Jet evolution and Monte Carlo

Giuseppe Marchesini
Milan-Bicocca University

- jet radiation
- resummation and problem with confinement
- branching structure and Monte Carlo
- perspective

Asymptotic freedom (1973) $\Rightarrow$ perturbative QCD for hard collisions

Since the beginning: confinement/hadronization gives problems
if hadrons involved: collinear and infrared divergences

Strategy: stay inclusive

even in inclusive observables

$$e + p \to e' + X \qquad F(Q, x) \qquad Q^2 = -(p_e - p_{e'})^2 \qquad x = \frac{M_X^2 + Q^2}{Q^2}$$

$$e^+ e^- \to h + X \qquad D(Q, x) \qquad Q^2 = (p_{e^+} + p_{e^-})^2 \qquad x = \frac{2E_h}{Q}$$

Way to solve (forget) the problem: factorization of collinear divergences

Predict Q-evolution giving distribution at $Q = Q_0$
Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Description of jet radiation (jet-shape observables)

Observables in $e^+e^- \to p_1\,p_2 \cdots p_n$: $V = T,\ B,\ C,\ \rho,\ D,\ y_{ij},\ K_{\rm out},\ \cdots$

$$B = \sum_h \frac{p_{ht}}{Q}\,, \quad \tau = 1 - T = \sum_h \frac{p_{ht}\,e^{-|\eta_h|}}{Q}\,, \qquad \text{thrust axis : minimize } \tau$$

Different V probe QCD radiation in different regions (e.g. at different η_h)

$$\text{Distributions :} \qquad \Sigma(V) = \sum_n \int \frac{d\sigma_n}{\sigma_{\rm tot}}\,\Theta\left(V - \sum_h v_h\right)$$

Problem with confinement/hadronization?

-Collinear safe: $\vec{p}_i, \vec{p}_j$ parallel, then substitute with $\vec{p}_i + \vec{p}_j$

-IR safe: $p_i \ll p_j$ then neglect p_i

Then PT possible (all PT coefficients finite): hadron-flow $\simeq$ parton-flow

But PT expansion non-convergent (renormalon) due to large distance in $\alpha_s(k_t)$

Status of PT computation (and PT non-convergence)

Examples in e^+e^-: $V = \tau,\ B,\ C,\ \rho,\ D,\ K_{\rm out}\cdots \quad B = \sum_h \frac{p_{ht}}{Q}$

$$\text{Distribution:} \qquad \Sigma(V) = \sum_n \int \frac{d\sigma_n}{\sigma_{\rm tot}} \Theta\Big(V - \sum_h v_h\Big)$$

Resummation of collinear+IR logs for $V \ll 1 \quad (L = \ln V)$:

$$\ln \Sigma(V) = \sum_{n=1}^{\infty} \Big\{ d_n \alpha_s^n L^{n+1} + d_n \alpha_s^n L^n \cdots \Big\}, \qquad \Sigma_{\rm res.}(V) = e^{-R(V)} \cdot \mathcal{F}(\alpha_s L)$$

At least d_n (collinear+infrared) and s_n (collinear or infrared) needed

$R(V)$ Sudakov (universal), $\mathcal{F}$ SL function (observable dependent)

Exact: $\quad \Sigma_{\rm PT}(V) = a(V)\,\alpha_s + b(V)\,\alpha_s^2 \cdots$

Matching: $\quad \Sigma_{\rm PT}(V) = C(\alpha_s) \cdot \Sigma_{\rm res}(V) = a(V)\,\alpha_s + b(V)\,\alpha_s^2 \cdots$

PT result valid for V finite and small

But PT expansion non-convergent (renormalon) due to large distance in $\alpha_s(k_t)$

In PT evaluation $\alpha_s(k_t)$ enters $\Sigma(V)$ at any scale $0 < k_t < Q$

-physics: probe final state hadronization (at virtual level)
-mathematics: non-convergence of PT expansion (renormalon)

$$\langle V \rangle_{\rm PT} = \int_0^Q \alpha_s(k_t) \frac{dk_t}{k_t} \mathcal{V}\left(\frac{k_t}{Q}\right) \sim \int_0^Q \alpha_s(k_t) \frac{dk_t}{Q} \sim \sum_n n! \left(\frac{\beta_0}{4\pi}\right)^n \alpha_s^n$$

Prescription 1: Y.Dokshitzer,B.Webber,&GM, NPB469(96)93

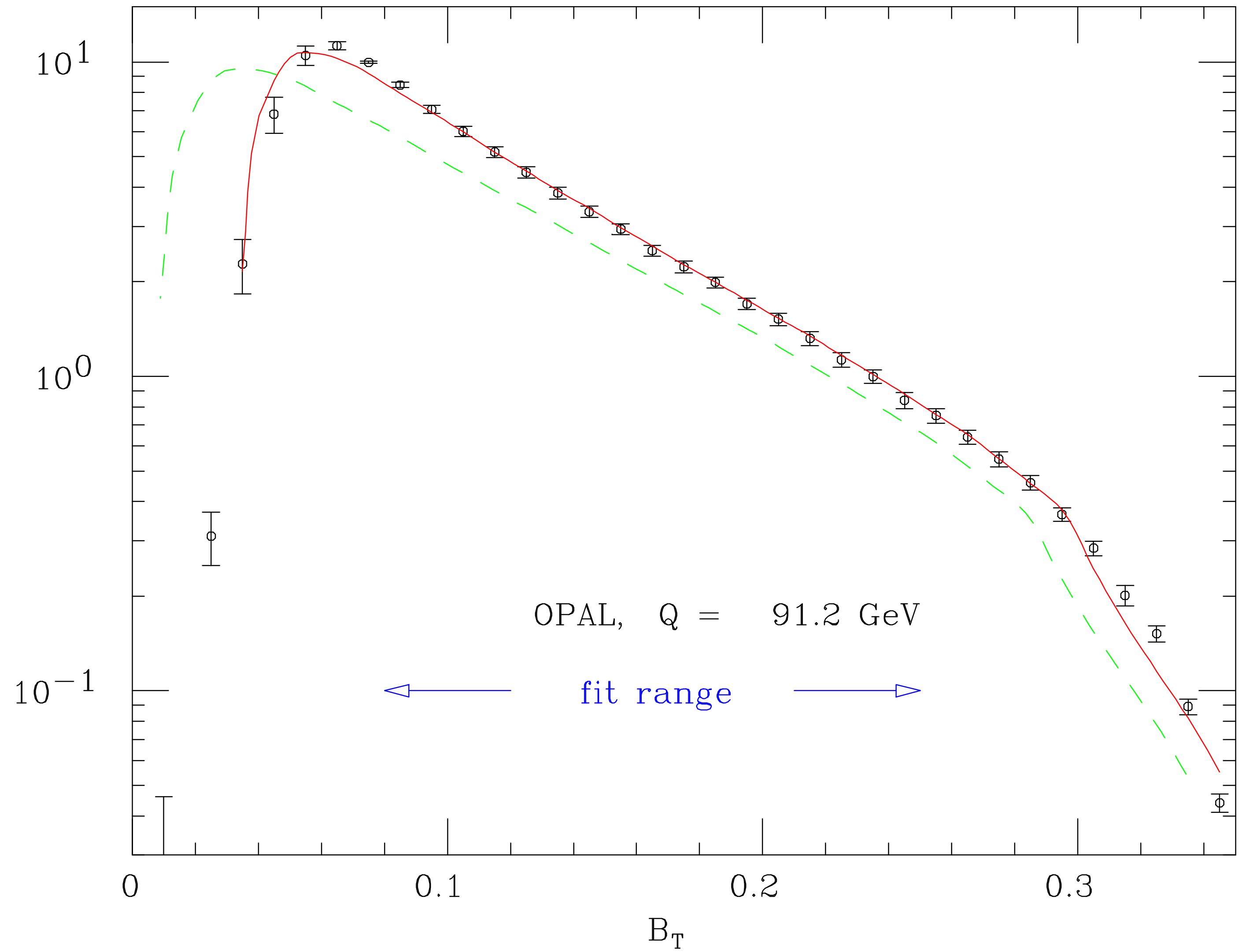
$$\alpha_0(\mu_I) = \int_0^{\mu_I} \frac{dk_t}{\mu_I} \alpha_s(k_t) \quad \langle V \rangle = \langle V \rangle_{\rm PT}^{(\ell)} + \frac{\mu_I}{Q} \left\{ C_V \, \alpha_0(\mu_I) + \sum_{n=1}^{\ell} \alpha_s^n \, A_V^{(n)} \right\}$$

