Simulation of Old and New Physics

Bryan Webber, University of Cambridge

• Event generators
• Old physics: multijets
• Old Physics: matching to NLO
• New physics: SUSY vs UED
• New physics: black holes
LHC Event Simulation
General-Purpose Event Generators

- **PYTHIA**
  - Virtuality/$k_T$-ordered shower, string hadronization
  - v6 Fortran; v8 C++

- **HERWIG**
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++

- **SHERPA**
  - Virtuality-ordered shower, string/cluster hadronization
  - C++
HERWIG Event Generator

- Most important SM & MSSM processes at LO
  - spin correlations included
  - parton showers at leading log (LL)
  - interface to JIMMY underlying event (J Butterworth et al.)
  - no showering from SUSY particles
  - G Corcella et al., hep-ph/0210213 & refs therein

- MC@NLO provides some SM processes at NLO
  - S Frixione & BW, hep-ph/0506182 & refs therein

- Interface to CHARYBDIS black hole generator
  - C Harris, P Richardson & BW, hep-ph/0307305
Multijets

- Important backgrounds to new physics
- Only LO available up to high parton multiplicity (ALPGEN, AMEGIC++, MADGRAPH, HELAC,...)
  - OK for hard, well-separated jets
  - Strong sensitivity to $\alpha_s$ scale
  - No jet structure, interjet flow, underlying event
- Combine LO matrix elements + parton showers
  - Define jet resolution scale
  - Cancel leading scale dependence
  - CKKW, Ariadne and MLM schemes
- See S Höche el al., hep-ph/0602031
W + Multijets (Tevatron)
W + Multijets (Tevatron)

ET(jet1)  Dots: Alpgen
Solid: Ariadne
Dashes: Sherpa

ET(jet2)

ET(jet3)

ET(jet4)
Comparisons with Tevatron data

from JM Campbell, JW Huston & WJ Stirling, hep-ph/0611148

→ M.E. + PYTHIA CKKW looks good
Comparisons with Tevatron data (2)

Several parton multiplicities contribute to jets
$W + \text{Multijets (LHC)}$

$\text{pt}_W$  \quad Dots: Alpgen

Dashes: Sherpa

$|\eta(1) - \eta(2)|$

$|\eta(W) - \eta(1)|$

$|\eta(2) - \eta(3)|$
W + Multijets (LHC)
Multiple parton interactions

→ Rise in activity between jets

→ Extrapolation from Tevatron still uncertain
Matching to NLO

- Must avoid double-counting at NLO
  - Modify NLO and/or parton shower (PS)
- MC@NLO: don’t touch shower
  - Subtract NLO PS terms from exact NLO
  - Stabilizes NLO but some weights < 0
- Nason; Nagy-Soper: modify shower
  - Can avoid negative weights
  - Difficult to implement coherence
<table>
<thead>
<tr>
<th>IPROC</th>
<th>IV</th>
<th>IL₁</th>
<th>IL₂</th>
<th>Spin</th>
<th>Process</th>
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<td>7</td>
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<td>$H_1H_2 \rightarrow H^0W^- + X$</td>
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<tr>
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<td>i</td>
<td></td>
<td>✓</td>
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<td>7</td>
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<tr>
<td>−2860</td>
<td>7</td>
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<td>$H_1H_2 \rightarrow W^-Z^0 + X$</td>
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</table>
**MC@NLO: B production at Tevatron**

- $B \rightarrow J/\psi$ results from Tevatron Run II $\Rightarrow$ B hadrons

![Graph](image)

| $|y(J/\psi)| < 0.6$ |
|-------------------|
| $\sigma(p_T(J/\psi)>1.25$ GeV): |
| Points: CDF, $19.9^{+3.8}_{-3.2}$ nb |
| Solid: FONLL, $19.0^{+8.4}_{-6.0}$ nb |
| Dashes: MC@NLO, 17.2 nb |

**CDF B hadrons (prelim.)**
- $m_b=4.75$, $\mu/\mu_0=1$
- $\sigma_{MC@NLO} = 20.52$ nb
- $\sigma_{Data}/\sigma_{MC@NLO}=1.19$


