

Title: TeV-Scale Physics in the LHC Era

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Abstract:

# TeV-Scale Physics in the LHC Era

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PASCOS, 6/2008

## Outline

Signals and QCD

Backgrounds and QCD

Masses from cascades

Missing energy

Spins from between endpoints

Underlying parameters

# Effective Standard Model in the LHC era

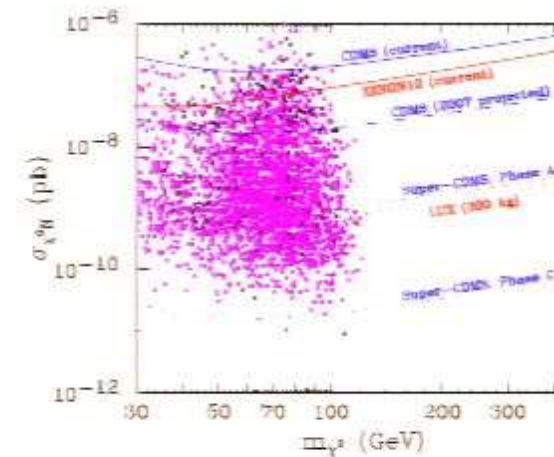
## Expectations from the LHC

- find light Higgs
- find new physics stabilizing Higgs mass [new strongly interacting particles]
- dream of producing dark-matter candidate [missing energy]

## Particle theory and new physics [recently labelled 'inverse problem']

- LHC and models too complex for model-independent analyses
- test testable hypotheses [models and simulations]  
discrete hypotheses: spins,....  
continuous hypotheses: masses,....
- link to Planck, direct detection,  $(g - 2)_{\mu} \dots$  [Hooper, TP, Valinotto; Altunkaynak et al]

⇒ **reconstruct TeV-scale Lagrangian**



# Effective Standard Model in the LHC era

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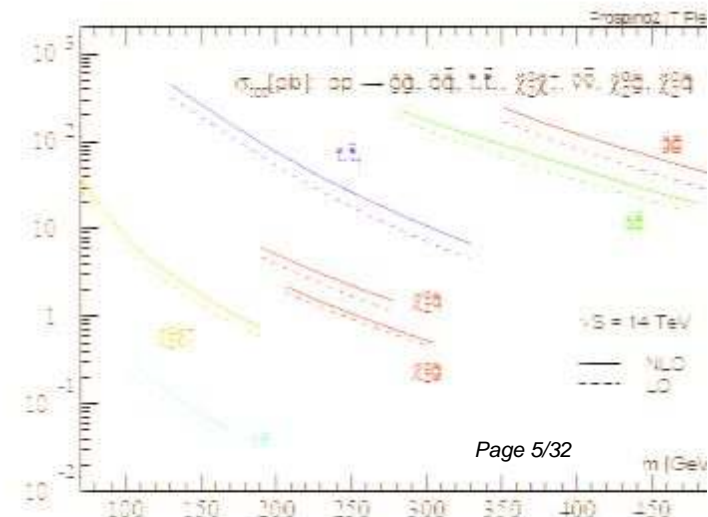
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- ⇒ **reconstruct TeV-scale Lagrangian**

## LHC means winning by luminosity

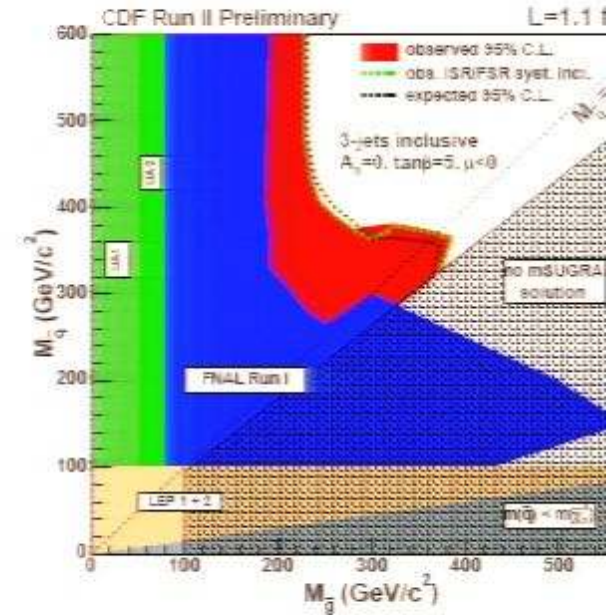
- beyond inclusive searches
- lots of strongly interacting particles
- cascade studies with DM candidate
- but hard to survive QCD