-$n!$ renormalon cancels, μ_I-independence (RG invariance)
-NP parameter α_0 (renormalon ambiguity) observable independent

Similar analysis for $\Sigma(V)$: $\quad \Sigma(V) = \Sigma_{\rm PT}(V + \Delta V)\,, \quad \alpha_0(\mu_I) \to \Delta V$

Prescription 2: Shape function to modulate radiator at large distance
G.Korchemsky,G.Sternam, NPB437(95)415
E.Gardi,J.Rathsman, NPB609(01)123

Broadening in e^+e^-

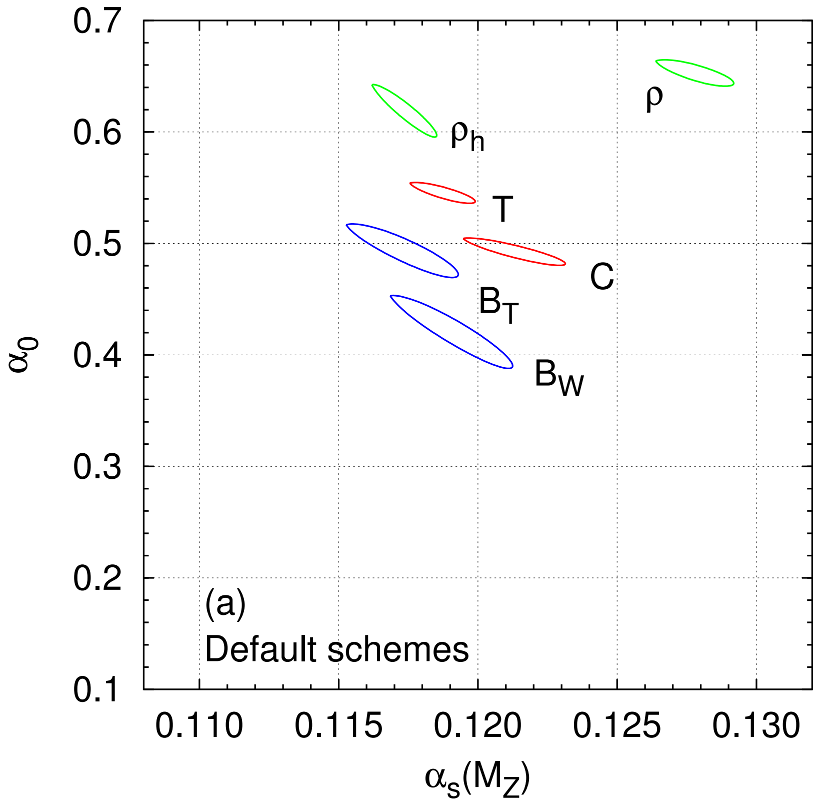


Y.Dokshitzer,G.Salam &GM, EPJ1(99)3

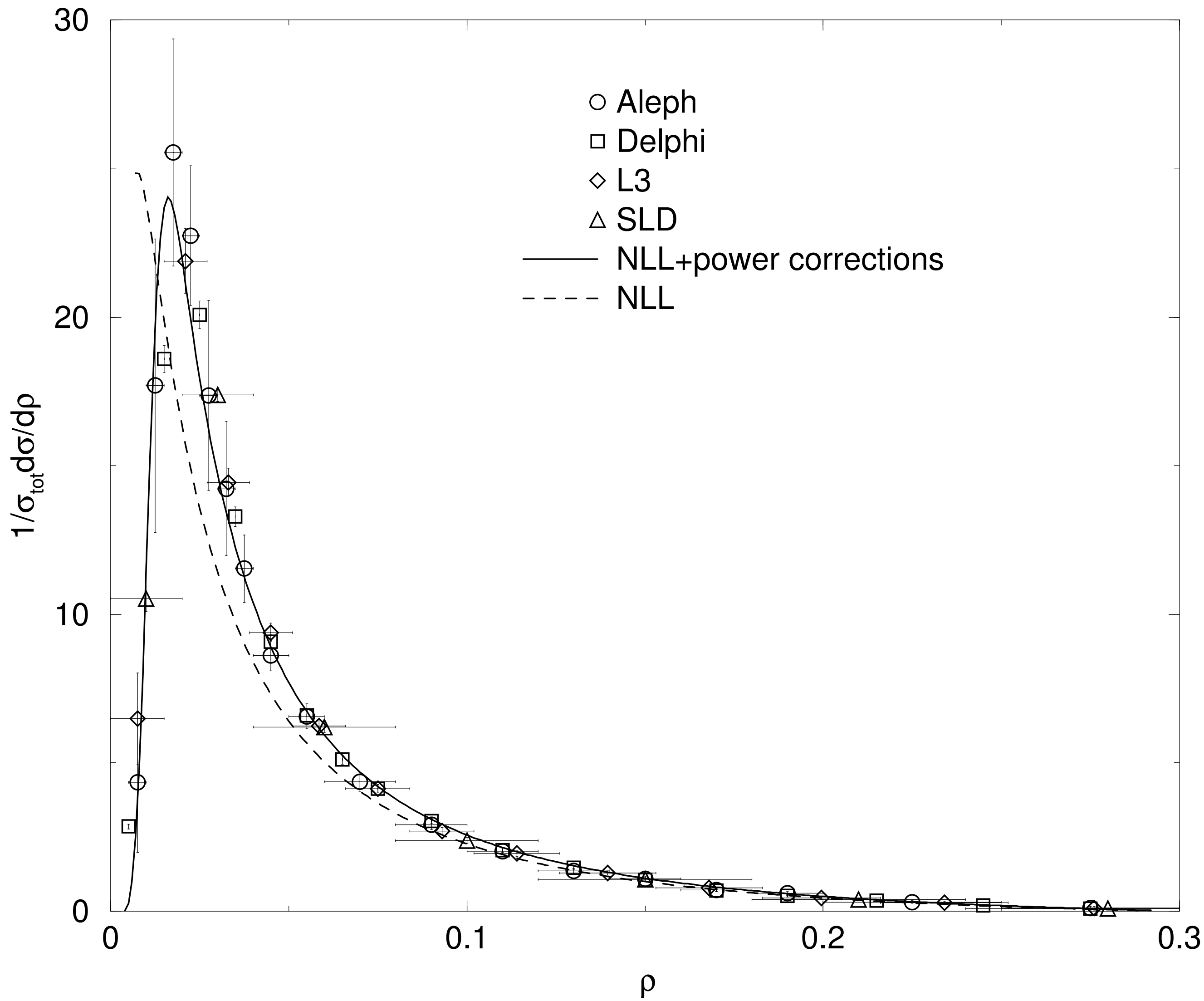
Testing universality

We can compare next-to-leading PT predictions plus NP contribution to data, fitting for α_s and α_0. If universality holds then both α_s and α_0 should be *independent of the observable.*

If we do it in e^+e^- we obtain (1-σ contours):



Heavy-jet-mass in e^+e^-

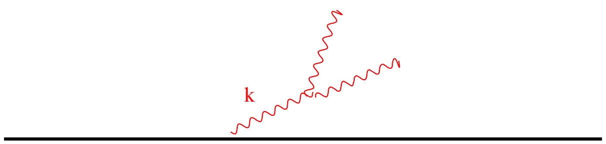


G.Korchemsky,S.Tafat, JHEP10(00)010

How to resum DL and SL (global jet-shale observables)

Method: factorization of (universal) collinear and IR pieces

Bremsstrahlung component:
Effective "independent emission"
DGLAP evolution $\longrightarrow$ Sudakov radiator



Branching:
relevant only for hard splitting $\longrightarrow \alpha_s(k_t)$

