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PROSPINO

A PROGRAM FOR THE PROduction of Supersymmetric Particles In Next-to-leading Order QCD

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Abstract

A Fortran-program for the production cross-sections of squarks and gluinos at hadron colliders is described. It includes full next-to-leading order SUSY-QCD corrections to all possible final states ($\tilde{q}\bar{\tilde{q}}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}$). The program allows to calculate total cross-sections as well as differential distributions in the transverse momentum p_t and the rapidity y of one of the outgoing particles. In addition cuts in p_t and y can easily be implemented.

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1 Introduction

One of the important quests of high-energy physics is the search for supersymmetric particles. Squarks and gluinos, the supersymmetric partners of the quarks and gluons, can be produced at present and future hadron colliders, if their masses are in the accessible range. The next-to-leading order (NLO) strong (SUSY-QCD) corrections increase the cross-sections for the various production processes by up to a factor of two with respect to the leading-order (LO) predictions and reduce the dependence on the renormalization and factorization scale significantly [1, 2]. Therefore a theoretically stable prediction for the cross-sections has to include these corrections.

In this paper we present the Fortran-program package PROSPINO, which calculates the production cross-sections for squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) in LO and NLO. This program complements the event-generator ISAJET [3], which includes the complete production and decay processes for supersymmetric particles in Born approximation. The calculation has been performed for the reactions

$$pp/p\bar{p} \to \tilde{q}\bar{\tilde{q}}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q} \qquad\qquad (\tilde{q} \neq \tilde{t}) \tag{1}$$

in a supergravity-inspired model in which all squarks have one common mass[1]. The program calculates differential cross-sections in the transverse momentum p_t and the rapidity y, as well as total cross-sections with possible cuts in p_t and y. The masses of the squarks ($m_{\tilde{q}}$), gluinos ($m_{\tilde{g}}$) and top quarks (m_t), the renormalization/factorization scale (Q), the collider type ($pp/p\bar{p}$), and the set of parton densities can be chosen. For numerical integration the VEGAS-routine [5] is used.

The program is written in Fortran, and has been tested on several Unix-workstations.

2 The Calculation

The total hadronic cross-sections for the various final states are calculated in the following way:

$$\sigma(pp/p\bar{p} \to \tilde{q} + \bar{\tilde{q}} + X) = \int_{p_t^{min}}^{p_t^{max}} dp_t \int_{y^{min}}^{y^{max}} dy \, \frac{d^2\sigma(\tilde{q} + \bar{\tilde{q}})}{dp_t\, dy} \tag{2}$$

$$\sigma(pp/p\bar{p} \to \tilde{g} + \tilde{g} + X) = \int_{p_t^{min}}^{p_t^{max}} dp_t \int_{y^{min}}^{y^{max}} dy \, \frac{d^2\sigma(\tilde{g} + \tilde{g})}{dp_t\, dy} \tag{3}$$

$$\sigma(pp/p\bar{p} \to \tilde{q} + \tilde{g} + X) = \int_{p_t^{min}}^{p_t^{max}} dp_t \int_{y^{min}}^{y^{max}} dy \, \frac{d^2\sigma(\tilde{q} + \tilde{g})}{dp_t\, dy} \tag{4}$$

$$\sigma(pp/p\bar{p} \to \tilde{q} + \tilde{q} + X) = \int_{p_t^{min}}^{p_t^{max}} dp_t \int_{y^{min}}^{y^{max}} dy \, \frac{d^2\sigma(\tilde{q} + \tilde{q})}{dp_t\, dy} \tag{5}$$

[1]This assumption is not correct for the stops. Nevertheless the induced error is very small, because we are including stops only in internal loops and not as final-state particles. The calculations for stop production are in progress [4] and will be implemented in PROSPINO in due course.

The quantities p_t and y are defined as the transverse momentum and the rapidity of the *second* particle[2] [e.g. of the gluino in Eq. (4)]. For the processes in Eqs. (2), (4), and (5) the summation over all possible squark flavors (except stop) and over both squark chiralities is implicitly understood. In addition Eqs. (4) and (5) include the sum over the charge-conjugated final states. The rapidity distributions are defined by adding the contributions of positive and negative rapidity. Thus the integration over y has to include only the range of positive rapidity [*i.e.* $y^{min} \geq 0$]. The factor 1/2 for identical particles in the final state is included in the double-differential cross-sections.

