Measuring the MSSM Lagrangean

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– TeV scale supersymmetry
– Inclusive + exclusive signals at LHC: Prospino2, Smadgraph
– Measurements at LHC (+ILC): Sfitter
– LHC pheno tools at work: split supersymmetry
Starting from data...

- ...which seem to indicate a light Higgs
- problem of light Higgs: scalar masses perturbatively unstable
  quadratic divergences $\delta m^2_h \propto g^2 \Lambda^2$
  all-orders Higgs mass driven to cutoff $m_h \to \Lambda$

$\Rightarrow$ solution: counter term for exact cancellation $\Rightarrow$ artificial, unmotivated, ugly

$\Rightarrow$ or new physics at TeV scale: supersymmetry
  extra dimensions
  little Higgs (pseudo–Goldstone Higgs)
  Higgsless/composite Higgs
  YourFavoriteNewPhysics...

$\Rightarrow$ all beautiful concepts and symmetries

$\Rightarrow$ in general problematic to realize at TeV scale $[$data seriously in the way$]$

Idea of supersymmetry: cancellation of divergences through statistics factor (-1)

$[$scalars vs. SM fermions; fermions vs. SM gauge bosons; fermions vs. SM scalars$]$
Bright side

- 3 running gauge couplings meet — GUT gauge group
- 2 Higgs doublets — radiative symmetry breaking
- R parity — stable proton yields dark matter
- local supersymmetry – including gravity?
- rich LHC phenomenology — no nasty surprises

Dark side

- unknown SUSY breaking
  → masses, couplings, phases...
  → e.g. hierarchical spectrum? [Split SUSY]
- flavor physics and SUSY breaking
  → CKM and lepton flavor?
- 2 Higgs doublet model
  → $\mu$ parameter and SUSY breaking?

$\Rightarrow$ as many as exclusive analyses as possible
Structures in the SUSY spectrum [Drees, Martin]

- gauginos–higgsinos mixing: $m_{\tilde{\chi}^0_2} \sim m_{\tilde{\chi}^+_1}$ or $m_{\tilde{\chi}^0_1} \sim m_{\tilde{\chi}^+_1}$ in MSSM

$$
\begin{pmatrix}
  m_\tilde{B} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\
  0 & m_\tilde{W} & m_Z c_w c_\beta & -m_Z c_w s_\beta \\
  -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\
  m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0
\end{pmatrix}
\begin{pmatrix}
  m_\tilde{W} & \sqrt{2} m_W s_\beta \\
  \sqrt{2} m_W c_\beta & -\mu
\end{pmatrix}
$$

- stop and sbottom mixing in MSSM

$$
\begin{pmatrix}
  m^2_\tilde{U} + m^2_t + \left(\frac{1}{2} - \frac{2}{3} s^2_w\right) m^2_Z c^2_\beta & -m_t \left(A_t + \mu \cot \beta\right) \\
  -m_t \left(A_t + \mu \cot \beta\right) & m^2_\tilde{d} + m^2_t + \frac{2}{3} s^2_w m^2_Z c^2_\beta
\end{pmatrix}
$$

- heavy gluinos and squarks through unification: $m_{\tilde{B}, \tilde{W}, \tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6$
  $m_{\tilde{\ell}, \tilde{q}}/m_{1/2} \sim 0.7, 2.5$ [$m_0 \ll m_{1/2}$]

[mass and coupling unification independent]
Supersymmetric parameter conventions

- comparison of specialized codes crucial [remember: e.g. Comphep–Pythia–Isajet]

⇒ fix SUSY conventions once for all

  soft breaking parameters [e.g. ±A_t]
  scale dependence of couplings, masses [e.g. m(q = TeV, v, m_t)?] 
  definitions of mass matrixes, mixing angles [e.g. ð_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
- SUSY parameter extraction: Fittino, Sfitter
- dark matter: Micromegas

⇒ fixed parameter convention and read-write format [list to be extended]
Supersymmetry at the LHC

1. possible discovery — signals for new physics, exclusion of parameter space
2. measurements — masses, cross sections, decays
3. parameter studies — MSSM Lagrangean, SUSY breaking

⇒ at least 10% precision to be matched at LHC [theorist’s nightmare, yet unsolved]

