SUSY TOOLS FOR THE LHC

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CERN

- Supersymmetry at the LHC
- Discoveries
- Measurements
- Parameter Studies

SUPERSYMMETRY AT TEV SCALE: 1

Starting from data...

- ⋆ ...which seem to indicate a light Higgs
- ⋆ problem of light Higgs:
  scalar masses perturbatively unstable
  quadratic divergences $\delta m_h^2 \propto g^2\Lambda^2$
  all–orders Higgs mass driven to cutoff $m_h \to \Lambda$
  solution: counter term for exact cancellation
  $\Rightarrow$ artificial, unmotivated, ugly [anthropic principle?]

$\Rightarrow$ alternative: new physics at TeV scale

$\Rightarrow$ supersymmetry
extra dimensions
little Higgs (pseudo–Goldstone)
topcolor (composite Higgs)
YourFavoriteNewPhysics...

$\Rightarrow$ beautiful concepts und symmetries

$\Rightarrow$ in general problematic to realize at TeV scala [data in the way]

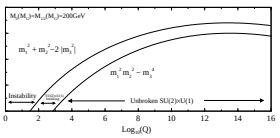
Idea of supersymmetry

- ⋆ cancellation of quadratic divergences through statistics (-1):
  scalar partner of SM fermions
  fermionic partner of SM gauge bosons
  fermionic partner of SM scalars

$\Rightarrow$ obviously broken symmetry

SUPERSYMMETRY AT TEV SCALE: 2

Bright side



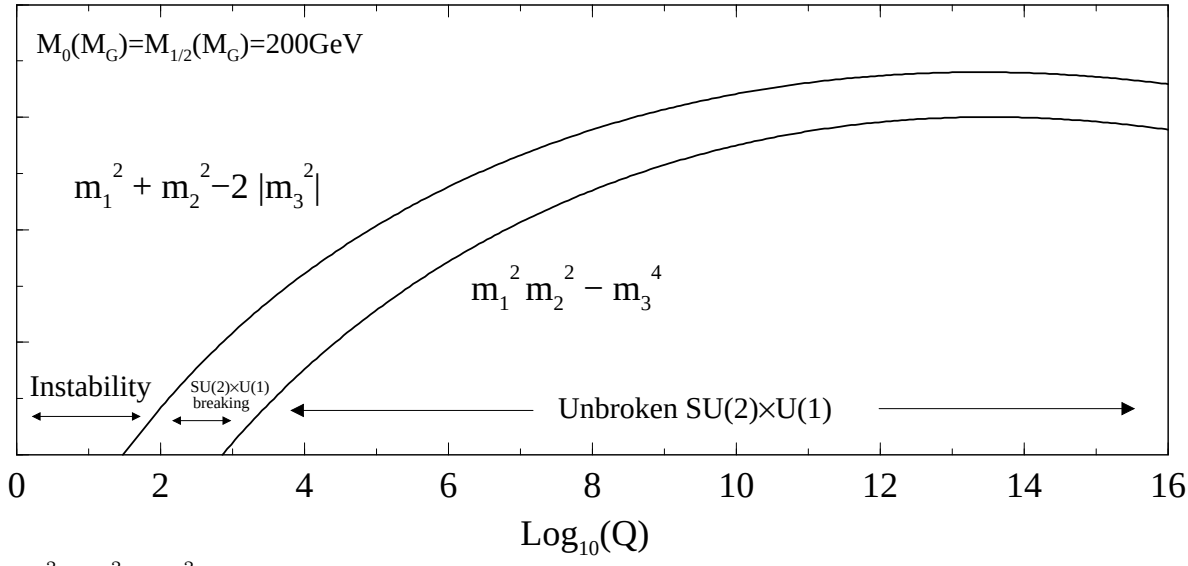
- ⋆ radiative symmetrie breaking — 2 Higgs doublets
- ⋆ R parity — stable proton yields dark matter
- ⋆ unification — 3 running couplings meet
- ⋆ local supersymmetry – unified theory including gravity?
- ⋆ rich LHC phenomenology — no nasty surprises

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

$\Rightarrow$ analyses independent of SUSY breaking?



$[m_i^2 = m_{H_i}^2 + \mu^2]$ [Dedes]

SUPERSYMMETRY AT TEV SCALE: 3

Struktures of SUSY spectrum

⋆ gauginos–higgsinos: $m_{\tilde{\chi}^0_2} \sim m_{\tilde{\chi}^+_1}$ or $m_{\tilde{\chi}^0_1} \sim m_{\tilde{\chi}^+_1}$ in MSSM

$$\begin{pmatrix} m_{\tilde{B}} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ 0 & m_{\tilde{W}} & m_Z c_w c_\beta & -m_z c_w s_\beta \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \end{pmatrix} \begin{pmatrix} m_{\tilde{W}} & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & -\mu \end{pmatrix}$$

