How low can SUSY go?

Jamie Tattersall

In collaboration with H Dreiner and M Krämer.
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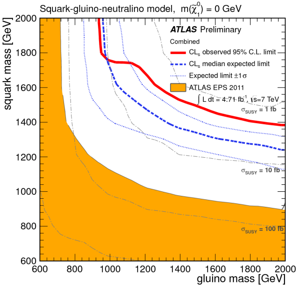
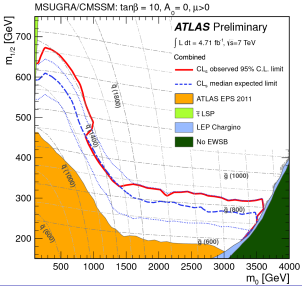
Current Limits

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.



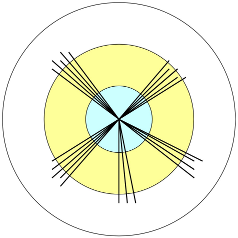


How can we evade these bounds?

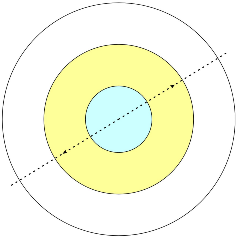
If we are interested in light $\tilde{q}$'s and $\tilde{g}$'s, is there an escape clause?

Two obvious possibilities:

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



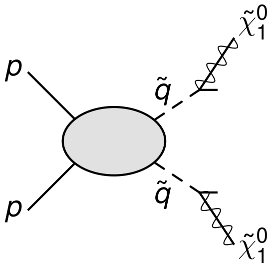
- Events containing only Missing Energy.
  - Signal can be invisible to the detector.



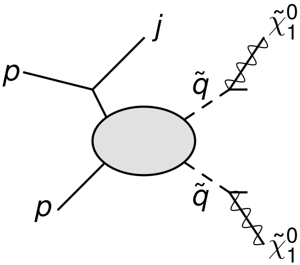
Events containing only MET

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.



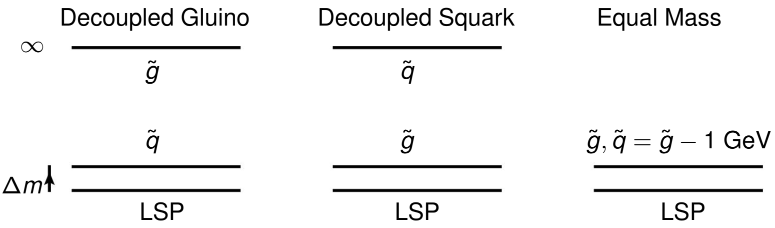
Process, $m_{\tilde{q}_i}$ = 500 GeV $p_T(j) > 100$ GeV	Xsec (fb)
$pp \to \tilde{q}\tilde{q}$	24
$pp \to \tilde{q}\tilde{q}\ j$	6.6
$pp \to \tilde{q}\tilde{q}\ j\ j$	1.1



Simplified Models

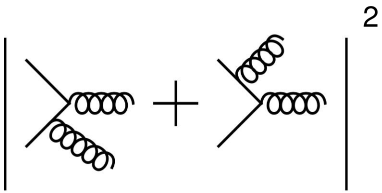
We take simplified models to capture the extremes.

- 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

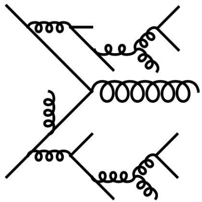
Matrix Element



- 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.

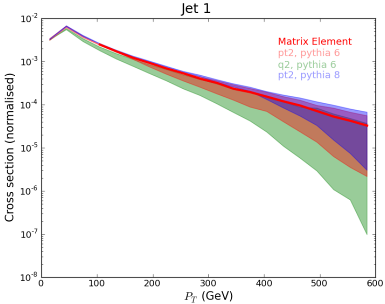
- Starting scale is the most important parameter (for high p_T^2 behaviour).
- For ISR, should be factorisation scale.
  - Often chosen as the transverse mass, $\mu_F = \sqrt{p_T^2 + \hat{m}^2}$.
  - 'Wimpy' shower.
  - Softer than matrix element.
- Phenomenologically better choice is far higher.
  - 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!

