

SUPERSYMMETRY AT THE LHC

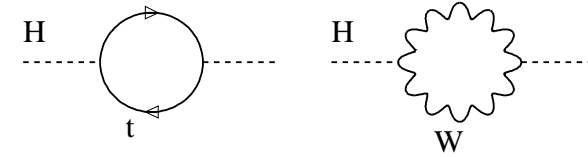
Tilman Plehn

MPI München & University of Edinburgh

- TeV–scale supersymmetry from a collider point of view
- Signals at Tevatron and LHC
- Measurements at LHC
- SUSY parameters at LHC (and ILC)

TeV-SCALE SUPERSYMMETRY: 1

Starting from data...



- ...which seem to indicate a light Higgs
- problem of light Higgs: mass driven to cutoff of theory
$$\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2$$
- ⇒ easy solution: counter term to cancel loops ⇒ **artificial, unmotivated, ugly**
- ⇒ or new physics at TeV scale: **supersymmetry**
extra dimensions
little Higgs (pseudo-Goldstone Higgs)
Higgsless, composite Higgs, TopColor,
YourFavoriteNewPhysics...
- ⇒ typically either cancellation with new particles or discussing away high scale
- ⇒ all beautiful concepts and symmetries
- ⇒ 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

SUSY idea: solve hierarchy problem by doubling spectrum

- stops (scalar) cancel top loop [couplings protected]
- gauginos (neutral or charged) cancel W, Z loop
- higgsinos cancel Higgs loop [mix with gauginos]
- postulate gluino for 2-loop, plus sleptons and squarks
- ⇒ hierarchy problem solved
- ⇒ unknown SUSY breaking means LHC has to measure stuff
- ⇒ **rich collider and non-collider phenomenology** [broken SUSY effective theory of everything]

Change in Higgs sector

- conjugate Higgs field not allowed in \mathcal{L}
- how to give mass to t and b?
- two Higgs doublets
- ⇒ SUSY Higgs alone interesting at LHC
- ⇒ would be another talk...

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
→ sfermion	\tilde{f}_L, \tilde{f}_R	0	1+1	
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
graviton	G	2	2	
→ gravitino	\tilde{G}	3/2	2	hard to catch

TeV-SCALE SUPERSYMMETRY: 3

Instead of SUSY breaking — structures in the MSSM spectrum

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

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

- off-diagonal elements the SUSY-protected Yukawas

TeV-SCALE SUPERSYMMETRY: 3

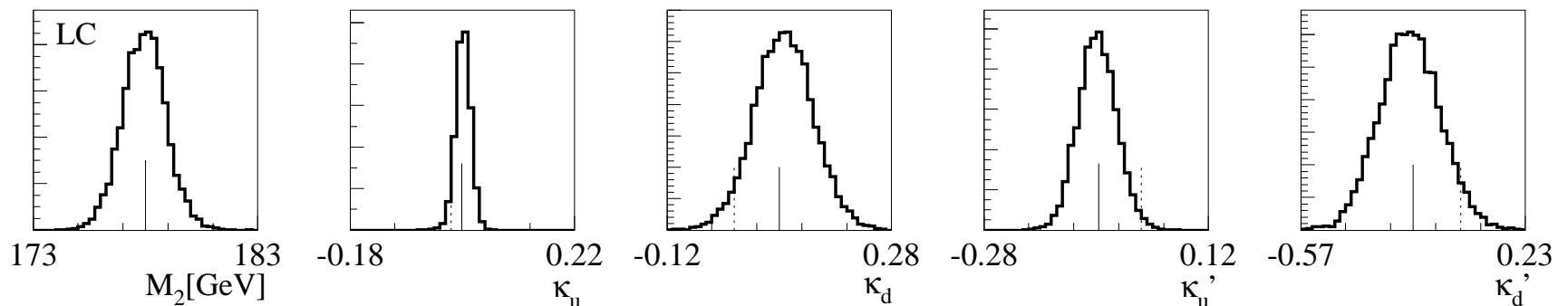
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- off-diagonal elements the SUSY-protected Yukawas

⇒ **test SUSY at ILC**: measure $m_Z s_W c_\beta \rightarrow m_Z s_W c_\beta (1 + \kappa_d), \dots$



[Kilian, TP, Richardson, Schmidt]

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- stop and sbottom mixing in **MSSM**

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

- heavy gluinos, squarks through **unification**: $m_{\tilde{B}, \tilde{W}, \tilde{g}}/m_{1/2} \sim 0.4, 0.8, 2.6$
 $m_{\tilde{\ell}, \tilde{q}}/m_{1/2} \sim 0.7, 2.5$ [$m_0 \ll m_{1/2}$]

[mass and coupling unification independent]

