

# 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)

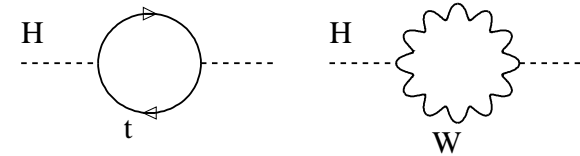
Higgsless, composite Higgs, TopColor,

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	$G_\mu$	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
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

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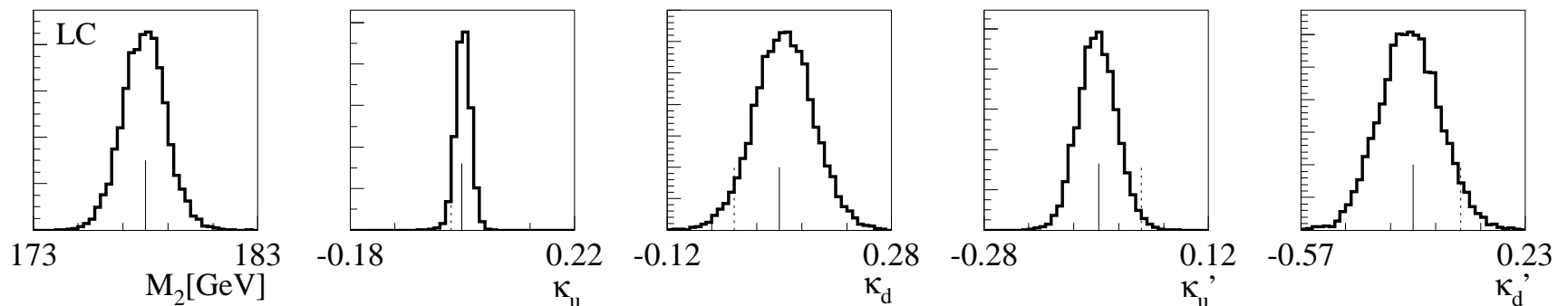
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- off-diagonal elements the SUSY-protected Yukawas

⇒ **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]

