## Confusions in Cascades – Disentangling New Physics in LHC cascades

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JRR/Wiesler, 1212.5559 [hep-ph], EPJC 73 (2013) 2355; Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148; JRR/Wiesler, PRD84 (2011) 015012; Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JRR/Schumann, PRD73 (2006) 055005

IFT Seminar, Madrid, March 21st, 2013

#### Standard Model Triumph: 2012: Discovery of a Higgs boson









1/33

#### ... and what now?

	ATLAS SUSY	' Searches* - 95% CL Lower Limits (Statu	s: Dec 2012)
MSUGRA/CMSSM : 0 lep + j's +	ET	1.50 TeV Q = Q mass	
MSUGRA/CMSSM : 1 lep + j's +	ET.miss L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV q = g mass	471 4.0
o Pheno model : 0 lep + j's +	ET.mics L=5.8 fb", 8 TeV [ATLAS-CONF-2012-109]	1.18 TeV g mass (m(q) < 2 TeV, light $\chi^0_1$	AILAS
Pheno model : 0 lep + j's +	ET,miss L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-109]	1.38 TeV Q MASS (m(g) < 2 TeV, light	χ <sup>*</sup> ) Preliminary
Gluino med. x̄ <sup>+</sup> (g→qqx̄ <sup>+</sup> ) : 1 lep + j's +	E L=4.7 fb <sup>-1</sup> , 7 TeV [1208.4688]	<b>900 GeV</b> $\hat{\mathbf{g}}$ mass $(m(\tilde{\chi}) < 200 \text{ GeV}, m(\tilde{\chi}) =$	$(m(\tilde{\chi})+m(\tilde{g}))$
GMSB (I NLSP) : 2 lep (OS) + j's +	E_T.miss L=4.7 fb <sup>-1</sup> , 7 TeV [1208.4688]	1.24 TeV g mass (tanβ < 15)	
GMSB (TNLSP): 1-2 T + 0-1 lep + j S +	E	1.20 TeV g mass (tanβ > 20)	ſ
GGM (wino NI SP) : v + lep +	E <sup>T,miss</sup>	1.07 TeV g mass (m(\chi_1) > 50 GeV)	Ldt = (2.1 - 13.0) fb <sup>-1</sup>
GGM (higgsing-bing NLSP) : y + b +	E-4.8 fb , 7 TeV [ATLAS-CONF-2012-144]	and any a most (and a contract	- 7 8 ToV
GGM (biggsing NLSP) : 7 + jets +	F T,miss	500 GeV 0 mass (m(X,) > 220 GeV)	s = 7, 8 lev
Gravitino LSP : 'monoiet' +	E-10.5 (b <sup>-1</sup> 8 TeV (ATL AS-CONE-2012-147)	555 Gov F <sup>1/2</sup> SCale (m(3) > 10 <sup>-4</sup> eV)	
n→bhy (virtualh): 0 lep + 3 b-i's +	F L=12.8 fb <sup>-1</sup> .8 TeV [ATLAS-CONF-2012-145]	1.24 TeV g mass (m(y) < 200 GeV)	
a→tty (virtual t) : 2 lep (SS) + i's +	E L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-105]	850 Gev g mass (m(x)) < 300 GeV)	
a d→tty (virtualt): 3 lep + i's +	ET	860 GeV $\tilde{g}$ mass $(m(\tilde{\chi}_{\lambda}^{b}) < 300 \text{ GeV})$	8 TeV results
p ∃ g→tty (virtual t) : 0 lep + multi-j's +	ET	1.00 TeV g mass (m(x) < 300 GeV)	7 TeV results
<sup>(5)</sup> G→tt y <sup>0</sup> (virtual t): 0 lep + 3 b is +	ET miss L=12.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-145]	1.15 TeV g mass (m(x) < 200 GeV)	
bb,b,→by : 0 lep + 2-b-jets +	ET.miss L=12.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-165]	620 GeV b mass (m(χ̃) < 120 GeV)	
bb,b,→ty : 3 lep + js +	ET.miss L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-151]	405 GeV b mass $(m(\tilde{\chi}_1) = 2 m(\tilde{\chi}_1))$	
$f(light), t \rightarrow b\chi^{-1}: 1/2 liep (+ b-jet) +$	E 7,miss L=4.7 fb <sup>-1</sup> , 7 TeV [1208.4305, 1209.2102]67 G	ev t mass $(m(\chi_1^2) = 55 \text{ GeV})$	
S tt (medium), t→by : 1 lep + b-jet + t (medium), t→by : 2 lep +	ET,miss L=13.0 fb ', 8 TeV [ATLAS-CONF-2012-166]	160-350 GeV t mass (m(x)) = 0 GeV, m(x)) = 150 GeV)	
