

Techniques for

Stop Searching!

2012

David Kaplan

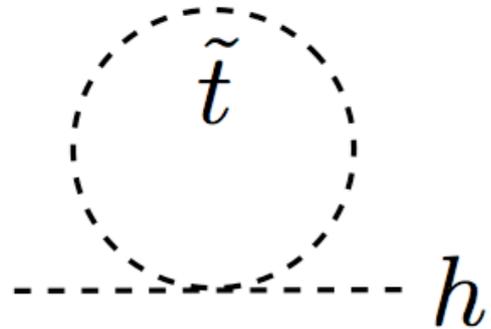
CERN QCD thingee just after they discovered the Higgs-like boson

Supersymmetry

- Naturalness (a la Wilson)
- Unification (LEP circa 1990)
- Dark Matter (LSP)

Susy: Naturalness

- For a weakly coupled Higgs, what cancels the top loop? Stop - but shouldn't be too heavy

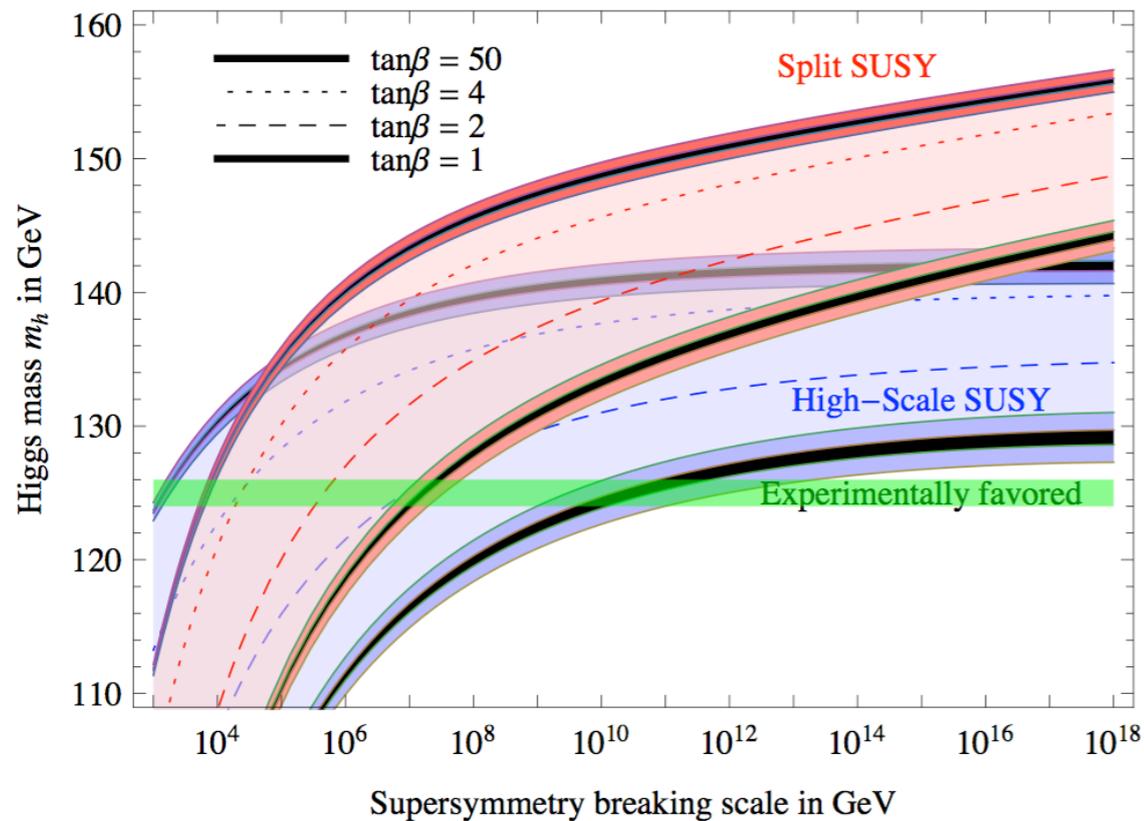


$$\delta m_{h_u}^2 \simeq -\frac{3y_t^2}{8\pi^2} (m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) \log \frac{M}{m_{\tilde{t}}}$$

Central question of our time:

EW-breaking Natural?

Last stand in SUSY naturalness



MSSM+S

non-decoupling D-terms

Dirac gauginos

Split families

compressed spectra

deconstructed gaugino mediation...

Cosmological constant?

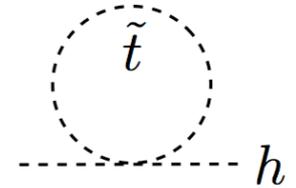
Look for stops?

- Most direct test of naturalness (dominant contribution to EW scale w/ simple cutoff).



- Naturalness requires very light stops ~ 400 GeV or less

$$\delta m_{h_u}^2 \simeq -\frac{3y_t^2}{8\pi^2} (m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) \log \frac{M}{m_{\tilde{t}}}$$



- Much much less model-dependent than the CMSSM
- Simple signature (tops plus missing E_T) $\tilde{t} \rightarrow t\tilde{\chi}_0$



- Direct production - small cross section.
- Huge $t\bar{t}$ background.
- SUSY infers other easier search channels

Easier than stops?

- Gluinos \rightarrow 400 GeV stop masses require 800 GeV gluinos (model dependent: dirac gauginos $m^2 = \frac{4\alpha_s M_{\tilde{g}}^2}{3\pi} \log(2)$)
- Sbottoms! also required to be light: “LH” sbottoms and stops in same doublet

$$\begin{pmatrix} m_Q^2 + m_t^2 + \Delta_{uL} & X_t \\ X_t^\dagger & m_U^2 + m_t^2 + \Delta_{uR} \end{pmatrix}$$

$$\begin{pmatrix} m_Q^2 + \Delta_{dL} & X_b \\ X_b^\dagger & m_D^2 + \Delta_{dR} \end{pmatrix}$$

$$m_Q^2 \tilde{q}^\dagger \tilde{q} + \lambda (h\tilde{q})^\dagger (h\tilde{q})$$

Same contribution

Supersymmetric

Aside: Split bottoms?

Add anti-generation:

$$Q_3 \begin{pmatrix} U_3^c & \bar{Q}_3 \\ yv_u & M_Q \end{pmatrix}$$
$$\bar{U}_3^c \begin{pmatrix} M_U & \bar{y}v_d \end{pmatrix}$$

