and Event Generation for the Large Hacin Collider Bryan Webber Cavendish Laboratory

University of Cambridge

Bryan Webber

Underlying Event



Multiple parton interactions in same collision

Depends on density profile of proton

- Assume QCD 2-to-2 secondary collisions
 - Need cutoff at low pT
- Need to model colour flow
 - Colour reconnections are necessary

Underlying Event



ATLAS CONF-2012-164

Colour Reconnection



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Burg Liebenzell, Sept 2014

Dijet Mass Distribution



No sign of deviation from Standard Model (yet)

Event Generators

• HERWIG

http://projects.hepforge.org/herwig/

- Angular-ordered parton shower, cluster hadronization
- ➡ v6 Fortran; Herwig++

• PYTHIA

http://www.thep.lu.se/~torbjorn/Pythia.html

- Dipole-type parton shower, string hadronization
- → v6 Fortran; v8 C++
- SHERPA

➡ C++

http://projects.hepforge.org/sherpa/

Dipole-type parton shower, cluster hadronization

"General-purpose event generators for LHC physics", A Buckley et al., arXiv:1101.2599, Phys. Rept. 504(2011)145

Generator Citations



Most-cited article only for each version

2014 is extrapolation (Jan to Aug x1.5)

Other relevant software (with apologies for omissions)

- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino, Charybdis, TrueNoir
- Mass spectra and decays: SOFTSUSY, SPHENO, HDecay, SDecay
- Feynman rule generators: FeynRules
- PDF libraries: LHAPDF
- Resummed (p_{\perp}) spectra: ResBos
- Approximate loops: LoopSim
- Jet finders: anti- k_{\perp} and FastJet
- Analysis packages: Rivet, Professor, MCPLOTS
- Detector simulation: GEANT, Delphes
- Constraints (from cosmology etc): DarkSUSY, MicrOmegas
- Standards: PDF identity codes, LHA, LHEF, SLHA, Binoth LHA, HepMC

Sjöstrand, Nobel Symposium, May 2013

Parton Shower Monte Carlo

Hard subprocess: $q\bar{q} \rightarrow Z^0/W^{\pm}$

http://mcplots.cern.ch/



- Leading-order (LO) normalization
 need next-to-LO (NLO)
- Worse for high p_T and/or extra jets need multijet merging

Summary on Event Generators

- Fairly good overall description of data, but...
- Hard subprocess: LO no longer adequate
- Parton showers: need matching to NLO
 - Also multijet merging
 - NLO showering?
- Hadronization: string and cluster models
 - Need new ideas/methods
- Underlying event due to multiple interactions
 - Colour reconnection necessary











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Matching & Merging

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
 - Frixione, BW, 2002 MC@NLO
 - POWHEG *

Nason, 2004

- Merging parton showers with LO n-jet matrix elements, minimizing jet resolution dependence
 - Catani, Krauss, Kühn, BW, 2001 CKKW Lönnblad, 2001 Dipole * Mangano, 2002
 - MLM merging *

MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

- Compute parton shower contributions (real and virtual) at NLO
 - Generator-dependent
- Subtract these from exact NLO
 - Cancels divergences of exact NLO!
- Generate modified no-emission (LO+virtual) and real-emission hard process configurations
 - Some may have negative weight
- Pass these through parton shower etc.
 - Only shower-generated terms beyond NLO

MC@NLO matching

$$d\sigma_{\rm NLO} = \begin{bmatrix} B(\Phi_B) + V(\Phi_B) - \int \sum_i C_i (\Phi_B, \Phi_R) d\Phi_R \end{bmatrix} d\Phi_B + R(\Phi_B, \Phi_R) d\Phi_B d\Phi_R$$

$$\equiv \begin{bmatrix} B + V - \int C d\Phi_R \end{bmatrix} d\Phi_B + R d\Phi_B d\Phi_R$$

$$d\sigma_{\rm MC} = B(\Phi_B) d\Phi_B \left[\Delta_{\rm MC} (0) + \frac{R_{\rm MC} (\Phi_B, \Phi_R)}{B(\Phi_B)} \Delta_{\rm MC} (k_T (\Phi_B, \Phi_R)) d\Phi_R \right]$$

