

Understanding TeV–Scale Physics at the LHC

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Aachen, 1/2008

Outline

New physics at the LHC

TeV–scale supersymmetry

Masses from cascades

Underlying parameters

Spins from cascades

Spins from jets

Standard-Model effective theory

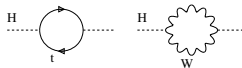
Remember the Standard Model

- gauge theory $SU(3) \times SU(2) \times U(1)$
 - massless $SU(3)$ and $U(1)$ gauge bosons
massive $SU(2)$ gauge bosons [spontaneous symmetry breaking]
 - massive Dirac fermions [via Yukawas]
 - perturbatively renormalizable Lagrangian [no effective theory]
 - one missing piece: Higgs [fundamental? minimal? mass?]
- ⇒ defined by particle content, interactions, renormalizability
- ⇒ **truly fundamental theory at high energies**

How complete experimentally?

- dark matter? [solid evidence! — for weak-scale new physics?]
 - $(g - 2)_\mu$? [possible 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]
 - gauge-coupling unification? [almost perfect, but proton stable]
 - gravity? [mostly negligible but perturbatively non-renormalizable]
- ⇒ **cut-off scale unavoidable: SM effective theory**

Standard-Model effective theory



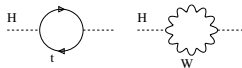
Consistency of fundamental theory

- problem of light Higgs: mass driven to cutoff of effective Standard Model

$$\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2$$
- cancelled by counter term, cosmological constant tuned anyway [a-word]
but problems not linked ['weakless universe': Harnik, Kribs, Perez]
- or new physics at TeV scale:
 - supersymmetry [my favorite]
 - extra dimensions [cool idea]
 - little Higgs [old idea, now working]
 - composite Higgs, no Higgs... [not pretty]

⇒ **fundamental Higgs without TeV-scale completion useless**

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- discrete symmetry for e-w precision constraints, proton decay
- stable lightest new particle: dark matter [weakly coupled, TeV range]

⇒ general: TeV-scale models in baroque state

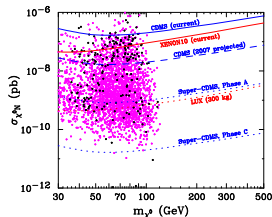
Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur's rule: 'there is always new physics at higher scales']

- find light Higgs?
- find new physics stabilizing Higgs mass?
- see dark-matter candidate?

Particle theory and new physics

- model-independent analyses likely not helpful
- testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
 - discrete hypotheses: spins,....
 - continuous hypotheses: masses,....
- link to other observations [DM+Tevatron: Hooper, TP, Valinotto]
- reconstruction of Lagrangian [theory+experiment]



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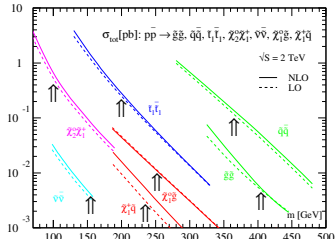
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Special about LHC [except bigger than Tevatron]

- beyond inclusive searches [that was Tevatron]
lots of strongly interacting particles
cascade decays to DM candidate
 - general theme: try to survive QCD
- ⇒ **aim at underlying theory**



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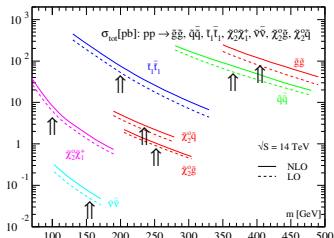
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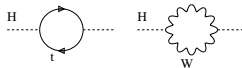
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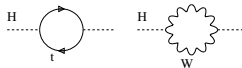
TeV-scale supersymmetry

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 — $\text{sign}(\mu), \tan \beta$
 - assume dark matter, stable lightest partner
- ⇒ **measure BSM spectrum with missing energy at LHC**



