FINDING SUPERSYMMETRY AT THE LHC

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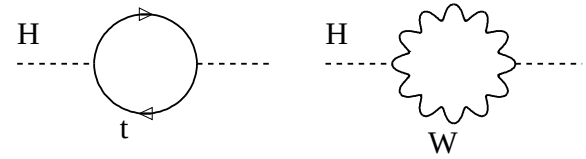
- TeV–scale supersymmetry
- Signals at Tevatron and LHC
- Measurements at LHC
- SUSY parameters at LHC (and ILC)

TeV–Scale Supersymmetry: 1

Starting from data...



- ...which seem to indicate a light Higgs
- problem of light Higgs: mass driven to cutoff of theory
  $\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, \Lambda^2$
  Veltman's condition $(\cdots) = 0$ would be fun
  problem preferably solved to arbitrary loop order

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

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

$\Rightarrow$ typically either cancellation with new particles or discussing away high scale

$\Rightarrow$ 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

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

$\Rightarrow$ hierarchy problem solved

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

$\Rightarrow$ extended Poincaré algebra, supergravity,...

Change in Higgs sector

- adjoint Higgs field not allowed in $\mathcal{L}$
  $\longrightarrow$ how to give mass to t and b?
  $\longrightarrow$ two Higgs doublets

$\Rightarrow$ SUSY Higgs 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
graviton	G	2	2	
$\longrightarrow$ gravitino	$\tilde{G}$	3/2	2	hard to catch

TeV–Scale Supersymmetry: 3

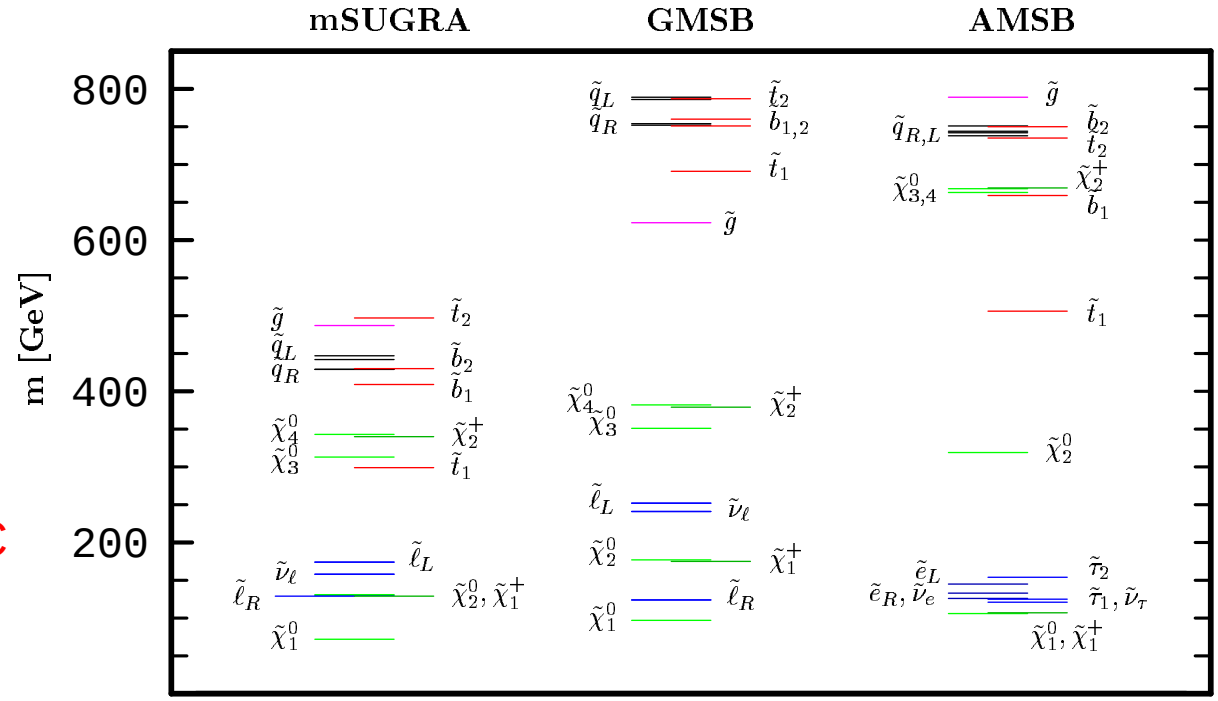
SUSY breaking: heavy partners

- mechanism for partner masses unknown [soft breaking keeps away quadratic divergences]
- link to flavor physics and baryogenesis/leptogenesis unknown
- SUSY breaking unknown [hidden sector, assume mediation to visible sector]
- maximally blind mediation at high scale: mSUGRA [not the LHC paradigm at all!]
  scalars: m_0, fermions: $m_{1/2}$, tri-scalar term: A_0
  plus $\mathrm{sign}(\mu)$ and $\tan\beta$ in Higgs sector [Higgs masses free: NUHM]

Alternatives [SoftSusy,...]

- gauge mediation
- anomaly mediation
- gaugino mediation
- ...?

