Multi-particle event generators for the MSSM

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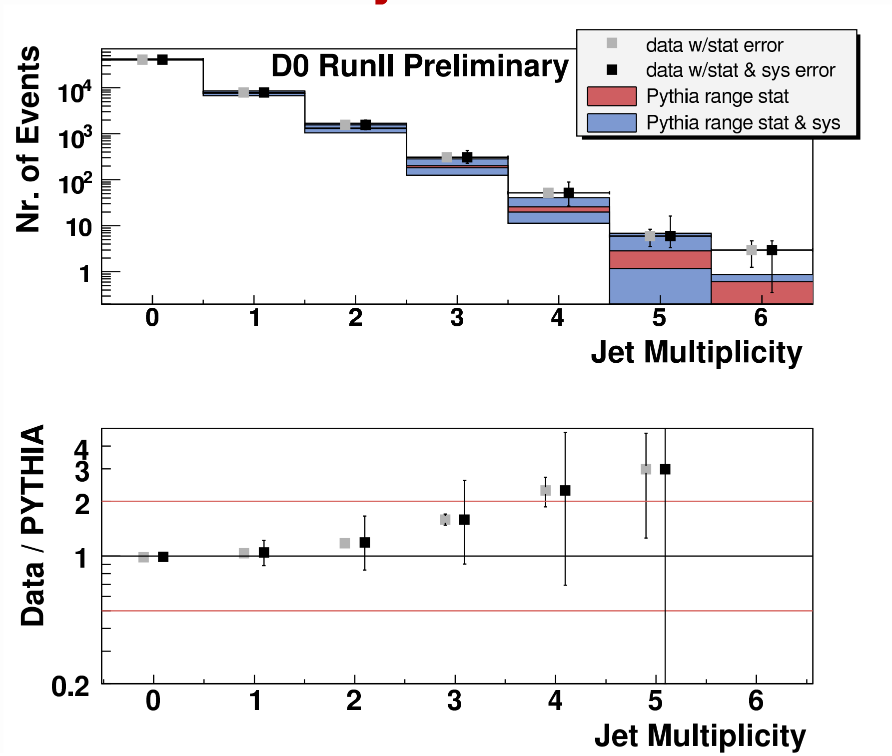
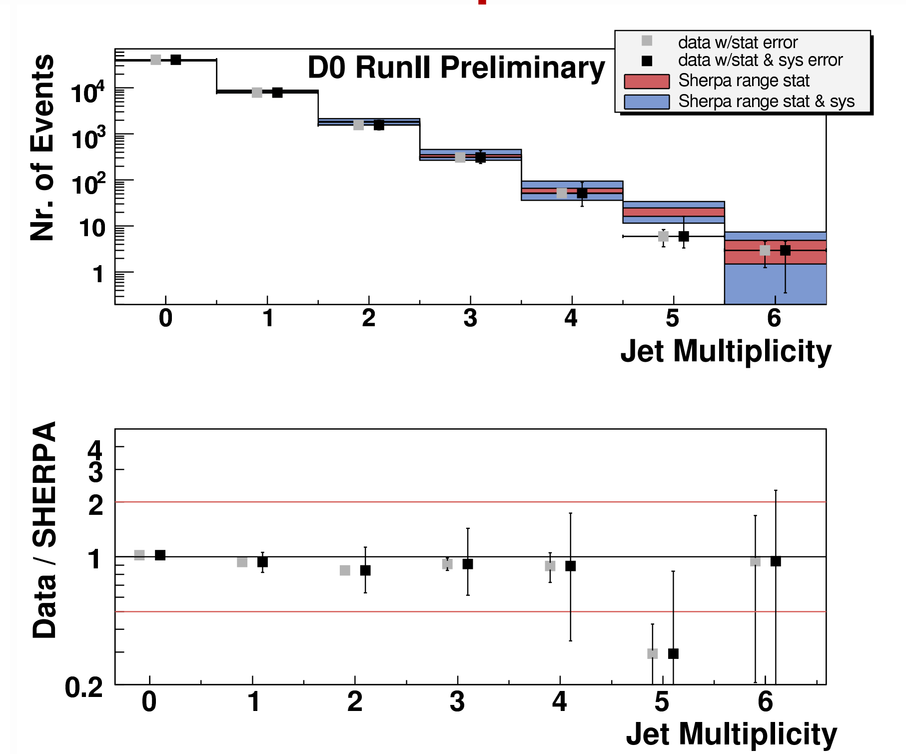
- The need for new event generators
- New matrix element generators for the MSSM
- First applications

