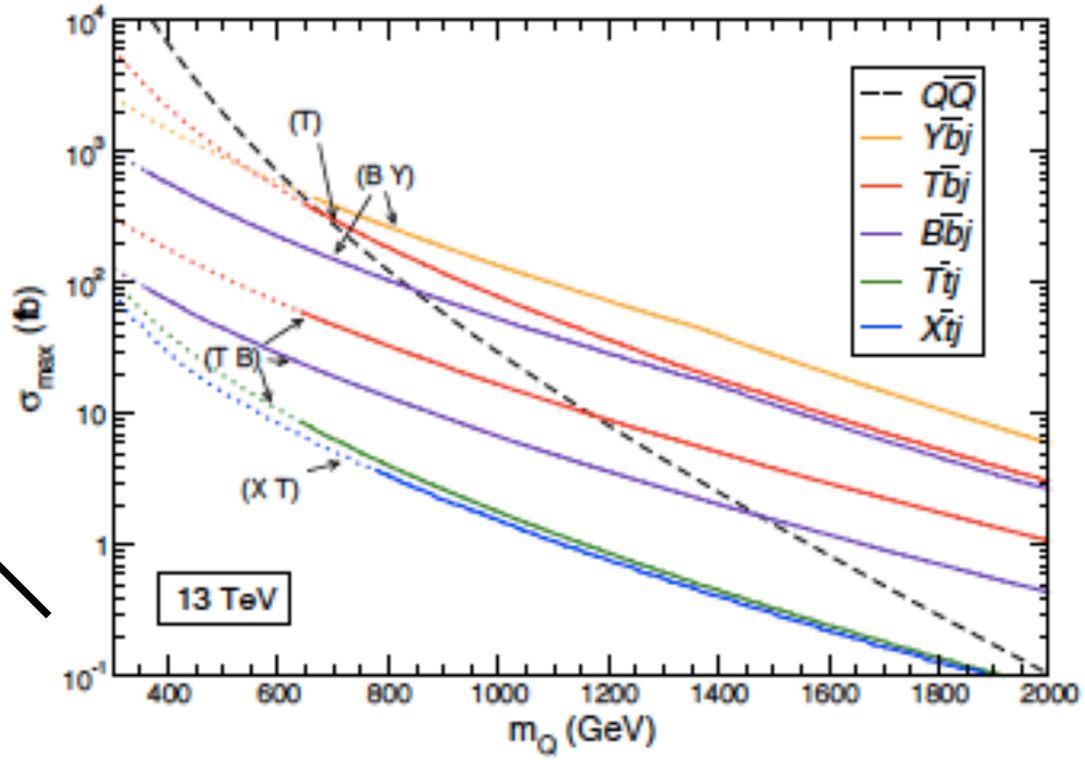
Aguilar-Saavedra '09

Single Production at LHC

QCD-electroweak processes, similar to top single production

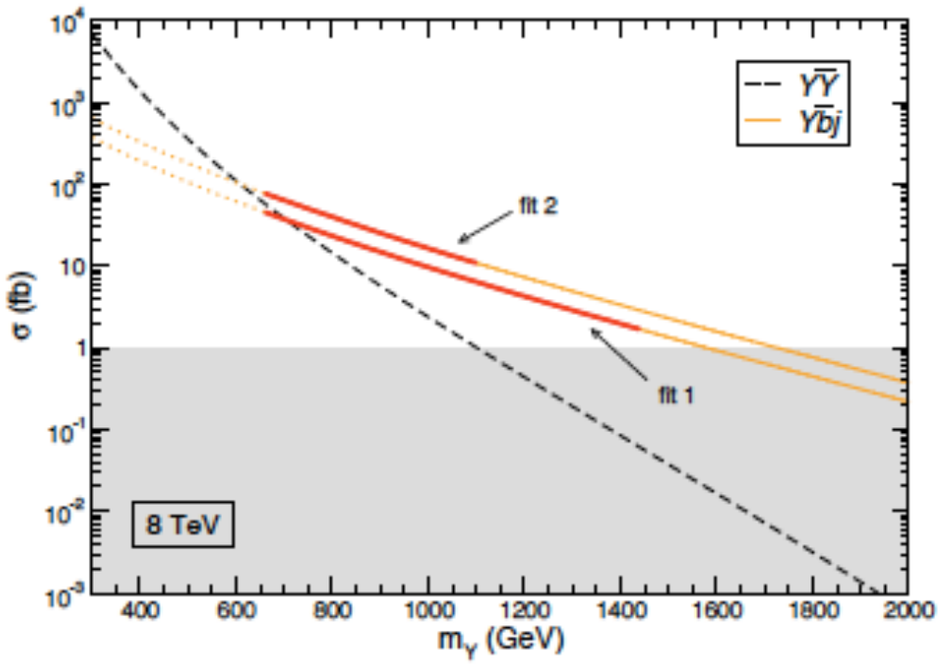
(proportional to mixing squared)