The double-differential cross-section can be written as

$$\frac{d^2\sigma}{dp_t\,dy} = 2p_t S \sum_{i,j=g,q,\bar{q}} \int_{x_1^-}^1 dx_1 \int_{x_2^-}^1 dx_2\, x_1 f_i^{h_1}(x_1,Q^2)\, x_2 f_j^{h_2}(x_2,Q^2)\, \frac{d^2\hat{\sigma}_{ij}(x_1 x_2 S, Q^2)}{dt\,du} \tag{6}$$

where Q is the renormalization/factorization scale[3], i and j indicate the initial-state partons, f_i are the parton densities (in the $\overline{MS}$ factorization scheme), and $\sqrt{S}$ is the center-of-mass energy of the collider. The invariants t and u are the usual Mandelstam variables, related to the momentum transfer from the initial-state partons to the detected final-state particle [2]. The program calculates the double-differential cross-sections in Eq. (6) in LO and NLO. The NLO results include the sum of leading and next-to-leading order contributions. For LO and NLO various sets of parton densities can be used. As two standard parametrizations the program includes the GRV94 [6] and the MRS(A') [7] parton densities. Moreover, the PDFLIB library [8] can be linked to the program, therefore other parton densities can be included rather easily.

The technical details, like the correct phase-space boundaries or the subtraction procedure for on-shell intermediate states, can be found in Ref. [2].

3 Computer Implementation

3.1 Organization

The program package PROSPINO consists of several files. Compiling and linking is done most efficiently with a **makefile**[4] under the operating system Unix. The executable files are:

totalsb.f calculation of the cross-sections for squark–antisquark production

totalgg.f calculation of the cross-sections for gluino–gluino production

[2]The distributions with respect to the *first* particle are identical for squark- and gluino-pair production. For squark–antisquark final states, the program allows to choose the particle for which p_t and y are defined (squark/antisquark/average of both). This facilitates adding the distributions with respect to both final-state particles if squarks and antisquarks are not discriminated in the experimental analyses.

[3]In NLO the scale must be fixed by an external (hadronic) scale. The natural value is given by the average mass of the produced massive particles or the transverse mass of the detected final-state particle.

[4]The command syntax is: **make 'executable'**.

totalsg.f calculation of the cross-sections for squark–gluino production

totalss.f calculation of the cross-sections for squark–squark production

The files that should be compiled to object files are the following (this is automatically done by the command **make library**):

matrixsb.f squared matrix elements for squark–antisquark production

matrixgg.f squared matrix elements for gluino–gluino production

matrixsg.f squared matrix elements for squark–gluino production

matrixss.f squared matrix elements for squark–squark production

hadronsb.f definition of the cross-sections for squark–antisquark production

hadrongg.f definition of the cross-sections for gluino–gluino production

hadronsg.f definition of the cross-sections for squark–gluino production

hadronss.f definition of the cross-sections for squark–squark production

layoutsb.f print routines for squark–antisquark production

layoutgg.f print routines for gluino–gluino production

layoutsg.f print routines for squark–gluino production

layoutss.f print routines for squark–squark production

integral.f scalar and angular integrals and the VEGAS routine

pdfgrv94.f GRV94 parton densities[5]

pdfmrsap.f MRS(A') parton densities

initpdf.f choice of the parton densities (PDFLIB) and α_s in LO and NLO

We strongly recommend to make *cautious* changes only in the **total*.f** and **layout*.f** files. For the long files (**matrix*.f**) some compilers need an increased table size; this can be changed in the **makefile** with the parameter longopt.

[5] For charm and bottom distributions, the older GRV densities are used.

3.2 Input Parameters

In this section the user-setable physical and numerical input parameters are described.

MS, MG, MT (*REAL*8*): masses (in GeV) of the squarks (MS), the gluino (MG), and the top quark (MT).

ICOLL (*INTEGER*): type of the hadron collider

- **0** $p\bar{p}$ collider
- **1** pp collider

ENERGY (*REAL*8*): center-of-mass energy of the collider (in GeV).

