## Event Generation for the Large Hadron Collider

#### Bryan Webber Cavendish Laboratory University of Cambridge

Event Generation for the LHC

Future of Collider Physics, KIPMU, 16/07/13

Event Generation for the Large Hadron Collider

- Monte Carlo event generation:
  - theoretical status and limitations
- Recent improvements:
  - perturbative and non-perturbative
- Overview of results:
  - W, Z, top, Higgs, BSM (+jets)
  - ✤ Test cases: top mass, Higgs pT

Monte Carlo Event Generation

#### Monte Carlo Event Generation

- Aim is to produce simulated (particle-level) datasets like those from real collider events
  - \* i.e. lists of particle identities, momenta, ...
  - simulate quantum effects by (pseudo)random numbers
- Essential for:
  - Designing new experiments and data analyses
  - Correcting for detector and selection effects
  - Testing the SM and measuring its parameters
  - Estimating new signals and their backgrounds

## A high-mass dijet event



CMS Experiment at LHC, CERN Data recorded: Fri Oct 5 12:29:33 2012 CEST Run/Event: 204541 / 52508234 Lumi section: 32



CMS Experiment at LHC, CERN Data recorded: Fri Oct 5 12:29:33 2012 CEST Run/Event: 204541 / 52508234 Lumi section: 32



• M<sub>ii</sub> = 5.15 TeV

#### CMS PAS EXO-12-059















Future of Collider Physics, KIPMU, 16/07/13









## **QCD** Factorization

$$\sigma_{pp \to X}(E_{pp}^2) = \int_0^1 dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij \to X}(x_1 x_2 E_{pp}^2, \mu^2)$$
  
momentum parton hard process fractions distributions cross section at scale  $\mu^2$ 

- Jet formation and underlying event take place over a much longer time scale, with unit probability
- Hence they cannot affect the cross section
- Scale dependences of parton distributions and hard process cross section are perturbatively calculable, and cancel order by order

## Parton Shower Approximation

- Keep only most singular parts of QCD matrix elements:
- **Collinear**  $d\sigma_{n+1} \approx \frac{\alpha_{\rm S}}{2\pi} \sum_{i} P_{ii}(z_i, \phi_i) dz_i \frac{d\xi_i}{\xi_i} \frac{d\phi_i}{2\pi} d\sigma_n \qquad \qquad \xi_i = 1 \cos\theta_i$ **Soft**  $d\sigma_{n+1} \approx \frac{\alpha_{\rm S}}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{p_i \cdot p_j}{p_i \cdot k \, p_j \cdot k} \omega \, d\omega \, d\xi_i \, \frac{d\phi_i}{2\pi} d\sigma_n$  $= \frac{\alpha_{\rm S}}{2\pi} \sum_{i,i} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{\xi_{ij}}{\xi_i \,\xi_j} \frac{d\omega}{\omega} d\xi_i \, \frac{d\phi_i}{2\pi} d\sigma_n$  $\approx \frac{\alpha_{\rm S}}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \Theta(\xi_{ij} - \xi_i) \frac{d\omega}{\omega} \frac{d\xi_i}{\xi_i} d\sigma_n$  $\int_{i} \frac{\partial e_{ij}}{\partial \theta_{ij}} = \theta_i \qquad \omega = (1 - z_i)E_i$   $i \qquad z_i E_i$

Angular-ordered parton shower (or dipoles)

Event Generation for the LHC

### Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory Ctreaks down in hidron ine formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Colour, flavour and momentum flows are only locally redistributed by hadronization



### Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory Ctreaks down in hidron ine formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Colour, flavour and momentum flows are only locally redistributed by hadronization



### Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory Preaks down and had mons are formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Colour, flavour and momentum flows are only locally redistributed by hadronization



## String Hadronization Model

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory Preaks down and had one are formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Colour flow dictates how to connect hadronic string (width ~ few x  $\Lambda_{QCD}$ ) with shower



## String Hadronization Model

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory **Preaks down and hadrons at** e formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Colour flow dictates how to connect hadronic string (width ~ few x  $\Lambda_{QCD}$ ) with shower



## **Cluster Hadronization Model**

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory Preaks down and had one are formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Decay of preconfined clusters provides a direct basis for hadronization



## **Cluster Hadronization Model**

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near  $\Lambda_{QCD}$ ~200 MeV, perturbation theory Preaks down and had one are formed
  - Before that, at scales  $Q_0 \sim \text{few x } \Lambda_{QCD}$ , there is universal preconfinement of colour
  - Decay of preconfined clusters provides a direct basis for hadronization



### Cluster Hadronization Model



- Mass distribution of preconfined clusters is universal
- Phase-space decay model for most clusters
- High-mass tail decays anisotropically (string-like)

### Hadronization Status

- No fundamental progress since 1980s
  - Available non-perturbative methods (lattice, AdS/QCD, ...) are not applicable
- Less important in some respects in LHC era
  - Jets, leptons and photons are observed objects, not hadrons
- But still important for detector effects
  - Jet response, heavy-flavour tagging, lepton and photon isolation, ...



