Phenomenology: Beyond the Standard Model

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Outline

Standard–Model effecive theory

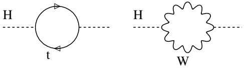
What is the Standard Model?

– 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
$\Rightarrow$ 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]
$\Rightarrow$ general effective–theory Lagrangian with those interactions and particles
$\Rightarrow$ cut-off obvious, scale negotiable, renormalizability desirable
$\Rightarrow$ who the hell cares....???

Standard–Model effective theory



...theorists care!

– compute loop corrections to scalar Higgs mass

– top loop in Higgs self energy Σ

$$\Sigma \sim - \left(\frac{g\, m_t}{v} \right)^2 \int \frac{d^4 q}{(2\pi)^4} \frac{(\not{q} + m_t)\,(\not{q} + \not{p} + m_t)}{[q^2 - m_t^2]\,[(q+p)^2 - m_t^2]} \sim - \frac{1}{(4\pi)^2} \left(\frac{g\, m_t}{v} \right)^2 \Lambda^2 + \cdots$$

– sum to Higgs–mass correction

$$\frac{1}{p^2 - m_H^2} \to \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \dots$$

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

– and watch desaster after collecting all loop functions

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

⇒ Higgs mass including loops wants to be cut-off scale Λ

⇒ Standard–Model effective theory destabilized between v and Λ

[Higgs wants to be at Λ, but would not function as Higgs there]

⇒ hierarchy problem: why not a Σ model if fundamental Higgs unworkable

Standard–Model effective theory

Problem with light Higgs (data–driven)

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

$\Rightarrow$ easy solution: tune counter term $\Rightarrow$ evil, not in 't Hooft's spirit

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

$\Rightarrow$ typically cancellation by new particles or discussing away high scale

$\Rightarrow$ 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]

$\Rightarrow$ all new physics models in baroque state

Standard–Model effective theory

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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(μ) and tan β in Higgs sector

– alternatives: gauge, anomaly, gaugino mediation...?

– link to flavor physics, dark matter,...?

⇒ LHC: measure spectrum

⇒ LHC: if a spectrum, identify BSM model

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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...

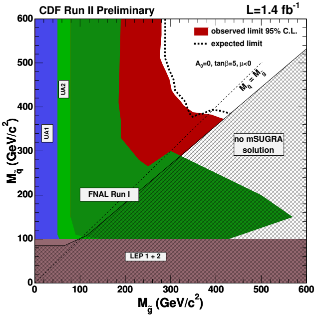
		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
→ sfermion	$\tilde{f}_L, \tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^o, H^o, A^o	0	3	
→ neutralinos	$\tilde{\chi}_i^o$	1/2	$4 \cdot 2$	LSP?
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$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

Supersymmetric signatures

Inclusive: squarks and gluinos at Tevatron

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

$\Rightarrow$ we know inclusive jets plus LSP



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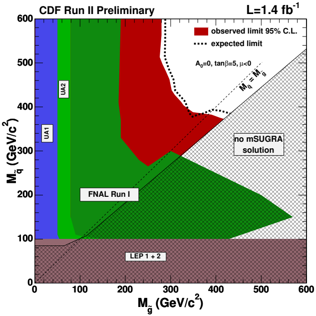
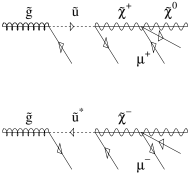


When do we see SUSY–QCD?

