Monte Carlo Event Generation for the LHC

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Monte Carlo Event Generators

- Traditionally (imprecise) general-purpose tools
- Much recent work to make them more precise
LHC Event Simulation

Hard subprocess
LHC Event Simulation

Parton showering
LHC Event Simulation

Hadronization
LHC Event Simulation

Hadronization and decays
LHC Event Simulation

Underlying event
MC Event Generators

- **HERWIG**
  - Angular-ordered parton shower, cluster hadronization
  - v6 Fortran; Herwig++
  - [http://projects.hepforge.org/herwig/](http://projects.hepforge.org/herwig/)

- **PYTHIA**
  - Dipole-type parton shower, string hadronization
  - v6 Fortran; v8 C++
  - [http://www.thep.lu.se/~torbjorn/Pythia.html](http://www.thep.lu.se/~torbjorn/Pythia.html)

- **SHERPA**
  - Dipole-type parton shower, cluster hadronization
  - C++
  - [http://projects.hepforge.org/sherpa/](http://projects.hepforge.org/sherpa/)
Parton Shower Monte Carlo

- Leading-order normalization
- Worse for high $p_T$ and/or extra jets

http://mcplots.cern.ch/
LHC Event Simulation

Hard subprocess
LHC Event Simulation

NLO Hard subprocess
LHC Event Simulation

NLO Hard subprocess
LHC Event Simulation

NLO Hard subprocess
+ Parton showering
= Double counting??
LHC Event Simulation

Multijet Hard subprocess
Multijet Hard subprocess + Parton showering = Double counting??
Matching & Merging

- Two rather different objectives:

- **Matching** parton showers to NLO matrix elements, without double counting
  - MC@NLO
  - POWHEG

- **Merging** parton showers with LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW
  - Dipole
  - MLM merging

(Also: matching NLO showers and matrix elements - see S Jadach et al., 1103.5015)
Outline

• Parton Shower Monte Carlo (PSMC)

• Matching PSMC to Next-to-Leading Order (NLOPS)
  ✤ MC@NLO
  ✤ POWHEG

• Merging PSMC with Multijet Matrix Elements (MEPS)
  ✤ CKKW-L
  ✤ MLM

• Combining MEPS with NLOPS (MENLOPS)

• NLOPS case study: top production asymmetry
**Parton Shower Monte Carlo**

LO (Born) \[ d\sigma_{MC} = B(\Phi_B) \, d\Phi_B \]

No (resolvable) emission \[ d\sigma_{MC} = B(\Phi_B) \, d\Phi_B + R_{MC}(\Phi_B, \Phi_R) \, d\Phi_B \, d\Phi_R \]

One emission \[ d\sigma_{MC} = B(\Phi_B) \, d\Phi_B + R_{MC}(\Phi_B, \Phi_R) \, d\Phi_B \, d\Phi_R \]

- **MC Sudakov form factor:**
  \[ \Delta_{MC}(\Phi_B, \Phi_R) = \exp \left[ - \int d\Phi_R \frac{R_{MC}(\Phi_B, \Phi_R)}{B(\Phi_B)} \theta(\Phi_B, \Phi_R) \right] \]

- **Unitarity:**
  \[ \int d\sigma_{MC} = \int B(\Phi_B) \, d\Phi_B \]

- **Expanded to NLO:**
  \[ d\sigma_{MC} = \left[ B(\Phi_B) - \int R_{MC}(\Phi_B, \Phi_R) \, d\Phi_R \right] \, d\Phi_B + R_{MC}(\Phi_B, \Phi_R) \, d\Phi_B \, d\Phi_R \]
MC@NLO matching

