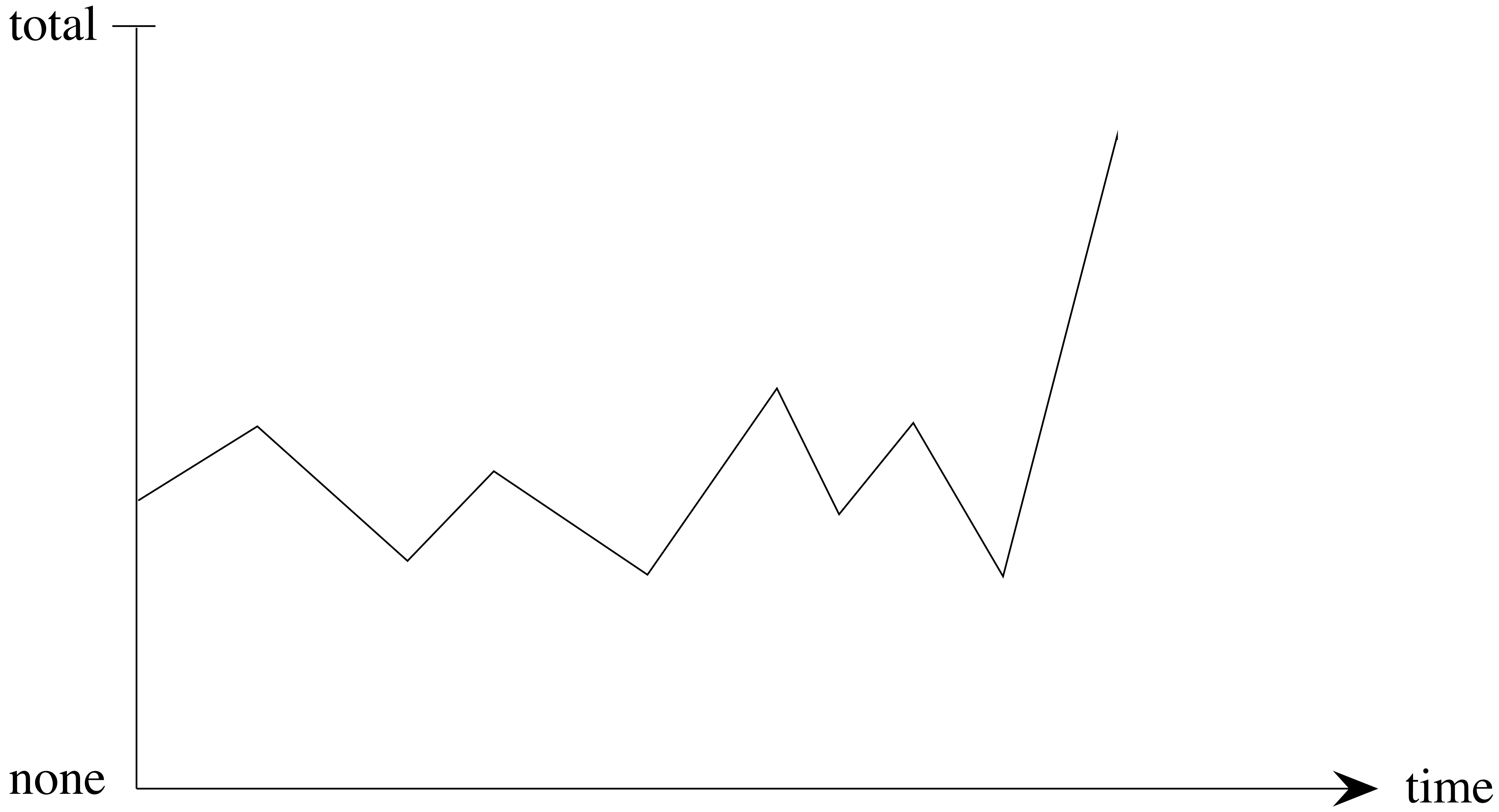
New Quarks: Exotic vs Strong

B. Holdom

TRIUMF Workshop on LHC Results

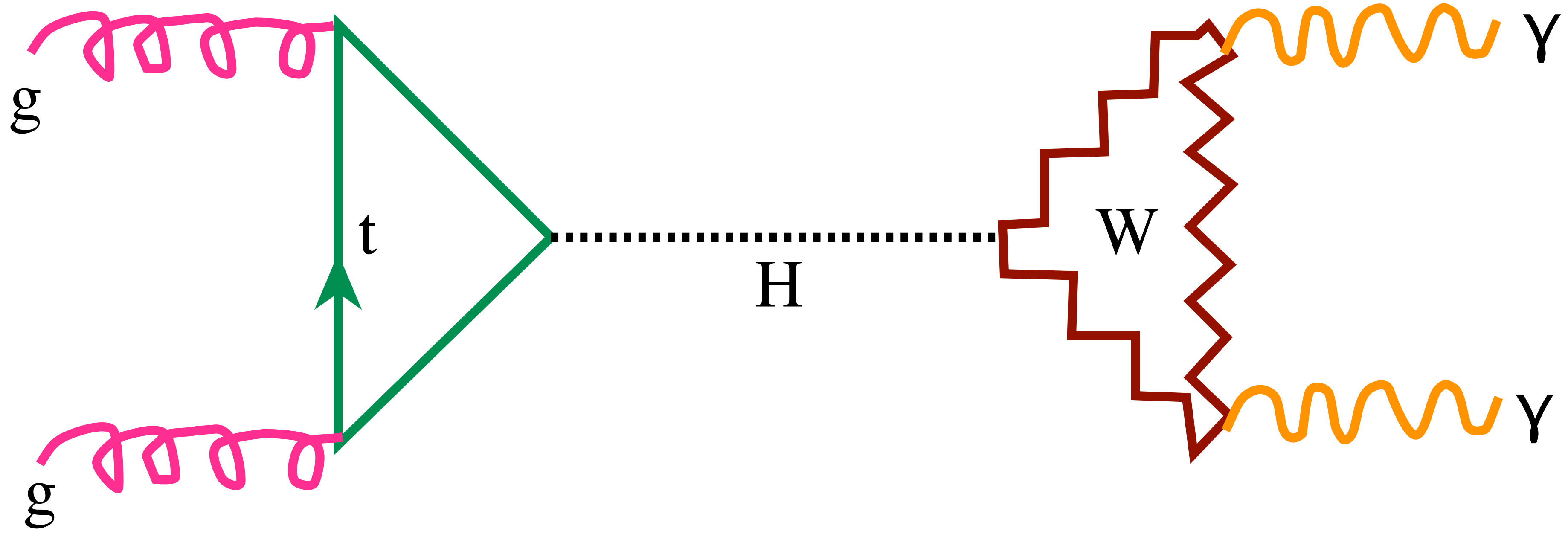
December 2011

Belief in a light Higgs



Belief in a light Higgs

- we need to 'recast' the LHC $\gamma\gamma$ results in another framework


g
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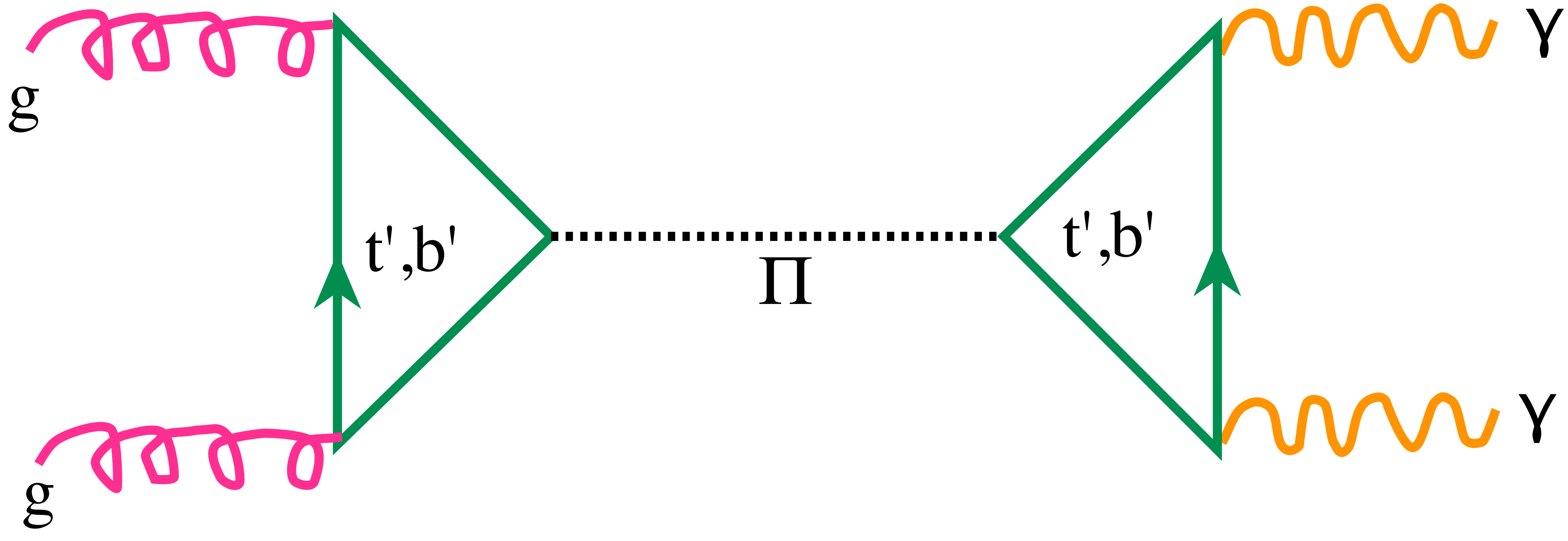

