Understanding the TeV Scale at the LHC

Tilman Plehn

University of Edinburgh

University of Liverpool, 10/2008

Outline

New physics at the LHC

TeV–scale supersymmetry

Masses from cascades

Underlying parameters

Spins from cascades

Spins from jets

Standard–Model effective theory

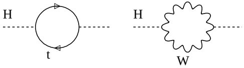
Remember the Standard Model

– 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
$\delta m_H^2 \propto g^2/m_W^2\ (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\ \Lambda^2$

– cancelled by counter term, cosmological constant tuned anyway
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... [tough]

$\Rightarrow$ fundamental Higgs without TeV–scale completion useless

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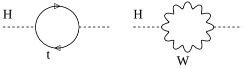

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⇒ fundamental Higgs without TeV–scale completion useless

– many new states around the TeV scale [subject to experimental constraints]

– discrete symmetry for e-w precision constraints, proton decay

– stable lightest new particle: dark matter [weakly coupled, below TeV range]

– additional symmetries for flavor constraints

⇒ 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?

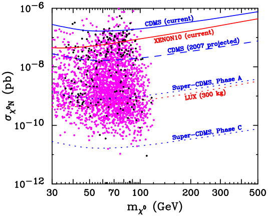
Particle theory and new physics

– 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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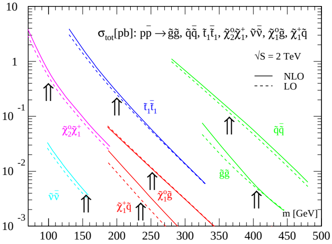
Special about LHC [except bigger than Tevatron]

– 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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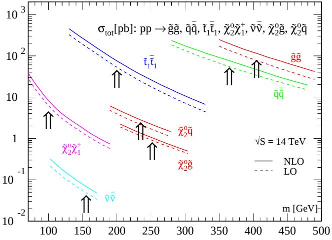
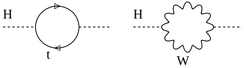


TeV–scale supersymmetry



Supersymmetry

– give each Standard–Model particle a partner [different spin, valid to all orders]

– 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), $\tan\beta$

– assume dark matter, stable lightest partner

⇒ measure BSM spectrum with missing energy at LHC

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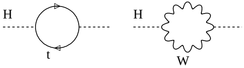

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LHC searches: MSSM

– conjugate Higgs field not allowed
→ give mass to t and b?
→ five Higgs bosons

– SUSY–Higgs alone interesting...

...(1) new heavy Higgs states

...(2) really type-II 2HDM

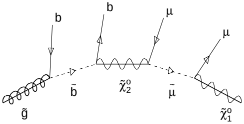
...(3) light state MSSM vs SM

...but another talk

⇒ list of SUSY partners

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
→ sfermion	$\tilde{f}_L, \tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^o, H^o, A^o	0	3	
→ 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	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	

Masses from cascades

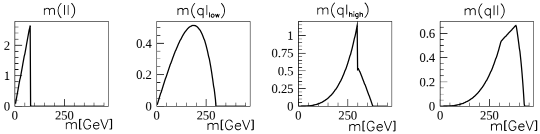


Cascade decays [Atlas-TDR, Cambridge]

- 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 [$10^7 \cdots 10^8$ 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

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

⇒ new–physics mass spectrum from cascade kinematics



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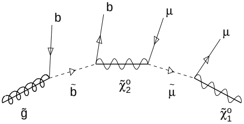

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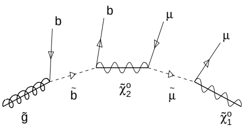

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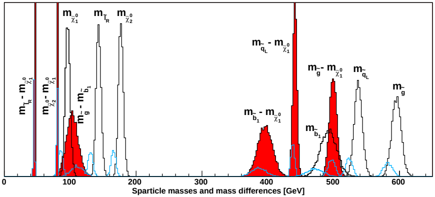
- gluino mass to $\sim 1\%$

⇒ but why physical masses?



