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ON THE SPA CONVENTION AND PROJECT*

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Reconstruction of the fundamental supersymmetric theory and its breaking mechanism will require high-precision tools. Here a brief introduction to SPA, the Supersymmetry Parameter Analysis (SPA) Convention and Project, is presented which is based on a consistent set of conventions and input parameters.

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1. Introduction

At future colliders, the LHC and the ILC, experiments can be performed in the supersymmetric particle sector with very high precision — experimental accuracies are expected at the per cent down to the per mille level [1–3]. This should be matched from the theoretical side [4]. Therefore a well defined theoretical framework is necessary for the calculational schemes in perturbation theory as well as for the input parameters. Motivated by the experience in analyzing data at the former e^+e^- colliders LEP and SLC, the SPA Convention and Project [5] has been proposed. It provides

- a convention for calculating masses, mixings, decay widths and production cross sections,
- a program repository of codes (RGE, spectrum calculators, fitting routines, event generators *etc.*) that will be expanded continuously in the future,
- a list of future tasks on both the theoretical and the experimental sides needed before data from future experiments could be evaluated at the desired level of accuracy,

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- a SUSY reference point SPS1a′ as a general setup for testing these tools in practice.

Combining the experimental information from LHC and ILC will provide a high-precision picture of supersymmetry at the TeV scale [6] which subsequently may lead to the reconstruction of the fundamental supersymmetric theory at a high scale and the mechanism of supersymmetry breaking [7].

The SPA Convention and Project is a joint inter-regional experimental and theoretical effort. The current status of the project is documented on the routinely updated web-page `http://spa.desy.de/spa/`

2. SPA Convention

Building on vast experience in SUSY calculations and data simulations and analyses, the SPA Convention consists of the following propositions:

- The masses of the SUSY particles and Higgs bosons are defined as pole masses.

- All SUSY Lagrangian parameters, mass parameters and couplings, including $\tan\beta$, are given in the $\overline{DR}$ scheme and defined at the scale $\tilde{M} = 1$ TeV.
- Gaugino/higgsino and scalar mass matrices, rotation matrices and the corresponding angles are defined in the $\overline{DR}$ scheme at $\tilde{M}$, except for the Higgs system in which the mixing matrix is defined in the on-shell scheme, the scale parameter chosen as the light Higgs mass.

- The Standard Model input parameters of the gauge sector are chosen as $G_{\rm F}$, α, M_Z and $\alpha_{\rm s}^{\overline{MS}}(M_Z)$. All lepton masses are defined on-shell. The t quark mass is defined on-shell; the b, c quark masses are introduced in $\overline{MS}$ at the scale of the masses themselves while taken at a renormalization scale of 2 GeV for the light u, d, s quarks.

- Decay widths, branching ratios and production cross sections are calculated for the set of parameters specified above.

The $\overline{DR}$ scheme, based on dimensional reduction and modified minimal subtraction, is designed to preserve supersymmetry and it is technically very convenient. Recently it has been shown that it can be formulated in a mathematically consistent way [8] and to comply with the factorization theorem, see [9]. The physical on-shell masses are introduced in the decay widths and production cross sections such that the phase space is treated in the observables closest to experimental on-shell kinematics.

3. Program repository

To use the highly developed $\overline{MS}$ infrastructure for proton colliders the repository contains the translation tools between the $\overline{DR}$ and $\overline{MS}$ schemes, as well as the on-shell renormalization schemes. The responsibility for developing codes and maintaining them up to the current theoretical state-of-the-art precision rests with the authors. The SLHA [10] convention is recommended for communication between the codes. The repository contains links to codes grouped in several categories:

1. Scheme translation tools for definitions and relations between on-shell, $\overline{DR}$ and $\overline{MS}$ parameters.
2. Spectrum calculators for transition from the Lagrangian parameters to a basis of physical particle masses and the related mixing matrices.
3. Calculation of other observables: decay tables, cross sections, low-energy observables *etc.*
4. Cosmological and astrophysical aspects: cold dark matter relics, cross sections for CDM particle searches, astrophysical cross-sections in the SUSY context *etc.*
5. Event generators that generate event samples for SUSY and background processes in realistic collider environments.
6. Analysis programs to extract the Lagrangian parameters from experimental data by means of global analyses.
7. RGE programs to connect the low-energy effective Lagrangian parameters to the high-scale where the model is supposed to be matched to a more fundamental theory.
8. Auxiliary programs and libraries: structure functions, beamstrahlung, numerical methods, SM backgrounds *etc.*

4. Testing the SPA: Ref. Point SPS1a′

The SPA Convention and Project is a very ambitious and extended experimental and theoretical effort. It is set up to cover general SUSY scenarios. However, to perform the first checks of its internal consistency and to explore the potential of such coherent data analyses a MSSM Reference Point SPS1a′ has been proposed as a testing ground. Of course, in future the SPA has to be tested in more extended MSSM as well as more complicated scenarios.

The roots defining the Point SPS1a′ are the mSUGRA parameters [in the conventional notation for cMSSM] in the set

$$\begin{array}{lclllcl} M_{1/2} & = & 250\ \text{GeV} & \text{sign}(\mu) & = & +1 \\ M_0 & = & 70\ \text{GeV} & \tan\beta(\tilde{M}) & = & 10 \\ A_0 & = & -300\ \text{GeV} & & & \end{array}$$

where the universal gaugino mass $M_{1/2}$, the scalar mass M_0 and the trilinear coupling A_0 [Yukawa couplings factored out], are defined at the GUT scale M_U. The point is close to the original Snowmass point SPS1a [11] and to point B′ of [12]. With the SM input parameters given explicitly in the SPA document [5], extrapolation of the above parameters down to the $\tilde{M} = 1$ TeV scale generates the MSSM Lagrangian parameters as shown in the left part of Table I. Here the RGE part of the program `SPheno` [13] has been used (for internal or external comparison, other codes can equally be used).

TABLE I

Left: The $\overline{DR}$ SUSY Lagrangian parameters at the scale $\tilde{M} = 1$ TeV in SPS1a′ from [13]. In addition, gauge and Yukawa couplings at this scale are given in the $\overline{DR}$ scheme. Right: Mass spectrum of supersymmetric particles [13] and Higgs bosons [14] in the reference point SPS1a′. The masses in the second generation coincide with the first generation. [Mass unit in GeV.]

g'	0.3636	M_1	103.3
g	0.6479	M_2	193.2
g_s	1.0844	M_3	571.7
Y_τ	0.1034	A_τ	-445.2
Y_t	0.8678	A_t	-565.1
Y_b	0.1354	A_b	-943.4
μ	396.0	$\tan\beta$	10.0
$M^2_{H_1}$	2.553×10^4	$M^2_{H_2}$	-14.31×10^4
$M^2_{L_1}$	3.278×10^4	$M^2_{L_3}$	3.214×10^4
$M^2_{E_1}$	1.338×10^4	$M^2_{E_3}$	1.210×10^4
$M^2_{Q_1}$	27.64×10^4	$M^2_{Q_3}$	22.22×10^4
$M^2_{U_1}$	25.73×10^4	$M^2_{U_3}$	15.04×10^4
$M^2_{D_1}$	25.50×10^4	$M^2_{D_3}$	25.09×10^4

h^0	116.0	$\tilde{\tau}_1$	107.9
H^0	425.0	$\tilde{\tau}_2$	194.9
A^0	424.9	$\tilde{\nu}_\tau$	170.5
H^+	432.7	$\tilde{u}_R$	547.2
$\tilde{\chi}^0_1$	97.7	$\tilde{u}_L$	564.7
$\tilde{\chi}^0_2$	183.9	$\tilde{d}_R$	546.9
$\tilde{\chi}^0_3$	400.5	$\tilde{d}_L$	570.1
$\tilde{\chi}^0_4$	413.9	$\tilde{t}_1$	366.5
$\tilde{\chi}^+_1$	183.7	$\tilde{t}_2$	585.5
$\tilde{\chi}^+_2$	415.4	$\tilde{b}_1$	506.3
$\tilde{e}_R$	125.3	$\tilde{b}_2$	545.7
$\tilde{e}_L$	189.9	$\tilde{g}$	607.1
$\tilde{\nu}_e$	172.5		

