Incorporating Event Rates Into MSSM Parameter Determinations

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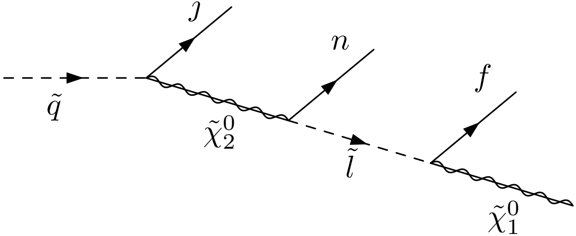
Outline

Cascade decays



- Most effort for determining SUSY parameters so far has gone into cascade decay kinematics [*e.g.* Gjelsten, Miller and Osland, (2004); Gjelsten, Miller, Raklev, 2005)]
- Expected that colored sparticles produced copiously, then decay in stages emitting observable SM particle each time (assuming R-parity conservation)
  - $\tilde{g}$ must decay via $\tilde{q}$, $\tilde{q}$ decays often to $\tilde{\chi}_2^0$, typically $\tilde{\chi}_2^0$ decays to $\tilde{l}$ which then must decay to $\tilde{\chi}_1^0$
- Unknown center of momentum + $\tilde{\chi}_1^0$ escaping detector = reconstruction difficult

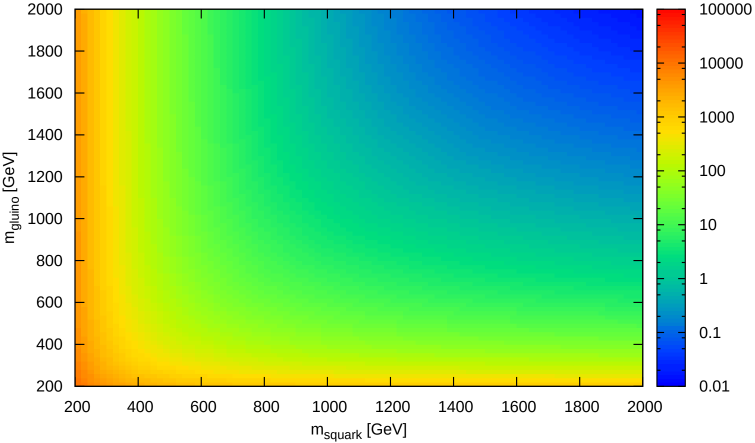
Endpoints

- Event-by-event reconstruction impossible, but various kinematic quantities have distributions with well-defined endpoints
  - *e.g.* $m_{qll}^2 = (p_q + p_n + p_f)^2$ has endpoint

$$\begin{cases} (m_{\tilde{q}}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\chi}_2^0}^2 & \text{if} \quad \frac{m_{\tilde{q}}}{m_{\tilde{\chi}_2^0}} > \frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{\chi}_1^0}} \\ (m_{\tilde{q}}^2 m_{\tilde{l}}^2 - m_{\tilde{\chi}_2^0}^2 m_{\tilde{\chi}_1^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)/m_{\tilde{\chi}_2^0}^2 m_{\tilde{l}}^2 & \text{if} \quad \frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{l}}} > \frac{m_{\tilde{q}} m_{\tilde{l}}}{m_{\tilde{\chi}_2^0} m_{\tilde{\chi}_1^0}} \\ (m_{\tilde{q}}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\chi}_2^0}^2 & \text{if} \quad \frac{m_{\tilde{l}}}{m_{\tilde{\chi}_1^0}} > \frac{m_{\tilde{q}}}{m_{\tilde{l}}} \\ (m_{\tilde{q}}^2 - m_{\tilde{\chi}_2^0}^2) & \text{otherwise} \end{cases}$$

Motivation for utilizing cross-sections

- More observables = better determination of parameters! (in general)
- LHC cross-sections very sensitive to colored sparticle masses

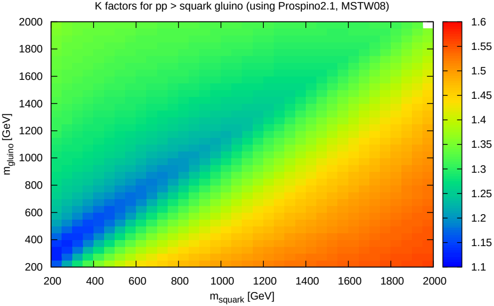


Further motivation for utilizing cross-sections

- Cascade decay endpoint mimic points exist – cross-sections can provide discrimination
- Cascade decay endpoints can be underconstraining for certain parameter regions and for certain hierarchies
- Non-supersymmetric models can have very similar spectra but with differing spins:
  - invariant mass distributions need to be well-measured to determine spin
  - cross-sections typically are an order of magnitude more for UED models than SUSY models with similar spectra