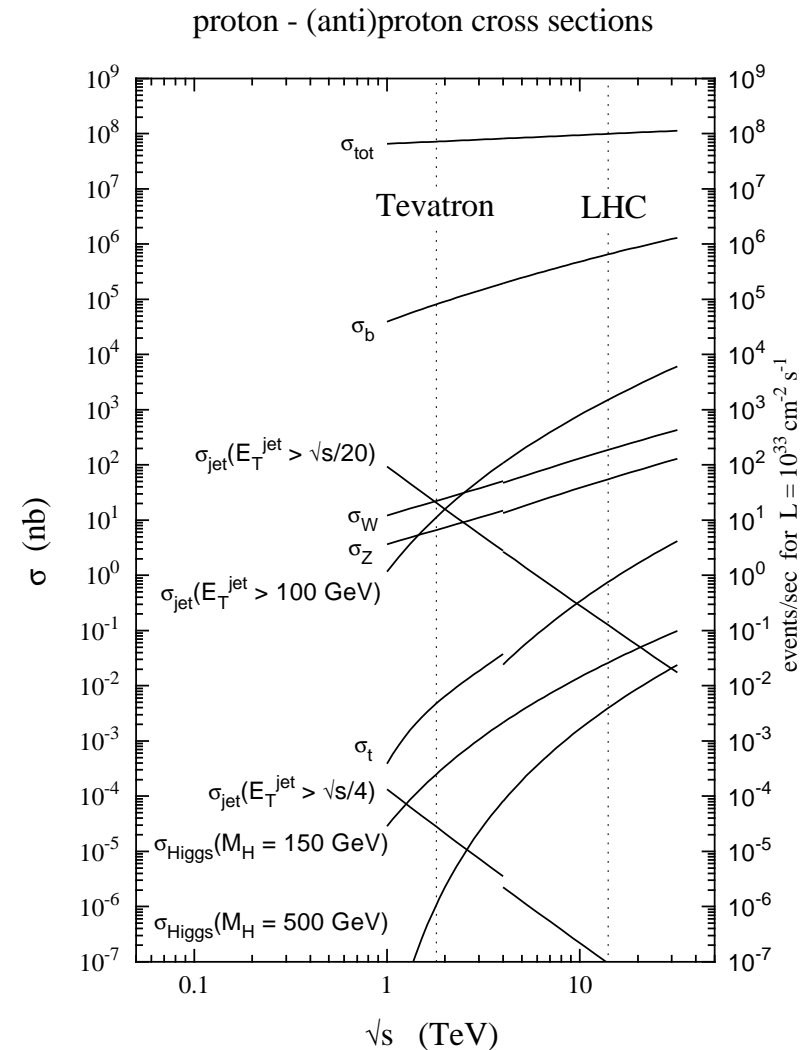
SUPERSYMMETRY AT HADRON COLLIDERS: 1

Produce new particles at colliders

- highest possible energies required
- e^+e^- colliders clean:
 - LEP: Z pole
 - LEP2: 206 GeV for e.g. ZH
 - ILC/CLIC: 1...4 TeV in future
- hadron colliders more powerful:
 - Tevatron: $p\bar{p}$ with 2 TeV [valence quarks]
 - LHC: pp with 14 TeV [gluons]
- **LHC mass reach ~ 3 TeV** [win by luminosity]

New physics at hadron colliders

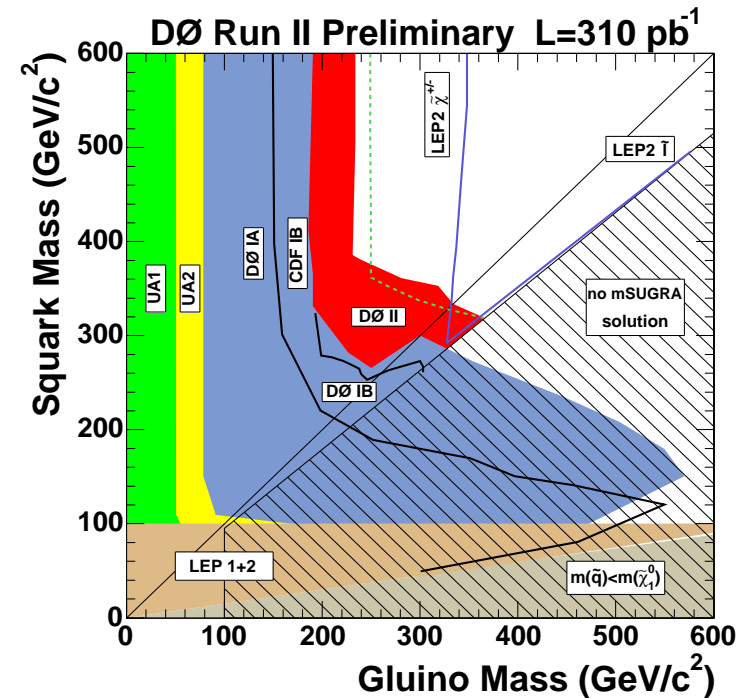
- what is a jet and what is inside? [b, τ tag]
- trigger: 'no lepton/photon — no data'
- LHC will not study QCD jets!
- **statistics: $S/\sqrt{B} > 5$ called discovery**



SUPERSYMMETRY AT HADRON COLLIDERS: 2

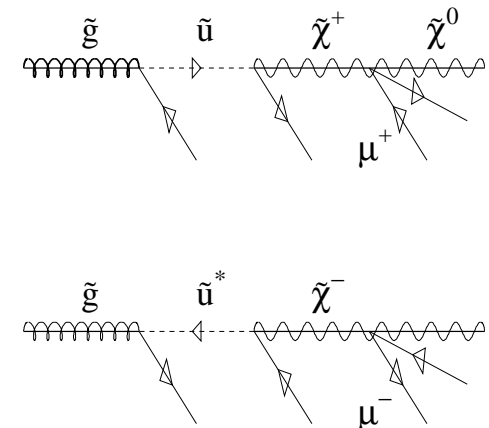
Inclusive: squarks and gluinos at Tevatron

- squarks, gluinos strongly interacting
 $p\bar{p} \rightarrow \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ [best if $m(\tilde{q}) \sim m(\tilde{g})$]
 - cross sections large at Tevatron [and LHC]
 - decays to jets and LSP
 [additional jets and leptons possible]
 - gaugino mass unification only for efficiency
- ⇒ **know how to do inclusive jets plus LSP**



How do we know it is SUSY?