- 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 $qq \to \tilde{q}\tilde{q}$

$\Rightarrow$ 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

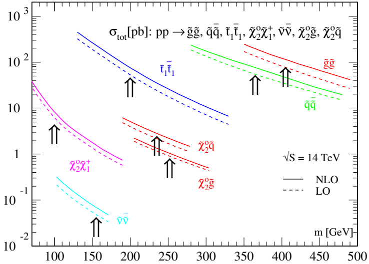
New physics at the LHC

(1) possible discovery — signals for new physics
(2) measurements — masses, cross sections, decays
(3) parameter studies — weak–scale Lagrangian
$\Rightarrow$ approach independent of new physics model

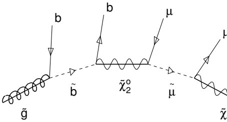
Some SUSY signals at LHC

- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- like–sign dileptons: $pp \to \tilde{g}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1 \tilde{t}_1^*$
- tri-leptons: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^-$
  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0 \ell\bar{\ell};\ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell\bar{\nu}]$

$\Rightarrow$ inclusive: similar to Tevatron
$\Rightarrow$ exclusive: enough events for studies



Masses and cascade decays



Spectra from cascade decays

– tough: $(\sigma \text{BR})_1/(\sigma \text{BR})_2$ [SFitter: focus point]

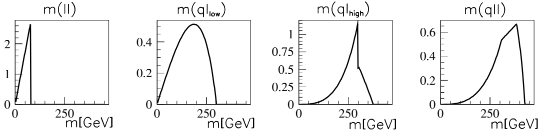
– decay $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$ [better not via Z or to τ]

– large cross sections [more than 100 pb means 3×10^7 events]

– thresholds & edges

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

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



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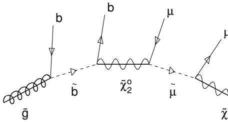

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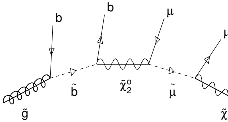
measurement		nominal	stat.	LES	JES	theo.
m_h		108.99	0.01	0.25		2.0
m_t		171.40	0.01		1.0	
$m_{\tilde{l}_L} - m_{\chi_1^0}$		102.45	2.3	0.1		2.2
$m_{\tilde{g}} - m_{\chi_1^0}$		511.57	2.3		6.0	18.3
$m_{\tilde{q}_R} - m_{\chi_1^0}$		446.62	10.0		4.3	16.3
$m_{\tilde{g}} - m_{\tilde{b}_1}$		88.94	1.5		1.0	24.0
$m_{\tilde{g}} - m_{\tilde{b}_2}$		62.96	2.5		0.7	24.5
$m_{ll}^{\max}$:	three-particle edge(χ_2^0,$\tilde{l}_R$,χ_1^0)	80.94	0.042	0.08		2.4
$m_{llq}^{\max}$:	three-particle edge($\tilde{q}_L$,χ_2^0,χ_1^0)	449.32	1.4		4.3	15.2
$m_{lq}^{\rm low}$:	three-particle edge($\tilde{q}_L$,χ_2^0,$\tilde{l}_R$)	326.72	1.3		3.0	13.2
$m_{ll}^{\max}(\chi_4^0)$:	three-particle edge(χ_4^0,$\tilde{l}_R$, χ_1^0)	254.29	3.3	0.3		4.1
$m_{\tau\tau}^{\max}$:	three-particle edge(χ_2^0,$\tilde{\tau}_1$,χ_1^0)	83.27	5.0		0.8	2.1
$m_{lq}^{\rm high}$:	four-particle edge($\tilde{q}_L$,χ_2^0,$\tilde{l}_R$,χ_1^0)	390.28	1.4		3.8	13.9
$m_{llq}^{\rm thres}$:	threshold($\tilde{q}_L$,χ_2^0,$\tilde{l}_R$,$\tilde{\chi}_1^0$)	216.22	2.3		2.0	8.7
$m_{llb}^{\rm thres}$:	threshold($\tilde{b}_1$,χ_2^0,$\tilde{l}_R$,$\tilde{\chi}_1^0$)	198.63	5.1		1.8	8.0

Masses and cascade decays



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- thresholds & edges

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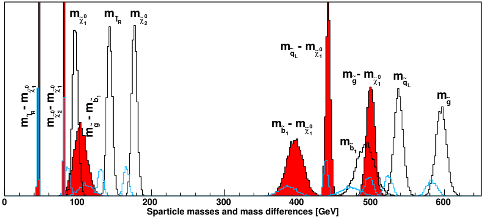
$\Rightarrow$ new–physics spectrum from cascade decays [mass differences with smaller errors]