$$\equiv B d\Phi_B \left[\Delta_{\rm MC} (0) + (R_{\rm MC}/B) \Delta_{\rm MC} (k_T) d\Phi_R \right]$$

$$d\sigma_{MC@NLO} = \begin{bmatrix} B + V + \int (R_{MC} - C) d\Phi_R \end{bmatrix} d\Phi_B [\Delta_{MC} (0) + (R_{MC}/B) \Delta_{MC} (k_T) d\Phi_R] \\ + (R - R_{MC}) \Delta_{MC} (k_T) d\Phi_B d\Phi_R$$

finite ≥ 0
MC starting from no emission
MC starting from one emission
Expanding gives NLO result

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POWHEG matching

P Nason, JHEP 11(2004)040

- POsitive Weight Hardest Emission Generator
- Use exact real-emission matrix element to generate hardest (highest relative p_T) emission configurations
 - No-emission probability implicitly modified
 - (Almost) eliminates negative weights
 - Some uncontrolled terms generated beyond NLO
- Pass configurations through parton shower etc

POWHEG matching

P Nason, JHEP 11(2004)040

$$d\sigma_{\rm MC} = B\left(\Phi_B\right) d\Phi_B \left[\Delta_{\rm MC}\left(0\right) + \frac{R_{\rm MC}\left(\Phi_B, \Phi_R\right)}{B\left(\Phi_B\right)} \Delta_{\rm MC}\left(k_T\left(\Phi_B, \Phi_R\right)\right) d\Phi_R\right]$$
$$d\sigma_{\rm PH} = \overline{B}\left(\Phi_B\right) d\Phi_B \left[\Delta_R\left(0\right) + \frac{R\left(\Phi_B, \Phi_R\right)}{B\left(\Phi_B\right)} \Delta_R\left(k_T\left(\Phi_B, \Phi_R\right)\right) d\Phi_R\right]$$
$$\overline{B}\left(\Phi_B\right) = B\left(\Phi_B\right) + V\left(\Phi_B\right) + \int \left[R\left(\Phi_B, \Phi_R\right) - \sum_i C_i\left(\Phi_B, \Phi_R\right)\right] d\Phi_R$$
$$\Delta_R\left(p_T\right) = \exp\left[-\int d\Phi_R \frac{R\left(\Phi_B, \Phi_R\right)}{B\left(\Phi_B\right)} \theta\left(k_T\left(\Phi_B, \Phi_R\right) - p_T\right)\right]$$

- NLO with (almost) no negative weights arbitrary NNLO
- High pT always enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_S)$

Multijet Merging

- Objective: merge LO n-jet matrix elements^{*}
 with parton showers such that:
 - Multijet rates for jet resolution > Q_{cut} are correct to LO (up to N_{max})



Leading (and next) Q_{cut} dependence cancels

* ALPGEN or MadGraph, n≤N_{max}
 CKKW: Catani et al., JHEP 11(2001)063
 -L: Lonnblad, JHEP 05(2002)063

MLM: Mangano et al., NP B632(2002)343

Qcut

Ε

θ

Vector boson production

Z^v at Tevatron

http://mcplots.cern.ch/



- Absolute normalization:
 LO too low
- POWHEG agrees with rate and distribution

Z⁰ at LHC



CMS, PRD85(2012)032002

CMS PAS SMP-12-025

- Normalized to data
- POWHEG agrees with distribution (and NNLO)

W asymmetry at LHC

Muon charge asymmetry in *W* decays



Asymmetry probes parton distributions

$$u\bar{d} \to W^+ \to \mu^+ \nu_\mu \quad \text{vs} \quad d\bar{u} \to W^- \to \mu^- \bar{\nu}_\mu$$

W+jets at LHC



 Very good agreement with predictions from merged simulations, while parton shower alone starts to fail for n_{jet} ≥ 2 Top quark pair production

Top pair production



Top mass & kinematics



Top mass & hadronization



Study dependence of reconstructed mass on "odd" clusters

Top mass & hadronization

Mangano, Top LHC WG, July 2012



Top mass & hadronization

m_{top} vs pt(top)

m_{top}(E+O) - 172.5



 $m_{top}(E+O) - m_{top}(E)$

Dependence of reconstructed mass on "odd" clusters ~ I GeV

Top+jets

- Matched NLO not adequate for >2 extra jets
- Merged multijets better there (for $d\sigma/\sigma$)

LHC Cross Section Summary

No significant deviations from SM (yet)

But all is not perfect ...

