Searching for scalar Leptoquarks at the LHC

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Work in progress, in collaboration with Ben Gripaios (CERN) and Kazuki Sakurai, Bryan Webber (Cambridge)

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Monte Carlo net

‘Other’ current research

- Calculation of effects of initial state radiation on ‘global inclusive variables’ (e.g. the total invariant mass) (AP, B. Webber, arXiv:0903.2013)
- Also considered effects of invisible particles and the underlying event (AP, B. Webber, arXiv:1004.4762).
- Calculation of resummed hadronic transverse energy for Drell-Yan and Higgs production. Also looked at underlying event effects (AP, J. Smillie, B. Webber, arXiv:1002.4375).

Current state of Leptoquark searches

- PDG review (Scalar Leptoquarks, 95% C.L., pair-production):
  - mass > 299 GeV (1st generation)
  - mass > 316 GeV (2nd generation)
  - mass > 229 GeV (3rd generation)
- Indirect or single production limits require making further assumptions, other than the mass.
- (Vector leptoquarks contain two extra parameters: one for electric quadrupole-type interactions and one for magnetic dipole-type interactions.)

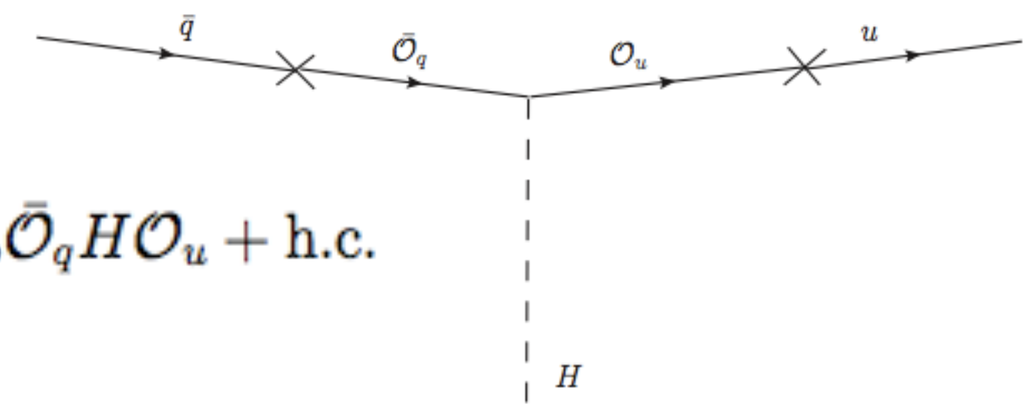
Why leptoquarks (1)?

- In models where electroweak symmetry breaking is driven by **strong dynamics**: usual to assume that fermion masses arise via Yukawa-type coupling with composite Higgs operator.
- **BUT**: Difficult to satisfy constraints coming from flavour-physics experiments, whilst simultaneously providing a natural explanation of the hierarchy between the weak and Planck scales.

Why leptoquarks (II)?

- **An alternative**: observed fermion masses arise by mixing of elementary fermions with composite, fermionic resonances of the strong sector:

$$\mathcal{L} = m_\rho \left(\frac{y^q}{g_\rho} \bar{q} \mathcal{O}_q + \frac{y^u}{g_\rho} \bar{u} \mathcal{O}_u + \bar{\mathcal{O}}_q \mathcal{O}_q + \bar{\mathcal{O}}_u \mathcal{O}_u \right) + g_\rho \bar{\mathcal{O}}_q H \mathcal{O}_u + \text{h.c.}$$



- => Automatic **suppression of flavour-changing processes**: light fermions are those which are least mixed with the flavour-changing dynamics of the strong sector.

Why leptoquarks (III)?

- => strongly-coupled sector must, at the very least, contain colour-triplet fermionic resonances that can mix with elementary colour-triplets to make the observed quarks.
- If it contains bosonic, coloured resonances, then, depending on the particular gauge charges (or other global charges) these may be able to couple to a lepton and a quark, thus playing the role of **leptoquark states**.
- e.g. the fermionic resonances may arise as technibaryons of a technicolour SU(3) interaction and such a model would contain leptoquarks arising as techni-mesons.

Why third gen. leptoquarks?

- Two effects guarantee decay of the present type of leptoquarks to almost exclusively to 3rd generation quarks:
  - Leptoquark couplings increase with the SM Yukawa couplings (a generic effect).
  - Derivative coupling leads to additional suppression in the decay to light fermions (non-generic).

