FINDING SUPERSYMMETRY AT THE LHC

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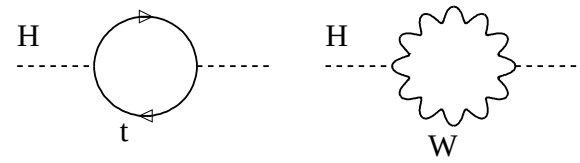
- TeV–scale supersymmetry
- Signals at Tevatron and LHC
- Measurements at LHC
- Parameters at LHC (and ILC)

TeV–Scale Supersymmetry: 1



Theory argument, starting from data...

- ...which seem to indicate a light Higgs
- problem of light Higgs: mass driven to cutoff of theory

$$\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, \Lambda^2$$

$\Rightarrow$ easy solution: cancel loops with counter term $\Rightarrow$ artificial, unmotivated, ugly

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

$\Rightarrow$ typically: cancellation with new particles or high scale discussed away

$\Rightarrow$ all beautiful concepts, problematic to realize at TeV scale [data seriously in the way]

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

[SM fermions to scalars; SM gauge bosons to fermions; SM scalars to fermions]

TeV–Scale Supersymmetry: 2

SUSY idea: solve hierarchy problem by doubling spectrum

- stop scalars to cancel top loop [couplings protected]
- gauginos, higgsinos (neutral or charged) to cancel W, Z and Higgs loops
- gluino for 2-loop, plus sleptons and squarks

$\Rightarrow$ rich collider and non-collider phenomenology [broken SUSY effective theory of everything]

$\Rightarrow$ gauge coupling unification, dark matter, string inspiration,... [1-800-FIND-SUSY]

$\Rightarrow$ argument turned around: big desert at LHC unexpected [historical extrapolation]

SUSY–Higgs sector

- hermitian Higgs field not allowed
  $\longrightarrow$ how to give mass to t and b?
  $\longrightarrow$ two Higgs doublets

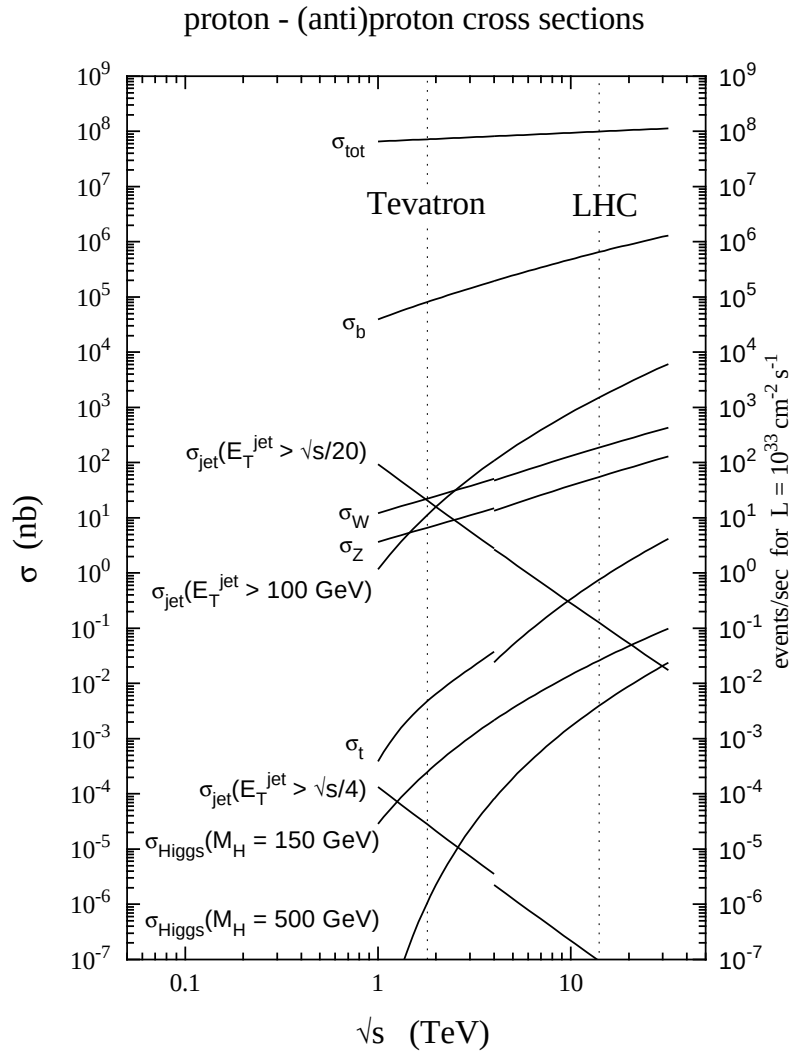
$\Rightarrow$ SUSY–Higgs alone interesting at LHC