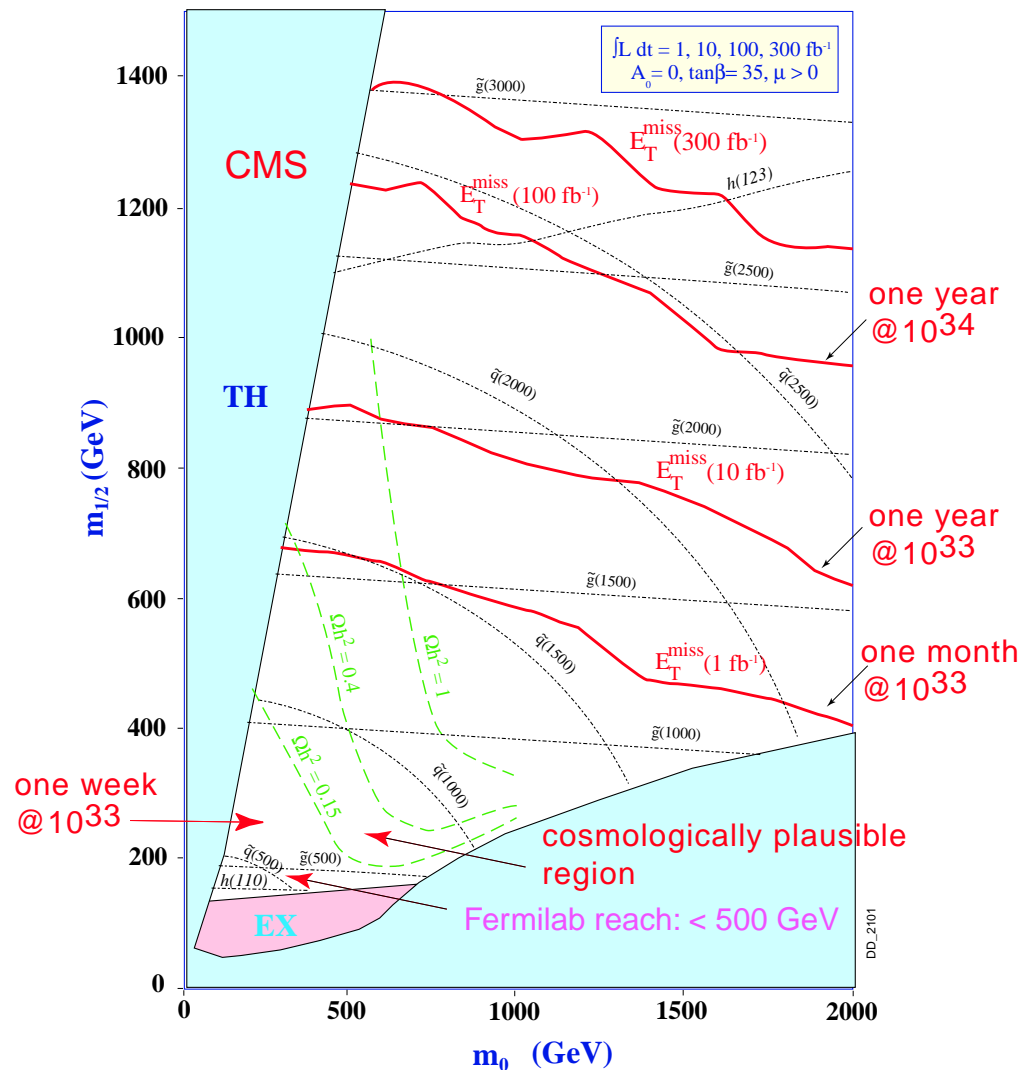
- remember: gluinos Majorana fermions
 - jet in gluino decay q or \bar{q}
- ⇒ final-state leptons with both charges
- ⇒ **like-sign dileptons from $\tilde{g}\tilde{g}$** [Barnett, Gunion, Haber]



SUPERSYMMETRY AT LHC: 1

Supersymmetry at the LHC

- (1) possible discovery — signals for new physics, exclusion of parameter space
- (2) measurements
- (3) parameter studies