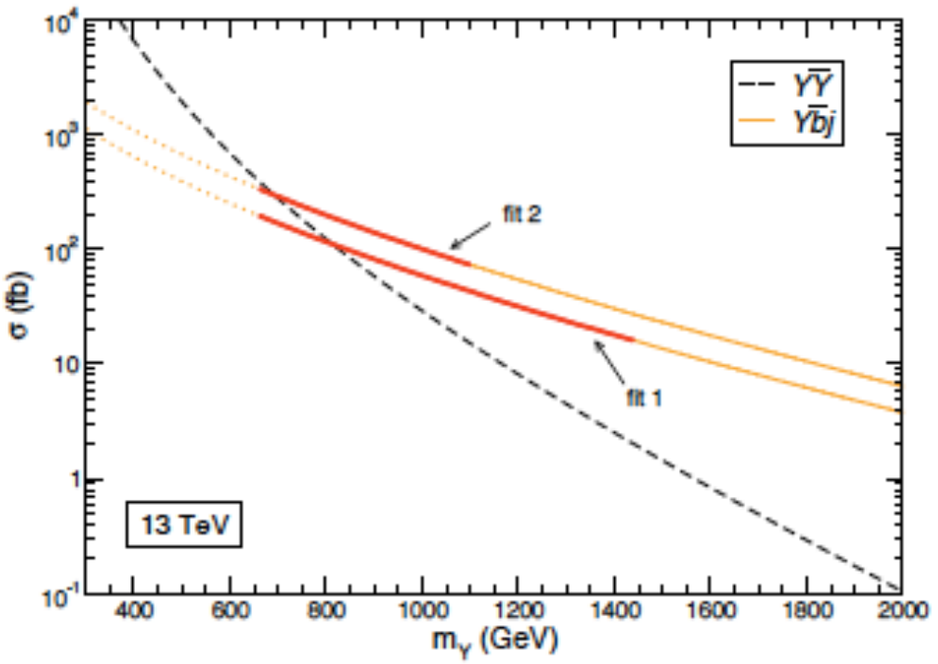




$\begin{pmatrix} B \\ Y \end{pmatrix}$:

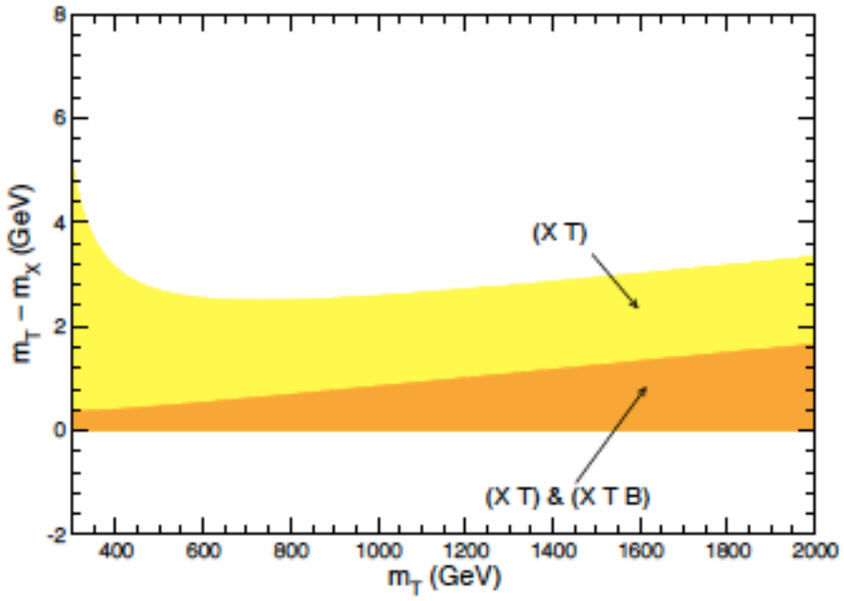
Single production for best-fit (1) mixing