E C ((neuluri), t→bχ . 2 lep +	E_T,miss L=13.0 fb , 8 feV [ATLAS-CONF-2012-167]	160-440 Gev (111255 (m(x,) = 0 Gev, m(t)-m(x,) = 10 Gev)	
$t_1 \to t_2$ . The p+ b-jet +	F 1 =4.7 (b) <sup>-1</sup> 7 TeV (1208 1447 1208 2510 1209 4	180 200 400 t mass (m(2,)=0)	
tt (natural GMSB) : Z(→II) + b-iet +	E L=2.1 fb <sup>-1</sup> , 7 TeV [1204.6736]	310 GeV 1 Mass (115 cm(x) c 230 GeV)	
1.1. 1→17 <sup>0</sup> · 2 len +	F	<b>5 GeV</b>   mass $(m(\tilde{y}^0) = 0)$	
$\geq \frac{1}{2}$ $\overline{\chi}^+ \overline{\chi}^-, \overline{\chi}^+ \rightarrow \overline{I} \sqrt{(\overline{V})} \rightarrow I \sqrt{\chi}^0 : 2 I ep +$	ET miss L=4.7 fb <sup>-1</sup> , 7 TeV [1208.2884]	<b>110-340 GeV</b> $\overline{\chi}_{+}^{\pm}$ mass $(m(\chi_{+}^{0}) < 10 \text{ GeV}, m(\widetilde{\chi}_{+}) = \frac{1}{2}(m(\chi_{+}^{0}) + m(\chi_{+}^{0})))$	
$\overline{\chi}, \overline{\chi}, \rightarrow \overline{I}, \overline{\chi}, \overline{I}, \overline{V}, \overline{I}, \overline{V}, \overline{I}, \overline{V}, $	EL=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-154]	580 GeV $\chi_{\perp}^{\pm}$ mass $(m(\chi_{\perp}^{\pm}) = m(\chi_{\perp}^{0}), m(\chi_{\perp}^{0}) = 0, m(\tilde{l}, \tilde{l})$ a	s above)
$\overline{\chi}_{\chi}^{\pm 0} \rightarrow W^{*} \overline{\chi}_{\chi}^{-2} \overline{\chi}_{\chi}^{0}$ : 3 lep +	ET miss L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-154]	140-295 GeV $\chi_1^{\pm}$ mass $(m(\chi_1^{\pm}) = m(\chi_2^{\pm}), m(\chi_1^{\pm}) = 0$ , sleptons decoupled)	
Direct x <sup>1</sup> páir prod. (AMSB) : long-li	Ved $\chi_1^{\pm}$ L=4.7 fb <sup>-1</sup> , 7 TeV [1210.2852]	220 GeV $\chi_1^+$ mass $(1 < \tau(\chi_1^+) < 10 \text{ ns})$	
Stable ğ R-hadrons : low β, βγ (full de	tector) L=4.7 fb <sup>-1</sup> , 7 TeV [1211.1597]	985 GeV g mass	
승 실 Stable t R-hadrons : low β, βγ (full de	tector) L=4.7 fb <sup>-</sup> , 7 TeV [1211.1597]	683 Gev t mass	
GMSB:s	table t L=4.7 16 7 Tev [1211.1597]	300 GeV 1 111855 (5 < tanp < 20)	
$\chi \rightarrow qq\mu (RPV) : \mu + neavy displaced$	Vertex L=4.4 tb , 7 TeV [1210.7451]	700 GeV Q HIASS (0.3×10 < 1,5×10 , 1 mm	< ct < 1 m,g decoupled)
LEV: pp y +X, v + e+µ resu	CODOC ( -16 0-1 7 Tel/ (Preliminary)	1 10 TeV V mass (2 -0.10, 2 -0.0	2 <sup>ee0.05</sup> )
Bilinear RPV CMSSM : 1 lep + 7 i's +	E	1 2 TeV 0 = 0 Mass (ct < 1 mm)	.,
$\vec{v} = \vec{v} \cdot \vec{v} \cdot \vec{v} + W \vec{v} \cdot \vec{v} + W \vec{v} \cdot \vec{v} + eev$ , euv : 4 lep +	EL=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-153]	700 GeV 7 mass (m(y) > 300 GeV. λ or λ	> 0)
1 L L → Iv + eev .euv : 4 lep +	E L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-153]	430 GeV I mass (m(χ <sup>0</sup> ) > 100 GeV, m(l <sub>a</sub> )=m(l <sub>a</sub> )=m(l <sub>a</sub> ), λ <sub>evi</sub> o	rλ>0)
g → ggg : 3-jet resonand	Ce pair L=4.6 fb <sup>-1</sup> , 7 TeV [1210.4813]	666 GeV g mass	
Scalar gluon : 2-jet resonand	CE pair L=4.6 fb <sup>-1</sup> , 7 TeV [1210.4826]	100-287 GeV Sgluon mass (incl. limit from 1110.2693)	
wime interaction (D5, Dirac χ) : 'monojet' +	E T miss . L=10.5 fb", 8 TeV [ATLAS-CONF-2012-047]	704 GeV M* SCale (m <sub>g</sub> < 80 GeV, limit of < 687 G	eV for D8)
		· · · · · · · · · · · · · · · · · · ·	
	10"	1	10

\*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty. Mass scale [TeV]