The physical [pole] masses of the supersymmetric particles are collected in the right part of Table I. The connection between the Lagrangian parameters and the physical pole masses can presently be controlled at the 1-loop level for the masses of the SUSY particles, and at the 2-loop level for the Higgs masses. The QCD effects on the heavy quark masses are accounted for at 2-loop accuracy.

For illustration, the left panel of figure 1 displays cross sections for the production of squarks and gluinos at the LHC as functions of the squark mass crossing the point SPS1a′, while the right panel shows the production cross section of pairs of charginos for the point SPS1a′ at the ILC as a function of the collider energy.

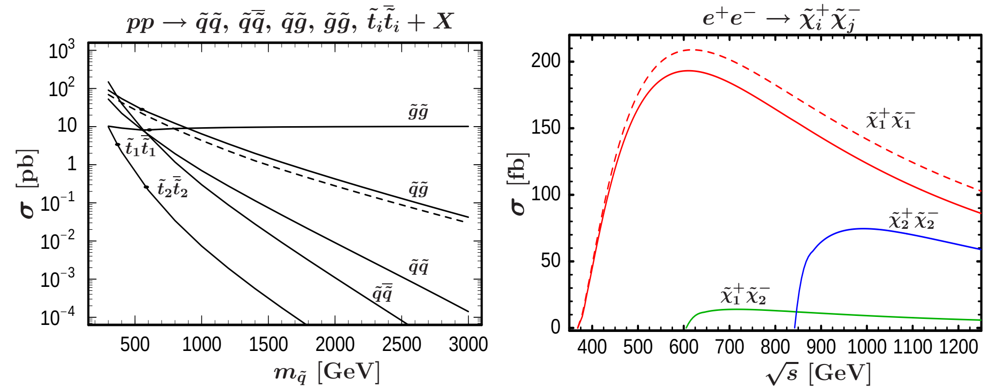

Fig. 1. Left: Total cross sections for squark and gluino pair production at the LHC [17] as a function of squark mass keeping the gluino mass fixed. Right: Total cross sections for chargino pair production in e^+e^- annihilation. The Born cross sections (broken lines) are shown for a few channels.

To perform experimental simulations, the branching ratios of the decay modes are crucial. The SPA Document and the SPA web page provide the results of calculations using `FeynHiggs` [14] and `SDECAY` [16].

If SPS1a′, or a SUSY scenario with mass scales similar to this point, is realized in nature, a plethora of interesting channels can be exploited to extract the basic supersymmetry parameters when combining experimental information from mass distributions at LHC with measurements of decay spectra and threshold excitation curves at an e^+e^- collider with energy up to 1 TeV [6]. From the simulated experimental errors the data analysis performed coherently for the two machines gives rise to a very precise picture of the supersymmetric particle spectrum as demonstrated in the left part of Table II.

In addition to evaluating the experimental observables channel by channel, global analysis programs have become available [18] in which the whole set of data, masses, cross sections, branching ratios etc, is exploited coherently to extract the Lagrangian parameters in the optimal way after including the available radiative corrections. The present quality of such an analysis can be judged from the results shown in the right part of Table II, where only experimental errors are included.

TABLE II

For the point SPS1a′ — Left: Accuracies for representative mass measurements of SUSY particles in individual LHC, ILC and coherent LHC+ILC analyses. $\tilde{q}_R$ and $\tilde{q}_L$ represent $q = u, d, c, s$. Right: Excerpt of extracted SUSY Lagrangian mass and Higgs parameters at the supersymmetry scale $\tilde{M} = 1$ TeV. [Masses in GeV.]

