How low can SUSY go?

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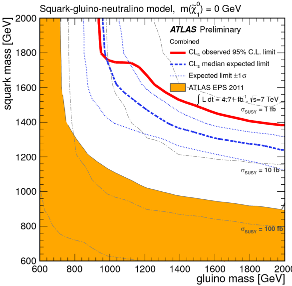
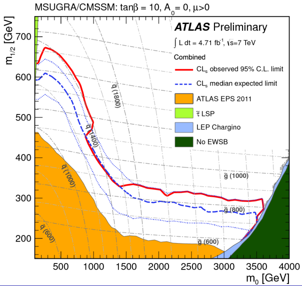
bctp Bethe Center for Theoretical Physics

LHC now sets very strict limits on the SUSY parameter space.

- Simplified Model ($m_{\tilde\chi_1^0} = 0$).
  - $m_{\tilde q} = m_{\tilde g} \gtrsim 1.5$ TeV.
  - $m_{\tilde g} \gtrsim 940$ GeV, ($m_{\tilde q} = 2$ TeV).
  - $m_{\tilde q} \gtrsim 1380$ GeV, ($m_{\tilde g} = 2$ TeV).
- mSugra ($\tan\beta = 10, A_0 = 0, \mu > 0$).
  - $m_{\tilde q} = m_{\tilde g} \gtrsim 1.4$ TeV.
- CMS gives very similar bounds (all a little weaker).
- Everything else has much weaker bounds.
  - $\tilde t$'s, $\tilde b$'s, $\tilde\ell$'s, $\tilde\chi$'s.



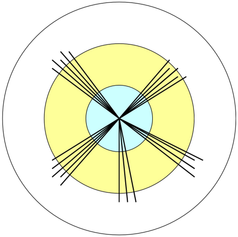


How can we evade these bounds?

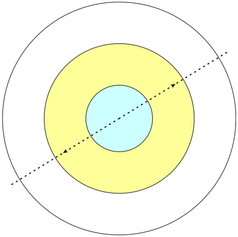
If we are interested in light $\tilde{q}$'s and $\tilde{g}$'s, is there an escape clause?

Two obvious possibilities:

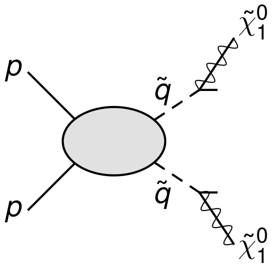
- Events containing no Missing Energy.
  - Signal can be hidden under QCD.



- Events containing only Missing Energy.
  - Signal can be invisible to the detector.

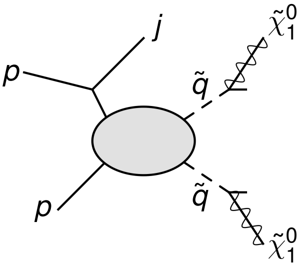


If the spectrum is compressed all momentum is carried by the LSP.



- Hard event is invisible.
- Possibility to use ISR to recoil against LSP.
- Hard ISR jets are common.

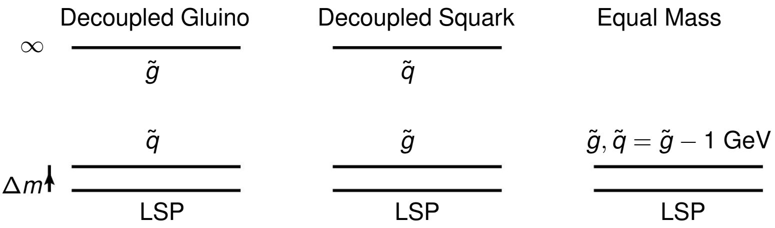
Process, $m_{\tilde{q}_i} = 500$ GeV $p_T(j) > 100$ GeV	Xsec (fb)
$pp \to \tilde{q}\tilde{q}$	24
$pp \to \tilde{q}\tilde{q}\, j$	6.6
$pp \to \tilde{q}\tilde{q}\, j\, j$	1.1



Simplified Models

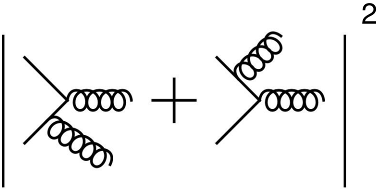
We take simplified models to capture the extremes.

