New Physics at the LHC

Tilman Plehn

University of Edinburgh

Oxford, 11/2007

Outline

TeV–scale new physics

TeV–scale supersymmetry

Masses from cascades

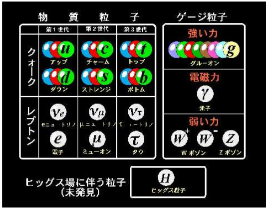
Underlying parameters

Spin from cascades

Spins from jets

Large extra dimensions

Standard–Model effective theory

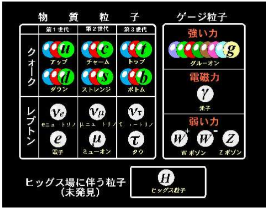


Remember the Standard Model?

- gauge theory with local $SU(3) \times SU(2) \times U(1)$
- massless $SU(3)$ and $U(1)$ gauge bosons
  massive W, Z bosons [Higgs mechanism with $v = 246$ GeV]
- Dirac fermions in doublets with masses = Yukawas
  generation mixing in quark and neutrino sector
- renormalizable Lagrangian [no 1/masses]
- only missing piece: Higgs [fundamental? minimal? mass unknown]

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

Standard–Model effective theory



Remember the Standard Model?

– gauge theory with local $SU(3) \times SU(2) \times U(1)$

– massless $SU(3)$ and $U(1)$ gauge bosons
massive W, Z bosons [Higgs mechanism with $v = 246$ GeV]

– Dirac fermions in doublets with masses = Yukawas
generation mixing in quark and neutrino sector

– renormalizable Lagrangian [no 1/masses]

– only missing piece: Higgs [fundamental? minimal? mass unknown]

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

How complete experimentally?

– dark matter? [solid 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?]

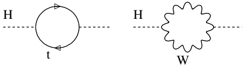
– matter–antimatter asymmetry? [universe mostly matter]

– gravity missing? [mostly negligible but definitely non-renormalizable]

$\Rightarrow$ cut-off scale unavoidable, size negotiable [SM an effective theory]

$\Rightarrow$ all philosophy — who the hell cares???

TeV–scale new physics



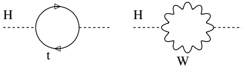
Theorists care — when looking at data which...

...indicates a light Higgs [e-w precision data]
...indicates higher–scale physics [at least dark matter]

– problem of light Higgs: mass driven to cutoff of effective Standard Model: $\delta m_H^2 \propto g^2(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\ \Lambda^2$
– easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly
– or new physics at TeV scale: supersymmetry [still my favorite]
  extra dimensions
  little Higgs
  composite Higgs, TopColor
  YourFavoriteNewPhysics...

$\Rightarrow$ beautiful concepts, but problematic in reality [data seriously in the way]

TeV–scale new physics



Theorists care — when looking at data which...

...indicates a light Higgs [e-w precision data]
...indicates higher–scale physics [at least dark matter]

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

– easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly

– or new physics at TeV scale: supersymmetry [still my favorite]
extra dimensions
little Higgs
composite Higgs, TopColor
YourFavoriteNewPhysics...

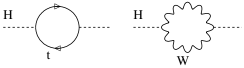
$\Rightarrow$ beautiful concepts, but problematic in reality [data seriously in the way]

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

– stable lightest new particle: dark matter [correct relic density]

$\Rightarrow$ TeV–scale models in baroque state

TeV–scale new physics



Theorists care — when looking at data which...

...indicates a light Higgs [e-w precision data]
...indicates higher–scale physics [at least dark matter]

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

– easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly

– or new physics at TeV scale: supersymmetry [still my favorite]
extra dimensions
little Higgs
composite Higgs, TopColor
YourFavoriteNewPhysics...