$$\Sigma_{\rm PT}(V) = e^{-R(V)} \cdot \mathcal{F}(\alpha_s \ln V)$$

New entry: non-global logs

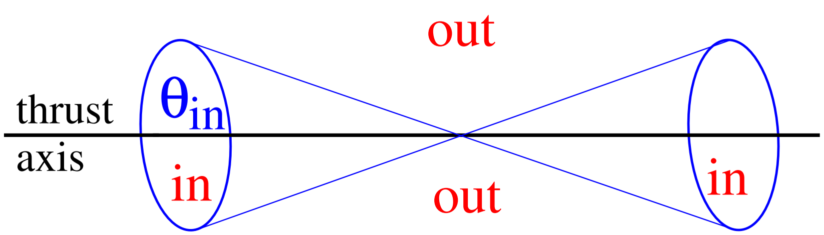
Jet-shape with only part of phase space involved

M.Dasgupta,G.Salam, PLB 512:323,2001, JHEP 3:017,2002

C.Berger,T.Kúcs,G.Sterman,PRD 65:094031,2002

A.Banfi,G.Smye&GM,JHEP 08:006,2002, Yuri Dokshitzer &GM, JHEP 03:040,2003

Simplest case: away-from-jet radiation in e^+e^-

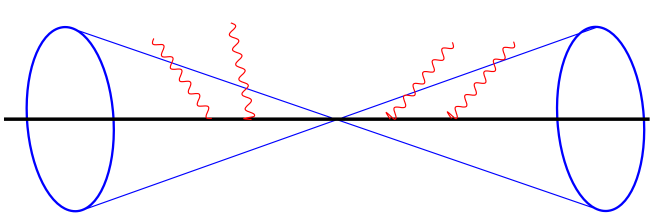


$$\Sigma_{e^+e^-} = \sum_n \int \frac{d\sigma_n}{\sigma_T} \, \Theta\left(E_{\rm out} - \sum_{\rm out} k_{ti}\right)$$

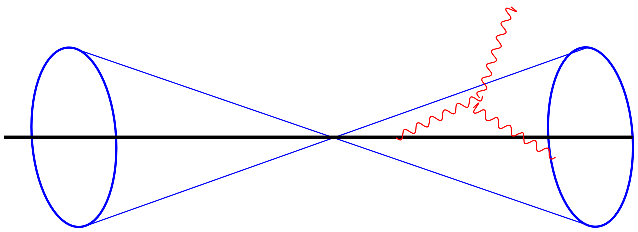
Many examples, e.g. Sterman-Weinberg distribution (energy in a cone)

Large angle soft emission (no collinear singularities involved)

Two components (soft radiation in out)



Bremsstrahlung component:
DGLAP $\longrightarrow$ $S_{q\bar{q}}$ (Sudakov factor)



Branching inside jet region
soft g-splitting $\longrightarrow$ $C_{q\bar{q}}$ correlation

$$\Sigma_{e^+e^-} = S_{q\bar{q}}(\tau, \theta_{\text{in}}) \cdot C_{q\bar{q}}(\tau, \theta_{\text{in}}), \qquad \tau = \int_{E_{\text{out}}}^{Q} \frac{dk_t}{k_t} \frac{N_c \alpha_s(k_t)}{\pi}$$

