Exotic Searches at the LHC





Wolfgang Ehrenfeld (DESY)

On behalf of the ATLAS and CMS Collaborations

DESY, February 8th, 2012





Introduction

- Several Exotics / New Physics searches at the LHC
- Can not cover all → focus on recent 1 5 fb⁻¹ results
- > ATLAS and CMS only (LHCb and ALICE also seek New Physics)
- Full repository of latest results
 - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
 - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- > This talk does not cover:
 - SUSY: see talk by Isabel Melzer-Pellmann
 - Higgs: see talks by Jana Schaarschmidt and Markus Klute
 - Top: see talk by Sebastian Naumann-Emme



Looking beyond the Standard Model

Standard Model (SM):

- An effective theory \rightarrow has worked very well at energy scales probed so far
- Expected to break down at higher energies

> Several limitations, many involving fine-tuning:

- Hierarchy Problem / Gravity: Reconciling m_W and m_Z with m_{Planck}
- Electroweak Symmetry Breaking: How does it really work?
- Dark Matter: What is it?
- Flavor
- Strong CP Problem
- • •
- Because we can with the Large Hadron Collider (LHC)







Large Hadron Collider (LHC)

> √s = 7 TeV pp

> Outstanding 2011 Performance

- ~ 3.5 × 10³³ cm⁻²s⁻¹ peak lumi
- ~ 5.6 fb⁻¹ delivered



- > Bunch spacing 50 ns
- > ~ 12 pp collisions / crossing (avg.)



Mean Number of Interactions per Crossing





CMS

Total weight 14000 t Overall diameter 15 m Overall length 28.7 m

39 Countries, 169 Institutes, 3170 scientists and engineers including 800 students

Emphasis on excellent resolution (energy, momentum, mass) of electrons, photons, muons





Emphasis on excellent jet and missing- E_{τ} (MET) resolution, particle identification, and standalone muon reconstruction

Acknowledgements



Long List of Models & Signatures Available

- Many extensions of the SM have been jets + MET developed over the past decades. Supersymmetry Extra-Dimensions Technicolor(s) Little Higgs No Higgs GUT Hidden Valley Z+MET Leptoquarks Compositeness 4th generation (t', b') LRSM, heavy neutrino etc... etc... (for illustration only)
 - 1 jet + MET
 - 1 lepton + MET
 - Same-sign di-lepton
 - **Dilepton resonance**
 - **Diphoton resonance**
 - Diphoton + MET
 - Multileptons
 - Lepton-jet resonance
 - Lepton-photon resonance
 - Gamma-jet resonance
 - Diboson resonance
 - W/Z+Gamma resonance
 - Top-antitop resonance
 - Slow-moving particles
 - Long-lived particles
 - Top-antitop production
 - Lepton-Jets
 - Microscopic blackholes
 - **Dijet resonance**



Courtesy of Henri Bachacou

Long List of Models & Signatures Available

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry^{*}
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')²
- LRSM, heavy neutrino
- etc...

(for illustration only)

Courtesy of Henri Bachacou

1 jet + MET jets + MET 1 lepton + MET Same-sign di-lepton **Dilepton resonance** Diphoton resonance Diphoton + MET Multileptons Lepton-jet resonance Lepton-photon resonance Gamma-jet resonance **Diboson resonance** Z+MET W/Z+Gamma resonance Top-antitop resonance Slow-moving particles Long-lived particles Top-antitop production Lepton-Jets Microscopic blackholes **Dijet resonance**

For Experimentalists:

- Complex 2D problem
- Signature approach:
 - Practical
 - Less modeldependent
- Important to seek as many signatures as possible



etc...