The need for new Event Generators

Example: Z+jets @ Tevatron RunII (D0 Note 5066)

Pythia **Sherpa**



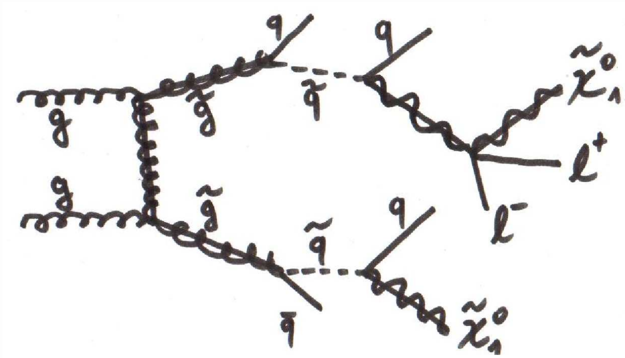


- Extra jets in Pythia originate from the parton showers only
- Sherpa uses tree-level matrix elements combined with the PS ala CKKW

Pythia lacks hard radiation. Sherpa describes the jet multiplicities (spectra, correlations, ...) very well.

The need for new Event Generators

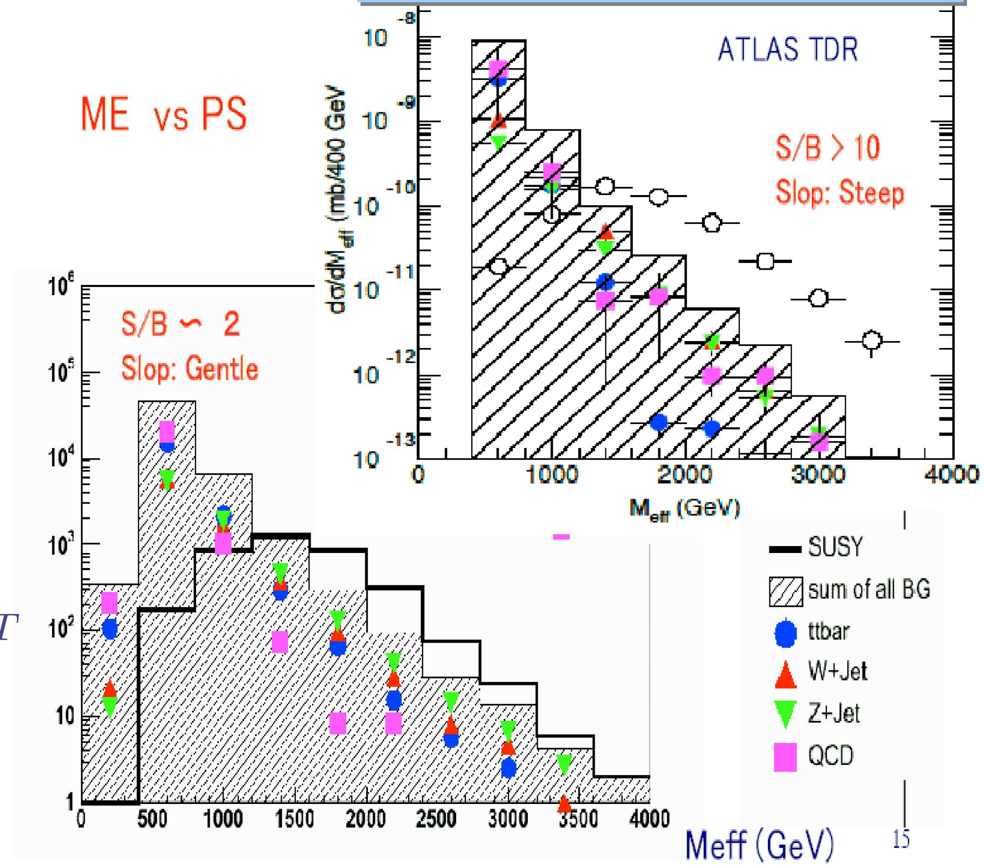
Example: SUSY cascade decays



- Large production cross sections
- Signal: high-$p_\perp$ jets + leptons + $\not{E}_T$
- $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ separated by # of jets
- BG: W/Z+jets, Jets, $t\bar{t}$+jets

ATLAS TDR plot done with pythia

→ only parton shower for extra jets

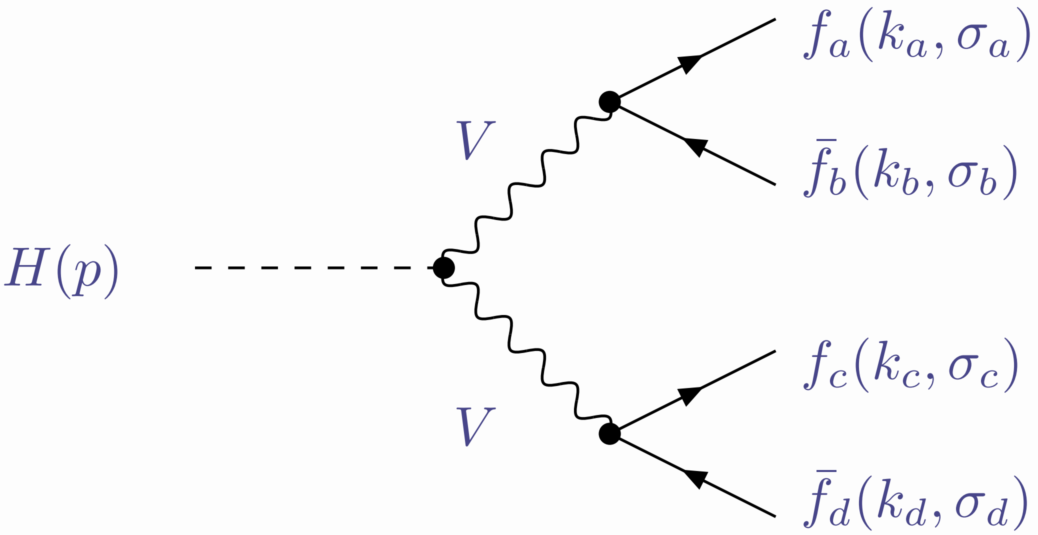


Improved BG description through multi-jet matrix elements merged with parton showers. What about hard extra radiation for the signal?

$\longrightarrow$ T. Plehn, D. Rainwater, P. Skands, hep-ph/0510144

The need for new Event Generators

Example: Off-shell effects in Higgs decays



- Consider M_H below the VV threshold
- $H \to VV$ and subsequent decays $V \to f\bar{f}$ not factorizable
- Have to include off-shell intermediate bosons
- Best we can do is a full matrix element calculation $H \to 4f$

The need for new Event Generators

For the SM and MSSM we need tools that

- provide matrix elements beyond $2 \to 2$ (plus decays)
- include quantum interferences and off-shell effects
- preserve all the information on spins and correlations
- account for hard extra radiation
- provide interfaces to parton showers and hadronization

State of the art for the SM:

➔ **Automatic tree-level matrix element generators**

- Alpgen, MadGraph, O'Mega/Whizard, Grace, Amegic++, ...
- They deliver helicity amplitudes for arbitrary processes up to $2 \to 8$
- Via their phase space integrators they provide parton level events that are passed to the parton showers and hadronization

