Search for the supersymmetry in the trilepton final state

Moritz v. Sivers

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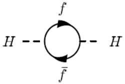
Outline

The supersymmetric extension of the SM
- The hierarchy problem
- Supersymmetry

SUSY and LHC
- Search for SUSY with LHC
- Trilepton analysis for ATLAS

Conclusion

The hierarchy problem



Feynman diagram of a fermion loop correction to the SM Higgs mass.

- Loop interactions from Fermions and Bosons yield corrections for Higgs mass:

$$\delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 ln(\frac{\Lambda}{m_f})...\right]$$

m_H: Higgs boson mass; m_f: fermion mass; λ_f: coupling between Higgs boson and fermion; Λ: energy cut-off scale of theory

The hierarchy problem

- if SM is assumed to be correct up to Planck scale then $\Lambda \sim \Lambda_{PL} \sim 10^{19}$ GeV results in divergence of Higgs mass
- experimetally Higgs mass is approximately 174 GeV from measurements of weak interactions
- compensation would need incredible fine tuning or limitation of $\Lambda \sim 1$ TeV $\Rightarrow$ new physics

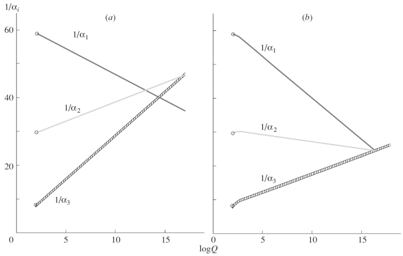
Supersymmetry

- SM Higgs mass with boson and fermion loop corrections:

$$m_H^2 = m_0^2 + \frac{\lambda_f^2}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 ln(\frac{\Lambda}{m_f})...\right] + \frac{\lambda_B}{16\pi^2}\left[\Lambda^2 - 2m_B^2 ln(\frac{\Lambda}{m_B})...\right] ...$$

- SUSY proposes a bosonic (scalar) super-partner for every SM fermion (and vice versa)
  $\longrightarrow$ extra contributions for the Higgs mass: two bosonic for every fermionic (due to degrees of freedom)
- if $\lambda_f^2 = \lambda_B$ the quadratic divergences cancel each other due to their opposite sign, for every Λ ☺
- remaining logarithmic divergences can be removed with little fine tuning

Grand Unification



- SM is assumed to be a low energy approximation of higher energy GUT but gauge couplings of SM do not exactly unify
- with new spectrum of SUSY particles couplings unify at $\sim 10^{16}$ GeV $\rightarrow$ theory cutoff scale

Minimal Supersymmetric Standard Model

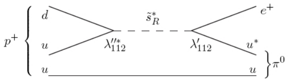
Superfields	Bosons	Fermions	$SU(3) \times SU(2) \times U_Y(1)$
Vector:			
G^a	Gluon g^a	Gluino $\tilde{g}^a$	8 1 0
V^k	Weak W^k $(W^\pm, Z)$	Wino, Zino $\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1 3 0
V'	Hypercharge B (γ)	Bino $\tilde{b}(\tilde{\gamma})$	1 1 0
Matter:			
L_i	Sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	Leptons $L_i = (\nu, e)_L$	1 2 −1
E_i	Sleptons $\tilde{E}_i = \tilde{e}_R$	Leptons $E_i = e_R$	1 1 2
Q_i	Squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	Quarks $Q_i = (u, d)_L$	3 2 1/3
U_i	Squarks $\tilde{U}_i = \tilde{u}_R$	Quarks $U_i = u_R^c$	3* 1 −4/3
D_i	Squarks $\tilde{D}_i = \tilde{d}_R$	Quarks $D_i = d_R^c$	3* 1 2/3
Higgs:			
H_1	Higgs bosons H_1	Higgsinos $\tilde{H}_1$	1 2 −1
H_2	Higgs bosons H_2	Higgsinos $\tilde{H}_2$	1 2 1

- The MSSM is the supersymmetric extension of the SM with minimal addition of particles

Minimal Supersymmetric Standard Model

- Every particle has a super partner with same mass and quantum numbers but spin differing by 1/2
- two Higgs fields needed to give mass to all leptons and quarks: $H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, H_2 = \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix}$
- neutral higgsinos and gauginos mix to give four mass eigenstates $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ called neutralinos, charged higgsinos and gauginos mix to give two mass eigenstates $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ called charginos

