

SUPERSYMMETRY AT THE LHC

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- News from the Higgs
- My personal 04-05 highlights: Susy at the LHC
- Split Susy at the LHC

n.b. Lots of figures in this talk stolen or preliminary!

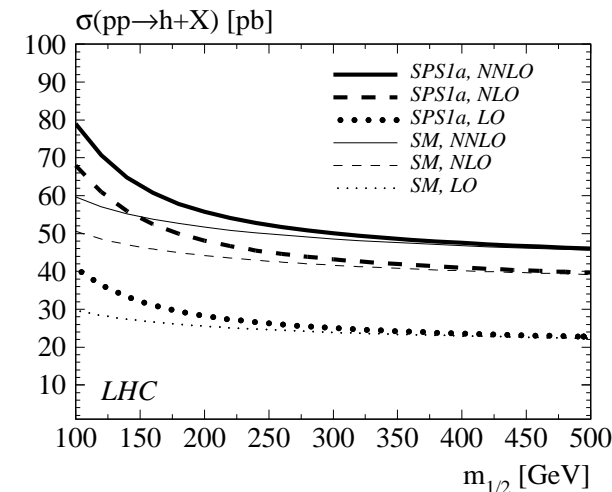
SUSY-HIGGS AT THE LHC

NLO and parton shower in MC@NLO [Frixione, Webber, DelDuca, O'Leari]

- combine collinear jets, hard jets, virtual corrections in Herwig
- THE tool for analyses, currently in use in Atlas & CMS
- unfortunately only Standard Model [DY, W, Z, H, $t\bar{t}$, ...]

Higher-order SUSY-Higgs production [Harlander, Steinhauser, Hofmann]

- Standard Model $gg \rightarrow H$ known to NLO [Spira]
- \Rightarrow exact NLO squark contributions large [talk Mühlleitner, Spira]
- (SUSY) Wilson coefficient for heavy particles
- \Rightarrow approximate NNLO cross section in heavy-mass limit



Bottom parton issues resolved [charged Higgs reach reduced]

- conceptual problem with bottom partons clarified [Boos, TP, Maltoni, Willenbrock,...]
- NLO $gg \rightarrow b\bar{b}H$ and NNLO $b\bar{b} \rightarrow H$ agree [Dittmaier, Spira,... ; Dawson,... ; Harlander & Kilgore]
- distributions checked for $gb \rightarrow tH^-$, $b\bar{b} \rightarrow H^+H^-$ [Berger, Han, Jiang, TP; Alves & TP]

SUSY SIGNALS AT LHC (AND TEVATRON)

10 years of discovering:

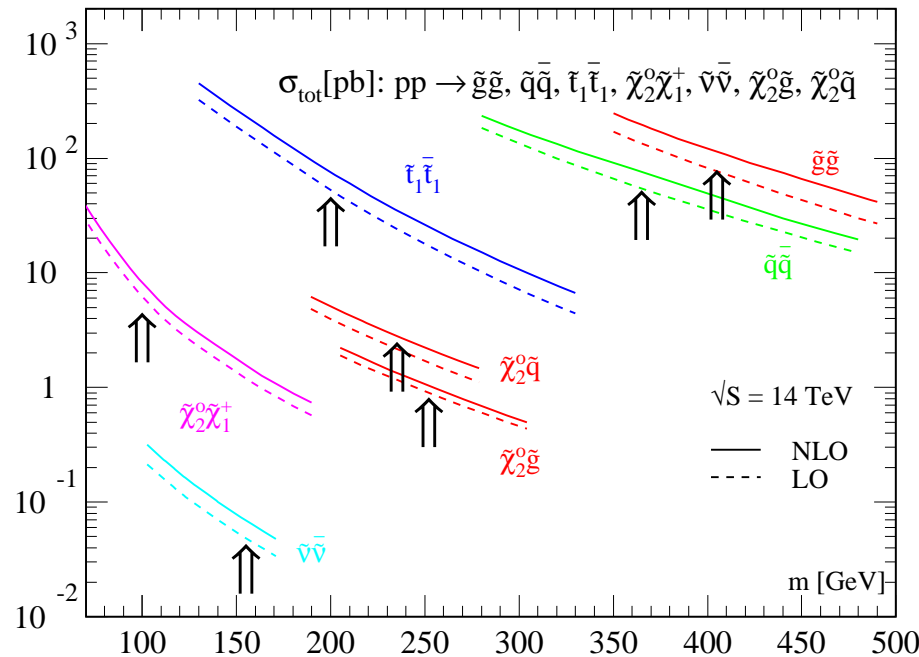
- (1) **possible discovery** — signals for new physics, exclusion of parameter space
- (2) **measurements** — masses, cross sections, decays
- (3) **parameter studies** — MSSM Lagrangean, SUSY breaking