⋆ stop and sbottom mixing in MSSM

$$\begin{pmatrix} m_Q^2 + m_t^2 + \left(\frac{1}{2} - \frac{2}{3} s_w^2\right) m_Z^2 c_{2\beta} & -m_t \left(A_t + \mu \cot\beta\right) \\ -m_t \left(A_t + \mu \cot\beta\right) & m_U^2 + m_t^2 + \frac{2}{3} s_w^2 m_Z^2 c_{2\beta} \end{pmatrix}$$

⋆ heavy gluinos and squarks through unification

$m_{\tilde{B},\tilde{W},\tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6$

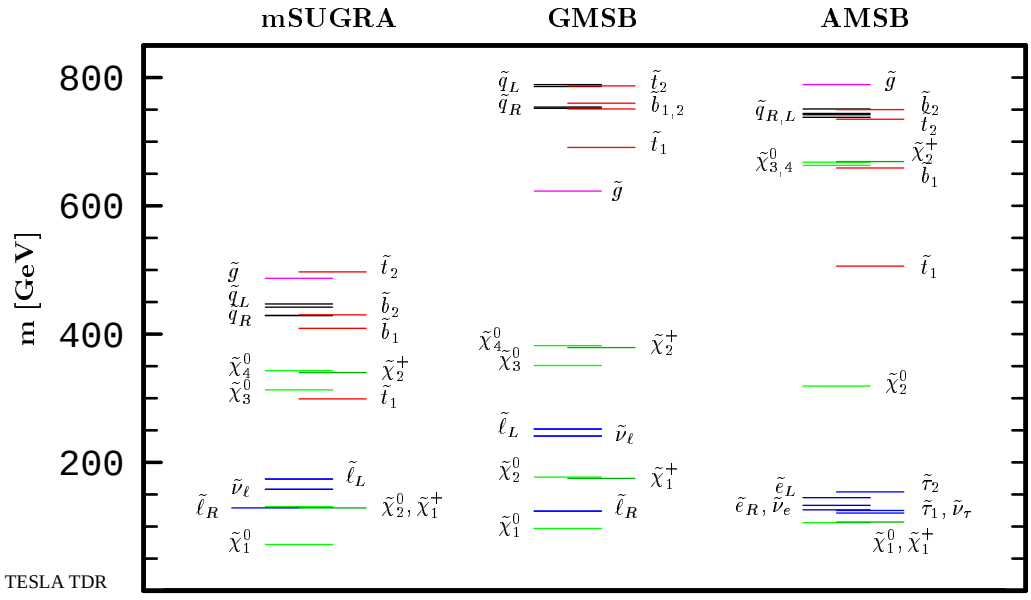
$m_{\tilde{\ell},\tilde{q}}/m_{1/2} \sim 0.7, 2.5 \quad [m_0 \ll m_{1/2}]$

n.b. mass and coupling unification independent [Hooper, TP]

⋆ lightest SUSY particle: $\tilde{\chi}^0_1, \tilde{\nu}$

→ including dark matter data: $\tilde{\chi}^0_1 \sim \tilde{B}, \tilde{W}$

examples



SUSY Signals at LHC: 1

Appearance of supersymmetry

1 dicovery — signals for new physics, possibly SUSY?

2 measurements — masses, cross sections, decays?

3 parameter studies — MSSM Lagrangean, SUSY breaking?

$\Rightarrow$ well founded doubts always expected

Challenge: find fool proof 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.]
- $\star$ tri-leptons, no Z–Pol: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$ [$\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0\ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\bar{\nu}$]
- $\star$ funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$ [$\tilde{t}_1 \to b\tilde{\chi}_1^+ \to b\bar{\ell}\nu\tilde{\chi}_1^0$]
- $\star$ ..... [more ideas your job...]

$\Rightarrow$ experience from Tevatron searches

Precise NLO prediction of production cross sections [Prospino]

