MEASURING THE MSSM LAGRANGEAN

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CERN

- SUSY Discoveries
- SUSY Measurements
- SUSY Parameter Studies

SUPERSYMMETRY AT TEV SCALE

Bright side

- ⋆ light Higgs – consistent with data
- ⋆ R parity — stable proton yields dark matter
- ⋆ unification — 3 running couplings meet
- ⋆ radiative symmetrie breaking — 2 Higgs doublets
- ⋆ local supersymmetry – unified theory including gravity?
- ⋆ rich LHC phenomenology — no nasty surprises

Dark side

- ⋆ unknown SUSY breaking
  → soft breaking without quadratic divergences
  → 100+ parameters: masses, scalar couplings, phases...
- ⋆ flavor physics — CKM and lepton flavor through SUSY breaking?
  2HDM — μ parameter through SUSY breaking? [Giudice, Masiero]
- ⋆ MSSM spectrum

		spin	charge	d.o.f.	
quark	q_L, q_R	1/2	2/3 , −1/3	1+1	
→ squark	$\tilde{q}_L, \tilde{q}_R$	0	2/3 , −1/3	1+1	6 flavors
gluon	G_μ	1	0	$n-2$	
→ gluino	$\tilde{g}$	1/2	0	2	Majorana
gauge bosons	γ, Z	1	0	2+3	
Higgs bosons	h^o, H^o, A^o	0	0	3	
→ neutralinos	$\tilde{\chi}_i^o$	1/2	0	$4 \cdot 2$	Majorana
gauge bosons	$W^\pm$	1	± 1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	± 1	2	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	± 1	$2 \cdot 4$	Dirac

⇒ analyses independent of SUSY breaking?

SUSY Signals at LHC: 1

Appearance of supersymmetry

1 discovery — signals for new physics, possibly SUSY?

2 measurements — masses, cross sections, decays?

3 parameter studies — MSSM Lagrangean, SUSY breaking?

$\Rightarrow$ well founded doubts always welcome

Challenge: inclusive SUSY signals at LHC

- $\star$ jets und $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$ $[\tilde{q} \to q\tilde{\chi}_1^0; \tilde{g} \to \tilde{q}\bar{q} \to q\bar{q}\tilde{\chi}_1^0]$
- $\star$ bottoms und $\not{E}_T$: $pp \to \tilde{b}_1\tilde{b}_1^*$ $[\tilde{b}_1 \to b\tilde{\chi}_1^0]$
- $\star$ like sign dileptons: $pp \to \tilde{g}\tilde{g}$ $[\tilde{g} \to \tilde{u}\bar{u} \to \tilde{\chi}_1^+ d\bar{u}$ oder c.c.]
- $\star$ funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$ $[\tilde{t}_1 \to b\tilde{\chi}_1^+ \to b\bar{\ell}\nu\tilde{\chi}_1^0]$
- $\star$ tri-leptons, no Z–Pol: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$ $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0\ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\bar{\nu}]$
- $\star$ ..... [talk: J.-F. Grivaz]

$\Rightarrow$ experience from Tevatron searches

Theory job: precise prediction of production cross sections [Prospino]

- $\star$ masses from inclusive analyses
  until now: exclusion limits for SUSY particles
- $\star$ branching fractions, couplings from cascades [Sdecay: Mühlleitner]