NLO SUSY cross-sections

- NLO needed since LO cross-sections can vary by 100%



- K-factors also different for different sparticle production,
  - *e.g.* at 7 TeV, $m_{\tilde{g}} \simeq 600$ GeV, $m_{\tilde{q}} \simeq 550$ GeV (close to SPS1a and LM1)
  - $K_{\tilde{g}\tilde{g}} = 1.45, K_{\tilde{g}\tilde{q}} = 1.20, K_{\tilde{q}\tilde{q}} = 1.18$
- This can lead to quite different amounts of *b*-jets from sbottoms from gluinos, for example

Technical Issues

- NLO SUSY-QCD calculations are not fast
- Dependent on unknown masses
  - $\Rightarrow$ Published studies restricted to single points in many-parameter space
- Not easily invertible
  - $\Rightarrow$ Unless Nature *really is* SPS1a, lots of trial-and-error finding masses if trying to make use of NLO
- Not easy to account for experimental cuts, such as on transverse momentum (though possible with a lot of computing power)
- Lester, Parker, White (hep-ph/0508143):
  - Markov chain exploration with full Monte Carlo simulation of SUSY events at each point
  - Supercomputer ran `ISAJET`, `HERWIG` then `ATLFAST` for LHC
  - restricted to 1000 events simulated per point - at leading order!
  - proof of principle, not intended to be repeated often

Our implementation - overview

Herbi Dreiner, Michael Krämer, Jonas Lindert, B. O'L.:
self-contained code which

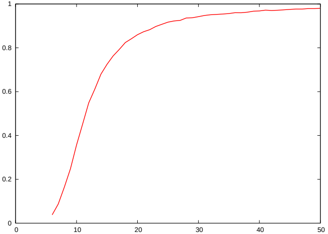
- takes LHC-scale SUSY spectrum (*e.g.* from SLHA-format file)
- looks up table of cross-sections for colored sparticle production
- works out relevant cascade decays and multiplies with relevant branching ratios (BRs taken from SLHA file, such as produced by `SPheno`)
- applies approximations for cut acceptances depending on sparticle masses
- returns event rates for particular signals

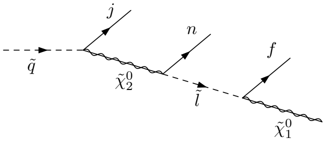
Error estimated to be 15% on cross-section (typical NLO error including PDF uncertainty *etc.*), 5% on cut acceptances (from comparison with full parton-level MC simulation with `Herwig++`).

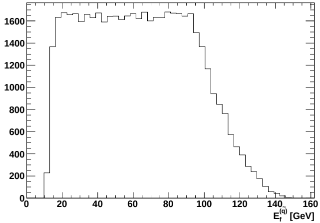
Some details of our implementation

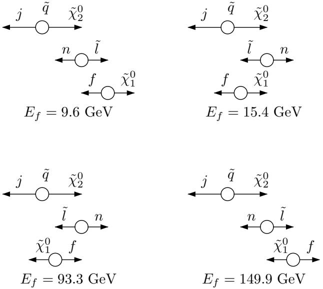
- currently 2 signals:
  - 2 or more jets passing p_T, η cuts with $\not{E}_T$ cut
  - $e\bar{e} + \mu\bar{\mu} - \mu\bar{e} - e\bar{\mu}$, with p_T, η cuts
- looks up table by $m_{\tilde{g}}, m_{\tilde{q}}$, for this point we have:
  - NLO cross-sections for $\tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}$ combinations, $\tilde{t}\tilde{t}$ also
  - numbers parameterizing cut acceptances for massless particles (e, μ, j assumed so) for given energies in $\tilde{q}$ rest frame
  - numbers parameterizing $\not{E}_T$ cut acceptances for given $m_{\tilde{\chi}^0}$
- works out relevant cascade decays and multiplies with relevant branching ratios
- applies approximations for cut acceptances depending on sparticle masses
  - distribution of lepton energies in $\tilde{q}$ rest frame calculated from sparticle masses
  - this distribution is convoluted with acceptances for given energies
- returns event rates for particular signals

Lepton acceptance example









Implementation into `Fittino`

- Thus far, only used in (private at the moment) version of `Fittino`
- Used as normal observables in `Fittino`