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

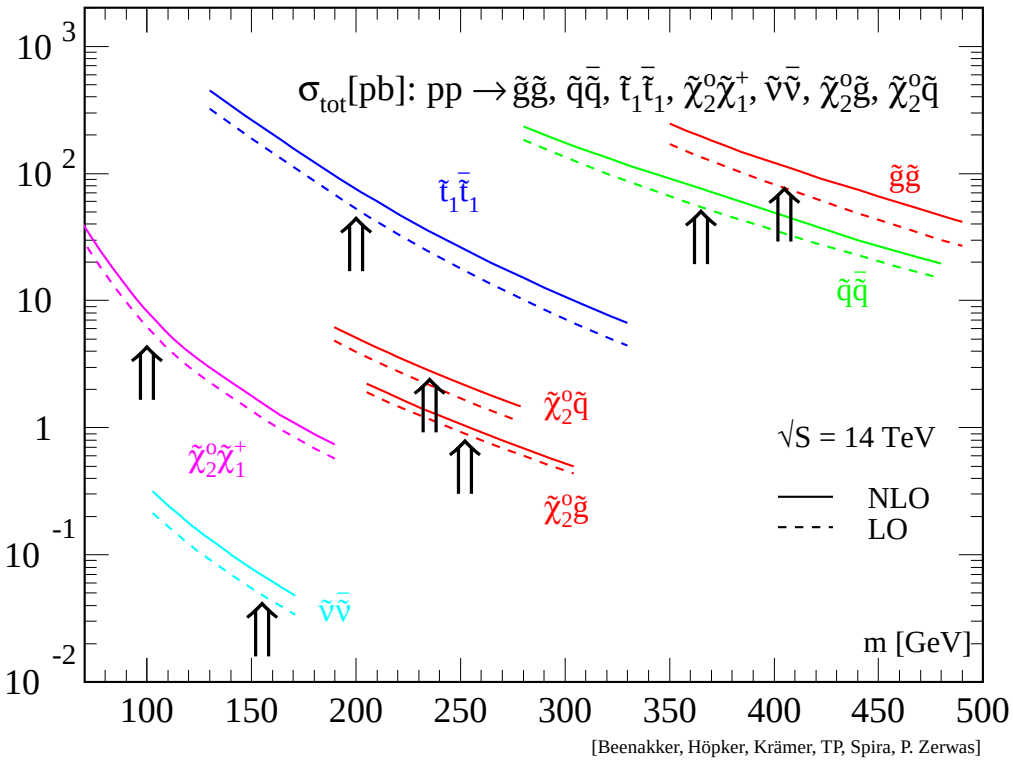
SUSY Signals at LHC: 2

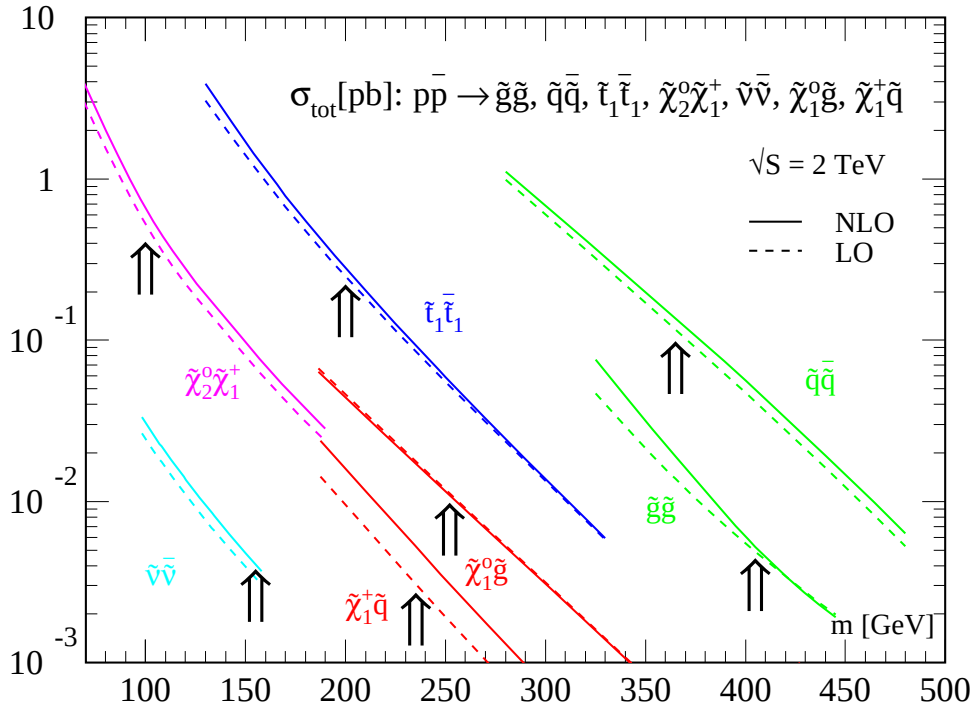
(SUSY)–QCD corrections for inclusive processes

