

# New Physics at the LHC

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Graduiertenkolleg Karlsruhe, 10/2007

# 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

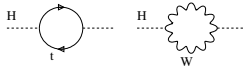
## What is the Standard Model?

- 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  $\Sigma$

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

- sum to Higgs–mass correction

$$\begin{aligned} \frac{1}{p^2 - m_H^2} &\rightarrow \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \dots \\ &= \frac{1}{p^2 - m_H^2} \sum_{j=0}^{\infty} \left( \frac{\Sigma}{p^2 - m_H^2} \right)^j = \frac{1}{p^2 - m_H^2} \frac{1}{1 - \frac{\Sigma}{p^2 - m_H^2}} = \frac{1}{p^2 - m_H^2 - \Sigma} \end{aligned}$$

- and watch disaster after collecting all loop functions

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

- ⇒ Higgs mass including loops wants to be cut-off scale  $\Lambda$
- ⇒ Standard–Model effective theory destabilized between  $v$  and  $\Lambda$

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

- ⇒ **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 ⇒ **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**

# 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 [not a LHC paradigm!]

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

plus  $\text{sign}(\mu)$  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

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## LHC phenomenology: MSSM

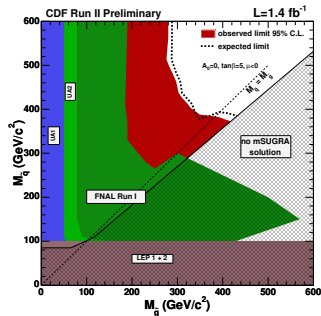
- conjugate Higgs field not allowed
    - give mass to  $t$  and  $b$ ?
    - avoid higgsino anomalies
    - two Higgs doublets
  - BSM-Higgs  $\neq$  SM-Higgs
- ⇒ would be another lecture...

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

# Supersymmetric signatures

## Inclusive: squarks and gluinos at Tevatron

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





# Supersymmetric signatures

Why?

Supersymmetry

LHC Signals

Masses

Spins 1

Jets

Spins 2

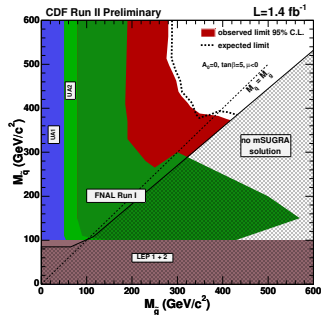
Parameters

Large dimensions

Warped dimensions

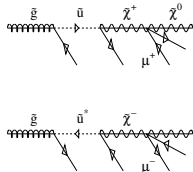
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## When do we see SUSY-QCD?

- 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  $qq \rightarrow \tilde{q}\tilde{q}$
- ⇒ **like-sign dileptons from gluinos**

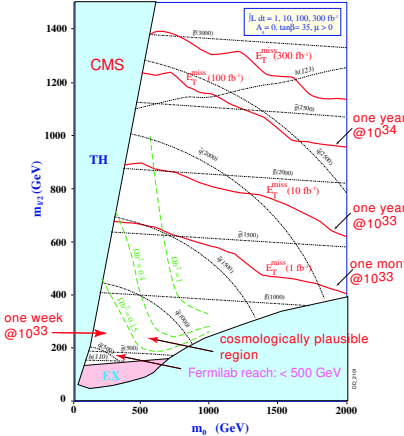


# Supersymmetric signatures

## New physics at the LHC

- (1) possible discovery — signals for new physics
- (2) measurements
- (3) parameter studies

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



# Supersymmetric signatures

Why?

Supersymmetry

LHC Signals

Masses

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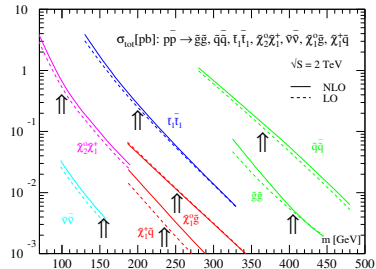
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## New physics at the LHC

- (1) **possible discovery** — signals for new physics
  - (2) **measurements** — masses, cross sections, decays
  - (3) **parameter studies** — weak-scale Lagrangian
- ⇒ approach independent of new physics model

