Event Generators for SUSY

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SUSY at TeV scale is well motivated extension of Standard Model. Included in several parton shower Monte Carlos:

- ISAJET 7.44 (incorporates ISASUSY)
- PYTHIA 6.1 (incorporates SPYTHIA)
- HERWIG 6.1 (links with ISAJET)

Need Monte Carlo approach both for SUSY decays and showering/hadronization.

Will discuss SUSY physics basis of all three:

- Minimal Supersymmetric Standard Model.
- Minimal SUGRA and GMSB models.
- Non-minimal extensions.
- SUGRA with $\tan\beta \gg 1$.
- Matrix elements in decays.

MSSM

Starting point is Minimal Supersymmetric Standard Model (MSSM) with minimal particle content:

- Each chiral $f_{L,R} \Leftrightarrow$ scalar $\tilde{f}_{L,R}$.
- Each gauge boson $\Leftrightarrow$ spin-1/2 gaugino.
- Two Higgs doublets $\Leftrightarrow$ spin-1/2 Higgsinos.

General MSSM allows proton decay. Must impose symmetry under

$$R = (\Leftrightarrow 1)^{3(B-L)+2S}$$

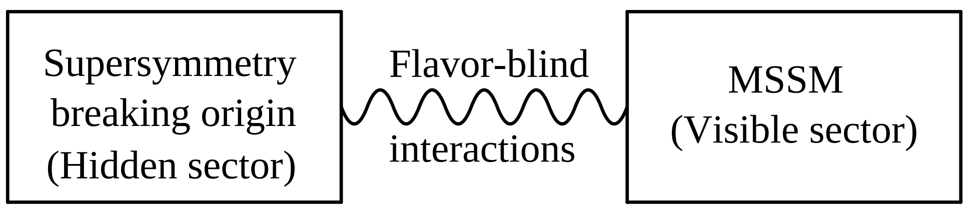
or B or L. If R conserved, SUSY particles produced in pairs and lightest (LSP) is stable.

R-violating couplings are Higgs-like. Some but not all must be small [Dreiner]. If small, can just decay LSP: $\tilde{\chi}_1^0 \to qqq$, $\tilde{\chi}_1^0 \to \ell^+\ell^-\nu$, $\tilde{\chi}_1^0 \to q\bar{q}\ell$. Only HERWIG includes R violating cascade decays.

SUSY must be broken $\Rightarrow$ model dependence.

Can add gauge-invariant masses for SUSY particles by hand — but 105 new parameters.

Breaking within MSSM fails. Assume SUSY broken in hidden sector at mass^2 F, coupled to MSSM at M:



Then $M_{\rm MSSM} \sim F/M$. Two limiting cases:

SUGRA: communicate via gravity at Planck scale $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}\,{\rm GeV}$, so $F \sim 10^{11}\,{\rm GeV}$.

GMSB: communicate via Standard Model gauge interactions at $M \ll M_P$ and $F \ll 10^{11}\,{\rm GeV}$.

Gravitino $\tilde{G}$ always gets mass via gravity.

SUGRA: $\tilde{G}$ is heavy and irrelevant.

GMSB: $\tilde{G}$ is light ($M_{\tilde{G}} \ll 1\,{\rm GeV}$). Couplings enhanced by $1/m_{\tilde{G}}$, so can be relevant.

After EWSB, gauginos and Higgsinos mix to give four neutralinos $\tilde\chi_i^0$ and two charginos $\tilde\chi_i^\pm$.

$\tilde\chi_1^0$, $\tilde\chi_2^0$, $\tilde\chi_1^\pm$ usually gauginos, with

$$M_{\tilde\chi_1^0} \approx \frac{1}{2} M_{\tilde\chi_2^0} \approx \frac{1}{2} M_{\tilde\chi_1^\pm} \approx \frac{1}{6} M_{\tilde g}$$

$\tilde\chi_3^0$, $\tilde\chi_4^0$, and $\tilde\chi_2^\pm$ are Higgsinos and heavy.

Third generation sfermions mix: $\tilde t_L, \tilde t_R \to \tilde t_1, \tilde t_2$.

Squarks and gluinos generally have similar masses.

$\tilde t_1$ is generally lightest squark.

Physical Higgs spectrum is $h, H, A, H^\pm$.

