Monte Carlo generators for high energy colliders

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Soft and collinear singularities in QCD

Parton shower algorithms

General-purpose event generators

Matrix-element corrections to parton showers

MC@NLO and matrix-element generators

Comparisons and concluding remarks

Multi-parton radiation in high-energy processes

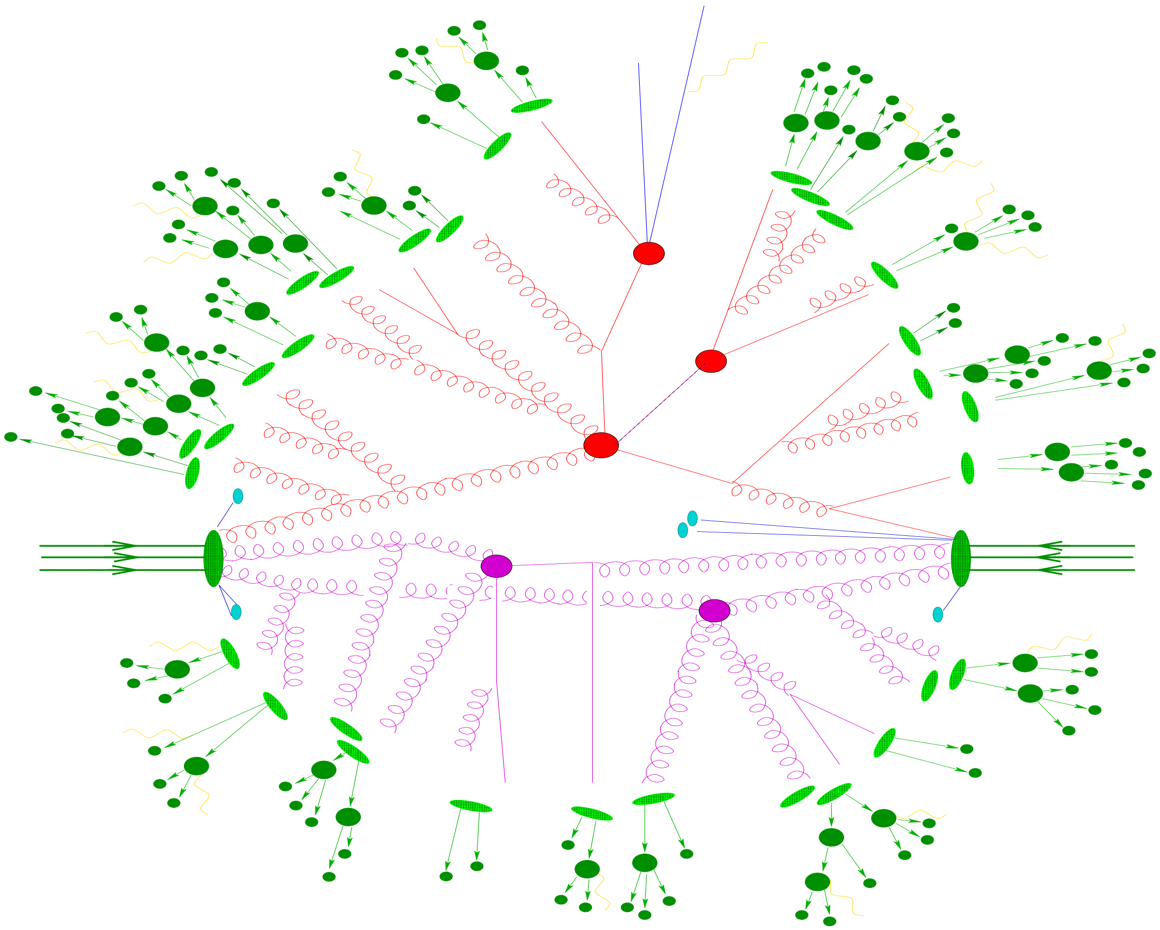


Figure by Frank Krauss

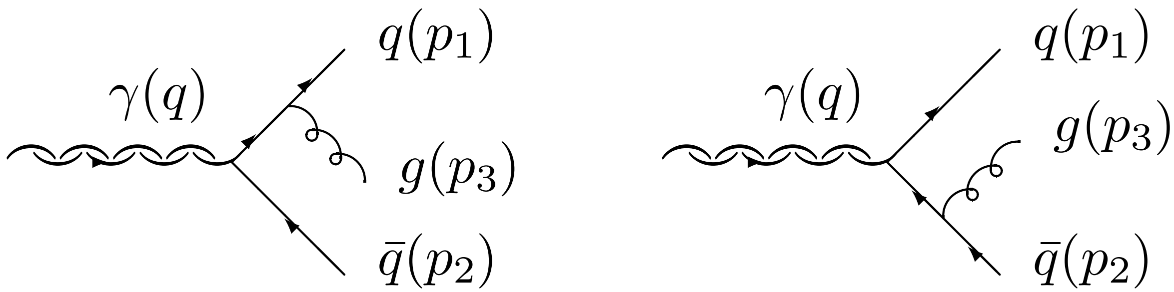
Standard Monte Carlo event generators (HERWIG/PYTHIA):

Hard $2 \rightarrow 2$ subprocess: leading-order (LO) matrix element

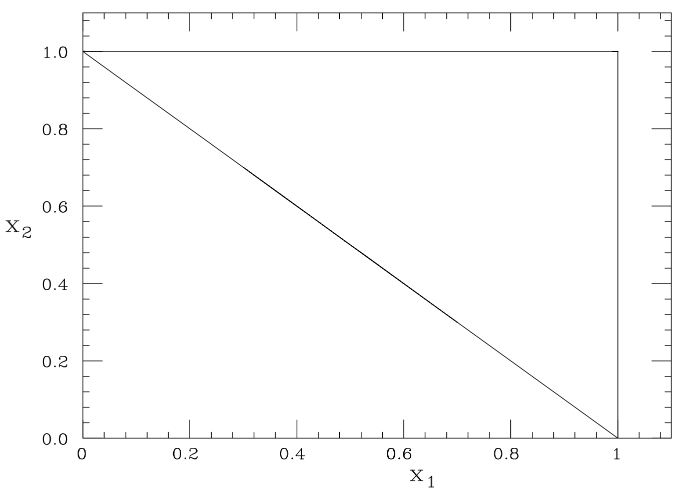
Parton showers in the soft or collinear approximation

Matrix-element corrections for hard and large-angle parton radiation

A simpler case: $e^+e^- \to \gamma(q) \to q(p_1)\bar{q}(p_2)g(p_3) \quad (m_i \simeq 0)$



$$\frac{d^2\sigma}{dx_1 dx_2} = \sigma_0 C_F \frac{\alpha_s}{2\pi} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \quad ; \quad x_i = \frac{2p_i \cdot q}{q^2} = \frac{2E_i}{\sqrt{s}} \quad ; \quad x_1 + x_2 + x_3 = 2$$



$$2p_i \cdot p_j = 2E_iE_j(1-\cos\theta_{ij}) \;\; ; \;\; 2p_i \cdot p_j = (q-p_k)^2 = q^2(1-x_k)$$

$x_1 \to 1$: $g \parallel \bar{q}$; $x_2 \to 1$: $g \parallel q$; $x_3 \to 0$: **soft-gluon radiation**

$$\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} = -2 + \frac{1+(1-x_3)^2}{x_3}\left(\frac{1}{1-x_1} + \frac{1}{1-x_2}\right)$$

Collinear approximation: $\theta = \theta_{23} \to 0 \;\; , \;\; x_1 \to 1$

$$z = \frac{E_3}{E_2+E_3} = \frac{x_3}{2-x_1} \simeq x_3 \quad ; \quad \theta^2 \simeq 2(1-\cos\theta) \simeq \frac{4(1-x_1)}{x_3(1-x_3)}$$

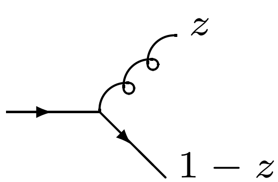
$$P(z) = C_F \frac{1+(1-z)^2}{z} : \;\; \textbf{Altarelli – Parisi splitting function}$$

$$\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \simeq \frac{1}{C_F}\frac{4}{x_3(1-x_3)}\frac{P(z)}{\theta^2}\ , \quad J = \frac{x_3(1-x_3)}{4}$$

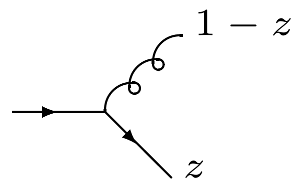
Differential cross section in terms of z and θ:

$$d^2\sigma = \sigma_0\ \frac{\alpha_S}{2\pi} P(z) dz\ \frac{d\theta^2}{\theta^2}$$