Effective theory

- Production:

$$\mathcal{L}_S^g = \left(D^\mu_{ij}\Phi^j\right)^\dagger \left(D^{ik}_\mu \Phi_k\right) - M^2_{LQ,i}\Phi^{i\dagger}\Phi_i$$

$$D^{ij}_\mu = \partial_\mu \delta^{ij} - i g_s t^{ij}_a \mathcal{A}^a_\mu$$

- Possible fermion couplings:

$$\begin{aligned}
\mathcal{L}_{nd} &= (g_{0L}\bar{q}^c_L i\tau_2 \ell_L + g_{0R}\bar{t}^c_R \tau_R) S_0 \\
&+ \tilde{g}_{0R}\bar{b}^c_R \tau_R \tilde{S}_0 + g_{1L}\bar{q}^c_L i\tau_2 \tau_a \ell_L S^a_1 \\
&+ (h_{1L}\bar{u}_R \ell_L + h_{1R}\bar{q}_L i\tau_2 \tau_R) S_{1/2} + h_{2L}\bar{d}_R \ell_L \tilde{S}_{1/2}
\end{aligned}$$

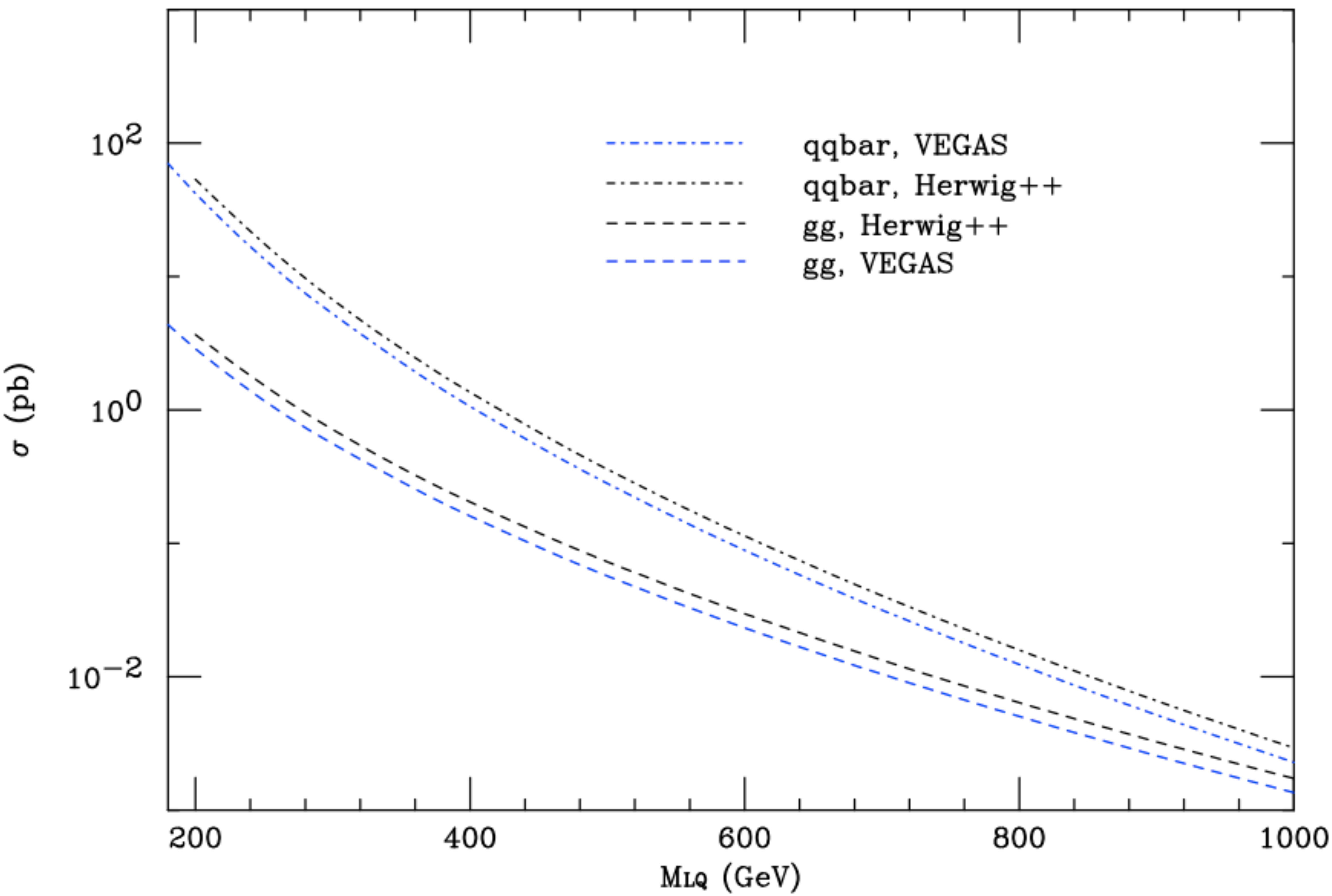
Derivative couplings

$$
\begin{aligned}
\mathcal{L}_d &= \frac{-i}{\sqrt{2}f}(g'_{0L,i}\bar{q}_L \overleftrightarrow{p}^{\mu,i}\gamma_\mu \ell_L + g'_{0R,i}\bar{b}_R \overleftrightarrow{p}^{\mu,i}\gamma_\mu \tau_R)S'_0 \\
