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- Split and TeV scale supersymmetry
- Signals at the LHC
- Signals at the ILC
- What stays [W. Kilian, P. Richardson, TP, E. Schmidt: EPC C39]
Starting from data...

- ...which seem to indicate a light Higgs

- problem of light Higgs: scalar masses perturbatively unstable
  quadratic divergences $\delta m_h^2 \propto g^2 \Lambda^2$
  all-orders Higgs mass driven to cutoff $m_h \to \Lambda$

⇒ solution: counter term for exact cancellation ⇒ artificial, ugly, fine tuned

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

⇒ all beautiful concepts and symmetries

⇒ 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]
**TeV Scale Supersymmetry: 2**

**Bright side**
- light fundamental Higgs by construction [data]
- 3 running gauge couplings meet — GUT gauge group [data]
- R parity — stable proton yields dark matter [data]
- 2 Higgs doublets — radiative symmetry breaking [beauty]
- local supersymmetry – including gravity? [beauty]
- rich LHC phenomenology [effective theory of everything short–lived]

**Dark side**
- unknown Susy breaking
  → masses, couplings, phases
- flavor physics and Susy breaking
  → CKM and lepton flavor?
- 2 Higgs doublet model
  → $\mu$ and Susy breaking? [Giudice, Masiero]

$\Rightarrow$ as many exclusive analyses as possible [never believe us theorists when we say we know...]

| spin | d.o.f. | spin | d.o.f. |
|------|--------|------|--------|
| $g$  | $\frac{1}{2}$ | $g$  | 2  |
| $\tilde{g}$ | 1/2 | $\tilde{g}$ | 2 |
| $h^0$, $H^0$, $A^0$ | 0 | $\tilde{A}^0$ | 3 |
| $\chi^0_1$ | $\frac{1}{2}$ | $\chi^0_1$ | $4 \cdot 2$ |
| $W^\pm$ | 1 | $W^\pm$ | $2 \cdot 3$ |
| $H^\pm$ | 0 | $H^\pm$ | 2 |
| $\tilde{\chi}^\pm_1$ | $\frac{1}{2}$ | $\tilde{\chi}^\pm_1$ | $2 \cdot 4$ |
| $f_L$, $f_R$ | $1/2$ | $f_L$, $f_R$ | 1+1 |
| $\tilde{f}_L$, $\tilde{f}_R$ | 0 | $\tilde{f}_L$, $\tilde{f}_R$ | 1+1 |
Gauginos and higgsinos in the SUSY spectrum  

- 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

\[
\begin{pmatrix}
m_{\tilde{B}} & 0 & -m_{Z}\sin\beta c_{\beta} & m_{Z}\sin\beta s_{\beta} \\
0 & m_{\tilde{W}} & m_{Z}\cos\beta c_{\beta} & -m_{Z}\cos\beta s_{\beta} \\
-m_{Z}\sin\beta c_{\beta} & m_{Z}\cos\beta c_{\beta} & 0 & -\mu \\
m_{Z}\sin\beta s_{\beta} & -m_{Z}\cos\beta s_{\beta} & -\mu & 0
\end{pmatrix}
\begin{pmatrix}
m_{\tilde{W}} \\
\sqrt{2}m_{Z}\cos\beta s_{\beta}
\end{pmatrix}
\]

- heavy gluinos through unification:  \( m_{\tilde{B},\tilde{W},\tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6 \)  
  [mass and coupling unification independent]

- lightest Susy partner  \( \tilde{\chi}^0_1, \tilde{\nu} \)  
  \( \Rightarrow \)  after dark matter data  \( \tilde{\chi}^0_1 \sim \tilde{B}, \tilde{W} \)  
  [Ellis, Falk, Olive...]

[Tilman Plehn: Split Supersymmetry at Colliders – p.4]
Split supersymmetry  [Dimopoulos, Arkani-Hamed; Giudice, Romanino]

– 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 from data]
– notice that scalars are evil  [lepton and quark flavor, Higgs mass and LEP2]
– remember simple facts about unification  [SU(5) multiplets decouple; Dawson, Georgi 1979]
⇒ make all scalars heavy  [hope: $\tilde{m} \rightarrow m_{\text{GUT}}$?]
⇒ protect all gaugino and higgsino masses  [ $m_{\tilde{\chi}_1^\pm}, m_{\tilde{g}} \lesssim \text{TeV}$ ]

Fine tuning no excuse for multi–billion dollar experiments  [trigger by popular vote of theorists?]

