UV–Completing the Standard Model at the LHC

Tilman Plehn

University of Edinburgh

University of Glasgow, 2/2008

Outline

TeV scale in the LHC era

Masses from cascades

Underlying parameters

Spins from cascades

Spins from jets

UV–complete extra dimensions

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, review by Dominik]

– 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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TeV scale

Masses

Parameters

Spins & cascades

Spin & jets

Extra dimensions

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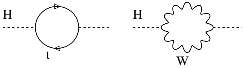

How consistent theorically?

– 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, against spirit of symmetries]

– why fundamental Higgs at all, if such poor high-energy behavior?

– tied in with new physics at TeV scale: supersymmetry [my favorite]
extra dimensions [cool idea]
little Higgs [old idea, now working]
no fundamental Higgs... [not pretty]

⇒ TeV scale: beautiful ideas — complicated realistic models

Effective Standard Model in the LHC era

UV completions 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 not helpful to understand TeV scale
- 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]
- reconstruction of Lagrangian

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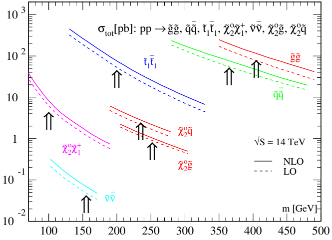
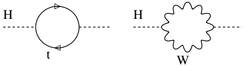
Special about LHC

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

$\Rightarrow$ (1) aim at underlying theory
(2) try to survive QCD [ask John]



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

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

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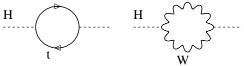

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LHC searches: MSSM

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

– SUSY–Higgs alone interesting...

...but not conclusive

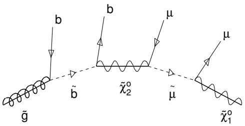
...and another talk

...invite Georg Weiglein

$\Rightarrow$ 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

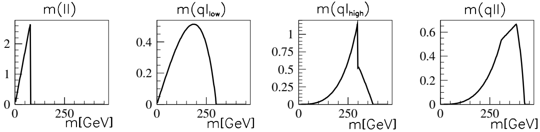
– like Tevatron: jets + missing energy

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

– thresholds & edges [RAL school exercise]

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

⇒ new–physics mass spectrum from cascade kinematics [Gjelsten, Miller, Osland, Raklev]



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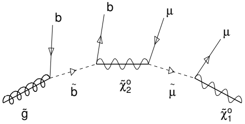

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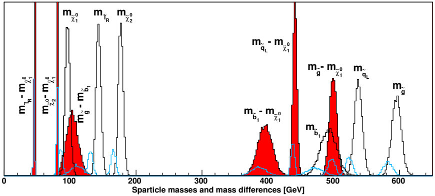
$\Rightarrow$ new–physics mass spectrum from cascade kinematics [Gjelsten, Miller, Osland, Raklev]

Gluino decay [Gjelsten, Miller, Osland, Raklev]

- no problem: additional jets [Rainwater, TP, Skands; Alwall, Wacker,...]
- no problem: off-shell effects [Catpiss collaboration; Kauer & Rainwater]
- all decay jets *b* quarks [otherwise dead by QCD]
- gluino mass to $\sim 1\%$

$\Rightarrow$ but why physical masses?



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,... [Prospino2]
B decays, $(g-2)_\mu$, dark matter, e-w precision data...

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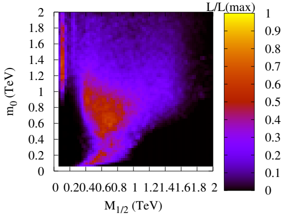
MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

– 'Which is the most likely parameter point?'

– 'How does dark matter annihilate/couple?'



Underlying parameters

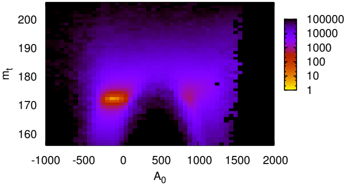
Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

– 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

$\Rightarrow$ 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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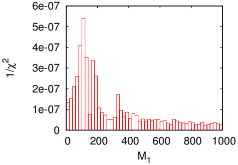
MSSM map from LHC

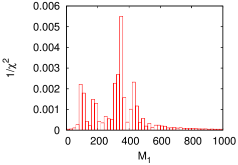
– shifting from 6D to 19D parameter space [killing grids, Minuit, laptop–style fits...]

– 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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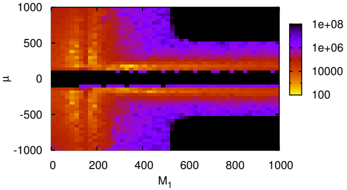
MSSM parameters beyond LHC [Sfitter+friends]

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



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- remember: unknown sign(μ) and believe–based tan β extraction
- tan β and sign(μ) from $(g-2)_\mu$ or $B_s \to \mu\mu$ [Les Houches 2007: Alexander et al]
- including $(g-2)$ very promising

	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]

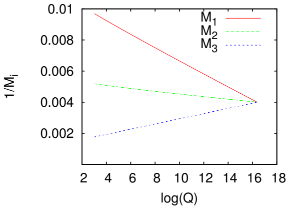
– SUSY breaking?