#### ... and what now?

		ATLAS Exotics	Searches* - 95% CL Low	ver Limits (Status: HCP 2	2012)
	Large ED (ADD) - managet + E			M (8-2)	
	Large ED (ADD) : monophoton + E-	1 =4.6 fb <sup>-1</sup> .7 TeV [1209.4625]	193 ToV M-	(6=2)	
S	Large ED (ADD) : diphoton & dilepton, m	L=4.7 fb <sup>-1</sup> , 7 TeV (1211,1150)	4.1	18 TeV M <sub>e</sub> (HLZ δ=3, NLO)	ATLAS
<u>0</u> ,	UED : diphoton + $E_{T miss}$	L=4.8 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-072]	1.41 TeV Compact	. scale R <sup>-1</sup>	Preliminary
NS	S <sup>1</sup> /Z <sub>2</sub> ED : dilepton, m <sub>1</sub>	L=4.9-5.0 fb <sup>-1</sup> , 7 TeV [1209.2535]		4.71 TeV M <sub>KK</sub> ~ R <sup>-1</sup>	
ле	RS1 : diphoton & dilepton, m	L=4.7-5.0 fb <sup>-1</sup> , 7 TeV [1210.8389]	2.23 TeV GI	raviton mass $(k/M_{p} = 0.1)$	
di.	RS1 : ZZ resonance, m	L=1.0 fb <sup>-1</sup> , 7 TeV [1203.0718]	845 GeV Graviton mass ()	$k/M_{\rm Pl} = 0.1$ )	
9	RS1: WW resonance, m <sub>T,hith</sub>	L=4.7 fb <sup>-1</sup> , 7 TeV [1208.2880]	1.23 TeV Graviton m	$lass(k/M_{p_1} = 0.1)$ $Lat = (1.0)$	J - 13.0) fb '
Xt	$RS y \rightarrow ii (BR=0.925) : ii \rightarrow i+jets, iii I, boosted$	L=4.7 fb", 7 TeV [ATLAS-CONF-2012-136]	1.9 TeV 9 0	nass -	s = 7.8 TeV
ш	ADD BH $(M_{TH}/M_D=3)$ : lentons + jets $\Sigma n$	L=1.3 fb ', 7 feV [1111.0050]	1.25 TeV M <sub>D</sub> (8=6)	-	
	Quantum black hole - dijet E (m)	LT1.01D , 7 TeV [1204.4646]	1.5 IEV M <sub>D</sub> (0-0	1 Toy M (8-6)	
	gggg contact interaction : 2(m)	/ =4.8 (b <sup>-1</sup> 7 TeV [ATI AS_CONF.2012.038]		7.8 TeV	
0	aall Cl : ee & uu. m	/ =4 9-5 0 fb <sup>-1</sup> 7 TeV [1211 1150]		13 9 TeV A (construct	ctive int )
0	uutt CI : SS dilepton + jets + ET mine	L=1.0 fb <sup>-1</sup> , 7 TeV [1202.5520]	1.7 TeV A		,
	Z' (SSM) : meeting	L=5.9-6.1 fb <sup>1</sup> , 8 TeV [ATLAS-CONF-2012-12	9] 2.49 TeV	Z' mass	
	Z' (SSM) : m <sub>et</sub>	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.6804]	1.4 TeV Z' mass		
5	W' (SSM) : m <sub>T,e/µ</sub>	L=4.7 fb <sup>-1</sup> , 7 TeV [1209.4448]	2.55 TeV	W' mass	
_	$W' (\rightarrow tq, g_p=1) : m_{tq}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1209.6593]	430 GeV W' mass		
	$W_R (\rightarrow tD, SSM) : m_{tb}$	L=1.0 fb <sup>-1</sup> , 7 TeV [1205.1016]	1.13 TeV W' mass		
	W : m <sub>Taba</sub>	L=4.7 fb <sup>-</sup> , 7 TeV [1209.4446]	2.42 TeV V	v- mass	
a	Scalar LQ pair ( $\beta$ =1) : kin. vars. in eejj, evjj Scalar LQ pair ( $\beta$ =1) : kin. vars. in eejj, evjj	L=1.0 fb <sup>-</sup> , 7 TeV [1112.4828]	660 GeV 1 gen. LQ mass		
7	Scalar LO pair (B-1) : kin vars in trii tvii	L=1.0 fb , 7 fev [1203.3172]	528 GeV 3 <sup>rd</sup> gen LO mass		
60	A <sup>th</sup> concration : tY , WhWh	1 =4.7 (b <sup>-1</sup> , 7 TeV [1210 5468]	sse gev t mass		
×	$4^{th}$ generation : b'b'(T_, T_{eq}) \rightarrow WtWt	L=4.7 fb <sup>1</sup> , 7 TeV [ATLAS-CONF-2012-130]	670 GeV b' (T) mass		
Мa	New quark b' : b'b → Zb+X, m	L=2.0 fb <sup>-1</sup> , 7 TeV [1204.1265]	400 GeV b' mass		
2	Top partner : $TT \rightarrow tt + A_0A_0$ (dilepton, $M_{r_0}^{20}$ )	L=4.7 fb <sup>-1</sup> , 7 TeV [1209.4186]	483 GeV T mass (m(A) < 100 Ge	(V)	
6	Vector-like quark : CC, m	L=4.6 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-137]	1.12 TeV VLQ mass (	charge -1/3, coupling $\kappa_{qq} = v/m_0$ )	
<	Vector-like quark : NC, mig	L=4.6 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-137]	1.08 TeV VLQ mass (c	sharge 2/3, coupling $\kappa_{qQ} = v/m_0$ )	
n.	Excited quarks : y-jet resonance, m	L=2.1 fb <sup>-1</sup> , 7 TeV [1112.3580]	2.46 TeV	* mass	
ЩĔ	Excited quarks : dijet resonance, m	L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-148]	3.84	TeV q* mass	
	Techni badrons (I STC) - dilanton m	L=13.0 fb ', 8 TeV [ATLAS-CONF-2012-146]	2.2 TeV	mass $(\Lambda = m(\Gamma))$	
1	Techni-hadrons (LSTC) · WZ resonance (vIII) m	L=4.9-5.0 fb 7 TeV [1209.2535]	850 GeV ρ <sub>1</sub> /ω <sub>τ</sub> mass ( <i>m</i> (ρ	$\sigma_{\tau}/\omega_{\tau}) - m(\pi_{\tau}) = M_{W}$	
~	Major poutr (LRSM po mixing) : 2-lop + jots	L=1.016 , 7 TeV (1204.1648)	483 Gev p_ mass (m(p_) = m(x_r) +	$(m(W_{1}) = 2 \text{ TeV})$	
he	W - (LRSM no mixing) : 2-lep + jets	1 = 2 1 fb <sup>-1</sup> 7 TeV (1203 5420)	2.4 TeV V	$V_{-mass}$ (m(N) < 1.4 TeV)	
õ	$H_{\pm}^{\pm}$ (DY prod., BR( $H_{\pm}^{\pm}\rightarrow II$ )=1) : SS ee ( $\mu\mu$ ), m	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.5070]	409 Gev H <sup>±±</sup> mass (limit at 398 GeV	for uu)	
	H <sup>±±</sup> (DY prod., BR(H <sup>±±</sup> →eµ)=1) : SS eµ, m	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.5070] 3	75 Gev H <sup>±±</sup> mass		
	Color octet scalar : dijet resonance, m	L=4.8 fb <sup>-1</sup> , 7 TeV [1210.1718]	1.86 TeV Scala	ar resonance mass	
		10-1			
		10	1	10	10
				Mass s	scale [TeV]

