SUSY Searches at CMS in the Fully Hadronic Channel

Project B2 - Supersymmetry at the Large Hadron Collider

Christian Autermann, Ulla Gebbert, Kolja Kaschube, Friederike Nowak, Benedikt Mura, Christian Sander, Peter Schleper, Torben Schum, Jan Thomsen

Institut für Experimentalphysik, Universität Hamburg

SFB 676 Workshop in Zeuthen - 15th February 2008

Universität Hamburg

bmb+f Großgeräte der physikalischen Grundlagenforschung

The Project B2

Supersymmetry at the Large Hadron Collider

The Goals

- Discovery of supersymmetry
- Determination of model parameters (in particular the sparticle masses)

The Challenges

- Understanding of the detector (reconstruction efficiencies, energy resolutions . . .)
- Separation of SUSY signal against **SM background**
- Suppression of **combinatorial** and **SUSY background** to access SUSY mass parameters by kinematic properties

Outline

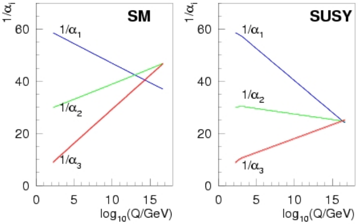
- Introduction
- SM background rejection and discovery of SUSY
- Determination of parameters by reconstruction of mass edges
- Constraining the parameter space
- Global kinematic fits
- Summary

Supersymmetry

Why is it so nice?

Problems of the Standard Model

- No gauge coupling unification
- Hierarchy problem
- Fine tuning problem
- No DM candidat



Simultanous Solution with Supersymmetry (SUSY)

- SUSY particles change running of couplings
- Hierarchy/fine tuning: SUSY-contributions have opposite sign $\rightarrow$ cancellation $\rightarrow$ logarithmic scale dependence
- DM: lightest neutralino is (often) perfect candidat (massive, stable, only weak interaction)

Supersymmetry

So far no discovery, only hints → **supersymmetry is broken**

mSUGRA → 5 new Parameters

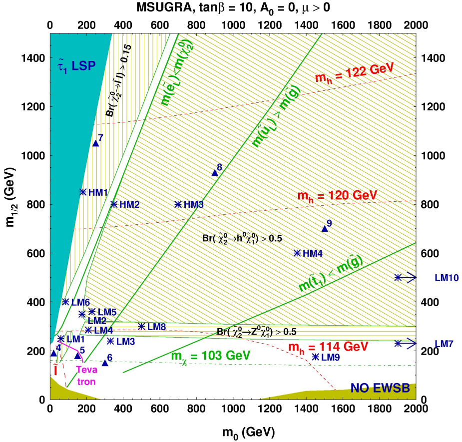
- m_0: unified mass of the fermion partners
- $m_{1/2}$: unified mass of the gauge boson partners
- $\tan\beta$: ratio of the VEVs of the 2 Higgs doublets
- unified trilinear coupling A_0, sign(μ)

Contraints on the Parameter Space

- Higgs mass $m_h > 114.4$ GeV
- $Br(b \to X_s\gamma) = (3.43 \pm 0.36) \times 10^{-4}$
- $\Delta a_\mu = (27 \pm 10) \times 10^{-10}$
- $\Omega_{DM} = 0.113 \pm 0.008$
- SUSY mass limits from LEP
- Theoretical constraints: EWSB, LSP neutral
- Direct detection limits from nuclear recoils and ν fluxes from sun or earth

