Next Generation Parton Shower MC's

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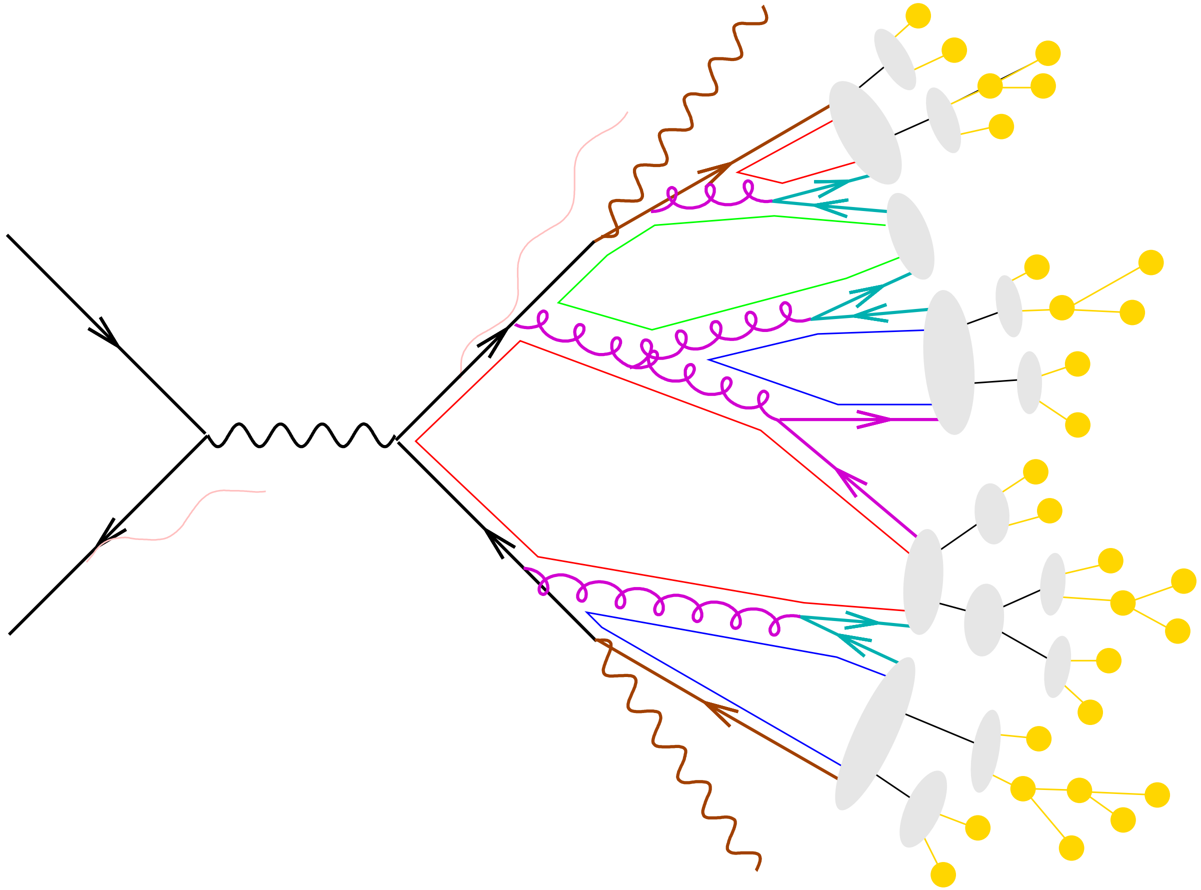
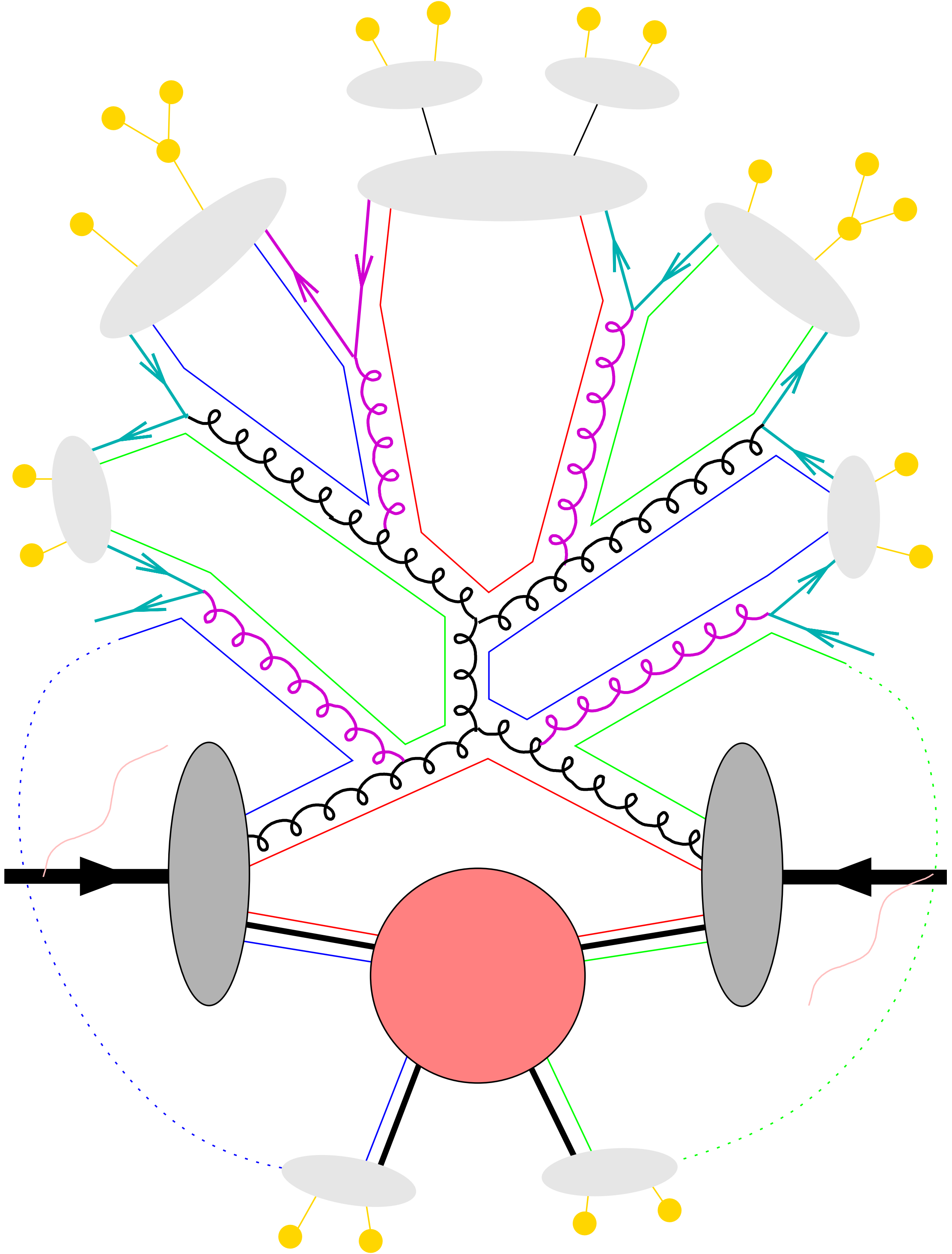
- Brief Introduction: Event Generators
- New Codes
  - SHERPA
  - Pythia7
  - Herwig++
- What's Next?