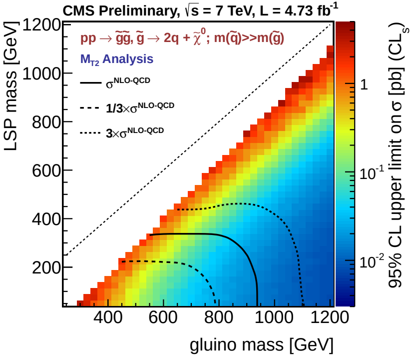
(Plehn, Rainwater, Skands; hep-ph/0510144)

Parton shower variation

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

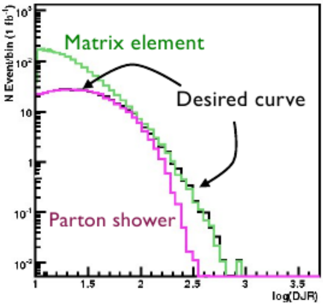
- Uncertainty in the ISR prediction is huge.
- Reason they don't show limits in compressed spectra.
- Depending on settings, parton shower can be harder than matrix element.





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

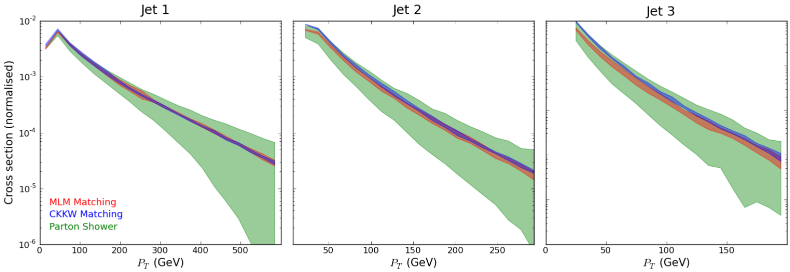
We wanted to understand QCD uncertainty in ISR.

- 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 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.

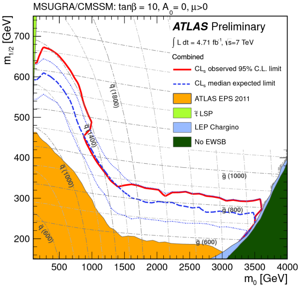


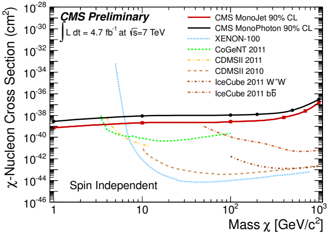
- Decoupled production of 500 GeV squarks, degenerate LSP.
- Parton shower varied between 'wimpy' and 'power' settings.
- Matching scale varied between 50 and 200 GeV.
- Factorisation and renormalisation scales varied.
- Large reduction in uncertainty.
- Parton shower 3rd jet (unmatched) uncertainty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

Searches

All 7 TeV hadronic SUSY and monojet searches are included.

- 'Jets and MET' search.
  - Both ATLAS and CMS have searches of this kind.
  - Give best limits on mSugra.
- 'Topology' based search.
  - CMS also has more complicated variables.
  - Razor, α_T and M_{T2}.
- Monojet search.
  - Used to search for ADD and model independent dark matter.
  - Also relevant for compressed SUSY.

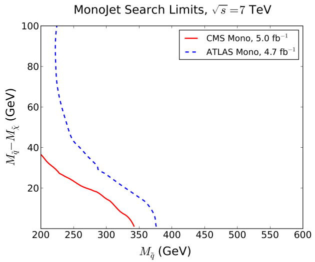


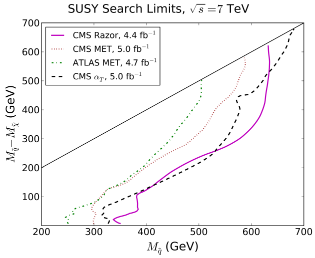


Results

Limit in decoupled gluino scenario, $m_{\tilde{q}} \gtrsim 380$ GeV.