$\Rightarrow$ would be another talk...

		spin	d.o.f.	
fermion	f_L , f_R	1/2	1+1	
$\longrightarrow$ sfermion	$\tilde{f}_L$, $\tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
$\longrightarrow$ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ , Z	1	2+3	
Higgs bosons	h^0 , H^0 , A^0	0	3	
$\longrightarrow$ neutralinos	$\tilde{\chi}_i^0$	1/2	$4 \cdot 2$	Majorana
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\longrightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	Dirac

Hadron colliders: signal vs. background

- LHC not built to study QCD jets
- what is a jet and what is inside? [b, τ tag]
- LHC trigger: 'no lepton/photon — no data'
- statistics: $S/\sqrt{B} > 5$ the LHC goal



SUPERSYMMETRY AT HADRON COLLIDERS

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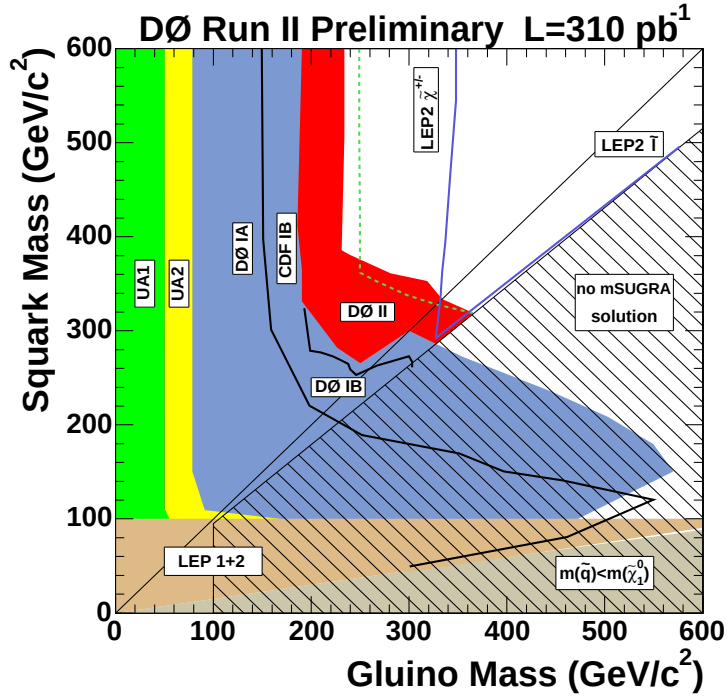
Tevatron: inclusive squarks and gluinos

- squarks, gluinos strongly interacting:
  $g\tilde{q}\bar{q}, q\tilde{g}\bar{q}, g\tilde{g}\tilde{g}$ fixed by QCD
- QCD cross sections:
  $p\bar{p} \to \tilde{q}\bar{q}^*, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ [best if $m(\tilde{q}) \sim m(\tilde{g})$]
- decays to jets and LSP [plus possible jets and leptons]
- gaugino mass unification only for efficiency