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 pp



+ backward parton evolution
+ soft underlying event

Parton Showers

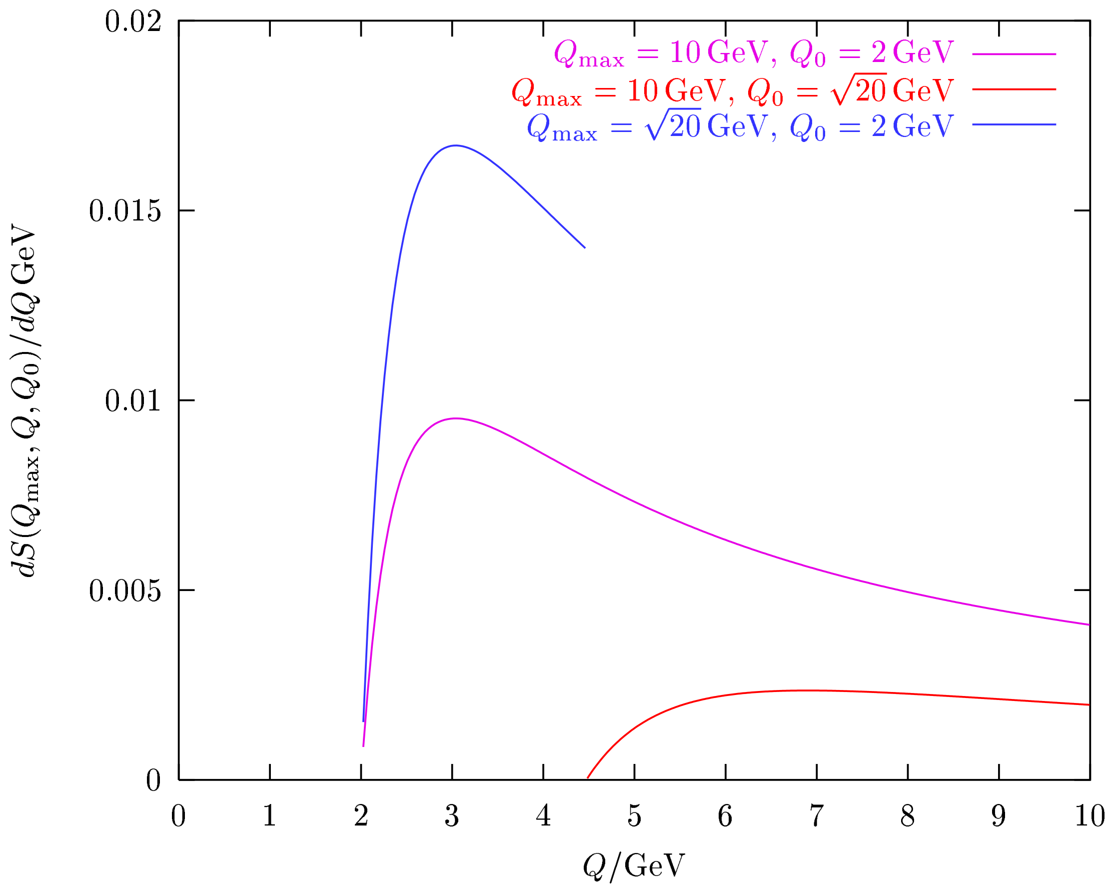
(timelike) Sudakov Form Factor: parton i at scale t_1 remains unresolved down to t when a minimum scale of t_0 is being resolved:

$$S_i(t, t_1; t_0) = \frac{\Delta_i(t_0, t)}{\Delta_i(t_0, t_1)}$$

with

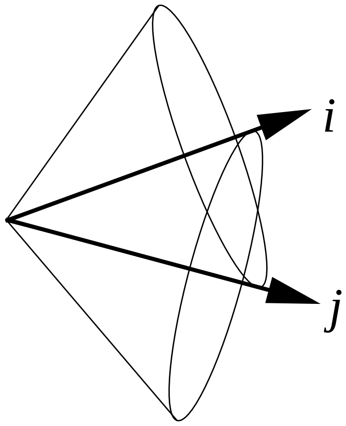
$$\log \Delta_i(t_a, t_b) = -\int_{t_a}^{t_b} \frac{dt}{t} \sum_j \int_{z_0(t)}^{z_1(t)} dz \frac{\alpha_s(z, t)}{4\pi} P_{ji}(z, t)$$

$$\Rightarrow P(\text{“next branching at } t\text{”}) = \frac{dS(t, t_1; t_0)}{dt}$$

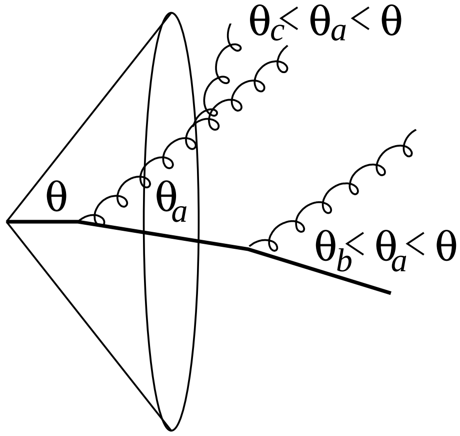


Colour Coherence/Angular Ordering

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.

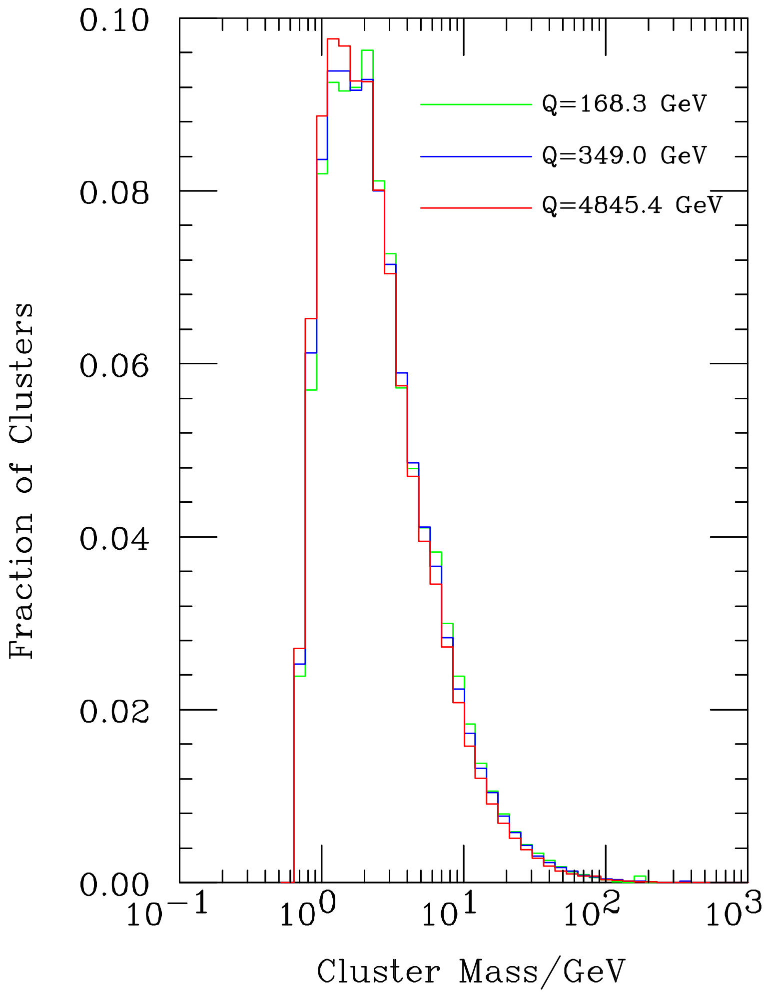


A must!

- `Herwig` evolves in opening angle
- `Pythia` incorporates appropriate vetos.
- `APACIC++`: `Pythia`-like.

