# Search for direct top squark pair production in events with two tau leptons with the ATLAS detector

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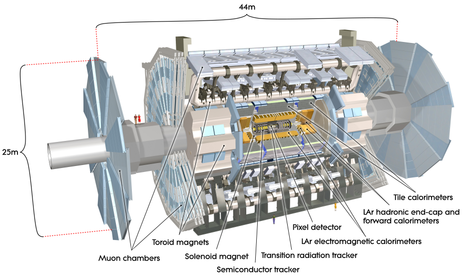
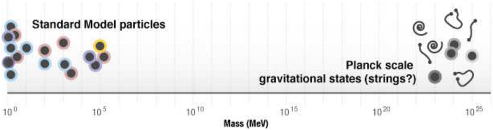
# ATLAS is searching for “new physics” to explain some open questions about the Standard Model

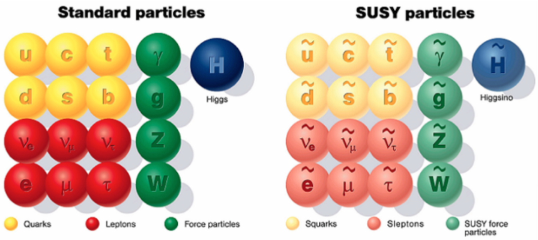



Dark matter




Hierarchy problem

# Supersymmetry to the rescue




$W^\pm\ W^0\ B \overset{mixing}{\rightarrow} W^\pm\ Z\ \gamma$

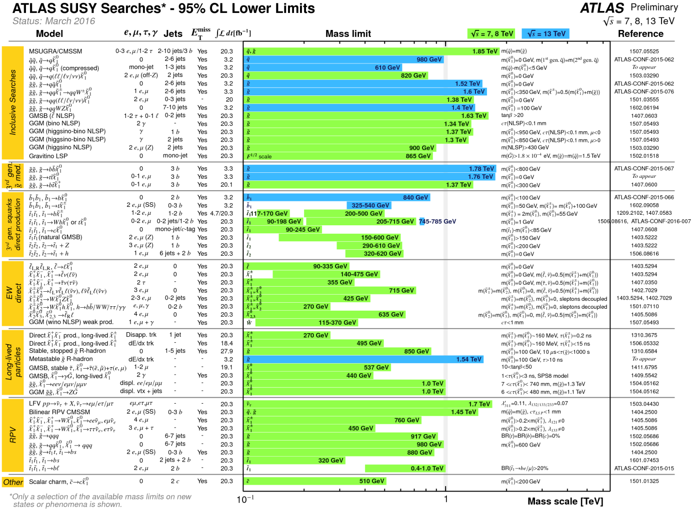
$\tilde{H}_u^0\ \tilde{H}_d^0\ \tilde{W}^0\ \tilde{B}^0 \overset{mixing}{\rightarrow} \tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$ neutralinos

$\tilde{H}_u^+\ \tilde{H}_d^-\ \tilde{W}^+\ \tilde{W}^- \overset{mixing}{\rightarrow} \tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$ charginos

Supersymmetry fixing SM:

- $\tilde{G}$ = dark matter candidate
- top squark ("stop", $\tilde{t}$) helps with hierarchy problem

# Many SUSY searches performed by ATLAS, including for top squarks

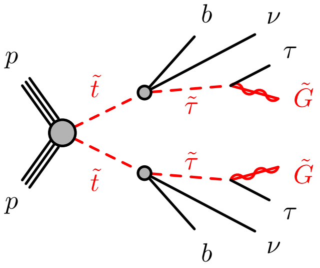



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

# Search for top squark to tau slepton signal over $t\bar{t}$ background



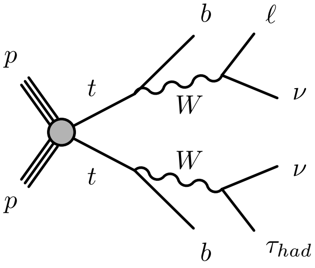
Signal (GMSB)




