Phenomenology: Beyond the Standard Model

Tilman Plehn

University of Edinburgh

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Outline

Standard–Model effective theory

TeV–scale supersymmetry

Supersymmetric signatures

Masses and cascade decays

Spins and cascade decays

New physics and jets

Spins and jets

Underlying parameters

Large extra dimensions

Warped extra dimensions
**Standard–Model effective theory**

What is the Standard Model?

- gauge theory with the group structure $SU(3) \times SU(2) \times U(1)$
- massless $SU(3)$ and $U(1)$ gauge bosons
- massive electroweak gauge bosons  
  [Higgs mechanism with $v = 246$ GeV, $m_H \lesssim 250$ GeV]
- Dirac fermions in doublets and with masses equal to Yukawas
- generation mixing in quark and neutrino sector
⇒ defined by particle content and (gauge) interactions

Data vs renormalizable Lagrangian  
[all operators to D4]

- dark matter?  
  [only solid evidence for new physics, weak–scale?]
- $(g - 2)_\mu$?  
  [loop effects around weak scale?]
- flavor physics?  
  [new operators above $10^4$ GeV?]
- neutrino masses?  
  [see-saw at $10^{11}$ GeV?]
- gauge–coupling unification?  
  [something happening above $10^{16}$ GeV?]
- gravity?  
  [mostly negligible below $10^{19}$ GeV, non-renormalizable in usual sense]
⇒ general effective–theory Lagrangian with those interactions and particles
⇒ cut-off obvious, scale negotiable, renormalizability desirable
⇒ who the hell cares....???
Standard–Model effective theory

...theorists care!

– compute loop corrections to scalar Higgs mass
– top loop in Higgs self energy $\Sigma$

$$\Sigma \sim - \left( \frac{g m_t}{v} \right)^2 \int \frac{d^4 q}{(2\pi)^4} \frac{(q + m_t)(q + p + m_t)}{[q^2 - m_t^2][(q + p)^2 - m_t^2]} \sim - \frac{1}{(4 \pi)^2} \left( \frac{g m_t}{v} \right)^2 \Lambda^2 + \cdots$$

– sum to Higgs–mass correction

$$\frac{1}{p^2 - m_H^2} \rightarrow \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \sum \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \sum \frac{1}{p^2 - m_H^2} \sum \frac{1}{p^2 - m_H^2} + \cdots$$

$$= \frac{1}{p^2 - m_H^2} \sum_{j=0}^{\infty} \left( \frac{\Sigma}{p^2 - m_H^2} \right) = \frac{1}{p^2 - m_H^2} \frac{1}{1 - \frac{\Sigma}{m^2 - m_H^2}} = \frac{1}{p^2 - m_H^2 - \Sigma}$$

– and watch desaster after collecting all loop functions

$$m_H^2 \rightarrow m_H^2 - \frac{3g^2}{32\pi^2} \frac{\Lambda^2}{m_W^2} \left[ m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 \right] + \cdots$$

$\Rightarrow$ Higgs mass including loops wants to be cut-off scale $\Lambda$

$\Rightarrow$ Standard–Model effective theory destabilized between $v$ and $\Lambda$

[Higgs wants to be at $\Lambda$, but would not function as Higgs there]

$\Rightarrow$ hierarchy problem: why not a $\Sigma$ model if fundamental Higgs unworkable
Standard–Model effective theory

Problem with light Higgs (data–driven)

- mass to cut-off of effective SM: \( \delta m_H^2/m_H^2 \propto g^2(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2 \)

⇒ easy solution: tune counter term \( \Rightarrow \) evil, not in 't Hooft’s spirit

⇒ or new physics at TeV scale: supersymmetry
- extra dimensions
- little Higgs (Goldstone Higgs)
- Higgsless, composite Higgs, TopColor, ...

⇒ typically cancellation by new particles or discussing away high scale

⇒ beautiful concepts, but problematic at TeV scale [data seriously in the way]

Supersymmetry: prototype of new physics

- cancellation of divergences through statistics factor (-1)
  [SM fermions to scalar; SM gauge bosons to fermions; SM scalars to fermions]

- Higgs–mass protection beyond one–loop [otherwise only stop, weak gaugino, higgsino]

- dark matter through \( R \) symmetry [removing D5 proton–decay operators]

- no clue about flavor physics

- decoupling theory [SUSY killed via Feyerabend, not Popper]

⇒ all new physics models in baroque state
Standard–Model effective theory

Problem with light Higgs (data–driven)

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  - supersymmetry
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Alternative motivations for TeV–scale new physics

- gauge coupling unification almost perfect [ask Graham]
- Uli Baur’s rule: new energy scales bring new physics
- field looking like solid–state physics otherwise...
TeV–scale supersymmetry

**SUSY broken: (yet) unobserved partners heavy**

- soft breaking: partner masses without quadratic divergencies
- mechanism for SUSY masses unknown [soft SUSY breaking mediated somehow?]

maximally blind mediation: mSUGRA [sooo not a LHC paradigm!]

scalars: $m_0$, fermions: $m_{1/2}$, tri-scalar term: $A_0$

plus sign($\mu$) and tan $\beta$ in Higgs sector

- alternatives: gauge, anomaly, gaugino mediation...?
- link to flavor physics, dark matter,...?