SUSY signals [also Tevatron]

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

Theory tools for high precision

- NLO ($2 \rightarrow 2$) cross sections: Prospino2
- NLO SUSY branching ratios: Sdecay [Mühlleitner]
- LO ($2 \rightarrow n$) matrix elements: Smadgraph, Sherpa, Whizard
- all SUSY input through Les Houches Accord [Allanach, Skands,...]



SUSY CASCADE ANALYSES

Spectra from cascade decays

– decay $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow \tilde{\chi}_2^0 q\bar{q} \rightarrow \mu^+ \mu^- q\bar{q} \tilde{\chi}_1^0$ [better not via Z or to τ]

– cross sections some 100 pb [more than 3×10^5 events]

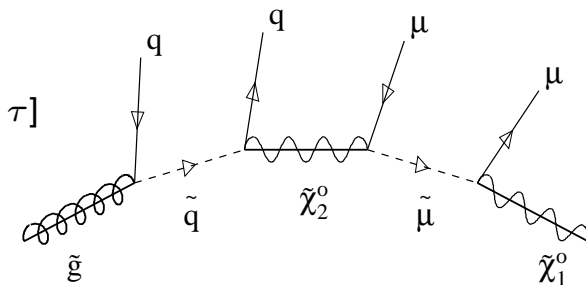
– thresholds & edges [Hinchliffe, Paige...; Cambridge ex-ph]

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

– detector resolution, calibration, systematic errors, shape analysis? [talk Miller]

– cross sections as additional input? [Lester...]

⇒ \tilde{q}_L cascade reconstruction great for SPS1a [mass differences better; talk Hinchliffe]



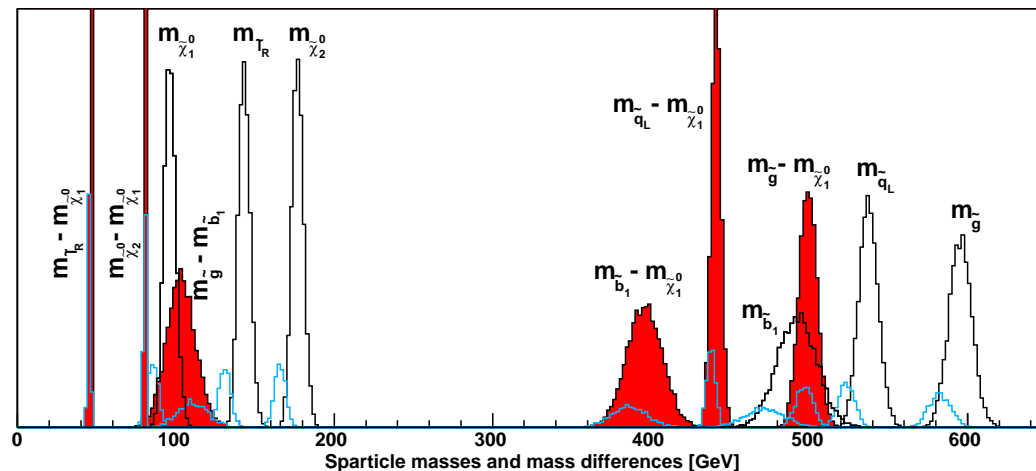
Glino mass [Gjelsten, Miller, Osland]