IPDFSET (*INTEGER*): set of parton densities and the corresponding α_s

- **0** GRV94 parton densities
- **1** MRS(A') parton densities
- **2** parton densities from the PDFLIB library[6]

IFLAVOR (*INTEGER*): initial states

- **0** sum over all initial states
- **1** gluon–gluon
- **2** quark–quark (= the sum over $q\bar{q}$, $q'\bar{q}$, qq, $q'q$, $\bar{q}\bar{q}$, and $\bar{q}'\bar{q}$)
- **3** quark–gluon (= the sum over gq and $g\bar{q}$)
- **4** the major contributions[7]
- **5** the minor contributions[8]

ITOTAL (*INTEGER*): the way of calculating the cross-section

- **0** total cross-section with cuts or differential cross-section (slower)
- **1** only total cross-section without cuts (faster)

ISCAPT (*INTEGER*): type of the default scale

[6] In addition, three things must be arranged: the correct cernlib directory must be given in the **makefile**; the three (dummy) routines (PDFSET, PFTOPDG, and ALPHAS2) in **initpdf.f** must be commented out; in the subroutines INILO and ININLO in **initpdf.f** the desired PDFLIB parameters must be chosen.

[7] The initial states that exist already in LO contribute nearly 100% of the NLO cross-section. Only these contributions will be calculated here.

[8] The initial states that start to contribute at NLO yield a tiny contribution to the NLO cross-sections. Due to the subtraction procedure for on-shell intermediate states in some regions of the parameter space, these contributions may require a higher integration precision to produce stable results. With this option they can be calculated separately and added to the main contributions.

0 the average mass of the outgoing massive particles; default for ITOTAL = 1

1 the transverse mass $\sqrt{m^2 + p_t^2}$ of the detected particle with mass m and transverse momentum p_t; only for ITOTAL = 0

SCAFAC (*REAL*8*): factor by which the default scale is multiplied

PTMIN, PTMAX (*REAL*8*): lower and upper bounds of the transverse-momentum (p_t) integration. Only positive values for PTMIN and PTMAX are allowed. The choice PTMIN = PTMAX yields $d\sigma/dp_t$.

YMIN, YMAX (*REAL*8*): lower and upper bounds of the rapidity (y) integration. The rapidity distributions are defined by adding the contributions of positive and negative rapidity, hence YMIN ≥ 0 is required. The choice YMIN = YMAX yields $d\sigma/dy$.

ICHARCONJ (*INTEGER*): only for squark–antisquark final states. The particle for which the differential cross-sections are defined

−1 antisquark

+1 squark

0 the average of squark and antisquark

IONLYLO (*INTEGER*): for calculating only the LO results (**1**) or both LO and NLO results (**0**).

ILO, INLO (*INTEGER*): number of VEGAS calls. VEGAS and VEGAS1 will be called by the routine INTEG (VEGAS1 with five times as many calls as VEGAS).

IPRINT (*INTEGER*): print intermediate results of VEGAS iterations (**10**) or not (**0**).

3.3 Results

The program prints the relevant physical parameters and the hadronic cross-sections in LO and NLO (in pb). If the lower and upper bounds in p_t and/or y are identical, the results correspond to the differential cross-sections $d\sigma/dp_t$, $d^2\sigma/dp_t/dy$, or $d\sigma/dy$, respectively.

3.4 How to get the programs

The program package PROSPINO is available upon request from the authors or can be picked up from the WWW address: http://wwwcn.cern.ch/˜mspira/. For any comments, questions, or problems please contact the authors.

