

# MEASURING THE MSSM LAGRANGEAN

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- Supersymmetry at the LHC
- Higher order cross sections: Prospino2
- SUSY plus jets: SmadGraph
- Parameter extraction: Sfitter

# TeV SCALE SUPERSYMMETRY

## Bright side

- ★ 3 running gauge couplings meet — GUT gauge group
- ★ 2 Higgs doublets — radiative symmetry breaking
- ★ R parity — stable proton yields dark matter
- ★ local supersymmetry – including gravity?
- ★ rich LHC phenomenology — no nasty surprises

## Dark side

- ★ unknown SUSY breaking
  - masses, scalar couplings, phases...
  - e.g. hierarchical spectrum? [Split SUSY]
- ★ flavor physics and SUSY breaking
  - CKM and lepton flavor?
- ★ 2 Higgs doublet model
  - $\mu$  parameter and SUSY breaking?

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

⇒ as many as exclusive analyses as possible

# SUSY LES HOUCHES ACCORD

## Problem: Supersymmetric parameter conventions

- comparison of specialized codes [remember: e.g. Comphep–Pythia–Isajet]
- ⇒ fix SUSY conventions once for all
- soft breaking parameters [e.g.  $\pm A_t$ ]
  - scale dependence of couplings, masses [e.g.  $m(q = \text{TeV}, v, m_t)$ ?]
  - definitions of mass matrixes, mixing angles [e.g.  $\tilde{t}_{L,R}$  up or down?]

## SUSY Les Houches Accord [P. Skands et al.]

- spectrum generators: SoftSusy, SPheno, FeynHiggs,...
  - multi-purpose Monte Carlos: Pythia, Herwig, Sherpa
  - matrix element generators: Whizard, SmadGraph
  - NLO cross sections: Prospino2
  - NLO decay rates: Sdecay
  - SUSY parameter extraction: Fittino, Sfitter
  - dark matter: Micromegas
- ⇒ **fixed parameter convention and read-write format**

# SUSY SIGNALS AT LHC: 1

## Supersymmetry at the LHC

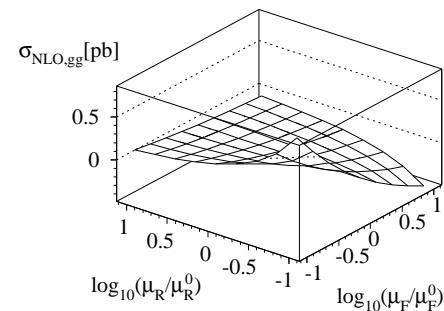
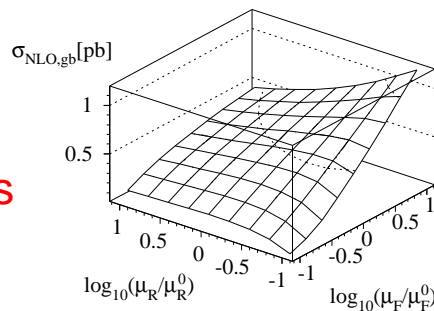
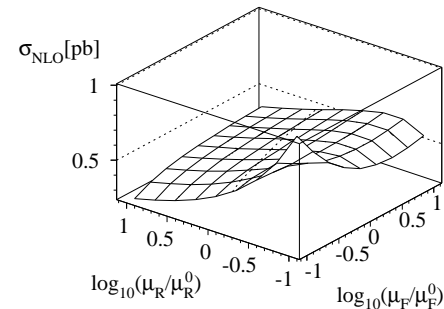
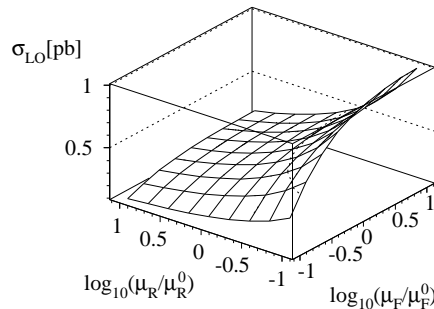
- (1) **possible discovery** — signals for new physics, exclusion of parameter space
  - (2) **measurements** — masses, cross sections, decays
  - (3) **parameter studies** — MSSM Lagrangean, SUSY breaking
- ⇒ at least 10% precision to be matched at LHC (theorist's nightmare)