- Squarks degenerate with LSP ($\Delta m = 2$ GeV). Gluino heavy.
- Gluino degenerate with LSP ($\Delta m = 2$ GeV). Squarks heavy.
- Gluino and squark degenerate with LSP ($\Delta m = 2$ GeV).
- We ignore third generation.
- Mass difference is varied.



Matrix Element vs Parton Shower

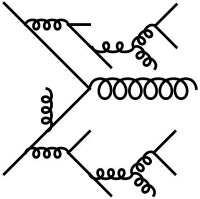
Matrix Element



- Pros:
  - Exact to fixed order.
  - Include interference effects.
- Cons:
  - Perturbation breaks down due to large logs.
  - Computationally expensive.

Valid when partons are hard and well separated.

Parton Shower



- Pros:
  - Resum logs.
  - Produce high multiplicity event.
- Cons:
  - Only an approximation to ME.
  - No interference effects.

Valid when partons are soft and/or collinear.

Parton Shower Tunes

Parton shower has to be tuned to match phenomenological data.

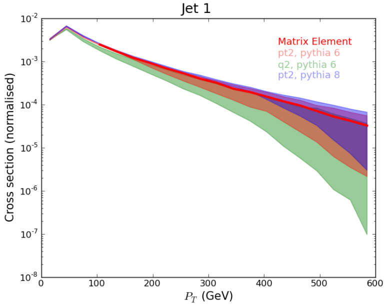
- Starting scale is the most important parameter (for high p_T^2 behaviour).
- For ISR, should be factorisation scale.
    - Often chosen as the transverse mass, $\mu_F = \sqrt{p_T^2 + \hat{m}^2}$.
    - 'Wimpy' shower.
    - Softer than matrix element.
- Phenomenologically better choice is far higher.
    - Allow parton shower to fill full phase space, $p_{T,j} = \sqrt{s}/2$.
    - 'Power' shower.
    - In conflict with factorisation assumption.
    - Can be harder than matrix element.
- Large differences depending upon choice.
    - Older tunes more 'wimpy'.
    - Newer tunes getting tougher!

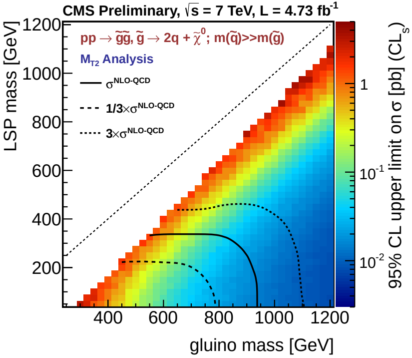
(Plehn, Rainwater, Skands; hep-ph/0510144)

Parton shower variation

Collaborations have until very recently only used parton showers when setting limits.

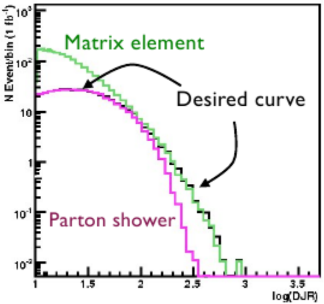
- Uncertainty in the ISR prediction is huge.
- Reason they don't show limits in compressed spectra.
- Depending on settings, parton shower can be harder than matrix element.





We must match the Matrix Element prediction to the parton shower.

- Reweight inclusive samples (no double counting).
- Smooth distributions between areas of validity.
- Small dependence on matching scale.
- Small dependence on parton shower.
- Should converge as we include higher multiplicities.



(Maltoni)

Our choice

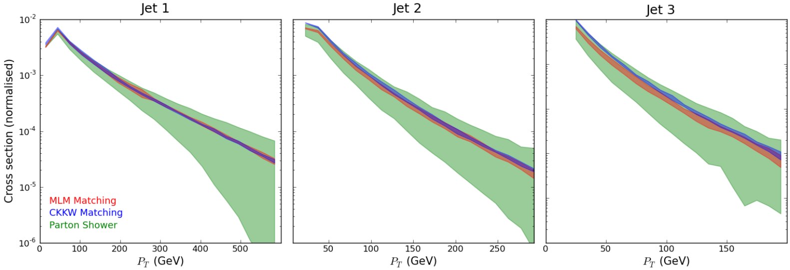
We wanted to understand QCD uncertainty in ISR.