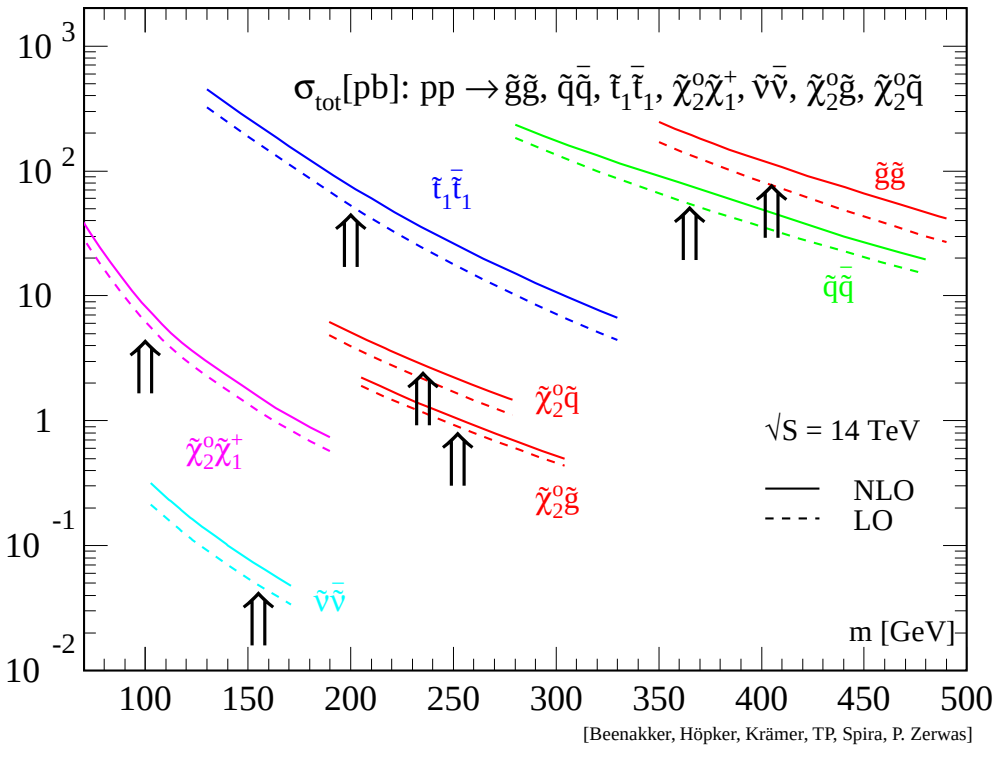
SUSY Signals at LHC: 2

(SUSY)–QCD corrections for inclusive processes

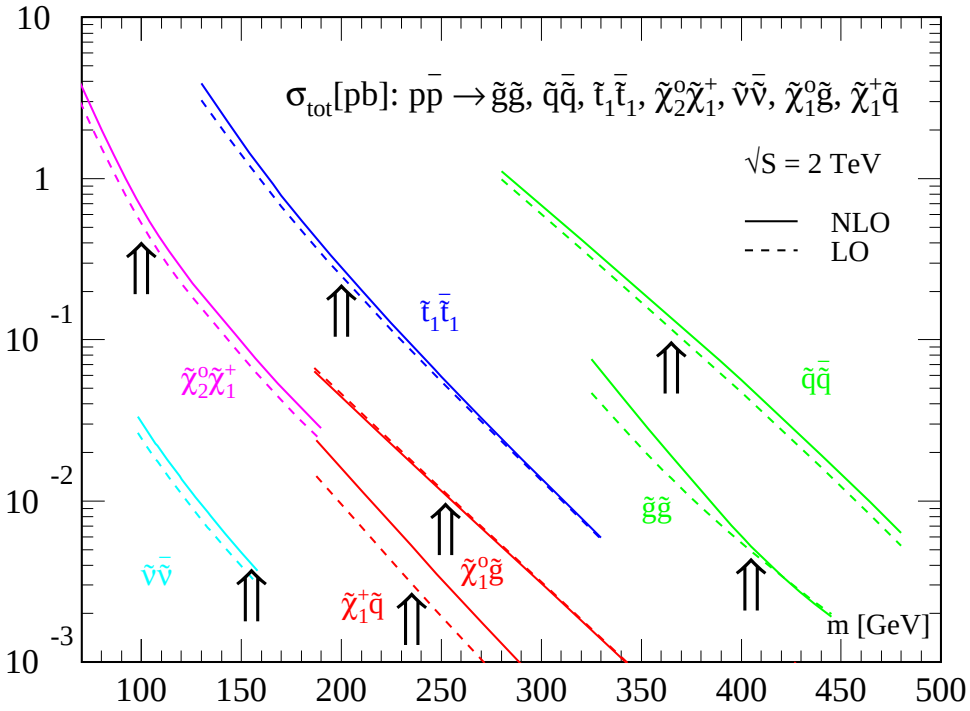
- ⋆ large QCD corrections for squarks, stops, gluinos
- ⋆ small SUSY effects for stops
- ⋆ DY type QCD corrections for neutralinos, charginos, sleptonen
- ⋆ sizeable QCD corrections for neutralino+squark
- ⋆ small QCD corrections for neutralino+gluino
- ⋆ (SUSY)-QCD charged Higgs corrections vital [Prospino2.1]
- ⋆ technically correct: divergent intermediate states, renormalization,...
- ⋆ Les Houches interface to Pythia, SoftSusy, etc.

