STOP SEARCHES AND NATURAL SUSY

UNIVERSITY OF MARYLAND 1856

DANIEL STOLARSKI

THE JOHNS HOPKINS UNIVERSITY BALTIMORE 1876

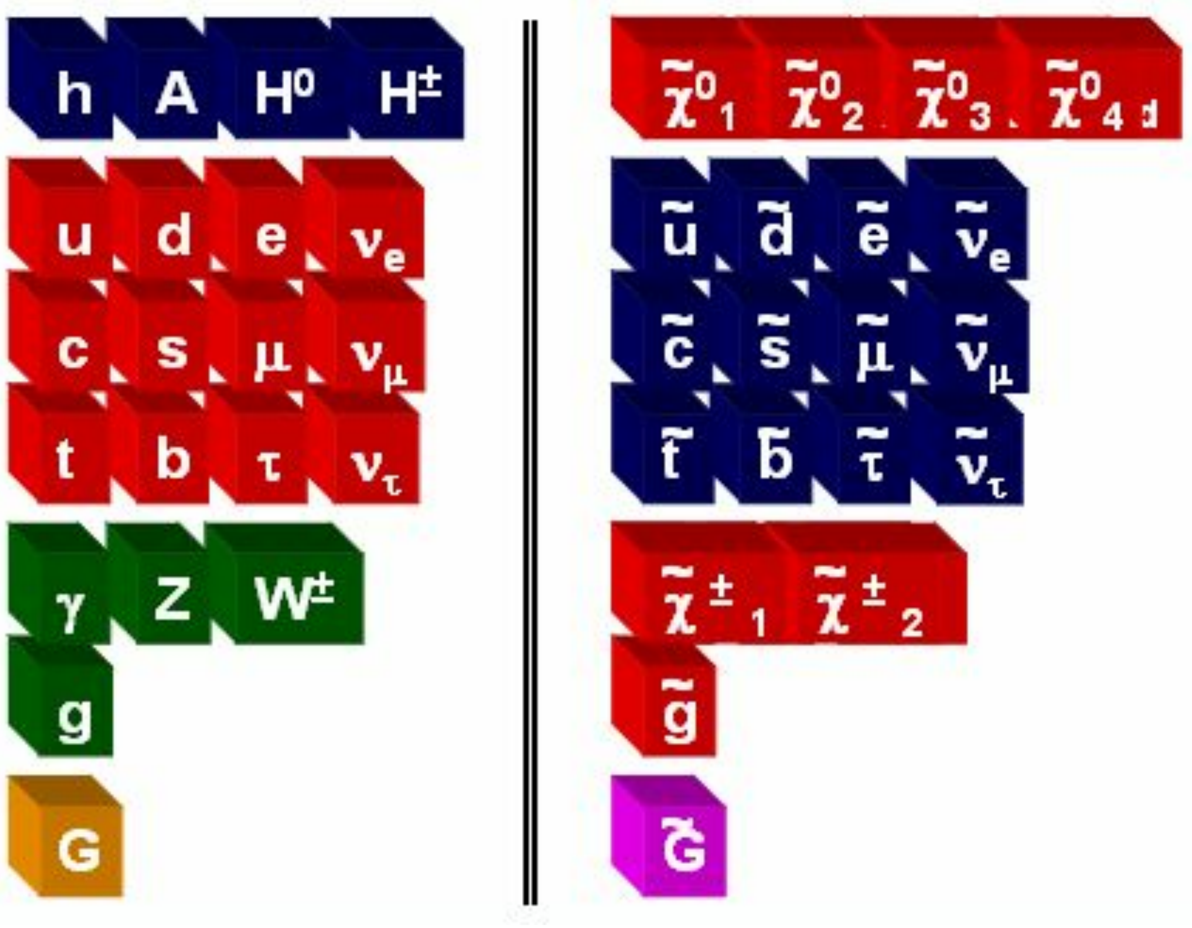
DAVID E. KAPLAN, KEITH REHERMANN, DS, arXiv:1205.5816

DISCLAIMER

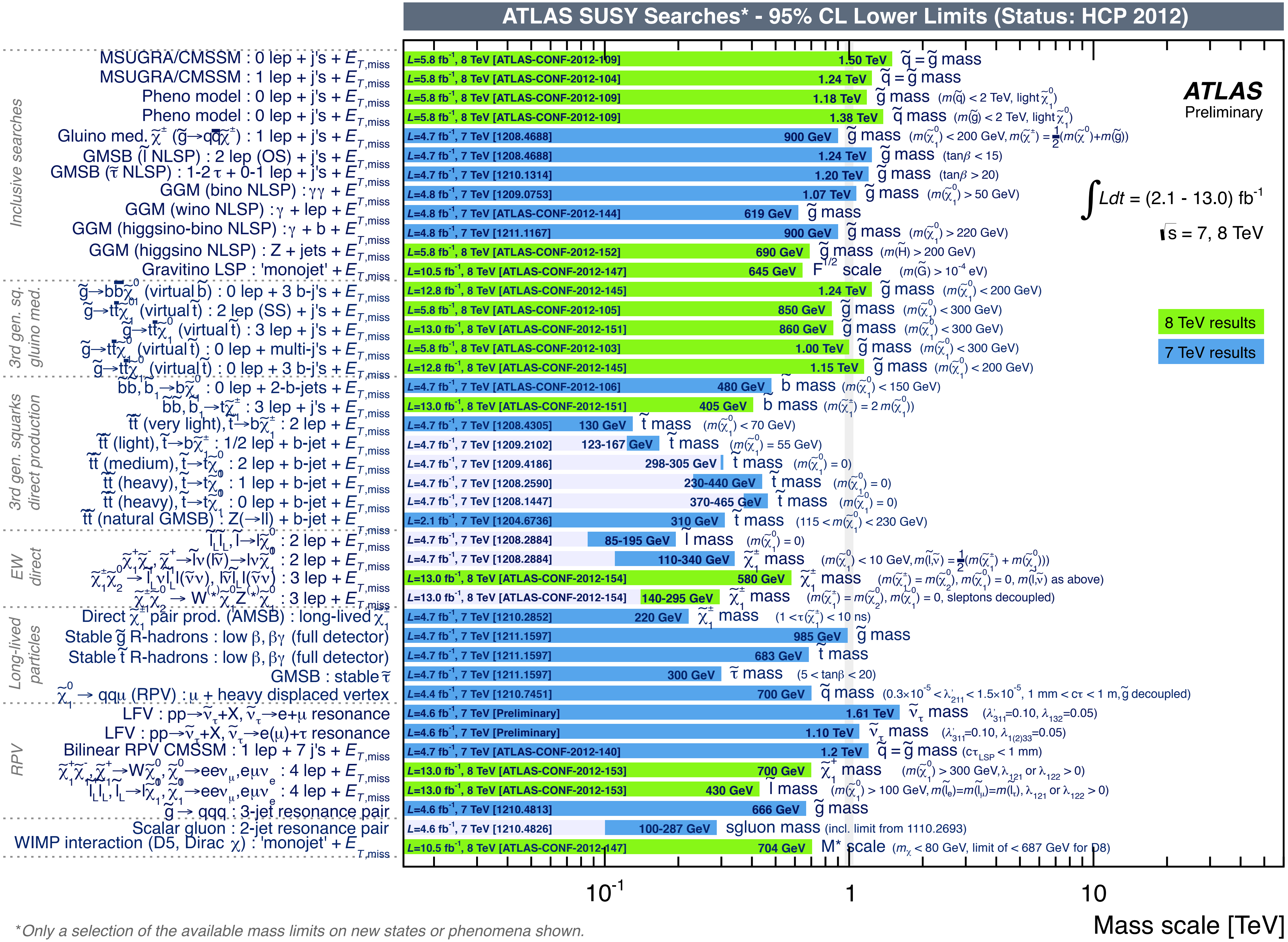
- Distilled the talk to the main points
- Talk may last less than an hour
- I’m happy to talk after about this or other things I’m working on

SUPERSYMMETRY IS GREAT!

- Elegant extension of spacetime symmetries
- Grand unification works better than SM
- Well motivated *R*-parity automatically gives dark matter candidate
- Solves hierarchy problem?



LHC ASSAULT



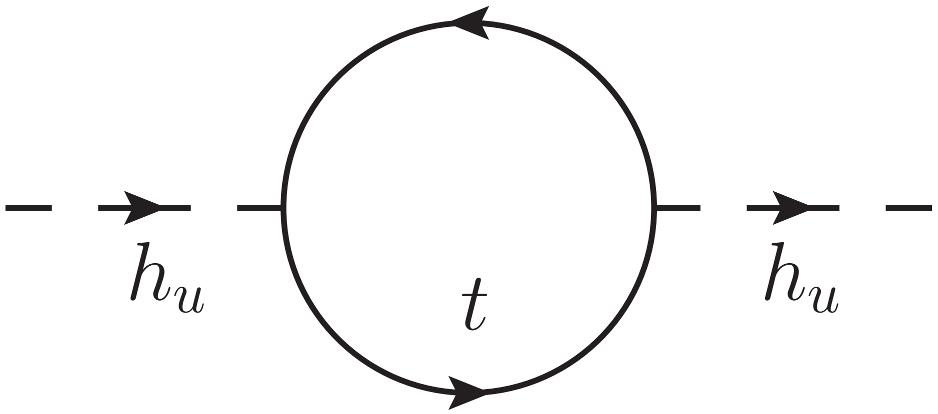
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

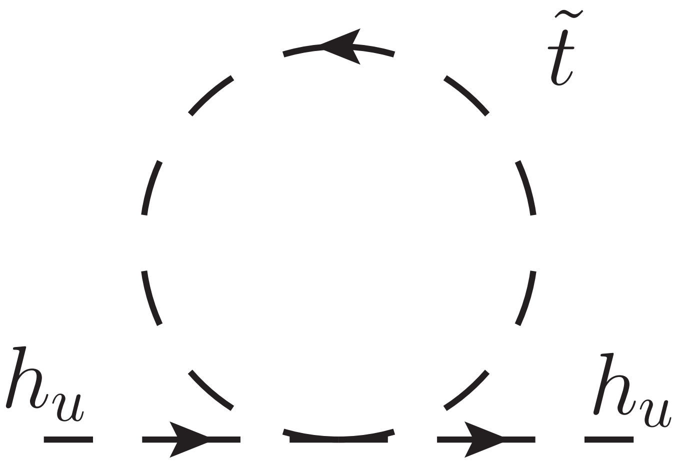
MINIMAL OR NATURAL SUSY

What is the minimal particle content needed for naturalness?

Brust, Katz, Lawrence, Sundrum, 1110.6670. Papucci, Ruderman, Weiler, 1110.6926.

Stops





$m_{\tilde{t}} \lesssim 400 \text{ GeV}$

*Get left handed sbottom also

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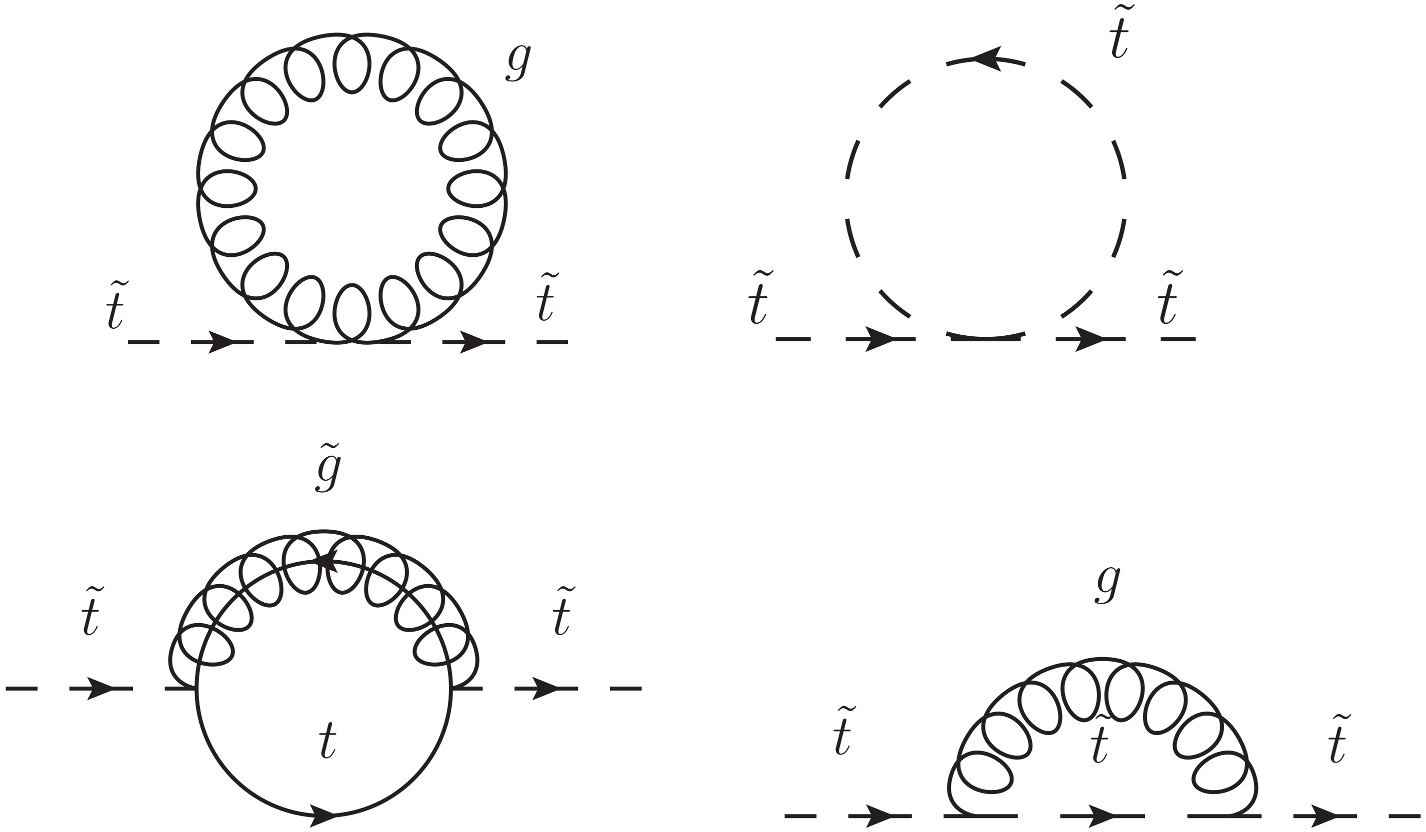
Gluino

$$\delta m_{\tilde t}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde g}^2 \ln\frac{\Lambda_{UV}}{m_{\tilde g}}$$



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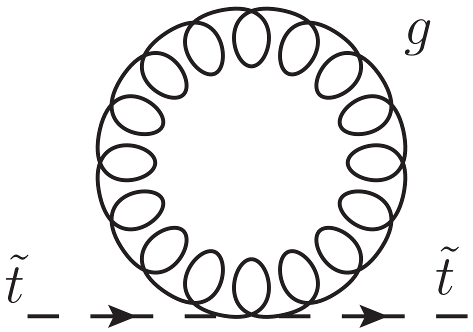

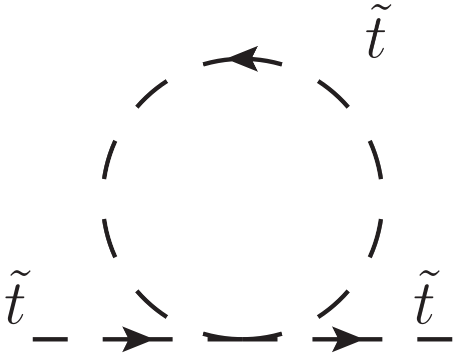

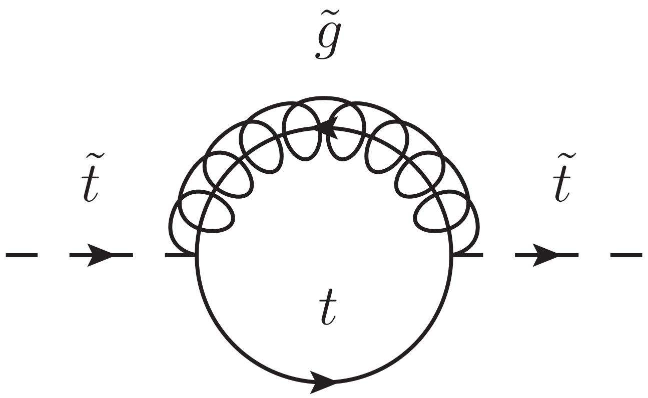

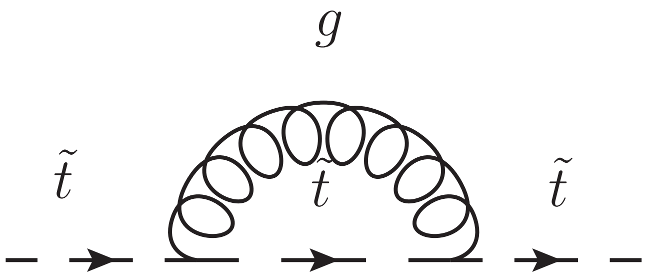

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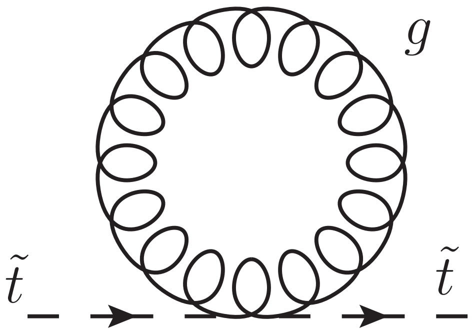

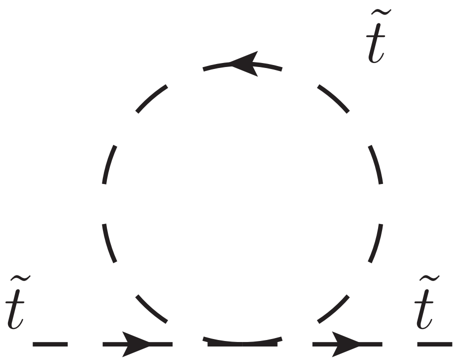

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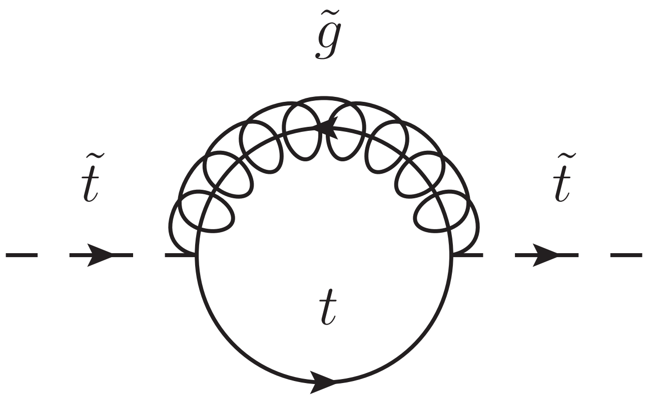

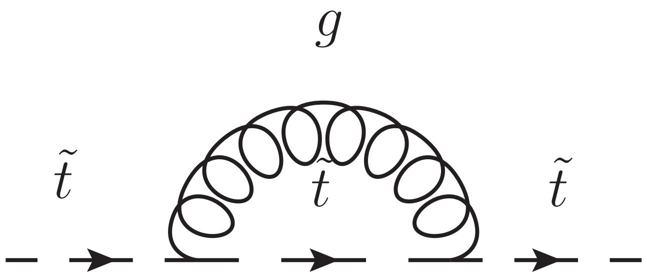

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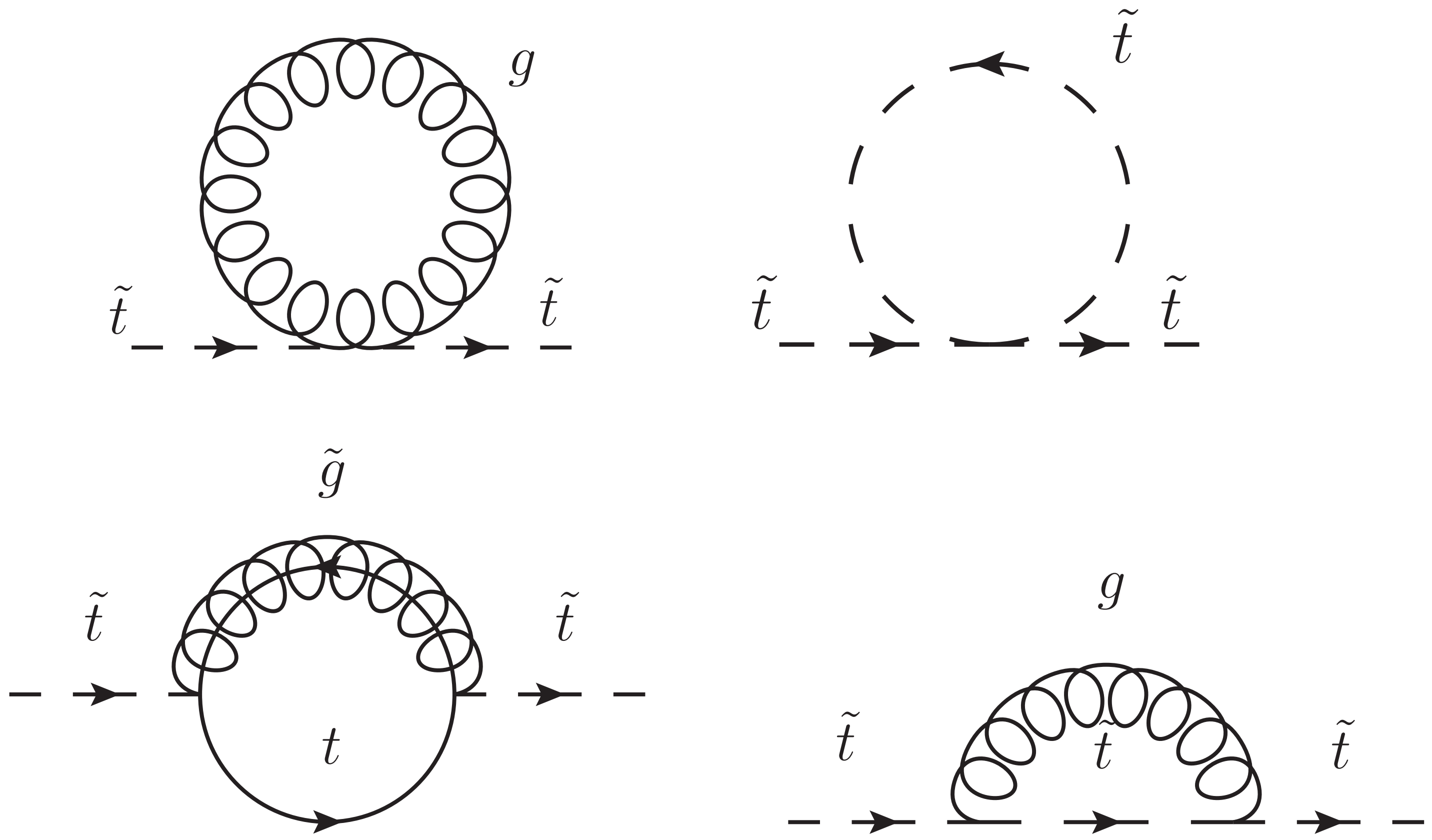

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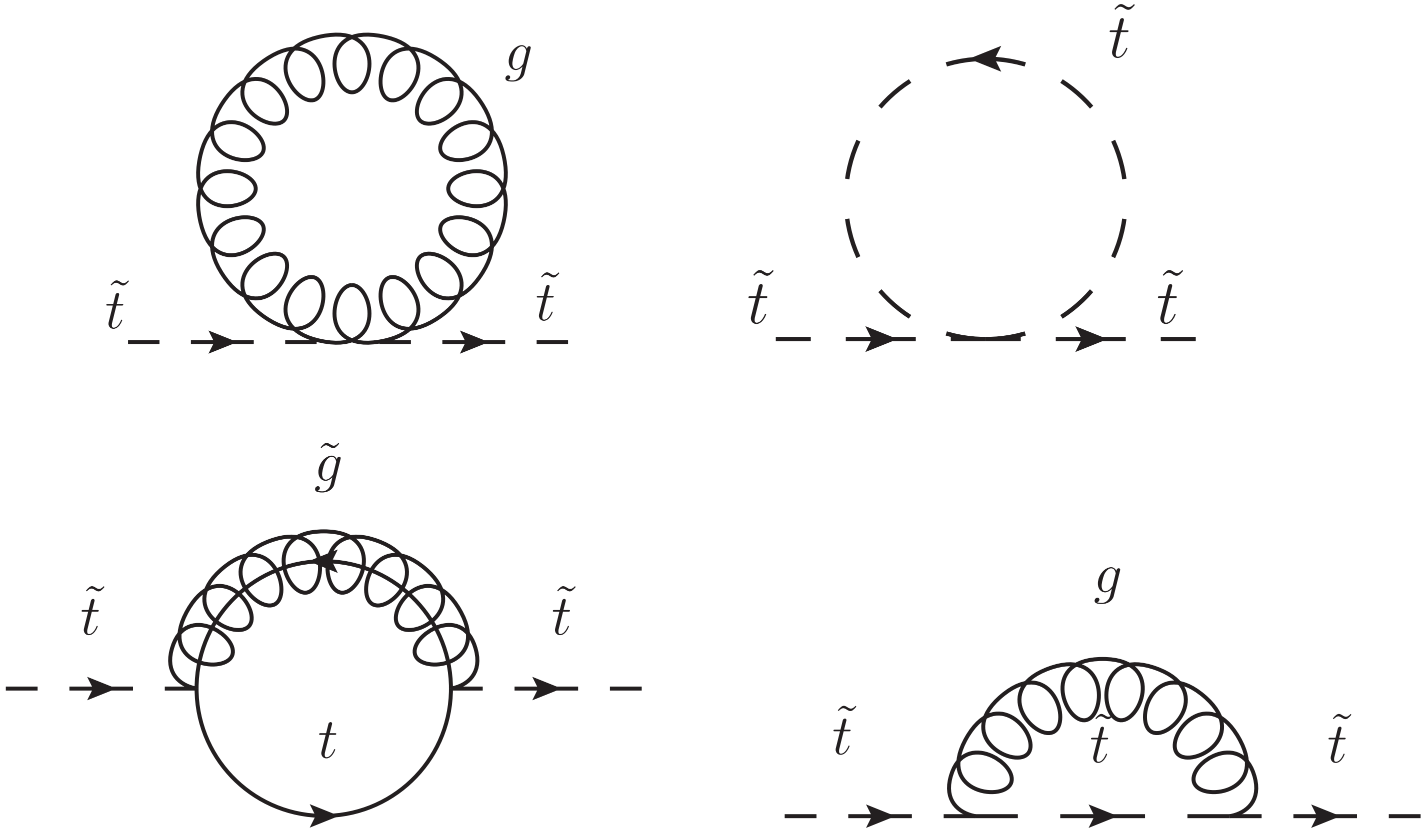