- Integrated MLM matching in MadGraph.
  - Interfaced with Pythia 6 shower.
  - First PS matching for SUSY.
- Newly developed CKKW matching in Pythia 8.
  - We have adapted code to work with SUSY.
  - Provides a cross-check with different matching scheme and shower.
  - Pythia 8 shower is far more advanced.
- We also test standalone Parton Showers without additional jets generated by the matrix element.
  - Herwig++, Pythia 6 (P_T^2), Pythia 6 (Q^2), Pythia 8 (P_T^2).
- We use NLL-Fast for cross-sections.
  - NLO with leading log soft gluon resummation.

    (http://web.physik.rwth-aachen.de/service/wiki/bin/view/Kraemer/SquarksandGluinos)

PS vs Matched

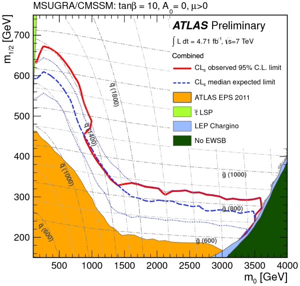
Comparison of Parton Shower and Matched Uncertainties.

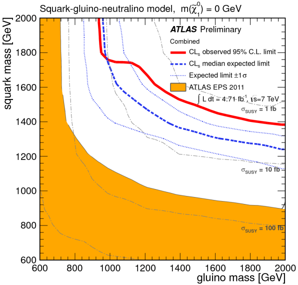


- Decoupled production of 500 GeV squarks, degenerate LSP.
- Parton shower varied between 'wimpy' and 'power' settings.
- Matching scale varied between 50 and 200 GeV.
- Factorisation and renormalisation scales varied.
- Large reduction in uncertainty.
- Parton shower 3rd jet (unmatched) uncertainty also improved.

Jets and MET.

- Take ATLAS search as example (very similar CMS search).
- Current mSugra world champion!
- $m_{eff}(incl) > 1200$ GeV ($\sum E_T^{jet} \gtrsim 750$ GeV).
- $E_T^{miss}/m_{eff}(Nj) > 0.15 - 0.4$.
- $p_T(j_1) > 130$ GeV.
- $p_T(j_2) > 60$ GeV.
- $\Delta\phi(j, E_T^{miss}) > 0.4$.





Shape based.

- Take CMS RAZOR search as example (CMS also has α_T and M_{T2}).
- Use topology to better discriminate signal and background.
  - Allows kinematical cuts to be set lower.
  - Removes need for explicit jet, MET collinearity cut.

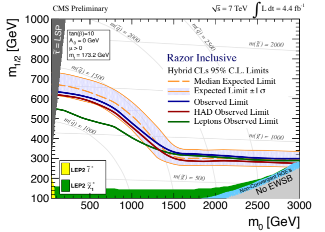
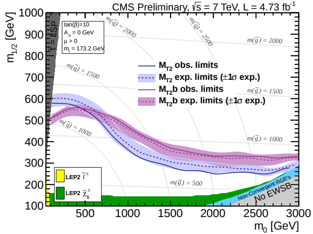


Figure 12: Observed (solid blue curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, $\mathrm{sgn}(\mu) = +1$ from the razor analysis. The $\pm$ one standard deviation equivalent variations in the uncertainties are shown as a band around the median expected limit. Shown separately the observed HAD-only (solid crimson) and leptonic-only (solid green) 95% CL limits.



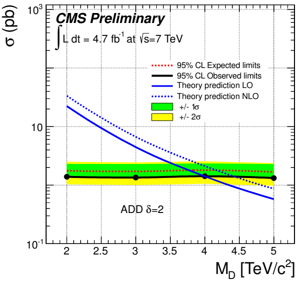
$$M_R = \sqrt{(E_{j1}+E_{j2})^2 - (p_z^{j1}+p_z^{j2})^2}$$

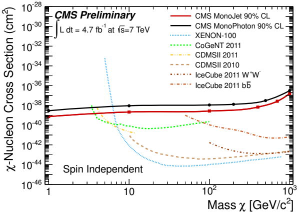
$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j1}+p_T^{j2}) - \vec{E}_T^{miss}(\vec{p}_T^{j1}+\vec{p}_T^{j2})}{2}}$$

$$R = \frac{M_T^R}{M_R}$$

Monojet.

