SUPERSYMMETRY AT THE LHC

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- TeV Scale Supersymmetry
- Signals at the LHC
- Tests at the LHC
- Split Supersymmetry

TeV Scale Supersymmetry: 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 $m_h \longrightarrow \Lambda$

$\Rightarrow$ solution: counter term for exact cancellation $\Rightarrow$ artificial, unmotivated, ugly

$\Rightarrow$ or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs (pseudo–Goldstone Higgs)
Higgsless/composite Higgs
YourFavoriteNewPhysics...

$\Rightarrow$ all beautiful concepts and symmetries

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

Idea of supersymmetry: cancellation of divergences through statistics factor (-1)

[scalars vs. SM fermions; fermions vs. SM gauge bosons; fermions vs. SM scalars]

TeV Scale Supersymmetry: 2

Bright side

- ⋆ original motivation — Higgs scalar mass stable [general problem in field theory]
- ⋆ R parity — stable proton yields dark matter [post–WMAP: weakly interacting?]
- ⋆ unification — 3 running couplings meet [additional degrees of freedom in beta functions]
- ⋆ radiative symmetry breaking — 2 Higgs doublets [linking weak and SUSY scale]
- ⋆ local supersymmetry – including gravity?
- ⋆ only one model, but rich collider phenomenology

Dark side

- ⋆ unknown SUSY breaking
  → masses, couplings, phases...
  → hierarchical spectrum [Split SUSY]
- ⋆ flavor physics and SUSY breaking
  → CKM and lepton flavor?
- ⋆ 2 Higgs doublet model
  → μ parameter and SUSY breaking?

⇒ as many analyses as possible

		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_μ	1	n − 2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, 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

SUPERSYMMETRY AT THE LHC: 1

One decade of discovering

(1) possible discovery — signals for new physics, exclusion of parameter space

(2) measurements — masses, cross sections, decays

(3) parameter studies — MSSM Lagrangean, SUSY breaking

$\Rightarrow$ at least 10% precision to be matched by phenomenology [QCD-theorist's nightmare]

Inclusive signals [Prospino2: http://pheno.physics.wisc.edu/~plehn]

- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$

  $[\tilde{g} \to \tilde{q}^* q$ and $\tilde{q} \to q\tilde{\chi}_1^0 + X]$

- funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$

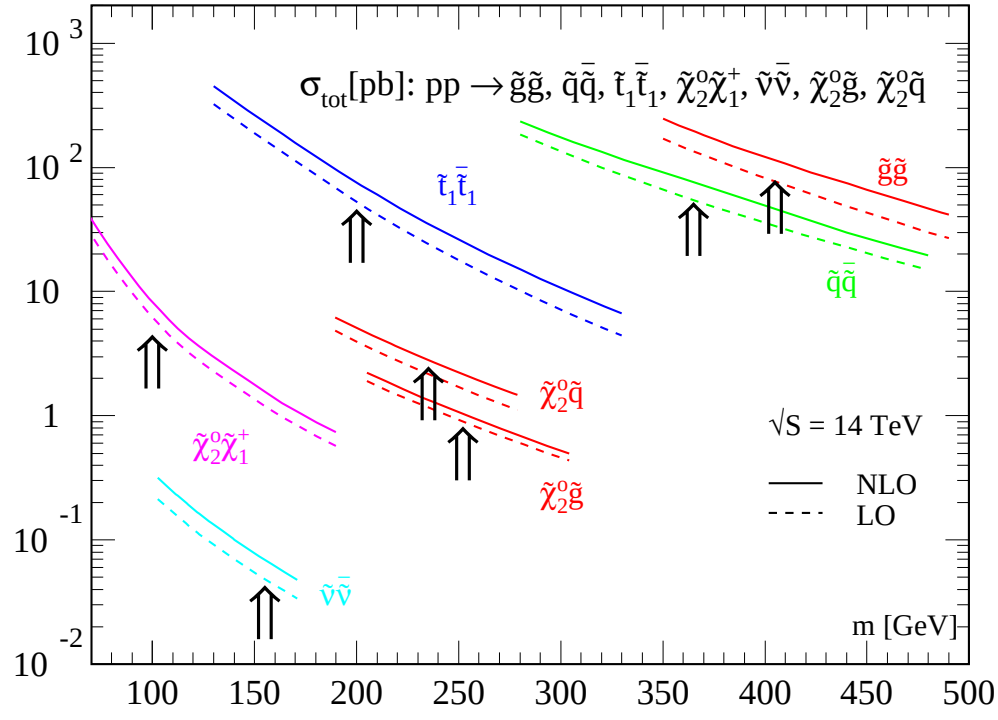
  $[\tilde{t} \to b\tilde{\chi}_1^+ \to bW^+\tilde{\chi}_1^0]$