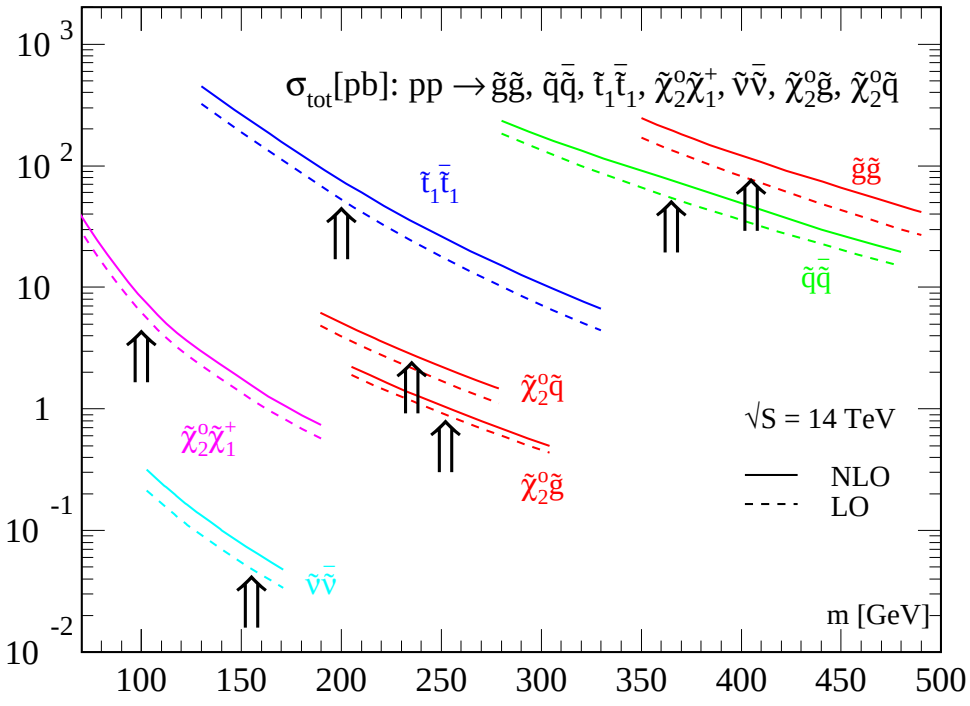
⇒ Prospino2.0beta publicly available [http://pheno.physics.wisc.edu/∼plehn]

Prospino propaganda plot

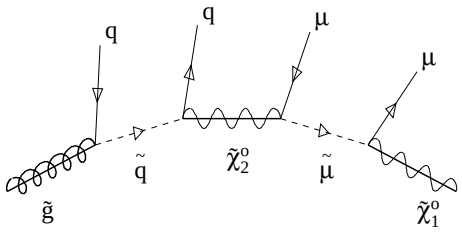


[Beenakker, Höpker, Krämer, TP, Spira, P. Zerwas]


σtot[pb]: pp̄ → g̃g̃, q̃q̃̄, t̃1t̃̄1, χ̃o2χ̃+1, ν̃ν̃̄, χ̃o1g̃, χ̃+1q̃
√S = 2 TeV
NLO
LO
t̃1t̃̄1
χ̃o2χ̃+1
q̃q̃̄
g̃g̃
ν̃ν̃̄
χ̃o1g̃
χ̃+1q̃
m [GeV]
10
1
10-1
10-2
10-3
100
150
200
250
300
350
400
450
500


σtot[pb]: pp → g̃g̃, q̃q̃̄, t̃1t̃̄1, χ̃o2χ̃+1, ν̃ν̃̄, χ̃o2g̃, χ̃o2q̃
t̃1t̃̄1
g̃g̃
q̃q̃̄
χ̃o2q̃
χ̃o2χ̃+1
χ̃o2g̃
ν̃ν̃̄
√S = 14 TeV
NLO
LO
m [GeV]
10 3
10 2
10
1
10-1
10-2
100
150
200
250
300
350
400
450
500

SUSY Measurements at LHC: 1



SUSY spectra from cascade decays

- ⋆ decay $\tilde{g} \to \tilde{q}\bar{q} \to \tilde{\chi}_2^0 q\bar{q} \to \mu^+\mu^- q\bar{q}\tilde{\chi}_1^0$ [hopefully not via Z]
- ⋆ cross sections some 100 pb [more than 3×10^5 events]
- ⋆ thresholds & edges in spectra [Allanach, Lester, Parker, Webber]
  classic example: $m_{\ell\ell}^2 < (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\ell}}^2$
  critical: enough thresholds and edges for all masses?

$\Rightarrow$ detector resolution, calibration, systematic errors?

Studies for SPS points [Polesello et al.]

