Event generators — new developments

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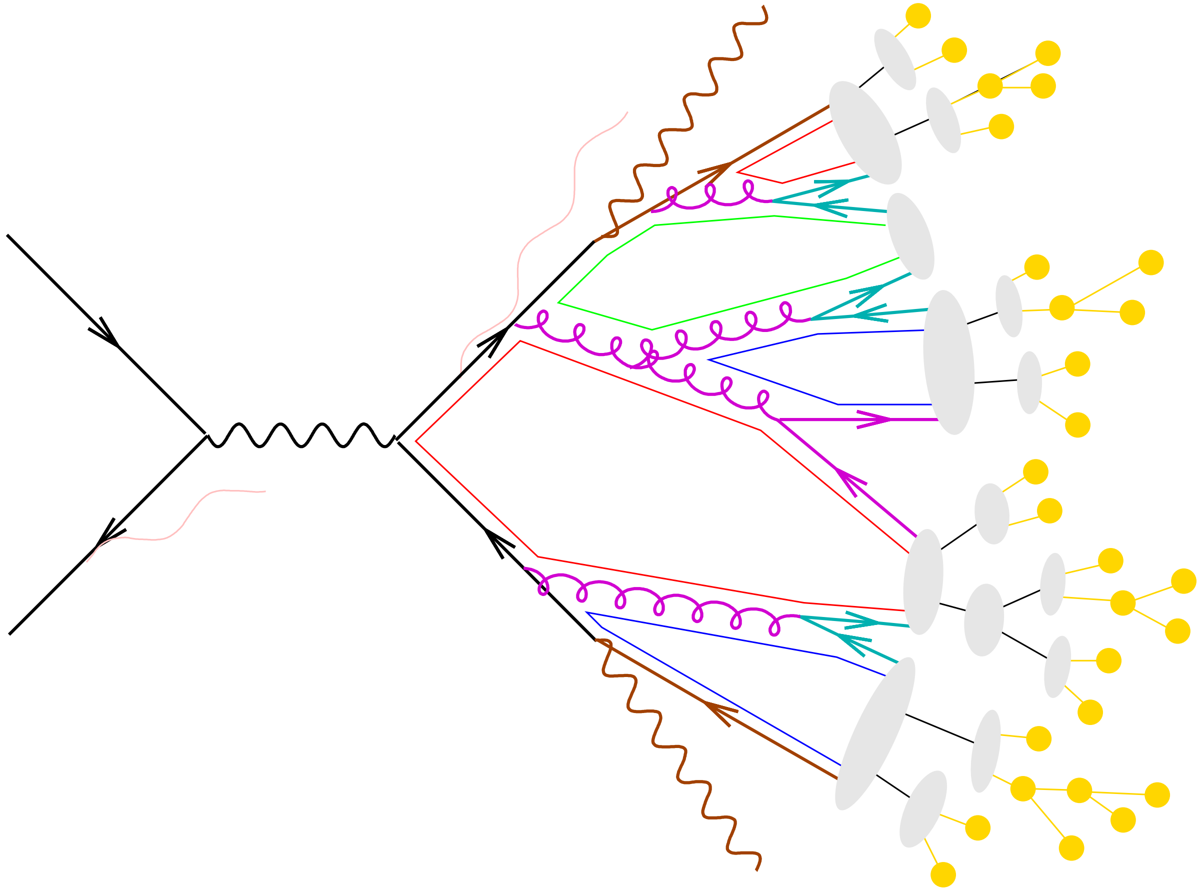
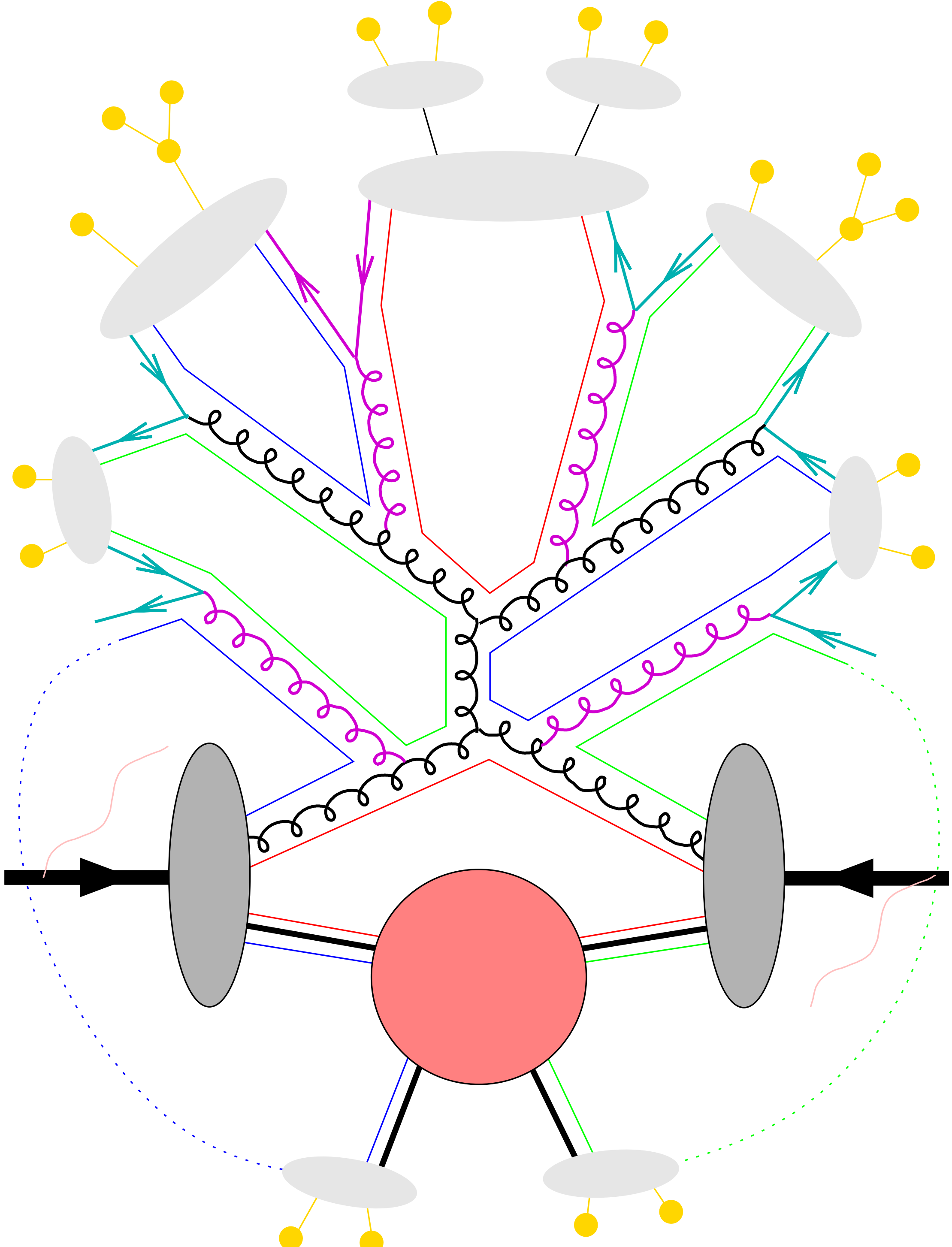
- Introduction: event generators
- Matrix elements and parton showers
  - Higher Orders (NLLA, NLO)
  - ME corrections (soft, hard)
  - Matching ME+PS (various attempts)
  - Merging NLO ME+PS: MC@NLO
- Development of Herwig++

MC Event Generators (e^+e^-)



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

Additional Complications in $p\bar{p}$

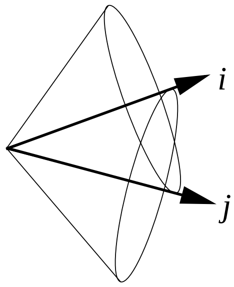


+ backward parton evolution

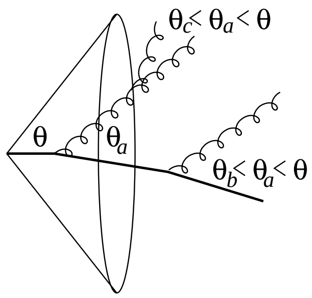
+ soft underlying event

Colour Coherence/Angular Ordering

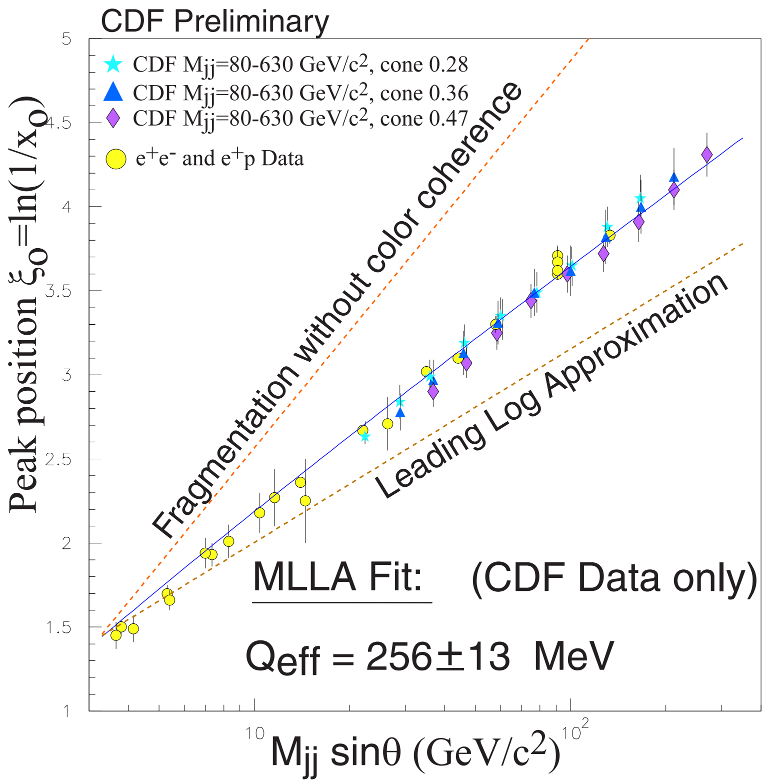
Radiation from parton i is bound to a cone, given by the colour partner parton j.



Results in angular ordered parton shower and suppresses soft gluons viz. hadrons in a jet.



