Event Generation of SM and SUSY Processes at LCs using Isajet v7.69

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Isajet overview

- Isajet the first of multi-purpose event generators to appear
- Created by Frank Paige and Serban Protopopescu in 1979 to model jet activity expected at the ill-fated BNL Isabelle pp collider
- Original algorithm contained:
  - Hard scattering processes (perturbative QCD)
  - Fox-Wolfram algorithm for final state parton showers
  - Field-Feynman independent hadronization (IH) algorithm
- Isabelle project terminated, but Isajet used for many analyses at CERN $\sqrt{s_{pp}}$ collider: UA1 and UA2
- Jetset/Pythia (Sjöstrand) programs appear circa 1983; string hadronization (SH) model gives correlated $q\bar{q}$ hadronization
- SH and IH models agree well over most of phase space for $e^+e^-$ two jet events, but SH model predicts a depletion of hadronic acxtivity in region between hard jets (verified): result of color flow
- 1983: Sjöstrand develops backward shower algorithm to treat initial state QCD radiation for hadron colliders; incorporated into Isajet as well
- 1985: Marchesini and Webber release Herwig algorithm; angle-ordered parton showers account for some interference effects in multiple gluon emission; Herwig uses a cluster
hadronization model (CH) which accounts for color flow as does SH model; CH model clusters partons that are nearby in phase space into hadrons, thereby eliminating non-local effects that arise in SH model

- all programs include most important $2 \rightarrow 2$ SM hard scattering processes for $e^+e^-$, $pp$ and $p\bar{p}$ colliders; degree of sophistication in modeling varies.

- The challenge of past 20 years is to merge PS algorithm with NLO QCD calculations; several attempts every year, so none appear overwhelmingly compelling (see e.g. Sjóstrand; HB/Reno; Soper; Collins; Webber; Mrenna; ⋯)
SUSY in Isajet

• 1984: primitive SUSY production processes plus one-step decays in Isajet used for UA1 and UA2 analyses
• 1989: HB and X. Tata develop SUSYSM program: parton level sparticle production with cascade decays
• 1990: interface with Pythia for SH model
• 1991: Jim Freeman (CDF) was entire SUSY group at FNAL; rough patch of SUSYSM into Isajet
• 1992: F. Paige and HB incorporate sparticle production and cascade decays into isajet 7.00; release 1993
• 1994 Colorado: $e^+e^- \rightarrow SUSY$ into Isajet while on honeymoon; add $WW$, $ZZ$ and $ZH$ production; Isasugra SUSY RGE solution incorporated into Isajet;
• 1995: Susygen (Katsanevas)
• 1996: Spythia (Mrenna)
• 1996: polarized beams into isajet
• 1997: brem/beamstrahlung into isajet with help from M. Drees; large $\tan \beta$ SUSY event generation; treatment of $\tau$ helicity states
• 1998: 3-body decay MEs
• 1998: Suspect spectrum calculator
• 2001: SoftSUSY spectrum calculator
• 2002: SUSY in Herwig using Isajet decay table (Isawig)
• 2003: Spheno spectrum and decay calculator
• 2003: full one loop sparticle mass formulae in Isajet
• 2003: Les Houches accord (Skands et al.) to allow various spectra calculators interface with event generators
SM processes versus beam polarization

- **$EPO{L}$** keyword stipulates $e^-$ and $e^+$ polarization
- $P_L(e^-) = (n_L - n_R)/(n_L + n_R)$
Models for SUSY in Isajet (all are MFV models)

- MSSM (weak scale inputs; no RGE solution)
  - MSSMA: $m_g$, $\mu$, $m_A$, $\tan \beta$
  - MSSMB: $m_{Q_1}$, $m_{D_1}$, $m_{U_1}$, $m_{L_1}$, $m_{E_1}$ (1st gen.)
  - MSSMC: $m_{Q_3}$, $m_{D_3}$, $m_{U_3}$, $m_{L_3}$, $m_{E_3}$, $A_t$, $A_b$, $A_{\tau}$ (3rd gen.)
  - MSSMD: $m_{Q_2}$, $m_{D_2}$, $m_{U_2}$, $m_{L_2}$, $m_{E_2}$ (2nd gen. optional)
  - MSSME: $M_1$, $M_2$ (independent gaugino masses; optional)

- mSUGRA model (invokes RGE running solution)
  - $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$

- SUGRA (non-universal soft terms)
  - NUSUG1: $M_1$, $M_2$, $M_3$
  - NUSUG2: $A_t$, $A_b$, $A_{\tau}$
  - NUSUG3: $m_{H_d}$, $m_{H_u}$
  - NUSUG4: $m_{Q_1}$, $m_{D_1}$, $m_{U_1}$, $m_{L_1}$, $m_{E_1}$ (1st/2nd gen.)
  - NUSUG5: $m_{Q_3}$, $m_{D_3}$, $m_{U_3}$, $m_{L_3}$, $m_{E_3}$ (3rd gen.)