$\Rightarrow$ know how to do jets plus LSP



SUPERSYMMETRY AT LHC: 1

Supersymmetry at the LHC

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

(2) measurements — masses, cross sections, decays

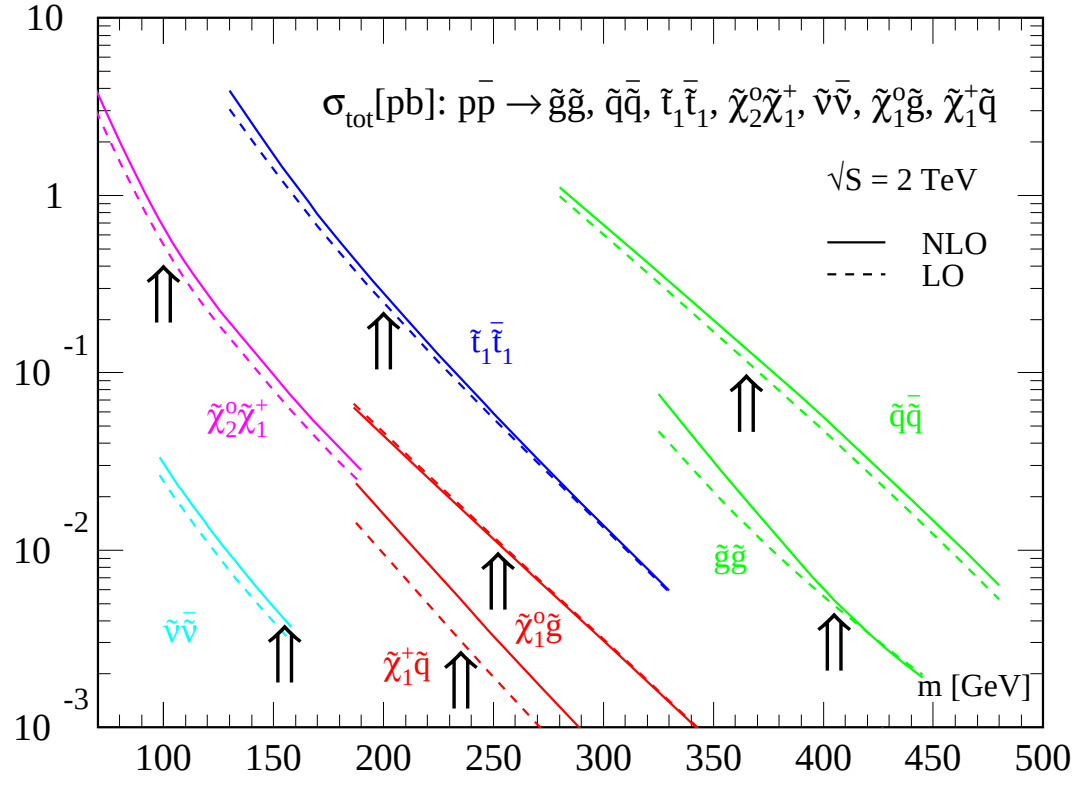
(3) parameter studies — MSSM Lagrangean, SUSY breaking

SUSY signals include [NLO: Prospino2]

- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$
- tri-leptons: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$

  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0\ell\bar{\ell};\ \tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\bar{\nu}]$
- like–sign dileptons: $pp \to \tilde{g}\tilde{g}$

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



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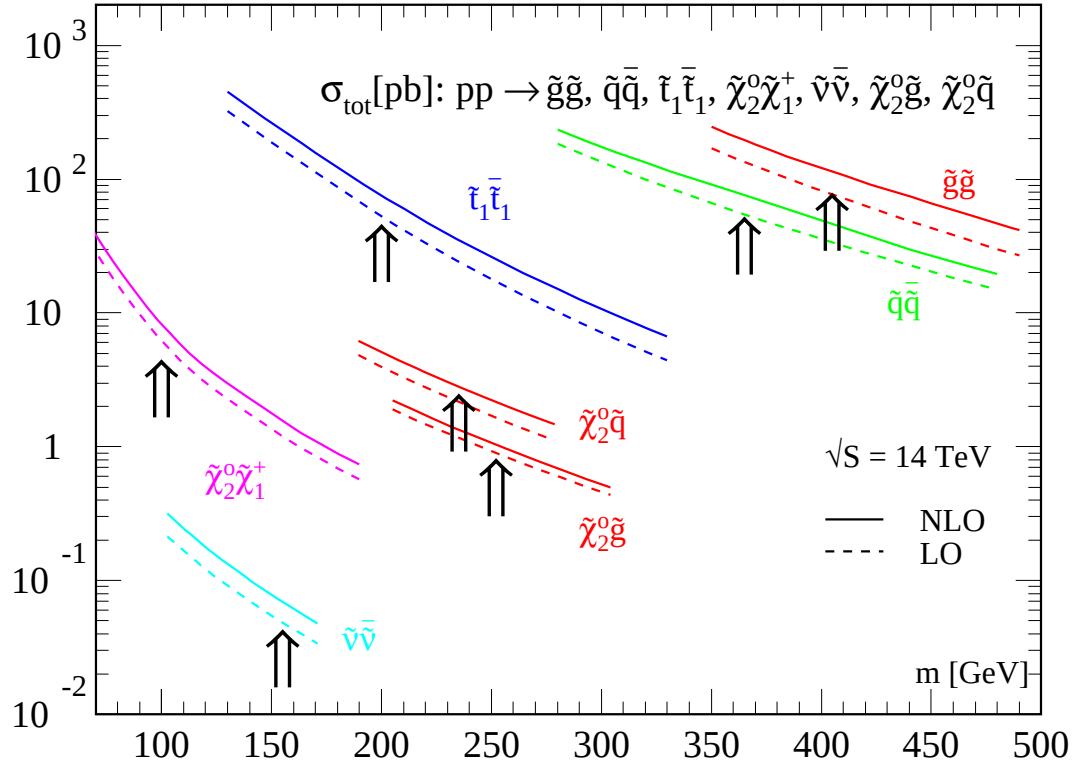