Supersymmetry

Agreed mSUGRA Benchmark Points

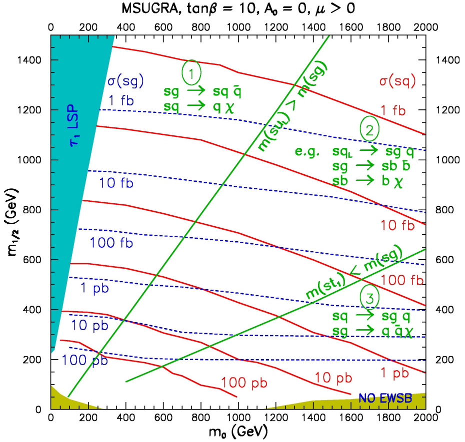


Point	m_0 [GeV]	$m_{1/2}$ [GeV]	$\tan\beta$	sign(μ)	A_0 [GeV]
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0

G. L. Bayatian *et al.*, Physics TDR vol. II, J. Phys. G **34** (2007) 995

Supersymmetry

Agreed mSUGRA Benchmark Points



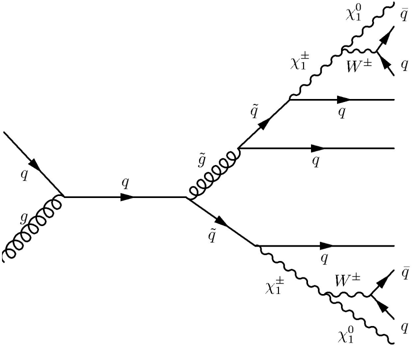
Point	$M(\tilde{q})$ [GeV]	$M(\tilde{g})$ [GeV]	σ_{tot} NLO(LO) [pb]
LM1	559	611	55(43)
LM2	779	834	9.4(7.3)
LM3	626	602	45(34)
LM4	661	695	25(19)
LM5	810	858	7.7(6.0)
LM6	860	940	4.9(3.8)
LM7	3004	678	6.8(3.8)
LM8	820	745	12(8.8)
LM9	1480	507	40(23)
LM10	3133	1295	0.076(0.041)
HM1	1721	1886	0.045(0.043)
HM2	1656	1785	0.065(0.061)
HM3	1762	1804	0.047(0.043)
HM4	1816	1434	0.10(0.077)

G. L. Bayatian *et al.*, Physics TDR vol. II, J. Phys. G **34** (2007) 995

Susy Signature

In the Fully Hadronic Decay Mode

Example diagram:

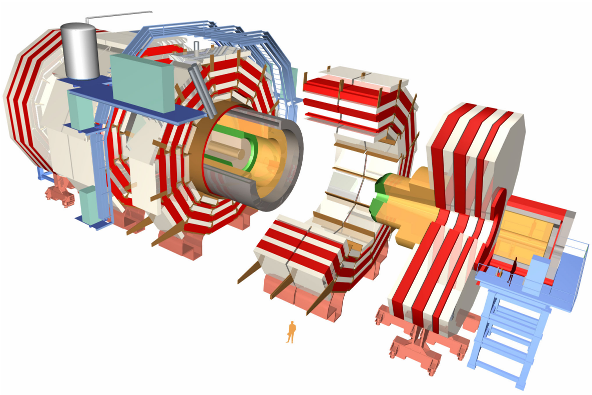


Signature

Cascade decay of primary produced SUSY particles

- R-parity conserving models
  $\rightarrow$ LSP at end of decay chain is stable
  $\rightarrow \not{E}_T$
- Many jets
- Jet pairs compatible with a $W^\pm$ or a Z

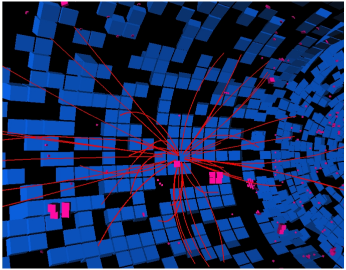
Compact Muon Solenoid



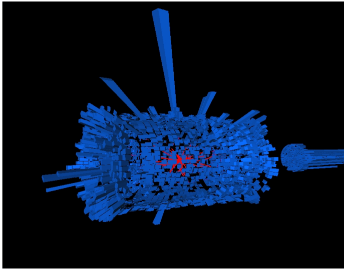
- Multi purpose detector at the LHC
- Operating at CM energy $\sqrt{s} = 14$ TeV
- Inner magnetic field $B \approx 4$ T
- HCAL mostly inside the magnet $\rightarrow 7 \ldots 10$ interaction length