\[ \begin{align*}
\frac{d\sigma_{\text{NLO}}}{d\Phi_B} &= \left[ B(\Phi_B) + V(\Phi_B) - \int \sum_i C_i (\Phi_B, \Phi_R) \, d\Phi_R \right] \, d\Phi_B + R(\Phi_B, \Phi_R) \, d\Phi_B \, d\Phi_R \\
&\equiv \left[ B + V - \int C \, d\Phi_R \right] \, d\Phi_B + R \, d\Phi_B \, d\Phi_R \\
\frac{d\sigma_{\text{MC}}}{d\Phi_B} &= B(\Phi_B) \, d\Phi_B \left[ \Delta_{\text{MC}}(0) + \frac{R_{\text{MC}}(\Phi_B, \Phi_R)}{B(\Phi_B)} \, \Delta_{\text{MC}}(k_T(\Phi_B, \Phi_R)) \, d\Phi_R \right] \\
&\equiv B \, d\Phi_B \left[ \Delta_{\text{MC}}(0) + \left( \frac{R_{\text{MC}}}{B} \right) \, \Delta_{\text{MC}}(k_T) \, d\Phi_R \right]
\end{align*} \]

\[ \begin{align*}
\frac{d\sigma_{\text{MC@NLO}}}{d\Phi_B} &= \left[ B + V + \int (R_{\text{MC}} - C) \, d\Phi_R \right] \, d\Phi_B \left[ \Delta_{\text{MC}}(0) + \left( \frac{R_{\text{MC}}}{B} \right) \, \Delta_{\text{MC}}(k_T) \, d\Phi_R \right] \\
&\quad + (R - R_{\text{MC}}) \, \Delta_{\text{MC}}(k_T) \, d\Phi_B \, d\Phi_R \\
&\geq 0
\end{align*} \]

- Expanding gives NLO result
- MC starting from no emission
- MC starting from one emission

S Frixione & BW, JHEP 06(2002)029
• MEC = Matrix Element Correction (not NLO)

• MC@NLO is MC-specific, but integral is NLO

S Frixione & P Torrielli, JHEP 04(2010)110
NLO is only LO for high $p_t$ jet

S Frixione & P Torrielli, JHEP 04(2010)110
Automatically generated events for LHC

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau, Stelzer, Torrielli

\( pp @ 7 \text{ TeV} \rightarrow Wb\bar{b}X \)

- \( b\bar{b} \) distributions softer than NLO

\( \sigma (\text{pb/bin}) \)

\( P_{Tb} \)

\( M_{b\bar{b}} \)
Pseudoscalar distribution harder

Automatic MC@NLO

pp @ 7 TeV $\rightarrow$ H/At$\bar{t}$X
POWHEG matching

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

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

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

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

Z\(^0\) at Tevatron

- **NLO is only LO at high** \(p_T\)

Hamilton, Richardson, Tully JHEP10(2008)015
Solid line: NLO Herwig++ POWHEG
Blue dashes: MC@NLO
Red dashes: Herwig++ with ME corrections

Drell-Yan vector boson production
W boson p_T spectrum compared to D0 run I data
W at Tevatron

• All agree (tuned) at Tevatron

Hamilton, Richardson, Tully JHEP10(2008)015
W & Z⁰ at LHC (14 TeV)

- Still in fair agreement at 14 TeV
Z^0 + jet POWHEG

- Cut now needed on ‘underlying Born’ p_t of Z^0
- Good agreement with CDF (not so good with D0)
- First jet is now NLO, second is LO (times B/B ...)

Alioli, Nason, Oleari, Re, JHEP01(2011)095
Again, cut needed on ‘underlying Born’ jet $p_t$.

- Good agreement with LHC at 7 TeV.