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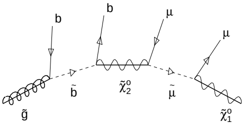

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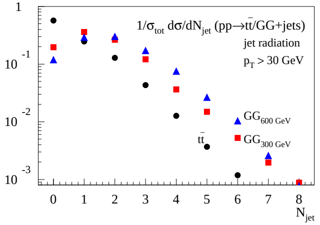
Likely bad ideas

– decay jets vs QCD radiation
– collinear initial state radiation [$p_{T,j} < M_{\text{hard}}$]
– proper description: CKKW/MLM [in MadEvent]
– $\langle N_{\text{jet}} \rangle$ dependent on hard scale
– study: scalar gluons [TP & Tait]

⇒ QCD basics always useful at LHC



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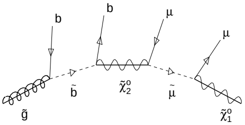

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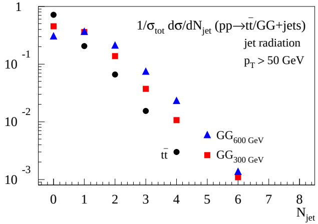

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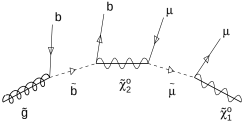

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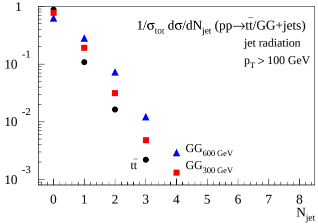

Underlying parameters

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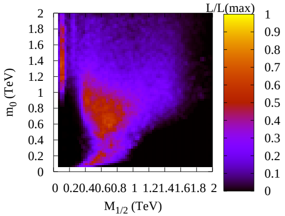
MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

– ‘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]

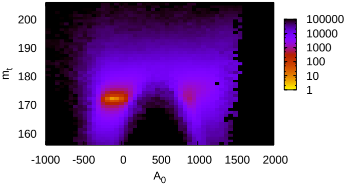
– weighted Markov chains: several times faster [similar to: Ferrenberg & Swendsen]

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

– 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]

⇒ correlations and secondary maxima significant



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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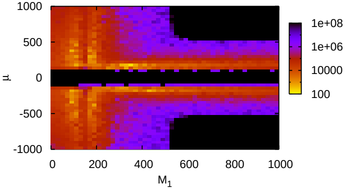
MSSM map from LHC

– let's do physics instead of religion [unless God told you how she breaks SUSY]

– 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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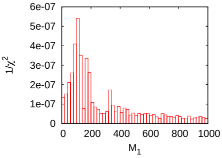
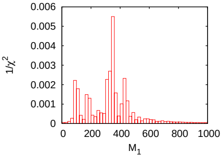
⇒ no golden approach to statistics





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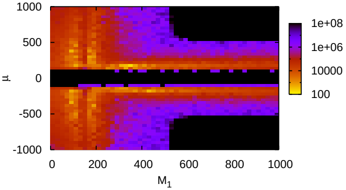
MSSM parameters beyond LHC

- remember: unknown sign(μ), believe–based tan β from m_h
- LHC rates: tan β from heavy Higgs tough [Kinnunen, Lehti, Moortgat, Nikitenko, Spira]



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

– strongly correlated and promising

	LHC		LHC $\otimes(g-2)$		SPS1a
$\tan\beta$	**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

Underlying parameters

Why theorists involved?

– want to learn statistics [usually get that badly wrong]
– theory errors not negligible [rates for focus–point scenarios]
– LHC link with other TeV–scale observations model dependent

MSSM parameters beyond LHC

– remember: unknown sign(μ), believe–based tan β from m_h
– LHC rates: tan β from heavy Higgs tough [Kinnunen, Lehti, Moortgat, Nikitenko, Spira]
(1) use current precision on $(g-2)_\mu \sim \tan\beta$ [ask Thomas, SFitter + Alexander, Kreiss]
– strongly correlated and promising
(2) use BR($B_s \to \mu\mu$) with stop–chargino sector [Hisano, Kawagoe, Nojiri]
– 7% error on f_{B_s} by 2015 crucial [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]
– perturbative effects secondary

	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

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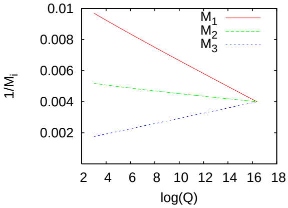
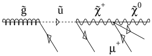
Renormalization group bottom–up [SFitter + Kneur]

– SUSY breaking, unification, GUT?
– scale-invariant sum rules? [Cohen, Schmalz]
⇒ solidly inference from weak scale

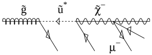


Spins from cascades

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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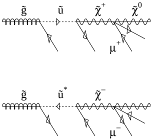