$\sigma(\tilde{t}\tilde{t}^*) \sim 0.5$ pb, $m(\tilde{t}) = 500$ GeV

- $\tilde{G}/\nu =$ undetected $\rightarrow E_{\mathrm{T}}^{\mathrm{miss}}$
- Final state objects:
  - 2 $b$-jets
  - $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $0 - 2$ e or $\mu$
  - $2 - 0$ $\tau_{had}$

Dominant background




$\sigma(t\bar{t}) \sim 8 \times 10^2$ pb

Channels:

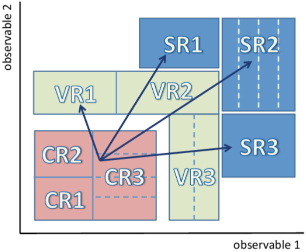
- lepton–lepton $= 2$ e or $\mu$
- lepton–hadron $=$ $1$ $\tau_{had}$ and (1 e or $\mu$)
- hardon–hadron $= 2$ $\tau_{had}$

# Selection cuts isolate regions of phase space to maximize/minimize signal to background



Just count # events in phase space regions:

- Control: scale simulation to data for dominant backgrounds
- Validation: check scaling
- Signal: maximized signal to background

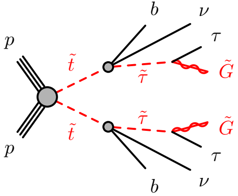



Analysis blinded to reduce human bias

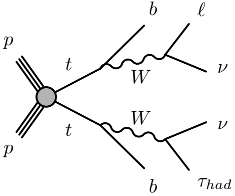
Data set from 2012: $8\ \mathrm{TeV}$, $20\mathrm{fb}^{-1}$