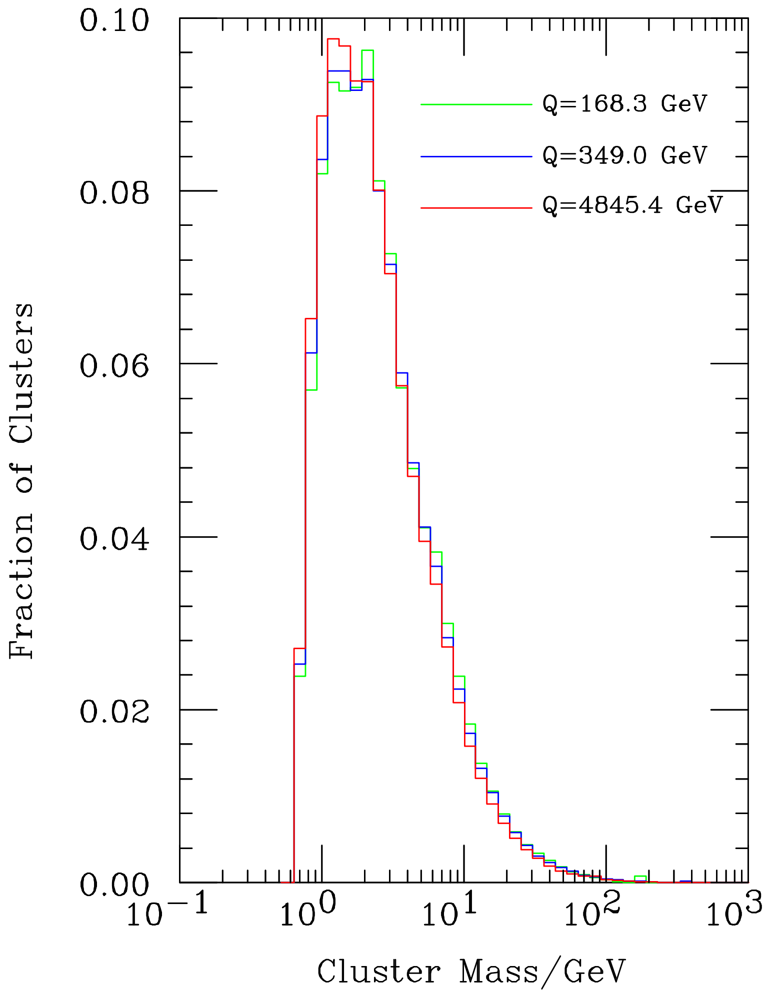
Confirmed by Tevatron data (CDF):



- `Herwig` evolves in opening angle
- `Pythia` incorporates appropriate vetos.

Cluster Hadronization

Cluster mass spectrum is independent of cm energy Q of the hard subprocess (universality, colour preconfinement CITE!)



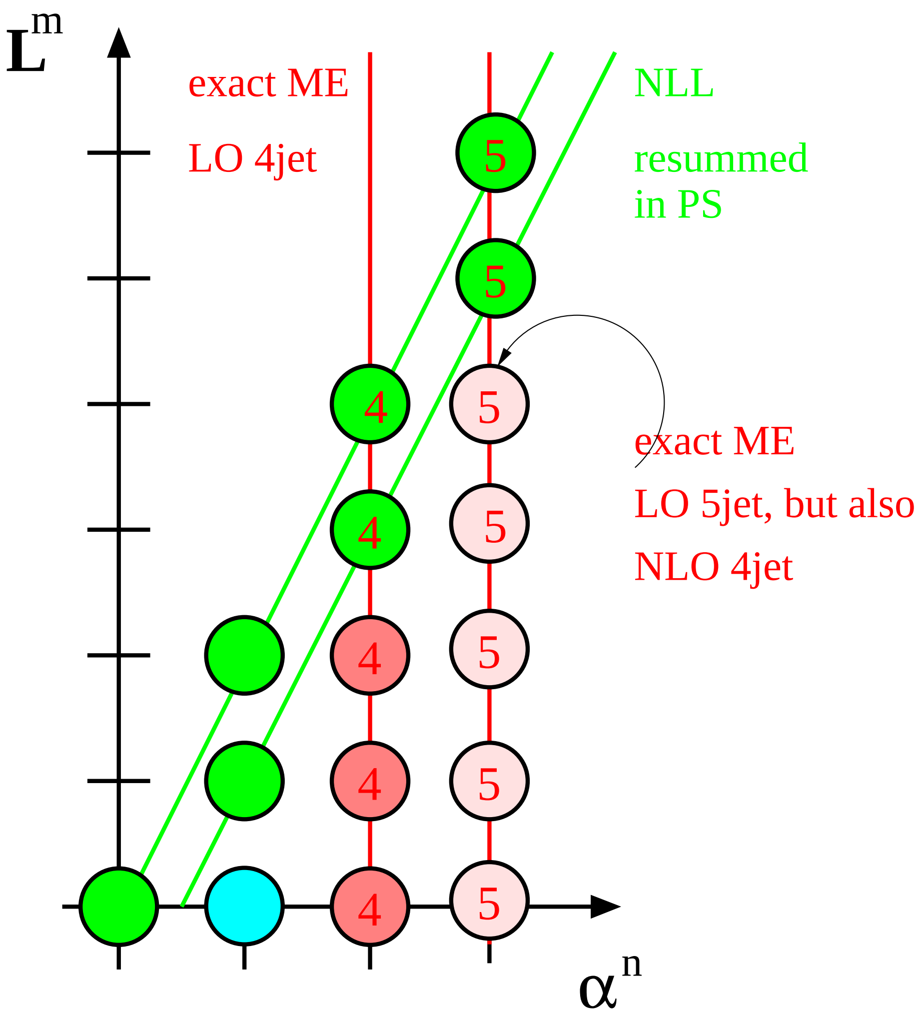
→ Lund String fragmentation: slightly better fits but many more parameters.

There's room for improvement:

3 approaches: ME corrections, ME+PS, MC@NLO

- ME corrections
- combining LO ME + LO PS
- matching NLO ME + LO PS

The problem:

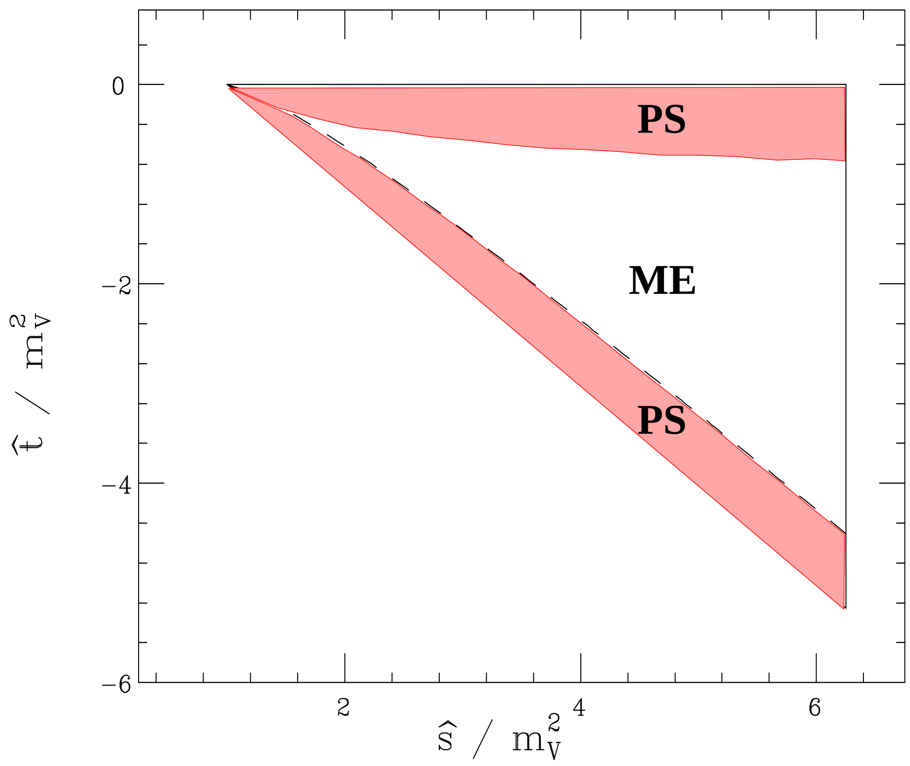


Very active. . .

- G. Corcella and M. H. Seymour, Phys. Lett. B **442** (1998) 417 [arXiv:hep-ph/9809451].
- M. H. Seymour, Comput. Phys. Commun. **90** (1995) 95 [arXiv:hep-ph/9410414].
- S. Catani, F. Krauss, R. Kuhn and B. R. Webber, JHEP **0111** (2001) 063 [arXiv:hep-ph/0109231].
- B. R. Webber, arXiv:hep-ph/0005035.
- F. Krauss, JHEP **0208** (2002) 015 [arXiv:hep-ph/0205283].
- L. Lonnblad, JHEP **0205** (2002) 046 [arXiv:hep-ph/0112284].
- M. Dobbs, Phys. Rev. D **65** (2002) 094011 [arXiv:hep-ph/0111234].
- B. Potter, J. Phys. G **28** (2002) 871 [arXiv:hep-ph/0110009].
- B. Potter and T. Schorner, Phys. Lett. B **517** (2001) 86 [arXiv:hep-ph/0104261].
- S. Frixione and B. R. Webber, JHEP **0206** (2002) 029 [arXiv:hep-ph/0204244].
- S. Frixione and B. R. Webber, arXiv:hep-ph/0207182.
- J. Collins, Phys. Rev. D **65** (2002) 094016 [arXiv:hep-ph/0110113].
- J. C. Collins and F. Hautmann, JHEP **0103** (2001) 016 [arXiv:hep-ph/0009286].
- F. Hautmann, arXiv:hep-ph/0101006.
- Y. Chen, J. C. Collins and N. Tkachuk, JHEP **0106** (2001) 015 [arXiv:hep-ph/0105291].
- Y. j. Chen, J. Collins and X. m. Zu, JHEP **0204** (2002) 041 [arXiv:hep-ph/0110257].
- J. C. Collins and X. m. Zu, JHEP **0206** (2002) 018 [arXiv:hep-ph/0204127].

Matrix element corrections

Consider W/Z production (G Corcella, MH Seymour, NP B665 (2000) 227), Parton Shower (PS) fills only part of the phase space.