## Signals and QCD

### LHC (and Tevatron) searches

- new particles strongly interacting  
dark-matter weakly interacting  
signature: jets + missing energy + X
  - SUSY: colored  $\tilde{g}$  — 2 jets while  $\tilde{q}$  — 1 jet
  - ADD: graviton means missing energy with jets
  - QCD: plenty additional jets  
not suppressed by  $\alpha_S/\pi$  [collinear logs]  
even possible new-physics trigger
- ⇒ need to understand jets in signals



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$\sigma$ [pb]	$t\bar{t}_{600}$	$g\bar{g}$	$q\bar{q}$
$\sigma_{0j}$	1.30	4.83	5.6
$\sigma_{1j}$	0.73	2.89	2.7
$\sigma_{2j}$	0.26	1.09	0.8
$p_T > 100$ GeV	[TP, Rainwater, Skands]		

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### Jets in final state

- high- $p_T$  jets: hard matrix elements  
low- $p_T$  jets: parton shower  
combination for multi-jet signals: CKKW, MLM [Catani, Krauss, Kuhn, Webber, Mangano]
  - signal: single hard scale, no nasty cuts
  - merging available in Alpgen, Sherpa, Madevent [Alwall, Le, Lisanti, Wacker]
- ⇒ jets with new physics fun and easy

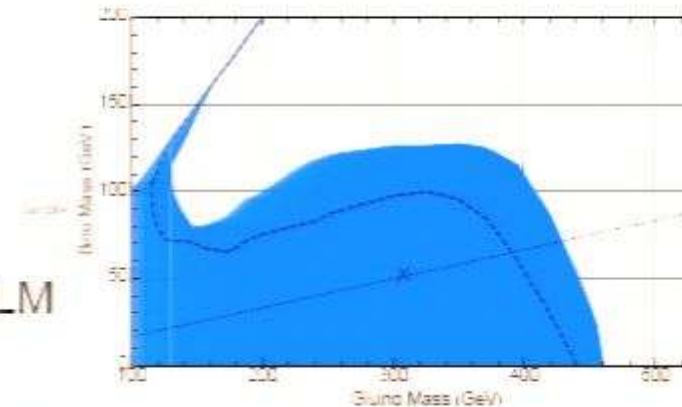
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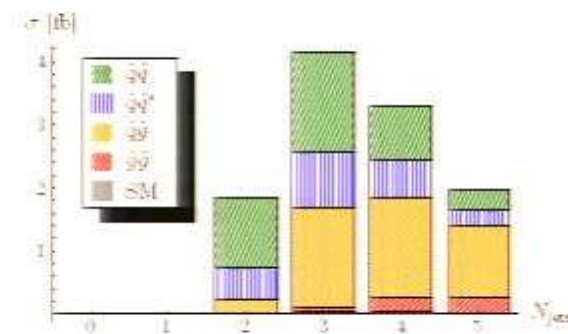


[Alwall, Le, Lisanti, Wacker]

## Backgrounds and QCD

### Backgrounds and jets

- simulate  $W$ +jets or  $Z$ +jets or  $t\bar{t}$ +jets or whatever  
extrapolate background region into signal region [bad cuts, many scales]
- parton shower: collinear jets not good approximation
- merging: valid over entire  $p_T$  range  
leading-order error on each channel  $[(\Delta\alpha_S/\alpha_S)^4 = 1.2^4 = 2.1]$
- higher orders: renormalization/factorization scale dependence reduced  
only fixed hard final state

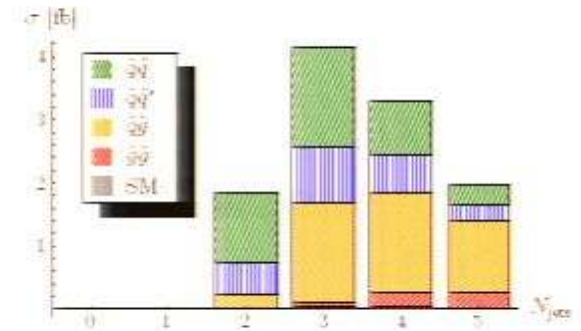


[Freitas, Skands, Spira, Zerwas]

