TeV–Scale Supersymmetry at the LHC

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Outline

TeV–scale new physics

TeV–scale supersymmetry

Masses from cascades

Underlying parameters

Spin from cascades

Spins from jets

Standard–Model effective theory

Remember the Standard Model?

- gauge theory with local $SU(3) \times SU(2) \times U(1)$
- massless $SU(3)$ and $U(1)$ gauge bosons
  massive W, Z bosons [Higgs mechanism with $v = 246$ GeV]
- Dirac fermions in doublets with masses = Yukawas
  generation mixing in quark and neutrino sector
- renormalizable Lagrangian [no 1/masses]
- only missing piece: Higgs [fundamental? minimal? mass unknown]

$\Rightarrow$ defined by particle content, interactions, renormalizability

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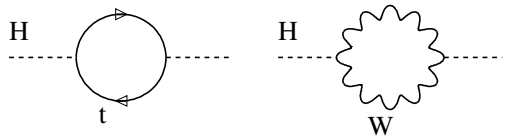
How complete experimentally?

- dark matter? [solid evidence! — for weak–scale new physics?]
- quark mixing — flavor physics? [new operators above 10^4 GeV?]
- neutrino masses and mixing? [see-saw at 10^{11} GeV?]
- matter–antimatter asymmetry? [universe mostly matter]
- gravity missing? [mostly negligible but definitely non-renormalizable]

$\Rightarrow$ cut-off scale unavoidable, size negotiable [SM an effective theory]

$\Rightarrow$ all philosophy — who the hell cares???

TeV–scale new physics



Theorists care — when looking at data which...

...indicates a light Higgs [e-w precision data]
...indicates higher–scale physics [at least dark matter is BSM]

– problem of light Higgs: mass driven to cutoff of effective Standard Model:
$\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, \Lambda^2$

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

– or new physics at TeV scale: supersymmetry [my favorite]
extra dimensions
little Higgs
composite Higgs, TopColor
YourFavoriteNewPhysics...

$\Rightarrow$ beautiful concepts, but problematic in reality [data seriously in the way]

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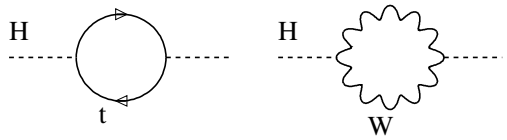

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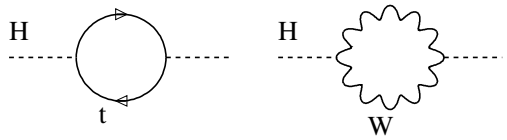
- stable lightest new particle: dark matter [correct relic density]

$\Rightarrow$ TeV–scale models in baroque state

TeV–scale new physics



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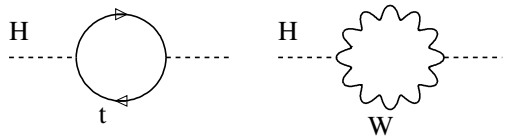
Alternative motivations for TeV–scale new physics

- alternatives to (fundamental) Higgs mechanism?
- gauge coupling unification almost perfect?
- Uli Baur's rule: new energy scales bring new physics!

TeV–scale supersymmetry



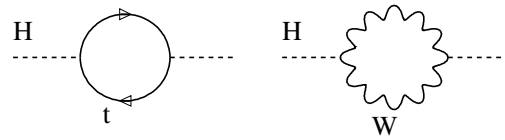
Supersymmetry

- give each Standard–Model particle a partner [with different spin, including strong interactions]
- SUSY obviously broken by masses [soft breaking, mechanism unknown]
- sooo not an LHC paradigm: maximally blind mediation [MSUGRA, CMSSM]

  scalars — m_0 fermions — $m_{1/2}$ tri-scalar — A_0 Higgs sector — sign(μ), tan β
- assume dark matter, stable lightest partner

$\Rightarrow$ measure BSM spectrum with missing energy at LHC

TeV–scale supersymmetry



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LHC searches: MSSM

- conjugate Higgs field not allowed
  $\longrightarrow$ give mass to t and b?
  $\longrightarrow$ five Higgs bosons
- SUSY–Higgs alone interesting...

  ...but not conclusive

  ...and another talk

$\Rightarrow$ list of SUSY partners

		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	$4 \cdot 2$	LSP
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\longrightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	