Basis for calculation: multi-soft-gluon distribution

-numerical study M.Dasgupta,G.Salam, JHEP 03(02)017

-analytical evolution equation Banfi,Smye&GM JHEP 08(02)006

Multi-soft-gluon distribution (large N_c)

A.Bassetto,M.Ciafaloni&GM, Phys.Rep. 100(83)201

$$\gamma^* \to q\bar{q}g_1\cdots g_n \qquad \mathcal{M}_n(p\bar{p}q_1\cdots q_n) = \sum_{\text{perm.}} \{\lambda^{a_{i_1}}\cdots\lambda^{a_{i_n}}\}_{\beta\bar{\beta}}\, M_n(i_1\cdots i_n)$$

Soft limit: factorization $\Rightarrow$ recurrent relation

$$M_n(\cdots\ell\, n\, \ell'\cdots) = g_s\, M_{n-1}(\cdots\ell\ell'\cdots)\cdot\left(\frac{q_\ell^\mu}{(q_\ell q_n)} - \frac{q_{\ell'}^\mu}{(q_{\ell'} q_n)}\right), \quad q_n \text{ softest gluon}$$

Distribution (colour and polarization sum, leading N_c)

$$|\mathcal{M}_n|^2 = \sum_{\text{perm.}} (N_c\alpha_s)^n\, W_{p\bar{p}}(i_1\cdots i_n), \qquad W_{ab}(1\cdots n) = \frac{(ab)}{(aq_1)\cdots(q_n b)}$$

In pure Yang-Mills $\Rightarrow$ Parke-Taylor MHV amplitude

Generating functional (soft and planar limit)

Introduce source $u(q)$ for each soft gluon

$$\Sigma_{ab}(Q,u)=\sum_n\int\frac{d\sigma_n}{\sigma_T}\prod_i u(q_i), \quad \frac{d\sigma_n}{\sigma_T}\simeq\prod_i\left\{\frac{dq_{ti}}{q_{ti}}\frac{d\Omega_{q_i}}{4\pi}\,u(q_i)\,\bar{\alpha}_s\right\}\cdot W_{ab}(1...n)$$

Use factorization structure of multi-soft gluon distribution

$$W_{ab}(1...n) = \frac{(ab)}{(a\ell)(\ell b)}W_{a\ell}(1...\ell-1)\cdot W_{\ell b}(\ell+1...n) \qquad (ij) = 1-\cos\theta_{ij}$$

Obtain evolution equation $(\bar{\alpha}_s = N_c\alpha_s/\pi)$ Banfi,Smye&GM,JHEP08:006,2002

$$Q\partial_Q\Sigma_{ab} = \bar{\alpha}_s\int\frac{d\Omega_q}{4\pi}\frac{(ab)}{(aq)(qb)}\left[u(q)\,\Sigma_{aq}\cdot\Sigma_{qb}-\Sigma_{ab}\right]$$

Include virtual corrections (Cauchy integration): IR cancellation $(\Sigma(Q,u\!=\!1)\!=\!1)$

QCD Monte Carlo simulation:

$$Q\partial_Q \Sigma_{ab} = \bar{\alpha}_s \int \frac{d\Omega_q}{4\pi} \frac{(ab)}{(aq)(qb)} \left[u(q)\, \Sigma_{aq} \cdot \Sigma_{qb} - \Sigma_{ab} \right]$$

can be numerically solved:

Split real-virtual and introduce Sudakov (cutoff Q_0 needed)

$$\ln S_{ab}(E) = -\int_{Q_0}^{E} \bar{\alpha}_s \frac{dE_q}{E_q} \int \frac{d\Omega_q}{4\pi} \frac{(ab)}{(aq)(qb)} \cdot \theta(k_{tab} - Q_0)$$

Introduce probability for dipole branching: $(ab) \to (aq)\,(qb), \;\; E \to E_q$

$$d\mathcal{P}(E_q, \Omega_q) = \bar{\alpha}_s \frac{dE_q}{E_q} \cdot \frac{d\Omega_q}{4\pi} \frac{(ab)}{(aq)(qb)} \cdot \frac{S_{ab}(E)}{S_{ab}(E_q)} \cdot \theta(k_{tab} - Q_0)$$

Leading soft gluon emission (no recoil): $P_{g\to gg}(z) = N_c \left(\frac{1}{z} + \frac{1}{1-z} + z(1-z) - 2 \right)$

Improve QCD Monte Carlo simulation:

- account for full collinear structure:
  - hard parton parton recoil (full large angle soft emission still missing)
  - include result terms in splitting function $g \to gg$
  - include other channels $g \to q\bar{q}$ and $q \to qg$
- apply to all hard processes (using collinear factorization)
  - e^+e^- annihilation
  - lepton-hadron DIS
  - hadron-hadron (largeE_T)
- include EW processes and beyond (using collinear factorization)
- account for some small-x physics results
- account for NLO and NNLO exact results

Result: partons (+EW particles) emission, no hadrons

Only partons, no hadrons

Preconfinement (D.Amati, G.Veneziano, PL83(79)87)

Sudakov suppression in mass of colour connected partons:

$\longrightarrow$ colour connected partons at small mass
$\longrightarrow$ small mass colour singlet $\longrightarrow$ hadronization model

