Supersymmetry at the Tevatron

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- SUSY Les Houches accord
- Prospino2: NLO cross section normalization
- Smadgraph: jet radiation, distributions
- Model of the year: Split Susy
- Amateur’s view of SUSY-B physics
Bright side

- original motivation — Higgs mass stable
- R parity — stable proton yields dark matter
- unification — 3 running couplings meet
- radiative symmetry breaking — 2 Higgs doublets
- local supersymmetry – including gravity?
- rich collider phenomenology

Dark side

- unknown SUSY breaking
  - masses, scalar couplings, phases...
  - hierarchical spectrum
    - [Split SUSY]
- flavor physics and SUSY breaking
  - CKM and lepton flavor?
- 2 Higgs doublet model
  - \( \mu \) parameter and SUSY breaking?

\[ \text{as many analyses as possible} \quad \text{[never believe us theorists when we claim we know better]} \]
Problem: Supersymmetric parameter conventions

- link between specialized codes  [remember: comparison CompHEP–Pythia–ISAJET]
- implementation of benchmark points  [e.g. SPS1a]
  - soft breaking parameters  [e.g. $\pm A_t$]
  - scale dependence of couplings, masses  [e.g. $m(q = \text{TeV}, v, m_t)$?]
  - definitions of mass matrixes, mixing angles  [e.g. $\tilde{t}_{L,R}$ up or down?]

SUSY Les Houches Accord  [P. Skands et al.]

- spectrum generators: SoftSusy, Spheno, FeynHiggs,...
- multi-purpose Monte Carlos: Pythia, Herwig, Sherpa
- matrix element generators: Whizard, Smadgraph
- NLO cross sections: Prospino2
- NLO decay rates: Sdecay
- MSSM parameter extraction: Fitutto, Sfitter
- dark matter calculators: Micromegas
⇒ fixed parameter convention and read-write format
Beyond Pythia/Herwig  [unnamed friend: ‘We only do shapes’]

– MCFM: parton level NLO integrator     [Standard Model; Campbell & K. Ellis]
– MC@NLO: matching of NLO and Monte Carlo   [Standard Model; Frixione & Webber]
– Prospino2: NLO total cross sections for SUSY    [normalization of Pythia/Herwig/Sherpa]
– Smadgraph/Smadevent: SUSY matrix element generator   [hard jet radiation, many legs]

Hadron colliders and theory errors

– renormalization scale from $\alpha_s, y_b, t$
– factorization scale from pdfs
    [scale dependence minimum error]
– perturbative series $N_c\alpha_s/\pi \sim 10\%$
    [fixed order naive error]
– finite terms
    [LO-NLO-NNLO: Drell-Yan, Higgs]

⇒ NLO neither for the fun nor for larger cross sections
NLO cross sections for Tevatron (and LHC)

- compute total cross sections for heavy particles  \[\text{[TeV scale input through SLHA]}\]
- all two-particle SUSY production channels included  \[\text{[q\bar{q} being tested]}\]
- extended version beyond Prospino2: pp → SS*...
- public Website and continuously maintained Fortran program

[W. Beenakker, R. Höpker, M. Krämer, M. Spira, P. Zerwas]

Getting started on Prospino2.0

1. download prospino.tar.gz from Prospino2 page:
   http://pheno.physics.wisc.edu/~plehn
2. edit path and compiler in Makefile  \[\text{[any F90 compiler I ever found will do]}\]
3. make, run executable
4. find results in file prospino.dat ⇒ normalize cross sections

| i1 | i2 | scafac | m1 | m2 | angle | LO[pb] | rel-error | NLO[pb] | rel-error | K |
|----|----|--------|----|----|-------|--------|-----------|---------|-----------|---|
| nn 1 1 | 0.00 | 0.00 | 1.00 | 96.27 | 96.27 | 0.00 | 0.908E-02 | 0.165E-03 | 0.118E-01 | 0.265E-02 | 1.3020 |
| nn 1 2 | 0.00 | 0.00 | 1.00 | 96.27 | 179.38 | 0.00 | 0.101E-02 | 0.179E-03 | 0.136E-02 | 0.181E-02 | 1.3477 |
| nn 1 3 | 0.00 | 0.00 | 1.00 | 96.27 | -364.09 | 0.00 | 0.204E-02 | 0.154E-03 | 0.260E-02 | 0.144E-03 | 1.2763 |
| nn 1 4 | 0.00 | 0.00 | 1.00 | 96.27 | 382.63 | 0.00 | 0.443E-03 | 0.164E-03 | 0.565E-03 | 0.301E-03 | 1.2747 |
program main
use xx_kinds ! defines integer and real variables
use xx_prospino_subroutine ! links the actual prospino code

integer :: nlo,icoll,ipart1,ipart2
character(len=2) :: final_state

!-------------------------------------nlo= 1 ! specify LO only[0] or complete NLO (slower)[1]
!-------------------------------------!-------------------------------------icoll= 1 ! specify the collider : tevatron[0] , lhc[1]
!-------------------------------------!-------------------------------------