- like sign dileptons: $pp \to \tilde{g}\tilde{g}$

  $[\tilde{g} \to \tilde{u}\bar{u} \to \tilde{\chi}_1^+ d\bar{u}$ or c.c.]

- tri-leptons: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$

  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0\ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\bar{\nu}]$



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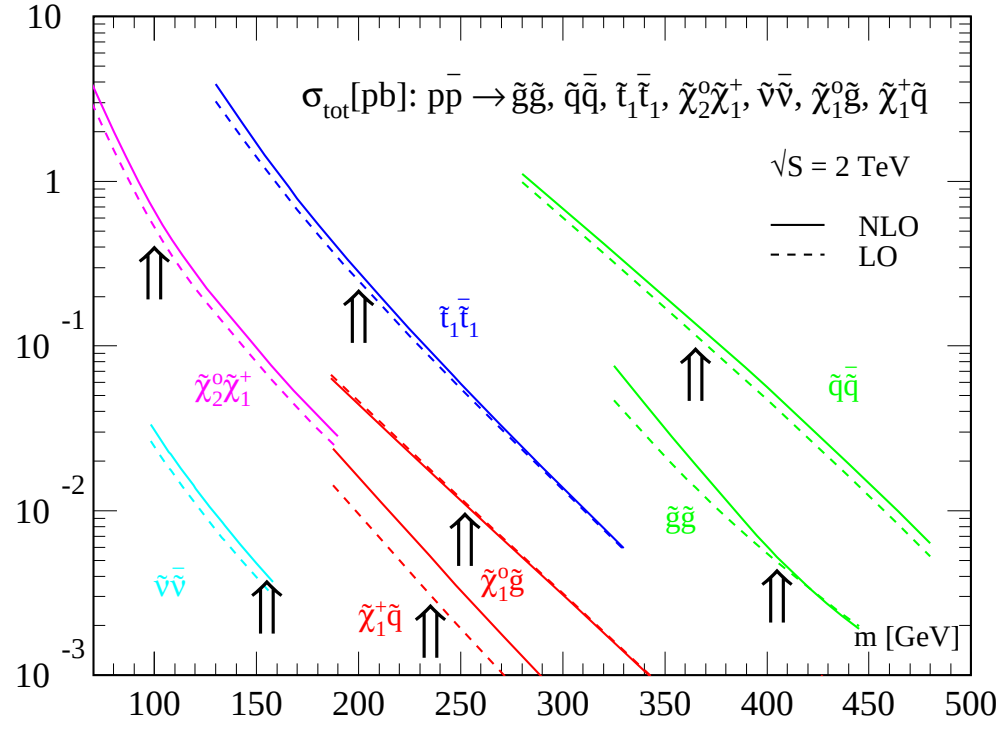
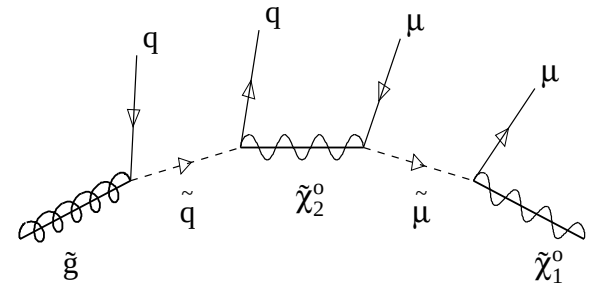


SUPERSYMMETRY AT THE LHC: 2

SUSY spectra from cascade decays



- example: $\tilde{g} \to \tilde{q}\bar{q} \to \tilde{\chi}_2^0 q\bar{q} \to \mu^+\mu^- q\bar{q}\tilde{\chi}_1^0$
- thresholds & edges [Hinchliffe, Paige...; Cambridge ex-th]

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

$\Rightarrow$ enough thresholds and edges available?