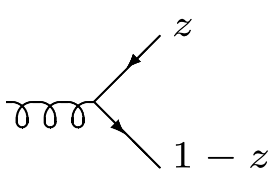
Universal in the collinear limit



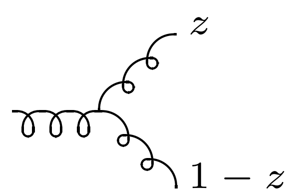
$P_{gq}(z) = C_F \frac{1+(1-z)^2}{z}$



$P_{qq}(z) = C_F \frac{1+z^2}{1-z}$



$P_{qg}(z) = C_F \left[1 + (1-z)^2\right]$



$P_{gg}(z) = C_A \frac{z^4+1+(1-z)^4}{z(1-z)}$

Soft approximation: $\gamma(q) \to q(p_1)\bar{q}(p_2)g(p_3,\epsilon)$ $\quad \omega = E_3 \ll E_{1,2}\ ;\ |\vec{p}_3| \ll |\vec{p}_{1,2}|$

$$\begin{aligned}\mathcal{M}^{a\mu} &= -ieg_S T^a \bar{u}(p_1)\left(\gamma^\mu \frac{i}{\not{p}_3 + \not{p}_1}\not{\epsilon} + \not{\epsilon}\frac{i}{\not{p}_2 + \not{p}_3}\gamma^\mu\right) v(p_2) \\ &= g_S T^a \epsilon_\nu \left(\frac{p_1^\nu}{p_1\cdot p_3} - \frac{p_2^\nu}{p_2\cdot p_3}\right) e\bar{u}(p_1)\gamma^\mu v(p_2)\end{aligned}$$

Eikonal factorization: universal in the soft limit

$$d^2\sigma = \sigma_0 C_F \frac{\alpha_S}{\pi}\frac{2d\omega}{\omega}\frac{d\cos\theta}{(1-\cos\theta)(1+\cos\theta)} = \sigma_0 C_F \frac{\alpha_S}{2\pi}\frac{2d\omega}{\omega}\left[\frac{d\cos\theta}{1-\cos\theta} + \frac{d\cos\theta}{1-\cos(\pi-\theta)}\right]$$

Collinear limit :

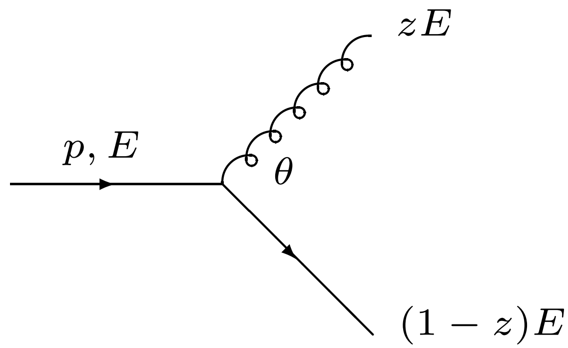
$$d^2\sigma = \sigma_0\ \frac{\alpha_S}{2\pi}\ P(z)dz\ \frac{d\theta^2}{\theta^2} \qquad P(z)dz = C_F\frac{1+(1-z)^2}{z}dz \simeq C_F\frac{2}{\omega}d\omega$$

Soft and/or collinear limit :

$$d^2\sigma = \sigma_0\ \frac{\alpha_S}{2\pi}\ P(z)dz\ \frac{d\cos\theta}{1-\cos\theta}$$

Starting point to simulate multiple radiation: need of ordering variable

In the collinear approximation, any $Q^2 \propto \theta^2$ is feasible to order multiple radiation



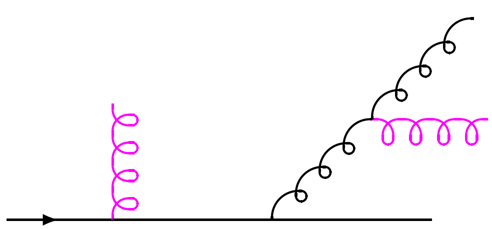
Gluon transverse momentum: $k_T^2 = z^2(1-z)^2E^2\theta^2$

Invariant mass: $p^2 = z(1-z)E^2\theta^2$

Collinear limit: $\ln k_T^2 \sim \ln p^2 \sim \ln \theta^2$

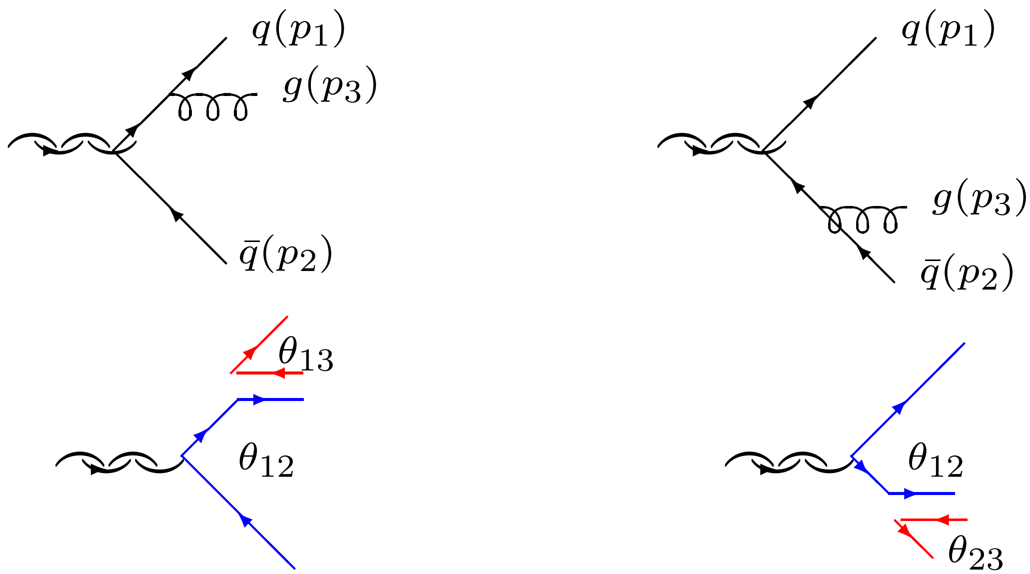
$$\frac{d\theta^2}{\theta^2} = \frac{dk_T^2}{k_T^2} = \frac{dp^2}{p^2}$$

Soft gluons can be emitted anywhere, at any angle



Angular ordering allows one to implement probabilistically multiple soft emissions

Angular ordering



$$|\mathcal{M}|^2 \sim W = \frac{\omega^2}{2}\left(\frac{p_1}{p_1 \cdot p_3} - \frac{p_2}{p_2 \cdot p_3}\right)^2 = \frac{1-\cos\theta_{12}}{(1-\cos\theta_{13})(1-\cos\theta_{23})} \quad \textbf{(soft \ \ limit)}$$

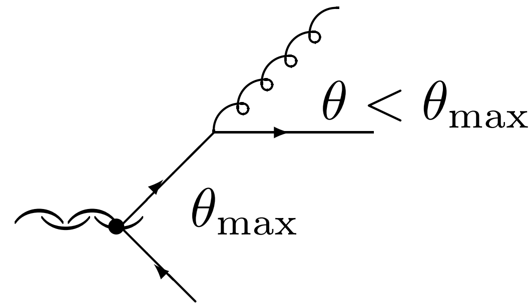
$$W = W_1 + W_2 \quad ; \quad W_1 = \frac{1}{2}\left(W + \frac{1}{1-\cos\theta_{13}} - \frac{1}{1-\cos\theta_{23}}\right)$$

$$\begin{aligned} \int_0^{2\pi} \frac{d\phi_{13}}{2\pi} W_1 &= \frac{1}{1-\cos\theta_{13}}, \ \text{if} \ \theta_{13} < \theta_{12} \\ &= 0 \qquad\qquad\qquad \text{if} \ \theta_{13} > \theta_{12} \end{aligned}$$

Colour coherence: a parton radiates up to its colour partner

Implementation of angular ordering

$$dP = \frac{d^2\sigma}{\sigma_0} = \frac{\alpha_S}{2\pi}\ P(z)dz\ \frac{d\cos\theta}{1-\cos\theta}$$



Need to evaluate probability of no branching at larger angles

Analogy with nuclear decay:

$$dP = \lambda dt \qquad dN = -N_0 \lambda dt \qquad N(t) = N_0 \exp(-\lambda t) = N_0 \exp[-\textstyle\int_0^t dP]$$

Probability of no decay in $[0,t]$:

$$\frac{N(t)}{N_0} = \exp\left[-\int_0^t dP\right]$$

Probability of no branching in $[\theta, \theta_{\max}]$:

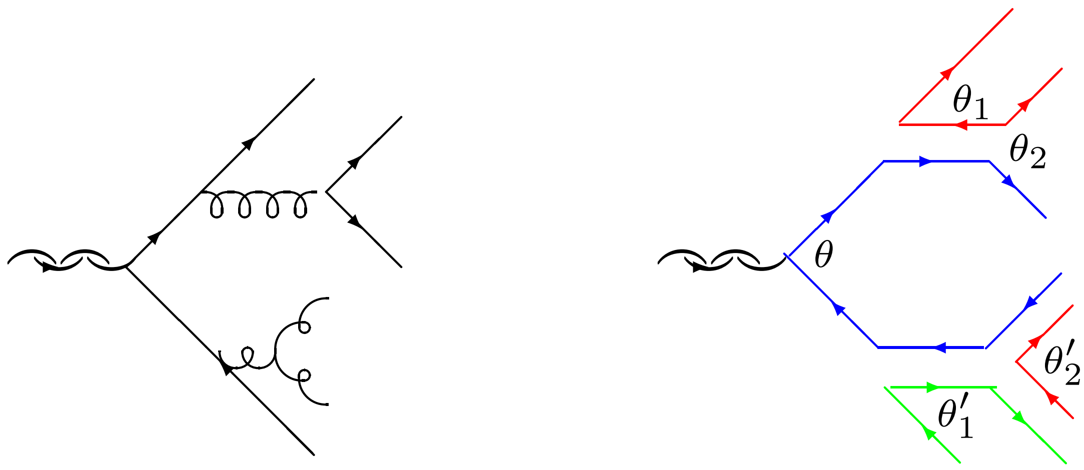
$$\Delta_S(\theta_{\max}, \theta) = \exp\left[-\frac{\alpha_S}{2\pi}\int_\theta^{\theta_{\max}} \frac{d\cos\theta'}{1-\cos\theta'} \int_{z_{\min}}^{z_{\max}} dz P(z)\right]$$