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



Event Generation for the LHC

#### Dijet Mass Distribution



No sign of deviation from Standard Model (yet)

#### MC Event Generators

#### HERWIG

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

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

#### 

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

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

#### SHERPA

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

→ C++

#### 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

Event Generation for the LHC

# The Big Question

- If no large signals of BSM physics are seen at LHC, they could still be hiding in large SM backgrounds.
  - Most likely in Higgs, 3rd generation and/or multijets production.
- At what level could we detect them?
  - Depends on improvements in SM (especially QCD) event generation.

## Consistency of SM



Future of Collider Physics, KIPMU, 16/07/13
# Vacuum Stability



### Parton Shower Monte Carlo

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



- Leading-order (LO) normalization 
   need next-to-LO (NLO)
- Worse for high p<sub>T</sub> and/or extra jets need multijet merging

http://mcplots.cern.ch/







### Improving Event Generation





### Improving Event Generation



# Matching & Merging

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

Nason, 2004

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



- 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

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

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

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

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

$$d\sigma_{MC@NLO} = \begin{bmatrix} B + V + \int (R_{MC} - C) d\Phi_R \end{bmatrix} d\Phi_B [\Delta_{MC} (0) + (R_{MC}/B) \Delta_{MC} (k_T) d\Phi_R] \\ + (R - R_{MC}) \Delta_{MC} (k_T) d\Phi_B d\Phi_R$$
  
finite  $\ge 0$   
MC starting from no emission  
MC starting from one emission  
**Expanding gives NLO result**

Event Generation for the LHC

### 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<sub>T</sub>) 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

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

$$d\sigma_{\rm PH} = \overline{B} \left( \Phi_B \right) \, d\Phi_B \, \left[ \Delta_R \left( 0 \right) + \frac{R \left( \Phi_B, \Phi_R \right)}{B \left( \Phi_B \right)} \, \Delta_R \left( k_T \left( \Phi_B, \Phi_R \right) \right) \, d\Phi_R \right]$$

$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int \left[ R(\Phi_B, \Phi_R) - \sum_i C_i(\Phi_B, \Phi_R) \right] d\Phi_R$$

$$\Delta_R (p_T) = \exp \left[ -\int \mathrm{d}\Phi_R \, \frac{R \left(\Phi_B, \Phi_R\right)}{B \left(\Phi_B\right)} \, \theta \left(k_T \left(\Phi_B, \Phi_R\right) - p_T\right) \right]$$

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

Event Generation for the LHC

# Multijet Merging

- Objective: merge LO n-jet matrix elements<sup>\*</sup>
   with parton showers such that:
  - Multijet rates for jet resolution > Q<sub>cut</sub> are correct to LO (up to N<sub>max</sub>)
  - Shower generates jet structure below Q<sub>cut</sub>
     (and jets above N<sub>max</sub>)
  - Leading (and next) Q<sub>cut</sub> dependence cancels

\* ALPGEN or MadGraph, n≤N<sub>max</sub> CKKW: Catani et al., JHEP 11(2001)063

-L: Lonnblad, JHEP 05(2002)063

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

Q<sub>cut</sub>

E

θ

# Top quark production

# Top quark pairs at LHC



# Top Mass





Future of Collider Physics, KIPMU, 16/07/13

 $Evant neneratio 2772 \pm 196 \pm 122 \text{ MeV}$ 

### 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<sub>top</sub> vs pt(top)

m<sub>top</sub>(E+O) - 172.5



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



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



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

# Vector boson production

# Z<sup>0</sup> at Tevatron



http://mcplots.cern.ch/

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

# Z<sup>0</sup> 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

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

Event Generation for the LHC

### W+jets at LHC



• Very good agreement with predictions from merged simulations, while parton shower alone starts to fail for  $n_{jet} \ge 2$ 

# LHC Cross Section Summary Standard Model in one slide



#### Tuesday, March 26, 2013

- Surprisingly good agreement
- No sign of non-Standard-Model phenomena (yet)

# But all is not perfect ... Dijet flavours versus jet pt ATLAS, arXiv:1210.0441



Interesting excess of (single) b quark jets

Event Generation for the LHC

### Combined matching+merging

- NLO calculations generally refer to inclusive cross sections e.g.  $\sigma(W+\ge n \text{ jets})$
- 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



UNLOPS: Lönnblad & Prestel, arXiv:1211.7278

Scale dependences almost eliminated

# Higgs boson production

### Higgs Production by Gluon Fusion

### Higgs Production by Gluon Fusion



### Higgs Production by Gluon Fusion














Forward jets

- Few central jets
- Central jet veto increases S/B

## Higgs Signal and Background Simulation

Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
W+jets, $Z/\gamma^*$ +jets	ALPGEN [59]+HERWIG
$t\bar{t}, tW, tb$	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \rightarrow WW$	MC@NLO+HERWIG
$gg \to WW$	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
$q\bar{q}/gg  ightarrow \gamma\gamma$	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)	<b>11.70(2)</b>	13.03(3)	<b>16.53(7)</b>	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)	<b>5.880(5)</b>	7.864(6)	<b>18.28(2)</b>	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.