SUPERSYMMETRY AT LHC: 1

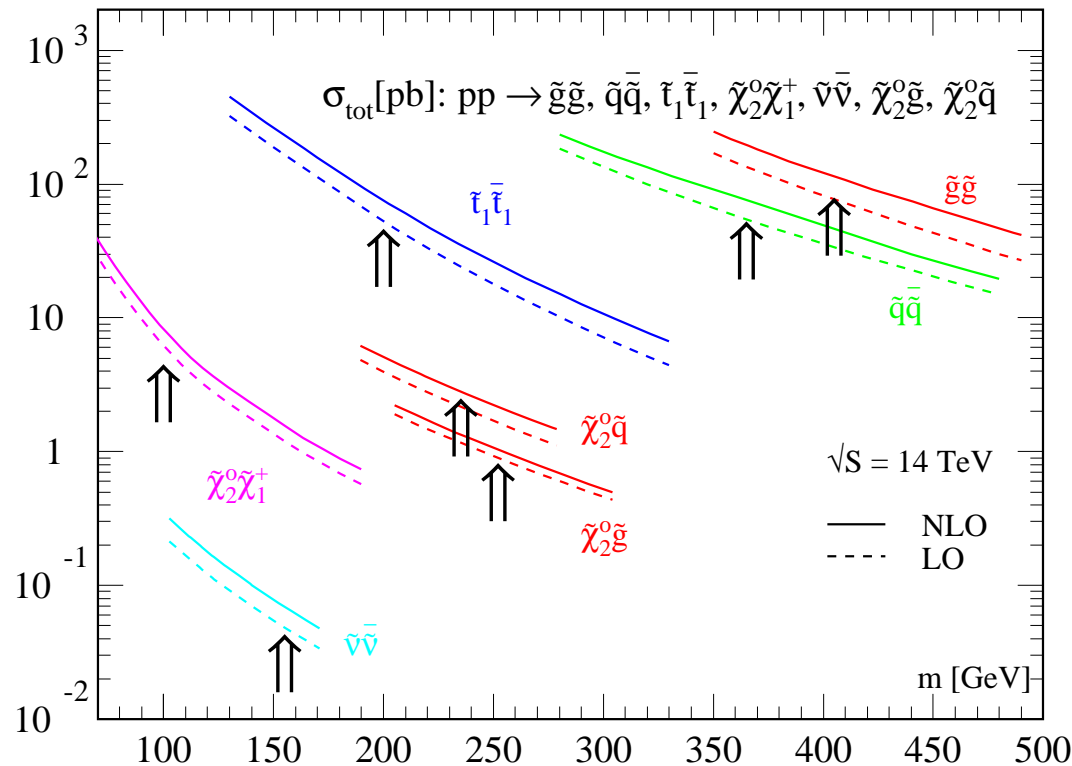
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- (2) **measurements** — masses, cross sections, decays
- (3) **parameter studies** — MSSM Lagrangean, SUSY breaking

SUSY signals include [NLO: Prospino2]

- QCD coupling $g\tilde{q}\tilde{q}, q\tilde{g}\tilde{q}, g\tilde{g}\tilde{g}$
- jets and E_T : $pp \rightarrow \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- funny tops: $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$
- tri-leptons: $pp \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^-$

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



SUPERSYMMETRY AT LHC: 1

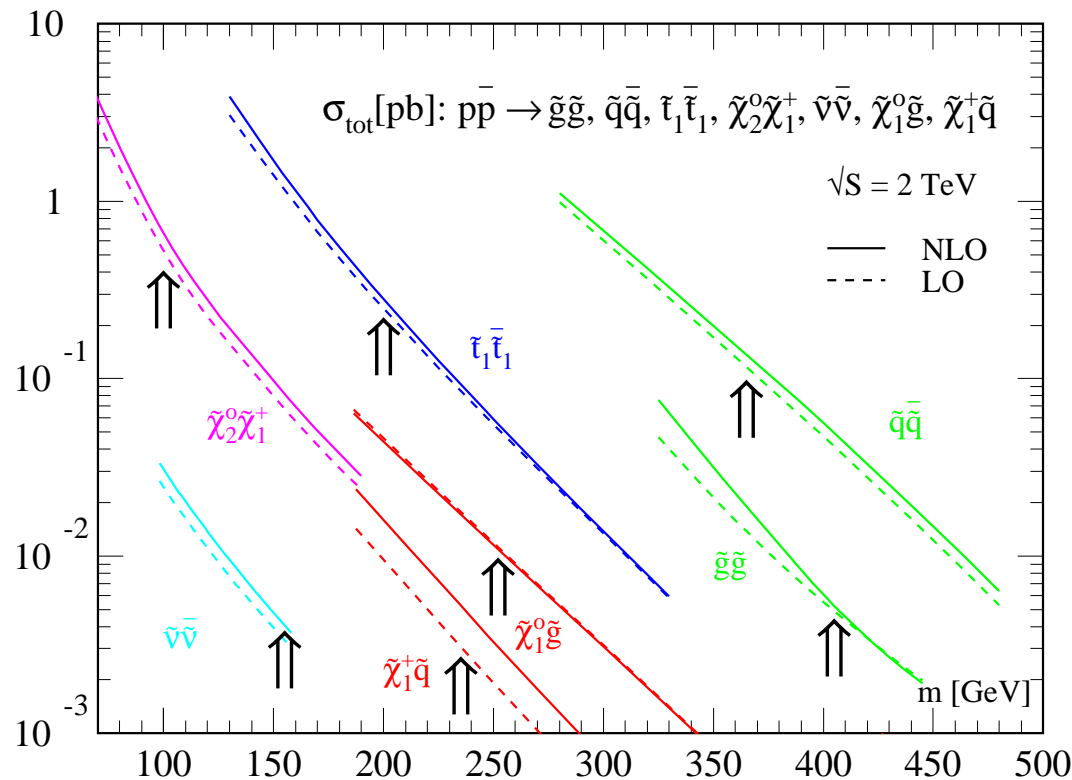
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SUSY signals include [NLO: Prospino2]