Dijet flavours versus jet pT

ATLAS, arXiv:1210.0441

Interesting excess of (single) b quark jets

Combined matching+merging

- NLO calculations generally refer to inclusive cross sections e.g. σ(W+≥n jets)
- Multijet merging does not preserve them, because of mismatch between exact real-emission and approximate (Sudakov) virtual corrections
- When correcting this mismatch, one can simultaneously upgrade them to NLO
- There remains the issue of merging scale dependence beyond NLO (large logs)

Combined matching+merging

- Many competing schemes (pp, under development)
 - MEPS@NLO (SHERPA) Höche et al., arXiv:1207.5030
 - FxFx (aMC@NLO) Frederix & Frixione, arXiv:1209.6215
 - UNLOPS (Pythia 8) Lönnblad & Prestel, arXiv:1211.7278
 - MatchBox (Herwig++) Plätzer, arXiv:1211.5467
 - * MiNLO (POWHEG) Hamilton et al., arXiv:1212.4504
 - GENEVA Alioli, Bauer et al., arXiv:1212.4504
- Some key ideas in LoopSim Rubin, Salam & Sapeta, JHEP1009, 084

Combined matching+merging

UNLOPS: Lönnblad & Prestel, arXiv:1211.7278

Scale dependences almost eliminated

Higgs boson production

Higgs Signal and Background Simulation

Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
W +jets, Z/γ^* +jets	ALPGEN [59]+HERWIG
$t\overline{t}, tW, tb$	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \rightarrow WW$	MC@NLO+HERWIG
$gg \rightarrow WW$	gg2WW [62]+HERWIG
$q\bar{q} \rightarrow ZZ$	POWHEG [63]+PYTHIA
$gg \rightarrow ZZ$	gg2ZZ [64]+HERWIG
WZ	MadGraph+PYTHIA, HERWIG
$W\gamma$ +jets	ALPGEN+HERWIG
$W\gamma^*$ [65]	MadGraph+PYTHIA
$q\bar{q}/gg \rightarrow \gamma\gamma$	SHERPA

ATLAS, Phys.Lett.B716(2012)1

gg→Higgs(+jet)

Higgs boson production total cross sections in pb at the LHC, 8 TeV							
K_R, K_F	1,1	1, 2	2, 1	$1, \frac{1}{2}$	$\frac{1}{2}, 1$	$\frac{1}{2}, \frac{1}{2}$	2,2
HJ-MINLO NLO	13.33(3)	13.49(3)	11.70(2)	13.03(3)	16.53(7)	16.45(8)	11.86(2)
H NLO	13.23(1)	13.28(1)	11.17(1)	13.14(1)	15.91(2)	15.83(2)	11.22(1)
HJ-MiNLO LO	8.282(7)	8.400(7)	5.880(5)	7.864(6)	18.28(2)	17.11(2)	5.982(5)
H LO	5.741(5)	5.758(5)	4.734(4)	5.644(5)	7.117(6)	6.996(6)	4.748(4)

Table 1: Total cross section for Higgs boson production at the 8 TeV LHC, obtained with the HJ-MiNLO and the H programs, both at full NLO level and at leading order, for different scales combinations. The maximum and minimum are highlighted.

Higgs+jets

FxFx: Match/merge MC@NLO+Herwig6

Frederix & Frixione, arXiv:1209.6215

VBF Higgs+jets

Matched MC@NLO and POWHEG Frixione, Torrielli, Zaro, arXiv: 1304.7927

Comparisons to data ($\gamma\gamma$ mode)

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Comparisons to data (ZZ* mode)

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Monte Carlo Higgs E_T

- RW = reweighted to agree with resummed+matched E_T
- Underlying event and hadronization NOT included

Grazzini, Papaefstathiou, Smillie, BW, 1403.3394

Monte Carlo Higgs q_T

• RW = reweighted to agree with resummed+matched E_T

• Reweighting improves agreement with HQT (= resummed+matched q_T)

Monte Carlo Higgs E_T

- RW = reweighted to agree with resummed+matched E_T
- Underlying event and hadronization INCLUDED
- Strong dependence on minimum hadron pT

Higgs E_T from jets?