UI Duthia

# gg→Higgs+jets (8 TeV)



### FxFx: Match/merge MC@NLO+Herwig6

Frederix & Frixione, arXiv:1209.6215

## gg→Higgs+jets (I3 TeV)



Event Generation for the LHC

1000

500

100

50

10 =

5

1.8

1.6

1.4

1.2

1.0

0.8

0.6

10<sup>5</sup>

 $10^{4}$ 

10<sup>3</sup>

10<sup>2</sup>

10<sup>1</sup>8

1.6

1.4

1.2

1.0

0.8

0.6

0

0

Future of Collider Physics, KIPMU, 16/07/13

## t,b mass effects on Higgs pr



## VBF Higgs+jets



Matched MC@NLO and POWHEG

Frixione, Torrielli, Zaro, arXiv: 1304.7927

## 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



• Background: mostly Sherpa LO multijet merging

## NLO Squark Production



NLO with POWHEG matching to different generators

Gavin et al., arXiv: 1305.4061

 $\tilde{q}_i$ 

## ATLAS SUSY Search

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

		· · · · · · · · · · · · · · · · · · ·		
	MSUGRA/CMSSM $\cdot$ 0 len + i's + $F_{-}$	/ =5.8 fb <sup>-1</sup> . 8 TeV [ATLAS-CONE-2012-109]	t 50 TeV õ −õ mass	
	MSUGBA/CMSSM : 1 lep + i's + $E$			
	Phono model : 0 lon $\downarrow$ i'c $\downarrow$ E	L=5.6 ID , 6 TeV [ATLAS-CONF-2012-104]		ΔΤΙΔς
es	Pheno model : 0 lep + $JS + E_{T,miss}$	L=5.8 fb <sup>-</sup> , 8 lev [AILAS-CONF-2012-109]	1.18 lev g mass ( <i>m</i> (q) < 2 lev, light χ	
ch	Prierio model . 0 lep + j s + $E_{T,miss}$	L=5.8 fb <sup>-+</sup> , 8 TeV [ATLAS-CONF-2012-109]	<b>1.38 TeV Q ITIASS</b> ( <i>m</i> (g) < 2 TeV, lig	$ht_{\chi_1}$ ) Preliminary
ear	Gluino med. $\chi^-$ (g $\rightarrow$ q $\overline{q}\chi^-$ ) : 1 lep + J's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1208.4688]	<b>900 GeV g</b> mass $(m(\widetilde{\chi_1}) < 200 \text{ GeV}, m(\widetilde{\chi_2}) = 2$	$(m(\tilde{\chi})+m(\tilde{g}))$
Se	GMSB (INLSP) : 2 lep (OS) + j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1208.4688]	<b>1.24 TeV ğ MASS</b> (tanβ < 15)	
NG	GMSB ( $\tau$ NLSP) : 1-2 $\tau$ + j's + E	L=20.7 fb <sup>-1</sup> , 8 TeV [1210.1314]	<b>1.40 TeV</b> $\tilde{g}$ mass (tan $\beta$ > 18)	
ISN	GGM (bino NLSP) $(\gamma \gamma + E_{T miss})$	L=4.8 fb <sup>-1</sup> , 7 TeV [1209.0753]	<b>1.07 TeV</b> $\widetilde{\mathbf{g}}$ <b>Mass</b> $(m\widetilde{\chi}_1^0) > 50$ GeV)	$\int dt dt (4, 4, 00, 7) th^{-1}$
Icli	GGM (wino NLSP) : $\gamma$ + lep + $E_{T_{mino}}$	L=4.8 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-144]	619 GeV g mass	Lat = (4.4 - 20.7) fb
1	GGM (higgsino-bino NLSP) : $\gamma + b + E_{T min}^{\gamma,mss}$	L=4.8 fb <sup>-1</sup> , 7 TeV [1211.1167]	900 GeV $\widetilde{\mathbf{g}}$ mass $(m(\widetilde{\chi}^0) > 220 \text{ GeV})$	
	GGM (higgsino NLSP) : Z + jets + $E_{T \text{ miss}}^{1,\text{miss}}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-152]	690 GeV $\widetilde{\mathbf{Q}}$ mass $(m(\widetilde{\mathbf{H}}) > 200 \text{ GeV})$	s = 7, 8 lev
	Gravitino LSP : 'monoiet' + $E_{T mino}$	L=10.5 fb <sup>-1</sup> . 8 TeV [ATLAS-CONF-2012-147]	<b>645 GeV</b> $F^{1/2}$ scale $(m(\tilde{G}) > 10^4 \text{ eV})$	
σ.	$\tilde{a} \rightarrow b \tilde{b} \tilde{v}^0 \cdot 0 \text{ len } \pm 3 \text{ b-i's } \pm F$	/=12.8 fb <sup>-1</sup> 8 TeV [ATLAS-CONE-2012-145]	1.24 TeV $\widetilde{\alpha}$ mass $(m\widetilde{\alpha}^0) < 200 \text{ GeV}$	
en. 10	$a_{-}tt_{0}^{0}: 2$ SS-lop (0-3b-)i's (F	$L_{-20.7}$ fb <sup>-1</sup> 8 ToV [ATLAS CONE 2012 007]	$\frac{1}{24} \frac{1}{100} \frac{1}{2} \frac{1}{100} \frac{1}{10$	8 TeV. all 2012 data
l uii dia	$g \rightarrow t g^{-1} $ $z = 0 - t c p + (0 - 5 b^{-1}) J + L_{T,miss}$	L = 20.7  Hz, 6 TeV [AT LAS-CONF-2013-007]	$\widetilde{\mathbf{a}}$ mass (ally $m(\chi_1)$ )	