- ⋆ gluino mass in $\tilde{g} \to \tilde{b}\bar{b}$
- ⋆ higgsino masses in $\tilde{q}_L \to q\tilde{\chi}_4^0, \tilde{q}_L \to \tilde{\chi}_2^\pm q$
- ⋆ chargino mass in $\tilde{q} \to q\tilde{\chi}_1^\pm \to qW_{\rm had}^\pm \tilde{\chi}_1^0$ [Nojiri, Polesello, Tovey]
- ⋆ slepton mass in $\tilde{\ell} \to \ell\tilde{\chi}_1^0$
- ⋆ ....

$\Rightarrow$ generic for small $\tan\beta$
b–jets und τ–leptons for large $\tan\beta$ [talk: F. Paige]

$\Rightarrow$ essentiel for SUSY parameters [SFitter results 2 pages down]

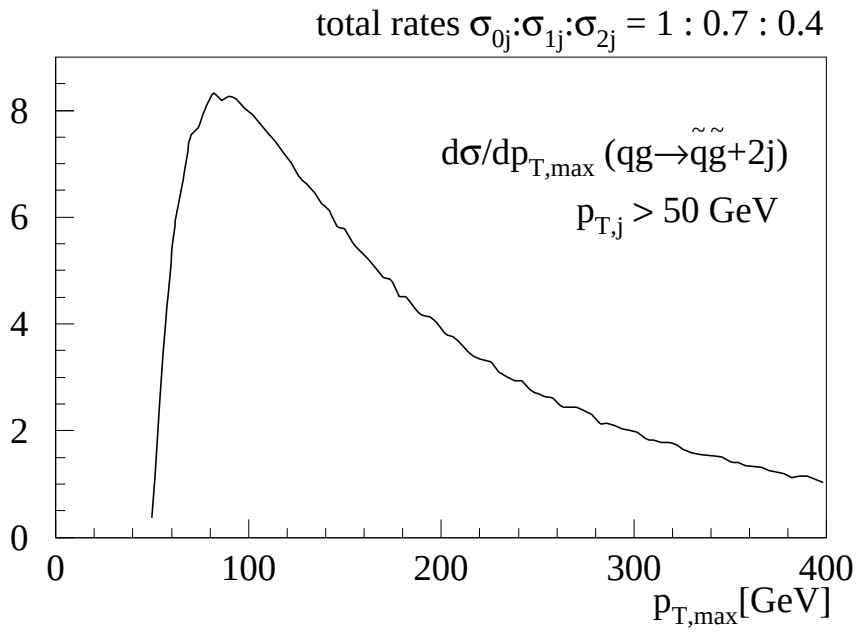
SUSY Measurements at LHC: 2

Problem in decay studies

- ⋆ typical cuts: $p_{T,j} > 150, 100, 50, 50$ GeV
  courageous analyses: $p_{T,j} > 100, 100, 40, 20$ GeV
- ⋆ (a) cuts on $p_{T,j}$ hierarchy?
  $\Rightarrow$ background matrix elements e.g. $pp \to ZZ+$ hard jets
- ⋆ (b) combinatorical background in cascades?
  $\Rightarrow$ matrix elements $pp \to X_{\rm SUSY} Y_{\rm SUSY}+$ hard jets
- ⋆ good experience for Higgs+jets [Zeppenfeld, Rainwater, TP; Jacobs, Mellado]

$\Rightarrow$ SMadgraph [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

Additional jets from $\tilde{q}\tilde{g}$ matrix element [problem for decay cascade?]



PARAMETER DETERMINATION AT LHC: 1

Theorist's point of view

⋆ measured masses, cross sections, decays secondary

⋆ parameters in SUSY Lagrangean from measurements

⇒ SUSY breaking parameters at scale $M_{\rm TeV}$

⇒ extrapolation to $M_{\rm GUT}$ [Blair, Porod, P. Zerwas]

Warmup exercise: Sugra top–down fit using SFitter

⋆ fit including theoretical errors [Allanach, Kraml, Porod]

	SPS1a	$\Delta^{\rm stat}_{\rm LHC}$	$\Delta^{\rm stat+theo}_{\rm LHC}$	$\Delta^{\rm stat}_{\rm LC}$	$\Delta^{\rm stat+theo}_{\rm LC}$	$\Delta^{\rm stat}_{\rm LHC+LC}$	$\Delta^{\rm stat+theo}_{\rm LHC+LC}$
m_0	100	4.0	4.7	0.09	0.6	0.08	0.6
$m_{1/2}$	250	1.8	2.6	0.13	0.6	0.11	0.5
$\tan\beta$	10	1.3	3.5	0.14	0.3	0.14	0.4
A_0	-100	31.8	32.4	4.43	8.5	4.23	12.6