– gluinos and gauginos at the LHC
– gauginos and higgsinos at the ILC
⇒ is it supersymmetry?
⇒ is it split?
HEAVY SCALARS AND THE HIGGS MASS

Giudice, Romanino; Arvantaki, Davis, Graham, Wacker

- known leading corrections increased: \( m_h \sim m_Z + G_F y_t^4 \log \left( \frac{m_t^2}{m_t^2} \right) \)

⇒ large \( m_h \) for heavy stops [out of LEP2 reach]

⇒ not a precision observable anymore [large logarithms]

⇒ light Higgs is a SM Higgs boson with \( m_h \gtrsim 140 \text{ GeV} \)
Physics of Split Supersymmetry: 2

Heavy scalars and the Higgs mass [Giudice, Romanino; Arvantaki, Davis, Graham, Wacker]

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Heavy scalars and the gluino life time [Arkani-Hamed, Dimopoulos; Giudice, Romanino]

- decay through squark \( \tau_g \sim \tilde{m}^4/m^5_g \)

- loop-induced decays? [Toharia, Wells]

- lifetime constrained by age of universe

- \( \tilde{m} \lesssim 10^{12}\text{GeV} \ll m_{\text{GUT}} \) [PeV? Wells]

\( \Rightarrow \) gluino hadronizes, decays much later

\( \Rightarrow \) long-lived gluino collider signature No.1

Tilman Plehn: Split Supersymmetry at Colliders – p.7
Renormalization group running

– argued unification, so make Split Susy a GUT
– gauge couplings unify
– gaugino masses as well
Renormalization group running

– argued unification, so make Split Susy a GUT
– gauge couplings unify
– gaugino masses assumed to unify as well

Anomalous ino Yukawa coupling

– gauginos–higgsinos mixing in MSSM:

\[
\begin{pmatrix}
    m_B & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\
    0 & m_W & m_Z c_w c_\beta & -m_Z c_w s_\beta \\
    -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\
    m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \\
\end{pmatrix}
\]

– Yukawas/gaugino–higgsino mixing fixed by Susy
– supersymmetric beta functions broken at \( Q = \tilde{m} \)
– anomalous Yukawas collider signal No.2: \( \tilde{g}/\tilde{g}_{\text{MSSM}} = 1 + \kappa \)
LHC production of gauginos and higgsinos

- cross sections not small \[\mathcal{M}_j(m_{\text{GUT}}) = 120\text{GeV}; \sigma \text{ in fb from Prospino2}\]

| \(\tilde{g}\tilde{g}\) | 1710 | \(\tilde{\chi}_1^0 \tilde{\chi}_1^0\) | 49.4 | \(\tilde{\chi}_1^0 \tilde{\chi}_2^0\) | 73.7 | \(\tilde{\chi}_1^+ \tilde{\chi}_2^-\) | 73.7 | \(\tilde{\chi}_2^+ \tilde{\chi}_2^-\) | 584 |
|-----------------|-------|------------------|-------|------------------|-------|------------------|-------|------------------|-------|
| \(\tilde{\chi}_1^- \tilde{\chi}_1^-\) | 2910  | \(\tilde{\chi}_1^- \tilde{\chi}_2^-\) | 914   | \(\tilde{\chi}_1^- \tilde{\chi}_3^-\) | 97.7  | \(\tilde{\chi}_1^- \tilde{\chi}_4^-\) | 97.7  | \(\tilde{\chi}_1^- \tilde{\chi}_4^-\) | 97.7  |
| \(\tilde{\chi}_2^- \tilde{\chi}_1^-\) | 2.7   | \(\tilde{\chi}_2^- \tilde{\chi}_2^-\) | 4.5   | \(\tilde{\chi}_2^- \tilde{\chi}_3^-\) | 97.7  | \(\tilde{\chi}_2^- \tilde{\chi}_4^-\) | 97.7  | \(\tilde{\chi}_2^- \tilde{\chi}_4^-\) | 97.7  |
| \(\tilde{\chi}_2^- \tilde{\chi}_1^-\) | 4.5   | \(\tilde{\chi}_2^- \tilde{\chi}_2^-\) | 4.5   | \(\tilde{\chi}_2^- \tilde{\chi}_3^-\) | 97.7  | \(\tilde{\chi}_2^- \tilde{\chi}_4^-\) | 97.7  | \(\tilde{\chi}_2^- \tilde{\chi}_4^-\) | 97.7  |
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- but best background rejection \(m_\ell\ell\) gone with the wind [higgsino searches?]

What’s new for LHC phenomenology?

