New Methods for New Physics

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Outline

New physics at the LHC

Mass measurements

Underlying parameters

Spin from cascades

Spins from jets

Large extra dimensions

New physics at the LHC

Expectations for the LHC era

- find light fundamental Higgs? [Stefan's talk]
- find new physics stabilizing Higgs mass? [why else fundamental Higgs? Apostolos' talk]
- see dark–matter candidate? [if not — ask Herbi]
- Uli Baur's rule: 'there is always new physics at higher scales'

Particle theory and new physics

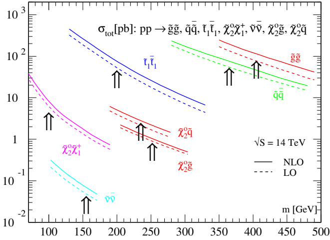
- no such thing as model–independent analyses
- new physics as hypothesis testing [Michael's talk]
  discrete hypotheses: spins,....
  continuous hypotheses: masses,...
- reconstruction of Larangian the final goal [try to answer Arthur's question]

Special about LHC [except it's bigger than Tevatron]

- beyond just inclusive searches [that was Tevatron]
- detailed studies of strongly interacting particles
- general theme: try to survive QCD [not much on that today]

$\Rightarrow$ determine underlying theory [the earlier the better for ILC]

Mass measurements

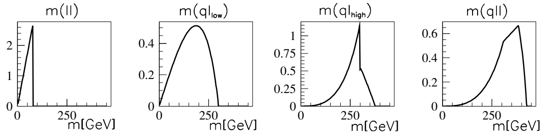


Cascade decays [Atlas-TDR, Cambridge]

- heavy SUSY partners strongly interacting LSP weakly interacting
- inclusive search: jets + missing energy
- tough: $(\sigma\mathrm{BR})_1/(\sigma\mathrm{BR})_2$ [SFitter: 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

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

⇒ new–physics mass spectrum from cascade kinematics



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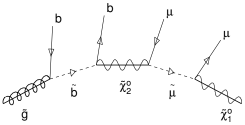

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Gluino decay [Gjelsten, Miller, Osland]

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

– no problem: jet radiation [TP, Rainwater, Skands (2006)]

– no problem: off-shell effects [Catpiss: Hagiwara et al. (2006)]

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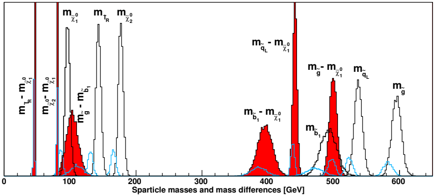
– gluino mass to $\sim 1\%$

⇒ why physical masses?



Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas (2007)]

– 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]

– 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

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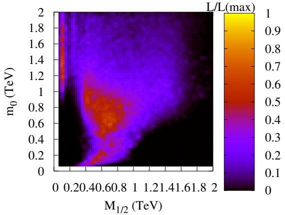
MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

– ‘Which is the most likely parameter point?’

– ‘How does dark matter annihilate/couple?’



Underlying parameters

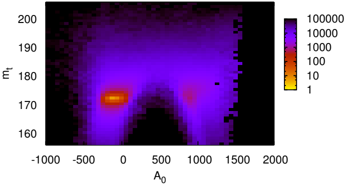
MSUGRA map from LHC [LHC endpoints with free y_t]

– 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

– 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

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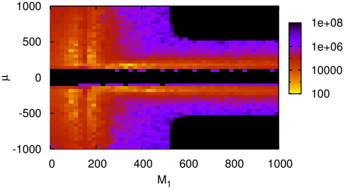
MSSM map from LHC

– 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 likelihoods]



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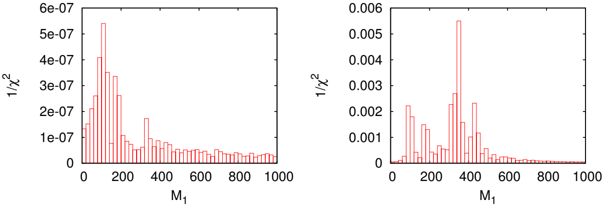