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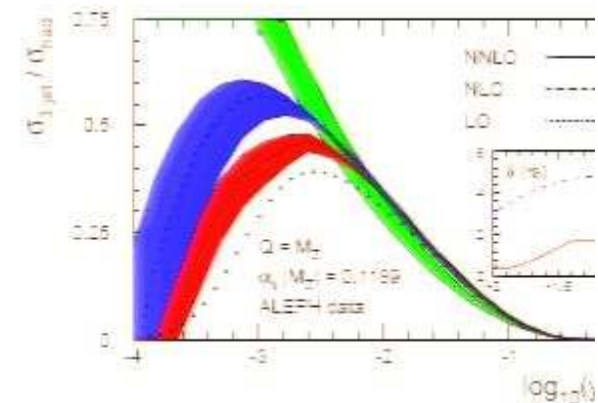
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### Jets and loops

- signal: easy 2 — 2 processes [Prospino2]
  - backgrounds: 2 — 3, 4 state of the art  
 $pp \rightarrow t\bar{t} + \text{jet}$  [Dittmaier, Uwer, Weinzierl]  
 $pp \rightarrow WWW$  [Hankele et al; Binoth et al; Lazopoulos et al]  
...
  - $pp \rightarrow t\bar{t}b\bar{b}$  on way [Bredenstein, Denner, Dittmaier, Pozzorini]
  - recent application:  
NNLO  $e^+e^- \rightarrow 3 \text{ jets}$  in  $\alpha_S$  measurement [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich]
- $\Rightarrow$  jets in backgrounds tough, boring, but impressive progress





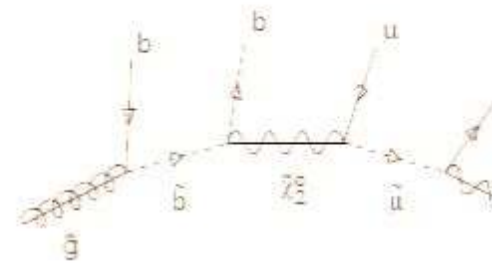
## Masses from cascades

### Cascade decays [Atlas-TDR, Cambridge]

- if new particles strongly interacting and LSP weakly interacting
- tough: counting events [only if totally unavoidable]  
better: cascade kinematics [ $10^7 \dots 10^8$  events]
- long chain  $\tilde{g} \rightarrow \tilde{b}\tilde{b} \rightarrow \tilde{\chi}_2^0 \tilde{b}\tilde{b} \rightarrow \mu^+ \mu^- \tilde{b}\tilde{b} \tilde{\chi}_1^0$
- thresholds & edges

$$0 < m_{\mu\mu}^2 < \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{b}}^2}{m_{\tilde{g}}^2} \frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{g}}^2}$$

$\Rightarrow$  new-physics mass spectrum from cascade kinematics



### Waiting to be tested in LHC environment

- edge for  $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ :  $M_{T,2}(\chi_{\text{LSP}}) = \min_{\alpha} \max_j m_{T,j}(\chi_{\text{LSP}}, \alpha) < m_{\chi_2}$  [Lester, Summers 99]
- modifications to  $M_{T,2}$  shape for  $\tilde{\chi}_2^0 \tilde{\chi}_2^0$  [Ross, Serna 07]
- kinks in  $M_{T,2}$  for  $\tilde{g}\tilde{g}$  etc [Cho et al, Barr et al 07]
- event-pair likelihood analysis for  $\tilde{g} + X$  [Kawagoe, Nojiri, Polesello 04]
- mass-space extrema for  $\tilde{\chi}_2^0 \tilde{\chi}_2^0$  [McElrath et al 07]
- event pair equations for  $\tilde{q}_L \tilde{q}_L^*$  [McElrath et al 08]
- hybrid methods for  $\tilde{q}_L \tilde{q}_L^*$  [Nojiri, Polesello, Tovey 07]