&+ \frac{-i}{\sqrt{2}f}\tilde{g}'_{0R,i}\bar{t}_R \overleftrightarrow{p}^{\mu,i}\gamma_\mu \tau_R \tilde{S}'_0 + \frac{-i}{\sqrt{2}f} g'_{1L,i}\bar{q}_L \overleftrightarrow{p}^{\mu,i}\gamma_\mu \tau_a \ell_L S'^a_1 \\
&+ \frac{-i}{\sqrt{2}f}(h'_{1L,i}\bar{b}^c_R \overleftrightarrow{p}^{\mu,i}\gamma_\mu \ell_L + h'_{1R,i}\bar{q}^c_L \overleftrightarrow{p}^{\mu,i}\gamma_\mu \tau_R)S'_{1/2} + \frac{-i}{\sqrt{2}f} h'_{2L,i}\bar{t}^c_R \overleftrightarrow{p}^{\mu,i}\gamma_\mu \ell_L \tilde{S}'_{1/2}
\end{aligned}
$$

- For on-shell decays these can be simplified by ‘operating’ with the derivatives and using the Dirac equation, e.g.:

$$g'_{0L,i}\bar{b}_L \overleftrightarrow{\not{p}}^{i}\tau_L S'_0 = g'_{0L,q} m_q \bar{b}_R S'_0 \ell_L + g'_{0L,\ell} m_\ell \bar{b}_L S'_0 \tau_R$$

Leptoquarks in Herwig++



Search strategies (preliminary)

