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- adding a fourth family to the standard model (with Higgs) is perhaps the simplest extension
- was receiving attention recently, after decades of neglect

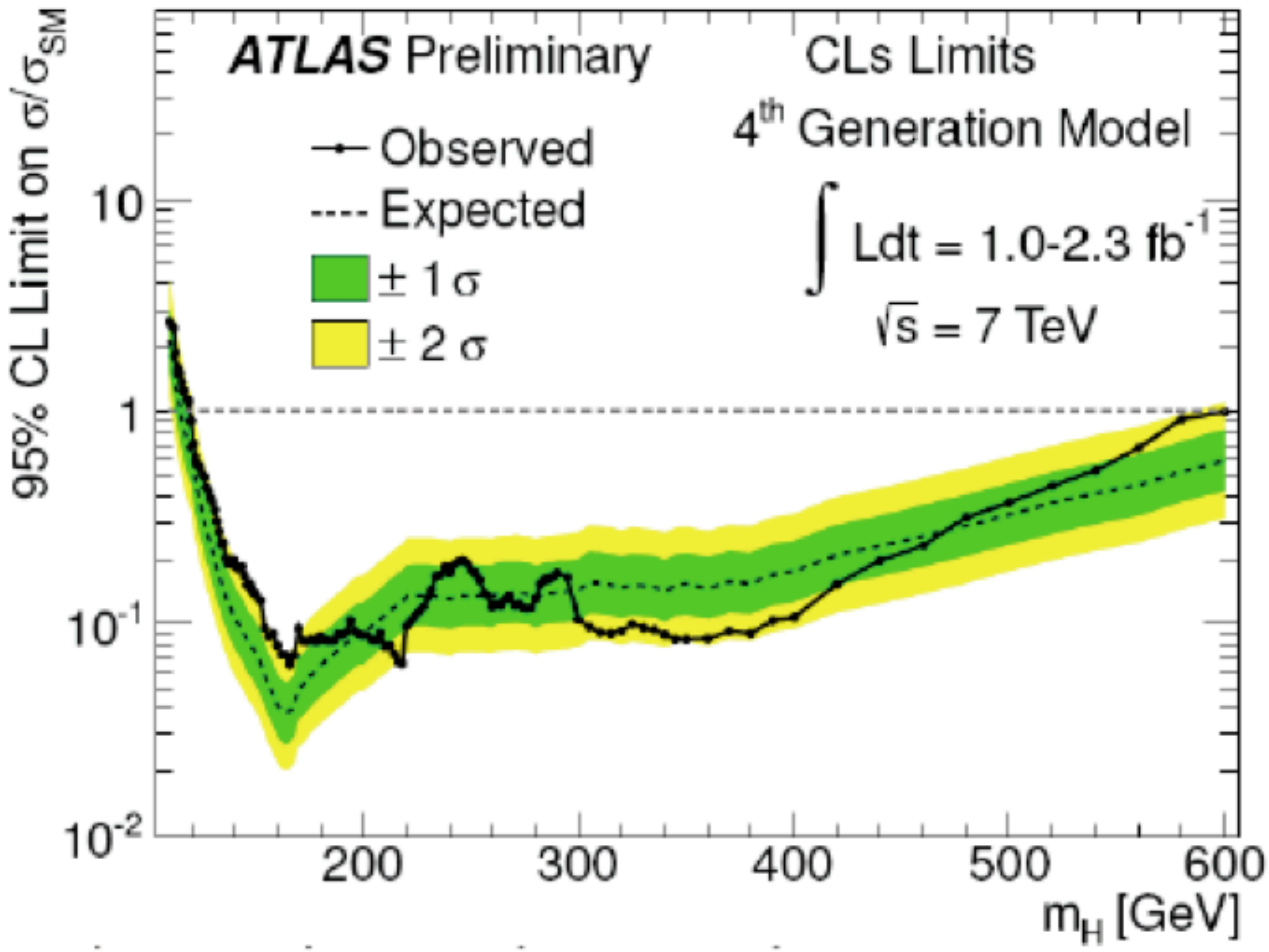
- Higgs couples to the heavy quarks in the standard way

$\Rightarrow$ enhancement of the $gg \to H$ cross section

Arik, Cakir, Cetin and Sultansoy, 2006

• from M. Peskin's summary talk at Lepton-Photon

Higgs limits assuming a 4th generation of quarks and leptons:



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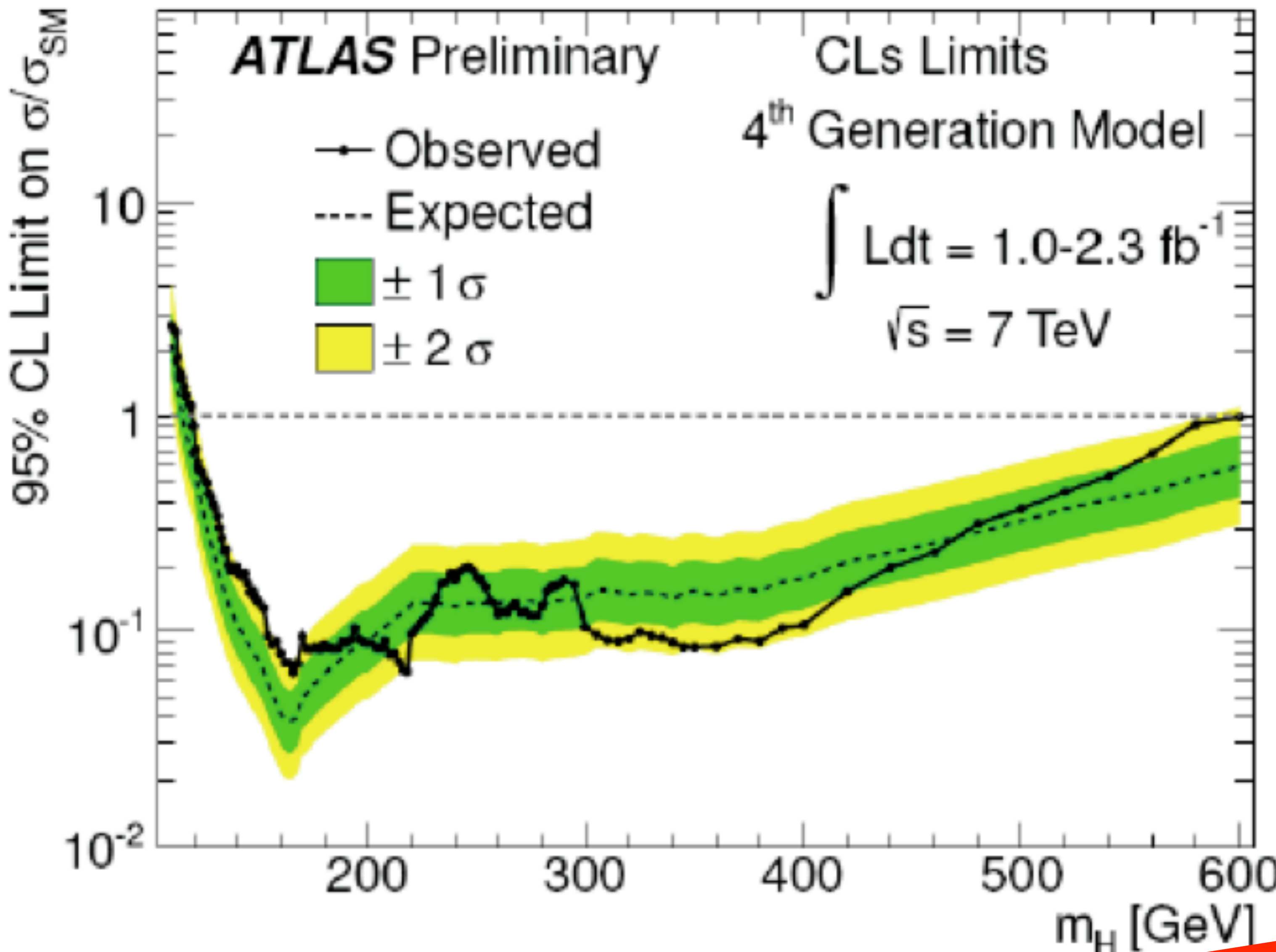

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- so why hasn't the fourth family search attracted more attention?

