Colored SUSY and R-hadron physics in the ATLAS detector

QCHS-06

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Outline

- SUSY reminders using SPS1a as an example
- Light $\tilde{t}$ scenario
- R-hadron phenomenology
- R-hadron measurements

Slide 2

RM6

OK, I might expand a little on this. Note how there is no detector part, as I couldn't find any other conference talks that described the detector.
Rasmus Mackeprang, 8/4/2006

Basic SUSY phenomenology

- Using SPS1a
- Defined in mSUGRA using parameters:
$$m_0 = -A_0 = 0.4 m_{\frac{1}{2}} = 100 \text{ GeV}$$
$$\tan \beta = 10, \mu > 0$$
- SUSY spectrum has $m_{\tilde{q}} > m_{\tilde{\chi}_2^0} > m_{\tilde{l}} > m_{\tilde{\chi}_1^0}$
so we have the squark decaying through a neutralino and a slepton to the χ_1^0 LSP which is stable and escapes the detector.

- Sequential decay:
SPS 1a

Snowmass paper
ISAJET 7.58

Mass spectrum plot showing various particles and their mass splittings (in GeV):

- H^0, A^0 and $H^\pm$ are near 380 GeV.
- $\tilde{g}$ is near 580 GeV.
- $\tilde{t}_2$ is near 550 GeV.
- $\tilde{u}_L, \tilde{d}_R$ and $\tilde{b}_2$ are near 520 GeV.
- $\tilde{u}_R, \tilde{d}_L$ and $\tilde{b}_1$ are near 480 GeV.
- $\tilde{\chi}_3^0$ and $\tilde{\chi}_2^\pm$ are near 380 GeV.
- $\tilde{\chi}_1^\pm$ is near 350 GeV.
- $\tilde{t}_1$ is near 350 GeV.
- $\tilde{l}_L$ and $\tilde{\tau}_2$ are near 200 GeV.
- $\tilde{\nu}_\tau$ is near 180 GeV.
- $\tilde{l}_R$ and $\tilde{\tau}_1$ are near 150 GeV.
- h^0 is near 120 GeV.
- $\tilde{\chi}_1^0$ is near 100 GeV.

Red arrows indicate mass splittings between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$, and between $\tilde{l}_L$ and $\tilde{l}_R$.

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RM1

Figures from JHEP09(2000)004

Rasmus Mackeprang, 8/2/2006

Kinematic variables

- As the χ_1^0 escapes the detector one may form these invariants: $m_{ll}, m_{l_1 q}, m_{l_2 q}, m_{llq}$
- Note that we don't know "near" from "far" lepton $\rightarrow$ Maximize/minimize in combination choice.

Kinematic edges and masses

$$(m_{ll}^2)^{edge} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

$$(m_{qll}^2)^{edge} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\chi}_2^0}^2}$$

$$(m_{ql}^2)_{min}^{edge} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)}{m_{\tilde{\chi}_2^0}^2}$$

$$(m_{ql}^2)_{max}^{edge} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

Choose to
minimize/maximize

Production and analysis cuts

- Events produced w PYTHIA 6.2 (100 fb^{-1}) and run through a fast detector simulation
- Analysis cuts:
 - ★ At least four jets satisfying
$$p_{t,1} > 150 \text{ GeV}, p_{t,2} > 100 \text{ GeV}, p_{t,3} > 50 \text{ GeV}$$
 - ★ $M_{eff} \equiv E_{t,miss} + p_{t,1} + p_{t,2} + p_{t,3} + p_{t,4} > 600 \text{ GeV}$
 - ★ $E_{t,miss} > \max(100 \text{ GeV}, 0.2 M_{eff})$
 - ★ Two isolated leptons (not τ) of opposite charge but same flavour (OSSF) with
$$p_t(l) > 20 \text{ GeV} \text{ and } p_t(l) > 10 \text{ GeV}$$

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RM19

Four jets stem from the other squark going through a $q \chi_1^+ \rightarrow q W^+ \chi_1^0 \rightarrow qqq \chi_1^0$

Rasmus Mackeprang, 8/29/2006

Lepton-lepton invariant mass

- Before and after OS-OF lepton background subtraction:

$$m(ll)^{\text{edge}} : 77.077^{\text{nominal}} \text{ vs. } 77.024^{\text{rec}} \pm 0.08^{\text{syst}} \pm 0.05^{\text{stat}}$$

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RM17

Following plots include subtraction

Rasmus Mackeprang, 8/28/2006

qll-edge

$$m(qll)^{\text{edge}} : 431.1^{\text{nominal}} \text{ vs. } 431.3^{\text{rec}} \pm 4.3^{\text{syst}} \pm 2.4^{\text{stat}}$$