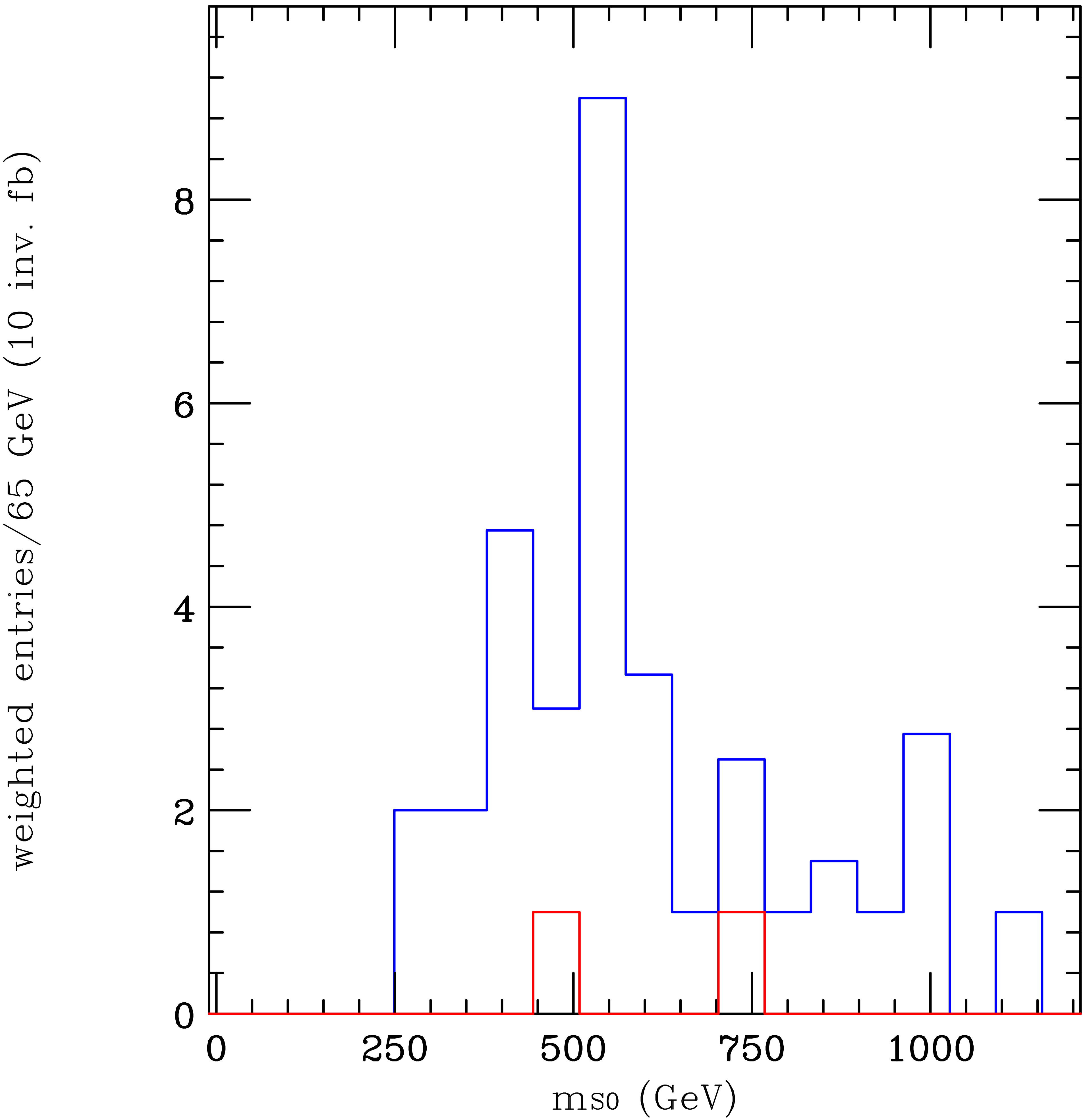
modes	types	technique	discrimination
$(t\tau)(b\nu)$	S_0, $S_1^{(0)}$	$j_\tau \parallel \nu_\tau$, mass constraints $\Rightarrow$ edge recon. ($\sim M_{T2}$)	helicities of $t\tau$ modes multiplet
$(t\tau)(t\tau)$	S_0, $S_1^{(0)}$, $S_{1/2}^{(+)}$, $\tilde{S}'_0$	two $j_\tau \parallel \nu_\tau$, mass constraints $\Rightarrow$ full recon.	helicity+multiplet (S_0,$S_1^{(0)}$), charge+other modes (S_0, S_1, $S_{1/2}^{(+)}$)
$(b\nu)(b\nu)$	S_0, $S_1^{(0)}$, $\tilde{S}_{1/2}^{(-)}$, $S_1'^{(-)}$	M_{T2}	other modes (S_0, S_1, $\tilde{S}_{1/2}^{(-)}$, $S_1'^{(-)}$)
$(b\tau)(b\tau)$	$S_1^{(+)}$, $\tilde{S}_{1/2}^{(-)}$ $\tilde{S}_0$, $S_{1/2}'^{(+)}$, $S_1'^{(0)}$	two $j_\tau \parallel \nu_\tau$, mass constraints $\Rightarrow$ full recon.	
$(t\nu)(t\nu)$	$S_1^{(-)}$, $S_{1/2}^{(-)}$ S'_0, $S_1'^{(0)}$, $\tilde{S}_{1/2}'^{(-)}$	M_{T2}	
$(t\nu)(b\tau)$	$S_{1/2}^{(-)}$, S'_0 $S_1'^{(0)}$	$j_\tau \parallel \nu_\tau$, mass constraints $\Rightarrow$ edge recon. ($\sim M_{T2}$)	

General analysis details

- Event generation: pair-production of 400 GeV scalar leptoquarks in Herwig++.
- 10 inverse fb.
- Including both ISR and Underlying Event.
- Fast detector simulation using the Delphes framework with the 'ATLAS' settings and anti-kt algorithm with R=0.7.
- Full combinatorics taken into consideration.
- Currently considering ttbar background, since it is usually very signal-like and quite large.