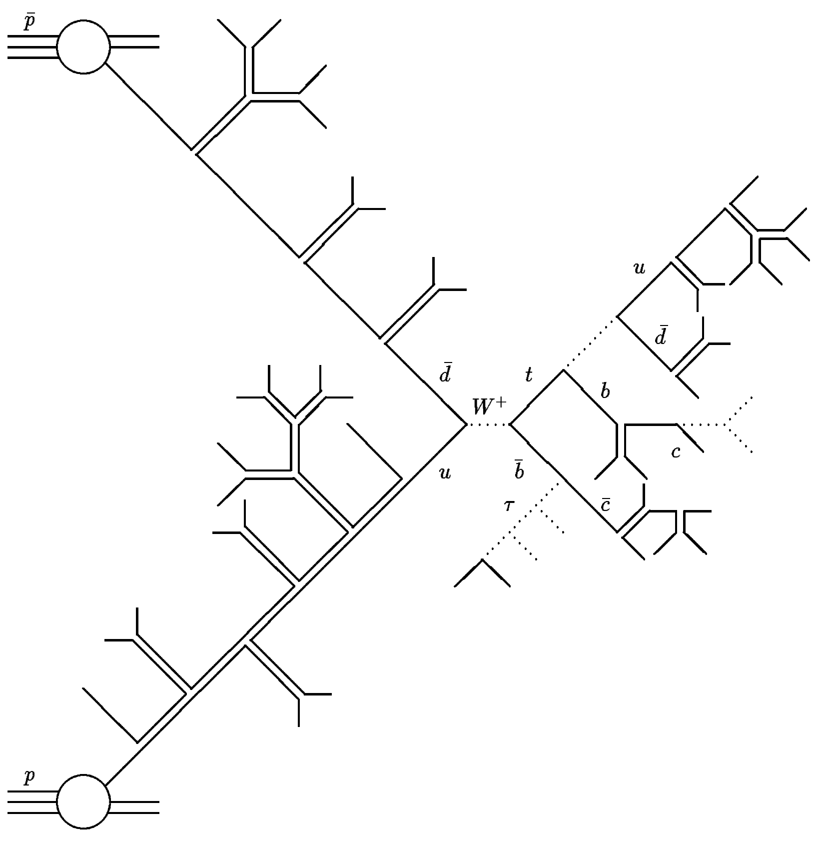
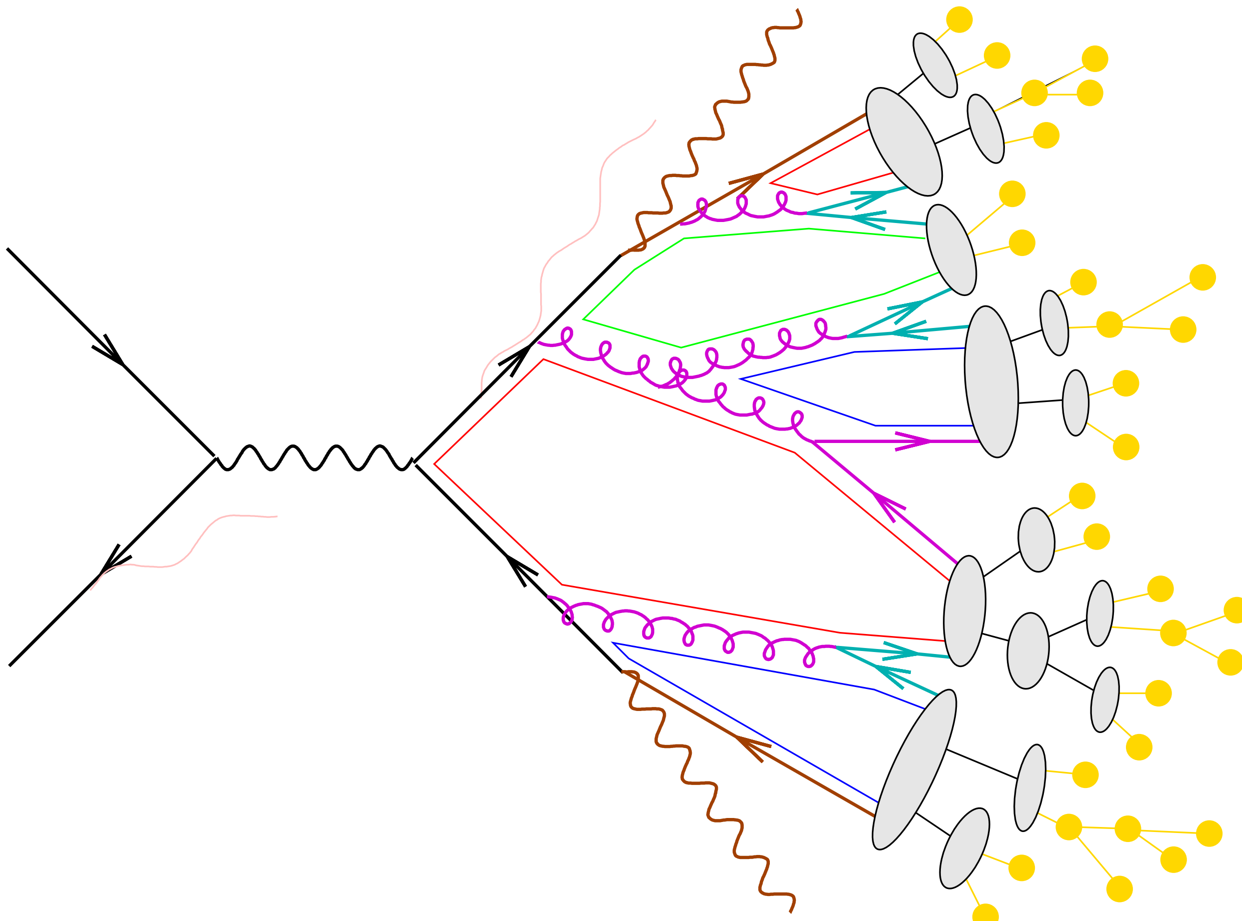


Figure 1: Colour structure of a $\bar{p}p \to W^+ + X$, $W^+ \to t\bar{b}$ event.

results not too sensitive
to hadronization model

Cluster Hadronization Model



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\to$ hadrons
- hadronic decays

QCD Monte Carlo simulation:

e^+e^-annihilation
lepton-hadron DIS
hadron-hadron (largeE_T)

- Herwig (B.Webber&GM, 1984): $e^+e^-,\ \ell-$h and h-h
- Pythia (T.Sjostrand 1986): $e^+e^-,\ \ell-$h and h-h
- Ariadna (L. Lonnblad 1992): e^+e^- mostly
- others for specific processes

Continuous upgrading: new theoretical, phenomenological and experimental results

An option to damp the parton distributions of off mass-shell photons relative to on-shell photons, according to the scheme of Drees and Godbole [52] has been introduced. The adjustable parameter `PHOMAS` defines the crossover from the non-suppressed to suppressed regimes. Recommended values lie in the range from `QCDLAM` to 1 GeV. The default value `PHOMAS`=0 corresponds to no suppression, as in previous versions.

4.2 Summary of subprocesses

We give here a list of the currently available hard subprocesses `IPROC`. More detailed descriptions are given in Sects. 4.3–4.12, and then in Sect. 4.13 there are instructions to users on how to add a new process.

