How low can SUSY go?

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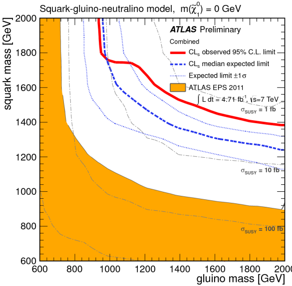
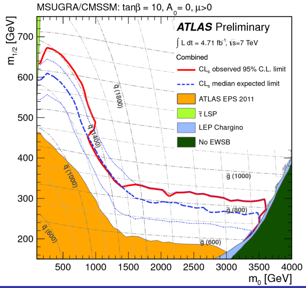
bctp Bethe Center for Theoretical Physics

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.

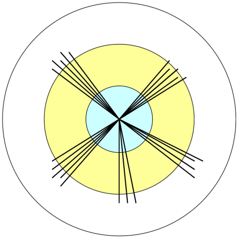




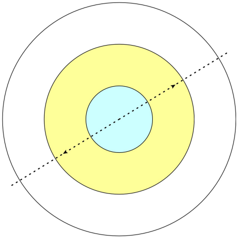
How can we evade these bounds?

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.

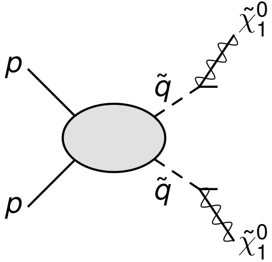


- Events containing only Missing Energy.
  - Signal can be invisible to the detector.

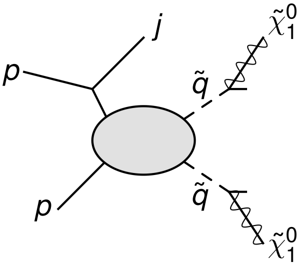
Events containing only MET

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



- I will concentrate on this possibility here.

Looking for SUSY with ISR

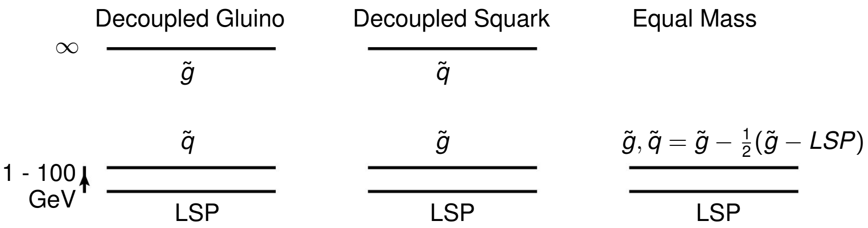
This is not the first idea to look for SUSY with ISR.

- Initially studied at the Tevatron. (Gunion, Mrenna; hep-ph/9906270)
- Re-analyses of ATLAS search for compressed SUSY.
  (LeCompte, Martin; 1105.4304, 111.6897)
  - We look at monojet searches.
    - ATLAS searches all require 2 jets > 60 GeV.
  - We take all hadronic SUSY searches.
    - CMS now has many 'shape' based searches.
  - We consider 'extreme' compression.
  - We explore uncertainties in ISR and the parton shower.
- Stops with ISR.
  (Carena, Freitas, Wagner; 0808.2298), (Drees, Hanussek, Kim; 1201.5714)...
- Model independent dark matter.
  (Bai, Fox, Harnik; 1005.3797), (Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu; 1005.1286)...

Simplified Models

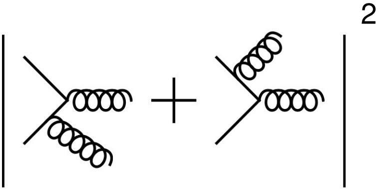
We take simplified models to capture the extremes.

- Squarks degenerate with LSP ($\Delta m = 1 - 100$ GeV). Gluino heavy.
- Gluino degenerate with LSP ($\Delta m = 1 - 100$ GeV). Squarks heavy.
- Gluino and squark degenerate with LSP ($\Delta m = 1 - 100$ GeV).
- We ignore third generation.