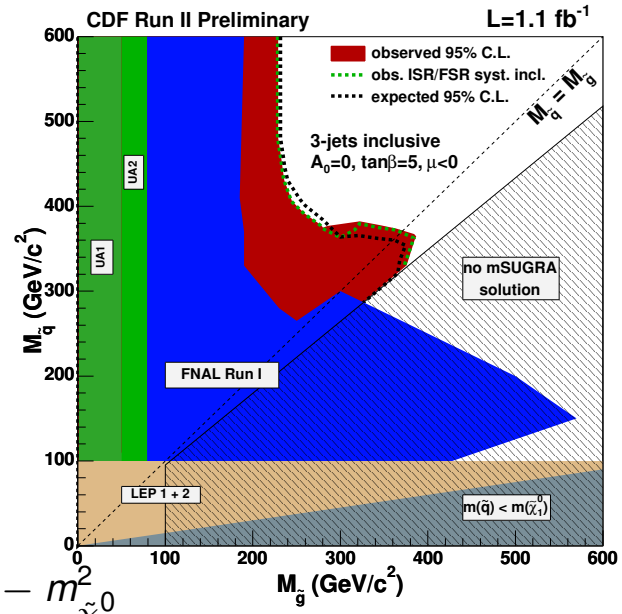
Masses from cascades

Cascade decays [Atlas-TDR, Cambridge]

- if new particles strongly interacting and LSP weakly interacting
- like Tevatron: jets + missing energy
- tough: $(\sigma \mathrm{BR})_1 / (\sigma \mathrm{BR})_2$ [unavoidable: focus point]
- easier: cascade kinematics [$10^7 \ldots 10^8$ events]
- long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- thresholds & edges

$$0 < m^2_{\mu\mu} < \frac{m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}}}{m_{\tilde{\ell}}} \; \frac{m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}$$

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



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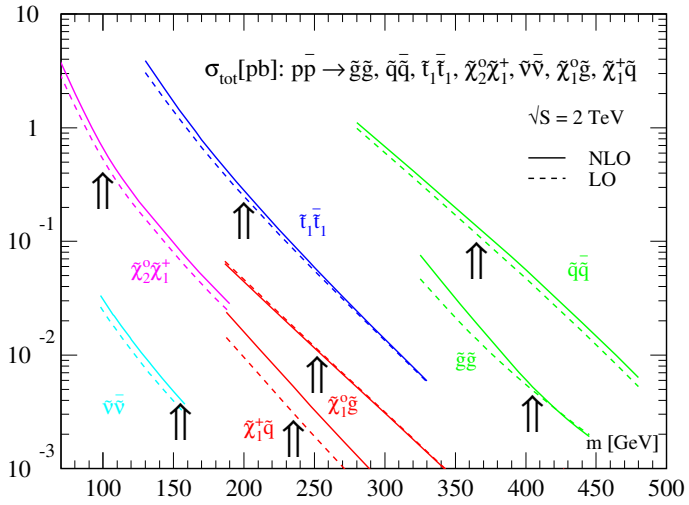

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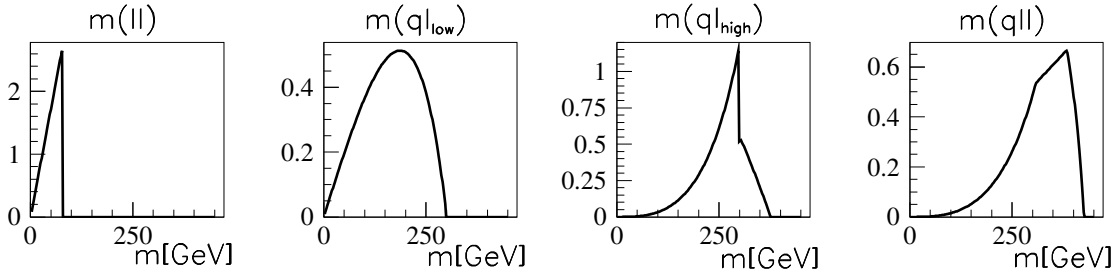

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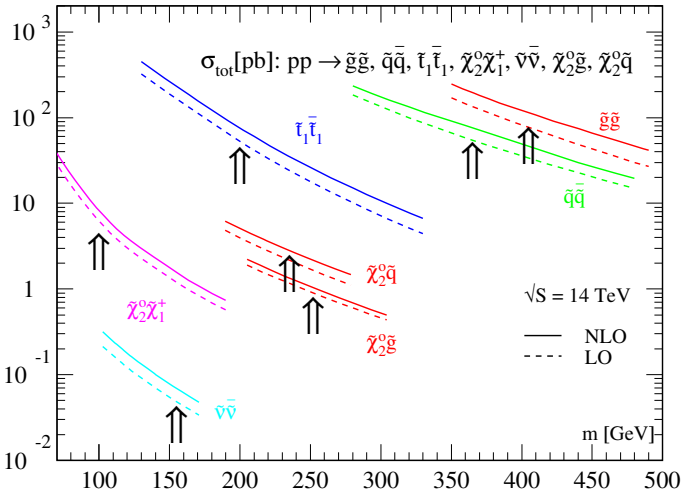

