UMN HEP Seminar

A Search for RPV Single Stop Production at CMS

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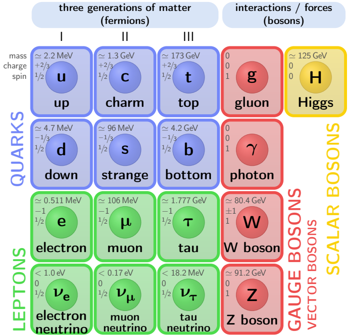
Introduction

The Standard Model

- The standard model (SM) of particle physics is one of our most successful physical theories.



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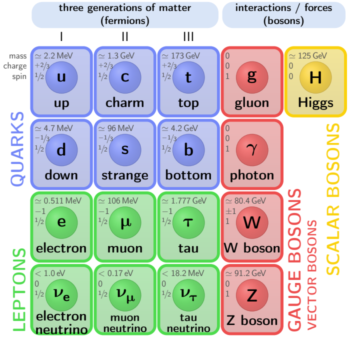
- With the 2012 discovery of the Higgs boson, all of the particles predicted by the SM have been experimentally detected.



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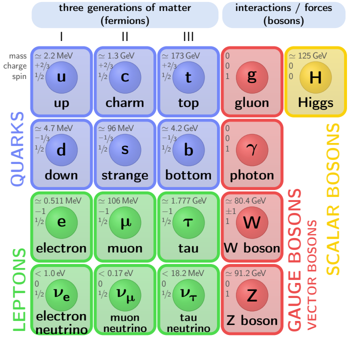

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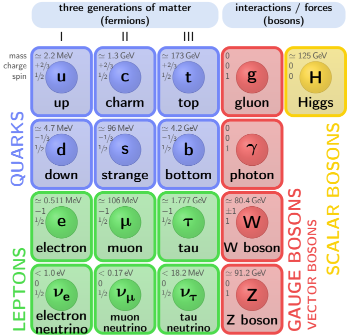

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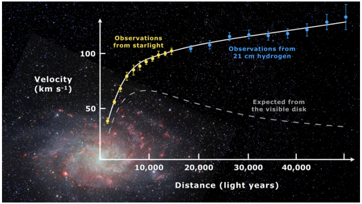
  - No explanation of dark matter and dark energy.



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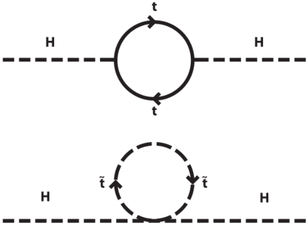
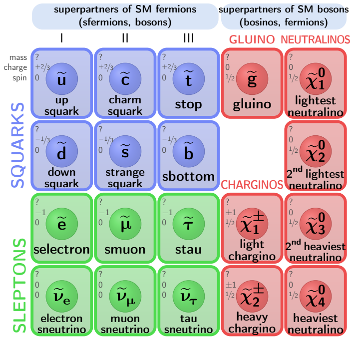
- With the 2012 discovery of the Higgs boson, all of the particles predicted by the SM have been experimentally detected.
- However, it has several inadequacies:
  - A large number of free parameters.
  - No explanation of dark matter and dark energy.
  - Requires fine tuning (hierarchy problem).



Supersymmetry

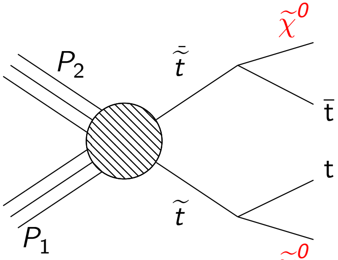
One of the most well motivated extensions to the standard model is supersymmetry (SUSY). In this theory, each SM particle gains a supersymmetric partner whose spin differs by $\frac{1}{2}$.