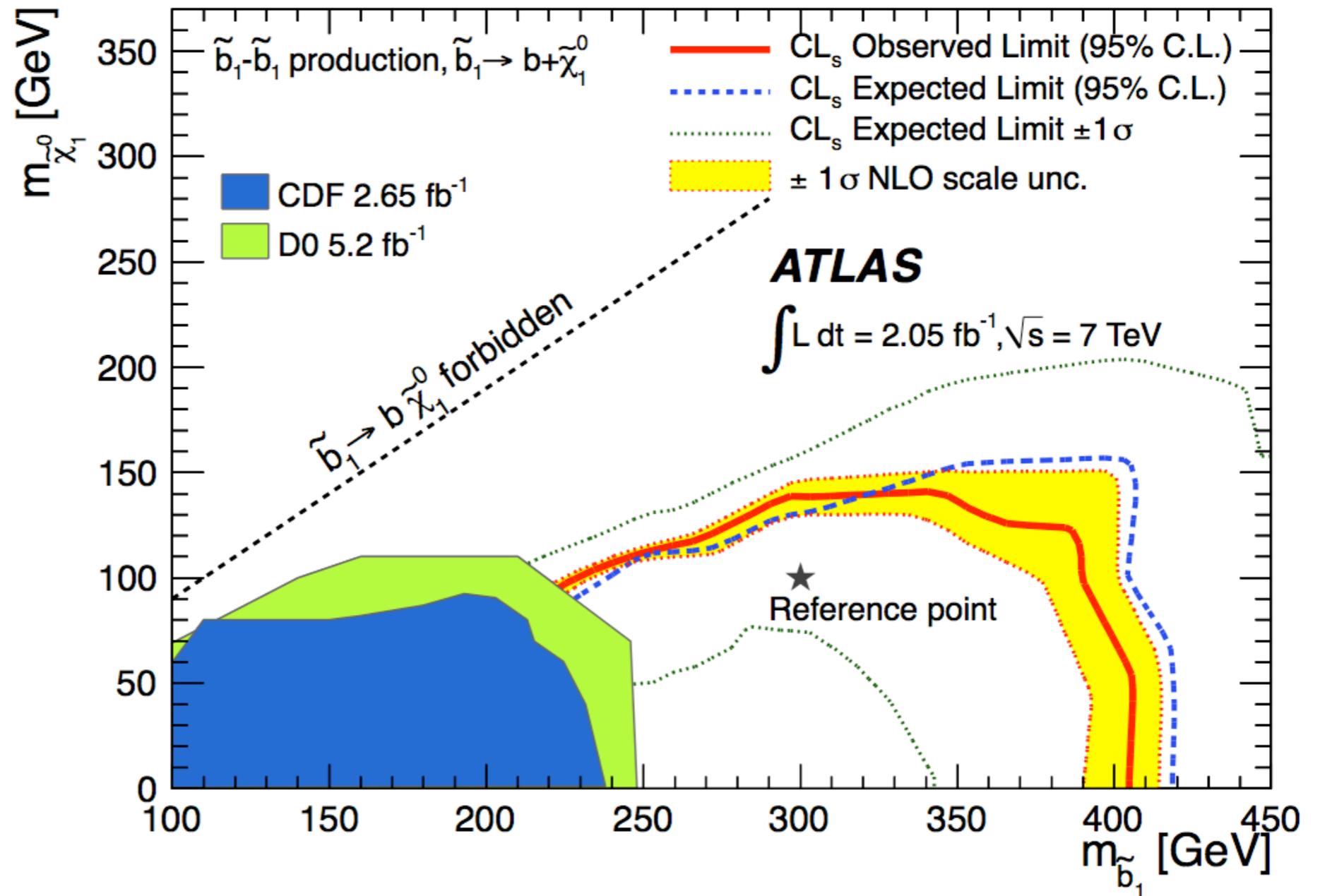
$$M_Q \gg M_U$$

Left-handed top could
be part singlet!

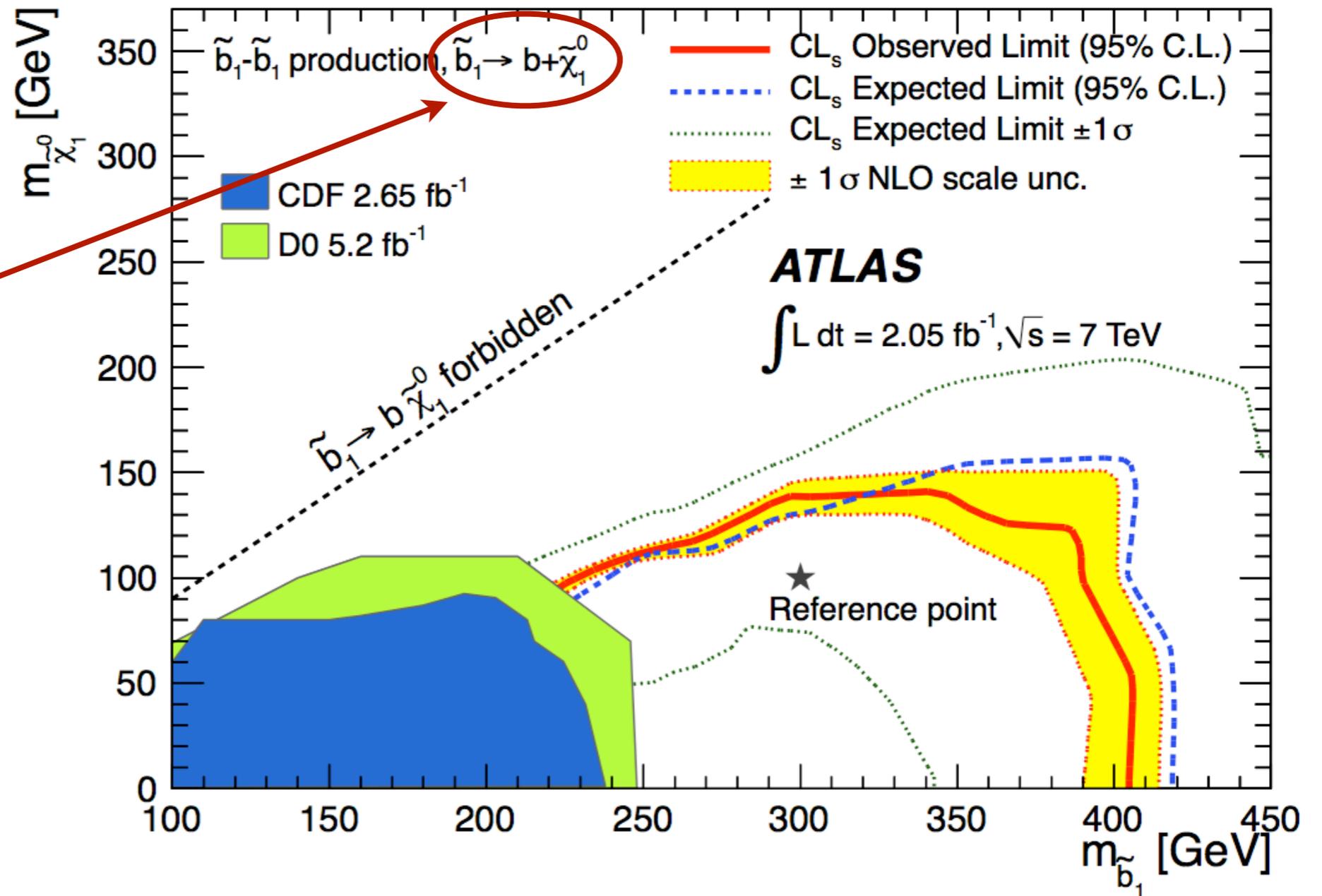
$$Q_3 \begin{pmatrix} D_3^c & \bar{Q}_3 \\ y_b v_d & M_Q \end{pmatrix}$$
$$\bar{D}_3^c \begin{pmatrix} M_D & \bar{y}_b v_u \end{pmatrix}$$

Requires either same
for bottom (bad for R_b)
or enormous Yukawas

Sbottom searches



Sbottom searches



Model-dependence.
Equally (or more) likely:

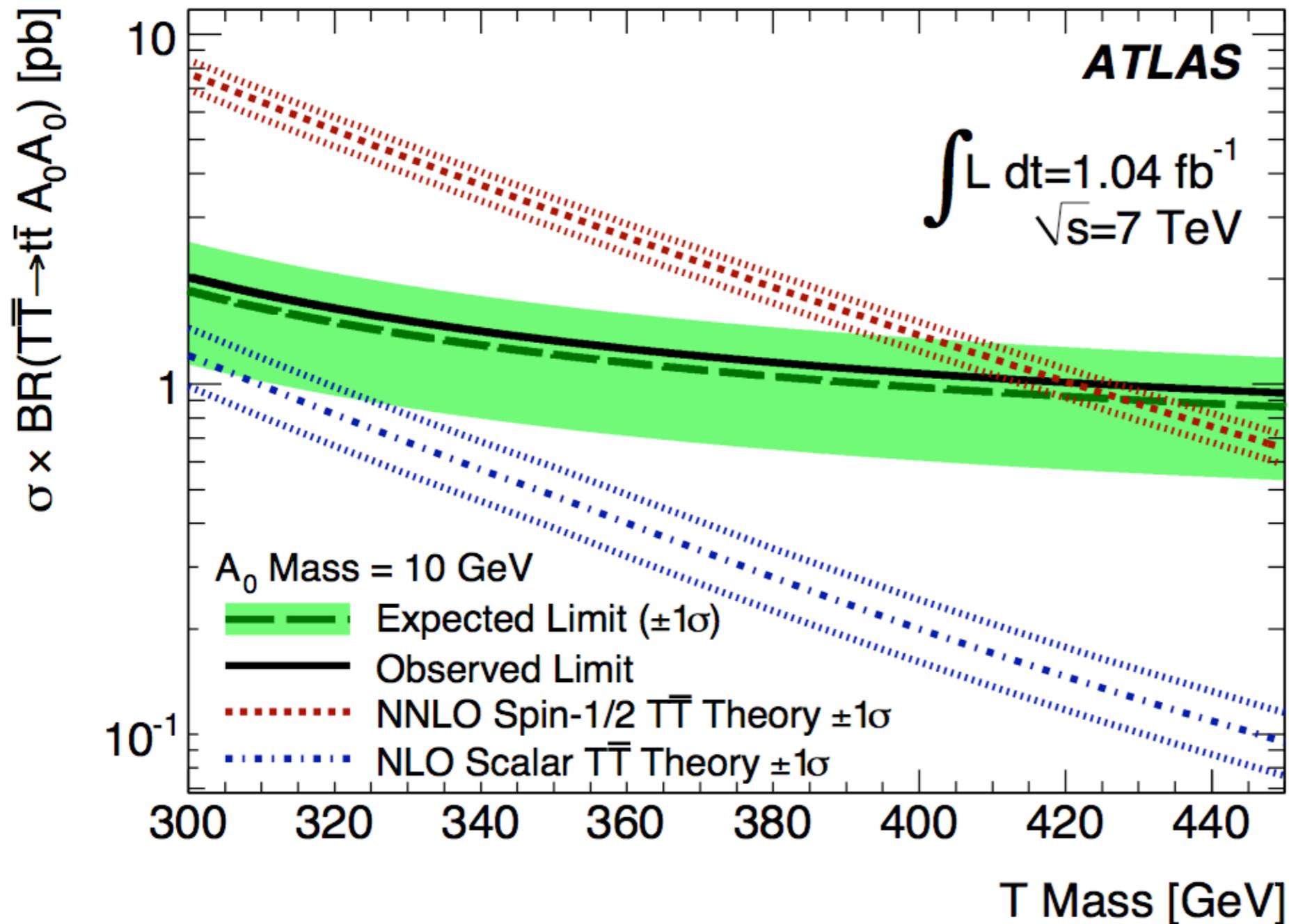
$$\tilde{b} \rightarrow \tilde{t} W \rightarrow \tilde{\chi}_0 t W$$

