Herwig: The Evolution of a Monte Carlo Event Generator

Peter Richardson

IPPP Durham

CERN: 23rd September

Outline

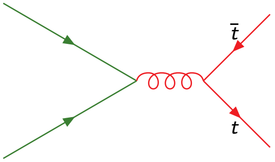
- Introduction to Event Generation
- Before C++
- The Start of Herwig++
- The Early Years of Herwig++
- Current Status
- Future Plans

Basics of Event Generation

- Monte Carlo event generators combine:
  - hard perturbative QCD calculations;
  - approximate QCD evolution from high to low energy scales using the parton shower;
  - perturbative multiple parton scattering models of the underlying event;
  - non-perturbative models of the hadronization process;
  - simulations of hadron decays;

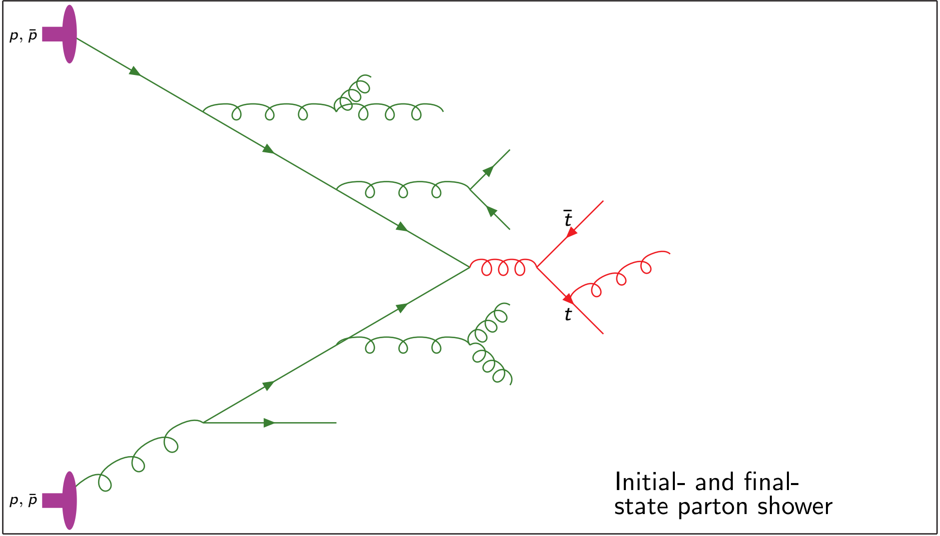
  to provide simulations of complete events.
- They have become essential tools as they both encapsulate the current theoretical understanding of hadronic collisions and produce simulated events which can be compared with data.