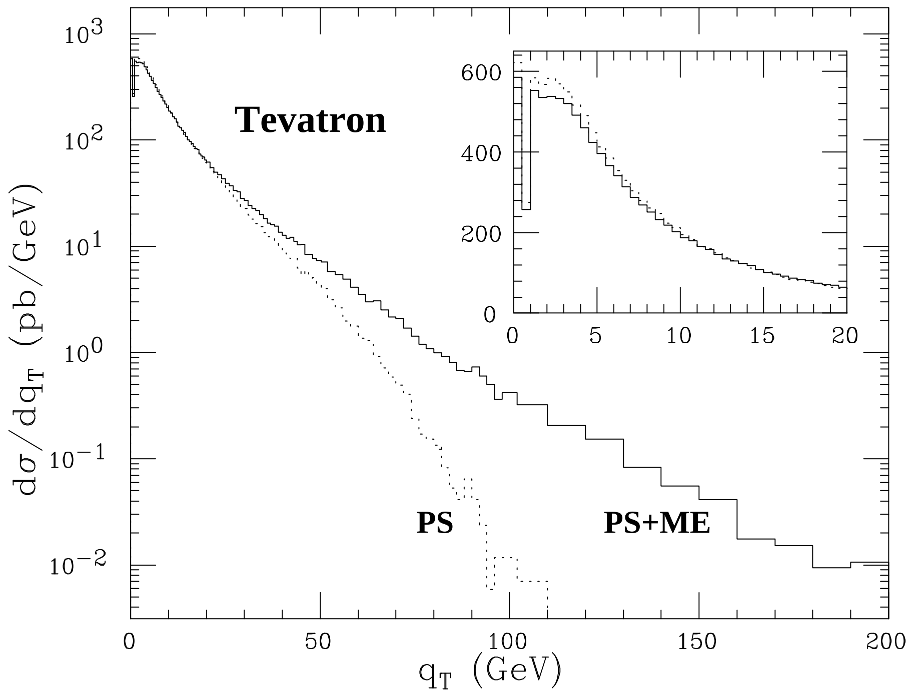


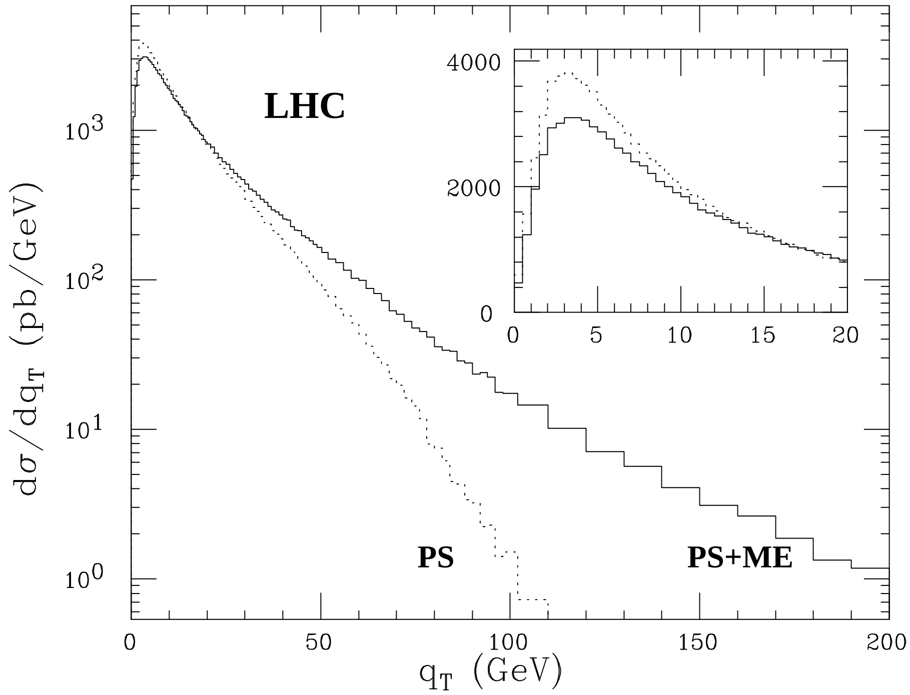
"Correct the parton shower with the matrix element"

- hard matrix element correction in the 'dead zone': phase space filled acc to the full matrix element for the production of a single hard gluon.
- soft matrix element correction: hardest emission of the parton shower suppressed by a factor 'ME/PS'.

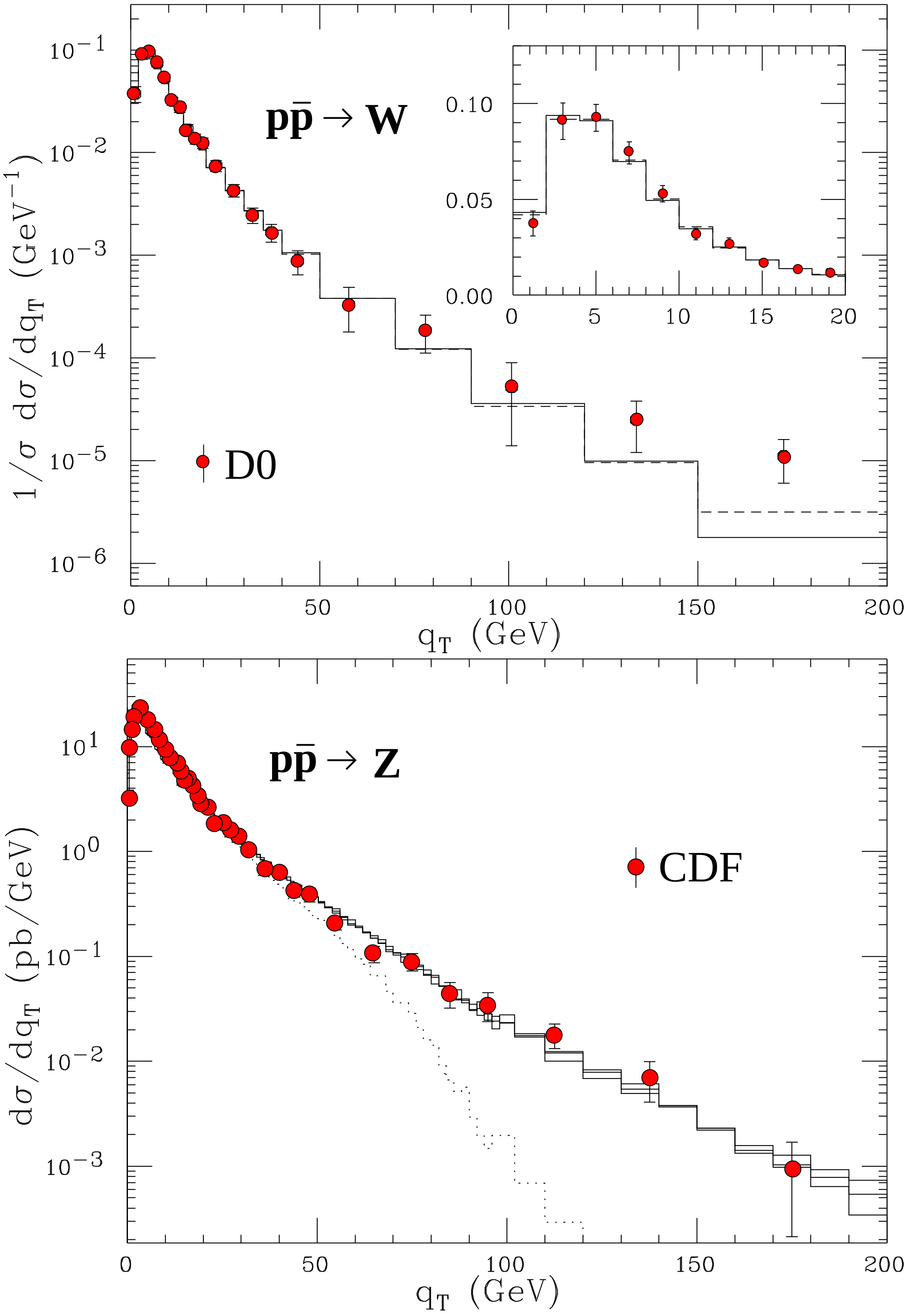
Results

The reagion governed by the hard matrix element is clearly enhanced





Comparison with data



$\longrightarrow$ Systematic approach highly desirable!

Matching ME+PS

Try to combine leading order ME and existing parton shower with a very general algorithm. In brief:

1. Generate a hard n-jet configuration acc to the known rate $R_n(Q_1, Q)$, with cm-energy Q and Durham-resolution $y_1 = Q_1^2/Q^2$.
2. Generate final state momenta acc to hard matrix element $|\mathcal{M}_n|^2$. evaluated at $\alpha_S(Q_1)$.
3. $k_\perp$-cluster backwards towards the $(n-1), (n-2), \ldots$-jet configuration and obtain the respective chain of resolutions

$$1 = y_2 > y_3 > \cdots > y_n > y_1$$

   which give characteristic nodal scales $q_j = Q\sqrt{y_j}$.
4. apply a coupling constant weight.
5. for a line i between scales $q_k < q_j$ apply a Sudakov-weight

$$\Delta_i(Q_1, q_j)/\Delta_i(Q_1, q_k) < 1$$

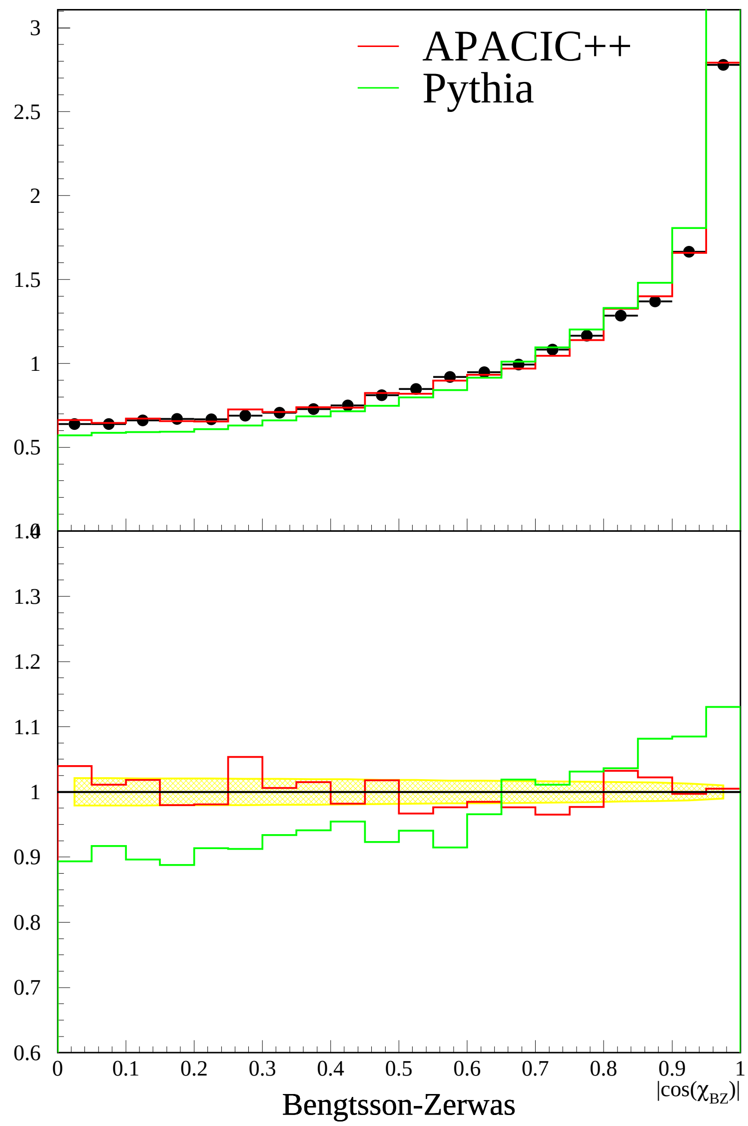
   and $\Delta(Q_1, q_j)$ for an external line from a node with scale q_j.
6. reject events with final weight smaller than random number.
7. apply a 'vetoed parton shower'.