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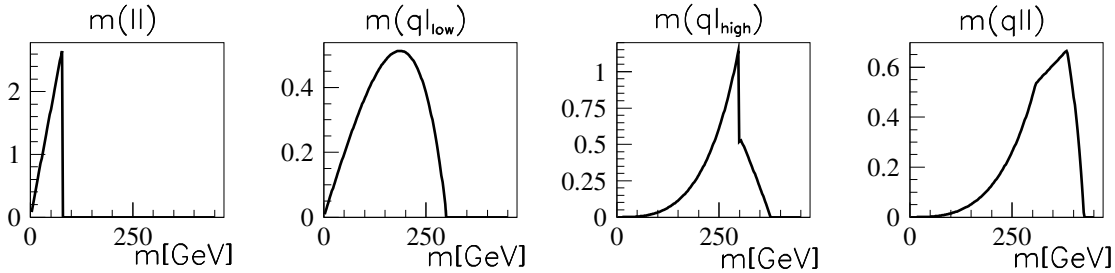

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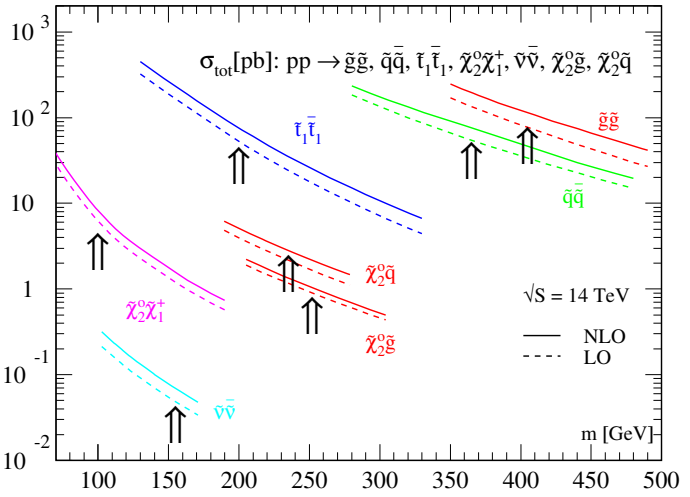

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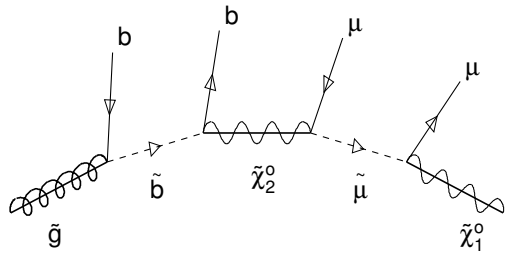
Alternative methods [Nojiri, Polessello]

- do not only use events at end points
- reconstruct masses from external momenta
- add events with identical topology until systems solves

$\Rightarrow$ LHC better than inclusive rates

Masses from cascades



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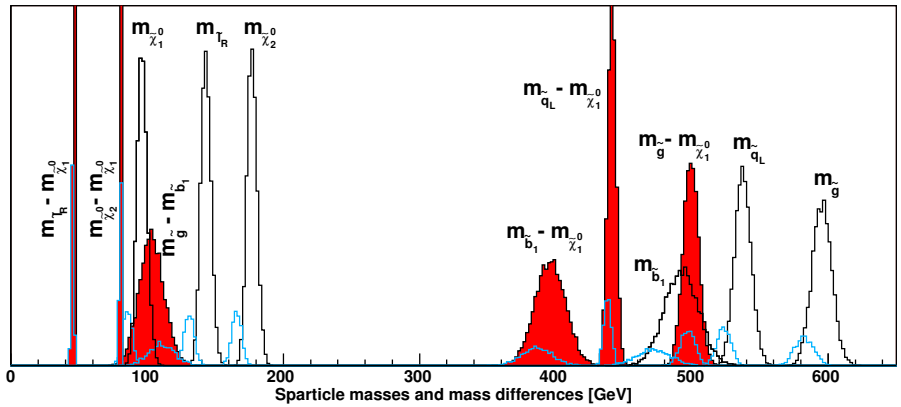
Gluino decay [Gjelsten, Miller, Osland]

- all decay jets b quarks [otherwise dead by QCD]
- no problem: off-shell effects
- no problem: jet radiation
- gluino mass to $\sim 1\%$

$\Rightarrow$ but why physical masses?