$M_h \lesssim 130\,\text{GeV}$ for MSSM.

Generally $M_A \gg M_Z$ in SUGRA. Then h has Standard Model couplings.

MSSM might be wrong even if SUSY is right.

Random choice of 105 MSSM parameters violates low-energy bounds on FCNC, CP, ...

Ansatz: ignore all phases and flavor mixings. Gives ISAJET MSSMi parameter set:

$M_{\tilde{g}}$, μ, M_A, $\tan\beta$

M_{Q_1}, M_{d_R}, M_{u_R}, M_{L_1}, M_{e_R}

M_{Q_3}, M_{b_R}, M_{t_R}, M_{L_3}, M_{τ_R}, A_t, A_b, A_τ

M_{Q_2}, M_{s_R}, M_{c_R}, M_{L_2}, M_{μ_R}

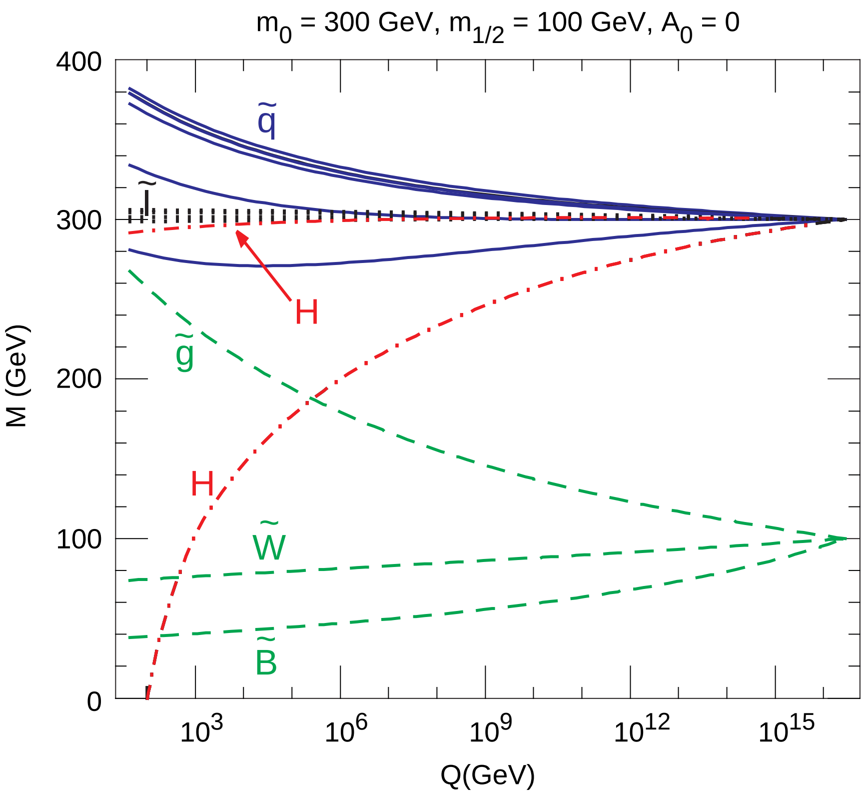
M_1, M_2

Can also turn on gravitino decays.

Pragmatic MSSM model. Plausible starting point, but has no good theoretical or phenomenological justification.

SUGRA and GMSB Models

Minimal SUGRA assumes universal masses at GUT scale from gravity. Large $y_t \Rightarrow$ RGE's drive Higgs mass driven negative, giving EWSB [Ibanez, Ross]:



Replace GUT-scale B, μ^2 with weak-scale M_Z^2, $\tan\beta$. Final parameters after EWSB:

$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta = \frac{v_u}{v_d}, \quad \operatorname{sgn}\mu = \pm 1$$

Alternative is GMSB: messenger sector contains N_5 $SU(5)$ $5+\bar{5}$ multiplets. SUSY breaking communicated by gauge interactions.

Gaugino masses $\propto \alpha\Lambda N_5$.

Scalar squared mases $\propto \alpha^2\Lambda^2 N_5$

Generation-independent masses $\Rightarrow$ no FCNC.

SUGRA/GMSB status for generators:

- All can input weak scale masses.
- PYTHIA has analytic approximation for SUGRA.
- ISAJET (HERWIG) has RGE numerical solution.