• Suggested by G Salam:

- Parton level $\approx E_T$ of leading n jets (anti-kt, R=0.7)
- Less sensitive to underlying event and hadronization

Papaefstathiou, BW, prelim.

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SelectingVBF

Monte Carlo Higgs q_T & E_T

53

- Massless coloured vs massive colourless exchange
 - ► Big difference in q_T
 - ► Small difference in E_T

A Papaefstathiou, BW Bryan Webber

Burg Liebenzell, Sept 2014

Leading jets pT

Two hard leading jets in VBF

Leading jets M_{jj} and $\Delta\eta_{jj}$

- Cuts (~CMS):
- ► p⊤(j1), p⊤(j2) > 30 GeV
- ► M(j1j2) > 500 GeV
- ► ∆η(j₁j₂) > 3.5

SelectingVBF

- Cuts enhance VBF/ggF by ~25
- For 300 fb⁻¹ at 14 TeV:

Mode	BR%	ggF(raw)	VBF(raw)	ggF(cut)	VBF(cut)
bb	56.10	10,000,000	720,000	96,000	170,000
WW	23.13	4,200,000	300,000	40,000	71,000
gg	8.49	1,500,000	110,000	15,000	26,000
tt	6.16	1,100,000	79,000	11,000	19,000
ZZ	2.90	520,000	37,000	5,000	8,900
СС	2.83	510,000	37,000	4,800	8,700
γγ	0.23	41,000	2,900	390	710
Ζγ	0.16	29,000	2,100	270	490

Beyond Standard Model Simulation

BSM Simulation

- Main generators have some BSM models built in
 - Pythia 6 has the most models
 - Herwig++ has careful treatment of SUSY spin correlations and off-shell effects
- Trend is now towards external matrix element generators: FeynRules + MadGraph, ...
- QCD corrections and matching/merging still needed

NLO Squark Production

NLO with POWHEG matching to different generators

Gavin et al., arXiv:1305.4061

ATLAS SUSY Search

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)