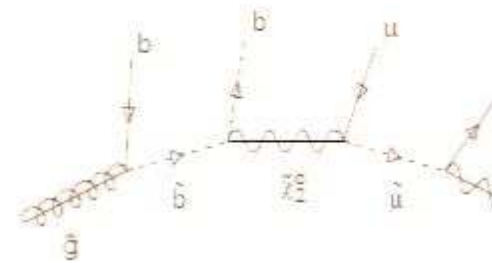
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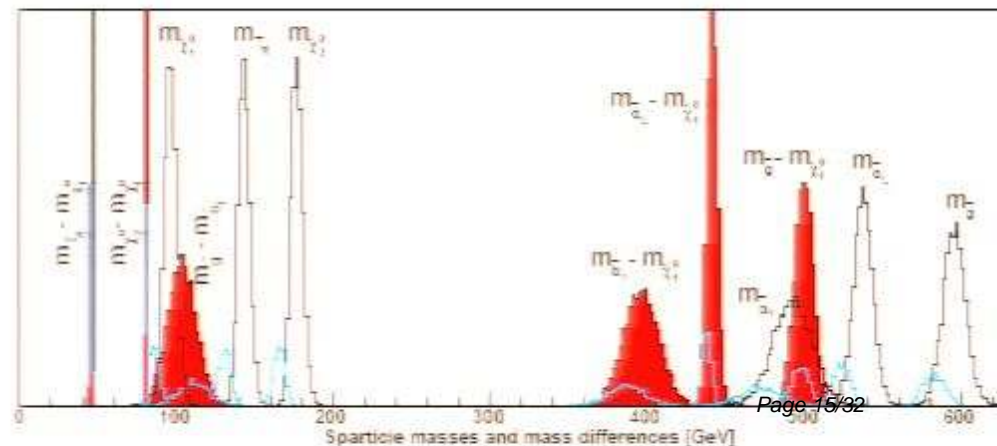
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$\Rightarrow$  new-physics mass spectrum from cascade kinematics



## Glauino decay [Gjelsten, Miller, Osland]

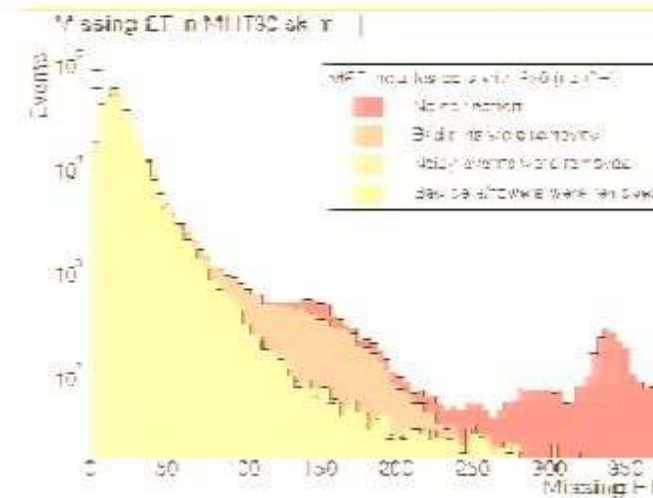
- all decay jets  $b$  quarks [otherwise dead by QCD]
  - gluino mass to  $\sim 1\%$
- $\Rightarrow$  but why physical masses?



# Missing energy

## Detector effects and missing energy

- electrons and muons fine [Z peak calibration, 500/200000 ATLAS calorimeter cells]  
jets harder, but still possible  
**missing energy all cells**
  - bad runs: check number and distribution of Z...  
coherent noise: many cells with correlated noise during event...  
bad cells: individual continuously hot cells...
  - typical smearing:  $0.5 \sqrt{\sum E_T} \gtrsim 20 \text{ GeV}$   
global corrections to individual events [calibration of energy scales, dead matter]
- ⇒ **missing energy in early data???** [Baer, Prosper, Summary]



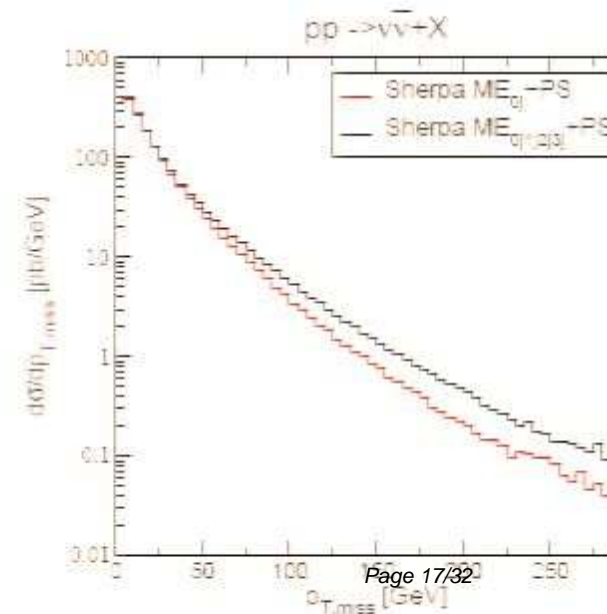
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## Simulation of missing energy