- No longer any significant discrepancy
MC@NLO: $W$ production at Tevatron

First results from MC@NLO with Herwig++
(intrinsic $p_T$ still missing)
MC@NLO: Higgs Production at LHC

Good agreement with state-of-the-art resummation

V Del Duca, S Frixione, C Oleari & BW, in prep.
New Physics at LHC

- SUSY vs UED *
- Black Holes +

* JM Smillie & BW, hep-ph/0507170
+ CM Harris et al., hep-ph/0411022
Spin Correlations in SUSY & UED

- **SUSY:** new particles are superpartners
  \[ q \leftrightarrow \tilde{q}, \ g \leftrightarrow \tilde{g}, \ l \leftrightarrow \tilde{l}, \ (\gamma, Z, \ldots) \leftrightarrow (\tilde{\chi}^0_1, \tilde{\chi}^0_2, \ldots) \]
  \[ \Rightarrow \text{spins differ by one-half} \]

- **UED:** new particles are KK excitations
  \[ q \leftrightarrow q^*, \ g \leftrightarrow g^*, \ l \leftrightarrow l^*, \ (\gamma, Z, \ldots) \leftrightarrow (\gamma^*, Z^*, \ldots) \]
  \[ \Rightarrow \text{spins are the same!} \]

- Suppose masses have been measured: how could we distinguish?
  \[ \Rightarrow \text{need evidence on spins to be sure} \]
SUSY and UED decay chains

Two distinct helicity structures, with different spin correlations:

- **Process 1:** \( \{q, l_{\text{near}}, l_{\text{far}}\} = \{q_L, l_L^-, l_L^+\} \) or \( \{\bar{q}_L, l_L^+, l_L^-\} \) or \( \{q_L, l_R^+, l_R^-\} \) or \( \{\bar{q}_L, l_R^-, l_R^+\} \);

- **Process 2:** \( \{q, l_{\text{near}}, l_{\text{far}}\} = \{q_L, l_L^+, l_L^-\} \) or \( \{\bar{q}_L, l_L^-, l_L^+\} \) or \( \{q_L, l_R^-, l_R^+\} \) or \( \{\bar{q}_L, l_R^+, l_R^-\} \).
UED and SUSY mass spectra

- **UED models tend to have quasi-degenerate spectra**
  
  \[ M_n \sim n/R \]
  
  (broken by boundary terms and loops, with low cutoff)

<table>
<thead>
<tr>
<th>$\gamma^*$</th>
<th>$Z^*$</th>
<th>$q_L^*$</th>
<th>$l_R^*$</th>
<th>$l_L^*$</th>
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<tr>
<td>501</td>
<td>536</td>
<td>598</td>
<td>505</td>
<td>515</td>
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</tbody>
</table>

**Table 1:** UED masses in GeV, for \( R^{-1} = 500 \text{GeV} \), \( \Lambda R = 20 \), \( m_h = 120 \text{GeV} \), \( \overline{m}_h^2 = 0 \) and vanishing boundary terms at cut-off scale \( \Lambda \).

- **SUSY spectra typically more hierarchical**
  
  (high-scale universality)

<table>
<thead>
<tr>
<th>$\tilde{\chi}_1^0$</th>
<th>$\tilde{\chi}_2^0$</th>
<th>$\tilde{u}_L$</th>
<th>$\tilde{e}_R$</th>
<th>$\tilde{e}_L$</th>
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<tr>
<td>96</td>
<td>177</td>
<td>537</td>
<td>143</td>
<td>202</td>
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</table>

**Table 2:** SUSY masses in GeV, for SPS point 1a.
## Production cross sections (pb)

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<tr>
<th>Masses</th>
<th>Model</th>
<th>$\sigma_{\text{all}}$</th>
<th>$\sigma_{q^*}$</th>
<th>$\sigma_{\bar{q}^*}$</th>
<th>$f_q$</th>
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<tr>
<td>UED</td>
<td>UED</td>
<td>253</td>
<td>163</td>
<td>84</td>
<td>0.66</td>
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<tr>
<td>UED</td>
<td>SUSY</td>
<td>28</td>
<td>18</td>
<td>9</td>
<td>0.65</td>
</tr>
<tr>
<td>SPS 1a</td>
<td>UED</td>
<td>433</td>
<td>224</td>
<td>80</td>
<td>0.74</td>
</tr>
<tr>
<td>SPS 1a</td>
<td>SUSY</td>
<td>55</td>
<td>26</td>
<td>11</td>
<td>0.70</td>
</tr>
</tbody>
</table>