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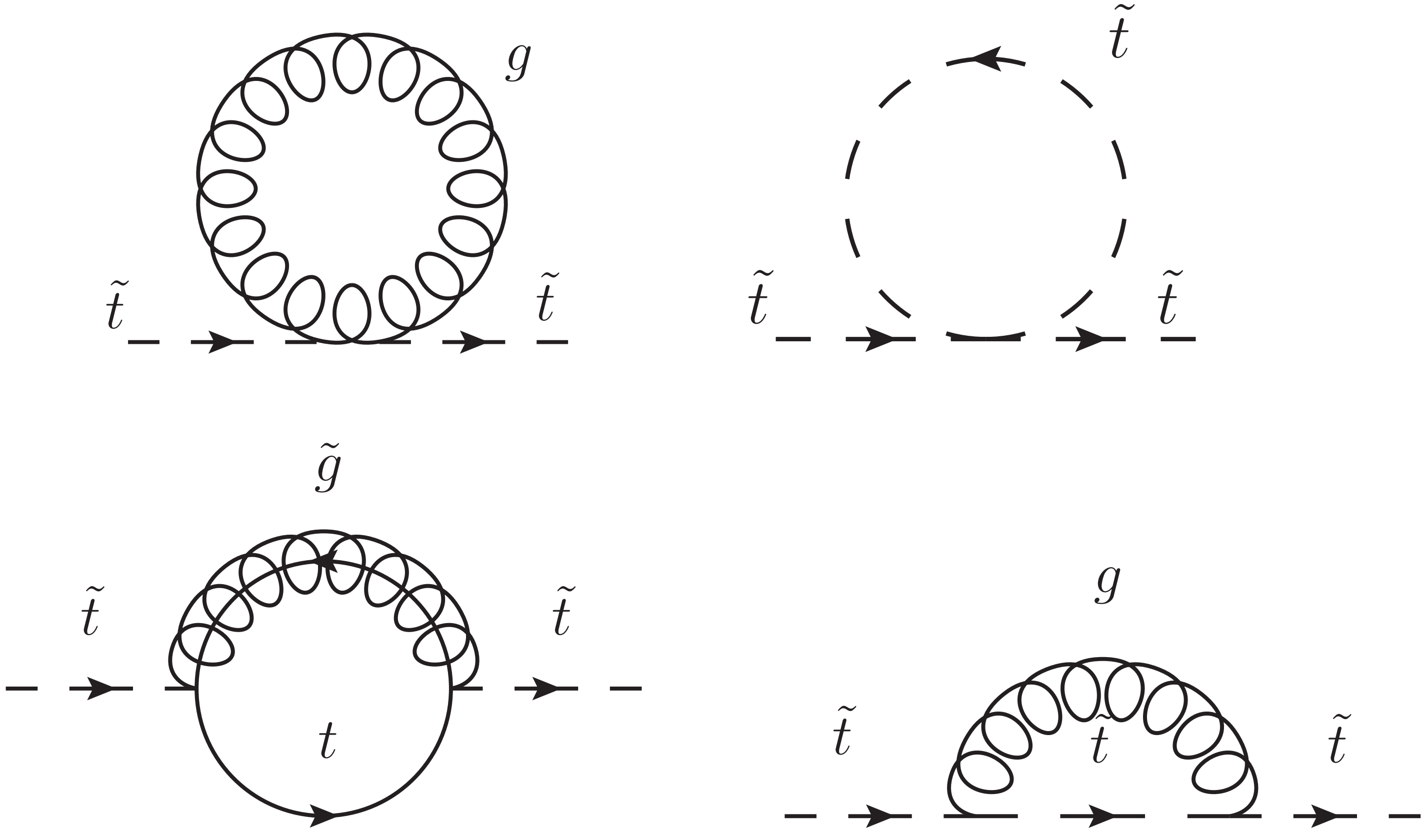
$$m_{\tilde{g}} \lesssim 4 m_{\tilde{t}}$$



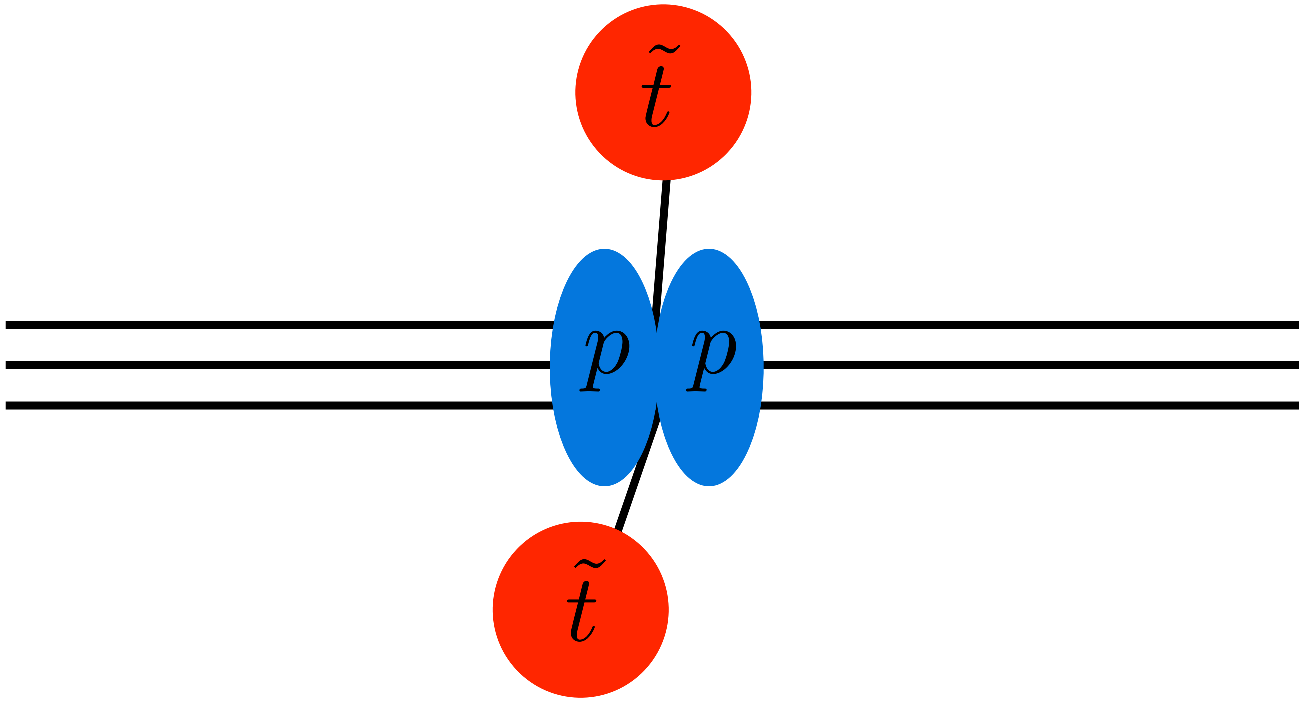
STOP SCENARIO

- Stop is lightest particle required by naturalness

- R-parity and neutralino LSP is well motivated

- Consider minimal spectrum with only right handed stop, light invisible particle, and $m_{\tilde{t}} > m_t + m_{\chi^0}$

STOP EVENTS



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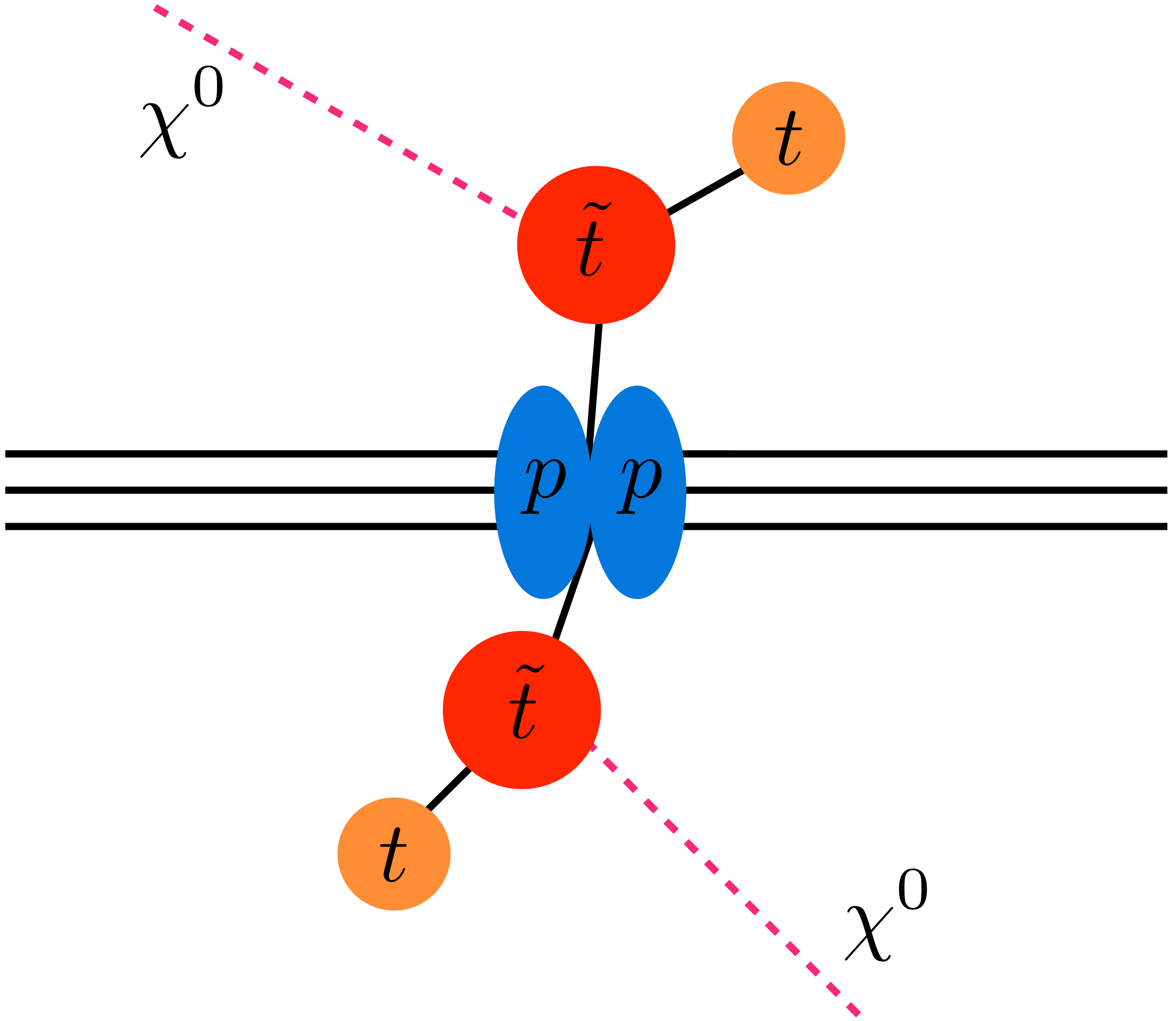

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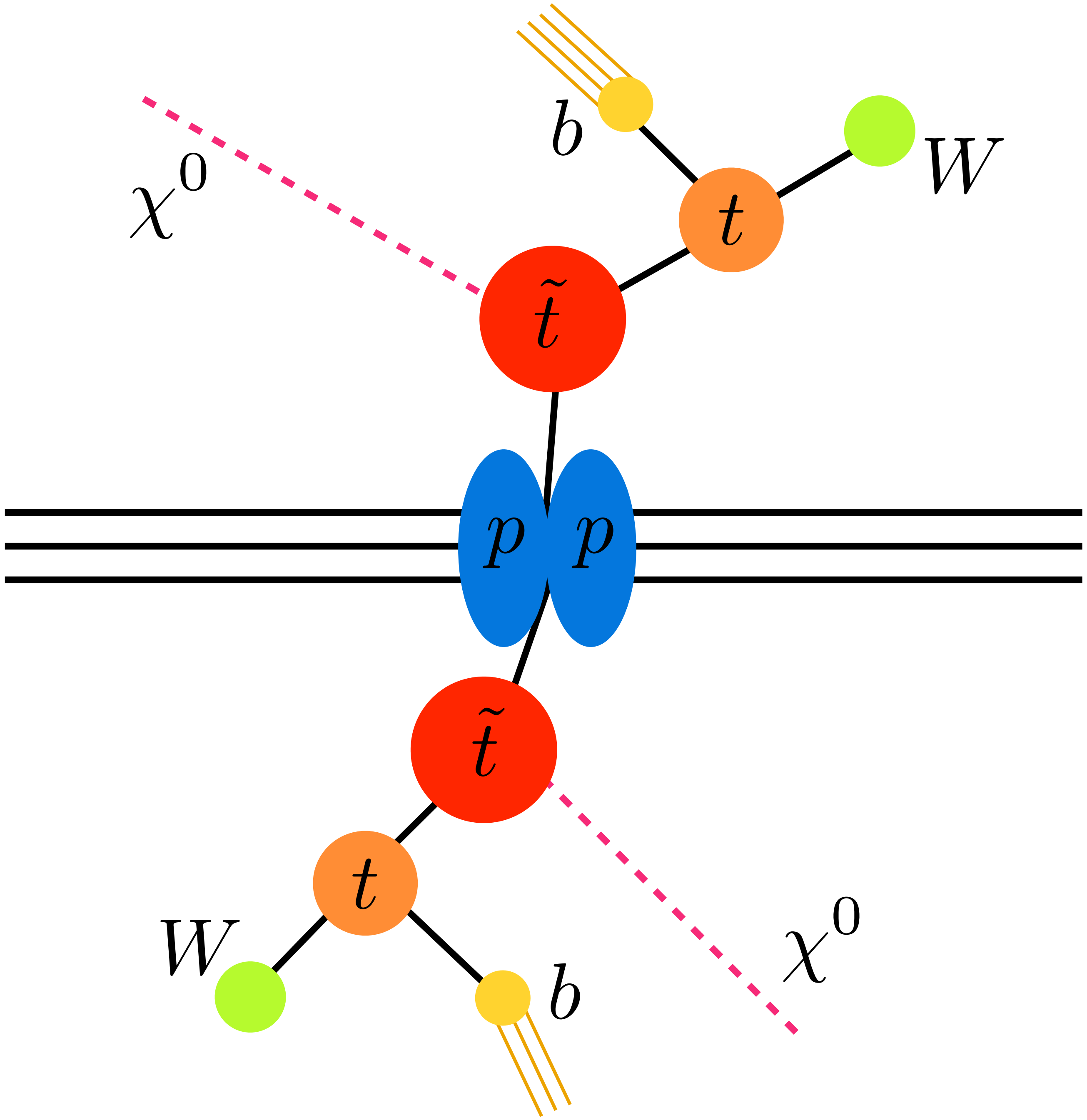

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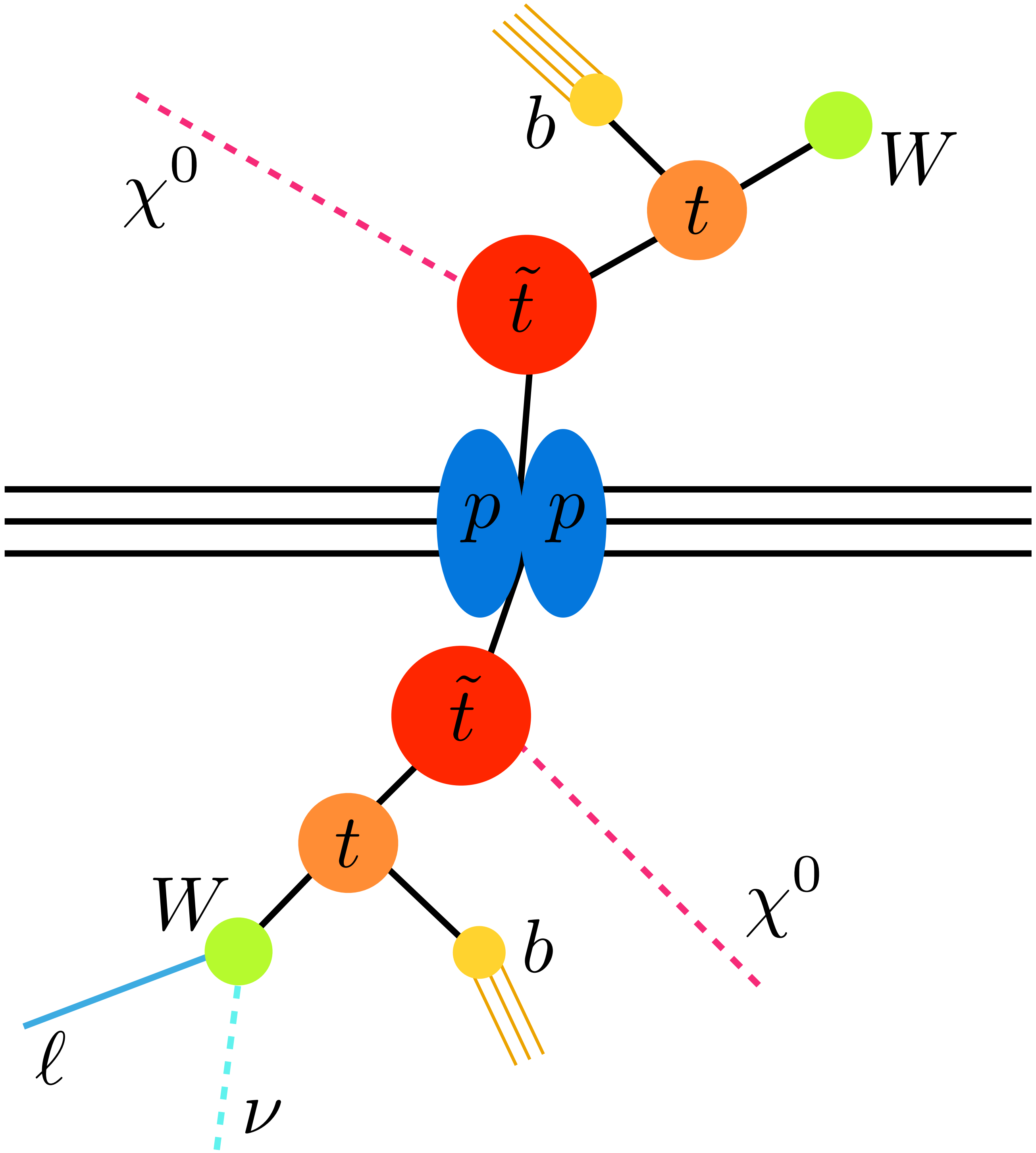

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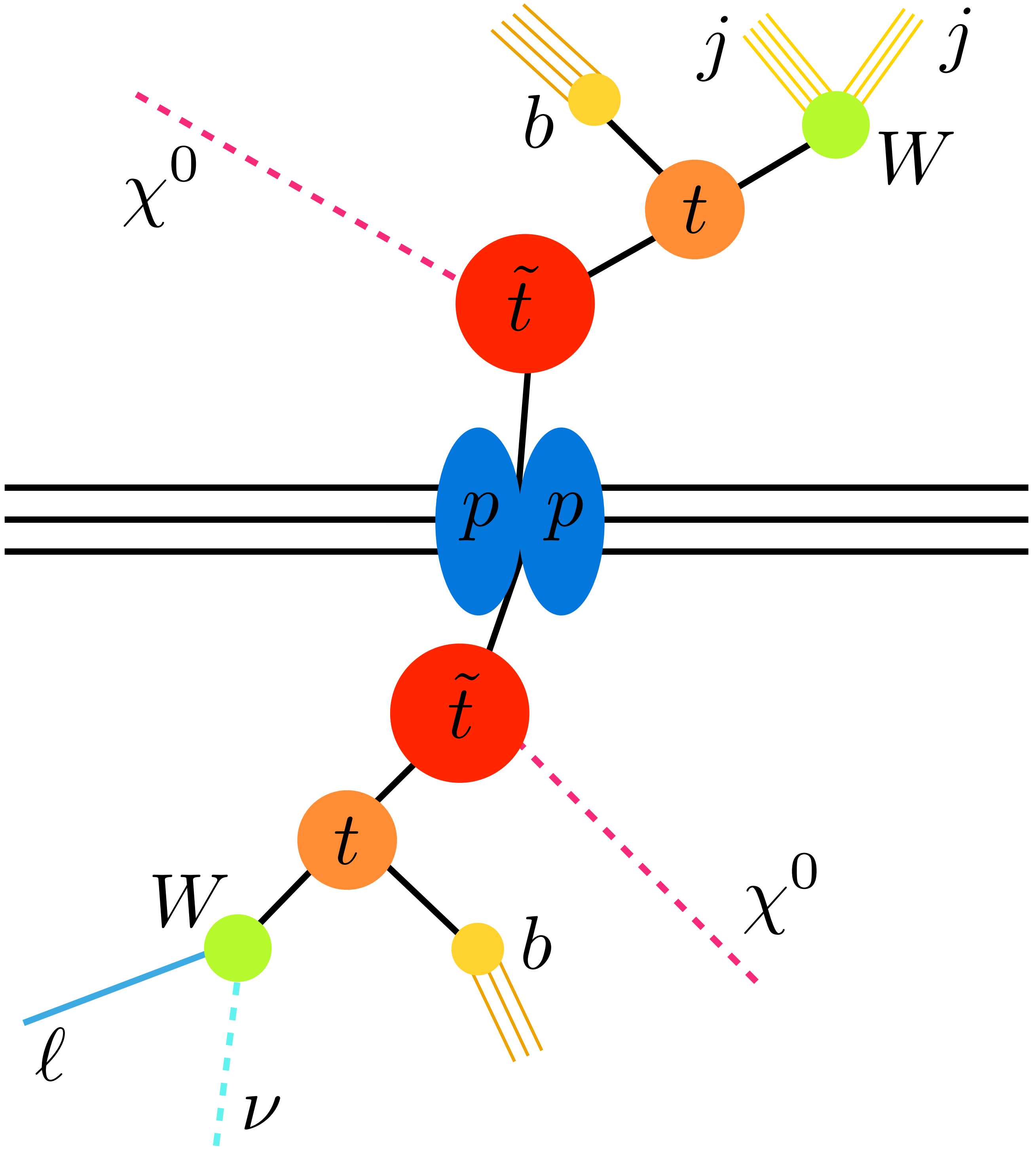
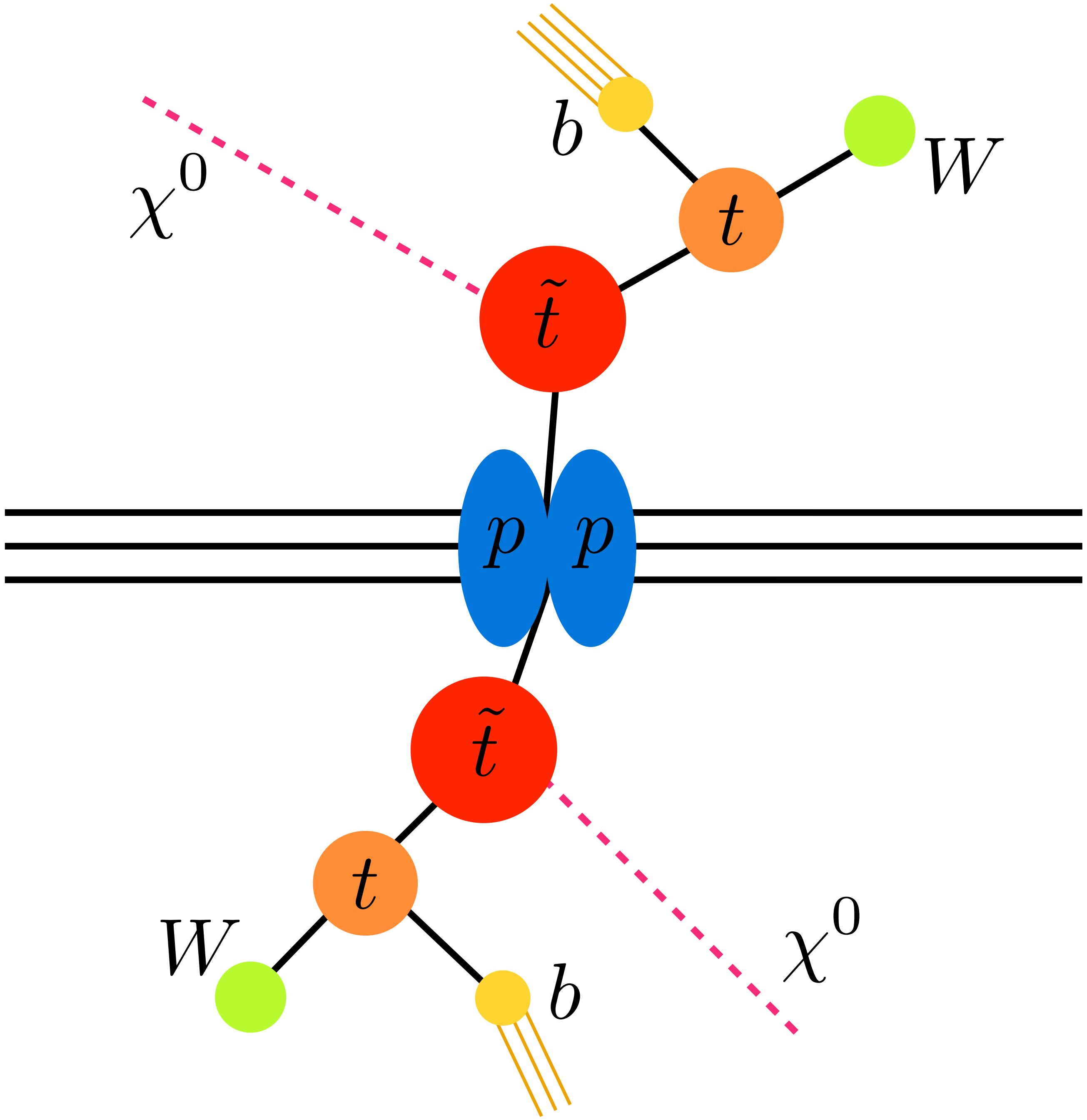