$\Rightarrow$ no best approach to BSM statistics

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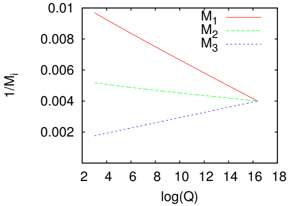
Theorists' goal [SFitter + Kneur (2007+)]

– unification and supersymmetry

– test mass unification with errors [Cohen, Schmalz]

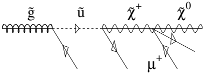
– properly: RGE running bottom–up

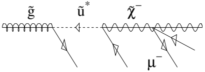
$\Rightarrow$ infer models from weak scale instead of believing



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

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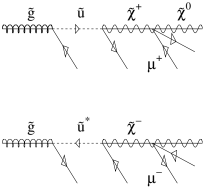


All new physics is hypothesis testing [Barr, Lester, Smillie, Webber]

– loop hole: ‘gluino is Majorana if it is a fermion’

– gluino a fermion?

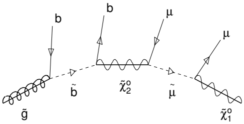
– assume gluino cascade observed

– 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]

⇒ compare distributions [Herwig++, MadEvent]



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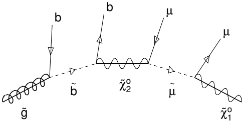
Gluino–bottom cascade [Alves, Eboli, TP (2006)]

– decay chain like for gluino mass [simulated for SUSY]

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

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



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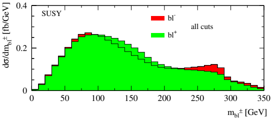
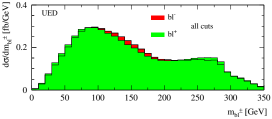
- better: asymmetry b vs. $\bar{b}$ [independent of production]

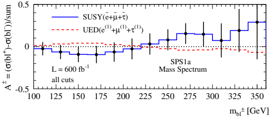
$$\mathcal{A}(m_{\mu b}) = \frac{\sigma(b\ell^+) - \sigma(b\ell^-)}{\sigma(b\ell^+) + \sigma(b\ell^-)}$$

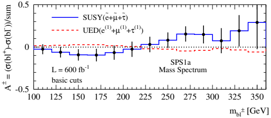
- stable w.r.t production channels and cuts
- backup: angle between b and $\bar{b}$ [3-body decays: Csaki,...]

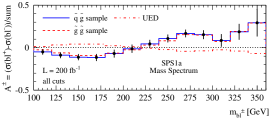
$\Rightarrow$ gluino = fermion with like-sign dileptons











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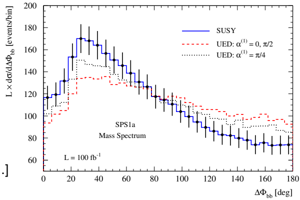
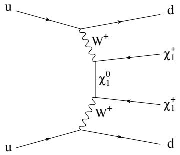


Spins from jets



More hypothesis testing: spin of LSP [Alwall, TP, Rainwater (2007)]

– Majorana LSP with like-sign charginos?

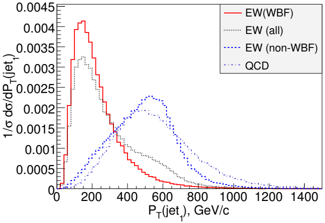
– hypotheses: like–sign charginos (SUSY)
like–sign scalars (scalar dark matter model)
like–sign vector boson (like litte Higgs)

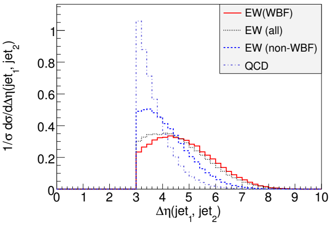
– stable for simplicity — chargino kinematics not used [SM backgrounds]