# Several kinematic variables separate signal from background

Signal

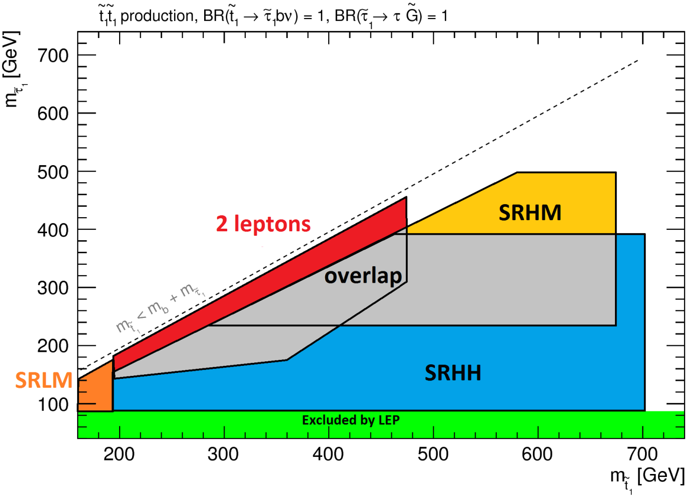



Dominant background



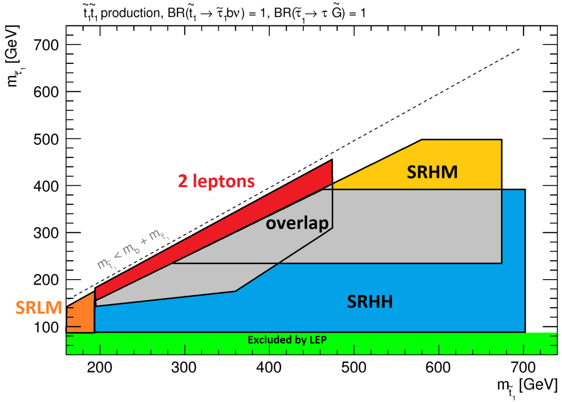

- Number of $b$-jets
- Probes of decaying particles' masses, e.g. $m_{\mathrm{T2}}(\mathrm{b}\ell, \mathrm{b}\tau)$
  - $m_{\mathrm{T2}}(\mathrm{a},\mathrm{b}) = \sqrt{\min_{\mathbf{q}_{\mathrm{T}}^{\mathbf{a}}+\mathbf{q}_{\mathrm{T}}^{\mathbf{b}}=\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}} \left(\max\left[m_{\mathrm{T}}^2\left(\mathbf{p}_{\mathrm{T}}^{\mathrm{a}},\mathbf{q}_{\mathrm{T}}^{\mathrm{a}}\right), m_{\mathrm{T}}^2\left(\mathbf{p}_{\mathrm{T}}^{\mathrm{b}},\mathbf{q}_{\mathrm{T}}^{\mathrm{b}}\right)\right]\right)}$
- Sums/ratios of momenta e.g.
  - $H_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{jet1}} + p_{\mathrm{T}}^{\mathrm{jet2}}$
  - $\frac{p_{\mathrm{T}}^{\ell}+p_{\mathrm{T}}^{\tau}}{\sum_i^{all} p_{\mathrm{T}}(i)}$

# Design analyses around unknown signal masses: $m(\tilde{t})$ and $m(\tilde{\tau})$




$$m(\tilde{t}) = ? \qquad m(\tilde{\tau}) = ? \qquad m(\tilde{G}) \ll 1 \text{ GeV}$$

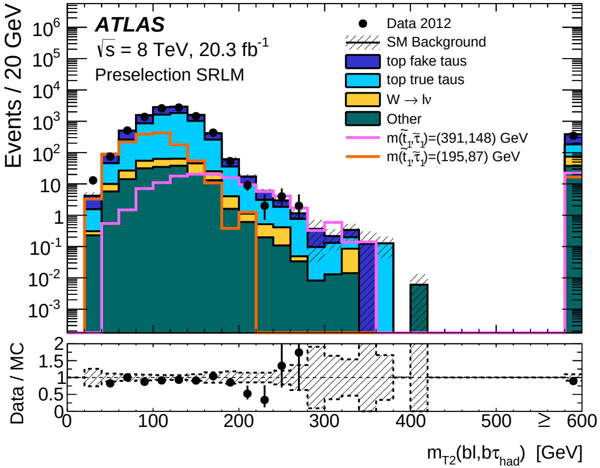
# Main cuts separating each channel/SR are $m_{T2}(t) \to m(\tilde{t})$ and $m_{T2}(W) \to m(\tilde{\tau})$




- SRHM $m_{T2}(W) > 120$ GeV vs SRHH $m_{T2}(W) > 50$ GeV
- SRHM $m_{T2}(t) > 180$ GeV vs SRHH all top squark masses
- 2 leptons $m_{T2}(W)$ and jet $p_T$ & multiplicity
- SRLM $m_{T2}(t) < 60$ GeV vs SRHH all top squark masses

# $t$ mass-probing variable






$$m_{T2}(t) = m_{T2}\,(b\ell, b\tau)$$

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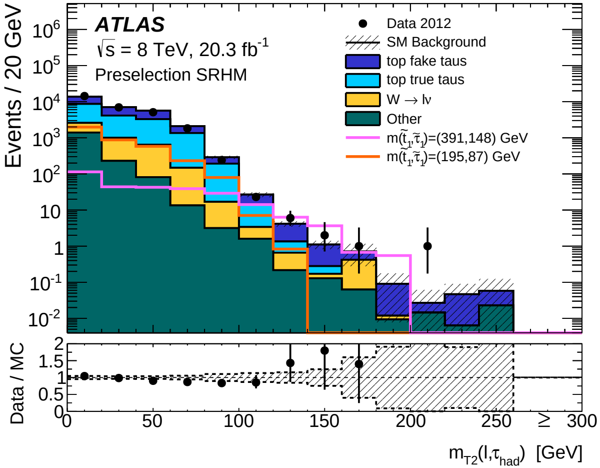
# $W$ mass-probing variable




$$m_{\mathrm{T2}}(W) = m_{\mathrm{T2}}\left(\ell, \tau\right)$$

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# No excesses seen in any signal region



| Analysis | Expected bkgd (nom. $\pm$ stat. & syst.) | Observed |
|---|---|---|
| Lepton–hadron low mass SRLM | $22.1 \pm 4.7$ | 20 |
| Lepton–hadron high mass SRHM | $2.1 \pm 1.5$ | 3 |
| Hadron–hadron SRHH | $3.1 \pm 1.2$ | 3 |

2-leptons channel has many SRs : no excess.