\*Only a selection of the available mass limits on new states or phenomena shown

## Doubts on the Standardmodel

- describes microcosm (too good?)
- 28 free parameters



- Higgs ?, form of Higgs potential ?





Most recent analysis: Metastable vacuum with lifetime longer than the age of the universe Degrassi et al., arXiv:1205.6497

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Could the Higgs field ever have fallen in the correct vacuum?

Hertzberg, arXiv:1210.3624

## **Open Questions**

- Unification of all interactions (?)
- Baryon asymmetrie  $\Delta N_B \Delta N_{\bar{B}} \sim 10^{-9}$  missing CP violation
- Flavour: three generations
- Tiny neutrino masses:  $m_{
  u} \sim rac{v^2}{M}$
- Dark Matter:
  - stable
  - only weakly interacting
  - $m_{DM} \sim 100 \,\mathrm{GeV}$
- Quantum theory of gravity
- Cosmic inflation
- Cosmological constant





#### Supersymmetry

Spin-Statistics:  $M_H$  stabilized to all orders

connects space-time & gauge symmetries



Partner particles shifted by half-interger in spin

Grand Unification: weak interactions to very high scales

R-Parity: Dark Matter

## Extra Dimensions

Hierarchy problem solved by elimination of hierarchy

Higher-dimensional space-time symmetry



Partner particles shifted by integer in spin

Possible strong interactions at TeV scale

KK-Parity: Dark Matter

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KK-Parity: Dark Matter

Decay products of heavy particles:

- ▶ high-p<sub>T</sub> Jets
- many hard leptons

Production of colored particles

weakly interacting particles only in decays

Dark Matter  $\Leftrightarrow$  discrete parity (R, T, KK)



- $\blacktriangleright$  only pairs of new particles  $\ \Rightarrow \$  high energies, long decay chains
- Dark Matter  $\Rightarrow$  large missing energy in detector ( $\not\!\!E_T$ )

#### Different Models/Decay Chains — same signatures



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Mass of new particles: end points of decay spectra





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- $\begin{array}{c|c} q & q & \ell \\ \hline q & q & \ell \\ \hline \tilde{q}_L & \tilde{\ell}_R & \ell \\ \hline q & \tilde{q}_R & \ell \\ \hline q & \ell \\ \end{array}$
- only pairs of new particles  $\Rightarrow$  high energies, long decay chains
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Spin of new particles: Spin of new particles: angular correlations, ...



