How low can SUSY go?

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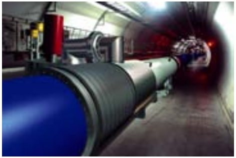
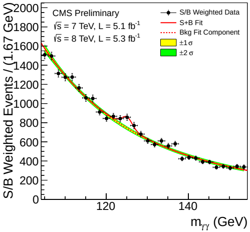
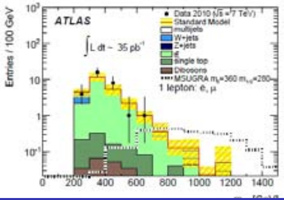
bctp Bethe Center for Theoretical Physics

The search for TeV physics is underway.

- 2012 LHC run went extremely well.
  - Collected over 23 fb^{-1} per experiment this year.
  - The Higgs has almost certainly been discovered at $\sim$125 GeV.
- We are all eagerly awaiting (praying for) any signs of new physics.
- Unfortunately so far we have only seen ....







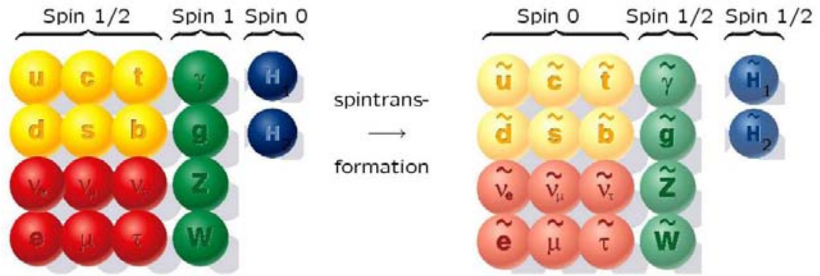
Supersymmetry (SUSY)

Supersymmetry relates fermions and bosons.

- $Q|boson>=|fermion>$
- $Q|fermion>=|boson>$

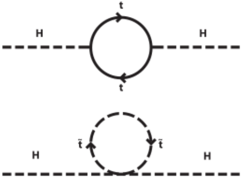
All SM particles get a 'Superpartner'.

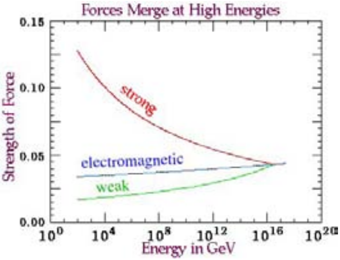
- Same quantum numbers.
- Differ in spin by 1/2.



SUSY is one of the best motivated extensions of the SM.

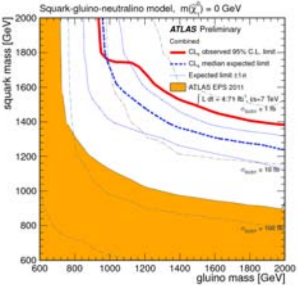
- Offers a solution to the hierarchy problem.
- Provides a 'natural' dark matter candidate.
  - If R-parity is assumed.
- Unique extension of the Poincaré group.
- Unification of coupling constants.

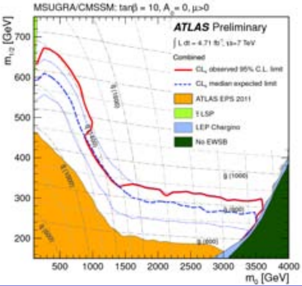




LHC now sets very strict limits on the SUSY parameter space.

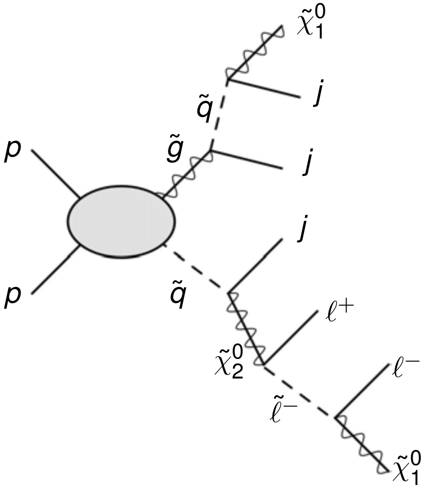
- Simplified Model ($m_{\tilde{\chi}_1^0} = 0$).
  - $m_{\tilde{q}} = m_{\tilde{g}} \gtrsim 1.5$ TeV.
  - $m_{\tilde{g}} \gtrsim 940$ GeV, ($m_{\tilde{q}} = 2$ TeV).
  - $m_{\tilde{q}} \gtrsim 1380$ GeV, ($m_{\tilde{g}} = 2$ TeV).
- mSugra ($\tan\beta = 10, A_0 = 0, \mu > 0$).
  - $m_{\tilde{q}} = m_{\tilde{g}} \gtrsim 1.4$ 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 are these limits set?