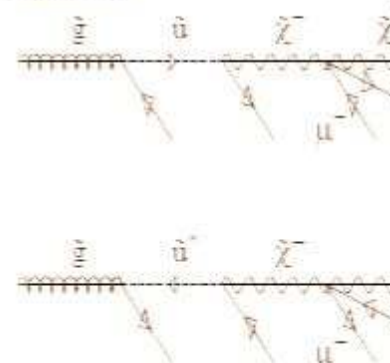
- physics background  $W/Z + \text{jets}$
- gauge boson recoiling against jets
- sensitive to jet simulation  
 $p_T$  range between collinear and hard jets  
parton shower vs. merging [Schumann (Sherpa)]
- $\Rightarrow$  **missing energy really means QCD**



## Spins from between endpoints

Gluginos: strongly interacting Majorana fermions [Barger, Barnett, Baer, ...]

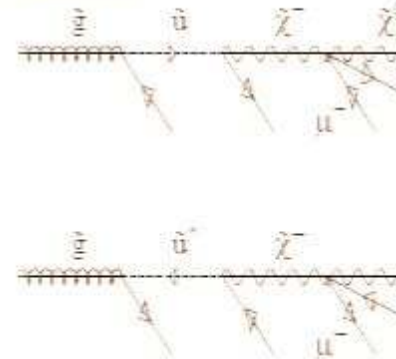
- LHC: first jet ( $q$  or  $\bar{q}$ ) fixes lepton charge
  - same-sign dileptons in 50% of events
  - similar:  $t$ -channel gluino in  $pp \rightarrow \tilde{q}\tilde{q}$
- $\Rightarrow$  gluino = like-sign dileptons in SUSY sample



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Loop hole: gluino is Majorana if fermion

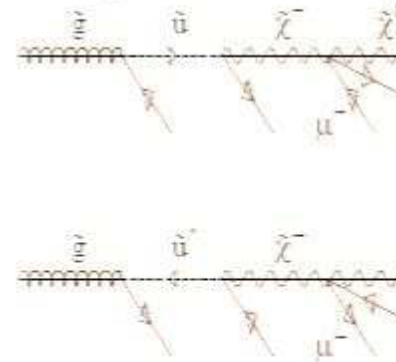
- use mass-measurement cascade [Gjei, Miller, Osland]  
now look for physics between the endpoints
- new physics is hypothesis testing [Barr, Lester, Smillie, Webber]



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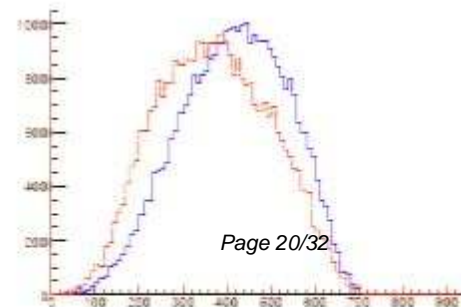
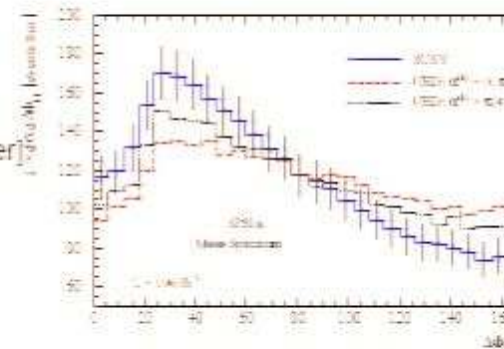
### Glunos: strongly interacting Majorana fermions [Barger,....; Barnett,....; Baer,...]