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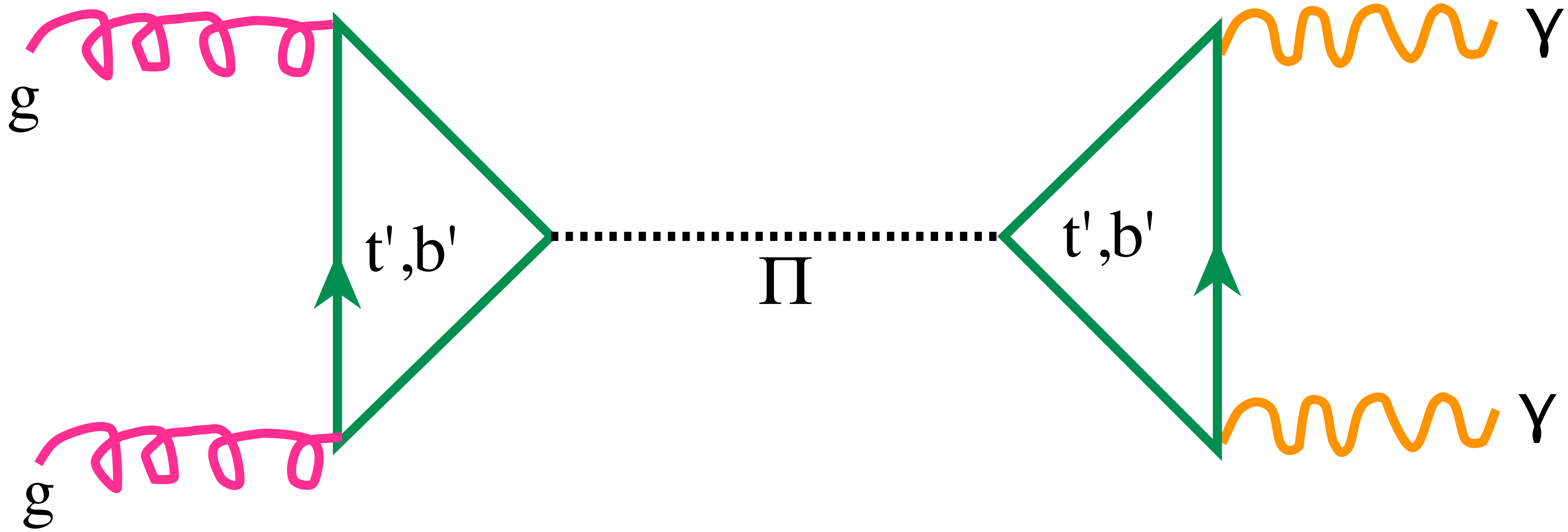
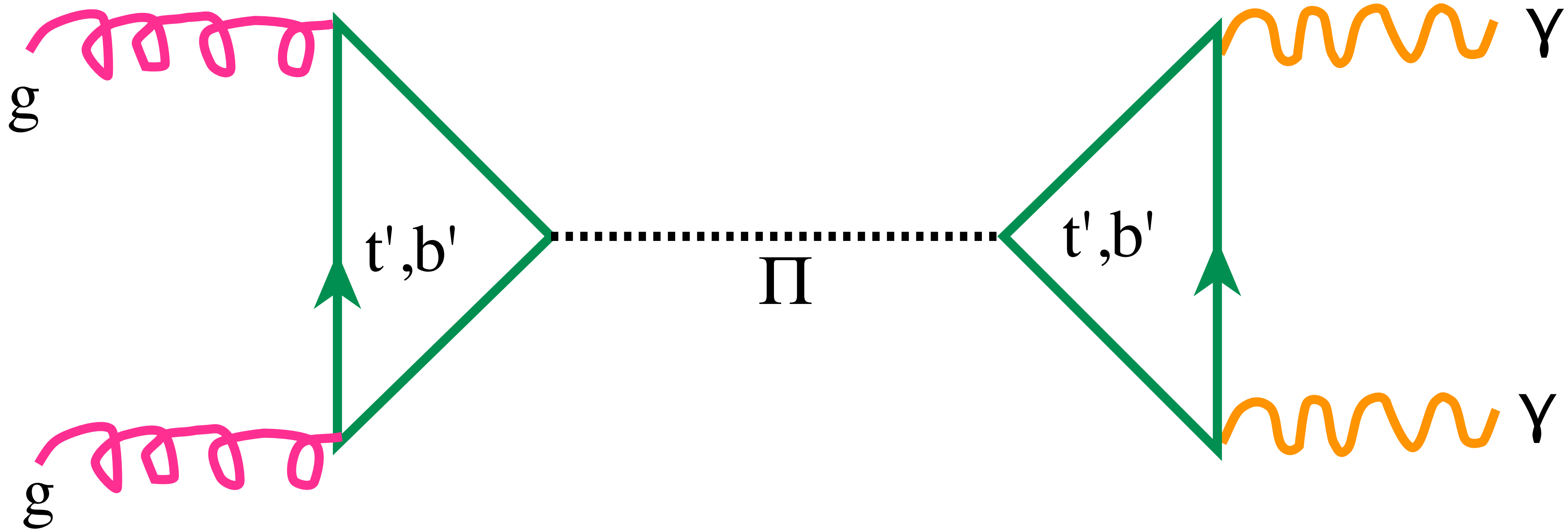


- Π is pseudo-Goldstone boson—a pseudoscalar (NOT some composite Higgs)
- couplings to gluons and photons are from chiral anomaly
- corrections are small $\approx (m_\Pi/1\ \mathrm{TeV})^2$



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- let t' and b' be fourth family quarks
- Π couples to $\overline{t'}\gamma_5 t' + \overline{b'}\gamma_5 b'$
- arises from $\langle \overline{t'} t' \rangle = \langle \overline{b'} b' \rangle \neq 0$

- compare to Higgs rate
- use full results for the Higgs since the corrections are large

$$\frac{\gamma\gamma \text{ rate from } \Pi}{\gamma\gamma \text{ rate from } H} \approx \left(\frac{\Gamma(\Pi \to gg)}{\Gamma(H \to gg)}\right) \times \left(\frac{BR(\Pi \to \gamma\gamma)}{BR(H \to \gamma\gamma)}\right)$$

$$\approx (\sim 5) \times \left(\sim \frac{1}{5}\right)$$

$$\approx 1 \;!!$$

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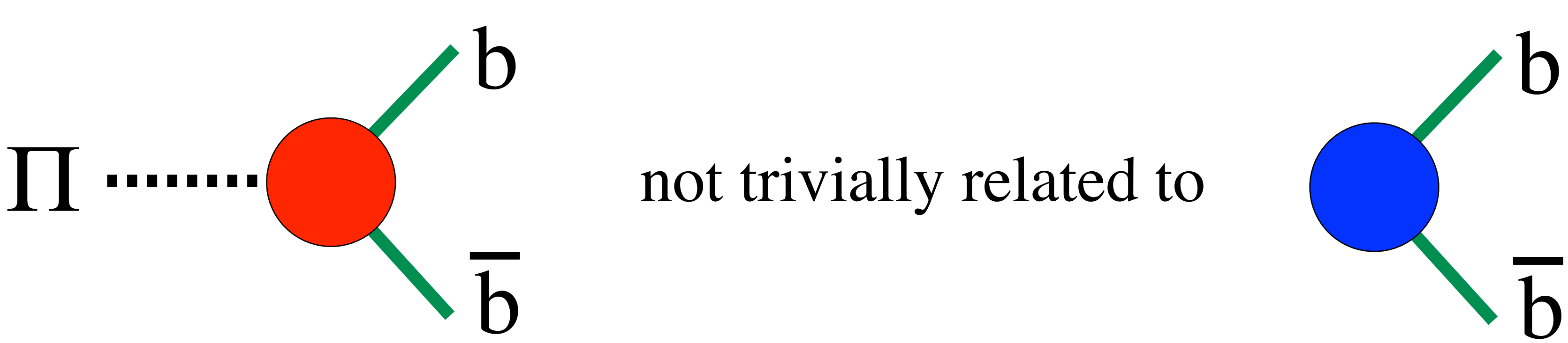
- uncertainty in $\Gamma(\Pi \to b\bar{b}, c\bar{c})$ gives main uncertainty



- relative contributions of $\langle \overline{t'}t' \rangle$, $\langle \overline{b'}b' \rangle$, $\langle \overline{\tau'}\tau' \rangle$ are different
- a "canonical" choice is to assume that b receives mass purely from $\langle \overline{b'}b' \rangle$, etc.

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- this is how Π and H are to be distinguished!

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  - "Thus there is one additional color singlet, neutral PGB. ... this PGB could be the lightest of the possible color and isospin singlet PGBs. The couplings of this PGB to the fourth family implies that it has loop-induced couplings to gg, $\gamma\gamma$, ZZ and WW."

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- some technicolor theories have a technipion P coupling to $\overline{Q}\gamma_5 Q - 3\overline{L}\gamma_5 L$
- recent LHC constraints on $\gamma\gamma$ and $\tau^+\tau^-$ production
  - only $N_{TC} = 2$ survives

Chivukula, Ittisamai, Ren, Simmons 2011

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- $\gamma\gamma$ rate is ≈ 1.5 times that of the Higgs, and $\tau^+\tau^-$ rate is ≈ 17 times larger
  - again assumes that τ receives mass purely from $\langle\overline{E}E\rangle$ etc.

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  - fourth family with Higgs
  - “strong” fourth family without Higgs
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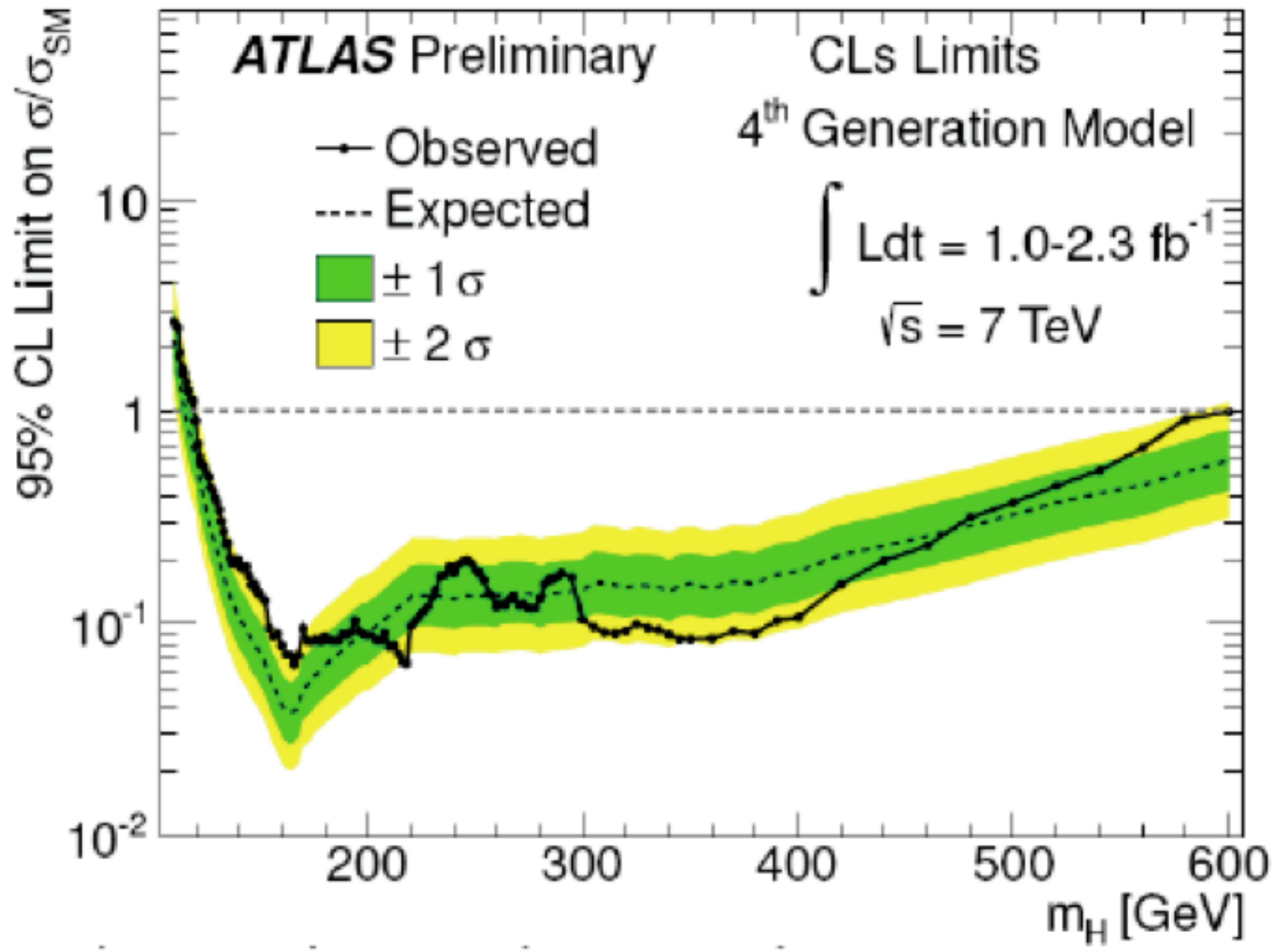
- adding a fourth family to the standard model (with Higgs) is perhaps the simplest extension
- was receiving attention recently, after decades of neglect