`IPROC`	Process
100	$\ell^+\ell^- \to q\bar{q}(g)$ (all q flavours)
100+`IQ`	$\ell^+\ell^- \to q\bar{q}(g)$ (`IQ` $=1,2,3,4,5,6$ for $q=d,u,s,c,b,t$)
107	$\ell^+\ell^- \to gg(g)$ (fictitious process)
110	$\ell^+\ell^- \to q\bar{q}g$ (all flavours)
110+`IQ`	$\ell^+\ell^- \to q\bar{q}g$ (`IQ` as above)
120	$\ell^+\ell^- \to q\bar{q}$ (all flavours, no hard gluon correction)
120+`IQ`	$\ell^+\ell^- \to q\bar{q}$ (`IQ` as above, no hard gluon correction)
127	$\ell^+\ell^- \to gg$ (fictitious process, no hard gluon correction)
150+`IL`	$\ell^+\ell^- \to \ell'\bar{\ell}'$ (`IL` $=1,2,3$ for $\ell=e,\mu,\tau$, N.B. $\ell\neq\ell'$)
200	$\ell^+\ell^- \to W^+W^-$ (see Sect. 4.3.2 on control of W/Z decays)
250	$\ell^+\ell^- \to Z^0Z^0$ (see Sect. 4.3.2 on control of W/Z decays)
300	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0q\bar{q}$ (all flavours)
300+`IQ`	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0q\bar{q}$ (`IQ` as above)
306+`IL`	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0\ell\bar{\ell}$ (`IL` as above)
310, 311	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0W^+W^-$, $Z^0Z^0Z^0$
312	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0\gamma\gamma$
399	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0$ anything
400+`ID`	$\ell^+\ell^- \to \nu\bar{\nu}H^0_{\rm SM} + \ell^+\ell^-H^0_{\rm SM}$ (`ID` as in `IPROC` $=300+$ `ID`)
500+`ID`	$\ell^+\ell^- \to \ell^+\ell^-\gamma\gamma \to \ell^+\ell^-q\bar{q}/\ell\bar{\ell}/W^+W^-$ (`ID`=0–10 as in `IPROC` $=300+$ `ID`)
550+`ID`	$\ell^+\ell^- \to \ell\nu_\ell\gamma W \to \ell\nu_\ell q\bar{q}'/\ell\bar{\ell}'$ (`ID`=0–9 as in `IPROC` $=300+$ `ID`))
600	$\ell^+\ell^- \to q\bar{q}gg, q\bar{q}q'\bar{q}'$ (all q flavours)
600+`IQ`	$\ell^+\ell^- \to q\bar{q}gg, q\bar{q}q'\bar{q}'$ (`IQ` as above)
	After generation, `IHPRO` is subprocess (see Sect. 4.3.5)

Available processes

IPROC	Process
700-99	Minimal Supersymmetric Standard Model (MSSM) processes
700	$\ell^+\ell^- \to$ 2-sparticle processes (sum of 710, 730, 740 and 760)
710	$\ell^+\ell^- \to$ neutralino pairs (all neutralinos)
706+4IN1+IN2	$\ell^+\ell^- \to \tilde\chi^0_{\rm IN1}\tilde\chi^0_{\rm IN2}$ (IN1,2=neutralino mass eigenstate)
730	$\ell^+\ell^- \to$ chargino pairs (all charginos)
728+2IC1+IC2	$\ell^+\ell^- \to \tilde\chi^+_{\rm IC1}\tilde\chi^-_{\rm IC2}$ (IC1,2=chargino mass eigenstate)
740	$\ell^+\ell^- \to$ slepton pairs (all flavours)
736+5IL	$\ell^+\ell^- \to \tilde\ell_{L,R}\tilde\ell^*_{L,R}$ (IL $= 1,2,3$ for $\tilde\ell = \tilde e, \tilde\mu, \tilde\tau$)
737+5IL	$\ell^+\ell^- \to \tilde\ell_L\tilde\ell^*_L$ (IL as above)
738+5IL	$\ell^+\ell^- \to \tilde\ell_L\tilde\ell^*_R$ (IL as above)
739+5IL	$\ell^+\ell^- \to \tilde\ell_R\tilde\ell^*_R$ (IL as above)
740+5IL	$\ell^+\ell^- \to \tilde\nu_L\tilde\nu^*_L$ (IL $= 1,2,3$ for $\tilde\nu_e, \tilde\nu_\mu, \tilde\nu_\tau$)
760	$\ell^+\ell^- \to$ squark pairs (all flavours)
757+4IQ	$\ell^+\ell^- \to \tilde q_{L,R}\tilde q^*_{L,R}$ (IQ $= 1,2,3,4,5,6$ for $\tilde q = \tilde d, \tilde u, \tilde s, \tilde c, \tilde b, \tilde t$)
758+4IQ	$\ell^+\ell^- \to \tilde q_L\tilde q^*_L$ (IQ as above)
759+4IQ	$\ell^+\ell^- \to \tilde q_L\tilde q^*_R$ (IQ as above)
760+4IQ	$\ell^+\ell^- \to \tilde q_R\tilde q^*_R$ (IQ as above)
800-99	R-parity violating supersymmetric processes
800	Single sparticle production, sum of 810–840
810	$\ell^+\ell^- \to \tilde\chi^0\nu_i$, (all neutralinos)
810+IN	$\ell^+\ell^- \to \tilde\chi^0_{\rm IN}\nu_i$, (IN=neutralino mass state)
820	$\ell^+\ell^- \to \tilde\chi^- e^+_i$ (all charginos)
820+IC	$\ell^+\ell^- \to \tilde\chi^-_{\rm IC} e^+_i$, (IC=chargino mass state)
830	$\ell^+\ell^- \to \tilde\nu_i Z^0$ and $\ell^+\ell^- \to \tilde\ell^+_i W^-$
840	$\ell^+\ell^- \to \tilde\nu_i h^0/H^0/A^0$ and $\ell^+\ell^- \to \tilde\ell^+_i H^-$
850	$\ell^+\ell^- \to \tilde\nu_i\gamma$
860	Sum of 870 and 880
870	$\ell^+\ell^- \to \ell^+\ell^-$, via LLE only
867+3IL1+IL2	$\ell^+\ell^- \to \ell^+_{\rm IL1}\ell^-_{\rm IL2}$ (IL1,2=1,2,3 for e, μ, τ)
880	$\ell^+\ell^- \to \bar d d$, via LLE and LQD
877+3IQ1+IQ2	$\ell^+\ell^- \to d_{\rm IL1}\bar d_{\rm IL2}$ (IQ1,2=1,2,3 for d, s, b)
1300	$q\bar q \to Z^0/\gamma \to q'\bar q'$ (all flavours)
1300+IQ	$q\bar q \to Z^0/\gamma \to q'\bar q'$ (IQ $= 1,2,3,4,5,6$ for $q = d, u, s, c, b, t$)
1350	$q\bar q \to Z^0/\gamma \to \ell\bar\ell$ (all lepton species)
1350+IL	$q\bar q \to Z^0/\gamma \to \ell\bar\ell$ (IL $= 1 - 6$ for $\ell = e, \nu_e, \mu, \nu_\mu$, etc.)
1399	$q\bar q \to Z^0/\gamma \to$ anything
1400	$q\bar q \to W^\pm \to q'\bar q''$ (all flavours)
1400+IQ	$q\bar q \to W^\pm \to q'\bar q''$ (q' or q'' as above)
1450	$q\bar q \to W^\pm \to \ell\nu_\ell$ (all lepton species)
1450+IL	$q\bar q \to W^\pm \to \ell\nu_\ell$ (IL $= 1,2,3$ for $\ell = e, \mu, \tau$)
1499	$q\bar q \to W^\pm \to$ anything
1500	QCD $2 \to 2$ hard parton scattering
	After generation, IHPRO is subprocess (see Sect. 4.6.2)