– unification, GUT?

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

– new & crucial: renormalization group bottom–up

$\Rightarrow$ LHC sensitive to UV models



Spins from cascades

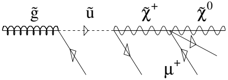
Remember gluinos: strongly interacting Majorana fermions [Barger,...; Barnett,...; Baer,...]

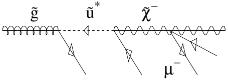
– LHC: first jet (q or $\bar{q}$) fixes lepton charge

– same–sign dileptons in 1/2 of events

– similar: t-channel gluino in $pp \to \tilde{q}\tilde{q}$

⇒ gluino = like–sign dileptons in SUSY sample





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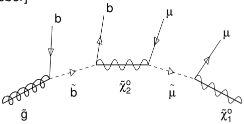
Loop hole: gluino is Majorana if fermion [Alves, Eboli, TP]

– start with mass–measurement cascade
– now: physics between the endpoints
– model–independent analysis difficult [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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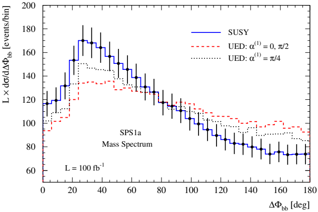

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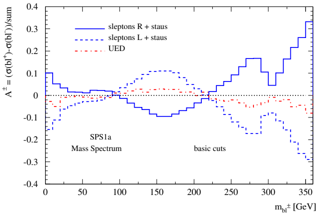
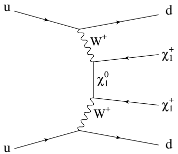
– sensitive to model's details

$\Rightarrow$ LHC requiring testable TeV-scale models



Spins from jets



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

– 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!

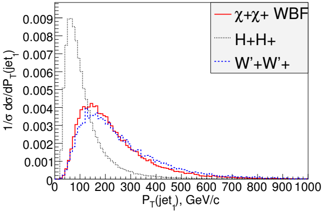
Weak boson fusion and unitarity

Like-sign scalars instead of fermions

- charged Higgs in 2HDM
- H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld; 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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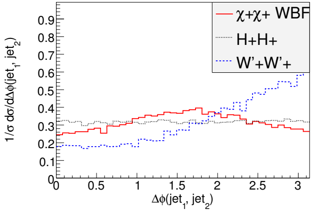
Like-sign vectors instead of fermions

– 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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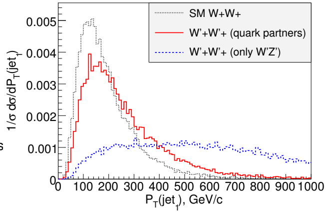
Heavy fermions in little–Higgs models

– part of unitary UV completion [Englert, Zeppenfeld]
– huge effects on distributions [strongly interacting Ws

$\Rightarrow$ LHC requiring testable TeV-scale models



UV–complete extra dimensions

Elegant solution to hierarchy problem [Arkani-Hamed, Dimopoulos, Dvali]

– highest scale: Planck scale $G_N \sim 1/M^2_\text{Planck}$ [$M_\text{Planck} \sim 10^{19}$ GeV]

– Einstein–Hilbert action in $4+n$ dimensions [on torus — periodic boundaries]

$$\int d^4x \sqrt{|g|}\, M^2_\text{Planck} R \to \int d^{4+n}x \sqrt{|g|}\, M_D^{2+n} R = (2\pi r)^n \int d^4x \sqrt{|g|}\, M_D^{2+n} R$$

$$M_\text{Planck} = M_D \; (2\pi r M_D)^{n/2} \gg M_D \sim 1 \text{ TeV}$$

– to get numbers right: $r = 10^{12}, 10^{-3}, ...10^{-11}$ m for $n = 1, 2, ...6$

$\Rightarrow$ fundamental Planck scale at TeV

Kaluza–Klein gravitons [Giudice, Ratazzi, Wells]

– periodic boundaries: Fourier–transform in extra dimensions [QCD massless]

$$(\Box + m_k^2)\; G^{(k)}_{\mu\nu} = -\frac{T_{\mu\nu}}{M_\text{Planck}} \qquad\qquad \delta m \sim \frac{1}{r} = 2\pi M_D \left(\frac{M_D}{M_\text{Planck}}\right)^{2/n} \lesssim 0.05 \text{ GeV}$$

– KK tower of single gravitons, each coupled as $1/M_\text{Planck}$

– IR spectrum: constraints from supernova cooling

– UV spectrum: LHC effects at TeV scale [Giudice, Strumia, TP; cosmic rays]

UV–complete extra dimensions

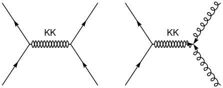
Hope for collider searches [Giudice, Rattazzi, Wells; Han, Lykken, Zhang]

– real radiation of continuous KK tower

$$\sigma^{\text{tower}} \sim \sigma^{\text{graviton}} \int dm\; S_{n-1} m^{n-1} r^n = \sigma^{\text{graviton}} \int dm\; \frac{S_{n-1}\; m^{n-1}}{(2\pi M_D)^n} \left(\frac{M_{\text{Planck}}}{M_D} \right)^2$$