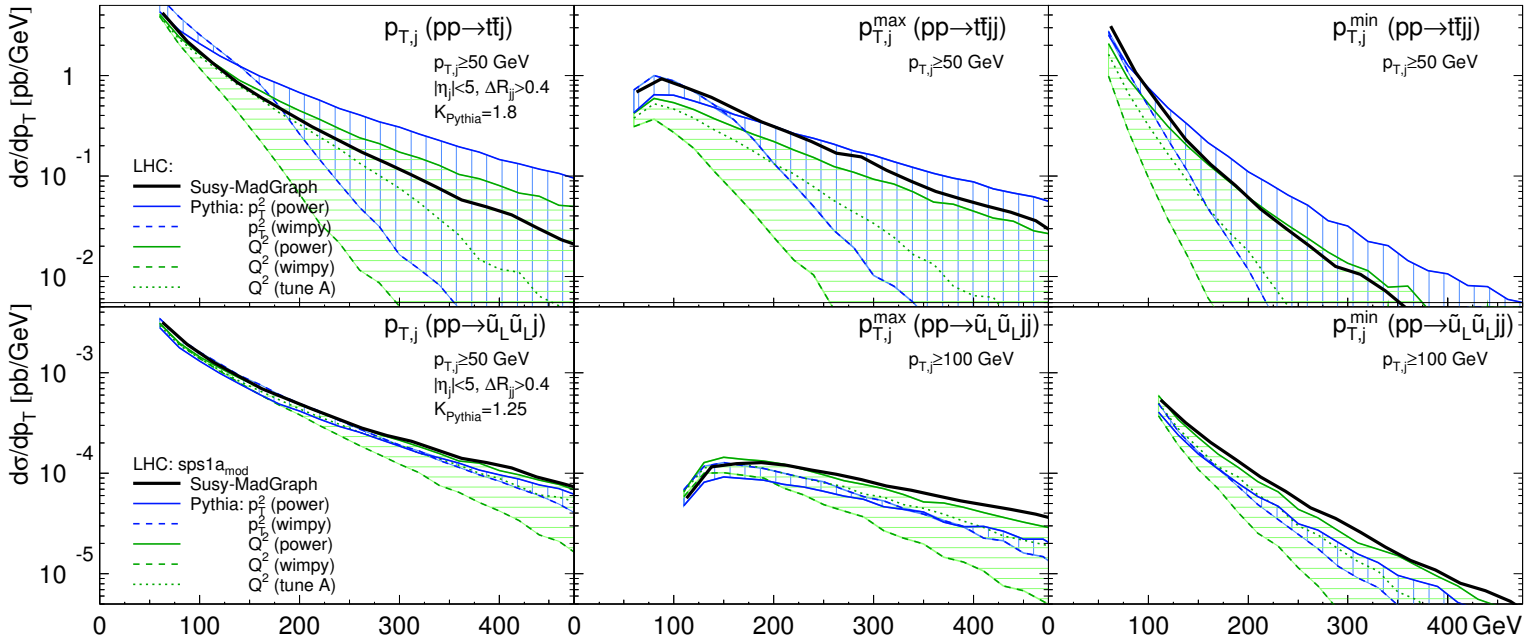
New physics and jets

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

- cascade studies sensitive to jet activity? [compare to Pythia shower]
- matrix element $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j $[p_{T,j} > 100$ GeV$]$
- hard scale μ_F huge for SUSY
- obvious: $p_{T,j}$ spectra fine with jet radiation
- miracle: angular correlations better than 10%

$\Rightarrow$ QCD not a problem in new–physics signals [Jay's next paper]

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



Underlying parameters

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

- back to question: parameters by weak-scale Lagrangian
- measurements: masses or edges,
  branching fractions, rates,... [Prospino]
  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,...; SFitter]

- fully exclusive likelihood map $p(d|m)$ over m [hard part]
- LHC problem: remove pathetic 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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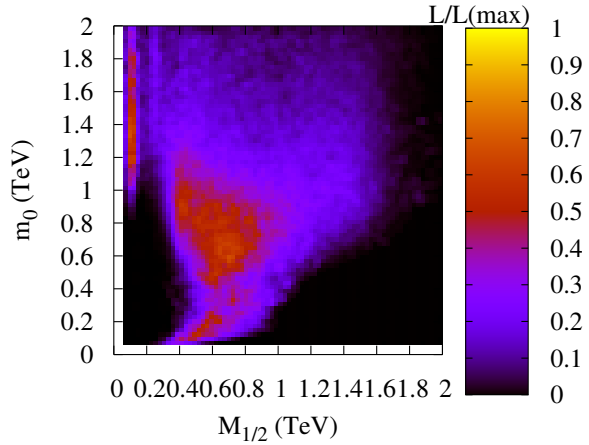
MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

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



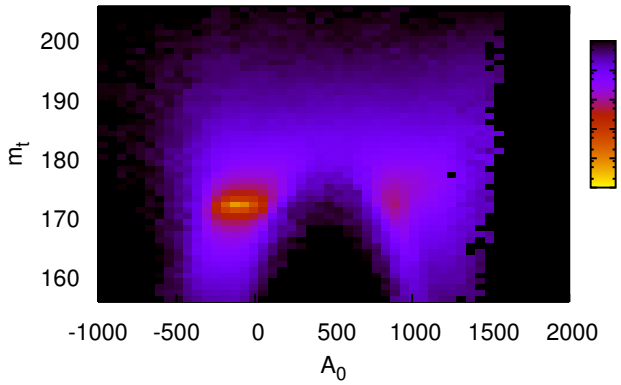
Underlying parameters

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

- weighted Markov chains: several times faster [similar to: Ferrenberg & Swendsen]

$$P_{\text{bin}}(p \neq 0) = \frac{N}{\sum_{i=1}^{N} 1/p}$$

- SFitter output #1: fully exclusive likelihood map
  SFitter output #2: ranked list of local maxima
- strong correlation e.g. of A_0 and y_t [including all errors]



χ^2	m_0	$m_{1/2}$	$\tan\beta$	A_0	μ	m_t
0.3e-04	100.0	250.0	10.0	-99.9	+	171.4
27.42	99.7	251.6	11.7	848.9	+	181.6
54.12	107.2	243.4	13.3	-97.4	-	171.1
70.99	108.5	246.9	13.9	26.4	-	173.6
88.53	107.7	245.9	12.9	802.7	-	182.7
...						