$\Rightarrow$ measure spectrum at LHC



TeV–Scale Supersymmetry: 4

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

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

– off-diagonal elements the SUSY-protected Yukawas

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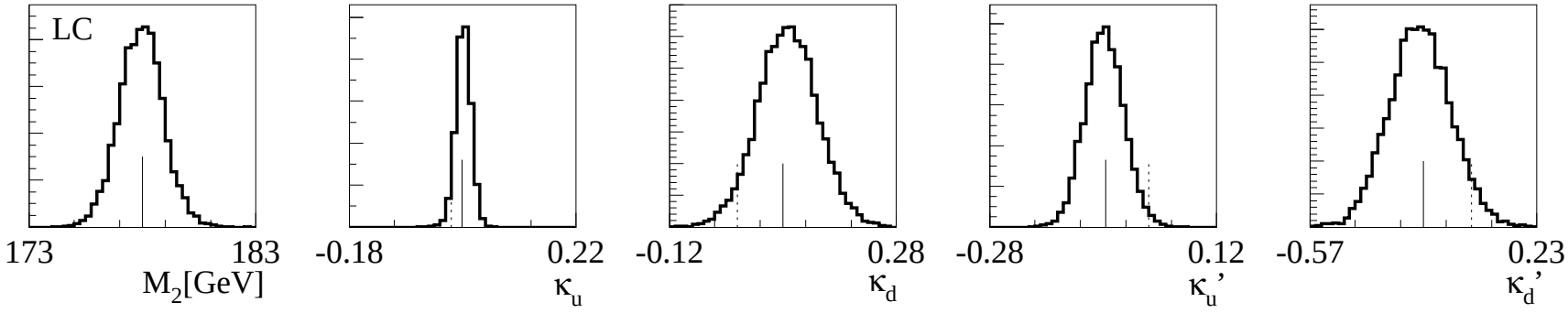
– off-diagonal elements the SUSY-protected Yukawas

$\Rightarrow$ test of SUSY at Linear Collider: measure $m_Z s_w c_\beta \to m_Z s_w c_\beta (1 + \kappa_d), \ldots$



[Kilian, TP, Richardson, Schmidt]

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– stop and sbottom mixing in MSSM

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

– 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]

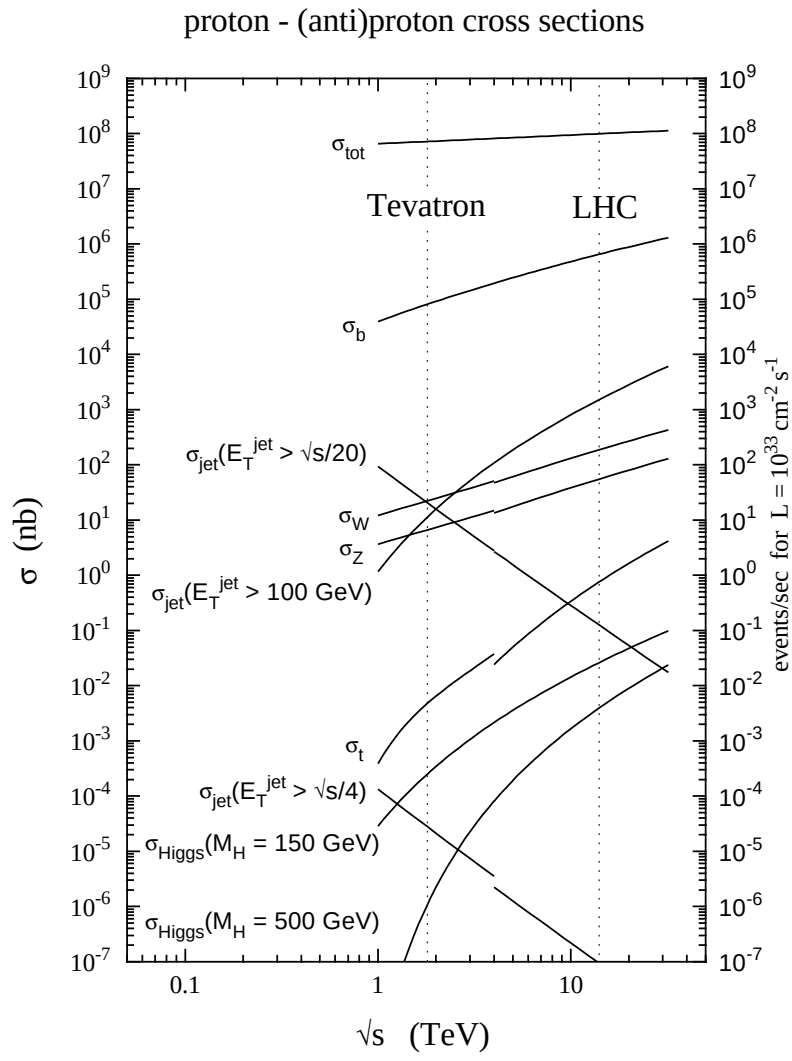
SUPERSYMMETRY AT HADRON COLLIDERS: 1

Produce new particles at colliders

- highest possible energies required
- clean e^+e^- colliders:
  LEP: Z pole
  LEP2: 206 GeV for e.g. ZH
  ILC/CLIC: 1...4 TeV in future
- powerful hadron colliders:
  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, τ tag]
- trigger: 'no leptons — no data'
- huge backgrounds pp $\to b\bar{b}$, WZ+jets,...
- statistics: $S/\sqrt{B} > 5$ called discovery