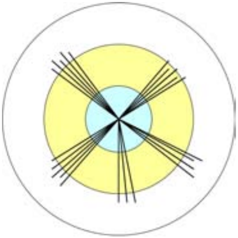
- Assume large mass gaps between states.
    - Lots of hard jets and leptons.
- Last particle in the chain is the dark matter candidate.
    - Missing energy to distinguish from background.
- Searches are not complicated (mostly).
    - Look for events with hard jets/leptons.
    - Lots of Missing Energy.



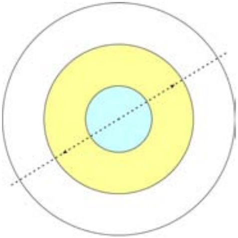
How can we evade these bounds?

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

Two obvious possibilities:



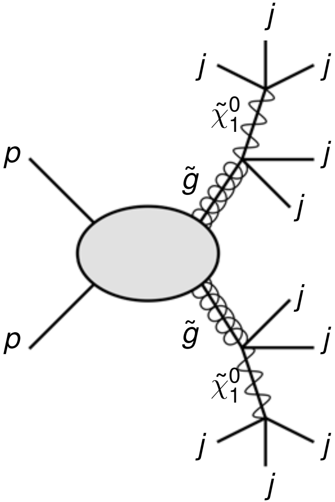
- Events containing no Missing Energy.
  - Signal can be hidden under QCD.
- Events containing only Missing Energy.
  - Signal can be invisible to the detector.



Events containing no MET

Without MET, QCD background is huge.

- Possible with R-parity violation in SUSY.
- Multi-jet topology that is very hard to separate from background.
- Need some kinematical discriminant.
    - CMS has searched for tri-jet resonance.
    - For gluino -> 3jets, $m_{\tilde{g}} > 280 - 460$ GeV.



Natural SUSY's Last Hope: R-parity Violation via UDD Operators (arXiv:1301.2336), Bhattacherjee, Evans, Ibe, Matsumoto, Yanagida.

Events containing only MET

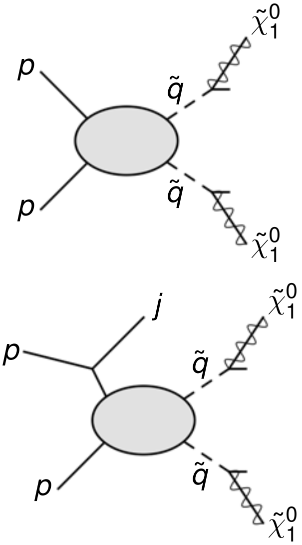
If the spectrum is compressed all momentum is carried by the LSP.

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

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

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.
- LHC 8 TeV reach in compressed spectra.

  (Bhattacherjee, Ghosh; 1207.6289)
- Stops with ISR.

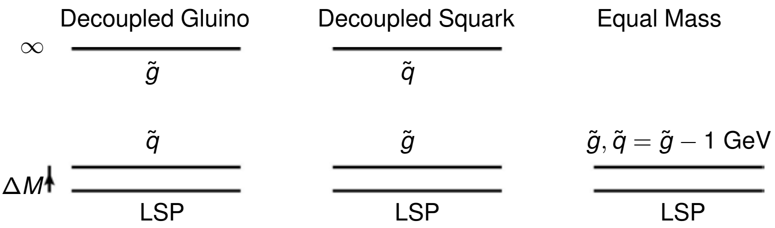
  (Carena, Freitas, Wagner; 0808.2298), (Drees, Hanussek, Kim; 1201.5714)...
- Model independent dark matter.

  (Bai, Fox, Harnik; 1005.3797), (Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu; 1005.1286)...