– higher-dimensional operator from virtual gravitons [UV dominated]

$$\mathcal{A}(s;m) = \frac{1}{M_{\text{Planck}}^2} T_{\mu\nu} T^{\mu\nu} \frac{1}{s-m^2} \to \frac{S_{n-1}}{2M_D^4} \left(\frac{\Lambda}{M_D} \right)^{n-2}$$



⇒ KK tower coupling with $1/M_D$ at LHC

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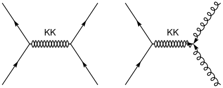


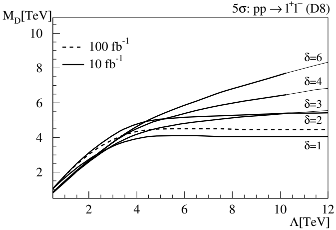
$\Rightarrow$ KK tower coupling with $1/M_D$ at LHC

Virtual gravitons at LHC

– s–channel $gg \to \mu^+\mu^-$

– LHC rates (or reach) dependent on cut-off Λ

$\Rightarrow$ effective theory poor at LHC



UV–complete extra dimensions

Renormalization flow of gravity [Reuter; Litim; Wetterich;...]

– Einstein–Hilbert action with running $G(\mu)$ and $\Lambda(\mu)$

– dimensionless coupling $g(\mu) = G(\mu)\,\mu^{2+n} = G_0\,Z_G^{-1}(\mu)\,\mu^{2+n}$

– attractive non–Gaussian UV fixed point [anomalous dimension: $\eta = -\mu\partial_\mu \log Z_G \propto g$]

$$\mu \frac{\partial}{\partial\mu}\, g_*(\mu) = (2 + n + \eta(g_*))\;\; g_*(\mu) = 0 \qquad \text{for} \qquad g_* \neq 0 \qquad \eta(g_*) = -2 - n$$

– gravity asymptotically free in UV $G(\mu) \sim g_* \mu^{-(2+n)}$

⇒ coupling weak enough for finite LHC predictions?

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UV–safe gravity [Weinberg (1979)]

– gravity non–fundamental effective theory $G \propto 1/M_D^{2+n}$?

– ’t Hooft’s perturbative renormalizability: finite number of counter terms

– Wilson’s (weaker) renormalizability: no unphysical UV divergences

– consistent theory beyond perturbation theory [no ghosts: Weinberg & Gomez]

– fixed point likely to $\sqrt{|g|}\,R^8$ and including matter [no proof; not perturbative series]

– great idea for gravity — great for LHC

UV–complete extra dimensions

UV–completed graviton production [Litim & TP]

– form factor for $G(\mu)$ [Hewett & Rizzo] $\frac{1}{M_D^{2+n}} \longrightarrow \frac{1}{M_D^{2+n}} \left[1 + \left(\frac{\sqrt{s}}{a M_D} \right)^{2+n} \right]^{-1}$

– alternative: changing anomalous dimension of graviton [QCD inspired]

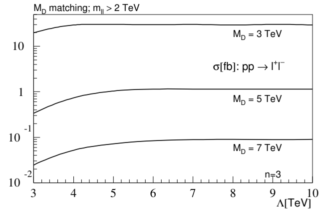
$$P(s,m) = \frac{1}{s+m^2} \longrightarrow \frac{M_D^{n+2}}{(s+m^2)^{n/2+2}} \qquad \text{around} \quad m \sim M_D$$

– integration kernel after integration over $m_{\rm KK}$

$$\frac{1}{M_D^{2+n}} \int_0^\infty \frac{dm}{m^{n-1}} P(s,m) = \frac{1}{n-2} \frac{1}{M_D^4} \left(\frac{a M_D}{M_D} \right)^{n-2} \left[1 + \frac{n-2}{4} \right] \left[1 + \mathcal{O}\left(\frac{s}{M_D^2} \right) \right]$$

– $\sqrt{s} > M_D$: kernel only function of $\sqrt{s}$ [matching at M_D?, black–hole solutions?]

⇒ UV–safe gravity safe at LHC



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String theory as UV completion [e.g. Cullen, Perelstein, Peskin]

– Veneziano form factor

$$\frac{\Gamma(1-\alpha' s)\,\Gamma(1-\alpha' t)}{\Gamma(1-\alpha'(s+t))} = \frac{\Gamma(1-s/M_S^2)\,\Gamma(1-t/M_S^2)}{\Gamma(1-(s+t)/M_S^2)} = 1 - \frac{\pi^2}{6} \frac{st}{M_S^4} + \mathcal{O}\left(M_S^{-6} \right)$$

– string resonances in UV: $\sqrt{n}\, M_S$

⇒ quantum gravity testable at LHC

New physics at the LHC

Physics in the LHC era

– understand e-w symmetry breaking

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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

– implement into realistic simulations

– avoid getting killed by QCD

$\Rightarrow$ LHC + testable TeV-scale models: more than discovery machine!