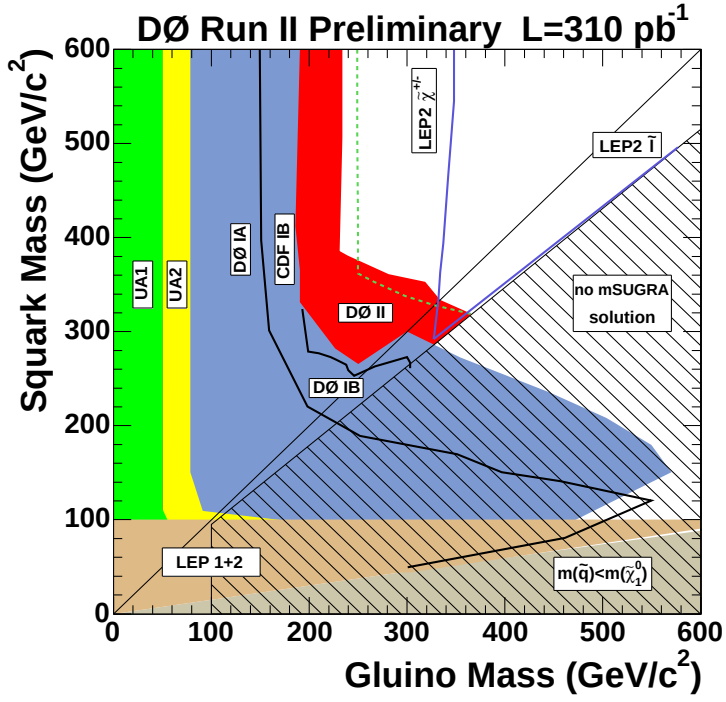
SUPERSYMMETRY AT HADRON COLLIDERS: 2

Inclusive: squarks and gluinos at Tevatron

- squarks, gluinos strongly interacting
  $p\bar{p} \longrightarrow \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ [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

$\Rightarrow$ know how to do inclusive jets plus LSP

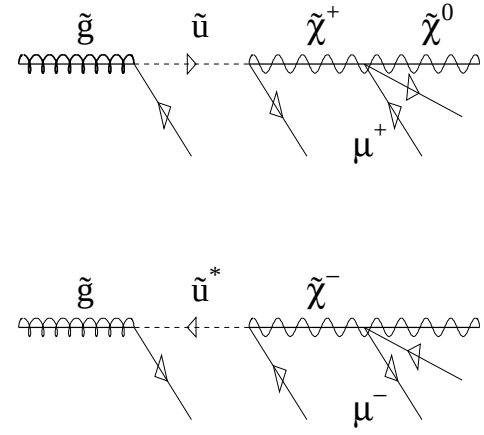


How do we know it is SUSY?

- remember: gluinos Majorana fermions
- jet in gluino decay q or $\bar{q}$

$\Rightarrow$ final–state leptons with both charges

$\Rightarrow$ like–sign dileptons from $\tilde{g}\tilde{g}$ [Barnett, Gunion, Haber]