⇒ LHC: measure spectrum

⇒ LHC: if a spectrum, identify BSM model
TeV–scale supersymmetry

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**LHC phenomenology: MSSM**

- conjugate Higgs field not allowed
  → give mass to $t$ and $b$?
  → avoid higgsino anomalies
  → two Higgs doublets
- BSM–Higgs $\neq$ SM–Higgs
⇒ would be another lecture...

<table>
<thead>
<tr>
<th></th>
<th>spin</th>
<th>d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>fermion $f_L, f_R$</td>
<td>1/2</td>
<td>1+1</td>
</tr>
<tr>
<td>fermion $\tilde{f}_L, \tilde{f}_R$</td>
<td>0</td>
<td>1+1</td>
</tr>
<tr>
<td>gluon $G_\mu$</td>
<td>1</td>
<td>n-2</td>
</tr>
<tr>
<td>gluon $\tilde{g}$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>gauge bosons $\gamma, Z$</td>
<td>1</td>
<td>2+3</td>
</tr>
<tr>
<td>Higgs bosons $H^0, H^0, A^0$</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>neutralinos $\tilde{\chi}_i^0$</td>
<td>1/2</td>
<td>4 · 2</td>
</tr>
<tr>
<td>gauge bosons $W^\pm$</td>
<td>1</td>
<td>2 · 3</td>
</tr>
<tr>
<td>Higgs bosons $H^\pm$</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>charginos $\tilde{\chi}_i^\pm$</td>
<td>1/2</td>
<td>2 · 4</td>
</tr>
</tbody>
</table>
Supersymmetric signatures

**Inclusive: squarks and gluinos at Tevatron**

- squarks, gluinos strongly interacting
  \[
  p\bar{p} \rightarrow \tilde{q} \tilde{q}^*, \tilde{q} \tilde{g}, \tilde{g} \tilde{g} \quad \text{[best if } m(\tilde{q}) \sim m(\tilde{g})]\]
- dark–matter weakly interacting \[\text{[not only SUSY]}\]
- signatures with jets and LSP
  \[
  \tilde{g} \rightarrow \tilde{q} \tilde{q}, \tilde{q}_L \rightarrow q \tilde{\chi}^0_2, \tilde{q}_R \rightarrow q \tilde{\chi}^0_1
  \]
  [additional jets and leptons possible]
- gaugino mass unification only for details

⇒ we know inclusive jets plus LSP
Supersymmetric signatures

Inclusive: squarks and gluinos at Tevatron

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  [additional jets and leptons possible]
- gaugino mass unification only for details

⇒ we know inclusive jets plus LSP

When do we see SUSY–QCD?

- gluinos: strongly interacting Majorana fermions
- first jet in gluino decay: \( q \) or \( \bar{q} \)
- final–state leptons with both charges
- similar for \( t \)–channel gluino in \( qq \rightarrow \tilde{q}\tilde{q} \)

⇒ like–sign dileptons from gluinos
Supersymmetric signatures

New physics at the LHC

(1) possible discovery — signals for new physics
(2) measurements — masses, cross sections, decays
(3) parameter studies — weak–scale Lagrangian
Supersymmetric signatures

New physics at the LHC

1. possible discovery — signals for new physics
2. measurements — masses, cross sections, decays
3. parameter studies — weak–scale Lagrangian
   \[ \Rightarrow \text{approach independent of new physics model} \]

Some SUSY signals at LHC

- jets and $\mathcal{E}_T$: $pp \rightarrow \bar{q}q^*, \bar{g}g, \bar{q}g$
- like–sign dileptons: $pp \rightarrow \bar{g}g$
- funny tops: $pp \rightarrow \tilde{t}_1 \tilde{t}_1^*$
- tri-leptons: $pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^-$
  \[ [\tilde{\chi}_2^0 \rightarrow \ell \bar{\ell}, \tilde{\chi}_1^0 \rightarrow \ell \bar{\nu}] \]
  \[ \Rightarrow \text{inclusive: similar to Tevatron} \]
  \[ \Rightarrow \text{exclusive: enough events for studies} \]
Masses and cascade decays

Spectra from cascade decays

- tough: \((\sigma BR)_1 / (\sigma BR)_2\) [SFitter: focus point]
- decay \(\tilde{g} \rightarrow b\bar{b} \rightarrow \tilde{\chi}^0_2 b\bar{b} \rightarrow \mu^+ \mu^- b\bar{b}\tilde{\chi}^0_1\) [better not via Z or to \(\tau\)]
- large cross sections [more than 100 pb means \(3 \times 10^7\) events]
- thresholds & edges
  \[m_{\ell\ell}^2 < \frac{m^2_{\tilde{\chi}^0_2} - m^2_{\ell}}{m_{\ell}} \frac{m^2_{\ell} - m^2_{\tilde{\chi}^0_1}}{m_{\ell}}\]

