Searching for New Exotic Physics at the LHC a.k.a. Searches Beyond Supersymmetry

Dave Charlton University of Birmingham

Before, Behind and Beyond he Discovery of the Higgs Boson Royal Society, 20-21 January 2014

Menu

Why search for exotic physics? Simple event types - "bump hunting" Top as a probe Long-lived particles Dark matter

Conclusions

The end of physics?

The Standard Model works fantastically, and is now completed by the H discovery

But it leaves so many questions unanswered...

- Why three families are there only three?
- Why the symmetry between quarks and leptons?
- Why the huge imbalances in particle masses?
- What is most of the matter in the universe?
- Where has the antimatter gone?
- What are the next steps in unification of forces?
- Unification with gravity?



This is not the end of fundamental physics - but where and what comes next? Previous talks laid the arguments for new physics at the TeV scale

"Exotic" searches

ATLAS and CMS design comprehensive search strategies for new physics beyond the Standard Model (BSM)

- Open perspective we do not know what we may find
- There are many many possible models and event signatures
- Searches started with simple signatures, expand to more complex events
- Models act as benchmarks and guides but we are open to as much as we can



D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London

"Exotic" searches

ATLAS and CMS design comprehensive search strategies for new physics beyond the Standard Model (BSM)

- Reconstruct high momentum (p_{τ}) objects (leptons, photons, jets...)
- Reconstruct decays of heavy objects (W, Z, top ...)
- Look for rare events with typically several such objects
- SM backgrounds derived from data where possible, guided by simulations

Measurement of detector performance is trickier at high p_{τ} , but generally only small effects on results from increased errors



D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Kuyac Juciecy, Lunuon

Some motivations for models (I)

The low-mass Higgs boson with "only" the SM requires "fine-tuning" → suggests new physics at TeV scale ("naturalness" problem)

SUSY provides a simple and elegant solution - but introduces many new particles

Can we solve this in other ways?



Some motivations for models (II)

Many other models have been suggested, predicting other new particles/effects in the TeV energy regime

Examples:

• New families of quarks - e.g. "vector-like" quarks (VLQs)

- Large extra dimensions the Planck scale (quantum gravity) is close to the electroweak scale
 - Solves the "hierarchy" problem
 - Predicts new particles and new physics effects





Run Number: 208184 Event Number: 77002566 Date: 2012-08-08, 06:22:57 CET

Simple Event Types "Bump Hunting"

Dilepton resonances

Historical guidance: Look for mass peaks in dilepton invariant mass distribution (ee, μμ, ττ)

Variety of models

- New SM Z-like sequential bosons Z'_{SSM}
- Grand Unified Theory inspired models ("E₆-motivated")
- Randall-Sundrum spin-2 gravitons G* in extra dimension models



Dilepton resonances

Select two high-p_{τ} e or μ , p_{τ}>~30 GeV Require isolated electrons -

suppresses (jet \rightarrow e) background

Acceptance x efficiency ~75% for 2 TeV invariant mass object decaying





Observed spectra extend well beyond 1 TeV

No statistically significant excesses

ery, Royal Society, London







Next step: 13 TeV LHC operation mass reach will ~double

In these models, mass of a new resonance must be more than 2-3 TeV

limits for specific models

Convert to lower mass

Upper limits placed on rate of events (cross-section times branching ratio $\sigma \cdot B(X \rightarrow \ell \ell)$ at 95%CL)

Dilepton resonances

Model	Mass limit (95%	CL)
Z' _{ssm}	2.96 TeV	CMS
Ζ'(ψ)	2.60 TeV	
Z' _{ssm}	2.86 TeV	ATLAS
Z'(E6 models)	2.38-2.54 TeV	
$G^*(k/M_{pl}=0.1)$	2.47 TeV	



Lepton-photon resonances





Production and decay model introduces a scale Λ , for $\Lambda = m(\ell^*)$ excited leptons excluded with mass below 2.2 TeV at 95% CL

Data 2012

🔣 Bkg. uncertainty

Z + jets, diboson, tt, W+ γ +jets

 $Z + \gamma$

900

Run Number: 208184 Event Number: 77002566 Date: 2012-08-08, 06:22:57 CET

0

ATLAS

High-mass eev event

W' decaying to leptons

Simplest case: $W' \rightarrow \ell v$

• Single high- p_{τ} lepton and E_{t}^{miss}

$$m_{\rm T}^W = \sqrt{2p_{\rm T}^\ell E_{\rm T}^{\rm miss}(1 - \cos(\Delta\phi))}$$

Again, no excess above backgrounds observed

```
Combining e,µ channels, SM-like W'
excluded by CMS for
m(W') > 3.35 TeV (95% CL)
```





Searches in dijets

Inclusive dijet mass spectrum - extends up to 5 TeV! Fit with smooth function, look for resonances