Hadron collider observables with errors

* masses from $\sigma_{\text{tot}}$
* branching fractions from $\sigma_{\text{tot}}$
  – renormalization scale from $\alpha_s$, $y_{b,t}$
  – factorization scale from pdf’s
  – perturbative series $N_c\alpha_s/\pi \sim 10\%$
  – finite terms [LO-NLO-NNLO: DY, Higgs]

⇒ NLO errors: 15...40 % for SUSY particles
Prospino2: NLO cross sections for Tevatron and LHC

- all two-particle SUSY production channels included
- download from Prospino2 page: http://pheno.physics.wisc.edu/~plehn
- extended version beyond Prospino2: \( pp \rightarrow SS^*, tH^- \)... 

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

SUSY signals included

- jets and \( E_T \): \( pp \rightarrow \bar{q}q^*, \bar{g}g, qg \)
- funny tops: \( pp \rightarrow \bar{t}_1t_1^* \)
- like sign dileptons: \( pp \rightarrow \bar{g}g \)
- \( \bar{g} \rightarrow \bar{u}u \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^- \) or c.c.
- tri-leptons: \( pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^- \)
- \( \tilde{\chi}_2^0 \rightarrow \bar{\ell}\ell \rightarrow \tilde{\chi}_1^0 \ell\ell; \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \ell\bar{\nu} \)
- bottoms and \( E_T \): \( pp \rightarrow \bar{b}_1\bar{b}_1^* \)
Regularization of supersymmetric theory: $\overline{\text{MS}}$ scheme

+ SUSY-QCD next-to-leading order is mostly QCD [i.e. $\alpha_s$, $y_b$, pdf,...]

$- \overline{\text{MS}}$ breaks SUSY, but does not violate Ward identities [d.o.f. of gluinos; Jack, Jones]

$\rightarrow$ correct vertices using additional ‘renormalization’ [Martin, Vaughn]

example: $qqh$, $q\bar{q}h$, $q\bar{q}\bar{h}$ vertices in naive $\overline{\text{MS}}$

$$ (mg)_{qqh} \equiv m_{g_{\overline{\text{MS}}}} \quad (mg)_{q\bar{q}h} = (mg)_{q\bar{q}h} \left( 1 + \frac{\alpha_s C_F}{4\pi} \right) \quad (mg)_{q\bar{q}\bar{h}} = (mg)_{q\bar{q}h} \left( 1 + \frac{3\alpha_s C_F}{8\pi} \right) $$

$\rightarrow$ complete set of corrections purely technical complication [Stöckinger]

$\overline{\text{DR}}$ scheme

+ assume gauge invariance not an issue [Siegel]

+ $\overline{\text{DR}}$ scheme explicitly supersymmetric [only shift in space-time dimension]

$- \quad$ inconvenient, missing QCD infrastructure

$- \quad$ additional contribution to collinear factorization with massive final states [Beenakker...; van Neerven, Smith]
SUSY spectra from cascade decays

- decay $\tilde{g} \rightarrow \tilde{q}\tilde{q} \rightarrow \tilde{\chi}_2^0 q\tilde{q} \rightarrow \mu^+\mu^- q\tilde{q}\tilde{\chi}_1^0$ [better not via Z or to $\tau$]
- cross sections some 100 pb [more than $3 \times 10^5$ events]
- thresholds & edges [Hinchliffe, Paige...; Cambridge ex-th]
critical: enough thresholds and edges available?

$$\text{classical } m_{\ell\ell}^2 < (m_{\chi_2^0}^2 - m_{\ell}^2)(m_{\ell}^2 - m_{\chi_1^0}^2)/m_{\ell}^2$$

$\Rightarrow$ detector resolution, calibration, systematic errors? [Polesello. Gjelsten, Miller, Osland]

Side remark: problem in decay studies

- typical cuts: $p_{T,j}>150,100,50,50$ GeV
- (a) cuts on $p_{T,j}$ hierarchy?
  (b) combinatorics through jet radiation?
$\Rightarrow$ matrix elements for SUSY + hard jets
$\Rightarrow$ Smadgraph [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]
Theorist’s point of view

- measured masses, cross sections, decays secondary
- parameters in SUSY Lagrangean from measurements