\(\Rightarrow\) new–physics spectrum from cascade decays [mass differences with smaller errors]
Masses and cascade decays

Spectra from cascade decays

- tough: \((\sigma BR)_1/(\sigma BR)_2\)  
  [SFitter: focus point]
- decay \(\tilde{g} \rightarrow \tilde{b}\tilde{b} \rightarrow \tilde{\chi}_2^0 b\bar{b} \rightarrow \mu^+ - b\bar{b}\tilde{\chi}_1^0\)  
  [better not via \(Z\) or to \(\tau\)]
- large cross sections  
  [more than 100 pb means \(3 \times 10^7\) events]
- thresholds & edges

\[
m^2_{\ell\ell} < \frac{m^2_{\tilde{\chi}_2^0} - m^2_{\ell}}{m^2_{\tilde{\chi}_1^0}}
\]

⇒ new–physics spectrum from cascade decays  
  [mass differences with smaller errors]

<table>
<thead>
<tr>
<th>measurement</th>
<th>nominal</th>
<th>stat.</th>
<th>LES</th>
<th>JES</th>
<th>theo.</th>
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</thead>
<tbody>
<tr>
<td>(m_h)</td>
<td>108.99</td>
<td>0.01</td>
<td>0.25</td>
<td>2.0</td>
<td></td>
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<tr>
<td>(m_t)</td>
<td>171.40</td>
<td>0.01</td>
<td>2.3</td>
<td>1.0</td>
<td>2.2</td>
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<tr>
<td>(m_{\tilde{t}} - m_{\chi_1^0})</td>
<td>102.45</td>
<td>2.3</td>
<td>0.1</td>
<td>18.3</td>
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<tr>
<td>(m_{\tilde{g}} - m_{\chi_1^0})</td>
<td>511.57</td>
<td>2.3</td>
<td>6.0</td>
<td>16.3</td>
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<tr>
<td>(m_{\tilde{q}R} - m_{\chi_1^0})</td>
<td>446.62</td>
<td>10.0</td>
<td>4.3</td>
<td>24.0</td>
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<tr>
<td>(m_{\tilde{g}} - m_{\tilde{b}_1})</td>
<td>88.94</td>
<td>1.5</td>
<td>1.0</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>(m_{\tilde{g}} - m_{\tilde{b}_2})</td>
<td>62.96</td>
<td>2.5</td>
<td>0.7</td>
<td>24.5</td>
<td></td>
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<tr>
<td>(m^\text{max}_{ll}) ((\chi_4^0))</td>
<td>three-particle edge((\chi_2^0, \tilde{\chi}_1^0, \chi_1^0)) (\rightarrow) 80.94</td>
<td>0.042</td>
<td>0.08</td>
<td>(m^\text{max}_{ll})</td>
<td></td>
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<tr>
<td>(m^\text{max}_{ll}) ((\chi_4^0))</td>
<td>three-particle edge((\tilde{q}_L, \chi_2^0, \chi_1^0)) (\rightarrow) 449.32</td>
<td>1.4</td>
<td>4.3</td>
<td>15.2</td>
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<tr>
<td>(m^\text{low}_{ll}) ((\chi_4^0))</td>
<td>three-particle edge((\tilde{q}_L, \chi_2^0, \tilde{\chi}_1^0)) (\rightarrow) 326.72</td>
<td>1.3</td>
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<td>13.2</td>
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<tr>
<td>(m^\text{max}_{ll}) ((\chi_4^0))</td>
<td>three-particle edge((\tilde{q}_L, \chi_2^0, \tilde{\chi}_1^0)) (\rightarrow) 254.29</td>
<td>3.3</td>
<td>0.3</td>
<td>4.1</td>
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<tr>
<td>(m^\text{max}_{ll}) ((\chi_4^0))</td>
<td>three-particle edge((\tilde{q}_L, \chi_2^0, \tilde{\chi}_1^0)) (\rightarrow) 83.27</td>
<td>5.0</td>
<td>0.8</td>
<td>2.1</td>
<td></td>
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<tr>
<td>(m^\text{low}_{ll}) ((\chi_4^0))</td>
<td>four-particle edge((\tilde{q}_L, \chi_2^0, \tilde{\chi}_1^0, \chi_1^0)) (\rightarrow) 390.28</td>
<td>1.4</td>
<td>3.8</td>
<td>13.9</td>
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<tr>
<td>(m^\text{thres}_{ll}) ((\chi_4^0))</td>
<td>threshold((\tilde{q}_L, \chi_2^0, \tilde{\chi}_1^0, \chi_1^0)) (\rightarrow) 216.22</td>
<td>2.3</td>
<td>2.0</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>(m^\text{thres}_{ll}) ((\chi_4^0))</td>
<td>threshold((\tilde{b}_L, \chi_2^0, \tilde{\chi}_1^0, \chi_1^0)) (\rightarrow) 198.63</td>
<td>5.1</td>
<td>1.8</td>
<td>8.0</td>
<td></td>
</tr>
</tbody>
</table>
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Why?
Supersymmetry
LHC Signals
Masses
Spins 1
Jets
Spins 2
Parameters
Large dimensions
Warped dimensions