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LHC searches: MSSM

- conjugate Higgs field not allowed
 - give mass to t and b ?
 - five Higgs bosons
 - SUSY-Higgs alone interesting...
 - ...but not conclusive
 - ...and another talk
- ⇒ **list of SUSY partners**

		spin	d.o.f.	
fermion	\tilde{l}_L, \tilde{l}_R	1/2	1+1	
→ sfermion	\tilde{t}_L, \tilde{t}_R	0	1+1	
gluon	\tilde{G}_μ	1	n-2	
→ gluino	\tilde{g}	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^0, H^0, A^0	0	3	
→ neutralinos	$\tilde{\chi}_i^0$	1/2	4 · 2	LSP
gauge bosons	W^\pm	1	2 · 3	
Higgs bosons	H^\pm	0	2	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	2 · 4	

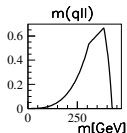
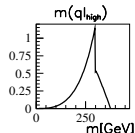
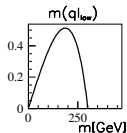
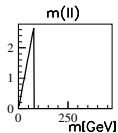
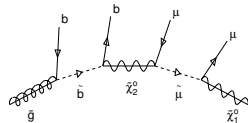
Masses from cascades

Cascade decays [Atlas-TDR, Cambridge, ask Alan]

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

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

⇒ **new-physics mass spectrum from cascade kinematics**



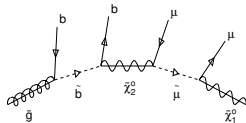
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⇒ new-physics mass spectrum from cascade kinematics



Glino decay [Gjelsten, Miller, Osland]

- all decay jets b quarks [otherwise dead by QCD]
- no problem: off-shell effects [Catpiss: Hagiwara et al.]
- no problem: jet radiation

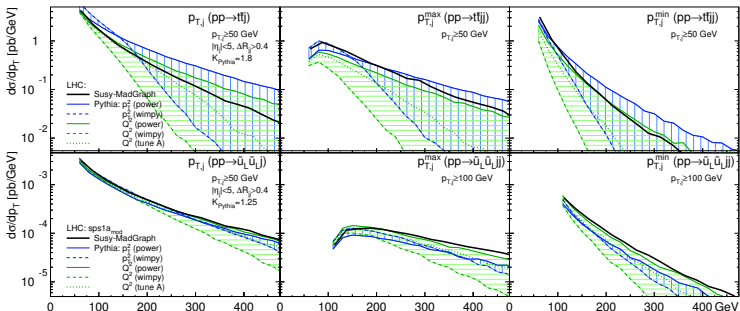
New physics and jets

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%

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

⇒ QCD not a problem in new-physics signals [but we will still merge...]



Underlying parameters

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

- parameters: weak-scale Lagrangian
- measurements: better edges than masses,
branching fractions, rates,... [NLO in Germany]
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

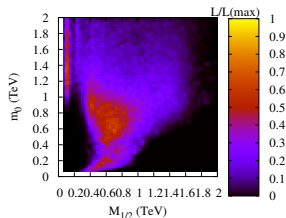
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MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

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



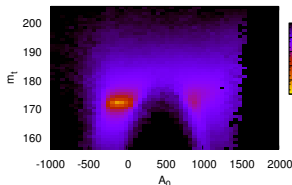
Underlying parameters

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
...						

⇒ correlations and secondary maxima significant

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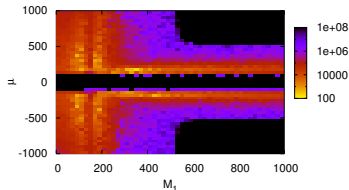
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MSSM map from LHC

- 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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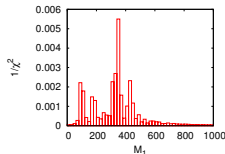
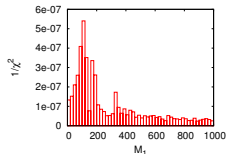
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- three neutralinos observed [left: Bayesian — right: likelihood]



⇒ no golden approach to BSM statistics

Underlying parameters

Why theorists involved?