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RM8

Just a visual confirmation that the method works

Rasmus Mackeprang, 8/4/2006

ql

$$m(ql)^{\text{Max}} : 380.3^{\text{nominal}} \text{ vs. } 379.4^{\text{rec}} \pm 3.8^{\text{syst}} \pm 1.8^{\text{stat}}$$

$$m(ql)^{\text{Min}} : 302.1^{\text{nominal}} \text{ vs. } 300.8^{\text{rec}} \pm 3.0^{\text{syst}} \pm 1.5^{\text{stat}}$$

Mass measurements

- Measure a number of parameters and constraints:

$$m_{ll}^{max}, m_{llq}^{max}, m_{lq}^{low}, m_{lq}^{high}, m_{llq}^{min}, m_{llb}^{min}, m(l_L) - m(\tilde{\chi}_1^0), \\ m_{ll}^{max}(\tilde{\chi}_4^0), m_{\tau\tau}^{max}, m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0), \dots$$

- Minimize chisquare function:

$$\chi^2 = \sum_j \left[\frac{E_j^{theory}(\vec{m}) - E_j^{exp}}{\sigma_j^{exp}} \right]^2$$

Atlas Performance Estimate

- Perform 10^5 "Atlas experiments" and study the RMS of the resulting distributions of parameters:

$\Delta m_{\tilde{\chi}_1^0}$	4.8	$\Delta m_{\tilde{l}_R}$	4.8
$\Delta m_{\tilde{\chi}_2^0}$	4.7	$\Delta m_{\tilde{q}_L}$	8.7
$\Delta m_{\tilde{b}_1}$	7.5	$\Delta m_{\tilde{g}}$	8.0
$\Delta m_{\tilde{q}_R}$	11.8	$\Delta m_{\tilde{b}_2}$	7.9
$\Delta m_{\tilde{l}_L}$	5.0	$\Delta m_{\tilde{\chi}_4^0}$	5.1

All errors in GeV.

$L = 300 \text{ fb}^{-1}$

Light $\tilde{t}$ Analysis

- Cosmological inspiration
 - Discard the demand for unification (no assumptions on SUSY breaking)
 - Require matter-antimatter asymmetry to be generated at EW scale (CPV + light $\tilde{t}$)
 - Fix MSSM parameters using cosmological observables.

Benchmark Point

- LHS-2 (Les Houches 2005)

MSSM Parameters (GeV):

1st. 2nd. gen. scalars	10000
3rd. gen. sleptons	1000
$m(Q_3)$	1500
$m(\tilde{t}_R)$	0
$m(\tilde{b}_R)$	1000
$A_{b,e,\mu,\tau}$	0
A_t	$-643 \exp \frac{i\pi}{2}$
M_1	60
M_2	120
μ	$400 \exp \frac{i\pi}{2}$
$\tan \beta$	7
$M(A)$	1000

SUSY Spectrum:

$\tilde{t}_1$	137
$\tilde{t}_2$	1510
$\tilde{g}$	948
$\tilde{\mu}, \tilde{e}$	~ 10000
$\tilde{\chi}_1^0$	58
$\tilde{\chi}_2^0$	112
χ_1^+	111
h	116

Basic Phenomenology

- Missing transverse energy
- Kinematics doesn't match t / W production
 - Jets too soft
 - Invariant mass combinations don't add up. (W's are virtual)

Basic Cuts

- One isolated e/μ with $p_t > 20$ GeV
- $E_{t,miss} > 20$ GeV
- 4 jets with $p_t > 25$ GeV (2 with $p_t > 35$ GeV)
- 2 b-jets

Efficiencies:

Signal: 0.47 % tt : 3.3 % $Wbbj$: 3.1 %

b/s ratio ~ 15 ☹ (but soft QCD is gone)

- Fast simulation study on 1.8 fb^{-1}

Excluding Ws

Demanding $m(jj)_{\min} < 60$ GeV removes a lot of W background $\rightarrow$ b/s ~ 10

After background subtraction

Next step would be fitting masses but that is a somewhat longer story...