– now four jets instead of two

– jet identification crucial

– \tilde{b}_L instead, all jets b-tagged

⇒ **gluino mass to $\sim 1\%$
statistical error dominant**



SUSY MATRIX ELEMENTS FOR THE LHC

Complex final states: SUSY-Madgraph [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

- Majoranas and fermion number violation in Madgraph [Denner, Eck, Hahn, Küblbeck]
- complete set of Feynman rules [400+ processes compared with Whizard and Sherpa]
- first physics projects started [talk Rainwater]

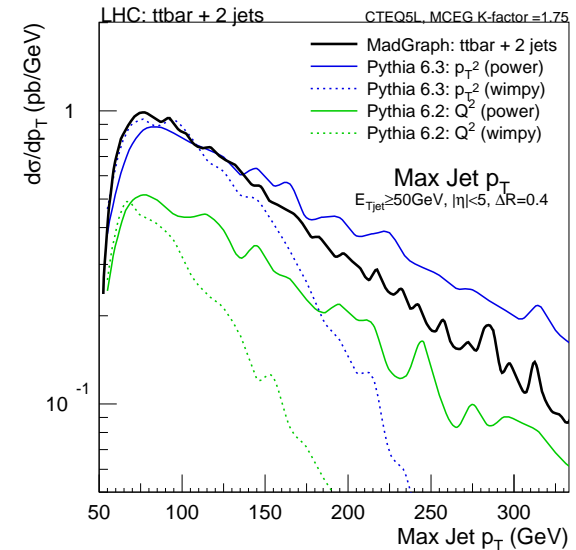
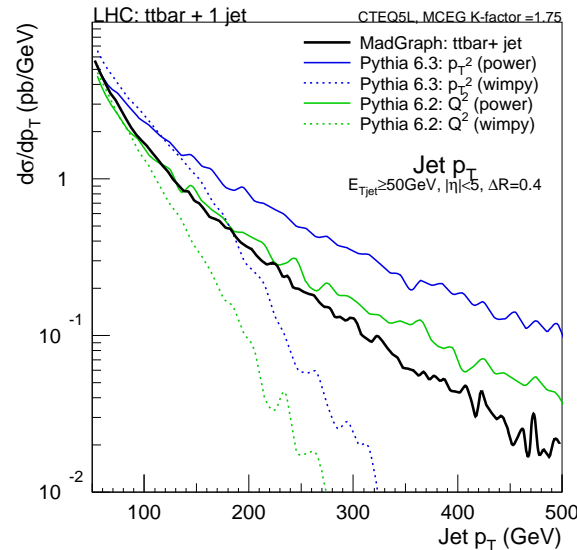
Squarks and gluinos plus jets [TP, Rainwater, Skands]

- cascade studies sensitive to jets?
- Smadevent: $\tilde{g}\tilde{g}+2j$ and $\tilde{u}_L\tilde{g}+2j$ [$p_{T,j} > 100\text{GeV}$]

| 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 |

⇒ Phythia shower?