Matrix Element vs Parton Shower

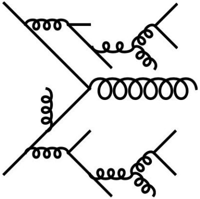
Matrix Element



- 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

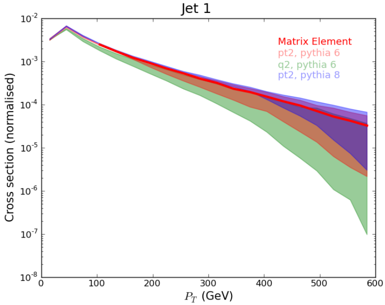
Parton shower has to be tuned to match phenomenological data.

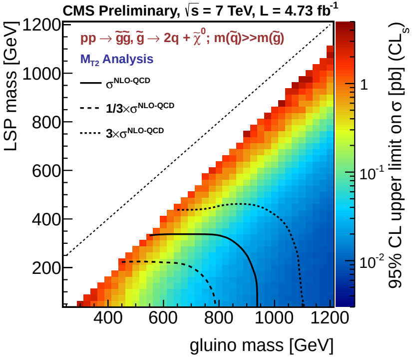
- Starting scale is the most important parameter (for high p_T^2 behaviour).
- For ISR, should be factorisation scale.
  - Often chosen as the transverse mass, $\mu_F = \sqrt{p_T^2 + \hat{m}^2}$.
  - 'Wimpy' shower.
  - Softer than matrix element.
- Phenomenologically better choice is far higher.
  -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

Collaborations have only used parton showers when setting limits so far.

- 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.

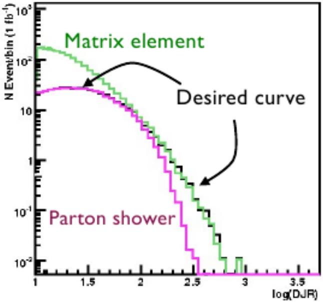




Matching the matrix element to the parton shower

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)

CKKW-L matching for Pythia-8

- Until recently, only matching algorithm that was implemented for new physics was MLM matching integrated with MadGraph and Pythia 6.
    - We wanted to test the matching and the parton shower.
- CKKW-L matching released for Pythia 8.
  (Lönnblad, Prestel; 1109.4829)
    - We have adapted to SUSY (with lots of help from the above).
- Pythia 8 has a far more sophisticated underlying event model.
    - Contains many colour connections between multiple interactions and hard event.
    - Results in far more soft QCD activity, 'the pedestal'.

Our choice

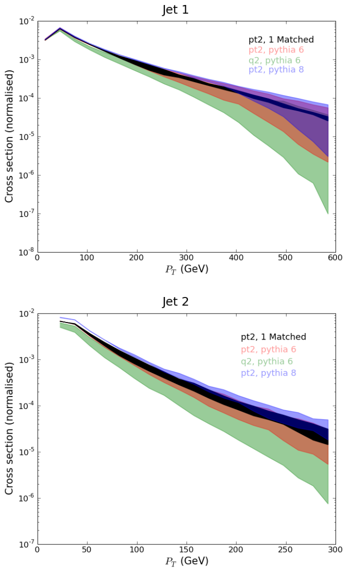
We use both matching schemes to test our predictions.

- 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.
- 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)

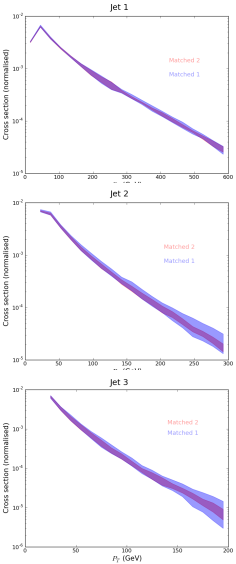
Comparison of Parton Shower and Matched Uncertainties.

- Decoupled production of 500 GeV squarks, degenerate LSP.
- Parton shower varied between 'wimpy' and 'power' settings.
- Matching scale varied between 50 and 200 GeV.
- Large reduction in uncertainty.
- Parton shower 2nd jet uncertainty also improved.



Comparison of Parton Shower and Matched Uncertainties.