Direct stop production

- It is an important channel for ruling out SUSY naturalness.
- It is psychologically pleasing to have a concrete statement about the stop (which cancels the top loop).
- For decoupled (colored) superpartners, cross section only depends on mass.

$$\tilde{t} \rightarrow t \tilde{\chi}$$

Top partner searches

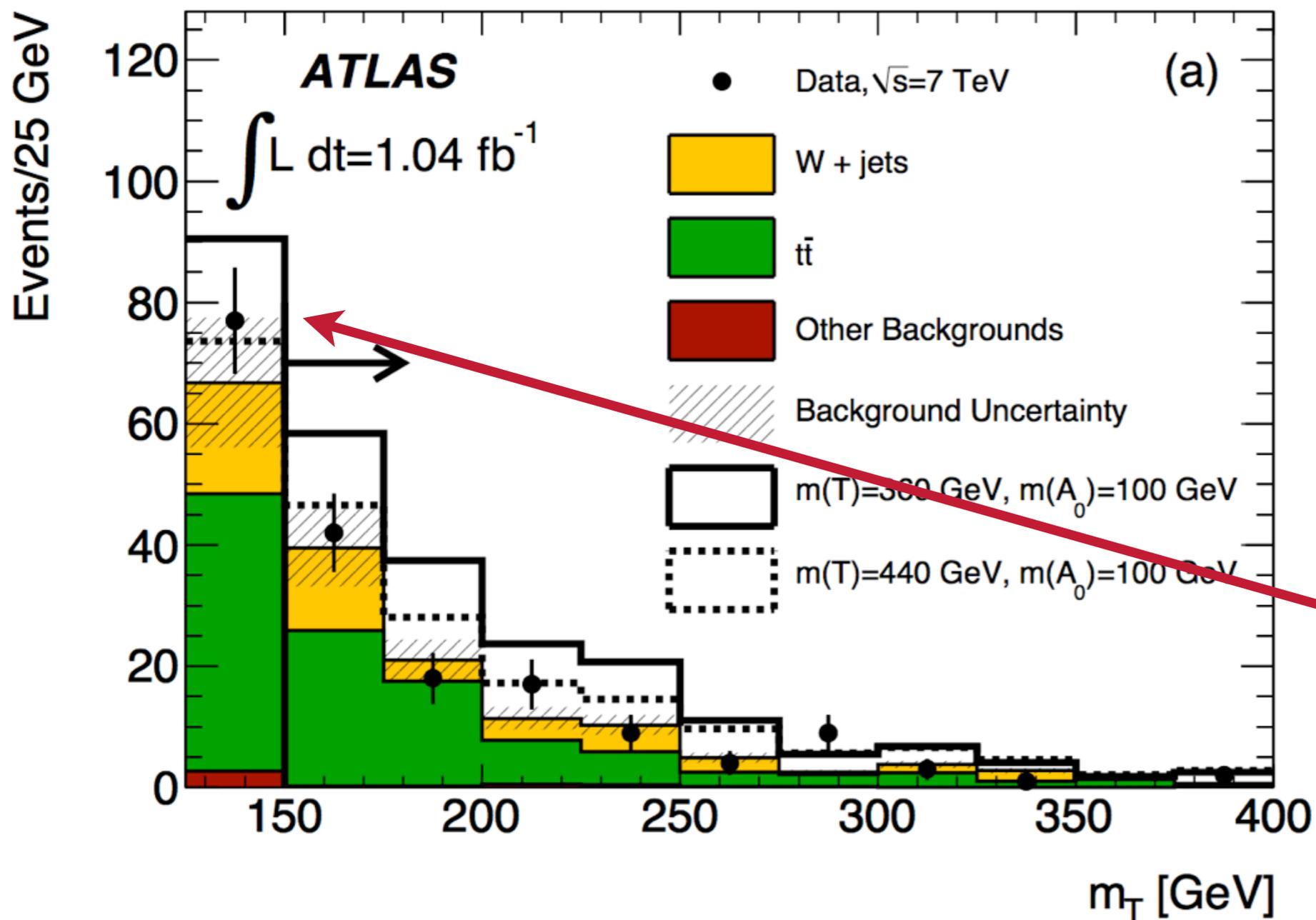


Semi-leptonic tops

stop have a small cross section - about 1/6 of Dirac Fermions



Top partner searches

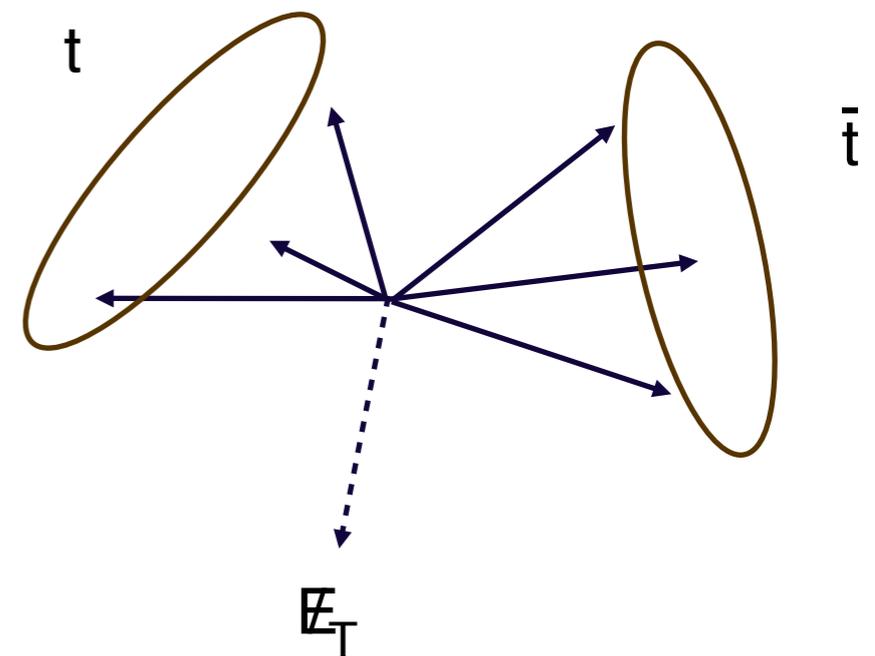


Semi-leptonic
tops

Neutrino in signal and
background affects
efficiency of cuts

Suggest: loose 'top tags'

- Look for fully hadronic tops: large BR and no neutrino
- Top tags kill combinatoric background for a very mild cost in signal



HEP TopTagger

a la Plehn, Spannowsky, Takeuchi and Zerwas, arXiv:1006.2833

- Cluster using Cambridge-Aachen with $R=1.2$
- De-cluster to find subjets. Each split to two, throw away one if other has $> 80\%$ of mass. Stop when all subjets have $m < 30$ GeV.
- Filter (a la Butterworth, et al: arXiv:0802.2470) with $R_{\text{filter}} = \min(0.3, R_{ij}/2)$. Keep up to five filtered subjets.
- Select three subjets whose combined invariant mass is closest to m_t . Require combined $p_T > 200$ GeV.
- Kinematic requirements on pairings of three subjets to loosely match W mass (details in paper)