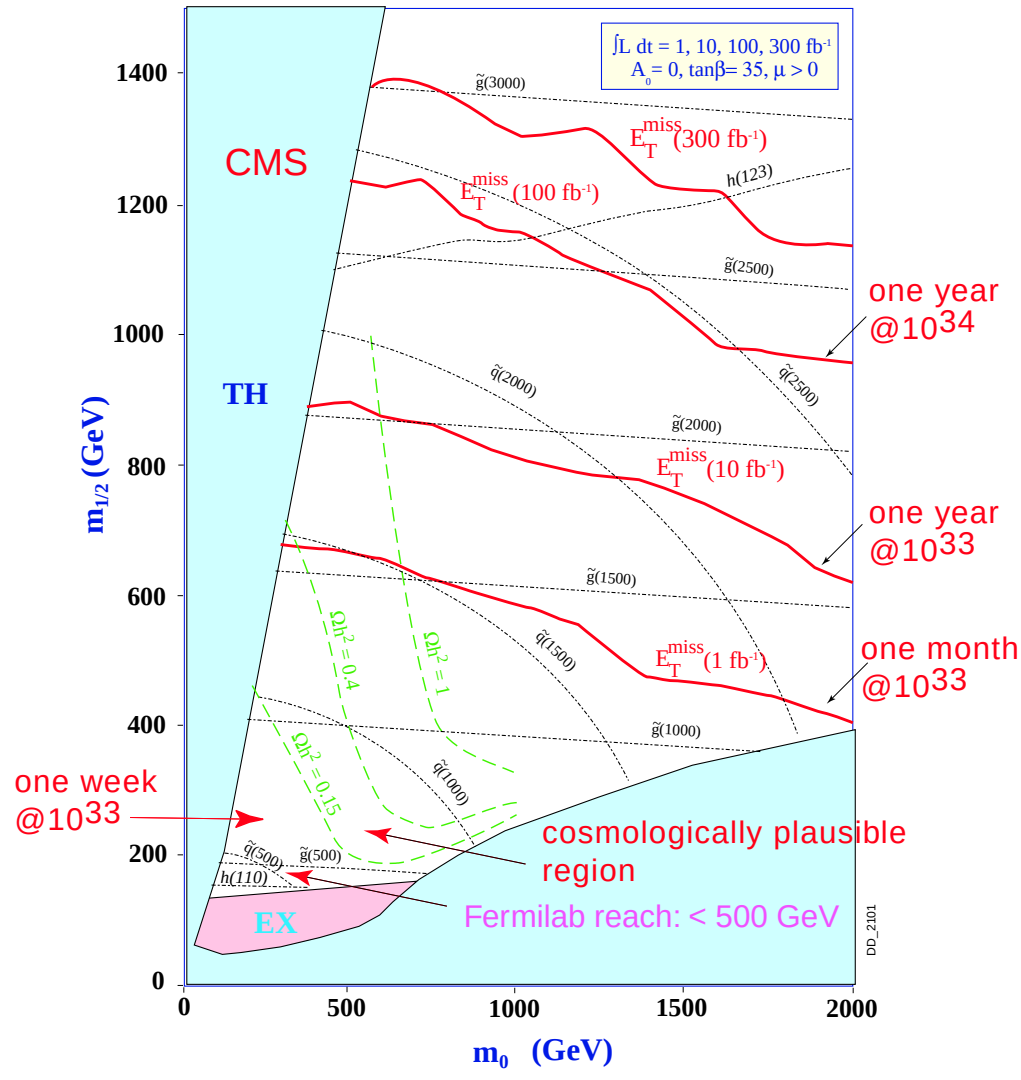
SUPERSYMMETRY AT LHC: 1

Supersymmetry at the LHC

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

(2) measurements

(3) parameter studies



SUPERSYMMETRY AT LHC: 1

Supersymmetry at the LHC

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

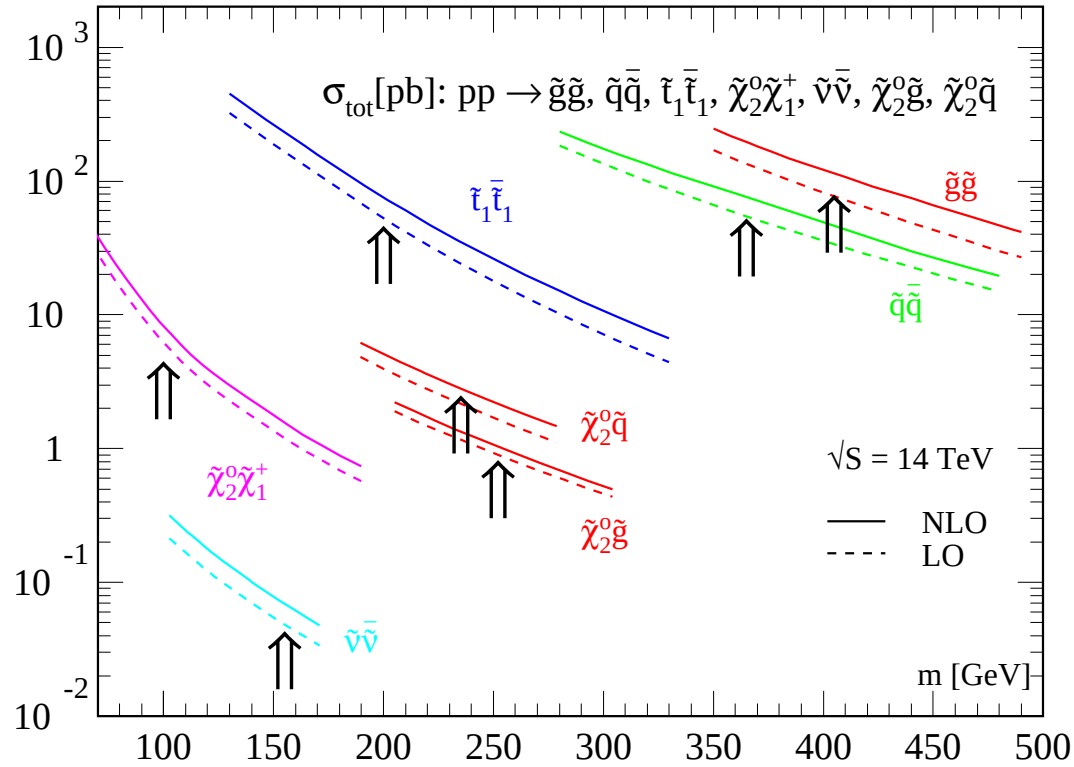
(2) measurements — masses, cross sections, decays

(3) parameter studies — MSSM Lagrangean, SUSY breaking

SUSY signals include [NLO: Prospino2]