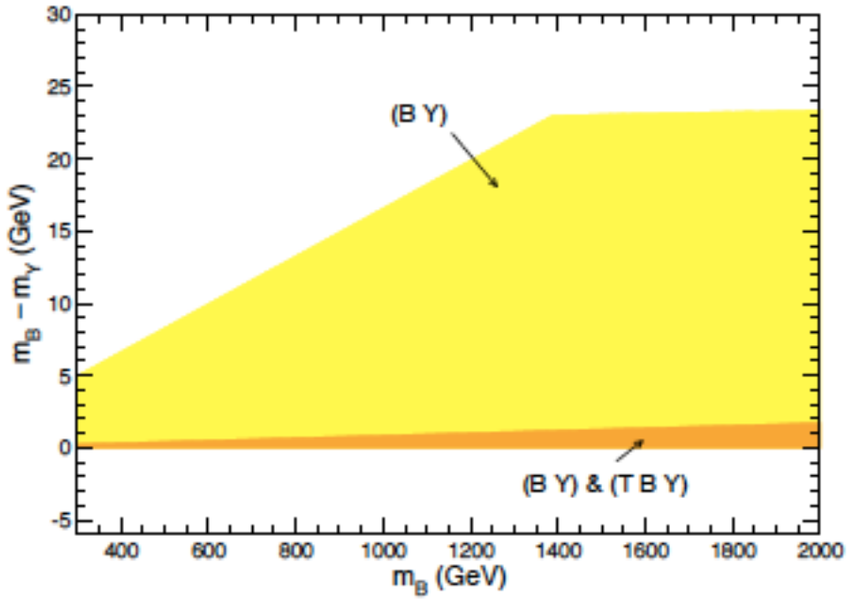


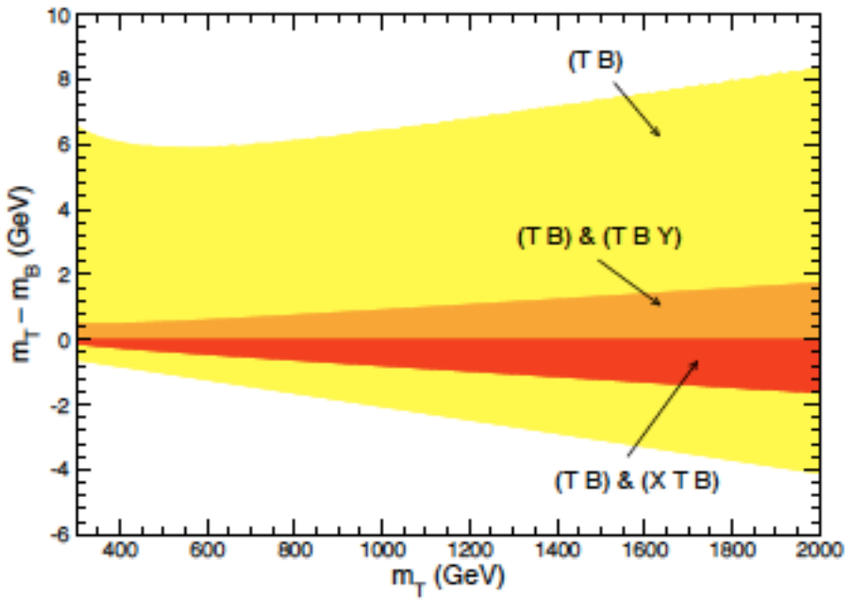


Mass splittings

(determined by M and mixings)