Signal/backgrounds

Process	Generator cuts and parameters	σ (fb) 7 TeV	σ (fb) 8 TeV
$\tilde{t}\tilde{t}^*$ (340 GeV)	$\tilde{t}\tilde{t}^* \rightarrow b\bar{b} + 4j + 2\chi$	254	1.04×10^3
$\tilde{t}\tilde{t}^*$ (440 GeV)		48.8	205
$\tilde{t}\tilde{t}^*$ (540 GeV)		11.8	51.1
$t\bar{t} + \text{jets}$	$W \rightarrow \ell\nu, p_{T_\nu} > 80\text{GeV}$	16.3×10^3	26.7×10^3
sing. top + jets	$p_{T_\nu} > 100 \text{ GeV}$	4.65×10^3	8.27×10^3
$V + b\bar{b} + \text{jets}$	$Z \rightarrow \nu\bar{\nu}, W \rightarrow \ell\nu$	1.08×10^3	1.53×10^3
$V + \text{jets}$	$\sum \mathbf{p}_{T_\nu} > 80 \text{ GeV}$	66.6×10^3	96.3×10^3

Leading order. Matrix elements via MadGraph + MLM matching

Preselection

- isolated lepton veto (80% of Energy in $R = 0.4$), $p_T > 4,8 \text{ GeV}$ (μ, e), $l_{\text{etal}} > 2.5$ (also hadronic tau veto)
- $\Delta\phi_{\cancel{E}_T j} > 0.4$ and $\cancel{E}_T / \sqrt{H_T} > 5\sqrt{\text{GeV}}$
- $H_T > 275 \text{ GeV}$

Cuts

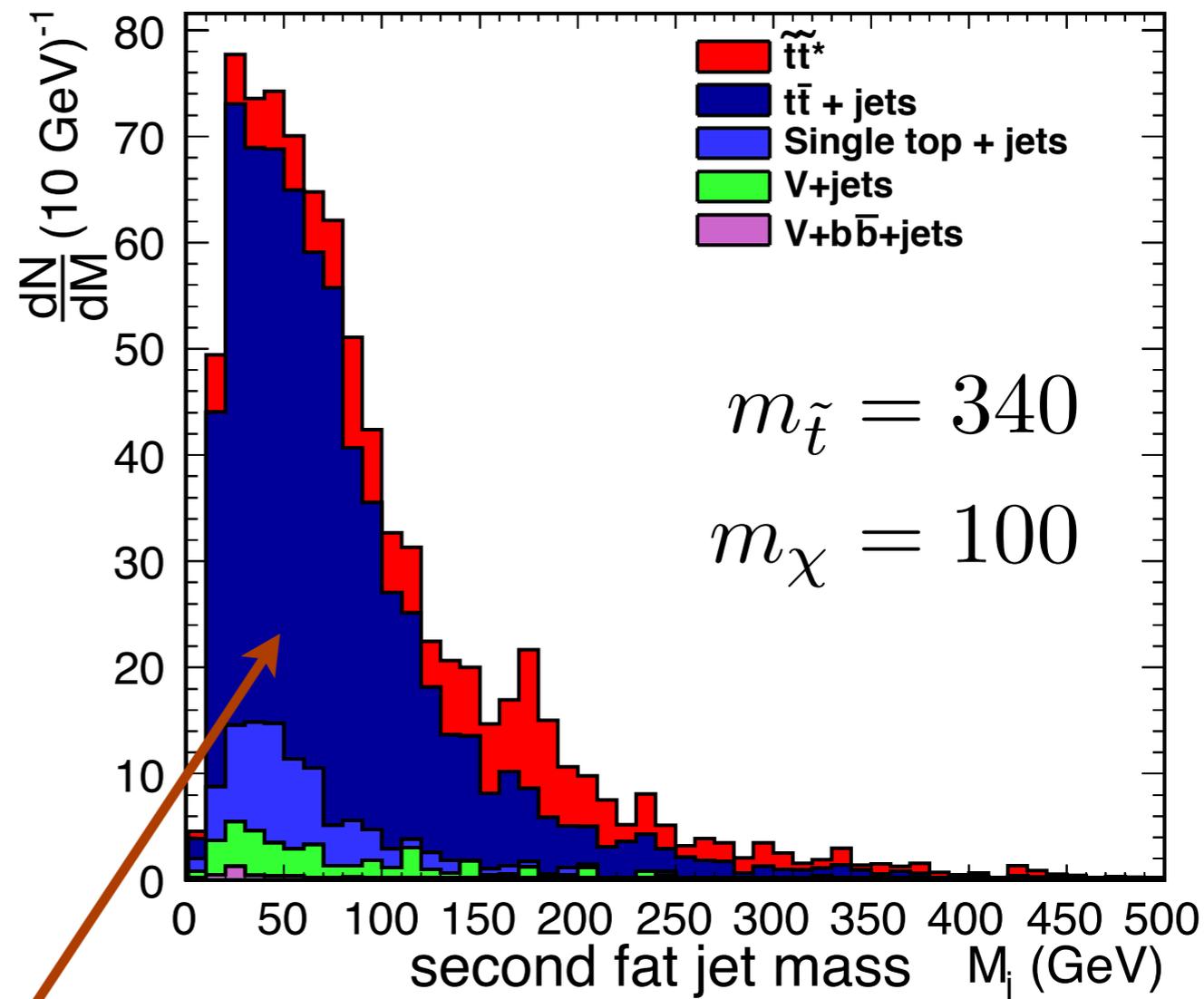
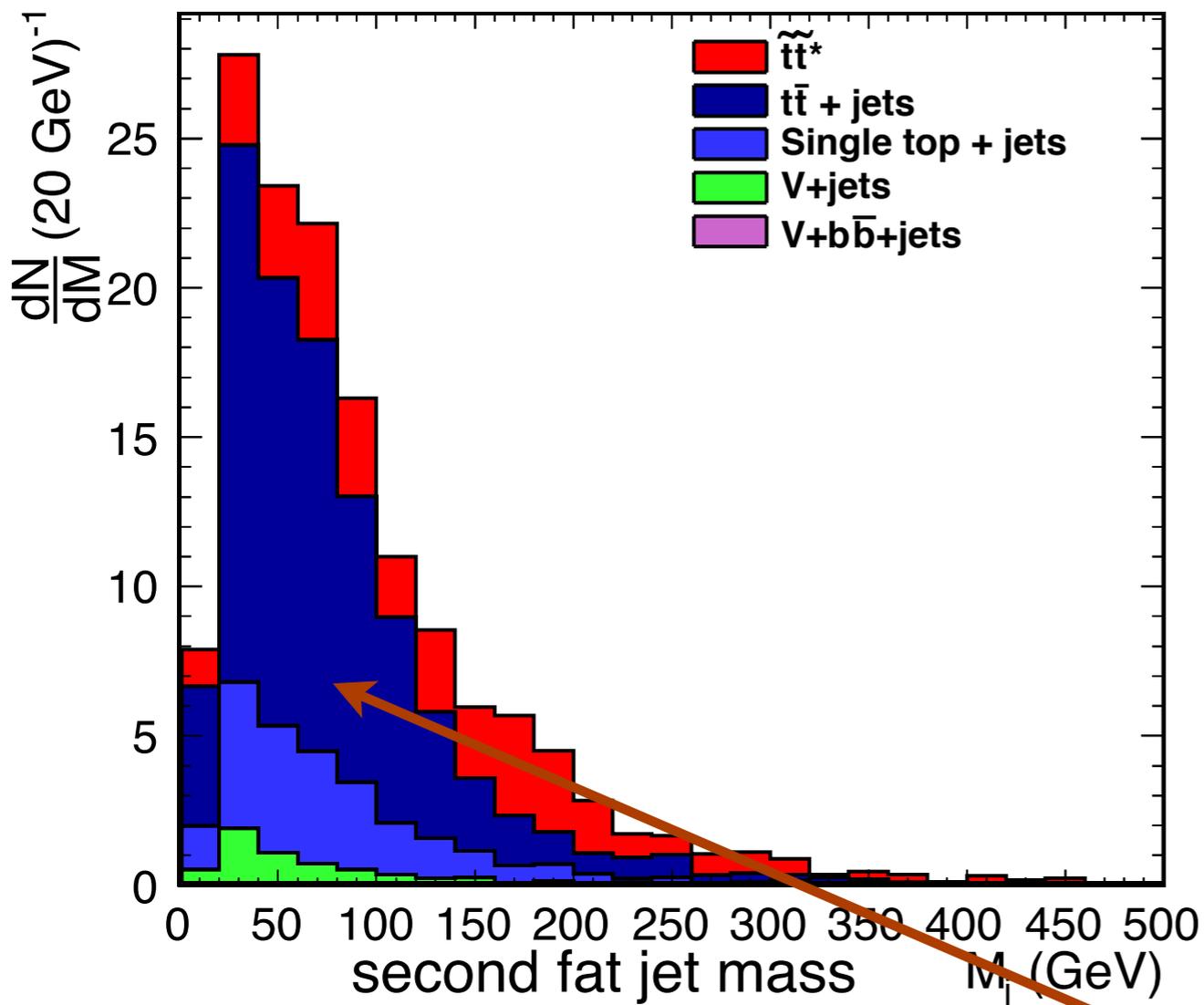
Require:

- Missing $E_T > 175$ GeV
- 2 fat jets, one 'top tagged'
- b-tag non-top-tagged subjets

Simulation

7 TeV, 5 fb⁻¹

8 TeV, 20 fb⁻¹

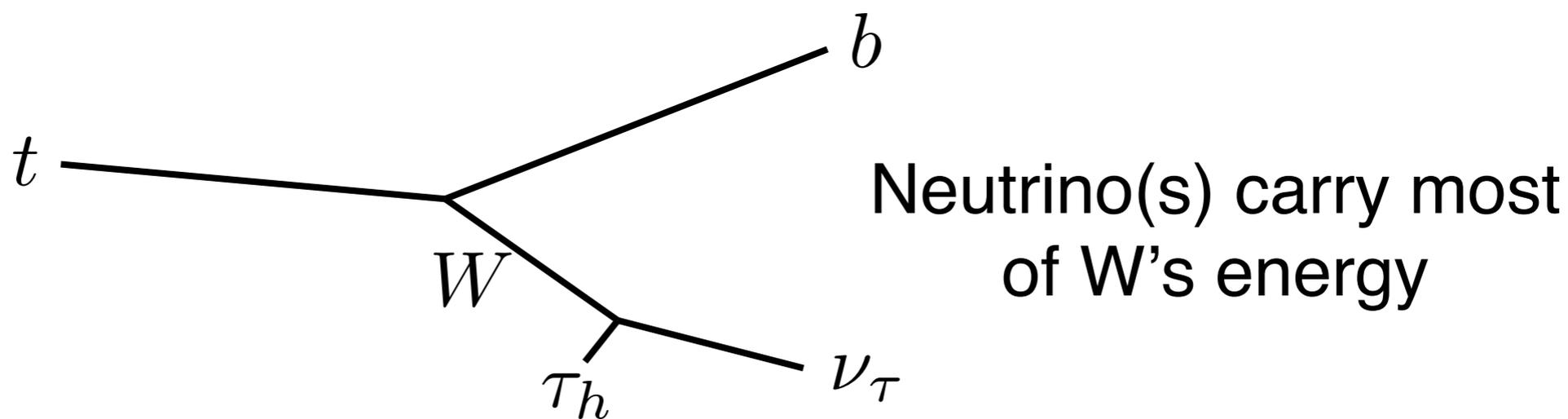


dominant background:

$$t\bar{t} + nj \rightarrow (bjj)(b\tau_h\nu_\tau) + nj$$

Dominant background

$$t\bar{t} + nj \rightarrow (bjj)(b\tau_h\nu_\tau) + nj$$



$$m_T^2 < \sqrt{m_t^2 - m_W^2} \simeq 155 \text{ GeV}$$

Transverse mass cuts

- m_{T2} cut on two fat jets and MET (>200 GeV)
- m_T cut on each of the two fat jets (>200 GeV)

$$m_T^2(\mathbf{p}_T^\alpha, m_\alpha, \mathbf{q}_T^\beta, m_\beta) = m_\alpha^2 + m_\beta^2 + 2(E_T^\alpha E_T^\beta - \mathbf{p}_T^\alpha \cdot \mathbf{q}_T^\beta)$$

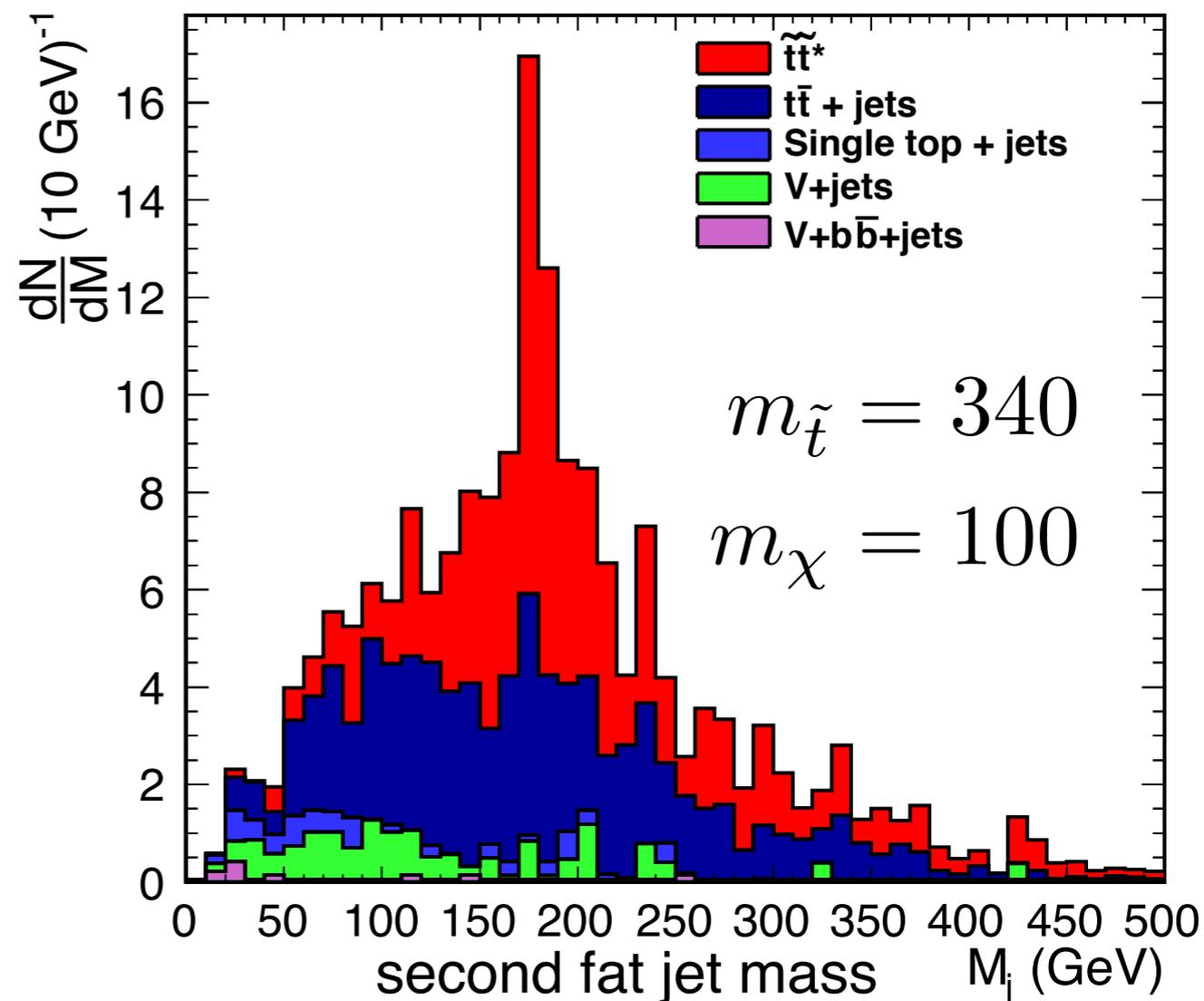
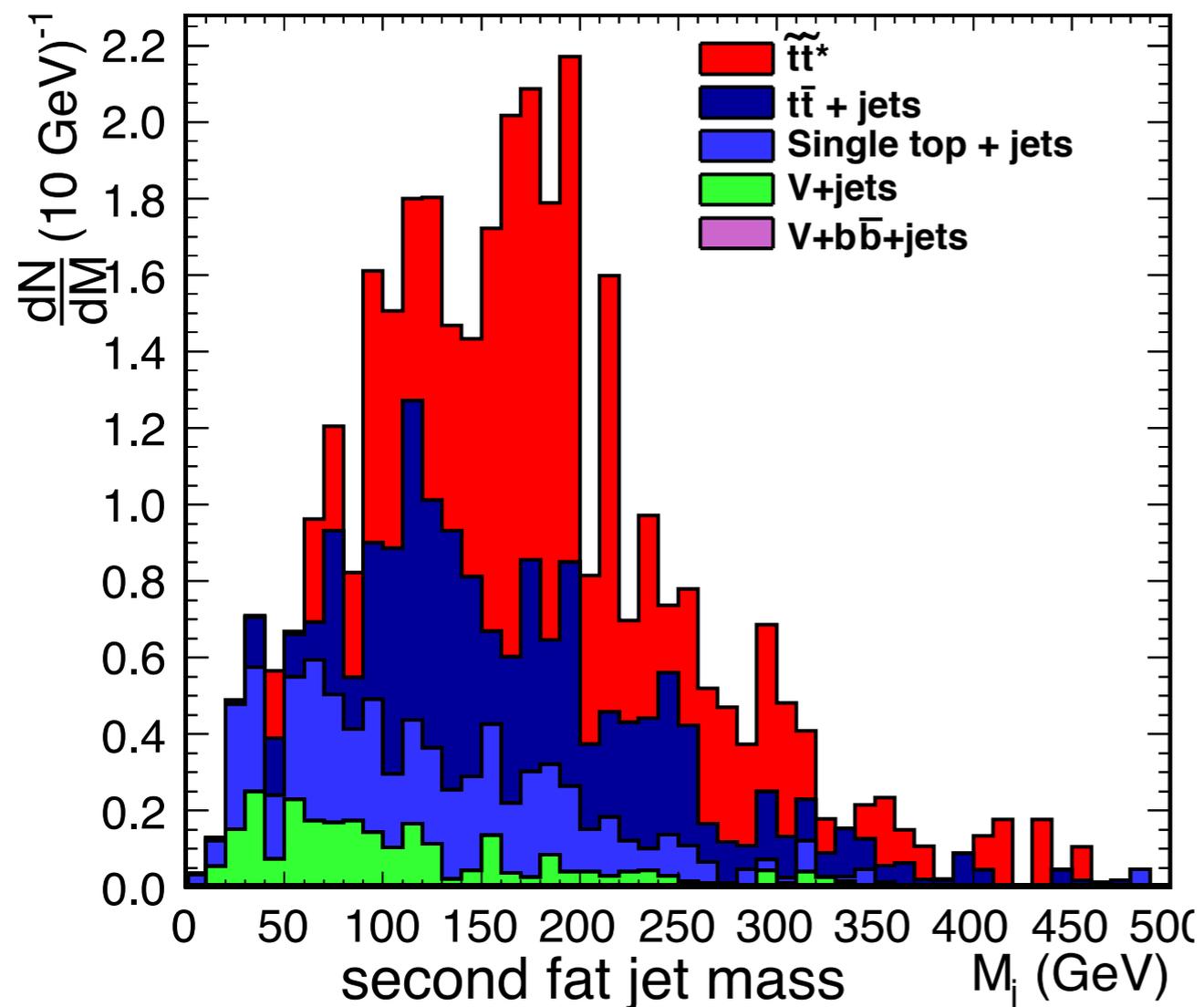
$$E_T^\alpha = \sqrt{m_\alpha^2 + (\mathbf{p}_T^\alpha)^2}$$

