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
  - → μ parameter and SUSY breaking?

		spin	d.o.f.	
quark	q_L , q_R	1/2	1+1	
→ squark	$\tilde{q}_L$, $\tilde{q}_R$	0	1+1	6 flavors
gluon	$\tilde{G}\mu$	1	n — 2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ , Z	1	2+3	
Higgs bosons	h^o , H^o , A^o	0	3	
→ neutralinos	$\tilde{\chi}_i^o$	1/2	4 · 2	Majorana
gauge bosons	$W^\pm$	1	2 · 3	
Higgs bosons	$H^\pm$	0	2	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	2 · 4	Dirac

⇒ as many analyses as possible   [never believe us theorists when we claim we know better]

SUSY LES HOUCHES ACCORD

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. $m(q = TeV, v, m_t)$?]
  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: FIttino, Sfitter

- dark matter calculators: Micromegas

$\Rightarrow$ fixed parameter convention and read-write format
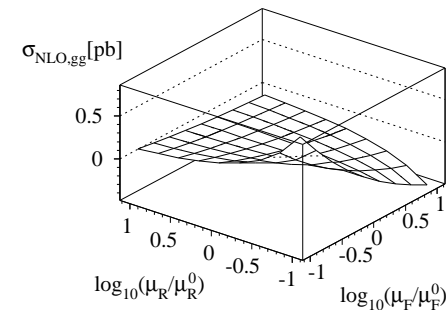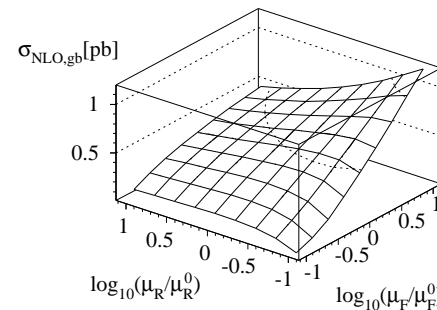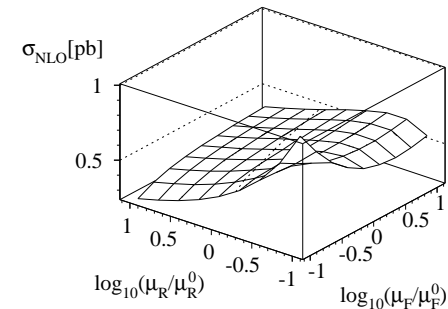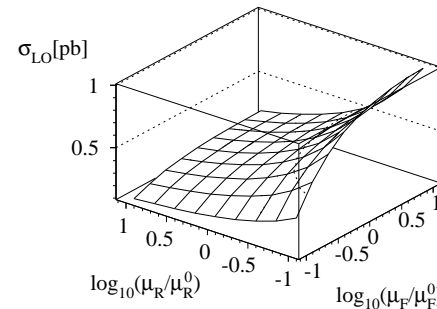
NLO Cross Sections

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]

$\Rightarrow$ NLO neither for the fun nor for larger cross sections

PROSPINO2 CODE

NLO cross sections for Tevatron (and LHC)

- compute total cross sections for heavy particles   [TeV scale input through SLHA]

- all two-particle SUSY production channels included   [$\tilde{q}\tilde{\chi}$ being tested]

- extended version beyond Prospino2: $p\bar{p} \to SS^*...$

- 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   [any F90 compiler I ever found will do]

(3) make, run executable

(4) find results in file prospino.dat $\Rightarrow$ normalize cross sections

```
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

  i1 i2        scafac  m1    m2 angle   LO[pb] rel-error   NLO[pb] rel-error   K
```