$\Rightarrow$ detector resolution, calibration, systematic errors? [Polesello; Gjelsten, Miller, Osland]

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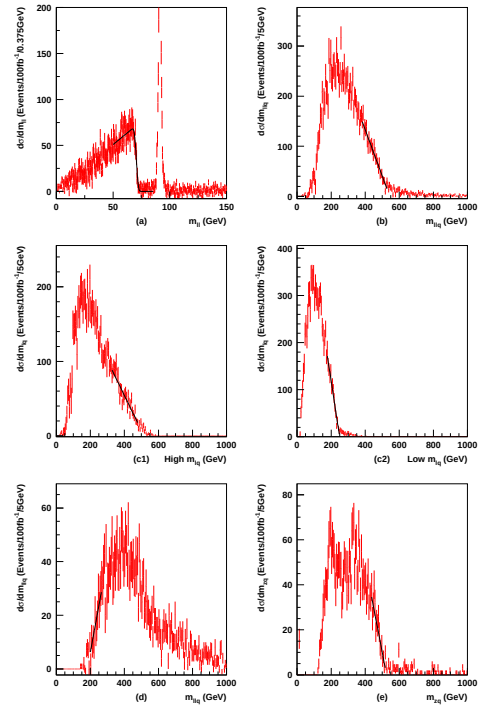


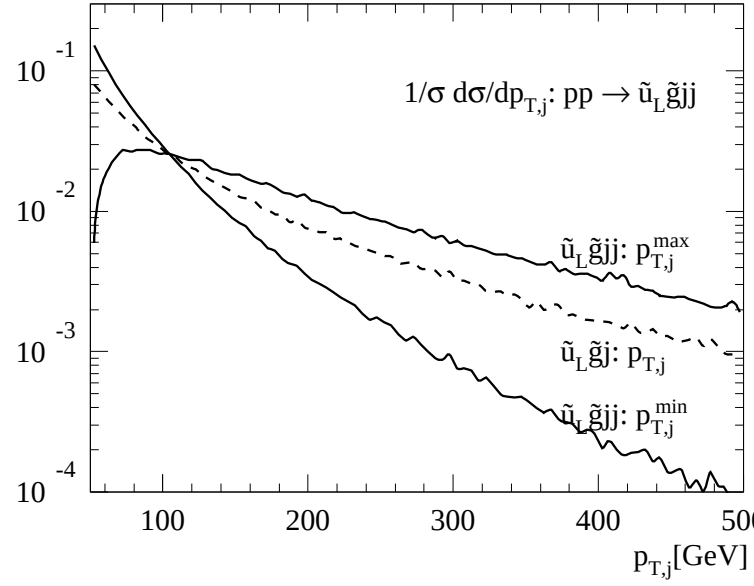
Complex collider signals [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

- cascade studies sensitive to additional jets?
- compute $\tilde{u}_L\tilde{g}$+2 jets [SPS1a, $p_{T,j} > 100$GeV]

σ[pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85

$\Rightarrow$ Smadgraph: automatic web-based amplitudes

[complete Feynman rules; 300+ processes checked]



SUPERSYMMETRY AT THE LHC: 3

SUSY parameters from observables [Les Houches Accord: Skands,...]