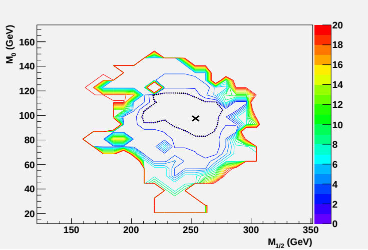
`Fittino`: a program by Philip Bechtle, Klaus Desch and Peter Wienemann (http://www.-flc.desy.de/fittino/)

- Explores SUSY parameter space (simulated annealing or Markov chain)
  - can explore LHC-scale Lagrangian parameter space or GUT-scale (uses `SPheno` to run from one scale to the other)
- Calculates χ^2 for each point visited based on supplied observables
- Eventually distills down to a value for the Lagrangian parameters (low scale or high scale) with errors

Some results from this implementation have been published in *JHEP* **4** (2010).

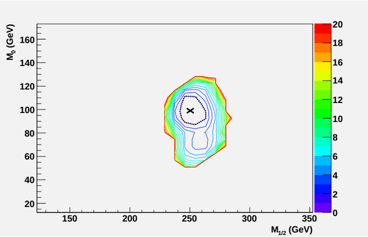
Plots for 7 TeV, M_0 against $M_{1/2}$

I, ~~rates~~



Two million MC steps.

I + rates



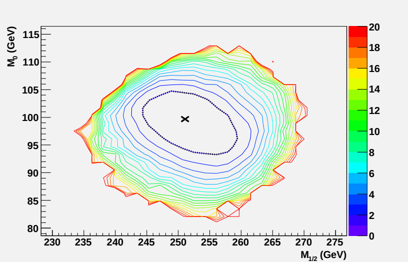
Ten thousand MC steps.

$$(\text{“I”} = m_{\ell\ell}^{\max}, m_{q\ell\ell}^{\max}, m_{q\ell}^{\text{low}}, m_{q\ell}^{\text{high}},\ \text{“II”} = m_{q\ell\ell}^{\text{thr.}}, m_{T2}^{\tilde{q}}, m_{\tau\tau}^{\max}, m_{tb}^{w})$$

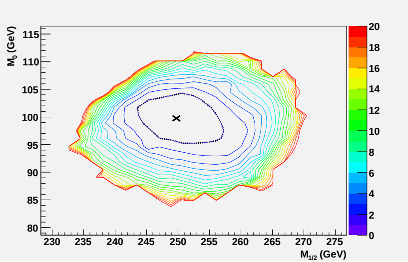
Data input was SPS1a:
$M_0 = 100$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan(\beta) = 10$.

Plots for 14 TeV, M_0 against $M_{1/2}$

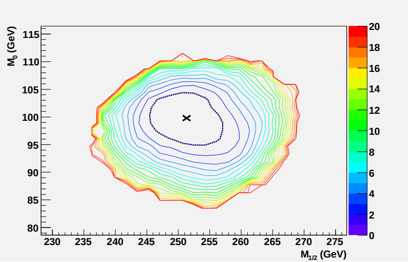
I + rates



I + II, ~~rates~~

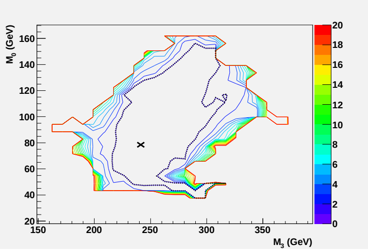


I + II + rates



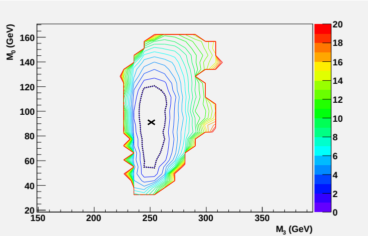
Plots for 7 TeV, M_0 against M_3

I, ~~rates~~



Two million MC steps.

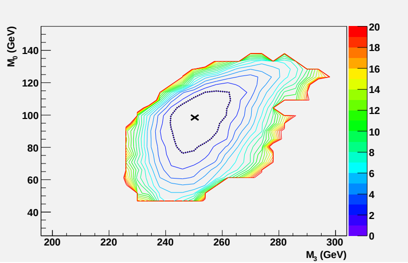
I + rates



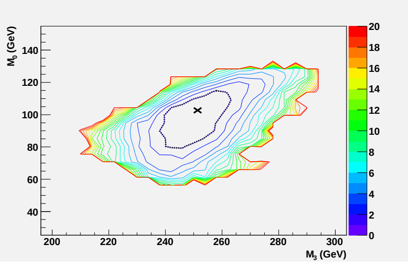
Ten thousand MC steps.