RGE solution also allows non-minimal models. ISAJET assumes no CP-violating phases or flavor mixings. Extra SUGRA parameters:

$$M_1, M_2, M_3, \quad A_t, A_b, A_\tau, \quad M_{H_d}, M_{H_u}$$

$$M_{u_L}, M_{d_R}, M_{u_R}, M_{e_L}, M_{e_R}$$

$$M_{t_L}, M_{b_R}, M_{t_R}, M_{\tau_L}, M_{\tau_R}$$

Also a few extra GMSB parameters:

- $R\!\!\!/$, extra factor for gaugino masses.
- $\delta M^2_{H_d}$, $\delta M^2_{H_u}$, Higgs mass-squared shifts.
- $D_Y(M)$, extra D-term $\propto Y$.
- N_{5_1}, N_{5_2}, and N_{5_3}, independent messengers.

LHC can tightly constrain minimal parameters.

Only limited study of non-minimal SUGRA. Extra parameters may be harder to constrain.

Initial NLC should study all 12 lightest SUSY particles:

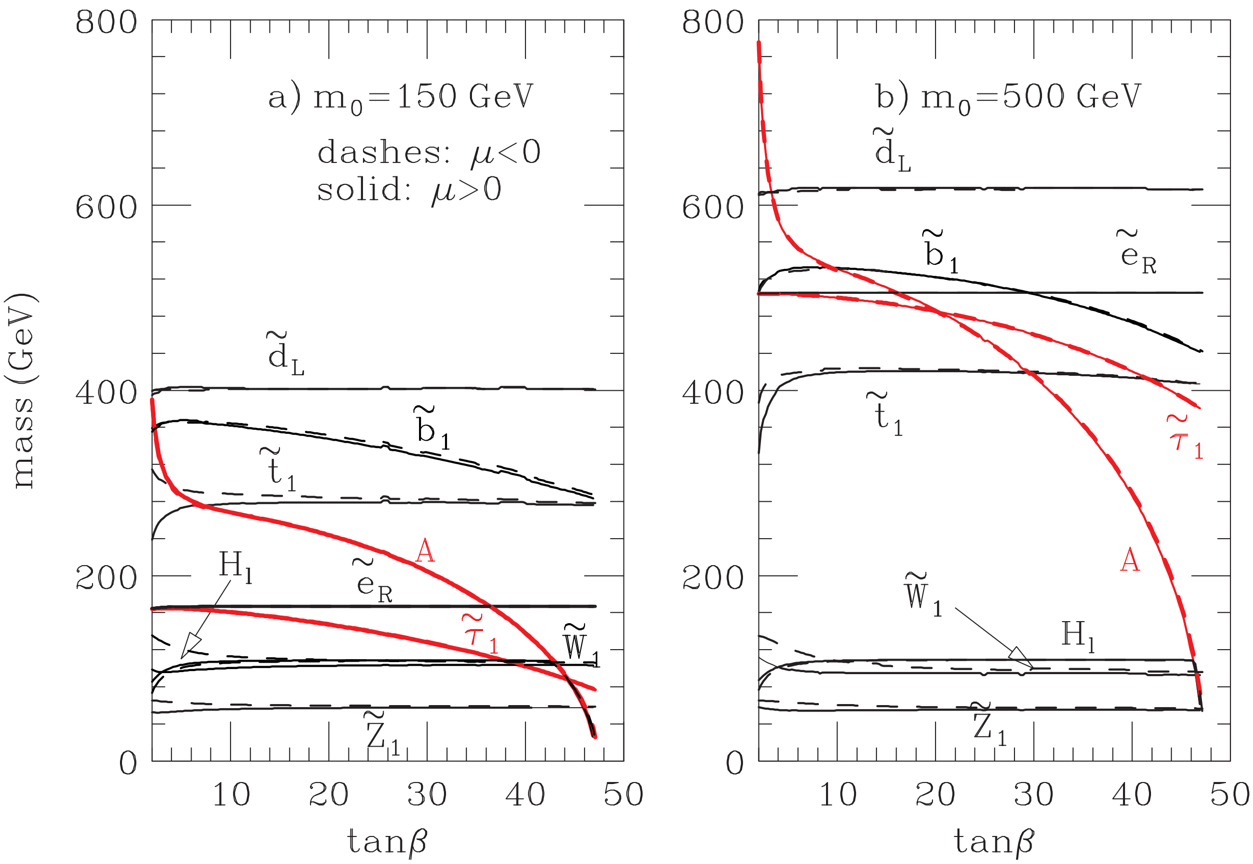
- Gauginos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$.
- Sleptons: $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_1$, $\tilde{e}_L$, $\tilde{\mu}_L$, $\tilde{\tau}_2$
- Sneutrinos: $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$.