3ra gi ne	$g \rightarrow it \chi$ . 0 lep + 11ulti-j S + $E_{T,miss}$	L=3.6 ID , 6 IEV [ATLAS-CONF-2012-103]	$\vec{n}_{1,00} = \vec{n}_{2,00} = \vec{n}_{1,00} = $	8 TeV, partial 2012 data
	$g \rightarrow i l \chi$ . 0 lep + 3 b-J S + $E_{T,miss}$	L=12.8 fb <sup>-</sup> , 8 lev [AILAS-CONF-2012-145]	1.15 lev $g$ IIIdSS ( $m(\chi_1) < 200 \text{ GeV}$ )	
	$\sum_{n \to \infty} DD, D \to D\chi^* : 0 \text{ lep } + 2\text{-D-Jets } + E_{T,\text{miss}}$	L=12.8 fb <sup>-+</sup> , 8 TeV [ATLAS-CONF-2012-165]	<b>620 GeV</b> D MASS $(m(\chi_1) < 120 \text{ GeV})$	7 TeV, all 2011 data
no n	bb, $b_1 \rightarrow t \tilde{\chi}_1^x$ : 2 SS-lep + (0-3b-)j's + $E_{T,miss}$	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-007]	<b>430 GeV</b> D MASS $(m(\widetilde{\chi}_1^{\pm}) = 2 m(\widetilde{\chi}_1^{\circ}))$	
cti	$\underbrace{\text{tt}}_{T,\text{miss}}$ (light), t $\rightarrow$ b $\tilde{\chi}_{1}^{\pm}$ : 1/2 lep (+ b-jet) + $E_{T,\text{miss}}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1208.4305, 1209.2102]	<b>167 GeV</b> t mass $(m(\tilde{\chi}_1^0) = 55 \text{ GeV})$	
np	tt (medium), t $\rightarrow$ b $\tilde{\chi}_{1}^{\pm}$ : 1 lep + b-jet + $E_{T,miss}$	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-037]	<b>160-410 GeV</b> $t \max_{1}^{0} (m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm}) = 150 \text{ GeV})$	
7. 3	tt (medium), t $\rightarrow$ b $\tilde{\chi}_{+}^{\pm}$ : 2 lep + $E_{T,\text{miss}}$	L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-167]	<b>160-440 GeV</b> t mass $(m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}, m(\tilde{t}) - m(\tilde{\chi}_{1}^{\pm}) = 10 \text{ GeV})$	
jei st p	$\widetilde{t}\widetilde{t}$ (heavy), $\widetilde{t} \rightarrow t \widetilde{\chi}^0$ : 1 lep + b-jet + $E_{T \text{ miss}}$	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-037]	<b>200-610 GeV</b> t mass $(m(\tilde{\chi}^0) = 0)$	
d g	$\widetilde{t}\widetilde{t}$ (heavy), $\widetilde{t} \rightarrow t\widetilde{\chi}^0$ : 0 lep + 6(2b-)jets + $E_{T \text{ miss}}$	L=20.5 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-024]	<b>320-660 GeV</b> t mass $(m(\tilde{\chi}_{4}^{0}) = 0)$	
31 di	$\widetilde{t}$ (natural GMSB) : Z( $\rightarrow$ II) + b-jet + E	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-025]	<b>500 GeV</b> $t \text{ mass}$ $(m(\tilde{\chi}^0) > 150 \text{ GeV})$	
	$\widetilde{t}_{0}\widetilde{t}_{0},\widetilde{t}_{0}\rightarrow\widetilde{t}_{1}+Z:Z(\rightarrow II)+1$ lep + b-jet + $E_{-}^{I,miss}$	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-025]	520 GeV $\widetilde{t}_{\alpha}$ mass $(m(\widetilde{t}_{\alpha}) = m(\widetilde{\chi}^0) + 180 \text{ GeV})$	
	$\widetilde{I} \widetilde{I} \rightarrow \widetilde{P}^{0}$ : 2 lep + $E_{-}$	L=4.7 fb <sup>-1</sup> . 7 TeV [1208.2884]	<b>85-195 GeV</b> $\prod_{n=1}^{\infty} \max_{m(\tilde{\chi}^0)} = 0$	
t	$\widetilde{\gamma}^+\widetilde{\gamma}^-\widetilde{\gamma}^+ \rightarrow \widetilde{W}( \widetilde{\gamma}) \cdot 2 \text{ lep } + F$	L=4.7 fb <sup>-1</sup> . 7 TeV [1208.2884]	<b>110-340 GeV</b> $\widetilde{\chi}^{\pm}$ <b>Mass</b> $(m(\widetilde{\chi}^0) < 10 \text{ GeV}, m(\widetilde{\chi}) = \frac{1}{2}(m(\widetilde{\chi}^{\pm}) + m(\widetilde{\chi}^0)))$	
M.	$\chi_{1}\chi_{2}\chi_{1}$ $\chi_{1}$ $\chi_{1}$ $\chi_{1}$ $\chi_{1}$ $\chi_{2}$ $\chi_$	/=20.7 fb <sup>-1</sup> 8 TeV [ATI AS-CONE-2013-028]	<b>180-330 GeV</b> $\tilde{\chi}^{\pm}$ <b>MASS</b> $(m(\tilde{\chi}^{0}) < 10 \text{ GeV} m(\tilde{\chi}^{0}) = (m(\tilde{\chi}^{\pm}) + m(\tilde{\chi}^{0})))$	