Matrix Element Generators for the MSSM

- **Three codes have now implemented the full MSSM Lagrangian**
  - **SMadGraph:** K. Hagiwara, T. Plehn, D. Rainwater
  - **O'Mega/Whizard:** W. Kilian, T. Ohl, J. Reuter
  - **Amegic++/Sherpa:** F. Krauss, S.S.
- All codes use a different set of MSSM Feynman rules (notations)
- Independent generation of diagrams and helicity amplitudes
- Three different approaches to integrate the phase space
- All programs calculate arbitrary cross sections and can generate events

Matrix Element Generators for the MSSM

Implementation issues

- We consider the R-parity conserving MSSM without CP violation
- Spectrum taken from SLHA input files (so masses etc governed by external codes)
- Ino mixing parameter taken to be real in SMadGraph and Amegic++/Sherpa but complex in O'Mega/Whizard

  (the former ansatz features negative ino masses in the matrix elements)
- Relative sign of amplitudes including Majorana fermions fixed using a general fermion flow (Denner et al., Nucl. Phys. B **387**, 467 (1992))
- So far SMadGraph & O'Mega/Whizard restricted to left-right mixing for third-generation squarks and sleptons only
- SMadGraph & O'Mega/Whizard provide parton shower interface via LHA
- Amegic++/Sherpa has its own parton showers, underlying event etc.

Validation

Validation of the codes described in

K. Hagiwara, W. Kilian, F. Krauss, T. Ohl, T. Plehn, D. Rainwater, J. Reuter, S.S,
Phys. Rev. D **73**, 055005 (2006)

- To test all SUSY vertices we checked several hundred $2 \to 2$ processes

  Initial states:

  $$e^+e^-,\ e^-\bar{\nu}_e,\ e^-e^-,\ \tau^+\tau^-,\ \tau^-\bar{\nu}_\tau,\ u\bar{u},\ d\bar{d},\ uu,\ dd,\ b\bar{b},\ b\bar{t},$$
  $$W^+W^-,\ W^-Z,\ W^-\gamma,\ ZZ,\ Z\gamma,\ \gamma\gamma,\ gW^-,\ gZ,\ g\gamma,\ gg,\ ug,\ dg$$

  Final states:

  All combinations of SUSY partners or Higgs bosons
- All $VV \to \mathrm{SUSY}$ pairs checked for unitarity
- Results of the comparison listed under
  http://www.sherpa-mc.de/susy_comparison/susy_comparison.html

Validation

Example: Two identical fermions

$\mathrm{ff} \to \mathrm{X}$						
Process	MADGRAPH/HELAS		O'MEGA/WHIZARD		AMEGIC++/SHERPA	
	0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV
$e^- e^- \to \tilde{e}_L \tilde{e}_L$	520.30(4)	36.83(3)	520.31(3)	36.836(2)	520.32(3)	36.832(2)
$e^- e^- \to \tilde{e}_R \tilde{e}_R$	459.6(1)	28.65(3)	459.59(1)	28.650(3)	459.63(3)	28.651(2)
$e^- e^- \to \tilde{e}_L \tilde{e}_R$	160.04(1)	56.55(2)	159.96(2)	56.522(8)	160.04(2)	56.545(3)
$uu \to \tilde{u}_L \tilde{u}_L$	—	716.9(1)	—	716.973(4)	—	716.99(4)
$uu \to \tilde{u}_R \tilde{u}_R$	—	679.6(1)	—	679.627(4)	—	679.54(4)
$uu \to \tilde{u}_L \tilde{u}_R$	—	1212.52(6)	—	1212.52(5)	—	1212.60(6)
$dd \to \tilde{d}_L \tilde{d}_L$	—	712.6(1)	—	712.668(4)	—	712.68(4)
$dd \to \tilde{d}_R \tilde{d}_R$	—	667.4(1)	—	667.448(4)	—	667.38(3)
$dd \to \tilde{d}_L \tilde{d}_R$	—	1206.22(6)	—	1206.22(5)	—	1206.30(7)