- ATLAS monojet and CMS Razor are competitive.
- 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.

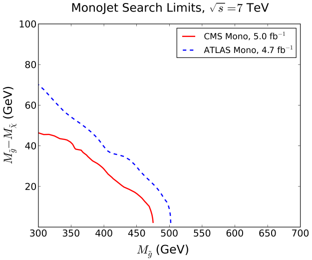


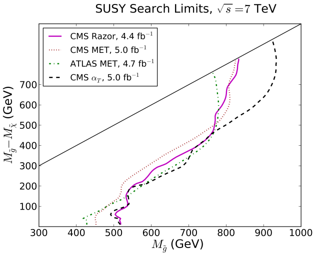


Results

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.

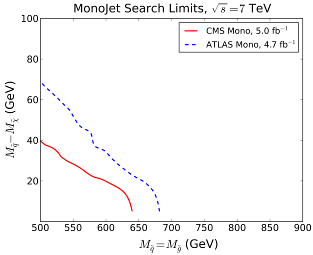


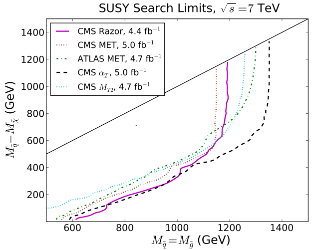


Results

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

- Limit is, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 670$ GeV.
  - ATLAS 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.





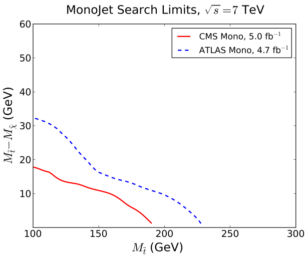
- Compressing the mass spectrum makes SUSY much harder to look for.
- ISR becomes vital to see any signal.
- Matching the matrix element to the parton shower to required to accurately model the ISR.
- Squark masses $\gtrsim$ 380 GeV.
- Gluino mass $\gtrsim$ 500 GeV.
- Equal squark and gluino masses $\gtrsim$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

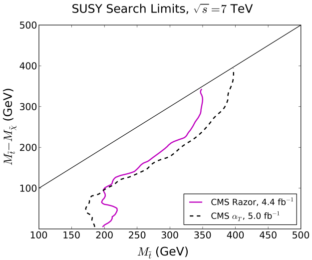
Backup Slides

Single eigenstate 'Stop' limits.

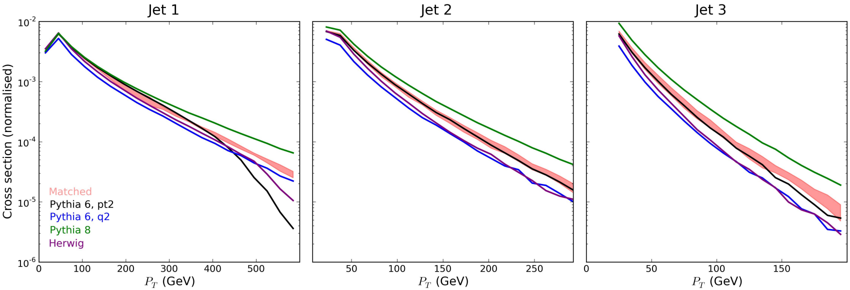
- Limit is, $M_{\tilde{t}} \gtrsim 200$ GeV.
  - Limit only valid for the decay $\tilde{t} \to c\tilde{\chi}_1^0$.
  - Decay is loop induced.
  - 100% branching ratio assumed.