## Some SUSY signals at Tevatron

- jets and  $\cancel{E}_T$ :  $pp \rightarrow \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- like-sign dileptons:  $pp \rightarrow \tilde{g}\tilde{g}$
- funny tops:  $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$
- tri-leptons:  $pp \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^-$   
 $[\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\tilde{\ell} \rightarrow \tilde{\chi}_1^0\ell\tilde{\ell}; \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\ell\tilde{\nu}]$



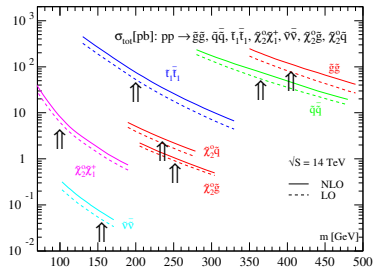
# Supersymmetric signatures

## New physics at the LHC

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## Some SUSY signals at LHC

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 $[\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\tilde{\ell} \rightarrow \tilde{\chi}_1^0\ell\tilde{\ell}; \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\ell\tilde{\nu}]$
- ⇒ inclusive: similar to Tevatron
- ⇒ **exclusive: enough events for studies**



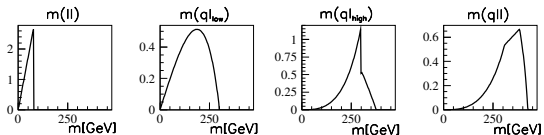
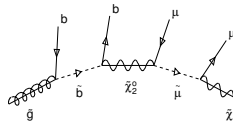
# Masses and cascade decays

## Spectra from cascade decays

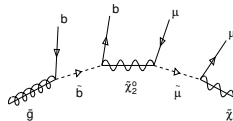
- tough:  $(\sigma BR)_1 / (\sigma BR)_2$  [SFitter: focus point]
- decay  $\tilde{g} \rightarrow \tilde{b}\tilde{b} \rightarrow \tilde{\chi}_2^0 b\tilde{b} \rightarrow \mu^+ \mu^- b\tilde{b}\tilde{\chi}_1^0$  [better not via Z or to  $\tau$ ]
- large cross sections [more than 100 pb means  $3 \times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

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

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



# Masses and cascade decays



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

measurement	nominal	stat.	LES	JES	theo.
$m_h$	108.99	0.01	0.25		2.0
$m_t$	171.40	0.01		1.0	
$m_{\tilde{L}} - m_{\tilde{\chi}_1^0}$	102.45	2.3	0.1		2.2
$m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$	511.57	2.3		6.0	18.3
$m_{\tilde{q}_R} - m_{\tilde{\chi}_1^0}$	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 $(\tilde{\chi}_2^0, \tilde{l}_R, \tilde{\chi}_1^0)$	80.94	0.042	0.08		2.4
$m_{llq}^{\max}$ : three-particle edge $(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$	449.32	1.4		4.3	15.2
$m_{lq}^{\text{low}}$ : three-particle edge $(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{l}_R)$	326.72	1.3		3.0	13.2
$m_{ll}^{\max}(\tilde{\chi}_4^0)$ : three-particle edge $(\tilde{\chi}_4^0, \tilde{l}_R, \tilde{\chi}_1^0)$	254.29	3.3	0.3		4.1
$m_{\tau\tau}^{\max}$ : three-particle edge $(\tilde{\chi}_2^0, \tilde{\tau}_1, \tilde{\chi}_1^0)$	83.27	5.0		0.8	2.1
$m_{lq}^{\text{high}}$ : four-particle edge $(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{\chi}_1^0)$	390.28	1.4		3.8	13.9
$m_{llq}^{\text{thres}}$ : threshold $(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{l}_R, h_1^0)$	216.22	2.3		2.0	8.7
$m_{llb}^{\text{thres}}$ : threshold $(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{l}_R, h_1^0)$	198.63	5.1		1.8	8.0



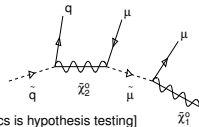




# Spins and cascade decays

## 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]

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

- compare with first KK 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  $\ell$ :  $dP_{1,2}^{\text{SUSY}}/d\cos\theta$
- mass variable:  $\hat{m} = m_{q\ell}/m_{q\ell}^{\text{max}} = \sin\theta/2$
- UED and SUSY distributions [SPS1a spectrum]

$$\frac{dP_1^{\text{SUSY}}}{d\hat{m}} = 4\hat{m}^3$$

$$\frac{dP_1^{\text{UED}}}{d\hat{m}} = 1.213\hat{m} + 3.108\hat{m}^3 - 2.310\hat{m}^5$$

$$\frac{dP_2^{\text{SUSY}}}{d\hat{m}} = 4\hat{m}(1 - \hat{m}^2)$$

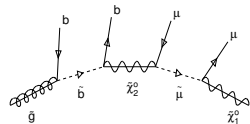
$$\frac{dP_2^{\text{UED}}}{d\hat{m}} = 2.020\hat{m} + 1.493\hat{m}^3 - 2.310\hat{m}^5$$