PROSPINO2 CODE

```fortran
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
```
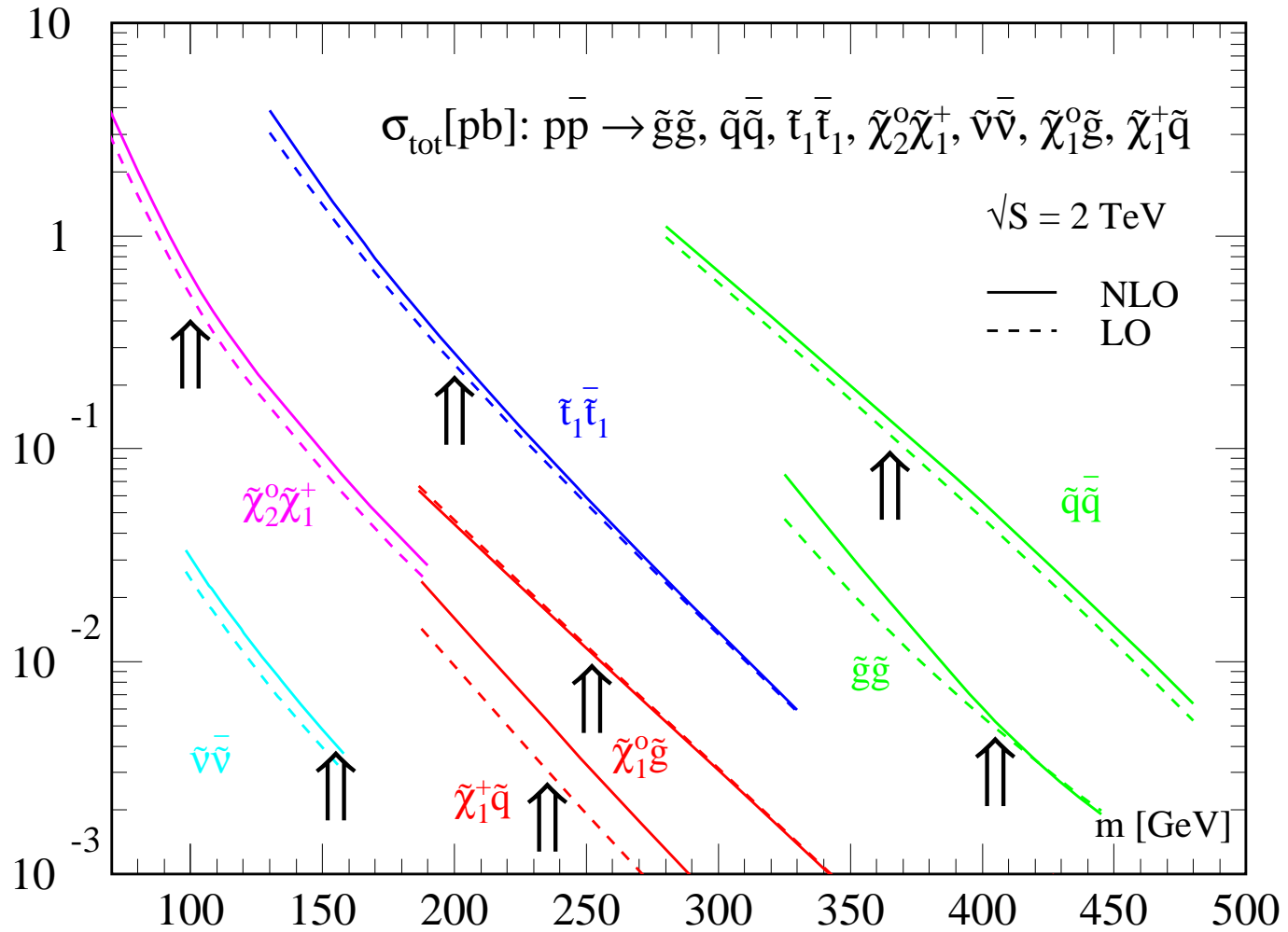
$\sigma_{tot}[pb]: p\bar{p} \rightarrow \tilde{g}\tilde{g}, \tilde{q}\bar{\tilde{q}}, \tilde{t}_1\bar{\tilde{t}}_1, \tilde{\chi}_2^o\tilde{\chi}_1^+, \tilde{\nu}\bar{\tilde{\nu}}, \tilde{\chi}_1^o\tilde{g}, \tilde{\chi}_1^+\tilde{q}$

$\sqrt{S} = 2$ TeV

NLO
LO

$\tilde{t}_1\bar{\tilde{t}}_1$

$\tilde{\chi}_2^o\tilde{\chi}_1^+$

$\tilde{q}\bar{\tilde{q}}$

$\tilde{\nu}\bar{\tilde{\nu}}$

$\tilde{\chi}_1^o\tilde{g}$

$\tilde{g}\tilde{g}$

$\tilde{\chi}_1^+\tilde{q}$

m [GeV]