4 Appendix

4.1 Sample File totalsb.f

```
C*********************************************************************
C***                                                               ***
C***  THIS PROGRAM CALCULATES                                      ***
C***  THE TOTAL CROSS-SECTION AND DISTRIBUTIONS                    ***
C***  FOR SQUARK-ANTISQUARK PRODUCTION AT HADRON COLLIDERS         ***
C***  INCLUDING FULL SUSY-QCD CORRECTIONS                          ***
C***                                                               ***
C***  WRITTEN BY: W. BEENAKKER, R. HOPKER AND M. SPIRA             ***
C***                                                               ***
C*********************************************************************

      PROGRAM TOTALSB
      IMPLICIT REAL*8 (A-H,M-Z)
      IMPLICIT INTEGER (I,J)
      COMMON/IOUT/IPRINT
      COMMON/CONST1/S,ENERGY,ALPHAS,MS,MG,MT
      COMMON/CONST2/SCALE,SCAFAC,ICOLL,ISCAPT
      COMMON/CONST3/IPDFSET
      COMMON/CONST5/ILO,INLO,IONLYLO
      COMMON/CUT1/PTMIN,PTMAX
      COMMON/CUT2/YMIN,YMAX
      COMMON/FLAVOR/IFLAVOR,ITOTAL
      COMMON/CHARCONJ/ICHARCONJ

C ---------------------------------------------------------------
C --- INPUT PARAMETERS, CAN BE CHANGED  -------------------------
C ---------------------------------------------------------------

C***  THE MASSES (IN GEV)

      MS = 280.D0
      MG = 200.D0
      MT = 175.D0

C***  THE COLLIDER TYPE ( P PBAR = 0, P P = 1 )

      ICOLL = 0

C***  THE CENTER OF MASS ENERGY (IN GEV)
```

```
      ENERGY = 1800D0

C***  THE SET OF PARTON DENSITIES (GRV = 0, MRSAP = 1, PDFLIB = 2)
C***  FOR PDFLIB PLEASE MAKE CHANGES IN SUBROUTINES INILO AND ININLO
C***  IN FILE INITPDF.F

      IPDFSET = 0

C***  THE INITIAL STATE
C***  ALL = 0, G G = 1, Q Q = 2, G Q = 3, MAJOR=4, MINOR=5

      IFLAVOR = 0

C***  THE CROSS-SECTION WITH CUTS (0)
C***  THE TOTAL CROSS-SECTION WITHOUT CUTS IN A FASTER WAY (1)

      ITOTAL = 0

C***  THE SCALE FOR RENORMALIZATION AND FACTORIZATION
C***  ISCAPT = 0  --> SCALE = MS * SCAFAC
C***  ISCAPT = 1  --> SCALE = SQRT(MS**2 +PT**2) * SCAFAC
C***                  ONLY FOR ITOTAL = 0
C***  DEFAULT FOR SCAFAC = 1.0

      ISCAPT = 0
      SCAFAC = 1.D0

C***  THE CUTS ON THE CROSS-SECTION IN PT (DEFAULT: 0,ENERGY )
C***  PT IS ONLY DEFINED FOR POSITIVE VALUES: PTMIN >= 0
C***  EQUAL LOWER AND UPPER CUT GIVES DSIGMA/DPT
C***  ITOTAL = 0 NECESSARY

      PTMIN = 0D0
      PTMAX = ENERGY

C***  THE CUTS ON THE CROSS-SECTION IN Y (DEFAULT: 0,+9.99)
C***  RAPIDITY IS ONLY DEFINED FOR POSITIVE VALUES: YMIN >= 0
C***  EQUAL LOWER AND UPPER CUT GIVES DSIGMA/DY
C***  ITOTAL = 0 NECESSARY

      YMIN = 0.D0
      YMAX = +9.99D0
```

```
C***  ONLY FOR DISTRIBUTIONS ( ITOTAL = 0 )
C***  DISTINGUISH BETWEEN SQUARKS AND ANTISQUARKS IN THE FINAL STATE
C***  DEFINES THE DIFFERENTIAL CROSS-SECTIONS WITH RESPECT TO
C***  ICHARCONJ =  1  <-- SQUARKS
C***  ICHARCONJ = -1  <-- ANTISQUARKS
C***  ICHARCONJ =  0  <-- AVERAGE OF SQUARKS AND ANTISQUARKS

      ICHARCONJ = 0

C***  IONLYLO = 0 CALCULATES BORN AND NLO CROSS-SECTIONS
C***  IONLYLO = 1 CALCULATES ONLY THE BORN CROSS-SECTION

      IONLYLO = 0

C***  THE NUMBER OF VEGAS CALLS ( DEFAULT = 1000 )

      ILO   = 1000
      INLO  = 500

C***  PRINT VEGAS STATISTICS (10) OR NOT (0)

      IPRINT = 0

C --- PRINT THE HEADER ------------------------------------------

      CALL PRIHEADSB

C --- INITIALIZE VEGAS ------------------------------------------

      CALL RSTART(12,34,56,78)

C -------------------------------------------------------------
C --- INTEGRATION BY VEGAS -------------------------------------
C --- CALCULATION OF CROSS-SECTIONS AND DISTRIBUTIONS -----------
C --- CAN BE CHANGED -------------------------------------------
C -------------------------------------------------------------

C***  CALCULATE THE TOTAL CROSS-SECTION WITHOUT CUTS
      ITOTAL = 1

C***  CALCULATE THE CROSS-SECTIONS IN LO AND NLO
      CALL INTEGSB(RESLO,ERRLO,RESNLO,ERRNLO)
```

```
C***  PRINT THE CROSS-SECTIONS IN LO AND NLO AND THEIR RELATIVE ERRORS
      CALL PRIRESSB(RESLO,ERRLO,RESNLO,ERRNLO)

      PRINT *

C***  CALCULATE THE DIFFERENTIAL CROSS-SECTION DSIGMA/DPT
C***  WITH THE SCALE Q**2 = MS**2 + PT**2
C***  FOR PT = 50, 100, 150 GEV
      ITOTAL = 0
      ISCAPT = 1
      DO 100 I = 1,3
         PTMIN = 50.D0 * I
         PTMAX = PTMIN
         CALL INTEGSB(RESLO,ERRLO,RESNLO,ERRNLO)
         CALL PRIRESSB(RESLO,ERRLO,RESNLO,ERRNLO)
 100  CONTINUE

      STOP
      END

C**********************************************************************
```