Sudakov form factor

$$dP = \frac{\alpha_S}{2\pi}\ P(z)dz\ \frac{d\cos\theta}{1-\cos\theta}\ \Delta_S(\theta_{\max}, \theta)$$

Unitarity: 1=R+V $\quad \Delta_S$ **sums virtual and unresolved emissions**

Angular-ordered parton showers



Parton shower $\Rightarrow$ colour flow $\Rightarrow$ angular ordering:

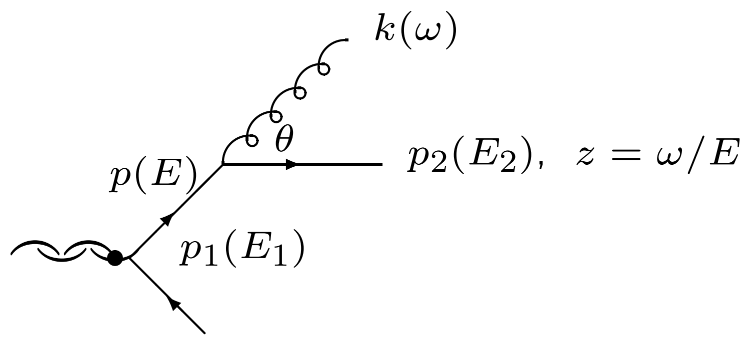
$\theta_1 < \theta$; $\theta_2 < \theta_1$; $\theta'_1 < \theta$; $\theta'_2 < \theta'_1$

$$dP_1 = \frac{\alpha_S}{2\pi}\, P(z_1) dz_1\, \frac{d\cos\theta_1}{1-\cos\theta_1} \Delta_S(\theta,\theta_1)$$

$$dP_2 = \frac{\alpha_S}{2\pi}\, P(z_2) dz_2\, \frac{d\cos\theta_2}{1-\cos\theta_2} \Delta_S(\theta_1,\theta_2) dP_1$$

Iterating dP one construct the multiple-radiation algorithm

Evolution variable in general-purpose event generators



HERWIG (G.C., I.Knowles,G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour, B.R. Webber) **:**
$Q^2 = E^2(1-\cos\theta) \simeq E^2\theta^2/2$; $Q_{\max} = \sqrt{p \cdot p_1}$; $E = Q_{\max}$; $\theta < \pi/2$

Soft approximation: angular ordering $Q_1^2 < Q_2^2 \Rightarrow \theta_1 < \theta_2$

HERWIG++ (S.Gieseke, A. Ribon, M. Seymour, P. Stevens, B. Webber)**:** $Q'^2 = Q^2 + \frac{\max(k^2,p^2)}{z^2} + \frac{k^2}{z^2(1-z)^2}$
(e^+e^- and Drell–Yan processes at the moment)

Angular ordering, better treatment of soft phase space and heavy quark masses

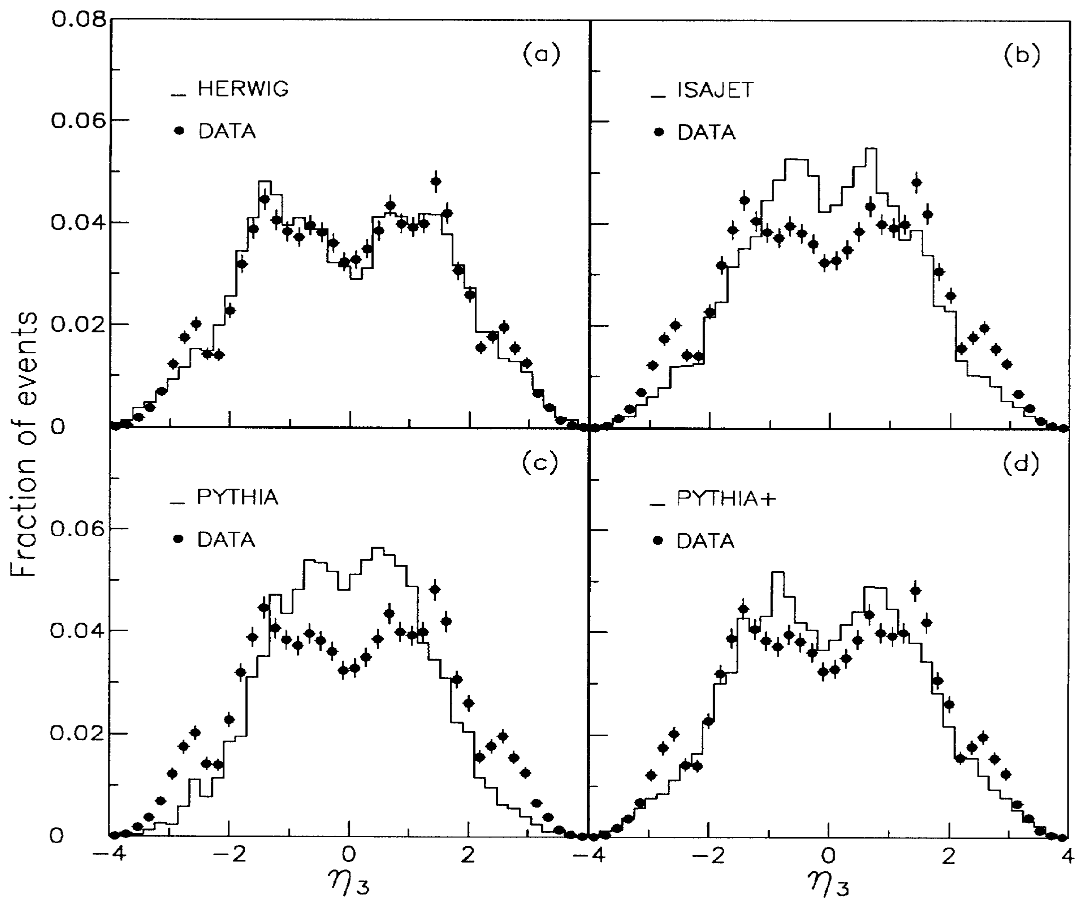
PYTHIA (up to 6.2 version) (T. Sjostrand, L. Lonnblad, S. Mrenna, P. Skands)**:** $Q^2 = p^2$

It includes angular ordering only by an additional veto (see CDF PRD 50 (1994) 5562)

PYTHIA 6.3: $Q^2 = k_T^2$

The Sudakov form factor will be: $\Delta_S(Q^2_{\max}, Q^2) = \Delta_S(Q^2_{\max}, Q_0^2)/\Delta_S(Q^2, Q_0^2)$

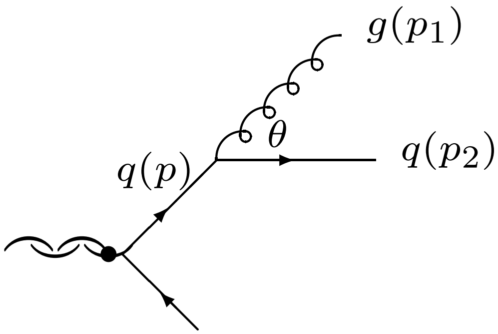
Angular ordering effects at CDF, PRD 50 (1994) 5562



0.08
0.06
0.04
0.02
0
Fraction of events
(a)
HERWIG
DATA
(b)
ISAJET
DATA
(c)
PYTHIA
DATA
(d)
PYTHIA+
DATA
−4
−2
0
2
4
η_3

Figure 10:

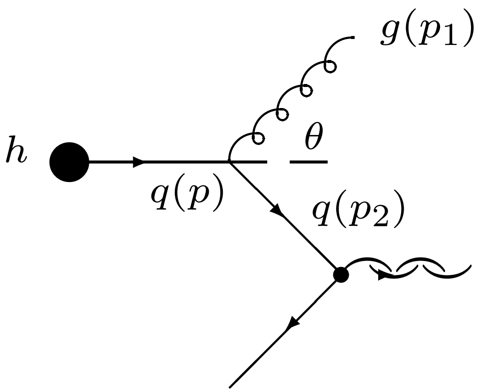
Branching algorithm for the final-state radiation (forward evolution)



$$z = \frac{E_1}{E}$$

$$dP = \frac{\alpha_S}{2\pi}\, P(z) dz\, \frac{dQ^2}{Q^2}\, \Delta_S(Q^2_{\max}, Q^2)$$

Initial-state radiation (backward evolution)