- also want to get it right sometimes [and usually get statistics wrong]
- theory errors not negligible [rates for focus-point scenarios]
- LHC link with other TeV-scale observations model dependent
- test fundamental concepts

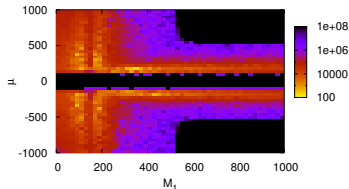
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MSSM parameters beyond LHC

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- $\tan \beta$ from $(g - 2)_\mu$

⇒ combination strongly correlated

	LHC		LHC $\otimes (g - 2)$		SPS1a
$\tan \beta$	10.0 ± 4.5		10.3 ± 2.0		10.0
M_1	102.1 ± 7.8		102.7 ± 5.9		103.1
M_2	193.3 ± 7.8		193.2 ± 5.8		192.9
M_3	577.2 ± 14.5		578.2 ± 12.1		577.9
$M_{\tilde{\mu}_L}$	193.2 ± 8.8		194.0 ± 6.8		194.4
$M_{\tilde{\mu}_R}$	135.0 ± 8.3		135.6 ± 6.3		135.8
$M_{\tilde{q}_3^L}$	481.4 ± 22.0		485.6 ± 22.4		480.8
$M_{\tilde{b}_R}$	501.7 ± 17.9		499.2 ± 19.3		502.9
$M_{\tilde{q}_L}$	524.6 ± 14.5		525.5 ± 10.6		526.6
$M_{\tilde{q}_R}$	507.3 ± 17.5		507.6 ± 15.8		508.1
A_τ	fixed 0		fixed 0		-249.4
A_t	-509.1 ± 86.7		-530.6 ± 116.6		-490.9
A_b	fixed 0		fixed 0		-763.4
m_A	$406.3 \pm \mathcal{O}(10^3)$		$411.1 \pm \mathcal{O}(10^2)$		394.9
μ	350.5 ± 14.5		352.5 ± 10.8		353.7

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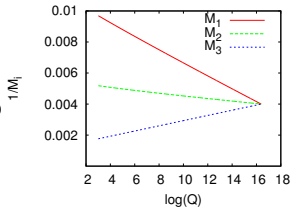
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Fundamental theory [SFitter + Kneur]

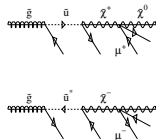
- SUSY breaking?
 - unification, GUT?
 - scale-invariant sum rules? [Cohen, Schmalz]
 - new & crucial: renormalization group bottom-up
- ⇒ solidly inference from weak scale



Spins from cascades

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

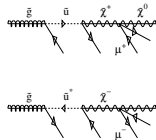
- LHC: first jet (q or \bar{q}) fixes lepton charge
 - same-sign dileptons in 1/2 of events
 - similar: t -channel gluino in $pp \rightarrow \tilde{q}\tilde{q}$
- \Rightarrow **gluino = like-sign dileptons in SUSY sample**



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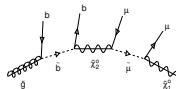
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Loop hole: gluino is Majorana if fermion

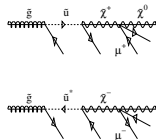
- all new physics is hypothesis testing [Barr, Lester, Smillie, Webber]
- start with mass-measurement cascade [Gjelsten, Miller, Osland]
- physics between the endpoints
- model-independent analysis unlikely [Smillie]



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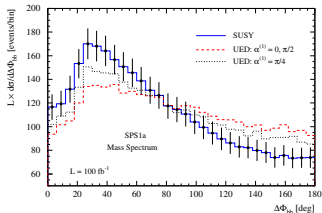


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- 'gluino' a boson: universal extra dimensions [spectra degenerate, cross sections, higher KK states — ignore]
- compare SUSY with excited KK g, b, Z, ℓ, γ
- simple distributions [3-body decays: Csaki,...]
- threshold behavior? [under study]

⇒ **gluino = fermion with like-sign dileptons**



Spins from cascades

Elegant LHC universe [Alves, Eboli, TP; like Cambridge squarks]

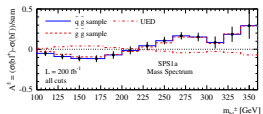
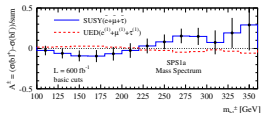
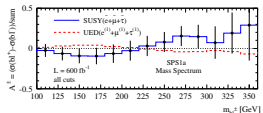
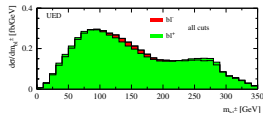
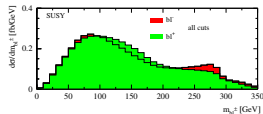
- remember: spins mean angular correlations
- 'invariant angles': $m_{j\ell}/m_{j\ell}^{\max} = \sin \theta/2$
- squark: production asymmetry $pp \rightarrow \tilde{q}/\tilde{q}^* + \tilde{g}$