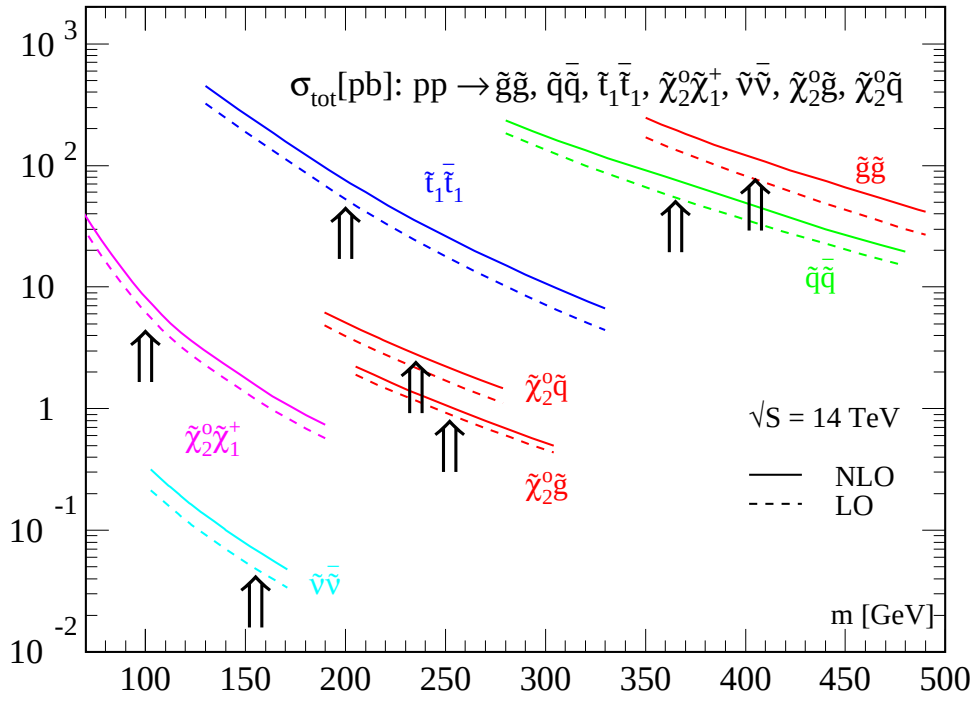
- ⋆ large QCD corrections for squarks, stops, gluinos
- ⋆ small SUSY effects for stops
- ⋆ DY type QCD corrections for neutralinos, charginos, sleptonen
- ⋆ sizeable QCD corrections for neutralino+squark
- ⋆ small QCD corrections for neutralino+gluino
- ⋆ technically correct: divergent intermediate states,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

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

Prospino propaganda plot

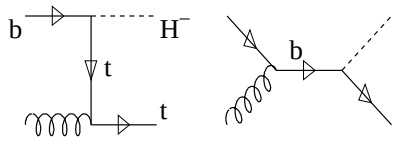



σtot[pb]: pp̄ → g̃g̃, q̃q̃̄, t̃1t̃̄1, χ̃o2χ̃+1, ν̃ν̃̄, χ̃o1g̃, χ̃+1q̃
√S = 2 TeV
NLO
LO
t̃1t̃̄1
χ̃o2χ̃+1
q̃q̃̄
g̃g̃
ν̃ν̃̄
χ̃o1g̃
χ̃+1q̃
m [GeV]
10
1
10-1
10-2
10-3
100
150
200
250
300
350
400
450
500


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

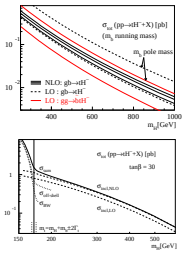
SUSY Signals at LHC: 3

Unusual SUSY signal: charged Higgs



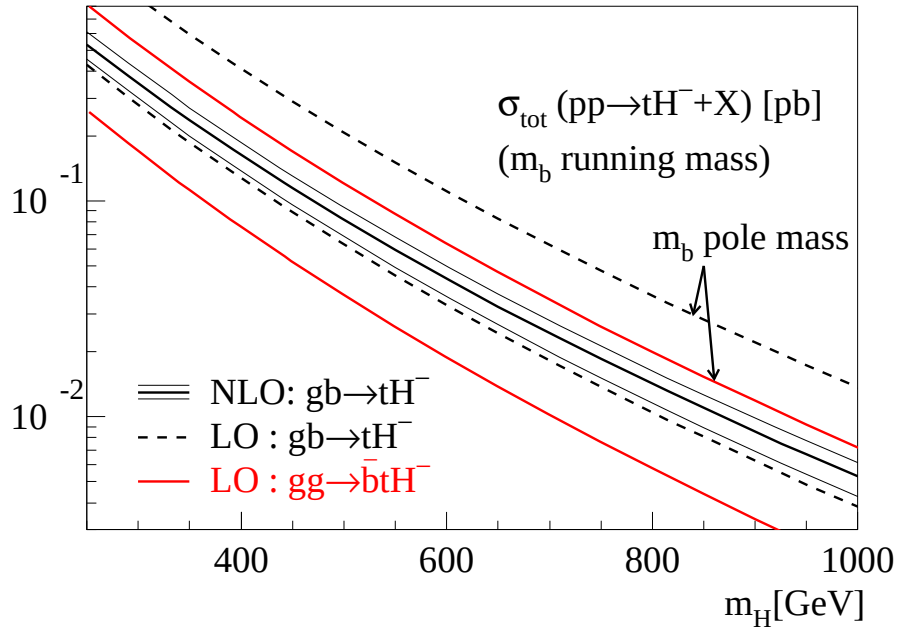
- ⋆ no adjoint Higgs field in superpotential
  → 2 doublets for top und bottom mass [$\tan\beta$]
  → charged Higgs scalar [$H^- \to \tau\bar{\nu}, \bar{t}b, W^- h^0$]
- ⋆ production $bg \to tH^-$ [Prospino2.1, CMS: Nikitenko, ATLAS: Assamagan]
  (a) conceptional: bottom partonen [Boos & TP]
  (b) experimental: measurement von $\tan\beta$ [LH 2003]