R-hadrons

- Scenarios with metastable squarks/gluinos
- Coloured SUSY particle binds with quarks to form R-(parity-stable) hadrons. Hence the name...
- Possible scenario is split-SUSY:
 - Abandon hierarchy problem
 - SUSY broken far above the TeV scale → heavy scalars, light Higgs and light fermions
 - Long lived gluino

Interactions of Physics model for R-hadrons

- Quark system interacts
- Gluino is "just" a reservoir of kinetic energy
- Interactions are thought to be pomeron / reggeon mediated:

Figure: A.C. Kraan

Basic Phenomenology

- R-hadrons can change charge in hadronic interactions.
- R-mesons tend to acquire baryon number
- Cross section ensures hadronic interactions in calorimeter.
- A pure sample of R-hadrons can be selected basically by requiring opposite sign tracks in ID and muon system.
- Simulation implemented in Geant3 and Geant4

Energy loss per collision

300 GeV/c² gluino in iron:

Triggering

- Charged R-hadrons in muon system will pass the single- μ 6 GeV trigger at even very moderate kinetic energies.
- $\beta > 0.7$ satisfies timing.

Losses:

25 % @ 300 GeV/c²

60 % @ 1 TeV/c²

Additional O(50%) loss from hadronic interactions in muon system

Seeing is believing...

- That's QCD all right
- One high- p_t track
- Nothing on the other side
- Signal back-to-back in the muon system (10 GeV track cut)

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RM9

This is just an event display I made for illustrative purposes. I hope it is OK to use it.

Rasmus Mackeprang, 8/4/2006

Charge Flipping Quantified

- Split SUSY scenario: (2 fb^{-1})

- $\frac{p_T^\mu}{|p_T^{\text{ID}}|}$ for negative ID track. R-hadron does not "remember" initial charge.

R-hadron Mass Measurement

- Gluino does not decay → Mass measurement requires β -measurement.
- Use drift time in muon chambers:

$$T_i = T_0 - \frac{L_i}{c\beta}$$

T_i : Drift time

T_0 : Time from creation to detection.

β -measurement

- Use β as an assumption in track fit.
- Divide events into momentum intervals
- Minimize chi-square as:
- Use that

$$p = mc\beta\gamma$$

to fit the mass.

ATLAS Prelim.

Fitted mass

- Input gluino mass was $300 \text{ GeV}/c^2$
 $\Rightarrow$ Mass scale can be determined to $O(5-10\%)$ using simple and generic methods.

Summary

- The Atlas detector is sensitive to a broad spectrum of SUSY phenomenologies
- Statistics of one year of nominal running should suffice for many phenomenologies
- Knowledge of SM background (and thus of QCD) of paramount importance
- We have yet to find the elusive SUSY
- But hope prevails

Backup slides

ATLAS layout

Trigger & luminosity

- Low luminosity: $10^{33} \text{ cm}^{-2}\text{s}^{-1} \rightarrow 10 \text{ fb}^{-1}\text{yr}^{-1}$
- High luminosity: $10^{34} \text{ cm}^{-2}\text{s}^{-1} \rightarrow 100 \text{ fb}^{-1}\text{yr}^{-1}$

Trigger rates:

- Raw: 23 collisions / 25 ns (40 mHz)
- LVL1: 75 kHz
- HLT: $\sim 100 \text{ Hz}$

Cascade decays

- Sequential decay: $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_R^\mp l_{near}^\pm q \rightarrow \tilde{\chi}_1^0 l_{far}^\mp l_{near}^\pm q$

Large m_0
excludes decay
through slepton

- Branched:

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{\chi}_1^0 X q \rightarrow \tilde{\chi}_1^0 l^\mp l^\pm q$$

Edges and thresholds

Choose to
minimize/maximize

$$(m_{ll}^2)^{edge} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

$$(m_{ql}^2)^{edge} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\chi}_2^0}^2}$$

$$(m_{ql}^2)^{edge}_{min} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)}{m_{\tilde{\chi}_2^0}^2}$$

$$(m_{ql}^2)^{edge}_{max} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

$$(m_{ql}^2)^{thres} = \frac{[(m_{\tilde{q}_L}^2 + m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2) - (m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2) \sqrt{(m_{\tilde{\chi}_2^0}^2 + m_{\tilde{l}_R}^2)^2 (m_{\tilde{l}_R}^2 + m_{\tilde{\chi}_1^0}^2)^2 - 16 m_{\tilde{\chi}_2^0}^2 m_{\tilde{l}_R}^4 m_{\tilde{\chi}_1^0}^2} + 2 m_{\tilde{l}_R}^2 (m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)]}{(4 m_{\tilde{l}_R}^2 m_{\tilde{\chi}_2^0}^2)}$$

$m_{ll}^{edge} / \sqrt{2} < m_{ll} < m_{ll}^{edge}$
($\theta_{ll} > \theta_{ll}^{FC}$ in $\tilde{l}$ -frame)

Showing these equations to illustrate the constraints between the SUSY spectrum and the mass edges.