Cluster Hadronization

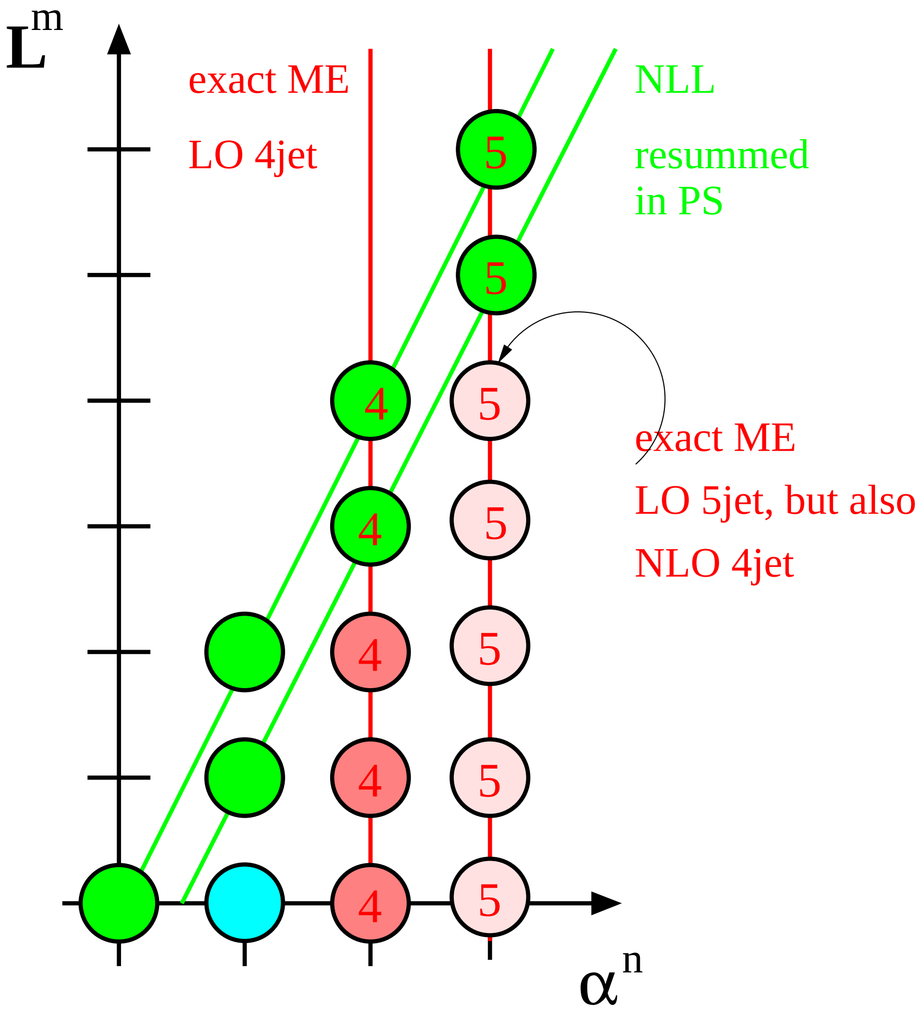
Cluster mass spectrum is independent of cm energy Q of the hard subprocess (universality, colour preconfinement)



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

Matching ME+PS

The problem:



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

(1) ME corrections (LO, case by case)

(2) combining LO ME + LO PS (general algorithm, see below)

(3) matching NLO ME + LO PS (still case by case, far from automatic, however!)

Matching ME+PS (ctd')

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

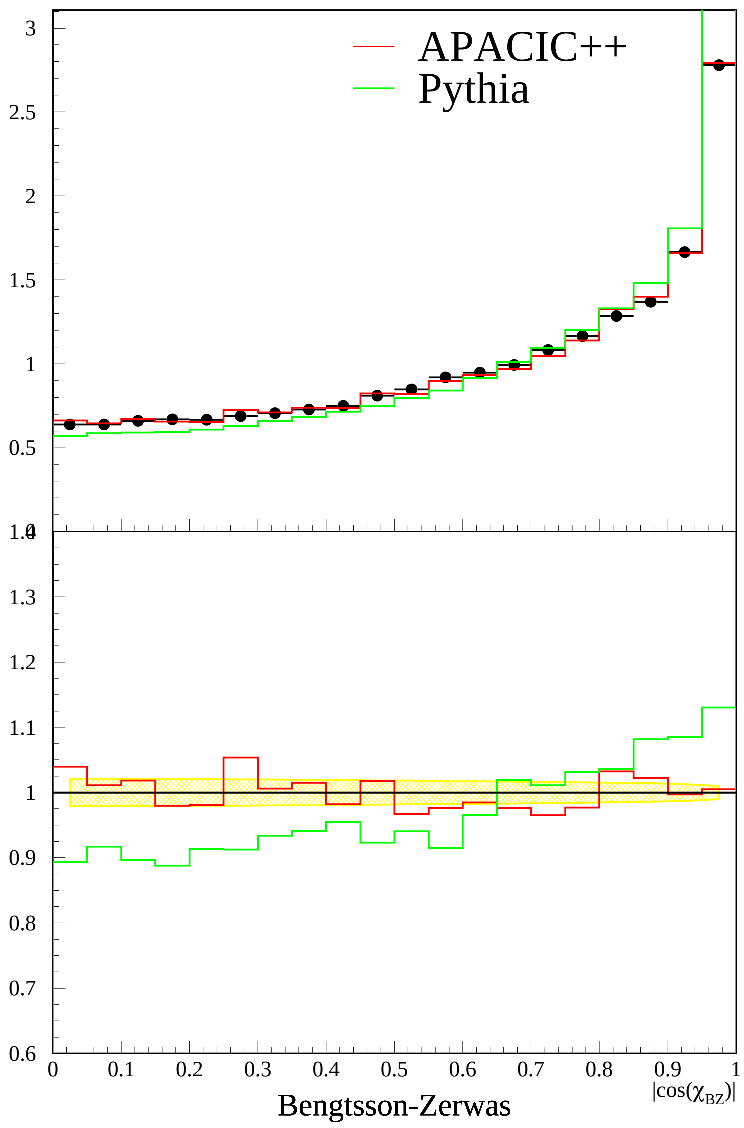
1. Generate a hard n-jet configuration acc to the known rate $R_n(Q_1, Q)$, with cm-energy Q and Durham-resolution $y_1 = Q_1^2/Q^2$.
2. Generate final state momenta acc to hard matrix element $|\mathcal{M}_n|^2$. evaluated at $\alpha_S(Q_1)$.
3. $k_\perp$-cluster backwards towards the $(n-1), (n-2),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



