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SUSY Parameter Determination at LHC using Kinematic Fits

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Fittino Workshop – 30th October 09





Part I: Inclusive distributions sensitive to model parameters

- Weak boson and top production rates
- Invariant multi jet masses

Part II: SUSY mass determination using kinematic fits

- Definition of over constrained problem
- Alternative fitting technique (genetic algorithm)
- First results
- Further discriminating variables

Summary and outlook





- $\int \bar{q} \cdot R$ -parity conserved:
 - SUSY particles are produced in pairs
 - Cascade decay down to stable LSP
 - $\not\!\!\!E_T$
 - large number of jets
 - jet pairs compatible with weak gauge boson masses
 - Fully hadronic decay mode has large branching ratio

Two goals:

- (1) Discover SUSY at the LHC
- (2) Determine model parameters of underlying theory

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Part I Inclusive Variables

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W/Z Boson Identification



- Jet algorithm: iterative cone 0.5
- Jet cuts $p_T > 20~{
 m GeV}$ and $|\eta| < 2.5$
- Candidates: dijets with

 $70 \text{ GeV} < M_{\text{inv}} < 110 \text{ GeV}$

• Large combinatorial background





- Low efficiency at small boson p_T due to small jet reconstruction efficiency
- Low efficiency at large boson p_T due to jet merging

Friederike Nowak



Supression of Combinatorial Bg





Discriminating variables:

- θ^* : angle (in the *W* rest frame) between a *W* jet and the flight direction
- p_T of W candidate
- Angle between \mathbb{E}_T and W candidate
- \rightarrow Reduction of combinatorial background by factor up to ~3
- If *W* candidate can be combined with third jet to $m_{top} \rightarrow top$ candidate



Constrain Parameter Space



- Scan hypothesis and compare (χ^2 test) with pseudo data (here: $m_0 = 800$ GeV and $m_{1/2} = 600$ GeV)
- Boson candidate rate contains information in addition to absolute event rate \rightarrow larger parts of the parameter space can be excluded

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Search for other discriminating variables:

- Hadronic decay of squarks: invariant trijet mass distribution
- No sharp peak but upper and lower mass edge (due to unmeasured LSPs)
- Non-degenerated squark mass spectra: define only 1. and 2. generation as signal





- *W/Z* candidate combined with one of two p_T hardest jets (large mass gap between \tilde{q} and $\tilde{\chi}^{\pm}$)
- Up to 20 combinations per event
- Start with small S/B of ~1/100

Ulla Gebbert



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Reconstruction of Mass Edges





correlated variables

- Use likelihood ratio method to separate signal from background
- Improve S/B from ~1/100 to ~1/10
- Background might be "signal like"





Constrain Parameter Space



- Scan over hypotheses
- Compare with pseudo data (here: $m_0 = 600$ GeV and $m_{1/2} = 400$ GeV) via binned maximum Likelihood (hypotheses normalized to data)
- Shape of trijet mass distribution provides enough information to constrain the parameter space



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Part II Susy Mass Determination using Kinematic Fits

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Reconstruction of full kinematics of SUSY events \rightarrow access to masses

- For one event: More unknowns (LSP momenta, SUSY masses) than constraints
 - (p_T balance, invariant masses)
- For more events: some unknowns (SUSY masses) are common → Problem can be over constrained
- Possible approach: Number of unknowns equals number of constraints → Look at parameter space covered by solutions
 Cheng, Gunion, Han, Marandella and McElrath 07

Cheng, Gunion, Han, Marandella and McElrath 07 Webber 09

• Our approach: Constrained least square fit of many events taking into account uncertainties of measurements



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Our hope: significant fraction of SUSY events with rather similar decay chains (degenerated masses, dominant branching ratios)

Potential problems: • Many jets → huge combinatorial bg (7 jets: 1260 combinations)

- Effect of SM and SUSY backgrounds
- Detector resolution and acceptance
- Initial and final state radiation
- No perfect mass degeneration
- Width of virtual particles

For N events:



4 global unknowns (SUSY masses)

N×6 local unknowns (2 LSPs)

 $N \times 7$ local constraints:

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Over constrained for N > 4



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[•] p_x , p_y





Method for constrained fits: Method of Lagrangian Multiplier

Invariant mass constraints in general not linear

- \rightarrow Linearization via Taylor expansion
- \rightarrow Iterative solution

Problems:

- Linearization of constraints only good approximation "near" solution → if "away" from solution iterative procedure might results in too large or too small steps, or even wrong direction
- Definition of convergence criterion

Used fitting code: KinFitter

- C++ implementation ... (V. Klose and J. Sundermann)
- ... of **ABCFIT** from ALEPH collaboration (O. Buchmüller and J. B. Hansen)
- Additional modifications (step scaling and scaling of constraints)



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- Formulation of constraints as additional X^2 term \rightarrow "cost function"
- Interpret cost function as $\chi^2 \rightarrow$ carefully chosen errors

$$\chi_{M^2}^2 = \left(\frac{M_{\text{inv}}^2(j_1, j_2, j_3) - M^2}{\sigma_{M^2}}\right)^2 \quad \text{and} \quad \chi_{p_{x/y}}^2 = \left(\frac{\sum_{\text{all particles}} p_{x/y}}{\sigma_p}\right)^2$$

Minimize cost function: gradient, simplex, LBFGS, simulated annealing and genetic algorithm (GA)

GA: Final state 4-momenta are genome of individual; jet combination is one additional gene. Fitness function (here X^2) defines which individual is fittest

Algorithm: 1) Create first generation of individuals (starting population)

