Event Generation for the Large Hadron Collider

Bryan Webber Cavendish Laboratory University of Cambridge

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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

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QCD Factorization

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

- 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:

\n- \n**Collinear**\n
$$
d\sigma_{n+1} \approx \frac{\alpha_{\rm S}}{2\pi} \sum_{i} P_{ii}(z_i, \phi_i) \, dz_i \frac{d\xi_i}{\xi_i} \frac{d\phi_i}{2\pi} \, d\sigma_n \qquad \xi_i = 1 - \cos\theta_i
$$
\n
\n- \n**Soft**\n
$$
d\sigma_{n+1} \approx \frac{\alpha_{\rm S}}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{p_i \cdot p_j}{p_i \cdot k p_j \cdot k} \omega \, d\omega \, d\xi_i \frac{d\phi_i}{2\pi} \, d\sigma_n
$$
\n
$$
= \frac{\alpha_{\rm S}}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{\xi_{ij}}{\xi_i \xi_j} \frac{d\omega}{\omega} \, d\xi_i \frac{d\phi_i}{2\pi} \, d\sigma_n
$$
\n
$$
\approx \frac{\alpha_{\rm S}}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \Theta(\xi_{ij} - \xi_i) \frac{d\omega}{\omega} \frac{d\xi_i}{\xi_i} \, d\sigma_n
$$
\n
$$
= \underbrace{\mathbf{J}_{\theta_{ij}} \mathbf{J}_{\theta_{ij}} \mathbf{J}_{\theta_{ij}} \mathbf{J}_{\theta_{ij}} \omega}_{i} = (1 - z_i) E_i
$$
\n
\n

Angular-ordered parton shower (or dipoles)

Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near Λ_{QCD} ~200 MeV, perturbation theory breaks down and hadrons are formed Precessairea Ageb 2001
- Before that, at scales $Q_0 \sim$ few x Λ_{QCD} , there is universal preconfinement of colour Planar approximation and the colour—anticolour—anticolour—anticolour—anticolour—anticolour—anticolour—anticolour
- **•** Colour, flavour and momentum flows are only locally redistributed by hadronization

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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 Perturbation theory acciding in surficient

* Depends on density profile of proton

- Assume QCD 2-to-2 secondary collisions
	- **❖** Need cutoff at low p⊤
- Need to model colour flow
	- ✤ Colour reconnections are necessary

Underlying Event

Event Generation for the LHC

Event Generation for the LHC **Future 21 Profiles of Collider Physics, KIPMU, 16/07/13**

Dijet Mass Distribution the Significance is plotted as positive (negative). In certain cases, the significance for individual bins is not plotted. ² data. No deviations that are statistically significant are observed between the distribution of the data points and the smooth fit through all through all through all the data. The highest mass event (5.15 TeV) is a smooth fit through a smooth fit through a smooth fit through a smooth contract mass event (5.15 TeV) i shown in Fig. 3. We proceed to set upper limits on the cross section of new physics processes.

• No sign of deviation from Standard Model (yet) negative values for deficits. If a *p*-value greater than 50% is found the corresponding significance is not prediction has been normalized to the data (see text). The error bars are statistical only. The **bin-by-bin-by-bin fitting** residuals, \bullet *n* \bullet *n* \bullet *n* \bullet *****n* \bullet *n* \bullet *n*

MC Event Generators

OHERWIG

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

- \rightarrow Angular-ordered parton shower, cluster hadronization
- → v6 Fortran; Herwig++

PYTHIA

[http://www.thep.lu.se/](http://www.thep.lu.se)∼torbjorn/Pythia.html

- \rightarrow Dipole-type parton shower, string hadronization
- \rightarrow 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

 \rightarrow C++

Other relevant software (with apologies for omissions)

- O 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
- **O** Special BSM scenarios: Prospino, Charybdis, TrueNoir
- Mass spectra and decays: SOFTSUSY, SPHENO, HDecay, SDecay \bullet
- Feynman rule generators: FeynRules
- PDF libraries: LHAPDF
- Resummed (*p*⊥) spectra: ResBos
- Approximate loops: LoopSim
- Jet finders: anti-*k*[⊥] and FastJet
- Analysis packages: Rivet, Professor, MCPLOTS \bullet
- Detector simulation: GEANT, Delphes \bullet
- **Constraints (from cosmology etc): DarkSUSY, MicrOmegas**
- Standards: PDF identity codes, LHA, LHEF, SLHA, Binoth LHA, HepMC

Sjöstrand, Nobel Symposium, May 2013

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

Event Generation for the LHC **Future of Collider Physics, KIPMU, 16/07/13**

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Vacuum Stability

Parton Shower Monte Carlo

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

- \bullet Leading-order (LO) normalization **notice** need next-to-LO (NLO)
- \bullet Worse for high p_T and/or extra jets **notify the multiged merging**