⇒ SUSY breaking parameters at TeV (or higher) scale

Warmup: Sugra top–down fit with errors

- fit including all errors
  [Allanach et al; Jack & Jones]

| m_0   | SPS1a | Δ at LHC | Δ at ILC | Δ at LHC+ILC |
|-------|-------|----------|----------|-------------|
|       | stat  | stat+theo| stat     | stat+theo   |
| 100   | 4.0   | 4.7      | 0.09     | 0.6         |
| 250   | 1.8   | 2.6      | 0.13     | 0.6         |
| 10    | 1.3   | 3.5      | 0.14     | 0.3         |
| -100  | 31.8  | 32.4     | 4.43     | 8.5         |

- spectrum from Suspect  [Djouadi, Kneur]
  fit Suspect and Softsusy  [Allanach]

⇒ no one best way to estimate theory errors
SUSY MEASUREMENTS AT LHC: 3

SUSY parameters from observables

- parameters: weak-scale MSSM Lagrangean
- measurements: masses  [Suspect, Softsusy, FeynHiggs...]
  branching fractions    [MSMlib, Sdecay]
  cross sections        [Prospino, 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+ILC with no assumptions
Split Supersymmetry [Dimopoulos, Arkani-Hamed; Giudice, Romanino; Wells; Drees]

- 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 all scalars heavy [hope: $\tilde{m} \rightarrow m_{\text{GUT}}$?]
⇒ protect all gaugino and higgsino masses [ $m_{\tilde{\chi}}, m_{\tilde{\gamma}} \lesssim \text{TeV}$ ]

What's new for phenomenology?

- no squarks, sleptons for colliders, astro-particle physics [Giudice, Romanino; Pierce]
- no cascade decays
- stable (hadronizing) gluinos [ $\tau \sim \tilde{m}^{-4} \sim 6.5s$ for $\tilde{m} = 10^9\text{GeV}$]
- heavy hadrons $R_g, R_{qq}, R_{qqq}$ [Farrar, Fayet; Baer, Cheung, Gunion; UKQCD; Kraan]
- renormalization group running without scalars [e.g. different ino Yukawa couplings by $\lesssim 20\%$]

Collider tests

(1) Is it supersymmetry?
(2) Is it split?
Split SUSY at the LHC [Kilian, TP, Richardson, Schmidt]

- neutralinos, charginos like in MSSM, poor precision [Prospino2]
- many gluinos pair-produced \([\sigma \gtrsim 1 \text{ pb}, \text{Prospino2}]\)
- gluinonium \(\bar{g}g \rightarrow jj\) [Kühn, Ono; Goldman, Haber; CMS; reach \(\sim \text{TeV}\)]
- neutral R hadrons missing \(\rightarrow\) missing energy signal
- charged R hadrons in tracker, calorimeter, muon chambers [Cambridge ex-th]
- mass measurement through time of flight tracker–muon chamber
Split Supersymmetry at the ILC  [Kilian, TP, Richardson, Schmidt]

– gluinos not produced because of decoupled squarks
– neutralino–chargino sector analysis as usual  [robust towards decay channels]
– anomalous Yukawas ≡ off-diagonal mass matrix entries  \([gs_\beta , gc_\beta , g's_\beta , g'c_\beta ]\)

⇒ (1) direct measurements of \(\chi\chi h\)  [Whizard, Smadgraph → distinctly unpromising]
(2) indirect determination of mass matrices  [poor man's Sfitter]

Indirect determination

– errors crucial  [0.5 % error on masses at ILC]
– \(10^4\) smeared pseudo-measurements to extract parameters from
⇒ analytic inversion impossible, fit instead
⇒ errors from distribution of \(10^4\) best fits
Split Susy at Colliders: 3B

\[ \sigma_{\text{tot}} [\text{fb}] \]

\[ e^+e^- \rightarrow \tilde{\chi}\tilde{\chi}H \]

\[ e^-\bar{\nu}W^+H \]

\[ \nu\bar{\nu}ZH \]

\[ \tilde{\chi}_1^+\tilde{\chi}_1^-H \]

\[ \tilde{\chi}_1^+\tilde{\chi}_2^-H \]

\[ e^-\bar{\nu}W^+ZH \]

\[ \tilde{\chi}_3^0\tilde{\chi}_4^0H \]

\[ \nu\bar{\nu}ZZH \]

\[ \tilde{\chi}_3^0\tilde{\chi}_3^0H \]

\[ \tilde{\chi}_1^0\tilde{\chi}_2^0H \]

\[ \begin{array}{c}
\sqrt{s} [\text{GeV}] \\
200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400
\end{array} \]
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Indirect determination