IPROC	Process
1600+ID	$gg/q\bar q \to H^0_{\rm SM}$ (ID as in IPROC $= 300 +$ ID)
1700+IQ	QCD heavy quark production (IQ as above)
	After generation, IHPRO is subprocess (see Sect. 4.6.2)
1800	QCD direct photon + jet production
	After generation, IHPRO is subprocess (see Sect. 4.6.5)
1900+ID	$q\bar q \to q'\bar q' W^+W^-/Z^0Z^0 \to q'\bar q' H$ (ID as in IPROC $= 300 +$ ID)
2000	t production via $W^\pm$ exchange (sum of 2001–2008)
2001–4	$\bar u\bar b \to \bar d\bar t$, $d\bar b \to u\bar t$, $\bar d\bar b \to \bar u\bar t$, $ub \to dt$
2005–8	$\bar c\bar b \to \bar s\bar t$, $s\bar b \to c\bar t$, $\bar s b \to \bar c t$, $cb \to st$
2100	$W^\pm$ + jet production
2110	$W^\pm$ + jet production (Compton only: $gq \to Wq$)
2120	$W^\pm$ + jet production (annihilation only: $q\bar q \to Wg$)
2150	Z^0 + jet production
2160	Z^0 + jet production (Compton only: $gq \to Zq$)
2170	Z^0 + jet production (snnihilation only: $q\bar q \to Zg$)
2200	QCD direct photon pair production
	After generation, IHPRO is subprocess (see Sect. 4.6.5)
2300+ID	QCD SM Higgs + jet production (ID as in IPROC=300+ID)
	After generation, IHPRO is subprocess (see Sect. 4.6.10)
2400	Mueller-Tang colour singlet exchange
2450	Quark scattering via photon exchange
2500+ID	$gg/q\bar q \to t\bar t H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2600+ID	$q\bar q' \to W^\pm H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2700+ID	$q\bar q \to Z^0 H^0_{\rm SM}$ (ID as in IPROC=300+ID)
3000-999	Minimal Supersymmetric Standard Model (MSSM) processes
3000	2-parton $\to$ 2-sparticle processes (sum of those below)
3010	2-parton $\to$ 2-sparton processes
3020	2-parton $\to$ 2-gaugino processes
3030	2-parton $\to$ 2-slepton processes
3310,3315	$q\bar q' \to W^\pm h^0, H^\pm h^0$ (all q, q' flavours – gauge bosons mediated only)
3320,3325	$q\bar q' \to W^\pm H^0, H^\pm H^0$ (")
3335	$q\bar q' \to H^\pm A^0$ (")
3350	$q\bar q \to W^\pm H^\mp$ (Higgstrahlung and Higgs mediated)
3355	$q\bar q \to H^\pm H^\mp$ (all q flavours – gauge bosons mediated only)
3360,3365	$q\bar q \to Z^0 h^0, A^0 h^0$ (")
3370,3375	$q\bar q \to Z^0 H^0, A^0 H^0$ (")
3410	$bg \to b\ h^0$ + ch. conj.
3420	$bg \to b\ H^0$ + ch. conj.
3430	$bg \to b\ A^0$ + ch. conj.
3450	$bg \to t\ H^-$ + ch. conj.
3610	$q\bar q/gg \to h^0$ (light scalar Higgs)
3620	$q\bar q/gg \to H^0$ (heavy scalar Higgs)
3630	$q\bar q/gg \to A^0$ (pseudoscalar Higgs)