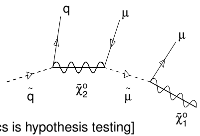
Gluino mass from kinematic endpoints

- 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]

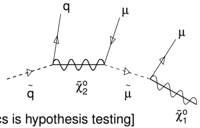
– assume squark cascade observed

⇒ 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 $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\ell\tilde{\ell} \to q\ell\bar{\ell}\tilde{\chi}_1^0$

– compare with first KK q, Z and ℓ [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 θ between q and ℓ: $dP_{1,2}^{\rm SUSY}/d\cos\theta$

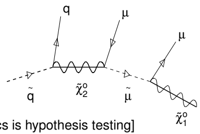
– mass variable: $\hat{m} = m_{ql}/m_{ql}^{\rm max}$

– UED and SUSY distributions [SPS1a spectrum]

$$\frac{dP_1^{\rm SUSY}}{d\hat{m}} = 4\hat{m}^3 \qquad \frac{dP_2^{\rm SUSY}}{d\hat{m}} = 4\hat{m}\left(1-\hat{m}^2\right)$$

$$\frac{dP_1^{\rm UED}}{d\hat{m}} = 1.213\,\hat{m} + 3.108\,\hat{m}^3 - 2.310\,\hat{m}^5 \qquad \frac{dP_2^{\rm UED}}{d\hat{m}} = 2.020\,\hat{m} + 1.493\,\hat{m}^3 - 2.310\,\hat{m}^5$$

Spins and cascade decays



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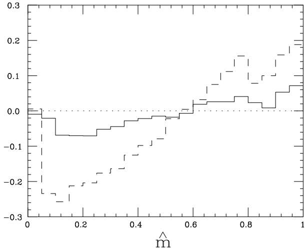
– compare with first KK q, Z and ℓ [near/far lepton?]

– mass variable: $\hat{m} = m_{ql}/m_{ql}^{\max}$

– typically largest rate $pp \to \tilde{q}\tilde{g}$

– production asymmetry $\tilde{q} : \tilde{q}^* \sim 2 : 1$
$\Rightarrow \mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$

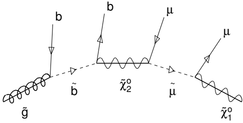


Masses or spin or both?

– masses from kinematic endpoints [use $m_{\ell j}, m_{\ell\ell}, m_{j\ell\ell}\dots$]

– 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

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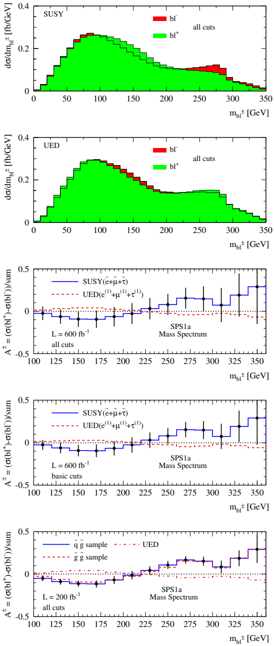
Gluino–bottom cascade

- decay chain like for gluino mass
- compare with first KK g, b, Z, ℓ, γ

- replace initial–state asymmetry by b vs. $\bar{b}$
- independent of production channels
- asymmetry to write down:
  $\mathcal{A} = [\sigma(b\ell^+) - \sigma(b\ell^-)]/[\sigma(b\ell^+) + \sigma(b\ell^-)]$

  [still visible after cuts and smearing]
- detector/machine upgrade? [we are so ignorant!]