$\Rightarrow$ correlations and secondary maxima significant

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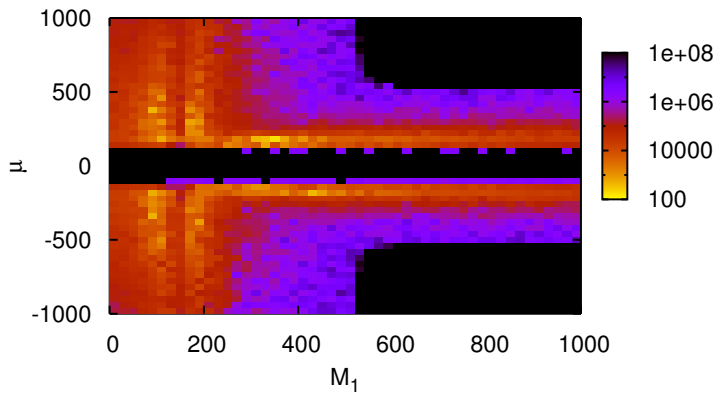
MSSM map from LHC

- shifting from 6D to 19D parameter space [killing grids, Minuit, laptop–style fits...]
- SFitter outputs #1 and #2 still the same [weighted Markov chain plus hill climber]
- three neutralinos observed [profile likelihood]



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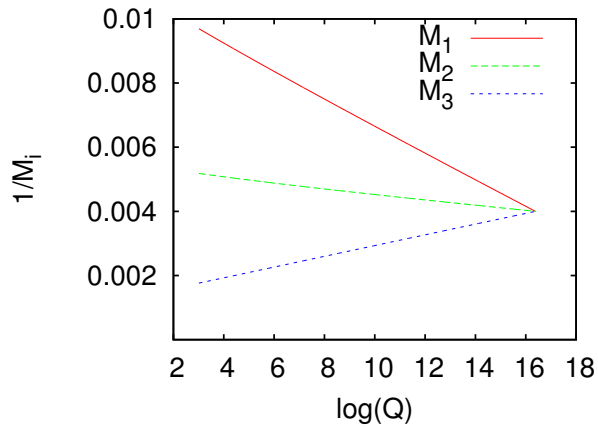
$\Rightarrow$ secondary maxima degenerate in MSSM

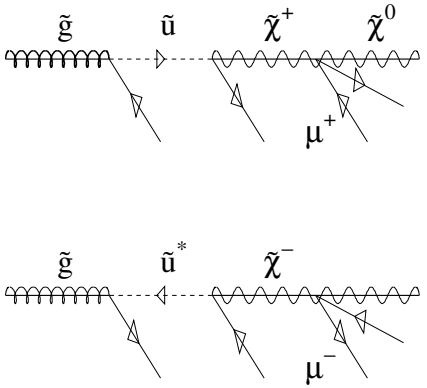
Theorists' goal [SFitter + Kneur]

- unification and supersymmetry
- test mass unification with errors [Cohen, Schmalz]
- properly: RGE running bottom–up

$\Rightarrow$ LHC: fundamental physics from weak scale



Spin from cascades



What kind of mass term? [Barger,...; Barnett,...; Baer,...]

- gluino = strongly interacting Majorana fermion
- first jet (q or $\bar{q}$) fixes lepton charge
- same–sign dileptons in 1/2 of events
- similar: t-channel gluino in $pp \to \tilde{q}\tilde{q}$
- refined: Dirac gluino mass term [Nojiri, Takeuchi]

$\Rightarrow$ like–sign dileptons in SUSY sample means gluino

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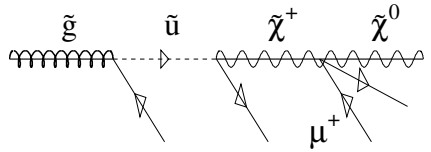

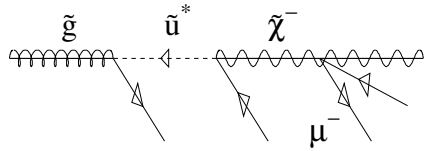

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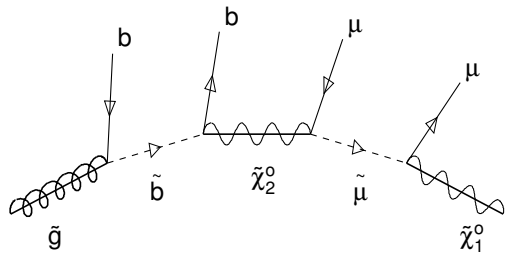
New physics is hypothesis testing [Barr, Lester, Smillie, Webber]



- loop hole: ‘gluino is Majorana if it is a fermion’
- gluino a fermion?
- assume gluino cascade observed
- model–independent analysis unlikely
- straw-man model where ‘gluino’ is a boson: universal extra dimensions

  [spectra degenerate — ignore; cross section larger — ignore; higher KK states — ignore; Higgs sector — ignore]

$\Rightarrow$ compare angular correlations

Spin from cascades

What kind of mass term? [Barger,...; Barnett,...; Baer,...]

