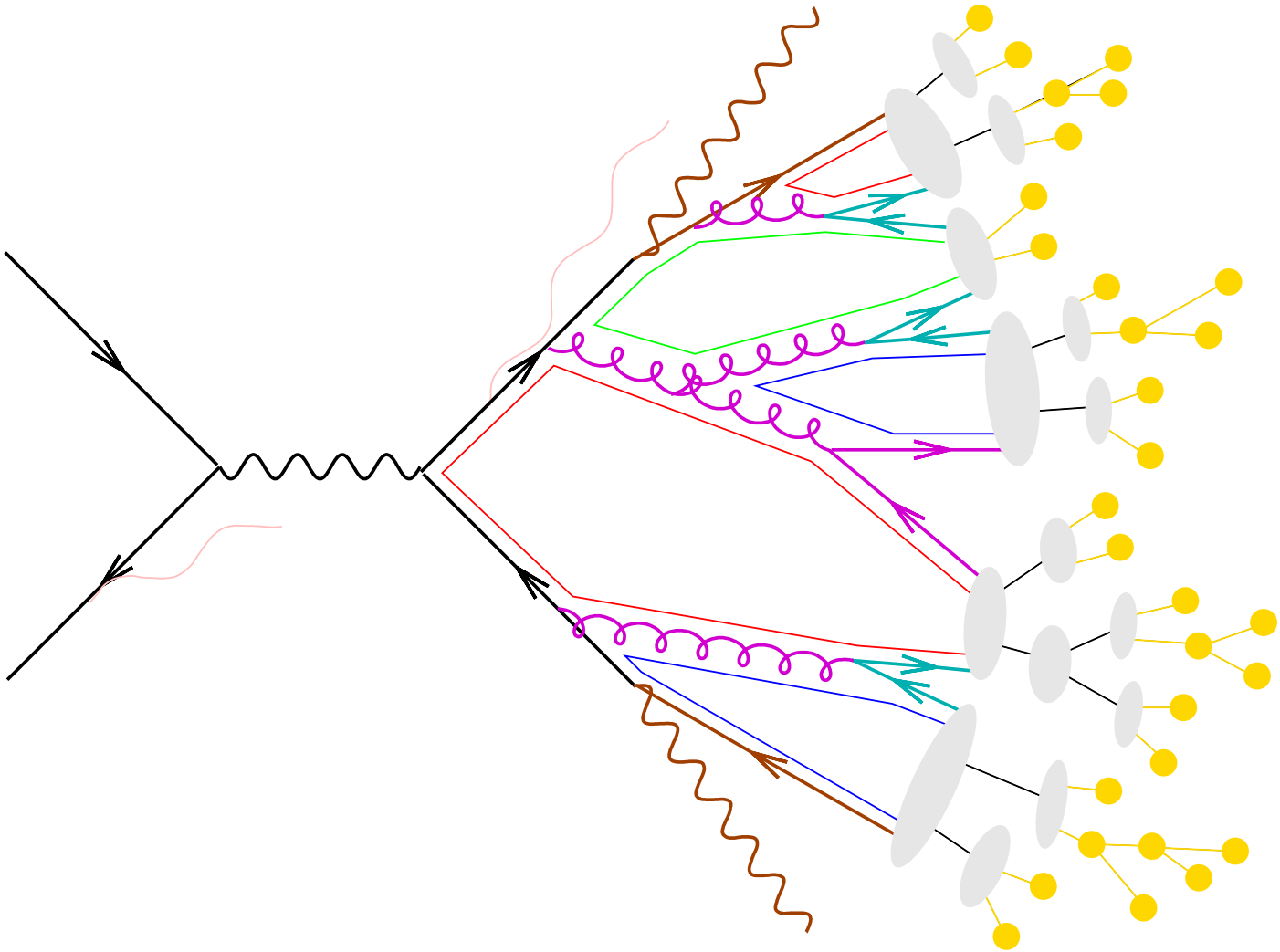
Event generation and parton shower

- Perturbative calculations describe final states in terms of quarks, gluons, leptons, photons
- Experiments observe mesons, baryons, leptons, photons
- Parton shower Monte Carlo programs like Herwig or Pythia provide the connection