- Higgs couples to the heavy quarks in the standard way

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

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

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



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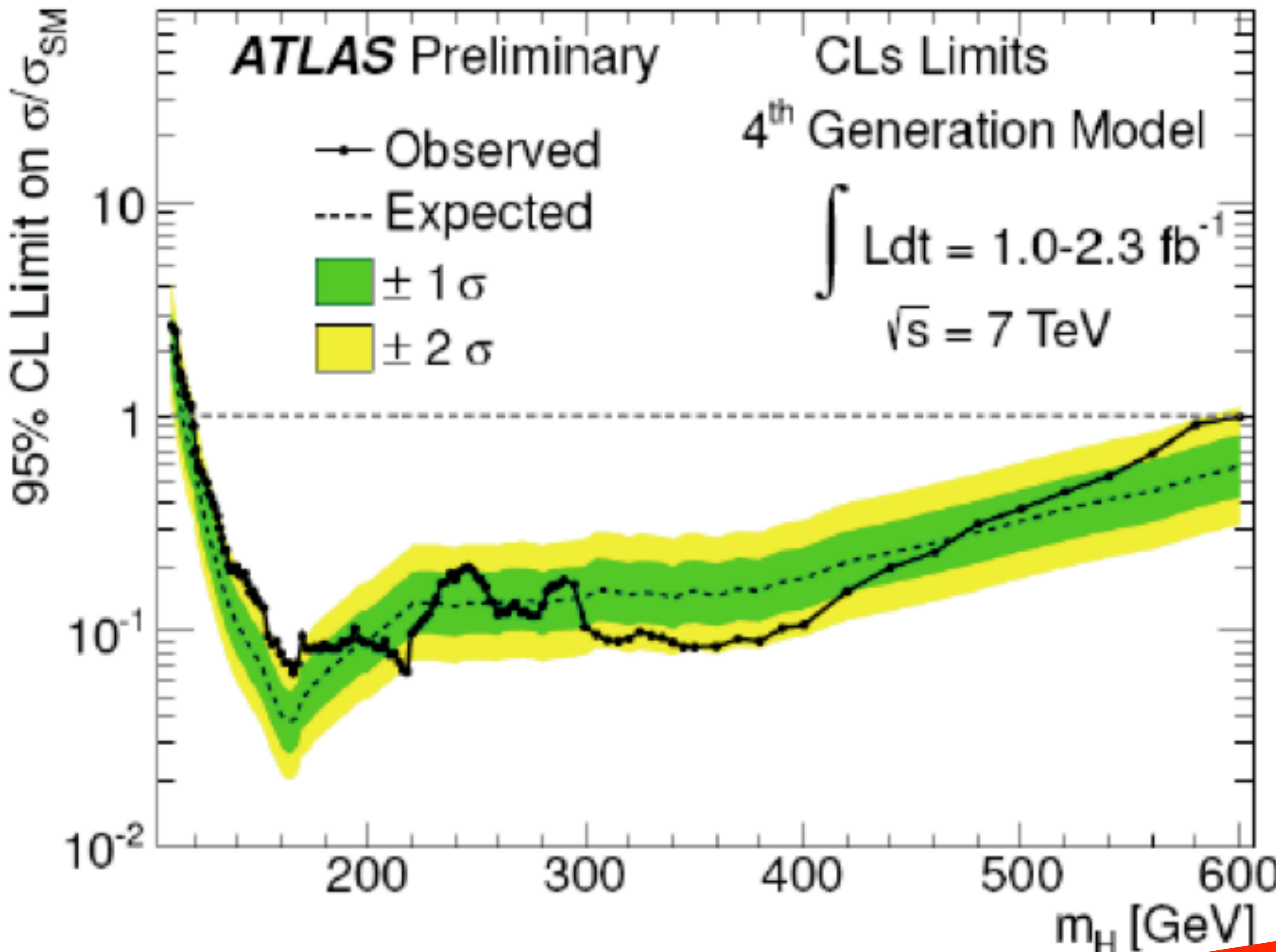

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- so why hasn't the fourth family search attracted more attention?

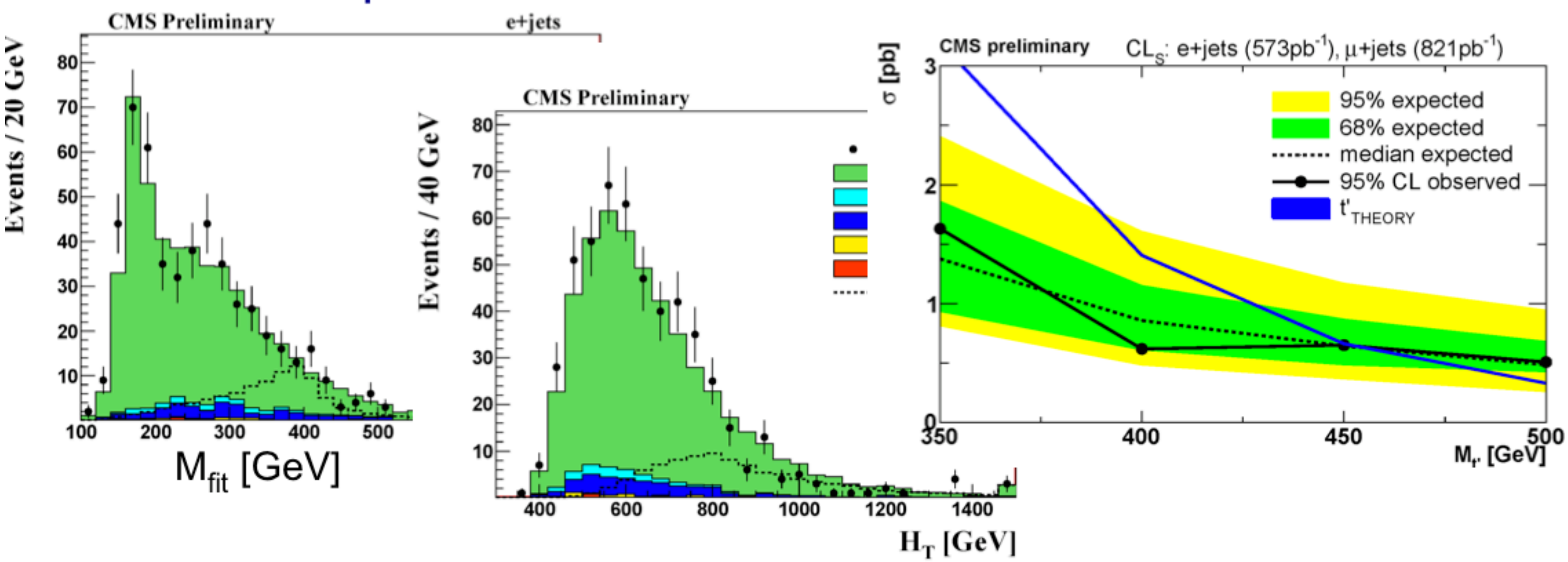
- nevertheless, direct searches are occurring

- lower limits on the fourth family quark masses are increasing

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

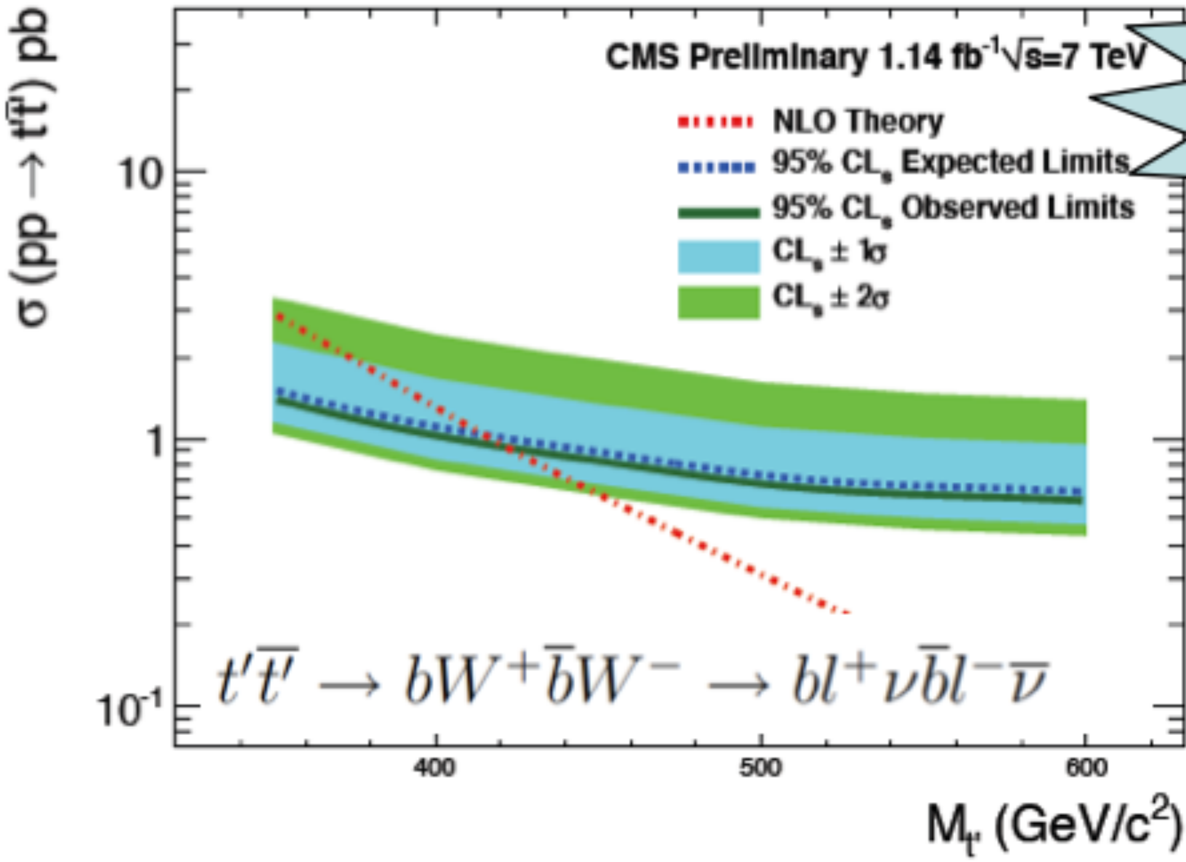
Search for a 4^{th} generation quark: $t' \rightarrow Wb$