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Error on anomalous Yukawa couplings

|       | Fit tanβ | $m_j$ | $\sigma_{ij}$ | $\Delta \kappa_u$ | $\Delta \kappa_d$ | $\Delta \kappa'_u$ | $\Delta \kappa'_d$ |
|-------|----------|-------|----------------|------------------|-----------------|-----------------|-----------------|
| ILC   | •        | •     | •             | $0.9 \times 10^{-2}$ | $3 \times 10^{-2}$ | $1.3 \times 10^{-2}$ | $4 \times 10^{-2}$ |
| ILC   | •        | •     | •             | $1.2 \times 10^{-2}$ | $5 \times 10^{-2}$ | $2 \times 10^{-2}$ | $5 \times 10^{-2}$ |
| ILC   | •        | •     | •             | $1.1 \times 10^{-2}$ | $5 \times 10^{-2}$ | $3 \times 10^{-2}$ | $8 \times 10^{-2}$ |
| ILC   | •        | •     | •             | $1.2 \times 10^{-2}$ | $11 \times 10^{-2}$ | $4 \times 10^{-2}$ | $8 \times 10^{-2}$ |
| LHC   | •        | •     | •             | $2.2 \times 10^{-1}$ | $6 \times 10^{-1}$ | $2.7 \times 10^{-1}$ | $8 \times 10^{-1}$ |

Verdict

- LHC: stable R hadrons, charginos and neutralinos
- ILC: anomalous Yukawa couplings
- IceCube: one event per year for low-mass R hadrons [Hewett, Lillie, Mazip, Rizzo]
- Pierre Auger: few events for $\tilde{m} < 10^{11}$ GeV [Anchordoqui, Goldberg, Nunez]

$\Rightarrow$ split supersymmetry identifiable at combination of colliders
$\Rightarrow$ what stays: exotic heavy hadrons visible at LHC

why did we ever assume MSSM-type ino Yukawas?
Outlook

Theory effort for SUSY at the LHC well advanced
- inclusive searches plus cascade reconstruction with great promise
- total cross sections available to NLO [Propino2]
- automatic matrix element generators being tested [Smadgraph, Whizard, Sherpa]
- parameter extraction tools in use for LHC–ILC studies [Sfitter, Fittino]
⇒ errors will be crucial at LHC

Showcase: Split Supersymmetry
- interesting phenomenology
- LHC: R hadrons observable with mass measurement
- ILC: anomalous weak-ino Yukawas accessible
⇒ some features always benefit future analyses
APPENDIX: 2

(a) $\sigma/dm_{ll}$ (Events/100fb$^{-1}$/0.375GeV)

(b) $\sigma/dm_{llq}$ (Events/100fb$^{-1}$/5GeV)

(c1) High $m_{ll}$ (GeV)

(c2) Low $m_{ll}$ (GeV)

(d) $\sigma/dm_{llq}$ (Events/100fb$^{-1}$/5GeV)

(e) $\sigma/dm_{zq}$ (Events/100fb$^{-1}$/5GeV)
The plot shows the relationship between the mass of the gluino (\( \tilde{m} \)) and its lifetime (\( \tau \)). The horizontal lines represent different energy thresholds: 2 TeV and 0.5 TeV, with the latter being the mass threshold for gluino hadronization. The vertical lines indicate key events:

- Gluino leaves detector
- Displaced vertex
- Gluino hadronizes

The plot also highlights the lifetime of the universe.
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- tri-leptons: pp → $\tilde{\chi}_2^0\tilde{\chi}_1^-$
  $[\tilde{\chi}_2^0 \to \ell\ell \to \tilde{\chi}_1^0\ell\ell;\tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\nu]$
- bottoms and $E_T$: pp → $\bar{b}_1\bar{b}^*_1$