$\Rightarrow$ beautiful concepts, but problematic in reality [data seriously in the way]

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

– stable lightest new particle: dark matter [correct relic density]

$\Rightarrow$ TeV–scale models in baroque state

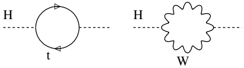
Alternative motivations for TeV–scale new physics

– 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

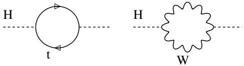


Supersymmetry

- give each Standard–Model particle a partner [with different spin, including strong interactions]
- 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 β
- assume dark matter, stable lightest partner

⇒ measure BSM spectrum with missing energy at LHC

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]
– 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 β
– assume dark matter, stable lightest partner

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

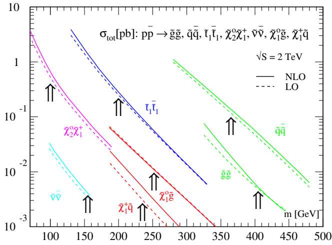
LHC searches: MSSM

– conjugate Higgs field not allowed
$\rightarrow$ give mass to t and b?
$\rightarrow$ five Higgs bosons
– SUSY–Higgs alone interesting...
...but not conclusive
...and another talk

$\Rightarrow$ list of SUSY partners

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

Masses from cascades

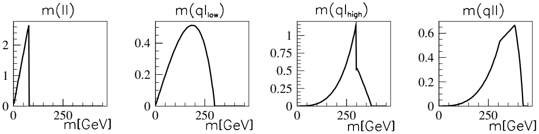


Cascade decays [Atlas-TDR, Cambridge, ask Alan]

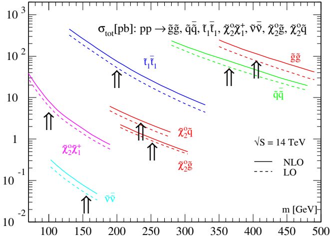
- if new particles strongly interacting and LSP weakly interacting
- like Tevatron: jets + missing energy
- tough: $(\sigma \mathrm{BR})_1/(\sigma \mathrm{BR})_2$ [unavoidable: focus point]
- easier: cascade kinematics [$10^7 \cdots 10^8$ events]
- long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- thresholds & edges

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

$\Rightarrow$ new–physics mass spectrum from cascade kinematics



Masses from cascades

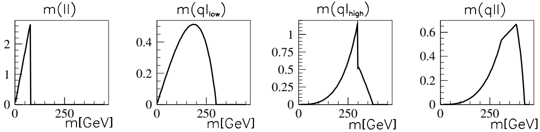


Cascade decays [Atlas-TDR, Cambridge, ask Alan]

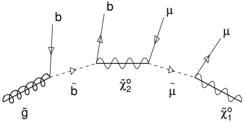
- if new particles strongly interacting and LSP weakly interacting
- like Tevatron: jets + missing energy
- tough: $(\sigma\text{BR})_1/(\sigma\text{BR})_2$ [unavoidable: focus point]
- easier: cascade kinematics [$10^7 \cdots 10^8$ events]
- long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- 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



Masses from cascades



Cascade decays [Atlas-TDR, Cambridge, ask Alan]

– 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

Gluino decay [Gjelsten, Miller, Osland]

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

– no problem: off-shell effects [Catpiss: Hagiwara et al.]

– no problem: jet radiation

Masses from cascades

Cascade decays [Atlas-TDR, Cambridge, ask Alan]

– 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

Gluino decay [Gjelsten, Miller, Osland]

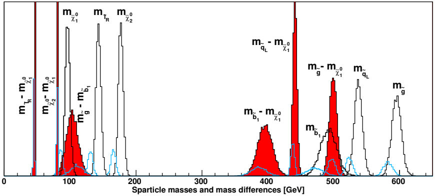
– all decay jets *b* quarks [otherwise dead by QCD]

– no problem: off-shell effects

– no problem: jet radiation

– gluino mass to $\sim 1\%$

⇒ but why physical masses?