The final rate (from ME + vetoed PS) is then independent of the cut y_1 and correct (up to NLLA) (Catani, Krauss, Kühn, Webber)

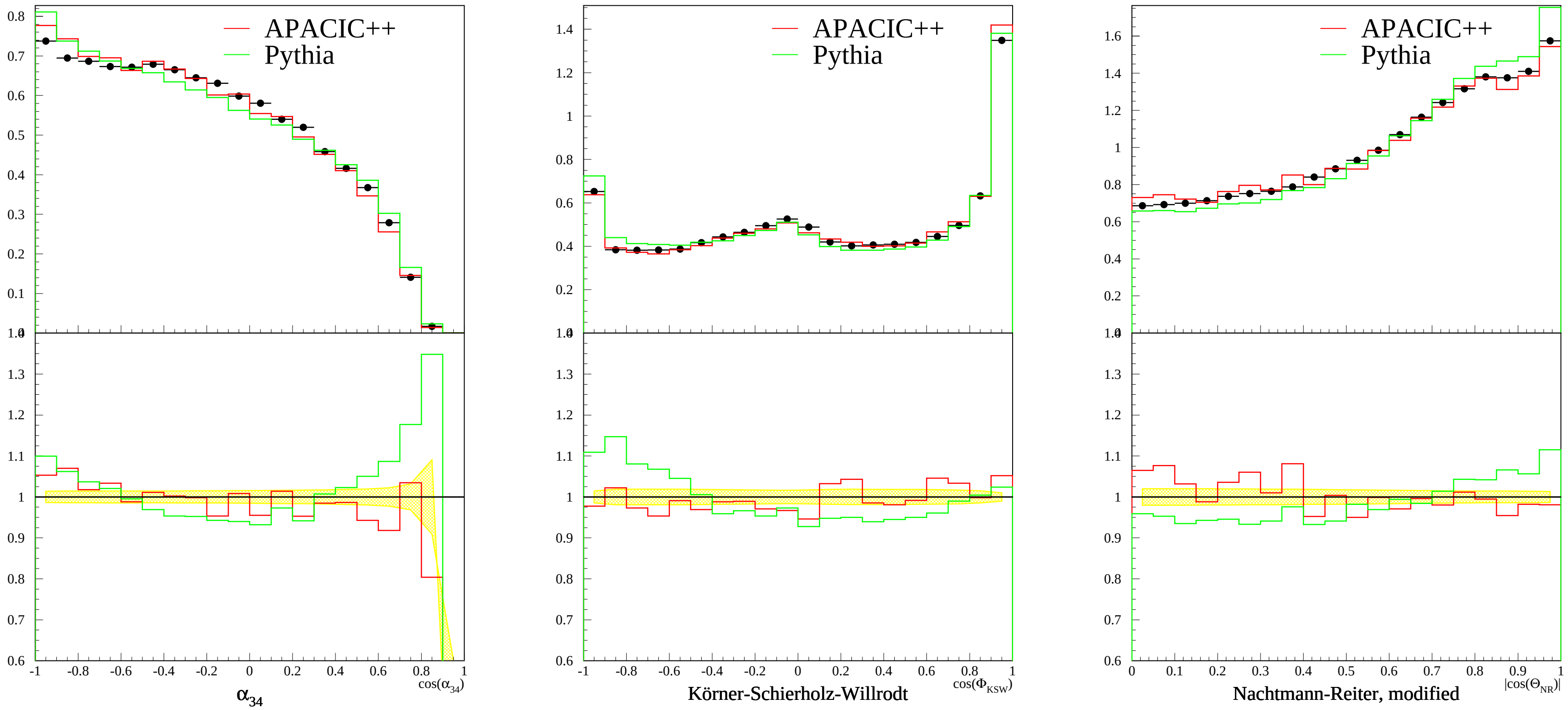
$\longrightarrow$ Recently generalized to $p\bar{p}$ by Krauss.

Results (ME+PS)

- Simultaneous description of PS and ME phase space up to NLLA and LO in the ME.
- Avoids double counting and 'dead regions' in phase space.
- Generalized and automatized easily.
- Implemented in `APACIC++` (Krauss et.al. 2000)) (with 5 jet ME so far) and will be powerfull together with ME generator `AMEGIC++` (Krauss et.al. 2001).



More results (ME+PS)

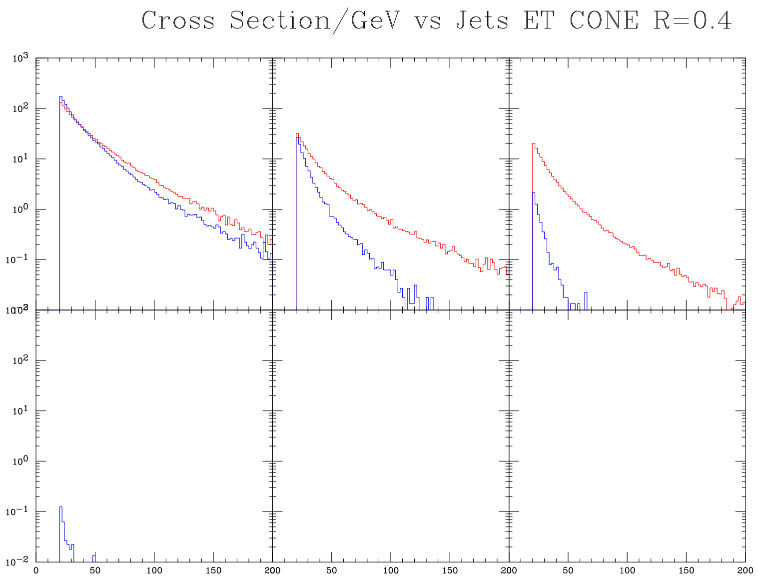


ME Generators

This approach is most powerful in accordance with an automatic ME Generator. Very nice example: AMEGIC++.

- Major issue: integrator/ps-generator comes with the ME code itself $\longrightarrow$ only realistic possibility to handle large number (> 5) of particles in FS.
- Very general.
- $e^+e^- \to VV + 4$jets feasible.
- $e^+e^- \to 4f$ comparable to state-of-the-art codes (Racoon_XX,) in precision and speed. No manual interference with the program necessary!

MadEvent/MadGraphII similar performance, written in Fortran. Some MadEvent results for $p\bar{p} \to WW + n$jets compared to Herwig:



Other examples: CompHEP, AlpGen, . . .

Some AMEGIC++ results

$\sigma(e^+e^- \to 4f)$

massless fermions, compared to Racoon (Denner et.al.):

	AMEGIC++	comp. Value
final state	σ_{EW} [fb]	σ_{EW} [fb]
$\nu_e\,\bar\nu_e\,e^-\,e^+$	256.7(4)	257.1(7)
$\nu_\mu\,\mu^+\,e^-\,\bar\nu_e$	227.3(1)	227.5(1)
$\nu_\mu\,\bar\nu_\mu\,\mu^-\,\mu^+$	228.8(1)	228.8(1)
$\nu_\mu\,\mu^+\,\tau^-\,\bar\nu_\tau$	218.5(1)	218.57(9)
$\mu^-\,\mu^+\,\mu^-\,\mu^+$	5.470(5)	5.478(5)
$\mu^+\,\mu^-\,\tau^-\,\tau^+$	11.02(2)	11.02(1)
...	...	...

massive fermions (compared to Jegerlehner et.al.):

	$\sqrt{s} = 200$ GeV		$\sqrt{s} = 500$ GeV	
final state	AMEGIC++	comp. Value	AMEGIC++	comp. Value
$u\,\bar u\,s\,\bar s$	83.72(4)	83.63(12)	32.595(20)	32.561(51)
$u\,\bar u\,b\,\bar b$	86.627(39)	86.565(95)	38.484(20)	38.475(45)
$c\,\bar c\,d\,\bar d$	84.34(4)	84.41(12)	32.692(20)	33.150(92)
$c\,\bar c\,b\,\bar b$	87.308(33)	87.209(83)	39.223(20)	39.237(42)
$t\,\bar t\,d\,\bar d$	–	–	0.9030(4)	0.903(1)
$t\,\bar t\,s\,\bar s$	–	–	0.9033(4)	0.903(1)
$d\,\bar d\,s\,\bar s$	79.75(3)	79.658(95)	29.809(18)	29.812(39)
$d\,\bar d\,b\,\bar b$	82.569(30)	82.486(87)	37.424(19)	37.435(39)
$u\,\bar u\,c\,\bar c$	87.12(4)	87.06(13)	35.349(22)	35.826(61)
$u\,\bar u\,t\,\bar t$	–	–	0.9074(4)	0.9071(11)
$u\,\bar u\,u\,\bar u$	42.51(4)	42.465(45)	17.433(69)	17.410(27)
$c\,\bar c\,c\,\bar c$	43.306(41)	43.323(44)	17.725(91)	18.076(23)
$d\,\bar d\,d\,\bar d$	39.229(45)	39.173(32)	14.616(99)	14.758(15)
...	...	...	...	...

MC with NLO Matrix Elements

Next step, NLO matrix elements (many of them are available) smoothly merged together with *existing* MC model.

Two approaches (Pötter & Schörner) and (Frixione & Webber). Basic features from toy model:

Condider Observable O in a Toy Model at NLO with three contributions

1. Born level,
$$O(0)$$
2. virtual corrections,
$$-\alpha O(0)\int_0^1 \frac{dx}{x} V(x)$$
3. real corrections,
$$\alpha \int_0^1 \frac{dx}{x} R(x) O(x)$$

$V(0) = R(0)$ for infrared safety.

Not directly applicable to generate MC events, because seperately divergent terms give many events (with positive and negative weights) that have to cancel in the sum. $\longrightarrow$ waste of computing time!