## Hadron collider observables with errors

- renormalization scale from  $\alpha_s, y_{b,t}$
- factorization scale from parton densities
- perturbative series  $N_c \alpha_s / \pi \sim 10\%$
- finite terms

[LO-NLO-NNLO: Drell-Yan, Higgs]

⇒ **NLO errors: 15...40 % for SUSY particles**



# SUSY SIGNALS AT LHC: 2

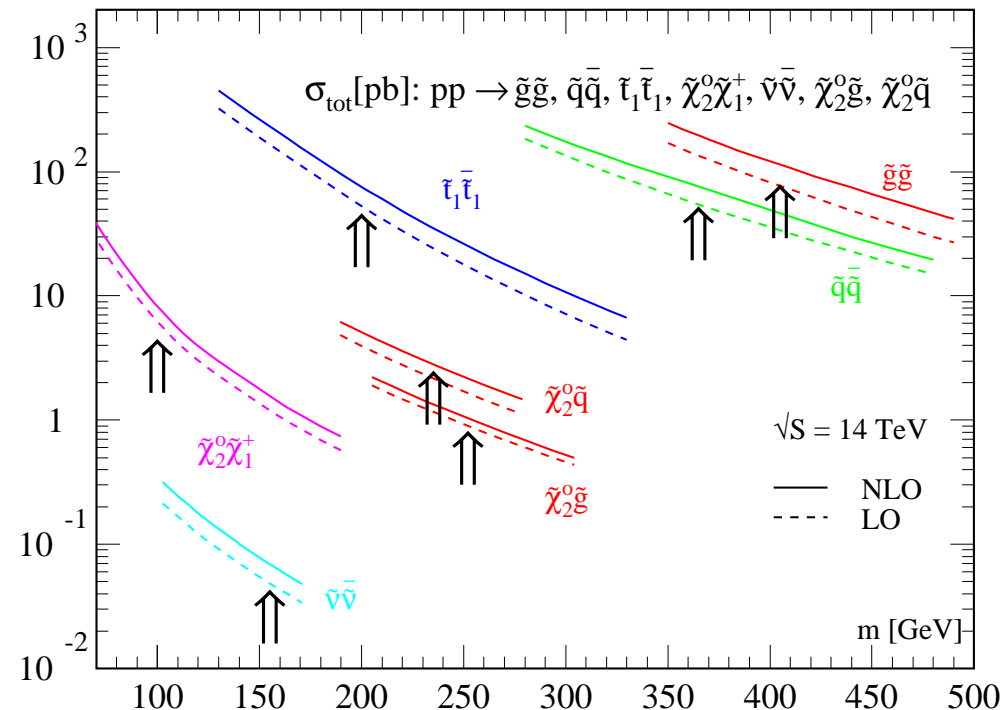
## Prospino2: NLO cross sections for Tevatron and LHC

- all two-particle SUSY production channels included
- download from Prospino2 page: <http://pheno.physics.wisc.edu/~plehn>
- extended version beyond Prospino2:  $pp \rightarrow SS^*, tH^- \dots$

[thanks to: W. Beenakker, R.Höcker, M. Krämer, M. Spira, P. Zerwas]

## SUSY signals included

- jets and  $\cancel{E}_T$ :  $pp \rightarrow \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- bottoms and  $\cancel{E}_T$ :  $pp \rightarrow \tilde{b}_1\tilde{b}_1^*$
- like sign dileptons:  $pp \rightarrow \tilde{g}\tilde{g}$   
[ $\tilde{g} \rightarrow \tilde{u}\tilde{u} \rightarrow \tilde{\chi}_1^+ d\bar{u}$  or c.c.]
- tri-leptons:  $pp \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^-$   
[ $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\bar{\ell} \rightarrow \tilde{\chi}_1^0\ell\bar{\ell}$ ;  $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\ell\bar{\nu}$ ]
- funny tops:  $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$