Simplified Models

We take simplified models to capture the extremes.

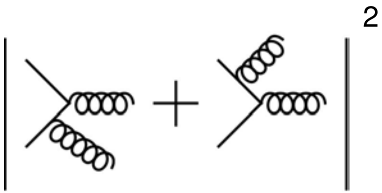
- Squarks degenerate with LSP (gluino decoupled).
- Gluino degenerate with LSP (squarks decoupled).
- Gluino and squark degenerate with LSP.
- Single eigenstate 'stop' model.
- LSP mass varied from,
  $M_{\chi_1^0} = M_{\tilde{q},\tilde{g}} - 2$ GeV $\rightarrow M_{\chi_1^0} = 0$ GeV.



Compact Supersymmetry, Phys.Rev D86 115014; Murayama, Nomura, Shirai.

Matrix Element vs Parton Shower

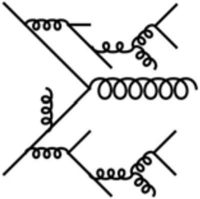
Matrix Element



- 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.

How does a Parton Shower work?

Use QCD evolution equations to describe the non-splitting probability, Δ_S, of a parton between two scales (ρ_i, ρ_{i+1}),

$$\Delta_S(\rho_i, \rho_{i+1}) = \exp\left[-\int_{\rho_{i+1}}^{\rho_i} d\rho \int dz \alpha_s(\rho) P_i(\rho, z)\right].$$

- Describes successive QCD emissions.
  - Uses soft/collinear approximation.
  - 'Evolves' from hard scattering scale down to hadronisation.
- Easily adapted into a Monte-Carlo code.
  - Between two scales throw random number R.
  - If $R > \Delta_S$, parton is split.

At a fixed low scale ($\sim$1 GeV) matched to a hadronisation model.

Parton shower has to be tuned to match phenomenological data.

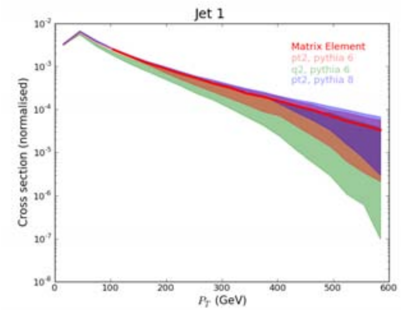
- Starting scale is the most important parameter (for high p_T^2 behaviour).
- For ISR, should be factorisation scale.
  - Often chosen as the transverse mass, $\mu_F = \sqrt{p_T^2 + \hat{m}^2}$.
  - 'Wimpy' shower.
  - Softer than matrix element.
- Phenomenologically better choice is far higher.
  -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

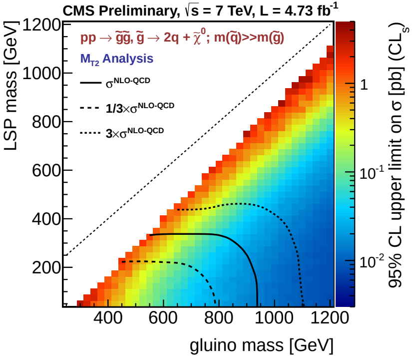
(Plehn, Rainwater, Skands; hep-ph/0510144)

Parton shower variation

Until recently collaborations had only used parton showers.

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





Matching the matrix element to the parton shower

Conclusion $\rightarrow$ We need the accuracy of the matrix element *but*...

- Can only include a finite number of additional jets (<=2).
- Only valid in the perturbative regime.
- Perturbative means something new at the LHC.
- To get accurate acceptances, we need to include soft physics as well.

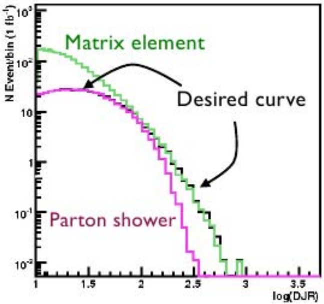
Conclusion $\rightarrow$ Add the parton shower to the matrix element prediction.

- We have already seen that the some parton showers can give harder radiation than the matrix element.
- We need to avoid double counting.

Matching the matrix element to the parton shower

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

- Reweight inclusive samples.
- Smooth distributions between areas of validity.
- Small dependence on matching scale.
- Small dependence on parton shower.
- Should converge as we include higher multiplicities.