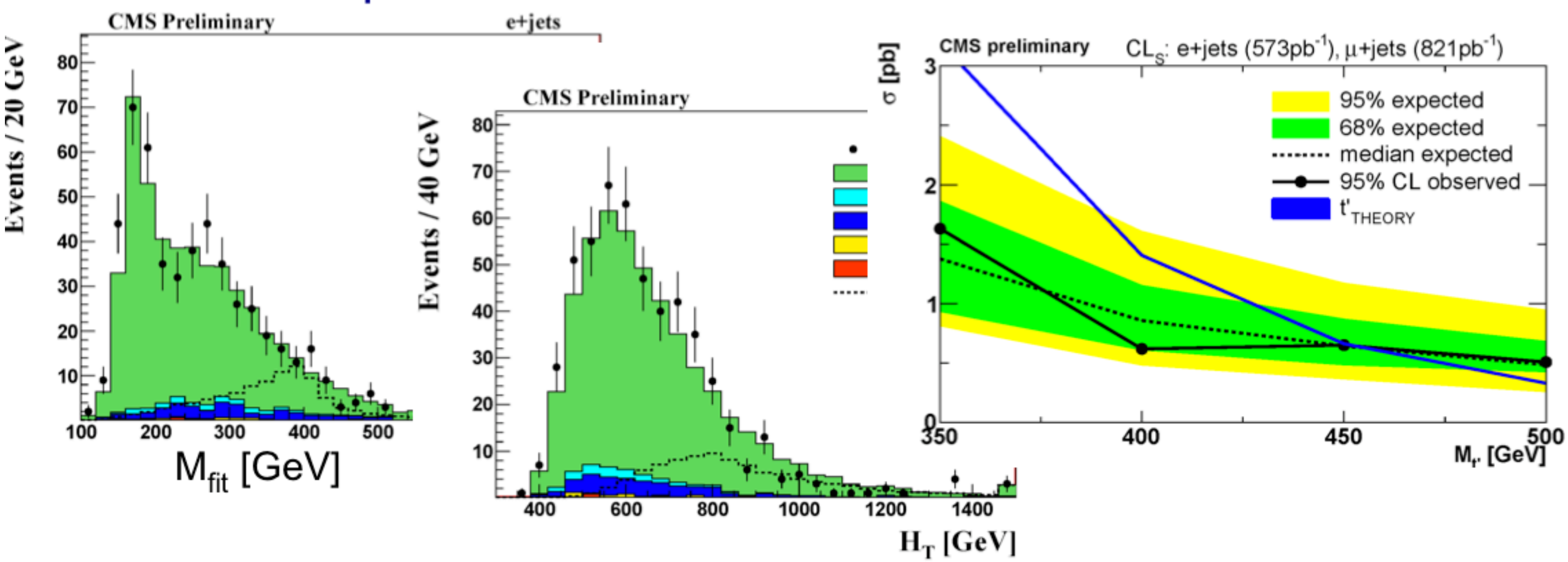
- nevertheless, direct searches are occurring

- lower limits on the fourth family quark masses are increasing

- from H. Bachacou's talk at Lepton-Photon

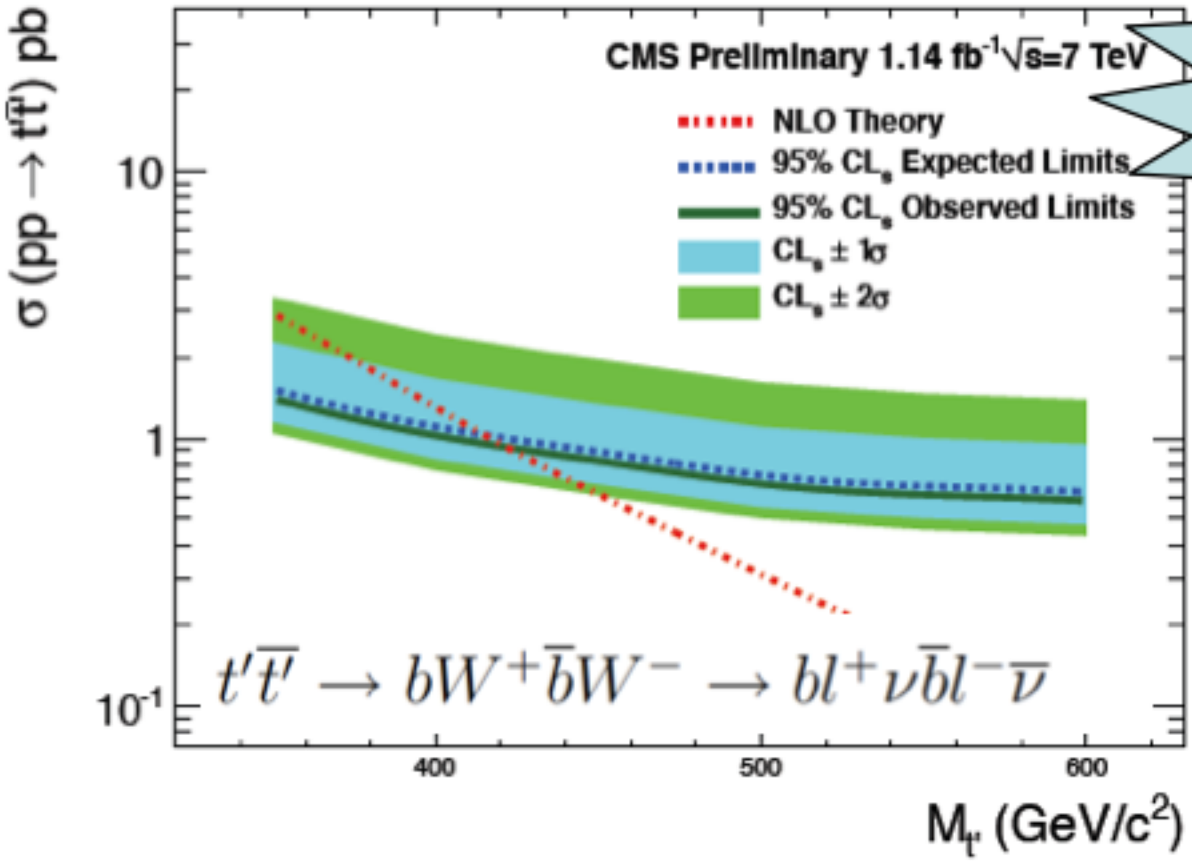
Search for a 4th generation quark: t' → Wb

- t' → Wb: top-like signal (l+jets, dilepton), but heavier
- Experimental challenge: large ttbar background, sensitive to calibration and to modelling
- Also searching dilepton channel: ATLAS-CONF-2011-022
- Excluded up to 450 GeV



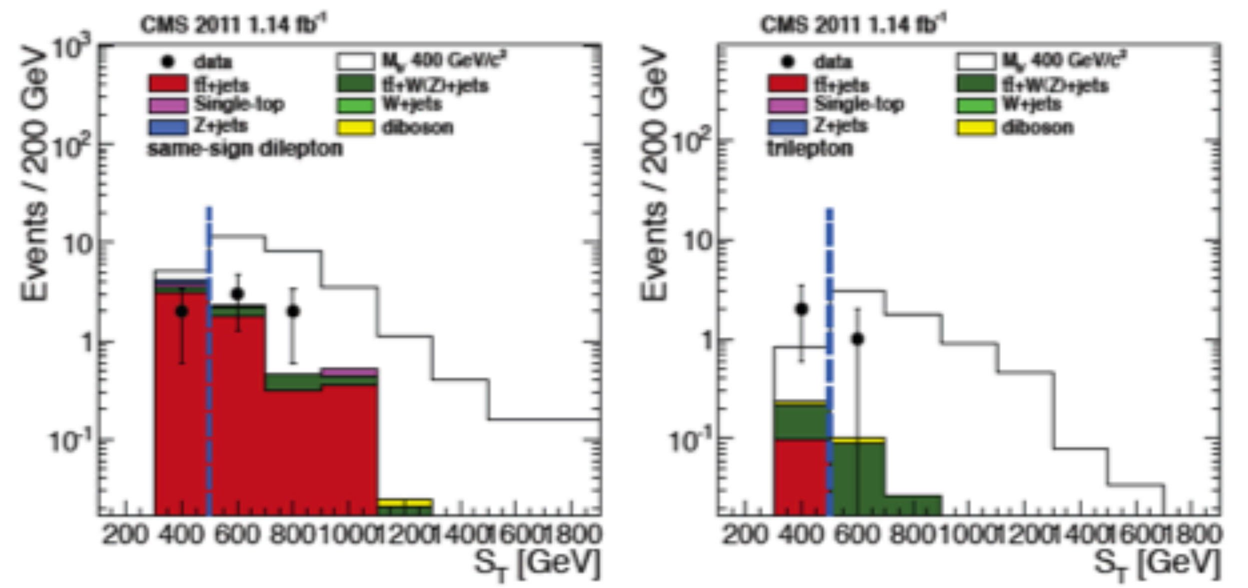
• from A. De Roeck's talk at Lepton-Photon