- gluino = strongly interacting Majorana fermion
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- same–sign dileptons in 1/2 of events
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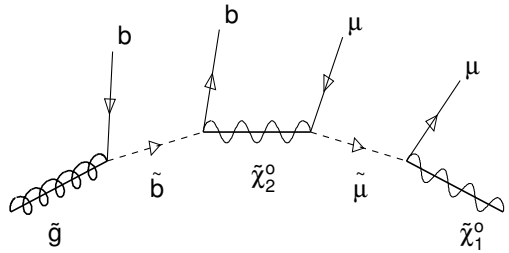
$\Rightarrow$ like–sign dileptons in SUSY sample means gluino

Gluino–bottom cascade [Alves, Eboli, TP; like Cambridge squarks]

- decay chain from gluino mass [simulated for SUSY]
- compare SUSY with excited KK g, b, Z, ℓ, γ
- below edge: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$



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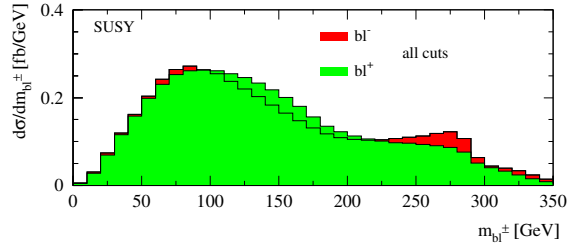

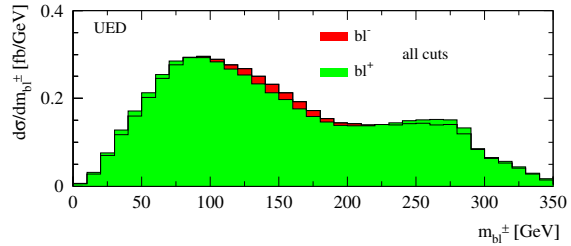

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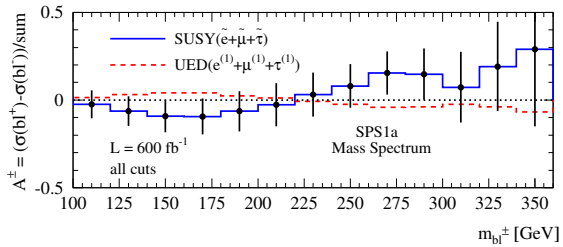
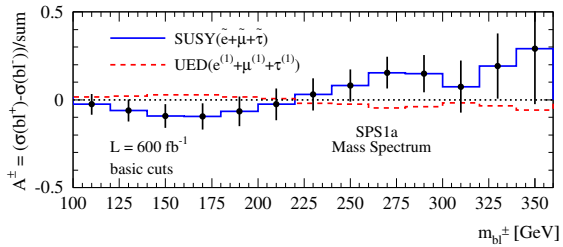
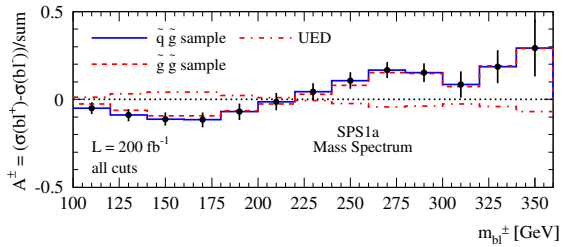
$$\mathcal{A}(m_{b\mu}) = \frac{\sigma(b\ell^+) - \sigma(b\ell^-)}{\sigma(b\ell^+) + \sigma(b\ell^-)}$$

- stable w.r.t production channels and cuts
- less cool: angle between b and $\bar{b}$ [3-body decays: Csaki,...]