$\sigma_{\text{UED}} \gg \sigma_{\text{SUSY}}$ for same masses (100 pb = 1/sec)

$q^*/\bar{q}^* \sim 2 \Rightarrow$ charge asymmetry
Angular variables

\[ \tilde{\chi}_0^0/Z^* \]
\[ \tilde{\chi}_1^0/\gamma^* \]

\( \theta^* \) defined in \( \tilde{\chi}_2^0/Z^* \) rest frame

\( \theta, \phi \) defined in \( \tilde{l}/l^* \) rest frame
Invariant masses

- $ql^{\text{near}}: \quad m_{ql}/(m_{ql})_{\text{max}} = \sin(\theta^*/2)$
- $l^{\text{near}}l^{\text{far}}: \quad m_{ll}/(m_{ll})_{\text{max}} = \sin(\theta/2)$
- $ql^{\text{far}}: \quad m_{ql}/(m_{ql})_{\text{max}} = \frac{1}{2} \left[ (1 - y)(1 - \cos \theta^* \cos \theta) + \right. \\
\left. + (1 - y)(\cos \theta^* - \cos \theta) - 2\sqrt{y} \sin \theta^* \sin \theta \cos \phi \right]^{\frac{1}{2}}$

where $x = m_{Z^*}^2/m_{q^*}^2$, $y = m_{l^*}^2/m_{Z^*}^2$, $z = m_{\gamma^*}^2/m_{l^*}^2$
Helicity dependence

- **Process 1 (SUSY)**

- **Process 1 (UED, transverse $Z^*$: $P_T/P_L = 2\times$)**

→ Both prefer high $(ql^{-})_{near}$ invariant mass
Jet + lepton mass distribution

UED masses

SPS 1a masses

Not resolvable for UED masses, maybe for SUSY masses

Charge asymmetry due to quark vs antiquark excess
Charge Asymmetry

\[ A = \frac{(j^l_+)-(j^l_-)}{(j^l_+)+(j^l_-)} \]

**UED masses**

- UED spins
- MSSM spins

Histograms:
- HERWIG detector level
- \(2\times10^6\) decay chains

\[ \hat{m} = \frac{m_{j^l}}{(m_{j^l})_{\text{max}}} \]

**SPS 1a masses**

- UED spins
- MSSM spins

Histograms:
- HERWIG detector level
- \(2\times10^6\) decay chains

\[ \hat{m} = \frac{m_{j^l}}{(m_{j^l})_{\text{max}}} \]

→ Similar form, different magnitude

→ Not detectable for UED masses
For $n$ extra dimensions compactified at scale $R$

\[ F(r < R) \sim G_{4+n} \frac{m_1 m_2}{r^{2+n}} \]

\[ F(r > R) \sim G_{4+n} \frac{m_1 m_2}{r^2 R^n} \]

\[ \Rightarrow G_4 = \frac{G_{4+n}}{R^n} \]
TeV-Scale Gravity

\[ G_4 = \frac{G_{4+n}}{R^n} \]
\[ G_{4+n} = M_{PL}^{-2-n} \]
\[ \Rightarrow M^{(4)}_{PL} = M_{PL} \left( \frac{M_{PLC}}{\hbar R} \right)^{n/2} \]

- Hence for \( M_{PL} = 1 \) TeV we need

\[ 10^{19} \text{ GeV} \sim 10^3 \text{ GeV} \times (10^4 R/fm)^{n/2} \]

\[ \leftrightarrow \text{ mm for } n=2, \text{ nm for } n=3, \text{ pm for } n=4 \]
Black hole production