- 2) Select best fitting individuals
- 3) Create new individuals by selecting randomly two parents and inherit randomly genes from either one or other parent
- 4) For each child mutate each genome with small probability
- 5) Back to step 2) until convergence

Advantage: no linearization needed \Leftrightarrow Disadvantage: high computational cost



Counting unknowns and constraints:

- 4 jets + 1 lepton = 15 measured parameters
- 1 neutrino = 3 unmeasured parameters
- 6 constraints (p_x , p_y , $2 \times M_W$ and $2 \times M_{top}$)

Combinatorics:

- No b-tagging used
 - \rightarrow 12 possible jet configurations

Event generation and detector simulation:

- **Pythia6** generated events including ISR and FSR
- Each final state jet smeared according to typical jet momentum and angular resolutions at ATLAS/CMS
- Jet/lepton selection cuts: Four jets and one lepton with
 - $p_T > 20 \text{ GeV}$
 - $|\eta| < 3.0$

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Proof of Principle: Semi-Leptonic $t\overline{t}$



Resolution of fitted neutrinos:



Scenario:

- No bg from other processes
- Full combinatorial bg
- ISR and FSR
- Detector resolution and acceptance

Genetic algorithm:

Right jet combinations has smallest χ^2 for **8523** of 13386 events

KinFitter:

Converged for 12917 of 13386 events

Right jet combinations has smallest χ^2 for **8194** events

→ Similar performance of both methods for neutrino resolution

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Proof of Principle: Semi-Leptonic $t\overline{t}$





- **Comparable** and **reasonable** results for both algorithms
- Increase at lowest fit probabilities due to non-Gaussian tail of invariant mass distributions



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SUSY Sample



225312

5.765

3.604

2807

9.149

2.613

1281

8.876

2.457

Entries

• mSUGRA test point:

• Parameters:
$$m_0 = 230 \text{ GeV}, m_{1/2} = 360 \text{ GeV}$$

 $A_0 = 0, \tan \beta = 10, \operatorname{sign} \mu = +$

• Masses:
$$m_{\tilde{q}} \approx 810 \text{ GeV}, m_{\tilde{g}} \approx 860 \text{ GeV}$$

 $m_{\chi_1^{\pm}} \approx 273 \text{ GeV}, m_{\chi_1^0} \approx 147 \text{ GeV}$

• Cross section at LHC:
$$\sigma_{tot} = 7.8 \text{ pb}(LO)$$

• Branching ratios:
$$Br(\chi_2^0 \to h^0 \chi_1^0) \approx 85\%$$

 $Br(\chi_1^\pm \to W^\pm \chi_1^0) \approx 97\%$



- **Pythia6** generated events including ISR and FSR
- Each final state jet smeared according to typical jet momentum and angular resolutions at ATLAS/CMS
- Jet selection cuts: 7 jets with
 - $p_T > 30 \,\,{\rm GeV}$
 - $|\eta| < 3.0$
- → Dominant background of other SUSY processes (S/B ~ 1/40)



Fit of SUSY Events with Genetic Algorithm

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Reduction Combinatorial Background







Similar probability distribution of SUSY background:

- "Signal like" cascade topologies, e.g. decays via heavier charginos or neutralinos
- Signal cascades but different squark mass (3rd generation)
- Signal cascades but one soft jet replaced by ISR jet
- Huge jet combinatorics

Fit probability distribution flat for signal (slight systematic shift toward higher probabilities due to combinatorics)

Background peaks at lower values: cut on 0.1(0.3) improves B/S from ~45 to ~19(~14)

- No SM bg
- Full SUSY bg
- Full combinatorial bg
- ISR and FSR
- Detector resolution and acceptance
- Mass hypothesis = true masses



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- Huge combinatorial background \rightarrow Large invariant mass combinations, e.g.
- In rest frame of SUSY particles: angular distribution $\cos \theta^*$ of decay products with respect to flight direction of decaying particle should be ~isotropic (for spin 0)
- $\cos \theta^*$ for typical background 4-vector configurations are not uniformly distributed (smaller angles preferred)



Many decay angles in SUSY cascades → Use event kinematics to reduce combinatorial bg reduction

 $\mathcal{L} = p \cdot$

 $N_{\rm decays}$

0.2

0.4

0.6

 $\cos \theta * (\chi_1^{\pm}/\chi_2^0)$

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- Fix gluino and neutralino mass to true values
- Vary two remaining masses (squark and chargino)

$$\log \mathcal{L} = \sum_{i=1}^{N_{\text{tot}}} \log \mathcal{L}_i \text{ with } \mathcal{L}_i = \mathcal{L}_{\text{cut}} \text{ for } \mathcal{L}_i < \mathcal{L}_{\text{cut}}$$

- No SM bg
- No SUSY bg
- Full combinatorial bg
- ISR and FSR
- Detector resolution and acceptance

Mass Scan

• Scan mass hypothesis



 Concordance between maximum likelihood and true values (bias due to non perfect momentum balance) UΗ

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Summary:

- Various distributions or rates provide additional information about SUSY parameters, but are convoluted by detector effects
- Genetic algorithm yields comparable results to Lagrangian Multipliers and is well suited for highly non linear problems
- Kinematic fits provide a powerful tool to reconstruct SUSY cascades
- Invariant mass constraints reduce combinatorial background of signal cascades $(0.08\% \rightarrow ~45\%)$
- Combinatorial SUSY background dominant for studied mSUGRA scenario \rightarrow further discriminating variables needed, e.g. $\cos \theta^*$

Outlook:

- Further discrimination of signal against SUSY bg
- Include final states with leptons (reduced combinatorics)
- Fit more than one hypothesis
- Study other models than one specific SUSY scenario





Backup

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Genetic Algorithm - Schematic Picture

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