⋆ spectrum from Suspect [Djouadi, Kneur]
fit Suspect and Softsusy [Allanach]

LHC	Suspect	Δ	Softsusy	Δ
m_0	100.00	4.7	97.9	4.6
$m_{1/2}$	250.00	2.7	252.5	2.9
$\tan\beta$	10.00	3.5	11.6	3.6
A_0	-99.96	32.4	14.7	58.9

LC	Suspect	Δ	Softsusy	Δ
m_0	99.94	0.61	98.7	0.5
$m_{1/2}$	250.52	0.58	250.7	0.7
$\tan\beta$	10.26	0.35	10.1	0.5
A_0	-90.15	8.54	-45.2	15.1

LHC+LC	Suspect	Δ	Softsusy	Δ
m_0	100.0	0.59	98.4	0.7
$m_{1/2}$	249.99	0.49	254.3	0.8
$\tan\beta$	9.99	0.44	7.3	0.3
A_0	-100.1	12.6	902.0	18

⇒ best way to estimate theory errors?

PARAMETER DETERMINATION AT LHC: 2

Problem with Sugra fit

- ⋆ example: gaugino mass unifaction major Sugra feature
- ⋆ SPS1a: gluino missing at LC, only seen at LHC

	SPS1a	LHC	LC	LHC+LC		SPS1a	LHC	LC	LHC+LC
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{q}_R$	551.0	19.0		16.0	$\tilde{q}_L$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

$\Rightarrow$ Sugra fit to LC $\Delta m_{1/2} = 0.6$ GeV
Sugra fit to LHC+LC $\Delta m_{1/2} = 0.5$ GeV

$\Rightarrow$ what is data and what are model assumptions?

$\Rightarrow$ stick to weak-scale MSSM fits (where possible)

$\Rightarrow$ need a proper fitting tool...

PARAMETER DETERMINATION AT LHC: 3

SUSY parameters from observables

- ⋆ parameters: weak-scale MSSM Lagrangean
- ⋆ measurements: masses [SuSpect, SoftSUSY, FeynHiggs...]
  branching fractions [MSMlib, Sdecay]
  cross sections [Prospino, MSMlib]
  additional measurements trivial to add
- ⋆ errors: general correlation, statistics & systematics & theory
- ⋆ problem in grid: huge phase space, local minimum?
  problem in fit: domain walls, starting values, global minimum?

SFitter [Lafaye, TP, D. Zerwas, also Fittino]

- ⋆ 1 grid for part of measurements and parameters
  2 fit of remaining parameters to all measurements
  3 complete fit

	LHC	LC	LHC+LC	SPS1a
$\tan\beta$	10.22±9.1	10.26±0.3	10.06±0.2	10
M_1	102.45±5.3	102.32±0.1	102.23±0.1	102.2
M_3	578.67±15	fi x 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fi x 500	197.68±1.2	199.25±1.1	197.8
$M_{\tilde{\tau}_R}$	129.03±6.9	135.66±0.3	133.35±0.6	135.5
$M_{\tilde{\mu}_L}$	198.7±5.1	198.7±0.5	198.7±0.5	198.7
$M_{\tilde{q}3_L}$	498.3±110	497.6±4.4	521.9±39	501.3
$M_{\tilde{t}_R}$	fi x 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fi x 500	504.35±61	525.6
A_τ	fi x 0	-202.4±89.5	352.1±171	-253.5
A_t	-507.8±91	-501.95±2.7	-505.24±3.3	-504.9
A_b	-784.7±35603	fi x 0	-977±12467	-799.4

⇒ LHC very powerful thanks to recent progress [additional measurements?]

OUTLOOK

SUSY signals at LHC

- ⋆ measurement of rates and decays first step
- ⋆ NLO cross sections using Prospino2.0 [standard at Tevatron]
- ⋆ QCD corrections relevant
- ⋆ SUSY–QCD corrections not always negligible

SUSY measurements at LHC

- ⋆ final state with jets essential for error determination
- ⋆ hard matrix elements using SMadgraph
- ⋆ analysis of complex cascade decays incredible strategy

SUSY parameters at LHC

- ⋆ SUSY observables secondary for theorists
- ⋆ determination of SUSY parameters using Sfitter
- ⋆ combination of experiments vital