- parameters: weak-scale MSSM Lagrangean
- measurements: masses or edges
  branching fractions [MSMlib, Sdecay]
  cross sections [Prospino2, 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]

- (1) grid for closed subset
  (2) fit of remaining parameters
  (3) complete fit

$\Rightarrow$ LHC better than expected

$\Rightarrow$ LHC+ILC without assumptions

	LHC	ILC	LHC+ILC	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	fix 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fix 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
$M_{\tilde{t}_R}$	fix 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fix 500	504.35±61	525.6
A_τ	fix 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	fix 0	-977±12467	-799.4

SPLIT SUPERSYMMETRY: 1

Split Supersymmetry [Dimopoulos, Arkani-Hamed; Giudice, Romanino; Wells]

- forget about fine tuning [Higgs will never be as bad as cosmological constant]
- remember all the good things SUSY did for you [dark matter, unification]

$\Rightarrow$ make scalars heavy [SU(5) multiplets decouple; Dawson, Georgi 1979]

$\Rightarrow$ protect gaugino and higgsino masses at TeV scale [Drees: might not be possible]

News for phenomenology [Kilian, TP, Richardson, Schmidt]

- hadronizing gluinos [$\tau \sim \tilde{m}^{-4} \sim 6.5$s for $\tilde{m} = 10^9$GeV]
  $\Rightarrow$ heavy R hadrons [Farrar, Fayet; Baer, Cheung, Gunion; UKQCD; Kraan]
  $\Rightarrow$ gluinonium [Kühn & Ono; Goldman & Haber; Cheung & Keung]
- renormalization group running without scalars
  $\Rightarrow$ corrections to couplings protected by SUSY [up to 20% for $\tilde{m} \sim 10^9$ GeV]

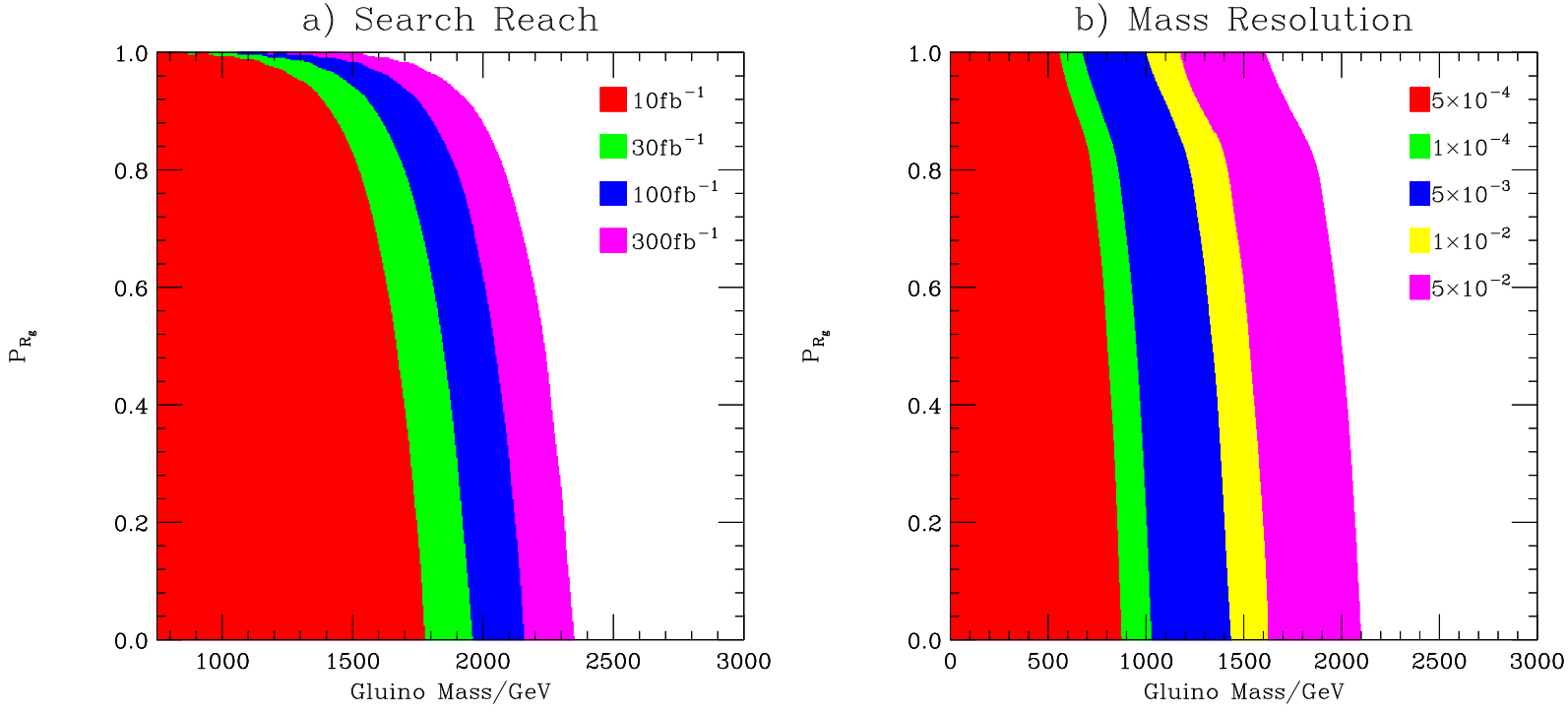
Experimental prospects [model aesthetics no argument for multi-billion machine]