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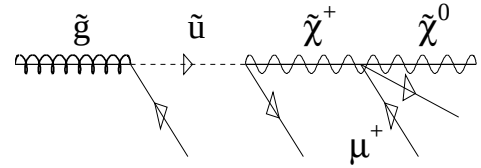

– like–sign dileptons: $pp \to \tilde{g}\tilde{g}$ [Barnett, Gunion, Haber]

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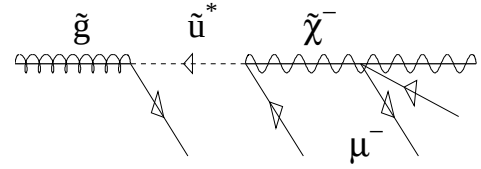
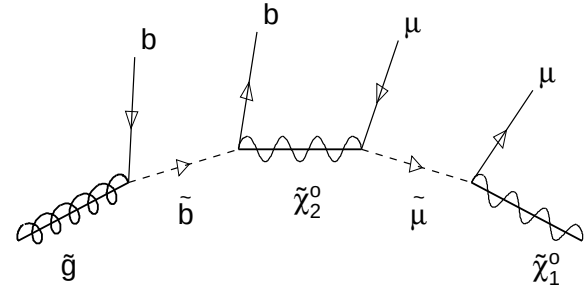


$\Rightarrow$ gluinos indeed QCD Majorana fermions

SUPERSYMMETRY AT LHC: 2

Spectra from cascade decays



- decay $\tilde{g} \to \tilde{q}\bar{q} \to \tilde{\chi}_2^0 q\bar{q} \to \mu^+\mu^- q\bar{q}\tilde{\chi}_1^0$ [better not via Z]
- cross sections some 100 pb [more than 3×10^7 events]
- thresholds & edges $m^2_{\ell\ell} < (m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0})/m^2_{\tilde{\ell}}$
- poor man's version of ILC threshold scans
- detector resolution, calibration, systematic errors, cross sections, off-shell effects... [Kauer, TP, Rainwater,...]

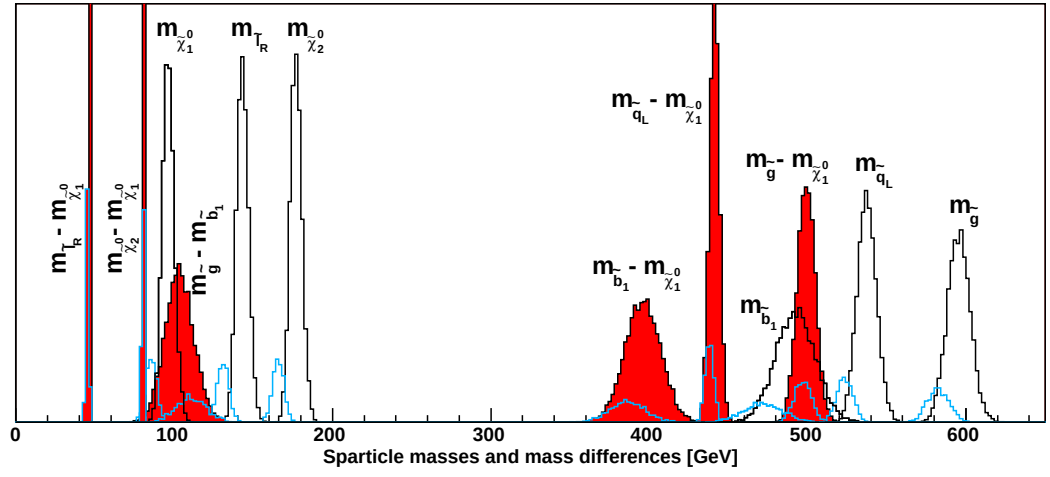
$\Rightarrow$ spectrum information sits in decay kinematics