Limits on many models: string resonances, excited quarks, axigluons, colorons, s8 resonances, E6 diquarks, W' and Z' bosons, and Randall-Sundrum gravitons, up to 5 TeV



Further searches in: dijet final states, look at angular distributions in the detector, look at b-tagged jets; multijet topologies searching for 3-jet resonances

hadronic top candidate

Top as a Probe

Run Number: 209995, Event Number: 51046560

Date: 2012-09-09 23:10:22 CEST

top condidate



D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London

High transverse momentum top quarks

Common experimental challenge for searches for heavy particles decaying to top quarks - identification of high-p₁ tops

At high- p_{τ} , the top decay products can merge into a single "fat" jet

Sophisticated "jet substructure" techniques to identify these









Search for $X \rightarrow t\bar{t}$

Search for a heavy particle decaying to tt

 Both semileptonic (tt → bℓvbqq') and hadronic (tt → bqq'bq"q") decays

Search both for resolved and merged jets \rightarrow extend to very high momentum top quarks



Candidate $t\bar{t}$ event with m($t\bar{t}$)=2.6 TeV



D Charlton 7 Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Roval Society, London

New heavy quarks ("vector-like")

New heavy quarks (T, B): decay modes

- T \rightarrow bW, T \rightarrow tZ, T \rightarrow tH
- $B \rightarrow bZ, B \rightarrow tW, (B \rightarrow bH)$

g_{Q} Q Z, H, W^{\mp} g_{Q} Z, H, W^{\mp} g_{Q} Z, H, W^{\pm} $\overline{q}, \overline{q'}$

Several event signatures:

- Single lepton plus jets/ E_{τ}^{miss}
- Same- and opposite-sign dileptons plus jets/E_τ^{miss}
- Trileptons plus jets/ E_{τ}^{miss}
- Use b-tagging to improve signal/background



Vector-like quarks

Put all the information together complex multidimensional exclusion



D Charlton / Birmingham - 21 January 2014, Before, Benind and Beyond the Higgs Discovery, Royal Society, London

Vector-like quarks

Combining all channels analysed, CMS obtain lower mass limits of m(T) > 690-782 GeV (95% CL) m(B) > 520-785 GeV (95% CL)



D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London

Run Number: 208184 Event Number: 77002566 Date: 2012-08-08, 06:22:57 CET

Long-lived Particles

Long-lived particles

Several models predict massive long-lived particles

- Split, Gauge Mediated and R-parity violating SUSY
- "Hidden valley" models
 - e.g. H(125) may decay to a pair of particles with long lifetime

Signatures in detector can be very different

- Heavy highly-ionising charged particles which stop, or which travel right out
- Displaced vertices in the tracking detectors
- Displaced vertices further out (calorimeter, muons...)
- Out-of-time decays in the detector, unassociated with interactions

Challenging both to trigger on such events, and to reconstruct them



Reconstructed displaced vertex in data - apparent hadronic interaction at back of hadron calorimeter

Stopped R-hadrons

Semi-stable massive particles (gluinos, squarks...) can hadronise, pass into detector and stop in calorimeter

If lifetime > tens of ns, decay products seen in a different event! Trigger on high energy deposit in empty bunch-crossings (no pp collisions)



Spectacular events!

D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs D



Backgrounds from cosmic rays and muons travelling along with the beam - can measure from early data (low luminosity)



Displaced vertices in tracker

New massive particles with decay lengths of ~10-20 cm could be seen as displaced vertices in the tracking system

Special charged particle track reconstruction to recovers inefficiencies of standard tracking for particles produced far from the beam-line





Run Number: 208184 Event Number: 77002566 Date: 2012-08-08, 06:22:57 CET

Dark Matter

Dark Matter pair-production

Traditional searches for dark matter interactions in matter - scattering of DM particles (χ) off nuclei

Crossed diagram at the LHC \rightarrow pair-production of DM particles, gives *missing* transverse momentum (E_{τ}^{miss})

To observe (trigger on) such events, we need additional activity, e.g. from initial-state radiation of a gluon, photon, W or Z particle





Mono-jet search

Leading jet p_T > ~120 GeV, high E_T^{miss} Cuts on further jets - reduces QCD background Veto isolated leptons



D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London

Mono-jet search

Dominant SM background from $Z \rightarrow vv+jet$ normalised using control regions in data (Z→ℓℓ+jet)

No excess above SM expectation \rightarrow place limits on $\chi\chi$ production, and reinterpret in terms of χN cross-sections



Events / 25 GeV 10⁶ 10⁵

10⁴

 10^{3}

 10^{2}

10

1⊧

200

300

400

CMS Preliminary

 $L dt = 19.5 \text{ fb}^{-1}$

√s = 8 TeV

W→h

QCD Z→ľſ

Data

700

600

500

ADD M_p= 2 TeV. δ = 3

 $DM \Lambda = 0.9 \text{ TeV}, M = 1 \text{ Ge}$

UNP $d_{ii}=1.7$, $\Lambda_{ii}=2$ TeV

800

900

1000

36

W + $\chi\chi$ production

In the case of DM pair-production in association with a W, interference effects are important