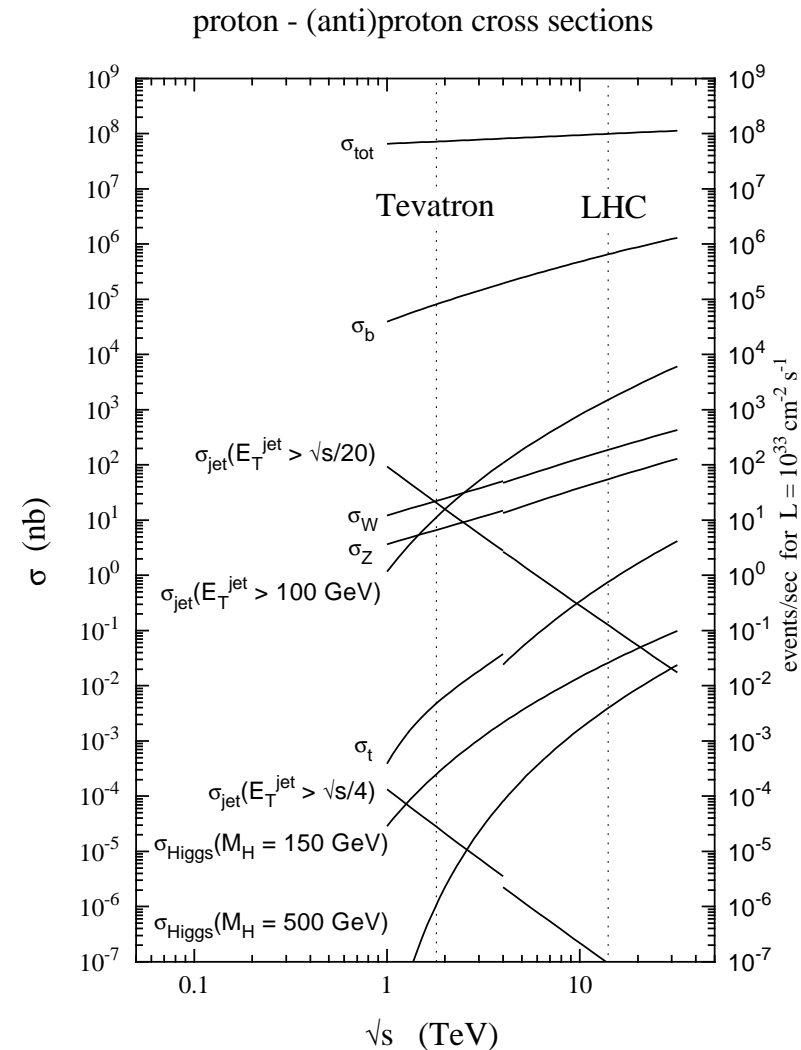
# SUPERSYMMETRY AT HADRON COLLIDERS: 1

## 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  $\sim 3$  TeV** [win by luminosity]

## New physics at hadron colliders

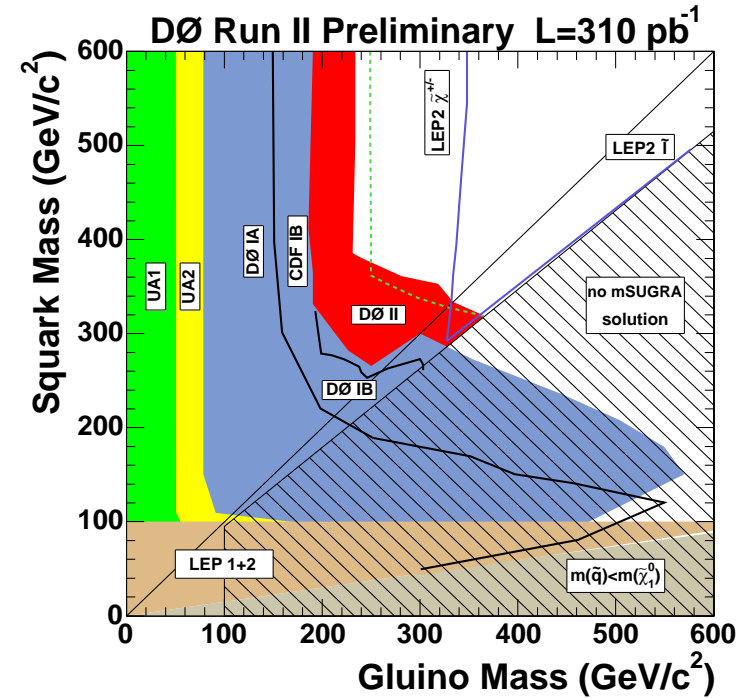
- what is a jet and what is inside? [b,  $\tau$  tag]
- trigger: 'no lepton/photon — no data'
- LHC will not study QCD jets!
- **statistics:  $S/\sqrt{B} > 5$  called discovery**



# SUPERSYMMETRY AT HADRON COLLIDERS: 2

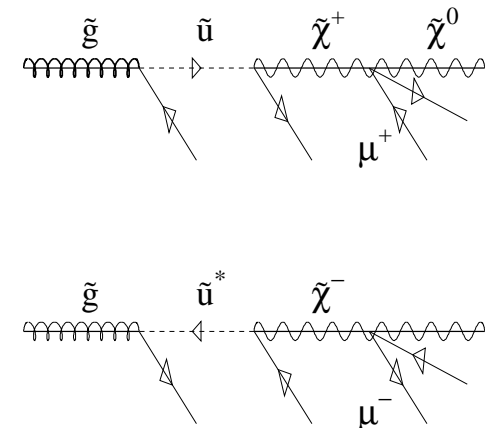
## Inclusive: squarks and gluinos at Tevatron

- 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]