New physics and jets

Squarks and gluinos always with many jets [Rainwater, TP, Skands]

– cascade studies sensitive to jet activity? [compare to Pythia shower]

– matrix element $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [$p_{T,j} > 100$ GeV]

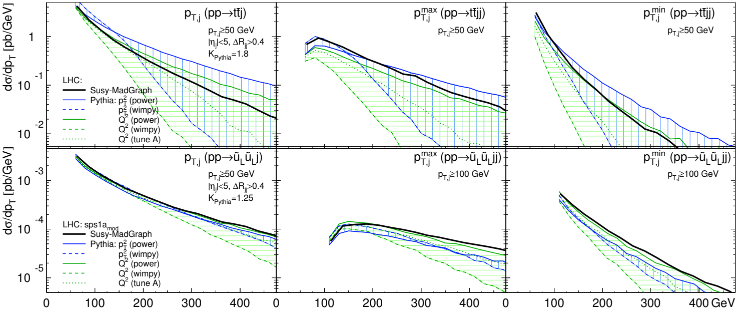
– hard scale μ_F huge for SUSY

– obvious: $p_{T,j}$ spectra fine with jet radiation

– miracle: angular correlations better than 10%

$\Rightarrow$ QCD not a problem in new–physics signals [Jay's next paper]

σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85



Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas]

– parameters: weak-scale Lagrangian

– measurements: masses or edges,
branching fractions, rates,... [Prospino]
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

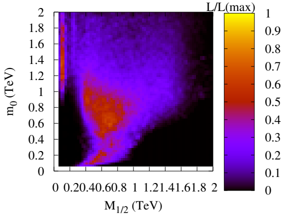
Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas]

– parameters: weak-scale Lagrangian
– measurements: masses or edges,
  branching fractions, rates,... [Prospino]
  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?

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

– 'Which is the most likely parameter point?'
– 'How does dark matter annihilate/couple?'



Underlying parameters

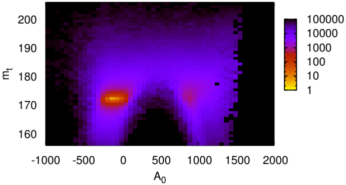
Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

– 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]



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
...						

$\Rightarrow$ correlations and secondary maxima significant

Underlying parameters

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

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

– 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]

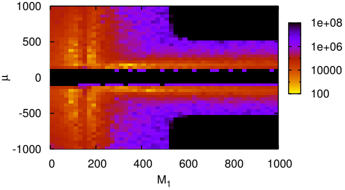
⇒ correlations and secondary maxima significant

MSSM map from LHC

– 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]



Underlying parameters

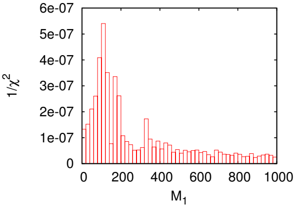
Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

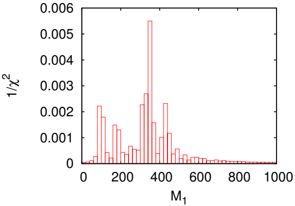
- weighted Markov chains: several times faster [similar to: Ferrenberg & Swendsen]
- SFitter output #1: fully exclusive likelihood map
  SFitter output #2: ranked list of local maxima
- strong correlation e.g. of A_0 and y_t [including all errors]

⇒ correlations and secondary maxima significant

MSSM map from LHC

- 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 [left: Bayesian — right: likelihood]





⇒ no best approach to BSM statistics

Underlying parameters

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

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

– 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]

$\Rightarrow$ correlations and secondary maxima significant

MSSM map from LHC

– 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]

$\Rightarrow$ no best approach to BSM statistics

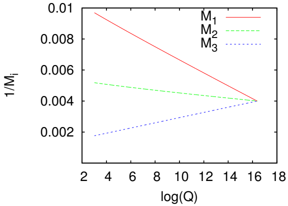
Theorists' goal [SFitter + Kneur]

– unification and supersymmetry

– test mass unification with errors [Cohen, Schmalz]

– properly: RGE running bottom–up

$\Rightarrow$ LHC: fundamental physics from weak scale

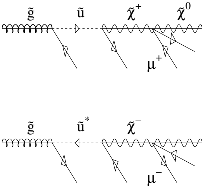


Spin from cascades

What kind of mass term? [Barger,...; Barnett,...; Baer,...]

- gluino = strongly interacting Majorana fermion [Gregoire,...]
- first jet (q or $\bar{q}$) fixes lepton charge
- same–sign dileptons in 1/2 of events
- similar: t-channel gluino in $pp \to \tilde{q}\tilde{q}$

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

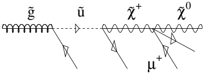


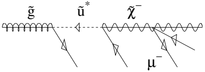
Spin from cascades

What kind of mass term? [Barger,...; Barnett,...; Baer,...]