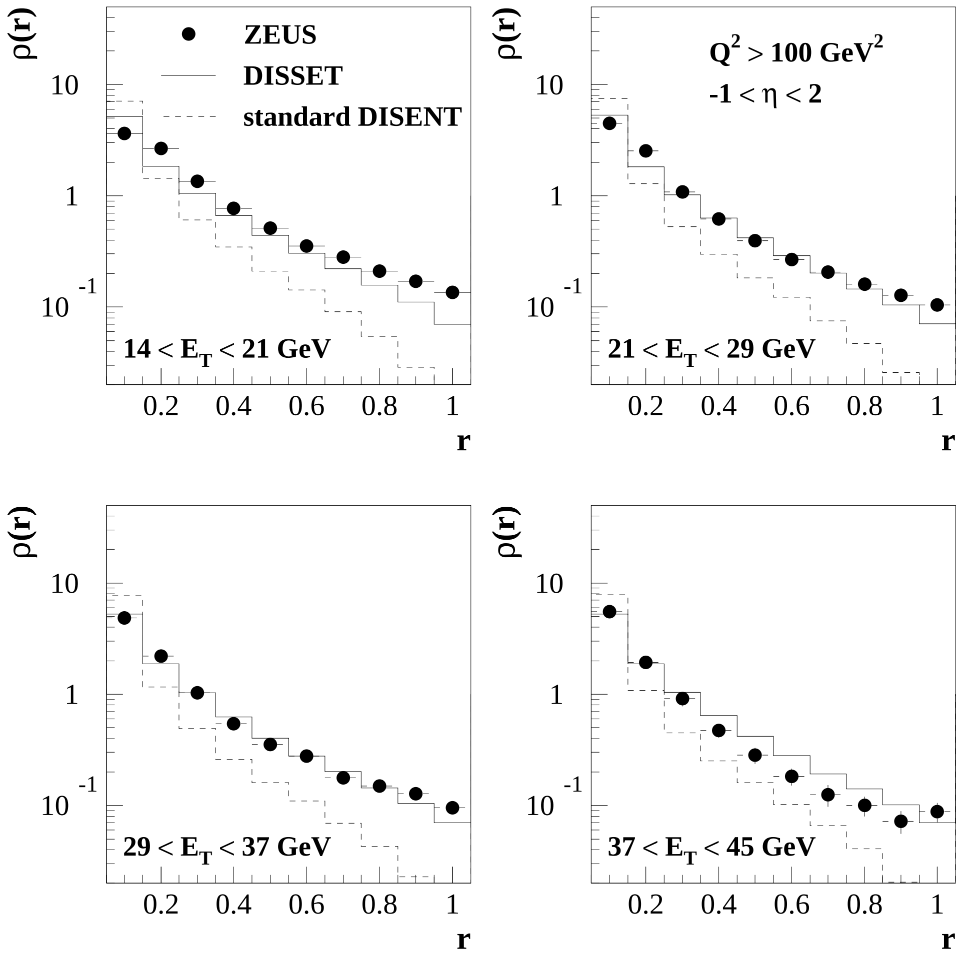
Phase Space Slicing

Applied by Pötter & Schörner and Dobbs

Roughly: introduce lower cutoff δ on the real corrections and treat emissions with $x < \delta$ as *unresolved*.

Next: introduce separation ρ between parton shower and ME emissions.

- $x > \rho$: generate hard emission with the Matrix element and start the shower to generate emissions below ρ.
- $x < \rho$: no hard emsission/parton shower only



MC@NLO

(Frixione & Webber): Use subtraction method to trade divergent terms. Usual advantages of smoothness, cancellation of large terms before integration (few events with positive/negative weights).

Write cross section as

$$\left(\frac{d\sigma}{dO}\right) = \int_0^1 dx \left[I_{\mathsf{MC},x} \frac{\alpha[R(x) - BQ(x)]}{x} \right.$$
$$\left. + I_{\mathsf{MC},0} \left(B + aV + \frac{\alpha B[Q(x) - 1]}{x} \right) \right]$$

i.e. add and subtract

$$I_{\mathsf{MC},x} \frac{\alpha BQ(x)}{x}$$

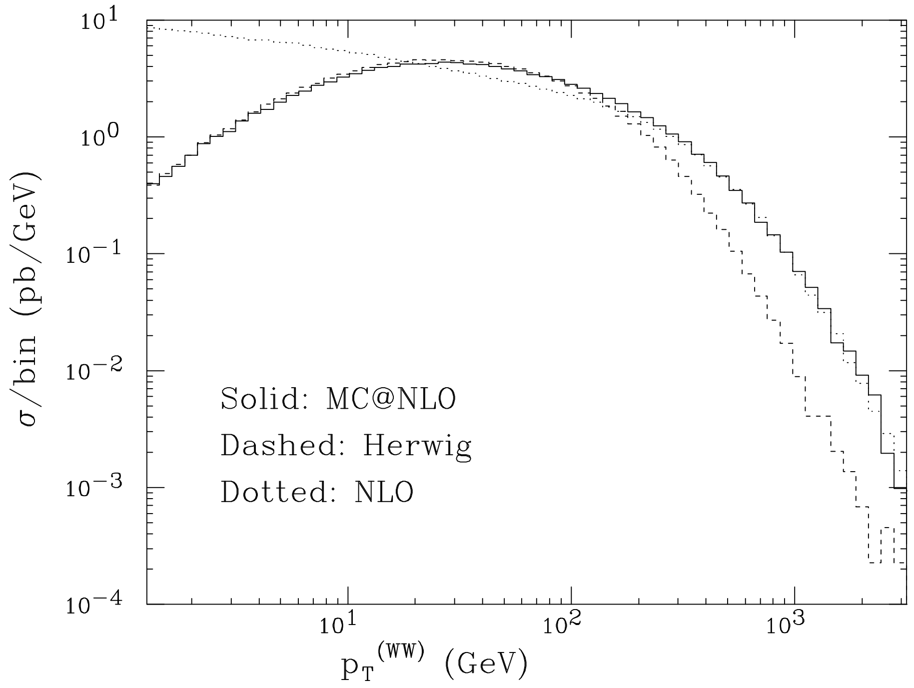
with $Q(x)$ appearing in the Sudakov form factor,

$$\Delta(x_1, x_2) = \exp\left[-\alpha \int_{x_1}^{x_2} \frac{dz}{z} Q(z) \right] .$$

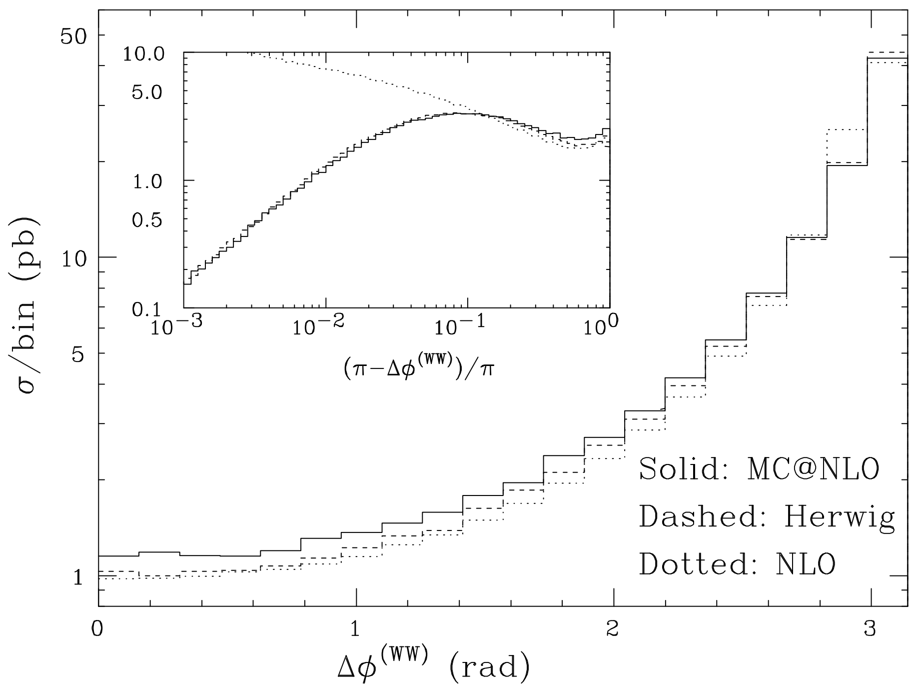
- Cross section matches explicitly matches NLO up to NNLO terms.
- Only few events with negative weight necessary.
- Approach very close to existing MC programs (implemented on top of existing `Herwig`).
- Generalization to physical ME's straightforward.

MC@NLO results for WW production

$p_\perp$ of W pair



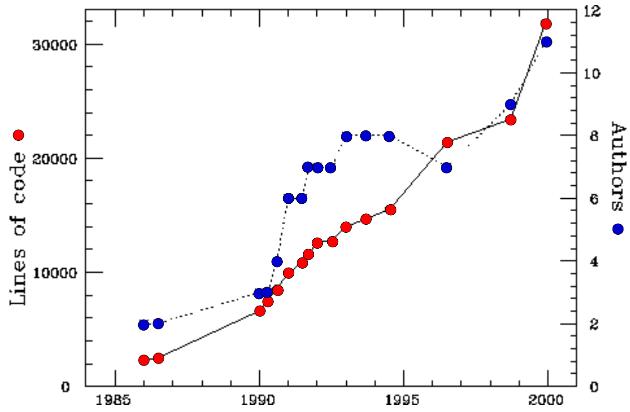
MC@NLO smoothly interpolates between NLO and Herwig.



Catch up, go C++!

Besides new projects, the two traditional programs `Pythia` and `Herwig` are in the process of being rewritten as `Pythia7` and `Herwig++`.

Why C++? Well. . .



- C++ is standard in the Unix/Linux world
- Experiments use it
- Maintenance
- Encapsulation of code
- Easy to implement new physics

Beware: Pythia7 stands for two types of new things

- A general class library for high energy physics event generators, making use of e.g. CLHEP and has many useful additions.
- A physics part, detached from the library and aims at reproducing/improving what is now known as `Pythia6.xxx`.

Herwig++ will use the *library only*!