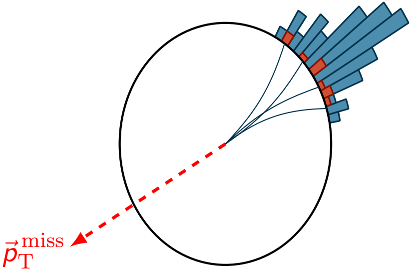
- Naturally addresses the hierarchy problem.
- Gauge couplings unify at high energy.
- Can offer a dark matter candidate.



Traditional Searches for Supersymmetry

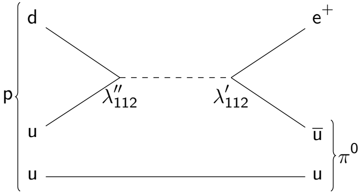
- The traditional searches for Supersymmetry have focused on such signals is that substantial energy escapes the detector ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$) in the form of a sparticle.
- The problem: decades of experiment has found no evidence of such phenomena.





R-parity

- Supersymmetry permits terms which violate B or L, and may lead to proton decay.



$$\left.\begin{array}{l} \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k \\ \lambda'_{ijk} L_i Q_j \bar{d}_k \\ \mu'_i L_i H_u \end{array}\right\} \Delta L = 1$$

$$\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k \} \; \Delta B = 1$$

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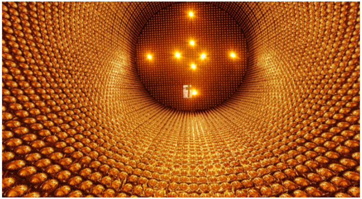

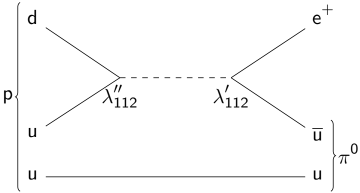

R-parity

- Supersymmetry permits terms which violate B or L, and may lead to proton decay.
- However, all signs indicate that the proton is stable.
- Traditional supersymmetry accounts for this by enforcing R-parity conservation. SM particles have $P_R = 1$, and SUSY particles have $P_R = -1$.

$$P_R = (-1)^{3(B-L)+2s}$$

$$\left.\begin{array}{l} \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k \\ \lambda'_{ijk} L_i Q_j \bar{d}_k \\ \mu'_i L_i H_u \end{array}\right\} \Delta L = 1$$

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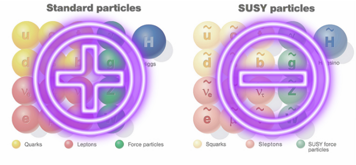
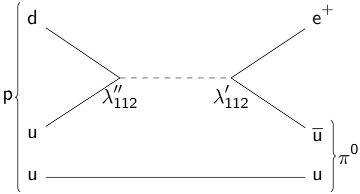


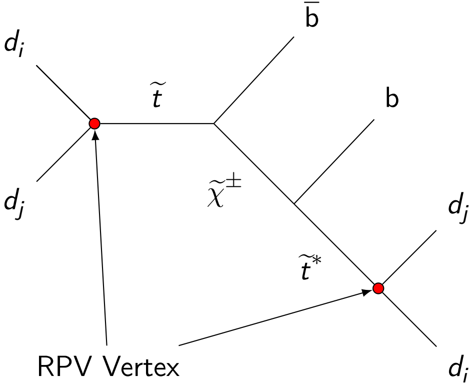
R-parity

- Supersymmetry permits terms which violate B or L, and may lead to proton decay.
- However, all signs indicate that the proton is stable.
- Traditional supersymmetry accounts for this by enforcing R-parity conservation. SM particles have $P_R = 1$, and SUSY particles have $P_R = -1$.
- **The proton can be also saved if we don't include both B and L violating coupling simultaneously (or keep couplings small).**



Single $\widetilde{t}$ Production

- We focus our efforts on the λ''_{3jk} terms, which allows a $\widetilde{t}$ to couple to SM quarks.
- The decay we focus on involved the production of a $\widetilde{t}$ through the λ''_{3jk} coupling, then the decay to a fully hadronic state.