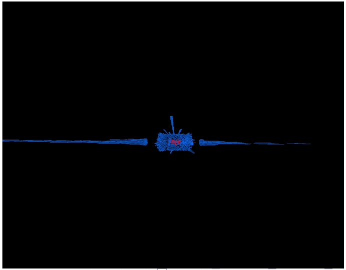
Compact Muon Solenoid

Event Display



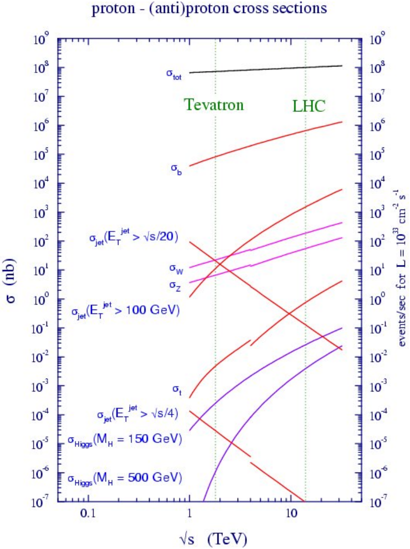
- Physic objects (jets or tracks) are composed from detector signals
- Response of HCAL towers is important for jet physics and $\not{E}_T$ → HCAL calibration
- Pile-Up from other interactions (~20 events at high lumi) makes it more difficult





SM Backgrounds

QCD, $t\bar{t}$, W+jets and Z+jets

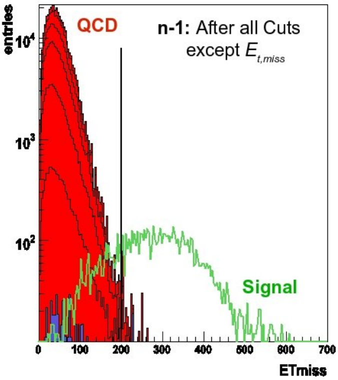


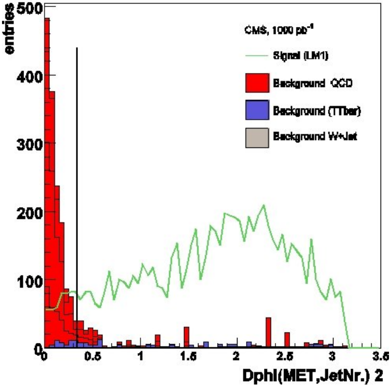
Preselection cuts

- $N_{jets} > 3$ (signal signature)
- $\not{E}_T > 200$ GeV (signal signature)
- $\Delta\phi(\not{E}_T, j_{1,2,3}) > 0.3$ (QCD rejection)
- $\not{E}_T + E_{t,j_2} + E_{t,j_3} + E_{t,j_4} > 500$ GeV (S/B optimization)
- $E_{t,j_1} > 180$ GeV and $E_{t,j_2} > 110$ GeV (S/B optimization)
- Indirect lepton veto, cleanup . . .

More than 7 orders of magnitude larger background (in optimistic SUSY scenarios)

SUSY Discovery



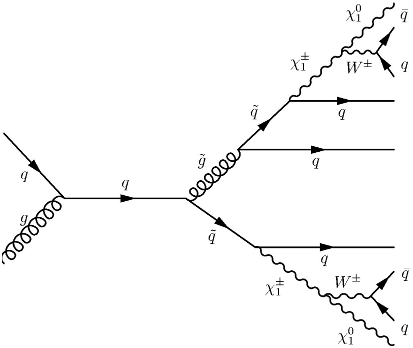


- S/B $\sim$ 300 can be achieved at LM1 with a signal efficiency of $\sim$ 10%
- For such optimistic scenarios with light SUSY masses $\rightarrow$ almost bg free SUSY sample; discovery might be more difficult for heavier masses