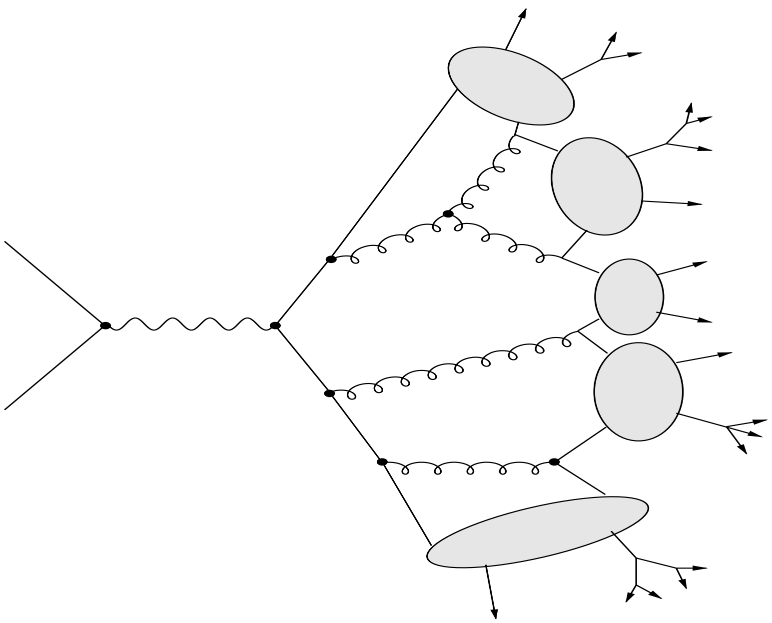
$$z = \frac{E_2}{E}$$

$$dP = \frac{\alpha_S}{2\pi}\, P(z) dz\;\; \frac{x/z}{x}\; \frac{f_b(x/z, Q^2)}{f_a(x, Q^2)}\; \frac{dQ^2}{Q^2}\; \frac{\Delta_{S,a}(Q^2_{\max}, Q^2_0)}{\Delta_{S,b}(Q^2, Q^2_0)}$$

Scale of α_S in parton showers: using the transverse momentum of the emitted parton allows one to resum a class of soft/collinear logarithms
(D. Amati et al. NPB (1980) 173)

$$\alpha_S(k_T^2) = \frac{\alpha_S(Q^2)}{1 + \alpha_S(Q^2) b_0 \ln(Q^2/k_T^2)} \simeq \alpha_S(Q^2)\left[1 - \alpha_S(Q^2) b_0 \ln\frac{Q^2}{k_T^2} + \ldots\right] \qquad b_0 = \frac{33 - 12 n_f}{12\pi} \;\; (\mathbf{LO})$$

Hadronization models



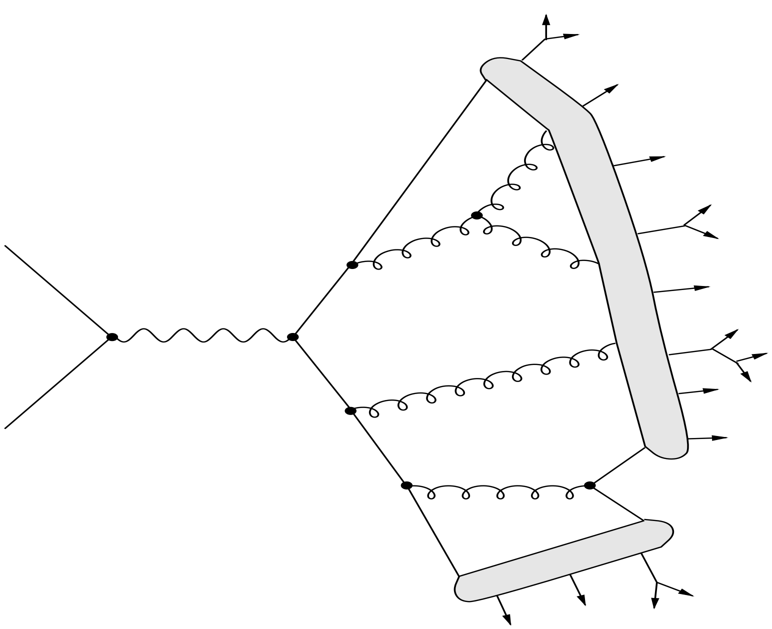
Cluster model (HERWIG)

Perturbative evolution ends at $Q^2 = Q_0^2$

Angular ordering $\Rightarrow$ colour preconfinement

Forced gluon splitting $(g \to q\bar{q})$

Colour-singlet clusters decay into the observed hadrons



String model (PYTHIA)

q **and** $\bar{q}$ **move in opposite direction**

The colour field collapses into a string, with uniform energy density

$q\bar{q}$ **pairs are produced**

The string breaks into the observed hadrons

Figures from R.K. Ellis, W.J. Stirling and B.R. Webber, QCD and Collider Physics

Matrix-element corrections

Standard parton shower algorithms implement multiple radiation in the soft or collinear approximation

They need to be corrected to describe hard and large-angle emissions

HERWIG: complementary phase spaces (matching)

In the neighbourhood of the soft/collinear singularities: use the branching probability $dP(z,\theta)$

Far from the soft/collinear phase space: use exact tree-level NLO matrix element, e.g. $e^+e^- \to q\bar{q}g$**, instead of its approximation**

Every time an emission is the hardest so far use exact matrix element

PYTHIA: merging strategy

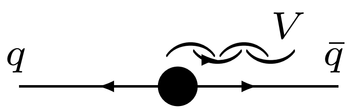
Use the soft/collinear approximation throughout all phase space

Use NLO tree-level matrix element to correct the first emission

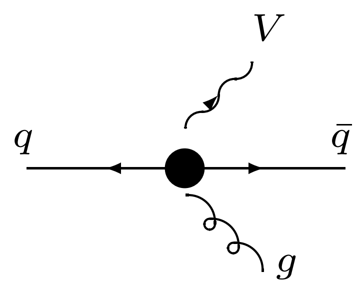
Both matrix-element corrected HERWIG and PYTHIA still give LO total cross section (e.g. $\sigma(e^+e^- \to q\bar{q})$)

Example of effects of matrix-element corrections (HERWIG)

Vector boson production $(V = W, Z)$: $q\bar{q} \to V$ **(LO)** $q\bar{q} \to Vg$ **. . . (NLO)**

