Understanding the TeV Scale at the LHC

Tilman Plehn

University of Edinburgh

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Outline

New physics at the LHC

Weak boson fusion and unitarity

Gluinos or else?

UV–complete extra dimensions

Final goal: Underlying theory

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?]

$\Rightarrow$ defined by particle content, interactions, renormalizability

$\Rightarrow$ 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?]

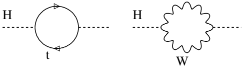
– matter–antimatter asymmetry? [universe mostly matter]

– gauge–coupling unification? [almost perfect, but proton stable]

– gravity? [mostly negligible but perturbatively non-renormalizable]

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

Standard–Model effective theory



Consistency of fundamental theory

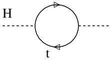
– problem of light Higgs: mass driven to cutoff of effective Standard Model
$\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, \Lambda^2$

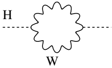
– cancelled by counter term, cosmological constant tuned anyway [a-word]
but problems not linked ['weakless universe': Harnik, Kribs, Perez]

– or new physics at TeV scale: supersymmetry [my favorite]
extra dimensions [cool idea]
little Higgs [old idea, now working]
composite Higgs, TopColor... [not pretty]

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

Standard–Model effective theory





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⇒ fundamental Higgs without TeV–scale completion useless

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

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

– skipping all introductions into models here

⇒ general: TeV–scale models in baroque state

Physics 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?

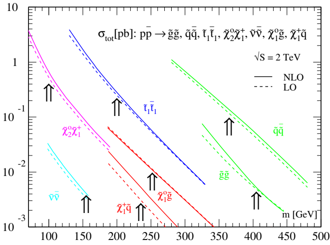
Particle theory and new physics

- 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 (2008)]
- reconstruction of Lagrangian [theory+experiment]

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 [not today]

⇒ aim at underlying theory



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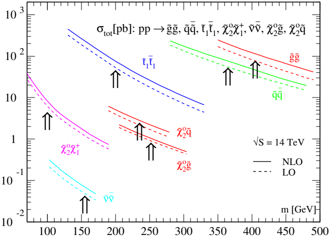
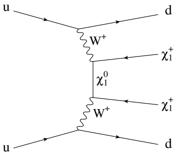


Weak boson fusion and unitarity



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

– Majorana LSP with like-sign charginos?

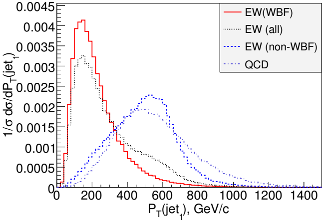
– hypotheses: like–sign charginos (SUSY)
like–sign scalars (scalar dark matter)
like–sign vector bosons (little–Higgs inspired)

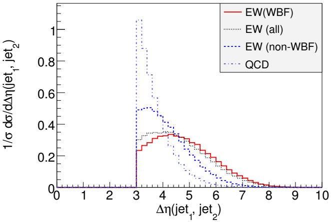
– chargino decay/kinematics not used

⇒ WBF : two key distributions $\Delta\phi_{jj}, p_{T,j}$ [like $H \to ZZ \to 4\mu$ 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





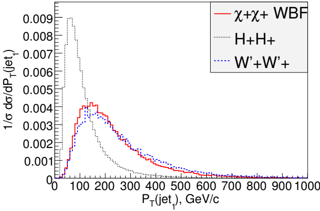
Weak boson fusion and unitarity

Like-sign scalars instead of fermions

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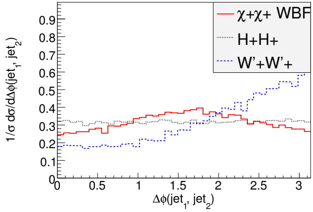
Like-sign vectors instead of fermions

- 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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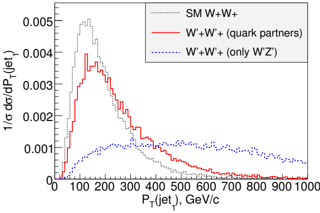
Heavy fermions in little–Higgs models

– part of unitary UV completion [Englert, Zeppenfeld]

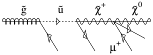
– huge effects on distributions [at low scales]

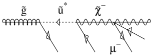
⇒ look-alike of strongly interacting Ws [Reuter,...]



Gluinos or else?

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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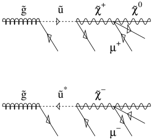

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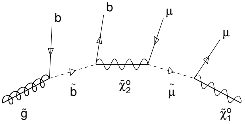
Loop hole: gluino is Majorana if fermion [Alves, Eboli, TP (2006)]

- 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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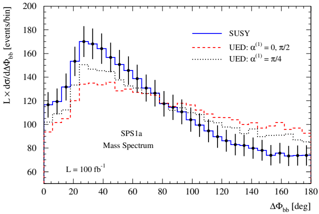
- 'gluino' as a boson: universal extra dimensions

  [spectra degenerate, cross sections, higher KK states — ignore]
- simple distributions [3-body decays: Csaki,...]
- threshold behavior? [under study]