	MSUGRA/CMSSM : 0 kep + its + Er	L-S.4 R-1, 8 Tex DATE AS-CONT-8018-1000	G = G mass
	MSUGRA/CMSSM : 1 len + /s + F-	success? a reaction and stress stores	a mass
_	Phone model: 0 lon + 70 + E		ATIAS
08	Bhone medial (0 iop + 75 + E r mas	Crock to the particulation of the set	
5	Priorio model : 0 lep + 1s + E (mas	LISTER TENDOLASICOM STRATEGY	cae two q mass (exp < zree, qerg) Promitiary
1	Giuino med. χ (g→qtχ): 1 lep + js + E r mas	Describely in two (received)	999 GeV g mass (m(c) < 200 GeV, m(c) = g(m(c) + m(g)
3	GMSB (INLSP) : 2 kp (OS) + js + E _{7 min}	2-4.7 fb ⁻¹ , 7 TeV (1208.4888)	1.24TeV g mass (avr = 10)
8	GMSB ((NLSP) : 1-2 x + js + E	2-20.7 (6 ⁻¹ , 8 YeV (1210, 1214)	1.40 TeV G MBSS (1.40) > 18)
20	GGM (bino NLSP) : yy + E	E-4LE IS ¹ , 7 TWV (1008-0785)	1.07 TeV 3 mass (mg) > 50 GeV
2	GGM (wino NLSP) : y + lep + E	LHL& B ¹ , T IVV (ATLAS-CONF-3013-144)	areaw 3 mass
-8	GGM (higgsino-bino NLSP) : y + b + E	CHURCH TWO DOM: THEY	933 GeV 0 mass (mg ²) > 200 GeV
	GGM (biocsing NLSP) : Z + lets + E	LICENS' A NUMBER OF THE OWNERS OF	3 mats (will) > 200 (cel) (s = 7, 8 TeV
	Gravition LSP : 'monoint' + E.	CONTRACT A DESCRIPTION OF COMPANY AND A STOR	
	Statistic cor indicati re com	CHESTS , S WY DATENS-CORE -SPIS-141	
503	g→bby :0 kp + 3 b-1s + E _{T,miss}	First Rule (R An Durive consistent	B TeV all 2012 data
8 5 8	g-my : 2 SS-lep + (0-3b-)['s + E r mas	L+86.7 (5", 6 WY (ATLAS-CONF-80/3-867)	soucev g mass ary #5,0 0 to to the com
593	g → try : 0 lep + multi-fs + E r mas	LISA 61, 6 TWO DATLAS-CONT-2012-161	1.00 TeV g mass (+6() < 300 GeV) 8 TeV, partial 2012 data
69 E	到→1版1:0 kp + 3 b-fs + E _{T miss}	Excala to", a two (ATEAN CONFIDERS 148)	115 TeV 0 mass (n(c) < 200 GeV)
	bb, b, →bg": 0 lep + 2-b-jets + E,	E-FE & IS', & TWO DATE AS: CONV-2012-1612	szopev b mass (+6,) < 129 GeV) 7 TeV, all 2011 data
20 10	56.5+17" : 2 \$\$-lep + (0-3b-)('s + E,	L-20 7 (s ² , a Twy (ATLAS CONFIGURATION)	sto day D mass $(m_{2}^{-1}) = 2 m_{2}^{-1} (1)$
16 Q	0 (icht), 1-+b2" : 1/2 lep (+ b-ief) + E-	L+4.7 fb ⁻¹ , 7 fb/4 (1008,4005, 1298,2102)	1 mass (m2 ⁴) = 55 GeV
2 3	It (medium), t + by : 1 lep + b-let + E-	LARCE INT, & TWO DATE AS COMPARED AND	100-010 Gav 1 (T1855 (110)) = 0 GaV (110) = 150 GaV
5 8	If (medium) 1-+b5" : 2 len + F.	Contractor in the last an other store card	1 mass (mass
5 8	W (hamas) Testil ⁰ : 1 lon a beat a E	2-30 Text & Second as cost and and	manager I man i sector
6, 22	The many has the second	CHEFTS , S WY (MCKS-COP - SPIS-SHI)	
24	II (nearly), they to the + 6(20) (tes + E) mas	C-SESTS , 6 WY (ATCAS-CON-SHI SOL	320400 Gav 1 (11855) (110, 1 = 3)
	II (natural GMOD) : 2(-+I) + 0-(et + E	Frank, with a wall burry and consideral	SOUGHY LITHESE PRE-15 GOAL
	$I_1I_2 \rightarrow I_1+Z : Z(\rightarrow I) + 1 100 + D - 101 + E$	E-86.7 (51), 6 TWO (ATLAS-CONF-8013-885)	STO DAY 1, mass (H(1) = H(2) + 180 GeV)