Selected Searches



> Heavy Resonances

- heavy gauge bosons
- dijet, paired dijet, jet+photon
- excited leptons



- Quark Sector
 - t'/b' quark
 - Ieptoquarks
 - vector-like quarks



Strong Gravity

- diphoton spectrum
- black holes



Charged Heavy Resonance: W'

- > Heavy charged gauge boson
- > Technirho, Little Higgs, UED, LH, RH
- > 1 electron or muon & missing E_T
- Seek Jacobian peak in m_T distribution





$$m_T = \sqrt{2p_T \not\!\!\!E_T (1 - \cos\Delta\phi_{\ell, \not\!\!\!E_T})}$$





CMS: PAS-EXO-11-024

W_R and Heavy Neutrinos

- Light neutrino masses could be m_v ~ m_D²/M_N
 - N are heavy neutrinos Majorana or Dirac particles → SS or OS events
- > Two models:
 - Effective Lagrangian (HNEO): qq → IN →IIjj
 - Left-right symmetric model (LRSM):
 qq → W_R → IN → Iljj
- > Signature
 - Two leptons + n_{jet} >= 2
 - Discriminating variables m_N, m_{WR}

> Good agreement between data and MC

- Limits on visible cross section between
 6 50 fb depending on channel (ee,eµ,µµ)
- Limits on model parameters



ATLAS: Preliminary

- Different final states possible
 - Dijet final state, jet+photon final state, paired dijet final state
- > Predicted by many models:
 - q*, axigluon, color-octet scalar, hyperpions, string resonances, ...
- Seek resonance above phenomenological fit to data



- > Different final states possible
 - Dijet final state, jet+photon final state, paired dijet final state
- > Predicted by many models:
 - q*, axigluon, color-octet scalar, hyperpions, string resonances, ...
- Seek resonance above phenomenological fit to data (BumpHunting)

Jet + Photon Resonances

- Replace one jet by a photon
 - Require one jet and one high energetic photon
- > BumpHunter search
 - \rightarrow no significant deviation from expectations

- q/\bar{q} q/\bar{q} q/\bar{q} q/\bar{q} q/\bar{q} q/\bar{q} q/\bar{q}
- > Limits on a generic Gaussian resonance and q* model

Events [qd] ATLAS $\sigma \times BR \times A \times \varepsilon$ [pb] ATLAS Ldt = 2.11 fb PYTHIA q^{*} prediction A×ε CL upper limits: Data $\sqrt{s} = 7 \text{ TeV}$ 10⁻¹ Observed 10 — Fit ∫ Ldt = 2.11 fb⁻¹ Expected X -O· q*(0.5 TeV) ±1σ 95% CL Limit on $\sigma \times BR$ 10^{3} σ**_/m**_ ±2σ 10 • q*(2.0 TeV) --- 10% 10² -- 7% 10^{-2} 10 10⁻² 1 Signif. [5]_____ ∖s = 7 TeV 10-3 Ldt = 2.11 fb⁻¹ 10⁻³ ATLAS 1000 2000 3000 1000 2000 3000 500 1000 1500 2000 2500 m_{γi} [GeV] m_{a*} [GeV] m_G [GeV]

Paired Dijet Resonances

- Extension of inclusive dijet resonance search >
- > 4 jets with p_T > 150 GeV
 - Require equal dijet masses \rightarrow use average mass
 - $p_T(jj_1) + p_T(jj_2) m_{avg} > 25 \text{ GeV}$
 - Largest fluctuation at ~615 GeV \rightarrow 2.7 (1.5) σ (after LEE)

CMS: PAS-EXO-11-016

Excited Leptons

- Compositeness models: mass of the excited lepton + scale parameter
- > Single production and EM radiative decays: $qq \rightarrow II^* \rightarrow II\gamma$
 - 2 leptons + 1 photon
 - Peak in I_γ inv. mass for some parameters, but excess in II_γ inv. mass more robust
 - Muon channel slightly less sensitive

ATLAS: arXiv:1201.3293

Excited Leptons

- Compositeness models: mass of the excited lepton + scale parameter
- > Single production and EM radiative decays: $qq \rightarrow II^* \rightarrow II\gamma$
 - 2 leptons + 1 photon
 - Peak in lγ inv. mass for some parameters, but excess in llγ inv. mass more robust
 - Muon channel slightly less sensitive

ATLAS: arXiv:1201.3293

Selected Searches

> Heavy Resonances

- heavy gauge bosons
- dijet, paired dijet, jet+photon
- excited leptons

- Quark Sector
 - t'/b' quarks
 - Ieptoquarks
 - vector-Like quarks

Strong Gravity

- diphoton spectrum
- black holes

4th Generation Quarks: $t' \rightarrow Wb$

- > t' \rightarrow Wb: top-like signal (I+jets or dilepton), but heavier
- > Select: dilepton channels (ee, $e\mu$, $\mu\mu$) with opposite sign + two b-jets
- Use minimum invariant mass between lepton and b-jet M_{bl}(min) to reduce large top background -