[http://mcplots.cern.ch/](http://projects.hepforge.org/herwig/)

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 ✤ Dipole ✤ MLM merging Catani, Krauss, Kühn, BW, 2001 Lönnblad, 2001 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

$$
\begin{aligned}\n\mathbf{M} \mathbf{C} \mathbf{Q} \mathbf{N} \mathbf{L} \mathbf{O} \mathbf{M} \mathbf{Z} \mathbf{C} \mathbf{h} \mathbf{I} \mathbf{R} \mathbf{S} \\
\text{finite virtual} \\
\mathrm{div} \mathbf{S} \mathbf{F} \mathbf{r} \mathbf{x} \mathbf{i} \mathbf{o} \mathbf{e} \mathbf{B} \mathbf{W}, \mathbf{J} \mathbf{H} \mathbf{E} \mathbf{P} \mathbf{0} \mathbf{6} \mathbf{Q} \mathbf{0} \mathbf{0} \mathbf{2} \mathbf{9} \\
\mathrm{finite \,\, virtual} \\
\mathrm{div} \mathbf{F} \mathbf{S} \mathbf{B} \mathbf{W} \mathbf{S} \mathbf{B} \math
$$

$$
\begin{pmatrix}\nd\sigma_{\text{MC@NLO}} &= \begin{bmatrix} B + V + \int (R_{\text{MC}} - C) \, d\Phi_R \end{bmatrix} d\Phi_B \left[\Delta_{\text{MC}}(0) + (R_{\text{MC}}/B) \, \Delta_{\text{MC}}(k_T) \, d\Phi_R \end{bmatrix}
$$
\nfinite ≥ 0 \n
\n**Write** ≥ 0 \n
\n**Expanding gives NLO result**\n
\n**EXECUTE:** The probability of the following formula for the following equations:\n
$$
C = \begin{bmatrix} B + V + \int (R_{\text{MC}} - C) \, d\Phi_R \, d\Phi_R \end{bmatrix}
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C = \begin{bmatrix} B + V + \int (R_{\text{MC}} - C) \, d\Phi_R \, d\Phi_R \end{bmatrix}
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C = \begin{bmatrix} B + V + \int (R_{\text{MC}} - C) \, d\Phi_R \, d\Phi_R \, d\Phi_R \end{bmatrix}
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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

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

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

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

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

- NLO with (almost) no negative weights arbitrary NNLO
- High p_T 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:
	- \cdot Multijet rates for jet resolution > Q_{cut} are correct to LO (up to N_{max})
	- ◆ Shower generates jet structure below Qcut (and jets above N_{max})
	- ✤ Leading (and next) Qcut dependence cancels

CKKW: Catani et al., JHEP 11(2001)063 -L: Lonnblad, JHEP 05(2002)063 * ALPGEN or MadGraph, n<Nmax

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

Top quark production

FIG. The distribution of \blacksquare of the data is shown as closed (black) circles with the statistical uncertainty of the MCQNLO prediction is no to the data and into the overflow events and into the solid (red) into the solid (red) into the final bin of e Top quark pairs at LHC

Top Mass still the worlds best in the worlds best to the worlds best Top rids

 $\Delta M_t^{\rm eneratio}$ for the LHO $\pm 122~{\rm MeV}$ and Δ and $\Delta M_t^{\rm or}$ and $\Delta M_t^{\rm or}$ and $\Delta M_t^{\rm or}$ and $\Delta M_t^{\rm or}$

Top mass & kinematics two top quarks (∆*R*bb and ∆*φ*bb). These are shown in Figs. 9, 10, 11 and 12, respectively. The limited sample sizes allow no clear separation of different models in events with high b-jet *p*^T tiplicity, transverse hadronic energy (*H*T, defined as the scalar sum of the *p*^T of the four leading jets), invariant mass and transverse momentum of the tt system. We note that the jet *p*^T threshold 30 GeV used in the angles in the angles from some and soften radiation. The results from some and radiation are shown in Figs. 5, 6, 7, and 8, respectively. that is well described by all of the simulations. Below *H*^T of 200 GeV and *m*tt of 400 GeV there is a strong turn-on effect. For the j as a function of increasing \blacksquare

Top mass & hadronization

Study dependence of reconstructed mass on "odd" clusters

Top mass & hadronization

Mangano, Top LHC WG, July 2012

e $\frac{1}{w}$ t $\overline{}$ \overline{a} $q \sim$ nu Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling Partly shower evolution, partly color reconnection, ambiguous paternity

Top mass & hadronization

mtop vs pt(top)

mtop(E+O) – 172.5

mtop(E+O) – mtop(E)