⇒ All will be tuned



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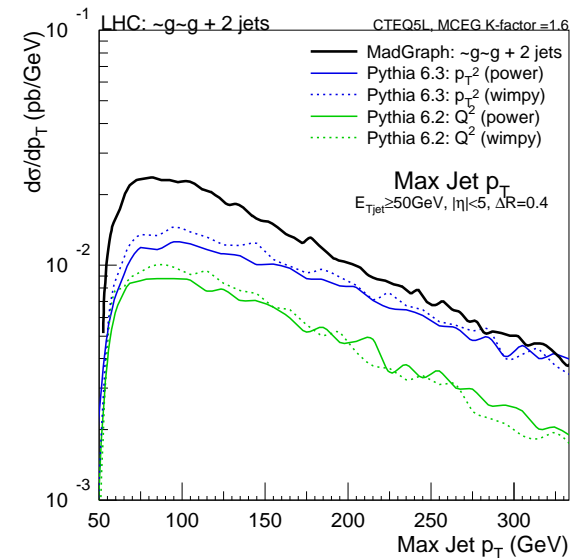
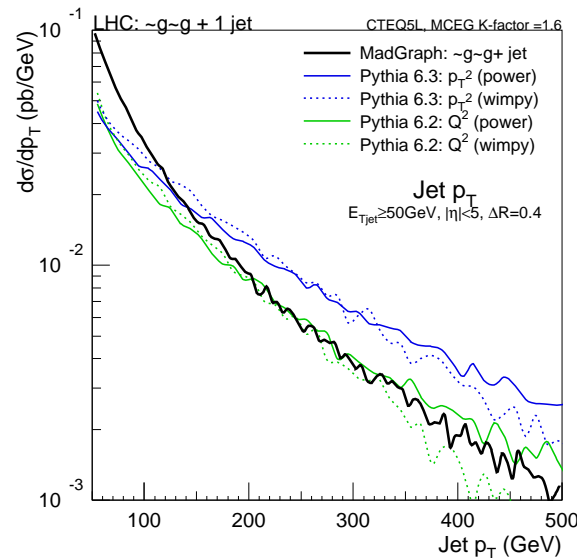
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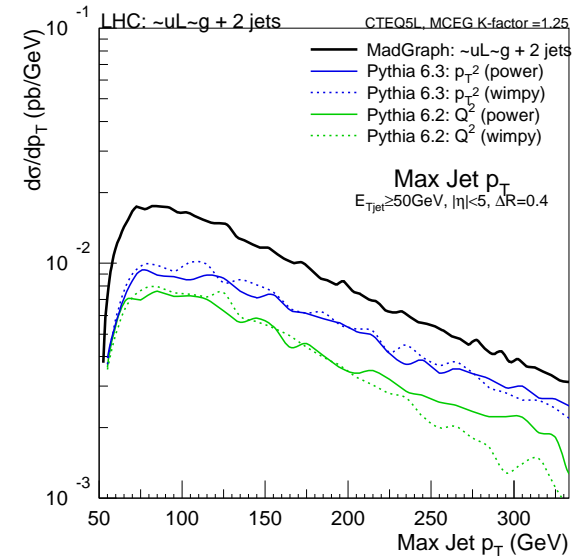
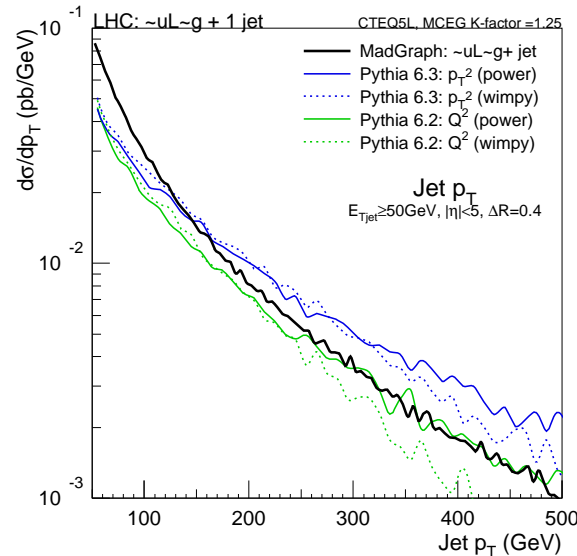
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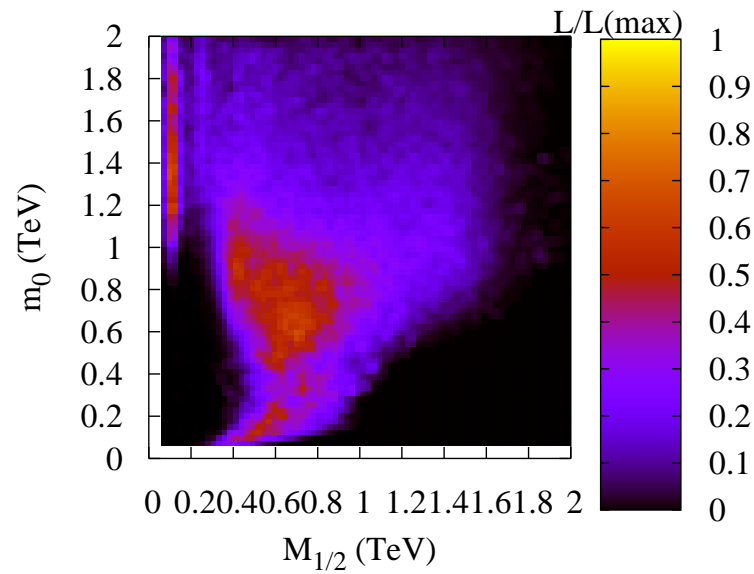
SUSY PARAMETERS FROM LHC DATA