(Maltoni)

MLM Matching

Developed later than CKKW but easier to implement...

(Mangano; 04)

(Mangano, Moretti, Piccinini, Treccani; hep-ph/0611129)

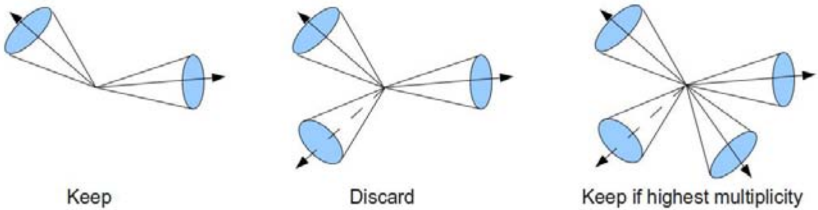
(Alwall, de Visscher, Maltoni; 0810.5350)

Matrix Element production:

- Generate multiparton event with a jet measure cut.
  $k_\perp^2 = \min\left\{\min(p_{T,i}^2, p_{T,j}^2), \min(p_{T,i}^2, p_{T,j}^2)\frac{(\Delta\eta_{ij})^2+(\Delta\phi_{ij})^2}{D^2}\right\}$
- Cluster event (into a series of $1 \to 2$ splittings) and use $k_\perp$ as factorisation scale (α_s and PDF's).
  - Reweight at each vertex (try to mimic parton shower behaviour).
  - Only allow clusterings given by diagrams.
  - For SUSY, ignore particles produced in a decay.

Adding the parton shower:

- Shower event starting from the maximum clustering scale (assumption tested).
- Cluster event with $k_\perp$ algorithm (ignoring showers initiated in SUSY decays).
- Match clustered jets to partons, $k_\perp(jet, parton) > k_\perp^{\rm cut}$.
- Reject event if any jets are unmatched.
- Subtlety for highest multiplicity sample.
  - Allow extra jets with, $k_\perp(jet, parton) < \min(k_\perp(parton, parton))$.



CKKW is the original matching algorithm.

(Catani, Krauss, Kuhn, Webber; hep-ph/0109231)

- Generate multiparton event with jet measure cut ($k_\perp^{\rm cut}$).
- Cluster event with $k_\perp$ and reweight each vertex.
- Reweight event with Sudakov factor,

$$\frac{\Delta_S(\rho_j, k_\perp^{\rm cut})}{\Delta_S(\rho_i, k_\perp^{\rm cut})},$$

  for each parton between vertices i and j (j can be $k_\perp^{\rm cut}$).
- Shower event, only allowing emissions with, $k_\perp < k_\perp^{\rm cut}$.
  - Known as vetoed shower.
- For highest multiplicity sample, allow emissions up to, $k_\perp^{\rm min}$.

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'.

Double counting on the matrix element level

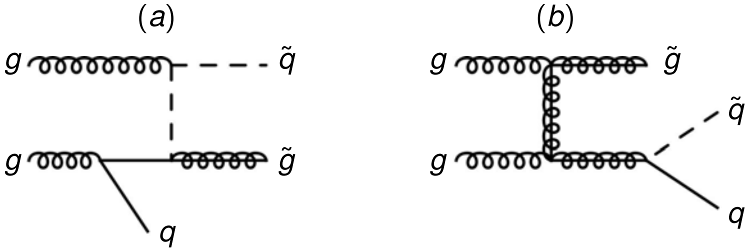
On-shell resonances can be double counted.

(Alwall, de Vischer, Maltoni; 0810.5350)

- (a) is a 'genuine' correction to $2 \to 2$ process.
- (b) contains a possible resonant contribution.
  - Already taken care of in $\tilde{g}\tilde{g}$ channel.

Solution $\to$ remove resonant propagators.

- Not gauge invariant.
- Lose interference between diagrams.
  - Works well if width is small ($\Gamma/m \ll 1$).