Diploma thesis of Jan Thomsen (Sep. 2007)

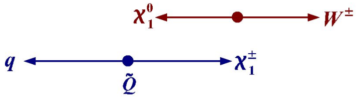
Determination of Mass Parameters

In the Fully Hadronic Decay Mode

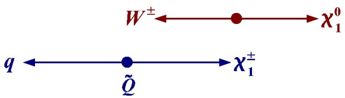


- For one decay chain: combine following objects to invariant squark mass
  - LSP χ^0
  - Two W-jets
  - Quark jet of the decaying squark
- LSP momenta not measured $\rightarrow$ no peak in the invariant trijet mass but ...
- Distribution of m_{jjj} with a **lower** and **upper mass edge**
- Big problem: **combinatorial background** (e.g. 7 jets $\rightarrow$ 720 dijet and 153 trijet combinations)

Mass Edges



maximum tri-jet mass



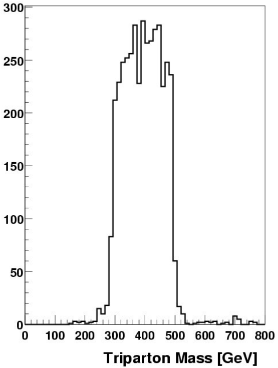
minimum tri-jet mass

$$(M_{Wq}^{max})^2 = M_W^2 + \frac{M_{\tilde{Q}}^2 - M_{\chi^\pm}^2}{2M_{\chi^\pm}^2} \cdot (M_{\chi^\pm}^2 - M_{\chi^0}^2 + M_W^2$$
$$+\sqrt{(M_{\chi^\pm}^2 - M_{\chi^0}^2 - M_W^2)^2 - 4M_{\chi^0}^2 M_W^2)}$$

$$(M_{Wq}^{min})^2 = M_W^2 + \frac{M_{\tilde{Q}}^2 - M_{\chi^\pm}^2}{2M_{\chi^\pm}^2} \cdot (M_{\chi^\pm}^2 - M_{\chi^0}^2 + M_W^2$$
$$-\sqrt{(M_{\chi^\pm}^2 - M_{\chi^0}^2 - M_W^2)^2 - 4M_{\chi^0}^2 M_W^2)}$$

Luc Pape, CMS internal note

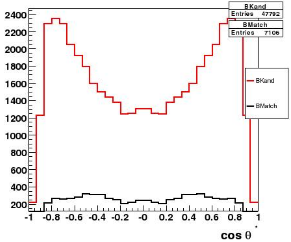
generator level:

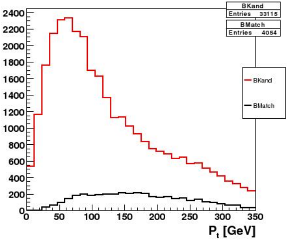


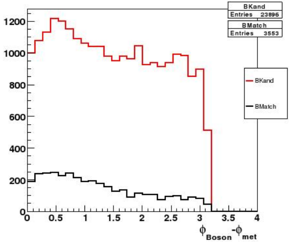
Find Hadronic $W^{\pm}$s and Zs

Suppression of Combinatorial Background

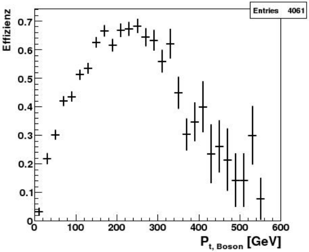
detector level:







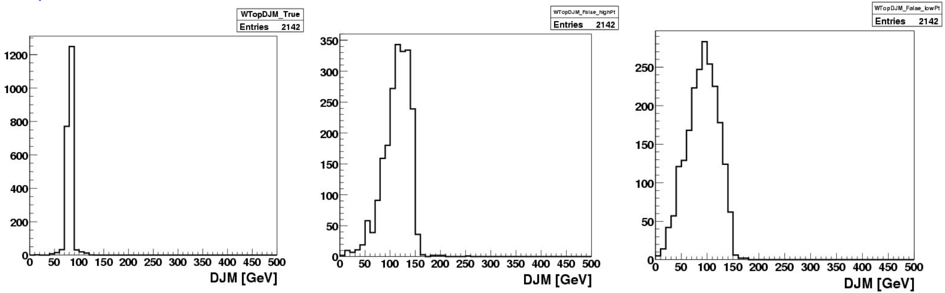
- Candidates are all jet pairs wich can be combined to an invariant mass between 60 and 110 GeV
- θ^* is the angle (in the W rest frame) of a W-jet to the flight direction of the W
- Other discriminating variables are: p_T of W candidate and angle $\Delta\phi$ between $\not{E}_T$ and W
- Low W reco efficiency at low p_T due to low jet reco eff.
- Low W reco efficiency at high p_T due to W-jet merging



Boson Candidate Rate

Tops in SUSY

generator level:



- One hadronic decaying top has one true dijet W combination
- Wrong dijet W combinations have invariant mass "near" the W mass $\rightarrow$ more than one W candidate per top due to detector smearing
- Separation of candidates in two classes
  - Top-W-candidates which can be combined with one further jet to top quark
  - SUSY-W-candidates which can not be combined to top

Boson Candidate Rate

Probing the mSUGRA Parameter Space

$\mathcal{L} = 3\ \mathrm{fb}^{-1}$	LM3	LM4	LM8	LM10	HM3	HM4
$N_{SUSY,tot}$	136400	71500	36300	230	140	310
N_{presel}	11600	9020	5740	15	48	80
N^{Cand}_{tot}	49600	33100	29000	88	140	514
$\epsilon_{Boson,tot}$	0.09	0.12	0.13	0.12	0.16	0.13
$N^{Cand}_{SUSY-cut}$	790	670	360	1.0	2.5	4.3
$\epsilon_{SUSY-Boson}$	0.24	0.45	0.42	0.3	0.4	0.21
$N^{Cand}_{top-cut}$	2640	1560	1520	3.9	5.0	24
$\epsilon_{top-Boson}$	0.14	0.11	0.28	0.33	0.26	0.47
R	0.30	0.43	0.57	0.26	0.5	0.18

- Purity of Boson from SUSY decays increased by a factor > 3
- Absolute number of W and Z candidates in different classes and ratios $R = N^{Cand}_{SUSY-cut}/N^{Cand}_{top-cut}$ are varying for different mSUGRA parameters
  $\rightarrow$ Possible to distinguish between different models?

Diploma thesis of Friederike Nowak (Feb. 2008)

Probing the mSUGRA parameter space

With χ^2 Methode

$\mathcal{L} = 3\ \text{fb}^{-1}$	N_{presel}	$N_B = N^{Cand}_{SUSY-cut} + N^{Cand}_{top-cut}$	$R = N^{Cand}_{SUSY-cut} / N^{Cand}_{top-cut}$
LM3	$11608 \pm 107,7$	$7826 \pm 88,5$	$0,286 \pm 0,010$
LM4	$9022 \pm 95,0$	$5101 \pm 71,4$	$0,378 \pm 0,016$
LM8	$5740 \pm 75,8$	$4423 \pm 66,5$	$0,223 \pm 0,010$
LM10	$17 \pm 4,1$	25 ± 5	$0,191 \pm 0,122$
HM3	$46 \pm 6,8$	16 ± 4	$0,143 \pm 0,123$
HM4	$86 \pm 9,3$	$73 \pm 8,5$	$0,159 \pm 0,062$

Test Data *d* against hypothesis *h*

In case of uncorrelated variables

$$\chi^2 = \sum_{i=1}^{n} \frac{(d_i - h_i)^2}{\sigma^2_{d,i} + \sigma^2_{h,i}}$$