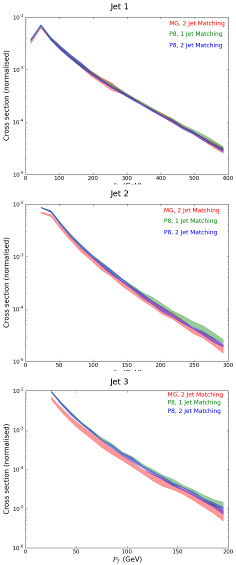
- Moving to 2 jet matching further reduces uncertainty.
- 3rd jet uncertainty also improved.
- Only matching 1 jet actually gives reasonable prediction.
- Parton shower varied between 'wimpy' and 'power' settings.
- Matching scale varied between 50 and 200 GeV.



MLM vs CKKW

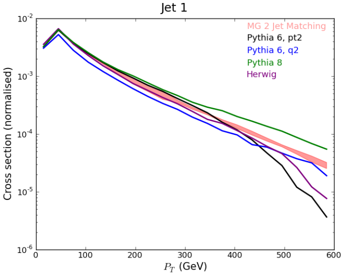
Comparison between MadGraph MLM matching and Pythia 8 CKKW.

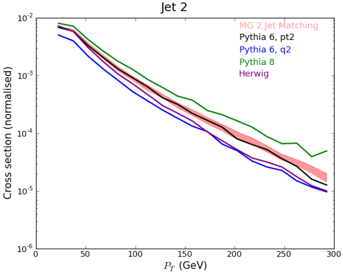
- CKKW matching with Pythia 8 gives very similar results.
- Pythia 8 underlying event gives more soft activity.
  - Need to test with latest Pythia 6 tunes.
- We can be confident in the predictions.
- Parton shower varied between 'wimpy' and 'power' (not in P8) settings.
- Matching scale varied between 50 and 200 GeV.



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

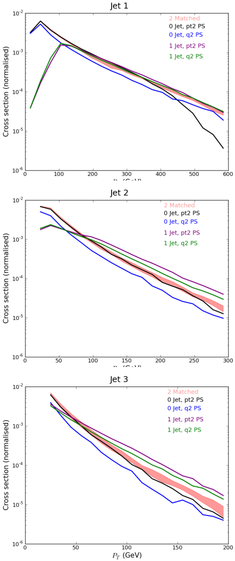




Double counting

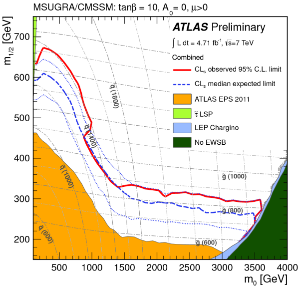
Double counting is a real problem!

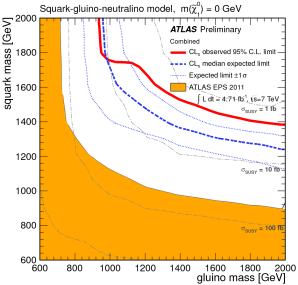
- Often considered to be a theoretical issue.
- Parton shower tunes are softer but still hard enough.
- Looking at the hardest jet can fool you.
- Comparison done with the relatively soft Pythia 6 showers.
    - With the default Pythia 8 shower, the situation would be even worse.



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.
- $\Delta\phi(j, E_T^{miss}) > 0.4$.





Searches

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.

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

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

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

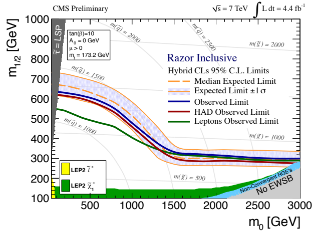
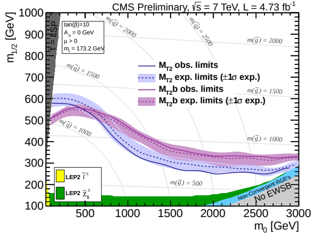
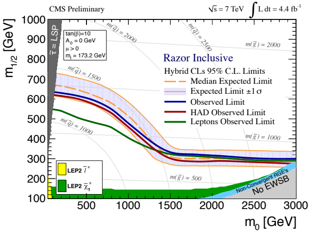


Figure 12: Observed (solid blue curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, $\mathrm{sgn}(\mu) = +1$ from the razor analysis. The ± one standard deviation equivalent variations in the uncertainties are shown as a band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



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.
- $M_R > 500$ GeV ($\sum E_T^{jet} \gtrsim 600$ GeV).
- $E_T^{miss} \gtrsim 200$ GeV.
- $p_T(j_2) > 60$ GeV.
- Difference is probably cosmetic for mSugra.