Masses and cascade decays

Spectra from cascade decays

- tough: \((\sigma \text{BR})_1 / (\sigma \text{BR})_2\) [SFitter: focus point]
- decay \(\tilde{g} \rightarrow \tilde{b}\tilde{b} \rightarrow \tilde{\chi}_2^0 b\bar{b} \rightarrow \mu^+ \mu^- b\bar{b} \tilde{\chi}_1^0\) [better not via \(Z\) or to \(\tau\)]
- large cross sections [more than 100 pb means \(3 \times 10^7\) events]
- thresholds & edges

\[
m_{\ell\ell}^2 < \frac{m_{\tilde{\chi}^0_2}^2 - m_{\tilde{\ell}}^2}{m_{\tilde{\ell}}^2} \quad \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}^0_1}^2}{m_{\tilde{\ell}}^2}
\]

\(\Rightarrow\) new–physics spectrum from cascade decays [mass differences with smaller errors]

Gluino mass from kinematic endpoints

- all decay jets \(b\)-tagged [otherwise dead by QCD]
- most of time: cascade assignments correct
- gluino mass to \(\sim 1\%\)

\(\Rightarrow\) what else from cascades?
Spins and cascade decays

Spin from angular distributions

- model–independent spin determination unlikely  [new physics is hypothesis testing]
- assume squark cascade observed
⇒ strongly interacting scalar?
⇒ straw-man model where ‘squark’ is a fermion: universal extra dimensions

[spectra degenerate — ignore; cross section larger — ignore; higher K states — ignore; Higgs sector — ignore]
Spins and cascade decays

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Squark cascade $\tilde{q}_L \rightarrow q\tilde{\chi}^0_2 \rightarrow q\ell\bar{\ell} \rightarrow q\ell\bar{\ell}\tilde{\chi}^0_1$

- compare with first KK $q, Z$ and $\ell$ [near/far lepton?]
- polarization: 1: $(q_L, \ell^+_L, \ell^+_L)$
  2: $(q_L, \ell^+_L, \ell^-_L) = (q_L, \ell^-_R, \ell^+_R) = (\bar{q}_L, \ell^-_L, \ell^+_L)$
- distribution of angle $\theta$ between $q$ and $\ell$: $dP^{\text{SUSY}}_{1,2} / d\cos\theta$
- mass variable: $\hat{m} = m_{ql}/m_{ql}^{\text{max}}$
- UED and SUSY distributions [SPS1a spectrum]

$$
\frac{dP^{\text{SUSY}}_1}{d\hat{m}} = 4\hat{m}^3 \\
\frac{dP^{\text{SUSY}}_2}{d\hat{m}} = 4\hat{m} \left(1 - \hat{m}^2\right)
$$

$$
\frac{dP^{\text{UED}}_1}{d\hat{m}} = 1.213 \hat{m} + 3.108 \hat{m}^3 - 2.310 \hat{m}^5 \\
\frac{dP^{\text{UED}}_2}{d\hat{m}} = 2.020 \hat{m} + 1.493 \hat{m}^3 - 2.310 \hat{m}^5
$$

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Squark cascade $\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow q\ell\bar{\ell} \rightarrow q\ell\bar{\ell}\tilde{\chi}_1^0$

- compare with first KK $q$, $Z$ and $\ell$ [near/far lepton?]
- mass variable: $\hat{m} = m_{q_L}/m_{q_L}^{\text{max}}$
- typically largest rate $pp \rightarrow \tilde{q}\tilde{g}$
- production asymmetry $\tilde{q} : \tilde{q}^* \sim 2 : 1$
⇒ $A = [\sigma(j\ell^+) - \sigma(j\ell^-)]/\sigma(j\ell^+) + \sigma(j\ell^-)]$

Masses or spin or both?

- masses from kinematic endpoints [use $m_{\ell j}, m_{\ell\ell}, m_{j\ell\ell} \ldots$]
- spins from distributions in between [endpoints identical in SUSY and UED]
Spins and cascade decays

Back to gluinos as proof of SUSY–QCD

- loop hole: like–sign dileptons from heavy gluon
- show gluino a fermion

⇒ compare with usual UED straw–man hypothesis
Spins and cascade decays

Back to gluinos as proof of SUSY–QCD

- loop hole: like–sign dileptons from heavy gluon
- show gluino a fermion
\[ \Rightarrow \text{compare with usual UED straw–man hypothesis} \]

Gluino–bottom cascade

- decay chain like for gluino mass
- compare with first KK \( g, b, Z, \ell, \gamma \)
- replace initial–state asymmetry by \( b \) vs. \( \bar{b} \)
- independent of production channels
- asymmetry to write down:
\[ A = \frac{\sigma(b\ell^+)}{\sigma(b\ell^-)} / \sigma(b\ell^+) + \sigma(b\ell^-) \]
[still visible after cuts and smearing]
- detector/machine upgrade? [we are so ignorant!]
**Phenomenology: Beyond the Standard Model**