#### LHC Warm-Up: Sbottom Production Hagiwara/.../JRR/..., PRD 73 (2006) 055005

 $ilde{b}_1$  production with subsequent decay  $ilde{b}_1 o ilde{\chi}_1^0 b$ 

Process  $A_1A_2 \rightarrow P^{(*)} \rightarrow F_1F_2$ , 3 different steps:

 $\begin{array}{ll} \text{Narrow Width (NWA)} & \sigma(A_1A_2 \to P) \times \text{BR}(P \to F_1F_2) \\ \text{Breit-Wigner} & \sigma(A_1A_2 \to P) \times \frac{M_P^2 \Gamma_P^2}{(s - M_P^2)^2 + \Gamma_P^2 M_P^2} \times \text{BR}(P \to F_1F_2) \\ \text{Full matrix element} & \sigma(A_1A_2 \to F_1F_2) \end{array}$ 



$$pp \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Main background:  $gg \rightarrow b\bar{b}\nu\bar{\nu}$ 

Signal jets harder

#### LHC Warm-Up: Sbottom Production Hagiwara/.../JRR/..., PRD 73 (2006) 055005

 $\tilde{b}_1$  production with subsequent decay  $\tilde{b}_1 \rightarrow \tilde{\chi}_1^0 b$ 

Process  $A_1A_2 \rightarrow P^{(*)} \rightarrow F_1F_2$ , 3 different steps:

Narrow Width (NWA)  $\sigma(A_1 A_2 \to P) \times BR(P \to F_1 F_2)$  $\sigma(A_1A_2 \to P) \times \frac{M_P^2 \Gamma_P^2}{(s-M_*^2)^2 + \Gamma_*^2 M_P^2} \times BR(P \to F_1F_2)$ **Breit-Wigner** Full matrix element  $\sigma(A_1A_2 \to F_1F_2)$ 



PS: Harder jet more central

Off-shell effects  $(b\bar{b}Z^*)$ : only for low  $p_{T,b} \longrightarrow \text{cut}$ out

Not generally guaranteed

## ISR: Bottom Jet Radiation

Hagiwara/.../JRR/..., PRD 73 (2006) 055005

 $g \rightarrow b\bar{b}$ -Splitting, b-ISR as combinatorial background

 $pp \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 b \bar{b} b \bar{b}$ : 32112 diagrams, 22 color flows,  $\sim 4000~{
m PS}$  channels

 $\sigma(pp \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 1177 \text{ fb} \longrightarrow \sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 130.7 \text{ fb}$ 

Forward discrimination of ISR and decay-b jets difficult:



Only the most forward b jet is softer

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Hagiwara/.../JRR/..., PRD 73 (2006) 055005

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Only small differences in  $p_{T,b}$ , PDF: maximum at a smaller value



shifted to smaller  $p_T$ : light particles balance out the event

Confusions in Cascades - Disentangling New Physics in LHC cascades

## WHIZARD

Kilian/Ohl/JRR: DESY/Freiburg/Siegen/Würzburg, hep-ph/0102195, EPJC 71 (2011) 1742



- Multi-Purpose event generator for collider and astroparticle physics
- Acronym: W, HIggs, Z, And Respective Decays (deprecated)
  - Fast adaptive multi-channel Monte-Carlo integration
  - Very efficient phase space and event generation
  - Optimized/-al matrix elements uses the color flow formalism

Kilian/Ohl/JRR/Speckner, JHEP 1210 (2012) 022

- Recent version: 2.1.1 (18.09.2012) [2.2.0 will come Apr 8, 2013] http://projects.hepforge.org/whizard
- Parton shower ( $k^{\perp}$ -ordered and analytic) Kilian/JRR/Schmidt/Wiesler, JHEP 1204 (2012) 013
- Underlying Event: preliminary version
- > 2.0 Features: ME/PS matching, cascades, shared library
- Working on: NLO automation, general Lorentz structures etc.
- ► Interface to FeynRules Christensen/Duhr/Fuks/JRR/Speckner, EPJC 72 (2012) 1990
- Versatile input language: SINDARIN

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Kilian/Ohl/JRR: DESY/Freiburg/Siegen/Würzburg, hep-ph/0102195, EPJC 71 (2011) 1742



Multi-Purpose event generator for collider and astroparticle physics

#### ► Focus: LHC, ILC, CLIC, SM, QCD, BSM

MODEL TYPE	with CKM matrix	trivial CKM
QED with $e, \mu, \tau, \gamma$	-	QED
QCD with $d, u, s, c, b, t, g$	-	QCD
Standard model	SM_CKM	SM
SM with anomalous couplings	SM_ac_CKM	SM_ac
SM with anomalous top couplings	—	SM_top
SM with K matrix	-	SM_KM
MSSM	MSSM_CKM	MSSM
MSSM with Gravitinos	-	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	-	PSSSM
Littlest Higgs	-	Littlest
Littlest Higgs with ungauged $U(1)$	-	Littlest_Eta
Littlest Higgs with T parity	-	Littlest_Tpar
Simplest Little Higgs (anomaly free)	-	Simplest
Simplest Little Higgs (universal)	-	Simplest_univ
UED	-	UED
3-Site Higgsless Model	-	Threeshl
Noncommutative SM (inoff.)	-	NCSM
SM with $Z'$	—	Zprime
SM with Gravitino and Photino	—	GravTest
Augmentable SM template	-	Template

easy to implement new models

Interface to FeynRules

Christensen/Duhr/Fuks/JRR/Speckner, EPJC 72 (2012) 1990

Versatile input language: SINDARIN

## I: Off-Shell Effects

### Confusions from Off-Shell Effects: Fat Gluinos

- ► SUSY: weakly coupled + discrete parity ⇒ Narrow resonances
- Exception: some Higgses ... and Gluino
- Width-to-mass ratio  $\gamma := \Gamma/M \sim$  few to 15-20 % Theoretical upper limit  $\gamma \sim 32\%$  (without invisible or exotic decays)
- Example realization: GMSB