CMS-EXO-11-50

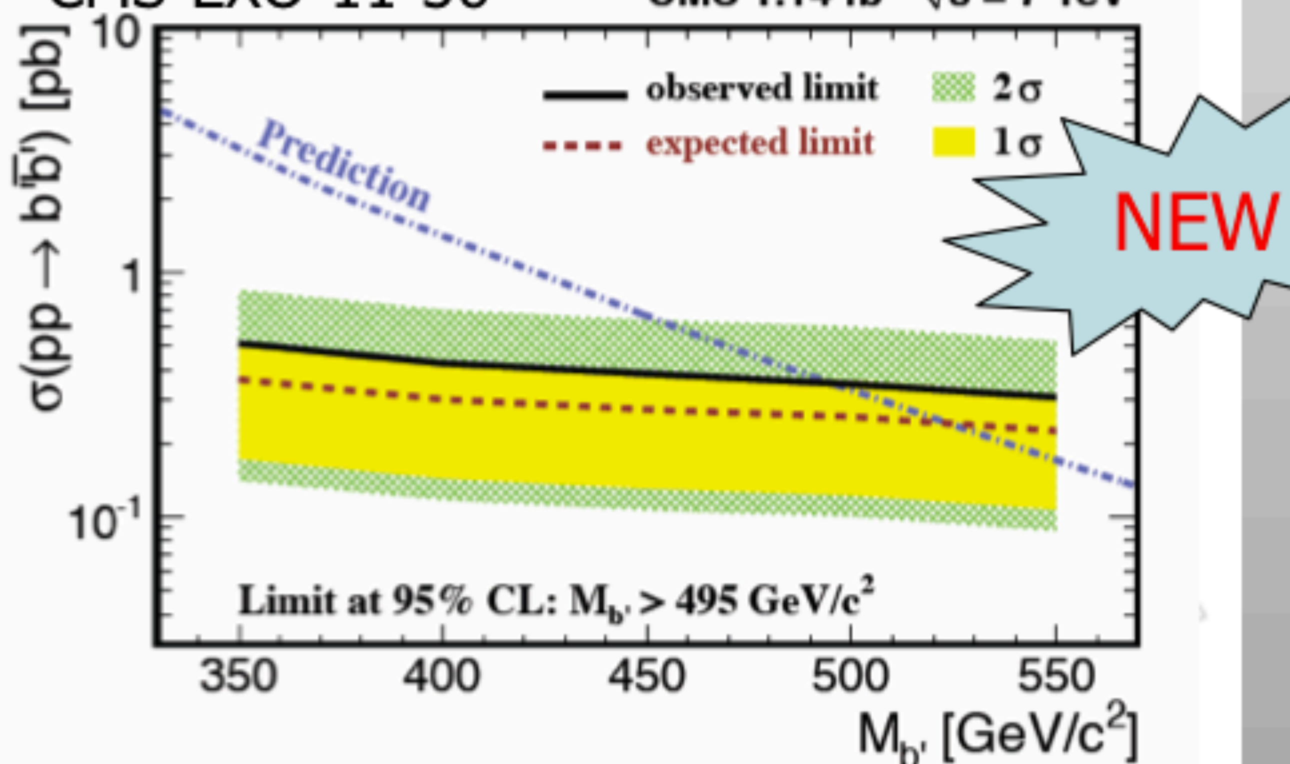


No t′ with found in the region of mass < 450 GeV at 95% CL

$b'\bar{b}' \to tW^-\bar{t}W^+ \to bW^+W^-\bar{b}W^-W^+$



CMS-EXO-11-36



No b′ quark with tW decay found with mass < 495 GeV at 95% CL

implications of fourth family above 500 GeV

- modifies running of quartic Higgs coupling: $\mu d\lambda/d\mu \propto \lambda y_{q'}^2 - y_{q'}^4 + ...$

$\Rightarrow$ allowed range of m_h decreases as $m_{q'}$ increases

Kribs, Plehn, Spannowsky, and Tait, 2007

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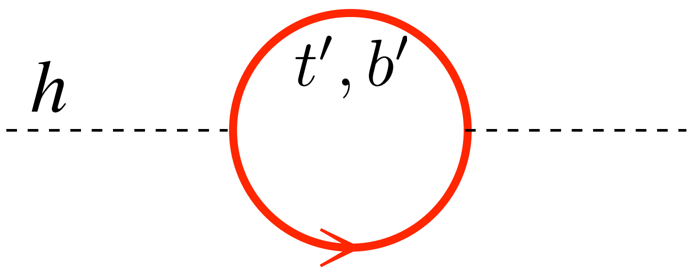

assume cutoff $\Lambda > m_{q'}$ $\longrightarrow$

$$\delta m_h^2 \approx \left[\frac{m_{q'}}{400 \text{ GeV}}\right]^2 \Lambda^2$$

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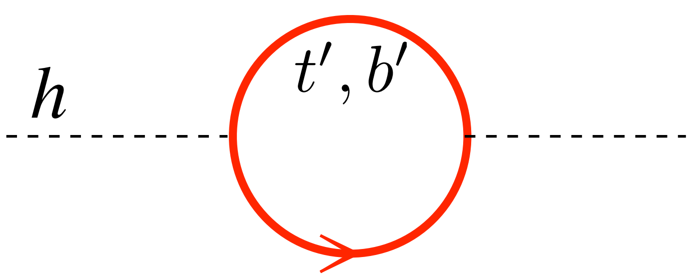

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$$\delta m_h^2 \approx \left[\frac{m_{q'}}{400\ \mathrm{GeV}}\right]^2 \Lambda^2$$

- heavy fourth family cannot co-exist with standard Higgs
- thus experimental result agrees with theory

search strategies

- b' search
  - count same-sign leptons
- t' search, dilepton mode
  - $M_{b\ell}$ distributions
- t' search, $\ell + $ jets mode
  - H_T and M_{recon} distributions

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  - 600 GeV masses would only give a few same-sign lepton events so far

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- are there better search strategies for larger quark masses?
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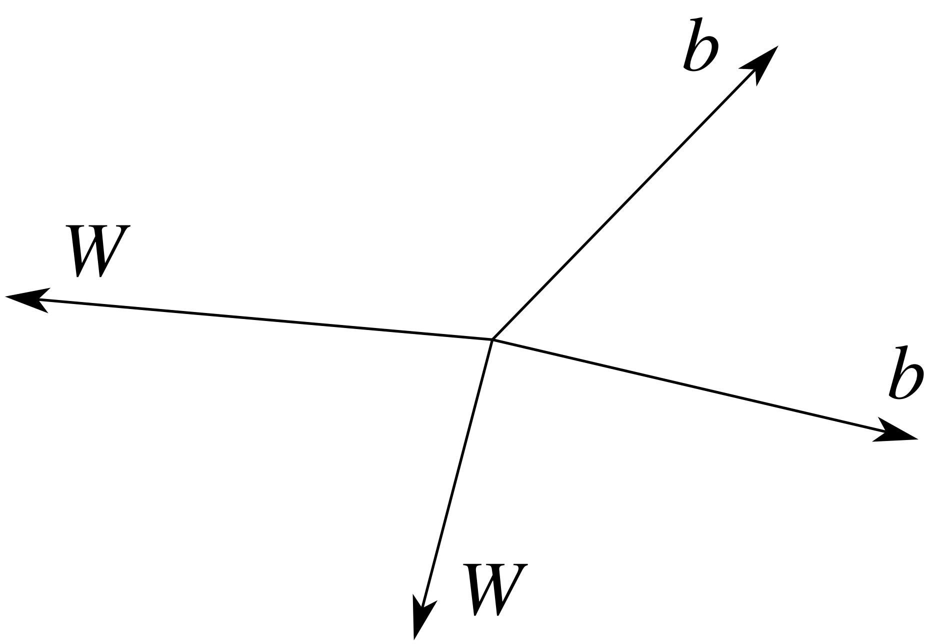
- ATLAS is strangely quiet
  - perhaps they have different strategies...