FULLY LEPTONIC STOPS



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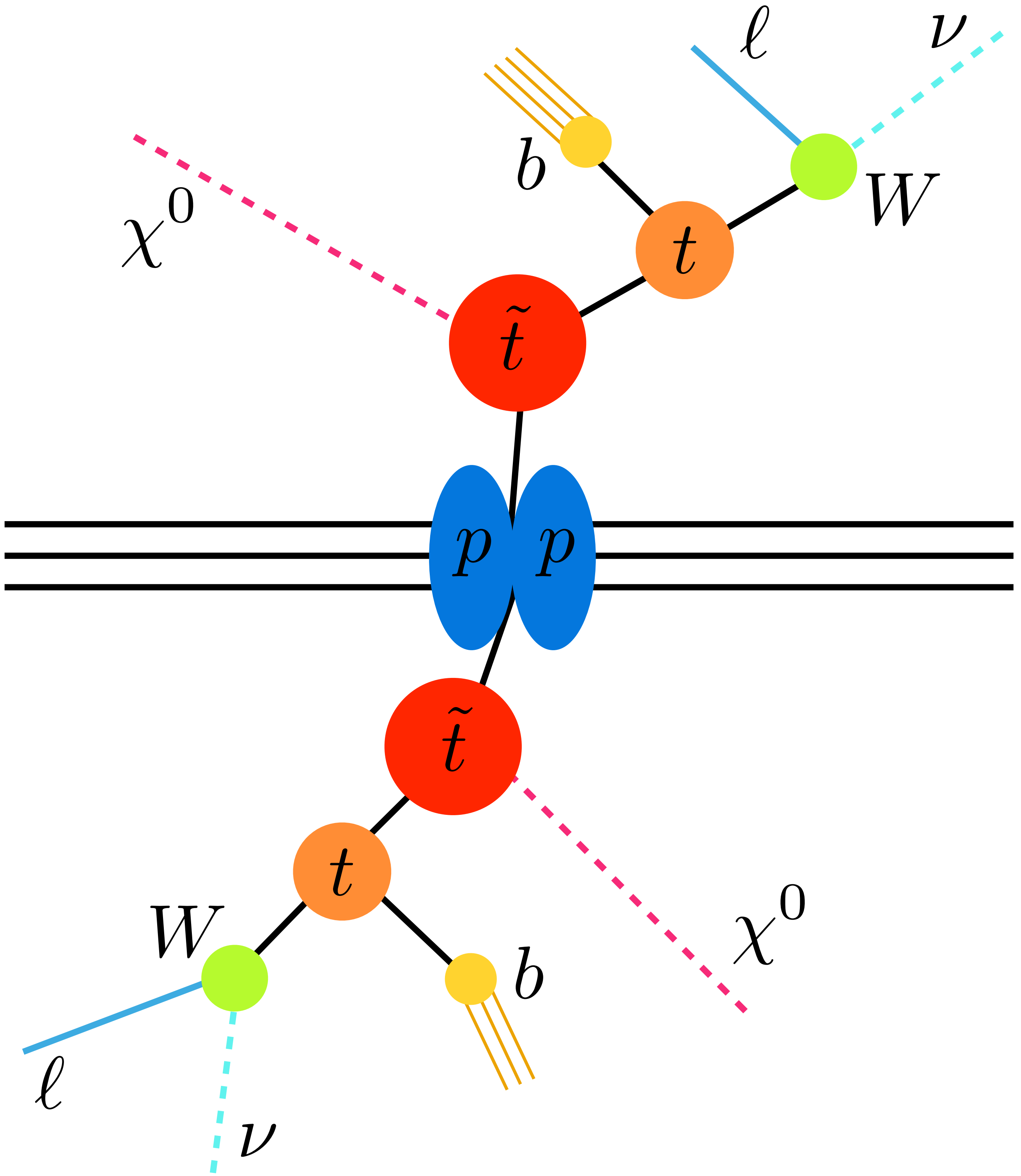
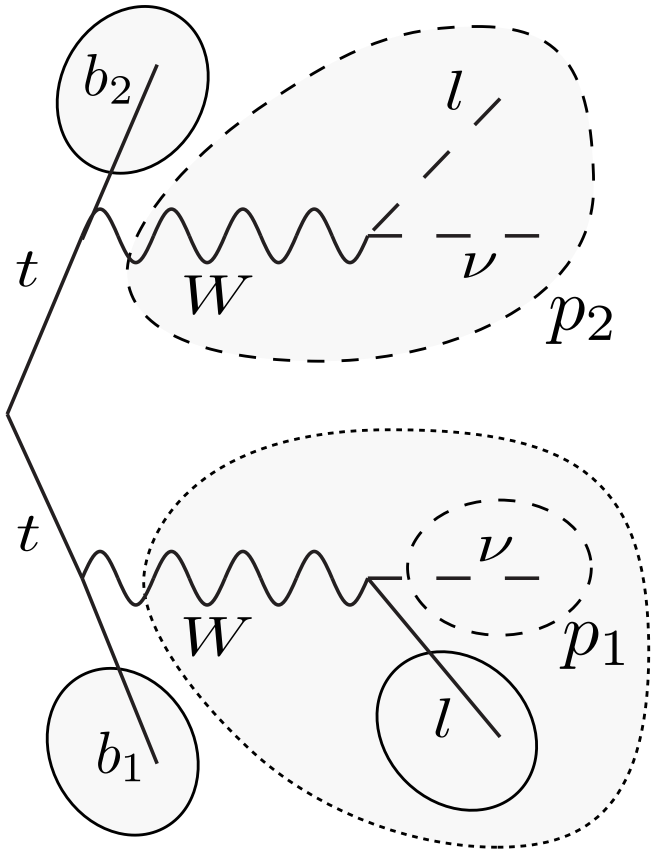


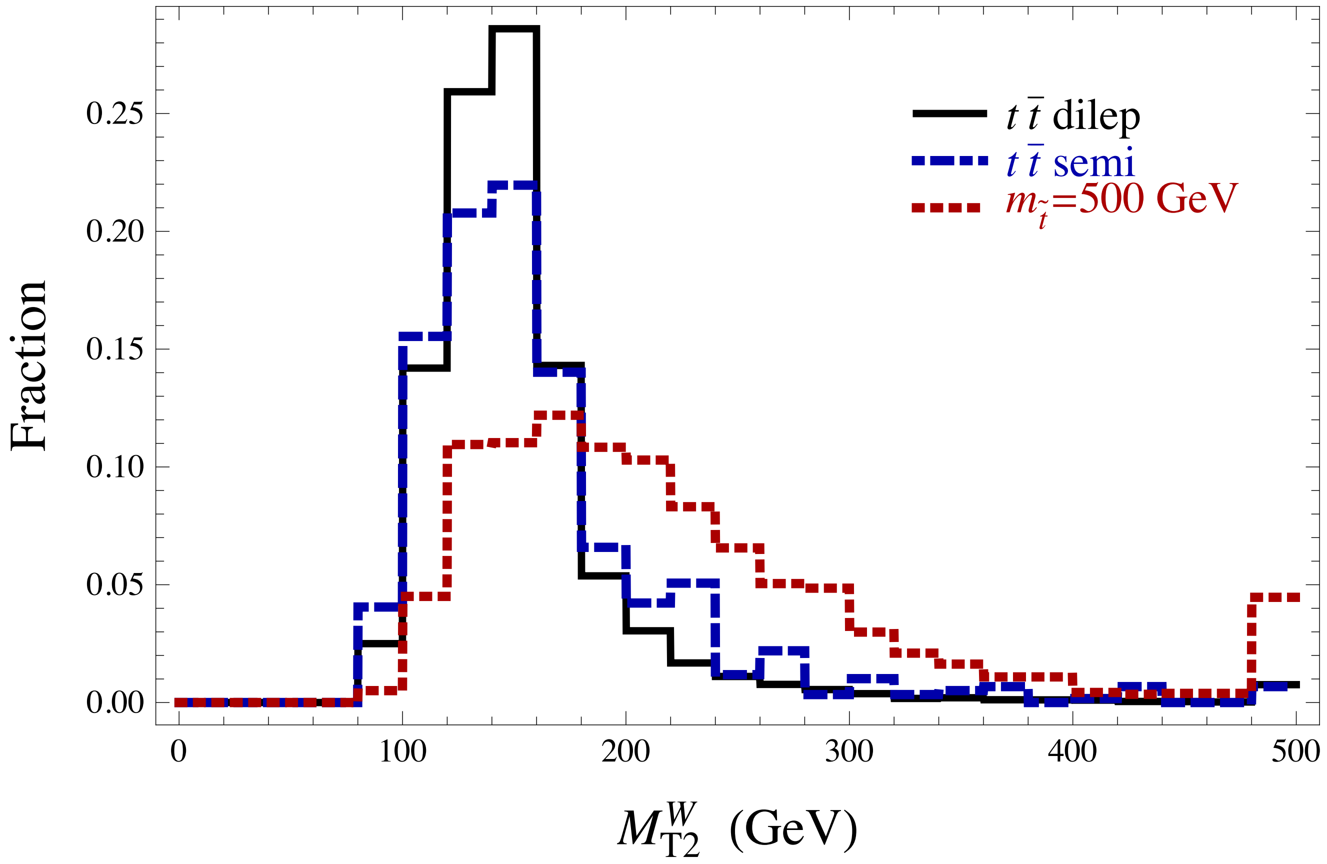
ADDITIONAL KINEMATIC VARIABLES

Search can be improved with additional kinematic variables

Bai, Cheng, Gallicchio, Gu 1203.4813.

$$M_{T2}^{W} = \min\left\{ m_y \text{ consistent with: } \left[\begin{array}{r} \vec{p}_1^{\,T} + \vec{p}_2^{\,T} = \vec{E}_T^{\text{miss}} \,,\ p_1^2 = 0 \,,\ (p_1 + p_\ell)^2 = p_2^2 = M_W^2 \,, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$





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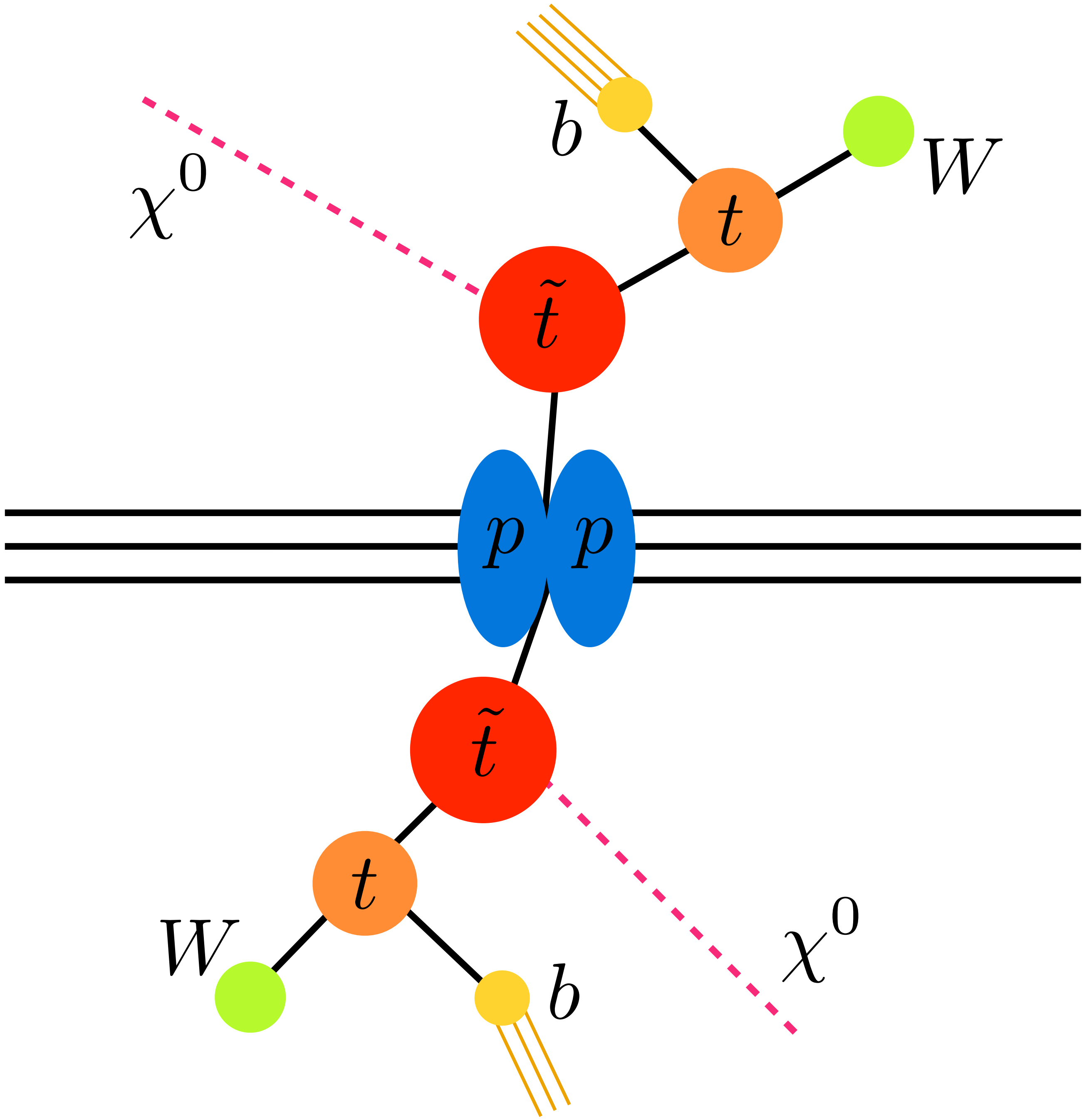

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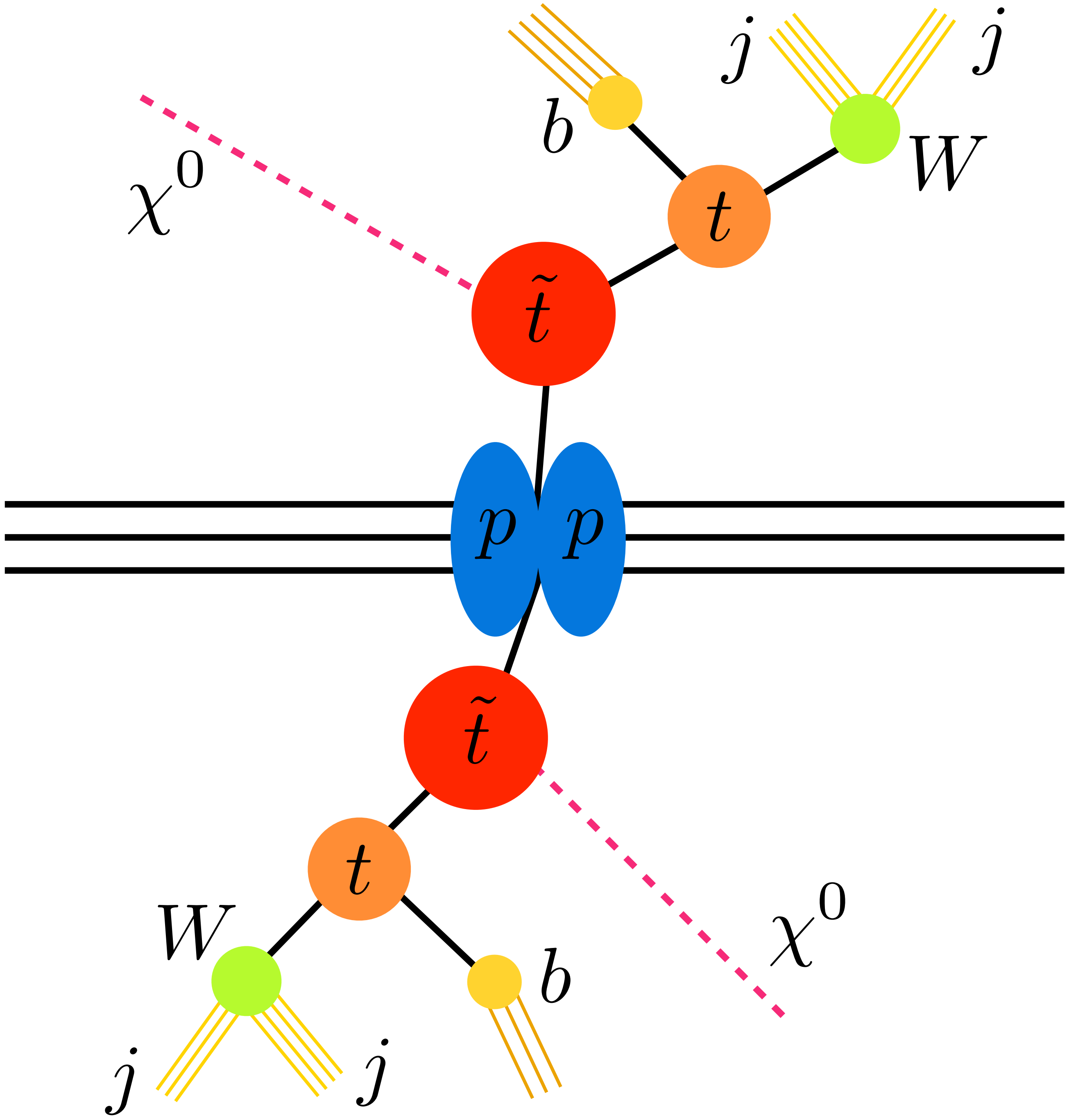

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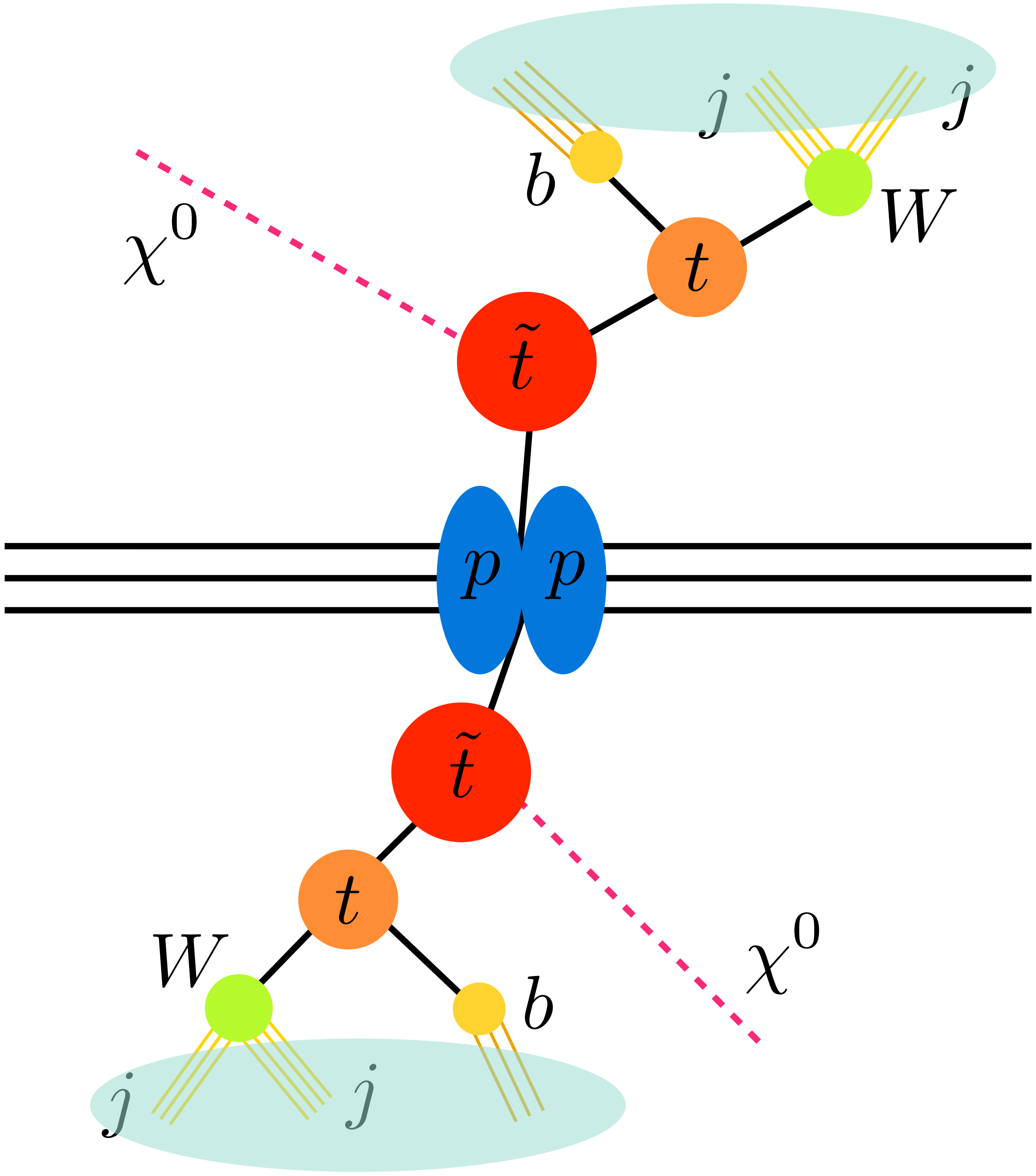

Fat jets
R=1.2

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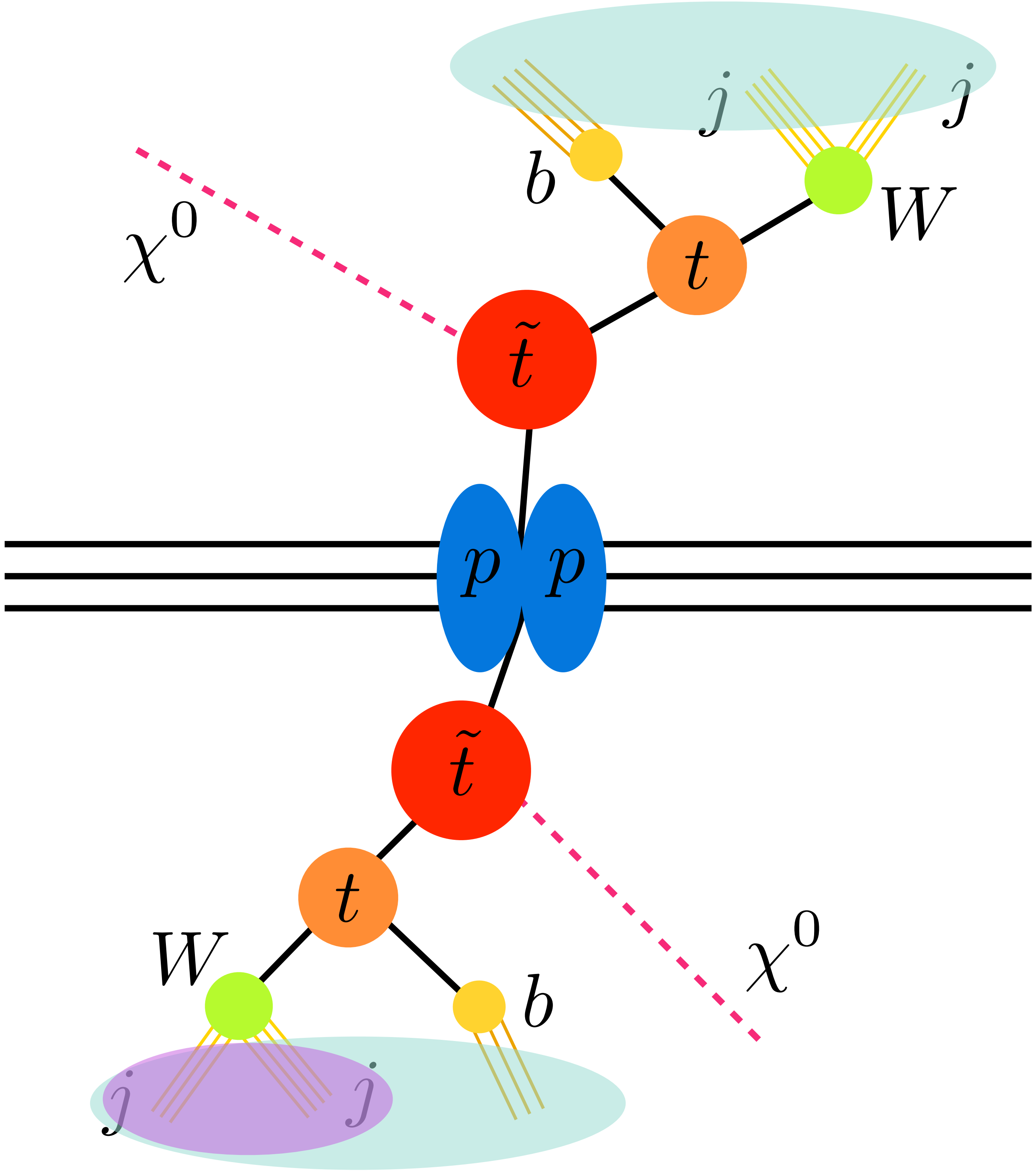

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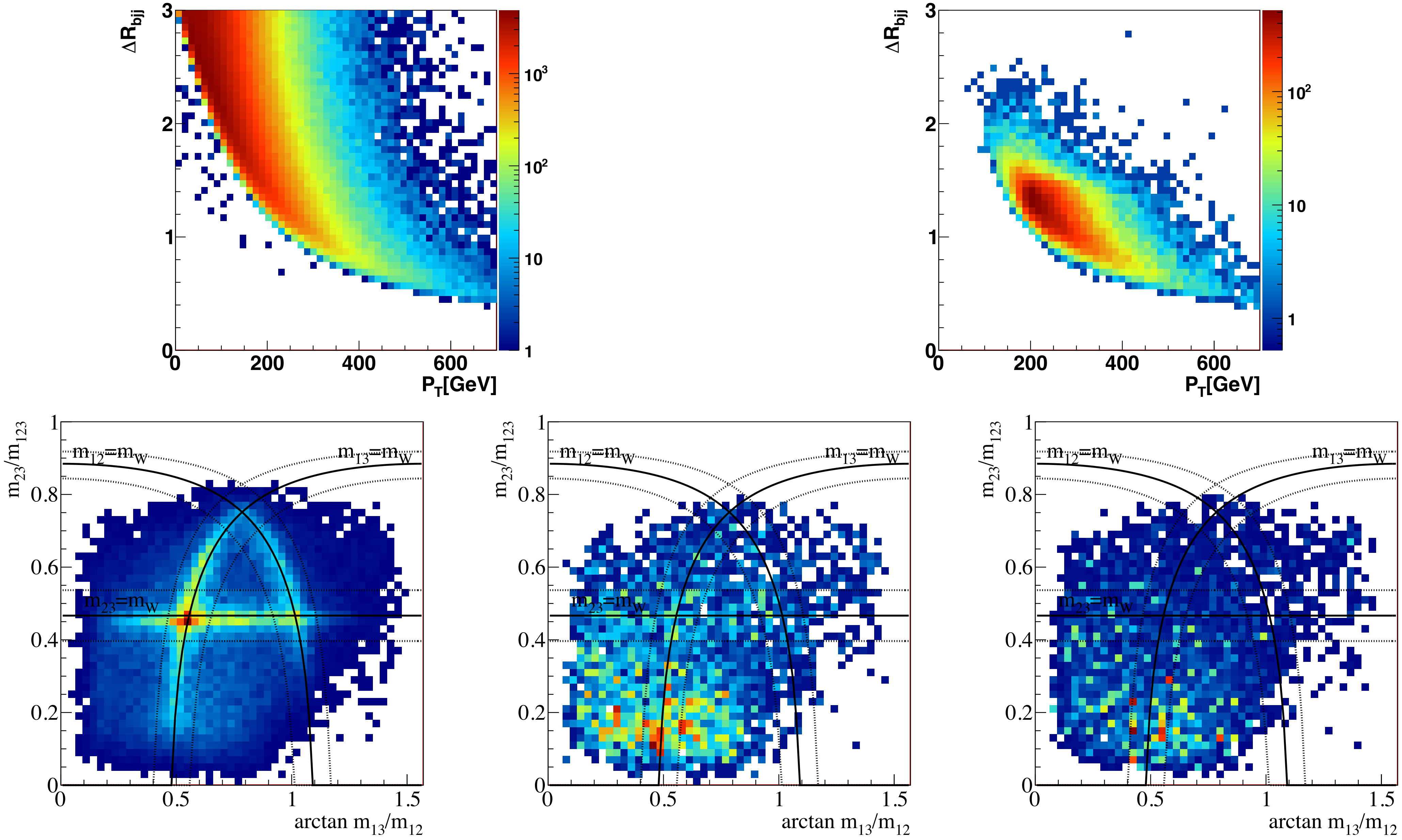
TOP TAGGING

Use HEPTopTagger to distinguish hadronic top **Plehn, Spannowsky, Takeuchi, Zerwas, 1006.2833. See also Thaler et. al. 0806.0023, Kaplan et. al. 0806.0848, Almeida et. al. 0807.0234.**



RELEVANT PROCESSES

Process	Generator cuts and parameters	σ (fb) 7 TeV
$\tilde{t}\tilde{t}^*$ (340 GeV)	$\tilde{t}\tilde{t}^* \to b\bar{b} + 4j + 2\chi$	254
$\tilde{t}\tilde{t}^*$ (440 GeV)		48.8
$\tilde{t}\tilde{t}^*$ (540 GeV)		11.8

*LO cross sections

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$t\bar{t}+$ jets	$W_{\to \ell\nu},\ p_{T_\nu} > 80\mathrm{GeV}$	16.3×10^3
sing. top + jets	$p_{T_\nu} > 100$ GeV	4.65×10^3

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$V + b\bar{b}$ + jets	$Z \to \nu\bar{\nu}$, $W \to \ell\nu$	1.08×10^3
V + jets	$\sum \mathbf{p}_{T_\nu} > 80$ GeV	66.6×10^3

*LO cross sections

BACKGROUNDS AND CUTS

Backgrounds

- QCD
- V + $b\bar{b}$ + jets
- V + jets
- Tops + jets

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Cuts

- Veto on isolated leptons, tau's, and bizarre missing energy events.