- **Parton-level cross section:**
  \[ \hat{\sigma}(\hat{s} = M_{BH}^2) = F_n \pi r_S^2 \]

- **\( r_S \) = Schwarzschild radius in 4+n dimensions:**
  \[
  r_S = \frac{1}{\sqrt{\pi M_{PL}}} \left[ \frac{8 \Gamma \left( \frac{n+3}{2} \right) M_{BH}}{(n + 2) M_{PL}} \right]^{\frac{1}{n+1}}
  \]

- **\( F_n \) = form factor of order unity (hoop conjecture)**

- **Usually set Planck scale \( M_{PL} = 1 \) TeV for illustration**

  (Dimopoulos-Landsberg \( M_{PL} \equiv \left[ G_{(4+n)} \right]^{-\frac{1}{n+2}} \))
BH formation factor (1)

\[ b_{\text{max}} = 2r_h = 2r_s \left[1 + a^2_\ast\right]^{-\frac{1}{n+1}} \]

\[ a_\ast = \frac{(n+2)J}{2r_h M_{\text{BH}}} \, , \, \, J \simeq b M_{\text{BH}} / 2 \]

\[ \hat{\sigma} = F_n \pi r_s^2 \simeq \pi b_{\text{max}}^2 \]

\[ F_n \simeq 4 \left[1 + \left(\frac{n+2}{2}\right)^2\right]^{-\frac{2}{n+1}} \]

("geometric")
BH formation factor (2)

\[ F_n \]

\[ n \]

H Yoshino & Y Nambu, gr-qc/0209003
H Yoshino & VS Rychkov, hep-th/0503171
Yoshino-Rychkov Bound on $\hat{\sigma}_{BH}$

- YN bound is $\pi b_{max}^2$ for AH on past lightcone (boundary of region I)
- YR bound is $\pi b_{max}^2$ for AH on future lightcone (boundary of regions II & III)
- Area of AH sets limits on $M_{BH}$ and $J_{BH}$

AH = apparent horizon (closed trapped surface)
Limits on $M_{BH}$ and $J_{BH}$

- $\mu \equiv \sqrt{\hat{s}}/2$, so $M/2\mu = 1$ implies $M_{BH}^2 = \hat{s}$

- We’ll assume $M_{BH} \sim 2\mu = \sqrt{\hat{s}}$, $J_{BH} \sim b\mu \sim bM_{BH}/2$
BH cross section vs Planck mass

Little sensitivity to n

Sensitive to assumption that \( M_{BH} \sim \sqrt{\hat{s}} \)
BH cross sections at LHC

$M_{PL} = 1 \text{ TeV}$

YR form factor

Several 5 TeV BH per minute at LHC!
Black hole decay (1)

- **Balding phase**
  - loses ‘hair’ and multipole moments, mainly by gravitational radiation

- **Spin-down phase**
  - loses angular momentum, mainly by Hawking radiation

- **Schwarzschild phase**
  - loses mass by Hawking radiation, temperature increases

- **Planck phase**
  - mass and/or temperature reach Planck scale: remnant = ??
Black hole decay (2)

- We’ll assume Schwarzschild phase is dominant
  - all types of SM particles emitted with Hawking spectrum

$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_H} \mp 1)T_H^{n+6}}$$

- Hawking temperature

$$T_H = \frac{n + 1}{4\pi r_{BH}} \propto (M_{BH})^{-\frac{1}{n+1}}$$

- $\gamma$ is (4+n)-dimensional grey-body factor
Grey-body factors

- Scalar
- Spinor

Emission on brane only
- Low-energy vector suppression
- CM Harris, hep-ph/0502005
Integrated Hawking flux

**N.B.** $F_{\text{tot}}^{r_s} \gg 1$ at large $n$

→ Transit time $\gg$ time between emissions

→ Decay no longer quasi-stationary at large $n$
Black hole lifetime

\[ \tau_{\text{MBH}} \sim 1 \text{ at large } n \]

\((M_{\text{BH}} = 5 \text{ TeV} \Rightarrow M_{\text{BH}}^{-1} \sim 10^{-28} \text{ s})\)

N.B. \(\tau M_{\text{BH}} \sim 1\) at large \(n\)

Black hole no longer well-defined?
Black Hole Event Generators

- **TRUENOIR** (Dimopoulos & Landsberg, hep-ph/0106295)
  - J=0 only; no energy loss; fixed T; no g.b.f.