R-Parity



- SUSY allows baryon and lepton number violation $\rightarrow$ proton could rapidly ($\sim 10^{-2}$ s) decay into lepton + meson
- R-Parity is a multiplicative QN defined by $R = (-1)^{2S+3(B-L)}$ SM particles have R-Parity +1, sparticles -1
- if R-Parity is conserved:
  $\rightarrow$ proton lifetime becomes $\sim 10^{32}$ y
  $\rightarrow$ in collider experiments only an even number of sparticles can be produced
  $\rightarrow$ every sparticle decays into an odd number of lighter sparticles
  $\rightarrow$ the LSP (in most cases the neutralino) is stable $\Rightarrow$ good candidate for CDM

SUSY symmetry breaking

- sparticles with same mass as their SM partners have not been observed
  $\rightarrow$ SUSY is assumed to be spontanously broken $\Rightarrow$ SUSY is also a low energy approximation of a higher energy theory
- to maintain solution to hierarchy problem sparticle masses must not be too large $\rightarrow$ soft symmetry breaking:

$$\mathfrak{L}_{MSSM} = \mathfrak{L}_{SUSY} + \mathfrak{L}_{soft}$$

- $\mathfrak{L}_{soft}$ contains SUSY violating terms and adds 105 unknown parameters to theory ☹
- exact symmetry breaking mechanism is unknown $\Rightarrow$ numerous models that decrease number of parameters

minimal SuperGravity

- in mSUGRA symmetry breaking is caused by gravitational interactions occuring above the Planck scale
- mSUGRA parameter space is characterised by four parameters and one sign:

$$m_0; m_{1/2}; A_0; tan\beta; sign(\mu)$$

m_0: GUT scale unified scalar mass; $m_{1/2}$: GUT scale unifed gaugino mass; A_0: trilinear coupling; β: ratio of the H_1 and H_2 VEVs; $sign(\mu)$: sign of the higgsino mass parameter

minimal SuperGravity

- if LSP accounts for CDM, cosmological measurements (WMAP data) can be used to tightly constrain mSUGRA parameter space

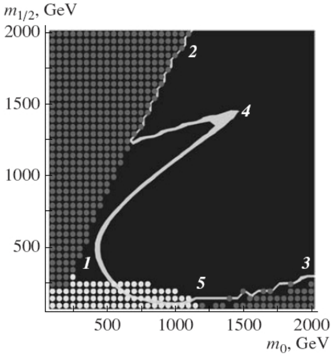


Fig. 5. Parameter-space region allowed by the WMAP requirements for $\tan\beta = 51$, $\mu > 0$, and $A_0 = 0.5m_0$ (light band). Circles cover the excluded regions: (left upper corner) region where the τ slepton is the lightest supersymmetric particle (LSP); (right lower corner) region where the radiative mechanism of electroweak-symmetry breaking does not work; and (left lower corner) region where the Higgs boson is overly light. The figures label (*1*) the bulk annihilation region, (*2*) the coannihilation region, (*3*) the focus-point region, (*4*) the funnel region, and (*5*) the EGRET region.

Benchmark scenarios

Benchmark Point	SU2	SU3	SU4
mSUGRA Parameters			
m_0	3550	100	200
$m_{1/2}$	300	300	160
A_0	0	-300	-400
$\tan\beta$	10	6	10
sign(μ)	+	+	+
Cross Sections			
σ_{tot} [pb]	7.18	27.68	402.19
$\sigma_{3\ell}$ [pb]	0.07	0.30	2.49

- different benchmark scenarios were studied for potential discovery of SUSY at ATLAS:
  $\Rightarrow$ SU2 (focus point region): squarks and sleptons too heavy to be produced, gauginos within reach of LHC
  $\Rightarrow$ SU3 (bulk region) and SU4 (low mass region): all sparticles within reach of LHC