SUSY parameters from observables

- 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?

First go at problem

- ask a friend who knows how SUSY is broken
- ⇒ mSUGRA [talk Falkowski, Weiglein]
- fit $m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
- no problem, include indirect constraints [Allanach]
- ⇒ who would bet a month's salary on mSUGRA?
- admittedly: **mSUGRA a very useful testing ground for methods**



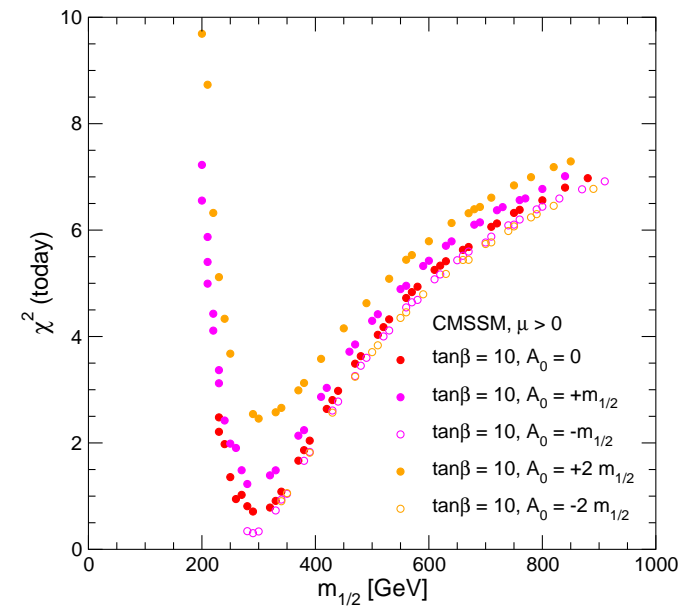
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Sfitter/Fittino [Lafaye, TP, Zerwas; Bechtle, Desch, Wienemann]

- (1) grid for closed subset
- (2) fit of remaining parameters
- (3) complete fit
- LHC better than expected
- **LHC+ILC without assumptions**
- SUSY breaking bottom–up

| | 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 |
| $M_{\tilde{q}_{3L}}$ | 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 |

DIMENSIONAL REDUCTION

Problem in renormalization group: consistent dimensional reduction [talk Stöckinger]

- $(4 - 2\epsilon)$ -dim. space-time, 4-dim. gauge fields and γ_μ [2 d.o.f. for gluons and gluinos]
- no general all-orders proof yet that Dred preserves SUSY
- mathematical inconsistency
- \Rightarrow new & consistent reformulation [c.f. Breitenlohner, Maison for $\overline{\text{MS}}$]
- \Rightarrow SUSY of Dred proven in several two-loop cases