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



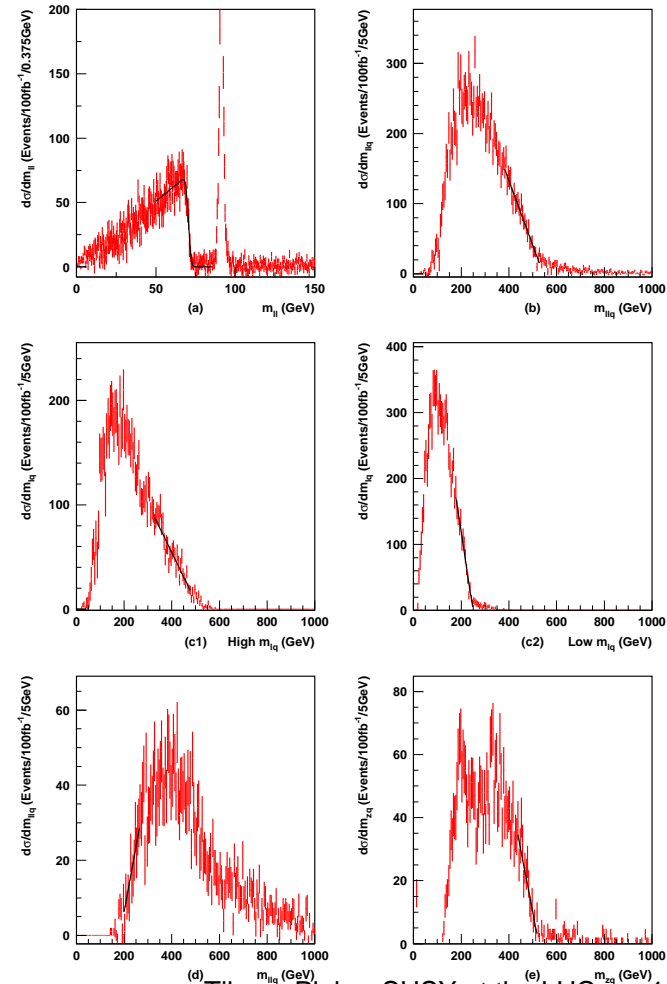
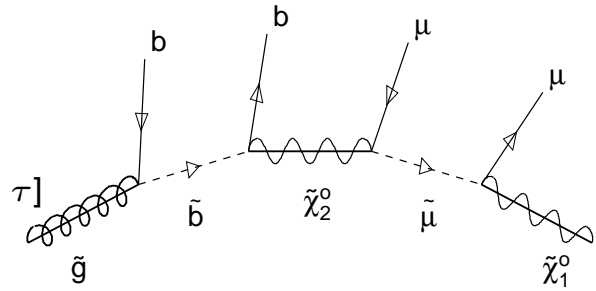
SUPERSYMMETRY AT LHC: 2

Spectra from cascade decays

- decay $\tilde{g} \rightarrow \tilde{b}\tilde{b} \rightarrow \tilde{\chi}_2^0 b\tilde{b} \rightarrow \mu^+ \mu^- b\tilde{b}\tilde{\chi}_1^0$ [better not via Z or to τ]
- cross sections some 100 pb [more than 3×10^7 events]
- thresholds & edges $m_{\ell\ell}^2 < (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\ell}}^2$
- detector resolution, calibration, systematic errors, shape analysis, cross sections as input?

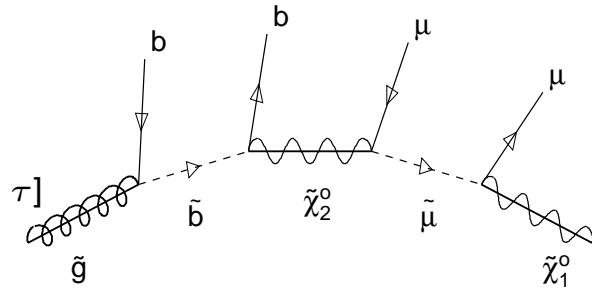
⇒ **spectrum information sits in decay kinematics**

[Hinchliffe,...;Allanach,...; not only SUSY!]



SUPERSYMMETRY AT LHC: 2

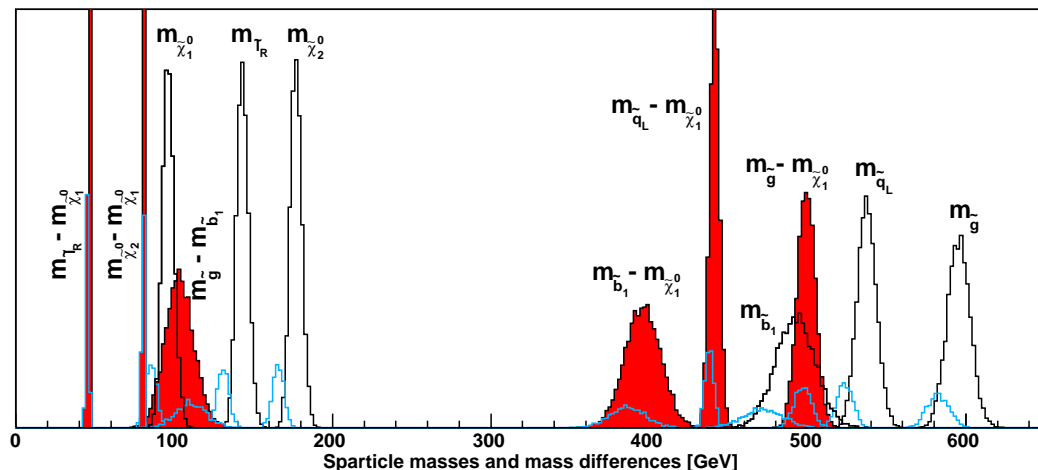
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 - detector resolution, calibration, systematic errors, shape analysis, cross sections as input?
- \Rightarrow **spectrum information sits in decay kinematics** [mass difference work better]