 $M_{\tilde{g}} \sim 2 \, \mathrm{TeV} \qquad \Gamma_{\tilde{g}} \sim 240 \, \mathrm{GeV}$ 

- Plan: scan over "fat gluinos" in "full" simulation
- Comparison between SUSY vs. UED
- Generic scan over 5 values:  $\gamma \in \{0.5\%, 2.5\%, 5\%, 10\%, 15\%\}$
- Look for impact on mass and spin observables

• Standard Gluino Cascade:  $2 \rightarrow 10$  Numerically challenging (PS!!!)



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Factorization in Narrow-Width-Approximation (NWA)



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• Trade-off accuracy vs. speed



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- Simulate production and first decay with full matrix elements
- Factorize additional decays with NWA

## Simulation Setup

Parton level studies with WHIZARD



- Investigation of ISR, combinatoris, detector effects later
   Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148
- For each point (UED and SUSY) normalized sets (5k events)

Corresponds roughly to event numbers for  $300 \text{ fb}^{-1}$ 

To study statistics vs. systematics some samples for 25k events

pMSSM19 benchmark scenario

$M_1$	$M_2$	$M_3$	$A_t$	$A_b$	$A_{\tau}$	μ	$M_A$	$m_{\tilde{l}_L}$	$m_{\tilde{\tau}_L}$
150	250	1200	4000	4000	0	1500	1500	1000	1000
$m_{\tilde{l}_R}$	$m_{\tilde{\tau}_R}$	$m_{\tilde{q}_L}$	$m_{\tilde{q}_L^3}$	$m_{\tilde{q}_R^u}$	$m_{\tilde{q}_R^d}$	$m_{\tilde{t}_R}$	$m_{\tilde{b}_R}$	$\tan\beta$	
200	1000	1000	1000	1000	1000	4000	1000	10	

- ... and similar datapoint for UED (for spin determination)
- Setup of (exclusive) decay chains

$$\begin{split} \tilde{g}[1] & \to b \tilde{b}_i \to b \bar{b} \tilde{\chi}_2^0 \to b \bar{b} l^{\pm} \tilde{l}_R^{\mp} \to b \bar{b} l^{\pm} l^{\mp} \tilde{\chi}_1^0 \\ \tilde{g}[2] & \to d \tilde{d}_L \to d \bar{d} \tilde{\chi}_1^0 \end{split}$$

Kilian/Ohl/JBB, EPJC 71 (2011) 1742

#### Mass determination and "fat" gluinos

- Decay chain:  $\tilde{g}[1] \rightarrow b\tilde{b}_i \rightarrow b\bar{b}\tilde{\chi}_2^0 \rightarrow b\bar{b}l^{\pm}\tilde{l}_R^{\mp} \rightarrow b\bar{b}l^{\pm}l^{\mp}\tilde{\chi}_1^0$
- Far b jet not affected, but the near one! black: 0.5%, red: 2.5%, green: 5%, blue: 10%, yellow: 15%



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Numerical Endpoint Estimation: Edge-to-bump method

- Trying to find edges by fitting lines very human-biased and error-prone
- Idea: do a naive kink fit  $\mathcal{O}(1000)$  times
- Edge-to-bump method Curtin, 2012

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Turns edge-localization into a bump search



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Turns edge-localization into a bump search



- Analyze resulting distribution of fit values
- Distribution of values measure/estimate for uncertainty
#### More Examples

•  $m_{bb\ell}^{low}$ ,  $m_{bb\ell}^{high}$ : two endpoints in  $m_{bb\ell}$ 



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•  $m_{bb\ell}^{low}$ ,  $m_{bb\ell}^{high}$ : two endpoints in  $m_{bb\ell}$ 



black: 0.5%, red: 2.5%, green: 5%, blue: 10%, yellow: 15%

Endpoints severely degraded (at parton level!!)

$$A^{\pm}[m_{b\ell}] = \frac{d\sigma/dm_{b\ell^+} - d\sigma/dm_{b\ell^-}}{d\sigma/dm_{b\ell^+} + d\sigma/dm_{b\ell^-}}$$



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Shape asymmetry not affected by fat gluino!

• Method II: Angular correlations and asymmetries

. 
$$\boxed{\cos\theta_{jj}^* = \tanh\left(\frac{\Delta\eta_{jj}}{2}\right)}_{\text{Moortgat-Pick/Rolbiecki/Tattersall, 2011}}$$



$$\Delta \phi_{bb} = |\phi(b_1) - \phi(b_2)|$$

Alves/Eboli/Plehn, 2006

1.