- $t' \rightarrow Wb$: 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



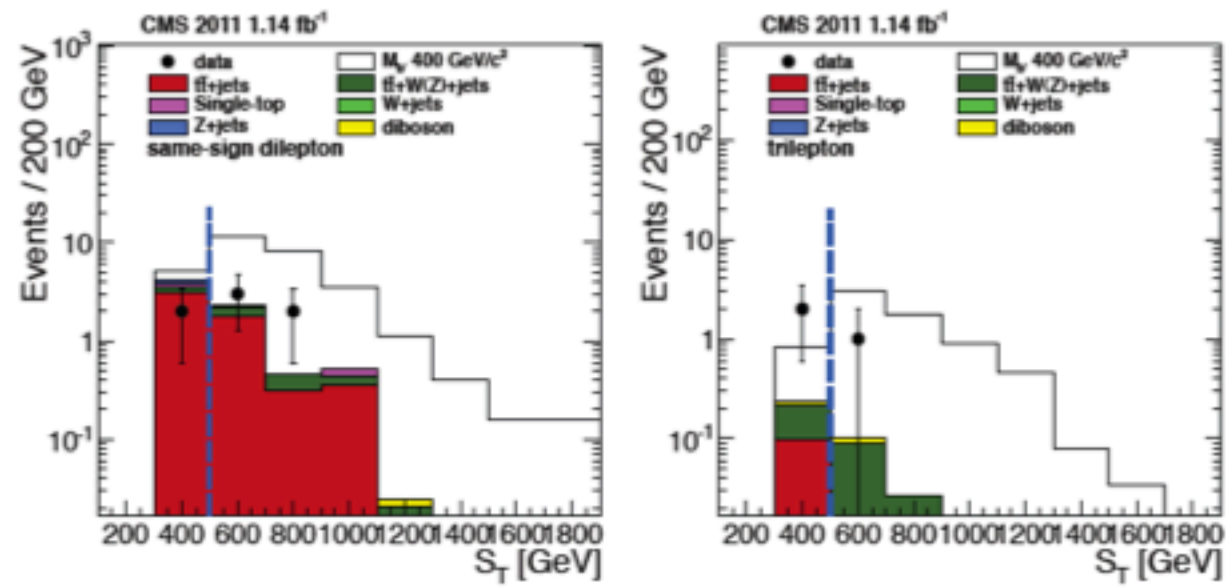
- from A. De Roeck's talk at Lepton-Photon

CMS-EXO-11-50

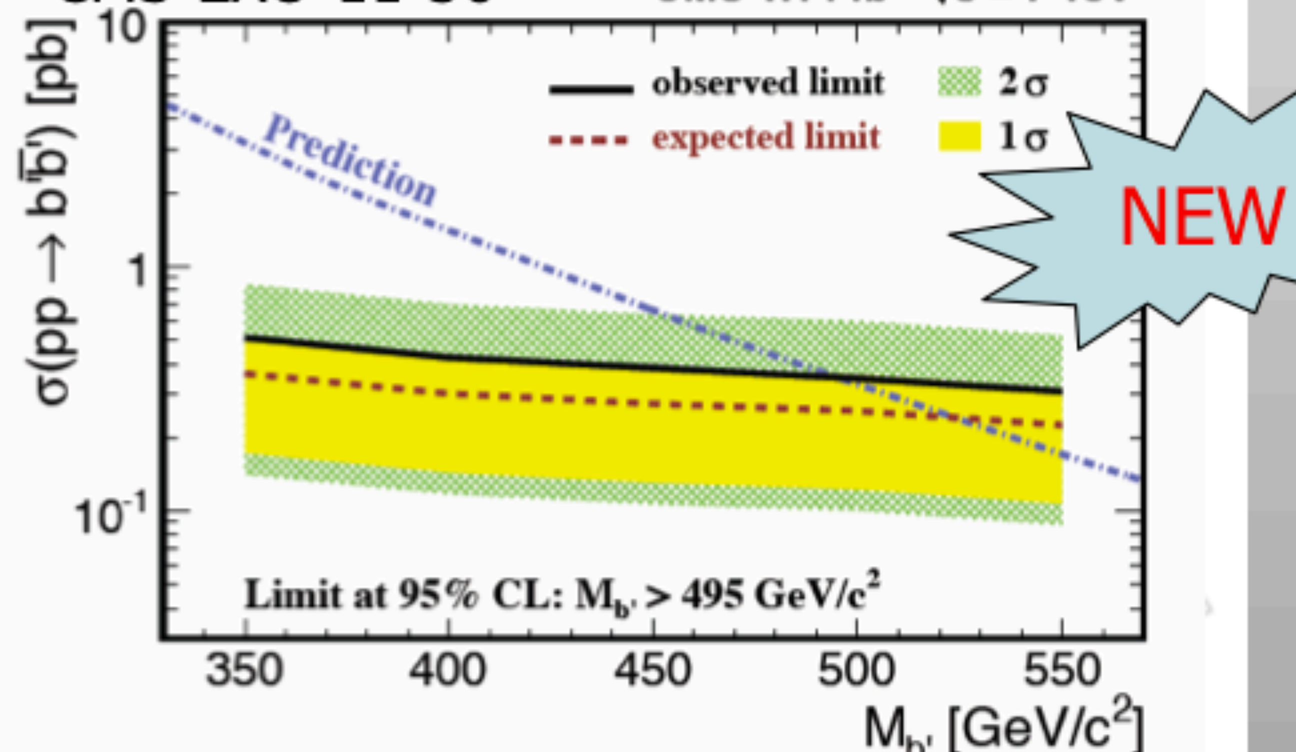


No t′ with found in the region of mass < 450 GeV at 95% CL

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



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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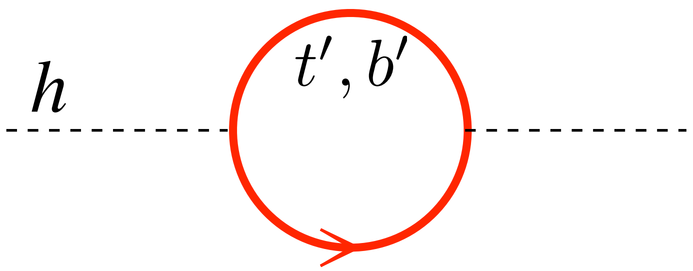

assume cutoff $\Lambda > m_{q'}$ $\longrightarrow$

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

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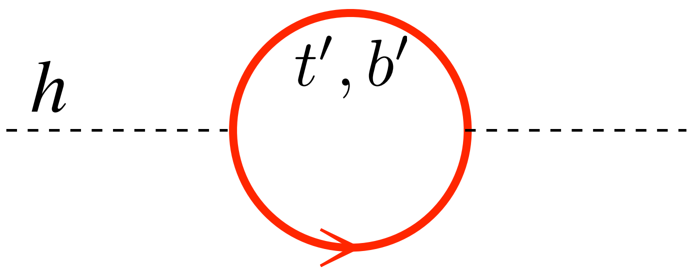

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$$\delta m_h^2 \approx \left[\frac{m_{q'}}{400\ \mathrm{GeV}}\right]^2 \Lambda^2$$

- 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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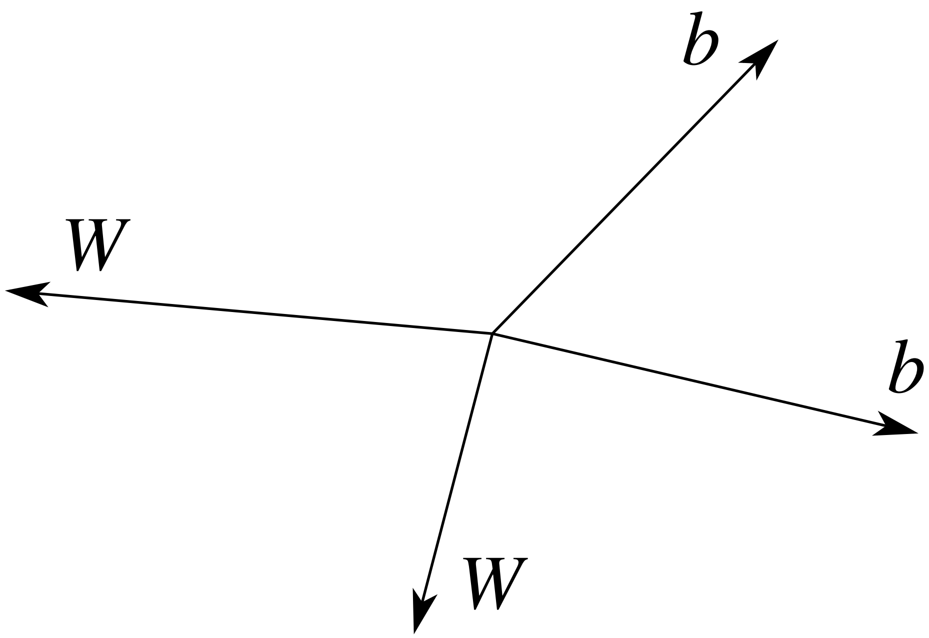
- ATLAS is strangely quiet
  - perhaps they have different strategies...