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### Loop hole: gluino is Majorana if fermion

- use mass-measurement cascade [Gjelsten, Miller, Osland]  
now look for physics between the endpoints
- new physics is hypothesis testing [Barr, Lester, Smillie, Webber]
- 'gluino' a boson: universal extra dimensions  
compare SUSY with KK  $g, b, Z, \ell, \gamma$  [Alves, Eboli, TP]
- $\Rightarrow$  **gluino = fermion with like-sign dileptons**
- 'gluino' composite: little Higgs  
compare SUSY with decays to top [Gregoire, Katz]
- $\Rightarrow$  **gluino = fermion decaying via correct cascades**



## Spins from between endpoints

### Asymmetries [Cambridge group: Alves, Eboli, TP]

- remember: spins mean angular correlations

'invariant angles':  $m_{j\ell} / m_{j\ell}^{\text{max}} = \sin \theta / 2$

- squark: production asymmetry  $pp \rightarrow \tilde{q} / \tilde{q}^* + \tilde{g}$

$$\mathcal{A}(m_{j\ell}) = \frac{\sigma(j\ell^+) - \sigma(j\ell^-)}{\sigma(j\ell^+) + \sigma(j\ell^-)}$$

- gluino: decay asymmetry  $b$  vs.  $\bar{b}$

$$\mathcal{A}(m_{\mu b}) = \frac{\sigma(b\ell^-) - \sigma(\bar{b}\ell^-)}{\sigma(b\ell^-) + \sigma(\bar{b}\ell^-)}$$

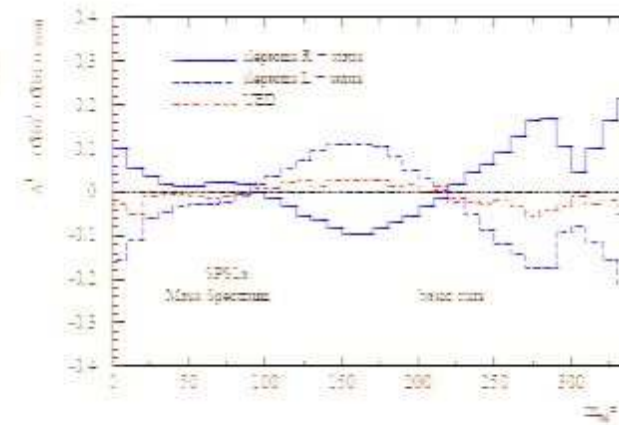
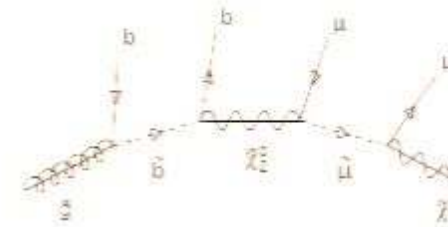
- stable w.r.t production channels and cuts

unstable w.r.t model details [use to measure: Hagiwara, Kim, Mawatari, Zerwas]

- 3-body decays [Csaki, Heinonen, Perelstein]

- more general decay analysis [Wang, Yavin]

⇒ LHC only as good as understood hypotheses



## Underlying parameters

### From kinematics to weak-scale parameters [Fittino; SFitter; Lafaye, TP, Rauch, Zerwas]

- parameters: weak-scale Lagrangian
- measurements: edges, branching fractions, rates,....  
flavor, dark matter, electroweak constraints,....
- errors: general correlation, statistics & systematics & theory [flat theory errors!]
- problem in grid: huge phase space, no local maximum?  
problem in fit: domain walls, no global maximum?  
**problem in interpretation: bad observables, secondary maxima?**

### Probability maps of new physics [Baltz.....; Roszkowski.....; Allanach.....; Ellis.....; SFitter]

- fully exclusive likelihood map  $p(d|m)$  over  $m$  [hard part]
- LHC problem: remove poor directions [e.g. endpoints or dark matter vs rates]
- Bayesian:  $p(m|d) \sim p(d|m) p(m)$  with theorists' bias  $p(m)$  [cosmology, BSM]  
frequentist: best-fitting point  $\max_m p(d|m)$  [flavor]
- LHC era: (1) compute high-dimensional map  $p(d|m)$   
(2) find and rank local maxima in  $p(d|m)$   
(3) Bayesian-frequentist dance to reduce dimensions