2.

# Spin Determination (II)

• Method II: Angular correlations and asymmetries

 $\boxed{\cos \theta_{jj}^* = \tanh\left(\frac{\Delta \eta_{jj}}{2}\right)}_{\text{Moortgat-Pick/Rolbiecki/Tattersall, 2011}}$ 

$$A_{ct}^{\pm} = \frac{N(|\cos\theta_{qq}^{*}| < 0.5) - N(|\cos\theta_{qq}^{*}| > 0.5)}{N(|\cos\theta_{qq}^{*}| < 0.5) + N(|\cos\theta_{qq}^{*}| > 0.5)}$$

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18/31

1.

2.

I Route

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# **II.** Combinatorics

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- Simultaneous production: Gluinos and squarks
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  Rajamaran/Yu, 2010; Baringer/Kong/McCaskey, 2011;
  Choi/Guadagnoli/Park, 2011
- Some methods <u>require</u> dijet endpoint measurement
- Dijet itself suffers a lot from both backgrounds
- Motivation: Study fully inclusive dijet measurement

Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148

## Simplified Models and Scenarios

- Sleptons, Higgsinos, third generation decoupled
- ▶ Higgs at 125 GeV  $\Rightarrow$  heavy scalars, light gauginos
- Gauginos fix, vary squark masses in three scenarios

$m_{\tilde{g}}$	$m_{ ilde w}$	$m_{\tilde{b}}$	Scenario	Α	В	С
1200 GeV	400 GeV	200 GeV	$m_{ ilde{q}}$	1300 GeV	1900 GeV	10000 GeV

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Three-body gluino decay into light gauginos:

wino edge	$m_{jj}^{max}(\tilde{w}) = m_{\tilde{g}} - m_{\tilde{w}}$	= 800 GeV
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- Small mass difference
  Squark decay to light gauginos
  - Associated production dominant One signal gluino / squark bg
- Moderate mass difference
  - Associated and pair production
- Squarks decoupled
  - Pair production only

- Squark decay also to gluino
- Two signal gluinos / many jets
- Two signal gluinos
- Lowest combinatorial bg

► Fully inclusive event samples from WHIZARD/Herwig++

Kilian/Ohl/JRR, 2007; Bär et al., 2008

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- A: 108,000
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Checked against CMS full simulation

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• anti 
$$-k_T, R = 0.5$$

• 
$$p_T > 50 GeV$$

• 
$$|\eta| < 2.5$$

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• 
$$p_T > 50 GeV$$

• 
$$|\eta| < 2.5$$

Baseline selection

CMS-SUS-10-005

- $H_T > 800 \, \text{GeV}$
- $E_T^{miss} > 200 \,\mathrm{GeV}$
- $\Delta \phi(j_{1,2}, E_T^{miss}) > 0.5$





• Couting number of visible decay products (parton level)



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ONLY bino edges in 3-4 partons



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BOTH bino and wino edges



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Use selection criterion



# Parton-Jet Correspondence

This was parton level? What about hadron level?


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- ⇒ Substantial correlation of parton and detector level jets
  - Refine selection criteria

Bino: 4-5 jets lepton veto

Wino:  $\geq$  6 jets one lepton

# Parton-Jet Correspondence

This was parton level? What about hadron level?



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Bino: 4-5 jets lepton veto

- Lepton indicates presence of wino
- ► Fewer jets ⇒ less combinatorics

Wino:  $\geq$  6 jets one lepton

## Origin of Jets

Abundances of jet origins in the *i*th hardest jet



Gluino jet very likely in the first 3 bins

### Origin of Jets

Abundances of jet origins in the *i*th hardest jet



- Gluino jet very likely in the first 3 bins
- ► Severe squark contamination for i = 1 in scenario A & B
  - Define new variables
  - min procedure reduces impact on combinatorics

 $\begin{array}{ccc} min_{3j} = & \min_{k=1,2} m_{3,k} \\ min_{123} = & \min_{i,j=1,2,3} m_{i,j} \\ min_{234} = & \min_{i,j=2,3,4} m_{i,j} \end{array}$ 

#### Compare to existing methods

- Hemisphere method CMS TDR 2007
  - 1. Hemisphere algorithm to divide event
  - 2. Combine two hardest objects from each side



- Topology method (for exclusive 4 jets + MET) Bai/Cheng, 2011
  - Dijet variables for identification of topology 3+1 or 2+2

$$F_{3}(p1, p2, p3, p4) = m_{k,l}, \text{ for } \epsilon_{ijkl} \neq 0 \text{ and } \max_{r,s=1,\dots,4} \{m_{r,s}\}$$

$$F_{4}(p1, p2, p3, p4) = \min_{i,j=1,\dots,4} \{\max(m_{i,j}, m_{k,l})\}, \quad \epsilon_{ijkl} \neq 0$$

#### Scenario A



- · Bino selection: slight overshoot of true endpoints
- Wino selection: diffuse endpoints & a visible kink
- min and hemisphere variables give best results