Preliminary results: (tτ)(tτ)

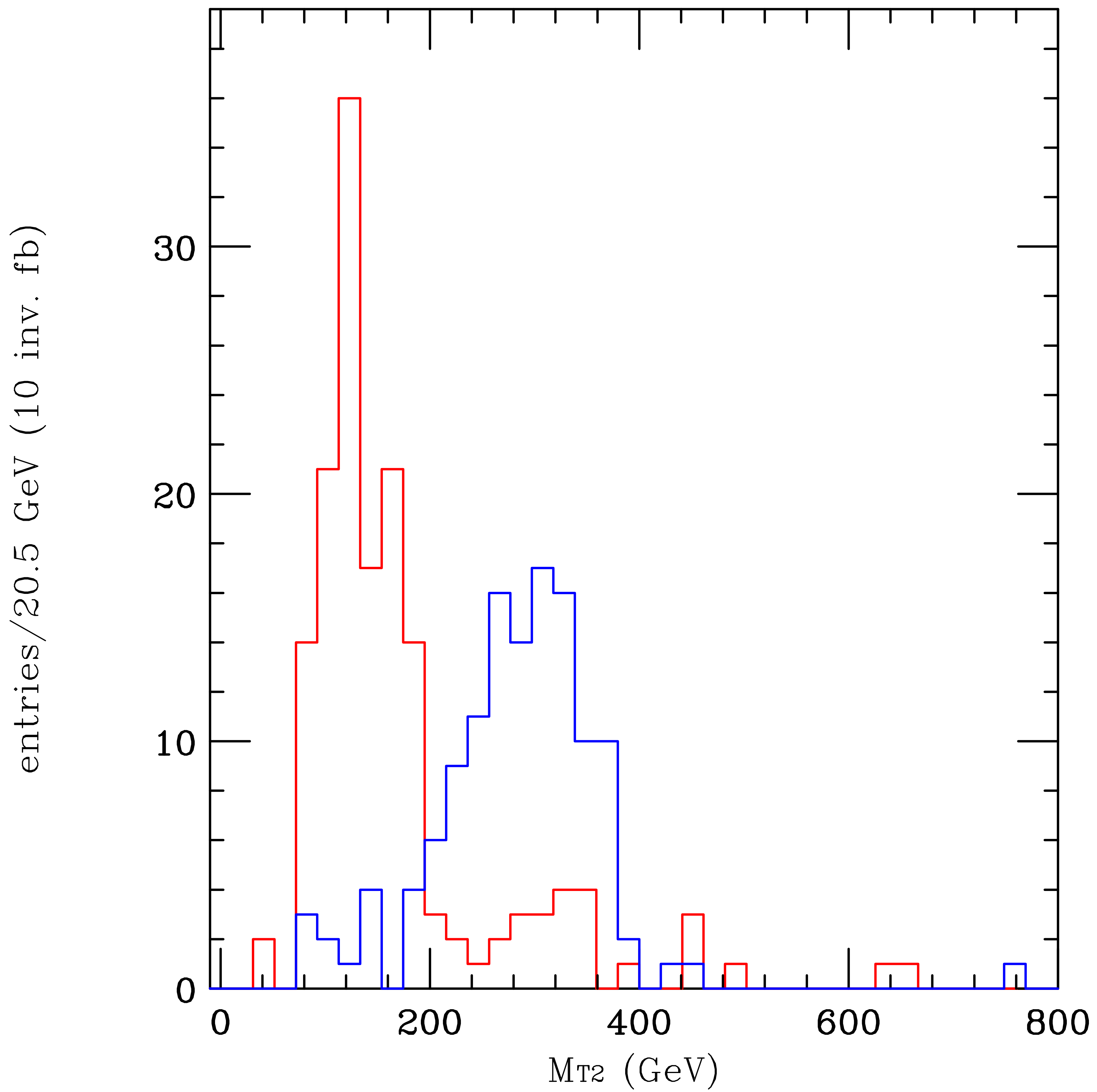
- Pair-production, decay to (tτ)(tτ).
- Reconstruct fully using collinearity of τ-jets to the τ missing momentum, quartic equation => multiple solutions but degenerate.
- Cuts: at least one lepton with pT > 20 GeV, minimum 6 jets, Missing transverse energy > 20 GeV, two tau-tagged jets with pT > 20 GeV.



- Blue: signal.
- Red: ttbar..
- 10 inverse fb.