BACKGROUNDS AND CUTS

Backgrounds

- ~~QCD~~
- V + $b\bar{b}$ + jets
- V + jets
- ~~Tops + jets~~

Cuts

- Veto on isolated leptons, tau’s, and bizarre missing energy events.
- Missing energy > 175 GeV

BACKGROUNDS AND CUTS

<u>Backgrounds</u>

- ~~QCD~~
- ~~V + $b\bar{b}$ + jets~~
- ~~V + jets~~
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- Veto on isolated leptons, tau's, and bizarre missing energy events.
- Missing energy > 175 GeV
- One HEPTopTagged fat jet

BACKGROUNDS AND CUTS

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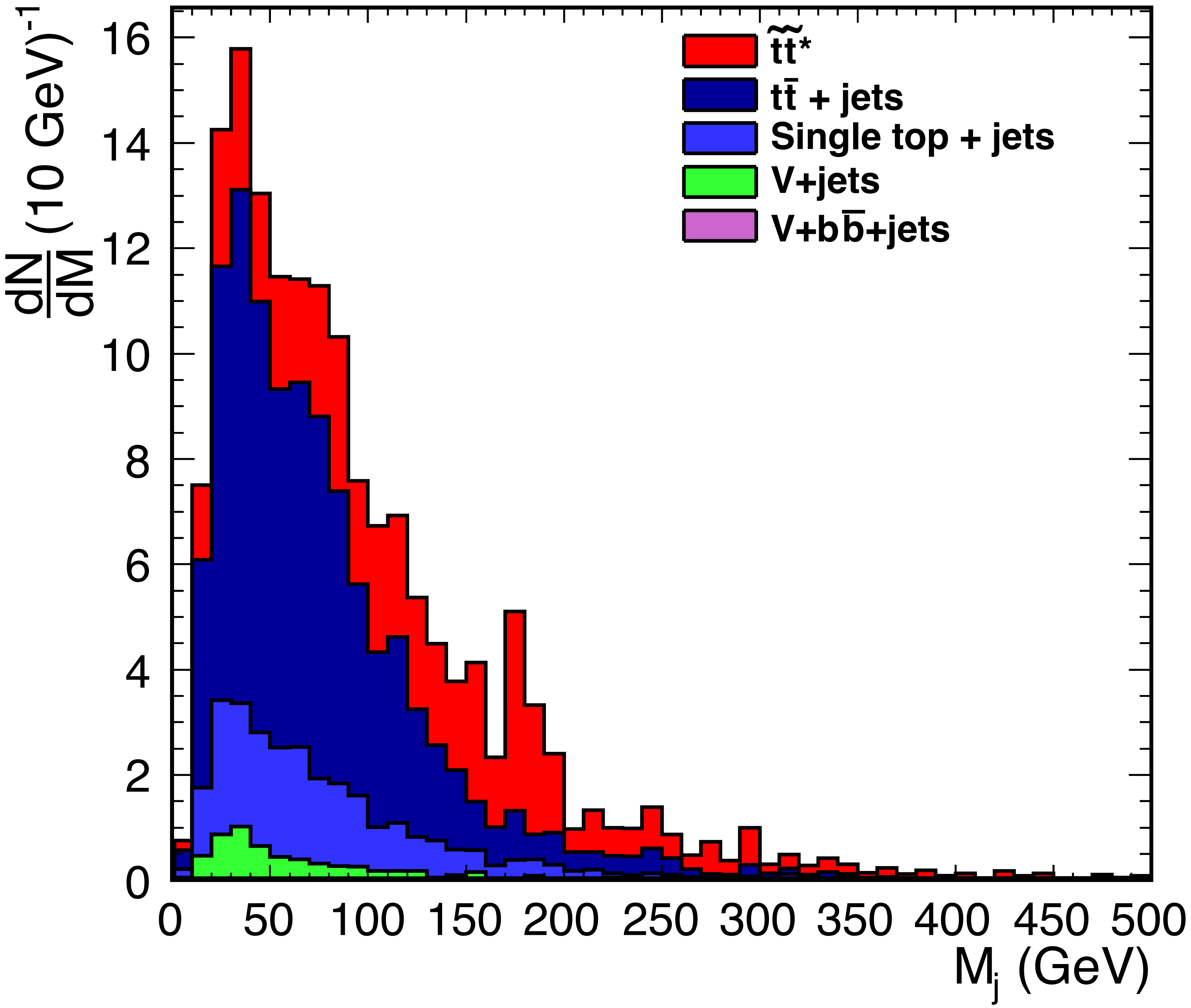
- ~~V + $b\bar{b}$ + jets~~
- ~~V + jets~~
- ~~Tops + jets~~

Cuts

- Veto on isolated leptons, tau's, and bizarre missing energy events.
- Missing energy > 175 GeV
- One HEPTopTagged fat jet
- Opposite fat jet is *b*-tagged

GOOD SIGNAL TO BACKGROUND



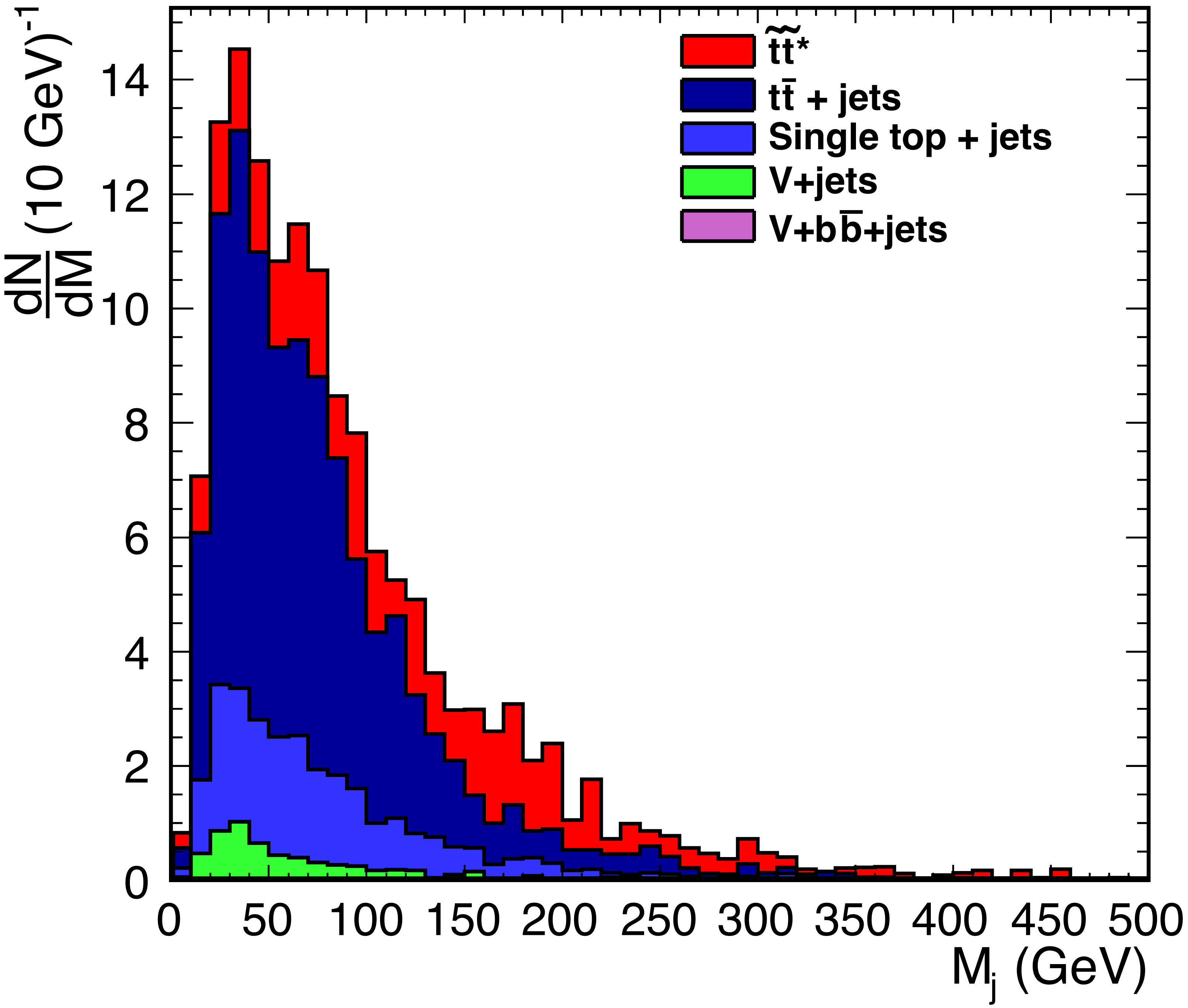
$$\sqrt{s} = 7\,\mathrm{TeV}$$

$$\mathcal{L} = 5\,\mathrm{fb}^{-1}$$

$$m_{\tilde{t}} = 340\,\mathrm{GeV}$$

$$m_\chi = 0\,\mathrm{GeV}$$

INCREASE NEUTRALINO MASS



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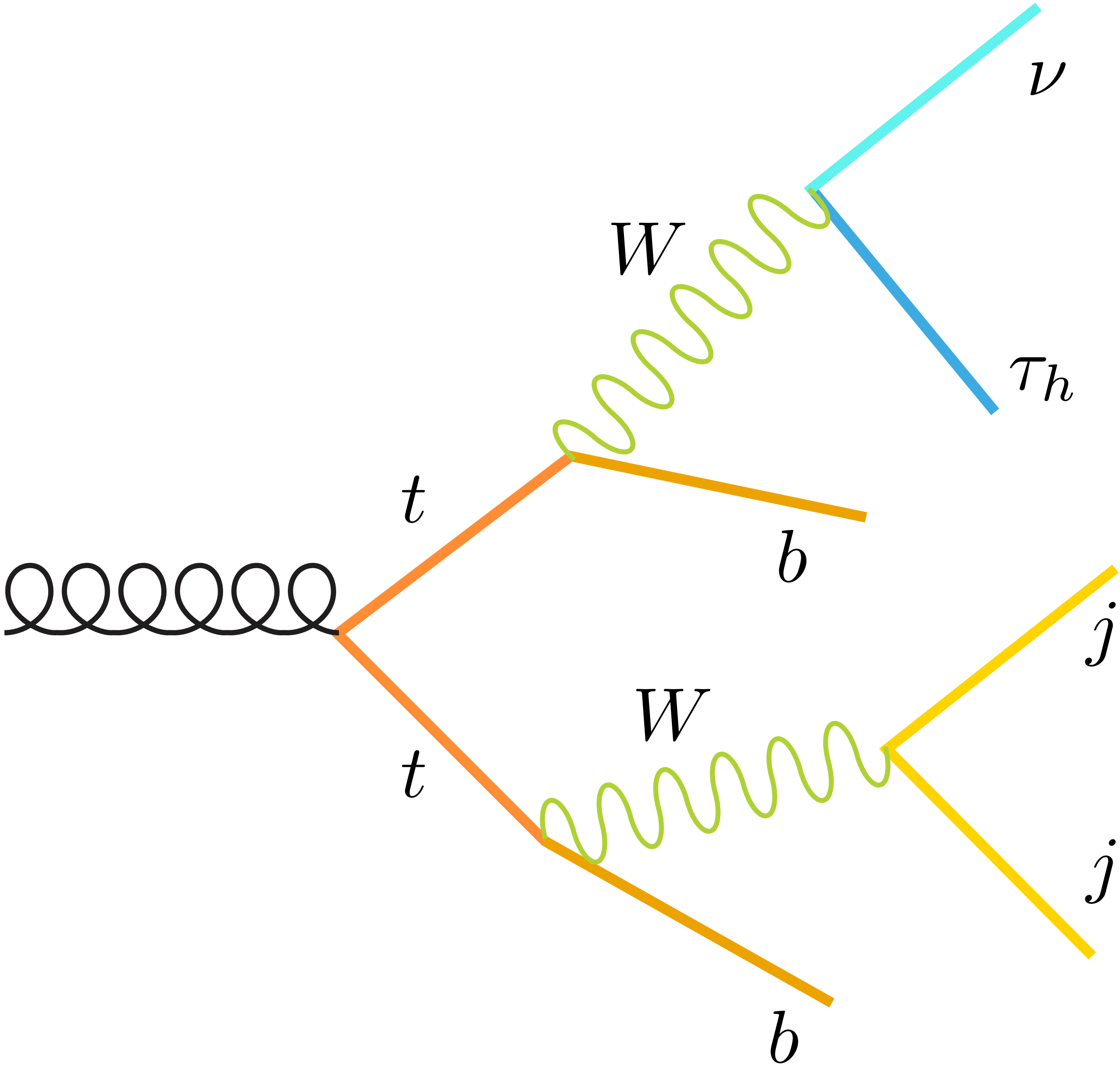

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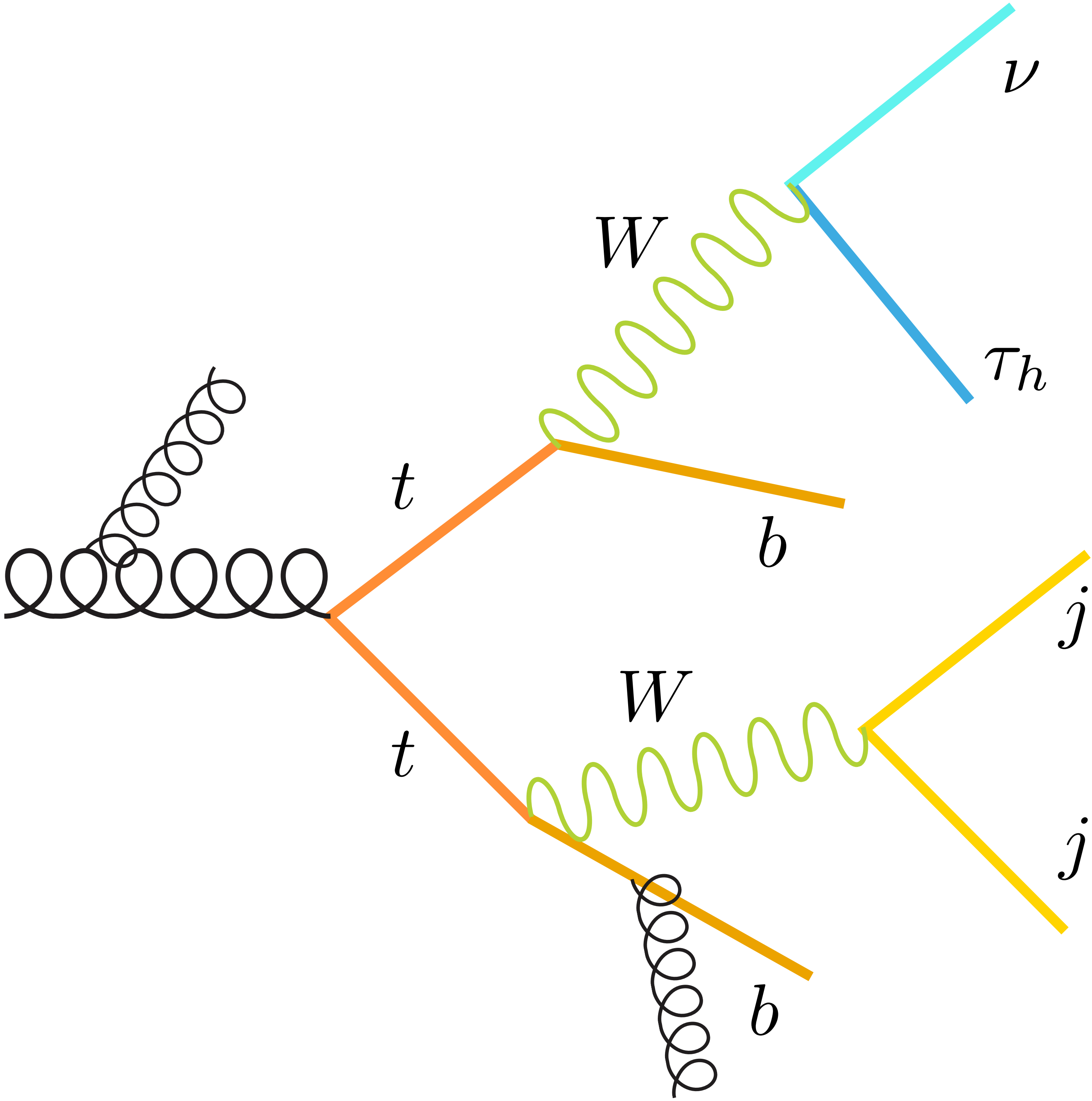
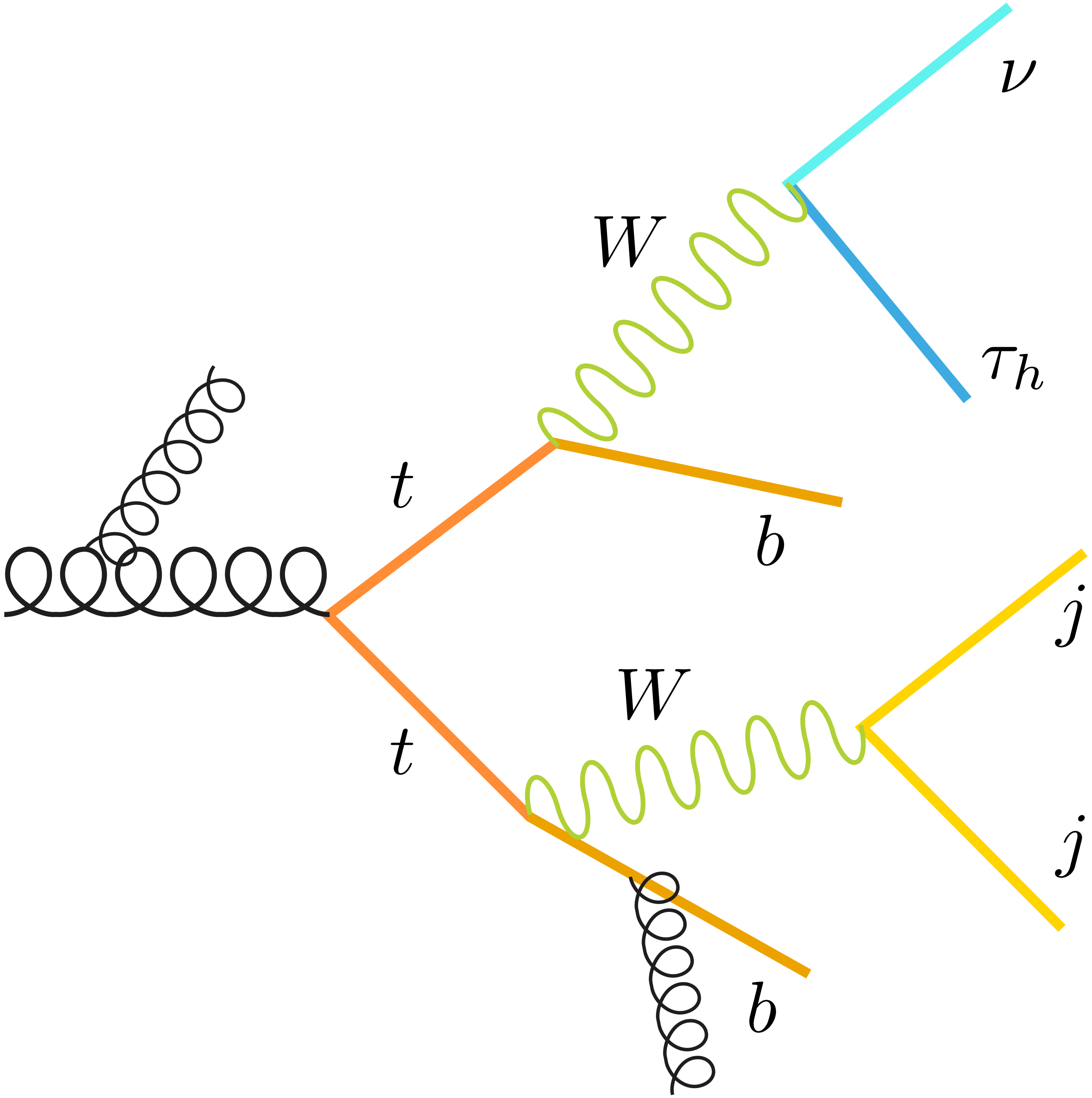


KINEMATIC CUTS

- Transverse mass of missing energy with both fat jets > 200 GeV

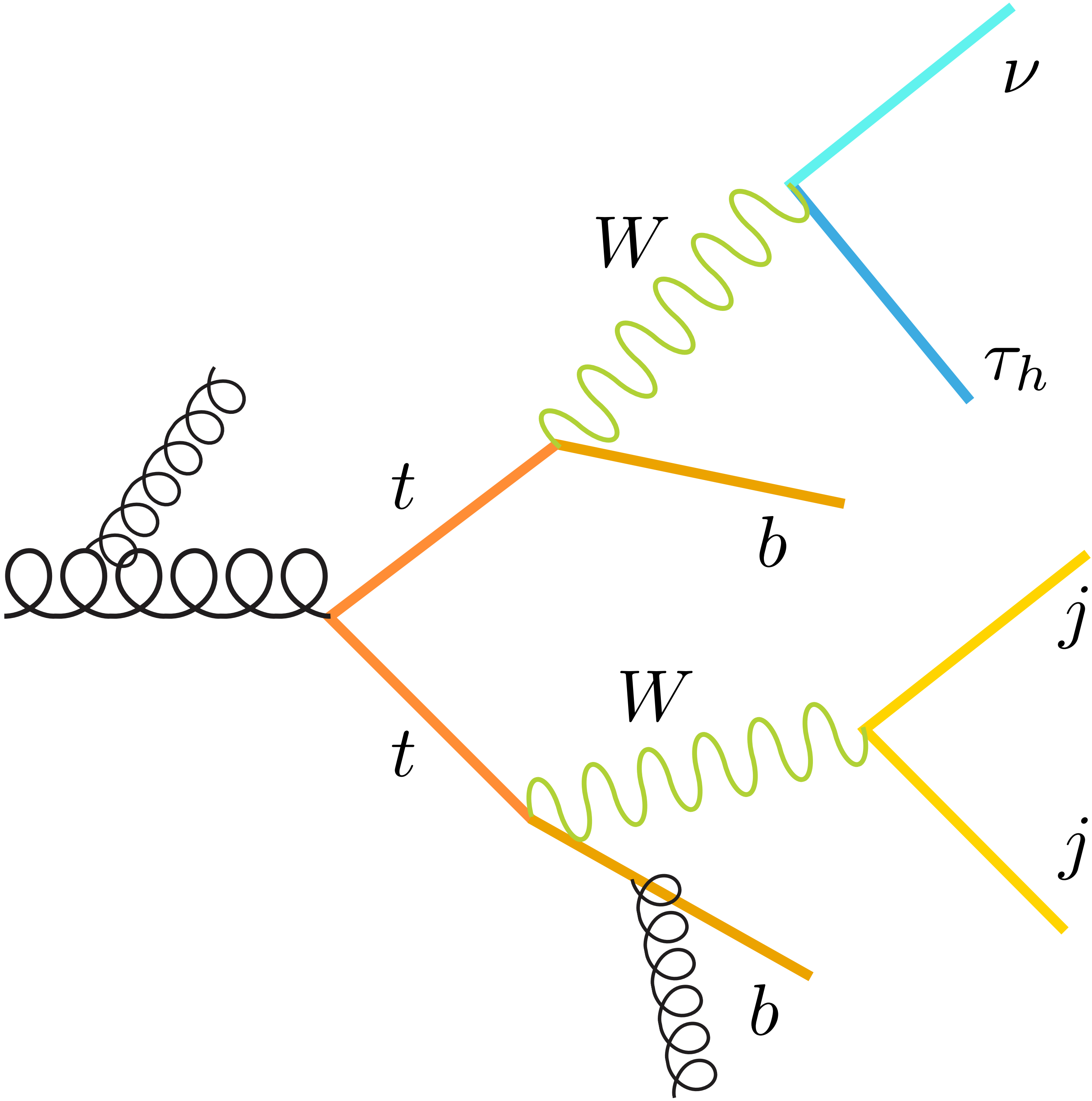


KINEMATIC CUTS

- Transverse mass of missing energy with both fat jets > 200 GeV

- mT2 > 200 GeV

  Lester et. al., hep-ph/9906349,
  Conlon et. al., hep-ph/0304226.