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---

**Why?**

- **Supersymmetry**
- **LHC Signals**
- **Masses**
- **Spins 1**
- **Jets**
- **Spins 2**
- **Parameters**
- **Large dimensions**
- **Warped dimensions**

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**Spins and cascade decays**

**Back to gluinos as proof of SUSY–QCD**

- loop hole: like–sign dileptons from heavy gluon
- show gluino a fermion

⇒ compare with usual UED straw–man hypothesis

**Gluino–bottom cascade**

- interchange \( \bar{\ell}_{LR} \) in cascade
- test of lepton-ino couplings

- purely hadronic \( \phi_{bb} \) [if asymmetry not possible]
- independent of weak decays
- sensitive to gluino/KK-gluon boost

⇒ gluino from cascade and like–sign dileptons

---

**Mass Spectrum**

- **SLEPTONS R + STAUS**
- **SLEPTONS L + STAUS**
- **UED**
- **SPS1a**

---

**DF**

- **bb**
- **events/bin**

---

**Plot**

- **L × dx/dy [events/deg]**
- **SPS1a**
- **Mass Spectrum**
- **L = 100 fb^{-1}**
- **ΔΦ_{bb} [deg]**

---

**Graphs**

- **SUSY**
- **UED: α_{SM} = 0, π/2**
- **UED: α_{SM} = π/4**

---

**Tables**

- **m_{1/2} [GeV]**
- **A_{0} ±**
- **(s_{BL-} - s_{BL+})/sum**

---

**Equations**

- \[ A^2 = (s_{BL+}) - s_{BL-}/sum \]
New physics and jets

Squarks and gluinos always with many jets

- cascade studies sensitive to jet simulation?
- matrix element \( \tilde{g}\tilde{g}+2j \) and \( \tilde{u}_L\tilde{g}+2j \) \( [p_{T,j} > 100 \text{ GeV}] \)
- compared with Pythia shower \( [\text{recent tune!}] \)
- hard scale \( \mu_F \) huge for SUSY

\[ \Rightarrow \text{QCD not a problem for new--physics searches} \]
More hypothesis testing: spin of LSP [no talk without WBF in Karlsruhe]

- Majorana LSP with like-sign charginos?
- hypotheses: like-sign charginos (SUSY)
  - like-sign scalars (scalar dark matter model)
  - like-sign vector boson (like little Higgs)
- stable for simplicity — chargino kinematics not used [SM backgrounds]
- WBF signal: two key distributions $\Delta \phi_{jj}, p_{T,j}$ [like $H \rightarrow ZZ \rightarrow 4\mu$ or WBF-Higgs]

\[ \Rightarrow \text{distinct WBF signal?} \quad [p_{T,j} \sim m_W, \text{forward jets}] \]

\[ \Rightarrow \text{visible over backgrounds?} \quad [\text{SUSY-QCD backgrounds dominant}] \]

\[ \Rightarrow \text{long shot, but not swamped by SUSY-QCD} \]
Spins and jets

Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
- $H^+H^-$ same as simple heavy $H^0$
- $W$ radiated off quarks  
  \[
  P_T(x, p_T) \sim \frac{1 + (1 - x)^2}{2x} \frac{1}{p_T^2}
  \]

$⇒$ scalars identified by softer $p_{T,j}$
Spins and jets

Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
- $H^+ H^-$ same as simple heavy $H^0$
- $W$ radiated off quarks \[ P_T(x, p_T) \sim \frac{1 + (1 - x)^2}{2x} \frac{1}{p_T^2} \]

\[ P_L(x, p_T) \sim \frac{(1 - x)^2}{x} \frac{m_W^2}{p_T^4} \]

$\Rightarrow$ scalars identified by softer $p_T, j$

Like-sign vectors instead

- alternative hypothesis like little Higgs
- start with copy of SM, heavy $W', Z', H', f'$ \[ \text{[H' necessary for unitarity, but irrelevant at LHC]} \]
- Lorentz structure reflected in angle between jets

$\Rightarrow$ vectors identified by peaked $\Delta \phi_{jj}$

\[ \frac{1}{\sigma \text{d} \sigma (\phi_{jet_1, jet_2})} \]
Spins and jets

Like-sign scalars instead

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- $H^+H^-$ same as simple heavy $H^0$
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⇒ vectors identified by peaked $\Delta \phi_{jj}$

Heavy fermions in little–Higgs models

- not part of the naive set of WBF diagrams
- huge effect on $p_{T,j}$

⇒ spin–effects visible in WBF signatures
Underlying parameters

From kinematics to weak–scale parameters

– parameters: weak-scale Lagrangian
– measurements: LHC edges, (σ·BR),...
  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?
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First and historic go at problem