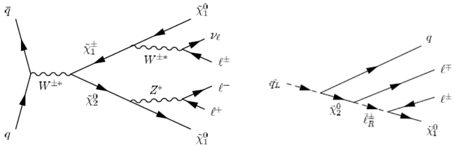
SUSY signature in LHC

Production	Main decay mode	Signature
$\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ q\bar{q}'\tilde{\chi}_1^\pm \\ g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$	$\not{E}_T$ + multijets (+ leptons)
	$\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell^\pm \nu, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$	Trilepton + $\not{E}_T$
	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$	Dileptons + jet + $\not{E}_T$
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \to \ell\tilde{\chi}_1^0 \ell^\pm \nu$	Dilepton + $\not{E}_T$
$\tilde{\chi}_i^0 \tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	Dilepton + jet + $\not{E}_T$
$\tilde{t}_1 \tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	Two noncollinear jets + $\not{E}_T$
	$\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$	Single lepton + $\not{E}_T$ + $b's$
	$\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell^\pm \nu$	Dilepton + $\not{E}_T$ + $b's$
$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}_i^0, \tilde{\ell}^\pm \to \nu_\ell \tilde{\chi}_i^\pm$	Dilepton + $\not{E}_T$
	$\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Single lepton + $\not{E}_T$

- typical SUSY signature includes leptons, hadron jets and large missing transverse energy $\not{E}_T$ due to escaping LSPs

SUSY trilepton processes

- different dominant processes for trilepton final states:
  $\Rightarrow$ SU2: direct chargino-neutralino production
  $\Rightarrow$ SU3 and SU4: long decay chains through multiple sparticles

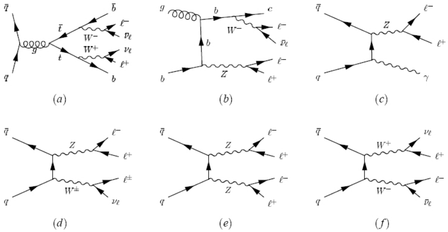


- exclusive signal: only trileptons from direct gaugino pair production are counted as signal $\Rightarrow$ only studied for SU2
- inclusive signal: all trilepton final states are counted

SM background

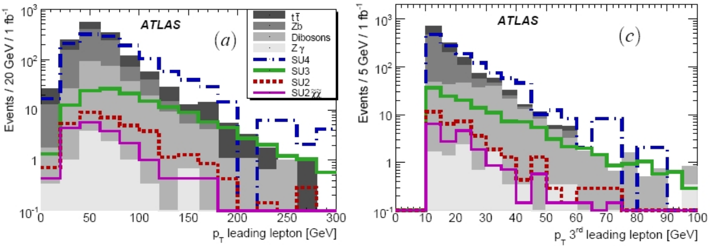
- considered SM background processes:

Process	Generator	σ_{LO} [pb]	$\sigma_{LO} \times \varepsilon_F$	k	$\sigma_{NLO} \times \varepsilon_F$ [pb]	$\int \mathcal{L}dt$ [fb^{-1}]
SU2	Herwig	5.2	5.2	1.39	7.2	6.9
SU3	Herwig	20.9	20.9	1.33	27.7	17.1
SU4	Herwig	294.5	294.5	1.37	402.2	0.5
$t\bar{t}$	MC@NLO	833.0	449.8	1.00	449.8	1.0
Zb	AcerMC	205.0	153.8	1.00	163.9	0.8
ZZ	Herwig	11.0	2.1	1.88	3.9	12.7
ZW	Herwig	27.0	7.8	2.05	16.1	3.0
WW	Herwig	70.0	24.5	1.67	40.9	1.2
$Z\gamma$	Pythia	3.8	2.6	1.30	3.4	3.0



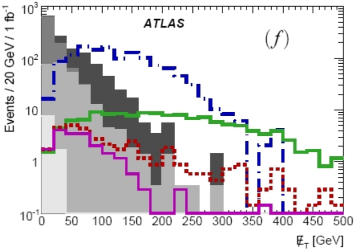
General analysing strategies

- low p_T threshold compared to lower lepton multiplicity events for particulary soft 3rd lepton: $p_T^{lep} > 10$ GeV

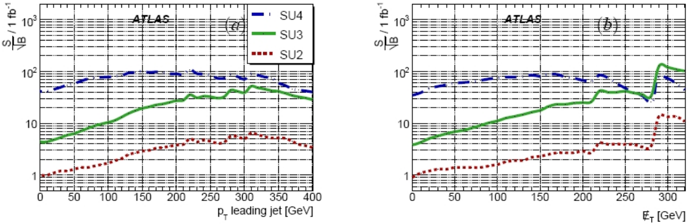


General analysing strategies

- large missing transverse Energy (less prominent for SU2)
- hadronic activity: large for inclusive signal, more quiet for exclusive signal
  $\longrightarrow$ different treatment in analysis