4.2 Control Results

The sample (main) program of Appendix 4.1 calculates for squark–antisquark final states:

- the total cross-section
- the differential cross-section $d\sigma/dp_t$, where p_t is averaged over squark and antisquark, for $p_t = 50, 100, 150$ GeV and the scale $Q = \sqrt{m_{\tilde{q}}^2 + p_t^2}$

It produces the following output:

```
CROSS-SECTIONS AND DISTRIBUTIONS FOR SQUARK-ANTISQUARK HADROPRODUCTION (IN PB)

PROTON-ANTIPROTON COLLIDER WITH ENERGY =  1800. GEV

IFLAVOR   SCAFAC ISCAPT                               ERR/SIG           ERR/SIG
|   MS    MG   |  | PTMIN PTMAX YMIN YMAX   SIGMA_LO    |     SIGMA_NLO   |
-----------------------------------------------------------------------------
0  280.  200. 1.0 0   0.  1800. 0.00 9.99  0.7028     .0017  0.8333     .0021
```

```
0  280.  200. 1.0 1  50.    50. 0.00 9.99   0.2488E-02 .0016  0.3547E-02 .0018
0  280.  200. 1.0 1 100.   100. 0.00 9.99   0.3565E-02 .0015  0.4549E-02 .0018
0  280.  200. 1.0 1 150.   150. 0.00 9.99   0.3102E-02 .0015  0.3683E-02 .0017
```

This test run takes about 35 minutes on a Silicon Graphics workstation. It should be noted that the above layout can be freely adapted to the user's wishes by making appropriate changes in the files **layout*.f**.

4.3 Conventions

The squared matrix elements (in **matrix*.f**) are labeled according to a fixed set of conventions.
The second and third letters are used to represent the type of production process:

SB: squark–antisquark

GG: gluino–gluino

SG: squark–gluino

SS: squark–squark

The fourth (fifth) letter represents the type of initial state of parton 1 (parton 2):

G: gluon

Q: quark

B: antiquark

For **QQ** and **QB** there is an additional flag **IFL** $= 1/0$ in the parameter list of the function call, indicating equal/unequal flavors in the initial state.
The sixth letter represents the type of contribution:

B: Born

V: virtual + soft

H: hard

D: $\log(\Delta)$

R: finite shift in the $\overline{MS}$-scheme to restore supersymmetry

S: pole part of $1/s_4^2$

T: pole part of $1/s_3^2$

U: $\mathrm{Im}[1/s_4]\ \mathrm{Im}[1/s_3]$

1: scale dependence of virtual + soft

2: scale dependence of $\log(\Delta)$

3: scale dependence of hard

e.g. **DSBGGV** = squark–antisquark production, gluon–gluon initial state, and virtual + soft corrections.

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