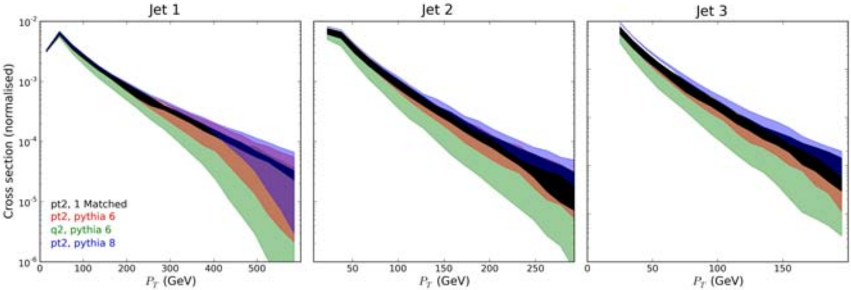
Our choice

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)

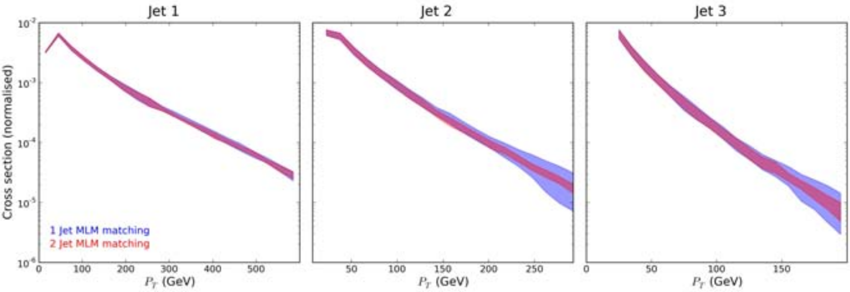
Comparison of Parton Shower and Matched Uncertainties.



- 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.

1 Jet vs 2 Jet Matching

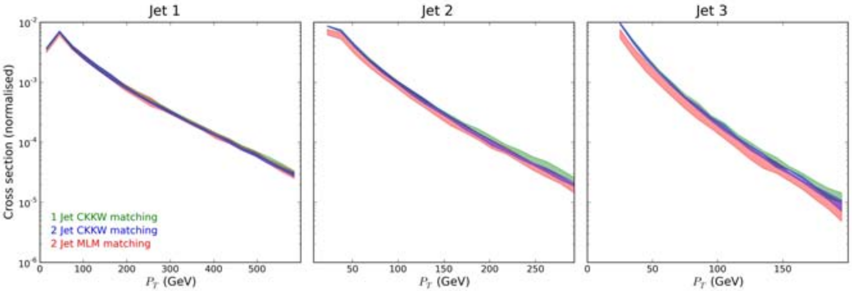
Matching more jets.



- 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.

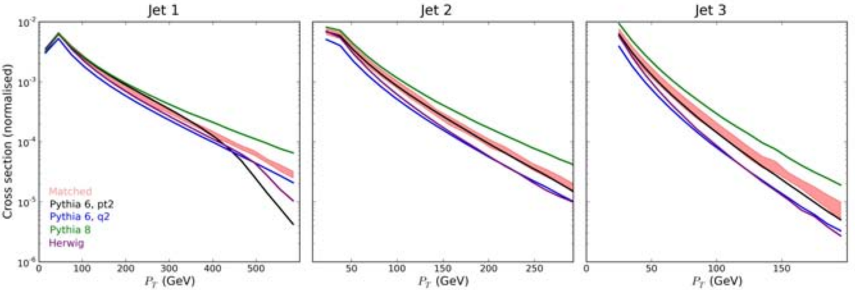
MLM vs CKKW

Comparison between MLM matching and CKKW.



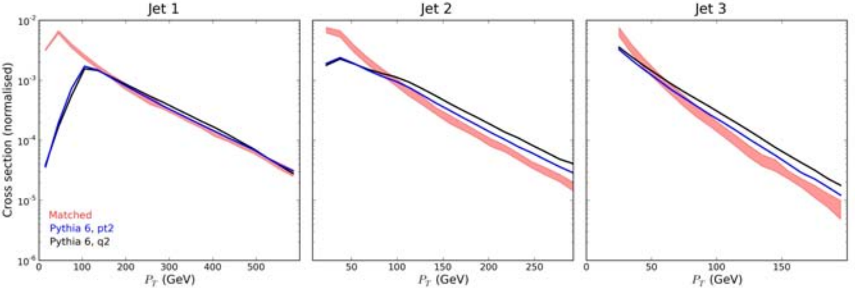
- CKKW matching with Pythia 8 gives very similar results.
- Pythia 8 underlying event gives more soft activity.
  - Need to test with latest Pythia 6 tunes.
- We can be confident in the predictions.
- Parton shower varied between 'wimpy' and 'power' (not in P8) settings.
- Matching scale varied between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