Below: outline of what is implemented in Herwig

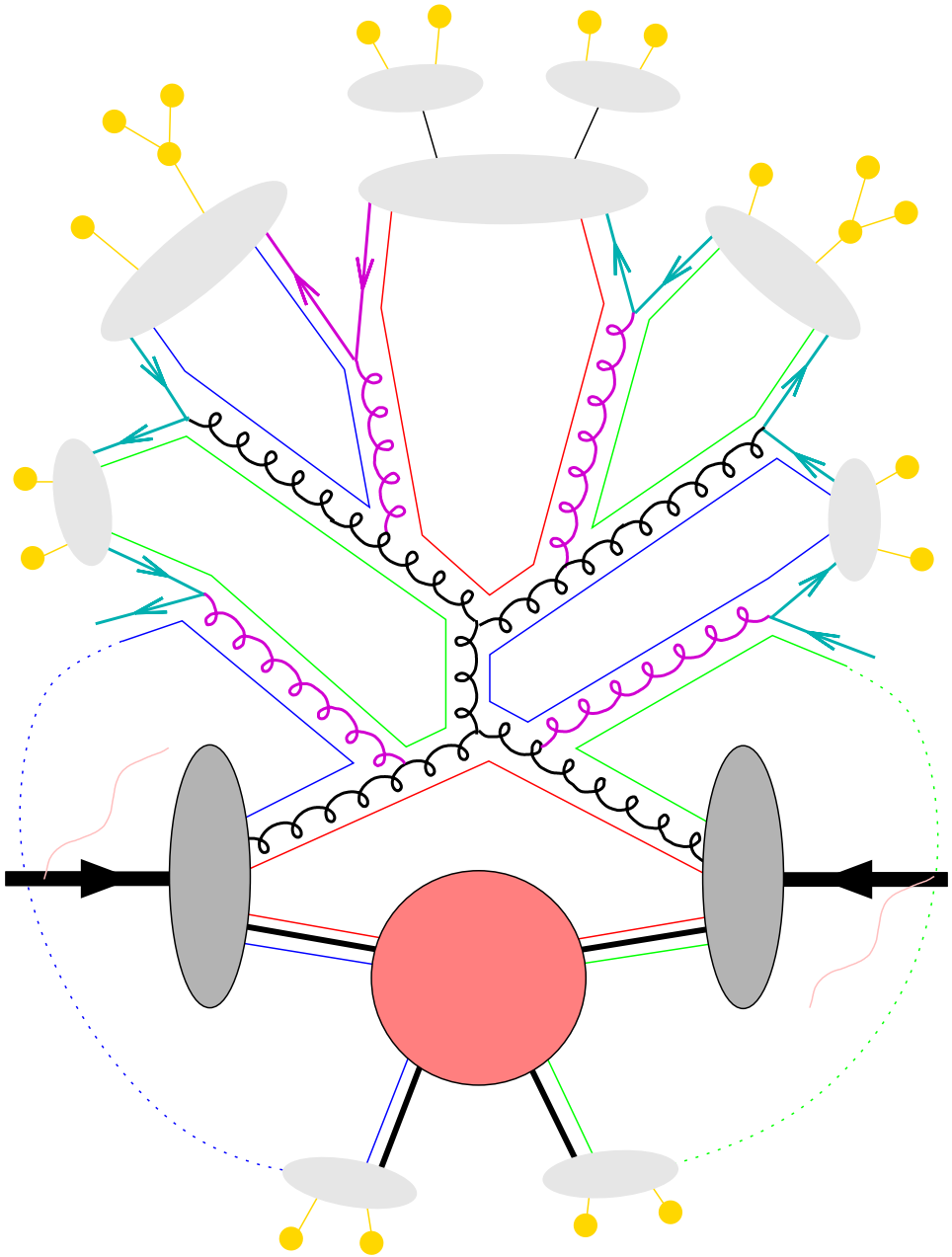
Many thanks to Stefan Gieseke for his help with the following discussion