# 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

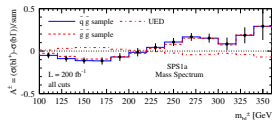
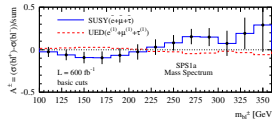
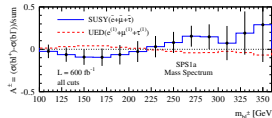
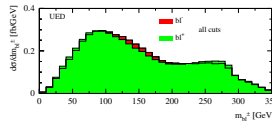
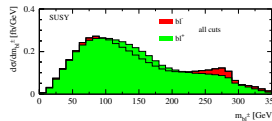
## Back to gluinos as proof of SUSY-QCD

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## 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:  

$$\mathcal{A} = [\sigma(bl^+) - \sigma(bl^-)] / [\sigma(bl^+) + \sigma(bl^-)]$$
 [still visible after cuts and smearing]
- detector/machine upgrade? [we are so ignorant!]



# Spins and cascade decays

Why?

Supersymmetry

LHC Signals

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Spins 1

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Large dimensions

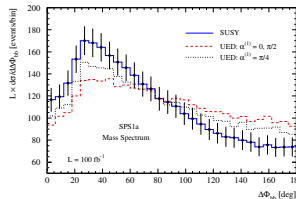
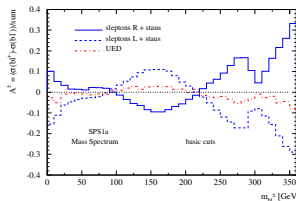
Warped dimensions

## Back to gluinos as proof of SUSY-QCD

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## Gluino-bottom cascade

- interchange  $\tilde{\ell}_{LR}$  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**



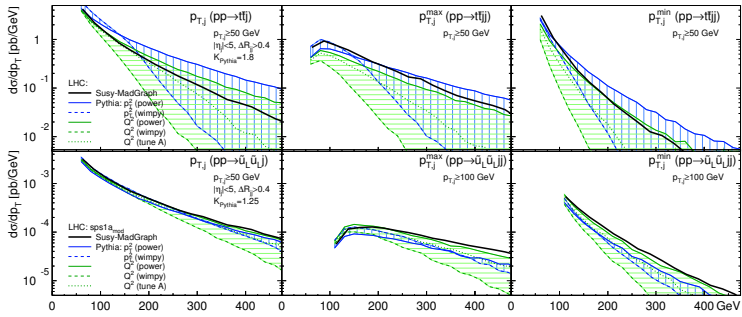
# New physics and jets

## 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  $\mu_F$  huge for SUSY

⇒ QCD not a problem for new-physics searches

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

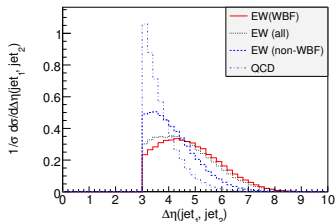
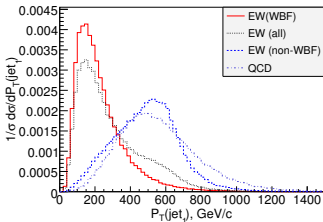
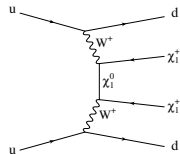


- Why?
- Supersymmetry
- LHC Signals
- Masses
- Spins 1
- Jets
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# Spins and jets

## 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  $\Delta\phi_{jj}, \rho_{T,j}$  [like  $H \rightarrow ZZ \rightarrow 4\mu$  or WBF-Higgs]
- ⇒ distinct WBF signal? [ $\rho_{T,j} \sim m_W$ , forward jets]
- visible over backgrounds? [SUSY-QCD backgrounds dominant]
- ⇒ **long shot, but not swamped by SUSY-QCD**



# Spins and jets

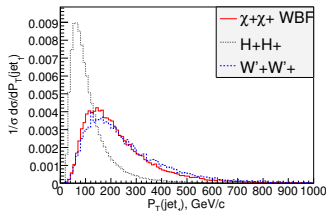
## Like-sign scalars instead

- 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]

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

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

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





## Spins and jets

Why?