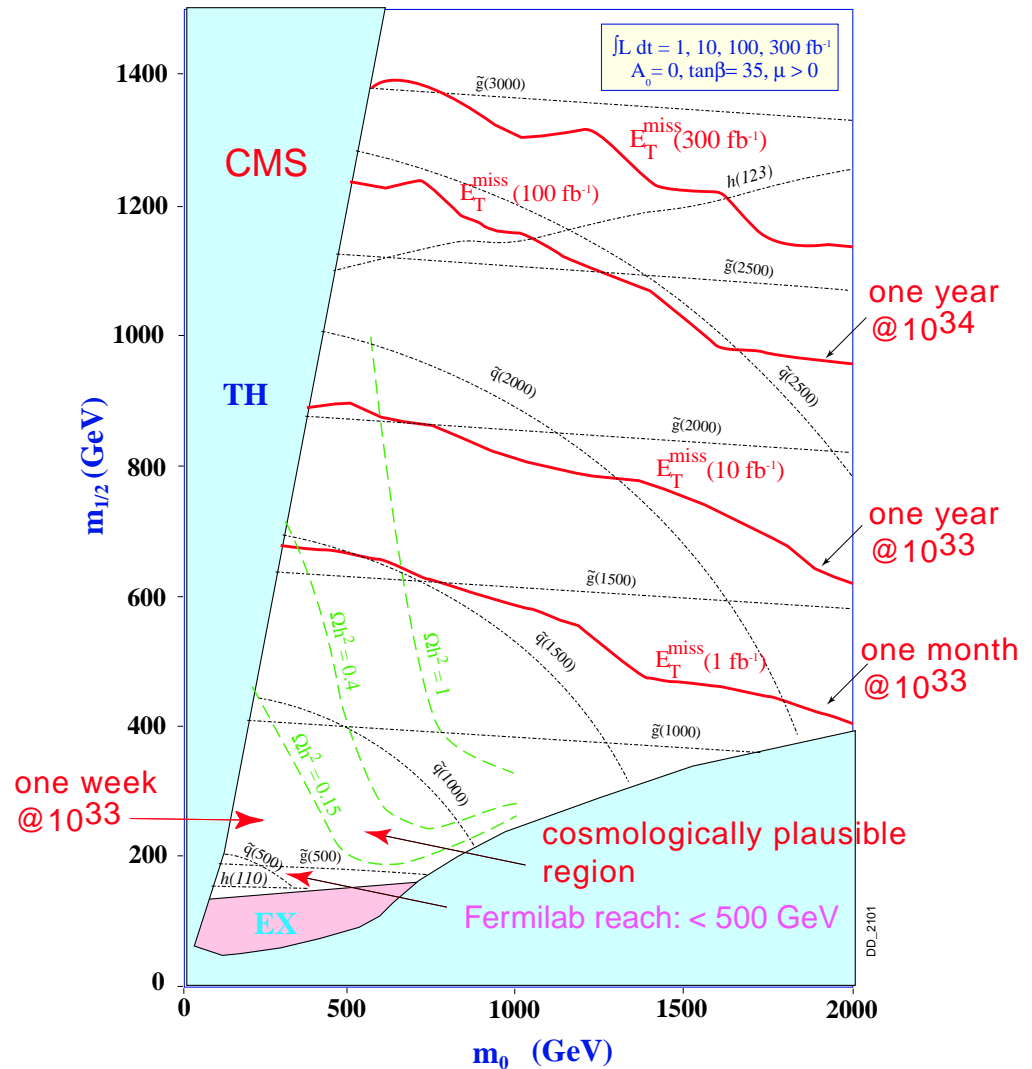




# SUPERSYMMETRY AT LHC: 1

## Supersymmetry at the LHC

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



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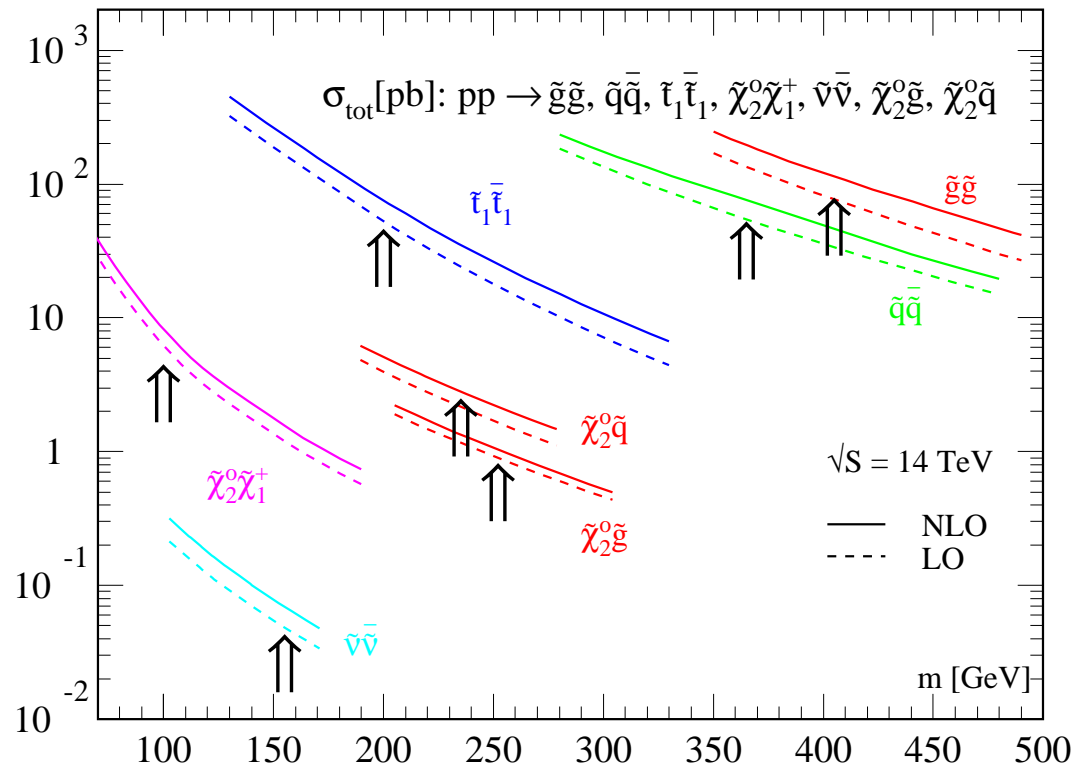
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## SUSY signals include [NLO: Prospino2]