4th Generation Quarks: b' \rightarrow **Wt**

ATLAS: Preliminary

b'b' → WtWt → Ivbbqqqq

> Signature:

- I lepton + missing E_T + n_{jet} >=6
- Use dijet system to tag W
- Enriched signal in high number of jets and one or two Ws
- Top background important

> ATLAS: 1 fb⁻¹

- b' → Wt search: m_{b'} > 480 (468) GeV
- t' \rightarrow Wb search: $m_{t'} > 404$ (394) GeV
- Q \rightarrow Wq search: m_Q > 350 (335) GeV

> CMS: 4.7 fb⁻¹

• t' \rightarrow Wt search: $m_{b'} > 552 (542) \text{ GeV}$

Leptoquarks (1st generation)

Leptoquarks (3rd generation)

> LQLQ → vvbb

2nd generation search: CMS: PAS-EXO-11-028 (2 fb⁻¹)

- 2 b-jets and missing E_T
- Define signal region via razor variables: M_R and R²
 - Broad peak in M_R expected

Wolfgang Ehrenfeld | Exotic Searches at the LHC | 8.2.2012 | Page 25

Vector-Like Quarks

ATLAS: arXiv:1112.5755

> qq \rightarrow qQ \rightarrow qW / qZ \rightarrow qlv / qll

- similar signature to leptoquarks but different underlying kinematics
- two leptons + n_{jet} >= 2

q

W/Z

Selected Searches

> Heavy Resonances

- heavy gauge bosons
- dijet, paired dijet, jet+photon
- excited leptons

- Quark Sector
 - t'/b' quarks
 - Ieptoquarks
 - vector-Like quarks

Strong Gravity

- diphoton spectrum
- black holes

Diphoton Final State

- ATLAS: arXiv:1112.2194 CMS: arXiv:1112.0688
- > Search for diphoton production: $qq/gg \rightarrow G \rightarrow \gamma\gamma$
 - Resonant production in Randal-Sundrum (RS) models
 - Non-resonant production in Arkani-Hamed, Dimopoulos, Dvali (ADD) models
 - Signature: two high energetic photons
 - Good agreement between data and MC expectations

Limits on RS and ADD models

CMS: ADD

K factor	GRW	Hewett		HLZ					
		pos.	neg.	$n_{\rm ED}=2$	$n_{\rm ED}=3$	$n_{\rm ED}=4$	$n_{\rm ED} = 5$	$n_{\rm ED}=6$	$n_{\rm ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

ATLAS: ADD

k-factor	GRW	Hewett		HLZ					
Value		Pos	Neg	n = 3	n = 4	n = 5	n = 6	n = 7	
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17	
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36	

ATLAS: arXiv:1112.2194 CMS: arXiv:1112.0688

- Limits improve with
 - decreasing n_{ED}
 - increasing k/M_{Pl}= k
- k-factor (NLO) give some boost

Limits on RS and ADD models

CMS: ADD

K factor	GRW	Hewett		HLZ					
		pos.	neg.	$n_{\rm ED}=2$	$n_{\rm ED}=3$	$n_{\rm ED}=4$	$n_{\rm ED} = 5$	$n_{\rm ED}=6$	$n_{\rm ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

ATLAS: ADD

k-factor	GRW	Hewett		HLZ					
Value		Pos	Neg	n = 3	n = 4	n = 5	n = 6	n = 7	
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17	
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36	

ATLAS: arXiv:1112.2194 CMS: arXiv:1112.0688

- > Limits improve with
 - decreasing n_{ED}
 - increasing k/M_{Pl}= k

median expected

68% expected

95% expected

 $G_{KK} \tilde{k} = 0.05$

800 1000 1200 1400 1600 1800 2000

95% CL limit

CMS Preliminary

2.2 fb⁻¹ at 7 TeV

M₁ [GeV]

k-factor (NLO) give some boost

Wolfgang Ehrenfeld | Exotic Searches at the LHC | 8.2.2012 | Page 30

600

RS graviton σ [pb]

