TeV–Scale Physics in the LHC Era

Tilman Plehn

University of Edinburgh

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Outline

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]

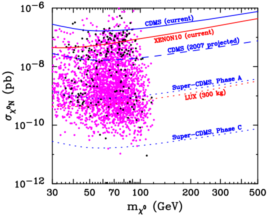
Particle theory and new physics [recently labelled 'inverse problem']

– 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, $(g-2)_\mu$... [Hooper, TP, Valinotto; Altunkaynak et al]

$\Rightarrow$ reconstruct TeV–scale Lagrangian



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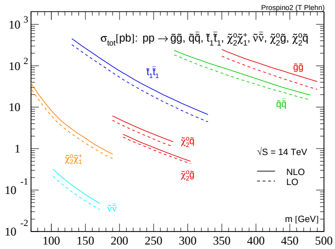
LHC means winning by luminosity

– 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

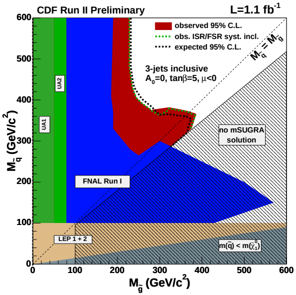
– new particles strongly interacting
  dark–matter weakly interacting
  signature: jets + missing energy + X

– SUSY: colored $\tilde{g} \rightarrow$ 2 jets while $\tilde{q} \rightarrow$ 1 jet

– ADD: graviton means missing energy with jets

– QCD: plenty additional jets
  not suppressed by α_s/π [collinear logs]
  even possible new–physics trigger

$\Rightarrow$ need to understand jets in signals



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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
$p_T > 100$ GeV	[TP, Rainwater, Skands]		

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⇒ need to understand jets in signals

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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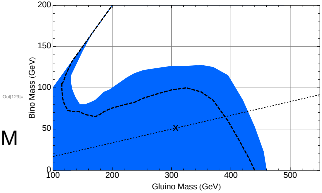
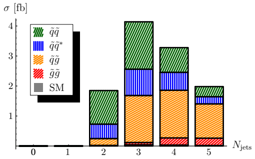


[Alwall, Le, Lisanti, Wacker]

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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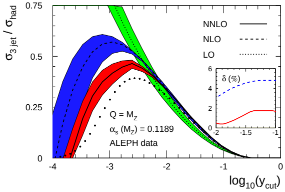
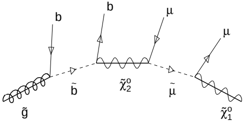
Jets and loops

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



⇒ jets in backgrounds tough, boring, but impressive progress

Masses from cascades

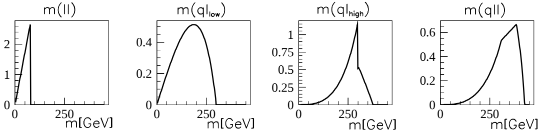


Cascade decays [Atlas-TDR, Cambridge]

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

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

⇒ new–physics mass spectrum from cascade kinematics



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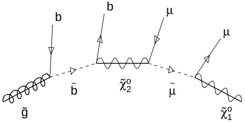

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⇒ new–physics mass spectrum from cascade kinematics

Waiting to be tested in LHC environment

– edge for $\tilde{\chi}_2^0\tilde{\chi}_2^0$: $M_{T,2}(\chi_{\mathrm{LSP}}) = \min_{\alpha p_T} \max_j m_{T,j}(\chi_{\mathrm{LSP}}, \alpha) < m_{\chi_2}$ [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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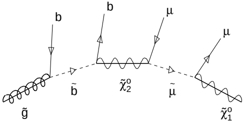

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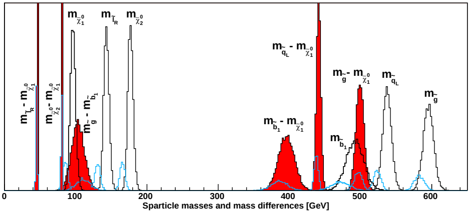
⇒ new–physics mass spectrum from cascade kinematics

Gluino decay [Gjelsten, Miller, Osland]

– all decay jets *b* quarks [otherwise dead by QCD]

– gluino mass to $\sim$ 1%

⇒ but why physical masses?