IPROC	Process
4000-99	R-parity violating supersymmetric processes via LQD
4000	single sparticle production, sum of 4010–4050
4010	$\bar{u}_j d_k \to \tilde{\chi}^0 l_i^-$, $\bar{d}_j d_k \to \tilde{\chi}^0 \nu_i$ (all neutralinos)
4010+IN	$\bar{u}_j d_k \to \tilde{\chi}^0_{\rm IN} l_i^-$, $\bar{d}_j d_k \to \tilde{\chi}^0_{\rm IN} \nu_i$ (IN=neutralino mass state)
4020	$\bar{u}_j d_k \to \tilde{\chi}^- \nu_i$, $\bar{d}_j d_k \to \tilde{\chi}^- e_i^+$ (all charginos)
4020+IC	$\bar{u}_j d_k \to \tilde{\chi}^-_{\rm IC} \nu_i$, $\bar{d}_j d_k \to \tilde{\chi}^-_{\rm IC} e_i^+$ (IC=chargino mass state)
4040	$u_j \bar{d}_k \to \tilde{\tau}_i^+ Z^0$, $u_j \bar{d}_k \to \tilde{\nu}_i W^+$ and $d_j \bar{d}_k \to \tilde{\ell}_i^+ W^-$
4050	$u_j \bar{d}_k \to \tilde{\ell}_i^+ h^0/H^0/A^0$, $u_j \bar{d}_k \to \tilde{\nu}_i H^+$ and $d_j \bar{d}_k \to \tilde{\ell}_i^+ H^-$
4060	Sum of 4070 and 4080
4070	$\bar{u}_j d_k \to \bar{u}_l d_m$ and $\bar{d}_j d_k \to \bar{d}_l d_m$, via LQD only
4080	$\bar{u}_j d_k \to \nu_j l_k^-$ and $\bar{d}_j d_k \to l_j^+ l_k^-$, via LQD and LLE
4100-99	R-parity violating supersymmetric processes via UDD
4100	single sparticle production, sum of 4110–4150
4110	$u_i d_j \to \tilde{\chi}^0 \bar{d}_k$, $d_j d_k \to \tilde{\chi}^0 \bar{u}_i$ (all neutralinos)
4110 +IN	$u_i d_j \to \tilde{\chi}^0_{\rm IN} \bar{d}_k$, $d_j d_k \to \tilde{\chi}^0_{\rm IN} \bar{u}_i$(IN as above)
4120	$u_i d_j \to \tilde{\chi}^+ \bar{u}_k$, $d_j d_k \to \tilde{\chi}^- \bar{d}_i$ (all charginos)
4120 +IC	$u_i d_j \to \tilde{\chi}^+_{\rm IC} \bar{u}_k$, $d_j d_k \to \tilde{\chi}^-_{\rm IC} \bar{d}_i$ (IC as above)
4130	$u_i d_j \to \tilde{g} \bar{d}_k$, $d_j d_k \to \tilde{g} \bar{u}_i$
4140	$u_i d_j \to \tilde{b}_1^* Z^0$, $d_j d_k \to \tilde{t}_1^* Z^0$, $u_i d_j \to \tilde{t}_i^* W^+$ and $d_j d_k \to \tilde{b}_i^* W^-$
4150	$u_i d_j \to \tilde{d}_{k1}^* h^0/H^0/A^0$, $d_j d_k \to \tilde{u}_{i1}^* h^0/H^0/A^0$, $u_i d_j \to \tilde{u}_{k\alpha}^* H^+$, $d_j d_k \to \tilde{d}_{i\alpha}^* H^-$
4160	$u_i d_j \to u_l d_m$, $d_j d_k \to d_l d_m$ via UDD.
4200-99	Graviton resonance production
4200	Sum of 4210, 4250 and 4270
4210	$gg/q\bar{q} \to G \to gg/q\bar{q}$ (all partons)
4210+IQ	$gg/q\bar{q} \to G \to q\bar{q}$ (IQ as above)
4220	$gg/q\bar{q} \to G \to gg$
4250	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (all leptons)
4250+IL	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ ($\mathtt{IL} = 1-6$ for $\ell = e, \nu_e, \mu, \nu_\mu$, etc.)
4260	$gg/q\bar{q} \to G \to \gamma\gamma$
4270	$gg/q\bar{q} \to G \to W^+W^-/Z^0Z^0/H^0_{\rm SM}H^0_{\rm SM}$
4271	$gg/q\bar{q} \to G \to W^+W^-$
4272	$gg/q\bar{q} \to G \to Z^0Z^0$
4273	$gg/q\bar{q} \to G \to H^0_{\rm SM}H^0_{\rm SM}$
5000	Pointlike photon-hadron jet production (all flavours)
5100+IQ	Pointlike photon heavy flavour pair production (IQ as above)
5200+IQ	Pointlike photon heavy flavour single excitation (IQ as above)
	After generation, IHPRO is subprocess (see Sect. 4.6.5)
5300	Quark-photon Compton scattering
5500	Pointlike photon production of light (u, d, s) L=0 mesons
5510,20	S=0 mesons only, S=1 mesons only
	After generation, IHPRO is subprocess (see Sect. 4.6.5)

IPROC	Process
6000	$\gamma\gamma \to q\bar{q}$ (all flavours)
6000+IQ	$\gamma\gamma \to q\bar{q}$ (IQ as above)
6006+IL	$\gamma\gamma \to \ell\bar{\ell}$ ($\mathtt{IL} = 1, 2, 3$ for $\ell = e, \mu, \tau$)
6010	$\gamma\gamma \to W^+W^-$
7000 –	Baryon-number violating and other multi-$W^\pm$ processes
7999	generated by HERBVI package
8000	Minimum bias soft hadron-hadron event
9000	Deep inelastic lepton scattering (all neutral current)
9000+IQ	Deep inelastic lepton scattering (NC on flavour IQ)
9010	Deep inelastic lepton scattering (all charged current)
9010+IQ	Deep inelastic lepton scattering (CC on flavour IQ)
9100	Boson-gluon fusion in neutral current DIS (all flavours)
9100+IQ	Boson-gluon fusion in neutral current DIS (IQ as above)
9107	J/ψ + gluon production by boson-gluon fusion
9110	QCD Compton process in neutral current DIS (all flavours)
9110+IP	QCD Compton process in NC DIS (IP=1–12 for $d - t, \bar{d} - \bar{t}$)
9130	All $\mathcal{O}(\alpha_s)$ NC processes (i.e. 9100+9110)
9140+IP	Heavy quark production by charged-current boson-gluon fusion
	IP: $1 = s\bar{c}, 2 = b\bar{c}, 3 = s\bar{t}, 4 = b\bar{t}$ (+ ch. conj.)
9500+ID	$W^+W^-/Z^0Z^0 \to H^0_{\rm SM}$ in DIS (ID as in $\mathtt{IPROC} = 300 + \mathtt{ID}$)
10000+IP	as $\mathtt{IPROC} = \mathtt{IP}$ but with soft underlying event
	(soft remnant fragmentation in lepton-hadron) suppressed

4.2.1 Treatment of quark masses

The extent to which quark mass effects are included in the hard process cross section is different in different processes. In many processes, they are always treated as massless: IPROC = 1300, 1800, 1900, 2100, 2300, 2400, 5300, 9000. In two processes they are all treated as massless except the top quark, for which the mass is correctly incorporated: 1400, 2000. In the case of massless pair production, only quark flavours that are kinematically allowed are produced. In all cases the event kinematics incorporates the quark mass, even when it is not used to calculate the cross section. In two processes, quarks are always treated as massive: 500, 9100. Finally, in several processes, the behaviour is different depending on whether a specific quark flavour is requested, in which case its mass is included, or not, in which case all quarks are treated as massless. These are: IPROC = 100, 110, 120, QCD $2 \to 2$ scattering (1500 vs. 1700+IQ), jets in direct photoproduction (5000 vs. 5100+IQ and 5200+IQ).

These differences can cause inconsistencies between different ways of generating the same process. The most noticeable example is in direct photoproduction, where one can use process 9130, which uses the exact $2 \to 3$ matrix element $e + g \to e + q + \bar{q}$, or process 5000, which uses the Equivalent Photon Approximation (EPA)

Final considerations

- Since 1973 exact+resummed PT produced enormous inside on QCD radiation and phenomenological "evidence"
- Confinement/hadronization always a pain, to be circumvented via factorization or phenomenological assumption parton flow $\sim$ hadron flow
- Field theory $\rightarrow$ theory of extended objects. Two natural questions
  - how PT "evidence" accounted for
  - how to inspire modeling of hadronization