Hadron colliders: dimensional reduction and factorization [Signer, Stöckinger]

- massive collinear factorization broken in Dred [Beenakker, Kuijf, v. Neerven, Smith]

$$\sigma_{\text{coll}} \neq f_{\text{parton}} \otimes \sigma_{\text{Born}}$$

- ‘non-factorizing terms’ rewritten with complete set of splittings $\sum_{g,\epsilon} f_i \otimes \sigma_i$
- from massless theory $f_\epsilon = f_g|_{m=0}$
- now ϵ -scalars in collinear limit [justifying usual pole subtraction]
- \Rightarrow factorization valid in consistently defined Dred

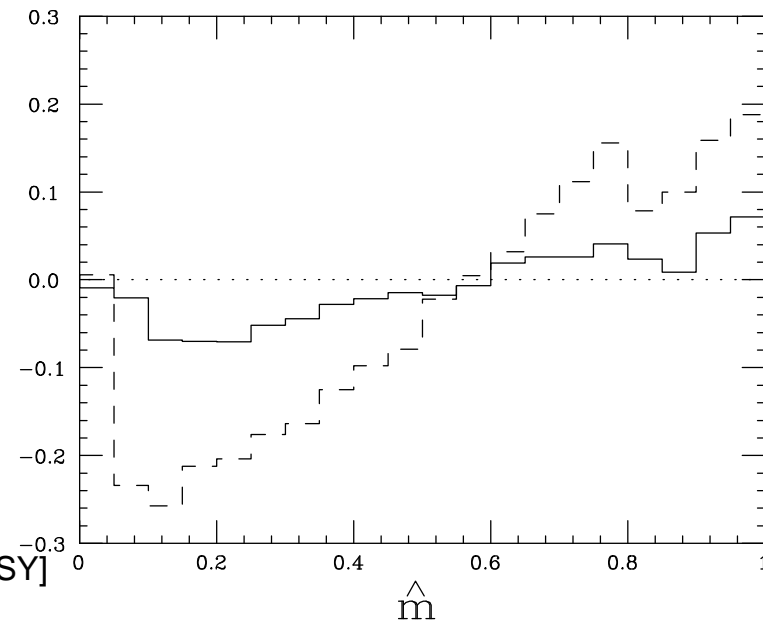
SUSY SPINS AT THE LHC

How to make sure it is SUSY

- assume neutralino is found in cascades
- ⇒ if fermion, then weakly interacting Majorana [that's what we call a neutralino]
- ⇒ compare with a model where gluino is a boson: universal extra dimensions
[Cheng, Dobrescu,...; mass spectra degenerate —ignore this information; cross section factor 10 larger —ignore this as well]

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 $pp \rightarrow \tilde{q} \tilde{g}$ [$\tilde{q}/\tilde{g} \sim 2$]
- trick: mass variables, 'normalized angles' [Barr]
- ⇒ $\hat{m} = m_{j\ell} / m_{j\ell}^{\max}$ most promising
- $$\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)] / [\sigma(j\ell^+) + \sigma(j\ell^-)]$$
- assume hierarchical SPS1a spectrum [dashed SUSY]
- ⇒ **more than proof of feasibility**