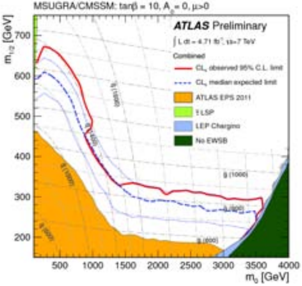


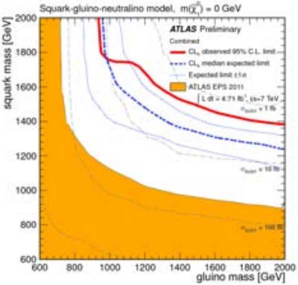
- Often considered to be a theoretical issue.
- Parton shower tunes are softer but still hard enough.
- Looking at the hardest jet can fool you.
- Comparison done with the relatively soft Pythia 6 showers.
    - With the default Pythia 8 shower, the situation would be even worse.

Searches

Jets and MET.

- Take ATLAS search as example (very similar CMS search).
- By far easiest search for stupid pheno guys to implement.
- 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.

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

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

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

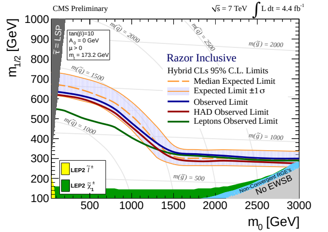
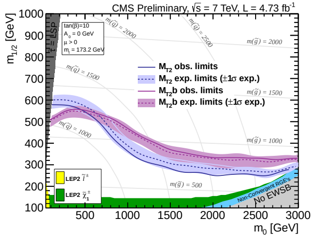
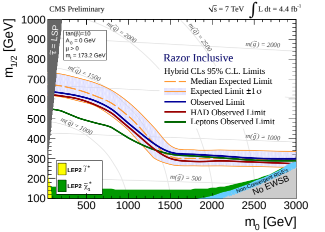


Figure 12: Observed (solid blue curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, $\mathrm{sgn}(\mu) = +1$ from the razor analysis. The $\pm$ one standard deviation equivalent variations in the uncertainties are shown as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



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 more cosmetic than real.



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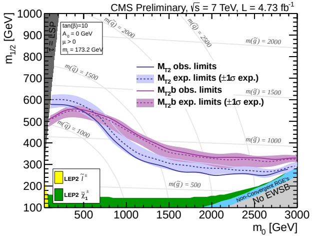
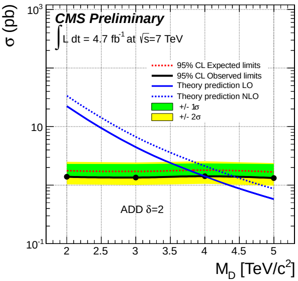
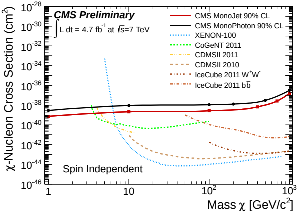


Monojet.

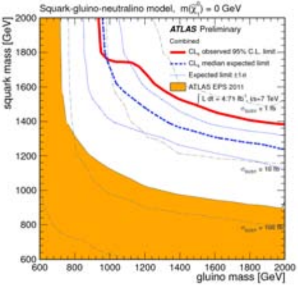
- Both CMS and ATLAS have a monojet search.
  - Designed to search for ADD extra dimensions.
  - Now also used for model independent dark matter
- $E_T^{miss} \gtrsim 350$ GeV.
- Both have a third jet veto.
- ATLAS also had 2nd jet veto, $p_T < 60$ GeV. (now removed for 4.7 fb^{-1}).
- For CMS $\Delta\phi(j_1,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

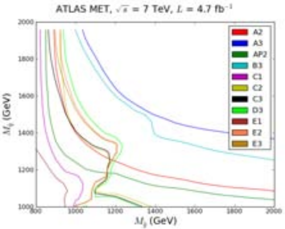




Verifying my implementation.

