Supersymmetry: Lecture 3
superpartners in action

Yael Shadmi
Technion
gauge bosons (s=1) + gauginos (s=1/2)

photon + photino

gluon + gluinos

W + wino  Z + zino
fermions + sfermions (scalars)

quark + squark

electron + selectron ..

neutrino + sneutrino

2x( Higgs (s=0) + Higgsino (s=1/2) )
each superpartner: same charges as SM particle

→ GAUGE + YUKAWA INTERACTIONS COMPLETELY DICTATED

by SUSY + SM
superpartners appear in pairs

R-parity: SM fields = even superpartners=odd
the only freedom is in:

spectrum (determined by soft terms)

[+ interactions:
  – are there R-parity breaking couplings or not?
  – are gaugino-scalar-fermion couplings flavor diagonal or not? ]
spectrum (soft terms): many possibilities
  (depend on the mediation of SUSY breaking)

so: don’t listen to theorists ...

.. if they tell you they know what the superpartner masses are
where can we observe superpartners?

• virtual corrections:
  electric and magnetic dipole moments
  flavor violating processes
  widths of known particles

• direct production: LHC
virtual corrections:

most relevant for LHC searches:
flavor violating processes: eg

\[ K^0 - \bar{K}^0 \]

\[ b \rightarrow s\gamma \]

\[ \mu \rightarrow e\gamma \ldots \]

let’s talk about sleptons (easier)
relevant parameters:

eg R-sleptons: \( \tilde{l}_1, \ldots, \tilde{l}_3 \)

- 3 masses: \( m_1, m_2, m_3 \)
- mixings:

\[
\begin{align*}
\text{gaugino} & \quad l_i \quad \tilde{l}_j \\
\propto & \quad K_{ij} \quad i \neq j
\end{align*}
\]
<5.7 \cdot 10^{-13} \quad (\text{MEG})

essentially constrains:

\[ \delta_{ij} = \frac{\Delta m_{ij}^2 K_{ij}}{m^2} \]
\[ < 5.7 \cdot 10^{-13} \quad \text{(MEG)} \]

essentially constrains:

\[ \delta_{ij} = \frac{\Delta m^2_{ij} K_{ij}}{m^2} \]

\[ K_{ij} \to 0 \quad Br \to 0 \]

\[ \Delta m^2_{ij} \to 0 : \quad K^*_1 K_{2j} = 0 \quad \text{(super-GIM)} \quad Br \to 0 \]
Suppressing SUSY Flavor Violation

3 obvious approaches: (or combination)

\[ \delta_{ij} = \frac{\Delta m_{ij}^2 K_{ij}}{m^2} \]

- small mass splittings → degeneracy
Suppressing SUSY Flavor Violation

3 obvious approaches: (or combination)

\[ \delta_{ij} = \frac{\Delta m_{ij}^2 K_{ij}}{m^2} \]

small mixings: \( \rightarrow \) alignment
slepton mass matrix “aligned”
with lepton mass matrix:
approximately diagonal together
Suppressing SUSY Flavor Violation

3 obvious approaches:
(or combination)

\[ \delta_{ij} = \frac{\Delta m_{ij}^2 K_{ij}}{m^2} \]

3. increase masses:
taken care of by ATLAS and CMS ..
Suppressing SUSY Flavor Violation

3 obvious approaches: (or combination)

\[ \delta_{ij} = \frac{\Delta m_{ij}^2 K_{ij}}{m^2} \]

there are viable models of each type

3. increase masses: taken care of by ATLAS and CMS ..
LHC SEARCHES
supersymmetry is NOT a single model so:

rather than a **model based** approach

use a **signature based** approach

(both CMS and ATLAS!)
the only freedom is in:

spectrum (determined by soft terms)

[+ interactions:
  – are there R-parity breaking couplings or not?
  – are gaugino-scalar-fermion couplings flavor diagonal or not? ]
general considerations: interactions:

R-parity conservation

• production: superpartners produced in pairs

• decay: superpartner $\rightarrow$ superpartner + SM

• the lightest superpartner (LSP) is stable
R-parity violating coupling(s) (RPV):

• production: single superpartner (resonant) production is possible

• decay: a superpartner can decay to SM (jets, leptons)

(see below)
R-parity violating coupling(s) (RPV):  if small:

- production: single superpartner (resonant) production is possible
  competitive with gauge couplings because of kinematics

- decay: a superpartner can decay to SM (jets, leptons)
  only the LSP decays via the RPV coupling
general considerations: interactions:

flavor mixing

\[ \text{gaugino} \quad l_i \quad \sim l_j \quad \propto K_{ij} \quad i \neq j \]

mainly affects decay
general considerations: **spectrum:**

- *gluino*
- *squarks*
- *sleptons*  *sneutrinos*
- *charginos*  *neutralinos*

**colored vs non-colored:**

- generically:
  - colored heavier
  - (factor of few-10)

- (* don’t know squark vs gluino ??)