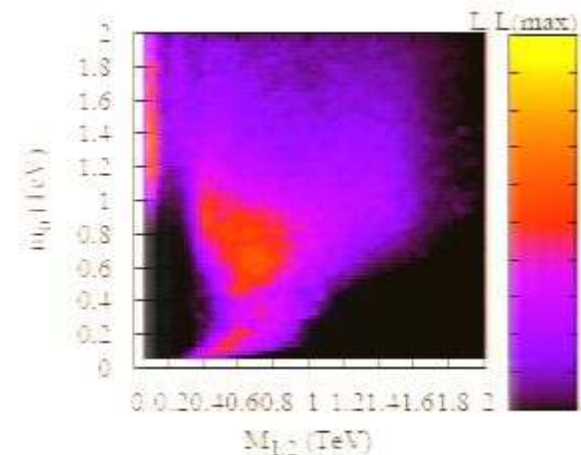
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### MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

- ‘Which is the most likely parameter point?’
- ‘How does dark matter annihilate/couple?’

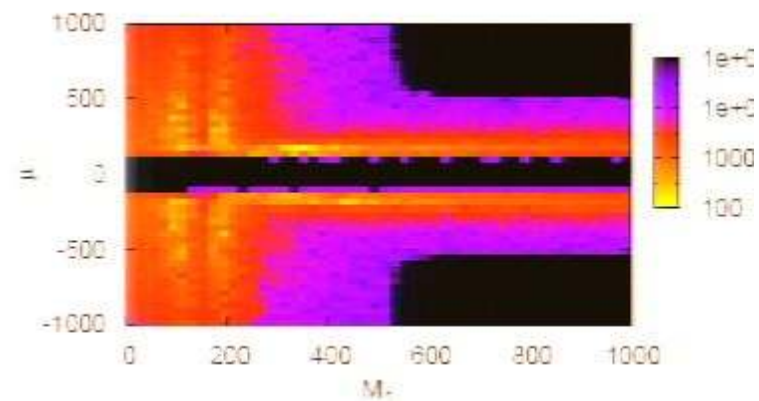


## Underlying parameters

### MSSM map from LHC [SPS1a]

- shifting to 19D parameter space [killing grids. Minuit, laptop-style fits...]
- SFitter output #1: fully exclusive likelihood map  
SFitter output #2: ranked list of local maxima
- six local maxima, unknown  $\text{sign}(\mu)$ , believe-based  $\tan \beta$  from  $m_{H^\pm}$

[profile likelihood]

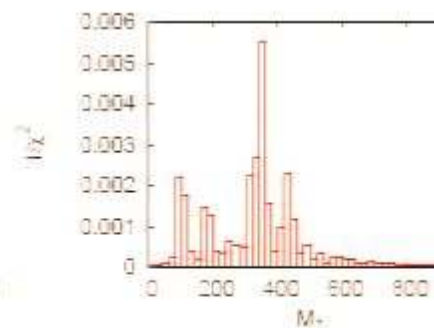
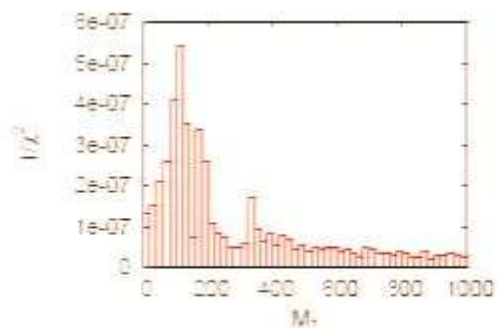


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[left: Bayesian — right: likelihood]



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- ⇒ **no golden approach to BSM statistics**

### MSSM map beyond LHC

- LHC rates:  $\tan \beta$  from heavy Higgs tough [Kinnunen, Lehti, Moortgat, Nikitenko, Spira]

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## MSSM map beyond LHC

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- (1) use current precision on  $(g - 2)_\mu \sim \tan \beta$  [SFitter + Alexander, Kreiss]
- strongly correlated and promising