Dependence of reconstructed mass on "odd" clusters \sim 1 GeV

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

Vector boson production

Z0 at Tevatron

[http://mcplots.cern.ch/](http://projects.hepforge.org/herwig/)

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

Z0 at LHC **10 5 Rapidity Distribution Results 14 6 Transverse Momentum Distribution Results 12 5 Results**

 \sim experimental statistical statistical and systematic uncertainties and \sim indicates the range of variation predicted by the POWHEG simulation for the uncertainties of and electron channels, compared to the predictions of the POWHEG generator interfaced with CMS, PRD85(2012)032002 CMS PAS SMP-12-025 ties added in quadrature. The band around the theoretical prediction includes the uncertainties

FEWZ for *q*^T *>* 20 GeV/*c*. The horizontal lines indicate the bin boundaries and the data points are positioned at the average of the entries in the bins. The bands in the upper plot represent $\sum_{i=1}^n$ is the property from the predictions from $\sum_{i=1}^n$

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

W asymmetry at LHC − at Tevatron Run II, *p*

Muon charge asymmetry in *W* decays

• Asymmetry probes parton distributions three different experiments ATLAS, CMS and LHCb. The asymmetry results of the asymmetry results of the LHCb and CMS a ES DAMUON CIST CHANNEL ONLY ARE ONLY A MUON CHANNEL ONLY A MUON CHANNEL ONLY AND HAVE BEEN COMMUNICATED WITH T Electroweak Working Group by representatives of the respective collaborations.

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

16 16 Results 16 **16 Results** 16 **16 Results** W+jets at LHC

• Very good agreement with predictions from me (bottom) in the electron channel compared with the expectations from two MADGRAPH tunes with Parton shower alone starts to fail for high $\frac{1}{2}$ is the fail form ≥ 2 while parton shower alone starts to fail for $n_{jet} \ge 2$ • Very good agreement with predictions from merged simulations,

LHC Cross Section Summary The 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 \mathcal{L} (f) \mathcal{L} (f) **Fig. 10** The unfolded dijet flavour fractions for each leading jet *p*^T bin (black points) with PYTHIA 6.423 (squares), Herwig++ 2.4.2 (circles) and POWHEG+PYTHIA 6.423 (filled triangles) predictions overlaid. The error bars on the data points show statistical uncertainties only, whereas the

 ϵ uncertainties appear as shaded bands.

Combined matching+merging

- NLO calculations generally refer to inclusive cross sections e.g. $\sigma(W+\geq n$ 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

UNLOPS: Lönnblad & Prestel, arXiv:1211.7278 Figure 9: Jet multiplicity in W-boson production, as measured by ATLAS [46]. The MC results

• Scale dependences almost eliminated anenden Chaine in were obtained by merging up to the contract up to the contract of the Scale department and \bullet ton at NLO. MC results are shown for the shown for the extensive scales (top panels) and for the panels) and f
In the extensive scales (top panels) and for the extensive scales (top panels) and for the extensive scales (

UNLOPS tMS=30 GeV, hh

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** Table 1: Event generators used to model the signal and background used for simulations of *simulatio* tively.

ZZ(∗) \mathbf{F} 16(ZUTZ) i ATLAS, Phys.Lett.B716(2012)1

$gs-Higgs(tjet)$ early contributed, which more renormalization scale for \mathbb{R}^n fixed order calculation, we choose as central renormalization and factorization scales the boson mass. From the table, it is clear that the integrated number of the integrated number of the integrated

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 maximum and minimum are highlighted. combinations. The maximum and minimum are highlighted.

ŦŸŢſĿ_ŶIJĦIJ $H_1 + D_{\tau}$ thia

$gs \rightarrow Higgs + jets$ (8 TeV)

• FxFx: Match/merge MC@NLO+Herwig6 \bullet \blacksquare \blacksquare \blacksquare ATA. FIGULITIIUI XU \blacksquare LU \sqcup reweighted merging; that is, we increase the largest multiplicity by one unit w.r.t. what at all in the patterns discussed above, except in a very few cases which we shall comment \blacksquare $56 -$

 Γ and Γ figs. 3, 4, and 5 respectively (with the exception of one panel in Γ The numerators of the ratios that appear in the upper insets are the same as before for $\mathbf{r} = \mathbf{r}$ are extremely content and normalization, to the \mathbf{r} α Frixione, ar X iv: 1.209.6.215. The individual is α Frederix & Frixione, arXiv:1209.6215

Event Generation for the LHC Future of Collider Physics, KIPMU, 16/07/13 central distribution, as anticipated in the discussion relevant to fig. 4, and brings it very close to the Compact \ldots _p ...,

$gg \rightarrow Higgs + jets$ (13 TeV)

1000

500

100

50

 $10₁$

 $\overline{5}$

1.8

1.6

 1.4

1.2

 1.0

 0.8

 0.6

 10^{5}

 10^{4}

 10^3

 10^{2}

 10^{18}

1.6

 1.4

 1.2

 1.0

 0.8

 0.6

 $\mathbf 0$

 Ω

aMC@NLO

aMC@NLO

Event Generation for the LHC 69 Future of Collider Physics, KIPMU, 16/07/13

t, b mass effects on Higgs pr with mage offeets an i contribution is included: the shape of the spectrum of the spectrum of the spectrum \mathbf{r}_1 p^T region and the spectrum becomes harder. We will come back to this point in Sec. 3.1.