$$m_{T2}^2(\mathbf{p}_T^\alpha, m_\alpha, \mathbf{p}_T^\beta, m_\beta, \cancel{\mathbf{p}}_T, m_\chi) = \min_{\mathbf{q}_T^{(1)} + \mathbf{q}_T^{(2)} = \cancel{\mathbf{p}}_T} \min$$

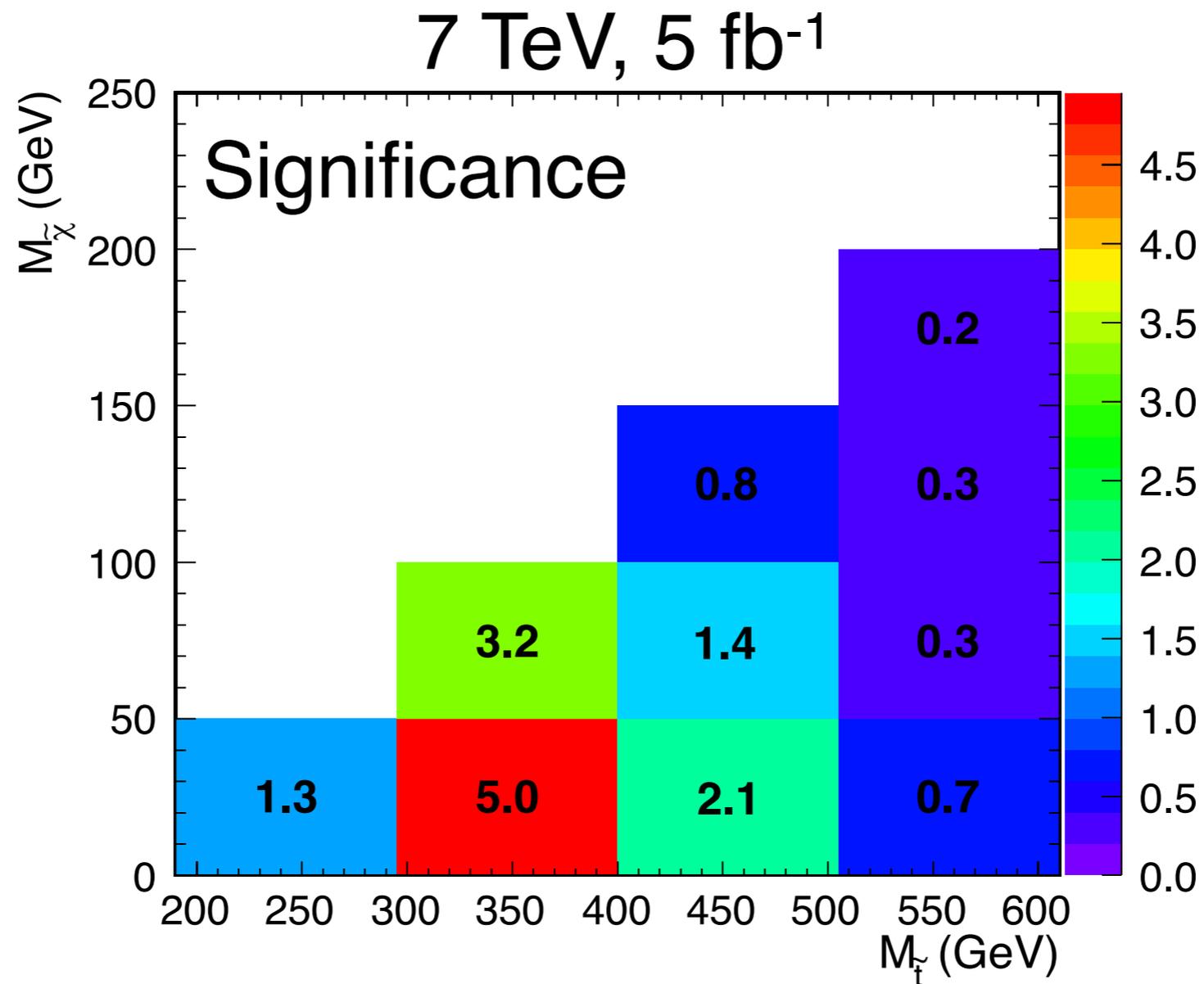
$$\left[\max\{m_T^2(\mathbf{p}_T^\alpha, m_\alpha, \mathbf{q}_T^{(1)}, m_\chi), m_T^2(\mathbf{p}_T^\beta, m_\beta, \mathbf{q}_T^{(2)}, m_\chi)\} \right]$$