- ask a friend how SUSY is broken ⇒ mSUGRA or CMSSM
- fit $m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu), y_t, \ldots$
- no problem, include indirect constraints
⇒ probability map as of today
⇒ best fit from LHC/ILC measurements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SPS1a</th>
<th>$\Delta \text{LHC}$ masses</th>
<th>$\Delta \text{LHC}$ edges</th>
<th>$\Delta \text{ILC}$</th>
<th>$\Delta \text{LHC+ILC}$</th>
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<tr>
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<td>0.11</td>
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<tr>
<td>$\tan \beta$</td>
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<td>0.9</td>
<td>0.12</td>
<td>0.12</td>
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<tr>
<td>$A_0$</td>
<td>-100</td>
<td>33</td>
<td>20</td>
<td>4.8</td>
<td>4.3</td>
</tr>
</tbody>
</table>
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The real thing: probability maps of new physics

- 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 problem: poorly constrained directions [e.g. endpoints or dark matter vs rates]
- 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
Underlying parameters

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- parameters: weak-scale Lagrangian
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MSUGRA as of today  [Bayesian or frequentist?]

- ‘Which is the most likely parameter point?’
- ‘How does dark matter annihilate/couple?’

\[
\begin{array}{c}
\text{L} / \text{L(max)} \\
0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 & 1.6 & 1.8 & 2 \\
0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 & 1.6 & 1.8 & 2 \\
\end{array}
\]
Underlying parameters

**MSUGRA map from simulated LHC data**  [endpoints with free $y_t$]

- weighted Markov chains: several times faster

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

- SFitter output #1: fully exclusive likelihood map
- SFitter output #2: ranked list of local maxima
- clear maximum, but strong correlation e.g. of $A_0$ and $y_t$  [including all errors ]

$$\begin{array}{cccccccc}
A_0 & m_0 & m_1/2 & \tan \beta & A_0 & \mu & m_t \\
0.3e-04 & 100.0 & 250.0 & 10.0 & -99.9 & + & 171.4 \\
27.42 & 99.7 & 251.6 & 11.7 & 848.9 & + & 181.6 \\
54.12 & 107.2 & 243.4 & 13.3 & -97.4 & - & 171.1 \\
70.99 & 108.5 & 246.9 & 13.9 & 26.4 & - & 173.6 \\
88.53 & 107.7 & 245.9 & 12.9 & 802.7 & - & 182.7 \\
\ldots
\end{array}$$

$\Rightarrow$ correlations and secondary maxima significant
Underlying parameters

**MSUGRA map from simulated LHC data**  
[endpoints with free $y_t$]
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**MSSM map from LHC data**
- 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]
- e.g. three neutralinos, six solutions  
  [profile likelihoods]
Underlying parameters

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[endpoints with free $y_t$]

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- e.g. three neutralinos, six solutions  
  [left: Bayesian — right: likelihood]

⇒ no best approach to BSM statistics
Underlying parameters

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**Theorists’ goal**

- unification and supersymmetry
- test mass unification with errors
  - properly: RGE running bottom-up
  ⇒ infer models from weak scale instead of believing

![Graph](image-url)
New physics in the LHC era

**Supersymmetry one well-studied example for BSM physics**

- inclusive signatures from Tevatron
- exclusive analysis only at LHC
- mass and spin measurements from cascade decays?
- spin measurements from WBF signatures?
- parameter extraction through probability maps!

....

**BSM theory in the LHC era**

- identify interesting TeV–scale models
- provide well–defined hypotheses to test
- develop search/test strategies
- implement in Monte-Carlo codes
- understand backgrounds
Large extra dimensions

Remember the hierarchy problem

- fundamental scalars cannot deal with a high scale in theory
- weakness of gravitational interaction means large Planck scale
  \[ G_N = \frac{1}{(16\pi M_{\text{Planck}})^2} \]

\[ \Rightarrow \text{solution: there is another reason why we see a huge } M_{\text{Planck}} \]

Large extra dimensions (ADD)

- Einstein–Hilbert action for fundamental Planck scale
  \[ S = -\frac{1}{2} \int d^4 x \sqrt{|g|} M_*^2 R \rightarrow -\frac{1}{2} \int d^{4+n} x \sqrt{|g|} M_*^{2+n} R \]

- compactify additional dimensions on torus
  \[ S = -\frac{1}{2} \int d^{4+n} x \sqrt{|g|} M_*^{2+n} R = -\frac{1}{2} (2\pi r)^n \int d^4 x \sqrt{|g|} M_*^{2+n} R \]

- match the two theories on our brane \[ [\text{also: match to measurements}] \]
  \[ -\frac{1}{2} (2\pi r)^n \int d^4 x \sqrt{|g|} M_*^{2+n} R \equiv -\frac{1}{2} \int d^4 x \sqrt{|g|} M_{\text{Planck}}^2 R \]

\[ \Rightarrow \text{express the 4D Planck scale in terms of fundamental Planck scale} \]

\[ M_{\text{Planck}} = M_* (2\pi r M_*)^{n/2} \]
Large extra dimensions

Remember the hierarchy problem

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\[ G_N = \frac{1}{(16\pi M_{\text{Planck}})^2} \]