Inclusive signal analysis



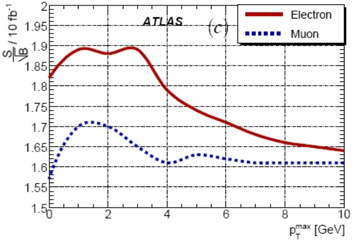
- correlation of leading jet p_T and missing transverse energy because of recoil
  $\rightarrow$ cut on p_T makes selection of $E\!\!\!/_T$ redundant and vice versa
- p_T is safer variable because of not yet understood $E\!\!\!/_T$ systematics and more effective in removing SM background
  $\rightarrow$ cut for leading jet: $p_T^{jet1} > 200$ GeV

Exclusive signal analysis

- lack of hadronic activity in direct gaugino production $\Rightarrow$ leptons are "clean" and isolated
  $\longrightarrow$ require lepton track isolation for discrimination against b-quark decay leptons: $E_T < 10$ GeV in a cone of $\Delta R = 0.2$

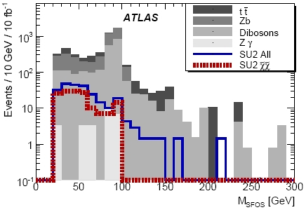
Exclusive signal analysis

- p_T^{max} distribution of well isolated SUSY leptons tends to be low $\rightarrow$ background discrimination against high p_T leptons from b-quark decay by setting $p_T^{lep} < 1$ GeV for muons and $p_T^{lep} < 2$ GeV for electrons



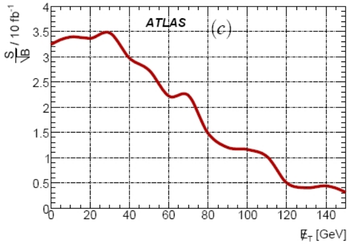
Exclusive signal analysis

- decay involves neutralino decaying via virtual Z Boson to "Same Flavour Opposite Sign" (SFOS) lepton pair
  $\rightarrow$ require ≥ 1 SFOS lepton pair for discrimination against $t\bar{t}$ background
- in Z boson background, SFOS lepton pair invariant mass clusters around Z boson mass
  $\rightarrow$ rejection of SFOS lepton pairs with mass around 10 GeV of Z boson mass: $|M_{SFOS} - M_Z| > 10$ GeV



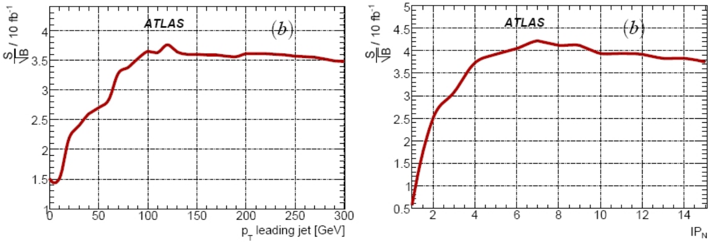
Exclusive signal analysis

- direct gaugino production leads to almost back to back LSPs in final state $\Rightarrow$ lower $\not{E}_T$
- even lower $\not{E}_T$ from background decays that do not produce neutrinos such as ZZ or $Z\gamma$
  $\rightarrow$ require $\not{E}_T > 30$ GeV

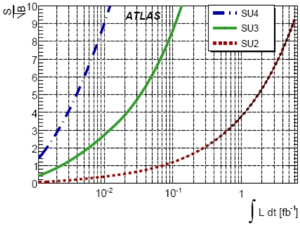


Exclusive signal analysis

- lack of hadronic activity
  $\longrightarrow$ jet veto: require leading jet $p_T^{jet1} < 100$ GeV to reduce $t\bar{t}$ background
- leptons from direct gaugino production will be prompt leptons
  $\longrightarrow$ require lepton impact parameter $IP_N < 6$ to reduce $t\bar{t}$ background