SUGRA with $\tan\beta \gg 1$

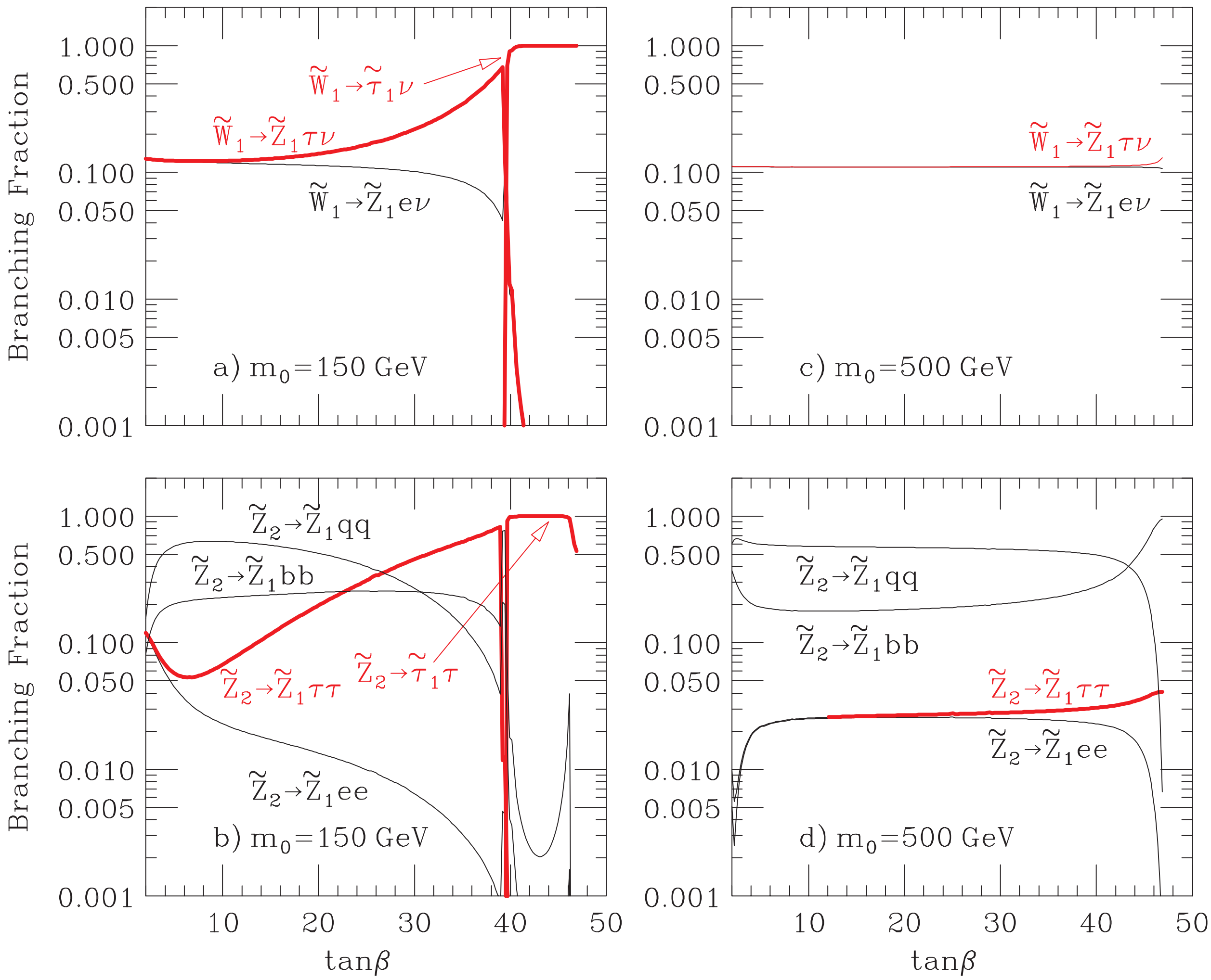
$\tan\beta \gg 1$ favored by $b \Leftrightarrow \tau$ unification + LEP Higgs bound. Implies effects in $g_\mu \Leftrightarrow 2$, etc.