- 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

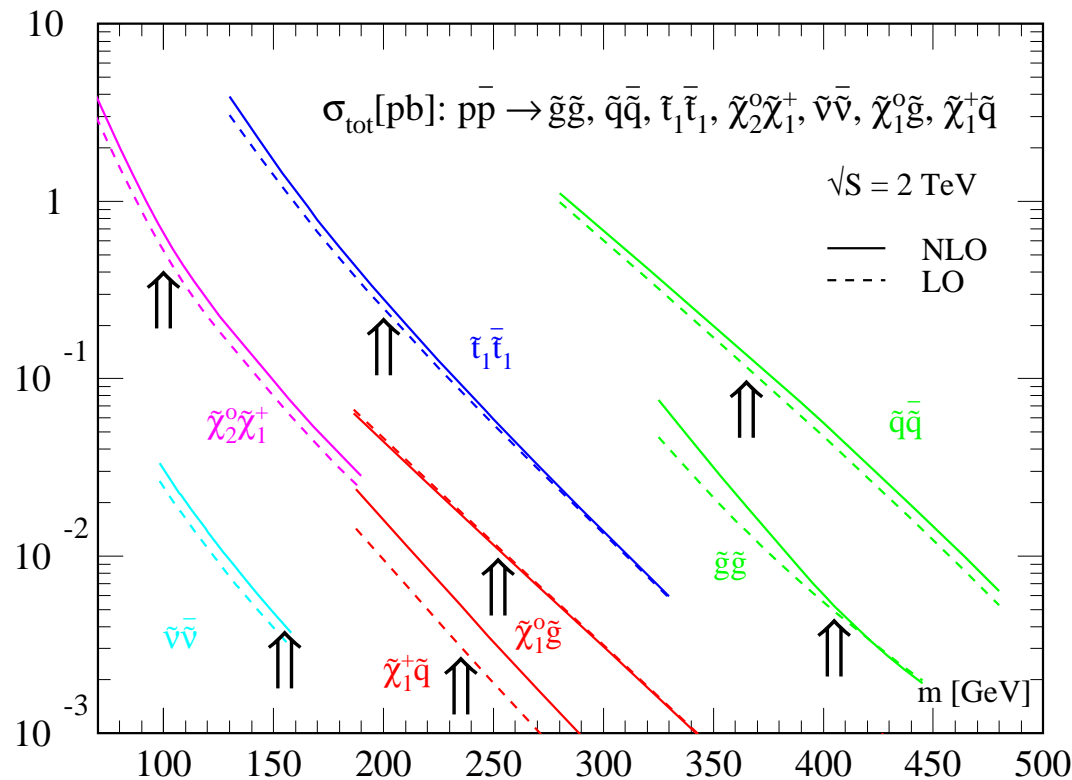
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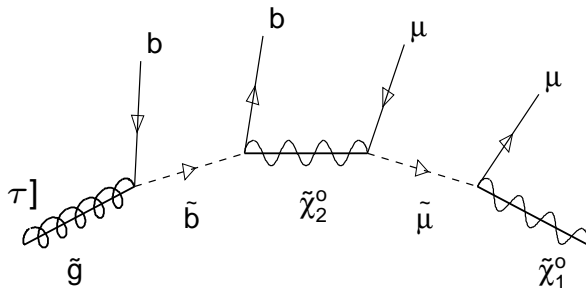
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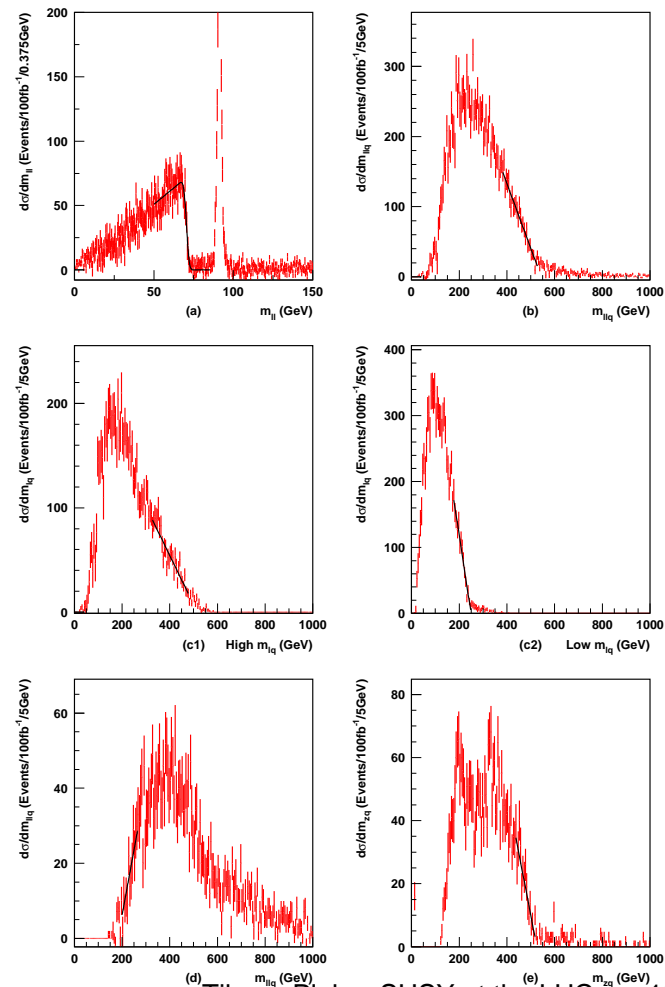
## Spectra from cascade decays