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



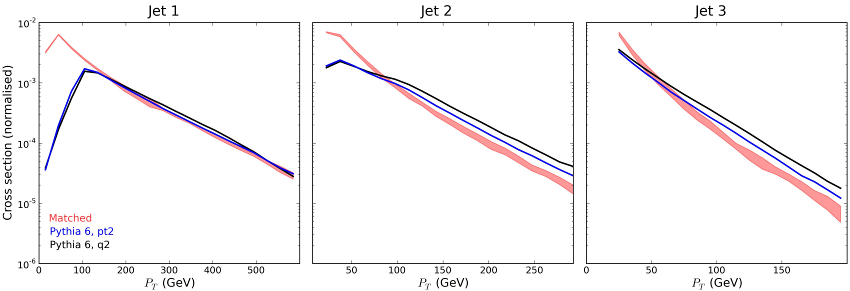


Comparison of Parton Shower and Matched Uncertainties.



- 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

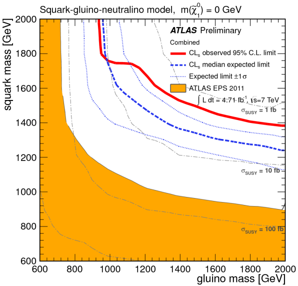
Double counting is a real problem!

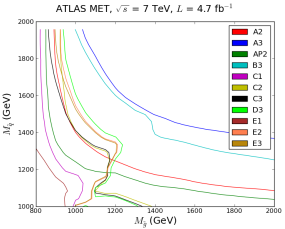


- Often considered to be a theoretical issue.
- Parton shower tunes are softer but still hard enough.
- Looking at the hardest jet can fool you.
- Comparison done with the relatively soft Pythia 6 showers.
  - With the default Pythia 8 shower, the situation would be even worse.

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.

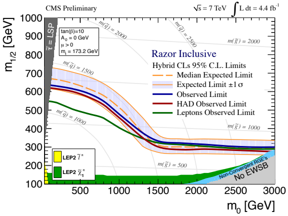
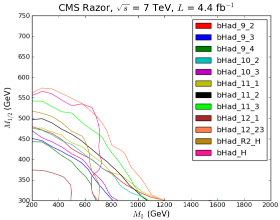


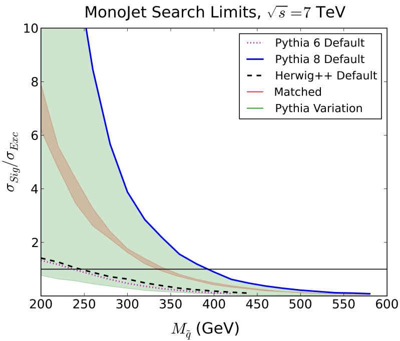
Figure 12: Observed (solid blue curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, $\mathrm{sgn}(\mu) = +1$ from the razor analysis. The ± one standard deviation equivalent variations in the uncertainties are shown as a band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



How does the Parton Shower perform?

Limits on squarks in decoupled gluino model.

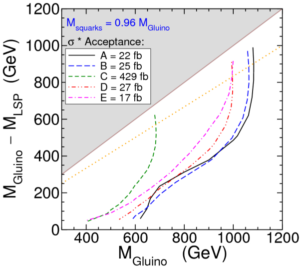
- Big variation on limit, 180 - 400 GeV.
- Default Herwig and Pythia 6 very close.
- Pythia 8 default is the power shower.

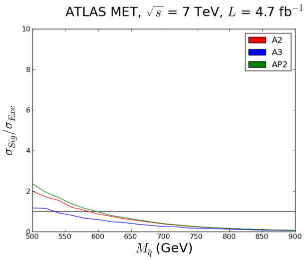


Agreement with LeCompte, Martin.

(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.

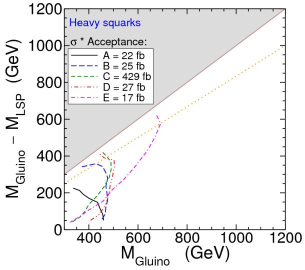


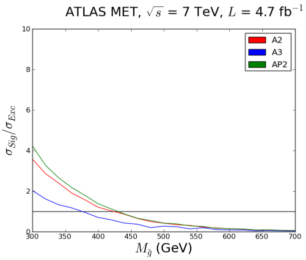


Differences with LeCompte, Martin.

(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.