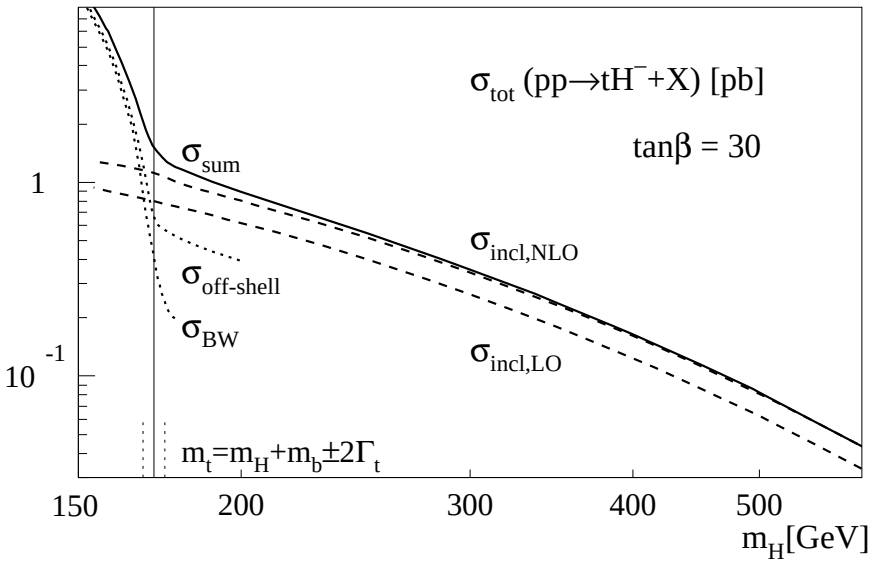
Signal: charged Higgs

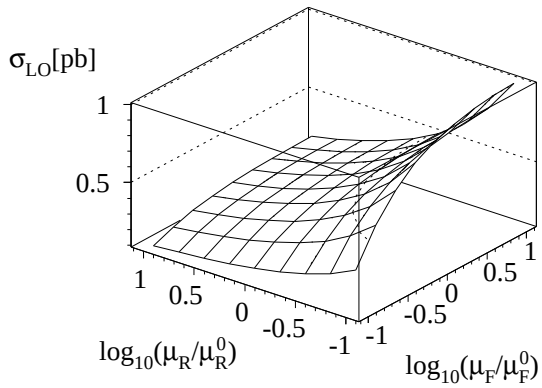


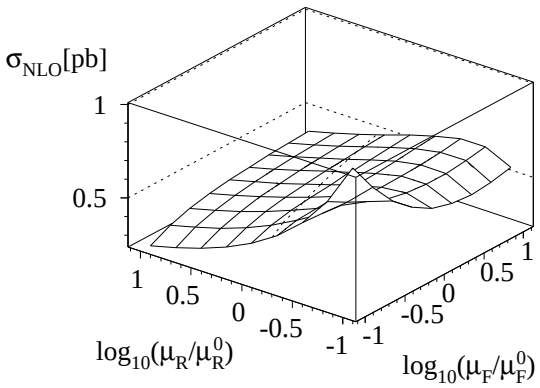
- ⋆ QCD corrections under control
- ⋆ intermediate top subtracted
- ⋆ factorizing SUSY contributions [resummed: Nierste,...]
  Yukawa coupling renormalization $\Delta_b = \alpha_s C_F/(2\pi) \times m_{\tilde{g}}\mu/M^2 \ \tan\beta$
- ⋆ explicit SUSY diagrams negligible

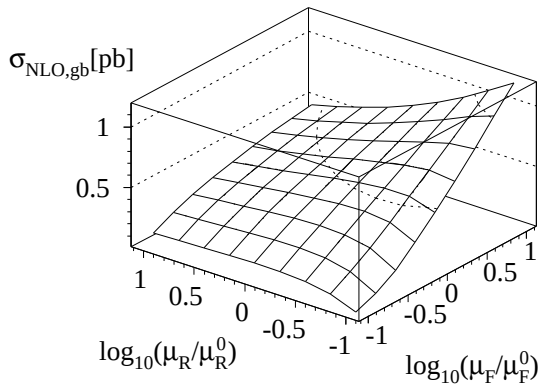
mSUGRA	m_H	$\tan\beta$	$m_{1/2}$	μ	$\sigma_{\rm NLO}$[fb]	Δ_b	$\Delta_b^{\rm resum}$	non–Δ_b
1a	402	10	250	352	25.6	-11.0%	-10.2%	-1.9%
1b	543	30	400	501	61.7	-27.9%	-23.5%	-4.6%
2	1446	10	300	125	0.13	-0.92%	-0.91%	-1.7%
3	578	10	400	509	8.02	-10.1%	-9.5%	-1.1%
4	416	50	300	377	395	-39.0%	-31.0%	-4.6%
5	699	5	300	640	5.73	-8.5%	-8.0%	0.8%
GMSB								
7	387	15		300	48.0	-8.5%	-8.1%	-0.9%
8	521	15		398	20.4	-7.5%	-7.1%	-0.5%
AMSB								
9	916	10		870	1.29	-10.6%	-9.9%	4.1%