In case of correlated variables

$$\chi^2 = (d - h)^T A^{-1} (d - h)$$

With the covariance matrix

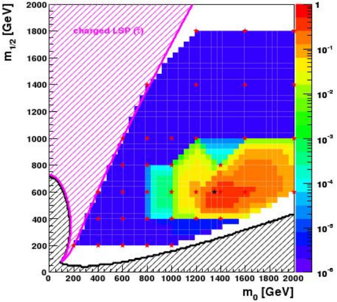
$$A = \begin{pmatrix} \sigma_i^2 + \epsilon^2 x_i^2 & \epsilon^2 x_i x_j \\ \epsilon^2 x_i x_j & \sigma_j^2 + \epsilon^2 x_j^2 \end{pmatrix}$$

Errors

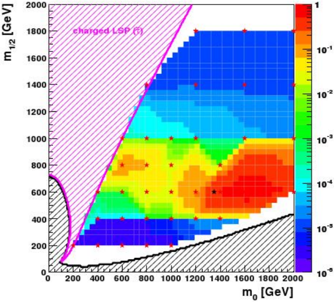
- Theory error from $\sigma_{tot} \sim 20\%$
- N_{presel} and N_B have correlated statistical errors ...
- ... and common systematic errors
  - Luminosity $\sim 5\%$
  - Jet energy scale $\sim 10\%$
  - ... conservative sum: $\sim 20\%$
- *R* almost independent on systematic uncertainties

Probing the mSUGRA parameter space

Scan including boson candidate rate



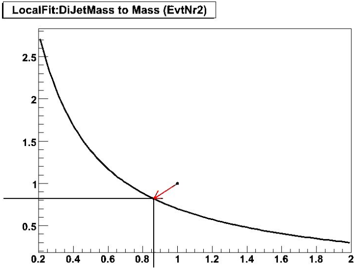
Scan with event rate only

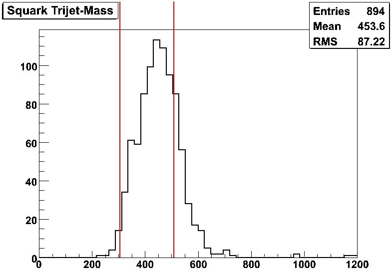


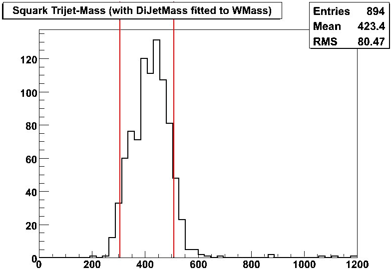
- Scan hypothesis and compare with pseudo data of HM4
- Boson candidate rate contains information in addition to absolute event rate → larger parts of the parameter space can be excluded
- **Plans:** include other observables (e.g. invariant 3-jet mass)

Mass Edges

detector level:







- Force the two W-jets on the invariant W mass $\rightarrow$ Improvement of position of kinematic mass edges
- **Plan:** use multivariate methods (e.g. maximum likelihood) to reduce combinatorial bg

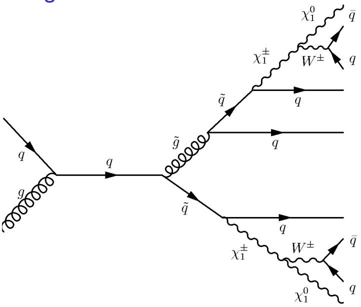
Ulla Gebbert

Global Kinematic Fit of SUSY masses

Determine masses of SUSY particles in chain with a global fit

Unknown quantities

- 6 unmeasured parameters (2$\times$ Neutralino momentum)
- 4 SUSY masses (global parameters: same for all events)



7 Constraints

- 2$\times$ E_T balance (E_x and E_y)
- 2$\times$ $p(\mathrm{q,q},\tilde{\chi}_1^0)^2 = \mathrm{M}(\tilde{\chi}_1^\pm)^2$
- 2$\times$ $p(\mathrm{q,q,q,q},\tilde{\chi}_1^0)^2 = \mathrm{M}(\tilde{q})^2$
- 1$\times$ $p(\mathrm{q,q,q,q,q},\tilde{\chi}_1^0)^2 = \mathrm{M}(\tilde{g})^2$

Overconstrained system . . .