- 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  $\tau$ ]
- cross sections some 100 pb [more than  $3 \times 10^7$  events]
- thresholds & edges  $m_{\ell\ell}^2 < (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\ell}}^2$



⇒ **spectrum information sits in decay kinematics**

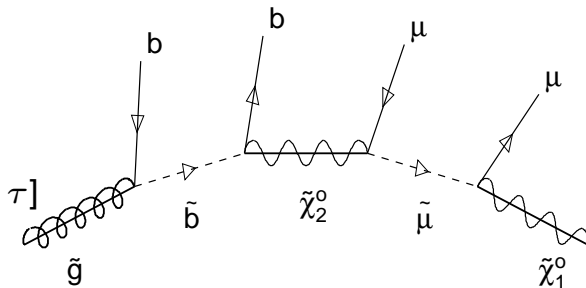
[Hinchliffe,...;Allanach,...; not only SUSY!]



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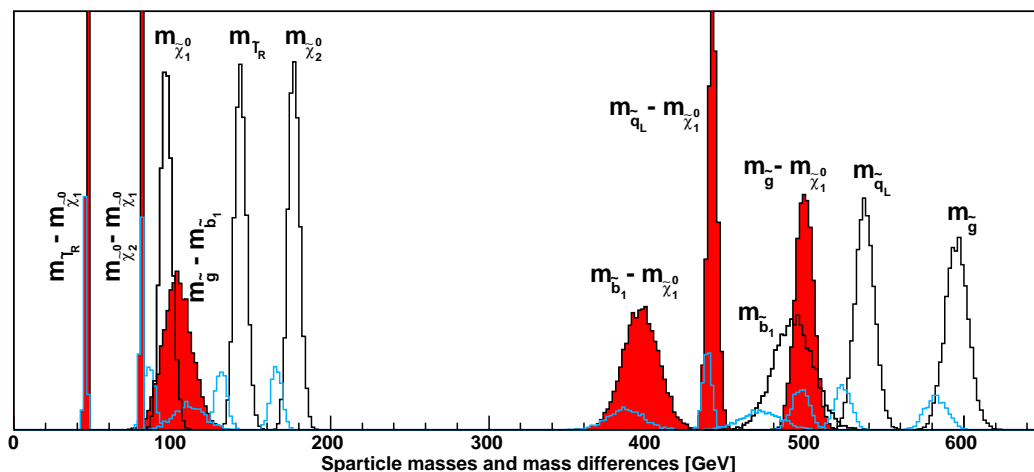
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  - detector resolution, calibration, systematic errors, shape analysis, cross sections as input?
- $\Rightarrow$  **spectrum information sits in decay kinematics** [mass difference work better]