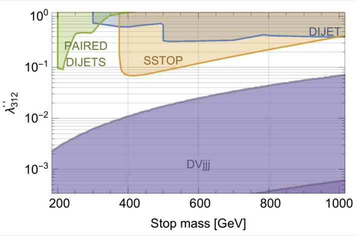


Signal Phenomenology

Process Regimes

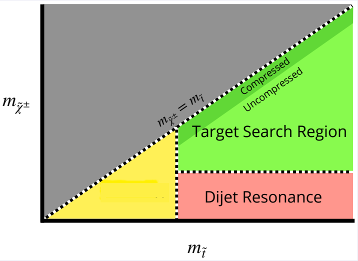
Coupling

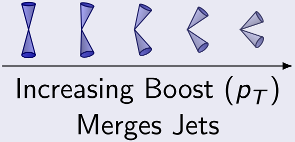
- Weak coupling ($\approx \lambda < 0.1$): the produced stop is long lived.
- Strong coupling ($\approx \lambda > 0.4$): the produced stop decays promptly back to quarks, resulting in dijets.
- The intermediate regime is an unexplored territory.



Process Regimes

Mass Regimes

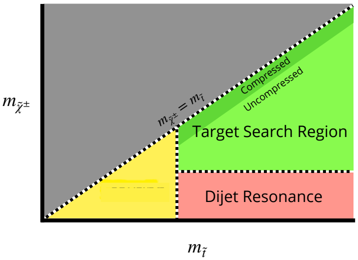




- Low $m_{\tilde{t}}$ lies below the "standard" triggers.
- When $m_{\tilde{\chi}^{\pm}} \ll m_{\tilde{t}}$ the $\tilde{\chi}^{\pm}$ daughters are merged, making the topology look like dijets, a very well studied model.
- The remaining region is unexplored.

Process Regimes

Compressed and Uncompressed Categories

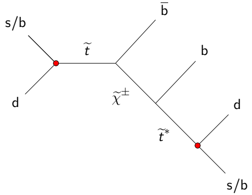


Within this unexplored space, distinct geometries emerge

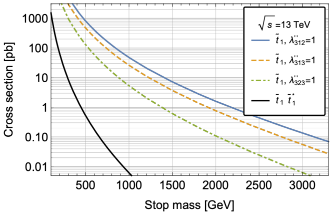
- When $m_{\widetilde{\chi}^{\pm}}$ is close to $m_{\widetilde{t}}$ we say the point is compressed
- Otherwise we say the point is uncompressed.

Target Signal Regime

- Target both λ''_{312} and λ''_{313}, both of which have a good balance of cross section and b-tagging (identifying if a jet originated from a b).

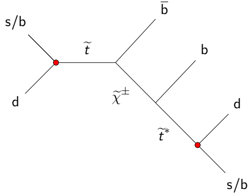


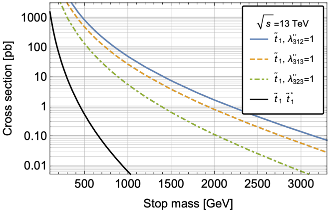
	Final State b's	Coupling Strength ($\propto\sigma^{1/2}$)
λ''_{312}	●●	●
λ''_{313}	●●●	●
λ''_{323}	●●●	●



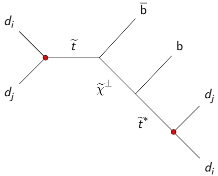
Target Signal Regime

- Target both λ''_{312} and λ''_{313}, both of which have a good balance of cross section and b-tagging (identifying if a jet originated from a b).
- For both couplings, target $0.1 < \lambda''_{3jk} < 0.4$.
- Examine both the compressed and uncompressed category.
- **Perform studies on conservative $\lambda''_{312} = 0.1$.**