Two diagrams interfere - relative sign of $uu\chi\chi$ and $dd\chi\chi$ coupling enters

Two channels analysed

- "Monolepton" channel where $W \rightarrow \ell v$ (CMS)
- "Fat jet" channel where $W \rightarrow q\overline{q}'$ (ATLAS)





W($\rightarrow q\bar{q}$) + $\chi\chi$ production

Monojet signature with a "fat jet" which could be from a W or Z decay





The highest-mass central dijet event. The two central high- p_{τ} jets have an invariant mass of 4.69 TeV

Conclusions

ATLAS EXPERIMENT

Run Number: 209580, Event Number: 179229707

Date: 2012–08–31 20:24:29 CEST





D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London



D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)

	Large ED (ADD) : monojet + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1210.4491]	4.37 TeV M _D (δ=2))	
10	Large ED (ADD) : monophoton + $E_{T,miss}$	L=4.6 fb ⁻¹ , 7 TeV [1209.4625]	1.93 TeV M _D (δ=2)	ATLAS	
ũ	Large ED (ADD) : diphoton & dilepton, m	L=4.7 fb ⁻¹ , 7 TeV [1211.1150]	4.18 TeV M _S (HLZ	8=3, NLO) Preliminary	
Sic	OED : dipnoton + $E_{T,miss}$	L=4.8 fb ⁻¹ , 7 TeV [1209.0753]	1.40 TeV Compact. scale R	-1	
ü	$S'/Z_2 ED$: dilepton, m_{\parallel}	L=5.0 fb ^{-*} , 7 TeV [1209.2535]	4.71 TeV M _{KK} ~ R		
ŭ	RS1: dilepton, m _{il}	L=20 fb", 8 TeV [ATLAS-CONF-2013-017]	Tev [ATLAS-CONF-2013-017] 2.47 TeV Graviton mass (k/M _{PI} = 0.1)		
di	RST: WWW resonance, m _{T,NN}	L=4.7 fb , 7 TeV [1208.2880]	1.23 TeV Graviton mass $(k/M_{\rm Pl} = 0.1)$) $\int dt = (1 - 20) \text{fb}^{-1}$	
Ľa	DO a 14 (DD=0.025) 14 1 11 inter m	L=7.2 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-150]	850 GeV Graviton mass (K/M _{PI} = 1.0)	$\int L dt = (1 - 20) ID$	
ž	$RS g \rightarrow tt (BR=0.925) : tt \rightarrow 1+jets, m$	L=4.7 fb ⁻¹ , 7 TeV [1305.2756]	2.07 lev g _{KK} mass	s = 7, 8 TeV	
ш	ADD BH $(M_{TH}/M_D=3)$: SS diffuon, $N_{ch. part.}$	L=1.3 fb ⁻¹ , 7 TeV [1111.0080]	1.25 TeV MD (0=0)		
	Ouantum black hole : dijet E (m)	L=1.0 fb ⁻¹ , 7 TeV [1204.4646]	1.5 lev M _D (0=0)		
	dood contact interaction : 2(m)	L=4.7 fb , 7 TeV [1210.1718]	4.11 IeV M _D (0=0)		
7	qqqq contact interaction : χ(m)	L=4.8 fb , 7 feV [1210.1718]	7.6 lev /	A constructive int)	
0	uutt CL: SS dilenton + jets + E	L=5.0 fb , 7 lev [1211.1150]	1 A (C=1)	3.9 lev A (constructive Int.)	
	7' (SSM) : m	L=14.3 fb , 8 TeV (ATLAS-CONF-2013-051)	3.3 lev A (C=1)		
	Z (SSM) . m	L=20 IB , 8 IEV [ATLAS-CONF-2013-017]	Z.00 TEV Z IIIdss		
	Z' (Jortophobic topoolor) : $t\bar{t}$) Liete m	L=4.7 ID , 7 IEV [1210.0004]	1.4 16V Z 11/255		
S 2 (leptopho	\simeq (repropriodic topcolor). If \rightarrow (repropriodic topcolor). W' (SSM): m_{\pm}^{tr}	L=14.3 ID , 8 IEV [AILAS-CONF-2013-052]	2 FE Tay W mass		
	$W' (\rightarrow ta, a = 1); m$	$L=4.7 \text{ fb}^{-1}$ 7 Tay (1209.4446)	2.55 TeV VV Mass		
	$W'_{-} (\rightarrow \text{th} \perp \text{BSM}) : m$	1-44.2 (b ⁻¹ & Toy (AT) AS CONE 2012 0501	1 R4 ToV W/ mass		
	Scalar I O pair (β =1) ; kin vare in equi evii	L=10.45 ⁻¹ 7 ToV (1112 4929)	660 Gov 1 ^{di} gen 10 mass		
Q	Scalar LQ pair $(\beta = 1)$: kin. vars. in eejj, evjj Scalar LO pair $(\beta = 1)$: kin. vars. in uuii uvii	L=1.0 fb ⁻¹ 7 ToV (1202 2172)	ses cov 2 nd don 10 mass		