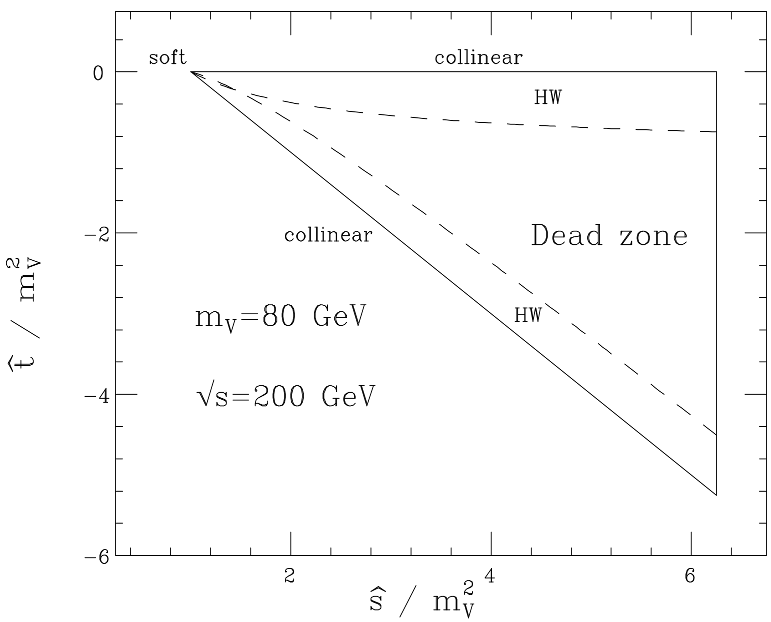


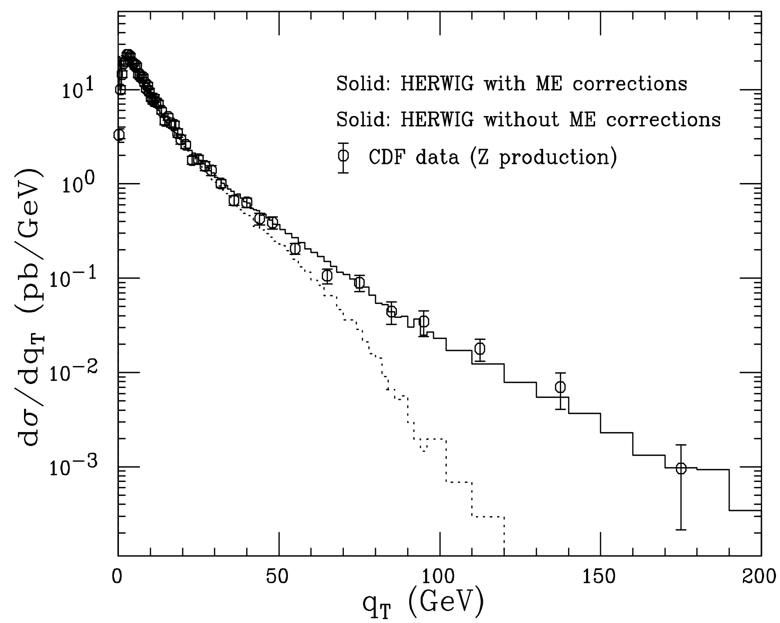
LO: $q_{T,V} = 0$



NLO: $q_{T,V} = q_{T,g} \neq 0$

Soft or collinear radiation: small q_T; hard and large-angle emission: large q_T





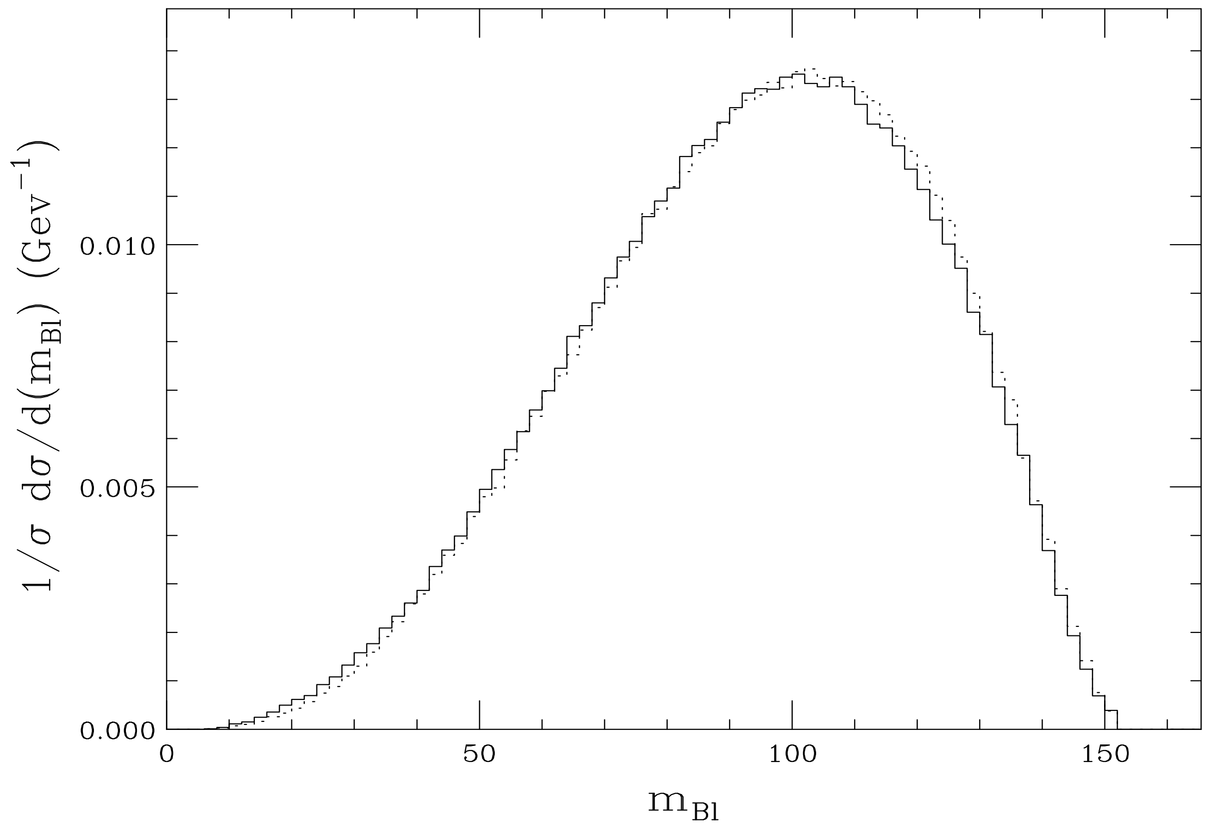
$\hat{s} = (p_q + p_{\bar{q}})^2$, $\hat{t} = (p_q + p_g)^2$, $\hat{u} = (p_q - p_g)^2$ G.C. and M.H. Seymour, NPB 565 (2000) 227

Exact result: $$d^2\sigma(q\bar{q} \to Vg) = \sigma_0 \frac{f_{q/1}(\chi_1) f_{\bar{q}/2}(\chi_2)}{f_{q/1}(\eta_1) f_{\bar{q}/2}(\eta_2)} \frac{C_F \alpha_S}{2\pi} \frac{d\hat{s}\ d\hat{t}}{\hat{s}^2 \hat{t}\hat{u}} \left[(q^2 - \hat{u})^2 + (q^2 - \hat{t})^2\right]$$

Top decay ($t \to bW$): invariant-mass $m_{B\ell}$ distributions

Possible interest: final states with leptons and J/ψ at the LHC

A. Kharchilava, PLB 476 (2000) 73: $\Delta m_t \simeq 1$ GeV using $m_{\ell J/\psi}$ or $m_{\ell\mu}$



Solid: after matrix-element corrections to top decay (6.5)

Dots: before matrix-element corrections (5.9)

Shift towards lower $m_{B\ell}$ after matrix-element corrections

All values of $m_{B\ell}$:

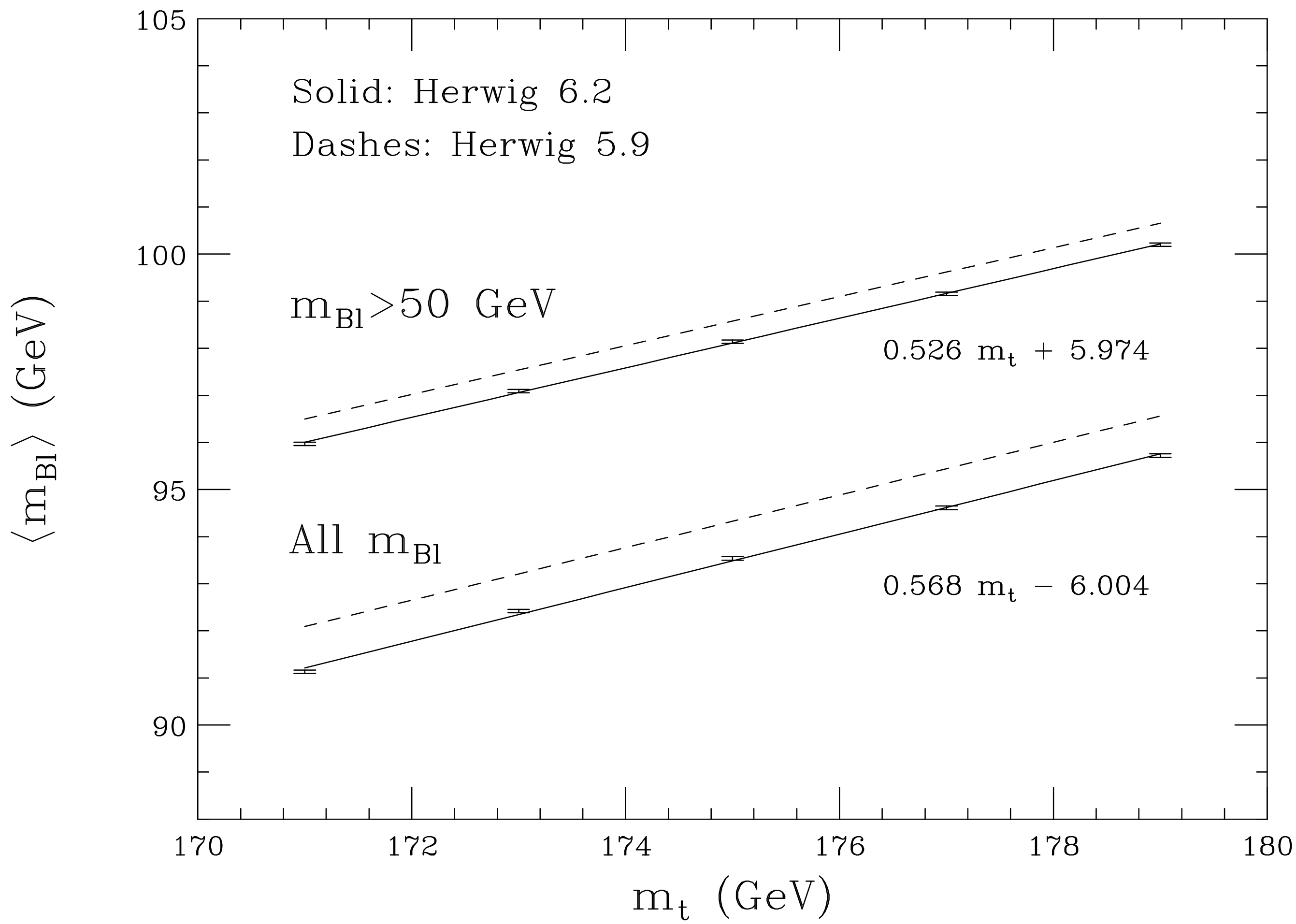
m_t	$\langle m_{B\ell}\rangle^{6.5}$	$\sigma(6.5)$	$\langle m_{B\ell}\rangle^{5.9}$	$\sigma(5.9)$	$\langle m_{Bl}\rangle^{5.9} - \langle m_{Bl}\rangle^{6.5}$
171 GeV	91.13 GeV	26.57 GeV	92.02 GeV	26.24 GeV	(0.891 ± 0.038) GeV
173 GeV	92.42 GeV	26.90 GeV	93.26 GeV	26.59 GeV	(0.844 ± 0.038) GeV
175 GeV	93.54 GeV	27.29 GeV	94.38 GeV	27.02 GeV	(0.843 ± 0.039) GeV
177 GeV	94.61 GeV	27.66 GeV	95.46 GeV	27.33 GeV	(0.855 ± 0.039) GeV
179 GeV	95.72 GeV	28.04 GeV	96.51 GeV	27.67 GeV	(0.792 ± 0.040) GeV