Transverse mass cuts

8 TeV, 20 fb⁻¹



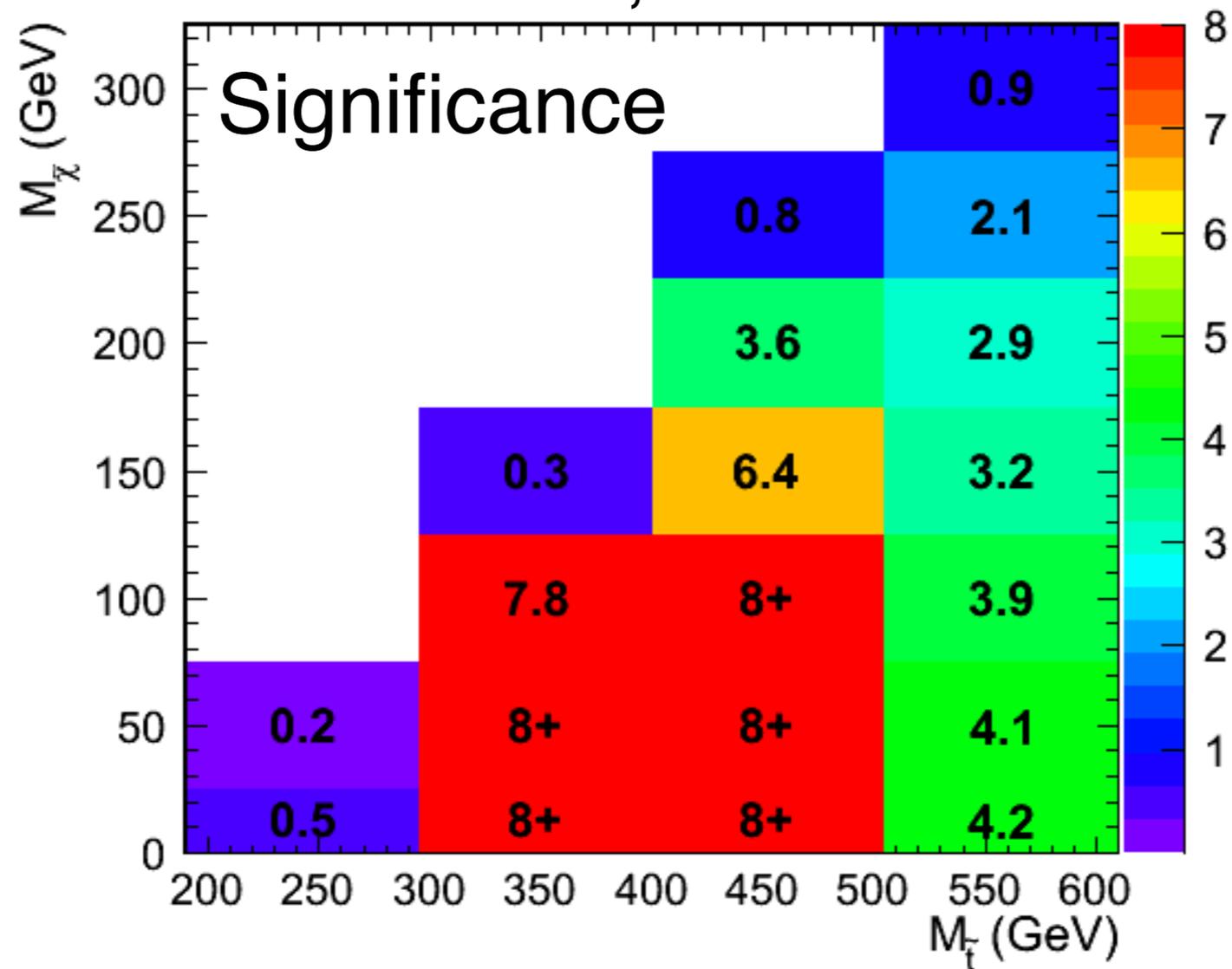
Parametric Reach



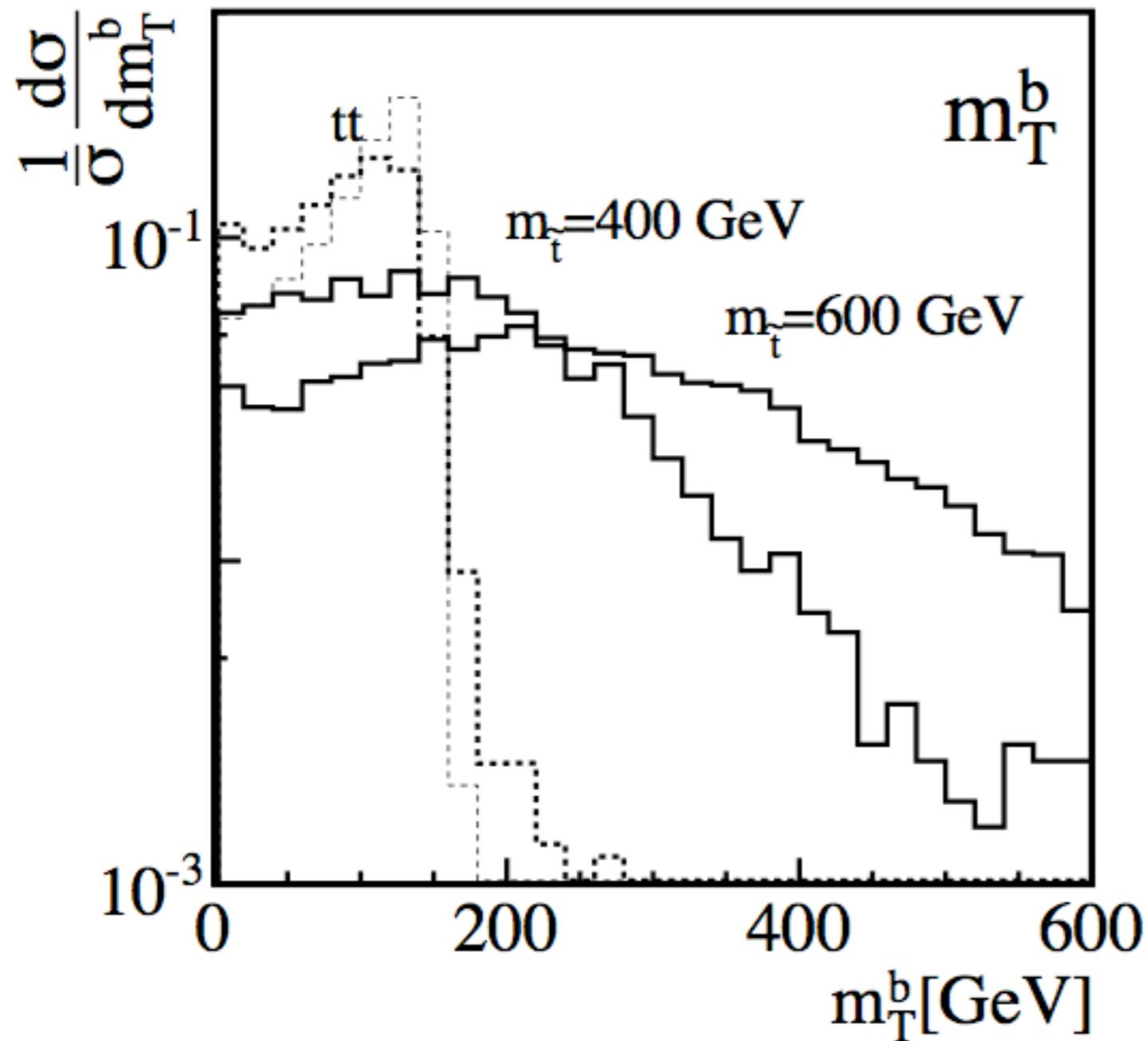
Can be done now!