Alioli, Hamilton, Nason, Oleari, Re, 1012.3380.
MEPS merging

- Objective: merge LO n-jet MEs* with PSMC such that
- Multijet rates for resolution $> Q_{\text{cut}}$ are correct to LO (up to $N_{\text{max}}$)
- PSMC generates jet structure below $Q_{\text{cut}}$
- $Q_{\text{cut}}$ dependence cancels to NLL accuracy

* ALPGEN or MadGraph, $n \leq N_{\text{max}}$

CKKW: Catani et al., JHEP 11(2001)063
-L: Lonnblad, JHEP 05(2002)063
MLM: Mangano et al., NP B632(2002)343
Z^0+jets at Tevatron

- CDF run II data
- Jet p_t and N_{jets}
- Insensitive to Q_{cut}
- Insensitive to N_{max}>1

Hoeche, Krauss, Schumann, Siegert, JHEP05(2009)053

Event Generation for LHC
Inclusive jet rates (anti-\(k_t\)-algorithm)

“Very good agreement with predictions from ME+PS simulation, while PS alone starts to fail for \(n_{\text{jet}} \geq 2\)”

V Ciulli, Moriond, 24/03/11
W+jets at LHC (CMS)

- Same conclusion as for Z^0
Event Generation for LHC

$Z^0 + \text{jets at LHC (ATLAS)}$

- Same conclusion as CMS ...

N Makovec, Moriond, 24/03/11
Matching & Merging: MENLOPS

\[ d\sigma_{\text{TOT}} = d\sigma_{\text{NLOPS}}(0 \text{jets}) + K_1 d\sigma_{\text{NLOPS}}(1 \text{jet}) + K_2 d\sigma_{\text{MEPS}}(\geq 2 \text{jets}) \]

- **Assume** \( \geq 2 \text{ jets} \) have K-factor

  \[ K_2 = \frac{\sigma_{\text{NLOPS}}(\geq 1 \text{jets})}{\sigma_{\text{MEPS}}(\geq 1 \text{jets})} \]

- **To retain NLO accuracy we need**

  \[ \sigma_{\text{TOT}} = \sigma_{\text{NLOPS}}(0 \text{jets}) + \sigma_{\text{NLOPS}}(\geq 1 \text{jets}) \]

- **Therefore**

  \[ K_1 = \frac{\sigma_{\text{MEPS}}(1 \text{jet})}{\sigma_{\text{MEPS}}(\geq 1 \text{jets})} \div \frac{\sigma_{\text{NLOPS}}(1 \text{jet})}{\sigma_{\text{NLOPS}}(\geq 1 \text{jets})} \]

Hamilton & Nason, JHEP06(2010)039

Hoeche, Krauss, Schonherr, Siegert, 1009.1127
d\sigma_{\text{TOT}} = d\sigma_{\text{NLOPS}}(0 \text{jets}) + K_1 d\sigma_{\text{NLOPS}}(1 \text{jet}) + K_2 d\sigma_{\text{MEPS}}(\geq 2 \text{jets})

K_2 = \frac{\sigma_{\text{NLOPS}}(\geq 1 \text{jets})}{\sigma_{\text{MEPS}}(\geq 1 \text{jets})}

K_1 = \frac{\sigma_{\text{MEPS}}(1 \text{jet})}{\sigma_{\text{MEPS}}(\geq 1 \text{jets})} / \frac{\sigma_{\text{NLOPS}}(1 \text{jet})}{\sigma_{\text{NLOPS}}(\geq 1 \text{jets})}

- Choose \( Q_{\text{cut}} \) such that \( \sigma_{\text{MEPS}}(\geq 2 \text{jets}) \leq \mathcal{O}(\alpha_S) \)
- Compute \( K_1, K_2 \) (in principle for each Born kinematics)
- Throw away MEPS 0- & 1-jet samples
- Replace them by NLOPS 0- & 1-jet samples
Z⁰ at Tevatron

- All treatments agree (MEPS rescaled)

Hoeche, Krauss, Schonherr, Siegert, 1009.1127
Z^0+jets at Tevatron

- MENLOPS good for N_{jet}=1,2,3 (no ME for 4)
**MENLOPS best for jets 2 & 3**
W(+jets) at Tevatron

- POWHEG best for $p_t(W)$, lacks ME for $N_{\text{jet}}>1$

Hoeche, Krauss, Schonherr, Siegert, 1009.1127
$W$ at LHC (14 TeV)