- 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 number of bins 'intelligently' and use best exclusion.
  - Worse reach than official analysis.

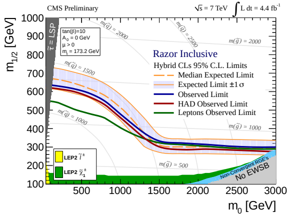
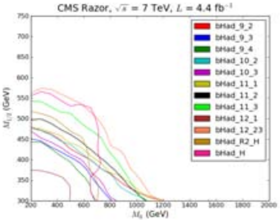
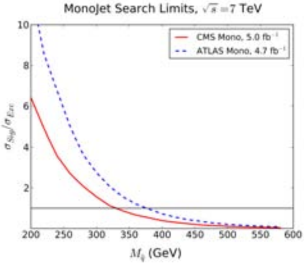


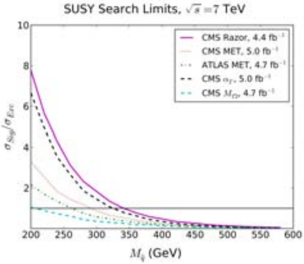
Figure 12: Observed (solid blue curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, sgn$(\mu) = +1$ from the razor analysis. The ± one standard deviation equivalent variations in the uncertainties are shown as a band around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



Comparison of squark limits.

- Limit in decoupled gluino scenario, $m_{\tilde{q}} \gtrsim 350$ 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.

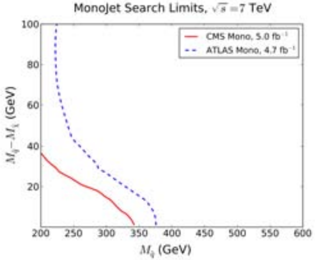


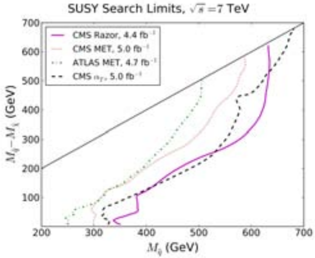


Results

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.

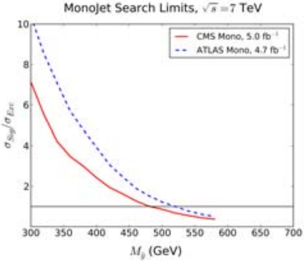


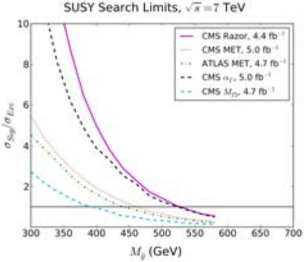


Results

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.





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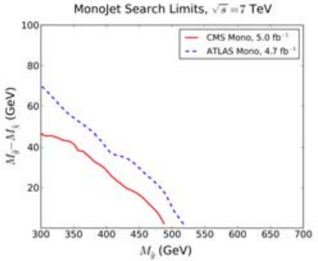
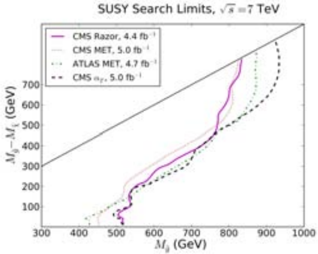
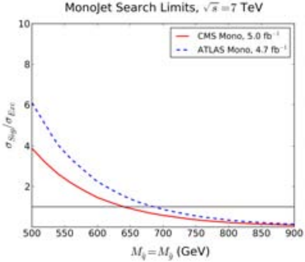
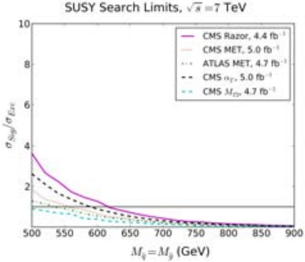




Equal mass ($M_{\tilde{q}} = M_{\tilde{g}}$) limits.