Gluino mass [Gjelsten, Miller, Osland]

- $\tilde{b}_L$ cascade, all jets b-tagged
- most of time: cascade correct

$\Rightarrow$ gluino mass to few percent

[mass difference even better]



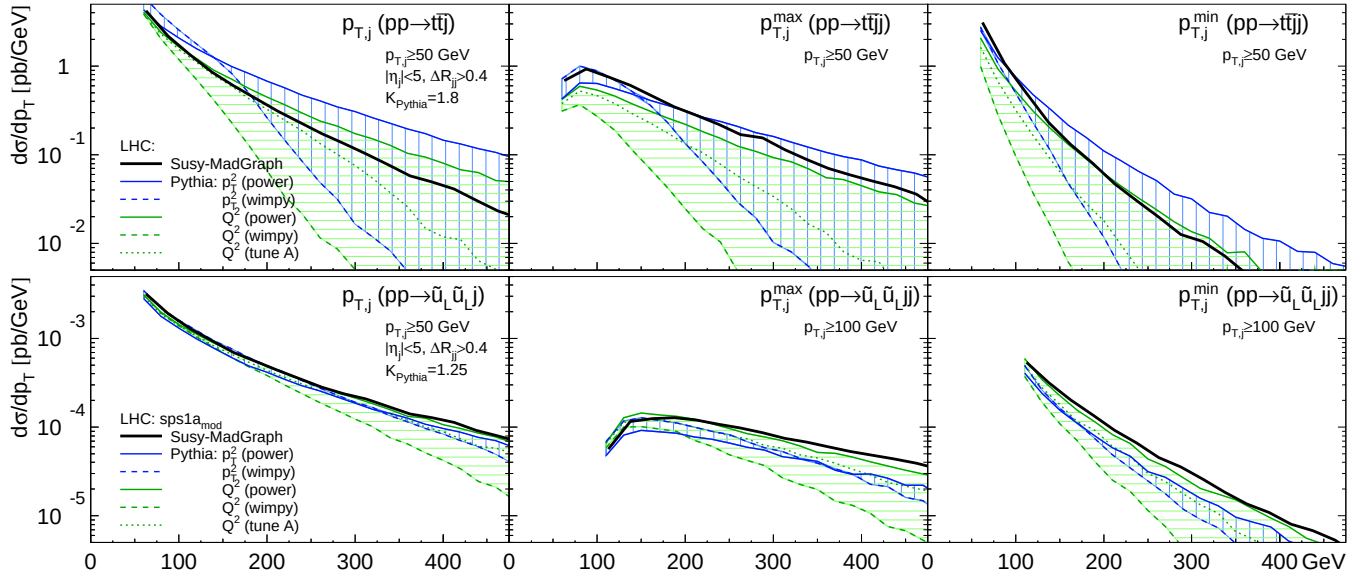
SUPERSYMMETRY AT LHC: 3

QCD: squarks and gluinos with (many) jets [TP, Rainwater, Skands]

- cascade studies sensitive to jet simulation?
- matrix element vs. Pythia: $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j

$\Rightarrow$ SUSY cascades easier than tops [QCD: the heavier the better]

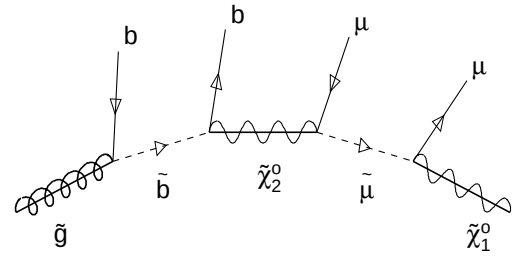
σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85



Complex new physics final states [Cho, Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

- Majoranas and fermion number violation in Madgraph/Madevent
- complete set of MSSM Feynman rules [400+ processes compared: Madgraph - Whizard - Sherpa]