kinematics of heavy quark search

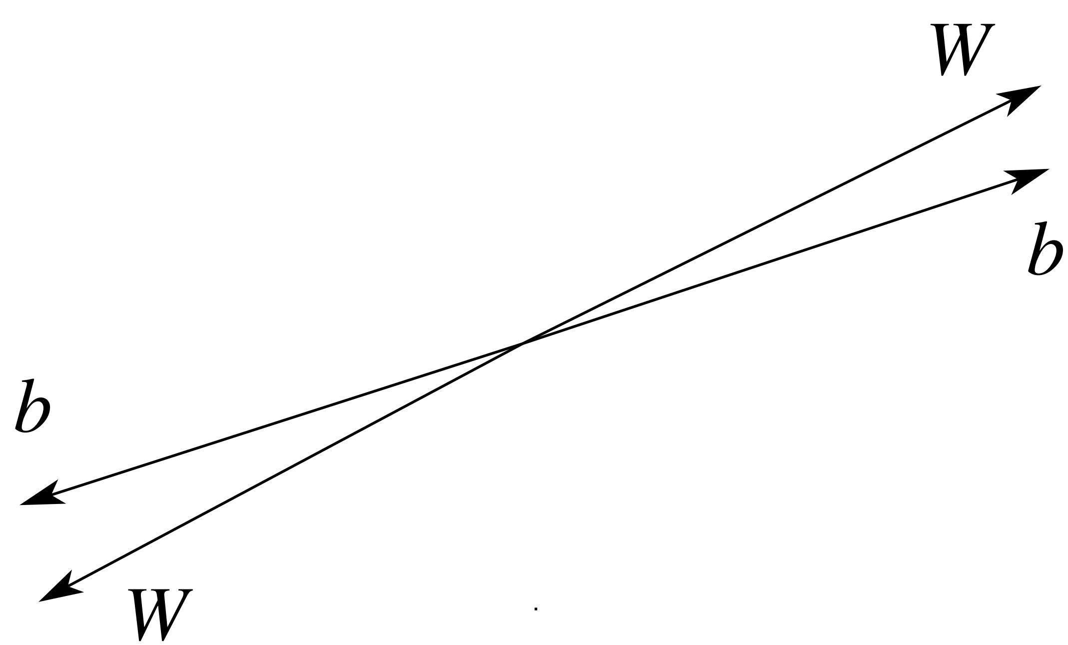


$t'\overline{t'} \to b\bar{b}WW$

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

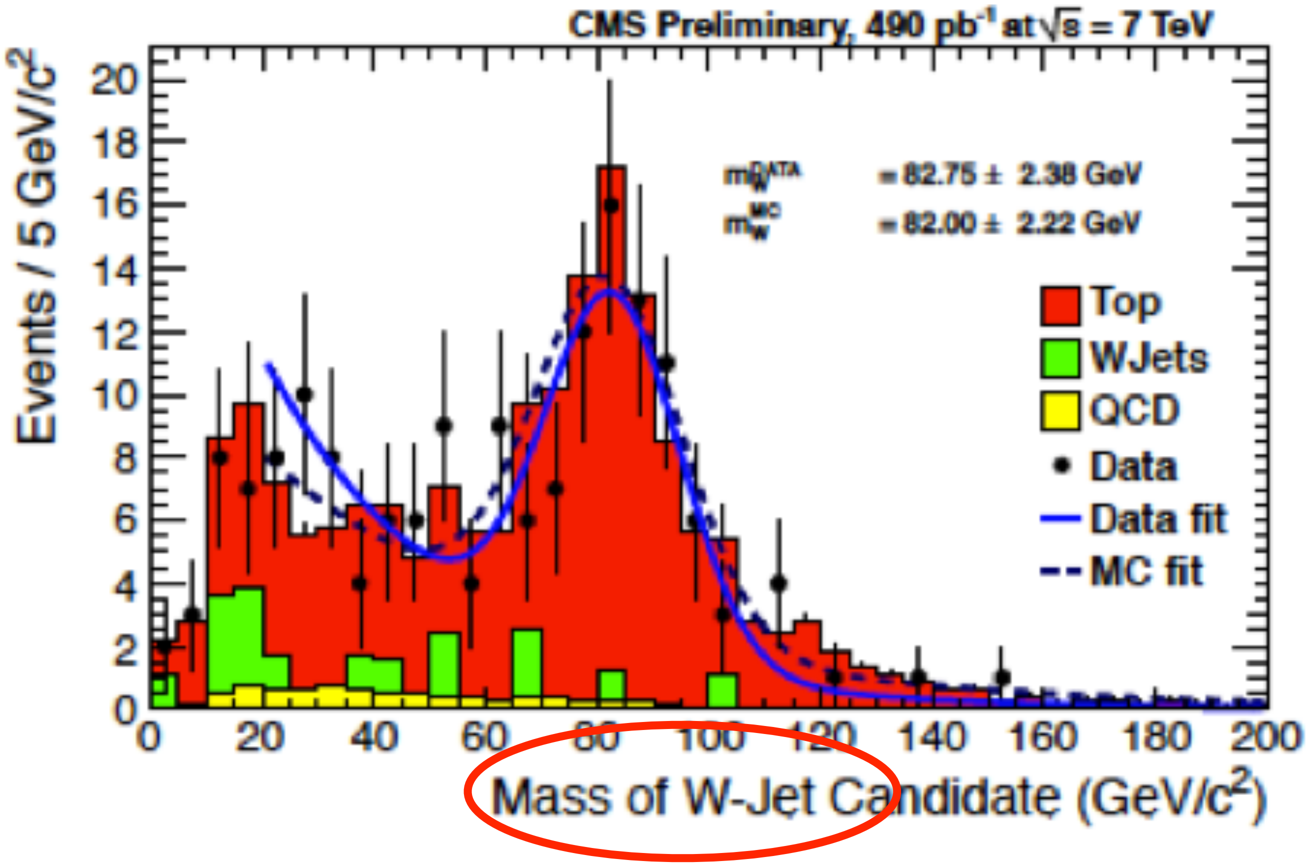
$t\bar{t}$ *background*

- 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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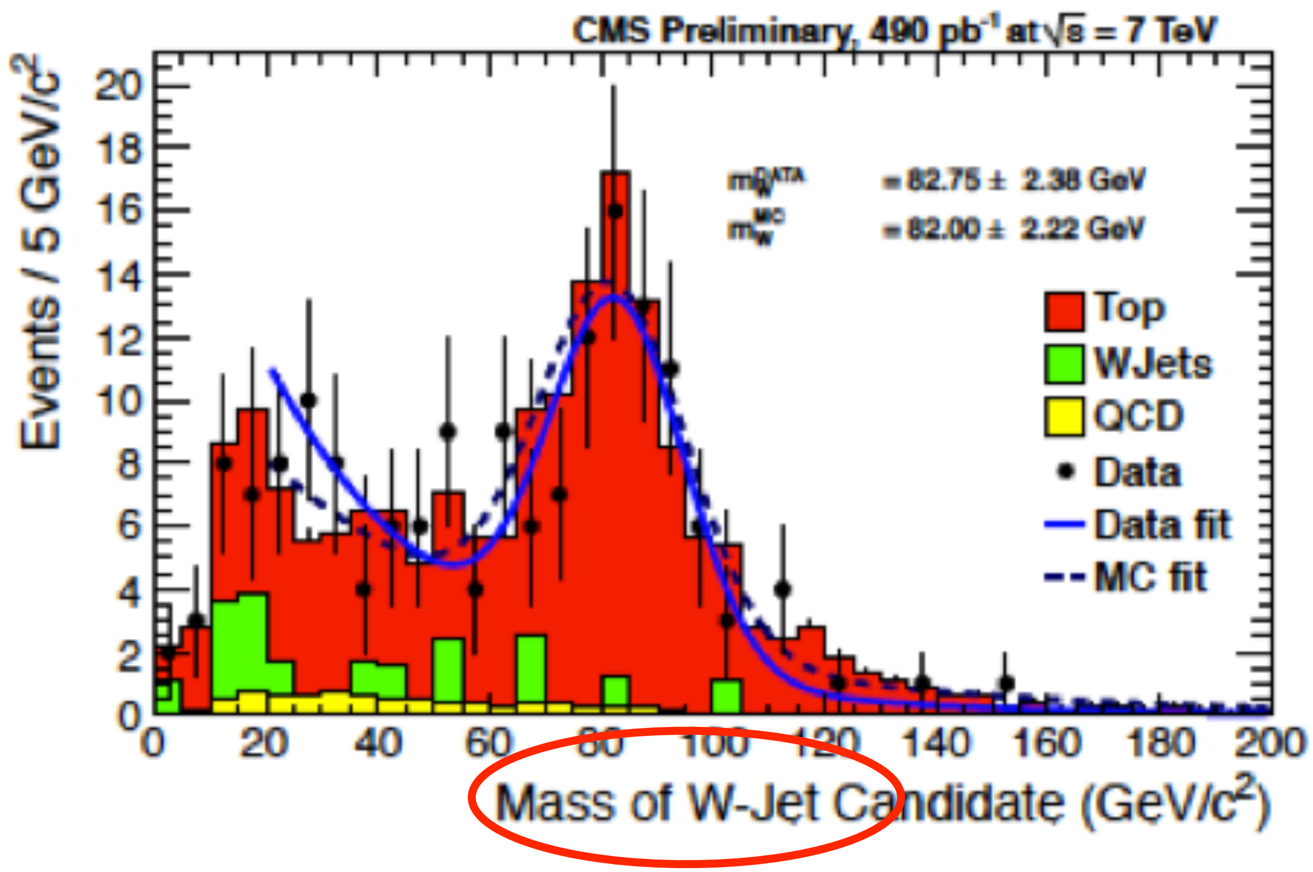