kinematics of heavy quark search

BH, 2007

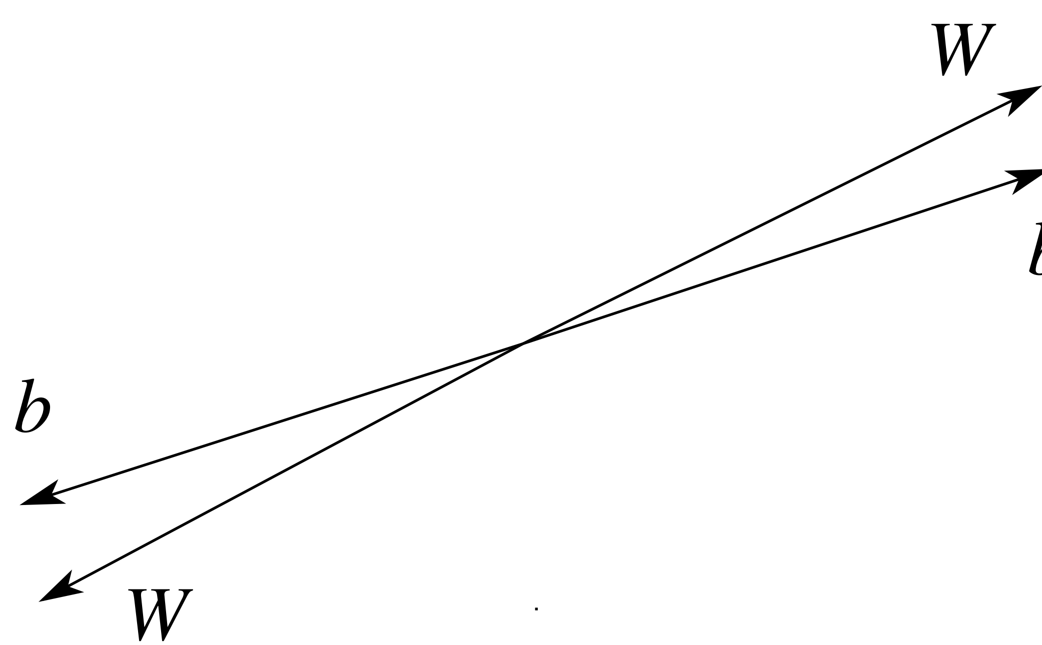


$t'\overline{t'} \to b\bar{b}WW$

- W's are boosted and isolated
- jets from W start to merge

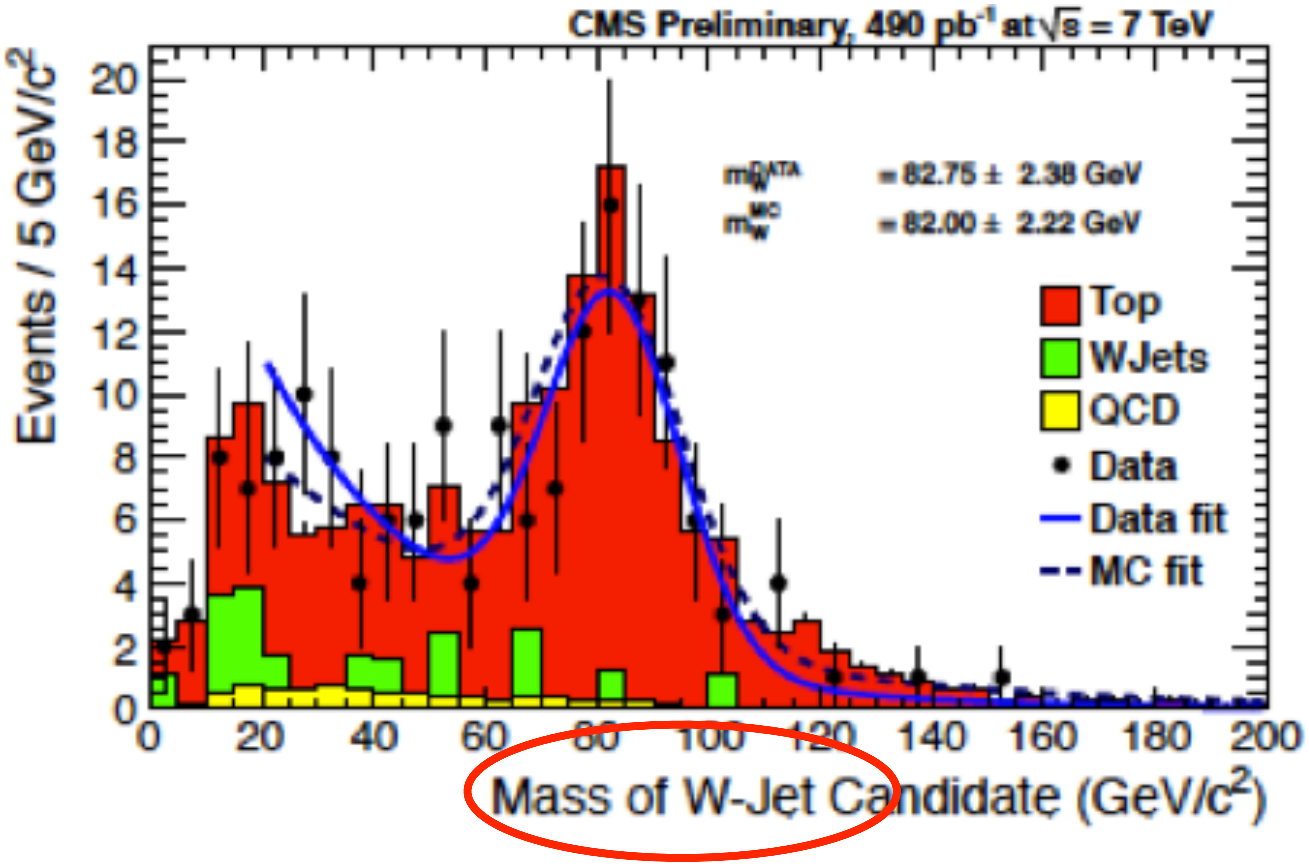
$t\bar{t}$ *background*

- impose $H_T \gtrsim 2m_{t'}$
- then often looks like boosted tops



there is interest in W-jets from boosted tops

- use large cone size, sophisticated jet pruning etc.



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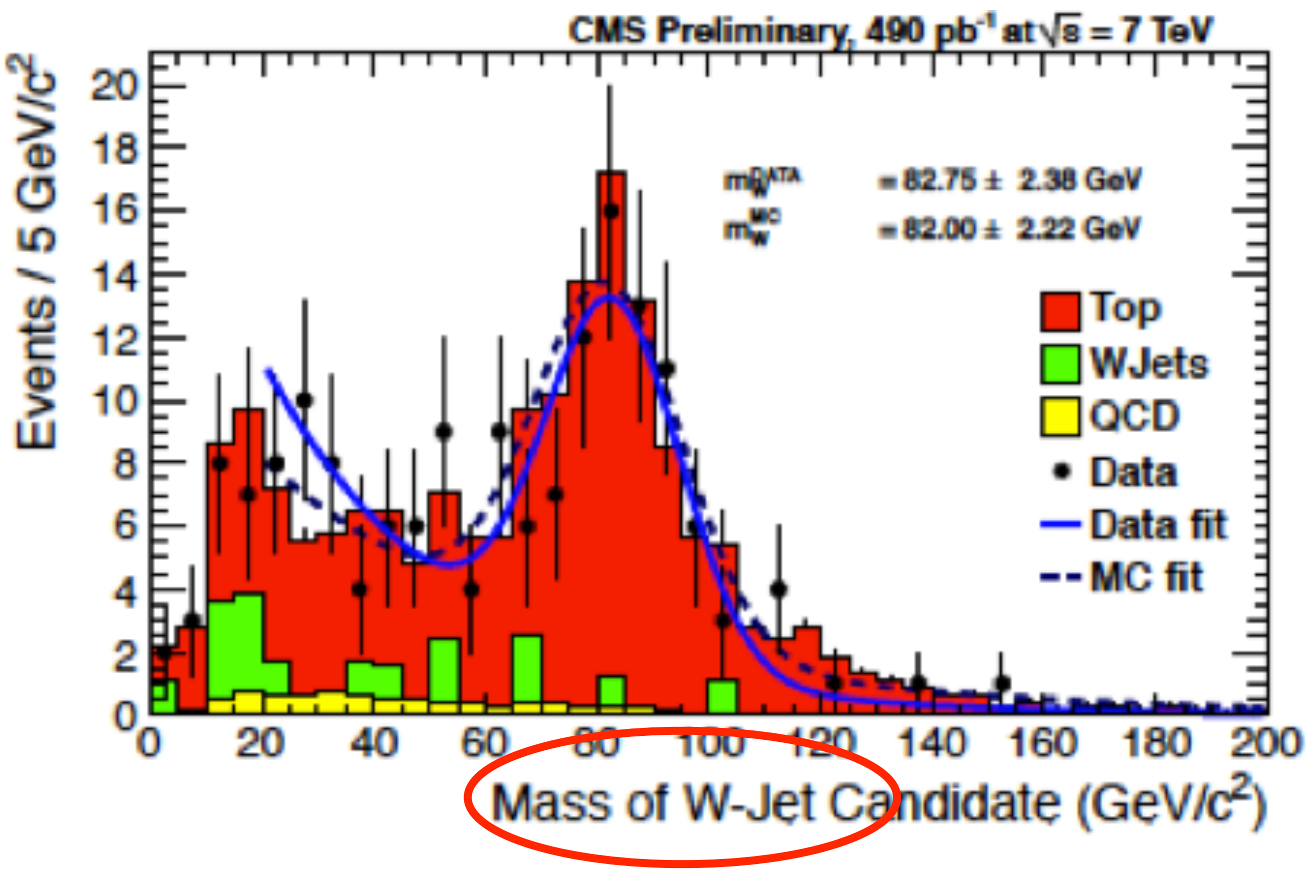