- Dashes are NLOPS & MEPS shapes
- Crosses are contributions to MENLOPS

Hamilton & Nason, JHEP06(2010)039
W+jets at LHC (14 TeV)

- NLOPS low for $N_{jets} > 1$
W+jets at LHC (14 TeV)

- MEPS dominates at small $\Delta \phi_{J1,W^-}$
Top at LHC (14 TeV)

- See later for importance of $Y_{t\bar{t}}$
Surprisingly, NLOPS is harder here
Forward-backward asymmetry in top quark production

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- SM predicts a smaller NLO effect
- MC@NLO and MCFM in good agreement

\[ A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]

\[ \Delta y = y_t - y_{\bar{t}} \]
\[ Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}}) \]
Top quark asymmetry at LHC

- **LHC is a pp collider** → no effect??
- **No!** Effect should increase with $Y_{t\bar{t}}$ ($q$ vs $\bar{q}$)
- **SM effect is small** (plots show MC truth for 2 fb$^{-1}$)

\[ A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]

\[ \Delta y = y_t - y_{\bar{t}} \]

\[ Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}}) \]
Top quark asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{tt}$ (q vs $\bar{q}$)
- Rapidity correlation should be as shown below

$$\Delta y = y_t - y_{\bar{t}}, \quad Y_{tt} = \frac{1}{2}(y_t + y_{\bar{t}})$$

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$
Top quark asymmetry at LHC

- LHC cuts assumed:
  - 1 charged lepton and at least 4 jets (inc. 2 b’s) with $p_T > 20 \text{ GeV/c}$, $|\eta| < 2.5$
  - Missing $E_T > 20 \text{ GeV}$
- 4 jet cut reduces gg contribution
Top quark asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect is small (plots show MC truth for 2 fb$^{-1}$)

$\Delta y = y_{t} - y_{\bar{t}}$, $Y_{t\bar{t}} = \frac{1}{2}(y_{t} + y_{\bar{t}})$

$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$
Top quark asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect enhanced by cut on $t\bar{t}$ invariant mass

$$\Delta y = y_t - y_{\bar{t}} \ , \ Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

$$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

![Graph showing SM, 4 jets with cuts and no cuts with $M_{t\bar{t}} > 500$ GeV]
Forward-backward asymmetry in top quark production (2)

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- Suppose this is new physics
- Model it by reweighting $q\bar{q}$ contribution

\[
\Delta y = y_t - y_{\bar{t}} , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})
\]

\[
A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]
Forward-backward asymmetry in top quark production (2)

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- Suppose this is new physics
- Model it by reweighting $q\bar{q}$ contribution by:
  \[
  1 + f(M_{t\bar{t}}) \tanh(\Delta y/2) \\
  \approx 1 + f(M_{t\bar{t}}) \beta_t^* \cos \theta_t^*
  \]

\[
\begin{align*}
  f(M_{t\bar{t}}) &= M_{t\bar{t}} / 200 - 2
\end{align*}
\]
Top quark asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{tt}$ ($q$ vs $\bar{q}$)
- SM effect enhanced by cut on $tt$ invariant mass

\[ \Delta y = y_t - y_{\bar{t}}, \quad Y_{tt} = \frac{1}{2}(y_t + y_{\bar{t}}) \]

\[ A_{tt} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]
CDF top asymmetry at LHC?

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Model CDF effect by reweighting SM by:

$$f(M_{t\bar{t}}) \tanh(\Delta y/2) \simeq 1 + f(M_{t\bar{t}})\beta^* \cos \theta^*$$

$$f(M_{t\bar{t}}) = \frac{M_{t\bar{t}}}{200} - 2$$

$LHC 7$ TeV

$M_{t\bar{t}} > 500$ GeV

$\sim 3\sigma$ difference
Conclusions

• Event generators continue to improve
• Many processes now reliable to NLO
• Multijets included to LO
• Multijets to NLO in progress
• Look for $t\bar{t}$ asymmetry at LHC!