ME Generators

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

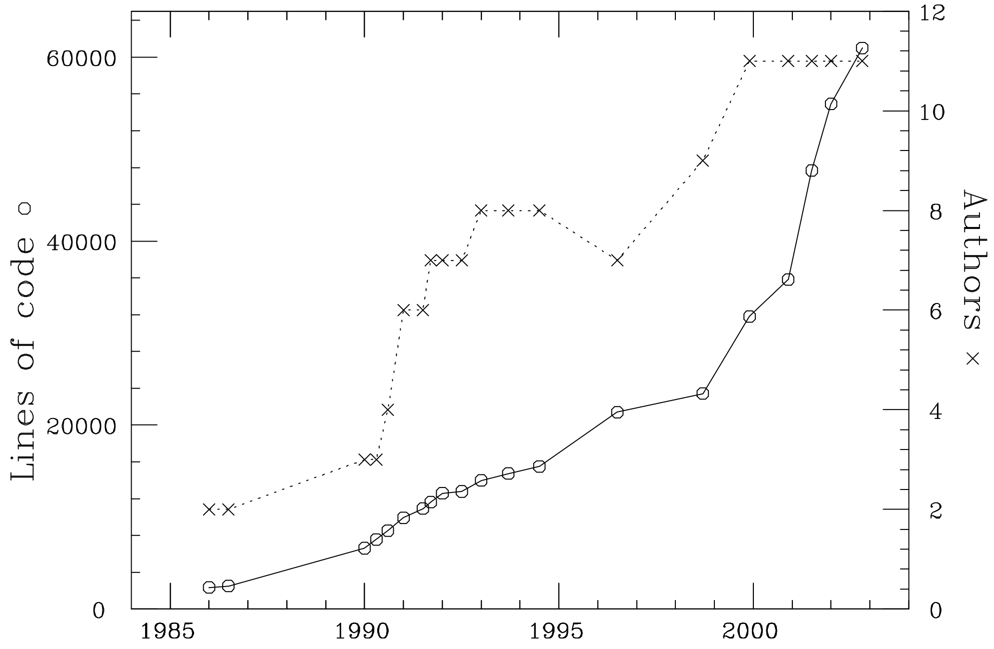
- Major issue: integrator/ps-generator comes with the ME code itself $\longrightarrow$ only realistic possibility to handle large number (> 5) of particles in FS.
- Very general.
- $e^+e^- \to VV + 4$jets feasible.
- $e^+e^- \to 4f, 6f$
- e.g. $pp \to (W \to \ell\nu) + (\leq 4)j$
- BSM, . . .

No manual interference with the program necessary! Performace in speed and precision comparable to highly specialized codes.

`MadEvent/MadGraphII` similar performance, written in Fortran.

Other examples: `CompHEP`, `AlpGen`, . . .

Why moving towards C++?



Why C++? Well. . .

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

The obvious advantages. . .

New C++ Generators

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

Pythia7 and Herwig++

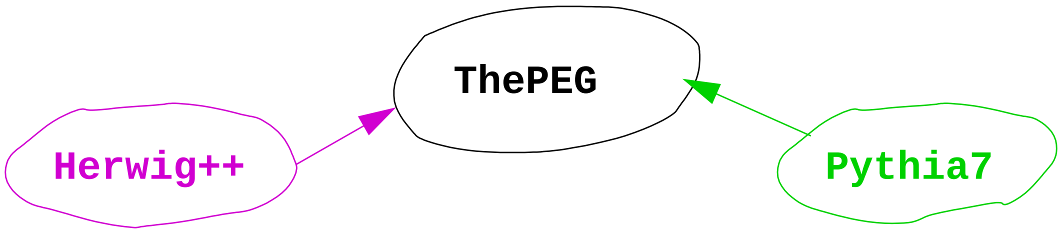
- will use a common administrative part ThePEG (formerly also known as Pythia7). Providing particle record, interfaces, overall structure.
- Pythia7, detached from the library and aims at reproducing/improving what is now known as `Pythia6.xxx`.
- Herwig++ is supposed to do the same job for what is know the latest version, `HERWIG 6.5`.