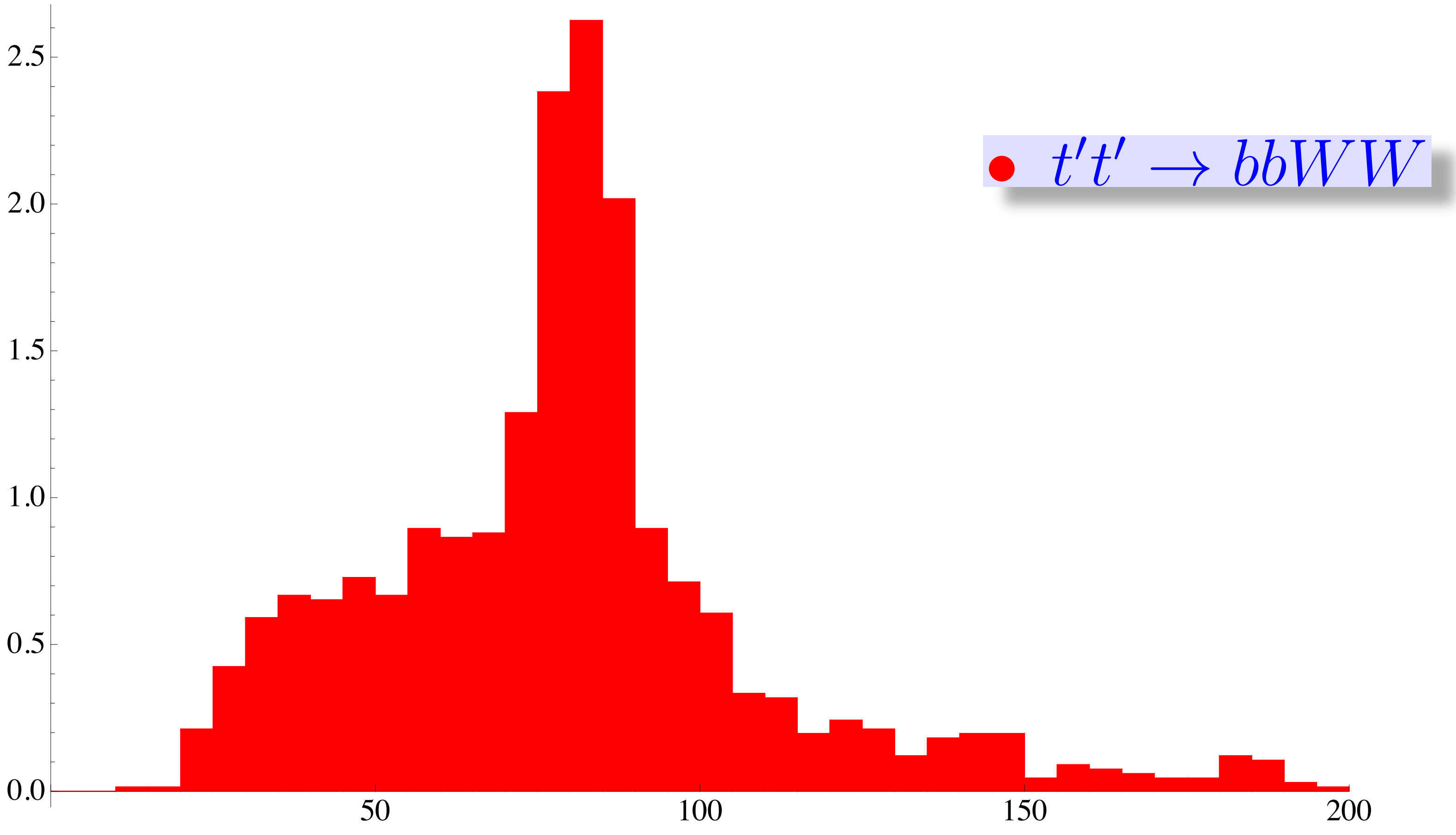
instead we want isolated W-jets

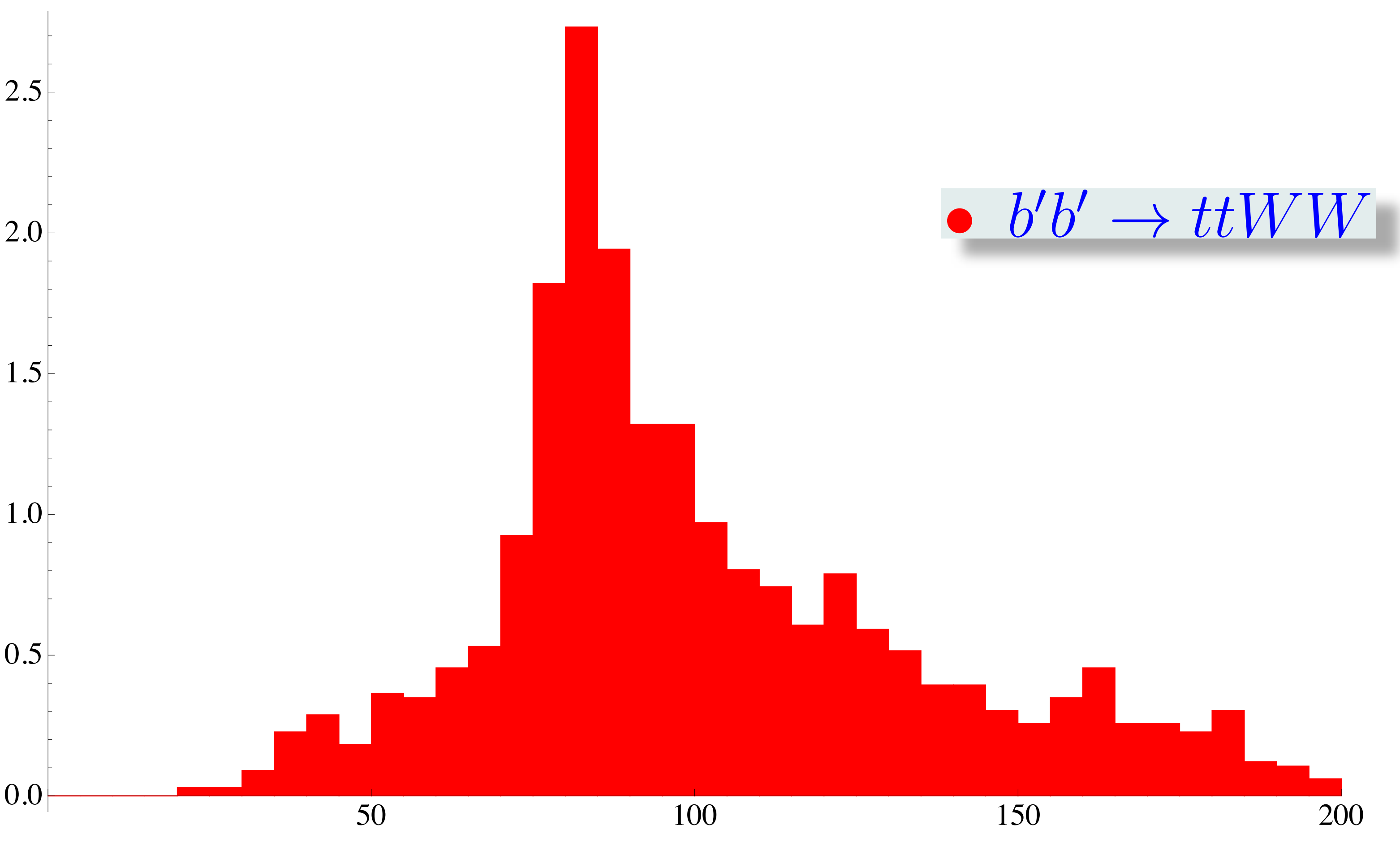
- we want low efficiency for finding W-jets from boosted tops (background)
- both $t' \to bW$ and $b' \to tW$ contribute to signal