$\Rightarrow$ SUSY = gluino = fermionic like-sign dileptons







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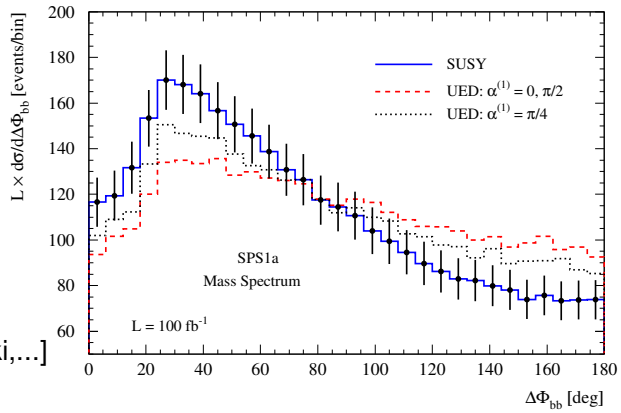

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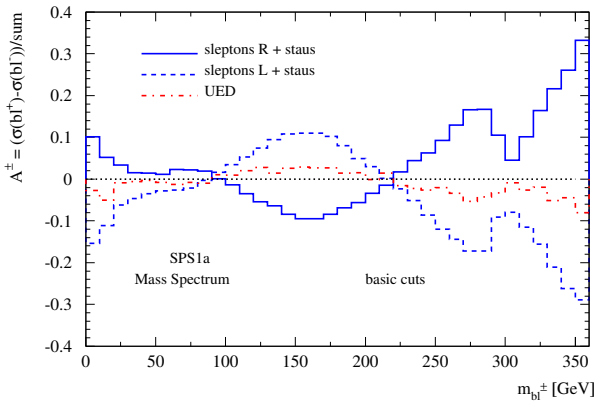
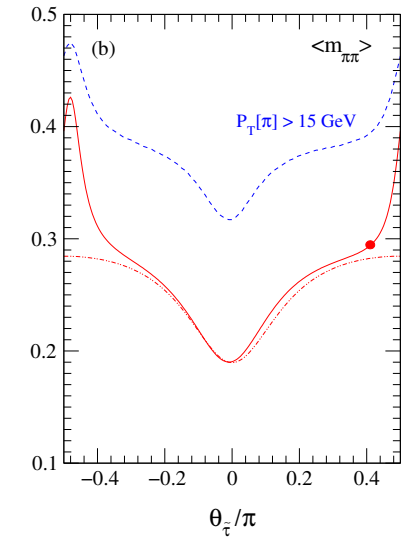


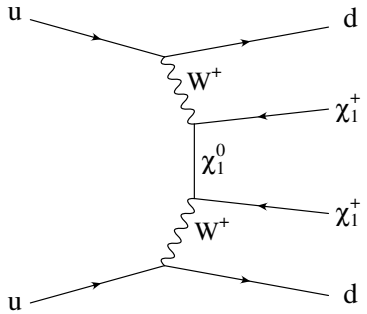
Problems with general analysis

- exchange $\tilde{\ell}_{LR}$ in cascade [Goto, Kawagoe, Nojiri]
- UED like strongly mixed sleptons
- test of lepton-wino couplings
- stau mixing [Choi, Hagiwara, Kim, Mawatari, Zerw

$\Rightarrow$ hypothesis tests...



Spins from jets

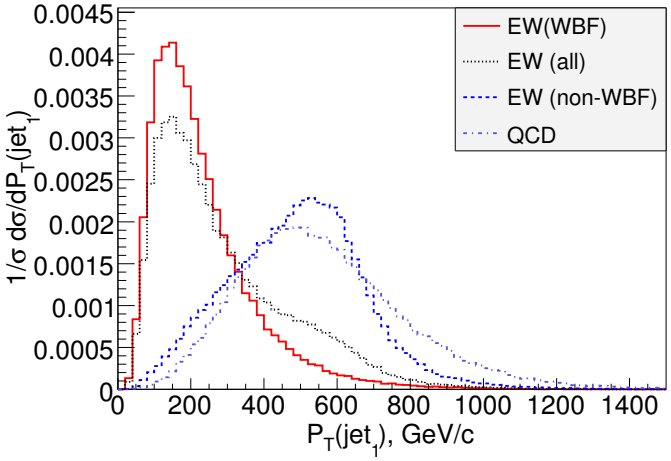


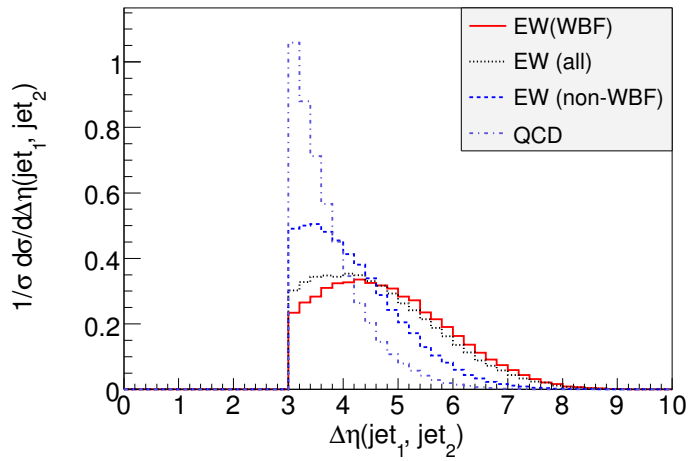
More hypothesis testing: spin of LSP [Alwall, TP, Rainwater]