VBF Higgs+jets

Figure 1: Higgs boson transverse-momentum (top) and rapidity (bottom) distributions. Matched With HERWIG6 (black solid), virtuality-ordered with \bullet Pythia6 (red dashed) and HERWIGHT (middle) insetting (middle) insetting (middle) $F: \mathcal{A} \cap \mathcal{A} \cap \mathcal{A}$ rapidity (bottom). \mathbf{S} same pattern as in figure 1 for the second hardest-jet transverse momentum hardest-jet transverse momentum \mathbf{S} **• Matched MC@NLO and POWHE** 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 **P-different background: mostly sherpal LO multijet •** Background: mostly Sherpa LO multijet merging *R* = 0.4 jets increases from eight (top) to nine (middle) and finally to ten jets (bottom). Other details as **B** background: mostly sherpa LO multijet merging

NLO Squark Production

HEG matching to different generators $\overline{}$ • NLO with POWHEG matching to different generators it is important to include for *i* "= *j* also \blacksquare die real emission matrix elements finite are organized in pairs finite are organized in pairs of pairs of pairs \blacksquare potential particle in a spectator with a spectator particle. contribute to the production of a square square \mathbb{R}^n \blacksquare is a necessary: The emitted are necessary: The emitted and \blacksquare initial state gluon while the spectator while the spectator particles can act a three particles can act a three particles can act as the spectator particle in the spectator particle. Hence, the spectator particle in the sp

> Gavin et al., arXiv:1305.4061 $\mathcal{L}_{\mathcal{A}}$ we observe that all showers essentially reproduce the NLO reproduce the second jet

 \tilde{q}_i

 \bar{q}_j

 \tilde{q}_j

 \tilde{q}_i

 \tilde{q}_j

ATLAS SUSY Search

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

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

ATLAS Exotica Search

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

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

Event Generation for the LHC **Future of Collider Physics, KIPMU, 16/07/13**

CMS Exotica Search

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Event Generation for the LHC **Future of Collider Physics, KIPMU, 16/07/13**

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!

 $\mathsf F$ vent Generation for the $\mathsf H\mathsf C$ 2

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

W & Z^o at Tevatron Drell-Yan vector boson production boson production of the U.S. of Taylor boson production of the U.S. of the U.S.

- Herwig++ includes W/Z+jet (MEC) \mathcal{L} + P et (IYIEC) Solid line: NLO Herwig++ POWHEG Blue dashes: MC@NLO **Red dashes: Herwig++ Include**
	- All agree (tuned) at Tevatron
	- Normalized to data

Hamilton, Richardson, Tully JHEP10(2008)015

gg at Tevatron *pp* → γγ at Tevatron Run II

- Absolute normalization \rightarrow 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 in the ratio of their masses, up to simple factors reflecting the particle spins. It is

- Spin and parity 0^+ : correlations in VV* decays \bullet Spin and parity 0^+ correlations in VV^* decays \mathcal{A} and \mathcal{A} and \mathcal{A} is the Standard Model \mathcal{A} is a large number of \mathcal{A}
- Production mechanisms: gg, VBF, WH,ZH, ttH • Production mechanisms: gg, VBF, WH, ZH, tth
- Self-coupling (HH production): difficult at LHC Gianotti put it in her July 4 lecture: "Thank you, Nature." Medicine of the phenomenology of the Standard Model Higgs boson at the mass of the mass boson at the mass boso
- Total width 4.2 MeV: impossible? **o** Total width 4.2 MeV: impossible? rameters" [23,24]. The predicted width of the boson is 4.2 MeV. The major branching
- Decay fractions: **fractions** and Dec

Achievable Precision?

Figure 1: Capabilities of LHC for model-independent measurements of Higgs boson couplings. The plot shows 1 σ confidence intervals for LHC at 14 TeV with 300 fb⁻¹. 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 σ confidence intervals for LHC at 14 TeV with 300 fb⁻¹, for ILC at 250 GeV and 250 fb⁻¹ ('ILC1'), for the full ILC program up to 500 GeV with 500 fb⁻¹ ('ILC'), and for a program with 1000 fb⁻¹ 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