SHERPA

- completely independent.
- unifies the codes APACIC++ and AMEGIC++ in a common framework.
- adds new modules.

Use of ThePEG in Herwig++

*T*oolkit for *h*igh *e*nergy *P*hysics *E*vent *G*eneration



Won't re-invent the wheel

Share administrative overhead, common to event generators with Pythia7

Independent *physics* implementation

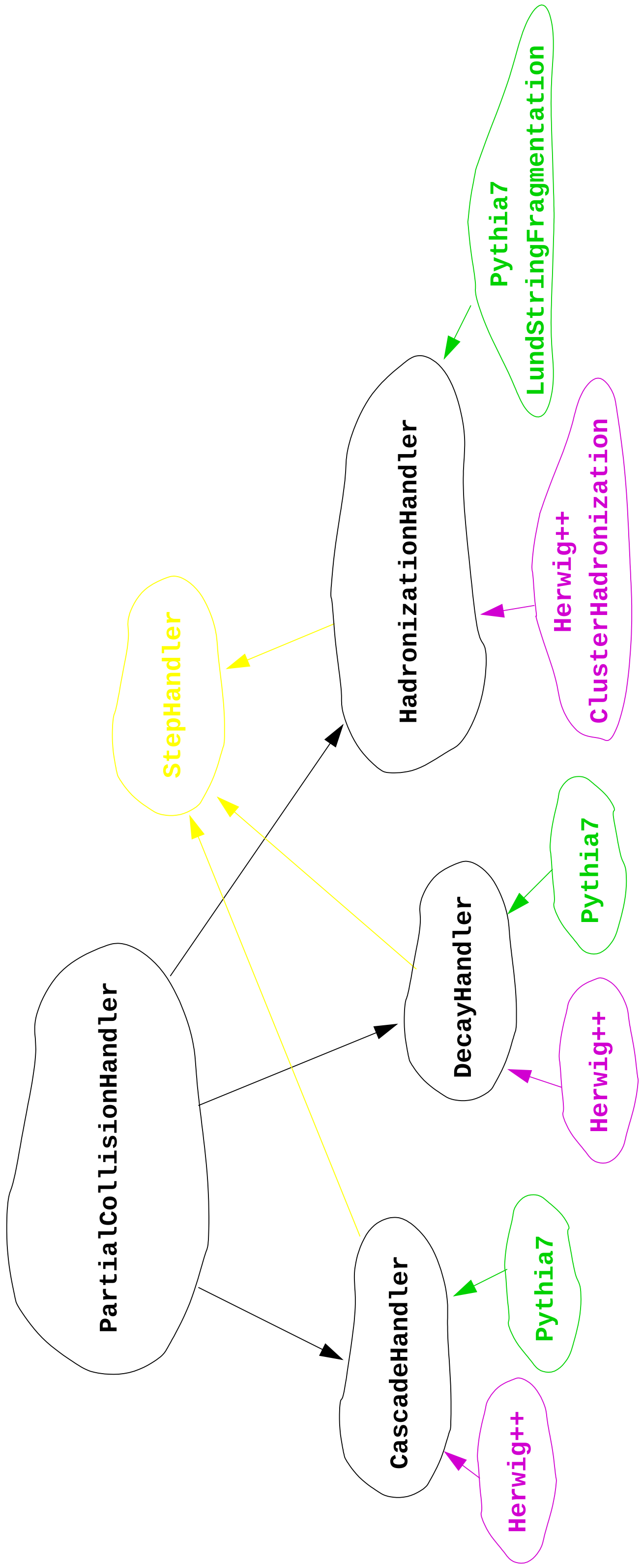
Large but very flexible implementation

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.
- Running Herwig++ with the Lund String Fragmentation from Pythia7 is very simple!

PartialCollisionHandlers

How Herwig++/Pythia7 link into ThePEG



Hard interactions

- Basic $2 \to 2$ processes included in ThePEG.
- Check them/provide our own extended set.
- `AMEGIC++` may provide arbitrary ME's for multiparton final states
- ME+PS matching will be implemented.
- other authors can easily include their own matrix elements ($\to$ *safety* of OO code) (NLO matrix elements?)