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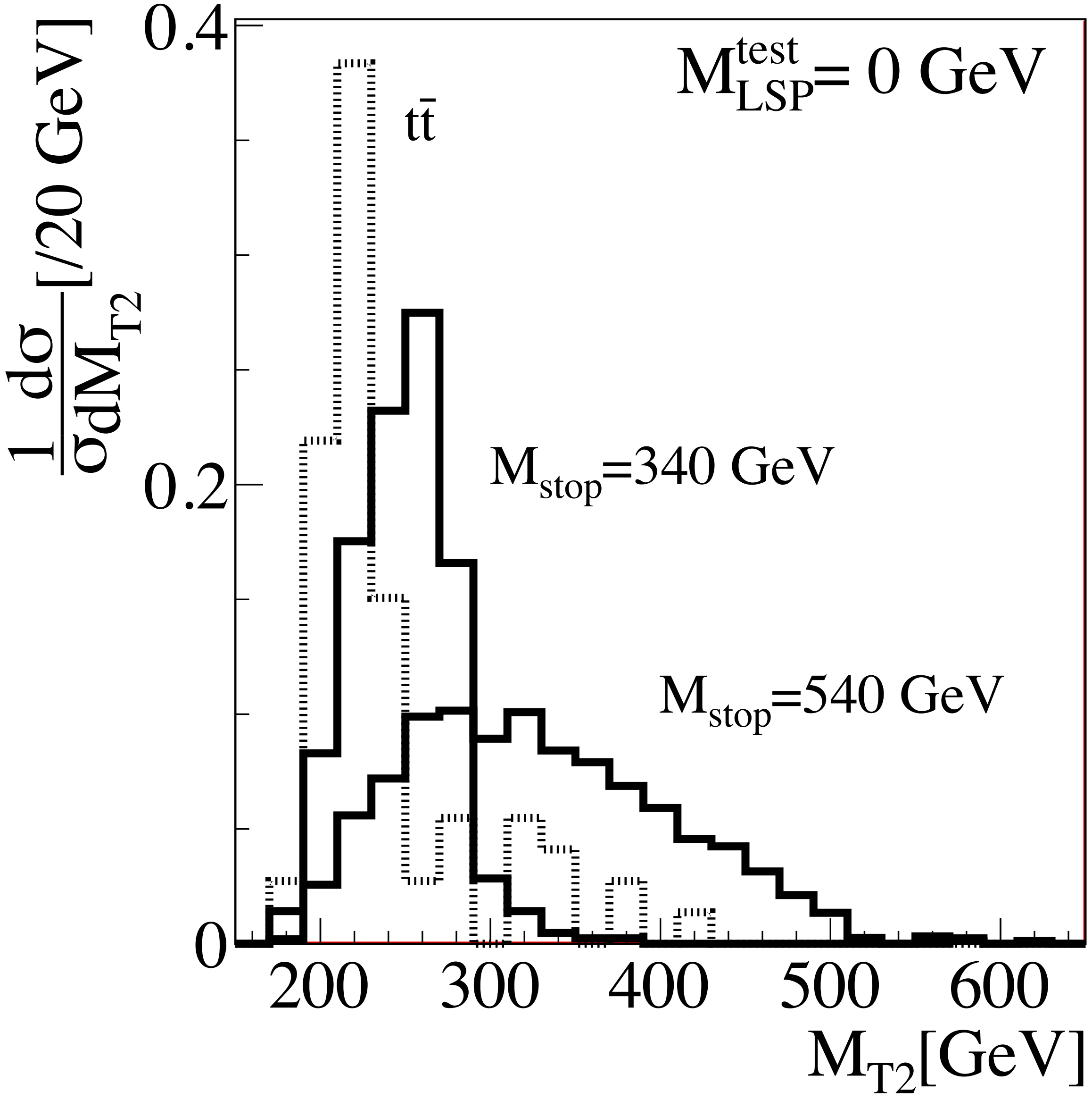
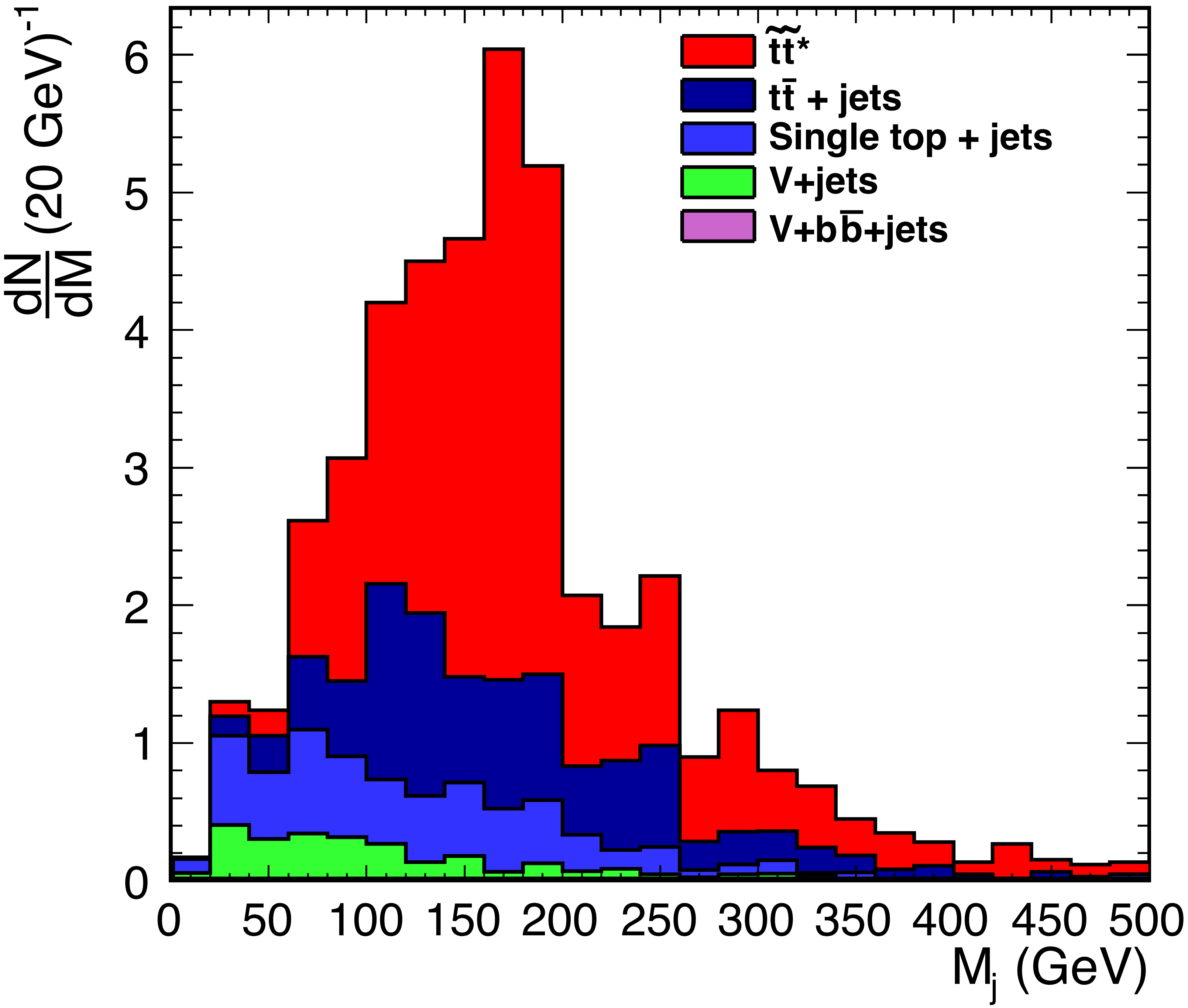


Plehn, Spannowsky, Takeuchi, Zerwas, 1006.2833

CLEAR SIGNAL DISCRIMINATION



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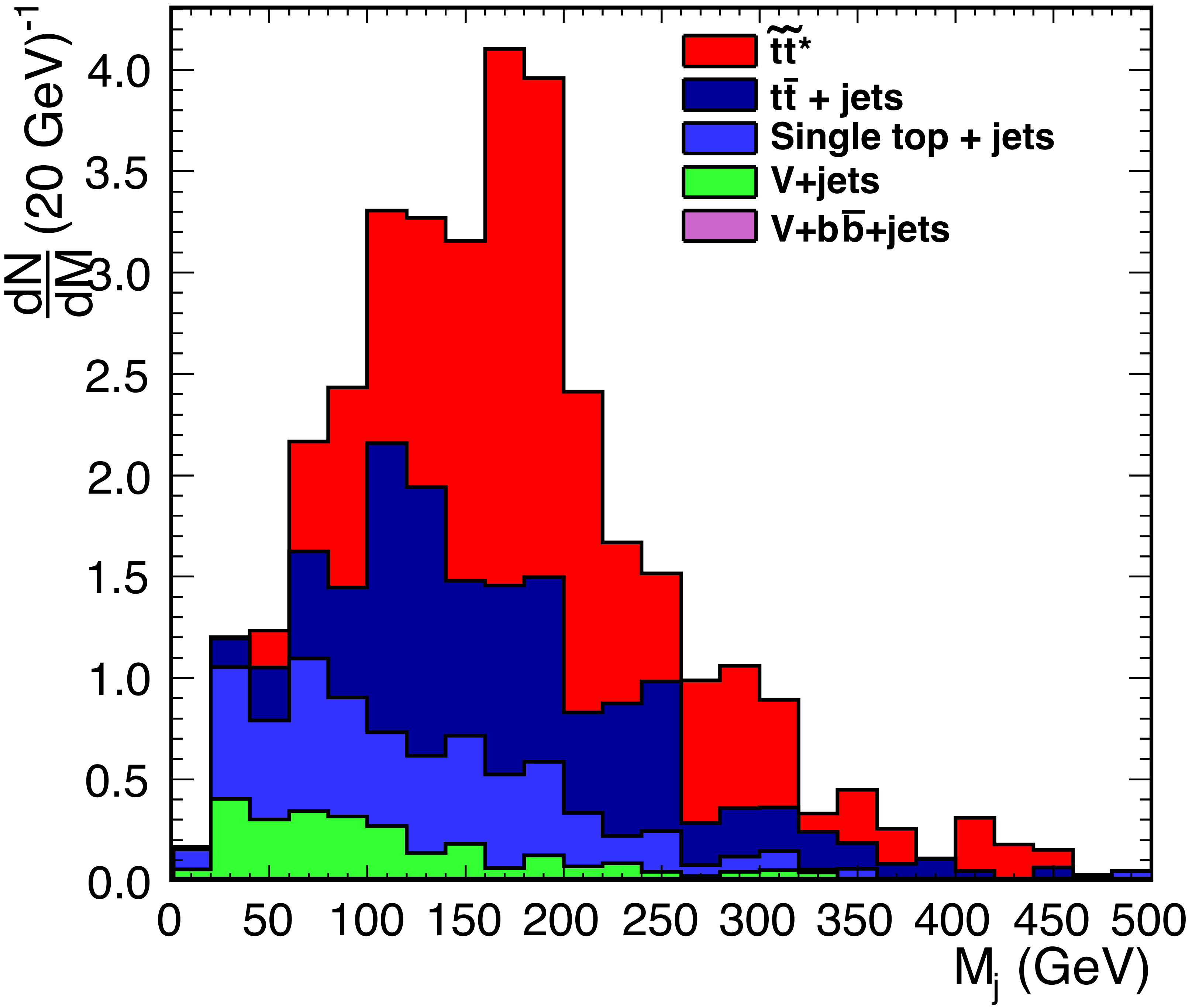
EVEN WITH SMALLER SPLITTING



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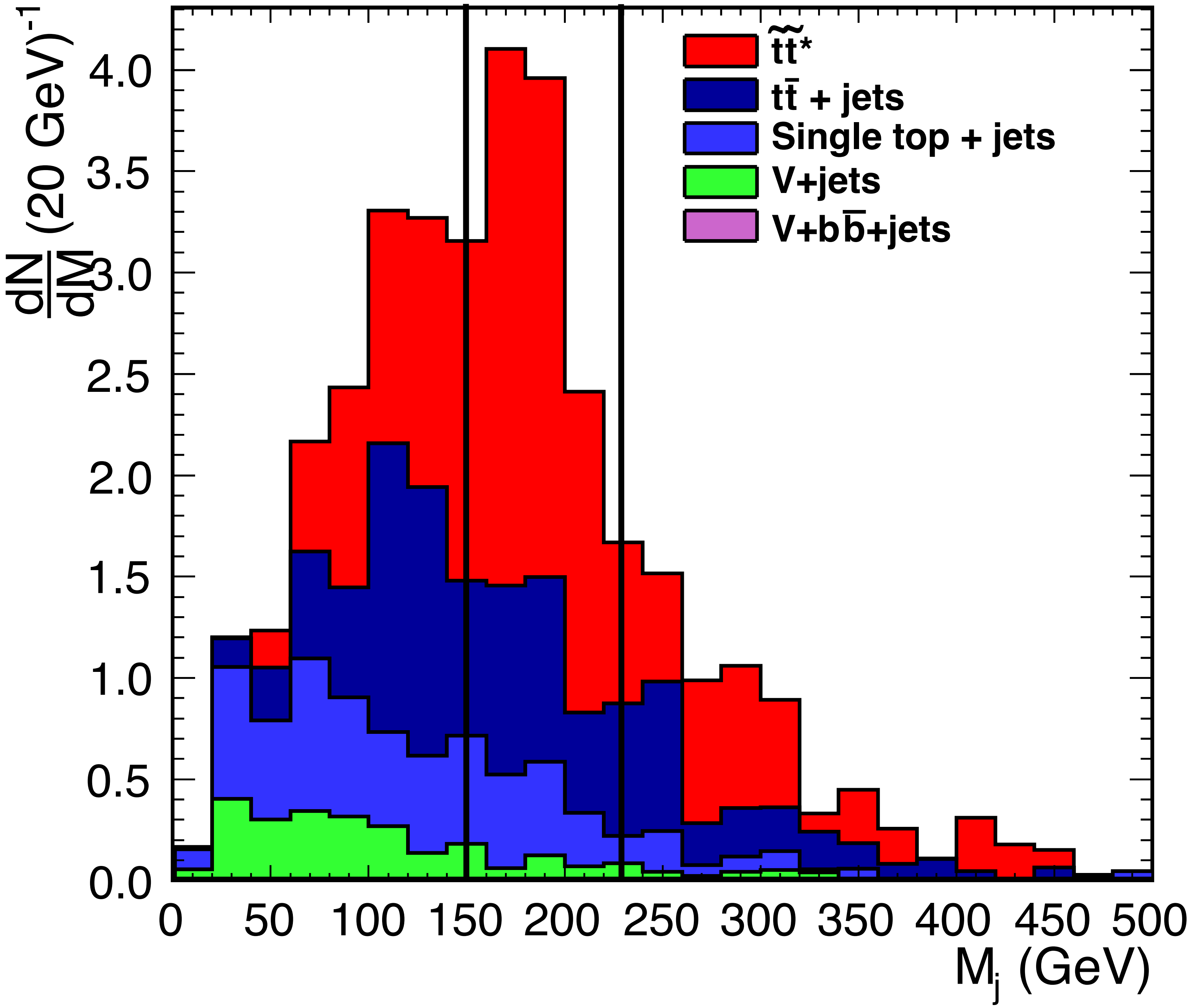

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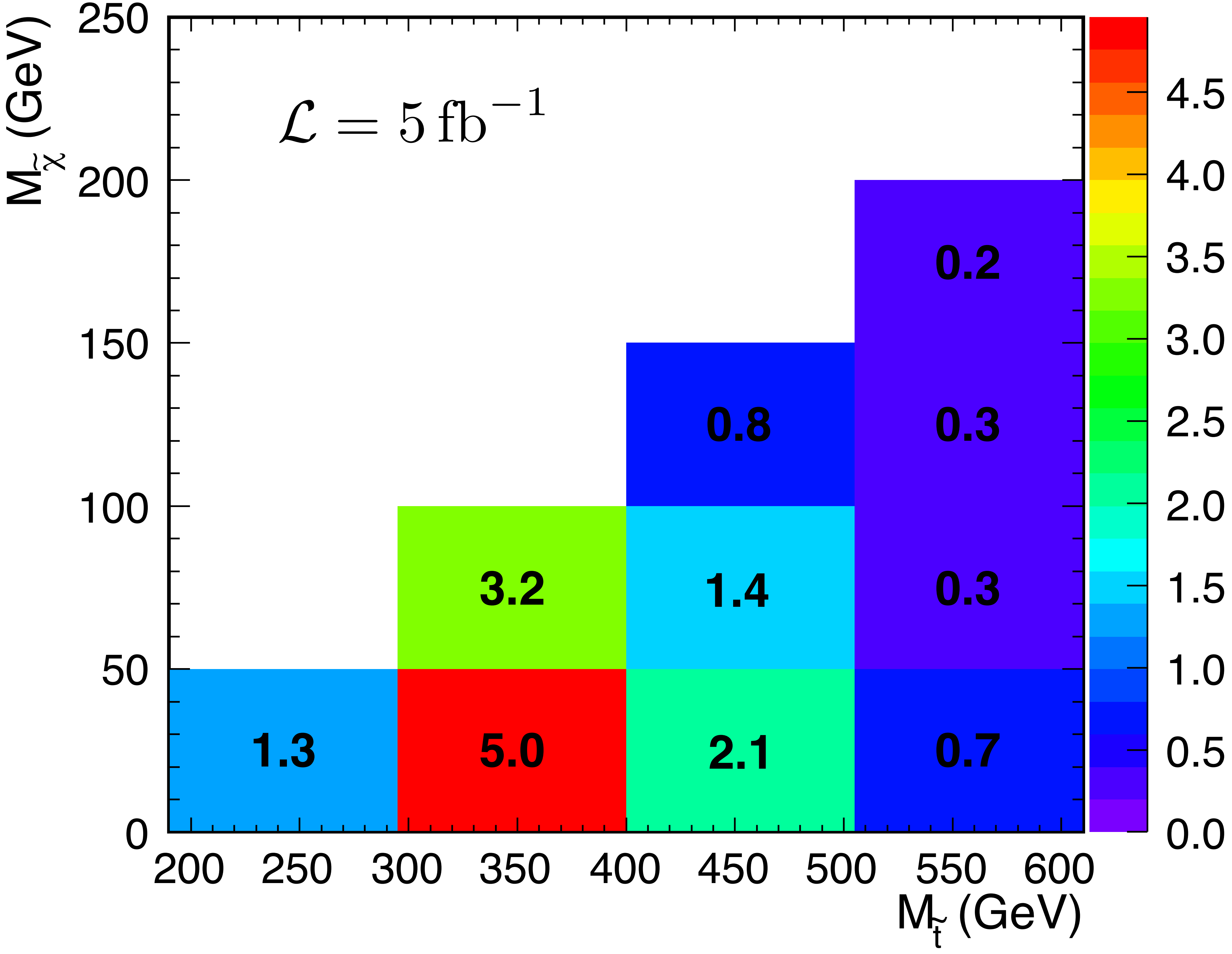
7 TeV RESULTS

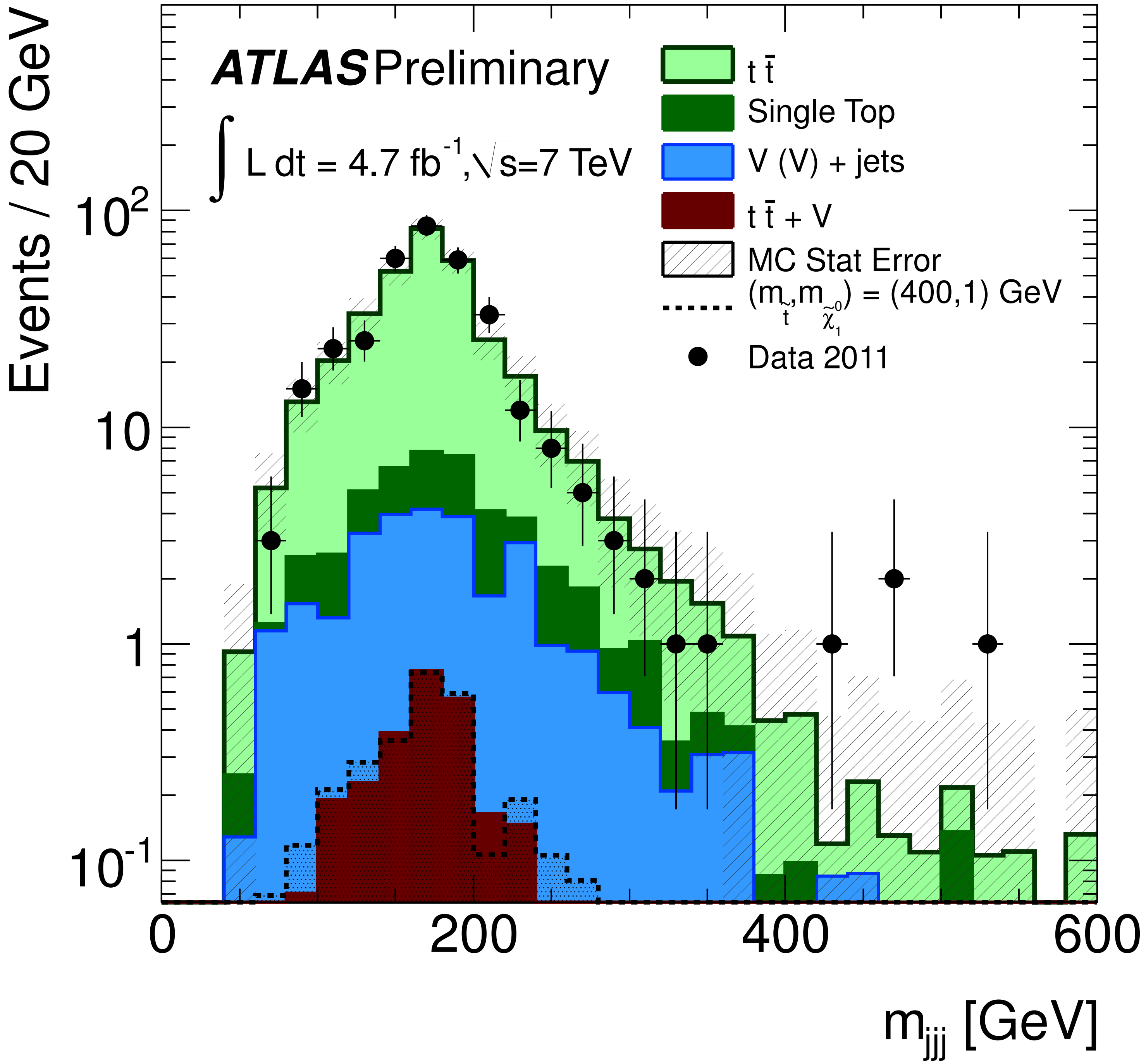


ATLAS RESULT

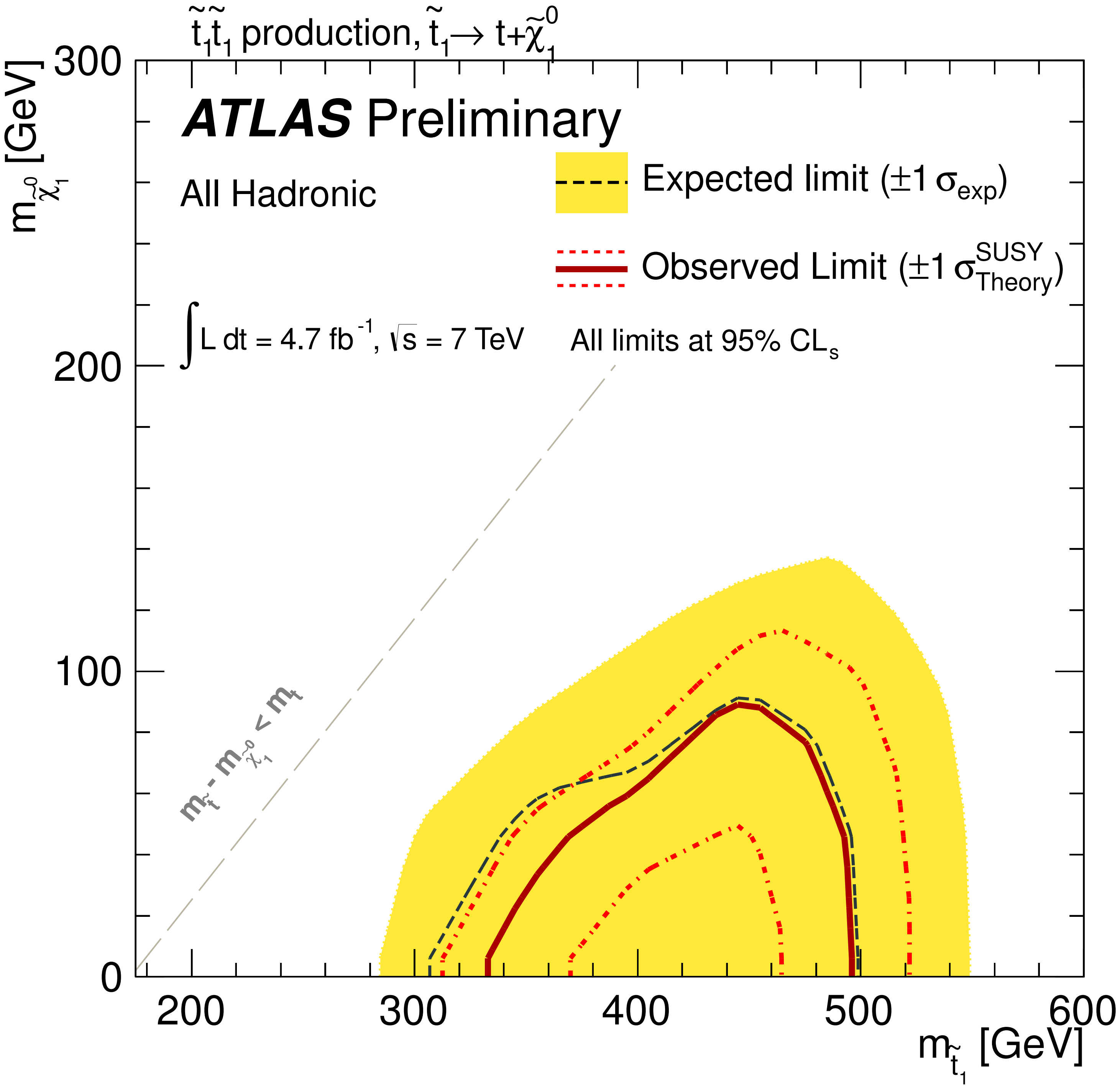
Cuts

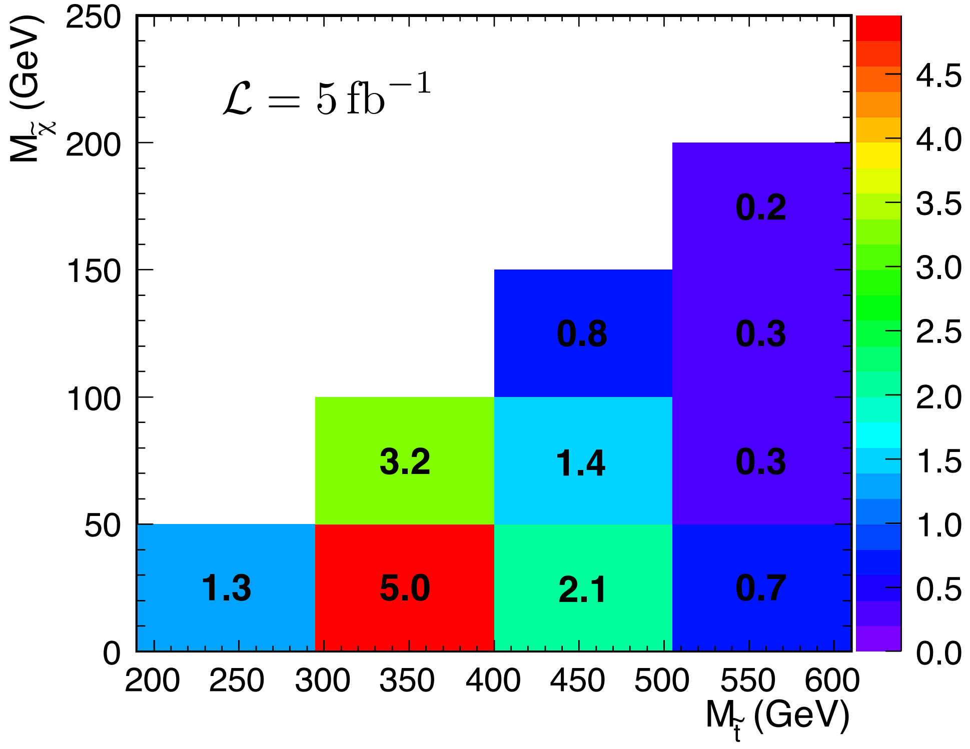
- 6 jets, $p_{T1} > 130$ GeV $p_T > 30$ GeV
- Missing energy > 150 GeV or 260 GeV
- 1 tight or 2 loose b-tags
- Invariant mass of 3 closest jets between 80 and 270 GeV
- Tau rejection cuts