Generation of an $e^+e^- \to t\bar{t} \to b\bar{b}W^+W^-$ event



- 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

A pp event at the LHC: dijet production via $gg \longrightarrow gg$



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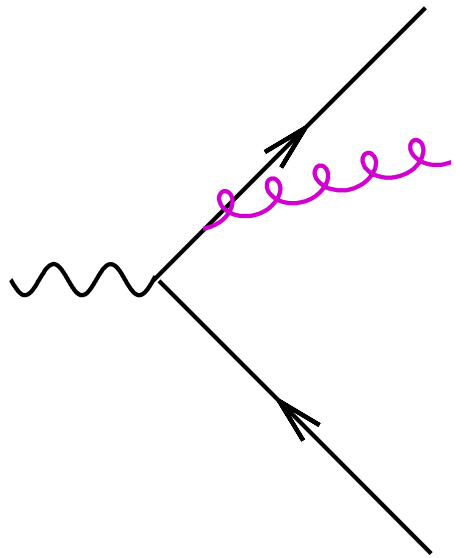
and in addition

+ backward parton evolution
+ soft (possibly not–so–soft) underlying event

Parton shower basics: collinear enhancement

ME for $g \longrightarrow q\bar{q}g$ or $Z \longrightarrow q\bar{q}g$ or ... strongly enhanced whenever emitted gluon is collinear to one of the quarks. Propagator factor

$$\frac{1}{(p_q + p_g)^2} \approx \frac{1}{2E_q E_g (1 - \cos\theta_{qg})}$$



- soft+collinear divergences.
- dominant contribution to the ME.
- still strong enhancement for massive quarks.

Collinear factorization

$$|M_{p+1}|^2 d\Phi_{p+1} \approx |M_p|^2 d\Phi_p \frac{dt}{t} \frac{C\alpha_s}{2\pi} P(z) dz$$

$\longrightarrow$ Parton shower MC.

Parton shower resums leading logarithmic contributions.

Collinear Splittings

Collinear limits for QCD radiation off partons,

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

$$P_{qg}(z) = T_R \left[1 - 2z(1-z)\right] \,,$$

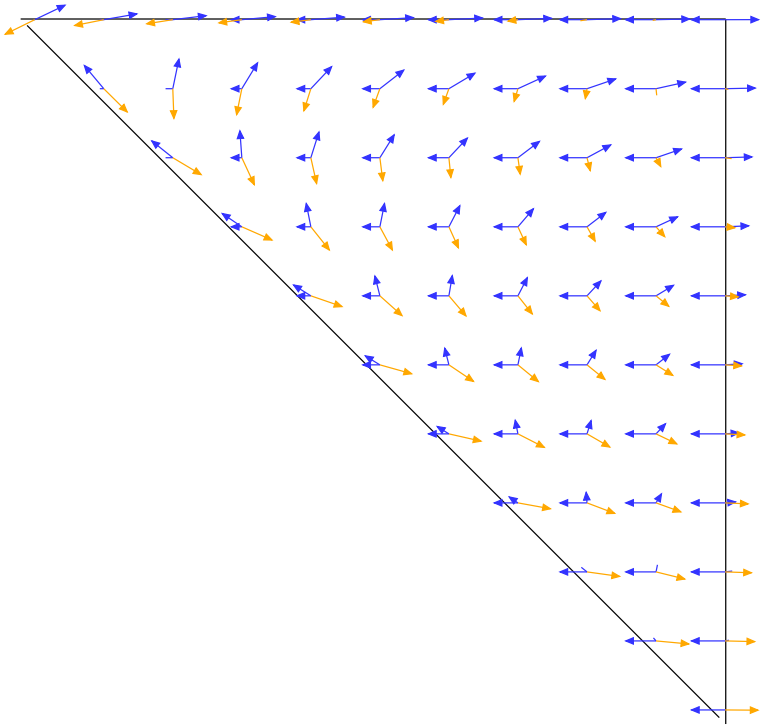
$$P_{gg}(z) = C_A \left[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)\right] \,.$$

$\longrightarrow$ z distributions (roughly $\sim$ Energy fraction carried away).