Interplay of Herwig++ and Pythia7

won't re-invent the wheel

share administrative overhead, common to event generators

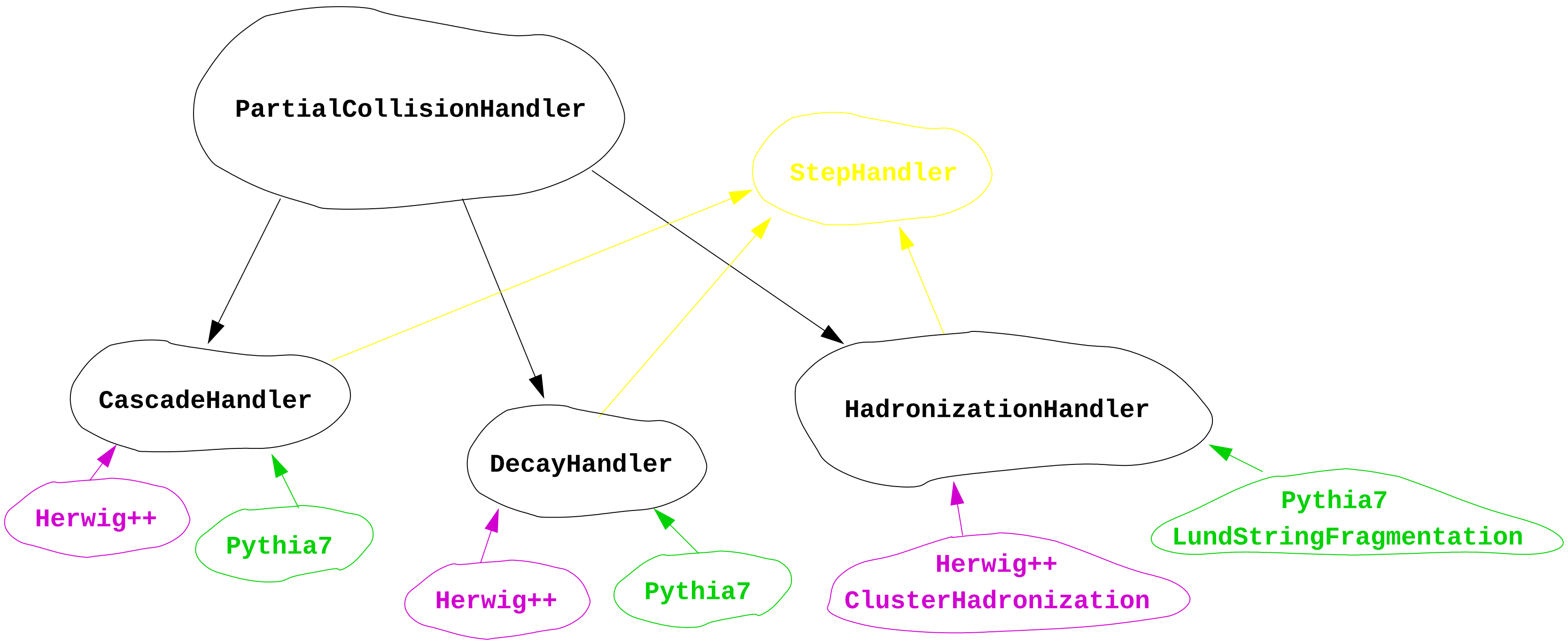
independent *physics* implementation

large but very flexible implementation taking full advantage of the object oriented paradigms

Common basis for Pythia7/Herwig++:

- lack of independence
- miss the possiblity to test codes against each other
- physics, however, is still independent
- beneficial for the user to have the same framework (even a graphical interface?)

PartialCollisionHandlers



New evolution variables

Kinematics to allow better treatment of heavy particles, avoiding

- overlapping regions in phase space, in particular for soft emissions
- dead cones

We choose $\tilde{q}^2$ as new evolution variable,

$$\tilde{q}^2 = \frac{\boldsymbol{p}^2}{z^2(1-z)^2} + \frac{m^2}{z^2}$$

with the agument of running α_S chosen according to

$$\alpha_S(z^2(1-z)^2\tilde{q}^2)$$

angular ordering

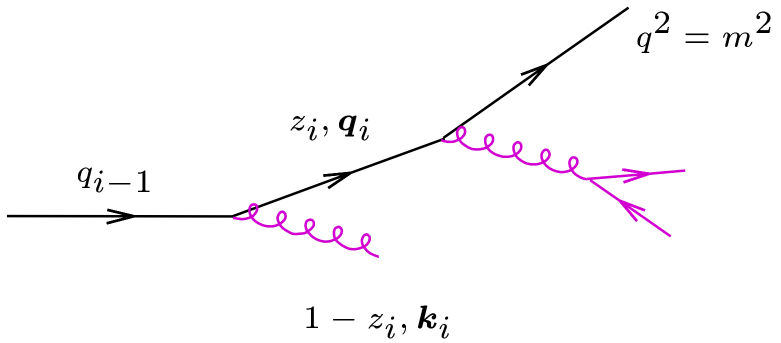
$$\tilde{q}_{i+1} < z_i\tilde{q}_i \qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_i$$

Technically: *reinterpretation* of known evolution variables, i.e. the branching probability for $a \to bc$ still is

$$dP(a \to bc) = \frac{d\tilde{q}^2}{\tilde{q}^2}\frac{C_i\alpha_S}{2\pi}P_{bc}(z)\,dz$$

$\longrightarrow$ Sudakov's etc. technically remain the same!

Kinematics



Sudakov basis p, n with $p^2 = m^2$, $n^2 = 0$,

$$q_i = \alpha_i p + \beta_i n + \boldsymbol{q}_i$$

Longitudinal splitting

$$\alpha_i = z_i \alpha_{i-1}$$

transverse momenta reconstructed from $\boldsymbol{p}_i$,

$$\boldsymbol{q}_i = \boldsymbol{p}_i + z_i \boldsymbol{q}_{i-1} \qquad \boldsymbol{k}_i = -\boldsymbol{p}_i + (1 - z_i)\boldsymbol{q}_{i-1}$$

Azimuthal angle φ still chosen randomly or as a result of *azimuthal spin correlations* (planned) β_i from virtuality q_i

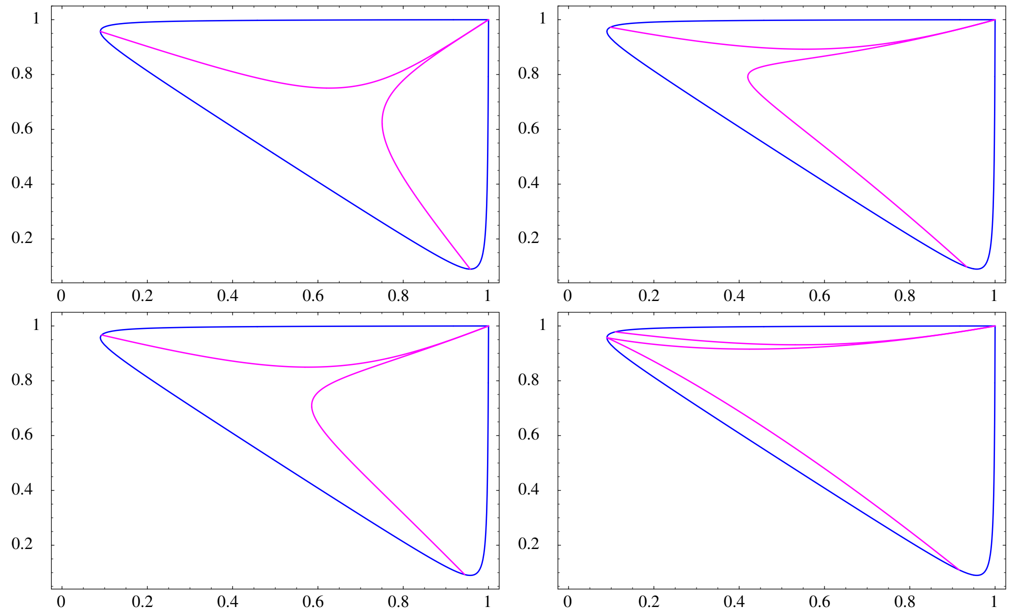
$$\beta_i = \frac{\boldsymbol{q}_i^2 + q_i^2 - \alpha_i^2 m^2}{2p \cdot n \alpha_i}$$

with recursive reconstruction of virtualities from

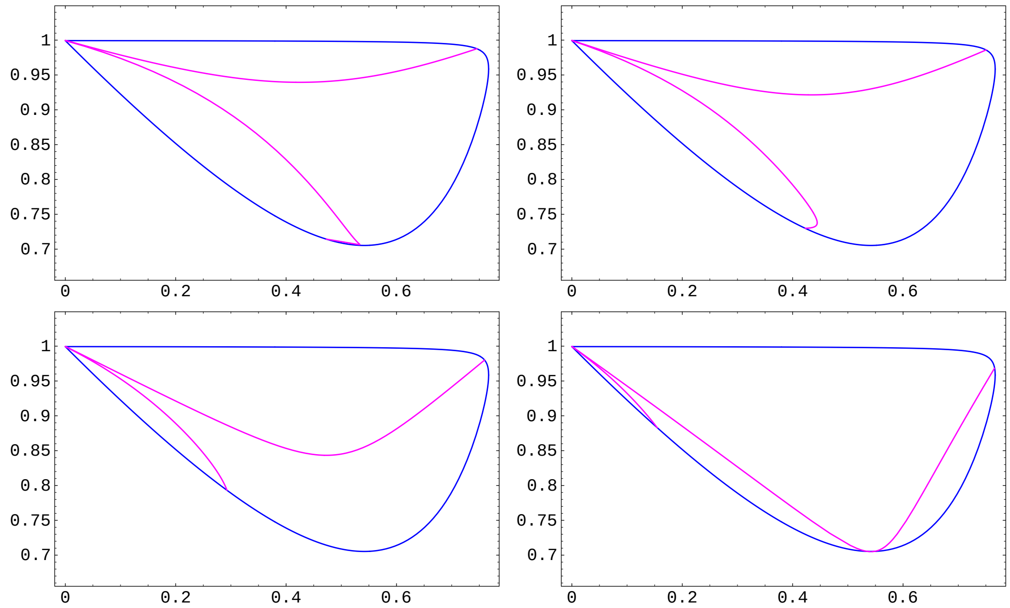
$$q_{i-1}^2 = \frac{q_i^2}{z_i} + \frac{k_i^2}{1 - z_i} + \frac{\boldsymbol{p}_i^2}{z_i(1 - z_i)}$$