	$\left(\left(, \left[+ Q\right] : 2 \text{ lep } + E_{T, \text{miss}}\right)\right)$	L-4.7 % ² , 7 %V (1308.2884)	as ras Gev mass (e6;) = 0
> 8	$\chi \chi, \chi' \rightarrow h(W) : 2 lop + E_{T,min}$	5+6.7 fb ⁻¹ , 7 fwV (1208.2884)	113-340 GeV $\tilde{\chi}_{1}^{*}$ ITIDSS $(m(\tilde{\chi}_{1}^{*}) \times 10 \text{ GeV}, m(\tilde{\chi}_{1}^{*}) = \frac{1}{2}(m(\tilde{\chi}_{1}^{*}) + m(\tilde{\chi}_{1}^{*}))$
2 2	$\overline{\chi}, \overline{\chi}, \overline{\chi} \rightarrow \overline{v}v(v\overline{v}): 2v + E_{row}$	Ex20.7 fs ⁻¹ , 8 WY (ATLAS-CONF-3013-838)	180-330 GeV 2, ITT 355 (m(2) < 10 GeV, m(12) = (m(2) = m(2))
	$\overline{\chi} \overline{\chi}^{\circ} \rightarrow \overline{(} \sqrt{(} \sqrt{v} \sqrt{)}, \overline{N} \overline{(} \sqrt{v} \sqrt{)} : 3 \log + E$	2-20 7 fs ² , 8 WY (ATLAS-CONF-2013-038)	600 GeV 2 mass (m2) = m2 (m2) = 0, m(2) as above)
	$\overline{y}^{*}\overline{y}^{*} \rightarrow W^{*}\overline{y}Z^{*}\overline{y}^{*}: 3 \text{ kp} + E_{*}$	LADE 7 107, 8 WY DATLASHOOM - 2013-2019	atsow 7 mass (m7) = m7 L m7 1=0, septons decoupled)
	Direct 2 "pair prod. (AMSB) : long-lived 2	CALCENT, THEY MERSONED	200 GeV 2 ¹ (T10155 (1 + 0.20)
¥ 2	Stable 7 R.badmen : Inv 8 Br	2-4.7 B-1.7 SW 0211.30871	500 DV 0 0000
÷ 2	CIMCD stable 7: low 8	CONTRACT TRACE AND ADDRESS	The second secon
55	CMCB 7 ² w ^B : con pointing shoters	Contraction of the participant	
3 6	GM36, $\chi \rightarrow \gamma G$: non-pointing photons	LINET BY, THEY (MEAN CONFIDENTIAL	200 Gen X 110 23 (34 41(2) 4218
	$\chi^{\prime} \rightarrow ddh (Hh_{h}h)$: h + lieanly disbraced velock	DHEATER, YINY (1210, HET)	700 GeV Q MidDS (1 mm < ci < 1 m,g cecuped)
	LPV : pp=+v,+X, v,-+e+µ resonance	CHECK IN , Y HAV (MITA 1273)	101 TW V, Maiss (x ₁₀ =0.10, x ₁₀ =0.05)
	LFV : pp→v,+X,v,→e(µ)+< resonance	2-4.6 B ⁻¹ , 7 NV (1012,1273)	5.10 Tw V, mass (X, 10.1, 10.1, 10.1)
5	Bilinear RPV CMSSM : 1 lep + 7 js + E _{1,max}	EHLT 10 ⁻¹ , T TVV (ATLAS-CONF-3013-140)	1.2 TeV Q = Q mass (cr _{ut} < 1 nm)
2	$\chi, \chi, \chi \rightarrow W\chi, \chi \rightarrow eev_e \mu v$; $4 \text{ lep + } E_{T_{max}}$	L+86.7 fb7, 8 TeV (ATLAS-CONT-8013-836)	No GeV 2 mass (m(5) > 300 GeV, k => 0)
and an	2 2,, 2 →ττν_, erv, :3 kp + 1τ + E.	2-26.7 (5 ⁻¹ , 8 TeV (ATLAS-CONT-2013-834)	350 GeV X mass (m52) > 80 GeV, A m > 01
	ã → qog : 3-iet resonance pair	CALS IS", 7 TWO (1010-4813)	565 GeV g mass
	6-40, 1-4bs : 2 SS-lep + (0-3b-)('s + E	CHER 2 IS 1, & TWO DATE AS COMPLICATE ACT.	and Gev I I massa (Jev Mill)
	Scalar oluon : 2-let resonance calc	And the Art Two Ingle Angel	100-387 GeV SQL000 mass (ind. instron 11102490)
WM	P interaction (D5, Dirac y) : 'monoiet' + E	LARDEN AND A DESIGN AN OWNER ADDRESS	Martine M* section on a section and a section of the
	T,rite		In the second seco
		10"	1 10