Spins and cascade decays

Back to gluinos as proof of SUSY–QCD

– loop hole: like–sign dileptons from heavy gluon

– show gluino a fermion

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Gluino–bottom cascade

– interchange $\tilde{\ell}_{LR}$ in cascade

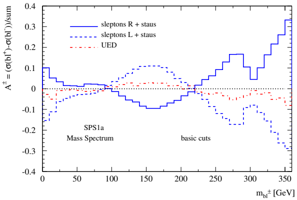
– test of lepton-ino couplings

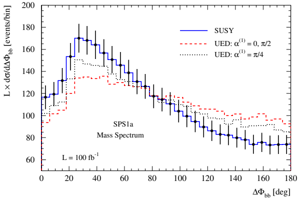
– purely hadronic ϕ_{bb} [if asymmetry not possible]

– independent of weak decays

– sensitive to gluino/KK-gluon boost

⇒ gluino from cascade and like–sign dileptons





New physics and jets

Squarks and gluinos always with many jets

– cascade studies sensitive to jet simulation?

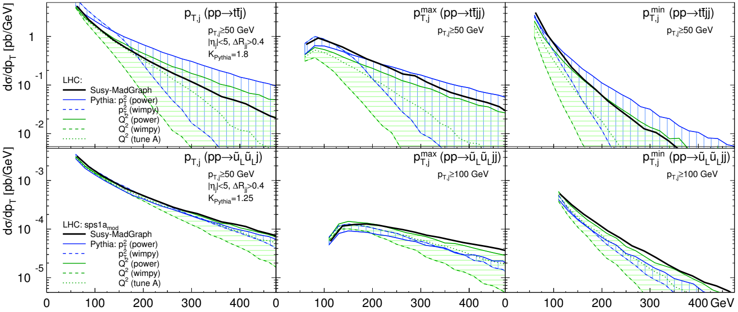
– matrix element $\tilde g\tilde g$+2j and $\tilde u_L\tilde g$+2j [$p_{T,j} >$ 100 GeV]

– compared with Pythia shower [recent tune!]

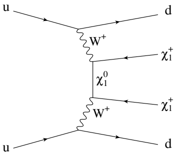
– hard scale μ_F huge for SUSY

$\Rightarrow$ QCD not a problem for new–physics seaches

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



Spins and jets



More hypothesis testing: spin of LSP [no talk without WBF in Karlsruhe]

– Majorana LSP with like-sign charginos?

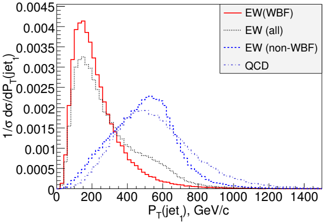
– hypotheses: like–sign charginos (SUSY)
like–sign scalars (scalar dark matter model)
like–sign vector boson (like litte Higgs)

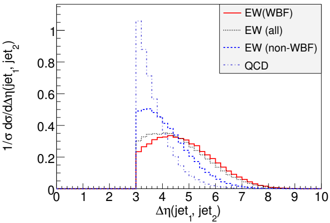
– stable for simplicity — chargino kinematics not used [SM backgrounds]

– 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 and jets

Like-sign scalars instead

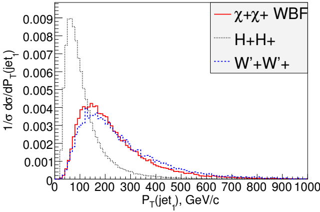
– assume stable charged Higgs (type-II two-Higgs doublet model)

– $H^+ H^-$ same as simple heavy H^0

– W radiated off quarks [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 $p_{T,j}$



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– Lorentz structure reflected in angle between jets

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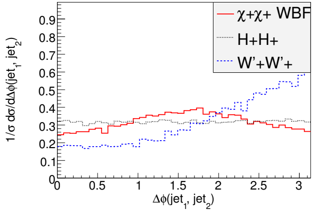

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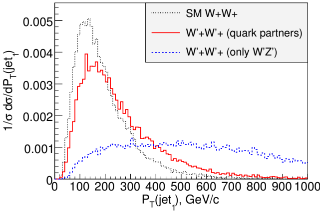
Heavy fermions in little–Higgs models