A Monte Carlo Event

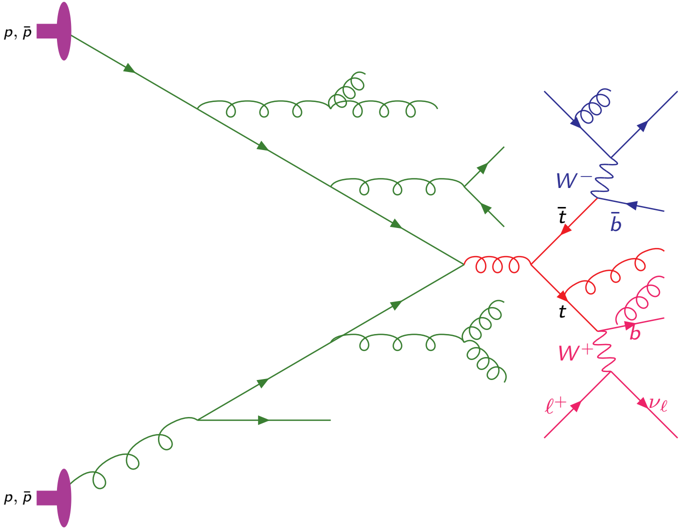


Hard Process, usually calculated at leading order

A Monte Carlo Event

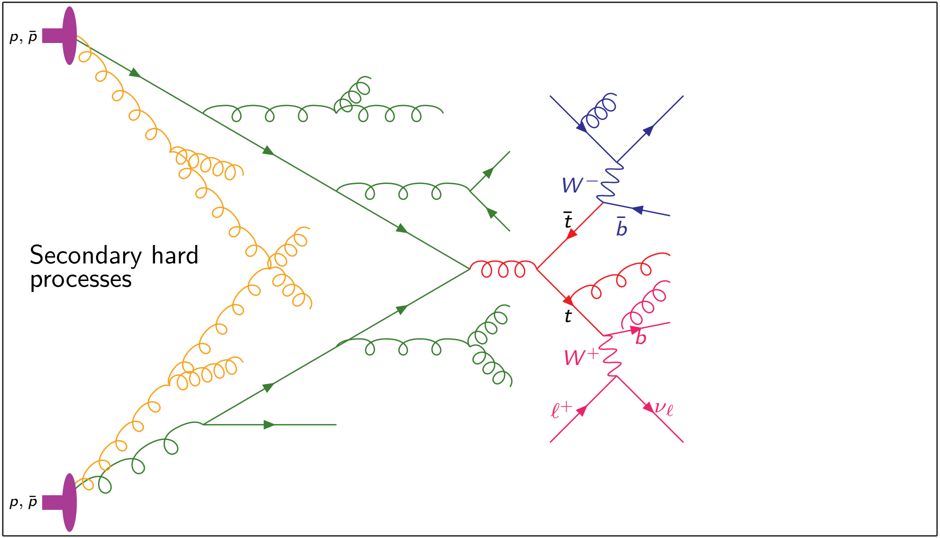


A Monte Carlo Event

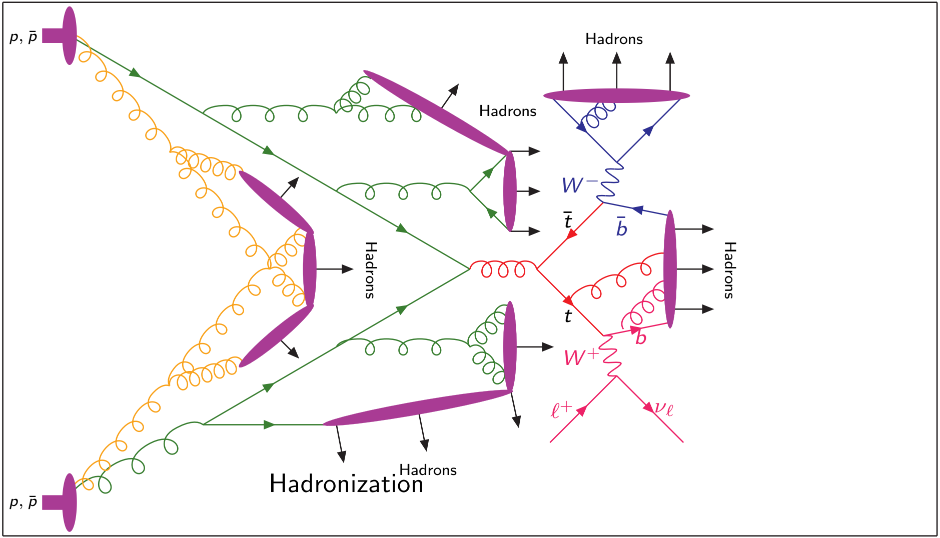


Perturbative decays of heavy particles

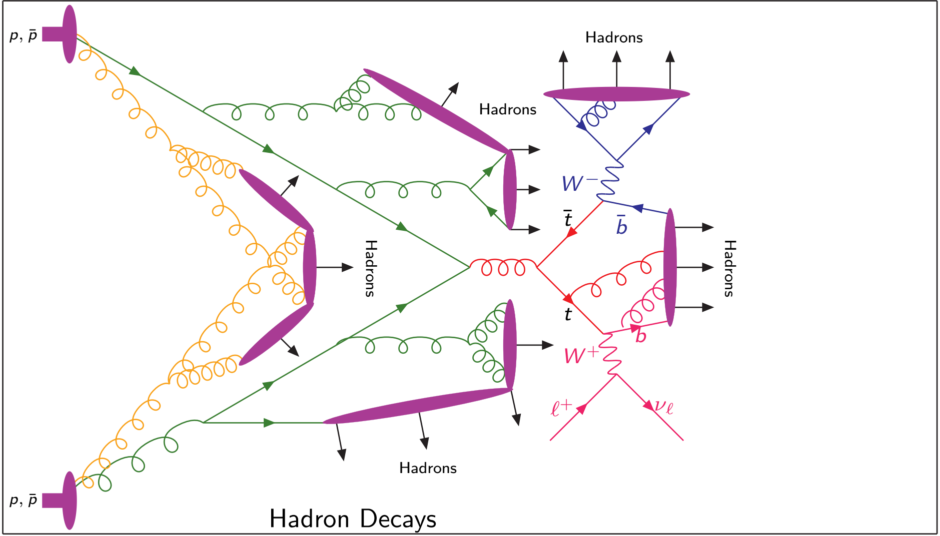
A Monte Carlo Event



A Monte Carlo Event



A Monte Carlo Event



HERWIG

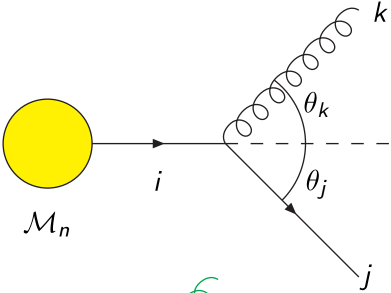
- All Monte Carlo simulations use different approximations in the parton shower evolution and different non-perturbative models.
- I will start by briefly reviewing the basic ideas of the different stages of the event generation process

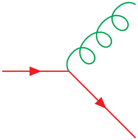
Parton Shower

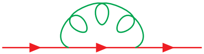
- In the collinear limit the cross section factorizes

$$\mathrm{d}\sigma_{n+1} = \mathrm{d}\sigma_n \frac{\mathrm{d}\theta^2}{\theta^2} \mathrm{d}z \frac{\alpha_S}{2\pi} P_{ji}(z).$$