New evolution variables

Kinematics to allow better treatment of heavy particles, avoiding overlapping regions in phase space, in particular for soft emissions

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

$$\tilde{q}^2 = \frac{\boldsymbol{p}^2}{z^2(1-z)^2} + \frac{m^2}{z^2} \quad \text{for} \quad q \to qg$$

and with the agument of running α_S chosen according to

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

angular ordering

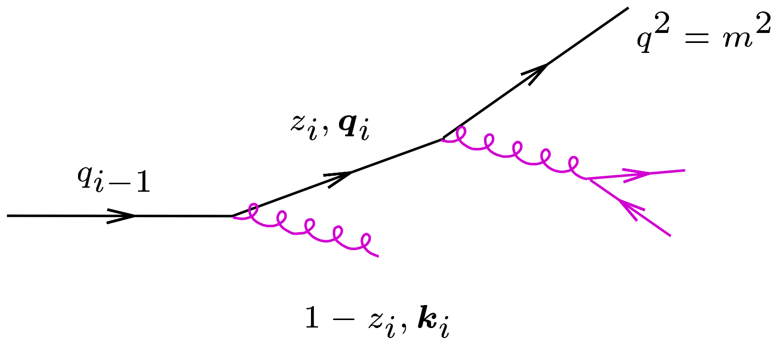
$$\tilde{q}_{i+1} < z_i \tilde{q}_i \qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_i$$

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

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

$\longrightarrow$ 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

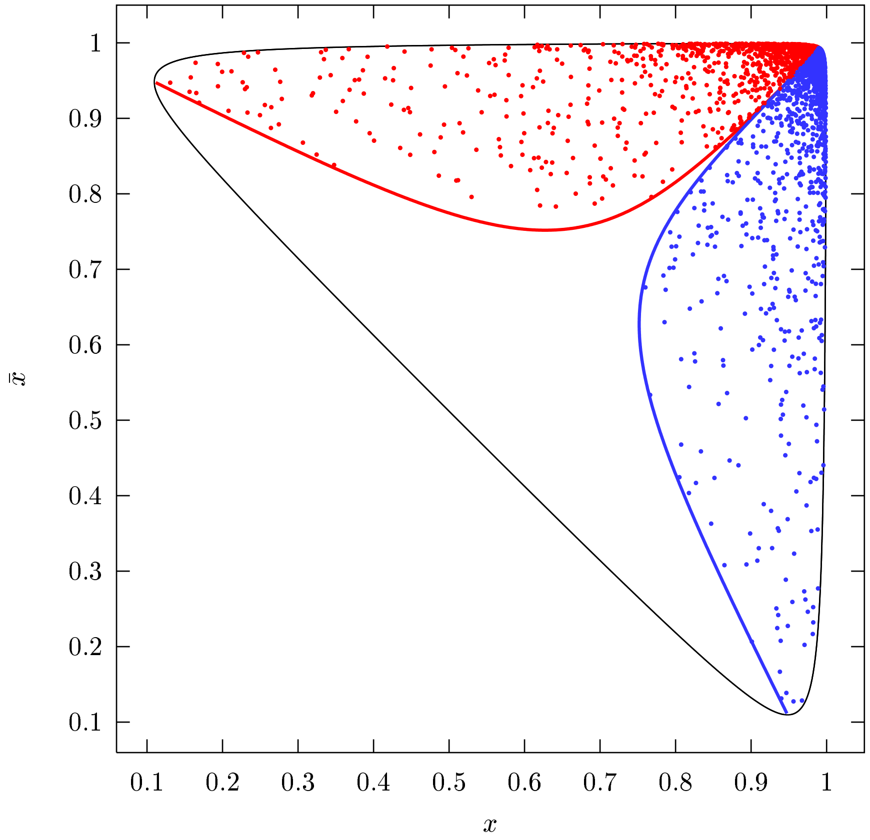
$$\beta_i = \frac{\boldsymbol{q}_i^2 + q_i^2 - \alpha_i^2 m^2}{2p \cdot n \alpha_i}$$

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

Consider $e^+e^- \to q\bar{q}g$ phase space (here: $b\bar{b}$ at LEP)

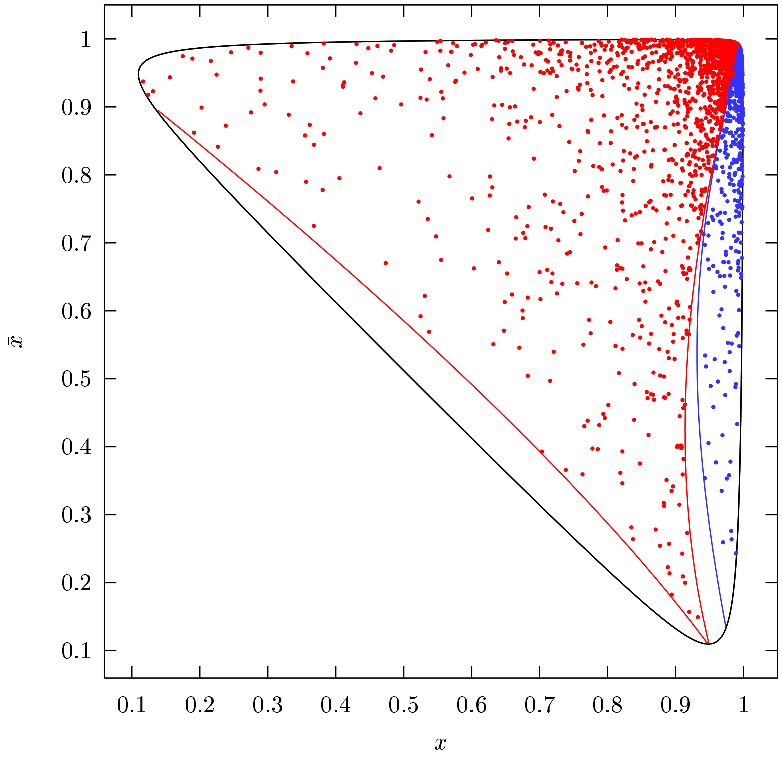


Only one gluon emitted, dots from Herwig++ parton shower with new variables.