Supersymmetry

LHC Signals

Masses

Spins 1

Jets

Spins 2

Parameters

Large dimensions

Warped dimensions

## Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
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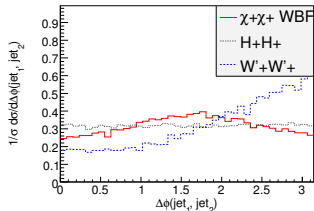
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## Like-sign vectors instead

- alternative hypothesis like little Higgs
- start with copy of SM, heavy  $W', Z', H', f'$  [ $H'$  necessary for unitarity, but irrelevant at LHC]
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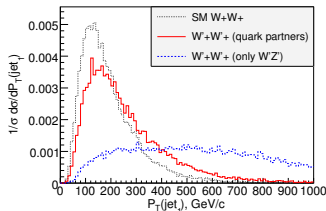
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## Heavy fermions in little-Higgs models

- not part of the naive set of WBF diagrams
- huge effect on  $p_{T,j}$  [careful with alternative hypotheses]

⇒ 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	$\Delta$ LHC masses	$\Delta$ LHC edges	$\Delta$ ILC	$\Delta$ LHC+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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## 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

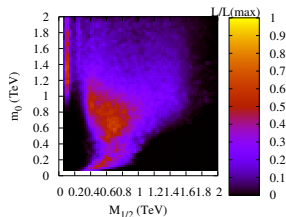
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## MSUGRA as of today [Bayesian or frequentist?]

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



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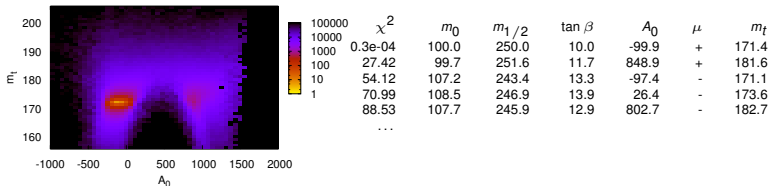
Warped dimensions

MSUGRA map from LHC [LHC endpoints with free  $y_t$ ]

- weighted Markov chains: several times faster [Ferrenberg & Swendsen]

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

- 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

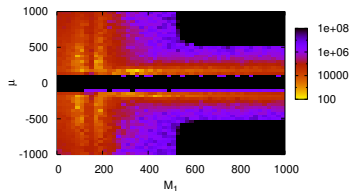
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## MSSM map from LHC

- 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]





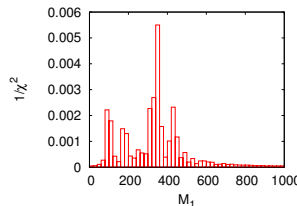
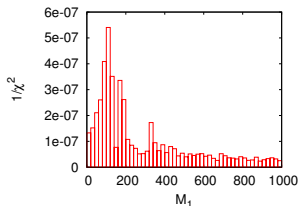
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⇒ **no best approach to BSM statistics**

## Underlying parameters

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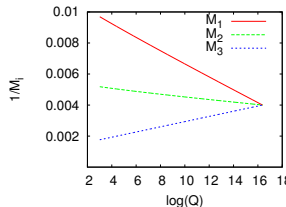
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### Theorists' goal

- unification and supersymmetry
  - test mass unification with errors [Cohen, Schmalz]
  - 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
- 
- next lecture: extra dimensions or QCD plus Madgraph tutorial?

# 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

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

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

## Large extra dimensions (ADD)

- Einstein–Hilbert action for fundamental Planck scale

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

- compactify additional dimensions on torus

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

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

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

⇒ express the 4D Planck scale in terms of fundamental Planck scale

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

# Large extra dimensions

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## Numbers to make it work

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

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

⇒ signatures of strong gravitation in extra dimension?