a simple-minded search for isolated W-jets

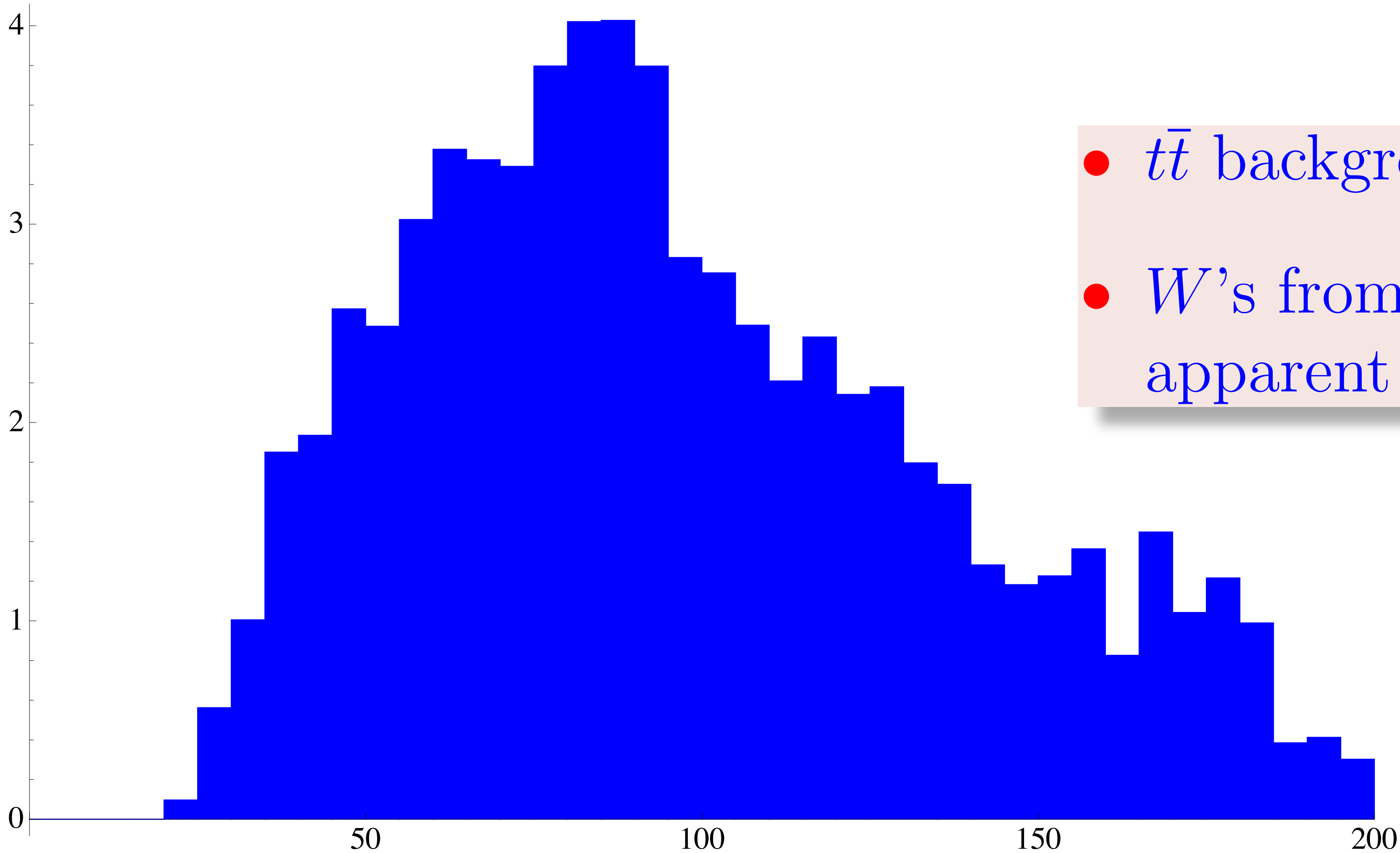
- use jet finder with $R \approx 0.8$
- in each event find jet with largest jet mass
  - keep if isolated ($\Delta R > 1$ from other objects)
  - form histogram of these jet masses
- to reduce background (to mainly $t\bar{t}$):
  - $H_T \gtrsim 2m_{q'}$ (or adjust H_T to maximize S/B)
  - three or more jets $p_T > 100$ GeV
  - one or more b-jets $p_T > 50$ GeV
  - isolated lepton $p_T > 20$ GeV **or** missing $E_T > 200$ GeV