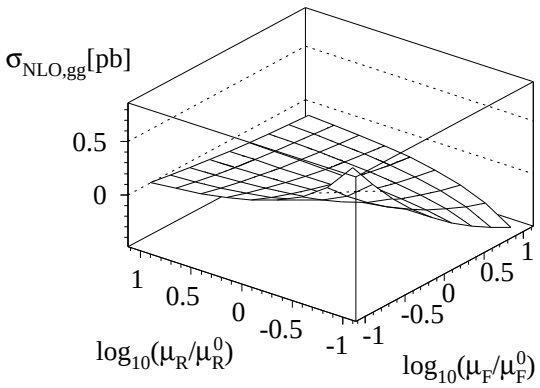

σtot (pp→tH⁻+X) [pb]
(mb running mass)
mb pole mass
NLO: gb→tH⁻
LO : gb→tH⁻
LO : gg→b̄tH⁻
10 -1
10 -2
400
600
800
1000
mH[GeV]


σtot (pp→tH⁻+X) [pb]
tanβ = 30
σsum
σincl,NLO
σoff-shell
σBW
σincl,LO
mt=mH+mb±2Γt
1
10 -1
150
200
300
400
500
mH[GeV]

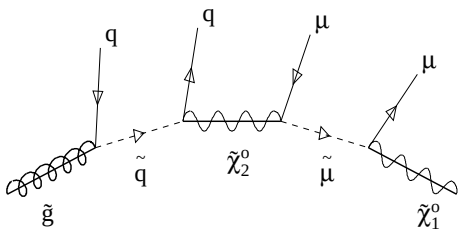

σ_{LO}[pb]
1
0.5
1
0.5
0
-0.5
-1
$\log_{10}(\mu_R/\mu_R^0)$
1
0.5
0
-0.5
-1
$\log_{10}(\mu_F/\mu_F^0)$


σ_{NLO}[pb]
1
0.5
1
0.5
0
-0.5
-1
$\log_{10}(\mu_R/\mu_R^0)$
1
0.5
0
-0.5
-1
$\log_{10}(\mu_F/\mu_F^0)$


$\sigma_{NLO,gb}$[pb]
1
0.5
1
0.5
0
-0.5
-1
$\log_{10}(\mu_R/\mu_R^0)$
1
0.5
0
-0.5
-1
$\log_{10}(\mu_F/\mu_F^0)$

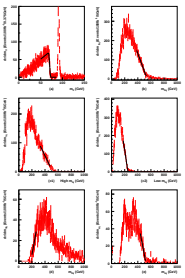

$\sigma_{NLO,gg}$[pb]
0.5
0
1
0.5
0
-0.5
-1
$\log_{10}(\mu_R/\mu_R^0)$
1
0.5
0
-0.5
-1
$\log_{10}(\mu_F/\mu_F^0)$

SUSY Measurements at LHC: 1



SUSY spektra 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 $m^2_{\ell\ell} < (m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0})/m^2_{\tilde{\ell}}$
  critical: enough thresholds and edges available?