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#### Scenario B



- · Bino selection: shallow endpoints, only vague kink structure
- Wino selection: gross overestimation, little difference to bino
- min<sub>234</sub> (wino) and hemi I (bino) work best

#### Scenario B



- · Bino selection: shallow endpoints, only vague kink structure
- Wino selection: gross overestimation, little difference to bino
- min<sub>234</sub> (wino) and hemi I (bino) work best

#### Scenario C



- Bino selection: clear endpoints, slight underestimation
- Wino selection: solid kinks, only few events beyond true endpoint
- all variables promising, good control of backgrounds

#### Scenario C



- Bino selection: clear endpoints, slight underestimation
- Wino selection: solid kinks, only few events beyond true endpoint
- all variables promising, good control of backgrounds

### Numerical Endpoint Estimation

Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148

$\sim$								
endpt.	$min_{123}$	$min_{234}$	$min_{3j}$	$m_{12}^{(1)}$	$m_{12}^{(2)}$	$F_3$	F4	
scenario A								
bino	$1106 \pm 52$	$570 \pm 14$	$1125 \pm 106$	$822 \pm 21$	$1012 \pm 104$	$686 \pm 33$	$1191 \pm 132$	
wino	$908\pm83$	$665 \pm 34$	$948\pm99$	$932\pm31$	$780\pm26$	794 $\pm$ 33	$1031\pm53$	
scenario B								
bino	986 $\pm$ 36	$773 \pm 147$	$1028 \pm 34$	$1010\pm 6$	$794 \pm 49$	$766 \pm 25$	$1046 \pm 66$	
wino	$895\pm23$	$\textbf{748} \pm \textbf{68}$	$892\pm18$	$958\pm10$	819 $\pm$ 47	$911 \pm 51$	$928\pm37$	
scenario C								
bino	$812 \pm 24$	$545\pm8$	921 ± 37	$816 \pm 29$	721 ± 90	$708 \pm 22$	894 ± 57	
wino	$778\pm23$	$577 \pm 19$	$804\pm 6$	$769 \pm 47$	$764 \pm 14$	$708\pm38$	793 $\pm$ 7	
							,,	

- Accurate estimates in all scenarios possible
- slight underestimation for bino in scenario A
- Very important to choose the correct variable!

# III. Combinatorics (fake)

Fake combinatorics: Wrong underlying model assumptions

- Fake combinatorics: Wrong underlying model assumptions
- ▶ Prime Example: Grand Unified SUSY models based on E<sub>6</sub>

Kilian/JRR, PLB 642 (2006) 81; Braam/Knochel/JRR, JHEP 1006 (2010) 013

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 Chiral Exotics with lepton and baryon number: scalar leptoquarks, SUSY partners: leptoquarkinos



Lentoquarking mass M (Ge)

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Identical exclusive final states:







# Mass Edges for Leptoquarkinos

JRR/Wiesler, PRD84 (2011) 015012

Mass edges clearer due to missing spin correlations

 $m_{ql,high} = \max\{m_{ql^+}, m_{ql^-}\} \qquad m_{ql,low} = \min\{m_{ql^+}, m_{ql^-}\}$ 





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- Mass edges clearer due to missing spin correlations

 $m_{ql,high} = \max\{m_{ql^+}, m_{ql^-}\} \qquad m_{ql,low} = \min\{m_{ql^+}, m_{ql^-}\}$ 



► Combinatorial background: combine softest jet and hardest lepton: m<sup>\*</sup><sub>ql</sub> = m(min<sub>E</sub>{q<sub>1</sub>, q<sub>2</sub>}, max<sub>E</sub> {l<sup>+</sup>, l<sup>-</sup>})



# Discrimination from standard SUSY

JRR/Wiesler, PRD 2011

• Dilepton spectrum: standard SUSY  $\Rightarrow$  same cascade, leptoquarkinos  $\Rightarrow$  different cascades

# Discrimination from standard SUSY

- Dilepton spectrum: standard SUSY ⇒ same cascade, leptoquarkinos ⇒ different cascades
- Cut on kinematic edge in standard dilepton spectra



• S/B estimate, 100 fb $^{-1}$ , 2 OSSF, 2 hard jets,  $\not\!\!\!E_T$ 

$m_{\tilde{D}}$	# N(LQino) & N(SUSY)	$\# N_{cut}$	$S/\sqrt{S+B}$
400	8763	5061	54
600	1355	540	15
800	684	102	4
1000	594	24	1

# Summary/Conclusions

- New Physics motivated by Hierarchy Problem/Vacuum Stability
- SUSY cascades as standard candles at LHC
- Combinatorial background and smearing from
  - ► ISR/FSR
  - Combinatorics through presence of two cascades
  - SUSY backgrounds ("signal backgrounds")
  - Off-shell (and threshold) effects
  - Wrong model assumptions
- Full analysis including all channels/backgrounds with WHIZARD
- Generally trade-off between precision and speed
- Waiting for a signal ...

## One Ring to Find them ... One Ring to Rule them Out

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## The Gluino – Did we miss the order date!?

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