Very suppressed decays into heavy partners

Decays

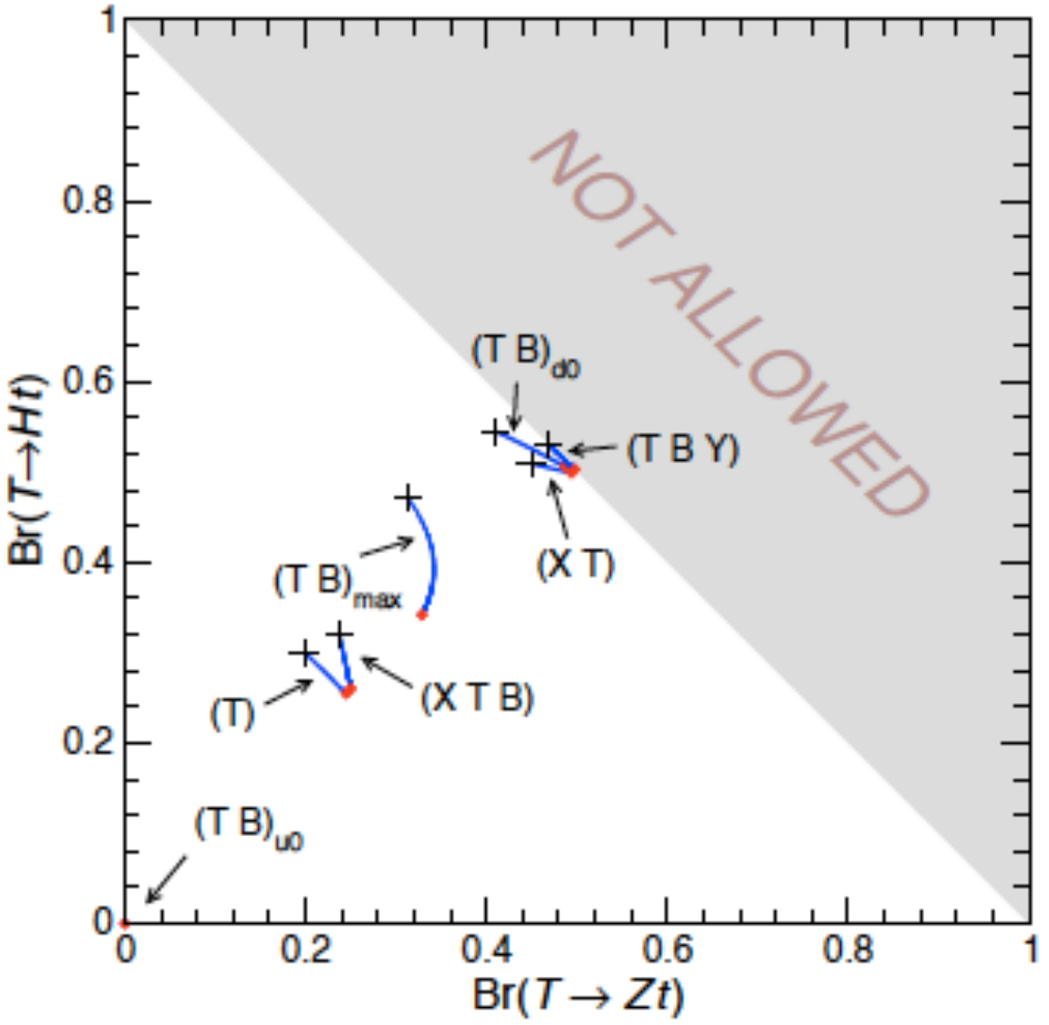
Charge +5/3: X → W t

Charge -4/3: Y → W b