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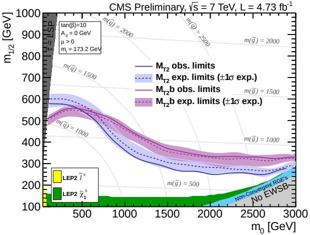
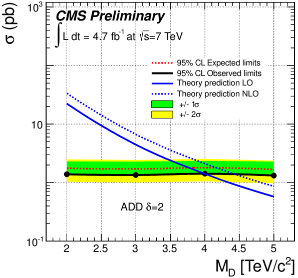
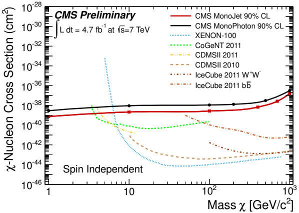


Monojet.

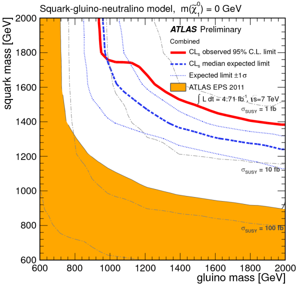
- Both CMS and ATLAS have a monojet search.
    - Designed to search for ADD extra dimensions.
    - Now also used for model independent dark matter
- $E_T^{miss} \gtrsim 350$ GeV.
- Both have a third jet veto.
- ATLAS also had 2nd jet veto, $p_T < 60$ GeV. (now removed for $4.7\ \mathrm{fb}^{-1}$).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

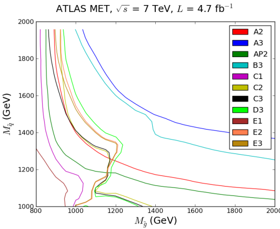




Verifying my implementation.

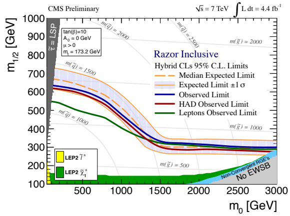
- Good agreement with all analyses.
    - Jets are easy when the hard work is done!
- Only use best expected box.
    - If exclusion is better than expected, use expected.
    - More conservative than ATLAS.
    - Allows a fairer comparison between searches and regions.
    - Relevant regions for compressed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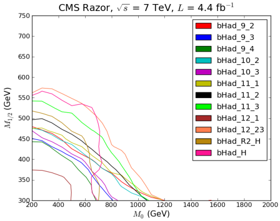
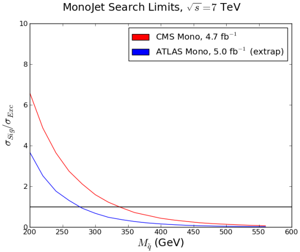
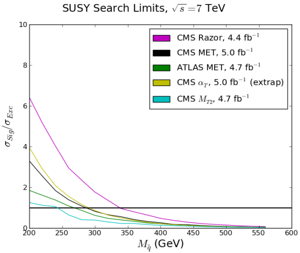


Comparison of squark limits.

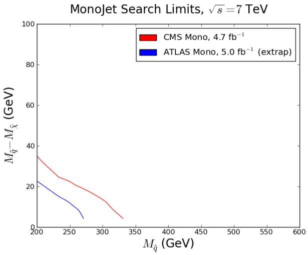
- Limit in decoupled gluino scenario, $m_{\tilde{q}} \gtrsim 340$ GeV.
  - CMS Monojet search provides the best limit (just)!
  - General SUSY searches almost match the limit.
  - CMS RAZOR is the most constraining of the SUSY searches.

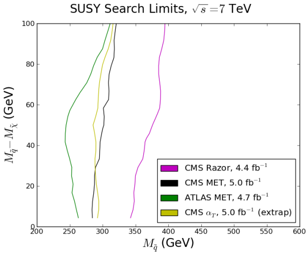




Moving away from full compression.