- Both CMS and ATLAS have a monojet search.
    - Designed to search for ADD extra dimensions.
    - Now also used for model independent dark matter
- $E_T^{miss} \gtrsim 350$ GeV.
- Both have a third jet veto.
- ATLAS also had 2nd jet veto, $p_T < 60$ GeV. (now removed for 4.7 fb^{-1}).
- For CMS $\Delta\phi(j_1, j_2) < 2.5$ ($\sim 140^\circ$).

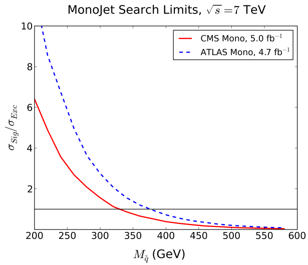


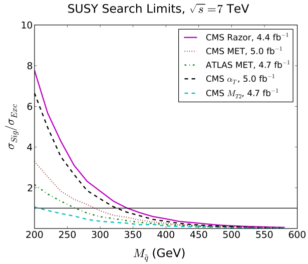


Results

Comparison of squark limits.

- Limit in decoupled gluino scenario, $m_{\tilde{q}} \gtrsim 380$ GeV.
  - ATLAS Monojet search provides the best limit (just)!
  - General SUSY searches almost match the limit.
  - CMS RAZOR is the most constraining of the SUSY searches.

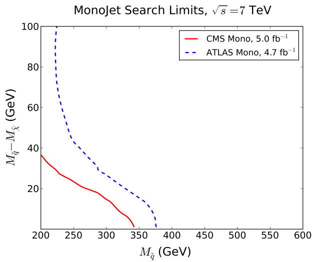


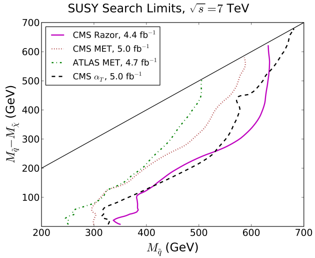


Results

Moving away from full compression.

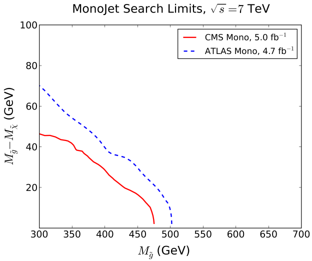
- Extra hadronic activity quickly hurts the monojet searches.
    - Maybe remove the jet vetoes or set these higher.
- SUSY searches rapidly improve as splitting is increased.
    - Limits 'only' reach 670 GeV.
        - t-channel gluino is dominant production mode for 'normal' SUSY.
    - Discontinuities caused by different search regions.

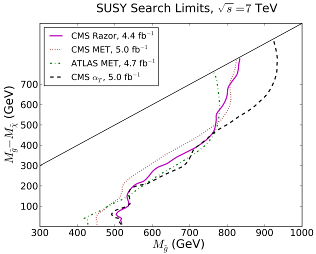




Comparison of gluino limits.

- Limit in decoupled squark scenario, $m_{\tilde{g}} \gtrsim 500$ GeV.
    - CMS RAZOR gives the best limit.
    - Monojet competitive near to degeneracy.
- Decoupled scenario is somewhat academic.
    - With $m_{\tilde{q}} = \infty$, gluino becomes stable.
    - With extreme compression gluino lifetime is large even for moderate squark masses.
    - Need stops and sbottoms around.

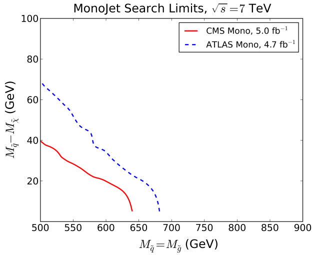


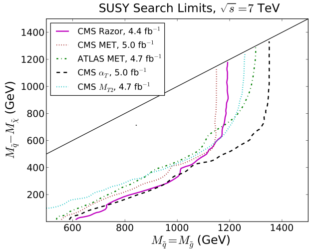


Results

Equal mass ($M_{\tilde{q}} = M_{\tilde{g}}$) limits.

- Limit is, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 670$ GeV.
  - CMS monojet search is competitive for spectrum degeneracy.
  - CMS-Razor provides the best limit from SUSY searches.
  - SUSY searches once again improve as degeneracy is broken.