Particle	Mass	LHC	ILC	LHC+ILC
h^0	116.9	0.25	0.05	0.05
H^0	425.0		1.5	1.5
$\tilde{\chi}_1^0$	97.7	4.8	0.05	0.05
$\tilde{\chi}_2^0$	183.9	4.7	1.2	0.08
$\tilde{\chi}_4^0$	413.9	5.1	3 – 5	2.5
$\tilde{\chi}_1^\pm$	183.7		0.55	0.55
$\tilde{e}_{\rm R}$	125.3	4.8	0.05	0.05
$\tilde{e}_{\rm L}$	189.9	5.0	0.18	0.18
$\tilde{\tau}_1$	107.9	5 – 8	0.24	0.24
$\tilde{q}_{\rm R}$	547.2	7 – 12	–	5 – 11
$\tilde{q}_{\rm L}$	564.7	8.7	–	4.9
$\tilde{t}_1$	366.5		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.1	8.0	–	6.5

Param.	Error
M_1	0.1
M_2	0.1
M_3	7.8
μ	1.1
$M_{\tilde{e}_{\rm L}}$	0.2
$M_{\tilde{e}_{\rm R}}$	0.4
$M_{\tilde{\tau}_{\rm L}}$	1.2
$M_{\tilde{u}_{\rm L}}$	5.2
$M_{\tilde{u}_{\rm R}}$	17.3
$M_{\tilde{t}_{\rm L}}$	4.9
$m_{\rm A}$	0.8
$A_{\rm t}$	24.6
$\tan\beta$	0.3

With the parameters extracted at the scale $\tilde{M}$, the reconstruction of the fundamental supersymmetric theory and the related microscopic picture of the mechanism breaking supersymmetry can be attempted. In the bottom-up extrapolation [7] from $\tilde{M}$ to the GUT/Planck scale by the renor-

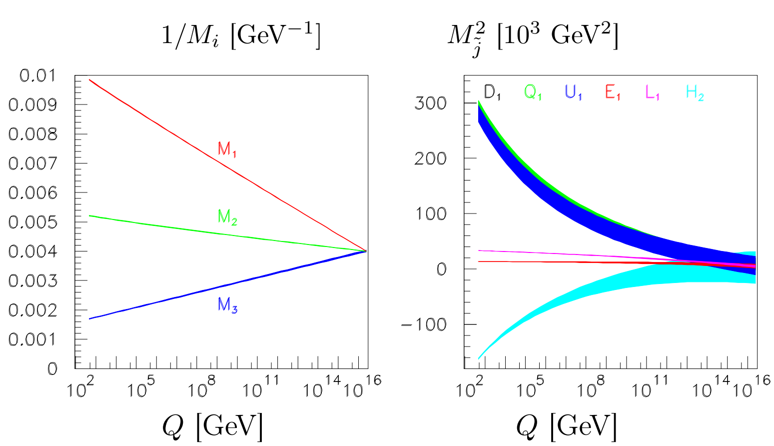

Fig. 2. Running of the gaugino and scalar mass parameters in SPS1a′ [13]. Only experimental errors are taken into account; theoretical errors are assumed to be reduced to the same size in the future.

malization group evolution for all parameters the experimental information is exploited to the maximum extent possible. The evolution of the gaugino and scalar mass parameters for SPS1a$'$ are presented in figure 2. While the reconstruction of the high-scale parameters in the gaugino/higgsino and slepton sectors is very precise, the picture of the colored scalar and Higgs sectors is still coarse and strong experimental efforts on improving mass and trilinear coupling measurements should be made to refine it considerably.

On the other hand, if the structure of the theory at the high scale was known *a priori* and only the experimental determination of the high-scale parameters were lacking, then the top-down approach would lead to a very precise parametric picture at the high scale. This is apparent from the fit of the mSUGRA parameters in SPS1a$'$ displayed in Table III.

TABLE III

Comparison of the ideal parameters with the experimental expectations in the top down approach.