Results for inclusive analysis

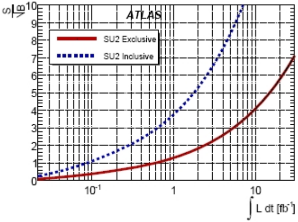


		No Cut	N_ℓ	p_T^{jet1}
SU2		7111.7	35.0	13.0
SU3		27304.3	139.3	94.3
SU4		396445.5	1283.9	311.7
$t\bar{t}$		440657.9	444.0	10.6
Zb		159115.7	661.6	0.0
ZW		15672.0	192.7	1.3
ZZ		3820.2	58.9	0.0
WW		40051.7	3.3	0.0
$Z\gamma$		3283.2	9.4	0.0
$\frac{S}{\sqrt{B}}$	SU2		0.9	3.8
	SU3		3.8	27.3
	SU4		34.7	90.3
$\frac{S}{B}$	SU2		0.0	1.1
	SU3		0.1	7.9
	SU4		0.9	26.2

normalised to 1 fb^-1

- 5σ discovery with statistics of a few hundred pb^{-1} to a few fb^{-1} depending on benchmark scenario (in absence of systematics)

Results for exclusive analysis



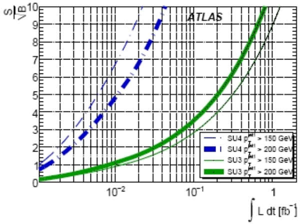
		No cut	N_ℓ	SFOS	Track Isol.	Z-window	$\not{E}_T$	Jet Veto	IP_N
	SU2 $\tilde{\chi}\tilde{\chi}$	64036.6	186.4	177.7	153.2	119.9	98.3	86.7	80.9
	SU2 non-$\tilde{\chi}\tilde{\chi}$	7080.5	163.3	127.2	95.4	85.3	83.8	0.0	0.0
	$t\bar{t}$	4406578.8	4440.2	2812.2	634.3	507.5	475.7	327.7	179.7
	Zb	1591156.7	6616.1	6562.8	2422.8	386.0	0.0	0.0	0.0
	ZW	156719.6	1926.8	1910.1	1682.2	321.7	217.8	214.5	204.4
	ZZ	38201.8	589.4	579.9	475.8	56.8	13.4	11.8	11.0
	WW	400516.9	32.7	24.5	8.2	8.2	8.2	8.2	0.0
	$Z\gamma$	32832.3	93.9	90.6	26.8	6.7	3.4	3.4	3.4
(i)	$\tilde{\chi}\tilde{\chi} = S$	$S/\sqrt{B}$	1.6	1.6	2.1	3.2	3.5	3.6	4.1
	SM+non-$\tilde{\chi}\tilde{\chi} = B$	S/B	0.0	0.0	0.0	0.1	0.1	0.2	0.2
(ii)	All SU2= S	$S/\sqrt{B}$	3.0	2.8	3.4	5.7	6.8	3.6	4.1
	SM= B	S/B	0.0	0.0	0.0	0.2	0.3	0.2	0.2

normalised to 10 fb^-1

- 5σ discovery with a few tens of fb^{-1} (in absence of systematics)

Preparation for first ATLAS data

- inclusive analysis for first LHC data of 200 pb^{-1} @ 10 TeV



		No Cut	N_ℓ	p_T^{jet1} >150 GeV	p_T^{jet1} >200 GeV
SU3		1630.0	7.2	5.5	4.7
SU4		34568.0	107.5	41.4	20.4
$t\bar{t}$		40572.0	32.1	1.9	0.9
$\frac{S}{\sqrt{B}}$	SU3	1.3	4.0	5.0	
	SU4	19.0	29.9	21.4	
$\frac{S}{B}$	SU3	0.2	2.9	5.2	
	SU4	3.3	21.6	22.5	

normalised to 200 pb^-1

- 5σ discovery for SU3 and SU4 can be achieved with original threshold of $p_T^{jet1} > 200$ GeV (in absence of systematics)

Conclusion

- SUSY elegantly solves the SM hierarchy problem
- SUSY is a GUT but also just a low energy approximation of a higher energy theory
- SUSY lacks description of quantum gravity but could provide a step towards it by its symmetry breaking mechanism
- trilepton analysis for ATLAS:
  $\longrightarrow$ exclusive trilepton signature is not an early data channel
  $\longrightarrow$ inclusive trilepton signature is excellent candidate for early discovery of new physics at ATLAS, particularly for low mass scenario
  $\longrightarrow$ essential is the further development of methods to estimate $t\bar{t}$ background

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