Control Sample



ATLAS RESULT





8 TeV RUNNING

ALICE: 8.27 pb^{-1} ATLAS: 21.6 fb^{-1} CMS: 21.42 fb^{-1} LHCb: 2.04 fb^{-1}

From: Apr 4, 2012 To: Nov 18, 2012

*As of Monday

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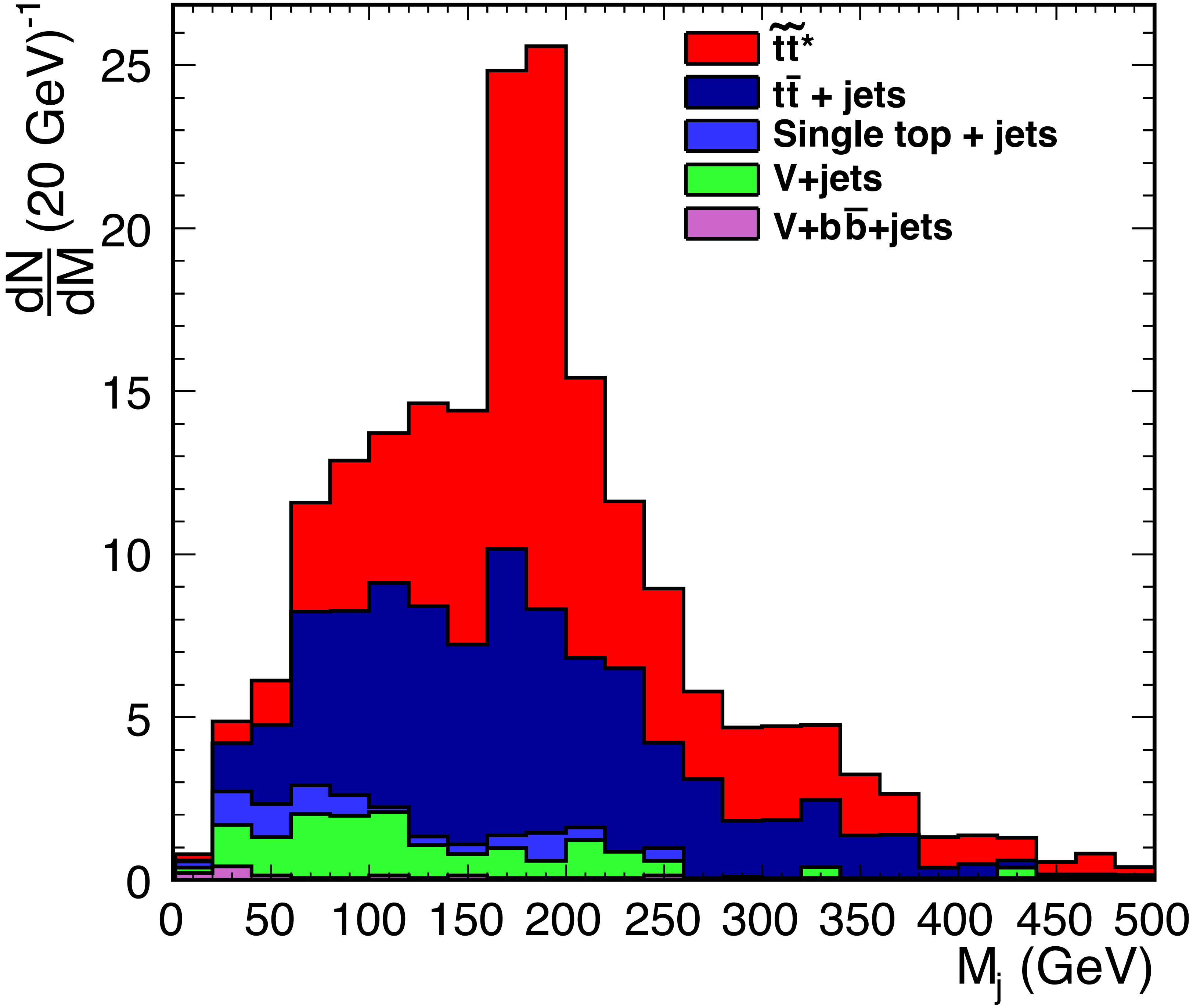
*LO cross sections

RELEVANT PROCESSES

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

*LO cross sections

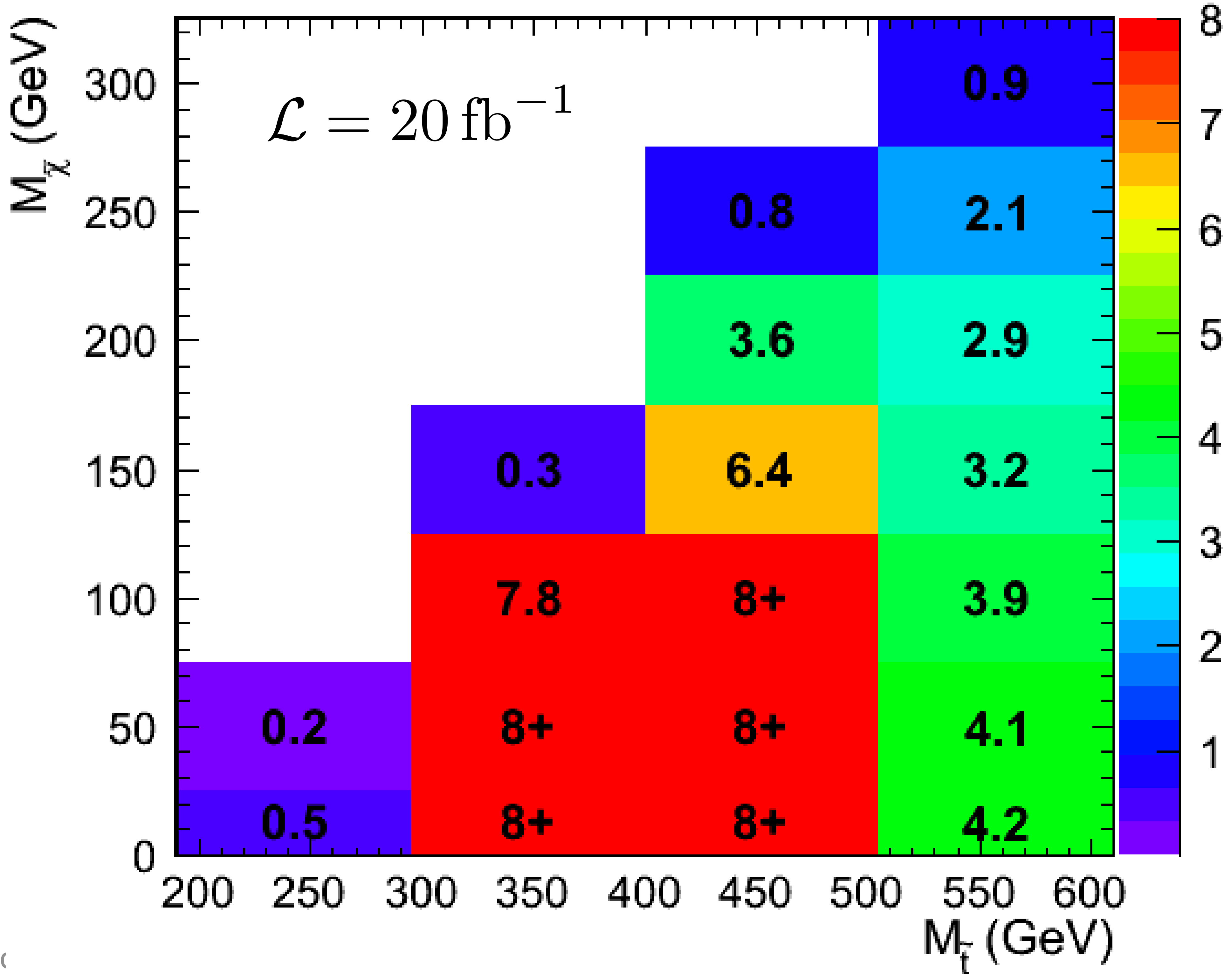
2012 PROSPECTS



$$\sqrt{s} = 8\,\text{TeV}$$
$$\mathcal{L} = 20\,\text{fb}^{-1}$$

$$m_{\tilde{t}} = 440\,\text{GeV}$$
$$m_{\chi} = 100\,\text{GeV}$$

8 TeV RESULTS

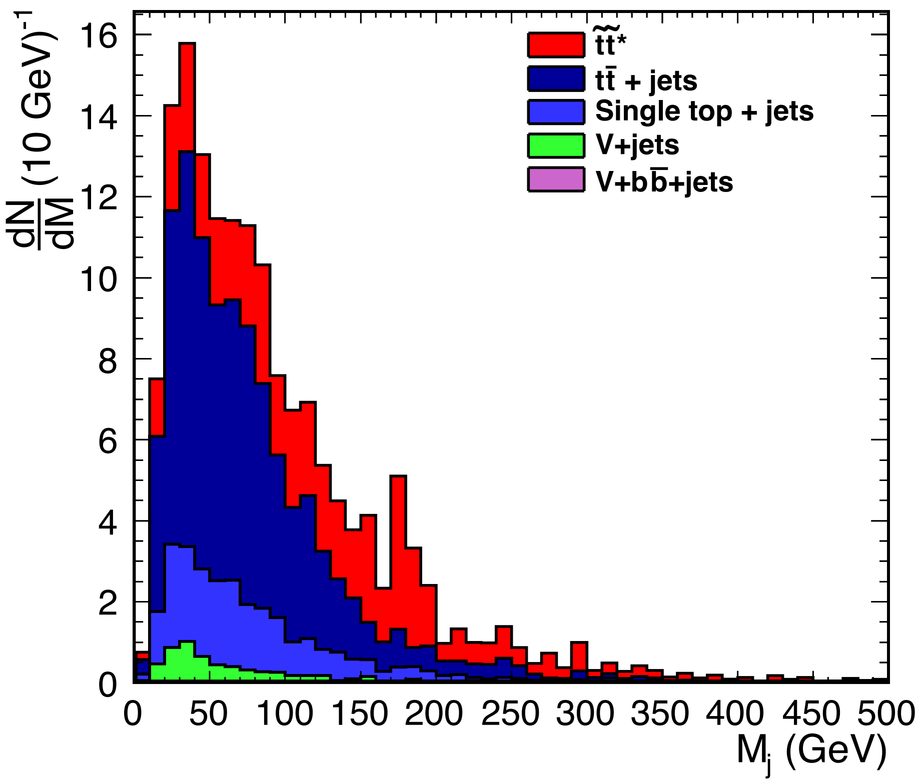


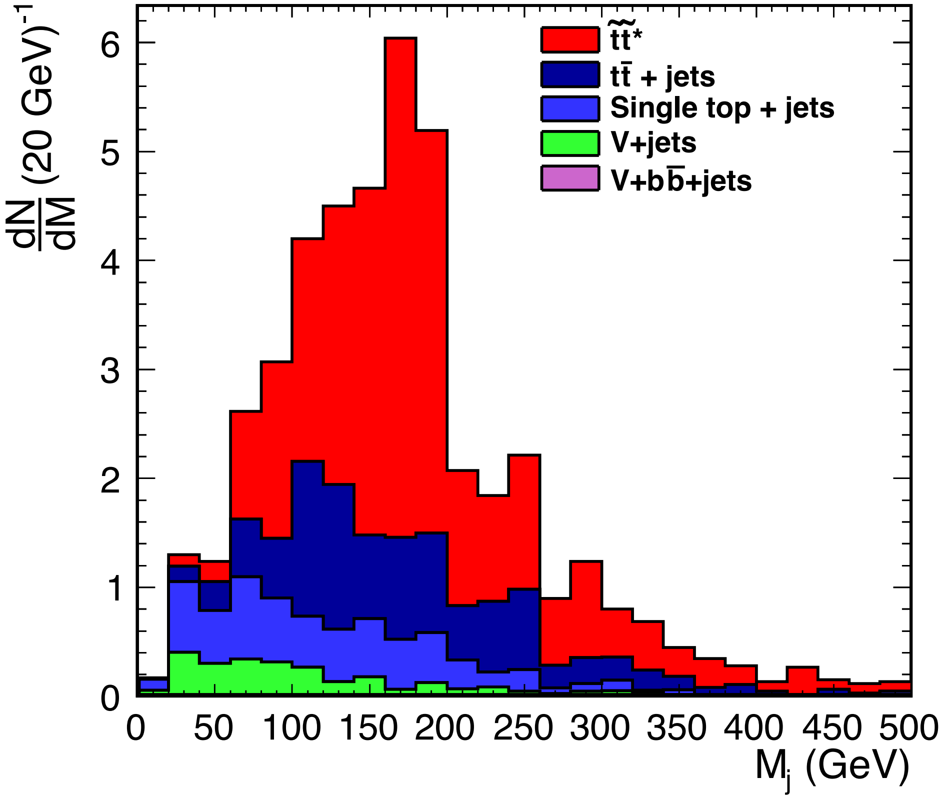
SYSTEMATICS

- Systematics such as BG x-section uncertainties not taken into account

- Can do more sophisticated shape analysis of distributions

- Can do data driven measurements of backgrounds





MULTI-JET BG

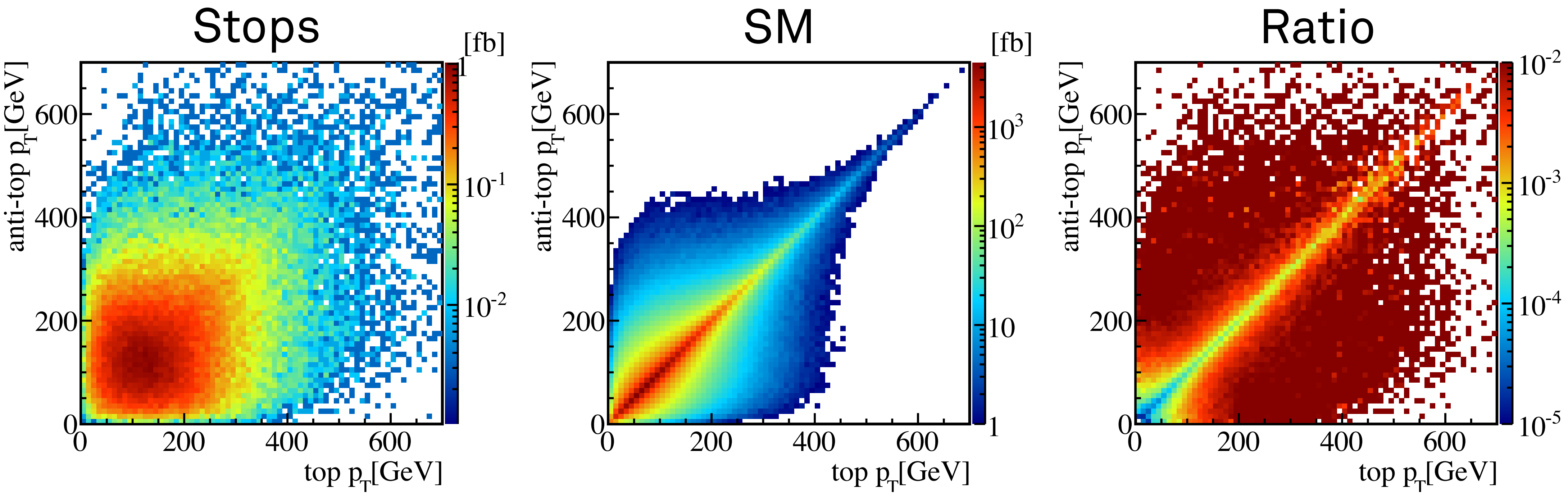
- Cutting hard on MET eliminates QCD bg. Is that necessary?

- Experimentalists can potentially make data driven measurement. Can we reduce MET cut?

- Allows us to push into lighter stop region

ANOTHER ANALYSIS

Similar analysis by a different group **Plehn, Spannowsky, Takeuchi 1205.2696.**



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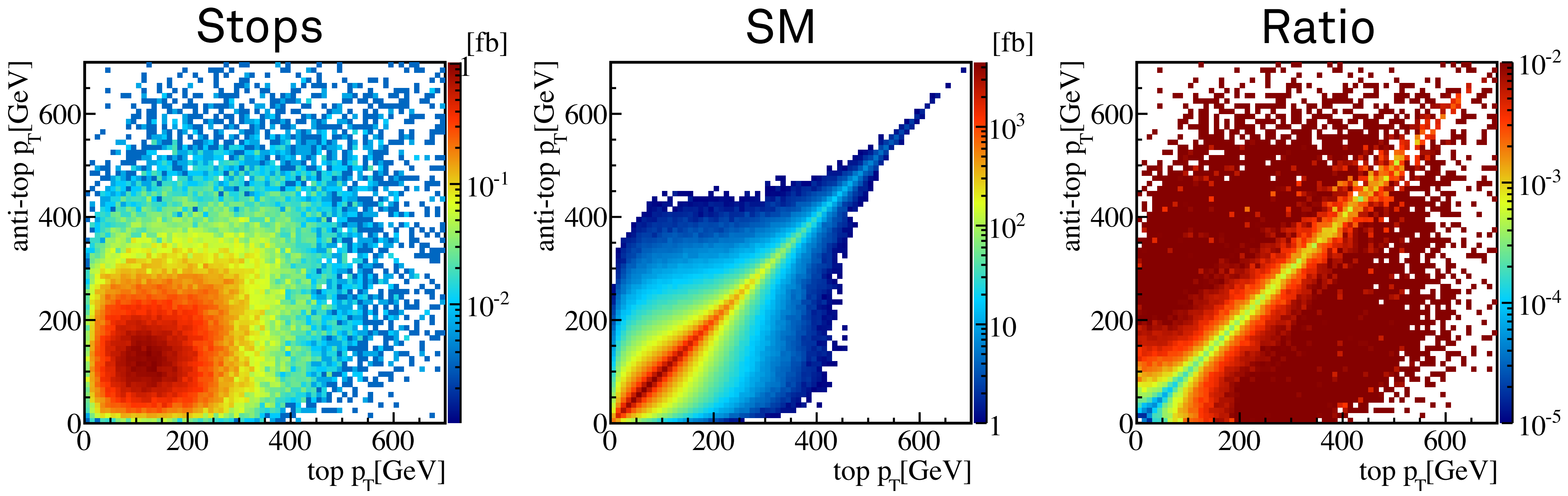

$\sqrt{s} = 8$ TeV	$\tilde{t}\tilde{t}^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	350	400	450	500	600	700					400	
ℓ veto, $n_{\text{fat}} \geq 1$	378	186	92.3	47.8	14.0	4.40	$6.9 \cdot 10^4$	$3.8 \cdot 10^7$	$1.9 \cdot 10^5$	$5.0 \cdot 10^4$	$5 \cdot 10^{-6}$	0.1
$\not{p}_T > 100$ GeV	264	149	78.6	42.1	12.9	4.15	$7.1 \cdot 10^3$	$3.8 \cdot 10^5$	$1.3 \cdot 10^4$	$3.2 \cdot 10^3$	$4 \cdot 10^{-4}$	0.7
$n_{\text{tag}} \geq 1$	48.8	32.6	19.9	12.0	4.29	1.54	959	$2.7 \cdot 10^3$	106	57.3	$9 \cdot 10^{-3}$	1.7
$n_{\text{tag}} = 1$, b-tag inside	13.0	8.57	5.34	3.14	1.15	0.42	322	26.4	1.05	0.57	0.024	1.4
additional b-tag	4.41	2.81	1.75	1.04	0.39	0.15	116	0.26	0.01	–	0.024	0.82
$m_T^{(b)} > 200$ GeV	0.92	0.90	0.73	0.50	0.24	0.10	1.20	–	–	–	0.73	2.6

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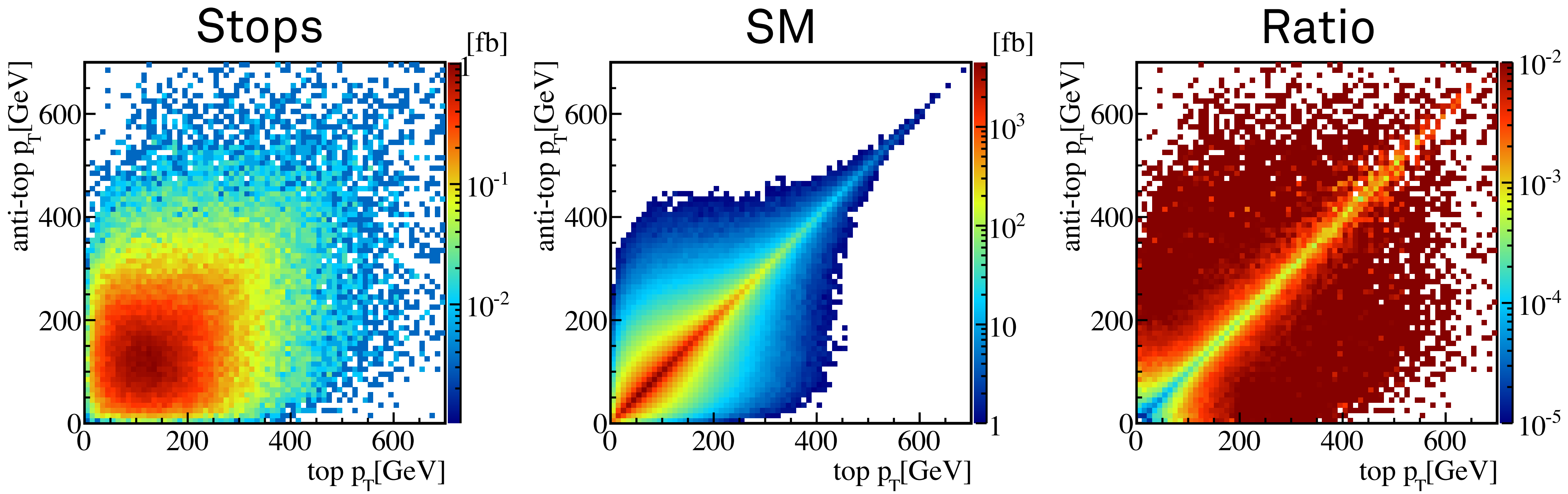

Stops SM Ratio

$\sqrt{s} = 8$ TeV	$\tilde{t}\tilde{t}^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
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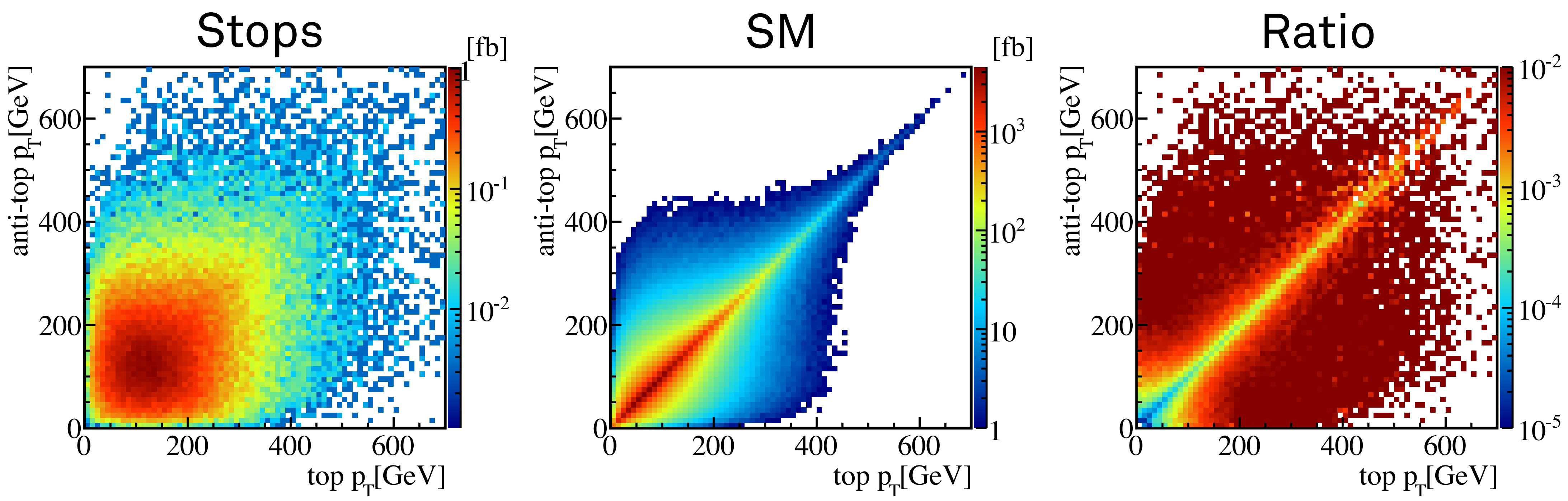