## Glino mass [Gjelsten, Miller, Osland]

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



# SUPERSYMMETRY AT LHC: 3

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

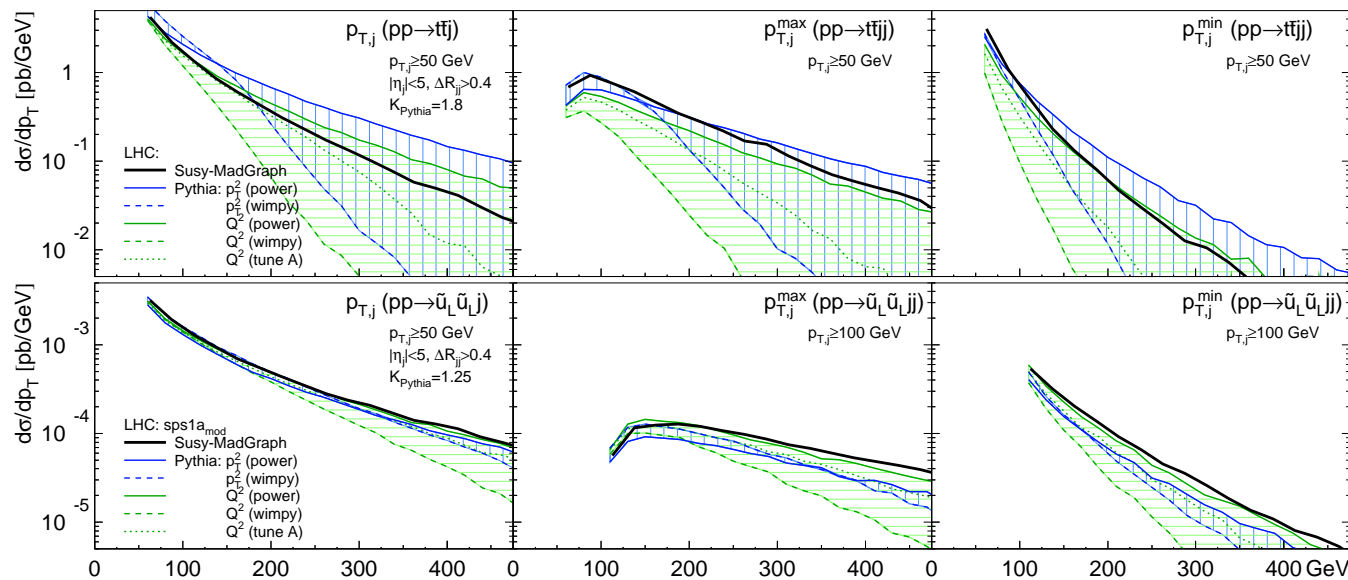
- Majoranas and fermion number violation in tools like Madgraph
- complete set of Feynman rules [400+ processes compared: Madgraph - Whizard - Sherpa]

## 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

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

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



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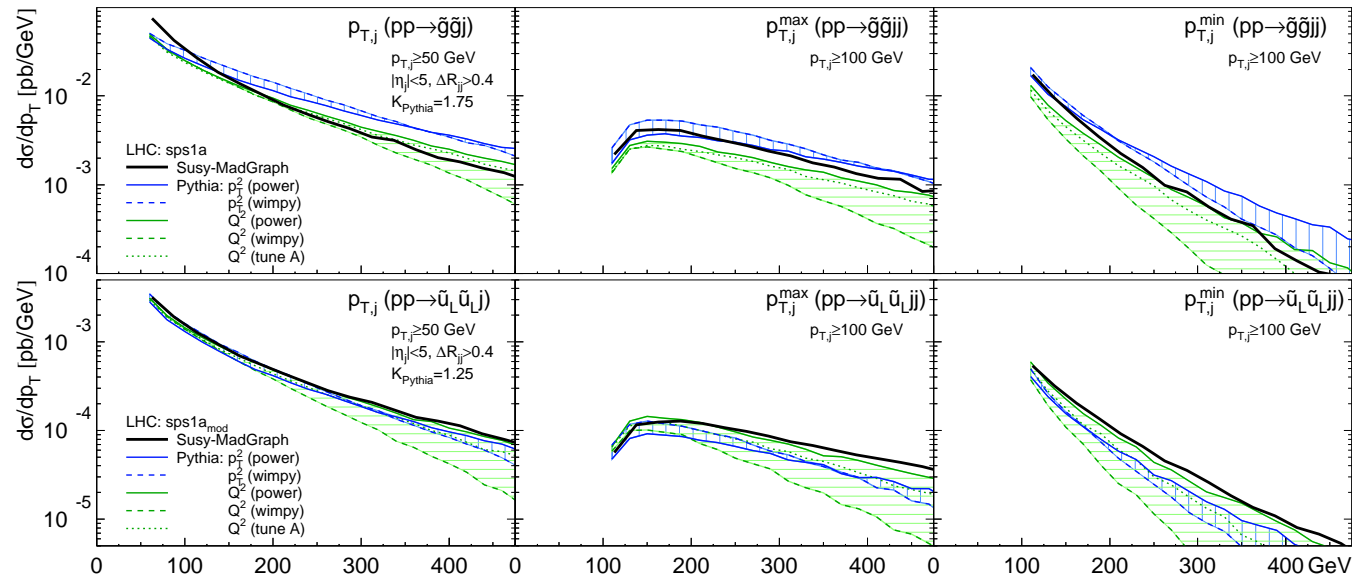
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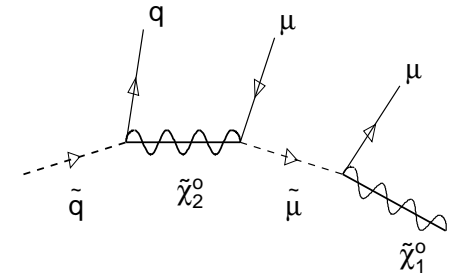
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# SUPERSYMMETRY AT LHC: 4