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

ATLAS Exotica Search

		ATLAS Exotics	Searches* - 95% CL Lov	wer Limits (Status: I	HCP 2012)
	Lorge ED (ADD) - monoiot - E			4 (1-2)	
	Large ED (ADD) : monojet + E _{7,miss}	E-4.7 (6) 7 feV [1210.4 (6)]		4.37 TeV M _D (0=2)	
93	Large ED (ADD) : diploton & dilecton m	Cardening of the processing	1.93 TeV - 201	M (HI 7 I-3 N ())	ATLAS
8	UED : diphoton + E-	Call and Tarry International Construction	LALTAN COMPA	ct scale B ⁻¹	Preliminary
50	S ¹ /Z ED : dilector m	Lates one ¹ , 2 her processione services	the compa	ATL THE Mar - R	
Đ,	BS1 : diphoton & dilepton, m	L=4.7-5.0 (b ⁻¹ , 7 TeV (1) 213, 818 K	2.93 Twv (Staviton mass $(k/M_{\odot} = 0.1)$	
E.	RS1 : ZZ resonance, m	Let 0 % ² , 7 TeV (1203/0718)	Ms Dev Graviton mass	(k/M_= = 0.1)	
0	RS1 : WW resonance, mr.	Lot.7 (b ¹ , 7 TeV (1208,2880)	1.23 Tev Graviton	mass $(k/M_{\odot} = 0.1)$ Let	$t = (1.0 - 13.0) \text{ fb}^{-1}$
ŝ.	$RS g \rightarrow tt (BR=0.925) : tt \rightarrow I+jets, m$	L+4.7 (5 ⁻¹ , 7 TeV [ATLAS-CONF-2012-136]	1.8 TeV Q	mass	E
ú	ADD BH (M _{nx} /M _n =3) : SS dimuon, N _n and	Cell 3 (6 ⁻¹ , 7 TeV [1111.0080]	1.25 TeV M., (b=6)		∎s = 7,8 TeV
	ADD BH (M _{n+} /M _p =3) : leptons + jets, 2p_	L-1.0 (6 ⁻¹ , 7 TeV (1204.4848)	1.5 TeV M ₀ (8-	-6)	
	Quantum black hole : dijet, F_(m_)	En4.7 (b ⁻¹ , 7 TeV [1210.1718]		.11 TeV M., (5=6)	
	qqqq contact interaction : $\chi(m)$	List 8 (6 ⁻¹ , 7 TeV (ATLAS-CONF-2012-008)		7.8 TeV A	
3	ggll CI : ee & µµµ, m	L=4.0-6.0 (b ⁻¹ , 7 TeV [1211.1160]		13.0 TeV A (constructive int.)
-	uutt CI : SS dilepton + jets + E _{7 mins}	L+1.0 (b ⁻¹ , 7 TeV [1203:5530]	1.7 TeV A		
	Z'(SSM): m _{min}	LISSIGN TH'S THY DATLAS COMP 2012-125	2.49 TeV	Z mass	
	Z [*] (SSM) : m.,	2-4.7 m ⁻¹ , 7 meV (1210,8404)	14 TeV Z' mass		
3	W (SSM) : m _{1.00}	L+4.7 (b ⁻¹ , 7 TeV [1209.4446]	2.55 TeV	W'mass	
2	$W'(\rightarrow tq, g_{a}=1): m_{a}$	Lot.7 (b ⁻¹ , 7 TeV (1209/8590)	430 GeV W' mass		
	$W_n (\rightarrow tb, SSM) : m_n$	2+1.0 m ⁻¹ , 7 meV (1205.1016)	1.18 TeV W' mass		
	W" : m _{1 m1}	L+4.7 (b ⁻¹ , 7 TeV [1209.4446]	2.42 TeV	W* mass	
~	Scalar LQ pair (B=1) : kin. vars. in eejj, evjj	Ex1.0 fb ⁻¹ , 7 TeV [1112.4626]	sso Gev 1 ^{er} gen. LQ mass		
9	Scalar LQ pair (β=1) : kin. vars. in μμj, μvjj	6+1.0 fb ⁻¹ , 7 TeV (1203-3172)	665 GeV 2 nd gen. LQ mass		
-	Scalar LQ pair (B=1) : kin. vars. in rrij, rvjj	Ex4.7 fb ⁻¹ , 7 TeV [Proliminary]	sas GeV 3 rd gen. LQ mass		
93	4 th generation : t't'→ WbWb	E-4.7 (6 ⁻¹ , 7 TeV [1210.5468]	656 GeV (1 mass		
1 Second	4 ⁿ generation : bb/(T _{so} T _{so})→ WtWt	L=4.7 fb ⁻¹ , 7 feV (ATLAS-CONF-2012-100)	ero ow b' (T_) mass		