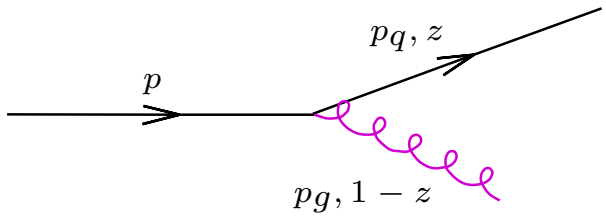
$$\begin{aligned} p_q &= z p_+ + \beta_q p_- - q_\perp \\ p_g &= (1-z) p_+ + \beta_g p_- + q_\perp \end{aligned}$$

$q_\perp$ from $t(\sim p_\perp^2)$–distribution (*evolution variable*).
`Pythia:` $t \sim Q^2$ (virtuality),
`HERWIG:` $t \sim (1 - \cos\theta)$ (opening angle).

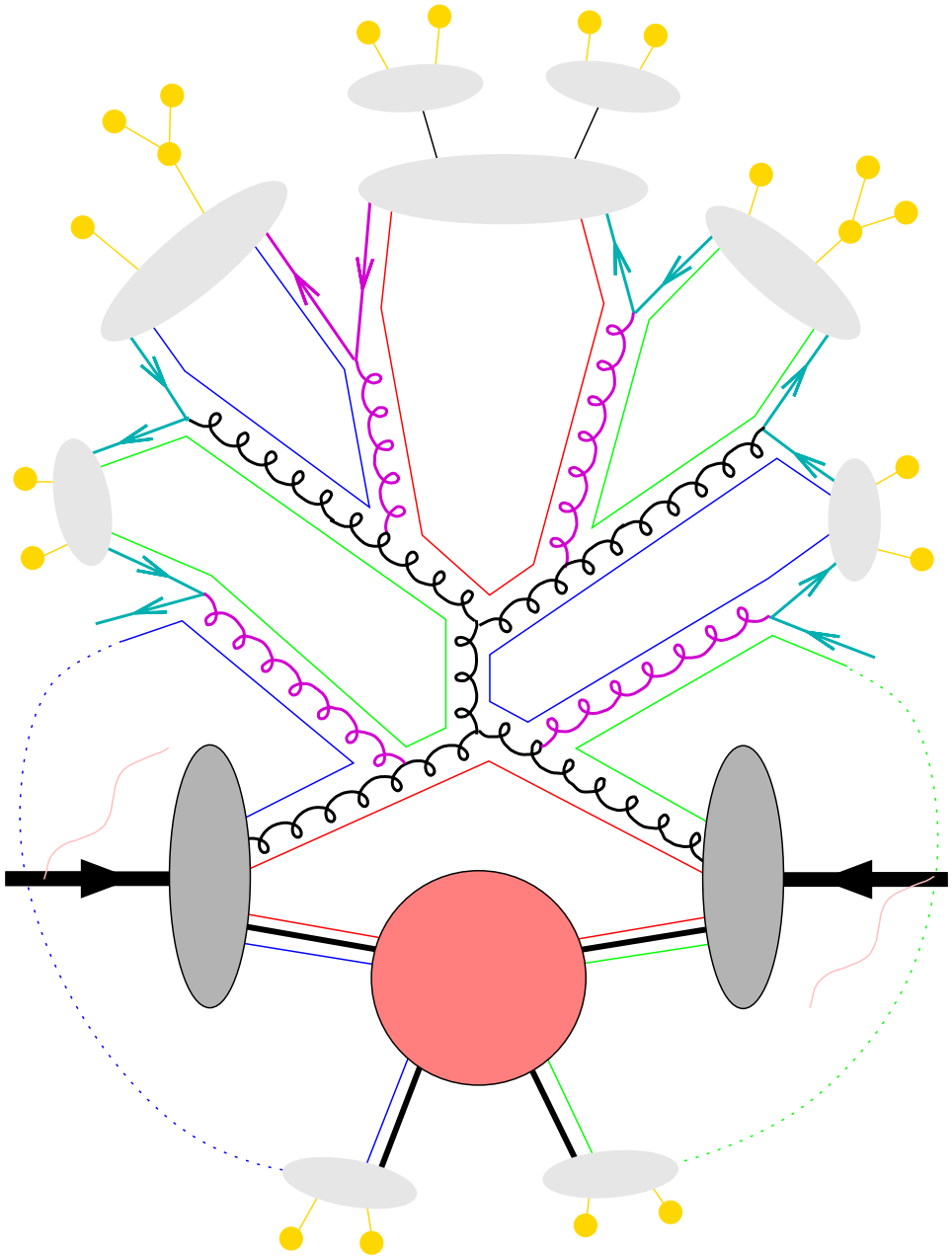
$q\bar{q}g$–Phase space $(E_q, E_{\bar{q}})$