## How to make sure it is SUSY

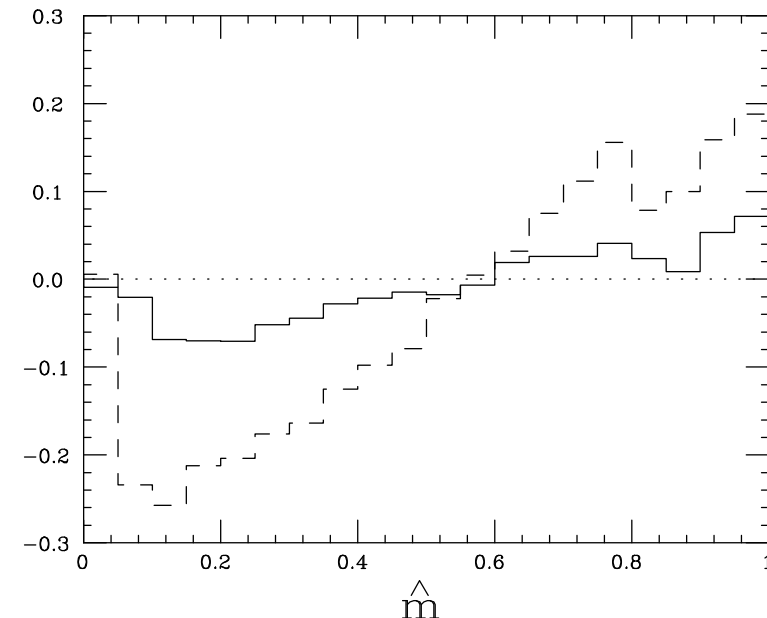
- assume squark is found in cascades
- ⇒ strongly interacting scalar? [first stop towards 'neutralino']
- ⇒ straw-man model where squark is a fermion: universal extra dimensions



[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  $\ell$
- 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]