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

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



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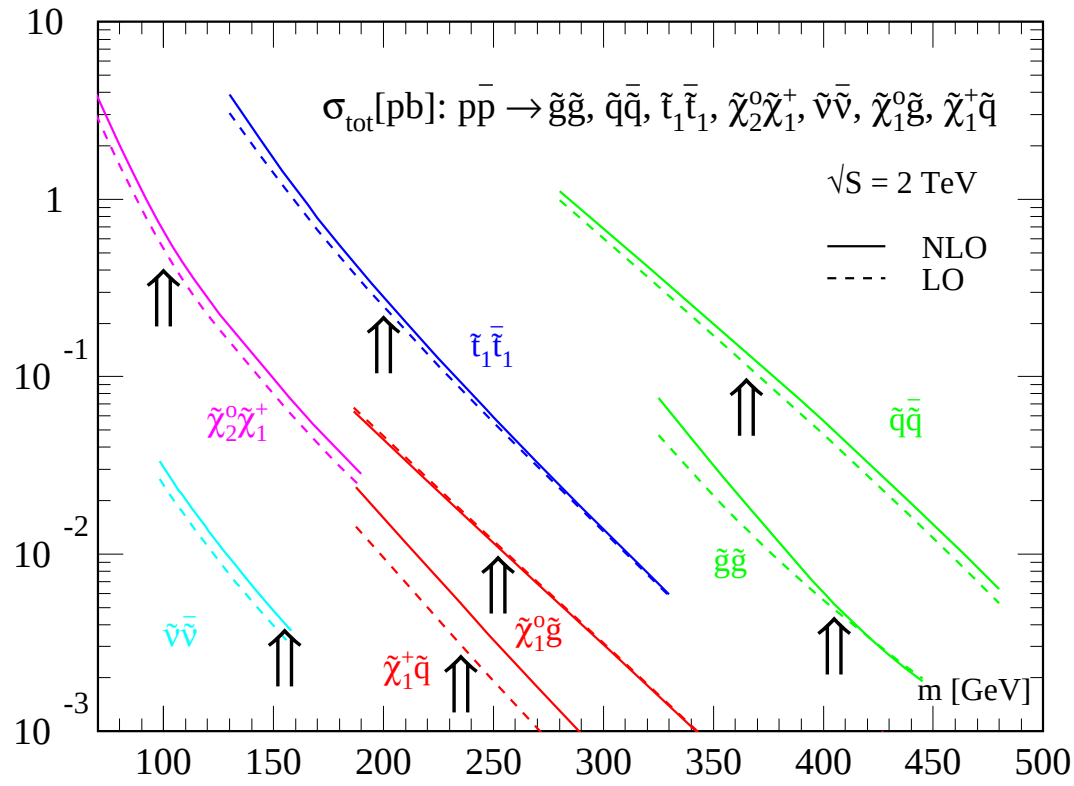


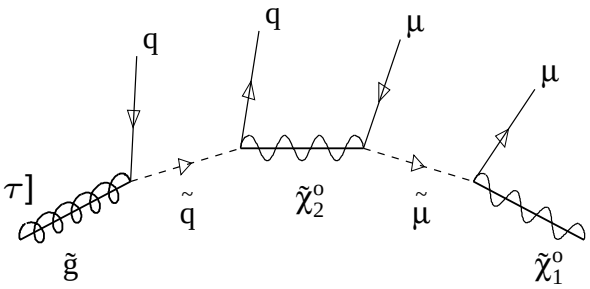
SUPERSYMMETRY AT LHC: 2

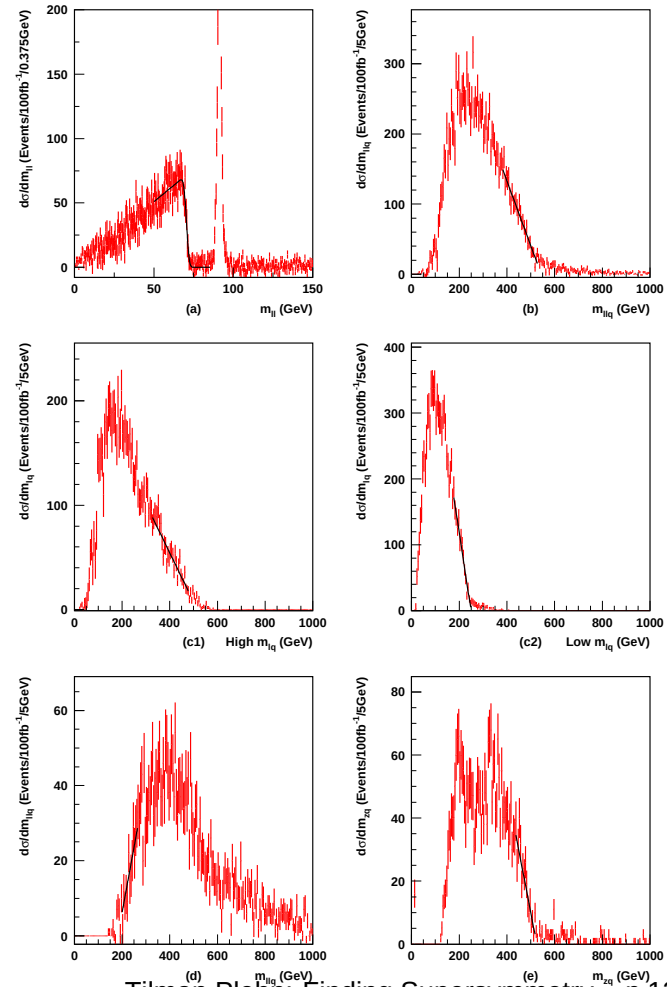
Spectra from cascade decays

- 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 or to τ]
- cross sections some 100 pb [more than 3×10^5 events]
- thresholds & edges $m^2_{\ell\ell} < (m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0})/m^2_{\tilde{\ell}}$
- detector resolution, calibration, systematic errors, shape analysis, cross sections as input?

$\Rightarrow$ spectrum information sits in decay kinematics

[Hinchliffe, Paige,...;Allanach, Parker, Webber,...]