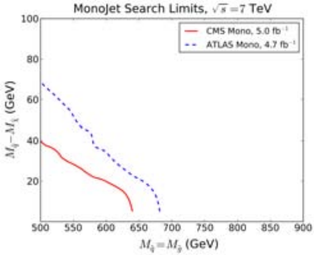
- Limit is, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 650$ GeV.
    - ATLAS monojet search is competitive for spectrum degeneracy.
    - CMS-Razor provides the best limit from SUSY searches.
- Even with an additional factor of 2 error, limit is $\gtrsim 600$ GeV.

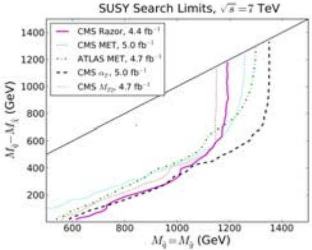




Equal mass ($M_{\tilde{q}} = M_{\tilde{g}}$) limits.

- Limit is, $M_{\tilde{q}} = M_{\tilde{g}} \gtrsim 650$ 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.

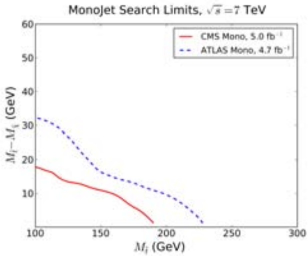


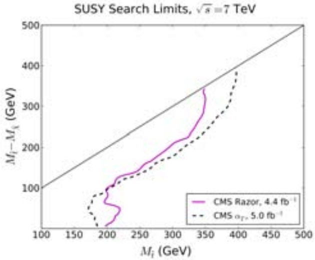


Single eigenstate ‘stop’ limits.

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

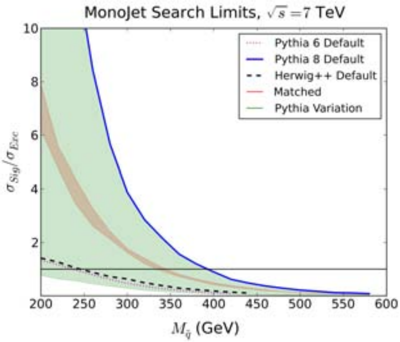
    - For more complicated decays, limits are still valid close to degeneracy.
- Also valid for a single light squark (or sbottom) eigenstate.





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.



Results

General discussion points.

- CMS Monojet is not optimized.
  - Search region with higher MET and/or jet p_T would do better.
  - $\sim$ 500 events in signal region c.f. $\sim$ 10 for SUSY searches.

  ATLAS Monojet showed how jet vetos hurt reach.
  - Would both monojet searches be better with no jet veto?
  - Still keep a geometrical cut with $\Delta R < 2.5$ between all jets.
- RAZOR searches have opposite problem.
  - Doesn't allow events with a monojet topology.
  - Relaxing this constraint may give better reach.
- Searches are (somewhat) orthogonal.

Future Directions

- Set limits in Universal Extra Dimension models.
  - Spectrum is naturally compressed.
- Can we search for electroweak states?
  - Especially interesting are Higgsinos.
- Examine ways to optimise searches.
  - Monojet search that does not veto extra jets.
  - Monojet search focusing on higher p_T jets.
- What is the ultimate reach for LHC@14 TeV.
- Encourage collaborations to start using matching in new physics searches.

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

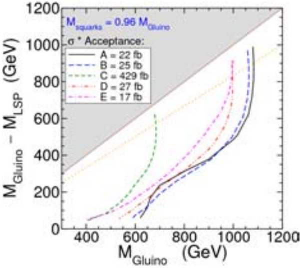
Backup Slides

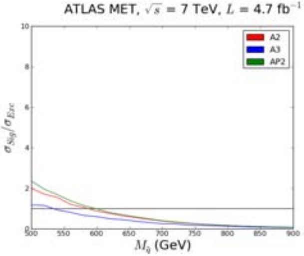
Results

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.



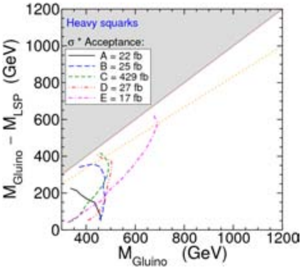


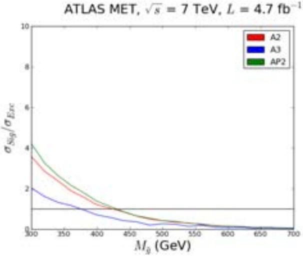
Results

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.