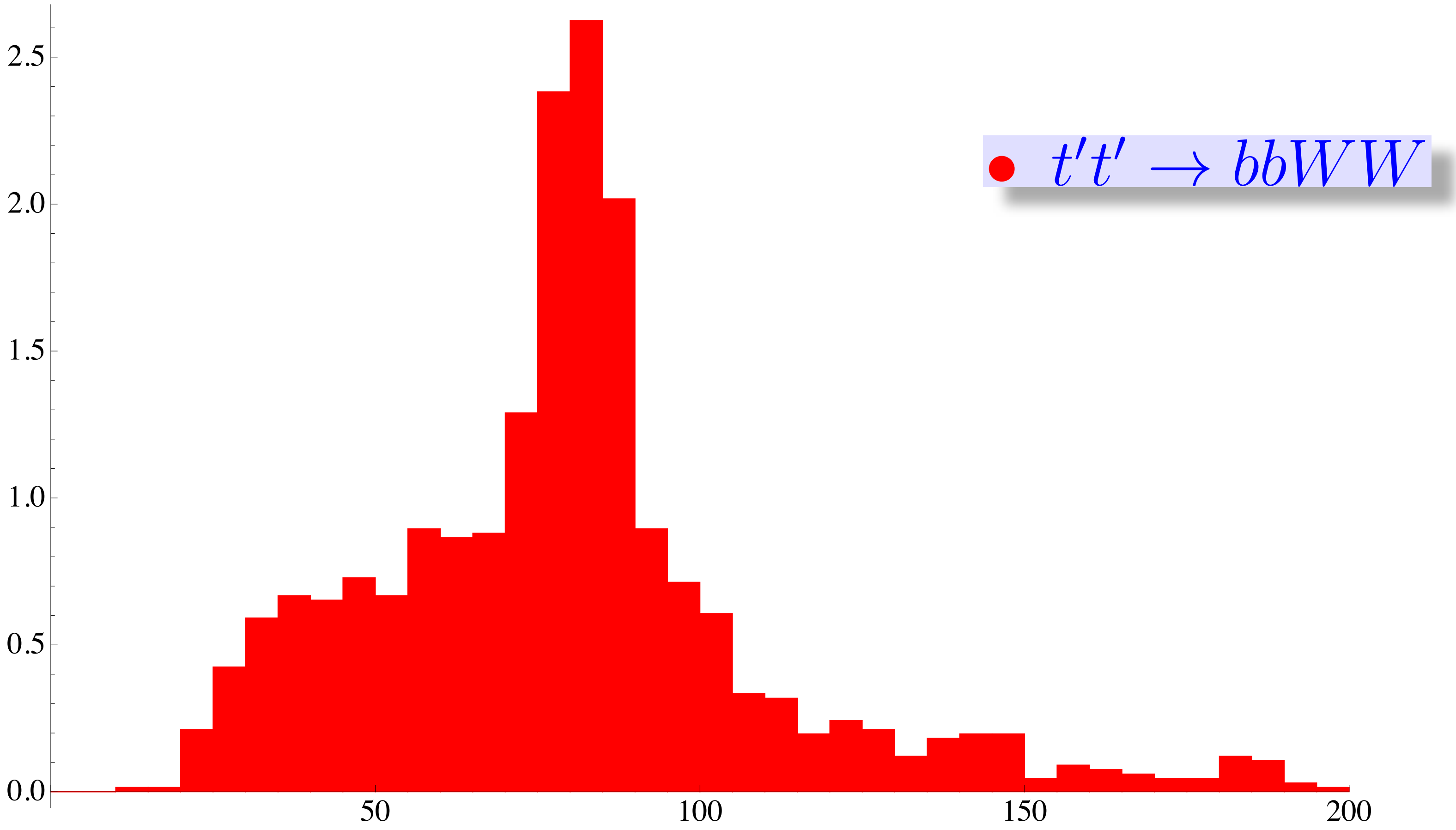
instead we want isolated W-jets

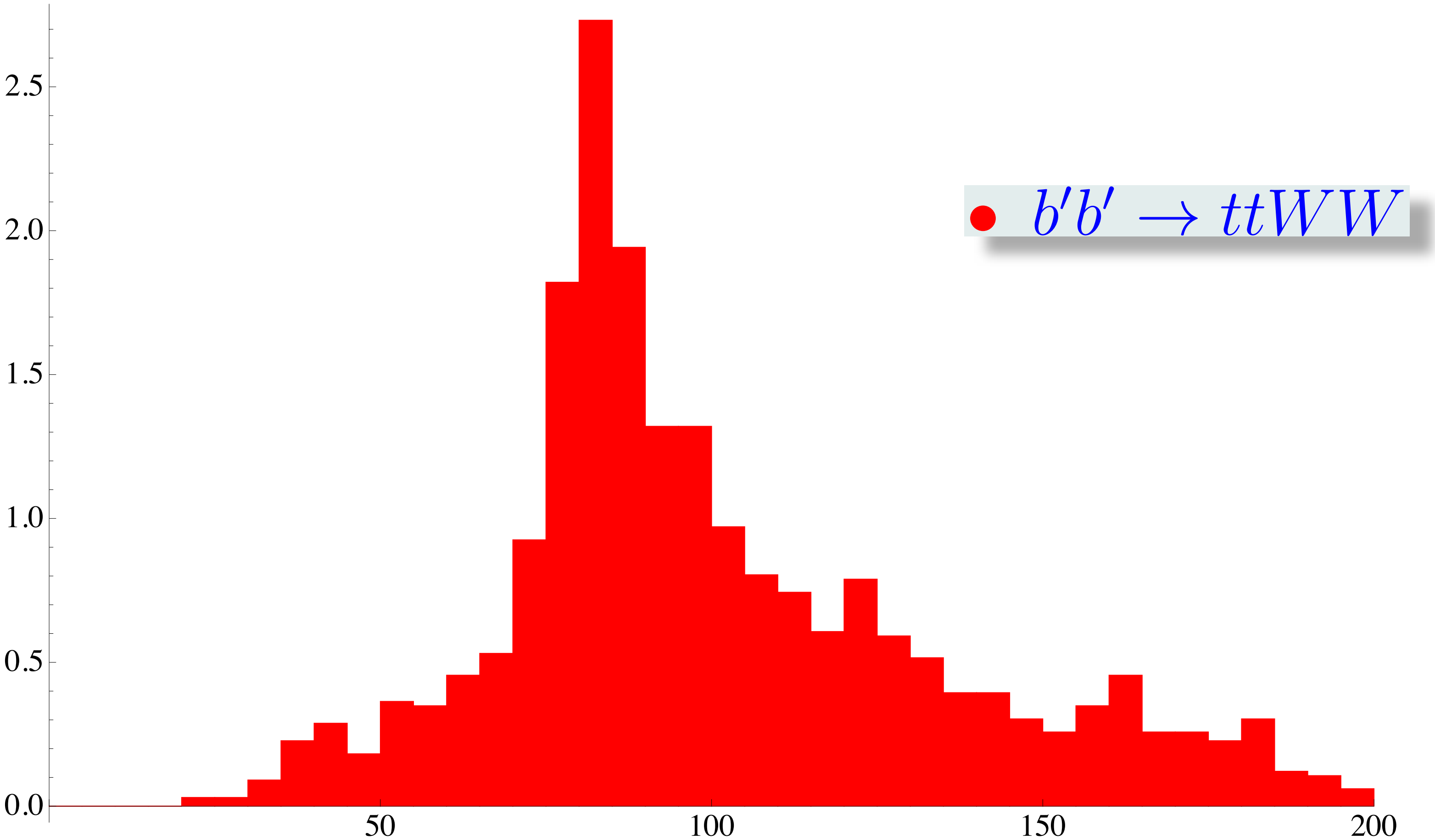
- we want low efficiency for finding W-jets from boosted tops (background)
- both $t' \to bW$ and $b' \to tW$ contribute to signal

a simple search for isolated W-jets

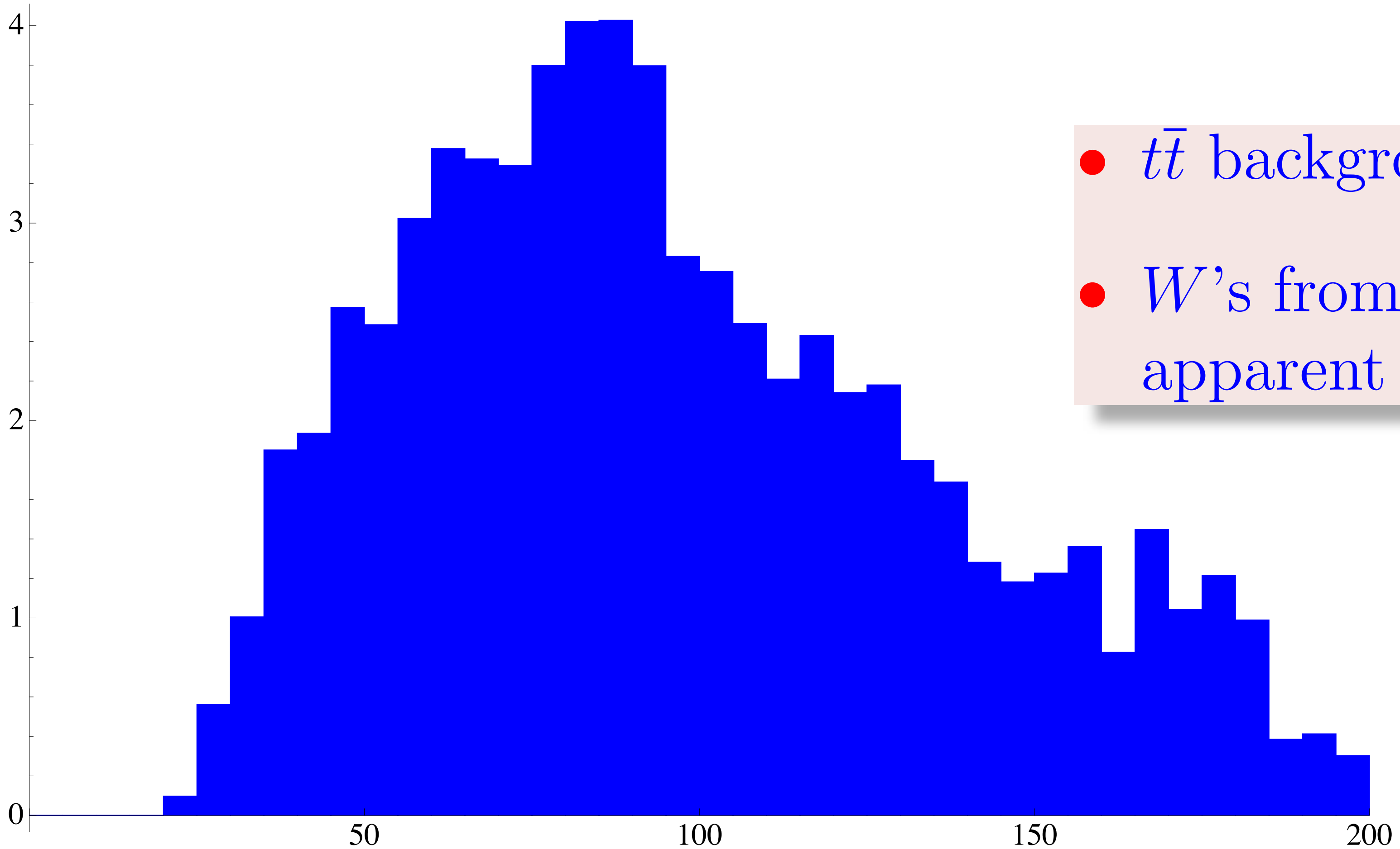
- use jet finder with $R \approx 0.8$
- in each event find jet with largest jet mass
  - keep if isolated ($\Delta R > 1$ from other objects)
  - form histogram of these jet masses