Plots for 14 TeV, M_0 against M_3

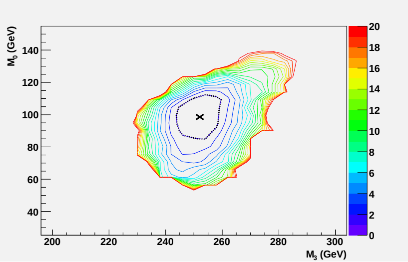
I + rates



I + II, ~~rates~~



I + II + rates



Summary and Outlook

Summary:

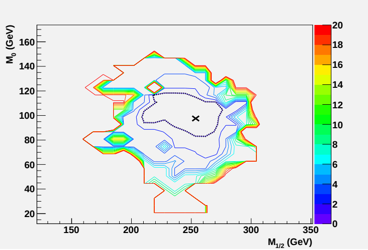
- Cross-sections can be calculated within 20% quickly
- Rates can make a big difference to reducing errors on $M_{1/2}$ and $\tan\beta$ in Fittino

Outlook:

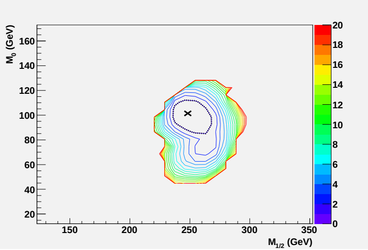
- Further signals to be added (*e.g.* multilepton signals without OSSF-OSDF subtraction)
- Correlations to be investigated
- Information from invariant mass distribution shapes is an intriguing possibility

Results for a fit to SPS1a data at 7 TeV, 1 fb^{-1}, 100% uncertainties

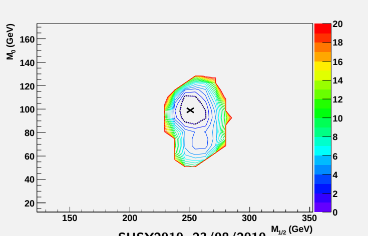
I, ~~rates~~



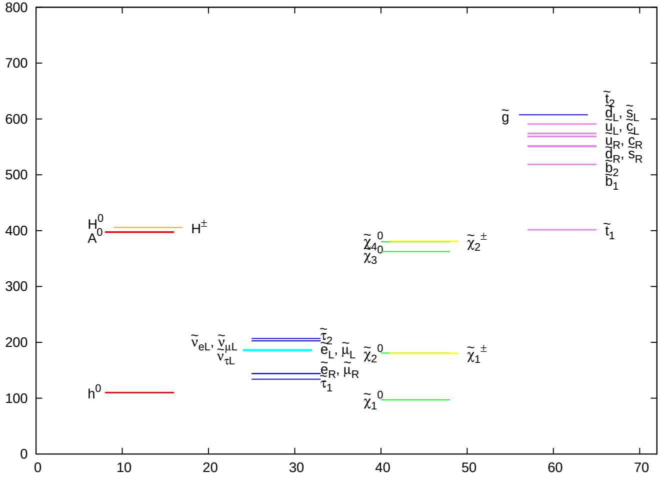
I + rates, 100%



I + rates, 20%



SPS1a spectrum



M_0	100
$M_{1/2}$	250
$\tan\beta$	10
A_0	-100
$\mathrm{sgn}(\mu)$	$+$

SPS1a inputs for 1 fb^{-1} at 7 and 14 TeV

observable	nominal value	statistical uncertainty for 7 TeV/1 fb^{-1}	for 14 TeV/1 fb^{-1}
group I			
$m_{\ell\ell}^{\max}$	80.4	4.4	1.5
$m_{q\ell\ell}^{\max}$	452.1	36.0	12.0
$m_{q\ell}^{\mathrm{low}}$	318.6	19.7	6.5
$m_{q\ell}^{\mathrm{high}}$	396.0	13.5	4.5
group II			
$m_{q\ell\ell}^{\mathrm{thr.}}$	215.6	-	22.8
$m_{T2}^{\tilde{q}}$	531.0	-	16.9
$m_{\tau\tau}^{\max}$	83.4	-	10.8
m_{tb}^{w}	359.5	-	37.0
$r_{\tilde{\ell}\tilde{\tau}\mathrm{BR}}$	0.076	-	0.008

Event rate [fb]	7 TeV		14 TeV	
	nominal value	uncertainty	nominal value	uncertainty
$R_{jj\not{E}_T}$	4.6×10^3	9.1×10^2	4.8×10^4	9.5×10^3
$R_{\ell\ell jj\not{E}_T}$	1.6×10^2	3.2×10^1	1.5×10^3	3.0×10^2