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

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

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

- stable w.r.t production channels and cuts



Spins from cascades

Elegant LHC universe [Alves, Eboli, TP; like Cambridge squarks]

- remember: spins mean angular correlations
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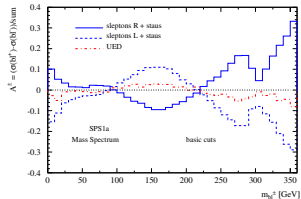
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- stable w.r.t production channels and cuts
- unstable w.r.t model details
- positive: use information [Hagiwara, Kim, Mawatari, Zerwas]

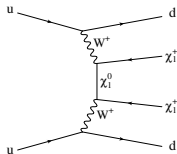
⇒ LHC only as good as understood hypotheses



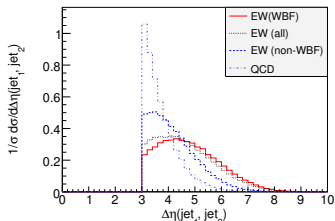
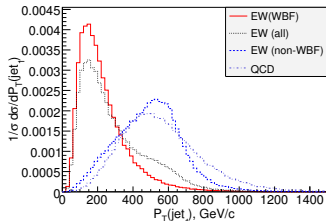
Spins from jets

Illustrating testable hypotheses: spin of LSP [Alwall, TP, Rainwater]

- Majorana LSP with like-sign charginos?
 - hypotheses: like-sign charginos (SUSY)
like-sign scalars (scalar dark matter)
like-sign vector bosons (little-Higgs inspired)
 - chargino decay/kinematics not used
- ⇒ WBF : two key distributions $\Delta\phi_{jj}, p_{T,j}$ [like $H \rightarrow ZZ \rightarrow 4\mu$ or WBF-Higgs]



- distinct WBF signal? [ask Karl; $p_{T,j} \sim m_W$, forward jets]
- visible over backgrounds? [SUSY-QCD backgrounds dominant]
- toy model, but not swamped by SUSY-QCD



Weak boson fusion and unitarity

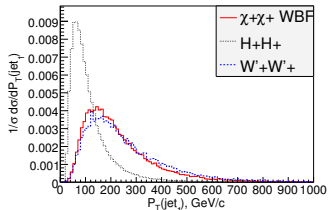
Like-sign scalars instead of fermions

- charged Higgs in 2HDM
- H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld; Buszello, Marquard, v.d.Bij]
- W radiated off quarks [Goldstone coupling to Higgs]

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

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

⇒ scalars with softer $p_{T,j}$



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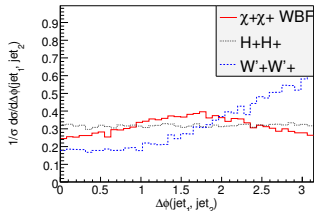
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Like-sign vectors instead of fermions

- little-Higgs inspired
- 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

⇒ vectors with peaked $\Delta\phi_{jj}$



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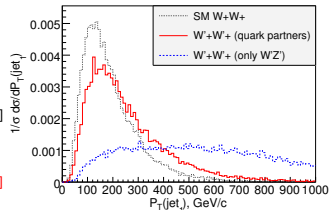
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Heavy fermions in little-Higgs models

- part of unitary UV completion [Englert, Zeppenfeld]
- huge effects on distributions [at low scales]

⇒ look-alike of strongly interacting Ws [Reuter,...]



New physics at the LHC

TeV-scale new physics at LHC

- know there is BSM physics [dark matter,...]
- solve hierarchy problem
- explain dark matter



Understanding the TeV scale

- (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
 - supersymmetry just one worked-out example
- ⇒ **LHC more than a discovery machine!**

Understanding
TeV-Scale Physics
at the LHC

Tilman Plehn

New Physics

Supersymmetry

Masses

Parameters

Spins & cascades

Spin & jets