L	Scalar LO pair (β =1) : kin vars in $\pi\pi$ i π vii	$l = 4.7 \text{ fb}^{-1}$ 7 TeV [1203.0526]	534 GeV 3 rd den LO mass		
	4 th concretion : t th > WhWh	$l = 4.7 \text{ fb}^{-1}$ 7 TeV [1210 5468]	656 GeV t mass		
N KS	4th generation : b'b' \rightarrow SS dilepton + jets + E_	/ =14.3 (b ⁻¹ .8 TeV (AT) AS-CONE-2013-0511	720 GeV b' mass		
le	Vector-like quark : TT→ Ht+X	/ =14.3 (b ⁻¹ , 8 TeV IATI AS-CONE-2013-018)	790 Gev T mass (isospin doublet)		
< 9	Vector-like guark : CC, m	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1.12 TeV VLQ mass (charge -1/3, cou	pling $\kappa_{-0} = v/m_{-}$	
	Excited quarks : y-jet resonance, m	L=2.1 fb ⁻¹ , 7 TeV [1112.3580]	2.46 TeV g* mass		
ы.	Excited guarks : dijet resonance, m	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-148]	3.84 TeV g* mass		
.х.б	Excited b guark : W-t resonance, mu	L=4.7 fb ⁻¹ , 7 TeV [1301,1583]	870 Gev b* mass (left-handed coupling)		
ш~	Excited leptons : I-γ resonance, m	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-146]	2.2 TeV * mass (Λ = m(l*))		
	Techni-hadrons (LSTC) : dilepton, mediu	L=5.0 fb ⁻¹ , 7 TeV [1209.2535]	850 GeV ρ_{-}/ω_{T} mass $(m(\rho_{-}/\omega_{T}) - m(\pi_{T}) = N$	U III	
	Techni-hadrons (LSTC) : WZ resonance (IvII), m	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-015]	920 GeV ρ_{-} mass $(m(\rho_{-}) = m(\pi_{-}) + m_{w}, m$	$(a_{-}) = 1.1 m(\rho_{-}))$	
	Major. neutr. (LRSM, no mixing) : 2-lep + jets	L=2.1 fb ⁻¹ , 7 TeV [1203.5420]	1.5 TeV N mass (m(W_) = 2 TeV)	
ЭH	eavy lepton N [±] (type III seesaw) ; Z-I resonance, m ₂ ,	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-019]	N^{\pm} mass (V_1 = 0.055, V_1 = 0.063, V_1 = 0)		
E S	$H_{i}^{\pm\pm}$ (DY prod., BR($H_{i}^{\pm}\rightarrow \parallel)=1$) : SS ee ($\mu\mu$), m_{i}^{\pm}	L=4.7 fb ⁻¹ , 7 TeV [1210.5070] 4	09 Gev H ^{±±} mass (limit at 398 GeV for μμ)		
0	Color octet scalar : dijet resonance, m	L=4.8 fb ⁻¹ , 7 TeV [1210.1718]	1.86 TeV Scalar resonance ma	ISS	
Multi	-charged particles (DY prod.) : highly ionizing tracks	L=4.4 fb ⁻¹ , 7 TeV [1301.5272]	490 GeV mass (q = 4e)		
Ма	gnetic monopoles (DY prod.) : highly ionizing tracks	L=2.0 fb ⁻¹ , 7 TeV [1207.6411]	862 GeV mass		
	un de la construcción de la constru				
		10 ⁻¹	1	$10 10^2$	
			-	Maga coolo (To)/J	
*0-4		sherence chown		wass scale [TeV]	

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

The highest-mass central dijet event. The two central high-p $_{\tau}$ jets have an invariant mass of 4.69 TeV

Conclusions ATL

The discovery of the Higgs boson at 125 GeV, with close-to-SM properties, has energised, and helped re-focus, searches beyond the Standard Model

A huge wealth of event signatures has been explored - but, as yet, no sustained hints of new physics beyond the Standard Model

The increase of centre-of-mass energy to 13-14 TeV in 2015 and beyond will double the mass reach, well into the TeV region

Thanks to Steven Worm and Paris Sphicas

D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London

D Charlton / Birmingham - 21 January 2014, Before, Behind and Beyond the Higgs Discovery, Royal Society, London