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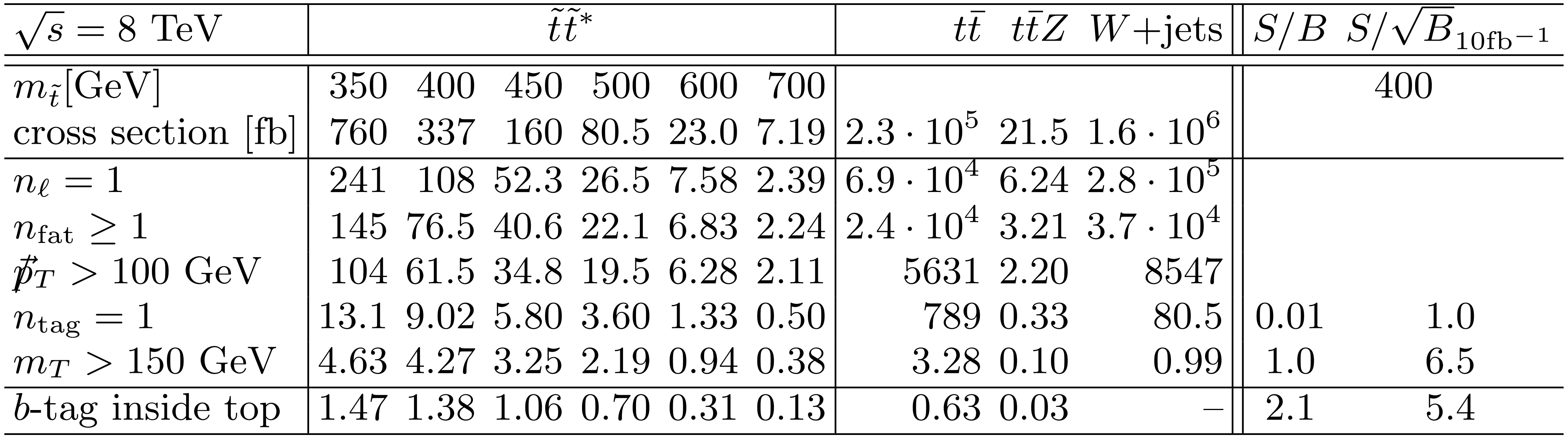
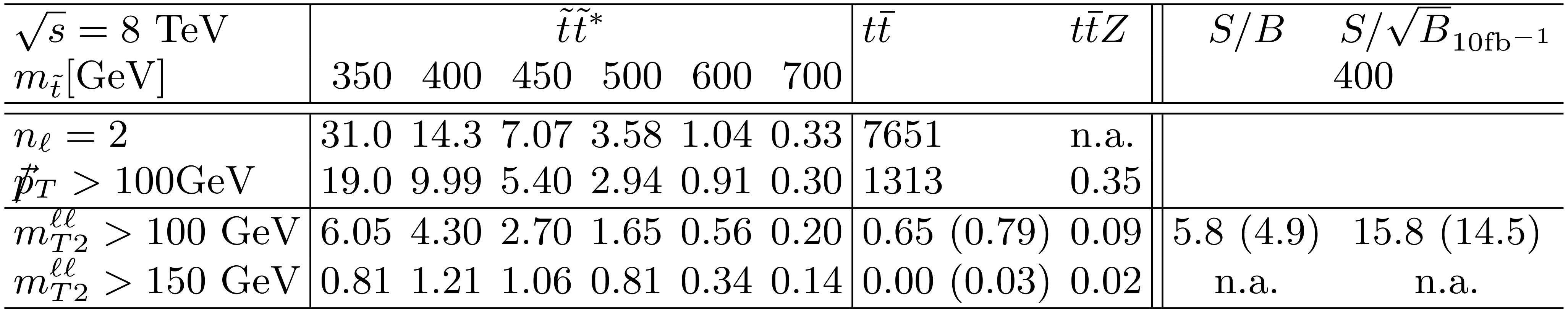


$\sqrt{s} = 8$ TeV	$\tilde{t}\tilde{t}^*$						$t\bar{t}$	$t\bar{t}Z$	W+jets	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	350	400	450	500	600	700				400	
cross section [fb]	760	337	160	80.5	23.0	7.19	$2.3 \cdot 10^5$	21.5	$1.6 \cdot 10^6$		
$n_\ell = 1$	241	108	52.3	26.5	7.58	2.39	$6.9 \cdot 10^4$	6.24	$2.8 \cdot 10^5$		
$n_{\text{fat}} \geq 1$	145	76.5	40.6	22.1	6.83	2.24	$2.4 \cdot 10^4$	3.21	$3.7 \cdot 10^4$		
$\not{\vec{p}}_T > 100$ GeV	104	61.5	34.8	19.5	6.28	2.11	5631	2.20	8547		
$n_{\text{tag}} = 1$	13.1	9.02	5.80	3.60	1.33	0.50	789	0.33	80.5	0.01	1.0
$m_T > 150$ GeV	4.63	4.27	3.25	2.19	0.94	0.38	3.28	0.10	0.99	1.0	6.5
b-tag inside top	1.47	1.38	1.06	0.70	0.31	0.13	0.63	0.03	–	2.1	5.4



$\sqrt{s} = 8$ TeV $m_{\tilde{t}}$[GeV]	$\tilde{t}\tilde{t}^*$ 350	400	450	500	600	700	$t\bar{t}$	$t\bar{t}Z$	S/B 400	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$n_\ell = 2$	31.0	14.3	7.07	3.58	1.04	0.33	7651	n.a.		
$\not{\vec{p}}_T > 100$GeV	19.0	9.99	5.40	2.94	0.91	0.30	1313	0.35		
$m_{T2}^{\ell\ell} > 100$ GeV	6.05	4.30	2.70	1.65	0.56	0.20	0.65 (0.79)	0.09	5.8 (4.9)	15.8 (14.5)
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See also:

Cao, Han, Wu, Yan, Zhang, 1206.3865. Dutta, Teruki, Kamon, Kolev, Sinha, Wang, 1207.1873.

WAYS OUT?

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Other paths to naturalness?

- Make stops lighter

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- Squeezed spectrum/ degeneracy

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Theory estimate Kats et. al, 1110.6444

$m_{\tilde{t}} \gtrsim 175\,\mathrm{GeV}$

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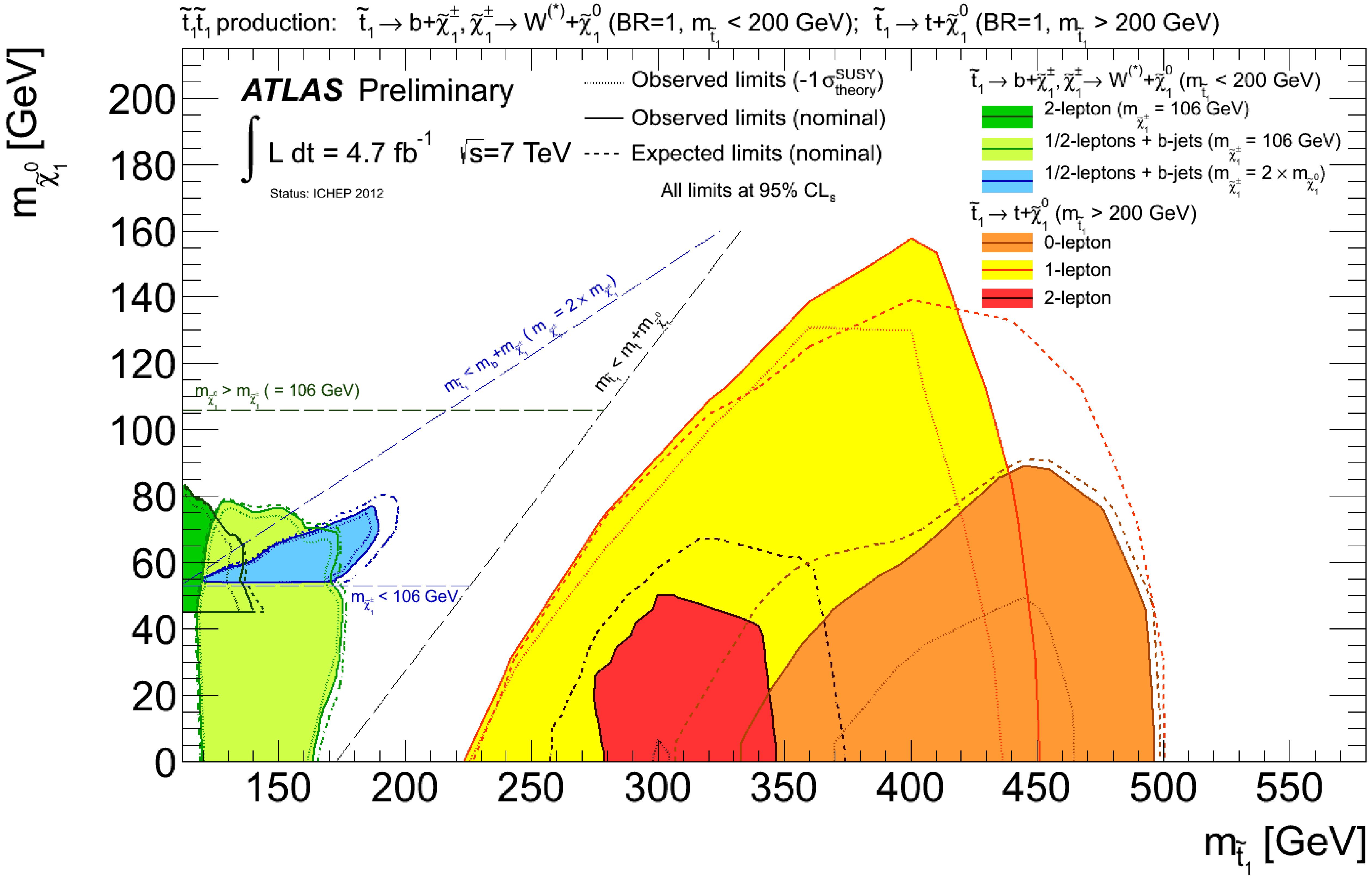
$m_{\tilde{t}} \gtrsim 180\,\mathrm{GeV}$ CDF 1203.4171
ATLAS ICHEP searches

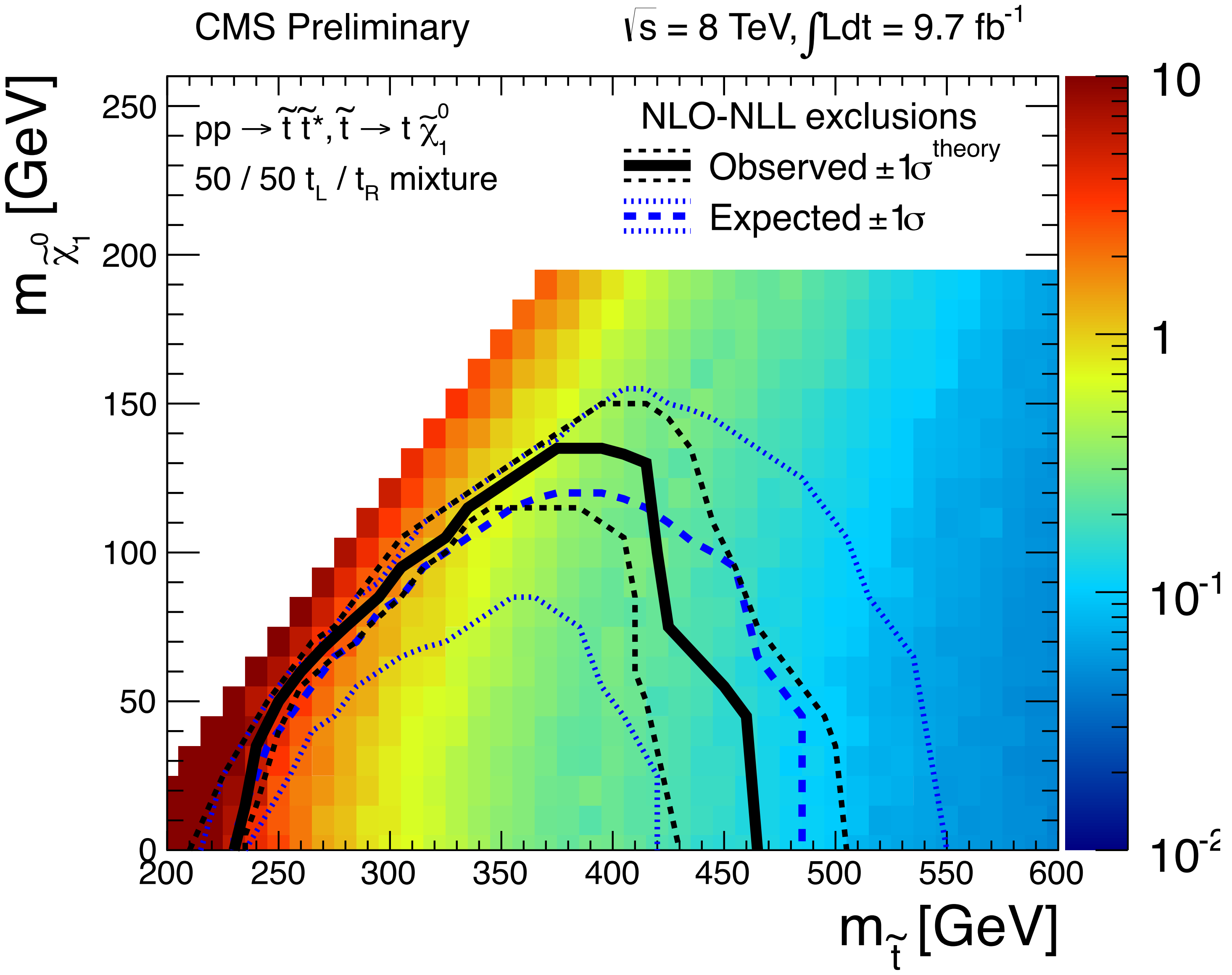
- *R*-parity violation

Various LHC searches ongoing

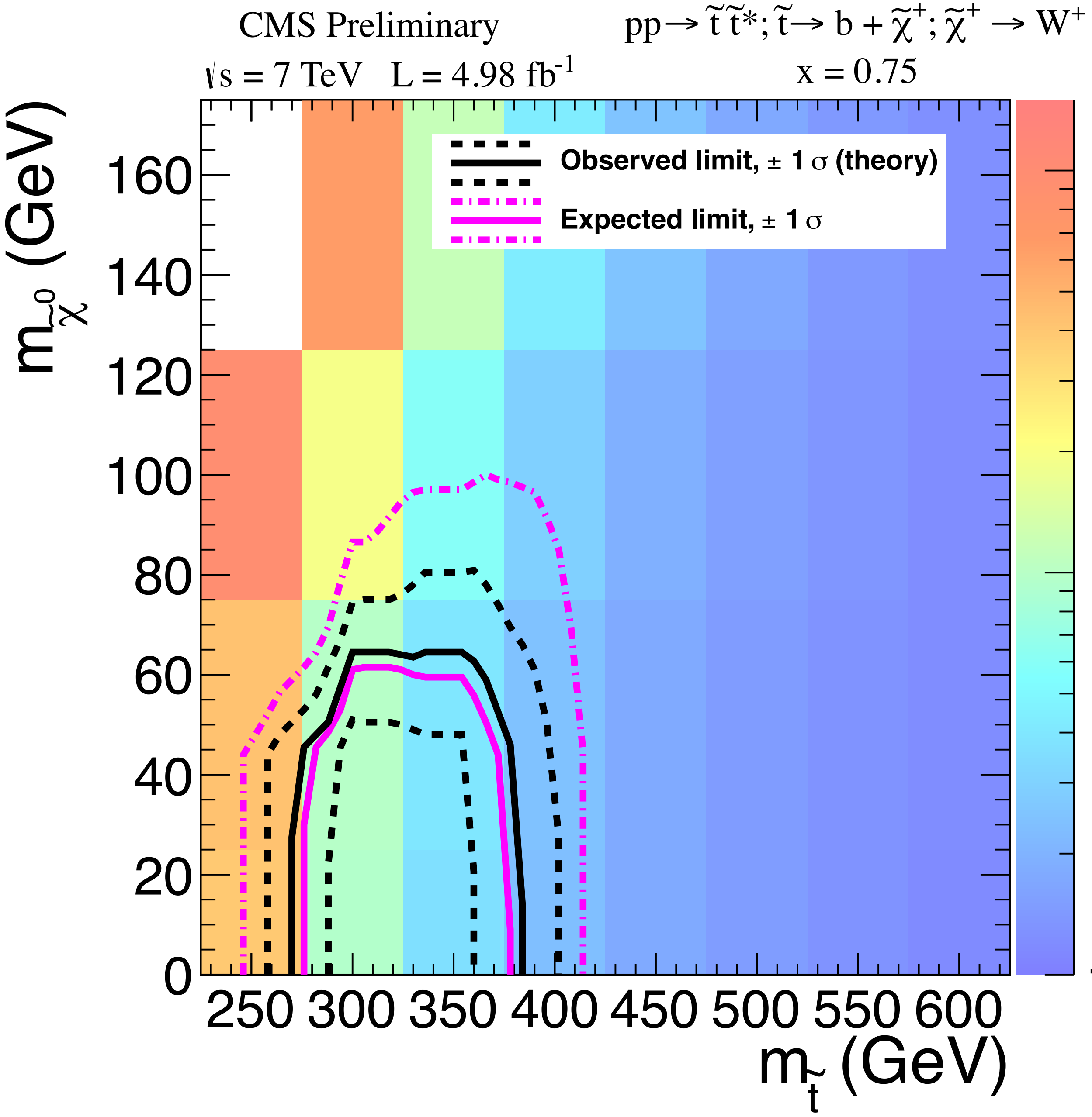
ATLAS RESULTS



CMS RESULTS



$n_\ell = 1$



$n_\ell = 0$

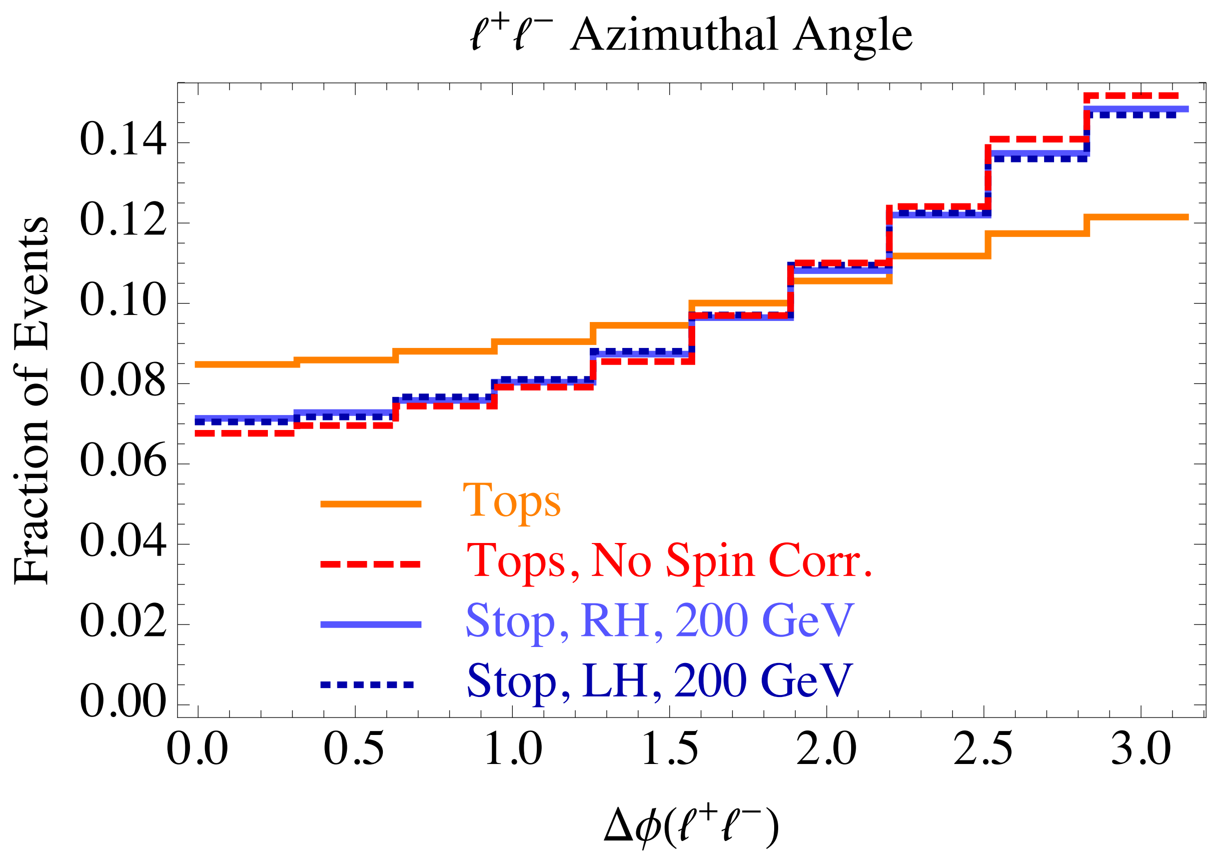
STEALTH STOPS

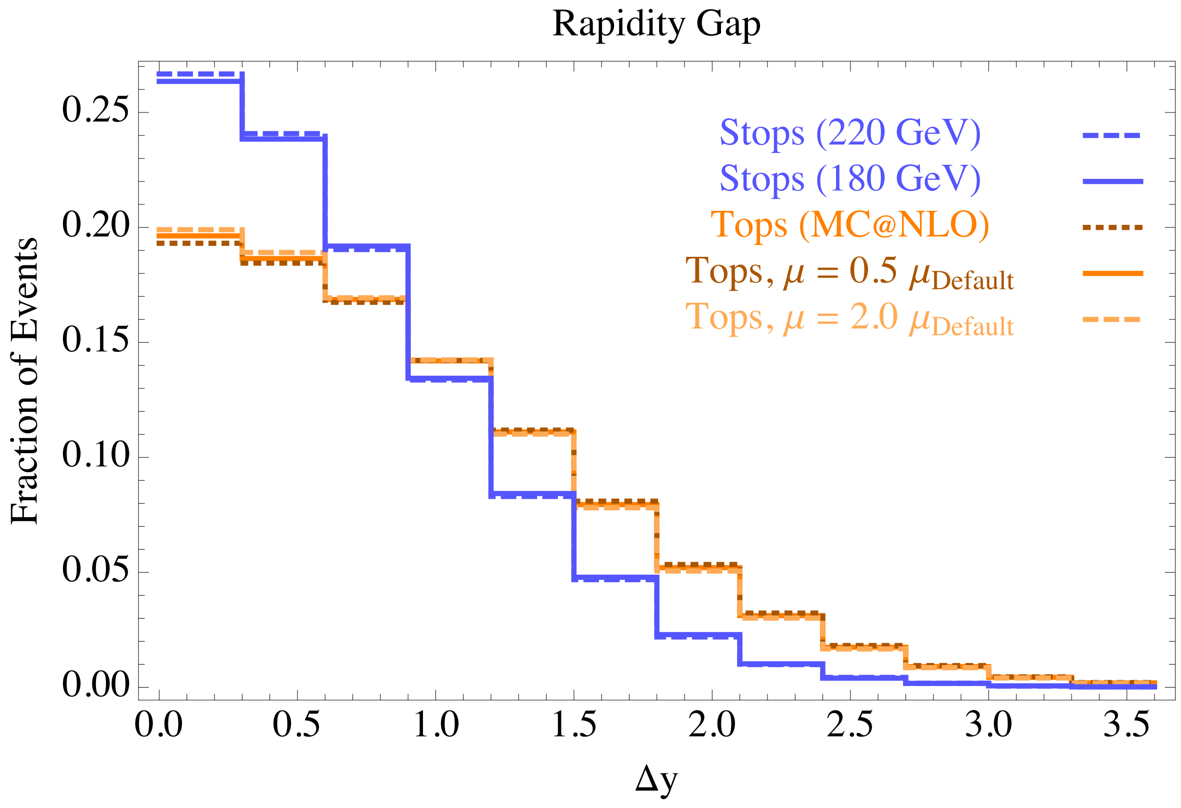
Stop mass near top mass recently studied **Han, Katz, Krohn, Reece, 1205.5808**