Gluino mass [Gjelsten, Miller, Osland]

- \tilde{b}_L instead, all jets b-tagged
 - most of time: cascade correct
- \Rightarrow **gluino mass to $\sim 1\%$**



SUPERSYMMETRY AT LHC: 3

Complex final states with Smadgraph [Cho, Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

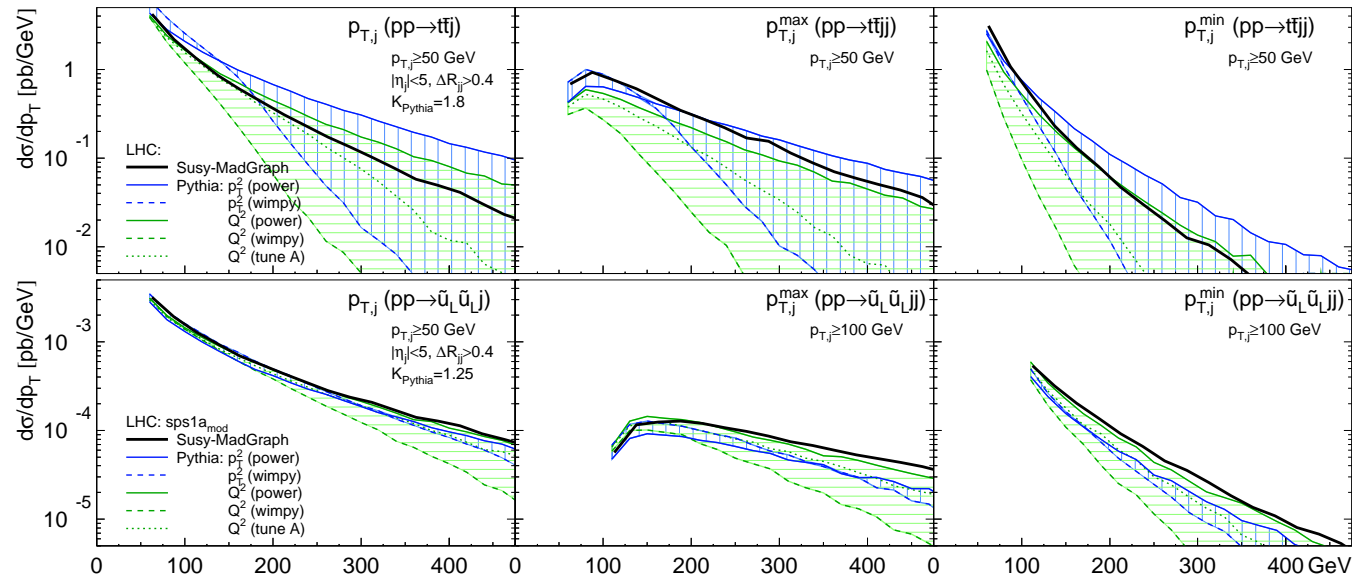
- Majoranas and fermion number violation in tools like Madgraph
- complete set of Feynman rules [400+ processes compared: Madgraph - Whizard - Sherpa]

Squarks and gluinos always with many jets [TP, Rainwater, Skands]

- cascade studies sensitive to jet simulation?
- matrix element $\tilde{g}\tilde{g}+2j$ and $\tilde{u}_L\tilde{g}+2j$ [$p_{T,j} > 100$ GeV]
- Pythia shower tuned at Tevatron

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

⇒ **SUSY easier than tops?** [QCD: the heavier the better]