BH, 2010

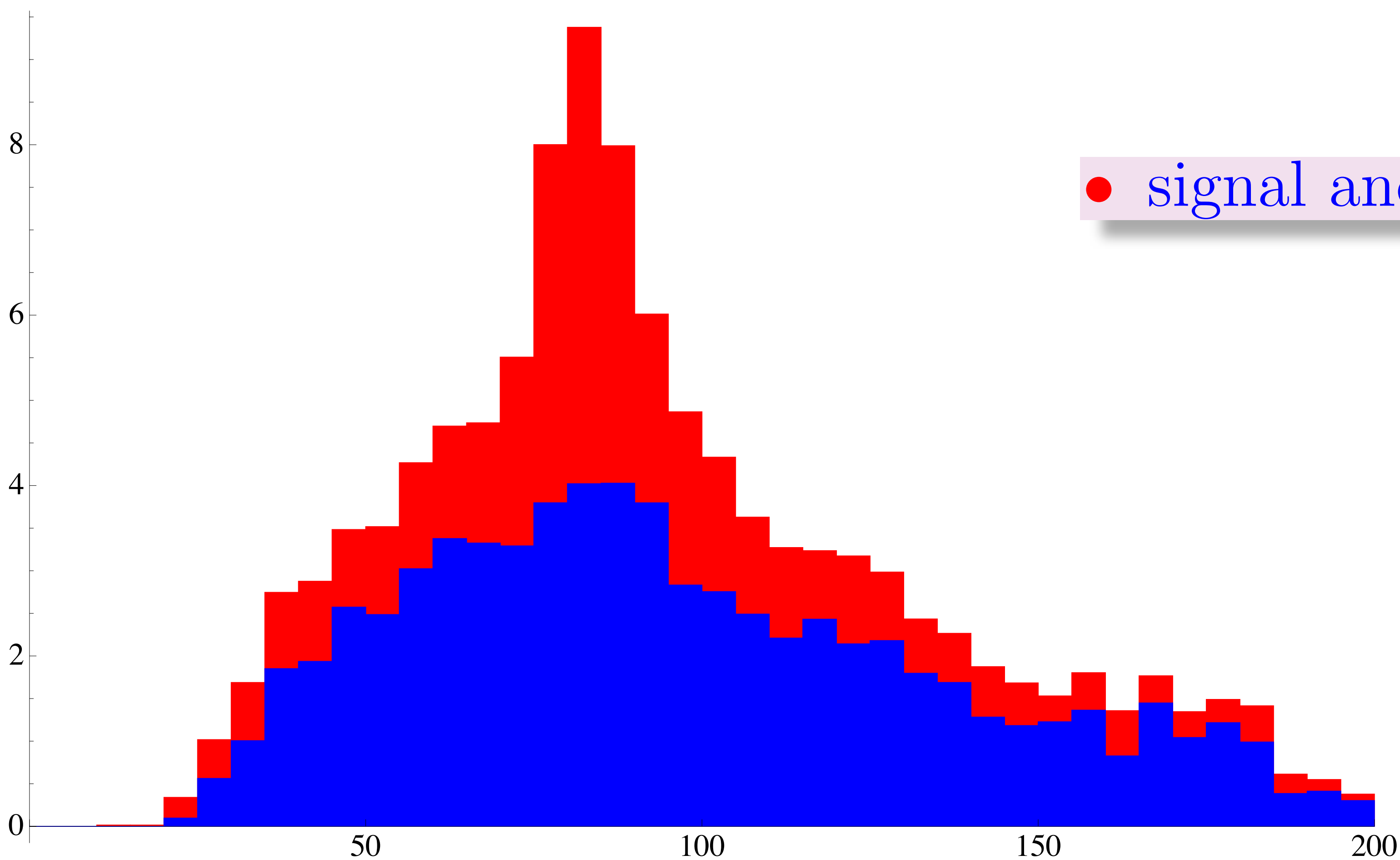




- 600 GeV mass quarks
- 2.5 fb^{-1} at 7 TeV
- $H_T > 1100$ GeV



- $t\bar{t}$ background
- W's from boosted tops not too apparent



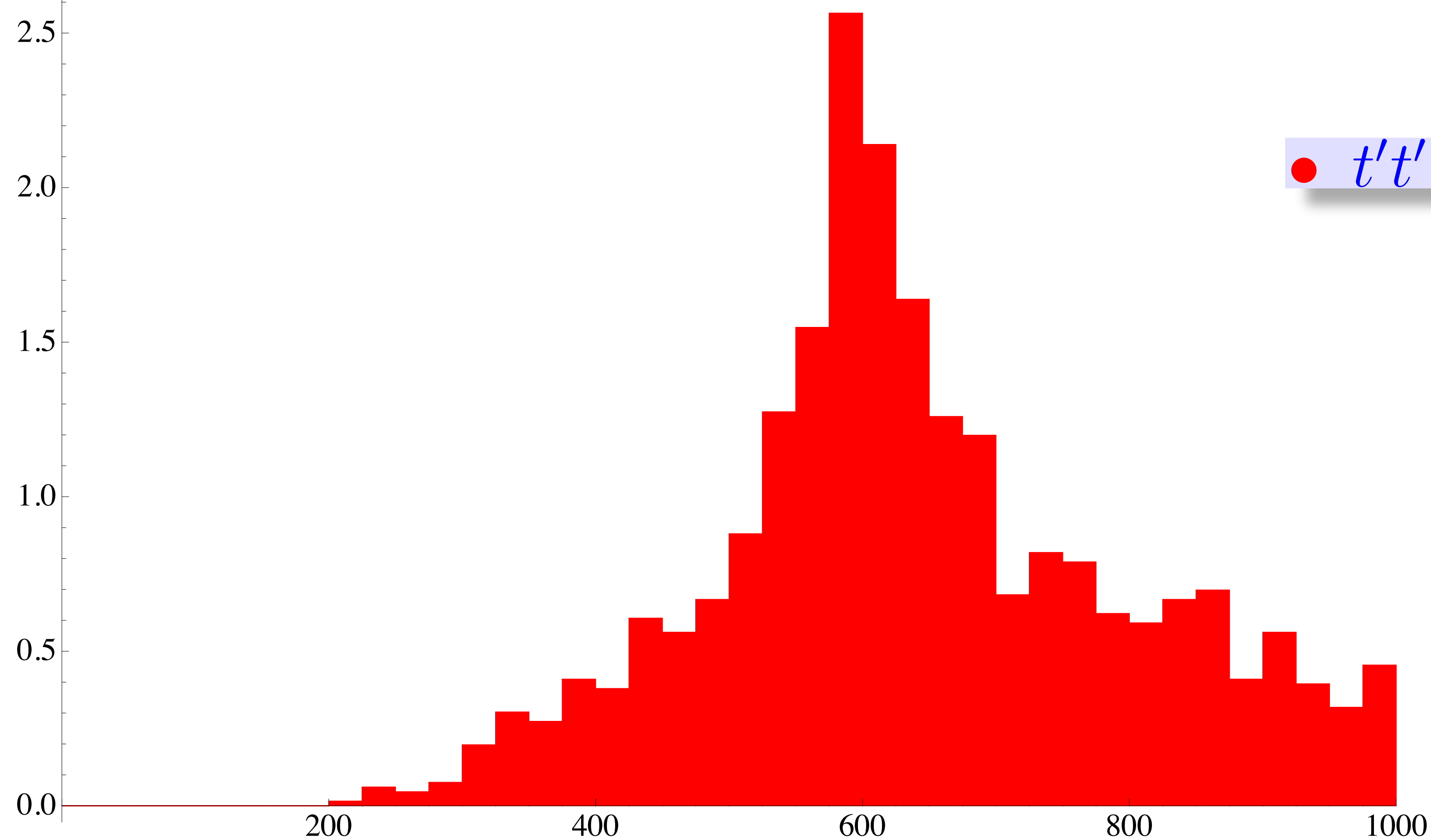
- signal and background

primitive t' mass reconstruction

- one W-jet
- one leptonic W
  - for a boosted W the lepton and neutrino are in the same direction
  - thus can reconstruct the W momentum (using $\not{E}_T$)
- one b-jet ($p_T > 50$ GeV) or non-W-jet ($p_T > 100$ GeV)

- for each jet of the latter type, pair with the W that gives the largest invariant mass
- histogram these invariant masses

- $t\bar{t}$ is again the main background if a b-jet is required



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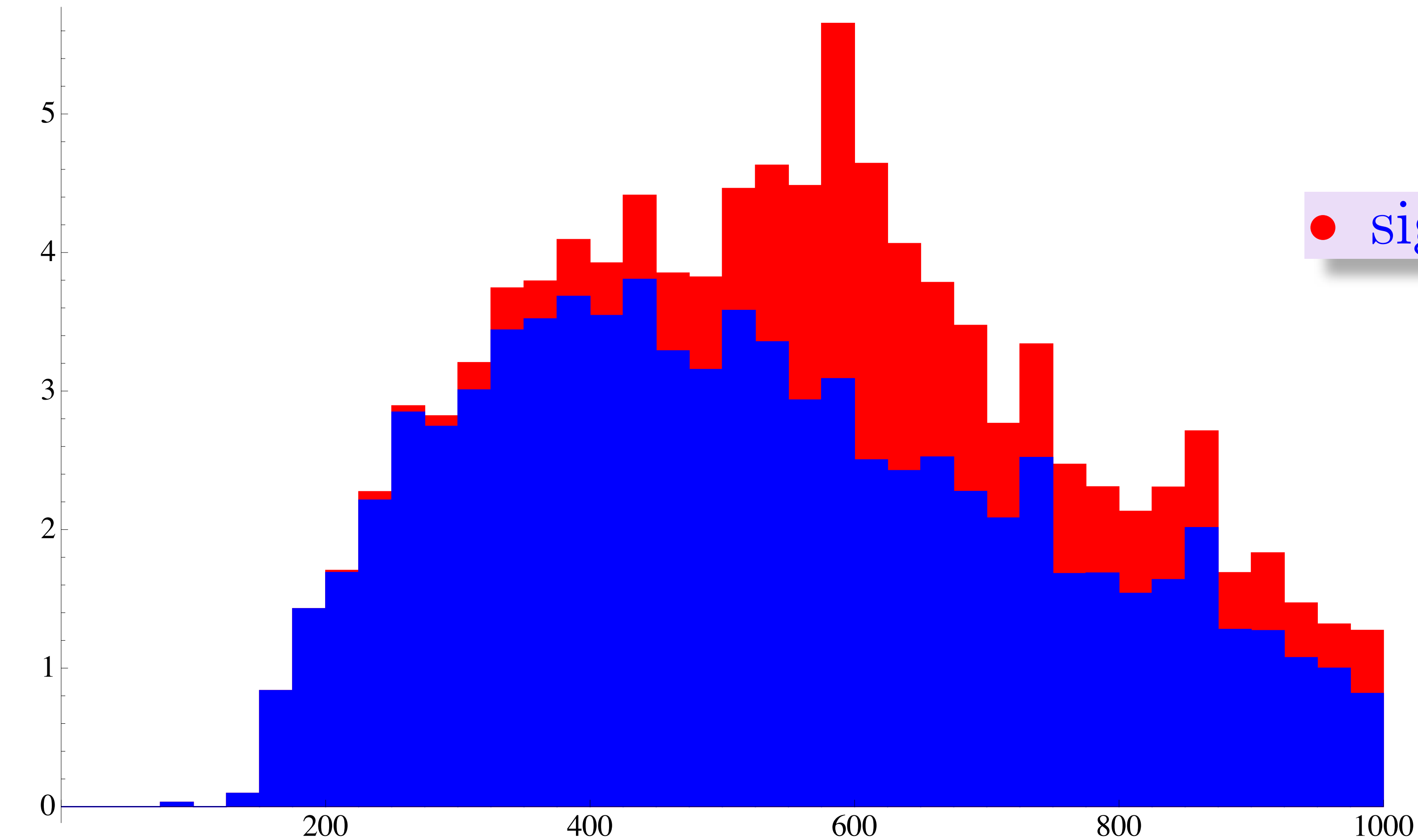

- signal and $t\bar{t}$ background

Exotic quarks

- "vector-like": L and R fields transform the same
- masses independent of electroweak symmetry breaking
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$Q^{(m)}$	U	D	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
isospin	0	0	1/2	1/2	1/2	1	1
hypercharge	2/3	−1/3	1/6	7/6	−5/6	2/3	−1/3

F. del Aguila, M. Perez-Victoria, and J. Santiago (2000)

- these vector-like quarks can mix with standard quarks through Yukawa terms

$$\text{e.g.} \quad \mathcal{L}_{\text{mixing}} = y\bar{q}_L U_R \tilde{\phi} + hc$$

- for a long period of time exotic quarks were the only game in town
- "a fourth generation of chiral fermions is excluded at 99% C.L. by the present limits on the S parameter" [e.g. previous reference]
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  - tree-level flavor changing neutral currents
  - flavor changing neutral currents mediated by Higgs
  - new right-handed neutral currents
  - right-handed charged currents

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- left mainly just with mixing with the third family
- third family is often special in models with exotic quarks

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- composite Higgs
  - quark masses 0.5 to 1 TeV (eg. charge 5/3)
  - emphasized a search using same sign leptons

Contino and Servant, 2008

Exotic quarks have exotic decays

- $SU(2)_L$ singlets U_L and U_R

$$\mathcal{L}_{\text{mixing}} = Y \overline{q}_L U_R \tilde{\phi} + hc$$

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- thus exotic quarks have quite a firm prediction for $Q\overline{Q} \rightarrow Z + X$ —unlike single production