Parametric Reach

8 TeV, 20 fb⁻¹



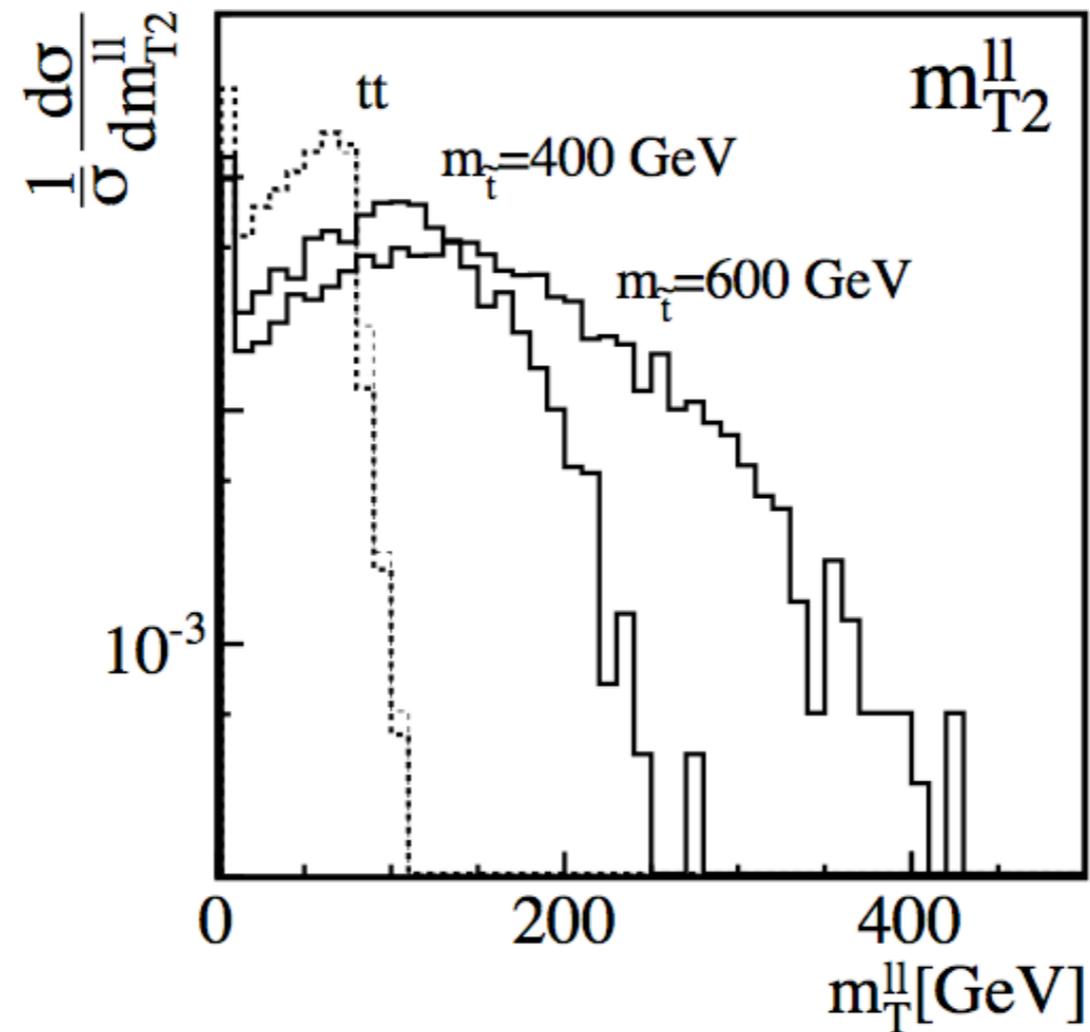
Semi-leptonic tops



$$m_T > 150 \text{ GeV}$$

Plehn, et al arXiv:1205.2696

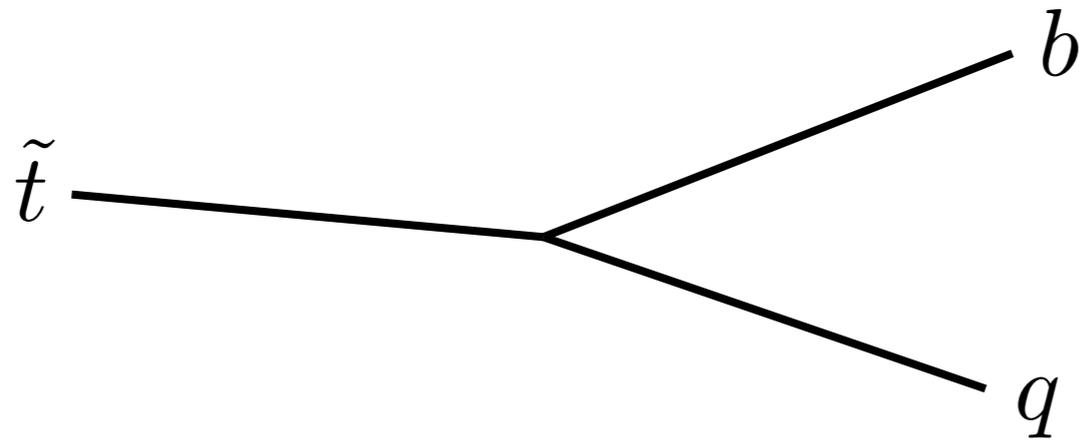
Fully leptonic tops



$$m_{T2}^{\ell\ell} = \min_{\vec{p}_T = \vec{p}_1 + \vec{p}_2} [\max(m_T(p_{\ell_1}, \vec{p}_1), m_T(p_{\ell_2}, \vec{p}_2))] > 100 \text{ GeV}$$

Other Models

R-parity violating decays kills missing energy



stop pair production = 4 jets!

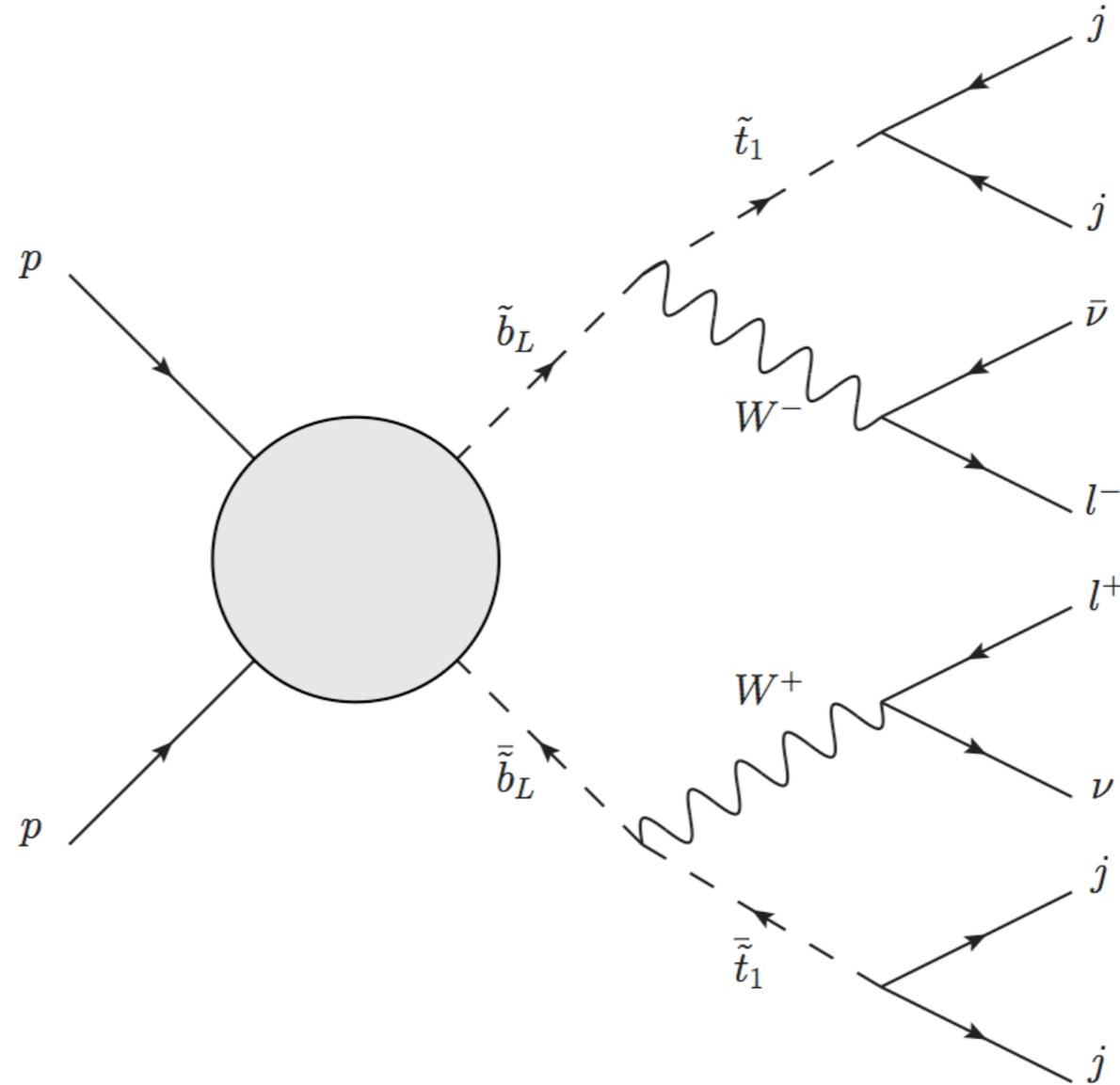
Displaced vertices?

Baryon number violation can wash out the B asymmetry unless:

- coupling is smaller than 10^{-7}
- the reheat temperature is very low (~ 1 GeV)

$$L \sim (1 \text{ mm}) \left(\frac{300 \text{ GeV}}{m_{\tilde{t}_R}} \right) \left(\frac{(2.5 \cdot 10^{-7})^2}{\sum \lambda_{3IJ}^2} \right)$$

RPV - sbottom decays



Brust, Katz, Sundrum arXiv:1206.2353

Conclusion: 2012 quests

- Higgs couplings SM or BSM?
- Top partners discoverable this year?
- Gluino mass limit straining MSSM?
- Can we kill a natural explanation for the electroweak scale?
- Did the Mayans predict this?