Summary

- Compressing the mass spectrum makes SUSY much harder to look for.
- ISR becomes vital to see any signal.
- Matching the matrix element to the parton shower to required to accurately model the ISR.
- Squark masses $\gtrsim$ 380 GeV.
- Gluino mass $\gtrsim$ 500 GeV.
- Equal squark and gluino masses $\gtrsim$ 670 GeV

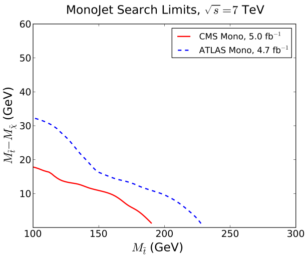
Backup Slides

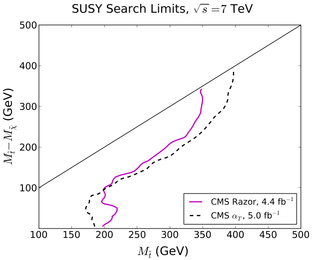
Results

Single eigenstate 'Stop' limits.

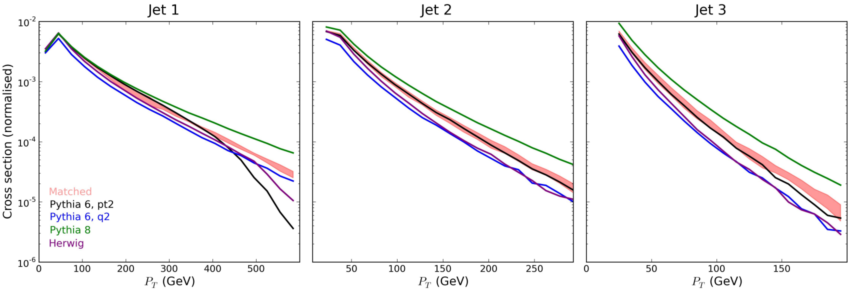
- Limit is, $M_{\tilde{t}} \gtrsim 200$ GeV.
  - Limit only valid for the decay $\tilde{t} \to c\tilde{\chi}_1^0$.
  - Decay is loop induced.
  - 100% branching ratio assumed.

  - For more complicated decays, limits are still valid in the limit of degeneracy.
- Also valid for a single light squark (or sbottom) eigenstate.



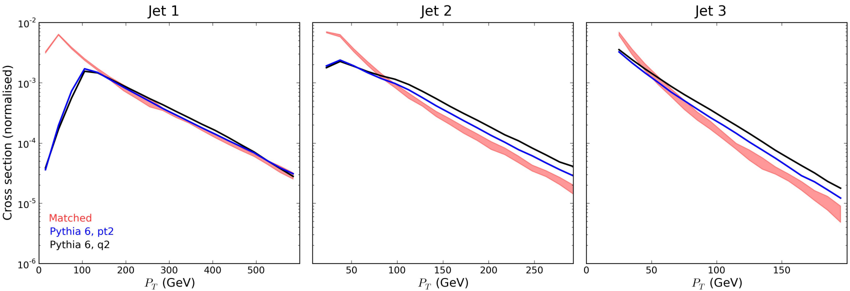


Comparison of Parton Shower and Matched Uncertainties.



- Different parton shower defaults give very different behaviour.
- No 'out of the box' setting is correct.
- Varying showers between 'wimpy' and 'power' settings is representative.
- Default Pythia 8 is now a power shower.
    - Significantly overestimates jet production

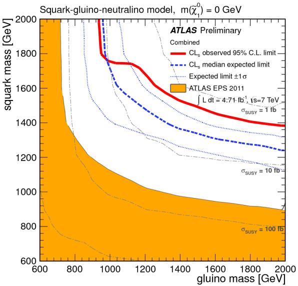
Double counting is a real problem!

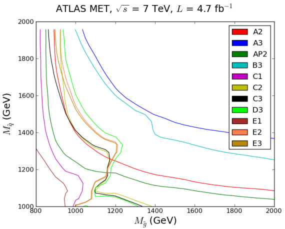


- Often considered to be a theoretical issue.
- Parton shower tunes are softer but still hard enough.
- Looking at the hardest jet can fool you.
- Comparison done with the relatively soft Pythia 6 showers.
  - With the default Pythia 8 shower, the situation would be even worse.

Verifying my implementation.