Many effects like $\tilde{b}_L \Leftrightarrow \tilde{b}_R$ and $\tilde{\tau}_L \Leftrightarrow \tilde{\tau}_R$ mixing important. Properly included in ISAJET $\geq$ 7.32.

Most important effect is on masses:



For $m_0 \sim m_{1/2}$, only 2-body modes may be $\tilde\chi_2^0 \to \tilde\tau_1^\pm \tau^\mp$ and $\tilde\chi_1^\pm \to \tilde\tau^\pm \nu_\tau$ for $\tan\beta \gg 1$. Branching ratios $> 99\%$:



If $\tan\beta \gg 1$ and $\tilde\chi_2^0 \not\to \tilde\chi_1^0 Z, \tilde\chi_1^0 h$, should see effect in $g_\mu \Leftrightarrow 2$ at BNL.

Measurements of τ's could be critical at NLC.

Probably easier than at LHC.

Important to study best strategy.

ATLAS study uses hadronic decays combining:

- Tracking for charged hadrons;
- EM calorimetry for photons.

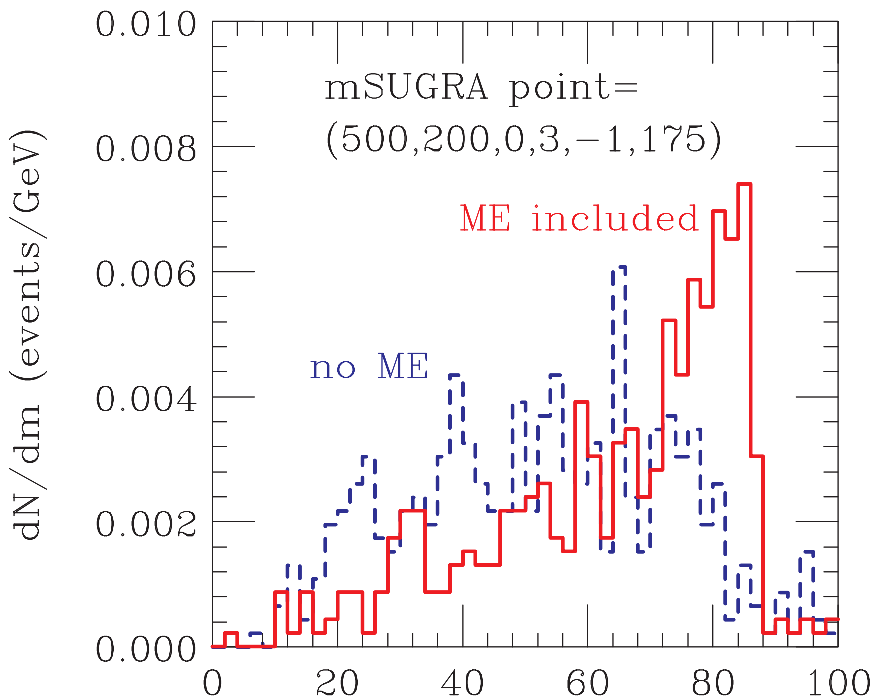
CMS study compares $e^+e^- + \mu^+\mu^-$ and $e^\pm\mu^\mp$.

Possible implications for vertex detector, EMCAL segmentation, and/or HCAL resolution.

Matrix Elements

Three-body decays often important for SUSY. Many matrix elements ⇒ generators have used phase space.

ISAJET 7.44 incorporates 3-body matrix elements. Can be very important. Example for dilepton mass for trilepton signal at Tevatron:



C.f. Nogiri and Yamada, hep-ph/9902201.

Concentrate on $\widetilde{A} \to \widetilde{B} f \bar{f}$. Had already calculated most general case:

- Scalars in $\widetilde{B} f$ and $\widetilde{B} \bar{f}$ channel.
- Vectors and scalars in $f \bar{f}$ channel.