- This expression is singular as $\theta \to 0$.
- Introduce a resolution criterion, e.g. $k_\perp > Q_0$.
- Combine the virtual corrections and unresolvable emission
- Unitarity: Unresolved $+$ Resolved $=1$







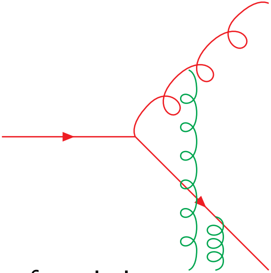
Sudakov Form Factor

- We can then exponentiate the real emission piece

$$
\begin{aligned}
P(\text{unresolved}) &= 1 - P(\text{resolved}), \\
&= 1 - \int_{q^2}^{Q^2} \frac{\mathrm{d}k^2}{k^2} \int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}} \mathrm{d}z \frac{\alpha_S}{2\pi} P_{ji}(z), + \ldots \\
&= \exp\left(- \int_{q^2}^{Q^2} \frac{\mathrm{d}k^2}{k^2} \int_{\frac{Q_0^2}{q^2}}^{1-\frac{Q_0^2}{q^2}} \mathrm{d}z \frac{\alpha_S}{2\pi} P_{ji}(z) \right).
\end{aligned}
$$

- The Sudakov form factor which is the probability of evolving between two scales and emitting no radiation.
- More strictly it is the probability of evolving from a high scale to the cut-off with no resolvable emission.