- gluino = strongly interacting Majorana fermion
- first jet (q or $\bar{q}$) fixes lepton charge
- same–sign dileptons in 1/2 of events
- similar: t-channel gluino in $pp \to \tilde{q}\tilde{q}$

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



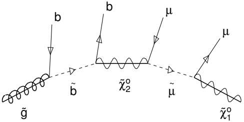


New physics is hypothesis testing [Barr, Lester, Smillie, Webber]

- loop hole: ‘gluino is Majorana if it is a fermion’
- gluino a fermion?
- assume gluino cascade observed
- model–independent analysis unlikely
- straw-man model where ‘gluino’ is a boson: universal extra dimensions

  [spectra degenerate — ignore; cross section larger — ignore; higher KK states — ignore; Higgs sector — ignore]

$\Rightarrow$ compare angular correlations



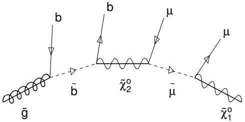
Spin from cascades

What kind of mass term? [Barger,...; Barnett,...; Baer,...]

– first jet (q or $\bar{q}$) fixes lepton charge
– same–sign dileptons in 1/2 of events
– similar: t-channel gluino in $pp \to \tilde{q}\tilde{q}$
⇒ like–sign dileptons in SUSY sample means gluino

Gluino–bottom cascade [Alves, Eboli, TP; like Cambridge squarks]

– decay chain from gluino mass [simulated for SUSY]
– compare SUSY with excited KK g, b, Z, ℓ, γ
– below edge: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$



Spin from cascades

What kind of mass term? [Barger,...; Barnett,...; Baer,...]

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

– same–sign dileptons in 1/2 of events

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

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

Gluino–bottom cascade [Alves, Eboli, TP; like Cambridge squarks]

– decay chain from gluino mass [simulated for SUSY]

– compare SUSY with excited KK g, b, Z, ℓ, γ

– below edge: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$

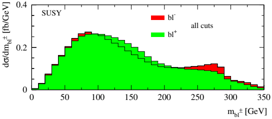
– better: asymmetry b vs. $\bar{b}$ [independent of production]

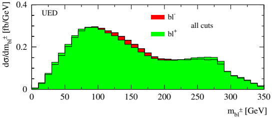
$$\mathcal{A}(m_{\mu b}) = \frac{\sigma(b\ell^+) - \sigma(b\ell^-)}{\sigma(b\ell^+) + \sigma(b\ell^-)}$$

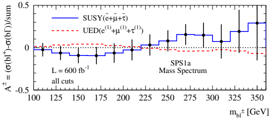
– stable w.r.t production channels and cuts

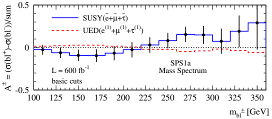
– less cool: angle between b and $\bar{b}$ [3-body decays: Csaki,...]

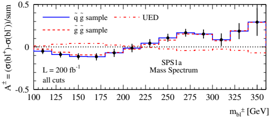
$\Rightarrow$ SUSY = gluino = fermionic like-sign dileptons











Spin from cascades

What kind of mass term? [Barger,...; Barnett,...; Baer,...]

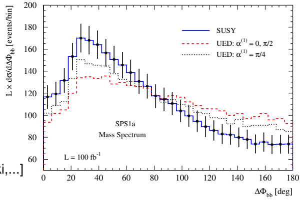
– first jet (q or $\bar{q}$) fixes lepton charge
– same–sign dileptons in 1/2 of events
– similar: t-channel gluino in $pp \to \tilde{q}\tilde{q}$
$\Rightarrow$ like–sign dileptons in SUSY sample means gluino

Gluino–bottom cascade [Alves, Eboli, TP; like Cambridge squarks]

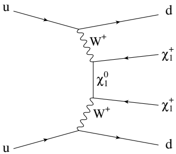
– decay chain from gluino mass [simulated for SUSY]
– compare SUSY with excited KK g, b, Z, ℓ, γ
– below edge: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$
– better: asymmetry b vs. $\bar{b}$ [independent of production]

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

– stable w.r.t production channels and cuts
– less cool: angle between b and $\bar{b}$ [3-body decays: Csaki,...]
$\Rightarrow$ SUSY = gluino = fermionic like-sign dileptons



Spins from jets



More hypothesis testing: spin of LSP [Alwall, TP, Rainwater]

– Majorana LSP with like-sign charginos?