Ш iē	$\tilde{\gamma}^{\pm}\tilde{\gamma}^{0} \rightarrow \tilde{I} \tilde{\chi} \tilde{I} (\tilde{\chi} \tilde{\chi}) \tilde{\chi} \tilde{I} (\tilde{\chi} \tilde{\chi}) \cdot 3 \text{ len } + F$		$\widetilde{\nabla}^{\pm} mass = (m(\lambda_1)^2 + m(\lambda_2)^2 + m(\lambda_1)^2 + m(\lambda_1)^2)$	
	$\lambda_1 \lambda_2 \sim \lambda_1^{(1)} \sim \lambda_2^{(1)} \sim \lambda_1^{(1)} \sim \lambda_2^{(1)} \sim \lambda_2^{($	L=20.7 fb , 6 fev [ATLAS-CONF-2013-035]	$\chi_1 = \frac{1}{2} \sum_{i=1}^{n} \frac{1}{2} \sum_{i=1}^{n$	s above)
	$\chi, \chi \rightarrow W \chi \Sigma \chi$ . Step + $E_{T,miss}$	L=20.7 ID , 8 TEV [ATLAS-CONF-2013-035]	$\widetilde{\chi_1} = m(\chi_2), m(\chi_1) = 0, \text{ siepton's decoupled}$	
s	Direct $\chi_1$ pair prod. (AIVISB) : long-lived $\chi_1$	L=4.7 fD , 7 lev [1210.2852]	$220 \text{ GeV}$ $\chi_1$ mass $(1 < \tau(\chi_1) < 10 \text{ ms})$	
·liv cle	Stable g, R-hadrons : low $\beta$ , $\beta\gamma$	L=4.7 fb <sup>-</sup> , 7 lev [1211.1597]	985 Gev g mass	
ng-	GINSB, stable $\tau$ : low $\beta$	L=4.7 fb <sup>-1</sup> , 7 TeV [1211.1597]	$\sim^{0}$ $\sim^{0}$ $\sim^{0}$ $\sim^{0}$	
pa	$GMSB, \tilde{\chi} \rightarrow \gamma G$ : non-pointing photons	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2013-016]	<b>230 GeV</b> $\chi_1$ <b>Mass</b> $(0.4 < \tau(\chi_1) < 2 \text{ ns})$	
	$\chi_{+} \rightarrow qq\mu (RPV) : \mu + heavy displaced vertex$	L=4.4 fb <sup>-1</sup> , 7 TeV [1210.7451]	<b>700 GeV Q Mass</b> (1 mm < $c\tau$ < 1 m, $\tilde{g}$ decoupled)	
	LFV : pp $\rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e + \mu$ resonance	L=4.6 fb <sup>-1</sup> , 7 TeV [1212.1272]	<b>1.61 TeV</b> $v_{\tau}$ mass $(\lambda'_{311}=0.10)$	, λ <sub>132</sub> =0.05)
	LFV : pp $\rightarrow \widetilde{v}_{\tau} + X, \widetilde{v}_{\tau} \rightarrow e(\mu) + \tau$ resonance	L=4.6 fb <sup>-1</sup> , 7 TeV [1212.1272]	<b>1.10 TeV</b> $\tilde{v}_{\tau}$ mass $(\lambda_{311}^{i}=0.10, \lambda_{1(2)33}^{i}=0.10, \lambda_{$	.05)
Bilinear RPV CMSSM : 1 lep + 7 j's + $E_{T,t}$	Bilinear RPV CMSSM : 1 lep + 7 j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-140]	<b>1.2 TeV</b> $\tilde{q} = \tilde{g}$ mass ( $c\tau_{LSP} < 1$ mm)	
P 2	$\widetilde{\chi}^+ \widetilde{\chi}^-, \widetilde{\chi}^+ \rightarrow W \widetilde{\chi}^0, \widetilde{\chi}^0 \rightarrow eev_{\mu}, e\mu v_{\mu} : 4 lep + E_{T miss}$	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-036]	<b>760 GeV</b> $\widetilde{\chi}_{1}^{+}$ <b>MASS</b> $(m(\widetilde{\chi}_{1}^{0}) > 300 \text{ GeV}, \lambda_{121} > 0)$	
Ц	$\widetilde{\chi}_{\tau} \widetilde{\chi}_{\tau},, \widetilde{\chi}_{\tau}^{01} \rightarrow \tau \tau v_{\sigma}, e \tau v_{\tau} : 3 \text{ lep } + 1\tau + E_{\tau \text{ miss}}$	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-036]	<b>350 GeV</b> $\tilde{\chi}_{4}^{+}$ <b>MASS</b> $(m(\tilde{\chi}_{2}^{0}) > 80 \text{ GeV}, \lambda_{133} > 0)$	
	$\tilde{q} \rightarrow qqq$ : 3-iet resonance bair	L=4.6 fb <sup>-1</sup> , 7 TeV [1210.4813]	666 Gev ĝ mass	
	$\tilde{q} \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow bs$ : 2 SS-lep + (0-3b-)i's + E	L=20.7 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2013-007]	<b>880 GeV</b> $\widetilde{\mathbf{q}}$ <b>Mass</b> (any $m(\widetilde{\mathbf{t}})$ )	
	Scalar gluon : 2-iet resonance pair	L=4.6 fb <sup>-1</sup> , 7 TeV [1210.4826]	100-287 GeV SQLUON MASS (incl. limit from 1110.2693)	
WIM	P interaction (D5, Dirac $\chi$ ) : 'monojet' + E	L=10.5 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-147]	<b>704 GeV</b> $M^*$ <b>SCale</b> ( <i>m</i> < 80 GeV limit of < 687 Ge	V for D8)
	T,miss			
		10 <sup>-</sup>	' 1	10