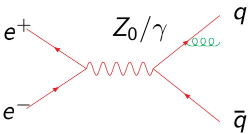
Soft Emission



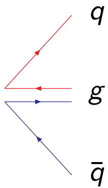
- We have only considered collinear emission. What about soft emission?
- HERWIG stared with the work of Bryan Webber and Pino Marchesini.
- Accurate treatment of QCD, in particular soft emission, was essential.
- In the soft limit the matrix element factorizes but at the amplitude level.
- Soft gluons come from all over the event.
- There is quantum interference
- Does this spoil the parton shower picture?

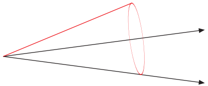
Angular Ordering

- The remarkable result is that if we take the large number of colours limit much of the interference is destructive.
- In particular if we consider the colour flow in an event.
- QCD radiation only occurs in a cone up to the direction of the colour partner.
- The best choice of evolution variable is an angular one

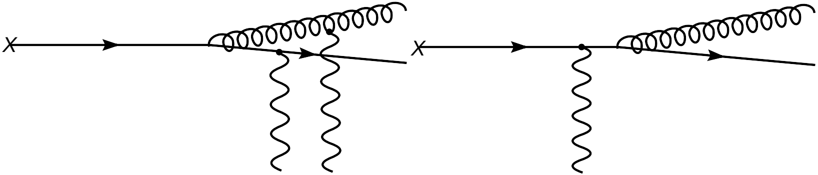


Feynman Diagram





Colour Coherence



- Wide angle soft gluons cannot resolve the difference between a gluon and "collinear" quark and gluon with the same quantum numbers, called Colour Coherence
- Angular ordering is one way of including this physics, but there are others.
- Historically the ARIADNE program handles this differently by considering the dipole emission from a pair of partons.
- In the last ten year there have been a number of developments using approaches based on Catani-Seymour subtraction "dipoles" and related approaches.

Dipole Showers

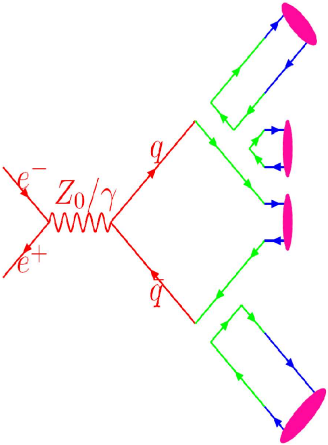
- Dipole showers have either:
  - true dipoles where the emission is from the two particles acting as a dipole;
  - the two particles forming the dipole emitting separately but with a combination of the soft and collinear emissions from the two particles treated in such a way that the correct soft and collinear limits are reproduced;
  - one particle emitting and a spectator locally absorbing the recoil to allow local momentum conservation.
- This can have important practical advantages but has comparable formal accuracy.

Hadronization

- Partons aren't physical particles: they can't propagate freely.
- We therefore need to describe the transition of the quarks and gluons in our perturbative calculations into the hadrons which can propagate freely.
- We need a phenomenological model of this process.
- There are two models which are commonly used:
  - Lund String Model;
  - Cluster Model.

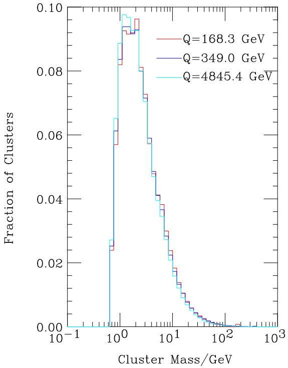
Preconfinement

- In the planar approximation, large number of colours limit: Gluon = colour-anticolour pair
- We can follow the colour structure of the parton shower.
- At the end colour-singlet pairs end up close in phase space.
- Non-perturbatively split the gluons into quark-antiquark pairs.



Preconfinement

- The mass spectrum of colour-singlet pairs is asymptotically independent of energy and the production mechanism.
- It peaks at low mass, of order the cut-off Q_0.