$m_{B\ell} > 50$ GeV:

m_t	$\langle m_{B\ell}\rangle^{6.5}$	$\sigma(6.5)$	$\langle m_{B\ell}\rangle^{5.9}$	$\sigma(5.9)$	$\langle m_{B\ell}\rangle^{5.9} - \langle m_{B\ell}\rangle^{6.5}$
171 GeV	95.97 GeV	22.24 GeV	96.45 GeV	22.26 GeV	(0.479 ± 0.036) GeV
173 GeV	97.09 GeV	22.69 GeV	97.56 GeV	22.68 GeV	(0.479 ± 0.034) GeV
175 GeV	98.14 GeV	23.12 GeV	98.64 GeV	23.15 GeV	(0.510 ± 0.035) GeV
177 GeV	99.16 GeV	23.54 GeV	99.62 GeV	23.52 GeV	(0.466 ± 0.035) GeV
179 GeV	100.20 GeV	23.96 GeV	100.62 GeV	23.90 GeV	(0.427 ± 0.036) GeV

G.C., M.L. Mangano and M.H. Seymour, JHEP 0007 (2000) 004

Linear fit:



All spectrum : $\Delta\langle m_{B\ell}\rangle \simeq 800$ MeV $\Rightarrow$ $\Delta m_t \simeq 1.5$ GeV

$\Delta m_{B\ell} > 50$ GeV : $\Delta\langle m_{B\ell}\rangle \simeq 500$ MeV $\Rightarrow$ $\Delta m_t \simeq 1.0$ GeV

CKKW matrix-element matching

(S. Catani, F. Krauss, R. Kühn and B.R. Webber, JHEP 11 (2001) 063)

Define a jet resolution variable $y_{\rm cut}$ and use the k_T (Durham) algorithm:

$$y_{ij} = 2\frac{\min\{E_i^2, E_j^2\}}{Q^2}(1-\cos\theta_{ij})$$

$y_{ij} > y_{\rm cut}$ **: i and j in two different jets**

$y_{ij} < y_{\rm cut}$ **: combine i and j into a pseudoparticle of momentum $p_{ij} = p_i + p_j$**

CKKW prescription:

$y_{ij} > y_{\rm cut}$ **(hard or large-angle partons): use matrix elements weighted by Sudakov form factors in the NLL approximation**

To avoid double counting, veto parton showers for y_{ij} above $y_{\rm cut}$

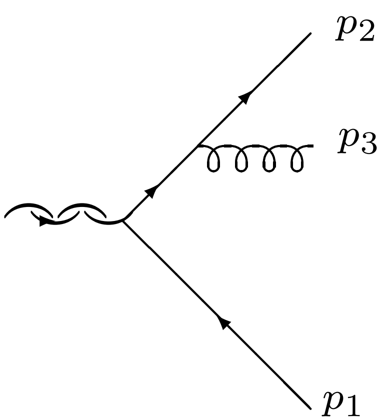
Advantages of this procedure:

Extends matrix-element matching to higher jet multiplicities

Sudakov form factors allow a smoother transition across $y = y_{\rm cut}$

CKKW: how it works

Start with three partons and compute y_{12}, y_{13}, y_{23}

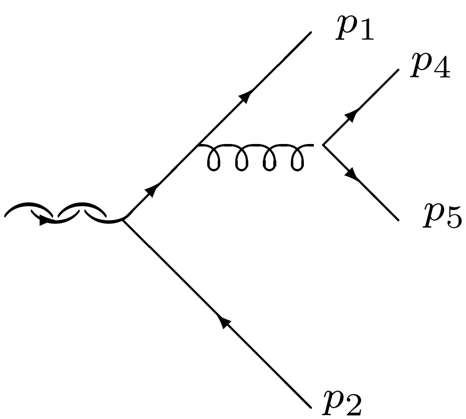


$y_{12},\ y_{13},\ y_{23} > y_{\rm cut}$**:**

generate three partons according to $|M_{q\bar{q}g}(p_1, p_2, p_3)|^2$

weighted by the Sudakov form factor $\Delta_q^2 \Delta_g$

Shower the event and generate one more branching (e.g. $g \to q\bar{q}$):



$y_{45} < y_{\rm cut}$**: accept the branching**

and continue the shower

$y_{45} > y_{\rm cut}$**: reject the branching**

to avoid double counting

It was proved that the results are independent of the choice of $y_{\rm cut}$

Extension to hadron collisions but NLL accuracy has not been proved
(F.Krauss, JHEP 08 (2002) 015)

SHERPA

(T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S. Schumann, J.-C. Winter, JHEP 02 (2004) 056)

It provides the framework for event generation, specific modules provide the physics content

Hard matrix elements: $2 \to 2$ amplitudes are computer analytically

Multipurpose parton-level generator AMEGIC++ generates $e^+e^- \to n$ partons ($n \leq 6$) and $2 \to 3$ QCD matrix elements

Clustering of jets using the k_T algorithm

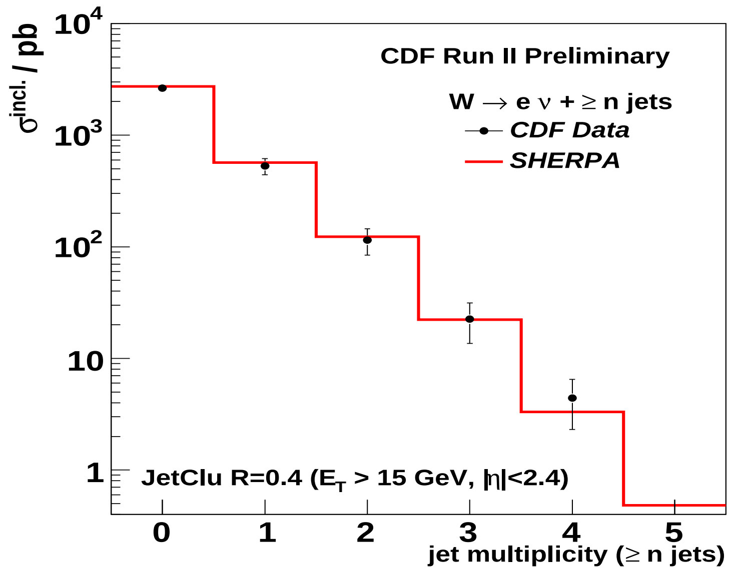
Parton showers (APACIC++): ordering in virtuality, with possible enforcement of angular ordering (like PYTHIA)

Hadronization: Lund string model

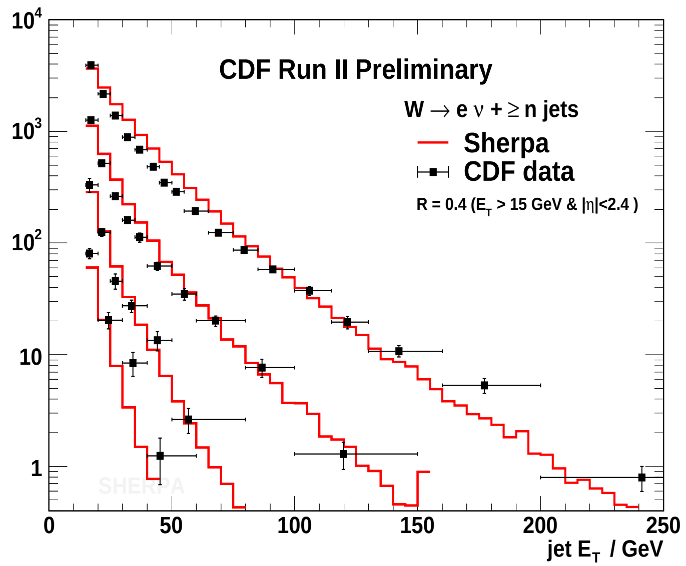
Matrix-element merging: CKKW method

Results with SHERPA: Jet multiplicity in $W + m$ jets, $m \geq n$ at the Tevatron

(G.Hesketh for D0 and CDF, hep-ex/0405067)



Jet transverse energy ($1st$ jet in $W + 1$ jet, $2nd$ jet in $W + 2$ jets, etc.)