⇒ solution: there is another reason why we see a huge \( M_{\text{Planck}} \)

Numbers to make it work

- wanted \( rM_* \gg 1 \)
- constraints from gravity tests above \( O(\text{mm}) \)
- \( M_* = 1 \text{ TeV} \ll M_{\text{Planck}} \) fine for \( n \gtrsim 2 \)

<table>
<thead>
<tr>
<th>( n )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 10^{12} \text{ m} )</td>
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<tr>
<td>2</td>
<td>( 10^{-3} \text{ m} )</td>
</tr>
<tr>
<td>3</td>
<td>( 10^{-8} \text{ m} )</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6</td>
<td>( 10^{-11} \text{ m} )</td>
</tr>
</tbody>
</table>

⇒ signatures of strong gravitation in extra dimension?
Large extra dimensions

Only gravitons in extra dimensions

- expand the metric in \((4 + n)\) dimensions [graviton field \(h\)]

\[
ds^2 = g^{(4+n)}_{MN} dx^M dx^N = \left( \eta_{MN} + \frac{1}{M_{*}^{n/2+1}} h_{MN} \right) dx^M dx^N
\]

- include matter into Einstein’s equation

\[
R_{AB} - \frac{1}{2 + n} g_{AB} R = - \frac{1}{M_{*}^{2+n}} \left( \begin{array}{cc} T_{\mu\nu}(x) \delta^{(n)}(y) & 0 \\ 0 & 0 \end{array} \right)
\]

- Fourier transformation of extra dimensions [KK excitations for periodic boundary conditions]

\[
h_{AB}(x; y) = \sum_{m_1 = -\infty}^{\infty} \cdots \sum_{m_j = -\infty}^{\infty} \frac{h^{(m)}_{AB}(x)}{\sqrt{(2\pi r)^n}} e^{i \frac{m_j y_j}{r}}
\]

- only the interacting (tensor) graviton \([h_{AB} \rightarrow G_{\mu\nu}, \text{QCD massless}]\)

\[
(\Box + m_k^2) G_{\mu\nu}^{(k)} = \frac{1}{M_{\text{Planck}}} \left[ -T_{\mu\nu} + \left( \frac{\partial_{\mu} \partial_{\nu}}{\hat{m}^2} + \eta_{\mu\nu} \right) \frac{T^\lambda_\lambda}{3} \right] = -\frac{T_{\mu\nu}}{M_{\text{Planck}}}
\]

- KK mass splitting \([M_{*} = 1 \text{ TeV}]\)

\[
\delta m \sim \frac{1}{r} = 2\pi M_{*} \left( \frac{M_{*}}{M_{\text{Planck}}} \right)^{2/n} = \begin{cases} 0.003 \text{ eV} & (n = 2) \\ 0.1 \text{ MeV} & (n = 4) \\ 0.05 \text{ GeV} & (n = 6) \end{cases}
\]
Large extra dimensions

Gravitons for LHC phenomenologists

- tower of KK tensor gravitons $G_{\mu\nu}^{(k)}$ with mass $m_k$
- mass splitting $\delta m \ll \text{GeV}$ [below mass resolution]
- universal couplings to massless SM particles via $-T_{\mu\nu}/M_{\text{Planck}}$

\[
f(k_1) - f(k_2) - G_{\mu\nu} : -\frac{i}{4M_{\text{Planck}}} (W_{\mu\nu} + W_{\nu\mu}) \quad \text{with} \quad W_{\mu\nu} = (k_1 + k_2)_{\mu} \gamma_{\nu} \]

$\Rightarrow$ KK gravitons light and weakly coupled

Hope for collider searches

- real radiation of continuous KK tower $[dm/d|k| = 1/r; (d\sigma) \propto 1/M_{\text{Planck}}^2]$

\[
d\sigma^{\text{tower}} = (d\sigma) \int dm \ S_{\delta-1} m^{n-1} r^n = (d\sigma) \int dm \ \frac{S_{\delta-1} m^{n-1}}{(2\pi M_*)^n} \left( \frac{M_{\text{Planck}}}{M_*} \right)^2 \]

- higher-dimensional operator from virtual graviton exchange [s-channel in DY]

\[
\mathcal{A} = \frac{1}{M_{\text{Planck}}^2} T_{\mu\nu} T_{\mu\nu} \frac{1}{s - m_{KK}^2} \Rightarrow \frac{S_{\delta-1}}{2} \frac{\Lambda^{n-2}}{M_*^{n+2}} \]

- UV completion needed to get rid of $\Lambda$ dependence

$\Rightarrow$ $1/M_*^2$ interactions after integration over KK tower
Large extra dimensions

**UV completion: renormalization flow of gravity**  
(strings also work)

- dimensionless coupling  
  \[ g(\mu) = G(\mu) \mu^{2+n} = G_0 Z^{-1}_G(\mu) \mu^{2+n} \]