Rasmus Mackeprang, 8/4/2006

qll

Edge and threshold

$m(qll)^{\text{edge}} : 431.1^{\text{nominal}}$ vs. $431.3^{\text{rec}} \pm 4.3^{\text{syst}} \pm 2.4^{\text{stat}}$
 $m(qll)^{\text{Thres}} : 203.0^{\text{nominal}}$ vs. $204.6^{\text{rec}} \pm 2.0^{\text{syst}} \pm 2.8^{\text{stat}}$

SPS1a

Edge	Nominal	Fit	$\sigma_{E-scale}^{syst}$	σ^{stat}
$m(ll)^{edge}$	77.077	77.024	0.08	0.05
$m(ql)^{edge}$	431.1	431.3	4.3	2.4
$m(ql)_{min}^{edge}$	302.1	300.8	3.0	1.5
$m(ql)_{max}^{edge}$	380.3	379.4	3.8	1.8
$m(ql)^{thres}$	203.0	204.6	2.0	2.8

- Four equations, four masses (in case of universal squark masses)

RM11

Comment needs to be made here, that one only measures a squark mass scale unless using b-tagging and measuring the sbottom mass.

Also I should mention that you don't do an inversion at this point, you measure more parameters and do a combined fit as described later.

Rasmus Mackeprang, 8/4/2006

Squark masses @ SPS1A

$$m_{\tilde{d}_L} = 543.0 \text{ GeV}$$

$$m_{\tilde{u}_L} = 537.2 \text{ GeV}$$

Stop Constraints

- $m_{\tilde{t}} \in [120 \text{ GeV}, 170 \text{ GeV}]$
(Strong 1st order phase transition at EW scale)
- $\tilde{t}$ mostly righthanded (LEP)
- $m_{\tilde{t}_R} > 1 \text{ TeV}$ (light Higgs limit)

$\Rightarrow \tilde{t}$ will be produced at the LHC.

Dark Matter Constraints

Higgsino LSP

$60 < m(\chi) < 105$ GeV, bino LSP
 $m(\tilde{t}) - m(\chi) < 25$ GeV

Input parameters:

$\tan\beta = 7$, $m_A = 1000$ GeV, $\text{Arg}(\mu) = 1.571$
 $M_2 = M_1 g_2^2/g_1^2$, $\text{Arg}(M_1) = \text{Arg}(M_2) = 0$, $M_3 = 1$ TeV
 $m_{U3} = 0$ GeV, $m_{Q3} = 1.5$ TeV, $X_1 = 0.7$ TeV
 $m_{L3}, m_{E3}, m_{D3} = 1$ TeV
 $m_{L1,2}, m_{E1,2} = 10$ TeV
 $m_{Q1,2}, m_{U1,2}, m_{D1,2} = 10$ TeV

Legend:

$m_{\tilde{t}_1} \Gamma m_{\tilde{t}_2}$ $m_{\tilde{t}_1} \Delta 103.5$ GeV
 $\Omega h^2 \Gamma 0.129$ $\Omega h^2 \Delta 0.095$
 $0.095 \Delta \Omega h^2 \Delta 0.129$
 $\sigma_{\text{SI}} = 3E-08 \quad 3E-09 \quad 3E-10$ pb
 $m_{\tilde{t}_1} = 120 \quad 100 \quad 60$ GeV
 $d_e = 1E-27 \quad 1.2E-27 \quad 1.4E-27$ e cm

$m(\chi) < 60$ GeV, bino LSP

Yellow allowed, green favoured. (Neutralinos supply dark matter)

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RM13

Gotta check w Tomasso if these things mean what I think they mean...

Rasmus Mackeprang, 8/4/2006

Signal vs Background

- Difference in shapes in s/b
- Background shape and normalization crucial.

R-hadrons

• Fits a bit unstable → Need unbinned method

R-hadrons

• Estimate of mass scale error

R-meson to baryon conversion

- R^0 -mesons with 300 GeV gluino sent through iron
- All mesons end up as baryons.

Search Strategies

- A number of quality cuts can be applied to the tracks used, and R-hadron likeness cuts imposed.
- Sensitivities exceeding the 5σ level to metastable gluinos up to 1 TeV in mass has been demonstrated.

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RM12

I decided against giving precise cuts here, because the point anyway is that all three scenarios from the notes have high significance.

Hvad er lower limit?

Rasmus Mackeprang, 8/17/2006

R-hadrons

- Assuming flat xsec (12 mbarn per light quark)
- Assume even weights
- Using phase space function to ensure asymptotic limits for $2 \rightarrow 2$ vs. $2 \rightarrow 3$.
- Using parameterised cascade treatment already in Geant4.

Figure: A.C. Kraan