MC@NLO (S. Frixione and B.R. Webber, JHEP06 (2002) 029)

NLO (real+virtual) hard scattering: parton showers and hadronization are taken from HERWIG

Identical to HERWIG in soft or collinear regions, and to NLO computations for hard or large-angle radiation

Main improvements: cross sections are NLO, predicted observables are NLO

It is based on a modification of the subtraction method to implement NLO calculations

Processes implemented in MC@NLO: single vector-boson, vector-boson pair, Higgs, heavy-quark pair, single top, $H + W/Z$ production at hadron colliders

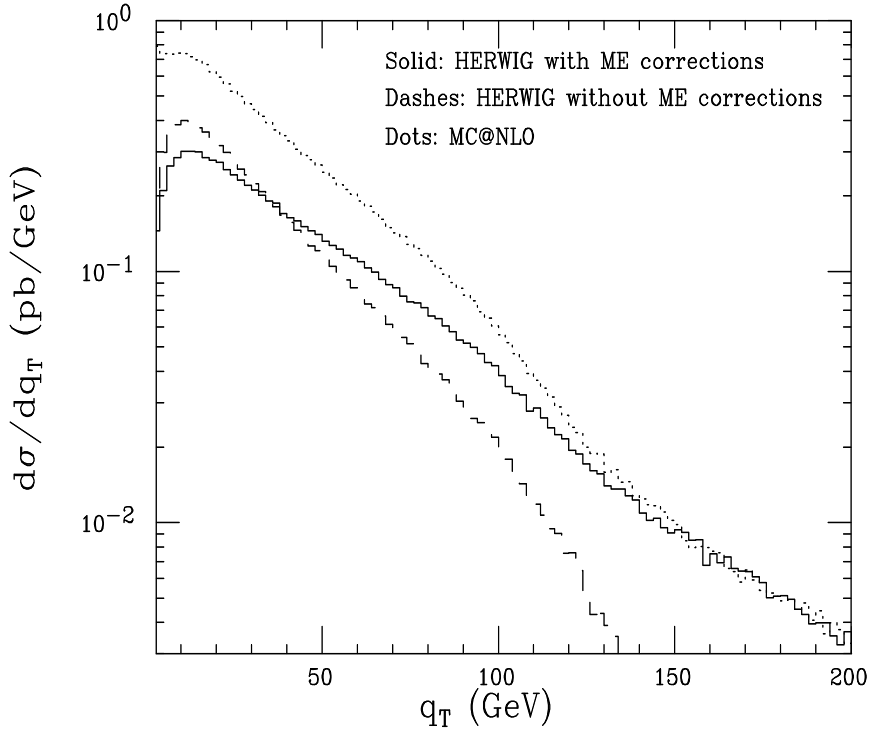
Contributions by E. Laenen, P. Motylinski and P. Nason

Comparison between MC@NLO and standard HERWIG

G.C. and S. Moretti, PLB 590 (2004) 249

Higgs production at the LHC: $pp \to H$ **,** $\sqrt{s} = 14$ **TeV**

Parton-level processes: $gg(q\bar{q}) \to H$ **,** $m_H = 115$ **GeV**



At large q_T real gluon radiation dominates: agreement with HERWIG provided with matrix-element corrections

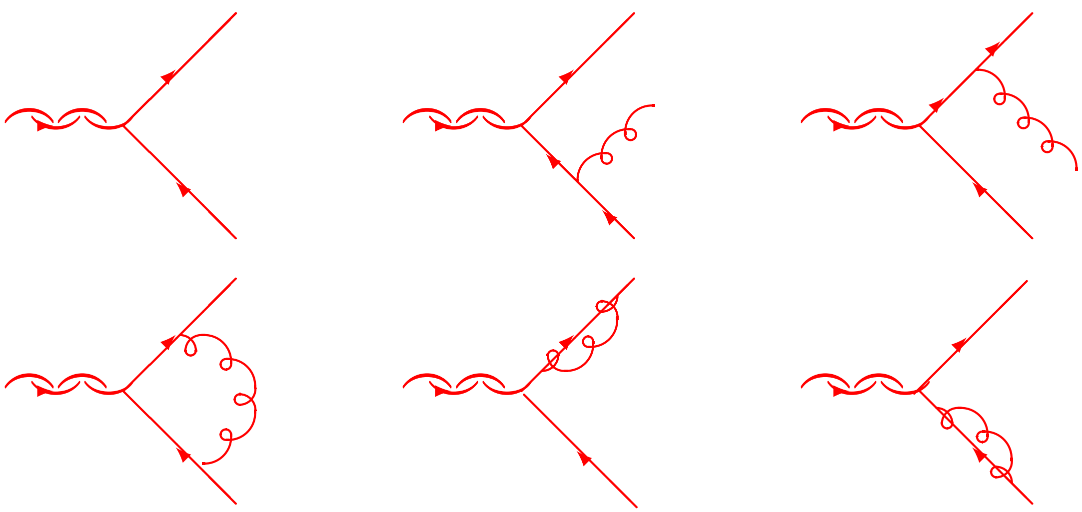
Difference at small q_T due to different normalization: LO in HERWIG, NLO in MC@NLO

Positive and negative weights

Monte Carlo programs like HERWIG or PYTHIA generate unweighted events, according to their natural distributions, i.e. z according $P(z)$ and Q^2 according to $\Delta_S(Q^2,Q_0^2)$, which are known

Tree level amplitudes are positive definite: positive weights (+1)

At NLO, a few generated events with a 2-body final state have negative weights, due to the $\mathcal{O}(\alpha_S)$ interference between Born and virtual graphs



$$|\mathcal{M}|^2 = |b+\alpha_S v|^2 + \alpha_S |r|^2$$

$$|b+\alpha_S v|^2 = |b|^2 + \alpha_S^2 |v|^2$$

$$+2\alpha_S [Re(b)Re(v)+Im(b)Im(v)]$$

Interference term is not positive definite

In MC@NLO, one gets negative weights, which are necessary to get NLO cross sections from differential distributions

They should be treated with weight -1 in histograms

Matrix-element Monte Carlo generators

(ALPGEN, MaDGraph/MadEvent, CompHEP, MCFM, GRACE, etc.)

Multi-parton leading-order matrix elements implement several tree-level processes (e.g. $W/Z+n$ jets), while parton-shower generators have multiple soft/collinear emissions and possibly only one hard parton

Efficient integration over the phase space

Event generation

Les Houches accord: interface to HERWIG or PYTHIA for parton showers and hadronization

ALPGEN

(M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A.D. Polosa, JHEP 0307 (2003) 001)

Generator of multiparton processes in hadronic collisions

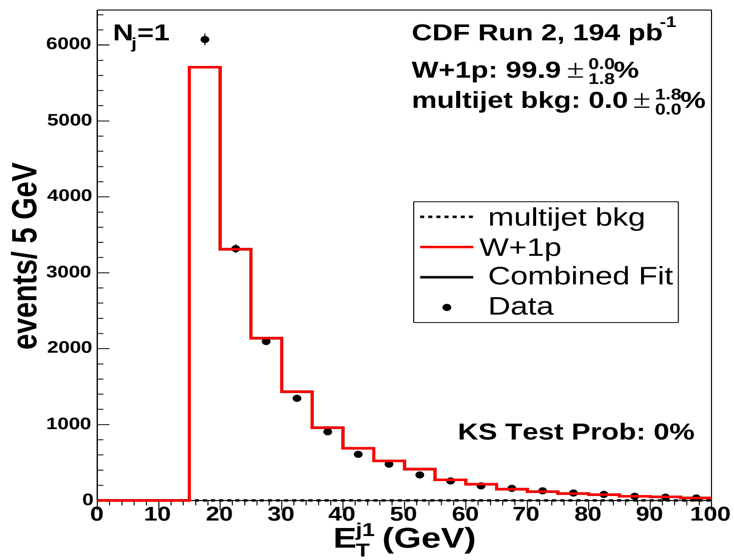
Leading order matrix elements, interfaced to HERWIG or PYTHIA for showering and hadronization

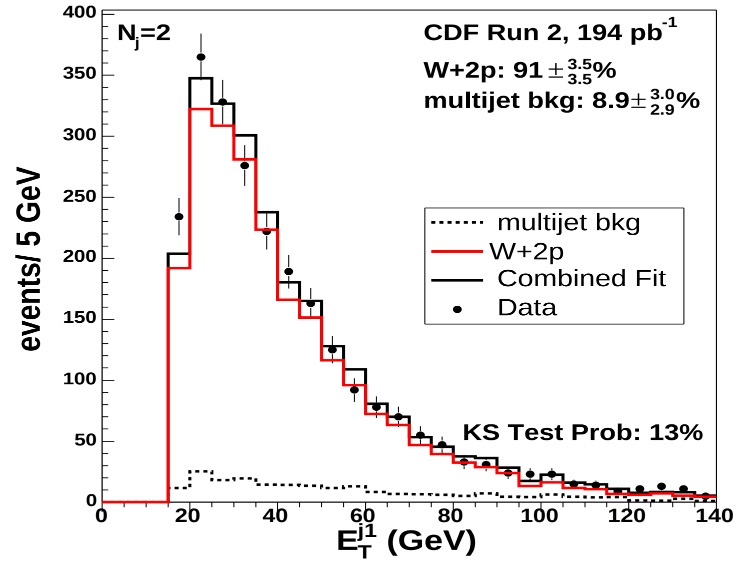
Available final states (q: light quark, Q: heavy quark, ℓ: lepton, $f = \ell, q$):

$(W \to f f')\ Q\bar{Q} + N$ jets, $N \leq 4$, $f = \ell, q$;
$(Z/\gamma^* \to \ell\bar{\ell})\ Q\bar{Q} + N$ jets, $N \leq 4$;
$(W \to f\bar{f}')+$ charm $+N$ jets, $N \leq 5$;
$(W \to f f') + N$ jets $(N \leq 6)$;
$(Z/\gamma^* \to \ell\bar{\ell}) + N$ jets $N \leq 6$;
$nW + mZ + lH + N$ jets $N \leq 3, n + m + l + N \leq 8$;
$Q\bar{Q} + N$ jets, $(t \to b f \bar{f}', N \leq 6)$;
$Q\bar{Q}Q'\bar{Q}' + N\ N \leq 4$;
$HQ\bar{Q} + N$ jets, $N \leq 4$;
N jets $N \leq 6$; $N\gamma + M$ jets, $N + M \leq 8$, $M \leq 6$