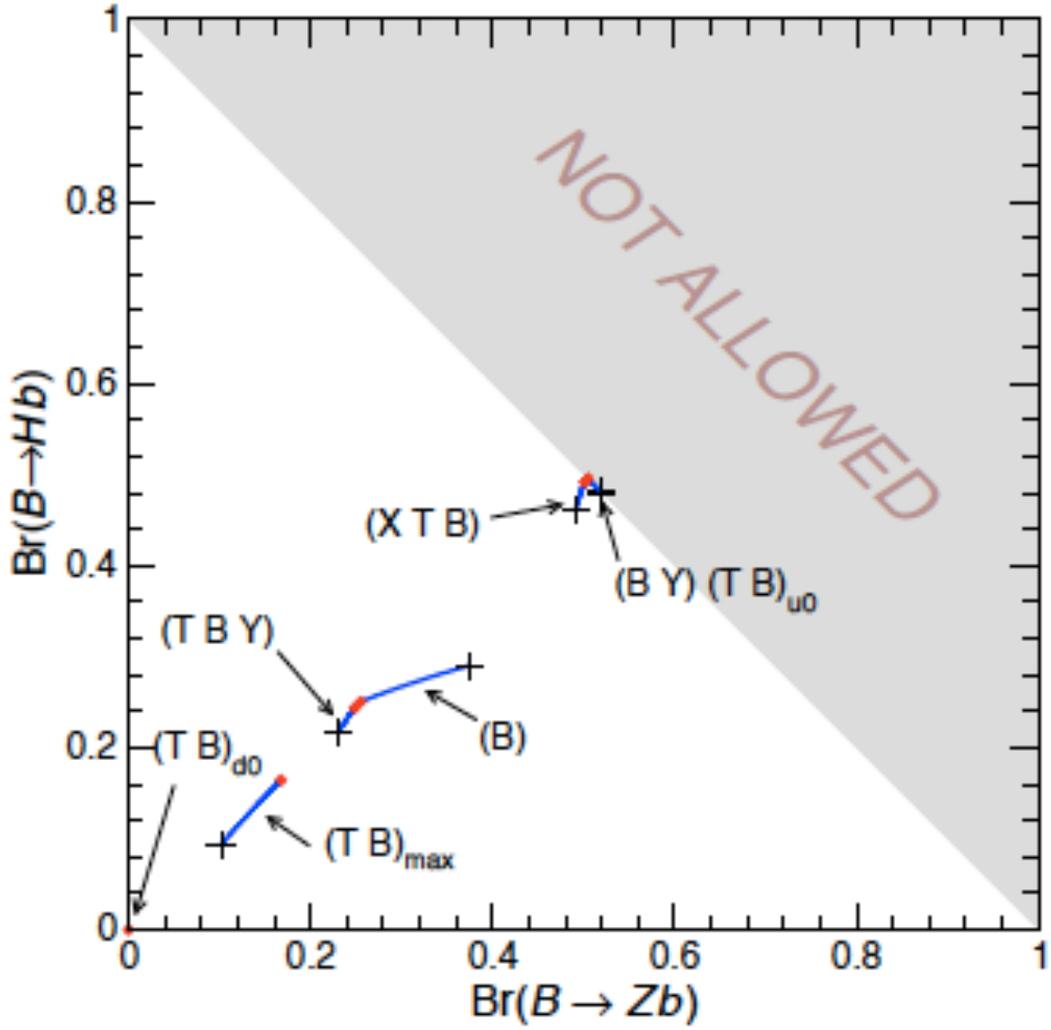
Charge +2/3: T → Wb, Zt, Ht

Charge -1/3: B → Wt, Zb, Hb

$BR(T \to Wb) + BR(T \to Zt) + BR(T \to Ht) = 1$



$BR(B \to Wt) + BR(B \to Zb) + BR(B \to Hb) = 1$



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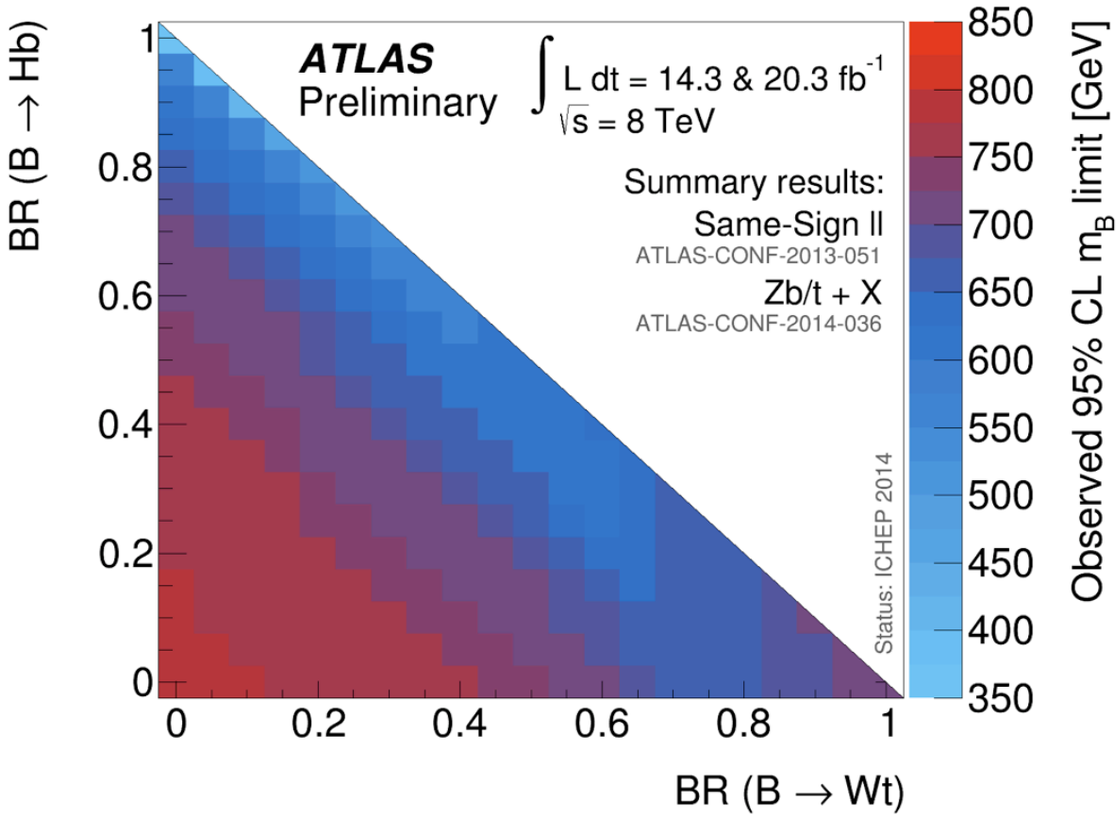
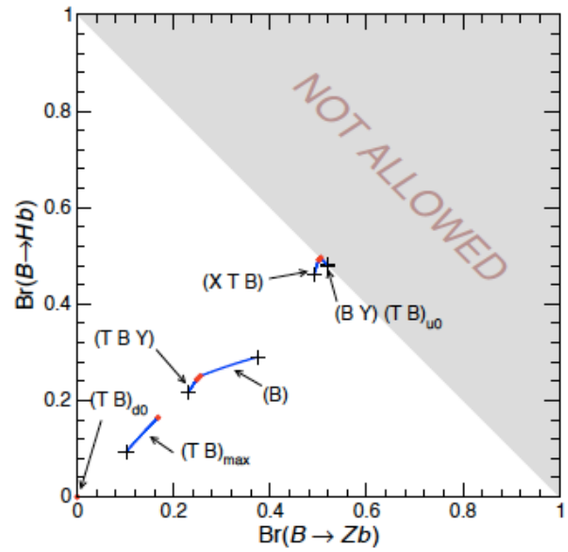
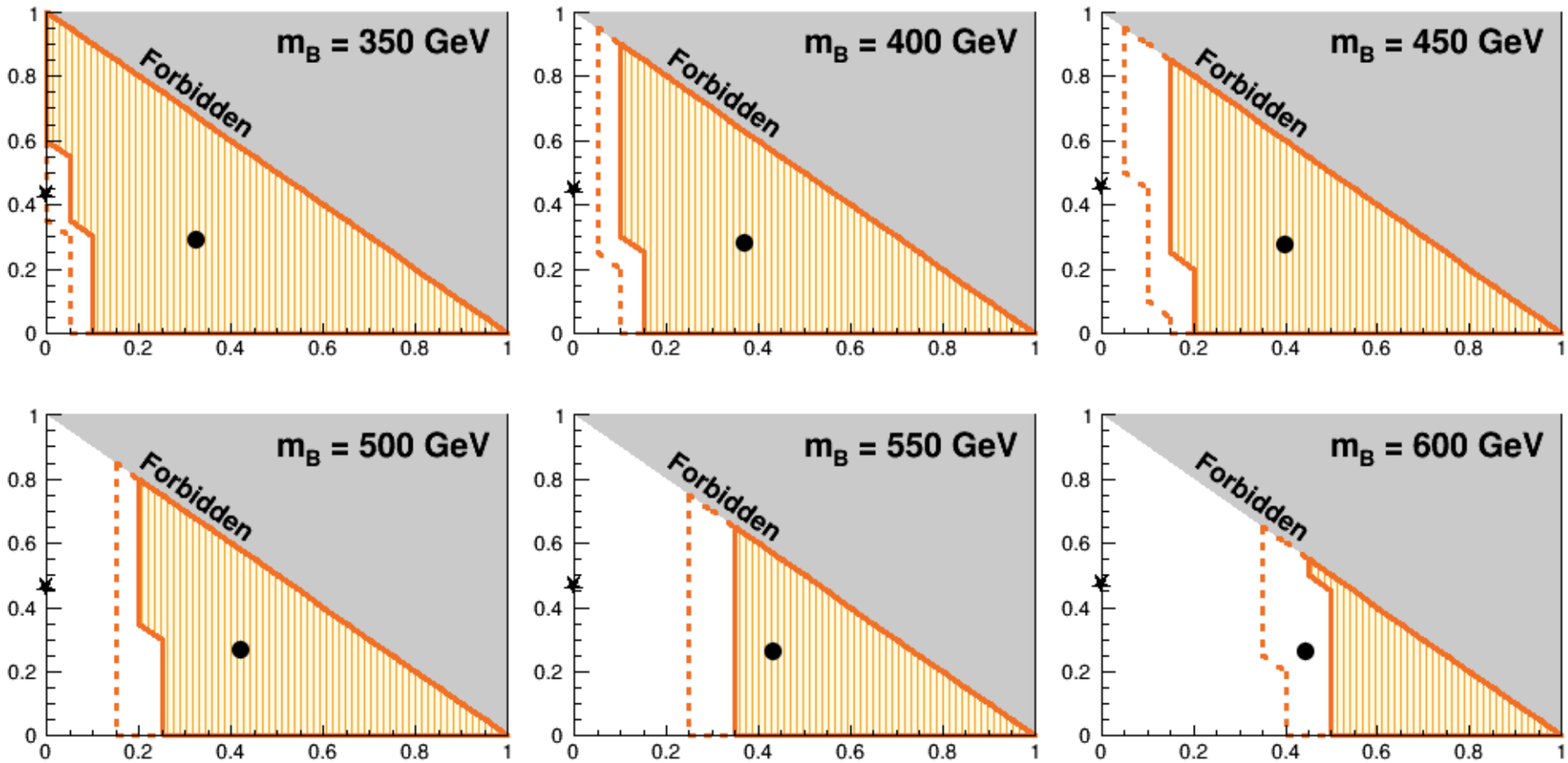