\*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.

#### Mass scale [TeV]

#### Event Generation for the LHC

### ATLAS Exotica Search

#### ATLAS Exotics Searches\* - 95% CL Lower Limits (Status: HCP 2012)

	Large ED (ADD) : monoiet + E			
	Large ED (ADD) : monophoton $\pm E$	L=4.7  id, 7 rev [1210.4491]	$4.37 \text{ TeV} M_D$	0-2)
S	Large ED (ADD) : monophoton + $L_{T,miss}$	L=4.6 fD , 7 lev [1209.4625]	1.93 TeV M <sub>D</sub> (0=2)	ATLAS
ИС	UED : diploton + F	L=4.7 ID, 7 IEV [1211.1150]	$4.16 \text{ lev} M_S (1)$	Preliminary
ISI	$S^{1}/Z$ ED : dilepton m	L=4.6  ID, 7 IEV [AILAS-CONF-2012-072]		$\sim B^{-1}$
en	$S/Z_2 ED$ . dilepton, $m_{\parallel}$ BS1 : diphoton & dilepton m	L=4.3-5.0 fb <sup>-1</sup> 7 TeV [1209.2555]	4.71 lev W <sub>KK</sub>	k/M = 0.1
in'	BS1 : 77 resonance $m_{\gamma\gamma/\parallel}$	L = 4.75.0 10 , 7 16V [1210.0505]	2.23  Rev Graviton mass $(k/M = 0.1)$	$S(n_{P_{1}} - 0.1)$
n d	$RS1 \cdot WW$ resonance $m_{\pi}$	L = 1.0  IB, $T  TeV [1203.0710]$	1 23 TeV Graviton mass $(k/M_{\odot})$	$Ldt = (1.0 - 13.0) \text{ fb}^{-1}$
tra	RS q $\rightarrow$ tt (BR=0.925) : tt $\rightarrow$ l+jets, m	/ =4.7 fb <sup>-1</sup> 7 TeV [ATLAS-CONE-2012-136]		<b>J</b> <sup>-</sup> <b>(</b> <sup>-</sup> <b>)</b> <sup>-</sup>
Х	ADD BH $(M_{-1}, M_{-}=3)$ SS dimuon N	$l = 1.3 \text{ fb}^{-1}$ 7 TeV [1111 0080]	1.25 TeV $M_{\rm e}$ ( $\delta$ =6)	s = 7, 8 TeV
	ADD BH $(M_{TH}/M_{D}=3)$ : leptons + jets, $\Sigma p$	L=1.0 fb <sup>-1</sup> , 7 TeV [1204.4646]	$15 \text{ TeV}$ $M_{\rm p}$ ( $\delta$ =6)	
	Quantum black hole : dijet, F $(m_{ij})$	L=4.7 fb <sup>-1</sup> . 7 TeV [1210.1718]	4.11 TeV M <sub>D</sub> (8	()=6)
	qqqq contact interaction : $\chi(m_{\perp})$	L=4.8 fb <sup>-1</sup> . 7 TeV [ATLAS-CONF-2012-038]	7.8 Ti	eV A
0	ggll CI : ee & μμ, m	L=4.9-5.0 fb <sup>-1</sup> . 7 TeV [1211.1150]		<b>13.9 TeV</b> $\Lambda$ (constructive int.)
0	uutt CI : SS dilepton + jets + $E_{T miss}$	L=1.0 fb <sup>-1</sup> , 7 TeV [1202.5520]	1.7 TeV $\Lambda$	
	$Z'(SSM): m_{ee/uu}$	L=5.9-6.1 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-129]	] 2.49 TeV Z' mass	
	$Z'$ (SSM) : $m_{rr}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.6604]	1.4 TeV Z' mass	
=	W' (SSM) : $m_{Telu}$	<i>L</i> =4.7 fb <sup>-1</sup> , 7 TeV [1209.4446]	2.55 TeV W' mass	
>	W' $(\rightarrow tq, g_{p}=1)$ : $m_{tq}^{\mu}$	<i>L</i> =4.7 fb <sup>-1</sup> , 7 TeV [1209.6593]	430 GeV W' mass	
	$W'_{R} (\rightarrow tb, SSM) : m_{tb}$	L=1.0 fb <sup>-1</sup> , 7 TeV [1205.1016]	1.13 TeV W' mass	
	W* : <i>m</i> <sub>T.e/u</sub>	L=4.7 fb <sup>-1</sup> , 7 TeV [1209.4446]	2.42 TeV W* mass	
$\sim$	Scalar LQ pair ( $\beta$ =1) : kin. vars. in eejj, evjj	L=1.0 fb <sup>-1</sup> , 7 TeV [1112.4828]	660 Gev 1 <sup>st</sup> gen. LQ mass	