Distinguishing exotic from fourth family quarks

- fourth family quarks do not produce Z's
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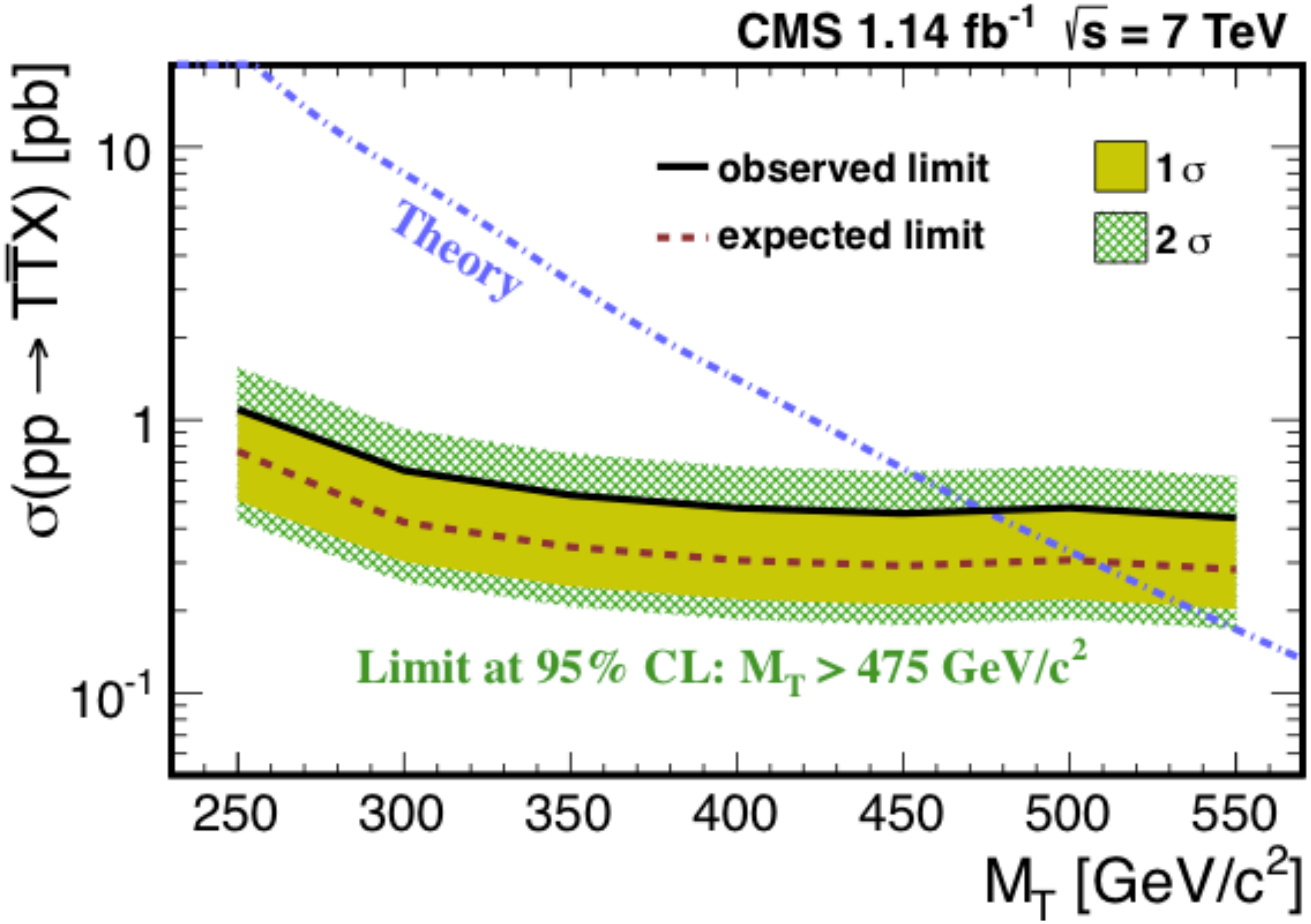
- eg. CMS search assuming $U \to tZ$ has 100% branching fraction



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- ρ-like vector meson resonances are usually thought to be a generic feature of new strong interactions (technicolor, Higgsless models etc.)

- but this need not be true!

- the new massive states to be seen first may be fermionic
- fermions that gain a dynamical mass but are not confined
- the physical states can correspond to the elementary fermions

Back to fourth family ...

- in this case the new fermion masses have some connection with electroweak symmetry breaking

- quark masses bounded by unitarity $\lesssim 600$ GeV
- if quark masses are $\gtrsim 500$ GeV then Goldstone bosons couple strongly to these quarks (coupling proportional to mass)

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- once again we see that the Higgs does not belong in this picture

BH, 1986, 2006

Underpinnings

- formation of quark condensates takes us back 50 years to the NJL model
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- a heavy fourth family not only teaches us something new about EWSB, it may also be the beginning of our understanding of flavor

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Guesses for related signatures

the X boson

BH, 2008

- simplest remnant flavor gauge interaction
- a $U(1)$ — call it the X boson

- simplest way to cancel gauge anomalies
- have it also couple to the third family

- helps with the top mass problem
- causes enhancement of top mass operator through anomalous scaling

- X couples equally strongly to all members of the third family
- thus distinctive decay mode $X \to \tau^+\tau^-$
- different from KK excitations of gluons for example

- doesn't couple to light quarks (unlike typical Z')
- X is produced through its coupling to the b quark

$$\begin{aligned} b\bar{b} &\rightarrow X & &(\approx 2/3 \text{ of cross section}) \\ g(b \text{ or } \bar{b}) &\rightarrow Xg(b \text{ or } \bar{b}) & &(\approx 1/4 \text{ of cross section}) \\ gg &\rightarrow Xb\bar{b} & & \\ q(b \text{ or } \bar{b}) &\rightarrow Xq(b \text{ or } \bar{b}) & &(q = \text{light quark}) \end{aligned}$$

- X is probably a broad resonance (also unlike a typical Z')

$$\Gamma_X \approx g_X^2 \left[\frac{M_X}{500 \text{ GeV}} \right] 60 \text{ GeV}$$

Diquarks

BH, 2011

- fourth family condensates can break approximate global symmetries
- resulting pseudo-Goldstone bosons have similarities to technipions

- there can be pairs (q_{1L}, q^c_{2L}) with the same X charge

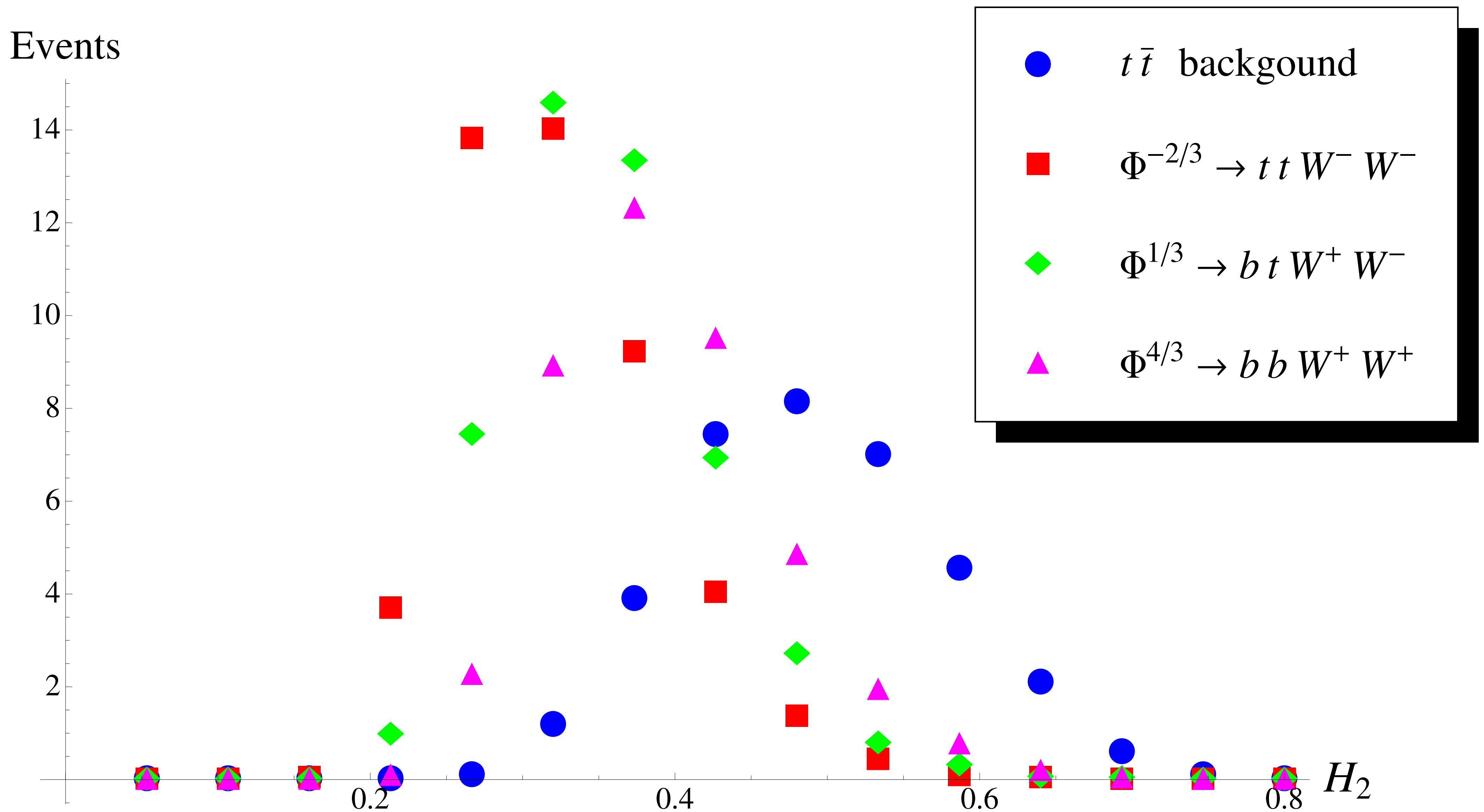
$\Rightarrow$ approximate symmetry when broken gives rise to diquark PGB

- diquarks can be 6 or $\overline{3}$ under $SU(3)_C$ and 3 or 1 under $SU(2)_L$
- diquarks either contain two fourth family quarks, or one fourth family and one third family quark

- decays to two fermions, but also weak decays that include one or two W's

- production cross section of diquark sextets is 20 times larger than diquark color triplets or leptoquarks
- can lead to spectacular events (many jets, b's, leptons, missing energy)

- require lepton, missing energy, b-jet, large H_T, and at least 6 jets
- 600 GeV diquarks, 7 TeV at 1 fb^{-1}



$$H_2 \equiv \frac{E_{1T} + E_{2T}}{H_T}$$