- 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

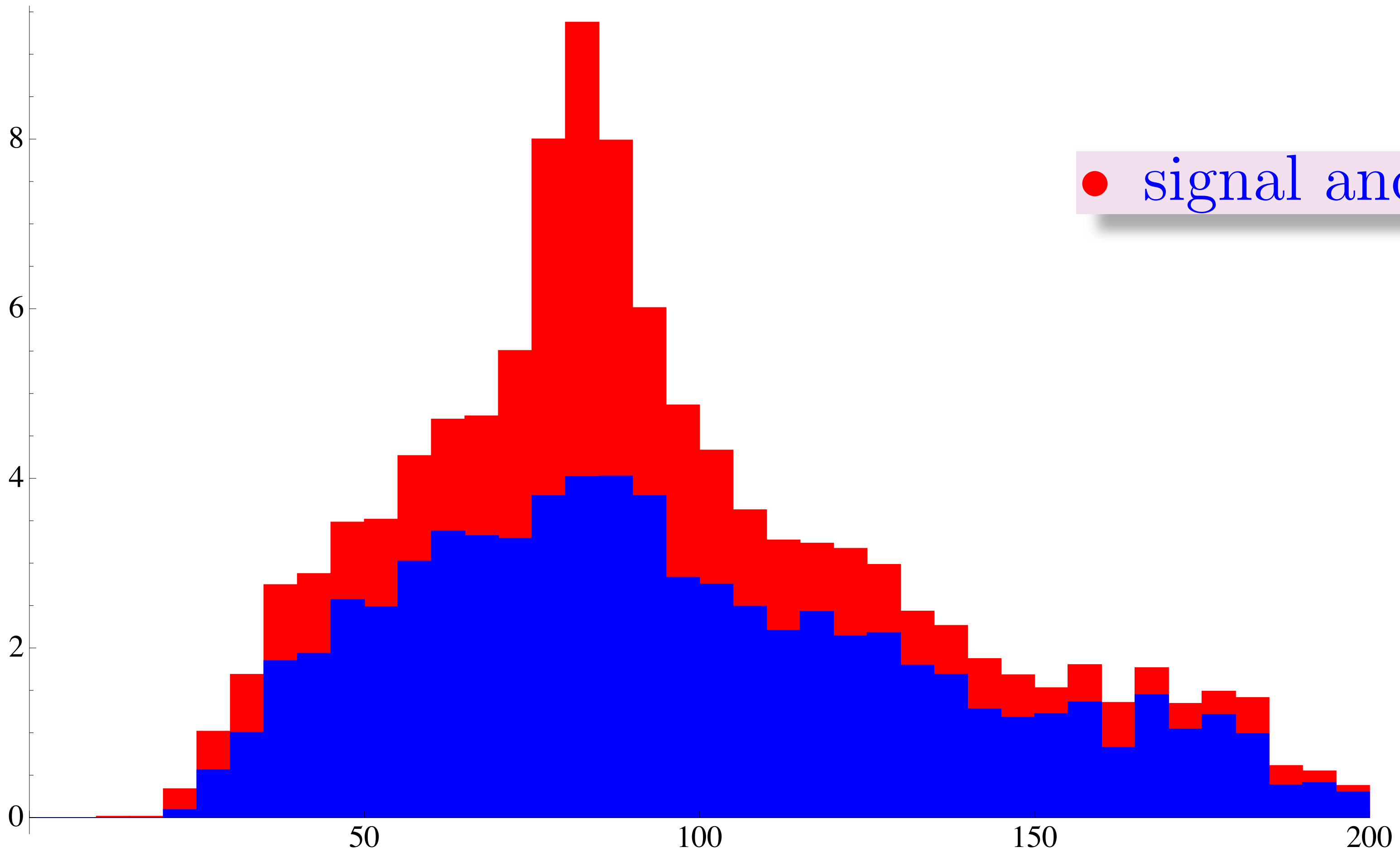




- 600 GeV mass quarks
- 2.5 fb^{-1} at 7 TeV
- $H_T > 1100$ GeV



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



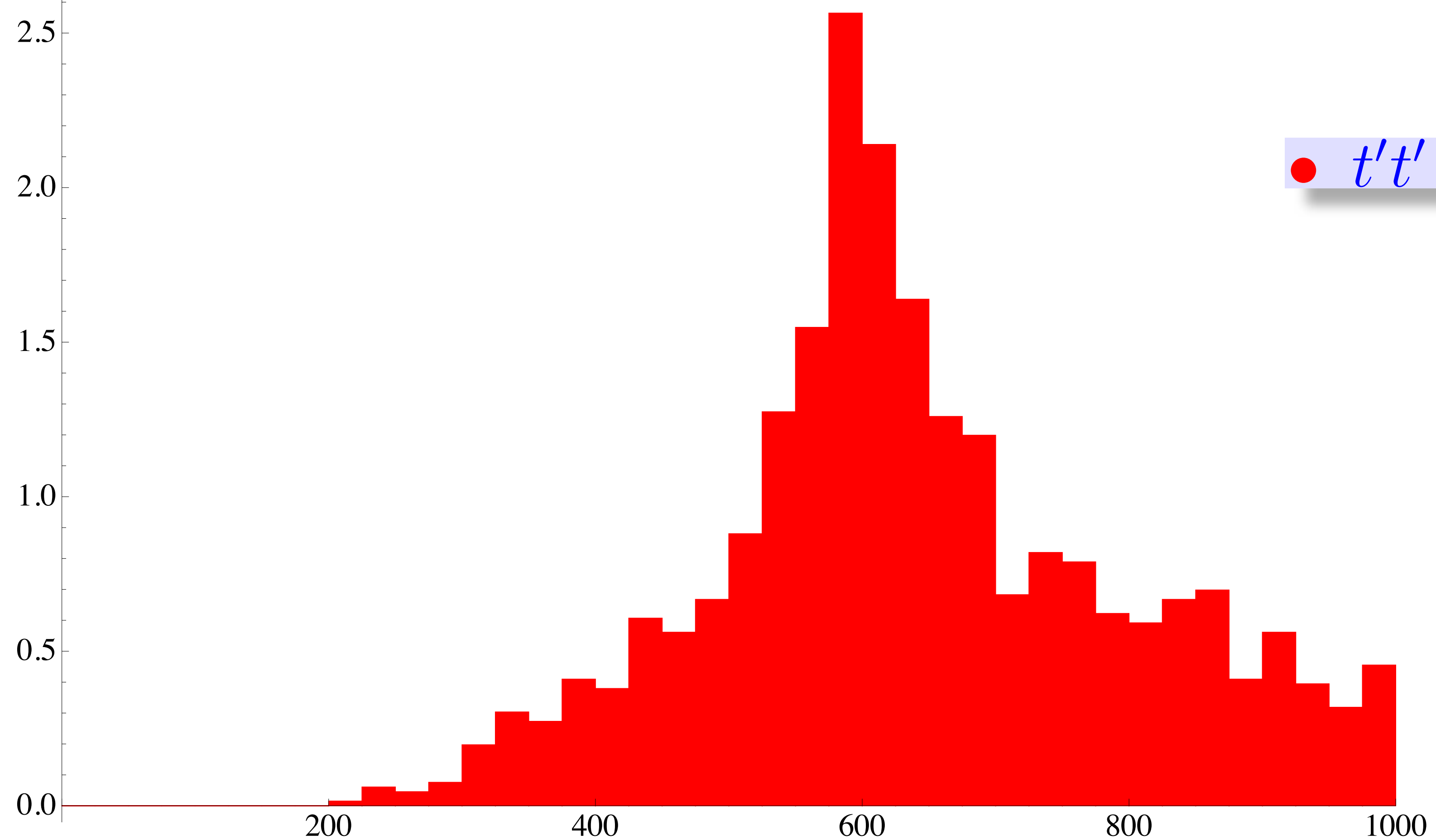
- signal and background

a simple 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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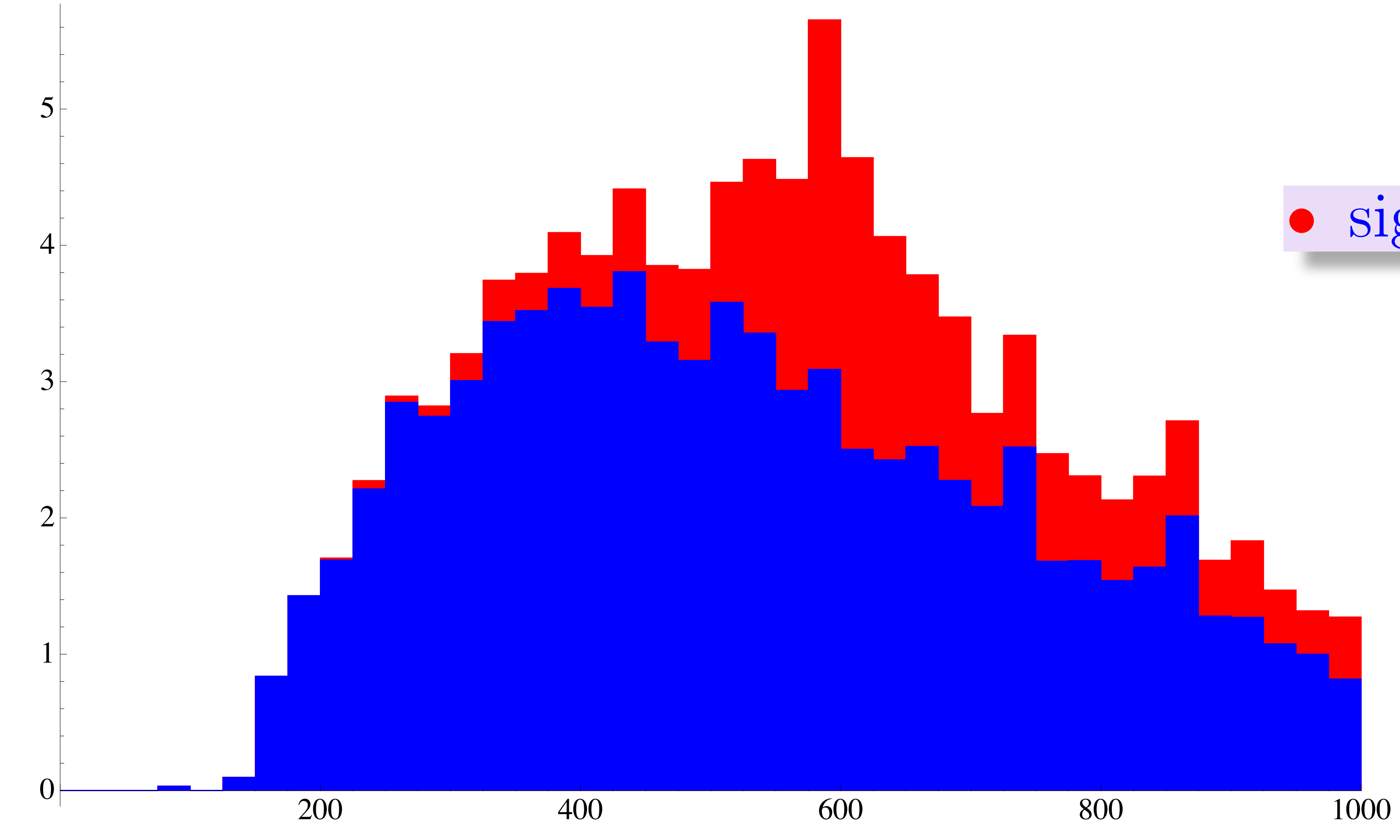