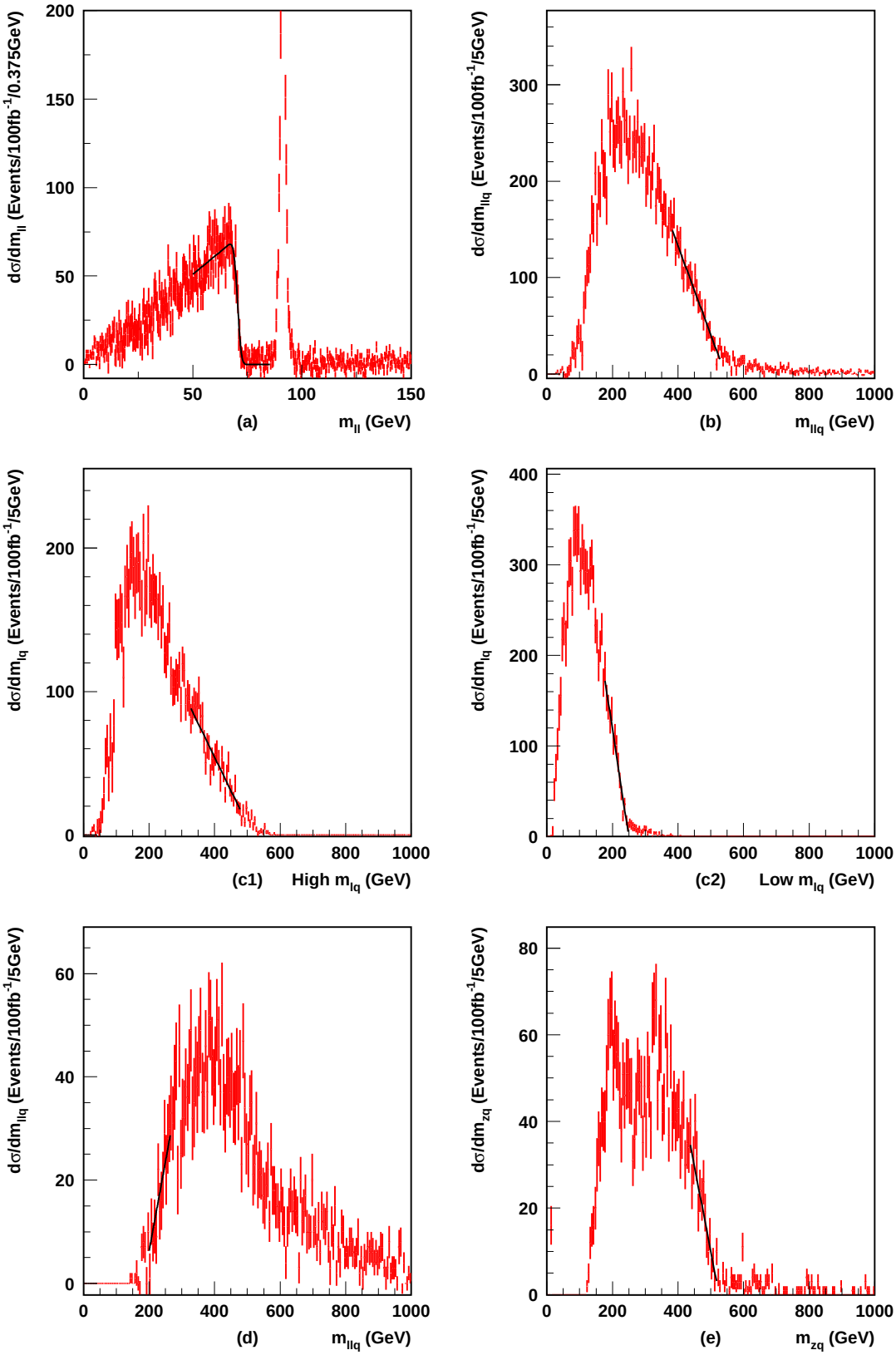
⇒ detector resolution, calibration, systematic errors?

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 $\tilde{q} \to q\tilde{\chi}_1^{\pm} \to qW^{\pm}_{\rm had}\tilde{\chi}_1^0$ [Nojiri, Polesello, Tovey]
- ⋆ slepton mass in $\tilde{\ell} \to \ell\tilde{\chi}_1^0$
- ⋆ ....

⇒ generic for small $\tan\beta$
problems with b–jets und taus for large $\tan\beta$

⇒ essentiel for SUSY parameters [SFitter results coming]



[Allanach, Lester, Parker, Webber]

SUSY Measurements at LHC: 2

Problem in decay studies

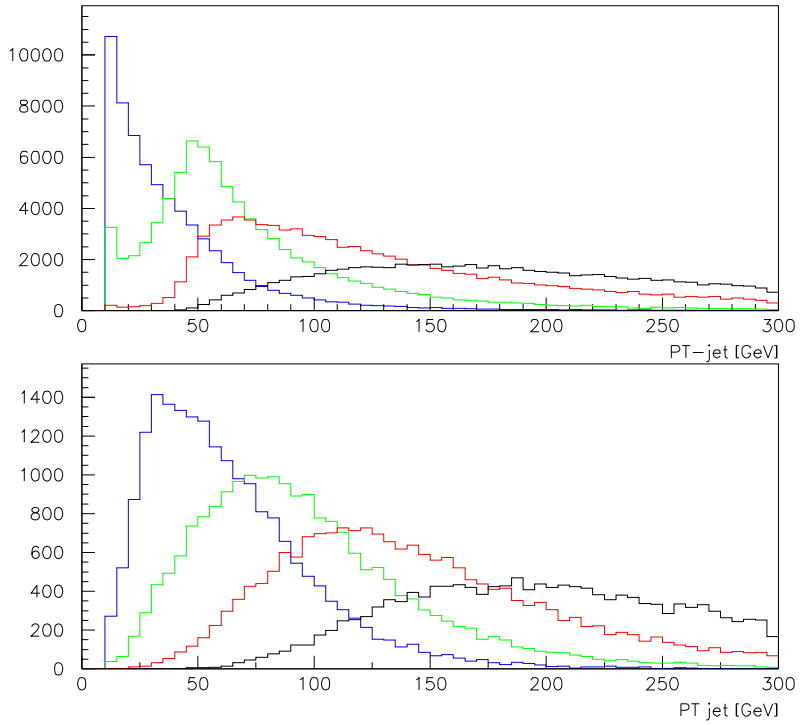
- ⋆ typical cuts: $p_{T,j} > 150, 100, 50, 50$ GeV
  courageous analyses: $p_{T,j} > 100, 100, 40, 20$ GeV
- ⋆ (a) cuts on $p_{T,j}$ hierarchy?
  (b) combinatorical background through jet radiation?