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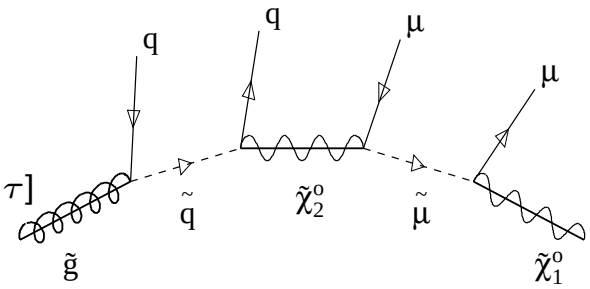

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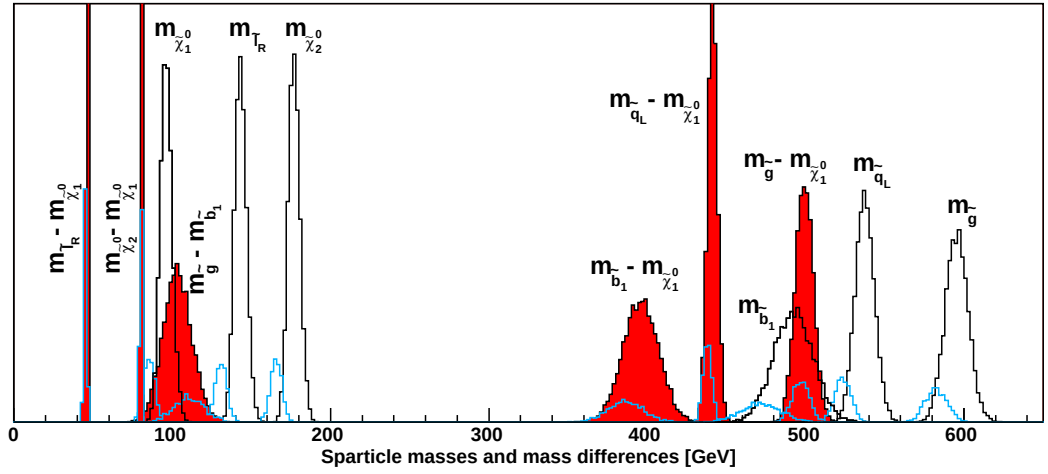
$\Rightarrow$ spectrum information sits in decay kinematics [mass difference work better]

Gluino mass [Gjelsten, Miller, Osland]

- now four jets instead of two
- $\tilde{b}_L$ 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]

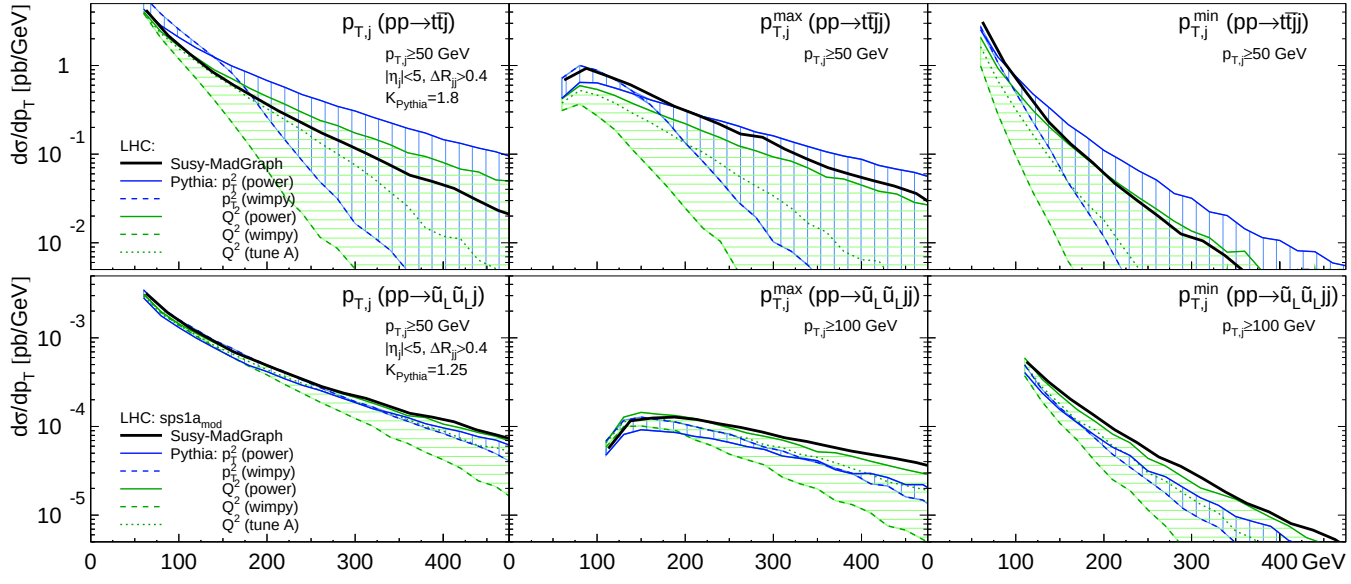
- Majoranas and fermion number violation in tools like Madgraph
- complete set of Feynman rules [400+ processes compared: Madgraph - Whizard - Sherpa]

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

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

$\Rightarrow$ SUSY easier than tops?