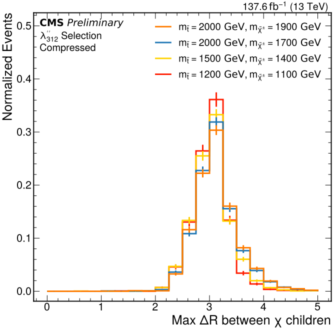


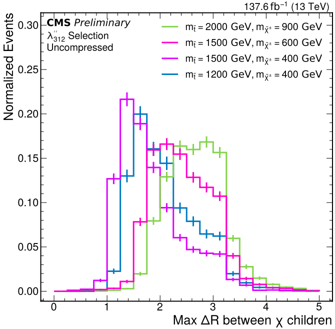


Signal Geometry



The maximum angular separation between any two of the $\tilde{\chi}^{\pm}$ children. The less compressed a mass point, the more collimated the children.





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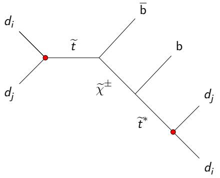
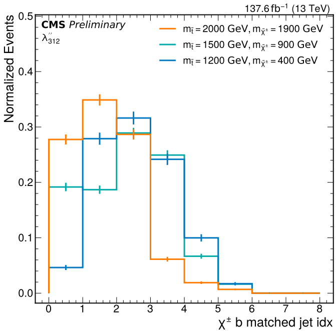
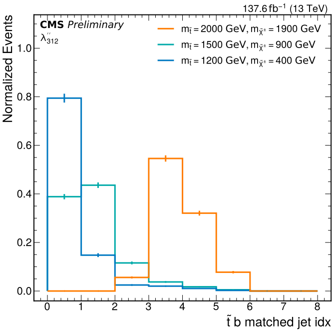


In the compressed category, the $\tilde{\chi}^{\pm}$ b is often one of the leading (highest p_T) three jets. In the uncompressed category, the $\tilde{t}$ b is often the leading jet.



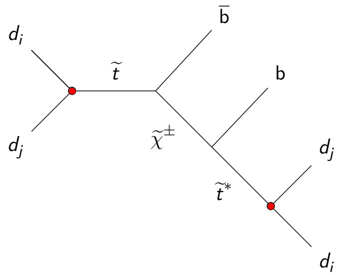


Event Selection

Key Event Characteristics

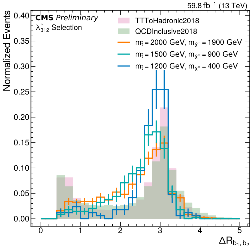
- No leptons.
- A moderate number of jets, several with high p_T.
- Multiple b-jets (jets identified to have come from a b), and large angular separation between b-jets.

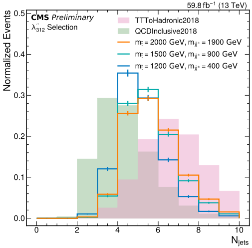
These signatures match most closely with QCD and $\mathbf{t\bar{t}}$

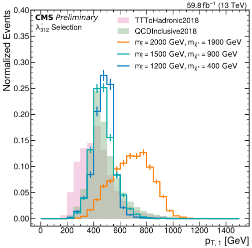


Key Event Characteristics

- To further reduce the QCD multijet and $t\bar{t}$ backgrounds we investigate inspecting N-1 plots (make all cuts except for the one in question).







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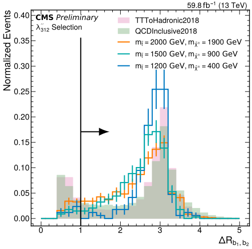
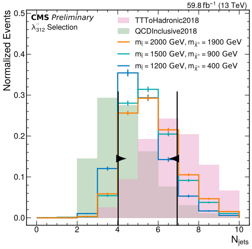
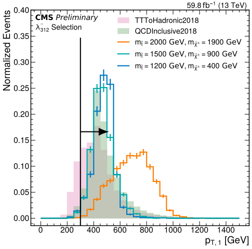
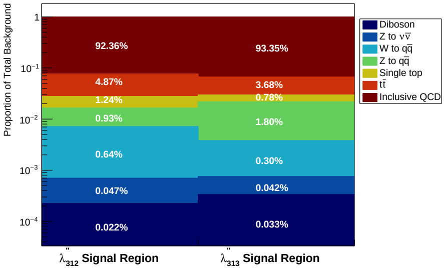






Key Event Characteristics

- We can make additional cuts to further reduce the QCD and $t\bar{t}$ backgrounds.
- The final signal region selection is shown below.