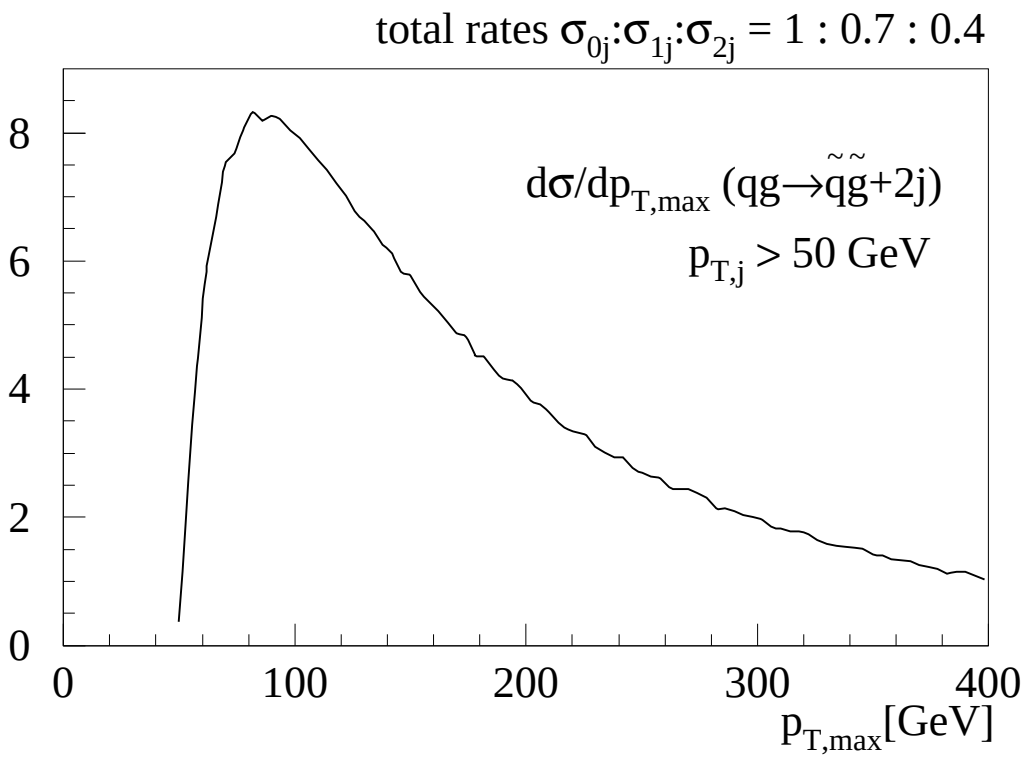
$\Rightarrow$ matrix elements $pp \to X_{\rm SUSY} Y_{\rm SUSY}+$ hard jets
great success for Higgs+jets [Zeppenfeld, Rainwater; Jacobs, Mellado]

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

While testing Smadgraph

- ⋆ ...preliminary Madevent results for $pp \to ZZ+$ jets
- ⋆ background to SUSY cascades including $\tilde{\chi}_3^0 \to Z$ [D. Zerwas, TP]
- ⋆ $p_{T,j} > 50$ GeV: $\sigma = \{2500, 1100, 560\}$ fb for $pp \to ZZ$+{1,2,3} jets




total rates $\sigma_{0j}:\sigma_{1j}:\sigma_{2j}$ = 1 : 0.7 : 0.4
$d\sigma/dp_{T,max}$ ($qg \to \tilde{q}\tilde{g}$+2j)
$p_{T,j} > 50$ GeV
0
2
4
6
8
0
100
200
300
400
$p_{T,max}$[GeV]

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: fit of mSUGRA using SFitter

- ⋆ fit with fixed sign of μ

	SPS1a	LHC	$\Delta_{\rm LHC}$	LC	$\Delta_{\rm LC}$	LHC+LC	$\Delta_{\rm LHC+LC}$
m_0	100	100.03	4.0	100.03	0.09	100.04	0.08
$m_{1/2}$	250	249.95	1.8	250.02	0.13	250.01	0.11
$\tan\beta$	10	9.87	1.3	9.98	0.14	9.98	0.14
A_0	-100	-99.29	31.8	-98.26	4.43	-98.25	4.13

⇒ impact of 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					

⇒ what is data and what are model assumptions?

PARAMETER DETERMINATION AT LHC: 2

SUSY parameters from observables

- ⋆ parameters: 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 Fit: phase space, starting values
  problem in Grid: huge grid, hard to completely cover

SFitter [Lafaye, TP, D. Zerwas]

- ⋆ 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

⇒ all but LHC+LC not without model assumptions [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 essentiel [Higgs at LHC]
- ⋆ hard matrix elements using SMadgraph
- ⋆ analysis of cascade decays promising strategy

SUSY parameters at LHC

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