- GMSB
  - $\Lambda$, $M$, $n_5$, $\tan \beta$, $\text{sign}(\mu)$, $C_{grav}$
  - $R$, $\delta m^2_{H_d}$, $\delta m^2_{H_u}$, $D_Y(M)$, $n_{51}$, $n_{52}$, $n_{53}$

- AMSB
  - $m_0$, $m_{3/2}$, $\tan \beta$, $\text{sign}(\mu)$
• SUGRHN
  \[ m_{\nu R}, \ M_N, \ A_{\nu}, \ m_{\tilde{\nu}_R} \]
• SSBCSC (select BC scale other than \( M_{GUT} \))
lsajet RGE solution (bottom-up approach)

- Begin with $\overline{DR}$ gauge and Yukawa couplings at $Q = M_Z$
- Evolve up in $E$ to where $g_1 = g_2$ (defines $M_{GUT}$)
- Impose soft SUSY breaking masses at $M_{GUT}$ and evolve down
- Calculate spectrum at $Q = M_{weak}$ using RG improved 1-loop eff. pot. evaluated at optimized scale choice (accounts for leading 2-loop terms)
- sparticle masses at 1-loop
- Evolve back up, this time include Yukawa threshold corrections at scale $Q = \sqrt{m_{iL} m_{iR}}$
- Iterate process until convergent solution is achieved
- Usually good agreement between lsajet, Suspect, SoftSUSY, Spheno (Kraml et al. study)
Isajet RGE solution for sparticle masses

- Isasugra soft term evolution

\[ m_0 = 100 \text{ GeV} \]
\[ m_{1/2} = 200 \text{ GeV} \]
\[ A_0 = 0; \tan \beta = 4; \mu > 0 \]
Isajet RGE solution for Yukawa couplings

- Note MSSM-SM threshold corrections at $Q = \sqrt{m_{t_L} m_{t_R}}$
SUSY processes versus beam polarization

- Case study from BMT: PRD54, 6735 (1996)

\[ \sqrt{s} = 500 \text{ GeV} \]
\[ m_0 = 150 \text{ GeV}, \ m_{1/2} = 170 \text{ GeV} \]
\[ A_0 = 0, \ \tan \beta = 5, \ \mu > 0 \]
Decays in Isajet

- Implement full set of sparticle cascade decays; valid at large $\tan \beta$ (not true for e.g. Pythia)
- Spin correlation: production/decay neglected
- 3-body decays include exact matrix elements for $E$ dependence
- $\tau$ decays: Isajet calculates rate to $\tau_L$ and $\tau_R$; decays them appropriately
SUSY event for LC

- Isajet $e^+e^- \rightarrow SUSY$ event from Norman Graf for LC
**Brem/beamstrahlung convolution**

- **Bremsstrahlung**: Fadin-Kurayev distribution
- **Beamstrahlung**: P. Chen encoded by M. Drees and HB
- **Convolution**: 
  \[ D_e(x) = \int_x^1 dz D_e^{brem}\left(\frac{x}{z}, Q^2\right) D_e^{beam}(z)/z \]
$e^+e^- \rightarrow \mu^+\mu^-$ including brem/beamstrahlung

- Note $\gamma$ and $Z$ peaks

\[ d\sigma/dQ \ (fb/GeV) \]

- $e^+e^- \rightarrow \mu^+\mu^-$
- $\sqrt{s}=500 \text{ GeV}$
- beam/brem effect
- $\Upsilon=.1072; \ \sigma_z=.12 \text{ mm}$
Future and conclusions

• need $\gamma\gamma \rightarrow SM$ processes included

• Isajet allows for production of a variety of SM and SUSY processes including beam polarization, brem/beamstrahlung, decay MEs, $|\tau u_L/\tau R|$-decays, ... 

• any future improvements usually depend on whether any one wants them implemented...