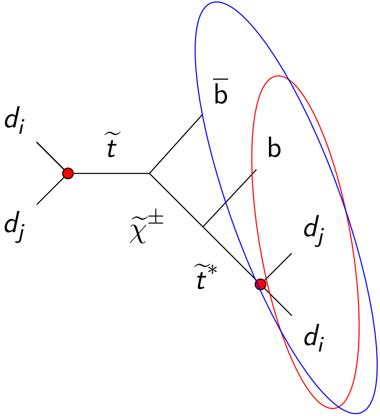


Baseline Selections			
$4 \leq \mathrm{N_j} \leq 6$ ($p_{\mathrm{T,j}} > 30$ GeV, $\lvert\eta_{\mathrm{j}}\rvert < 2.4$) $p_{\mathrm{T,j_1}} > 300$ GeV $\mathrm{N}_e, \mathrm{N}_\mu = 0$ $\Delta R_{\mathrm{b_1,b_2}} > 1$ $m_4 \equiv m_{\mathrm{j_1,j_2,j_3,j_4}}$			
λ_{312} Uncompressed SR	λ_{312} Compressed SR	λ_{313} Uncompressed SR	λ_{313} Compressed SR
$\mathrm{N_b} \geq 2$ $m_3 \equiv m_{\mathrm{j_2,j_3,j_4}}$	$\mathrm{N_b} \geq 2$ $m_3 \equiv m_{\mathrm{j_1,j_2,j_3}}$	$\mathrm{N_b} \geq 3$ $m_3 \equiv m_{\mathrm{j_2,j_3,j_4}}$	$\mathrm{N_b} \geq 3$ $m_3 \equiv m_{\mathrm{j_1,j_2,j_3}}$

Analysis Strategy

Strategy Overview

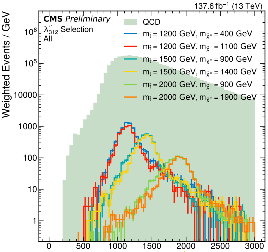
1. Reconstruct the signal resonances for $\widetilde{t}$ and $\widetilde{\chi}^{\pm}$.
2. Estimate the SM background.
3. Perform a one or two dimensional bump hunt for these resonances.



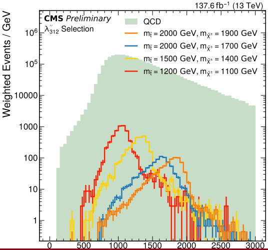
Mass Reconstruction

- Resonant masses can be reconstructed using the invariant mass of a well chosen set of jets.
- Simplest Reconstruction:
  - $m_{\tilde{t}} = m\left(j_1 + j_2 + j_3 + j_4\right)$
  - Compressed: $m_{\tilde{\chi}^{\pm}} = m\left(j_1 + j_2 + j_3\right)$
  - Uncompressed: $m_{\tilde{\chi}^{\pm}} = m\left(j_2 + j_3 + j_4\right)$

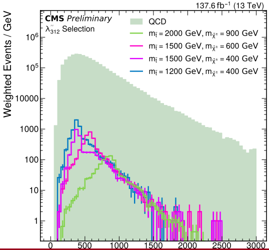
All



Compressed



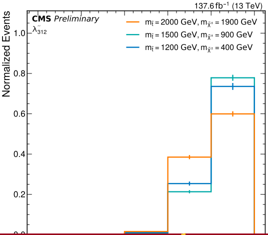
Uncompressed



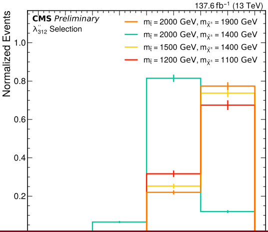
Mass Reconstruction

- Resonant masses can be reconstructed using the invariant mass of a well chosen set of jets.
- Different categories need different treatment
  - For both the $\widetilde{t}$ and compressed $\widetilde{\chi}^{\pm}$, the simplest algorithm works reasonably well.
  - For the uncompressed $\widetilde{\chi}^{\pm}$, the naive estimation is quite poor.
- Ongoing work: We can take advantage of both flavor and kinematic information to improve our reconstruction.

