Understanding the TeV Scale at LHC

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Outline

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 1/M terms]
- one missing piece: Higgs [fundamental? minimal? mass?]

$\Rightarrow$ truly fundamental theory

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]

$\Rightarrow$ cut-off scale unavoidable: SM effective theory

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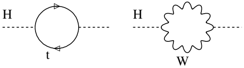

Consistency of fundamental theory

– problem of light Higgs: mass driven to cutoff of effective Standard Model
  $\delta m_H^2 \propto g^2 (2 m_W^2 + m_Z^2 + m_H^2 - 4 m_t^2)\, \Lambda^2$
– cancelled by finely tuned counter term? [ugly, unpopular]
– why fundamental Higgs with poor high-energy behavior??
– better new physics at TeV scale: supersymmetry [my favorite]
  extra dimensions [cool idea]
  little Higgs [old idea, now working]
  composite Higgs, no Higgs... [not pretty]

$\Rightarrow$ TeV-scale: beautiful ideas — complicated realistic models

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

– testable TeV-scale models [e.g. Higgs sector vs. underlying theory?]

continuous data-driven hypotheses: masses,...
discrete data-driven hypotheses: spins,....

– link to other observations [DM+Tevatron: Hooper, TP, Valinotto (2008)]

– reconstruction of Lagrangian

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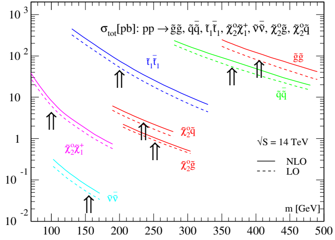
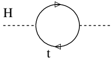
Special about LHC [NLO rates from Prospino2 (2006)]

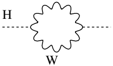
– beyond inclusive searches [that was Tevatron]
millions of new strongly interacting particles

⇒ (1) aim at underlying theory
(2) try to survive QCD



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]

– assume dark matter, stable lightest partner

⇒ measure BSM spectrum with missing energy at LHC

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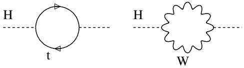

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LHC searches: MSSM

– conjugate Higgs field not allowed
$\longrightarrow$ give mass to t and b?
$\longrightarrow$ five Higgs bosons

– SUSY–Higgs alone interesting...

...but not conclusive

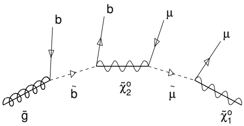
...and another talk

...and covered by Georg

$\Rightarrow$ 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^o, H^o, A^o	0	3	
$\longrightarrow$ neutralinos	$\tilde{\chi}_i^o$	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

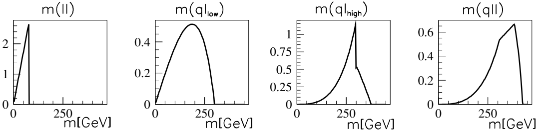
– like Tevatron: jets + missing energy

– easiest: cascade kinematics [$10^7 \cdots 10^8$ events, rates tought because of QCD]

– 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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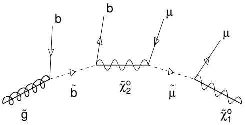

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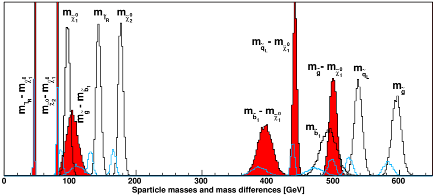
$$0 < m^2_{\mu\mu} < \frac{m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\ell}}}{m_{\tilde{\ell}}} \; \frac{m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}^0_1}}{m_{\tilde{\ell}}}$$

⇒ new–physics mass spectrum from cascade kinematics

Gluino decay [Gjelsten, Miller, Osland]

- no problem: additional jets [Rainwater, TP, Skands (2004); Michael Krämer,...]
- no problem: off-shell effects [Catpiss: Hagiwara et al.(2006)]
- all decay jets b quarks [otherwise dead by QCD]
- gluino mass to $\sim 1\%$

⇒ and why physical masses?



Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas (2007)]

– parameters: weak-scale Lagrangian

– measurements: better edges than masses,
branching fractions, rates,... [Prospino2]
flavor, dark matter, electroweak constraints,...

– errors: general correlation, statistics & systematics & theory [flat theory errors!]

– problem in grid: no local maximum!
problem in fit: no global maximum!
problem in physics: secondary maxima!

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

– fully exclusive likelihood map $p(d|m)$ over m [hard part]

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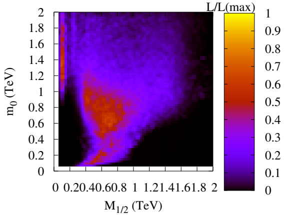
MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

– ‘Which is the most likely parameter point?’

– ‘How does dark matter annihilate/couple?’



Underlying parameters

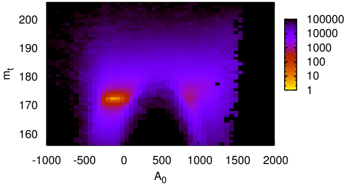
Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

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

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

– SFitter output #1: fully exclusive likelihood map
SFitter output #2: ranked list of local maxima

⇒ strong correlations even in MSUGRA



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
...						

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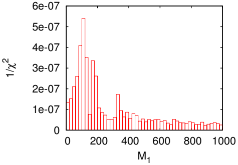
MSSM map from LHC

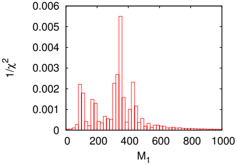
– shifting from 6D to 19D parameter space [killing grids, Minuit, laptop–style fits...]