➔ Note that in general sQCD and electro-weak contributions occur

First applications

Off-shell effects in sbottom production & decay at LHC

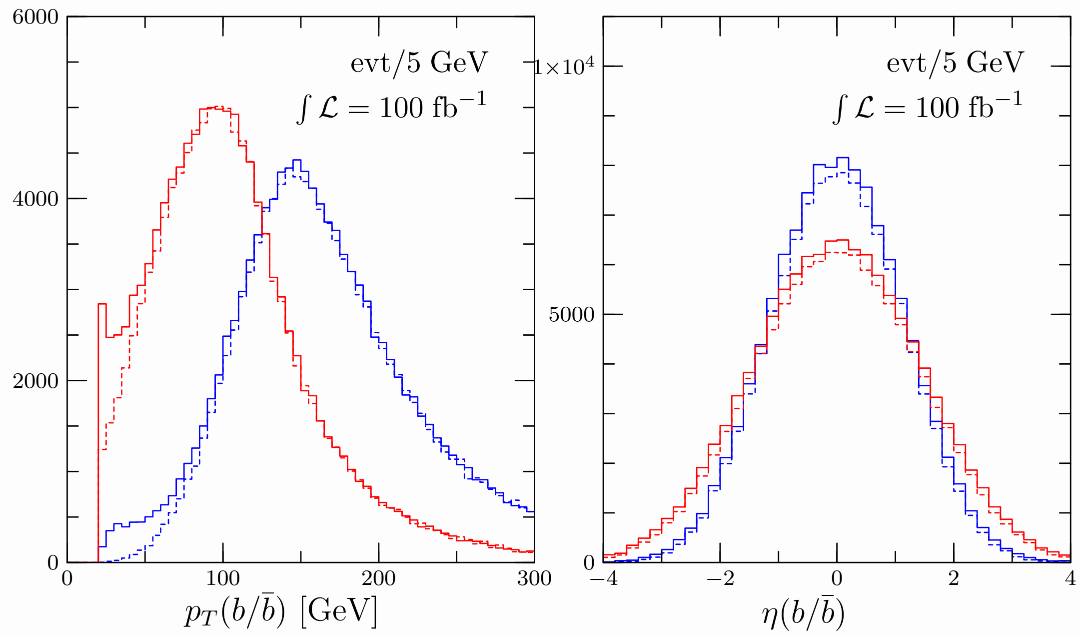
K. Hagiwara et al., Phys. Rev. D **73**, 055005 (2006)

- Consider $\tilde{b}_1$ pair production and the decay $\tilde{b}_1 \to b\tilde{\chi}_1^0$

  ($m_{\tilde{b}_1} = 295.3$ GeV, $\Gamma_{\tilde{b}_1} = 0.53$ GeV, $m_{\tilde{\chi}_1^0} = 46.8$ GeV)

- Compare Breit-Wigner approximation $gg \to \tilde{b}_1\tilde{b}_1^* \to b\bar{b}\chi_1^0\chi_1^0$ (dashed)

  with the full set of diagrams for $gg \to b\bar{b}\chi_1^0\chi_1^0$ (solid)



- Off-shell effects sizable in the low $p_{T,b}$ region $\to$ can be cut out here

First applications

sbottom production & decay at the ILC

K. Hagiwara et al., Phys. Rev. D **73**, 055005 (2006)

- Consider $e^+e^- \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ @ $\sqrt{s} = 800$ GeV
- Apply cuts on $M_{b\bar{b}}$ to remove resonances