10⁻¹

10⁻²

- Similar to diphoton final state search for non-resonant dilepton production (ADD models)
- > ee or $\mu\mu$ selection

HLZ model (n = 3) 3.8 TeV \rightarrow 3.9 TeV

Black Holes: Multi-Object, Multi-Jet, Same-Sign

- Microscopic black holes decaying via Hawking radiation
- Models uncertain due to lack of knowledge about quantum gravity (m_{BH} ~ M_D)
- Semi-classical models: m_{BH} >> m(threshold) = M_{TH}
- Safe bet: decay is democratic and isotropic, likely high particle multiplicity
 → look for many jets and leptons at high mass

Black Holes: Multi-Object, Multi-Jet, Same-Sign

- Inclusive search: sum energy of all objects (e, µ, jets)
- Can also select peculiar events: e.g., same-sign dilepton with very high track multiplicity

Events / 100 GeV

N ≥ 8

Data

Background Uncertainty

 $M_{\rm D} = 1.5 \, \text{TeV}, \, M_{\rm D}^{\rm mi}$

CMS Data 20

 $M_D = 2.0 \text{ TeV}, M_{BH}^{min} = 4.0 \text{ TeV}, n = 4$ $M_D = 2.5 \text{ TeV}, M_{DH}^{min} = 3.5 \text{ TeV}, n = 2$ CMS: PAS-EXO-11-071

f)