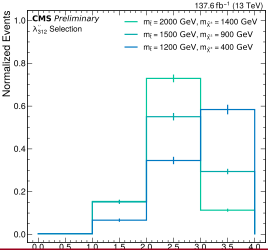
All



Compressed

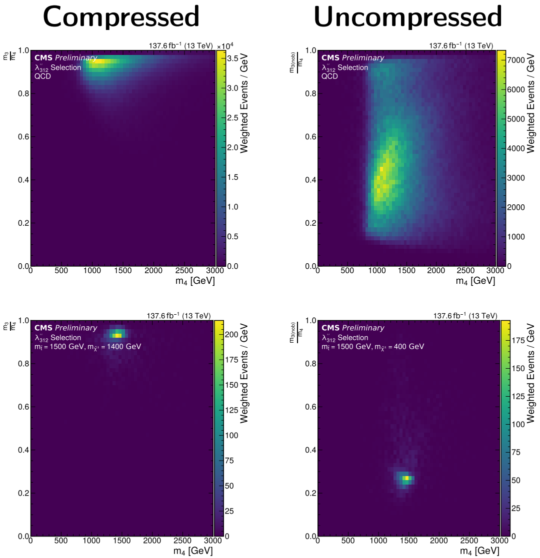


Uncompressed



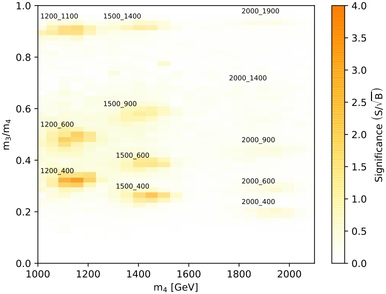
2D Resonance Fitting

- There are two resonances that we expect to form a peak over the background.
- In the uncompressed case, since the leading jet is expected to in $m_{\tilde{t}}$ but not $m_{\tilde{\chi}^{\pm}}$, we can these reconstructed masses to partially decorrelate.
- In the compressed case, a 1D fit is sufficient.



Expected Sensitivity

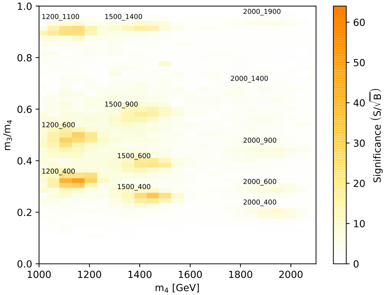
- A naive significance can be estimated bin-by-bin using $\frac{S}{\sqrt{B}}$.



$\lambda'' = 0.1$

Expected Sensitivity

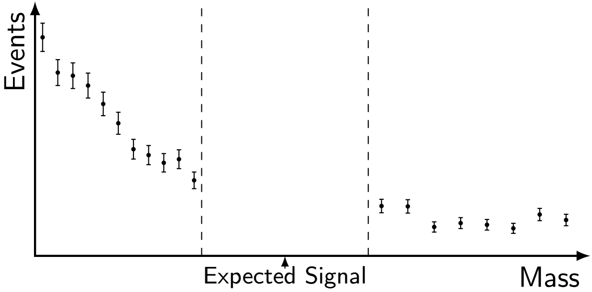
- A naive significance can be estimated bin-by-bin using $\frac{S}{\sqrt{B}}$.
- Increasing the coupling to the upper range of our parameter regime yields even greater significances, since the cross section scales as $\left(\lambda''_{3jk}\right)^2$.