Can express matrix element as sum of these poles.

Strategy is to save mass plus initial and final 1 and γ_5 couplings for each pole. Data structure:

```
+KEEP,DKYSS3
C
C          Data for SUSY 3-body matrix elements. There is a double
C          pointer structure, first to modes, and then to poles that
C          make up the matrix element for that mode:
C          MELEM=-I in /DKYTAB/ points to the mode information:
C            J1SS3(I) = start of pole list for this mode
C            J2SS3(I) = end of pole list for this mode
C            WTSS3(I) = maximum weight for this mode
C          J1SS3<J<J2SS3 points to the corresponding poles:
C            KSS3(J)    = pole type
C            AMSS3(J)   = pole mass
C            ZISS3(2,J) = initial couplings
C            ZFSS3(2,J) = final couplings
C          For gaugino -> gaugino f fbar, the pole types are
C            KSS3=1: spin-1 pole in f-fbar channel
C            KSS3=2: spin-0 pole in gaugino-f channel
C            KSS3=3: spin-0 pole in gaugino-fbar channel
C            KSS3=4: spin-0 pole in f-fbar channel
C          The two couplings are the coefficients of 1,gamma_5 or of
C          gamma_mu,gamma_mu*gamma_5.
C
      INTEGER MXMSS3,MXPSS3
      PARAMETER (MXMSS3=1000)
      PARAMETER (MXPSS3=2000)
      COMMON/DKYSS3/NMSS3,NPSS3,
     $J1SS3(MXMSS3),J2SS3(MXMSS3),WTSS3(MXMSS3),
     $KSS3(MXPSS3),AMSS3(MXPSS3),ZISS3(2,MXPSS3),ZFSS3(2,MXPSS3)
      INTEGER NMSS3,NPSS3,KSS3,J1SS3,J2SS3
      REAL WTSS3,AMSS3
      COMPLEX ZISS3,ZFSS3
```

Use with generic matrix element inside generator:

- First decay: sample phase space to find maximum matrix element.
- Subsequent decays: use standard rejection algorithm and update maximum.

Spin correlations are not incorporated.

Probably less important in general.

ISAJET does include τ polarization effects for $\ell\nu\bar{\nu}$, $\pi\nu$, $\rho\nu$, and $a_1\nu$ in ad hoc fashion. No attempt to propagate spin information to τ decay products.

Can be important: $P = -1$ for $W \to \tau\nu$ but $P = +1$ for $H \to \tau\nu$.