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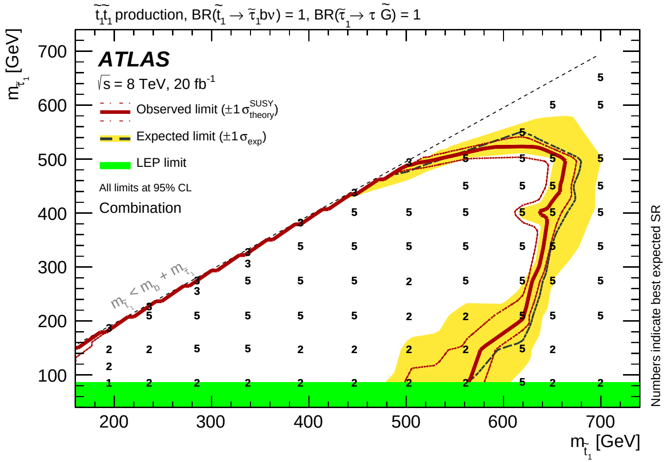
# Use SR/channel that gives best expected CLs for combination






3=lepton–lepton 5=lepton–hadron high mass

1=lepton–hadron low mass 2=hadron–hadron

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# Summary

- Top squark could help fix an open problem in the Standard Model
- Low and high $\tilde{t}$ masses probed as a function of the $\tilde{\tau}$ mass
- No excesses observed.
- Set limits on $m(\tilde{t})$ as a function of $m(\tilde{\tau})$
  - Heaviest top squark mass excluded $\sim 660$ GeV
- Expecting $\sim 25\text{fb}^{-1}$ this year
  - Should be sensitive to $m(\tilde{t}) \sim 800$ GeV

# Region cuts are all orthogonal to each other

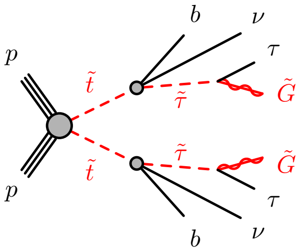
| Region | $N_{\tau_{\text{had}}}$ | $N_{\mu}$ | $N_{\text{jet}}$ | $N_{b-\text{jet}}$ | $E_{\text{T}}^{\text{miss}}$ | $\Delta\phi(j_{1,2}, p_{\text{T}}^{\text{miss}})$ | $m_{\text{T2}}(\tau_{\text{had}}, \ell)$ | $m_{\text{T}}^{\text{sum}}(\tau_{\text{had}}, \ell)$ |
|---|---|---|---|---|---|---|---|---|
| SRHH | 2 | 0 | $\geq 2$ | $\geq 1$ | $> 150$ GeV | $\geq 0.5$ | $> 50$ GeV | $> 160$ GeV |
| CRHHTop | 1 | 1 | $\geq 2$ | $\geq 1$ | $> 100$ GeV | $\geq 0.5$ | - | [70,120] GeV |
| CRHHWjets | 1 | 1 | $\geq 2$ | 0 | $> 100$ GeV | $\geq 0.5$ | $< 40$ GeV | [80,120] GeV |
| VRHHTop | 1 | 1 | $\geq 2$ | $\geq 1$ | $> 120$ GeV | $\geq 0.5$ | $< 40$ GeV | [120,140] GeV |
| VRHHWjets | 1 | 1 | $\geq 2$ | 0 | $> 120$ GeV | $\geq 0.5$ | $< 40$ GeV | [120,150] GeV |
| CRHHQCD | $\geq 2$[a] | 0 | $\geq 2$ | $\geq 1$ | $> 150$ GeV | $\leq 0.5$[b] | - | - |

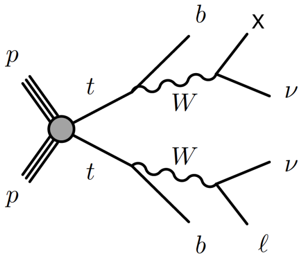
[a]For the multi-jet control region (CRHHQCD), no identification criteria are applied to tau leptons.
[b]The $\Delta\phi$ requirement only applies to the sub-leading jet $j_2$.