Difficult because $\sigma_{\text{top}} \sim 6\sigma_{\text{stop}}$

Spin correlations

Rapidity gap





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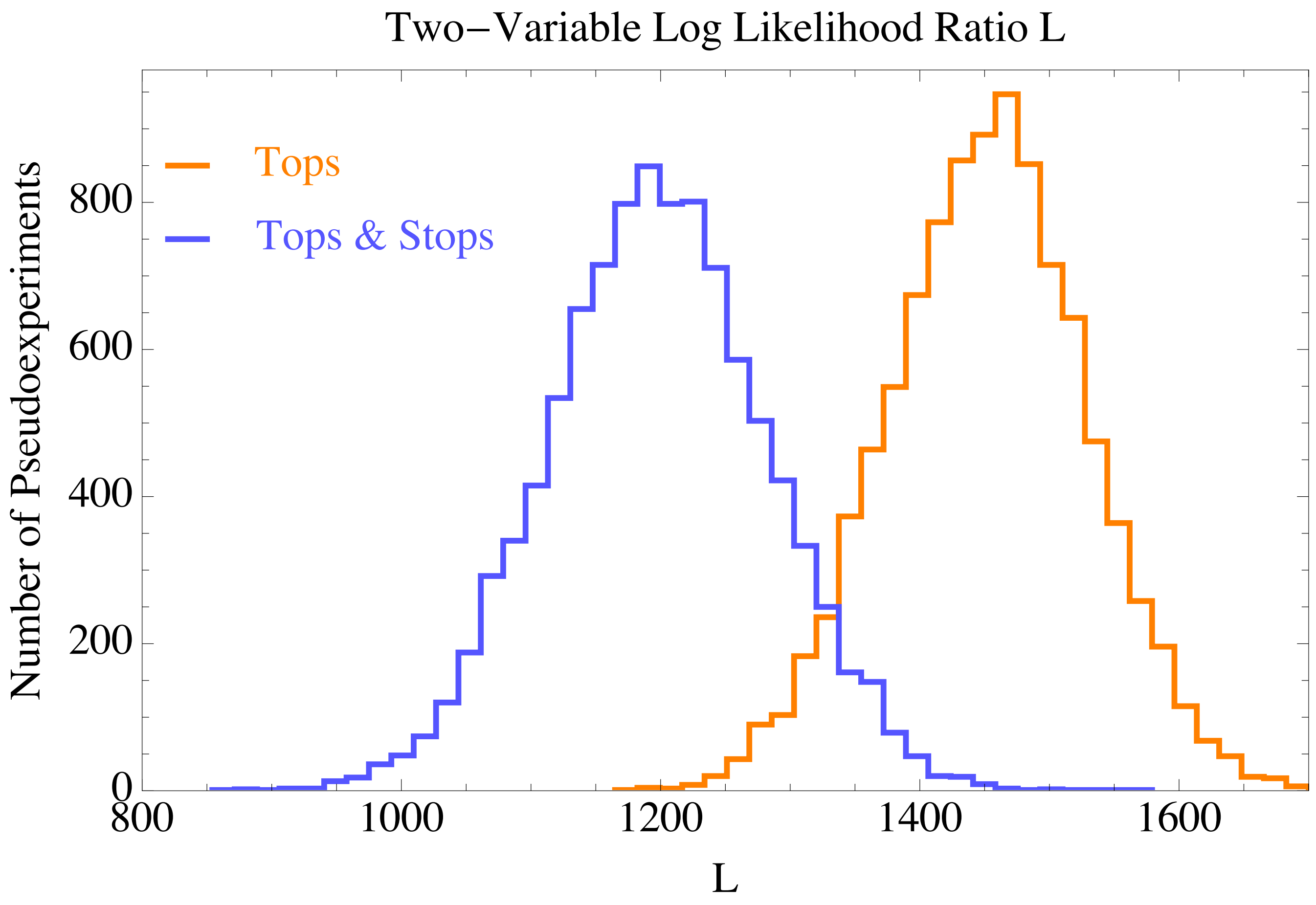

Can get ~ 3σ evidence
with combination

STEALTH STOPS

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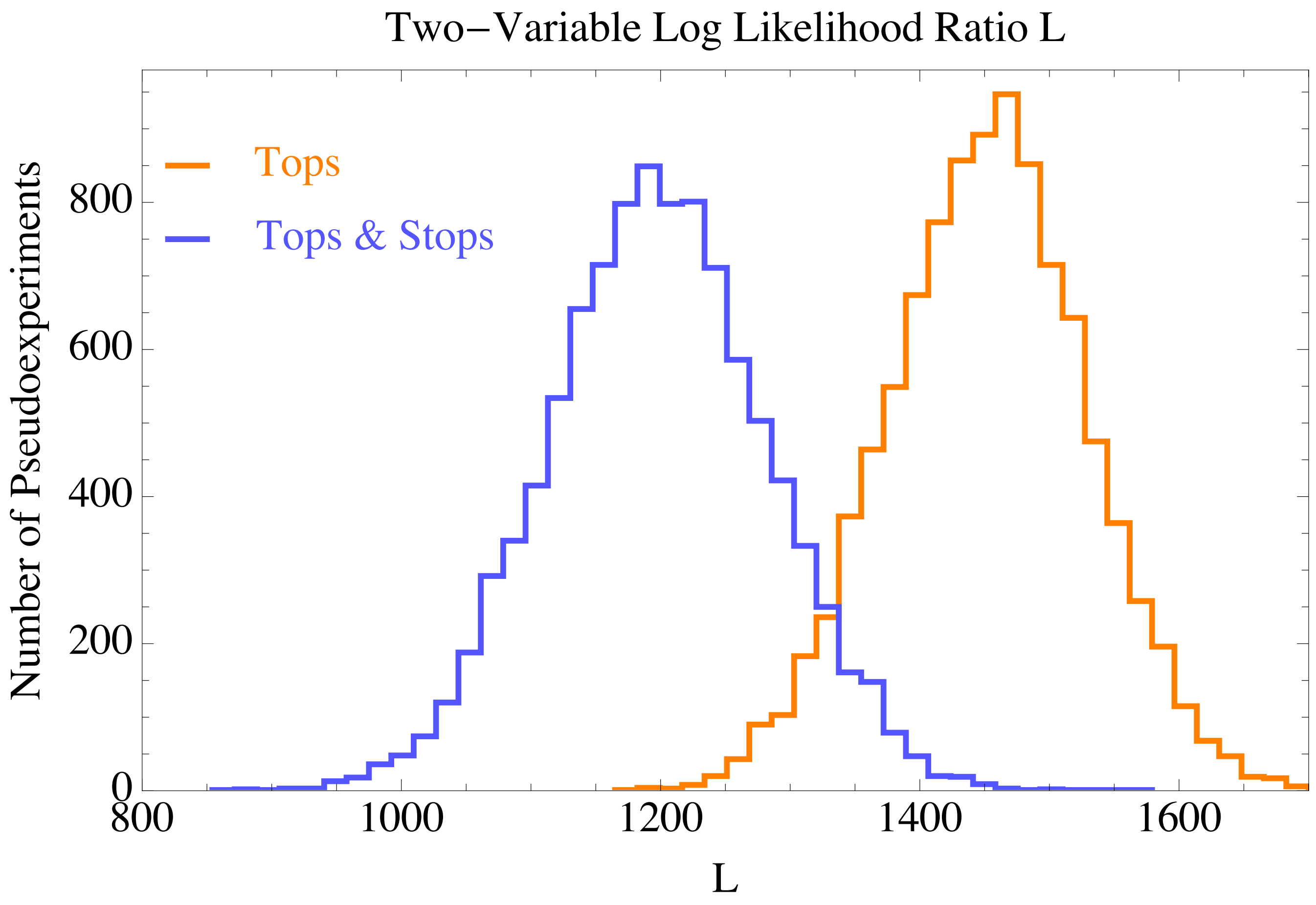


See also:

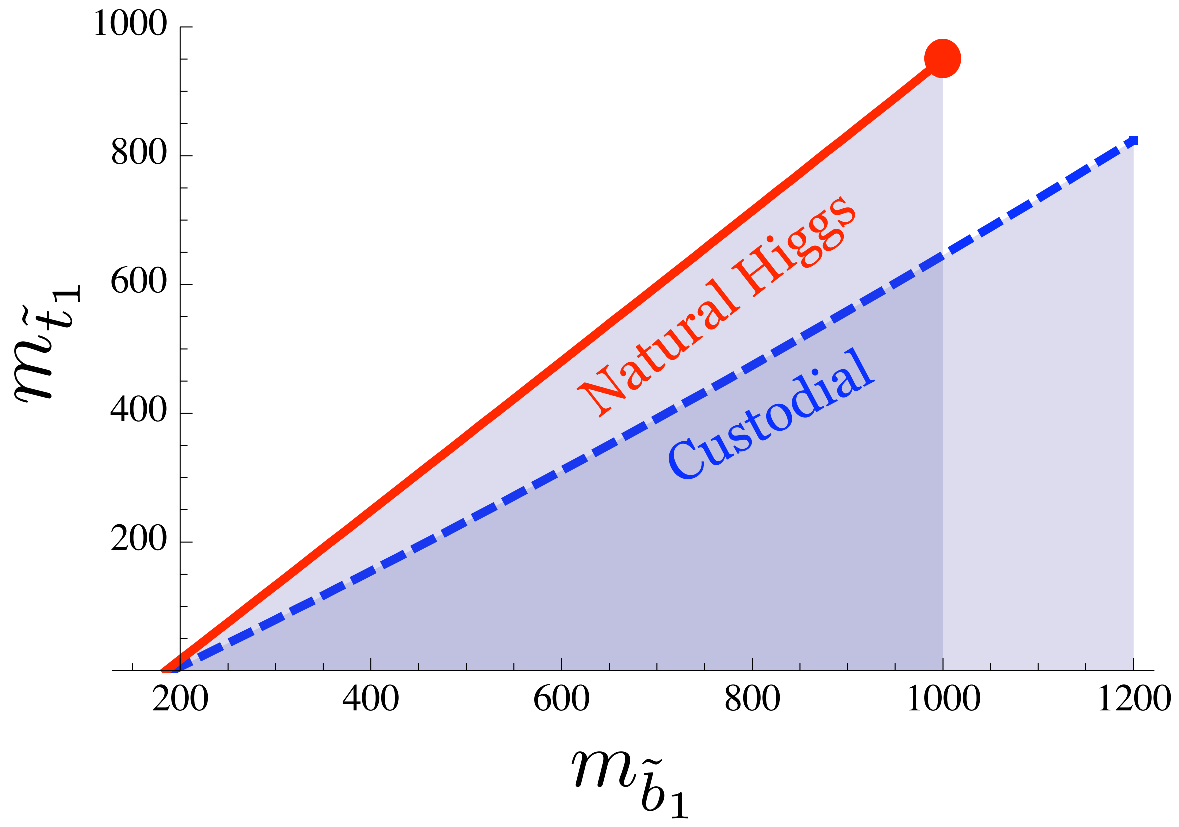
Alves, Buckley, Fox, Lykken, Yu, 1205.5805

Can get ~ 3σ evidence with combination

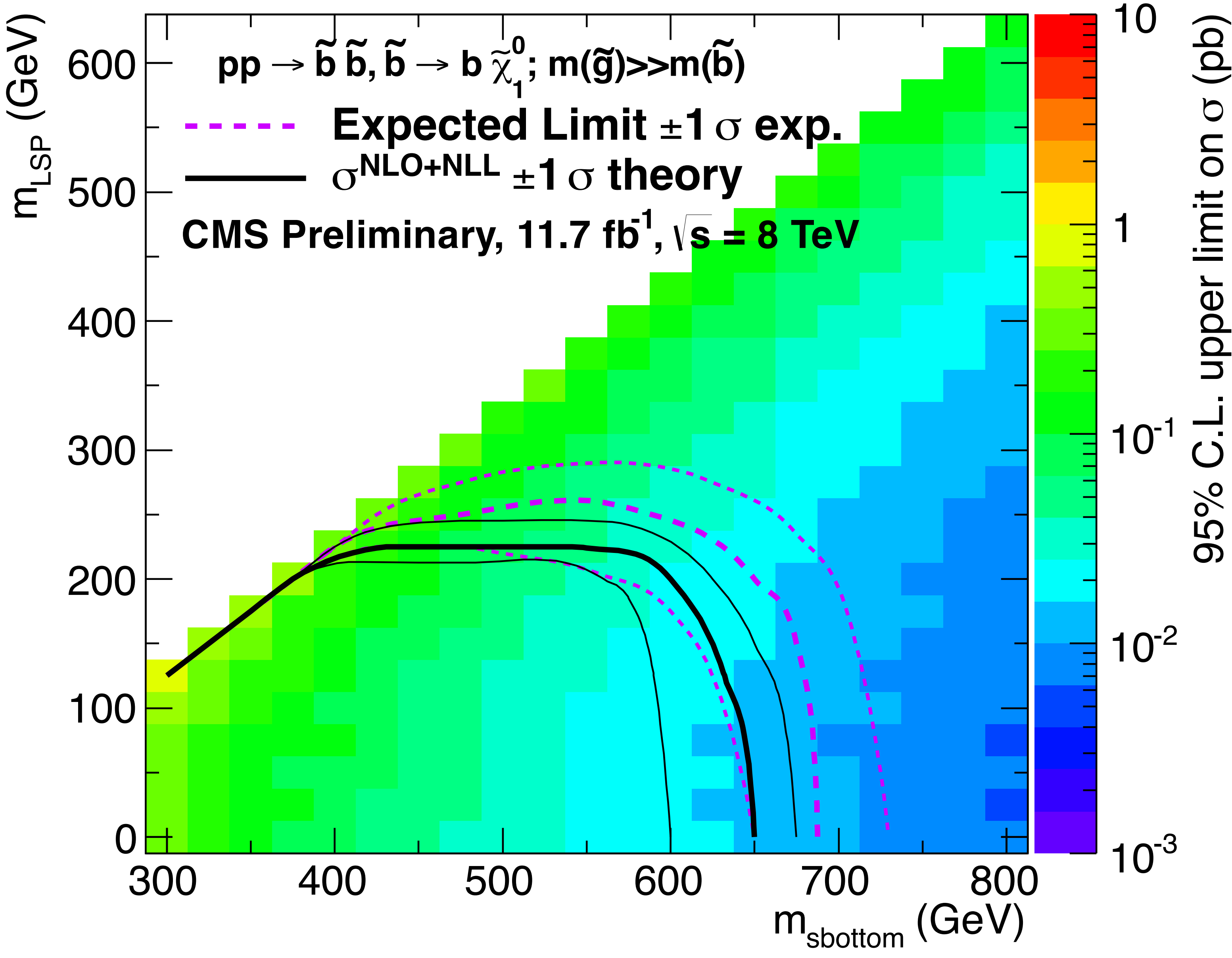
WHAT ABOUT SBOTTOM?

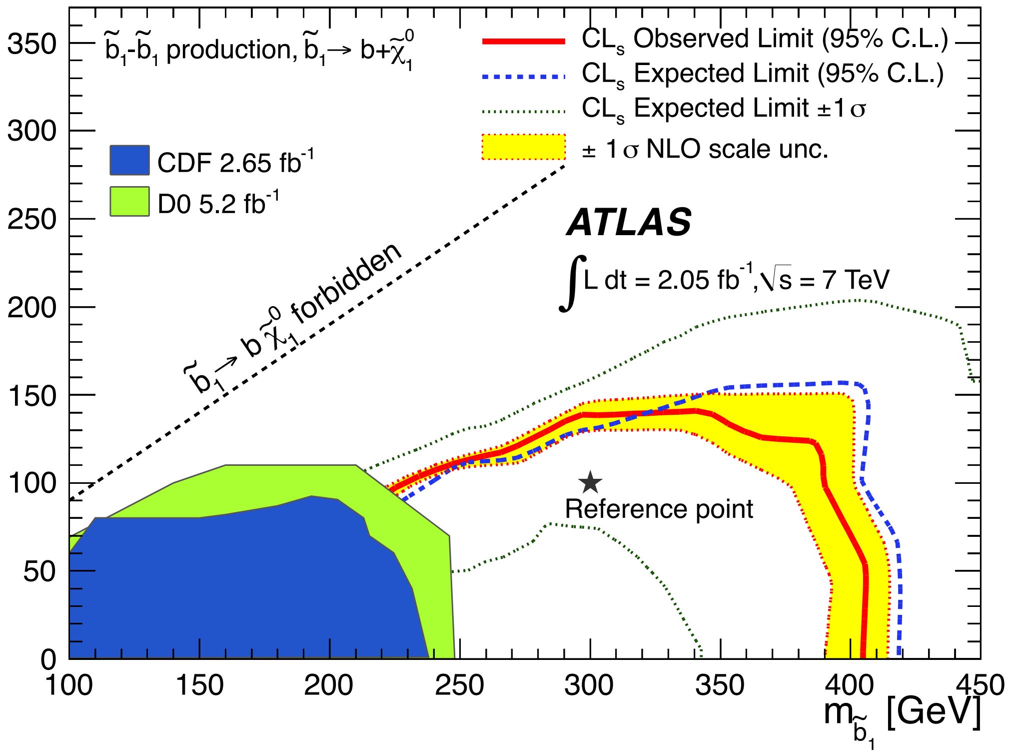
- Naturalness requires left handed sbottom
- $\tilde{b} \rightarrow b\,\chi^0$ has more missing energy than corresponding stop
- 2012 data can probe up to ~ 800 GeV sbottom
- Natural SUSY sbottoms out

Lee, Sanz, Trott, 1204.0802



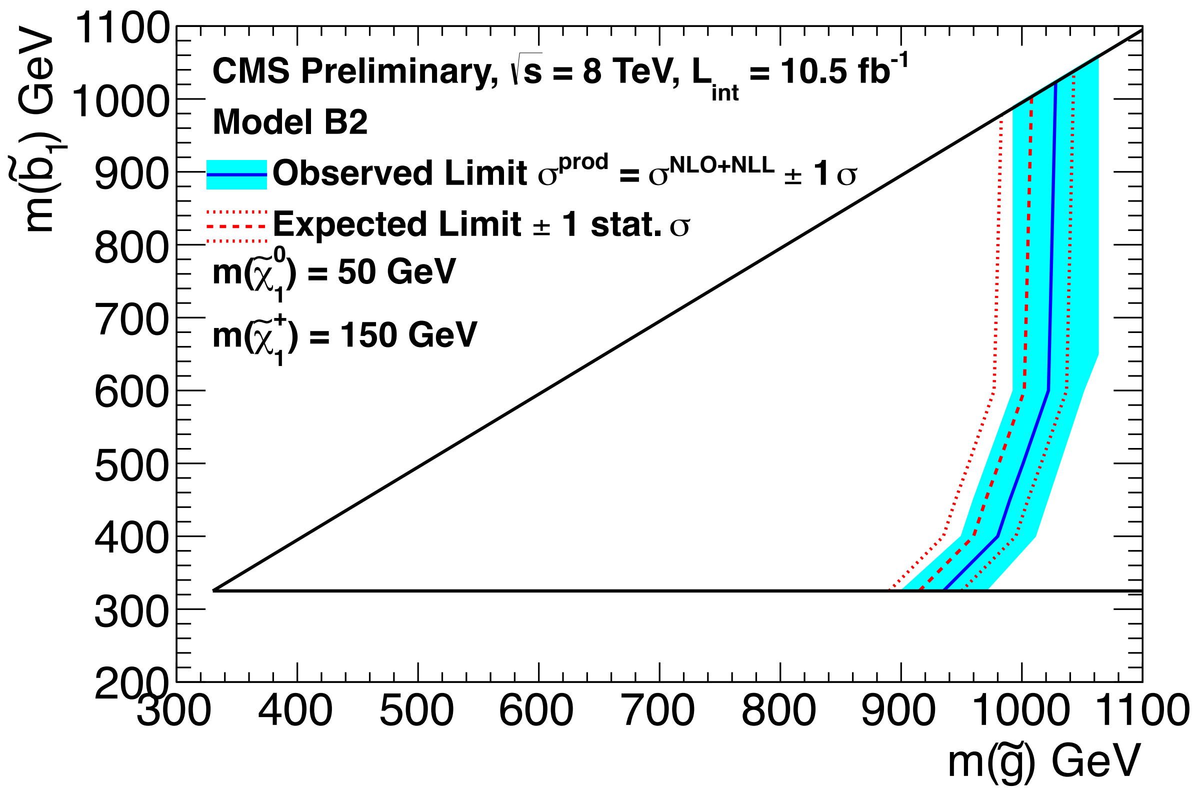
SBOTTOM BOUNDS



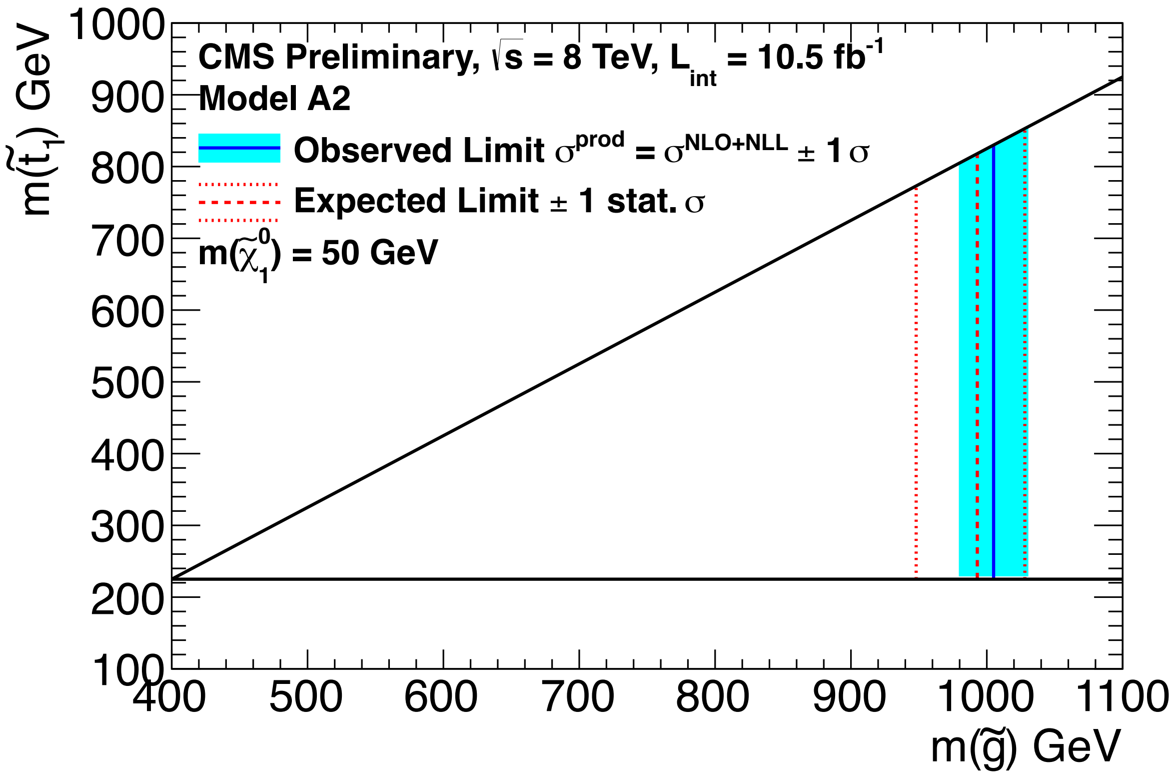


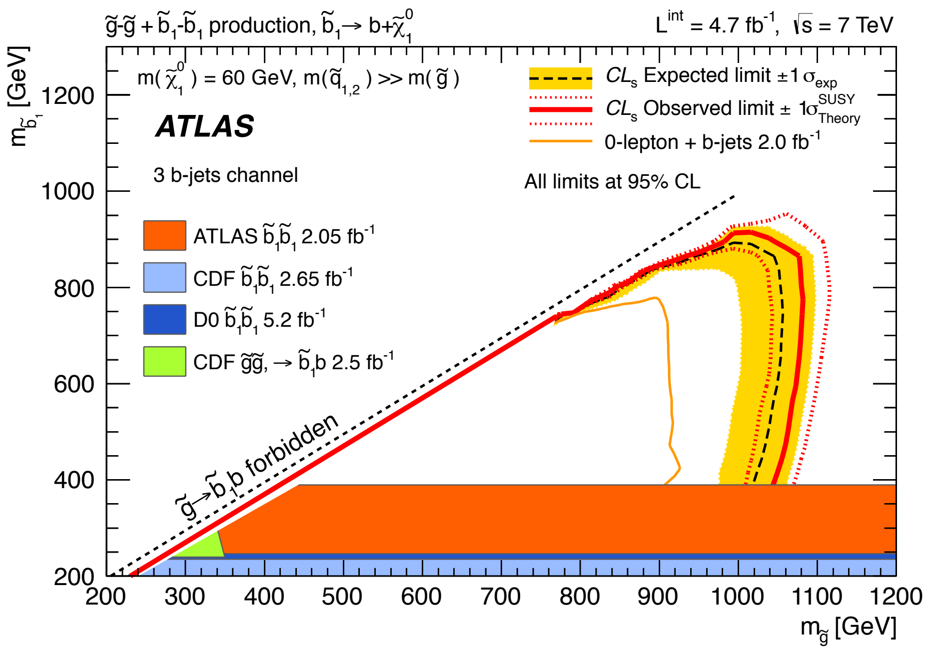
GLUINO BOUNDS

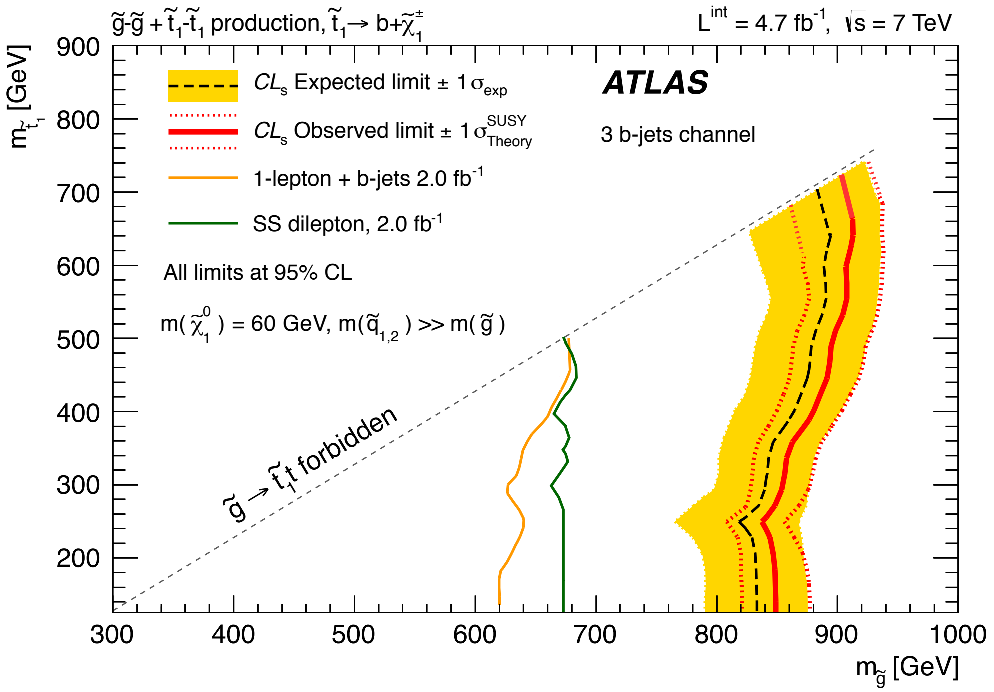
$\tilde{g} + \tilde{b}$



$\tilde{g} + \tilde{t}$







CONCLUSIONS

- Stops are lightest indication of naturalness
- All hadronic final states are good way to search for missing energy
- Top tagging combined with other simple cuts can bring out stop signal with data already taken
- Many other stop scenarios, a lot of work has been done
- Searches for stops and gluinos are well underway
- Modern techniques helped disfavor natural vanilla stops

THANK YOU