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



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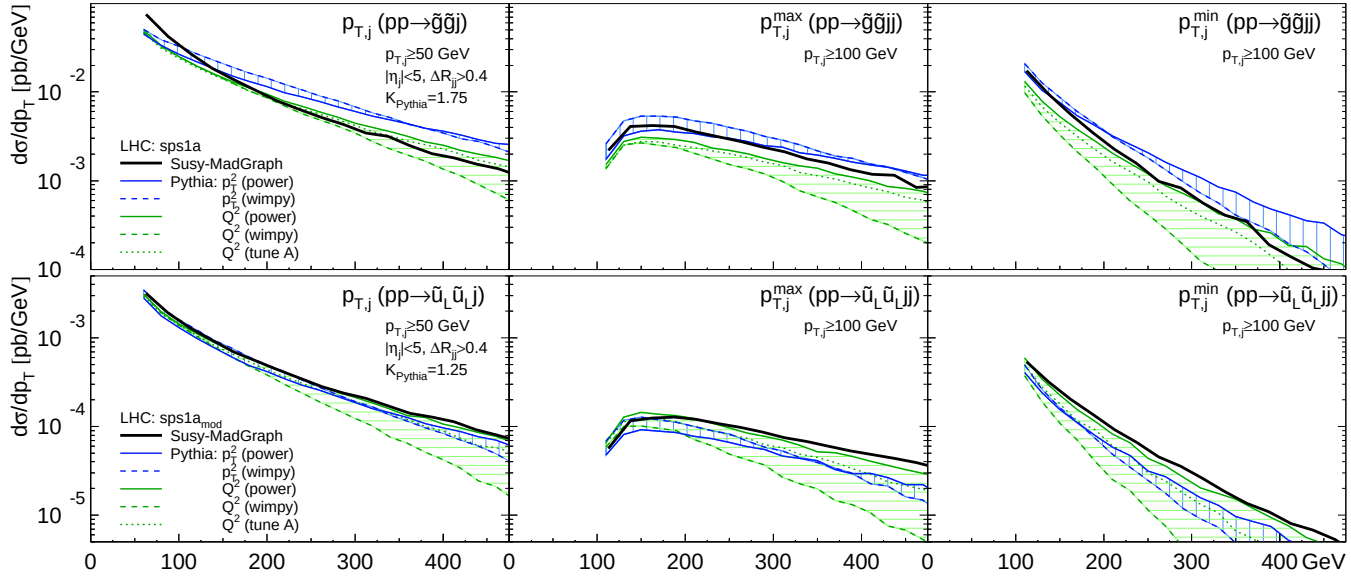
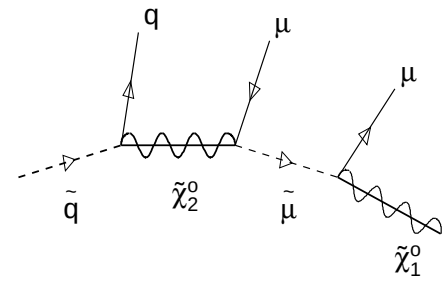


SUPERSYMMETRY AT LHC: 4



How to make sure it is SUSY

- assume squark is found in cascades

$\Rightarrow$ strongly interacting scalar? [first stop towards 'neutralino']

$\Rightarrow$ straw-man model where squark is a fermion: universal extra dimensions

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

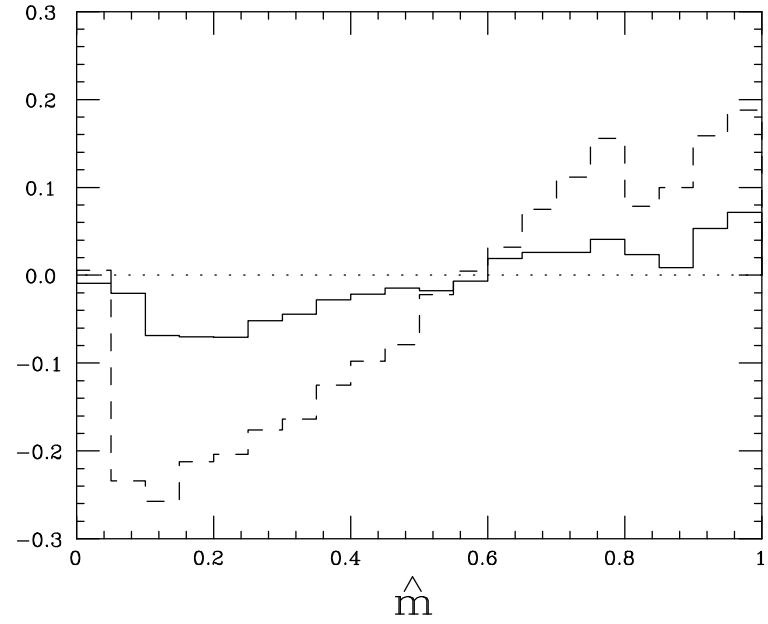
Squark–slepton cascade [Smillie, Webber]

- decay chain $\tilde{\chi}_2^0 \to \ell\tilde{\ell}^* \to \ell\bar{\ell}\tilde{\chi}_1^0$
- compare with first KK Z and ℓ
- typically largest pp $\to \tilde{q}\tilde{g}$ [$\tilde{q} : \tilde{q}^* \sim 1 : 2$]
- trick: mass variables, 'normalized angles' [Barr]

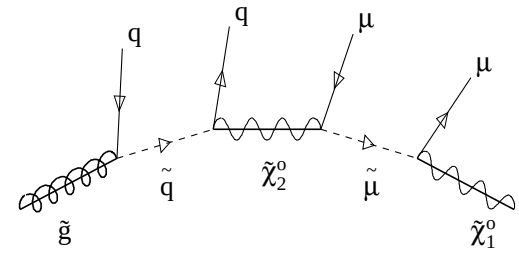
$\Rightarrow$ $\hat{m} = m_{j\ell}/m_{j\ell}^{max}$ most promising

$\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$

$\Rightarrow$ more than proof of feasibility [dashed SUSY]