| Region | $N_{b-\text{jet}}$ | $H_{\text{T}}/m_{\text{eff}}$ | $\frac{p_{\text{T}}^{\ell}+p_{\text{T}}^{\tau_{\text{had}}}}{m_{\text{eff}}}$ | $m_{\text{T2}}(b\ell, b)$ | $m_{\text{T2}}(b\ell, b\tau_{\text{had}})$ | $m_{\text{T}}(\ell, p_{\text{T}}^{\text{miss}})$ | $m_{\text{eff}}$ |
|---|---|---|---|---|---|---|---|
| SRLM | $\geq 2$ | $< 0.5$ | $> 0.2$ | $< 100$ GeV | $< 60$ GeV | - | - |
| CRTtLM | $\geq 2$ | - | $> 0.2$ | $< 100$ GeV | $110 - 160$ GeV | $> 100$ GeV | - |
| CRTfLM | $\geq 2$ | - | $> 0.2$ | $< 100$ GeV | $110 - 160$ GeV | $< 100$ GeV | - |
| CRWLM | 0 | $< 0.5$ | $> 0.2$ | - | - | $> 40$ GeV | $< 400$ GeV |
| VRTLM | $\geq 2$ | $> 0.5$ | $> 0.2$ | $< 100$ GeV | $60 - 110$ GeV | - | - |

| Region | $N_{b-\text{jet}}$ | $E_{\text{T}}^{\text{miss}}$ | $m_{\text{eff}}$ | $H_{\text{T}}/m_{\text{eff}}$ | $m_{\text{T2}}(b\ell, b\tau_{\text{had}})$ | $m_{\text{T2}}(\ell, \tau_{\text{had}})$ | $m_{\text{T}}(\ell, p_{\text{T}}^{\text{miss}})$ |
|---|---|---|---|---|---|---|---|
| SRHM | $\geq 1$ | $> 150$ GeV | $> 400$ GeV | $< 0.5$ | $> 180$ GeV | $> 120$ GeV | - |
| CRTtHM | $\geq 1$ | $> 150$ GeV | $> 400$ GeV | $< 0.5$ | $> 180$ GeV | 20-80 GeV | $> 120$ GeV |
| CRTfHM | $\geq 1$ | $> 150$ GeV | $> 400$ GeV | $< 0.5$ | $> 180$ GeV | 20-80 GeV | $< 120$ GeV |
| CRWHM | 0 | $> 150$ GeV | $> 400$ GeV | $< 0.5$ | - | 20-80 GeV | 40-100 GeV |
| VRHM | $\geq 1$ | $< 150$ GeV | $> 400$ GeV | $< 0.5$ | $> 180$ GeV | $> 80$ GeV | - |

# $m_{\mathrm{T2}}$ Upper Limits




| $m_{\mathrm{T2}}$ | Max Value for Signal | Max Value for $t\bar{t}$ background |
|---|---|---|
| $m_{\mathrm{T2}}\left(\mathrm{b}\ell, \mathrm{b}\tau\right)$ | top squark mass | top mass |
| $am_{\mathrm{T2}}\left(\mathrm{b}\ell, \mathrm{b}\right)$ | | top mass |
| $m_{\mathrm{T2}}\left(\ell, \tau\right)$ | If chargino not virtual (not true here): chargino mass | W mass |

# Fake and $\tau$ background estimation done with MC

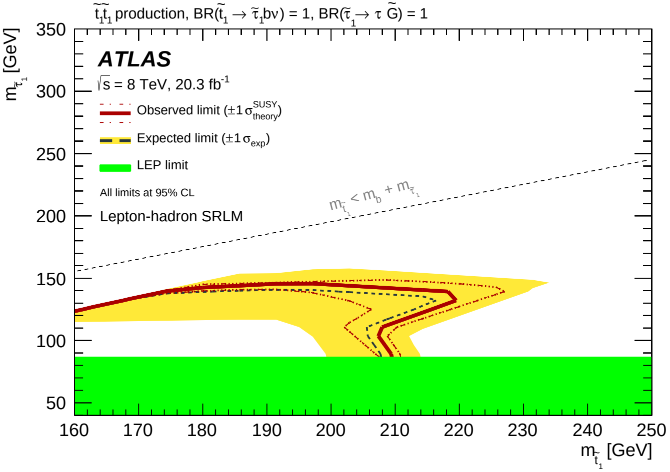
- Fit for $t\bar{t}(\tau^{true})$, $t\bar{t}(\tau^{fake})$, and W+jets seperately in the background-only fit with a CR for each.
- W+jets CRs: Use b-veto to isolate.
- $t\bar{t}$ CRs: Use an $m_{T2}$ variable to isolate $t\bar{t}$ and then $m_T^{\ell}$ to distinguish true and fake taus.
- The same-sign method (tau has same sign charge as e/$\mu$) was also tested