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



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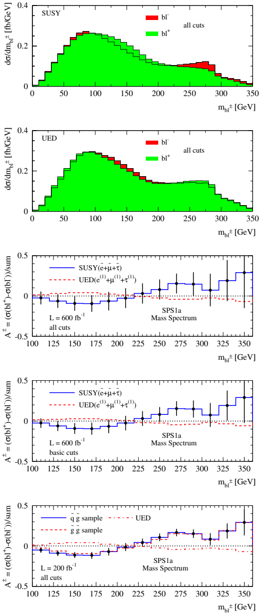
Elegant LHC universe [Alves, Eboli, TP (2006)]

– angular correlation: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$
– asymmetry b vs. $\bar{b}$ [independent of production]

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

– stable w.r.t production channels and cuts



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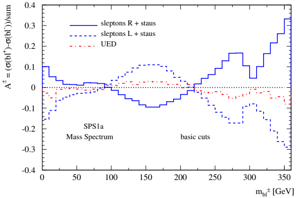
– stable w.r.t production channels and cuts

– unstable w.r.t model details

– positive: use information [Hagiwara, Kim, Mawatari, Zerwas]

$\Rightarrow$ LHC only as good as understood hypotheses



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

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

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

– KK tower of single gravitons, each coupled as $1/M_{\text{Planck}}$ [Giudice, Ratazzi, Wells]

– constraints from supernova cooling only on IR spectrum

– LHC effects from TeV–scale UV spectrum [Giudice, Strumia, TP (2005); cosmic rays]

$\Rightarrow$ KK effective theory at LHC?

UV–complete extra dimensions

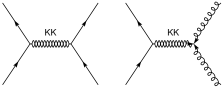
Hope for collider searches [Giudice, Rattazzi, Wells; Han, Lykken, Zhang]

– 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]

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



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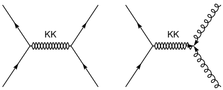


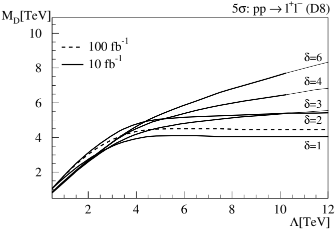
⇒ KK tower coupling with $1/M_D$ at LHC

Virtual gravitons at LHC [e.g. Giudice, TP, Strumia (2005)]

– s–channel $gg \to \mu^+\mu^-$

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

⇒ 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 $G(\mu) \sim g_*\mu^{-(2+n)}$

$\Rightarrow$ coupling small enough for 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 (2007)]

– 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]

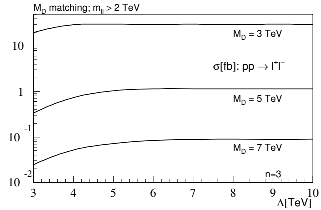
$$P(s,m) = \frac{1}{s+m^2} \longrightarrow \frac{M_D^{n+2}}{(s+m^2)^{n/2+2}} \qquad \text{around} \quad m \sim M_D$$

– integration kernel after integration over m_{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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$\Rightarrow$ UV–safe gravity safe at LHC

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: $\sqrt{n}\, M_S$

$\Rightarrow$ quantum gravity testable at LHC

Final goal: Underlying theory

From LHC to high scales [Fittino; SFitter: Lafaye, TP, Rauch, D. Zerwas; Arkani–Hamed et al]

– parameters: weak-scale Lagrangian and up from there

– measurements: LHC and beyond [dark matter, e-w precision,...?]

– errors challenge: statistics & systematics & theory [flat theory errors!]

– statistics challenge: get it right in many dimensions [Bayesian and frequentist]

Final goal: Underlying theory

From LHC to high scales [Fittino; SFitter: Lafaye, TP, Rauch, D. Zerwas; Arkani–Hamed et al]

– parameters: weak-scale Lagrangian and up from there
– measurements: LHC and beyond [dark matter, e-w precision,...?]
– errors challenge: statistics & systematics & theory [flat theory errors!]
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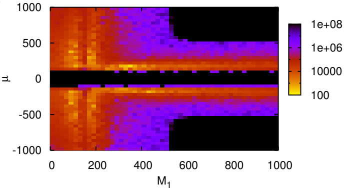
MSSM parameter space in LHC era

– one degeneracy: three of four neutralinos



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– beyond LHC: $\tan\beta$ using $(g-2)_\mu$

[SFitter (2008)]

	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
A_τ	fixed 0		fixed 0		-249.4
A_t	-509.1$\pm$	86.7	-530.6$\pm$	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$\pm$	14.5	352.5$\pm$	10.8	353.7

Final goal: Underlying theory

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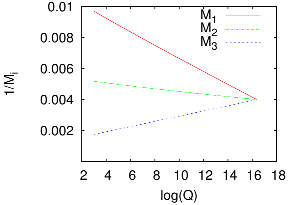
Fundamental theory [SFitter + Kneur (2007+)]

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



New physics in LHC era

TeV–scale physics understood

- find Higgs sector
- confirm BSM physics
- solve hierarchy problem
- explain dark matter

- test testable hypotheses
- determine fundamental theory
- never fly through Heathrow

- LHC more than discovery machine
- LHC physics is fun physics, even on Saturday afternoon!