. . . for $\geq$ 5 intermediate particles

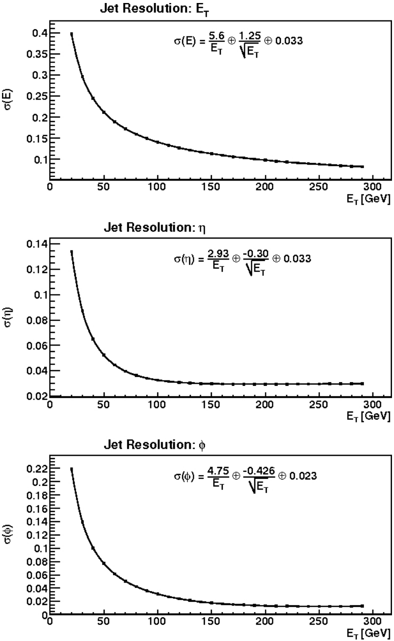
Example for 100 events:

7×100	constraints
-6×100	unknown parameters
-4	global parameters
96	constraints "left"

Benedikt Mura

Global Fit of 3 Masses

- **Problem:** squark mass has large decay width → use MC squark mass in calculations
- **Problem:** E_T balance not perfect due to initial transverse momentum of sparticles → from MC information
- Use "toy" Monte Carlo
  - Take parton kinematics E_T, η, ϕ from generator info
  - Assume jet resolution as given in PTDR (barrel jet E_T)
  - Apply gaussian smearing for input quantities according to this resolution
- Choose arbitrary start values for unknown parameters



Very preliminary results

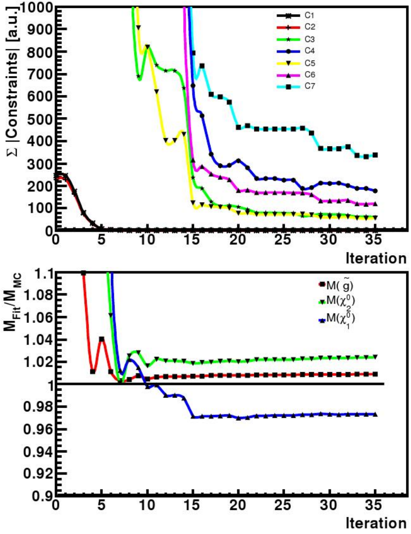
146 Events

Startvalues:

- $M(\tilde{g}) = 500$ GeV
- $M(\tilde{\chi}_1^{\pm}) = 200$ GeV
- $M(\tilde{\chi}_1^0) = 100$ GeV
- $p_x = p_y = p_z = 100$ GeV for both neutralinos

Fit Result

- $M(\tilde{g}) = 397.3$ GeV (MC: 394 GeV)
- $M(\tilde{\chi}_1^{\pm}) = 127.4$ GeV (MC: 124 GeV)
- $M(\tilde{\chi}_1^0) = 68.8$ GeV (MC: 71 GeV)



Summary

SUSY Searches in the Fully Hadronic Channel

- Discovery of SUSY might be easy (if nature is kind)
- Access to SUSY parameters might be much more difficult (if nature is unkind)
- Understanding of detector and suppression of combinatorial background is crucial
- Probing the mSUGRA parameter space by new observales like weak boson production rate
- Local kinematic fits to improve resolution of mass edges
- Global kinematic fits to determine sparticle masses?