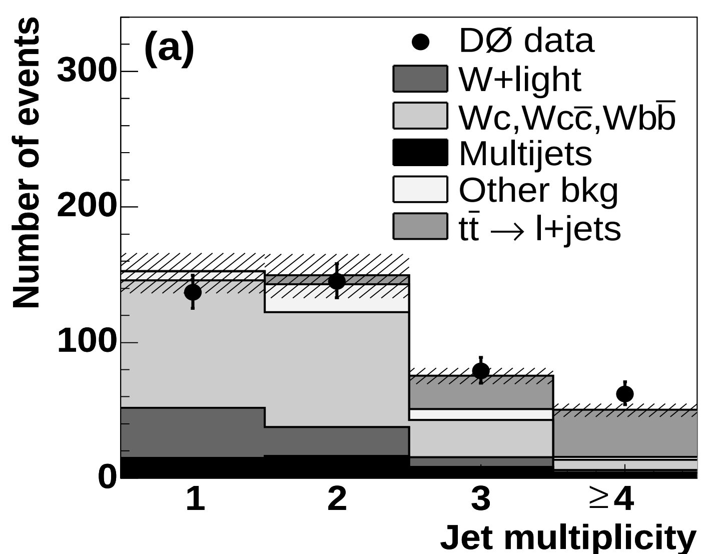
Comparison of ALPGEN with Tevatron data (hep-ex/0504053, hep-ex/0411084)

$W+1$ and $W+2$ jet from CDF, compared with ALPGEN+HERWIG, in $t\bar{t}$ events





D0 data on $W+$ jets in $t\bar{t}$ processes, compared with ALPGEN+PYTHIA



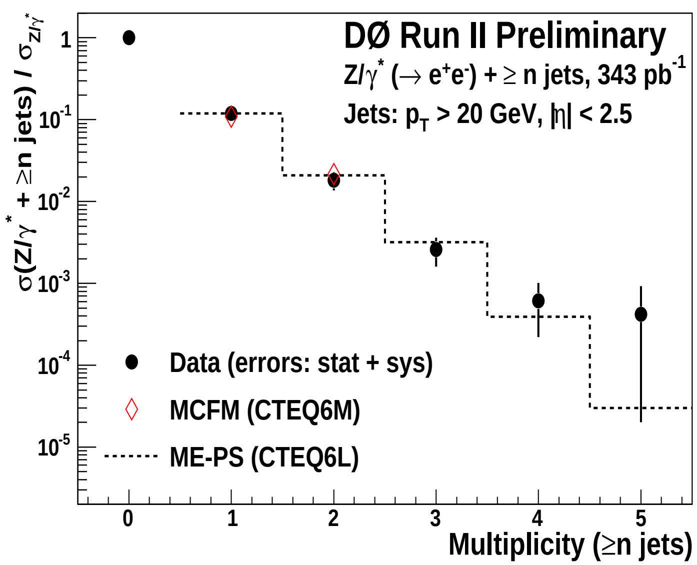
MadGraph and MadEvent

(T. Stelzer and W.F. Long, CPC 81 (1994) 357; F. Maltoni and T. Stelzer, JHEP 02 (2003) 027)

MadGraph calculates tree-level amplitudes using helicity amplitude methods (HELAS)

$e\nu_e + 4$ jets; $e^+e^- + 4$ jets; $e\nu_e b\bar{b} + 2$ jets; $e^+e^- b\bar{b} + 2$ jets; $W^+W^-, WZ, ZZ + 2$ jets

Comparison of MaDGraph (ME-PS) with D0 data on $Z+$ jets (D0 note 4794-CONF)



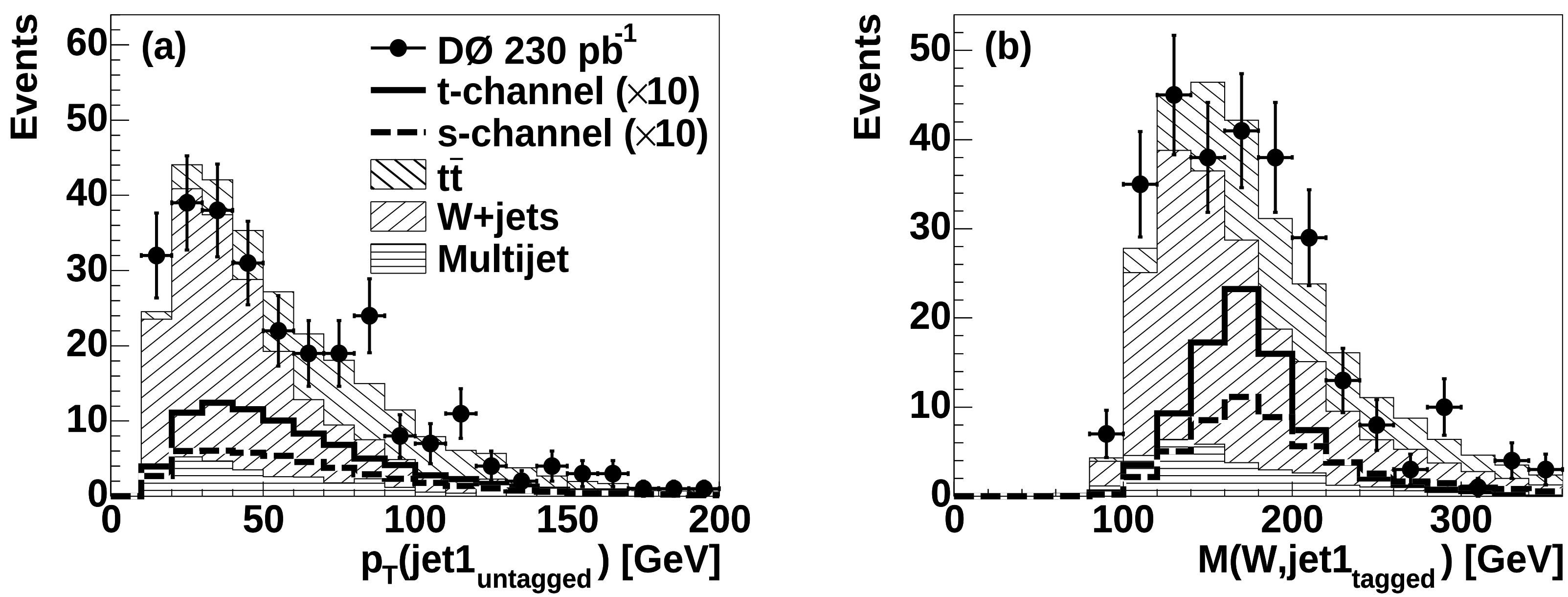
CompHEP

(E.Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Ilyin, A. Kryukov, V. Edneral, V. Savrin, A. Semenov, A. Sherstsnev)

Four models are implemented: QED, four-fermion electroweak interaction, Standard Model in unitary and Feynman gauges

LO $2 \to 2$ and tree-level $2 \to 3$ processes

Single-top searches at D0 (hep-ex/0505063): p_T of the leading untagged jet and the invariant mass of the top quark, using CompHEP for the signal



Workshop MC4LHC: comparisons of different Monte Carlo generators

Jet cross sections after cuts:

$p_{i,T} > 20$ GeV, $|\eta_i| < 2.5$, $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.4$ (table by F. Piccinini)

Cross sections in pb for $(Z/\gamma^* \to e^+e^-) + n$ jets

$e^+e^- + n$ QCD jets	0	1	2	3	4	5	6
ALPGEN	723.4(9)	188.3(3)	69.9(3)	27.2(1)	10.95(5)	4.6(1)	1.85(1)
SHERPA	723.9(7)	189.6(9)	71.4(4)	30(2)			
CompHEP	730.9(1)	190.20(7)	70.22(7)				
MadEvent	723(1)	188.6(3)	69.3(1)	27.1(2)	10.6(1)		
GR@APPA	744(7)	182.77(8)	67.70(3)				

Cross sections in pb for $(Z/\gamma^* \to e^+e^-) + b\bar{b} + n$ jets

$e^+e^- + b\bar{b} + n$ QCD jets	0	1	2	3	4
ALPGEN	18.95(8)	6.80(3)	3.13(2)	1.58(1)	0.80(1)
SHERPA	18.8(2)				
CompHEP	19.45(2)				
MadEvent	18.7(1)	6.72(2)	2.96(1)		

Good news: whenever a given process is implemented, the four compared generators agree

Conclusions

Parton showers (HERWIG, PYTHIA) in the soft or collinear approximation

Different ordering variables and hadronization models

Matrix-element corrections to parton showers allow one to generate hard and large-angle radiation (W/Z , Higgs at large q_T, top decay, etc.)

CKKW method allows matching for multi-jet events (SHERPA)

MC@NLO: observables and normalization are accurate at NLO

Matrix-element event generators of N-jet final states, interfaced to HERWIG or PYTHIA for showering and hadronization

Ongoing work to implement new processes within the existing programs, to extend CKKW matching in other generators, to convert codes in C++

There is no perfect tool for all kinds of analyses

Most likely, we will find Monte Carlo programs suitable for our studies

It is advisable using at least two codes for comparison