$\lambda'' = 0.4$

Background Estimation

- To determine the presence of a signal bump, we need an estimation of the shape of background (mostly QCD).
- We estimate the background by doing a fit to data.
  - The region around the signal peak is blinded.



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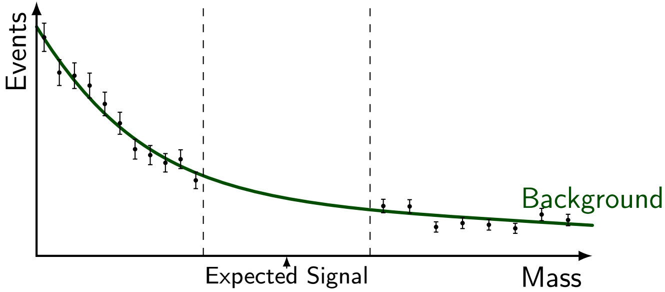

Background Estimation

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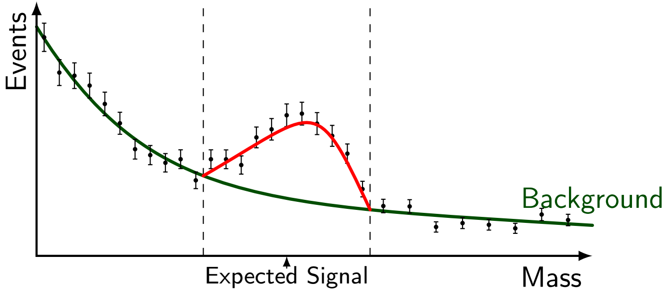
- We estimate the background by doing a fit to data.
  - The region around the signal peak is blinded.
  - The remaining data is fit.
  - The resulting fit is used as the background estimation near the peak.

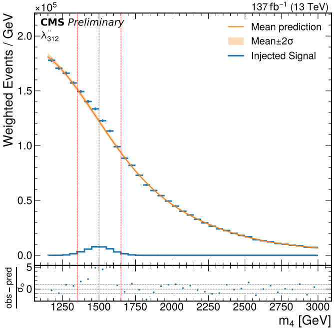


Background Estimation

- Many bump-hunt style searches use a parametric fit to the background with an ad-hoc function.
- We are currently developing a fit procedure that does Bayesian inference over the space of all possible functions using *Gaussian Process Regression*.

Background Estimation

- The background contribution from QCD simulation “data,” can be estimated by performing a regression on data away from an injected the signal peak.
- The signal appears as a deviation from this estimation.



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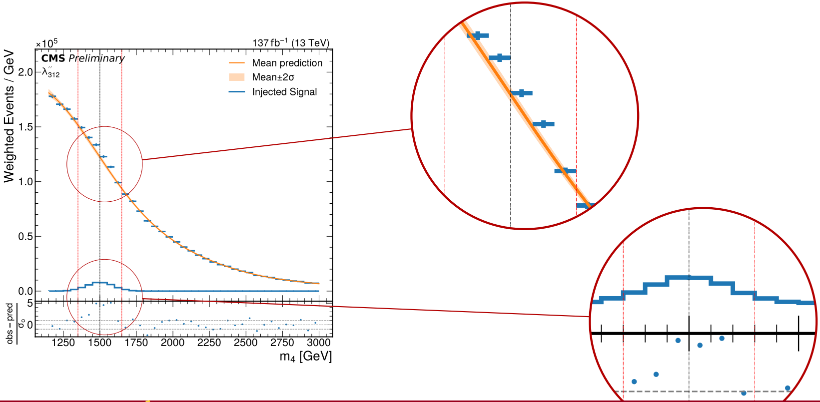

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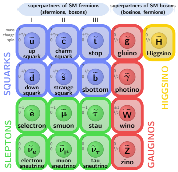
- SUSY remains a well motivated theory for physics beyond the standard model, and RPV couplings are a rich and largely unexplored parameter space.
- We investigate the RPV production and decay of a single $\widetilde{t}$.
- Taking advantage of jet kinematics and flavor information allows substantial reduction of background and reconstruction of the two sparticle resonances.
- A one or two dimensional bump hunt can be performed for these mass peaks, using non-parametric background estimation.