- no squarks, sleptons for cascades [Giudice, Romanino; astro-particle: Pierce]
- stable (hadronizing) gluinos \([\tau \sim \tilde{m}^{-4} \sim 6.5s \text{ for } \tilde{m} = 10^9\text{GeV}, \text{LHC time scale 25 ns}]\]
- heavy hadrons \(R_g, R_{q\bar{q}}, R_{qqq}\) [Farrar, Fayet 1978; Baer, Cheung, Gunion 1999; UKQCD 1999]
- gluinonium [Kühn, Ono 1984; Goldman, Haber 1985; Cheung]
Charged R hadrons

- many gluinos pair-produced \( [\sigma \gtrsim 1 \text{ pb}] \)
- charged R hadrons in tracker, calorimeter, muon chambers [Cambridge ex-th]
- level-1 trigger without muon chamber? [25...75 ns delay]
- effect of conversion to R baryons because of light pions? [Kraan]

\( \Rightarrow \) fraction of charged R hadrons crucial
\( \Rightarrow \) effective (not calculable) parameter \( P_{Rg} \)

![Graph showing search reach vs gluino mass/GeV for different data sets (10 fb⁻¹, 30 fb⁻¹, 100 fb⁻¹, 300 fb⁻¹).]
Split Susy at the LHC: 2

Charged R hadrons
- many gluinos pair-produced \[ \sigma \gtrsim 1 \text{ pb} \]
- charged R hadrons in tracker, calorimeter, muon chambers \[ \text{[Cambridge ex-th]} \]
- level-1 trigger without muon chamber? \[ \text{[25...75 ns delay]} \]
- effect of conversion to R baryons because of light pions? \[ \text{[Kraan]} \]

\[ \Rightarrow \text{fraction of charged R hadrons crucial} \]
\[ \Rightarrow \text{effective (not calculable) parameter } P_R g \]

Beyond BSM signal
- mass measurement through time of flight \[ P_R g \]
- charge flipper \[ \text{[Kraan; Hewett, Rizzo,...]} \]
- energy deposition: no heavy lepton
Neutral R hadrons
- jets plus missing energy  \([\sim 10\% \text{ energy loss}]\)
- trigger dependent on cross section in calorimeter
- improved in combination with charged R hadron  \([\text{missing energy trigger}]\)
- mass measurement from gluinoonium
- R hadron flavor physics?
⇒ charged R hadrons preferable
Neutral R hadrons

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⇒ charged R hadrons preferable
Signals at the ILC

- gluinos not produced because of decoupled squarks
- neutralino–chargino sector analysis as usual  
  \[ \text{robust with changed decay channels} \]
- measurement of anomalous Yukawas  
  \[ \tilde{g}_u, \tilde{g}_d, \tilde{g}'_u, \tilde{g}'_d \text{ different by } \sim 10\% \]

\[ \Rightarrow (1) \text{ direct measurements of } \chi \chi H \]
Signals at the ILC

- gluinos not produced because of decoupled squarks
- neutralino–chargino sector analysis as usual [robust with changed decay channels]
- measurement of anomalous Yukawas [\(\tilde{g}_u, \tilde{g}_d, \tilde{g}_u', \tilde{g}_d'\)]

\[\Rightarrow\] (1) direct measurements of \(\chi\chi H\) [Whizard, Smadgraph; unpromising!]
(2) indirect determination of mass matrices

Extracting parameters from neutralino/chargino sector

- \(10^4\) smeared measurements of six masses (and cross sections)
- \(10^4\) fits of \(M_1, M_2, \mu\) and one or more \(\kappa_i\)
- LHC data alone not promising [masses only, 5% error]
Neutralinos/charginos at the ILC
- mass measurements to 0.5%
- error propagation through $10^4$ smeared pseudo-measurements

$\Rightarrow$ one $\kappa$ at the time to $\lesssim 5\%$
Neutralinos/charginos at the ILC

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- error propagation through $10^4$ smeared pseudo-measurements

$\Rightarrow$ one $\kappa$ at the time to $\lesssim 5\%$

$\Rightarrow$ four $\kappa$ simultaneously to $\lesssim 10\%$
Neutralinos/charginos at the ILC

- mass measurements to 0.5%, cross sections statistical error
- error propagation through $10^4$ smeared pseudo-measurements

⇒ one $\kappa$ at the time to $\lesssim 5$
⇒ four $\kappa$ simultaneously to $\lesssim 10$

So can we tell it is Split Susy?

- mass measurement errors conservative
- only mass and cross section measurements yet  [Sfitter-Fittino next step]

|       | $\text{Fit tan}\beta$ | $m_i$ | $\sigma_{ij}$ | $\Delta\kappa_u$ | $\Delta\kappa_d$ | $\Delta\kappa'_u$ | $\Delta\kappa'_d$ |
|-------|------------------------|------|---------------|------------------|------------------|------------------|------------------|
| 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   |                        |      |               | $2.2 \times 10^{-1}$ | $6 \times 10^{-1}$ | $2.7 \times 10^{-1}$ | $8 \times 10^{-1}$ |

⇒ anomalous Yukawas promising at ILC
Showcase for state-of-the-art LHC phenomenology: Split Supersymmetry
   – interesting phenomenology
   – LHC: R hadrons observable with mass measurement
   – ILC: anomalous weak-ino Yukawas accessible

What stays
   – exotic heavy hadrons visible at LHC [trigger issues]
   – why did we always assume MSSM-type ino Yukawas? [missed Susy test]