– 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



Underlying parameters

From kinematics to weak–scale parameters

– parameters: weak-scale Lagrangian

– measurements: LHC edges, ($\sigma \cdot$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 $\Rightarrow$ mSUGRA or CMSSM

– fit $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu), y_t, ...$

– no problem, include indirect constraints

$\Rightarrow$ probability map as of today

$\Rightarrow$ best fit from LHC/ILC measurements

	SPS1a	ΔLHC masses	ΔLHC edges	ΔILC	ΔLHC+ILC
m_0	100	3.9	1.2	0.09	0.08
$m_{1/2}$	250	1.7	1.0	0.13	0.11
$\tan\beta$	10	1.1	0.9	0.12	0.12
A_0	-100	33	20	4.8	4.3

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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

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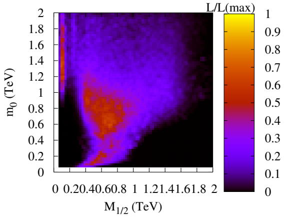
MSUGRA as of today [Bayesian or frequentist?]

– 'Which is the most likely parameter point?'

– 'How does dark matter annihilate/couple?'



Underlying parameters

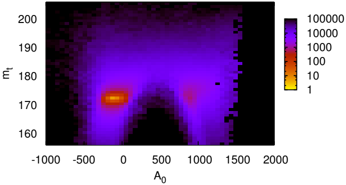
MSUGRA map from simulated LHC data [endpoints with free y_t]

– weighted Markov chains: several times faster

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

– SFitter output #1: fully exclusive likelihood map
SFitter output #2: ranked list of local maxima

– clear maximum, but 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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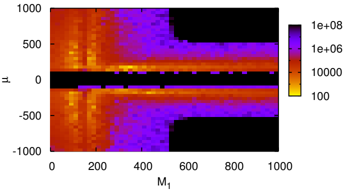
MSSM map from LHC data

– 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]



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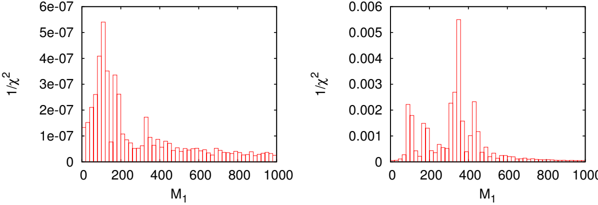

⇒ no best approach to BSM statistics

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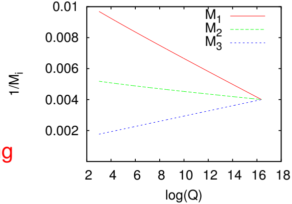
Theorists' goal

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



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 $G_N = 1/(16\pi M_{\text{Planck}})^2$

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

Large extra dimensions (ADD)

– Einstein–Hilbert action for fundamental Planck scale

$$S = -\frac{1}{2}\int d^4x \sqrt{|g|}\, M_*^2\, R \to -\frac{1}{2}\int d^{4+n}x \sqrt{|g|}\, M_*^{2+n}\, R$$

– compactify additional dimensions on torus

$$S = -\frac{1}{2}\int d^{4+n}x \sqrt{|g|}\, M_*^{2+n}\, R = -\frac{1}{2}(2\pi r)^n \int d^4x \sqrt{|g|}\, M_*^{2+n}\, R$$

– match the two theories on our brane [also: match to measurements]

$$-\frac{1}{2}(2\pi r)^n \int d^4x \sqrt{|g|}\, M_*^{2+n}\, R \equiv -\frac{1}{2}\int d^4x \sqrt{|g|}\, M_{\text{Planck}}^2\, R$$

$\Rightarrow$ express the 4D Planck scale in terms of fundamental Planck scale

$$M_{\text{Planck}} = M_*(2\pi r M_*)^{n/2}$$

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⇒ solution: there is another reason why we see a huge $M_{\rm Planck}$