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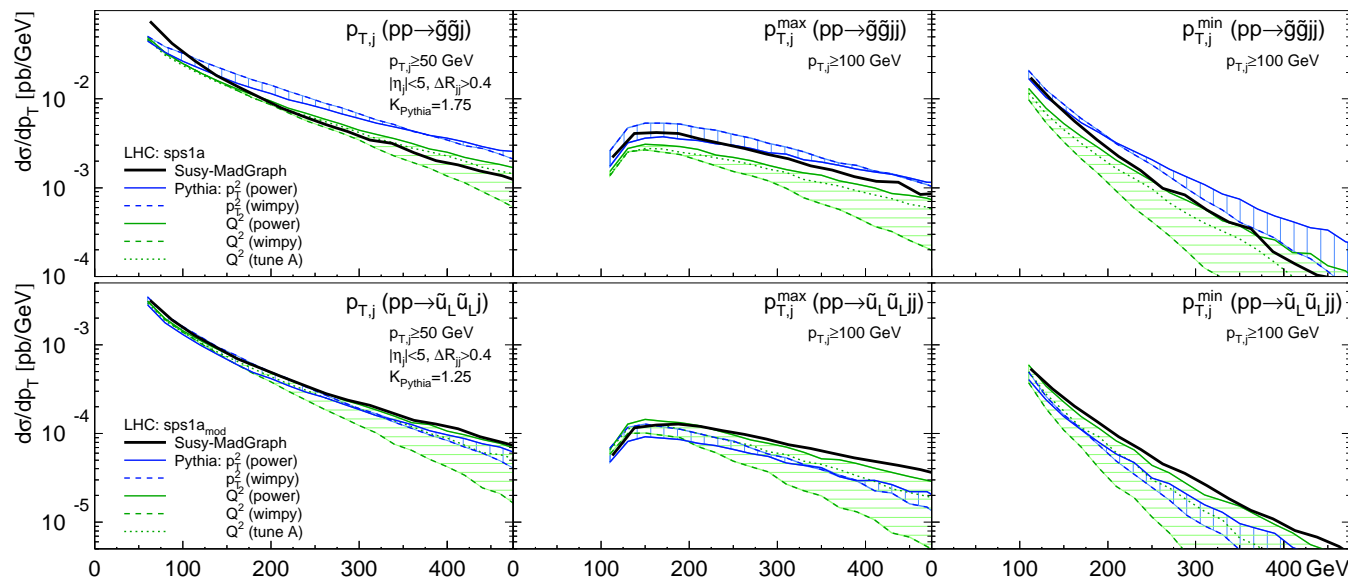
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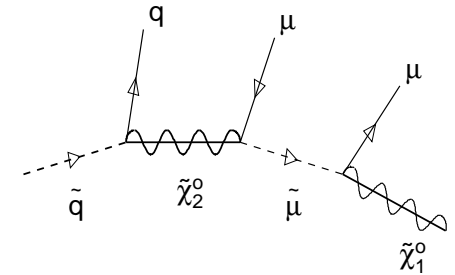
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SUPERSYMMETRY AT LHC: 4

How to make sure it is SUSY

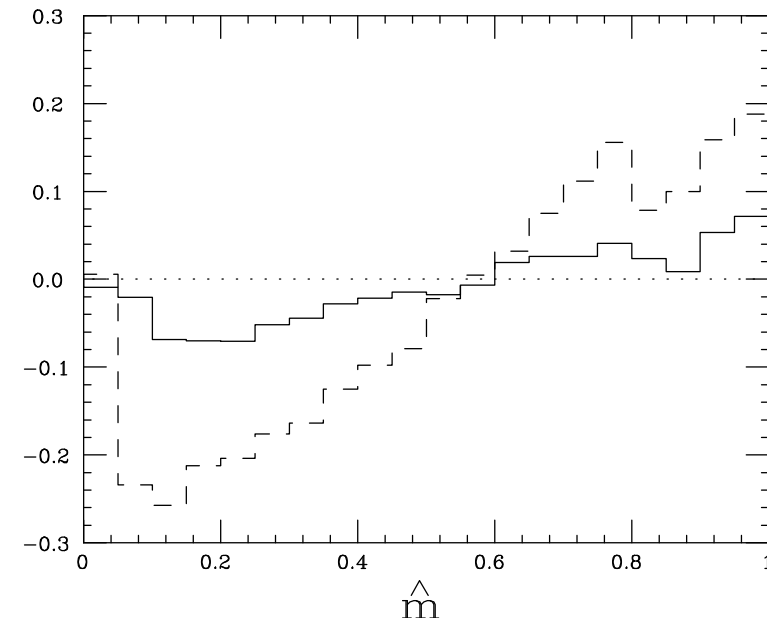
- assume squark is found in cascades
- ⇒ strongly interacting scalar? [first stop towards 'neutralino']
- ⇒ straw-man model where squark is a fermion: universal extra dimensions



[Cheng, Matchev, Schmaltz; mass spectra degenerate —ignore this information; cross section factor 10 larger —ignore this as well]

Squark–slepton cascade [Smillie, Webber]

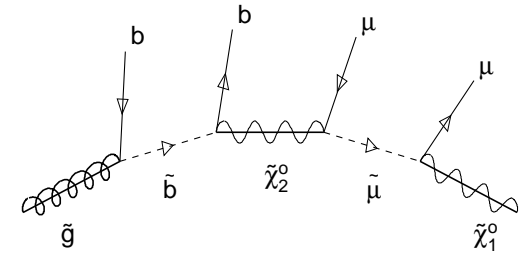
- decay chain $\tilde{\chi}_2^0 \rightarrow \ell \tilde{\ell}^* \rightarrow \ell \bar{\ell} \tilde{\chi}_1^0$
- compare with first KK Z and ℓ
- typically largest $pp \rightarrow \tilde{q} \tilde{q}^*$ [$\tilde{q} : \tilde{q}^* \sim 1 : 2$]
- trick: mass variables, 'normalized angles' [Barr]
- ⇒ $\hat{m} = m_{j\ell} / m_{j\ell}^{\max}$ most promising
- $\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)] / [\sigma(j\ell^+) + \sigma(j\ell^-)]$
- ⇒ **more than proof of feasibility** [dashed SUSY]