- signal and $t\bar{t}$ background

Exotic quarks

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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

del Aguila, Perez-Victoria, and 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
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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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  - Higgs as a pseudo-Goldstone boson
- composite Higgs with top quark having large mixing to composite sector
  - quark masses $\lesssim 1$ TeV as initially proposed
  - but flavor constraints ($b \to s\gamma$) probably push masses above a TeV

Exotic quarks have exotic decays

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

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

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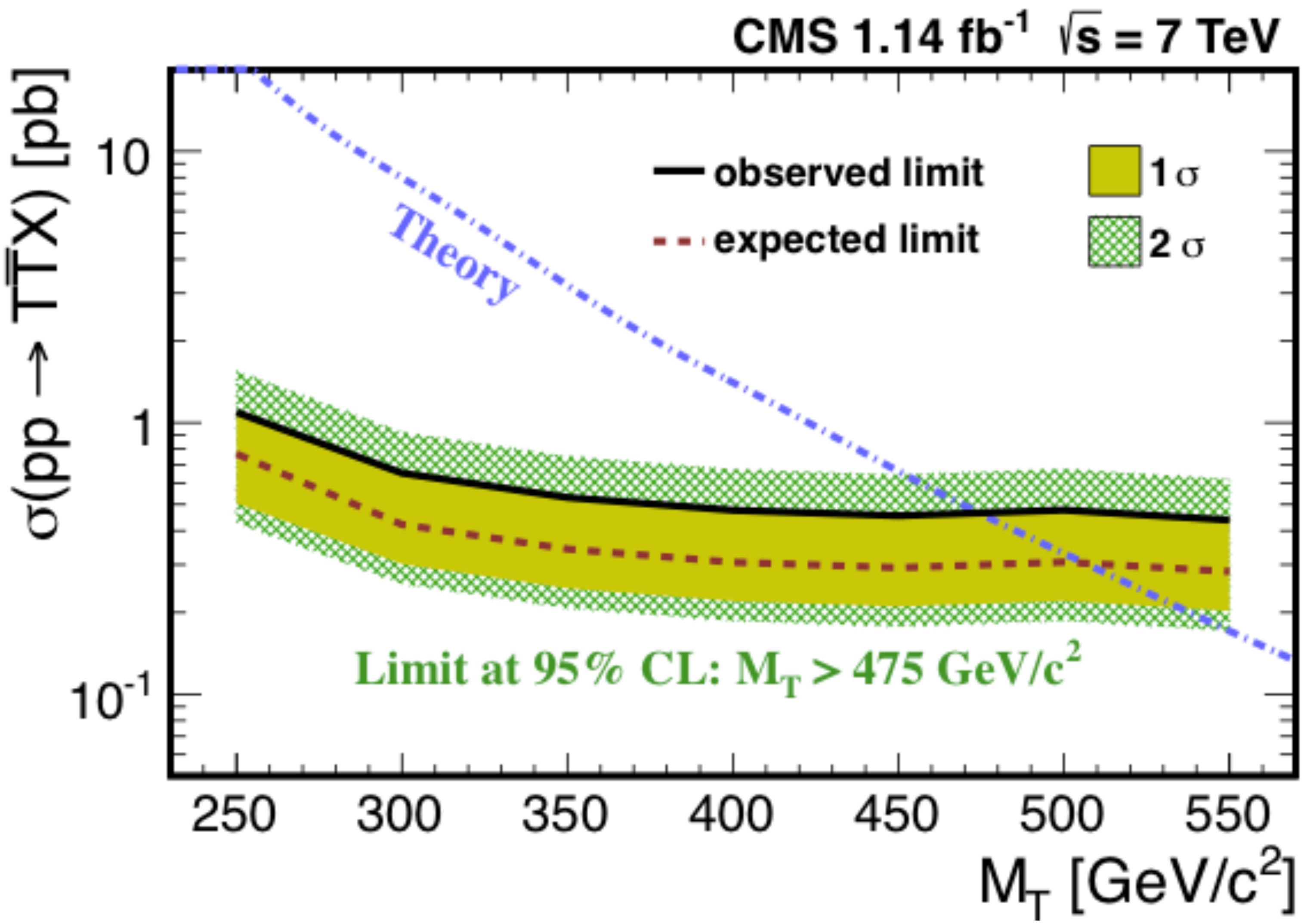
- eg. CMS search assuming $U \to tZ$ has 100% branching fraction



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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 ...

- fourth family condensates are electroweak symmetry breaking order parameters

- Goldstone bosons couple strongly to fourth family quarks (masses $\gtrsim$ 500 GeV)

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- fourth family condensates are electroweak symmetry breaking order parameters
- Goldstone bosons couple strongly to fourth family quarks (masses $\gtrsim$ 500 GeV)
- quark masses bounded by unitarity $\lesssim$ 600 GeV
- experimentalists, what more do you want?
- formation of quark condensates takes us back 50 years to the NJL model
- 4-fermion operators can be generated by strong broken gauge interaction
- note: "NJL with no fine tuning" has no light composite scalar

	unbroken	broken
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- X can also be a remnant of broken flavor gauge interactions
- breakdown of the original flavor gauge interactions at a higher scale gives other 4-fermion operators
- can connect different families and have the effect of feeding mass down from heavy to light

$$\frac{1}{\Lambda^2}\overline{\Psi}\Psi\overline{\psi}\psi \quad \Rightarrow \quad \psi \text{ mass}$$

the X boson

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

- simplest way to cancel gauge anomalies is to have it also couple to the third family, with opposite charges

- produced through its coupling to the b
- distinctive decay mode $X \to \tau^+\tau^-$
  - this final state can be reconstructed since τ's are highly boosted

- unlike typical Z'
  - doesn't couple to light quarks
  - most likely a broad resonance

Diquark PGBs

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  - made likely by the required anomaly cancellation

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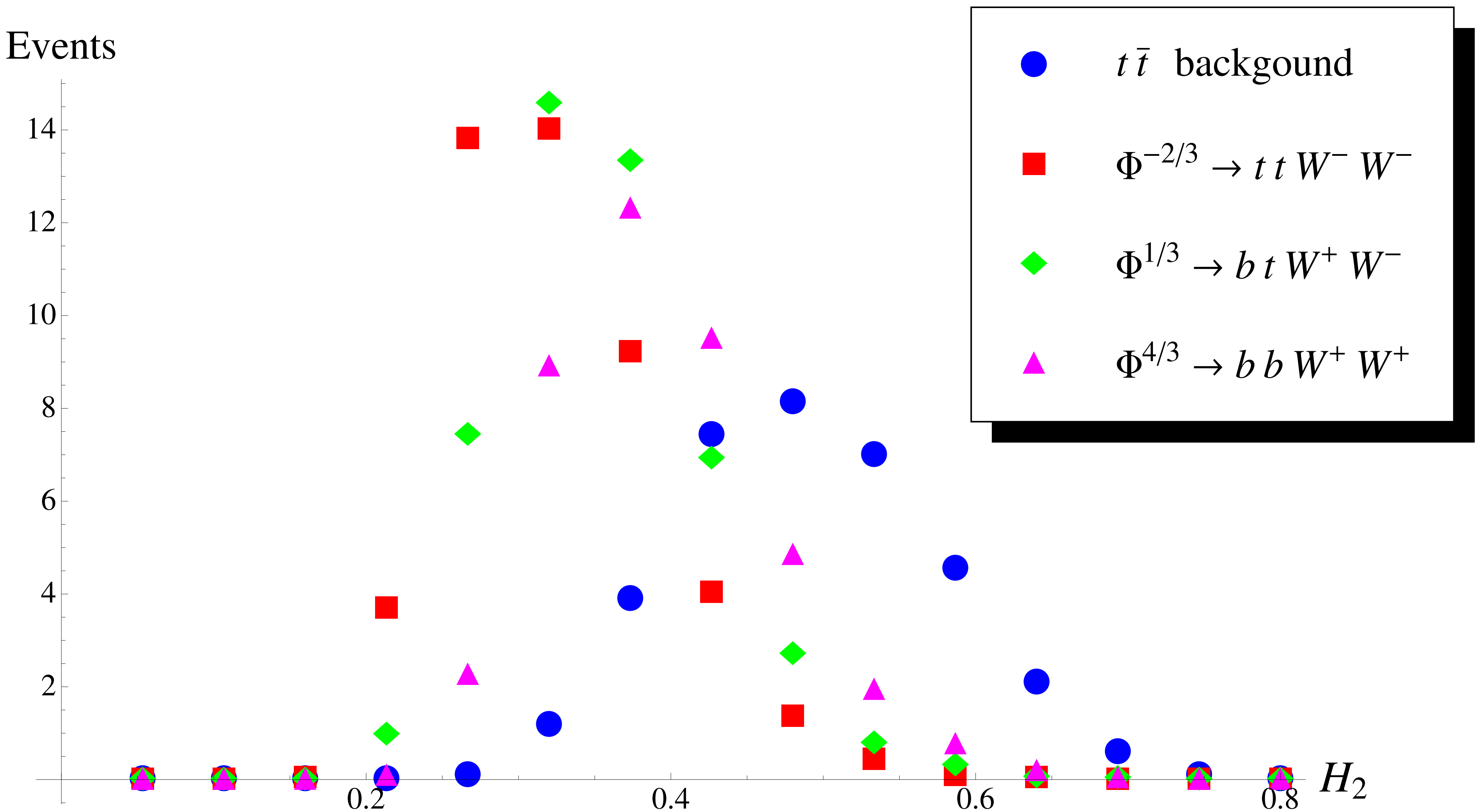
- pair production cross section of diquark sextets is 20 times larger than diquark color triplets or leptoquarks
- can lead to spectacular events (many jets, b's, leptons, missing energy)

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



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

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- theorists are attracted to the “exotic” while avoiding the “strong”
- thus the fourth family has been and still is overlooked and under appreciated
- rather than helping to protect the Higgs, it replaces it
- will it be the David to the Higg’s Goliath?