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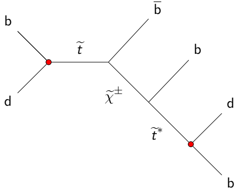

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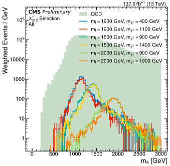

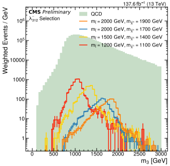

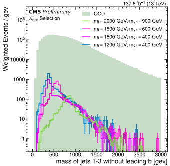

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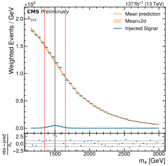

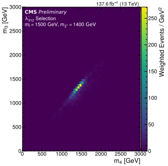

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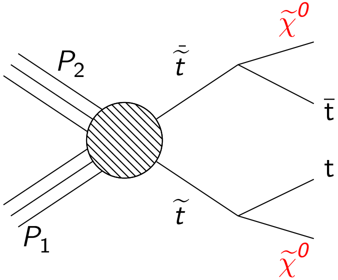
Thank You

Bibliography I

Appendix

R-parity

- R-parity violating (RPV) models open up a largely unexplored world of parameters and decay modes that do *not* include $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$.



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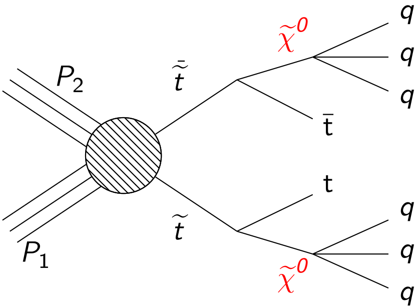
- R-parity violating (RPV) models open up a largely unexplored world of parameters and decay modes that do *not* include $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$.
- R-parity allows SUSY particles to decay to SM hadrons, resulting in a fully visible final state.



Triggers

- Using PFHT1050 | AK8PFJet400_TrimMass30.

Hadronic	$\mathcal{L}_{eff}$ (fb^{-1})	Semileptonic	$\mathcal{L}_{eff}$ (fb^{-1})
	2016		
PFHT800	27.71	IsoMu24	36.47
PFHT900	36.47	IsoTkMu24	36.47
PFHT650_WideJetMJJ900DEtaJJ1p5	36.47	HLT_Ele27_WPTight_Gsf	36.47
AK8PFHT650_TrimR0p1PT0p03Mass50	20.20	HLT_Photon175	36.47
AK8PFHT700_TrimR0p1PT0p03Mass50	36.47		
AK8PFJet450	33.64		
AK8PFJet360_TrimMass30	36.47		
AK8DiPFJet280_200_TrimMass30	36.47		
AK8DiPFJet280_200_TrimMass30_BTagCSV_p20	36.47		
	2017		
PFHT1050	41.54	IsoMu27	41.54
AK8PFHT800_TrimMass50	36.75	HLT_Ele35_WPTight_Gsf	41.54
PFJet320	41.54	HLT_Photon200	41.54
PFJet500	41.54		
AK8PFJet320	41.54		
AK8PFJet500	41.54		
AK8PFJet400_TrimMass30	36.75		
AK8PFJet420_TrimMass30	36.75		
	2018		
PFHT1050	59.96	IsoMu24	59.96
AK8PFHT800_TrimMass50	59.96	HLT_Ele32_WPTight_Gsf	59.96
PFJet500	59.96	HLT_Photon200	59.96
AK8PFJet500	59.96		
AK8PFJet400_TrimMass30	59.96		
AK8PFJet420_TrimMass30	59.96		

4j2b Trigger

- New trigger deployed in 2023 triggers on 4 jet with 2 b jets
- Nearly ideal for the single $\widetilde{t}$ signal!
- HT threshold at 280GeV, substantially expanding the search range.