LO LO	Scalar LQ pair ( $\beta$ =1) : kin. vars. in µµjj, µvjj	L=1.0 fb <sup>-1</sup> , 7 TeV [1203.3172]	685 GeV 2 <sup>nd</sup> gen. LQ mass	
	Scalar LQ pair (β=1) : kin. vars. in ττjj, τvjj	L=4.7 fb <sup>-1</sup> , 7 TeV [Preliminary]	538 GeV 3 <sup>rd</sup> gen. LQ mass	
S	$4^{\text{th}}$ generation : t't' $\rightarrow$ WbWb	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.5468]	656 GeV t' mass	
ark	$4^{m}$ generation : b'b'( $T_{5/3}T_{5/3}$ ) $\rightarrow$ WtWt	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-130]	670 GeV b' (T <sub>5/3</sub> ) mass	
nk	New quark b' : b'b' $\rightarrow$ Zb+X, m <sub>zb</sub>	L=2.0 fb <sup>-1</sup> , 7 TeV [1204.1265] 4	00 GeV b' mass	
~	Top partner : TT $\rightarrow$ tt + A <sub>0</sub> A <sub>0</sub> (dilepton, M <sub>12</sub> )	<i>L</i> =4.7 fb <sup>-1</sup> , 7 TeV [1209.4186]	<b>483 GeV</b> T mass ( $m(A_0) < 100 \text{ GeV}$ )	
le\	Vector-like quark : CC, mivq	L=4.6 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-137]	1.12 TeV VLQ mass (charge -1/3,	coupling $\kappa_{qQ} = v/m_Q$
<	Vector-like quark : NC, m <sub>ilq</sub>	L=4.6 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-137]	1.08 TeV VLQ mass (charge 2/3, c	$coupling \kappa_{qQ} = v/m_Q)$
л;	Excited quarks $\gamma$ -jet resonance, m	L=2.1 fb <sup>-1</sup> , 7 TeV [1112.3580]	2.46 TeV q* mass	
eri T	Excited quarks : dijet resonance, m	L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-148]	3.84 TeV q* mas	SS
ш-		L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-146]	2.2 TeV I* mass ( $\Lambda$ = m	n(l*))
т	Iechni-hadrons (LSTC) : dilepton, $m_{ee/\mu\mu}$	L=4.9-5.0 fb <sup>-1</sup> , 7 TeV [1209.2535]	<b>850 GeV</b> $\rho_{\rm T}/\omega_{\rm T}$ mass $(m(\rho_{\rm T}/\omega_{\rm T}) - m(\pi_{\rm T}))$	$() = M_{\rm W}$
. 1		L=1.0 fb <sup>-1</sup> , 7 TeV [1204.1648]	<b>483 GeV</b> $\rho_{T}$ mass $(m(\rho_{T}) = m(\pi_{T}) + m_{W}, m(a_{T}) =$	$= 1.1 m(\rho_{T}))$
ler	Major. neutr. (LRSM, no mixing) : 2-lep + jets	L=2.1 fb <sup>-1</sup> , 7 TeV [1203.5420]	1.5 TeV N mass $(m(W_R) = 2$	
Oth	W <sub>R</sub> (LRSM, no mixing) : 2-lep + jets	L=2.1 fb <sup>-1</sup> , 7 TeV [1203.5420]	2.4 TeV $W_R$ mass (m	(N) < 1.4 IeV)
0	$\Pi_{L} (DY prod, BR(\Pi \rightarrow II)=1) . 55 ee (\mu\mu), III$	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.5070] 4	<b>109 GeV</b> $H_L^-$ mass (limit at 398 GeV for $\mu\mu$ )	
	$\Pi_{L}$ (D1 plot, D1( $\Pi_{L} \rightarrow e\mu$ )=1). 33 $e\mu$ , $\Pi_{e\mu}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1210.5070] 37	5 GeV H <sup>-</sup> Mass	
	Color octer scalar . uljet resonance, $m_{\rm ji}$	L=4.8 fb <sup>-</sup> , 7 lev [1210.1718]		
		10-1	1	$10   10^2$
		10	I	10 10
* • • •				Mass scale [TeV]