Missing energy

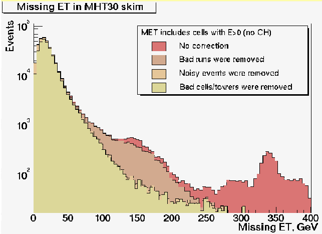
Detector effects and missing energy

– 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: $0.5\sqrt{\Sigma E_T} \gtrsim 20$ GeV
  global corrections to individual events [calibration of energy scales, dead matter]

$\Rightarrow$ missing energy in early data??? [Baer, Prosper, Summy]



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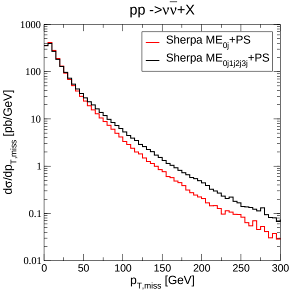
Simulation of missing energy

– physics background $W/Z+$ jets

– gauge boson recoiling against jets

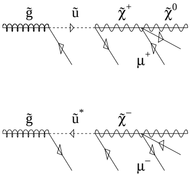
– sensitive to jet simulation
p_T range between collinear and hard jets
parton shower vs. merging [Schumann (Sherpa)]

$\Rightarrow$ missing energy really means QCD



Spins from between endpoints

Gluinos: 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 $pp \to \tilde{q}\tilde{q}$

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

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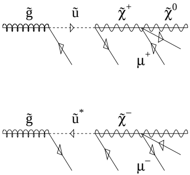

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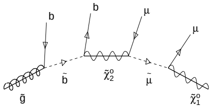
Loop hole: gluino is Majorana if fermion

– use mass–measurement cascade [Gjelsten, Miller, Osland]
now look for physics between the endpoints

– new physics is hypothesis testing [Barr, Lester, Smillie, Webber]



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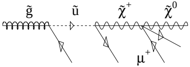

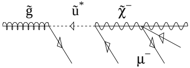

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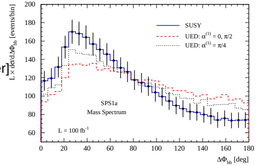
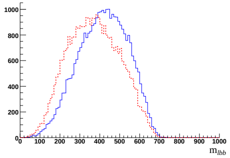
- use mass–measurement cascade [Gjelsten, Miller, Osland]
  now look for physics between the endpoints
- new physics is hypothesis testing [Barr, Lester, Smillie, Webber]
- ‘gluino’ a boson: universal extra dimensions
  compare SUSY with KK g, b, Z, ℓ, γ [Alves, Eboli, TP]

$\Rightarrow$ 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



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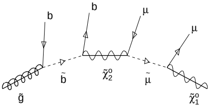


Asymmetries [Cambridge group; Alves, Eboli, TP]

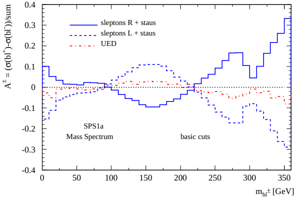
– remember: spins mean angular correlations
  'invariant angles': $m_{j\ell}/m_{j\ell}^{\max} = \sin\theta/2$

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

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

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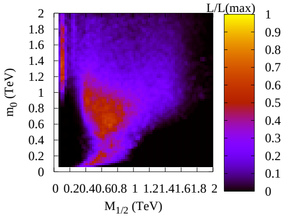
MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

– 'Which is the most likely parameter point?'

– 'How does dark matter annihilate/couple?'



Underlying parameters

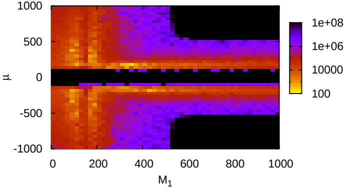
MSSM map from LHC [SPS1a]

– 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 sign(μ), believe–based tan β from m_h

[profile likelihood]



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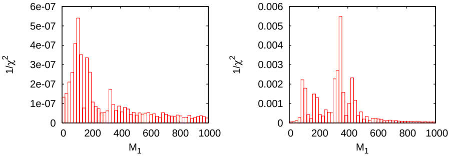
[left: Bayesian — right: likelihood]



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MSSM map beyond LHC

– LHC rates: tan β from heavy Higgs tough [Kinnunen, Lehti, Moortgat, Nikitenko, Spira]

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

– strongly correlated and promising

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

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(2) use BR($B_s \to \mu\mu$) with stop–chargino sector [Hisano, Kawagoe, Nojiri]

– error on f_{B_s} means ratios? [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]

	no theory error			$\Delta\mathrm{BR}/\mathrm{BR} = 15\%$	
	true	best	error	best	error
tan β	**30**	**29.5**	**3.4**	**29.5**	**6.5**
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
μ	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]

– 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 sign(μ), believe–based $\tan\beta$ from m_h

$\Rightarrow$ no golden approach to BSM statistics

MSSM map beyond LHC

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

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

– strongly correlated and promising

(2) use $\text{BR}(B_s \to \mu\mu)$ with stop–chargino sector [Hisano, Kawagoe, Nojiri]

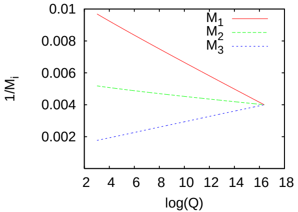
– error on f_{B_s} means ratios? [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]

Renormalization group bottom–up [SFitter + Kneur]

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

– UV completion, unification, GUT?

$\Rightarrow$ means I can retire happily



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 ony talking about SUSY

$\Rightarrow$ LHC more than a discovery machine!