= 4.5 TeV, n = 6

ATLAS Exotic Searches: Summary

		ATLAS Exotics	Searches* - 95% CL Lo	ower Limits (Sta	tus: Dec. 2011)	
						Γ
	Large ED (ADD) : monojet	L=1.0 fb ⁻¹ (2011) [ATLAS-CONF-2011-096]	3.3	TeV M_D ($\delta=2$)	ΛΤΙ ΛΟ	
		L=2.1 fb ⁻¹ (2011) [Preliminary]	3.0	Tev M _S (GRW cut-off)	Preliminary	
S	BS with $k/M_{\rm T} = 0.1$ vy ee uu combined m	L=1.1 fb (2011) [arXiv:1111.4116]	1.23 TeV Compa	ct. scale 1/R (SPS8)		
sion	PS with $k/M = 0.1$; 77 reconcerned, $m_{\gamma\gamma,\parallel}$	L=1.1-2.1 fb (2011) [Preliminary, arXiv:110]	3.1582] 1.95 TeV	araviton mass	$\int dt = (0.03 - 2.1) \text{ fb}^{-1}$	
nen	BS with $a = 0.20 \cdot H_{-+} F_{}$	L=1.0 fb ⁻⁺ (2011) [ATLAS-CONF-2011-144]	575 GeV Graviton mass			
i din	Ouantum black hole (OBH): $m = F(\gamma)$	L=1.0 fb ⁻⁺ (2011) [ATLAS-CONF-2011-123]	840 GeV KK gluon ma	M (S C)	IS = / IeV	
xtra	OBH : High-mass σ	L=36 pb ⁻ (2010) [arXiv:1103.3864]	3	.67 TeV IVI _D (0=0)		
Ш	$\Delta DD BH (M / M - 3)$: multijet $\Sigma p = N$	L=33 pb (2010) [ATLAS-CONF-2011-070]	2.35 TeV			
	ADD BH $(M_{TH}, M_{D}=3)$: Multijet, $2p_T, M_{jets}$	L=35 pb ' (2010) [ATLAS-CONF-2011-068]	1.37 TeV /// _D (0	=0)		
	ADD BH $(M_{TH}/M_D=3)$: SS difficult, $N_{ch. part.}$	L=1.3 fb ⁺ (2011) [arXiv:1111.0080]	1.25 TeV M _D (δ=	·6)		
	arga contact interaction : $F(m_{TH})$	L=1.0 fb (2011) [ATLAS-CONF-2011-147]	1.5 TeV M _D	0=6)		
CI	and contact interaction : ee uu combined m	L=36 pb ⁻⁺ (2010) [arXiv:1103.3864 (Bayesia	n limit)]	6.7 TeV A	(constructive int)	
	$SSM \cdot m$	L=1.1-1.2 fb ⁺ (2011) [Preliminary]	7	10.2 TeV T	(constructive int.)	
2	SSM : m	L=1.1-1.2 fb ⁺ (2011) [arXiv:1108.1582]	1.83 IeV Z	M' mass		
	Scalar I O paire $(B-1)$: kin vare in acii. avii	L=1.0 fb (2011) [arXiv:1108.1316]	2.15 IEV	vv mass		
ГO	Scalar LQ pairs (β =1) : kin. vars. in eejj, evjj	L=1.0 fb (2011) [Preliminary]	an cave 2 nd don LO mass			
ц.	4^{th} generation : coll mass in $O \overline{O} \rightarrow WgWg$	L=33 pb ⁻¹ (2010) [arXiv:1104.4481] 270 Ge ⁻¹				
ı ge	$4^{\text{th}} \text{ generation : d} \overrightarrow{d} \rightarrow \text{WtWt} (2\text{-lep SS})$	L=37 pb (2010) [CONP-2011-022]				
4-th	$TT \longrightarrow tT + A A : 1-lep + jets + F$	L=34 pb (2010) [1108.0300] 230 Ge	$\frac{1}{420} \operatorname{cov}_{4} \operatorname{mass}(m(A) < 140)$	GeV		
	Techni-hadrons : dilepton, $m_{1,1}$	L=1.0 10 (2011) [arXiv:1105.4725]	$420 \text{ GeV} = 1 \text{ mass} (m(n_0) < 140)$	$(\pi - m(\pi) = 100 \text{ GeV})$		
	Major, neutr. (LRSM, no mixing) : 2-lep + jets	L=34 pb ⁻¹ (2010) [ATLAS-CONE-2011-115]	780 GeV N mass $(m(p_T) \otimes T)$	$f_{\rm T} = 1$ TeV)		
	Major neutr (LRSM no mixing) : 2-lep + jets	L=34 pb ⁻¹ (2010) [ATLAS-CONE-2011-115]	1 350 ToV W o m	$R^{\prime} = 1.000$ ass (230 < $m(N) < 700$) GeV)	
	$H_{\pm\pm}^{\pm\pm}$ (DY prod., BR($H^{\pm\pm} \rightarrow \mu\mu$)=1) : m	<i>L</i> = 1.6 fb ⁻¹ (2011) [CONE-2011-127] 3				
9L	Excited quarks : γ -jet resonance, m	<i>l</i> = 2.1 fb ⁻¹ (2011) [Preliminary]	2.46 Tel	a* mass		
Othe	Excited quarks : dijet resonance, m_{dijet}	$l = 1.0 \text{ fb}^{-1}$ (2011) [arXiv:1108.6311]	2.40 104			
0	Axigluons : m_{dijet}	$l = 1.0 \text{ fb}^{-1}$ (2011) [arXiv:1108.6311]	3.3	2 TeV Axialuon mass		
	Color octet scalar : m_{dilet}	$l = 1.0 \text{ fb}^{-1}$ (2011) [arXiv:1108.6311]	1.92 TeV	calar resonance mass	4	
	Vector-like quark : CC, m	L=1.0 fb ⁻¹ (2011) [Preliminary]	900 GeV Q mass (co	$vupling \kappa_{ro} = v/m_{o}$)		
	Vector-like quark : NC, m_{llo}	L=1.0 fb ⁻¹ (2011) [Preliminary]	760 Gev Q mass (cour	pling $\kappa_{ro} = v/m_{o}$		
						Ц
		10 ⁻¹	1	10	f	10
*0-	ly a calentian of the qualitable require loading to more limite	chour			Mass scale [Te\	/]
On	y a selection of the available results leading to mass limits	SHOWH			-	
		Wolfgang Ehr	enfeld Exotic Searches	at the LHC 8.2.	.2012 Page 34	

CMS Exotic Searches: Summary

Conclusion and Outlook

- > ATLAS and CMS have produced an impressive number of papers/conference notes using the 2010 and 2011 data
- In the channels searched so far, no significant excess above the Standard Model was found
- > New physics is not "just around the corner"
- Many limits have surpassed those from Tevatron/LEP
- > At the moment the full dataset of 5 fb⁻¹ are being analysed
- Extend the reach for new physics in 2012 if the LHC runs at 8 TeV centre-of-mass energy and delivers 20 fb⁻¹.