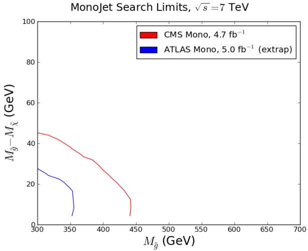
- Extra hadronic activity quickly hurts the monojet searches.
    - Maybe remove 2nd and 3rd Jet vetoes or set these higher.
- SUSY searches seem to be rather stable.
    - Multijet ATLAS search shows fast improvement when we use new search region.

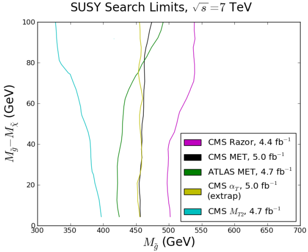




Comparison of gluino limits.

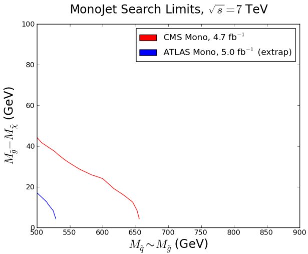
- Limit in decoupled squark scenario, $m_{\tilde{g}} \gtrsim 500$ GeV.
  - CMS RAZOR search provides the best limit.
  - Monojet is also competitive.
- Decoupled scenario is somewhat academic.
  - With $m_{\tilde{q}} = \infty$, gluino becomes stable.
  - With extreme compression gluino lifetime is large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

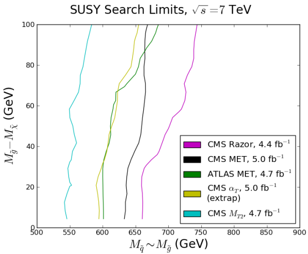




Equal mass ($M_{\tilde{q}} = M_{\tilde{g}}$) limits.

- Limit is, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 650$ GeV.
  - CMS monojet search is competitive for spectrum degeneracy.
  - CMS-Razor provides the best limit from SUSY searches.
  - SUSY searches improve as degeneracy is broken.

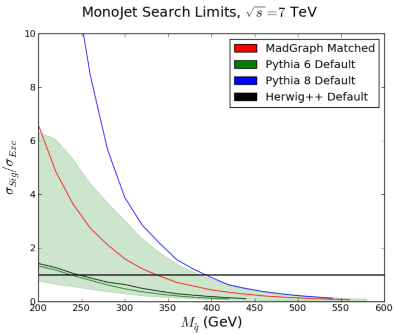




How does the Parton Shower perform?

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.



Summary

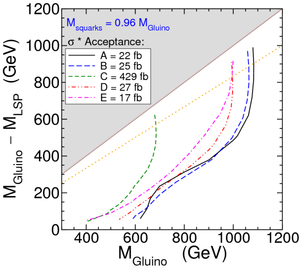
- Compressing the mass spectrum makes SUSY much harder to look for.
- ISR becomes vital to see any signal.
- Matching the matrix element to the parton shower to required to accurately model the ISR.
- Squark masses $\gtrsim$ 340 GeV.
- Gluino mass $\gtrsim$ 500 GeV.
- Equal squark and gluino masses $\gtrsim$ 650 GeV

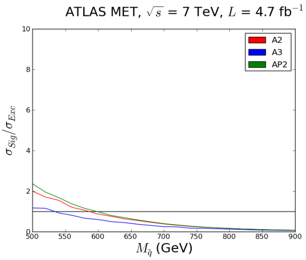
Backup Slides

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.

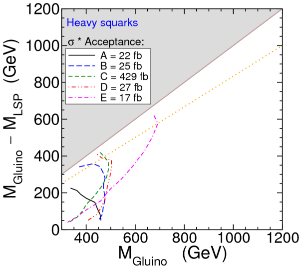


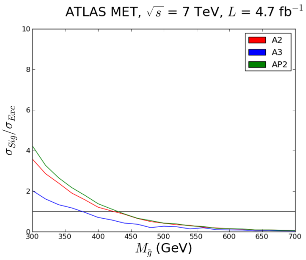


Differences with LeCompte, Martin.

(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.