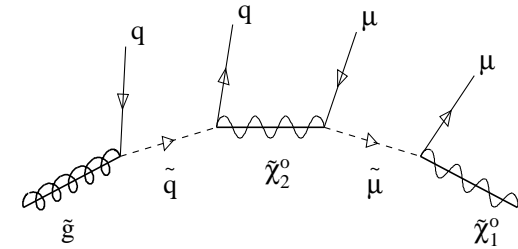
# SUSY MEASUREMENTS AT LHC: 1

## SUSY spectra from cascade decays

- decay  $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow \tilde{\chi}_2^0 q\bar{q} \rightarrow \mu^+ \mu^- q\bar{q}\tilde{\chi}_1^0$  [hopefully not via  $Z$ ]
- cross sections some 100 pb [more than  $3 \times 10^5$  events]
- thresholds & edges in spectra [Hinchliffe, Paige...;Allanach, Parker,...]  
critical: enough thresholds and edges available?

$$\text{classical } m_{\ell\ell}^2 < (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\ell}}^2$$

⇒ detector resolution, calibration, systematic errors?

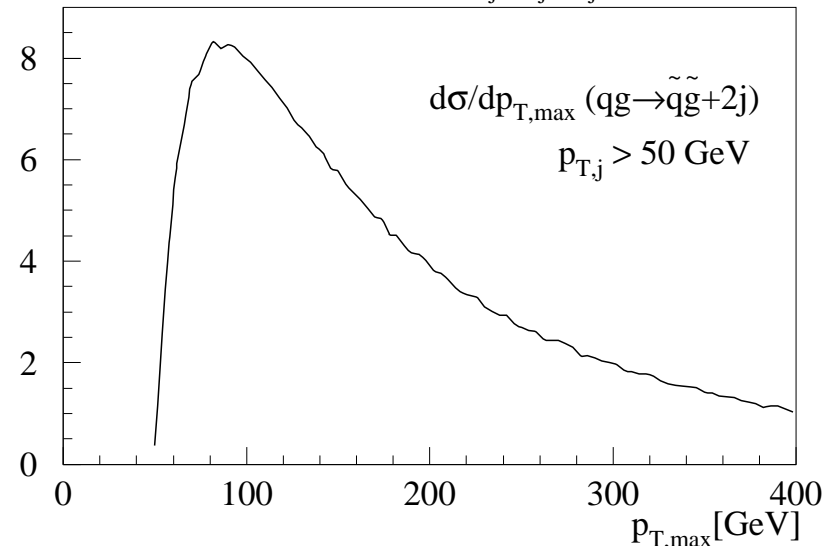


## Problem in decay studies

- typical cuts:  $p_{T,j} > 150, 100, 50, 50$  GeV
  - (a) cuts on  $p_{T,j}$  hierarchy?
  - (b) combinatorics through jet radiation?
- ⇒ matrix elements for SUSY + hard jets

⇒ **Smadgraph** [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

total rates  $\sigma_{0j}:\sigma_{1j}:\sigma_{2j} = 1 : 0.7 : 0.4$



# SUSY MEASUREMENTS AT LHC: 2

## Theorist's point of view

- measured masses, cross sections, decays secondary
  - parameters in SUSY Lagrangean from measurements
- ⇒ SUSY breaking parameters at TeV (or higher) scale

## Warmup exercise: SUGRA top-down fit

- fit including all errors

[Allanach, Kraml, Porod; Jack & Jones]

abs. errors	SPS1a	$\Delta$ at LHC		$\Delta$ at LC		$\Delta$ at LHC+LC	
		stat	stat+theo	stat	stat+theo	stat	stat+theo
$m_0$	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	$\Delta$	Softsusy	$\Delta$
$m_0$	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

- ⇒ **best way to estimate theory errors?**

LHC+LC				
$m_0$	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

# SUSY MEASUREMENTS 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],...
- 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 closed subset
- (2) fit of remaining parameters
- (3) complete fit

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

⇒ LHC+LC without model assumptions



## Theory tools for supersymmetry at LHC

- spectrum generators → LHC cross sections all available with SLHA
- major progress on errors for SUSY at LHC
- many tools in testing phase or beyond, for example...

**Prospino2** — NLO cross sections at Tevatron/LHC

**SmadGraph** — MSSM matrix elements

**Sfitter** — MSSM parameter extraction