- LHC: stable gluino [charge of hadrons the key]
- ILC: anomalous Yukawa couplings [indirect fit or direct measurement]
- IceCube: one event per year for low-mass R hadrons [Hewett, Lillie, Mazip, Rizzo]
- Pierre Auger: few events for $\tilde{m} < 10^{11}$ GeV [Anchordoqui, Goldberg, Nunez]

Split Supersymmetry: 2

LHC Searches [Kilian, TP, Richardson, Schmidt]

- neutralinos, charginos like higgsinos in MSSM
- many gluinos produced [100 pb for 400 GeV gluinos]
- gluinonium $\tilde{g}\tilde{g} \to jj$ [CMS: reach $\sim$ TeV? decay to $\gamma\gamma$?]
- charged R hadrons in tracker, calorimeter, muon chambers [neutral: missing energy]
- mass measurement through time of flight tracker–muon chamber [CDF?]



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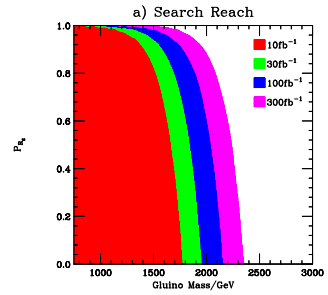

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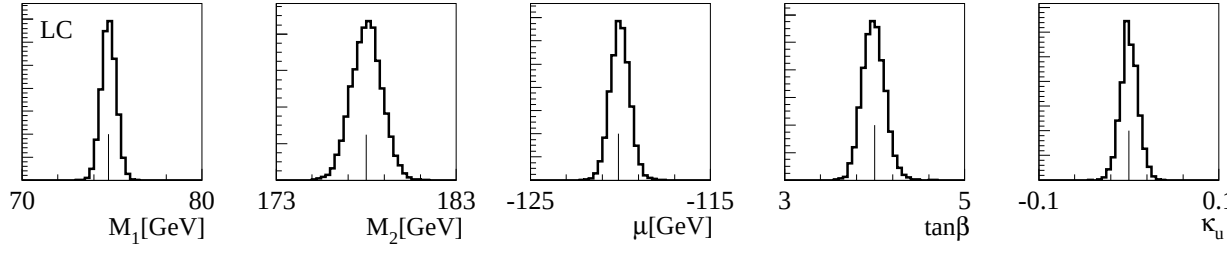
Linear Collider Searches [Kilian, TP, Richardson, Schmidt]

- gluinos not produced because of decoupled squarks
- neutralino–chargino sector analysis as usual [robust towards decay channels]
- anomalous Yukawas $\equiv$ neutralino mass matrix entries [coupling to $h\tilde{H}\tilde{W}$]

$\Rightarrow$ (1) direct measurements of $\chi\chi h$ [Whizard, Smadgraph $\to$ errors distinctly unpromising]

(2) indirect determination of mass matrices $\Rightarrow$ coupling measurement to $\lesssim 10\%$



OUTLOOK

Supersymmetry at the LHC

- inclusive analyses tested at Tevatron
- measurements in cascade decays in great shape
- extrapolation to high scales preferably with ILC data

$\Rightarrow$ LHC phenomenology desperately needed

Future of phenomenology

- exciting times ahead of us: LHC will produce data
- interface between experiment and model building crucial
- we will understand (more about) electroweak symmetry breaking

$\Rightarrow$ New data will be the key!