– SFitter outputs still the same, but best points degenerate

– e.g. three neutralinos observed [left: Bayesian — right: likelihood]

Bayesian pdf noisy
profile likelihood no pdf





⇒ no golden approach to BSM statistics

Underlying parameters

Why theorists involved?

- way to learn statistics
- non–negligible theory errors
- model–dependent LHC link with other TeV–scale observations
- test of fundamental concepts

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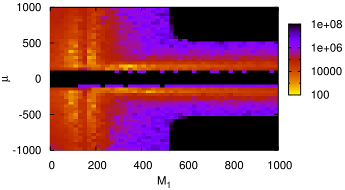
MSSM parameters beyond LHC [Sfitter+friends (2008)]

– remember: unknown sign(μ) and believe–based tan β extraction



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- tan β and sign(μ) from $(g-2)_\mu$
- effect of $(g-2)$ strongly correlated

	LHC	LHC $\otimes (g-2)$	SPS1a
tan β	**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
$M_{\tilde{q}_L}$	524.6±14.5	525.5± 10.6	526.6
$M_{\tilde{q}_R}$	507.3±17.5	507.6± 15.8	508.1
μ	350.5±14.5	352.5± 10.8	353.7
	etc		

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Fundamental theory [SFitter + Kneur]

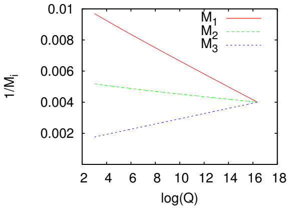
– SUSY breaking?

– unification, GUT?

– scale-invariant sum rules? [Cohen, Schmalz]

– new & crucial: renormalization group bottom–up

$\Rightarrow$ solidly inference from weak scale

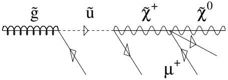


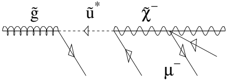
Spins from cascades

Remember gluinos: 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 $pp \to \tilde{q}\tilde{q}$

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





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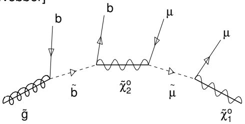
Loop hole: gluino is Majorana if fermion [Alves, Eboli, TP (2006)]

– start with mass–measurement cascade

– now: physics between the endpoints

– model–independent analysis pointless [Barr, Lester, Smillie, Webber]



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– ‘gluino’ a boson: universal extraD

[spectrum, cross sections, higher KK states — ignore]

– compare SUSY vs. KK g, b, Z, ℓ, γ

– simple distributions $\Delta\phi_{bb}$ [3-body decays: Csaki,...]

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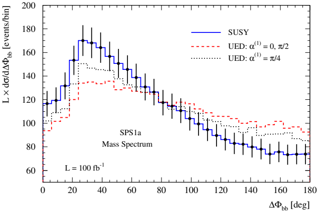

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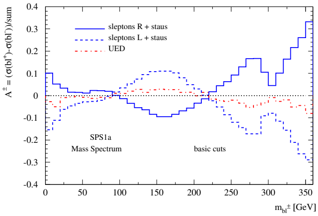
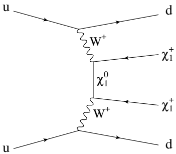
- sensitive to model's details

$\Rightarrow$ LHC only as good as understood hypotheses



Spins from jets



Illustrating hypotheses tests: spin of LSP [Alwall, TP, Rainwater(2007)]

– Majorana LSP with like-sign charginos?

– hypotheses: like–sign charginos (SUSY)
like–sign scalars (stable scalars)
like–sign vector bosons (little–Higgs inspired)

– chargino decay/kinematics not used!

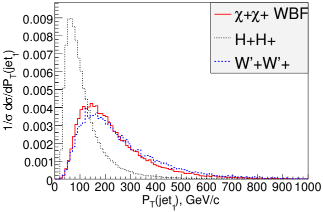
Weak boson fusion and unitarity

Like-sign scalars instead of fermions

- charged Higgs in 2HDM
- H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld (2001); Buszello, Marquard, v.d.Bij]
- W radiated off quarks [Goldstone coupling to Higgs]

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

$\Rightarrow$ scalars with softer $p_{T,j}$



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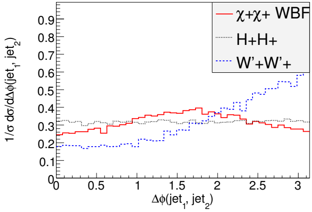
Like-sign vectors instead of fermions

- 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

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



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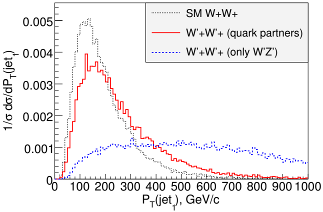
Heavy fermions in little–Higgs models

– part of unitary UV completion [Englert, Zeppenfeld]

– huge effects on distributions [strongly interacting Ws

⇒ LHC needs testable models



New physics at the LHC

Physics in the LHC era

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LHC physics is fun physics!

– look for solid new–physics signals
– measure weak–scale Lagrangian
– determine fundamental physics

– construct testable new–physics hypotheses [SUSY just one example]
e.g. four generations [Kribs, TP, Spannowsky, Tait (2007)]
e.g. large extra dimensions [TP, Litim (2007)]
e.g. stable gluinos [Kilian, TP, Richardson, Schmidt (2005)]
– implement into realistic simulations [Madevent (2007)]
– avoid getting killed by QCD

$\Rightarrow$ LHC more than a discovery machine!