Preliminary results: $(b\nu)(b\nu)$

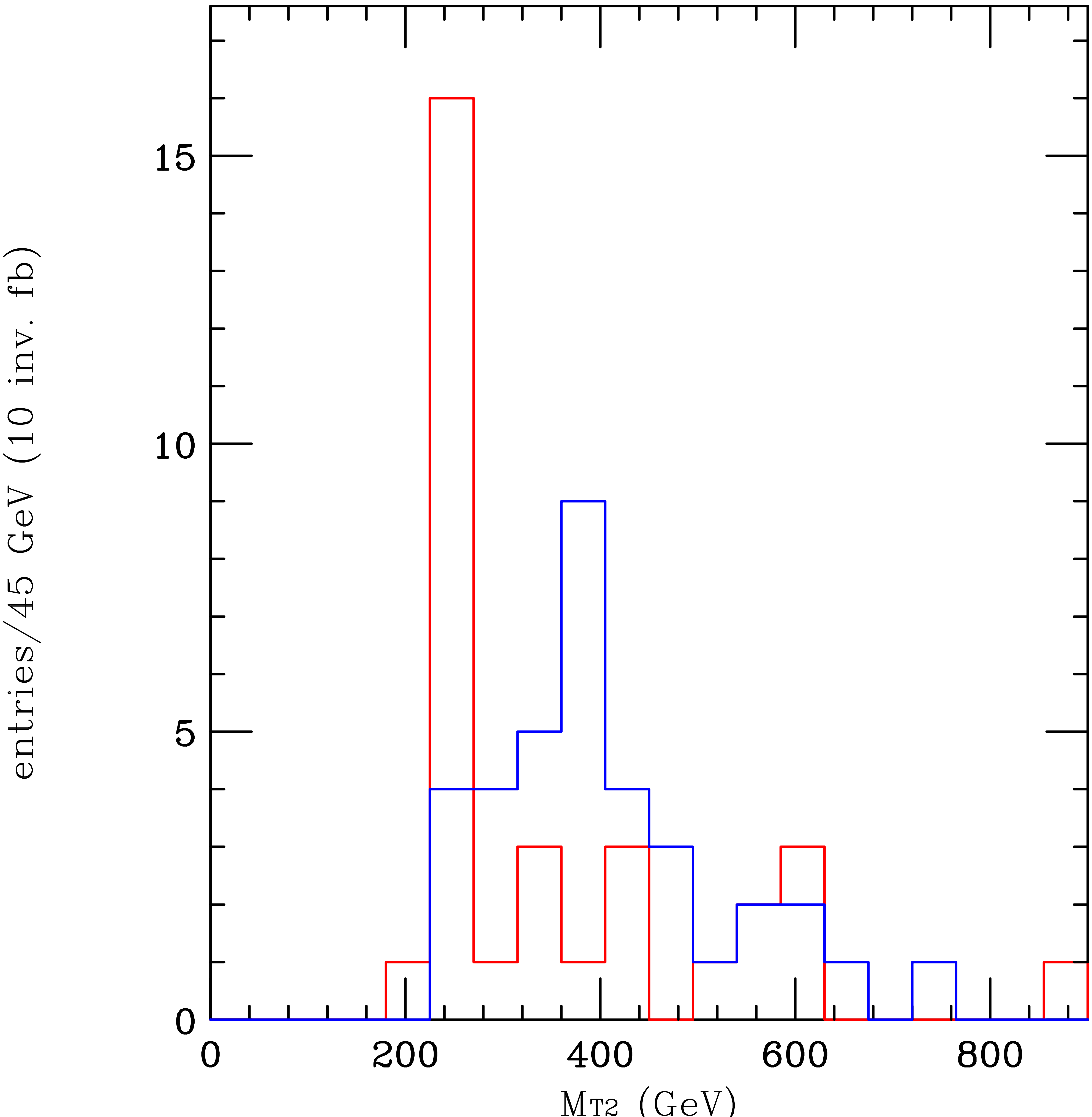
- Pair-production, decay to $(b\nu)(b\nu)$.
- Reconstruction using MT2.
- Cuts: two b-tagged jets with pT > 120 GeV each, no electrons/muons present, Missing transverse energy > 250 GeV.



- Blue: signal.
- Red: ttbar..
- 10 inverse fb.

Preliminary results: $(b\nu)(t\tau)$

- Pair-production, decay to $(b\nu)$ $(t\tau)$.
- Reconstruction using MT2.
- Cuts: b-jets with pT > 60 GeV each, one tau-tagged jet with pT > 20 GeV, Missing transverse energy > 180 GeV, minimum 4 jets.
- pT(b-jet) - pT(tau-jet) > -25 GeV: devastating for ttbar.



- Blue: signal.
- Red: ttbar..
- 10 inverse fb.

TO BE CONTINUED....

Summary

- Leptoquarks have not been completely excluded by experiment. They may arise in theories in which the electroweak symmetry is broken via strong dynamics.
- They may couple to the third generation primarily and decay modes are challenging for the LHC.
- Our study has been successful thus far in inventing methods for finding leptoquarks in the ttbar-stack!