Numbers to make it work

– wanted $rM_* \gg 1$

– constraints from gravity tests above $\mathcal{O}$(mm)

– $M_* = 1$ TeV $\ll M_{\rm Planck}$ fine for $n \gtrsim 2$

n	r
1	10^{12} m
2	10^{-3} m
3	10^{-8} m
...	...
6	10^{-11} m

⇒ 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]

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

– include matter into Einstein's equation

$$R_{AB} - \frac{1}{2+n} g_{AB} R = - \frac{1}{M_*^{2+n}} \begin{pmatrix} T_{\mu\nu}(x)\, \delta^{(n)}(y) & 0 \\ 0 & 0 \end{pmatrix}$$

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

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

– only the interacting (tensor) graviton [$h_{AB} \to G_{\mu\nu}$, 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 [$M_* = 1$ 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 $\delta m \ll$ GeV [below mass resolution]

– universal couplings to massless SM particles via $-T_{\mu\nu}/M_{\text{Planck}}$

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

⇒ 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]

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

– UV completion needed to get rid of Λ dependence

⇒ $1/M_*^2$ interactions after integration over KK tower

Large extra dimensions

UV completion: renormalization flow of gravity [strings also work]

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

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

$\Rightarrow$ gravity weak enough for well-defined predictions?

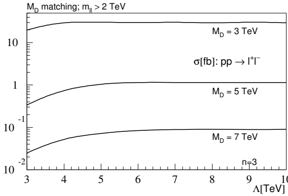
Graviton propagator

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

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

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

$\Rightarrow$ UV fixed point regularizing KK integral



Warped extra dimensions

Alternative Solution

– try one extra dimension, but not flat [TeV brane at $y = b$]

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \quad \Leftrightarrow \quad g_{AB} = \begin{pmatrix} e^{-2k|y|}\eta_{\mu\nu} & 0 \\ 0 & \eta_{jk} \end{pmatrix}$$

– integration measure in our usual Lagrangian $d^4\tilde{x}\; e^{-4kb}, \tilde{g}_{\mu\nu} = \eta_{\mu\nu}$

$$S = \int dy\delta(y)\; d^4\tilde{x}\, e^{-4kb}\,\mathcal{L} = \int\; d^4\tilde{x}\, e^{-4kb}\,\left[|D_\mu H|^2 - \lambda(|H|^2 - v^2)^2 + ...\right]$$

– write effecive 4D theory on TeV brane scaling all fields

$$\begin{aligned} \tilde{H} &= e^{-kb}H && \text{scalars} \\ \tilde{A}_\mu &= e^{-kb}A_\mu && \text{or } \tilde{D}_\mu = e^{-kb}D_\mu \\ \tilde{\Psi} &= e^{-3kb/2}\Psi && \text{fermions} \\ \tilde{m} &= e^{-kb}m && \\ \tilde{v} &= e^{-kb}v && \end{aligned}$$

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

$\Rightarrow$ 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

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

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

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

$$-\partial_z^2 \Phi + \frac{15}{4} \frac{k^2}{(kz+1)^2} \Phi = m^2 \Phi$$

⇒ masses given by roots of Bessel functions $J_1(x_j) = 0$

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

– couplings via wave-function overlap in z [approximately, neglect Bessel functions]

$$\frac{\Phi(z)\big|_\text{TeV}}{\Phi(z)\big|_\text{Planck}} \sim \frac{\sqrt{kz+1}\big|_\text{Planck}}{\sqrt{kz+1}\big|_\text{TeV}} \sim \frac{1}{\sqrt{e^{ky}}\big|_\text{TeV}} \sim \frac{1}{e^{kb/2}}$$

⇒ universal couplings except for zero mode graviton

$$\mathcal{L} \sim \frac{1}{M_\text{Planck}} T^{\mu\nu} h^{(0)}_{\mu\nu} + \frac{1}{M_\text{Planck}\, e^{-kb}} T^{\mu\nu} \sum h^{(m)}_{\mu\nu}$$

⇒ 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?