- UV fixed point  
  \[ \mu \frac{\partial}{\partial \mu} g(\mu) = (2 + n + \eta(g)) \quad g(\mu) = 0 \quad \text{for} \quad g \neq 0 \]
  \[ \eta(g) = -2 - n \]

- asymptotic safety  
  \[ G(\mu) \sim Z^{-1}_G \sim \mu^{-(2+n)} \to 0 \]

\[ \Rightarrow \quad \text{gravity weak enough for well-defined predictions?} \]

**Graviton propagator**

- iterative approach: start with anomalous dimension  
  \[ \text{[similar to QCD analyses]} \]

- UV: dressed scalar propagator  
  \[ 1/(Z_G(|p|) p^2) \sim 1/p^{4+n} \]

\[ P(s, m) = \begin{cases} 
\frac{1}{s + m^2} & m < \Lambda_{\text{trans}} \sim M_* \\
\frac{M_*^{n+2}}{(s + m^2)^{n/2+2}} & m > \Lambda_{\text{trans}} \sim M_* 
\end{cases} \]

\[ \Rightarrow \quad \text{UV fixed point regularizing KK integral} \]
Warped extra dimensions

Alternative Solution

- try one extra dimension, but not flat [TeV brane at $y = b$]
  \[ ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \quad \iff \quad g_{AB} = \begin{pmatrix} e^{-2k|y|} \eta_{\mu\nu} & 0 \\ 0 & \eta_{jk} \end{pmatrix} \]

- integration measure in our usual Lagrangian $d^4 \tilde{x} \ e^{-4kb}$, $\tilde{g}_{\mu\nu} = \eta_{\mu\nu}$
  \[ S = \int dy \delta(y) \ d^4 \tilde{x} \ e^{-4kb} \mathcal{L} = \int d^4 \tilde{x} \ e^{-4kb} \left[ |D_\mu H|^2 - \lambda (|H|^2 - v^2)^2 + \ldots \right] \]

- write effective 4D theory on TeV brane scaling all fields
  \[ \tilde{H} = e^{-kb} H \] scalars
  \[ \tilde{A}_\mu = e^{-kb} A_\mu \] or $\tilde{D}_\mu = e^{-kb} D_\mu$
  \[ \tilde{\Psi} = e^{-3kb/2} \Psi \] fermions
  \[ \tilde{m} = e^{-kb} m \]
  \[ \tilde{v} = e^{-kb} v \]

- assume $kb \sim 35$ and large $M^* \sim k \sim M_{\text{Planck}} \sim v \sim \ldots$

\[ \Rightarrow \text{mass scale on TeV brane shifted} \]
\[ \tilde{v} \sim e^{-kb} M_{\text{Planck}} \lesssim 1 \text{ TeV} \]
Warped extra dimensions

Gravitons in one warped extra dimension

- re-write the metric including 4D graviton

\[ ds^2 = \frac{1}{(1 + k z)^2} \left( \eta_{\mu\nu} + h_{\mu\nu}(x, z) \, dx^\mu \, dx^\nu - dz^2 \right) \]

- solve Einstein’s equations separating variables \( \tilde{h}_{\mu\nu}(x, z) = \hat{h}_{\mu\nu}(x) \Phi(z) \)

\[ \partial_\mu \partial^\mu \hat{h}_{\mu\nu} = m^2 \hat{h}_{\mu\nu} \]

\[ -\partial_z^2 \Phi + \frac{15}{4} \frac{k^2}{(k z + 1)^2} \Phi = m^2 \Phi \]

\( \Rightarrow \) masses given by roots of Bessel functions \( J_1(x_j) = 0 \)

\[ m_j = x_j \, k \, e^{-kb} \sim \text{TeV} \quad x_j = 3.8, 7.0, 10.2, 16.5, \ldots \]

- couplings via wave-function overlap in \( z \)  

\[ \frac{\Phi(z)_{\text{TeV}}}{\Phi(z)_{\text{Planck}}} \sim \frac{\sqrt{k z + 1}_{\text{Planck}}}{\sqrt{k z + 1}_{\text{TeV}}} \sim \frac{1}{\sqrt{e^{ky}_{\text{TeV}}} \sim \frac{1}{e^{kb/2}}} \]

\( \Rightarrow \) universal couplings except for zero mode graviton

\[ \mathcal{L} \sim \frac{1}{M_{\text{Planck}}} \, h_{\mu\nu}^{(0)} + \frac{1}{M_{\text{Planck}} e^{-kb}} \, T_{\mu\nu} \sum h_{\mu\nu}^{(m)} \]

\( \Rightarrow \) TeV-scale resonances to e.g. leptons, revisited...
Extra Dimensions

Extra dimensions alternative scenario for LHC

- interesting new model
- signal: missing energy and narrow graviton towers (ADD)
  TeV–spaced resonances (RS)
- no challenge for LHC trigger
- identification of model parameters?
Phenomenology: Beyond the Standard Model

Tilman Plehn

Why?
Supersymmetry
LHC Signals
Masses
Spins 1
Jets
Spins 2
Parameters
Large dimensions
Warped dimensions