ž	New quark b' : $bb' \rightarrow Zb+X, m_{2b}$	Ex2.0 (6 ⁻¹ , 7 TeV [1204.1265] 4	as GeV b' mass		
2	Top partner : TT $\rightarrow tt + A_0A_0$ (dilepton, M_)	L=4.7 (6 ⁻¹ , 7 TeV [1208.4188]	483 GeV T mass (m(A,) < 100 G	ieV)	
ē.	Vector-like quark : CC, mine	LHLE 15 ⁻¹ , 7 TeV [ATLAS-CONF-2012-127]	1.12 TeV VLQ mass	(charge -1.3, coupling K _{q0} = 1	v/m _o)
< _	Vector-like quark : NC, m _{eq}	LHLE 15 ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1.00 TeV VLQ mass	(charge 2/3, coupling $\kappa_{\alpha 0} = v$)	m_)
청 년	Excited quarks : y-jet resonance, m	Ex2.1 (6-1, 7 TeV [1112.3680]	2.46 TeV	q* mass	
<u>8</u> 8	Excited quarks : dijet resonance, m	Ex133 (5 ¹), 8 Nev (ATEAS-CONF-2012-148)	3.	A TeV q" mass	
щ÷	Excited lepton : I-y resonance, m	Ex12.0 (b), 8 TeV [ATEAS-CONF-2012-146]	2.2 ToV	mass $(\Lambda = m(l^*))$	
	Techni-hadrons (LSTC) : dilepton, marcing	En4.9-5.0 fb ⁻¹ , 7 TeV [1208.2535]	sso GeV μ/ω, mass (m	$(p_1/m_1) - m(n_1) = M_{p_1}$	
	Techni-hadrons (LSTC) : WZ resonance (vIII), m T.WZ	6-1.0 million TeV (1204.1648)	483 GeV ρ_{γ} mass $(m(\rho_{\gamma}) = m(\pi_{\gamma})$	$+ m_{uv}, m(a_{-}) = 1.1 m(p_{-}))$	
9	Major. neutr. (LRSM, no mixing) : 2-lep + jets	Lig.1 fb ⁻¹ , 7 TeV [1203.5493]	1.5 TeV N mas	$s(m(W_p) = 2 \text{ TeV})$	
£	W _{it} (LRSM, no mixing) : 2-lep + jets	£+2.1 (b ⁻¹ , 7 TeV [1803.5499]	2.4 TeV	W_{R} mass (m(N) < 1.4 TeV)	
0	H_{i}^{m} (DY prod., BR($H_{i}^{m} \rightarrow II$)=1) : SS ee (µµ), m	L=4.7 fb ⁻¹ , 7 feV (1210.5070) 4	cs Gev H[" mass (limit at 398 Ge	V for µµ)	
	$H^{-}(DY \text{ prod.}, BH(H^{-} \rightarrow e\mu)=1) : SS e\mu, m_{e_{\mu}}$	L-4.7 fb ⁻¹ , 7 feV (1210.5370) 37	s Gev H [*] , mass		
	Golor octet scalar : dijet resonance, m	L=4.6 fe ⁻¹ , 7 feV (1210.1718)	1.06 TeV Sci	lar resonance mass	
		401	4	10	102
		10		10	10
	k a selection of the sumfable mass limits or new states of	abanamana abaun		M	ass scale [TeV]

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

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CMS Exotica Search

Bryan Webber

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Burg Liebenzell, Sept 2014

Conclusions and Prospects

- Standard Model has (so far) been spectacularly confirmed at the LHC
- Monte Carlo event generation of (SM and BSM) signals and backgrounds plays a big part
- Matched NLO and merged multi-jet generators have proved essential
 - Automation and NLO merging in progress
 - NNLO much more challenging
- Still plenty of scope for new discoveries!

Thanks for listening!