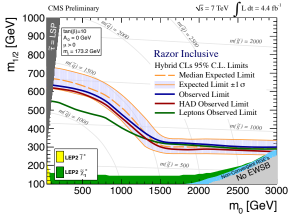
- Good agreement with all analyses.
    - Jets are easy when the hard work is done!
- Only use best expected box.
    - If exclusion is better than expected, use expected.
    - More conservative than ATLAS.
    - Allows a fairer comparison between searches and regions.
    - Relevant regions for compressed spectra unaffected.





Verifying my implementation.

- Good agreement with all analyses.
  - Jets are easy when the hard work is done!
- Only use best expected box.
  - CMS RAZOR use complicated unbinned likelihood.
  - Impossible to replicate but provide fine binning (60 bins) on wiki.
  - I reduce to 20 bins and use best exclusion.
  - Worse reach than official analysis.



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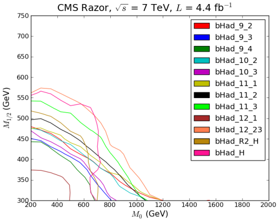
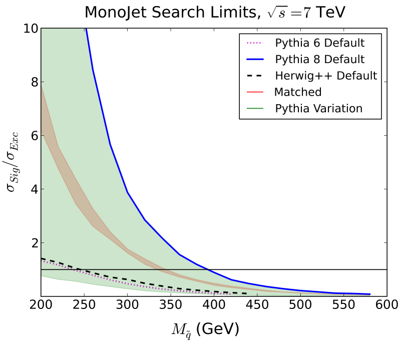


Limits on squarks in decoupled gluino model.

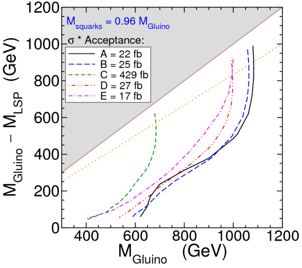
- Big variation on limit, 180 - 400 GeV.
- Default Herwig and Pythia 6 very close.
- Pythia 8 default is the power shower.

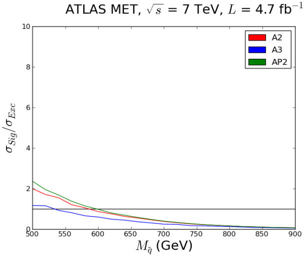


Agreement with LeCompte, Martin.

(LeCompte, Martin; 1105.4304, 111.6897)

- Equal mass scenario, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 600$ GeV.
- Our ATLAS limit, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 600$ GeV.
    - New search region for ATLAS with high MET.
    - $\sim$ 5x luminosity.
    - We set limits slightly more conservatively.
- Monojet/Razor search, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 650$ GeV.

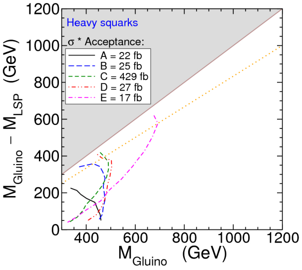


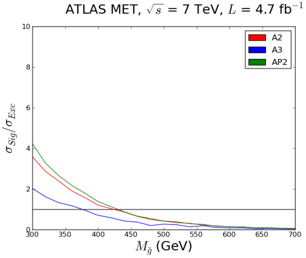


Differences with LeCompte, Martin.

(LeCompte, Martin; 1105.4304, 111.6897)

- Decoupled squark scenario, $M_{\tilde{g}} \gtrsim 450$ GeV.
- Our ATLAS limit, $M_{\tilde{g}} \gtrsim 440$ GeV.
  - New search region for ATLAS with high MET.
  - $\sim$ 5x luminosity.
  - We set limits slightly more conservatively.
- RAZOR search, $M_{\tilde{g}} \gtrsim 500$ GeV.





Comparison with 'Supersoft Supersymmetry is Super-Safe'.

(Kribs, Martin; 1203.4821)

- Motivation for a decoupled gluino.
  - Add Dirac gaugino masses.
  - No issues with naturalness.
- Limits for pure squark production with decoupled gluino.
  - Apply all current SUSY searches.
  - For $0 < M_{LSP} < 100$ GeV, $M_{\tilde{q}} \gtrsim 750$ GeV.
  - For $M_{LSP} = 200$ GeV, $M_{\tilde{q}} \gtrsim 650$ GeV.
  - For $M_{LSP} = 300$ GeV, no limit on $M_{\tilde{q}}$.
- Different to our result.
  - Have only included default parton shower.