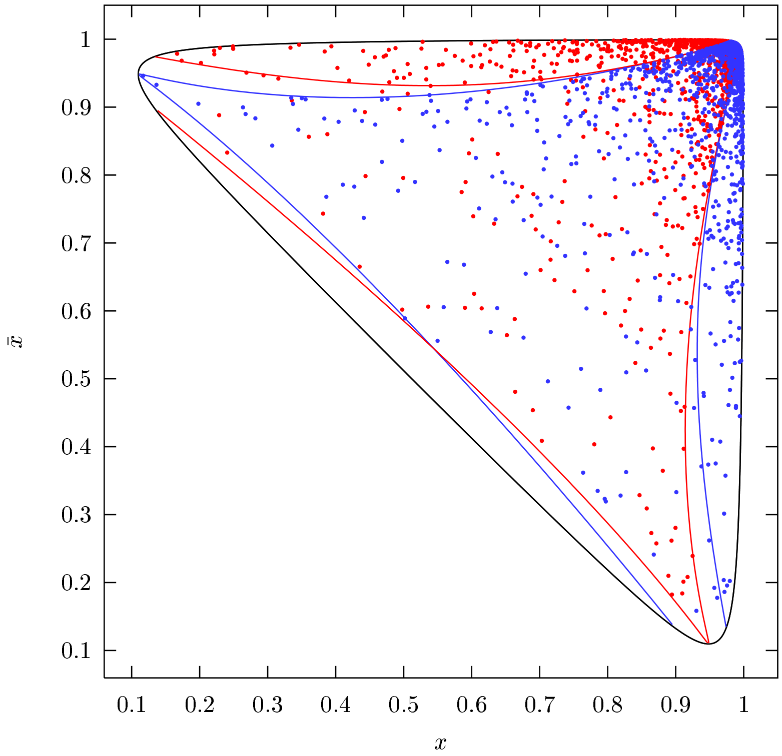
- smooth coverage of the soft region is achieved by choosing appropriate initial conditions for the parton shower
- soft ME correction can be applied without double counting

More Phase Space Coverage

Choose most asymmetric initial conditions. . .



. . . and symmetrize the phase space randomly



Status of Herwig++

S. Gieseke, A. Ribon, M.H. Seymour, P. Stephens, B.R. Webber
(Cambridge, Manchester, CERN)
http://www.hep.phy.cam.ac.uk/~gieseke/Herwig++

Hard Matrix Elements

- Simple $2 \to 2$ ME so far.
- We have a working interface to AMEGIC++. For e^+e^- this will do the job for up to 6 jets.
- The ME+PS matching algorithm of Catani, Krauss, Kühn and Webber will be implemented.
- More processes straightforward.
- Users can easily and safely include their own matrix elements.

Parton Shower

- New parton shower developed.
- *Multiscale shower* designed for general treatment of instable particles (no physics implementation yet).
- New evolution variables for better treatment of heavy quarks and smooth coverage of phase space.
- Extension to spacelike shower for pp and ep ongoing.

Status of Herwig++ (ctnd')

Decays

- HERWIG–decays are reproduced with a class Hw64Decayer using the same Matrix element codes as before.
- DecayerAMEGIC gets final states for a decay mode (eg. for t decay, SUSY in the future) directly from AMEGIC++
- works very well, further thorough tests required.
- More to come (EvtGen,. . .)?

Hadronization

- Cluster Hadronization is designed and implemented completely.
- Works very well, further thorough tests ongoing.
- Aside, the Lund String Fragmentation model is implemented in Pythia7 and will work together with Herwig++.
- Hadronic decays $\rightarrow$ above.

Status of Pythia7

Marc Bertini, Leif Lonnblad, Torbjorn Sjostrand
Lund University, Dept. of Theoretical Physics
http://www.thep.lu.se/~leif/Pythia7/Welcome.html

ThePEG

- Developed and tested with Pythia7 and Herwig++.
- Simple Interfaces, like conversion of event record to HepMC.

Pythia7

- Simple Matrix Elements available for e^+e^- and pp collisions.
- Parton Shower under development (planned to be ready very soon).
- Lund String Fragmentation is implemented.

What's next?

Ongoing. . .

- B fragmentation: study the effects of the new shower variables and test the shower in all respects.
- Jet multiplicities/rates: tell us about QCD physics, α_s, angular ordering etc.
- Event Shapes: test of parton shower and its interplay with hadronization.

Near Future. . .

- Initial state shower:
  - Complete implementation and tests.
- Refine e^+e^-:
  - Full CKKW ME+PS matching.
  - Precision tune to LEP data should be possible.
- with IS and FS showers running:
  - we can start to test Drell–Yan and jets in pp collisions.
  - cross check with Tevatron data and finally make predictions for the LHC.
- Underlying Event
- Hadronic Decays

Schedule?

- Ready for LHC!