	LHC		LHC $\oplus (g - 2)$		SPS1a
$\tan \beta$	$10.0 \pm 4.5$	$4.5$	$10.3 \pm 2.0$	$2.0$	$10.0$
$M_1$	$102.1 \pm 7.8$	$7.8$	$102.7 \pm 5.9$	$5.9$	$103.1$
$M_2$	$193.3 \pm 7.8$	$7.8$	$193.2 \pm 5.8$	$5.8$	$192.9$
$M_3$	$577.2 \pm 14.5$	$14.5$	$578.2 \pm 12.1$	$12.1$	$577.9$
$M_{\tilde{\mu}L}$	$193.2 \pm 6.8$	$6.8$	$194.0 \pm 6.8$	$6.8$	$194.4$
$M_{\tilde{\mu}R}$	$135.0 \pm 8.3$	$8.3$	$135.6 \pm 6.3$	$6.3$	$135.8$
$M_{\tilde{q}3L}$	$481.4 \pm 22.0$	$22.0$	$485.6 \pm 22.4$	$22.4$	$480.8$
$M_{\tilde{q}3R}$	$501.7 \pm 17.9$	$17.9$	$499.2 \pm 19.3$	$19.3$	$502.9$
$M_{\tilde{q}L}$	$524.6 \pm 14.5$	$14.5$	$525.5 \pm 10.6$	$10.6$	$526.6$
$M_{\tilde{q}R}$	$507.3 \pm 17.5$	$17.5$	$507.6 \pm 15.8$	$15.8$	$508.1$
$m_A$	$406.3 \pm \mathcal{O}(10^3)$		$411.1 \pm \mathcal{O}(10^2)$		$394.9$
$\mu$	$350.5 \pm 14.5$	$14.5$	$352.5 \pm 10.8$	$10.8$	$353.7$

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	no theory error			$\Delta \text{BR} / \text{BR} = 15\%$	
	true	best	error	best	error
<b><math>\tan \beta</math></b>	<b>30</b>	<b>29.5</b>	<b>3.4</b>	<b>29.5</b>	<b>6.5</b>
$M_A$	344.3	344.4	33.8	344.3	31.2
$M_1$	101.7	100.9	16.3	100.9	16.4
$M_2$	192.0	200.3	18.9	200.3	18.8
$M_3$	586.4	575.8	28.8	575.8	28.7
$\mu$	345.8	325.6	20.6	325.6	20.6
$M_{\tilde{t},R}$	430.0	400.4	79.5	399.8	79.5

## Underlying parameters

### MSSM map from LHC [SPS1a]

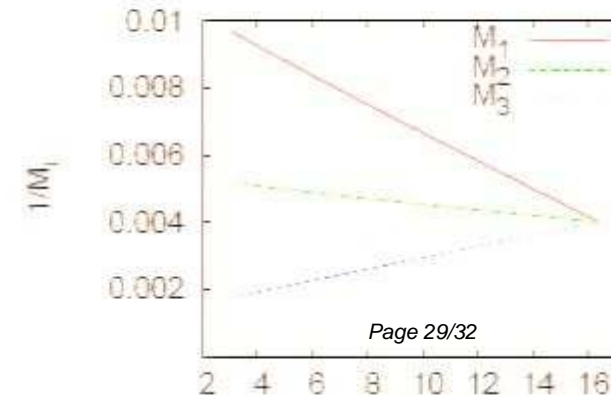
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### Renormalization group bottom-up [SFitter + Kneur]

- scale-invariant sum rules? [Cohen, Schmalz]
  - UV completion, unification, GUT?
- ⇒ **means I can retire happily**



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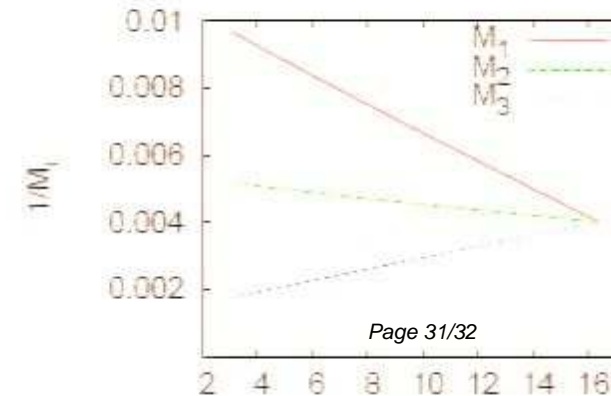
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# New physics at the LHC

## Understanding the TeV scale in a few easy steps

- (1) look for solid new-physics signals [missing energy?]
  - (2) avoid getting killed by QCD [no excuses]
  - (3) measure weak-scale Lagrangian [highD parameter spaces]
  - (4) combine with everything we know
  - (5) determine fundamental physics
  - (6) do not get fooled by people only talking about SUSY
- ⇒ **LHC more than a discovery machine!**