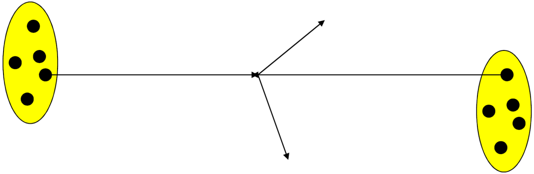


Cluster Model

- Project the colour-singlet clusters onto the continuum of high-mass mesonic resonances (=clusters).
- Decay to lighter well-known resonances and stable hadrons using a pure 2-body phase-space decay and phase space weight.
- The hadron-level properties are fully determined by the cluster mass spectrum, i.e. by the properties of the parton shower.
- The cut-off Q_0 is the crucial parameter of the model.

The Underlying Event

- Protons are extended objects.
- After a parton has been scattered out of each in the hard process what happens to the remnants?
- It is possible for the remnants to interact giving more than one scattering per proton-proton interaction.

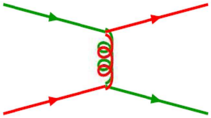


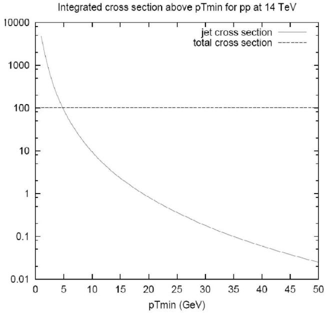
Multiparton Interaction Models

- The cross-section for $2 \rightarrow 2$ scattering is dominated by t-channel channel gluon exchange.
- It diverges like

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp^2} = \frac{1}{p_\perp^4} \quad \text{for} \quad p_\perp \rightarrow 0$$

- This must be regulated used a cut $p_\perp > p_{\perp\mathrm{min}}$.
- For small values of $p_{\perp\mathrm{min}}$ this is larger than the total hadron–hadron cross section.



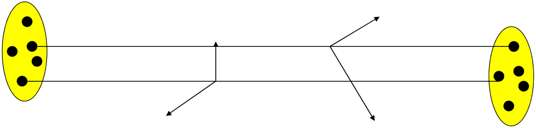


Multiparton Interaction Models

- More than one parton-parton scattering per hadron collision.
- If the interactions occur independently obeys Poissonian statistics

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

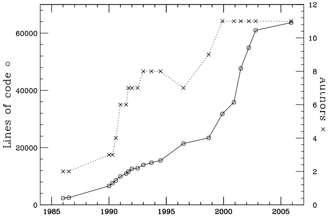
- However energy-momentum conservation tends to suppressed large numbers of parton scatterings.



- Also need a model of the spatial distribution of partons within the proton.

HERWIG

- HERWIG was originally designed as a program for understanding hadronic physics.
- In the late 1990's was used as a major simulation package for hadronic effects in
  - electroweak physics
  - searches
  - jet and heavy quark physics
  - ...
- But in ten years it had grown by a factor of 10 to 25000 lines of code without restructuring.



(Based on Mike Seymour's 1998 PPESP Presentation)

Herwig++: Beginnings

HERWIG^{++}
PPESP Presentation
Mike Seymour
November 30th 1998

HERWIG^{++} — the need for a new program

HERWIG has outgrown its original structure
Modifying or adding code very difficult due to side effects
Structure is very inflexible, eg sparton showers $\sim$ impossible

More modern modular design much more flexible and much easier to use, maintain and expand

Many important physics upgrades cannot be done without major rewriting anyway, eg:
NLL parton shower, simple matrix element matching
Improved hadronization models, eg for baryon production
Improved treatment of small x effects
Smoother perturbative $\rightarrow$ non-pert transition? (renormalon inspired)

10

HERWIG^{++}
PPESP Presentation
Mike Seymour
November 30th 1998

Aims

- To take advantage of modern developments in computing, in particular the conceptual and organizational power of object-oriented programming, embodied in languages like C^{++}.
- To include improved physics understanding that cannot readily be included within the existing framework of the program.
- To include a wider range of physics processes, especially those beyond the Standard Model which are likely to be explored at future colliders.
- To make it simpler to include further processes, both for the primary authors of the program and for other phenomenologists wishing to use it for model studies.
- To simplify the input-output and create interfaces to the detector simulation and analysis packages being developed for the LHC, which are also being written in C^{++}.
- To facilitate the understanding of the program and the physics it simulates by non-experts in general, especially students and experimentalists. In this connection we would also propose to develop an educational interface and graphic output display which would be a valuable Public Understanding resource for the whole of particle physics.