SUPERSYMMETRY AT LHC: 5

Show it is SUSY-QCD

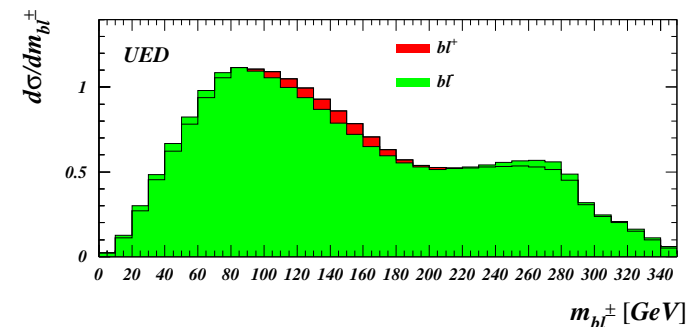
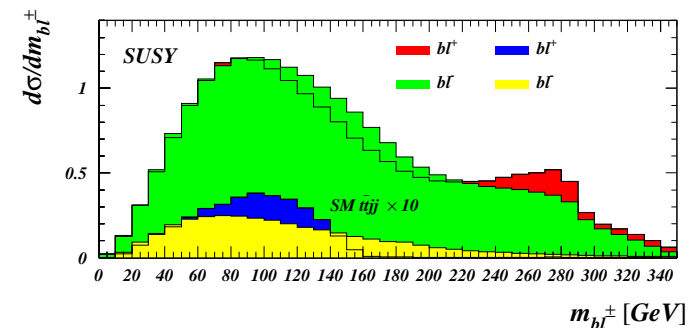
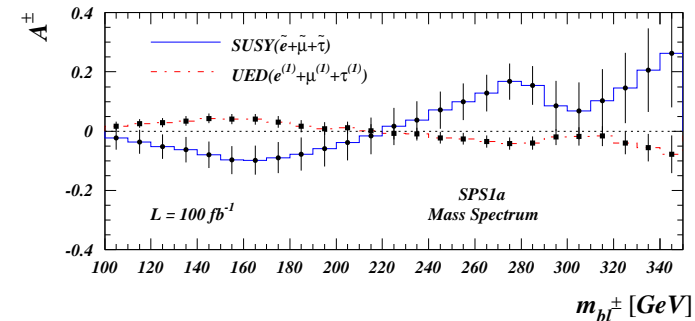
- given like-sign dileptons, gluino would be better
- outgoing particles all fermions
- ⇒ if fermion, then definitely Majorana [call it gluino]
- ⇒ compare with our straw man



Gluino-bottom cascade [Alves, Eboli, TP]

- decay chain as for gluino mass measurement
- compare with first KK g, q, Z, and ℓ
- replace initial-state asymmetry by b vs. \bar{b}
- the one asymmetry we can write down:

$$A = [\sigma(bl^+) - \sigma(bl^-)] / [\sigma(bl^+) + \sigma(bl^-)]$$
- asymmetry still there after cuts and smearing
- ⇒ **gluino spin accessible at LHC**



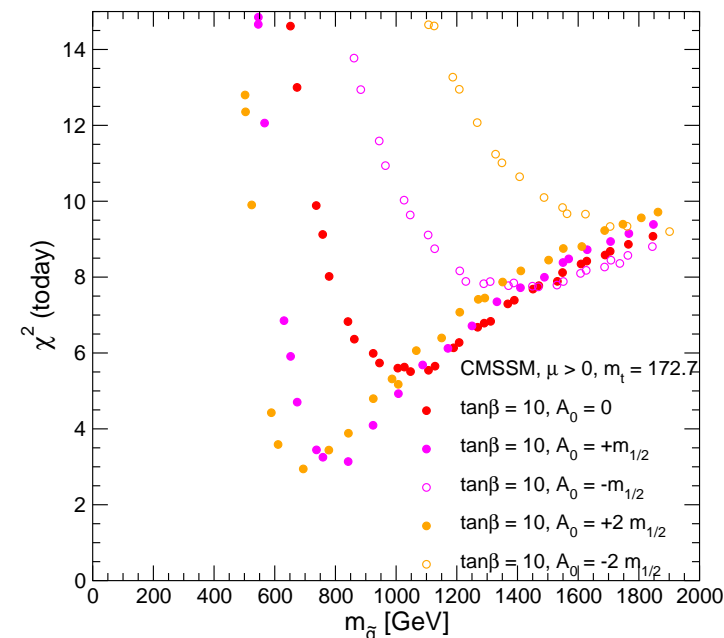
SUPERSYMMETRIC PARAMETERS

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

- ask a friend who knows how SUSY is broken
- ⇒ mSUGRA
- fit $m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
 - no problem, include indirect constraints
- ⇒ likelihood map today [John E. & friends]



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

	SPS1a	Δ LHC masses	Δ LHC edges	Δ ILC	Δ LHC+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 alternatives:
simulated annealing
Markov Chains
- ⇒ **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	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
$M_{\tilde{q}_{3L}}$	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

LHC phenomenology beyond the Standard Model

- New Physics at LHC (in the ideal world) is about
 - (A) QCD in signals and backgrounds [trying to kill us]
 - (B) decay kinematics [hiding all good information]
 - (C) error bars & statistics [remember your 2nd year labs]
- Tevatron perfect training ground
- many new ideas: QCD matching, parameter extraction, spin measurement,...
- many new tools: Prospino2, Smadgraph, Sfitter,...
- lots of more work to be done, need help!
- ⇒ experiment and theory have to work together
- ⇒ **LHC will be the coolest experiment ever!**