- Majorana LSP with like-sign charginos?
- hypotheses: like–sign charginos (SUSY)
  like–sign scalars (scalar dark matter model)
  like–sign vector boson (like litte Higgs)
- stable for simplicity — chargino kinematics not used [SM backgrounds]
- WBF signal: two key distributions $\Delta\phi_{jj}, p_{T,j}$ [like $H \to ZZ \to 4\mu$ or WBF-Higgs]

$\Rightarrow$ distinct WBF signal? [$p_{T,j} \sim m_W$, forward jets]
visible over backgrounds? [SUSY–QCD backgrounds dominant]

$\Rightarrow$ long shot, but not swamped by SUSY-QCD





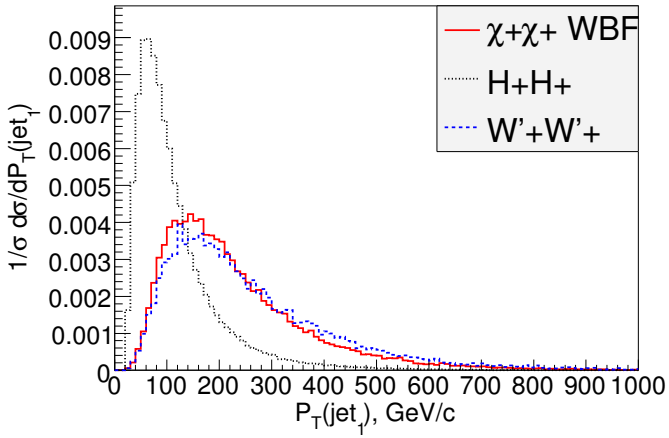
Spins from jets

Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
- H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld; Hankele, Klamke, Figy]
- W radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x,p_T) \sim \frac{1+(1-x)^2}{2x}\,\frac{1}{p_T^2} \qquad P_L(x,p_T) \sim \frac{(1-x)^2}{x}\,\frac{m_W^2}{p_T^4}$$

$\Rightarrow$ scalars identified by softer $p_{T,j}$



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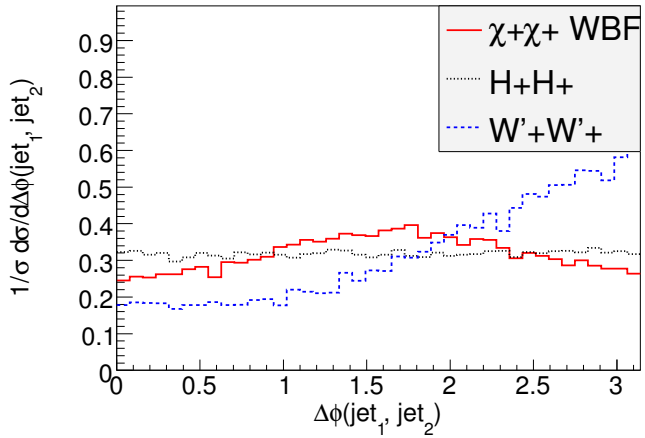
Like-sign vectors instead

- alternative hypothesis like little Higgs
- start with copy of SM, heavy W', Z', H', f' [H' necessary for unitarity, but irrelevant at LHC]
- Lorentz structure reflected in angle between jets

$\Rightarrow$ vectors identified by peaked $\Delta\phi_{jj}$



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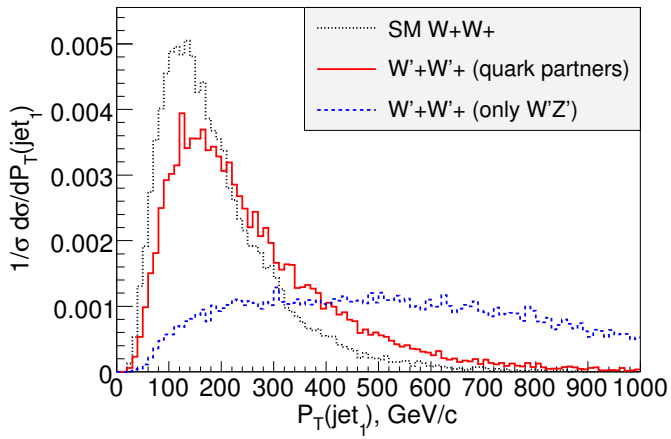
Heavy fermions in little–Higgs models

- not part of the naive set of WBF diagrams
- huge effect on $p_{T,j}$

$\Rightarrow$ well–defined hypothesis mandatory



Supersymmetry at the LHC

TeV–scale new physics

- know there is BSM physics
- trust solution of hierarchy problem
- explain dark matter

Theory/Phenomenology in the LHC era

(1) look for solid new–physics signals [missing energy?]

(2) measure weak–scale Lagrangian [highD parameter spaces?]

(3) determine fundamental physics
- test discrete new–physics properties
- construct sensible new–physics hypotheses
- avoid getting killed by QCD
- never talk about CMSSM analyses again

$\Rightarrow$ LHC more than a discovery machine!