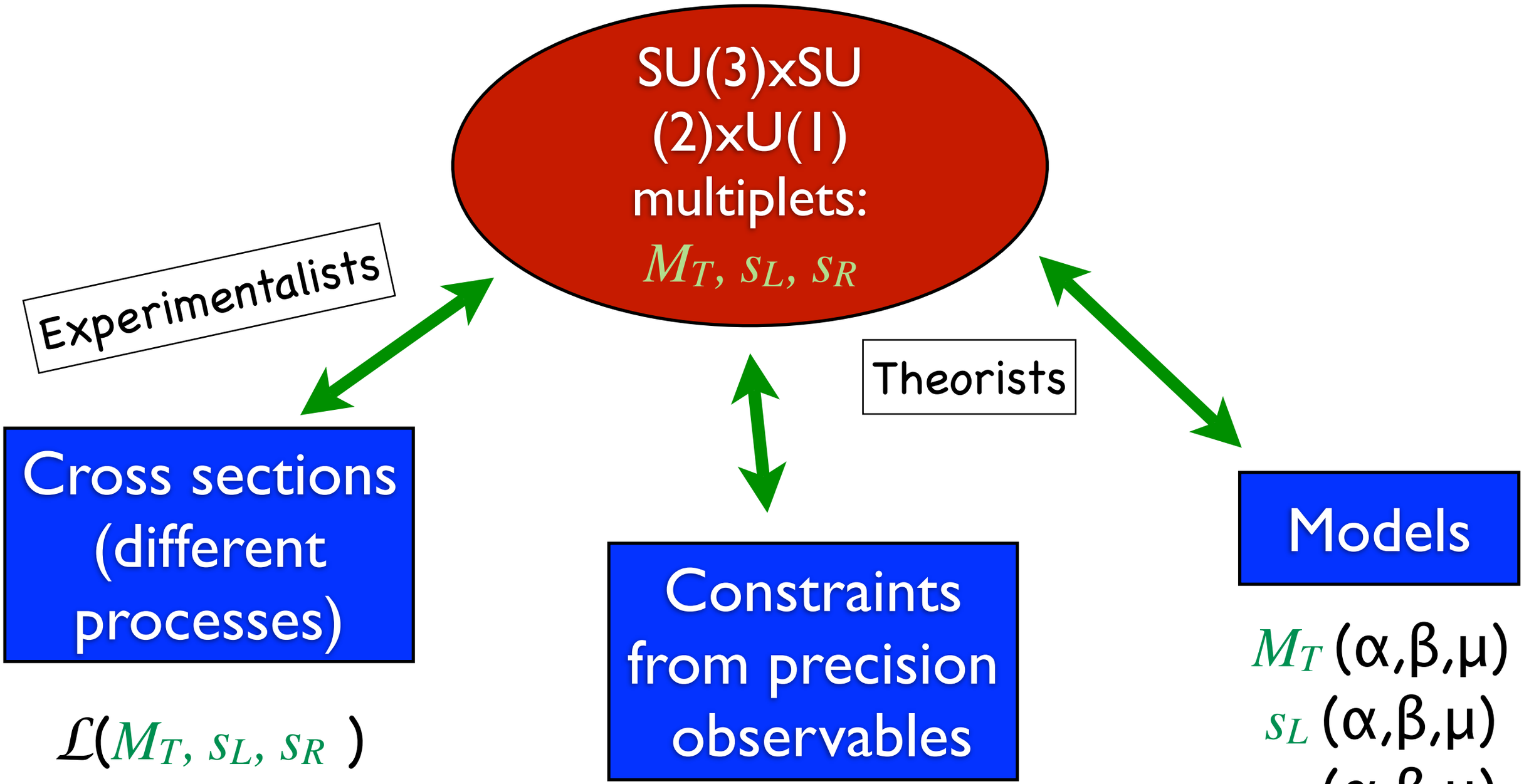
Charge -1/3: B → Wt, Zb, Hb





Outlook

The standard gauge-invariant approach allows allows for a model-independent interpretation of VLQ searches



Outlook

The standard gauge-invariant approach allows allows for a model-independent interpretation of VLQ searches

SU(3)xSU(2)xU(1) multiplets:

M_T, s_L, s_R

Experimentalists

Cross sections (different processes)

$\mathcal{L}(M_T, s_L, s_R)$

- ✓ Interference
- ✓ Combinations of final states
- ✓ Discovery and model discrimination
- ✓ …