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

#### Event Generation for the LHC

## CMS Exotica Search



Event Generation for the LHC

## **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
- Best possible SM precision is essential for BSM searches

## Thanks for listening!





Event Generation for the LHC



## $W\&Z^0$ at Tevatron



- Herwig++ includes W/Z+jet (MEC)
- All agree (tuned) at Tevatron
- Normalized to data

Hamilton, Richardson, Tully JHEP10(2008)015

## $\gamma\gamma$ at Tevatron



- Absolute normalization 

   LO too low
- POWHEG agrees with rate and distribution
- At LHC, important background for Higgs search

D'Errico & Richardson, JHEP02(2012)130

## To Be Confirmed

- Spin and parity 0<sup>+</sup>: correlations in VV<sup>\*</sup> decays
- Production mechanisms: gg,VBF,WH,ZH, ttH
- Self-coupling (HH production): difficult at LHC
- Total width 4.2 MeV: impossible?
- Decay fractions:

$b\overline{b}$	56%	$ au^+ au^-$	6.2%	$\gamma\gamma$	0.23%
$WW^*$	23%	$ZZ^*$	2.9%	$\gamma Z$	0.16%
gg	8.5%	$C\overline{C}$	2.8%	$\mu^+\mu^-$	0.02%

## Achievable Precision?



Figure 1: Capabilities of LHC for model-independent measurements of Higgs boson couplings. The plot shows 1  $\sigma$  confidence intervals for LHC at 14 TeV with 300 fb<sup>-1</sup>. No error is estimated for g(hcc). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

#### M Peskin, arXiv: 1207.2516

## Achievable Precision?



Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1  $\sigma$  confidence intervals for LHC at 14 TeV with 300 fb<sup>-1</sup>, for ILC at 250 GeV and 250 fb<sup>-1</sup> ('ILC1'), for the full ILC program up to 500 GeV with 500 fb<sup>-1</sup> ('ILC'), and for a program with 1000 fb<sup>-1</sup> for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

M Peskin, arXiv:1207.2516

#### Event Generation for the LHC