Summary of results:

- Both methods give similar results to within the uncertainties.
- MC method was chosen because of a lack of statistics in the same-sign method.

# Exclusion plot for lepton-hadron Low Mass channel



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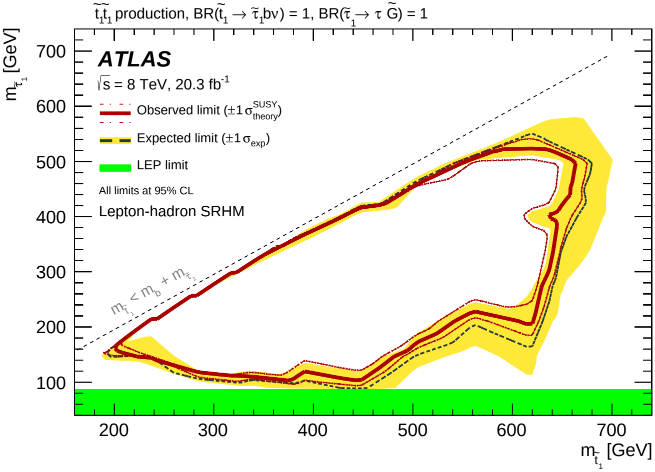
# Exclusion plot for lepton-hadron High Mass channel



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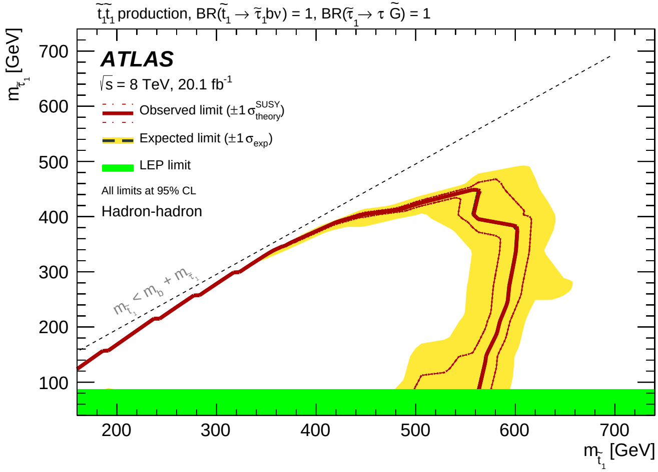
# Exclusion plot for hadron-hadron channel



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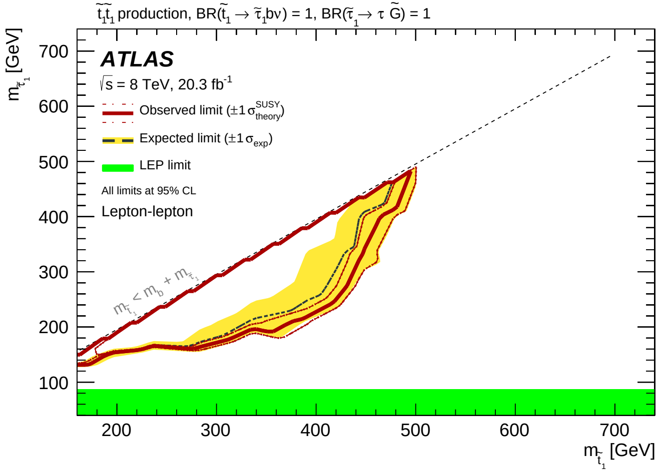
# Exclusion plot for lepton-lepton channel



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