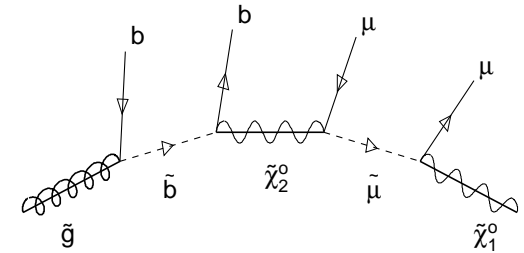




# SUPERSYMMETRY AT LHC: 5

## Show it is SUSY-QCD

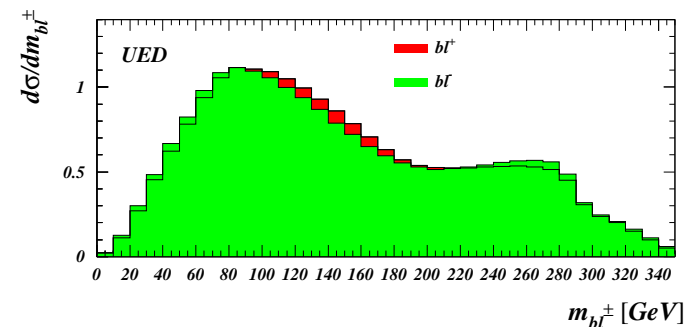
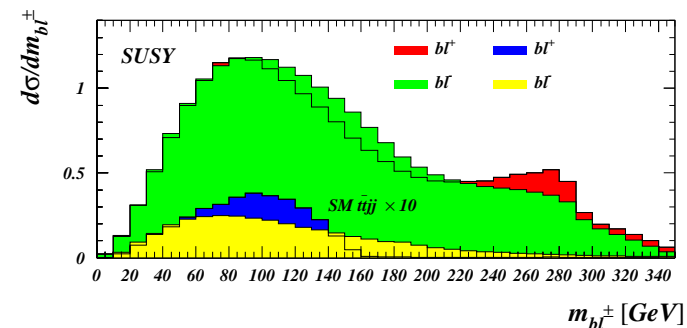
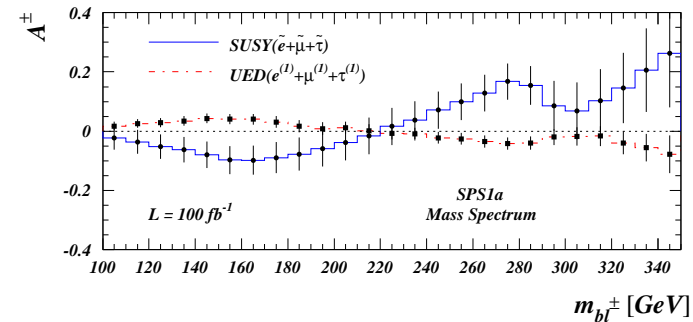
- given like-sign dileptons, gluino would be better
- outgoing particles all fermions
- ⇒ if fermion, then definitely Majorana [call it gluino]
- ⇒ compare with our straw man



## Gluino-bottom cascade [Alves, Eboli, TP]

- decay chain as for gluino mass measurement
- compare with first KK g, q, Z, and  $\ell$
- 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**



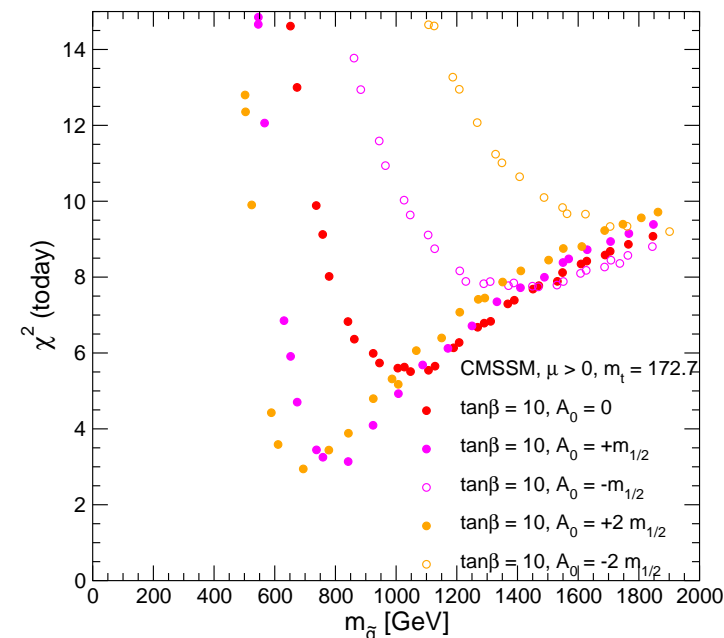
# SUPERSYMMETRIC PARAMETERS

## 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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- LHC edges or masses?
- ⇒ **edges better**

	SPS1a	$\Delta$ LHC masses	$\Delta$ LHC edges	$\Delta$ ILC	$\Delta$ 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
$\tan\beta$	$10.22 \pm 9.1$	$10.26 \pm 0.3$	$10.06 \pm 0.2$	10
$M_1$	$102.45 \pm 5.3$	$102.32 \pm 0.1$	$102.23 \pm 0.1$	102.2
$M_3$	$578.67 \pm 15$	fix 500	$588.05 \pm 11$	589.4
$M_{\tilde{\tau}_L}$	fix 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
$M_{\tilde{q}_{3L}}$	$498.3 \pm 110$	$497.6 \pm 4.4$	$521.9 \pm 39$	501.3
$M_{\tilde{t}_R}$	fix 500	$420 \pm 2.1$	$411.73 \pm 12$	420.2
$M_{\tilde{b}_R}$	$522.26 \pm 113$	fix 500	$504.35 \pm 61$	525.6
$A_\tau$	fix 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
$A_b$	$-784.7 \pm 35603$	fix 0	$-977 \pm 12467$	-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!**