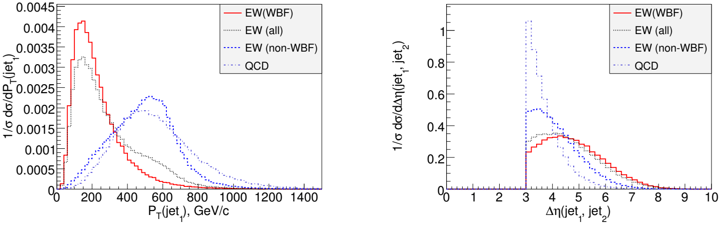
– hypotheses: like–sign charginos (SUSY)
like–sign scalars (scalar dark matter model)
like–sign vector boson (like litte Higgs)

– stable for simplicity — chargino kinematics not used [SM backgrounds]

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

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

$\Rightarrow$ long shot, but not swamped by SUSY-QCD



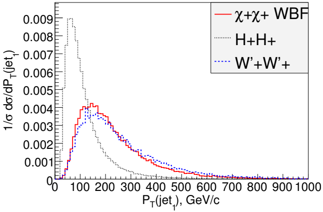
Spins from jets

Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
- H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld; Hankele, Klamke, Figy]
- W radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x,p_T) \sim \frac{1+(1-x)^2}{2x}\,\frac{1}{p_T^2} \qquad\qquad P_L(x,p_T) \sim \frac{(1-x)^2}{x}\,\frac{m_W^2}{p_T^4}$$

$\Rightarrow$ scalars identified by softer $p_{T,j}$



Spins from jets

Like-sign scalars instead

– assume stable charged Higgs (type-II two-Higgs doublet model)
– H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld; Hankele, Klamke, Figy]
– W radiated off quarks [Goldstone coupling to Higgs]

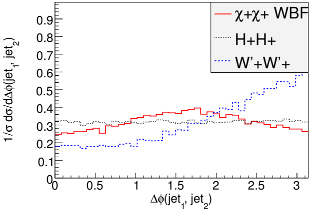
$$P_T(x, p_T) \sim \frac{1+(1-x)^2}{2x} \, \frac{1}{p_T^2} \qquad\qquad P_L(x, p_T) \sim \frac{(1-x)^2}{x} \, \frac{m_W^2}{p_T^4}$$

⇒ 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' [H' necessary for unitarity, but irrelevant at LHC]
– Lorentz structure reflected in angle between jets

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



Spins from jets

Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
- H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld; Hankele, Klamke, Figy]
- W radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x, p_T) \sim \frac{1+(1-x)^2}{2x} \, \frac{1}{p_T^2} \qquad\qquad P_L(x, p_T) \sim \frac{(1-x)^2}{x} \, \frac{m_W^2}{p_T^4}$$

$\Rightarrow$ scalars identified by softer $p_{T,j}$

Like-sign vectors instead

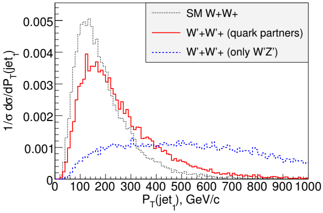
- alternative hypothesis like little Higgs
- start with copy of SM, heavy W', Z', H', f' [H' necessary for unitarity, but irrelevant at LHC]
- Lorentz structure reflected in angle between jets

$\Rightarrow$ 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 $p_{T,j}$

$\Rightarrow$ well–defined hypothesis mandatory



Large extra dimensions

Also solving the hierarchy problem [Arkani-Hamed, Dimopoulos, Dvali]

- weak gravity = large 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]

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

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

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

$\Rightarrow$ fundamental Planck scale at TeV

Kaluza–Klein gravitons

- Fourier–transform extra dimensions [QCD massless]