- sleptons vs neutralinos??

ESHEP2014

Yael Shadmi  Technion
**general considerations: spectrum:**

- gluino
- squarks
- sleptons
- sneutrinos
- charginos
- neutralinos

**colored vs non-colored:**
- generically: colored heavier (factor of few-10)

**expect:** squark gluino production dominates
general considerations: spectrum:

- gluino
- squarks
- sleptons
- sneutrinos
- charginos
- neutralinos

colored vs non-colored:

- if larger hierarchy (colored masses go up)
- EWK production more important (slepton, neutralino, chargino production)

LSP
general considerations: **spectrum:**

- gluino
- squarks
- **sleptons**  **sneutrinos**
- charginos  neutralinos

**identity of LSP**

neutral or charged?

(usually: neutralino or slepton)

**missing energy** or something else

**main distinguishing feature of SUSY**
general considerations: **spectrum:**

- **gluino**
- **squarks**

- **sleptons**  **sneutrinos**
- **charginos**  **neutralinos**

- **small mass differences**
- soft decay products
- long lifetimes

**LSP**
general considerations: spectrum:

- gluino
- squarks
- sleptons sneutrinos
- charginos neutralinos

extreme case: squished spectrum

- soft decay products
- little missing energy

ESHEP2014

Yael Shadmi  Technion
general considerations: spectrum:

- gluino
- squarks: flavor dependent or not? up squark=charm squark? d squark= s squark?
- sleptons sneutrinos
- charginos neutralinos: smuon=selectron?
- LSP
**production:** colored vs EWK

**strong:**

\[ p \rightarrow p \quad \tilde{q} \quad \tilde{q} \quad q \]
squark pair or squark gluino or gluino gluino

**EWK:**

\[ p \rightarrow p \quad \tilde{\ell} \quad \tilde{\ell} \quad \ell \]
slepton pair chargino pair ...

relative importance depends on colored masses vs EWK masses
**production:** flavor dependence

**strong:**

- squark pair
- or squark gluino
- or gluino gluino

**some channels flavor blind:**

- eg: \( gg \rightarrow \tilde{q} \tilde{q} \)

**some channels flavor sensitive:**

- larger for u-squark, d-squark
production: with R-parity violating coupling

in principle

\[ p \rightarrow q \]

single squark or slepton

coupling may be small but kinematics can win
**decay:**

(with no RPV coupling)

LSP = neutralino

- $q$
- wino
- $e$
- $q$
- $q$
- selectron

LSP = DM?

- LSP = DM?
- missing energy
decay: (with no RPV coupling)

LSP = slepton (stau?)
LSP = neutralino

- stable, neutral: good DM candidate (WIMP)
- LHC: transverse momentum imbalance: ``missing E_T``
- main handle against SM bgnds:
  - squark mass (or other mother particle) goes up: missing E_T goes up (LSP more boosted)
  - LSP mass goes up
    missing E_T goes down (LSP less boosted)
  efficiency goes down with mass difference
LSP = charged slepton

cosmology ?? ruled out if the slepton is stable
but it can be metastable:

- gluino
- squarks
- sleptons sneutrinos
- charginos neutralinos
  ____________ slepton = NLSP
LSP = charged slepton

cosmology ?? ruled out if the slepton is stable

but it can be metastable: remember the gravitino?