SUSY-MADGRAPH/MADEVENT

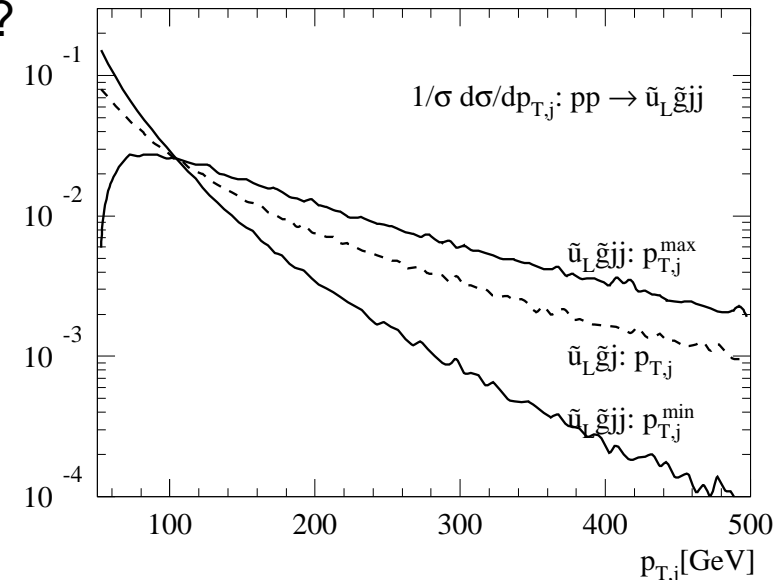## Smadgraph: we are done! [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

– 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, $p_{T,j} > 100$ GeV]

σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85

$\Rightarrow$ where from: gluon radiation vs. initial states?

$\Rightarrow$ modelling: comparison with Phythia6.2/6.3

$1/\sigma\ d\sigma/dp_{T,j}: pp \rightarrow \tilde{u}_L\tilde{g}jj$

$\tilde{u}_L\tilde{g}jj: p_{T,j}^{max}$

$\tilde{u}_L\tilde{g}j: p_{T,j}$

$\tilde{u}_L\tilde{g}jj: p_{T,j}^{min}$

$p_{T,j}$[GeV]

SUSY-MADGRAPH/MADEVENT

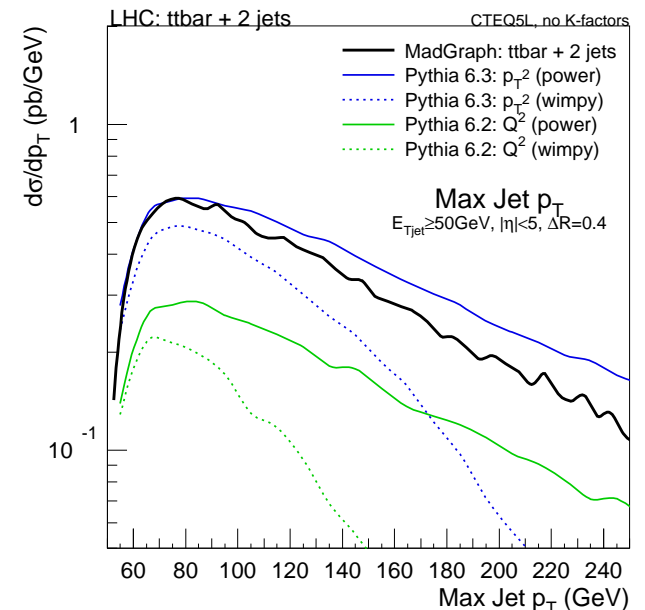## Smadgraph: we are done! [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

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Tilman Plehn: Supersymmetry – p.9

Jet ratiation: 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]

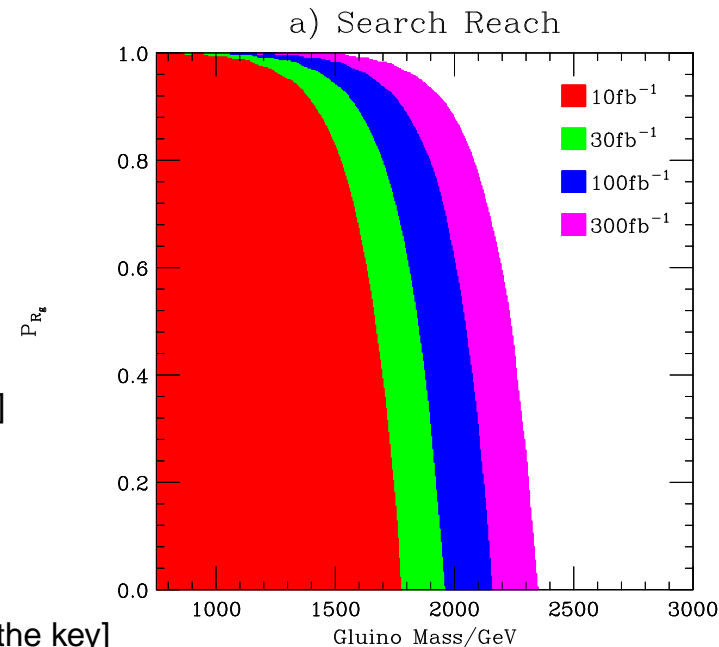## Split Supersymmetry   [Dimopoulos, Arkani-Hamed; Giudice, Romanino; Wells]