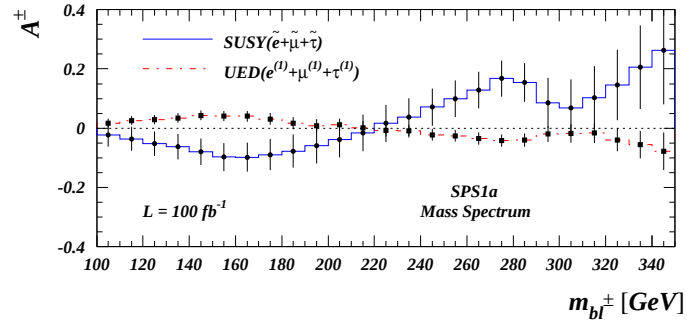
SUPERSYMMETRY AT LHC: 4



Show it is SUSY–QCD [Barr; Smillie & Webber]

- straw-man 'bosonic SUSY': universal extra dimensions
- compare entire cascade [instead of angles: e.g. $m_{\ell b}$]
- only use normalized distributions

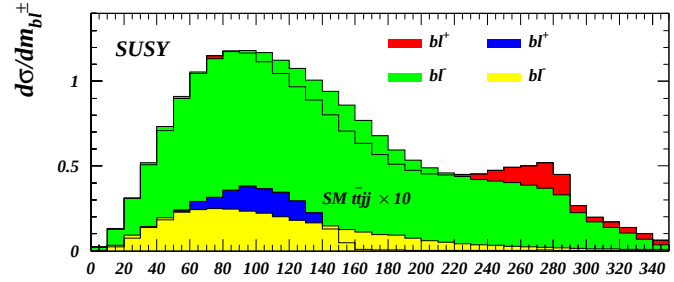
$\Rightarrow$ if fermionic gluino, then Majorana [like–sign dileptons]

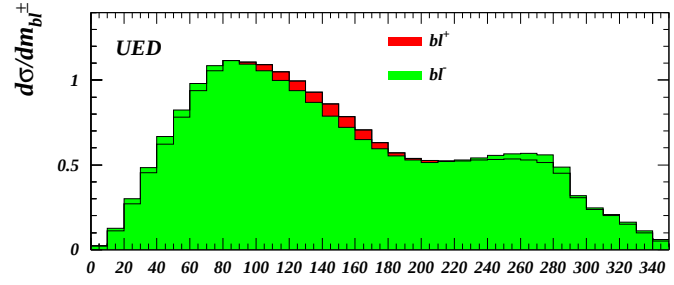


Gluino–bottom cascade [Alves, Eboli, TP]

- decay chain as for gluino mass
- compare with first KK g, q, Z, and ℓ
- asymmetry like for q̃:
  $\mathcal{A} = [\sigma(b\ell^+) - \sigma(b\ell^-)]/[\sigma(b\ell^+) + \sigma(b\ell^-)]$
- difference surviving cuts and smearing
- other distributions possible: ϕ_{bb},...

$\Rightarrow$ gluino spin also sits in decay kinematics





SUPERSYMMETRIC PARAMETERS

Sfitter: SUSY parameters from observables [Lafaye, TP, Zerwas; Fittino; Arkani-Hamed,...]

- parameters: weak-scale MSSM Lagrangean
- measurements: masses or edges
  branching fractions
  cross sections
- errors: general correlation, statistics & systematics & theory
- problem in grid: huge phase space, local minimum?
  problem in fit: domain walls, starting values, global minimum?

First go at problem [TP, Lafaye, Zerwas]

- ask a friend who knows how SUSY is broken

$\Rightarrow$ mSUGRA

- fit $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$
- LHC edges or masses?

	SPS1a	ΔLHC masses	ΔLHC edges	ΔILC	ΔLHC+ILC
m_0	100	3.9	1.2	0.09	0.08
$m_{1/2}$	250	1.7	1.0	0.13	0.11
$\tan\beta$	10	1.1	0.9	0.12	0.12
A_0	-100	33	20	4.8	4.3

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Combination of methods [TP, Lafaye, Zerwas]

- (1) grid for closed subset
  (2) fit of remaining parameters
  (3) complete fit
- more modern alternaives:
  simulated annealing
  Markov Chains

$\Rightarrow$ LHC+ILC with no 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	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

OUTLOOK

LHC phenomenology beyond the Standard Model

- serious new physics at LHC is about

  (a) QCD in signals and backgrounds [trying to kill us]
  (b) decay kinematics [hiding all good information]
  (c) error bars & statistics [forgot to talk about my last paper...]

- many new ideas: beyond inclusive excess
- many new tools: Prospino2, Smadgraph, Sfitter,...

$\Rightarrow$ experiment and theory need to work together

$\Rightarrow$ LHC will be the coolest experiment ever!