SUPERSYMMETRY AT LHC: 5

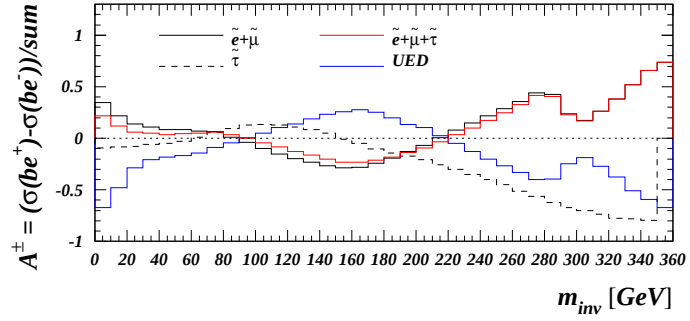


Show it is SUSY–QCD

- given like–sign dileptons, gluino would be better

$\Rightarrow$ if fermion, then definitely Majorana [call it gluino]

$\Rightarrow$ compare with our straw man

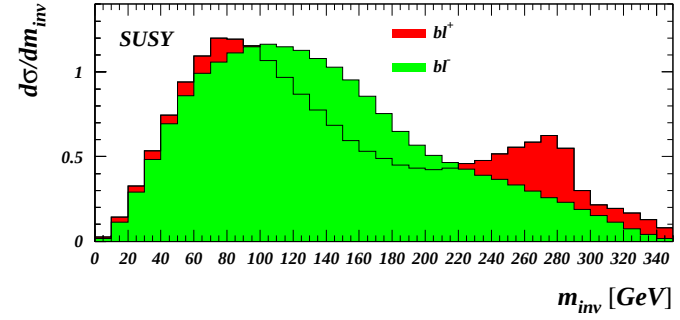


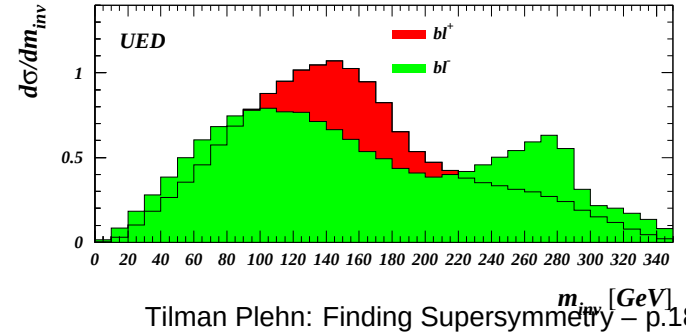
Gluino–bottom cascade [Alves, Eboli, TP]

- decay chain as for gluino mass measurement
- compare with first KK g, q, Z, and ℓ
- replace initial–state asymmetry by b vs. $\bar{\text{b}}$
- $\hat{\text{m}} = \text{m}_{\text{b}\ell}/\text{m}_{\text{b}\ell}^{\text{max}}$

  $\mathcal{A} = [\sigma(\text{b}\ell^+) - \sigma(\text{b}\ell^-)]/[\sigma(\text{b}\ell^+) + \sigma(\text{b}\ell^-)]$
- very preliminary

$\Rightarrow$ 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?

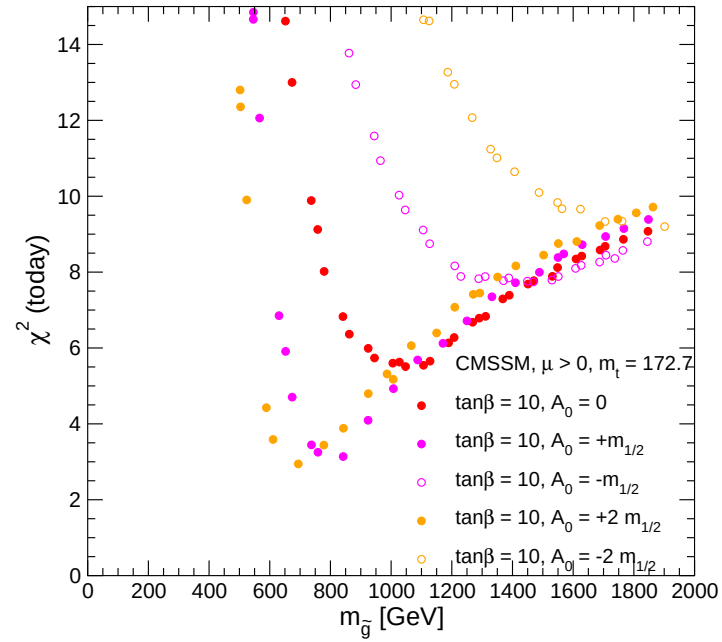
First go at problem

- ask a friend who knows how SUSY is broken

$\Rightarrow$ mSUGRA

- fit $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$
- no problem, include indirect constraints

$\Rightarrow$ likelihood map today [Georg & friends]



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First go at problem [TP, Lafaye, Zerwas]

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$\Rightarrow$ mSUGRA

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

$\Rightarrow$ edges much more powerful

	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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- 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

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	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

OUTLOOK

LHC phenomenology beyond the Standard Model

- Tevatron perfect training ground for SUSY at LHC
- many new ideas: QCD matching, parameter extraction, spin measurement,...
- many new tools: Prospino2, Smadgraph, Sfitter,...
- lots of more work to be done

$\Rightarrow$ experiment and theory have to work together

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