- gluino
- squarks

- sleptons
- sneutrinos

- charginos
- neutralinos

__________ slepton = NLSP

gravitino = LSP
• lifetime only depends on SB scale (gravitino mass) and slepton mass
• a whole range
• in particular: slepton can exit detector: looks like a muon
• if it’s seen: how do we know it’s not a muon?
• but will it be seen?
• it’s slow: $\beta < 1$
  
  trigger? reconstruction? usually assume $\beta = 1$
{this is a good example of
a ``practical application” of thinking about SUSY (other BSM) models

you could say (should say?) we will have this amazing machine
why not look for long-lived charged particles
(regardless of any BSM) }

low beta: is it lost (forever..)?
high beta: fake muon?

by now: good coverage in beta
muon detector (ATLAS) TOF
inner detector (CMS) dE/dx
apply to the simplest process:

Drell-Yan slepton production

with "zero SM bkgnd".
completely model independent: (almost)

any long-lived scalar with charges of slepton

(old result)
this is our first example of possible SUSY signatures
it’s the simplest: just DY production
no SM bgnd IF you identify the long-lived slepton
let’s move to harder examples

in the process:
  – see how the different considerations we listed come into play
  – learn about different handles for distinguishing signal from bgnd: usually the main challenge
Drell-Yan slepton production: but LSP=neutralino

final state: opposite sign (OS) leptons + missing ET
efficiency goes down with mass difference

• flavor: l=e, mu
what if not degenerate?
• flavor: l=e, mu
what if not degenerate?

Calibbi Galon Masiero Paradisi YS
in progress
• more info: separate info on selectron, smuon
squark/gluino pair production (neutralino LSP)
or a shorter squark decay

gluino decay

costs another jet
squark/gluino pair production (neutralino LSP)

- missing ET + at least 2-4 jets
- missing ET: main tool in fighting SM bgnd
- more: pair production of heavy particles

\[ m_{\text{eff}} = |\vec{p}_T^{\text{miss}}| + \sum_{\text{jets/vis}} |\vec{p}_T^i| \]
\[ H_T = \sum_{\text{jets}} |\vec{p}_T^i| \]

- SM falls
- heavy particle production kicks in,
- then falls more slowly
Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s} = 8$ TeV proton–proton collision data

signature based (simplified model)
efficiency goes down with mass difference
Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration

signature based (simplified model)
CMS, \( L = 19.5 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \)

\[ pp \rightarrow \tilde{q} \tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}^0_1 \] NLO+NLL exclusion

- Observed: \( \pm 1\sigma_{\text{theory}} \)
- Expected: \( \pm 1\sigma_{\text{experiment}} \)

- \( \tilde{q}_L + \tilde{q}_R \) (\( \bar{u}, \bar{d}, \bar{s}, \bar{c} \))
- One light \( \tilde{q} \)

95\% C.L. upper limit on cross section (pb)

\[ m_{\tilde{\chi}^0_1} \text{ [GeV]} \]

\[ m_{\tilde{q}} \text{ [GeV]} \]
more sophisticated kinematic variables:

**kinematic edges:**

$e^+ e^-$ from successive 2-body decays

\[ m_{e^+e^-}^2 \propto (m_{N2}^2 - m_{\tilde{e}}^2)(m_{\tilde{e}}^2 - m_{N1}^2) \]

signal is peaked whereas SM flat
event has to sides:

combinatorial bgnds

but there`s also an advantage:
``double” the number of kinematic variable
same number of unknowns (neutralino, slepton masses..)
construct variables that exploit this: $M_{T2}$
let`s go back and think about other things we mentioned:

**flavor: production:** squarks not necessarily degenerate
if gluino not very heavy: more sensitive to up, down

but efficiency drops with squark mass: light charm squarks hiding? (CMS plot: around 400 GeV)

**flavor: decay:** slepton mixing: not just e-e but also e-mu
**flavor: top:** the top is special:

theory:

- **RGE:** large top Yukawa: stop mass goes down stop usually lightest squark
- **top:** large contribution to quadratic divergence in Higgs mass
to avoid fine tuning: OK if just the stop is around the weak scale (with other squarks heavy)
  ```
  “natural supersymmetry”
  ```

this motivates dedicated stop searches
to conclude:

supersymmetry is a beautiful and powerful theoretical idea:

it`s an extension of space-time symmetry

it exchanges fermions and bosons

supersymmetric theories: only log divergences

(even when supersymmetry broken by mass splittings)
supersymmetric extensions of the SM:

no quadratic divergence in Higgs mass: natural theory (already some fine-tuning since superpartners are heavy)

field content + gauge and Yukawa interactions dictated (by SM + supersymmetry)

supersymmetry-breaking terms can be generated through spontaneous supersymmetry breaking
many different possibilities for the mediation (often just a few parameters determine all the 100 or so supersymmetry-breaking terms in the MSSM)

→ a variety of LHC signatures
when you discover something in the coming run:

is it supersymmetry?