- **CHARYBDIS** (Harris, Richardson & BW, hep-ph/0307305)
  - J=0 only; no energy loss; variable T; g.b.f. included

- **CATFISH** (Cavaglia et al., hep-ph/0609001)
  - J=0 only; energy loss option; variable T; g.b.f. included

All need interfacing to a parton shower and hadronization generator (PYTHIA or HERWIG)
## Main CHARYBDIS parameters

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<tr>
<th>Name</th>
<th>Description</th>
<th>Values</th>
<th>Default</th>
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<td>TOTDIM</td>
<td>Total dimension (n+4)</td>
<td>6-11</td>
<td>6</td>
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<tr>
<td>MPLNCK</td>
<td>Planck mass (GeV)</td>
<td>real</td>
<td>1000</td>
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<td>GTSCA</td>
<td>Use scale (1/r_S) not M_BH</td>
<td>logical</td>
<td>.FALSE.</td>
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<tr>
<td>TIMVAR</td>
<td>Use time-dependent T_H</td>
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<td>.TRUE.</td>
</tr>
<tr>
<td>MSSDEC</td>
<td>Include t, W, Z(2), h(3) decay</td>
<td>1-3</td>
<td>3</td>
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<tr>
<td>GRYBDY</td>
<td>Include grey-body factors</td>
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<tr>
<td>KINCUT</td>
<td>Use kinematic cutoff</td>
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</table>
CHARYBDIS Event at LHC

\[ \text{TOTDIM} = 10 \quad \text{MPLNCK} = 1 \text{ TeV} \quad \text{M}_{BH} = 8 \text{ TeV} \]
Effects of grey-body factors

Primary photons from 5 TeV BH (n=2)

- Neglecting g.b.f.
- Neglecting T var.
- Including both

Particle emissivity (%)

<table>
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<tr>
<th>Particle type</th>
<th>Generator</th>
<th>Theory</th>
<th>Generator</th>
<th>Theory</th>
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<td>61.8</td>
<td>58.2</td>
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<tr>
<td>Gluons</td>
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<td>16.9</td>
<td>16.8</td>
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<td>10.3</td>
<td>8.4</td>
<td>9.4</td>
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<td>2.1</td>
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</tr>
<tr>
<td>W⁺ and W⁻</td>
<td>4.7</td>
<td>5.3</td>
<td>5.7</td>
<td>6.3</td>
</tr>
<tr>
<td>Higgs boson</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Vector boson suppression 20-30%
Generator-theory differences due to masses & charge conservation
Exploring Higher Dimensional Black Holes at the Large Hadron Collider

C.M. Harris†, M.J. Palmer†, M.A. Parker†, P. Richardson†, A. Sabetfakhri† and B.R. Webber†

† Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, UK.
‡ Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, UK.


Missing transverse energy

Typically larger $\not{p}_T$ than SM or even MSSM
Measuring black hole masses

- Need $E_T < 100 \text{ GeV}$ for adequate resolution

$$\frac{\Delta M_{BH}}{M_{BH}} \sim 4\%$$
Effect of energy cutoff $E < \frac{M_{BH}}{2}$

Energy distribution of primary emissions vs $M_{BH}$

Cutoff affects spectrum at low mass and/or high $n$
Effects of time dependence

Fits to primary electron spectrum for n=2

Neglecting time variation of $T_H$ leads to over-estimate of n
Combined measurement of $M_{PL}$ and $n$

\[ \Delta M_{PL} / M_{PL} \sim 15\% , \ \Delta n \sim 0.75 \]
Conclusions

• Several event generators available for LHC
• Starting to describe multijets better
• (Slow) progress on matching to NLO
• Simulations of BSM scenarios also necessary
• Need spin correlations to confirm SUSY
• Black holes are a fun option (for now)
• LHC will tell!