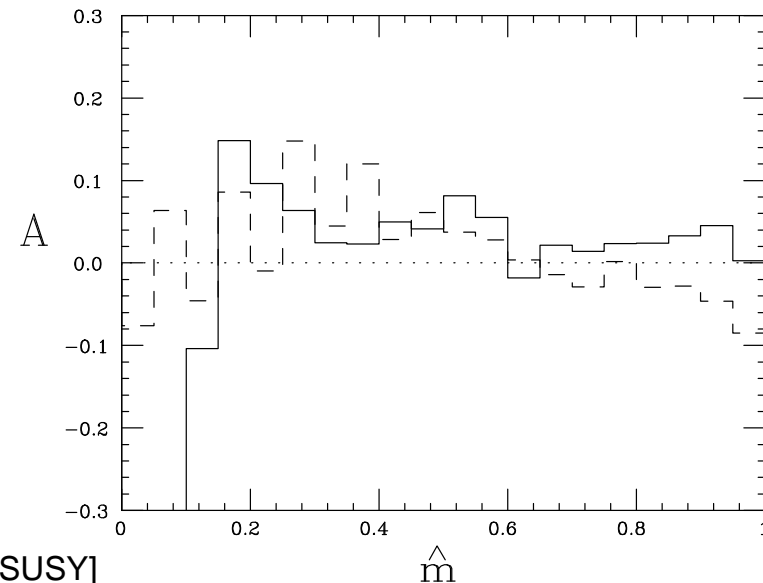
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- $$\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)] / [\sigma(j\ell^+) + \sigma(j\ell^-)]$$
- assume non-hierarchical UED spectrum [dashed SUSY]
- ⇒ **more than proof of feasibility**



STABLE MASSIVE PARTICLES

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

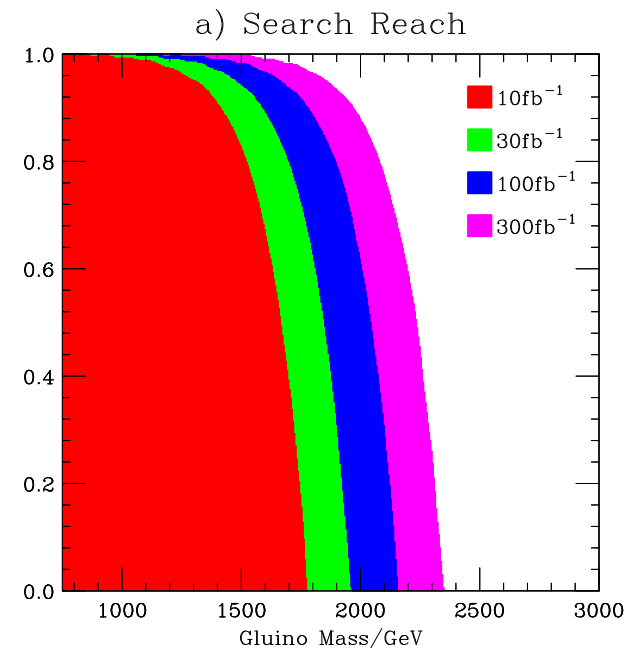
- forget about fine tuning [Higgs will never be as bad as cosmological constant]
- remember all the good things SUSY did for you [dark matter, unification]
- ⇒ make scalars heavy
- ⇒ protect gaugino and higgsino masses

News for phenomenology [Kilian, TP, Richardson, Schmidt; Hewett, Lillie, Mazip, Rizzo]

- no cascade decays
- ⇒ hadronizing gluinos [$\tau \sim \tilde{m}^{-4} \sim 6.5\text{s}$ for $\tilde{m} = 10^9\text{GeV}$]
- heavy R hadrons [Farrar, Fayet; Baer, Cheung, Gunion; UKQCD; Kraan]
- gluonium, late decays,... [many unnamed talks]
- renormalization group running without scalars
- ⇒ corrections to protected couplings [ino Yukawas 20%]

Collider prospects [with proper errors, talk Richardson]

- LHC stable gluino to $\sim 2\text{TeV}$ [charge the key]
- ILC error on anomalous Yukawas $\lesssim 10\%$ [indirect fit]



LHC phenomenology

- pheno-experimental efforts going very strong
- lots of new tools on the market, waiting to be tested
- ⇒ we will be able to do amazing things at the LHC
- ⇒ we still need the ILC for precision studies

Remember

- errors are tough, but the key to new physics
- we need more serious LHC man power
[you can sign up in the back of this room after the talk]

Thanks to all the people whose work I presented, all those whose great work I did not manage to include, and to T. Falk