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

- graviton couplings to quarks and gluons

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

$\Rightarrow$ single gravitons tightly spaced and coupled as $1/M_{\text{Planck}}$

Large extra dimensions

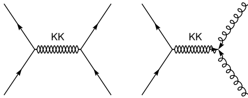
Hope for collider searches

– real radiation of continuous KK tower $[dm/d|k| \sim 1/r]$

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

– higher-dimensional operator from virtual gravitons

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



$\Rightarrow$ $1/M_*$ coupling for KK tower

Large extra dimensions

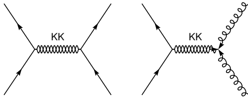
Hope for collider searches

– real radiation of continuous KK tower $[dm/d|k| \sim 1/r]$

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

– higher-dimensional operator from virtual gravitons

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



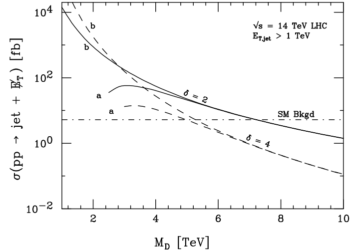
⇒ $1/M_*$ coupling for KK tower

Graviton radiation at LHC [Giudice, Rattazzi, Wells]

– off single–jet production
jets plus missing energy — like SUSY

– background $Z \to \nu\bar{\nu}$

⇒ no challenge at LHC



Large extra dimensions

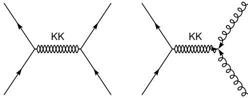
Hope for collider searches

– real radiation of continuous KK tower $[dm/d|k| \sim 1/r]$

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

– higher-dimensional operator from virtual gravitons

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



⇒ $1/M_*$ coupling for KK tower

Virtual gravitons at LHC

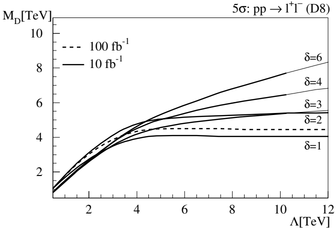
– s–channel $gg \to \mu^+\mu^-$

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

– effective theory not useful at LHC

⇒ UV completion necessary

[Antoniadis, Benakli, Laugier; Cullen, Perelstein, Peskin,...]



Large extra dimensions

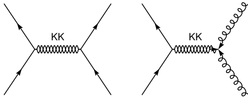
Hope for collider searches

– real radiation of continuous KK tower $[dm/d|k| \sim 1/r]$

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

– higher-dimensional operator from virtual gravitons

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



$\Rightarrow$ $1/M_*$ coupling for KK tower

Virtual gravitons at LHC

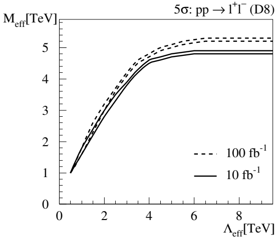
– s–channel $gg \to \mu^+\mu^-$

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

– effective theory not useful at LHC

$\Rightarrow$ UV completion necessary

[Antoniadis, Benakli, Laugier; Cullen, Perelstein, Peskin,...]



Large extra dimensions

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

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

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

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

– asymptotic safety $G(\mu) \sim Z_G^{-1} \sim \mu^{-(2+n)} \longrightarrow 0$ [Weinberg]

⇒ gravity weak enough for LHC predictions?

Graviton propagator [Litim, TP; Hewett & Rizzo]

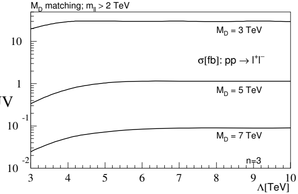
– iterative approach: start with anomalous dimension [similar to QCD analyses]

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

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

– fixed point regularizing integrated $\mathcal{A} = \mathcal{A}_\text{IR} + \mathcal{A}_\text{UV}$

⇒ LHC sensitive to UV completions



New physics at the LHC

TeV–scale new physics

– know there is BSM physics [dark matter,...]
– trust solution of hierarchy problem
– explain dark matter

Theory/Phenomenology in the LHC era

(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
$\Rightarrow$ LHC more than a discovery machine!