! final_state = ng neutralino/chargino + gluino
! ns neutralino/chargino + squark
! nn neutralino/chargino pair combinations
! ll slepton pair combinations
! sb squark-antisquark
! ss squark-squark
! tb stop-antistop
! gg gluino pair
! sg squark + gluino
! lq leptoquark pairs (using stop1 mass)
!-------------------------------------final_state = 'ng'

! final_state = ng,ns,nn
! ipart1 = 1,2,3,4 neutralinos
!-------------------------------------ipart1 = 1
ipart2 = 1

!-------------------------------------call PROSPINO_OPEN_CLOSE(0) ! open all input/output files
call PROSPINO(nlo,icoll,final_state,ipart1,ipart2) ! actual prospino call
call PROSPINO_OPEN_CLOSE(1) ! close all input/output files

end program main
\[ \sigma_{\text{tot}}[\text{pb}]: \text{pp} \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{t}_1\tilde{t}_1, \tilde{\chi}_2^0\tilde{\chi}_1^+, \tilde{\nu}\tilde{\nu}, \tilde{\chi}_1^0\tilde{\tilde{g}}, \tilde{\chi}_1^+\tilde{\tilde{q}} \]

\[ \sqrt{S} = 2 \text{ TeV} \]

\[ \sigma_{\text{tot}}[\text{pb}]: \text{pp} \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{t}_1\tilde{t}_1, \tilde{\chi}_2^0\tilde{\chi}_1^+, \tilde{\nu}\tilde{\nu}, \tilde{\chi}_1^0\tilde{\tilde{g}}, \tilde{\chi}_1^+\tilde{\tilde{q}} \]
Smadgraph: we are done!  [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

- Majoranas and fermion number violation in Madgraph  [Denner, Eck, Hahn, Küblbeck]
- complete set of Feynman rules  [300+ processes compared with Whizard and Sherpa]
- beta version upon request, Smadevent in test phase  [TeV scale spectrum through SLHA]
- first physics project: SUSY pairs in weak boson fusion
- second physics project: heavy particles plus jets
- Tevatron search channels?

Smadevent for LHC: squarks and gluinos plus jets  [TP, Rainwater, Skands]

- cascade studies sensitive to hard jet radiation?
- compute \( \tilde{g}\tilde{g}+2j \) and \( \tilde{u}_L\tilde{g}+2j \)  [SPS1a, \( p_{T,j} > 100\text{GeV} \)]

| \( \sigma [\text{pb}] \) | \( t\bar{t}_{600} \) | \( \tilde{g}\tilde{g} \) | \( \tilde{u}_L \tilde{g} \) |
|----------------|----------------|----------------|----------------|
| \( \sigma_0 \) | 1.30 | 4.83 | 5.65 |
| \( \sigma_1 \) | 0.73 | 2.89 | 2.74 |
| \( \sigma_2 \) | 0.26 | 1.09 | 0.85 |

\( \Rightarrow \) where from: gluon radiation vs. initial states?
\( \Rightarrow \) modelling: comparison with Phythia6.2/6.3
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| $\sigma [\text{pb}]$ | $t\bar{t}_{600}$ | $\tilde{g}\tilde{g}$ | $\tilde{u}_L\tilde{g}$ |
|----------------------|----------------|-----------------|----------------|
| $\sigma_{0j}$        | 1.30           | 4.83            | 5.65           |
| $\sigma_{1j}$        | 0.73           | 2.89            | 2.74           |
| $\sigma_{2j}$        | 0.26           | 1.09            | 0.85           |

⇒ where from: gluon radiation vs. initial states?
⇒ modelling: comparison with Phythia6.2/6.3
Jet radiation: Smadgraph–Pythia6.2–Pythia6.3 [no result yet, under study]

- LHC: problem with combinatorics in SUSY searches
- Tevatron: QCD problem in top physics [until SUSY is discovered, of course]

⇒ collinear approximation describing hard jets after tuning?
  [1j:0j above 50 GeV — 7% Pythia6.2; 14% Pythia6.3; 14% Madevent, 2j:1j similar]

⇒ factorization: Z+jets, t\bar{t}+jets and SUSY+jets the same?

⇒ reasonable extrapolation Tevatron → LHC?