Parameter	SPS1a$'$ value	Experimental error
$M_{\frac{1}{2}}$	250 GeV	0.2 GeV
M_0	70 GeV	0.2 GeV
A_0	-300 GeV	13.0 GeV
μ	396.0 GeV	0.3 GeV
$\tan\beta$	10	0.3

5. Future developments

The results for SPS1a$'$ presented here are based on preliminary experimental simulations and extrapolations from earlier analyses for SPS1a and other reference points as a substitute of missing information necessary for a first comprehensive test of all aspects of the SPA Project. Although current SPA studies are very encouraging, much additional work both on the theoretical as well as on the experimental side will be needed to achieve the SPA goals. In particular:

- The present level of theoretical calculations still does not match the expected experimental precision, particularly in coherent LHC+ILC analyses. New efforts in higher-order SUSY calculations are necessary for the interpretation of experimental analyses.

- There is no complete proof that $\overline{DR}$ scheme preserves supersymmetry and gauge invariance in all cases. As the precision of SUSY calculations is pushed to higher orders, the SPA Project also requires an improved understanding of the $\overline{DR}$ scheme. Recently it has been shown that for massive final state particles spurious density functions for the $(4-D)$ gluon components have to be introduced to comply with the factorization theorem [9] which opens a way to formulating an efficient combination of the most attractive elements of $\overline{DR}$ and $\overline{MS}$ schemes in describing hadronic processes.

- A limited set of observables included in experimental analyses by no means exhausts the opportunities which data at LHC and at ILC are expected to provide in the future. Likewise, in most analyses errors are purely experimental and do not include the theoretical counterpart which must be improved considerably before matching the experimental standards. This is particularly important for the coherent combination of future data obtained at LHC and ILC. Feedback and coherently combined analyses, which will greatly benefit from a concurrent running of both colliders, are indispensable for a meaningful reconstruction of the underlying theory [3].

- Astrophysical data play an increasingly important role in confronting supersymmetry with experiments. Models with R-parity conservation predict a stable weakly interacting, massive particle. In this case on the one hand their relic abundance imposes crucial limits on supersymmetric scenarios and specific requirements on the accuracies must be achieved when the CDM particle is studied in high-energy physics laboratory experiments [19]. On the other hand, predictions based on the comprehensive parameter analysis of high-energy experiments determine the cross sections for astrophysical scattering experiments by which the nature of the cold dark matter particles can be established. For example, a study of the SPS1a point at LHC, based on very large statistics [20], indicates that the relic density can be determined to $\sim 6\%$ for the SPS1a$'$ scenario. At the ILC a precision of $\sim 1.5\%$ should be achievable.

- The parameter set SPS1a$'$ chosen for a first study provides a benchmark for developing and testing the tools needed for a successful analysis of future SUSY data. However, neither this specific point nor the MSSM itself may be the correct model for low-scale SUSY. While versions of mSUGRA and of gaugino mediation have also been analyzed in some detail, the analyses have to be extended systematically to other possibilities. In particular, CP violation, R-parity violation, flavor violation, NMSSM and extended gauge groups are among scenarios which might be realized in the SUSY sector. The SPA conventions are general enough to cover all these scenarios.

6. Summary

The SPA Project, a joint theoretical and experimental effort, aims at providing

- a well defined framework for SUSY calculations and data analyses,
- all necessary theoretical and computational tools,
- a testground scenario SPS1a′,
- a platform for future extensions and developments.

First results for the reference point SPA1a′ are very encouraging, however it is clear that much work is still needed on the experimental and theoretical sides to achieve the desired level of accuracy. The SPA Project is a dynamical system expected to evolve continuously and to encompass more general supersymmetry scenarios.

I would like to thank all the SPA members for their efforts to make the SPA Projects a success. Special thanks go to Peter Zerwas and Uli Martyn. I am also deeply indebted to Prof. Wojciech Marczyński, MD, Dr. Tomasz Skrok, MD, and the whole personnel of the Department of Traumatology and Orthopedics of the Central Clinical Hospital of WAM, Warsaw, for their hospitality and care while this write-up has been prepared.

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