Single emission:



Dijet production detail. Next step: hadronization



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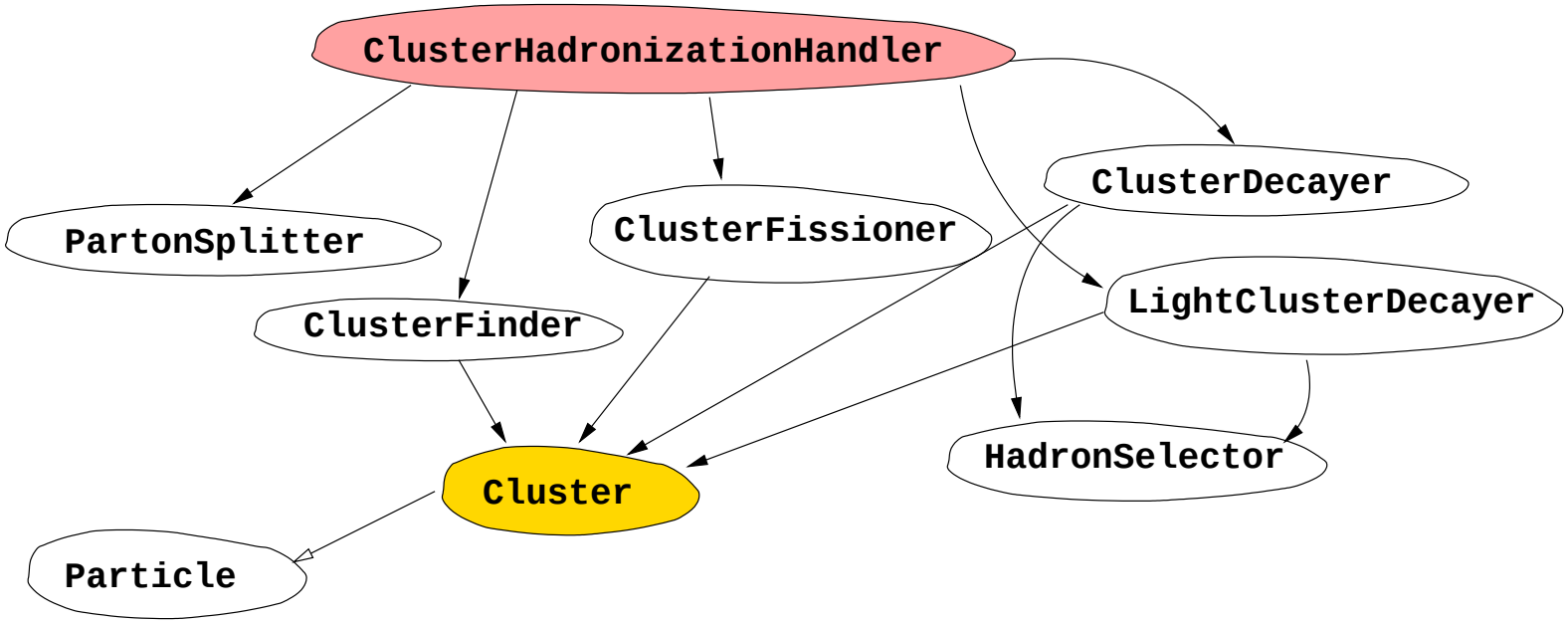
ClusterHadronization