Phase space coverage

$e^+e^- \to q\bar{q}g$

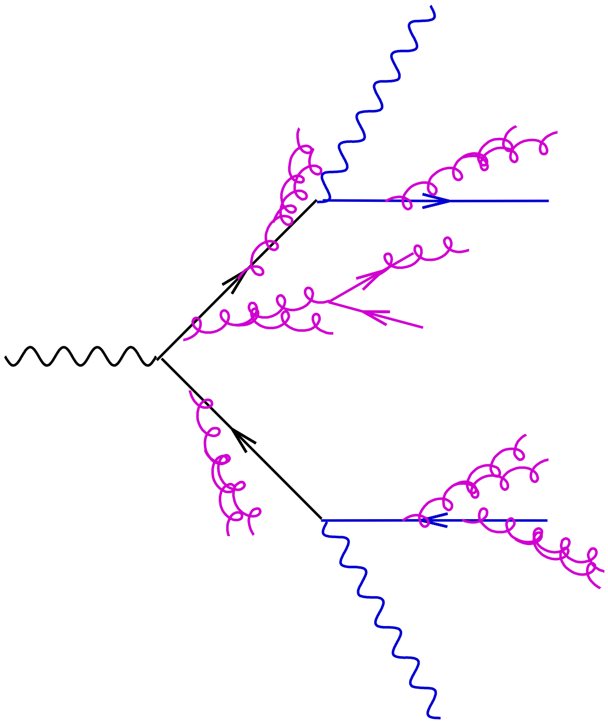


$t \to Wbg$



- smooth coverage of the soft region is achieved by choosing appropriate limiting values for the parton shower
- soft ME correction can be applied without double counting

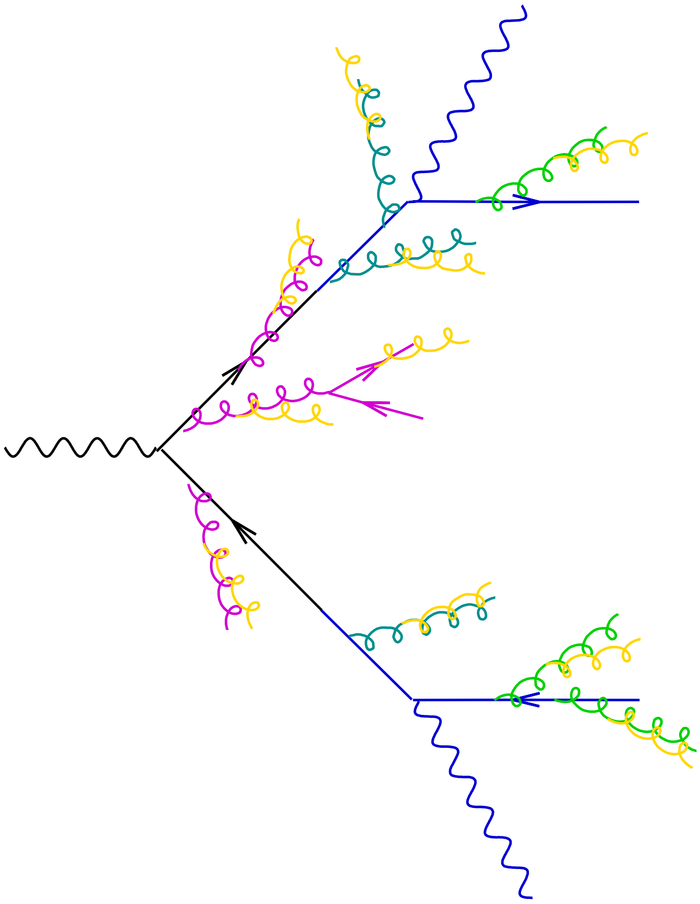
t-decay in recent Herwig



1. hard process $e^+e^- \to t\bar{t}$
2. radiation from t, $\bar{t}$ ($\hat{s} \to \mu_0$)
3. decay $t \to Wb$, $\bar{t} \to W\bar{b}$,
4. radiation from b, $\bar{b}$ ($m_t \to \mu_0$)

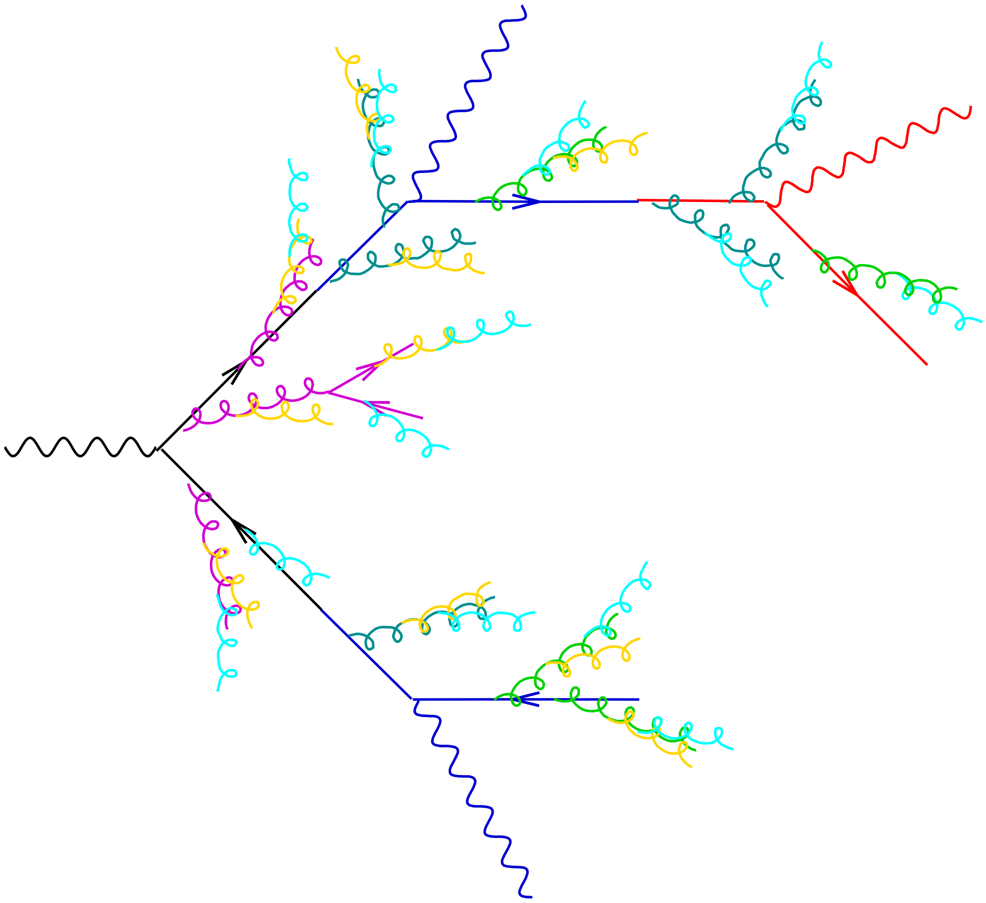
Radiation down to μ_0, ignoring the finite width Γ_t.

Multiscale Shower I



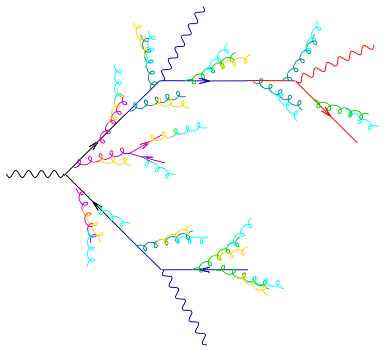
1. hard process $e^+e^- \to t\bar{t}$
2. `showerNormally()` ($\hat{s} \to \Gamma_t$) from t, $\bar{t}$
3. decay $t \to Wb$, $\bar{t} \to W\bar{b}$,
4. `showerDecay()` ($m_t \to \Gamma_t$) from t, $\bar{t}$ (DIS-like)
5. `showerDecay()` ($m_t \to \Gamma_t$) from b, $\bar{b}$
6. `showerGlobally()` ($\Gamma_t \to \Gamma_b$) everywhere

Multiscale Shower II



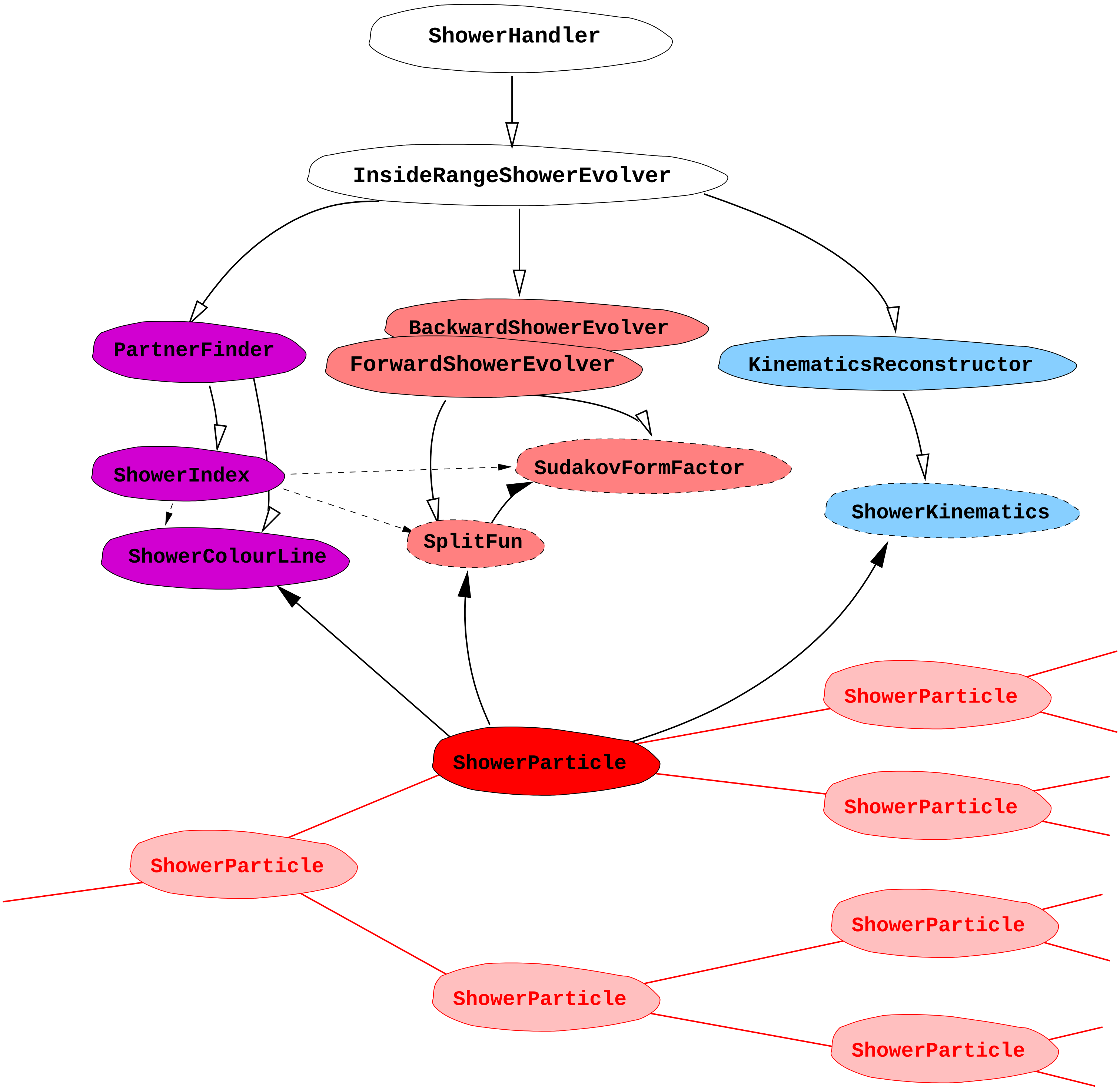
1. hard process $e^+e^- \to t\bar{t}$
2. `showerNormally()` ($\hat{s} \to \Gamma_t$) from t, $\bar{t}$
3. decay $t \to Wb$, $\bar{t} \to W\bar{b}$,
4. `showerDecay()` ($m_t \to \Gamma_t$) from t, $\bar{t}$ (DIS-like)
5. `showerDecay()` ($m_t \to \Gamma_t$) from b, $\bar{b}$
6. `showerGlobally()` ($\Gamma_t \to \Gamma_b$) everywhere
7. suppose b is some unstable particle, $b \to \mathrm{whatever};$ $\mu_0 \to \Gamma_b$
8. `showerDecay()` ($m_b \to \Gamma_b$) from b, $\bar{b}$ (DIS-like) and `showerDecay()` ($m_b \to \Gamma_b$) from b', $\bar{b}'$
9. `showerGlobally()` ($\Gamma_b \to \mu_0$) everywhere