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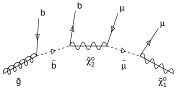
Loop hole: gluino is Majorana if fermion

- 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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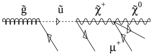

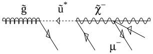

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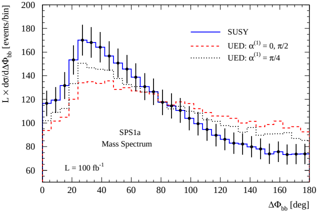
- ‘gluino’ a boson: universal extra dimensions

  [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]

$\Rightarrow$ gluino = fermion with like-sign dileptons



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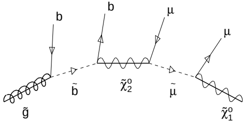

Elegant LHC universe [Alves, Eboli, TP; like Cambridge squarks]

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

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

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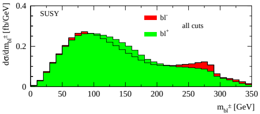
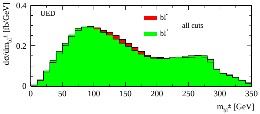
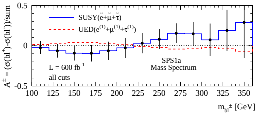
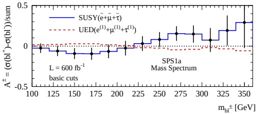
– b vs. $\bar{b}$: example for advanced LHC requirement

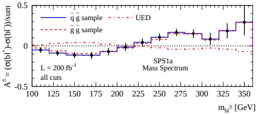
– stable w.r.t production channels and cuts











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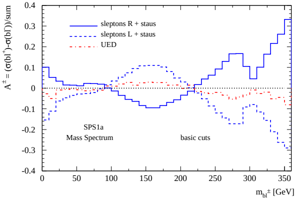


– b vs. $\bar{b}$: example for advanced LHC requirement

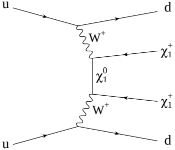
– stable w.r.t production channels and cuts

– unstable w.r.t model details

– all messy once neutralinos and charginos involved
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?

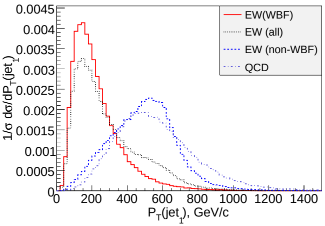
– hypotheses: like–sign charginos (SUSY)
like–sign scalars (scalar dark matter)
like–sign vector bosons (little–Higgs inspired)

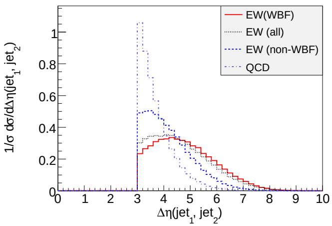
– chargino decay/kinematics not used

$\Rightarrow$ WBF : two key distributions $\Delta\phi_{jj}, p_{T,j}$ [like $H \to ZZ \to 4\mu$ or WBF-Higgs]

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

– toy model, but not swamped by SUSY-QCD





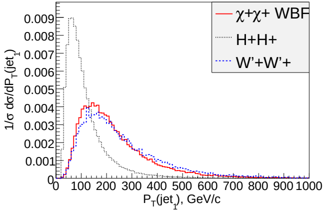
Weak boson fusion and unitarity

Like-sign scalars or fermions?

- charged Higgs in 2HDM
- $H^+ H^-$ same as simple 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 with softer $p_{T,j}$



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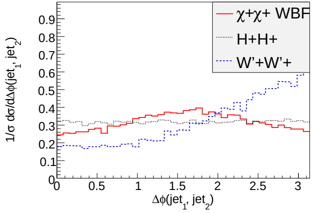
- little–Higgs inspired
- start with copy of SM, heavy W', Z', H', f' [H' necessary for unitarity, but irrelevant at LHC]
- Lorentz structure reflected in angle between jets

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



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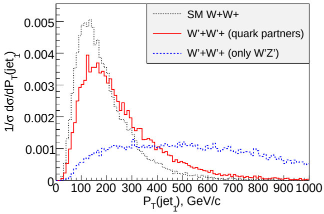
Heavy fermions in little–Higgs models

– part of unitary UV completion [Englert, Zeppenfeld]

– huge effects on distributions [at low scales]

$\Rightarrow$ more like strongly interacting Ws



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

$\Rightarrow$ LHC more than a discovery machine!