– 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]

$\Rightarrow$ make scalars heavy   [limited by cosmology]

$\Rightarrow$ protect gaugino and higgsino masses at TeV scale   [Drees: might not be possible]

News for phenomenology   [Kilian, TP, Richardson, Schmidt]

– no cascade decays

$\Rightarrow$ hadronizing gluinos $[\tau \sim \tilde{m}^{-4} \sim 6.5\text{s}$ for $\tilde{m} = 10^9 \text{GeV}]$
heavy R hadrons   [e.g. Kraan]
gluinonium   [e.g. Cheung & Keung]

– renormalization group running without scalars

$\Rightarrow$ corrections to protected couplings   [ino Yukawas 20%]

Collider prospects   [no matter what you or I think about model]
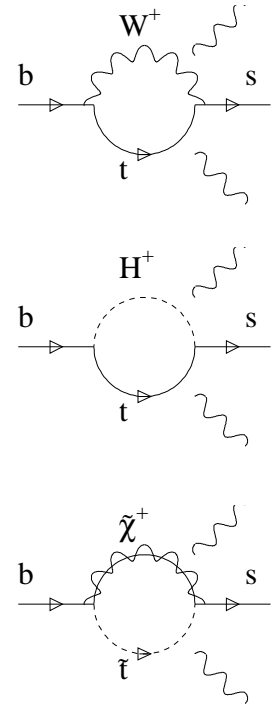
– LHC: stable gluino to ~ 2 TeV   [time of fight and charge the key]

– direct neutralino/chargino production without lepton-lepton edge?

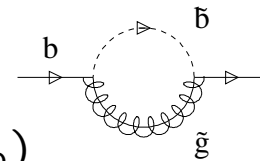a) Search Reach

$P_{R_{\tilde{g}}}$

10fb^{-1}
30fb^{-1}
100fb^{-1}
300fb^{-1}

Gluino Mass/GeV

Tevatron channel: $B_s \to \mu\mu$

- s-channel exchanges dominant: H, Z, γ
  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   [$BR_{2HDM} \propto \tan^6\beta/m_A^4$]
  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: $y_b \to y_b/(1 + \Delta_b)$

- 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+μ
    [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

OUTLOOK

Supersymmetry at hadron colliders

–   direct searches for SUSY: mass peaks

–   indirect searches for BSM: B physics etal.

–   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...

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

$\Rightarrow$ LHC better than expected

$\Rightarrow$ LHC+ILC without assumptions

$\Rightarrow$ P. Zerwas' talk: SUSY breaking

	LHC	ILC	LHC+ILC	SPS1a
$\tan\beta$	10.22 ± 9.1	10.26 ± 0.3	10.06 ± 0.2	10
M_1	102.45 ± 5.3	102.32 ± 0.1	102.23 ± 0.1	102.2
M_3	578.67 ± 15	fix 500	588.05 ± 11	589.4
$M_{\tilde{\tau}_L}$	fix 500	197.68 ± 1.2	199.25 ± 1.1	197.8
$M_{\tilde{\tau}_R}$	129.03 ± 6.9	135.66 ± 0.3	133.35 ± 0.6	135.5
$M_{\tilde{\mu}_L}$	198.7 ± 5.1	198.7 ± 0.5	198.7 ± 0.5	198.7
$M_{\tilde{q}3_L}$	498.3 ± 110	497.6 ± 4.4	521.9 ± 39	501.3
$M_{\tilde{t}_R}$	fix 500	420 ± 2.1	411.73 ± 12	420.2
$M_{\tilde{b}_R}$	522.26 ± 113	fix 500	504.35 ± 61	525.6
A_τ	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

PROSPINO2 STRUCTURE

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