Multiscale Shower

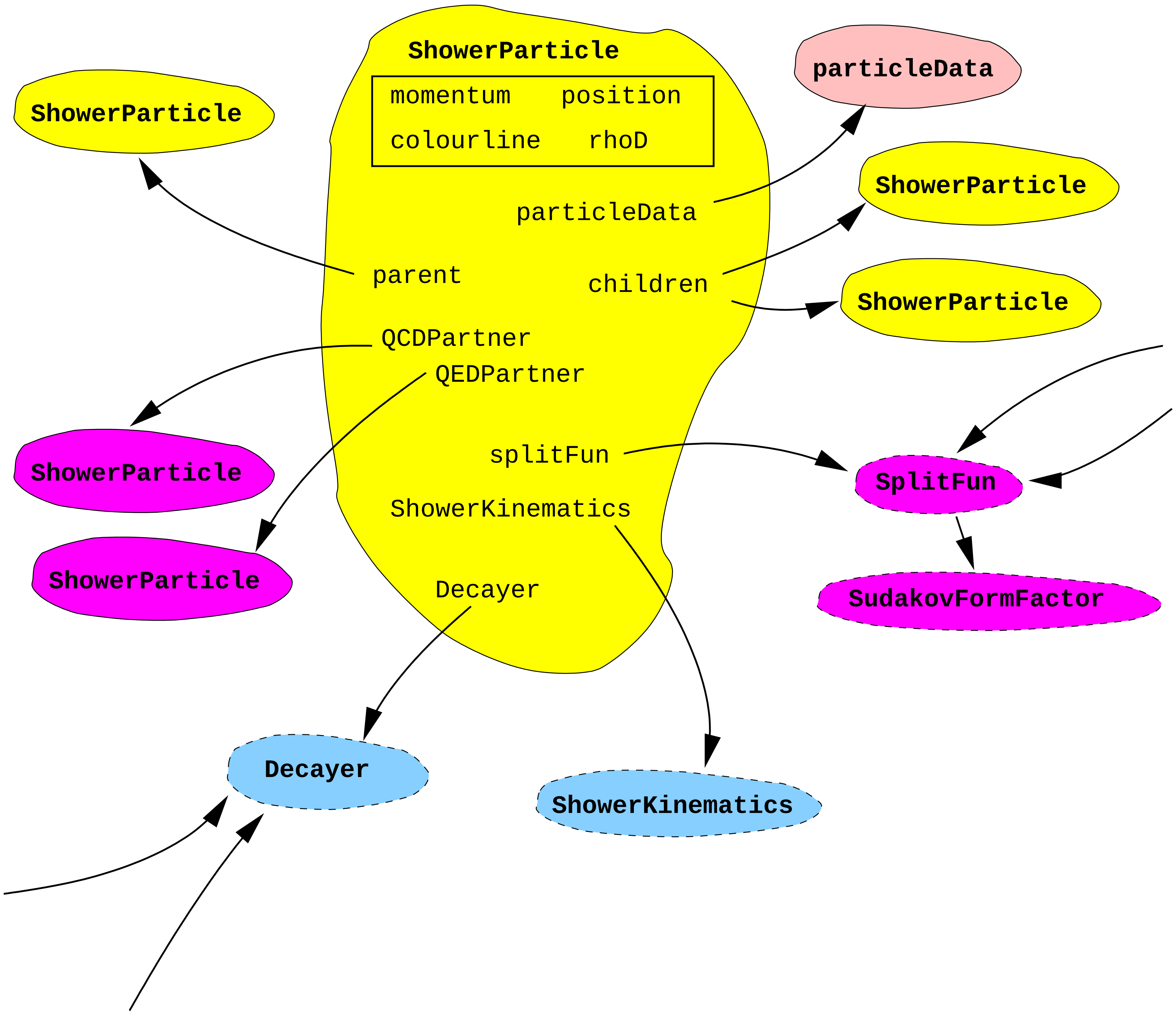


- Classes for multiscale shower are implemented and algorithms are designed appropriately.
- 'concrete' code yet incomplete.
- `FORTRAN HERWIG` should be reproduced with appropriate switches (`multiScaleShower=OFF`) and (`decayBeforeShower=ON`) for SUSY particles.
- SUSY particles might shower as well.
- photon radiation already implemented
- EW interactions foreseen, can be included easily

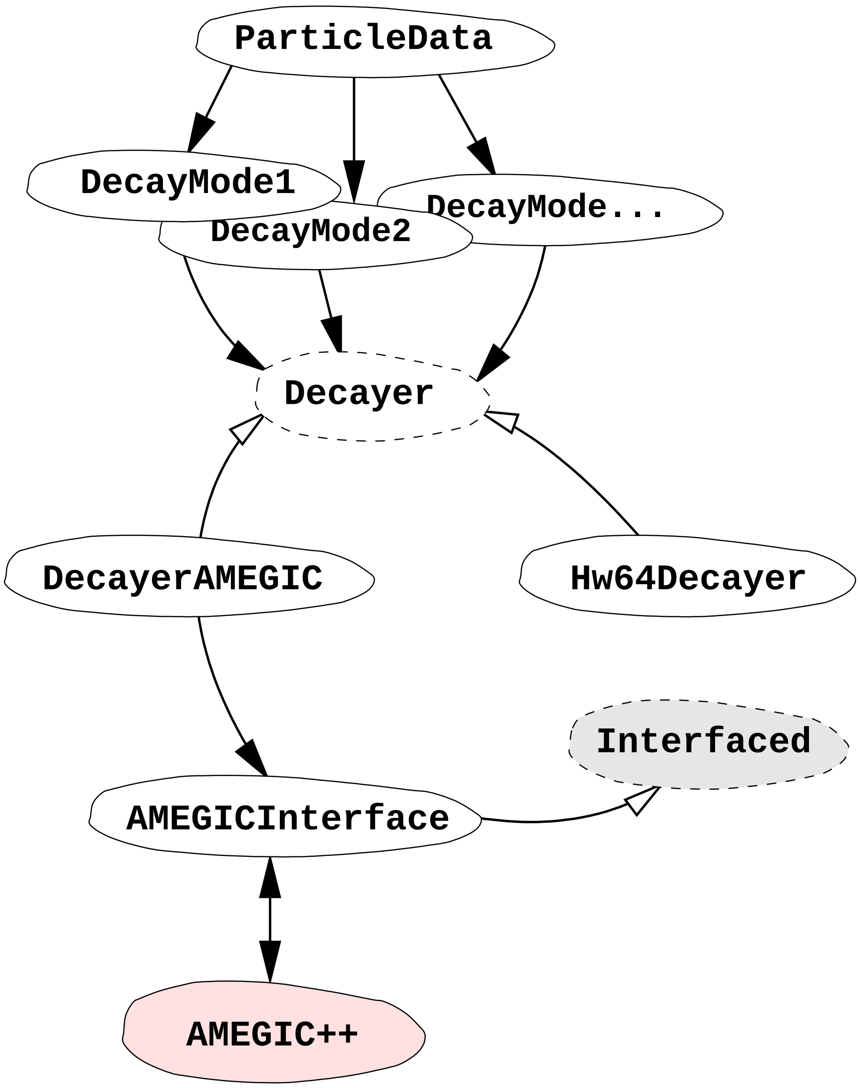
Shower Classes



ShowerParticle



Decays



- FORTRAN HERWIG is reproduced with Hw64Decayer using the same Matrix element codes as before (will be used for hadronic decays right now)
- DecayerAMEGIC gets final states for a decay mode directly from AMEGIC++
- works fine in principle, further tests required

Hard interactions

- some basic ME's included in Pythia7
- check them/provide our own extended set
- `AMEGIC++` may provide arbitrary ME's for multiparton final states
- ME corrections are foreseen in parton shower. At least one of the previously discussed possibilities to include higher orders will be implemented.
- other authors can easily include their own matrix elements ($\rightarrow$ *safety* of OO code) (NLO matrix elements?)

Hadronization

- Cluster Hadronization is designed, implemented and debugged
- works fine, however, further running with the full event generator might discover yet hidden bugs
- aside, also the Lund String model is implemented already in Pythia7 and will work together with `Herwig++`
- this requires that final state gluons are on-shell
  $\rightarrow$ foreseen in the design of the shower

Summary/Conclusions/Future

Matrix elements and parton showers (Thanks to F. Krauss, P. Richardson, B. Webber for helpful comments)

- Higher Orders (NLLA, NLO)
- ME corrections (soft, hard)
- Matching ME+PS (various attempts)
- Merging NLO ME+PS: MC@NLO

Herwig++ (in collaboration with A. Ribon, M.H. Seymour, P. Stephens, B. Webber)

- Herwig++ is on its way!
  - new variables under control
  - very general shower design complete
  - implementation of shower, first `FORTRAN HERWIG`-like, ongoing and appears to work fine so far
  - multiscale shower will be developed continuously
- partonic decays from `AMEGIC++` work
- hadronic decays `FORTRAN HERWIG`-like work
- cluster hadronization complete
- a very preliminary schedule is
  - end of 2002: β-version for LEP1-events with `FORTRAN HERWIG` features.
  - 2003: complete multiscale shower, first release?
  - 2004: a version for LHC?