Flow-chart of the hadronization section of the new Herwig++ program



Goals:

- build physics model which captures main non-perturbative aspects of QCD
- parameterize observable details like multiplicities of hadrons, meson/baryon ratios, measured decay branching fractions etc.
- physics model should provide reasonably robust extrapolation to new machines, higher energies
- physics model of hadronization should not depend on specifics of hard scattering process

Cluster hadronization in a nutshell

- Nonperturbative $g \longrightarrow q\bar{q}$ splitting ($q = uds$) isotropically. Here, $m_g \approx 750\,\text{MeV} > 2m_q$.
- Cluster formation, universal spectrum (see below)
- Cluster fission, until

$$M^p < M^p_{\text{max}} + (m_1 + m_2)^p$$

where masses are chosen from

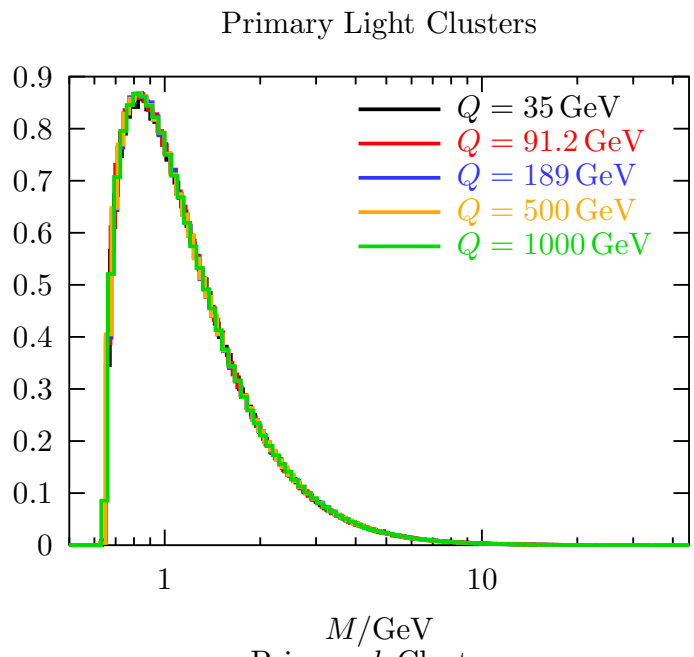
$$M_i = \left[\left(M^P - (m_i + m_3)^P\right) r_i + (m_i + m_3)^P\right]^{1/P},$$

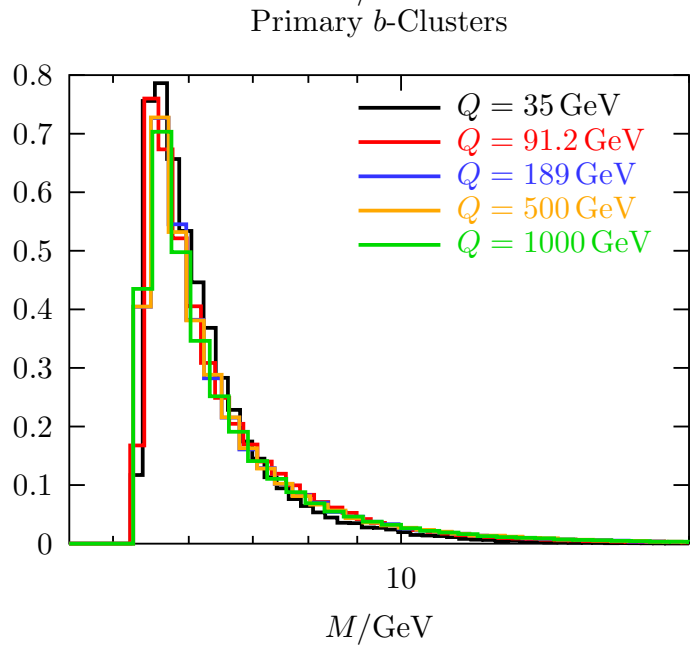
with additional phase space contraints. Constituents keep moving in their original direction.