## Large extra dimensions

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## 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 [ $h_{AB} \rightarrow G_{\mu\nu}$ , QCD massless]

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

- 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  $-T_{\mu\nu}/M_{\text{Planck}}$

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

⇒ **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]

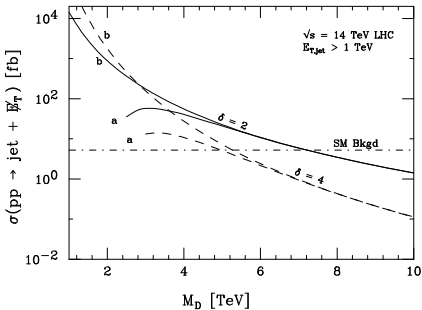
$$\mathcal{A} = \frac{1}{M_{\text{Planck}}^2} T_{\mu\nu} T^{\mu\nu} \frac{1}{s - m_{\text{KK}}^2} \rightarrow \frac{S_{\delta-1} \Lambda^{n-2}}{2 M_*^{n+2}}$$

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

# Large extra dimensions

## Gravitons radiation

- off single-jet production [huge rate]
- off DY production [precise knowledge]
- background: radiation of  $Z \rightarrow \nu\bar{\nu}$  [measure  $Z \rightarrow \ell\ell$  and subtract]



⇒ jet channel no challenge at LHC



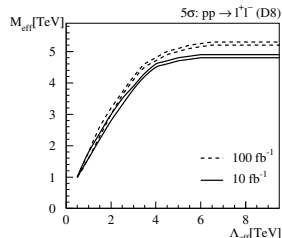
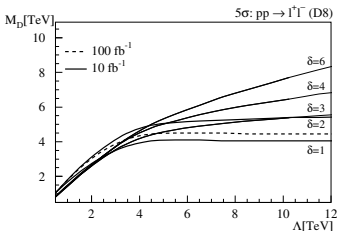
# Large extra dimensions

## Gravitons radiation

- off single-jet production [huge rate]
  - off DY production [precise knowledge]
- ⇒ **jet channel no challenge at LHC**

## Virtual gravitons

- $s$  channel  $gg \rightarrow \mu^+ \mu^-$  new at LHC
- $s$  channel  $gg \rightarrow$  jets useless [QCD background uncertainty huge]
- effective field theory in  $M_{\text{plank}}$  [ $1/M_{\text{eff}}^4$  better]



# Large extra dimensions

## Renormalization flow of gravity

- 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:  $\eta = -\mu \partial_\mu \log Z_G \propto g$ ]

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

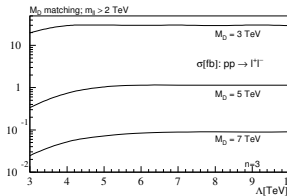
- asymptotic safety  $G(\mu) \sim Z_G^{-1} \sim \mu^{-(2+n)} \rightarrow 0$
- ⇒ gravity weak enough for LHC predictions?

## Graviton propagator

- iterative approach: start with anomalous dimension [similar to QCD analyses]
- UV: dressed scalar propagator [ $1/(Z_G(|p|) p^2) \sim 1/p^{4+n}$ ]

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

⇒ 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  $d^4\tilde{x} e^{-4kb}$ ,  $\tilde{g}_{\mu\nu} = \eta_{\mu\nu}$

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

- write effective 4D theory on TeV brane scaling all fields

$$\tilde{H} = e^{-kb} H \quad \text{scalars}$$

$$\tilde{A}_\mu = e^{-kb} A_\mu \quad \text{or } \tilde{D}_\mu = e^{-kb} D_\mu$$

$$\tilde{\psi} = e^{-3kb/2} \psi \quad \text{fermions}$$

$$\tilde{m} = e^{-kb} m$$

$$\tilde{v} = e^{-kb} v$$

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

$\Rightarrow$  **mass scale on TeV brane shifted**

$$\tilde{v} \sim 0.1 e^{-kb} M_{\text{Planck}} \sim 0.1 \text{ TeV}$$

# 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  $\tilde{h}_{\mu\nu}(x, z) = \hat{h}_{\mu\nu}(x)\Phi(z)$

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

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

⇒ Bessel functions, masses given by roots  $J_1(x_j) = 0$  [Neumann boundary conditions]

$$m_j = x_j k e^{-kb} \quad x_j = 3.8, 7.0, 10.2, 16.5, \dots$$

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

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

⇒ universal couplings except for zero mode graviton

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

# Warped extra dimensions

TeV-scale resonances to e.g. leptons, revisited...

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# Extra Dimensions

## Extra dimensions alternative scenario for LHC

- interesting new model
- signal: missing energy or resonances
- no challenge for LHC trigger
- identification of model parameters?

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**New Physics at the  
LHC**

**Tilman Plehn**

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