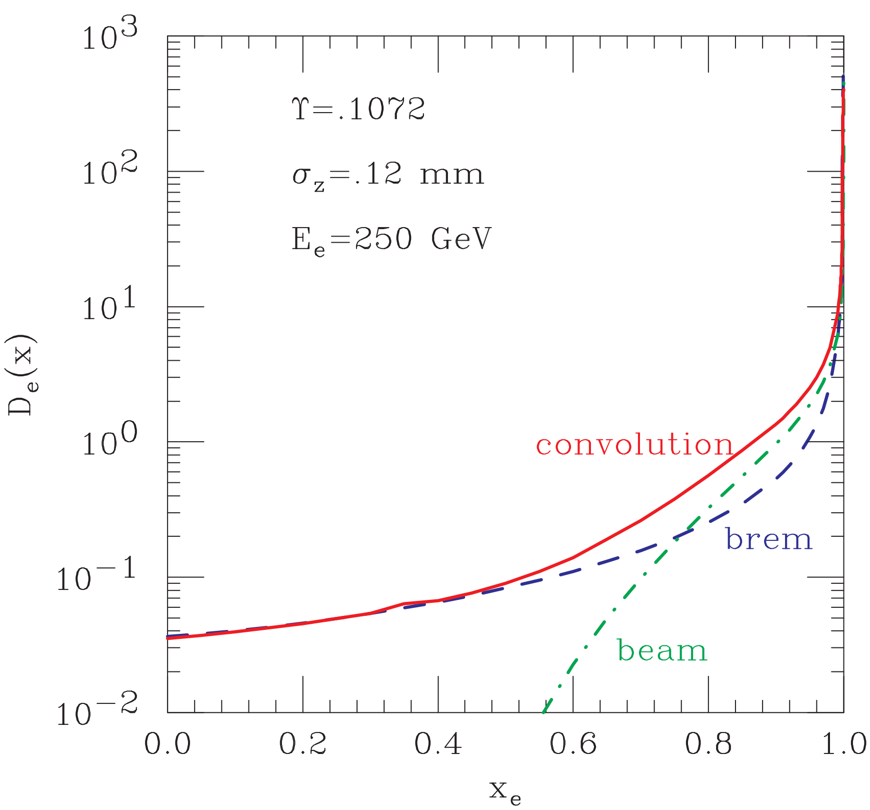
ISAJET Bremsstrahlung/Beamstrahlung

Included in Version 7.44.

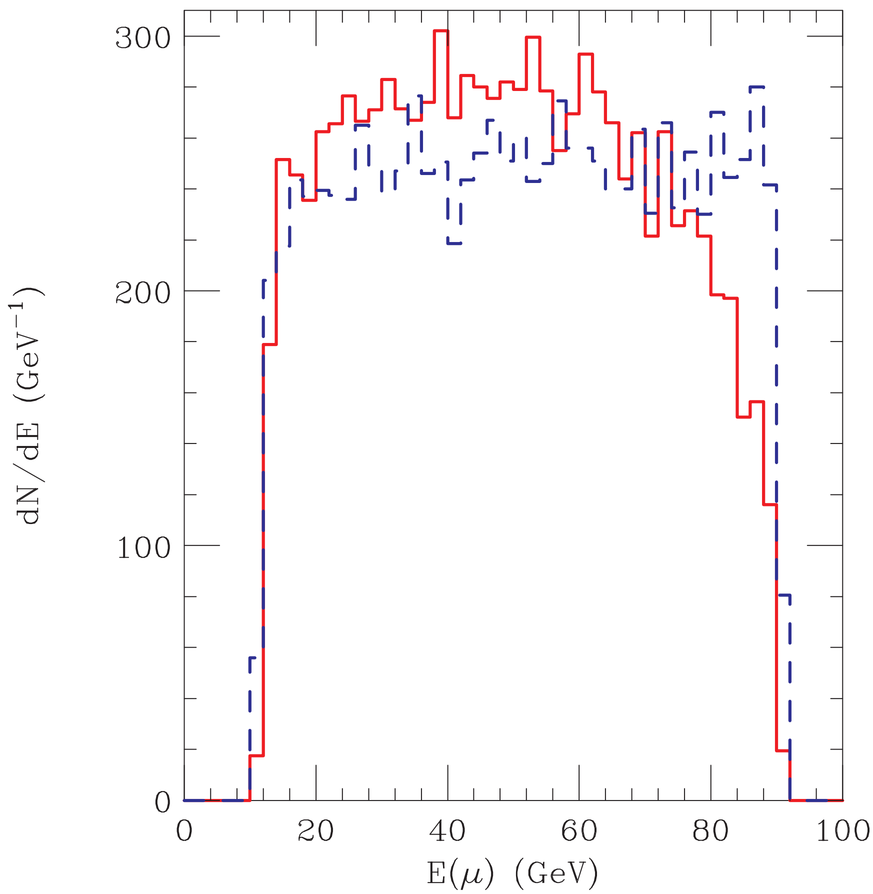
Bremsstrahlung uses Fadin-Kuraev e^- distribution function. Specify $\sqrt{s}_{\text{min}}$ and $\sqrt{s}_{\text{max}}$ with `EEBREM`.

Beamstrahlung also implemented [Chen, Barklow and Peskin]. Specify Υ and σ_z with `EEBEAM`.

Resulting convolution:



Important effects on visible endpoint distributions, e.g., for $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$:



ISAJET C++ Interface

Interface exists to convert ISAJET output to C++. Two main classes:

- MCparticle: particle 4-vector with pointers to

  ⇔ parent vertex

  ⇔ daughter vertex

  ⇔ particle type

- MCvtx: vertex 4-vector with lists of pointers to

  ⇔ parent particle

  ⇔ daughter particles

- Event is linked chain of these classes.

Code and more information on usage and additional classes is available from

http://ox3.phy.bnl.gov/ serban/mcpp/index.html