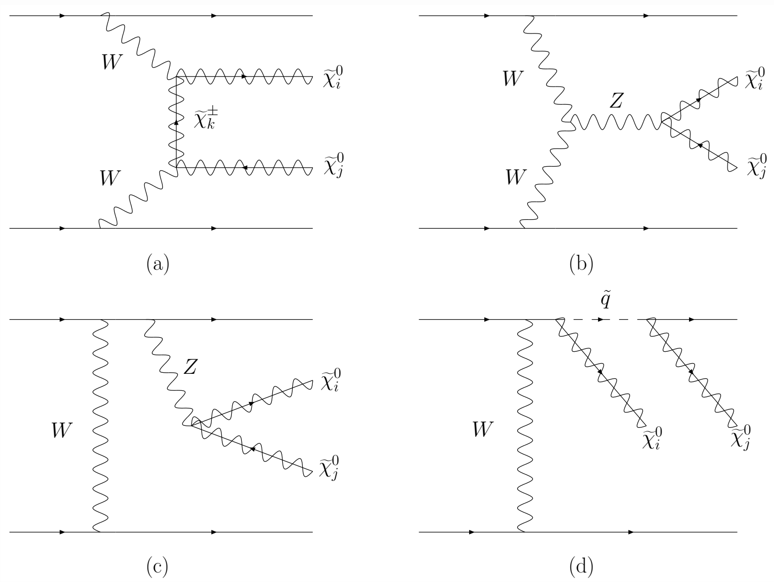
Channel	$\sigma_{2\to2}$ [fb]	$\sigma \times \mathrm{BR}$ [fb]	σ_{BW} [fb]	$\sigma_{\mathrm{BW}}^{\mathrm{cut}}$ [fb]
Zh	20.574	1.342	1.335	0.009
ZH	0.003	0.000	0.000	0.000
hA	0.002	0.001	0.000	0.000
HA	5.653	0.320	0.314	0.003
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	69.109	13.078	13.954	0.458
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	24.268	3.675	4.828	0.454
$\tilde{\chi}_1^0\tilde{\chi}_4^0$	19.337	0.061	0.938	0.937
$\tilde{b}_1\tilde{b}_1$	4.209	0.759	0.757	0.451
$\tilde{b}_1\tilde{b}_2$	0.057	0.002	0.002	0.001
Sum		**19.238**	**22.129**	**2.314**
Exact			**19.624**	**0.487**

First applications

SUSY pairs in WBF at LHC using SMadGraph

G. C. Cho et al., Phys. Rev. D **73**, 054002 (2006)

- Weak boson fusion production of weakly interacting particles, e.g. $\chi_i^0\chi_j^0$, $\chi_i^0\chi_j^\pm$, $\chi_i^+\chi_j^-$, $\chi_i^\pm\chi_j^\pm$, $\tilde{l}^\pm\tilde{\nu}$, $\tilde{l}^+\tilde{l}^-$



- Expect small QCD backgrounds due to colour singlet exchange
- For the SPS benchmark scenarios studied rates are rather tiny
- There are few exceptions like same sign chargino production

Summary and Outlook

- **There are new tools for matrix element calculations in the MSSM**

  SMadGraph, O'Mega/Whizard, Amegic++/Sherpa

- **They allow to study new aspects of SUSY phenomenology**
  - production processes beyond $2 \rightarrow 2$
  - appropriate description of extra hard jets
  - systematic inclusion of off-shell effects
  - incorporation of non-resonant contributions and interferences

    ➔ we can check the validity of some common approximations

- **They are easy to extend**
  - O'Mega/Whizard has little Higgs, plans to include NMSSM, ED, ...
  - Amegic++/Sherpa: has ADD model included, bilinear RPV and gravitinos currently being implemented, plans to include UED, ...

- **Sources**
  - SMadGraph: `www.ph.ed.ac.uk/~tplehn/smadgraph/smadgraph.html`
  - O'Mega/Whizard: `http://www-ttp.physik.uni-karlsruhe.de/whizard`
  - Amegic++/Sherpa: `http://www.sherpa-mc.de`