- Cluster Decay

$$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$

New in HERWIG++: Meson/Baryon ratio is parametrized in terms of diquark weight. In HERWIG the sum ran over all possible hadrons.





Hadron Multiplicities

Particle	Experiment	Measured	Old Model	Herwig++	Fortran
All Charged	M,A,D,L,O	20.924 ± 0.117	20.22*	20.814	20.532*
γ	A,O	21.27 ± 0.6	23.032	22.67	20.74
π^0	A,D,L,O	9.59 ± 0.33	10.27	10.08	9.88
$\rho(770)^0$	A,D	1.295 ± 0.125	1.235	1.316	1.07
$\pi^\pm$	A,O	17.04 ± 0.25	16.30	16.95	16.74
$\rho(770)^\pm$	O	2.4 ± 0.43	1.99	2.14	2.06
η	A,L,O	0.956 ± 0.049	0.886	0.893	0.669*
$\omega(782)$	A,L,O	1.083 ± 0.088	0.859	0.916	1.044
$\eta'(958)$	A,L,O	0.152 ± 0.03	0.13	0.136	0.106
K^0	S,A,D,L,O	2.027 ± 0.025	2.121*	2.062	2.026
$K^*(892)^0$	A,D,O	0.761 ± 0.032	0.667	0.681	0.583*
$K^*(1430)^0$	D,O	0.106 ± 0.06	0.065	0.079	0.072
$K^\pm$	A,D,O	2.319 ± 0.079	2.335	2.286	2.250
$K^*(892)^\pm$	A,D,O	0.731 ± 0.058	0.637	0.657	0.578
$\phi(1020)$	A,D,O	0.097 ± 0.007	0.107	0.114	0.134*
p	A,D,O	0.991 ± 0.054	0.981	0.947	1.027
Δ^{++}	D,O	0.088 ± 0.034	0.185	0.092	0.209*
Σ^-	O	0.083 ± 0.011	0.063	0.071	0.071
Λ	A,D,L,O	0.373 ± 0.008	0.325*	0.384	0.347*
Σ^0	A,D,O	0.074 ± 0.009	0.078	0.091	0.063
Σ^+	O	0.099 ± 0.015	0.067	0.077	0.088
$\Sigma(1385)^\pm$	A,D,O	0.0471 ± 0.0046	0.057	0.0312*	0.061*
Ξ^-	A,D,O	0.0262 ± 0.001	0.024	0.0286	0.029
$\Xi(1530)^0$	A,D,O	0.0058 ± 0.001	0.026*	0.0288*	0.009*
Ω^-	A,D,O	0.00125 ± 0.00024	0.001	0.00144	0.0009

Hadron Multiplicities (ctd')

Particle	Experiment	Measured	Old Model	Herwig++	Fortran
$f_2(1270)$	D,L,O	0.168 ± 0.021	0.113	0.150	0.173
$f_2'(1525)$	D	0.02 ± 0.008	0.003	0.012	0.012
$D^{\pm}$	A,D,O	0.184 ± 0.018	0.322^*	0.319^*	0.283^*
$D^*(2010)^{\pm}$	A,D,O	0.182 ± 0.009	0.168	0.180	0.151^*
D^0	A,D,O	0.473 ± 0.026	0.625^*	0.570^*	0.501
$D_s^{\pm}$	A,O	0.129 ± 0.013	0.218^*	0.195^*	0.127
$D_s^{*\pm}$	O	0.096 ± 0.046	0.082	0.066	0.043
J/Ψ	A,D,L,O	0.00544 ± 0.00029	0.006	0.00361^*	0.002^*
Λ_c^+	D,O	0.077 ± 0.016	0.006^*	0.023^*	0.001^*
$\Psi'(3685)$	D,L,O	0.00229 ± 0.00041	0.001^*	0.00178	0.0008^*

of $*$'s = observables with more than 3σ deviation:

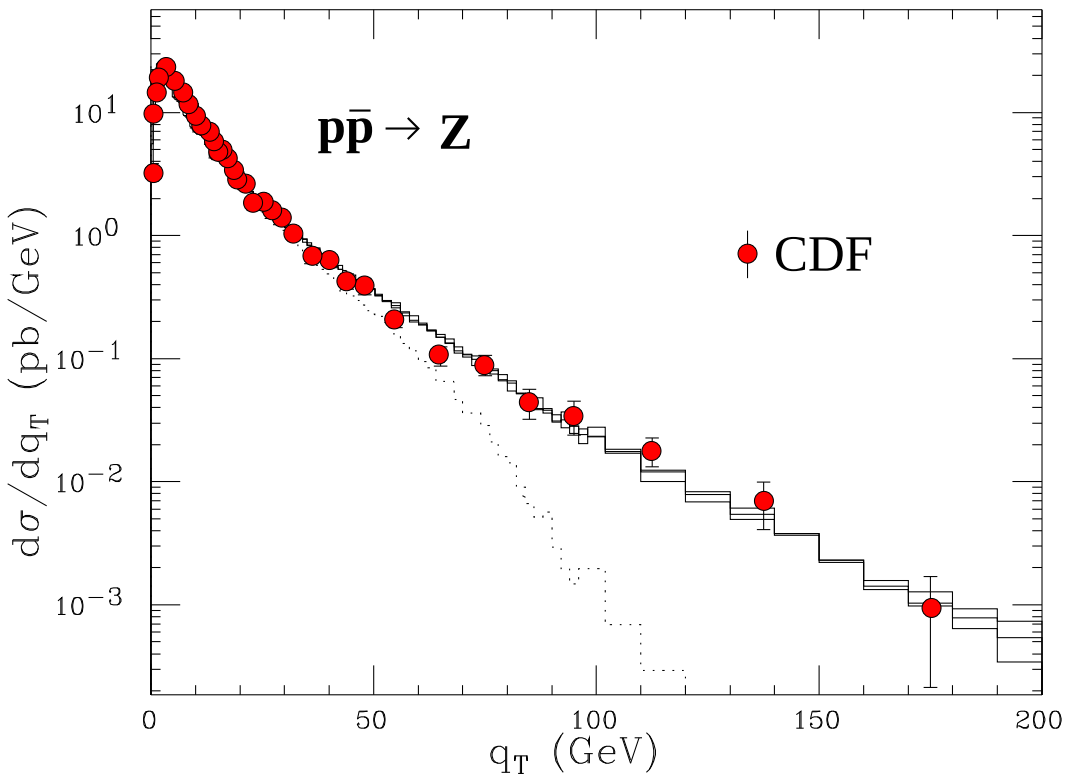
$$\text{OldModel} : \text{Herwig++} : \text{Fortran} = 9 : 7 : 13$$

Old Model = Herwig++ implementation as close as possible to the Fortran `HERWIG` implementation.

Herwig++ = refinements concerning Baryon/Meson ratio, treatment of light clusters.

Fortran = results from running Fortran `HERWIG 6.4` with default parameters.

What is it good for?



HERWIG histograms. ME correction on (solid), off (dotted).
[Corcella, Seymour, NPB 565 (2000) 227]

- Universal tool to compute *any* experimental observable distribution with a reasonable precision.
- Relied upon heavily by experimenters.
- Same event record as data.
- No substitute for higher order computations: complementary approach.
- Experimenters can use same software to analyse MC output and real data.
- *Indispensable* for estimates of detector acceptance, efficiencies etc.