– 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

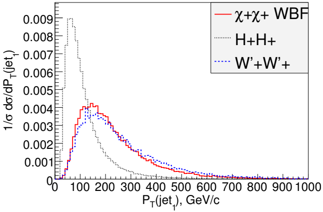
– assume stable charged Higgs (type-II two-Higgs doublet model)

– H^+H^- same as simple heavy H^0 [TP, Rainwater, Zeppenfeld (2001); Hankele, Klamke, Figy]

– W radiated off quarks [Goldstone coupling to Higgs]

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

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



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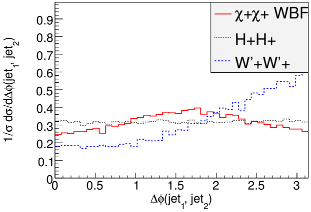
Like-sign vectors instead

- 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 $\Delta\phi_{jj}$



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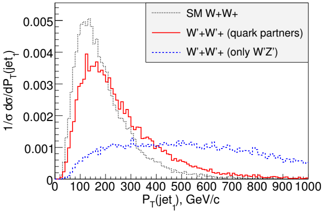
Heavy fermions in little–Higgs models

– not part of the naive set of WBF diagrams

– huge effect on $p_{T,j}$ [careful with alternative hypotheses]

$\Rightarrow$ spin–effects visible in WBF signatures



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: $r = 10^{12}, 10^{-3}, \dots 10^{-11}$ m for $n = 1, 2, \dots 6$

$\Rightarrow$ fundamental Planck scale at TeV

Kaluza–Klein gravitons

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

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

– 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

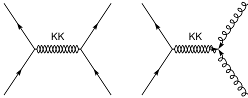
Hope for collider searches

– 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 [$dm/d|k| \sim 1/r$]

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

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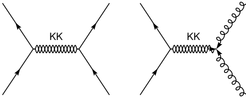


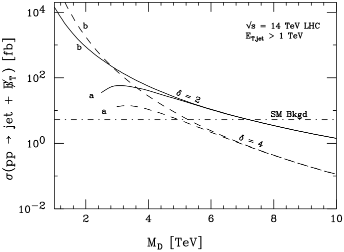
⇒ $1/M_*$ coupling for KK tower

Graviton radiation at LHC [Giudice, Rattazzi, Wells]

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

– background $Z \to \nu\bar{\nu}$
measure $Z \to \mu\mu$ and subtract ['falsify SM']

⇒ no challenge at LHC



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Hope for collider searches

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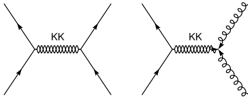


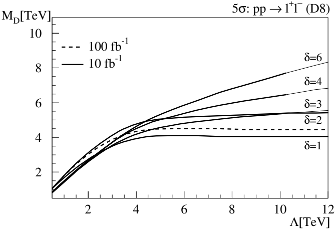
⇒ $1/M_*$ coupling for KK tower

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 not useful at LHC



Large extra dimensions

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

– golden rule: don't talk about things everyone in the audience knows better...

– 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 $G(\mu) \sim Z_G^{-1} \sim \mu^{-(2+n)} \to 0$

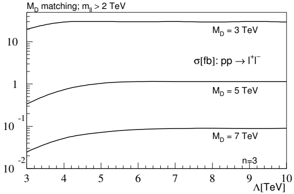
⇒ gravity weak enough for LHC predictions?

Graviton propagator [Litim, TP (2007): Hewett & Rizzo]

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

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

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



⇒ UV fixed point regularizing KK integral

New physics at the LHC

TeV–scale new physics

- know there is BSM physics [dark matter,...]
- trust solution of hierarchy problem
- might explain dark matter
- LHC not just a discovery machine!

Some plans...

- construct sensible new–physics scenarios implement them [into MadEvent]
- define solid discovery channels
- find ways to measure weak–scale Lagrangian study highD parameter spaces [e.g. SFitter]
- avoid getting killed by QCD
- look beyond BSM physics at LHC [dark matter, EDMs, Higgs,...]
- see whatever comes up...

$\Rightarrow$ show that LHC physics can also be fun physics