⇒ general question: how to predict shapes best? [in principle: Pythia resumming beyond NLO]
Split Supersymmetry

- forget about fine tuning [Higgs will never be as bad as cosmological constant]
- remember all the good things SUSY did for you [dark matter, unification]

⇒ make scalars heavy [limited by cosmology]
⇒ protect gaugino and higgsino masses at TeV scale [Drees: might not be possible]

News for phenomenology

- no cascade decays

⇒ hadronizing gluinos $[\tau \sim \tilde{m}^{-4} \sim 6.5\;s\;\text{for}\;\tilde{m} = 10^9\;\text{GeV}]$
⇒ heavy R hadrons [e.g. Kraan]
⇒ gluonium [e.g. Cheung & Keung]
- renormalization group running without scalars

⇒ corrections to protected couplings [ino Yukawas 20%]

Collider prospects

[no matter what you or I think about model]
- LHC: stable gluino to $\sim 2\;\text{TeV}$ [time of flight and charge the key]
- direct neutralino/chargino production without lepton-lepton edge?
Tevatron channel: $B_s \rightarrow \mu \mu$
- $s$-channel exchanges dominant: $H, Z, \gamma$
  suppressed in Standard Model \[BR_{SM} \sim (2.4 \pm 0.5) \times 10^{-9}\]
- more Higgs bosons in 2HDM
  $\tan \beta$ enhancement of s channel Higgses \[BR_{2HDM} \propto \tan^6 \beta/m_A^2\]
  additional Higgs loop
- charginos in MSSM
  $\tan \beta$ enhancement for Higgsinos
  gluino loop for non-minimal flavor physics...

Bottom Yukawa in the MSSM [Nierste, ...]
- gluino-sbottom loops universal: $y_b \rightarrow y_b/(1 + \Delta_b)$
- large, leading in $\tan \beta$ & resummable $\Delta_b \sim \alpha_s \tan \beta m_\tilde{g} \mu/\max^2(m_{\tilde{b}, \tilde{g}})$
  $\Rightarrow$ decoupling in MSSM, but not in MSSM$+\mu$
  [similar terms for chargino/neutralino exchange]
- easy to implement in MC, numerically great for $\tan \beta > 10$
  $\Rightarrow$ good for SUSY signals, but pain in analyses
Supersymmetry at hadron colliders

- direct searches for SUSY: mass peaks
- indirect searches for BSM: B physics et al.
- continuous theory/phenomenology progress for many years
- new SUSY tools: SLHA, Prospino2, Smadgraph, Sdecay, Sfitter, Fittino,...

Future

- phenomenologists want to work with you, not steal results
- we can maybe help to understand some things better
- (reasonable) requests are good for the development of tools
- we are lacking man power, but who I am telling this to...
**SUPERSYMMETRIC PARAMETERS**

**SUSY parameters from observables** [Les Houches Accord: Skands,...]

- parameters: weak-scale MSSM Lagrangean
- measurements: masses or edges
  - branching fractions [MSMlib, Sdecay]
  - cross sections [Prospino2, MSMlib],...
- errors: general correlation, statistics & systematics & theory
- problem in grid: huge phase space, local minimum?
- problem in fit: domain walls, starting values, global minimum?

**Sfitter** [Lafaye, TP, D. Zerwas, also Fittino]

- (1) grid for closed subset
- (2) fit of remaining parameters
- (3) complete fit

⇒ LHC better than expected
⇒ LHC+ILC without assumptions
⇒ P. Zerwas’ talk: SUSY breaking

|                | LHC      | ILC      | LHC+ILC  | SPS1a |
|----------------|----------|----------|----------|-------|
| tanβ           | 10.22±9.1| 10.26±0.3| 10.06±0.2| 10    |
| M₁             | 102.45±5.3| 102.32±0.1| 102.23±0.1| 102.2 |
| M₃             | 578.67±15 | fix 500 | 588.05±11 | 589.4 |
| M~ₗ              | fix 500 | 197.68±1.2 | 199.25±1.1 | 197.8 |
| M~ₗ L            | 129.03±6.9 | 135.66±0.3 | 133.35±0.6 | 135.5 |
| M~ₗ R            | 198.7±5.1  | 198.7±0.5  | 198.7±0.5  | 198.7 |
| M~ₗ L           | 498.3±110  | 497.6±4.4  | 521.9±39  | 501.3 |
| A_r            | fix 0     | -202.4±89.5| 352.1±171 | -253.5 |
| A_t            | -507.8±91 | -501.95±2.7 | -505.24±3.3 | -504.9 |
| A_b            | -784.7±35603 | fix 0 | -977±12467 | -799.4 |
Structure of Prospino2 code

- driver file: `prospino_main.f90`

- user subdirectories:
  - Pro2_doc: getting started, documentation, reference output
  - Pro2_interface: interface for SUSY spectrum and pdfs
    [default: SLHA, Cteq6]

- global parameters: `Xvital.f90` [e.g. $m_W$, $m_t$, $G_F$]

- advanced user: `Xprospino_subroutine.f90`
  collider energy
  input-output file initialization

- professional user: `Xinitialize.f90`
  SUSY spectrum initialization
  numerical cutoff parameters
  number of points and iteration for integration

- directories not to be touched:
  - Pro2_integrals: routines for angular integrals and loop integrals
  - Pro2_matrix: matrix elements squared
  - Pro2_sq-gl: old Prospino for squark and gluino production
  - Pro2_subroutines: all subroutines