Table of results

	M_0 [GeV]	$M_{1/2}$ [GeV]	$\tan\beta$	A_0 [GeV]
SPS1a	100	250	10	-100
7 TeV and 1 fb^{-1}				
I + rates	$99.0^{+9.9}_{-9.1}$	$250.0^{+8.7}_{-6.5}$	$10.7^{+4.0}_{-8.8}$	55.2^{+1048}_{-254}
14 TeV and 1 fb^{-1}				
I + rates	$99.7^{+4.3}_{-5.7}$	$251.1^{+7.5}_{-5.8}$	$11.2^{+3.5}_{-5.1}$	-50.9^{+1233}_{-350}
I + II, ~~rates~~	$99.8^{+3.3}_{-4.4}$	$249.7^{+6.6}_{-5.2}$	$10.1^{+3.8}_{-3.2}$	-94.1^{+1610}_{-216}
I + II + rates	$99.8^{+3.9}_{-4.2}$	$251.3^{+5.0}_{-5.0}$	$10.7^{+3.1}_{-3.1}$	-55.7^{+263}_{-233}

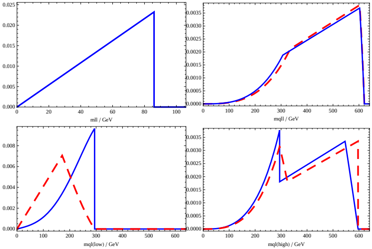
Table of results

	M_0 [GeV]	M_1 [GeV]	M_2 [GeV]	M_3 [GeV]
SPS1a	100	250	250	250
7 TeV				
I + rates	$91.1\ ^{+27.3}_{-36.1}$	$236.5\ ^{+67.1}_{-57.9}$	$242.6^{+51.6}_{-33.7}$	$251.0^{+9.5}_{-8.5}$
14 TeV				
I + rates	$98.5\ ^{+16.5}_{-18.4}$	$245.8\ ^{+55.7}_{-40.7}$	$244.2\ ^{+42.1}_{-19.4}$	$250.3\ ^{+11.1}_{-7.0}$
I + II, ~~rates~~	$102.7\ ^{+9.4}_{-21.4}$	$258.0\ ^{+32.5}_{-51.1}$	$255.4\ ^{+43.6}_{-41.7}$	$251.4\ ^{+9.9}_{-12.2}$
I + II + rates	$98.6\ ^{+12.6}_{-11.2}$	$249.6\ ^{+31.7}_{-24.7}$	$248.7\ ^{+24.9}_{-15.5}$	$252.1\ ^{+6.0}_{-7.1}$

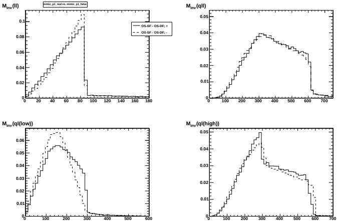
Invariant mass distribution shapes

There is also information in the shape of the distribution [*e.g.* Gjelsten, Miller, Osland (2005, 2006)]...

... *in theory*



... but maybe not so much in practice, such as when jet combinatorics are considered.



Motivation for NLO

- Lot of effort has gone into supersymmetric QCD NLO processes [*e.g.* Beenakker, Höpker, Spira, Zerwas (1996)]
  - necessary to know if signals will be visible
  - may need to know SUSY backgrounds to some processes
  - may learn about sparticle masses
  - limits on sparticle masses if not seen at a collider
- Automated calculation available (*e.g.* Prospino2)

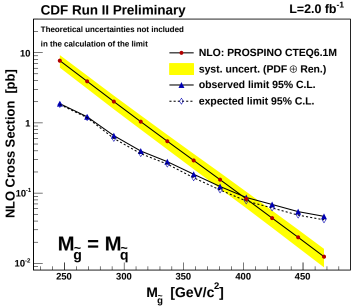


Figure: Sparticle mass exclusion plot, taken from CDF's website

Other implementations

- Cross-section information has been used for SUSY parameter space explorations in the literature
- Lester, Parker, White (hep-ph/0508143):
  - Markov chain exploration with full Monte Carlo simulation of SUSY events at each point
  - Supercomputer ran `ISAJET`, `HERWIG` then `ATLFAST` for LHC
  - restricted to 1000 events simulated per point - at leading order!
  - proof of principle, not intended to be repeated often
- Our implementation is *fast* - $\mathcal{O}(100)$ floating-point operations
- Our aim, in context of `Fittino`, is to improve errors on fit, be reproducible, be flexible