11

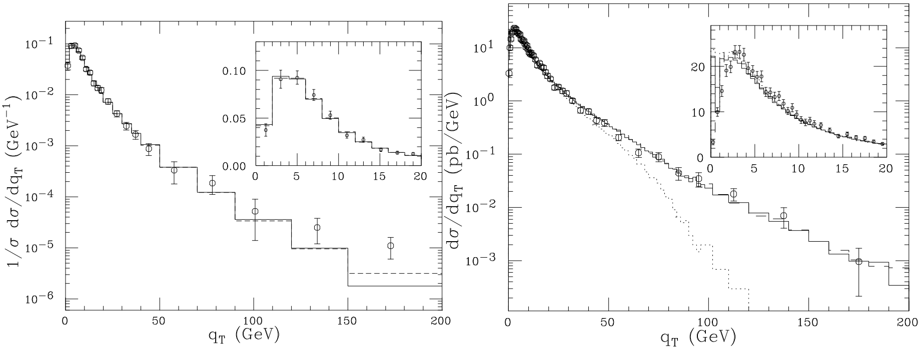
(From Mike Seymour's 1998 PPESP Presentation)

Monte Carlo event generators in 2000

It is worth considering the state-of-the-art Monte Carlo event generators in 2000.

- There were two major programs HERWIG and PYTHIA, both written in FORTRAN.
- HERWIG used an angular-ordered parton shower and PYTHIA an improved q^2 ordered shower.
- HERWIG used the cluster model and PYTHIA the string model for hadronization.
- PYTHIA had a built-in multiple parton scattering model and HERWIG used the external JIMMY package.
- All the matrix elements were leading order, with some corrections to hard radiation for specific processes.

Electroweak Gauge Boson $p_\perp$



- Matrix Element Corrections with HERWIG6, from

  Corcella and Seymour Nucl.Phys. B565 (2000) 227-244.

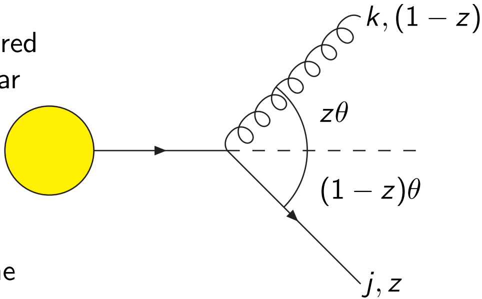
Herwig++

- Started work in 2000 with two postdocs Alberto Ribon and Stefan Gieseke implementing the simulation, together with Mike Seymour and Bryan Webber providing direction on the physics.
- The first release for e^+e^- collisions only in 2003,

  S. Gieseke, A. Ribon, M. Seymour, P. Stephens, Bryan Webber, JHEP 0402 (2004) 005
- Major improvements to the parton-shower algorithm together with more incremental developments of the cluster hadronization model.

Improved Angular-Ordered Parton Shower

S. Gieseke, P. Stephens, B. Webber JHEP 0312 (2003) 045



- The Herwig++ angular-ordered parton shower uses an angular evolution variable

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

  q and m are the virtuality the mass of radiating parton.
- Using this choice the emission probability is

$$\mathrm{d}\sigma_{n+1} = \mathrm{d}\sigma_n \frac{\mathrm{d}\tilde{q}^2}{\tilde{q}^2} \mathrm{d}z \frac{\alpha_S}{2\pi} P_{ji}(z),$$

  using quasi-collinear splitting functions to include mass effects.

Improved Angular-Ordered Parton Shower

S. Gieseke, P. Stephens, B. Webber JHEP 0312 (2003) 045

- A Sudakov decomposition is use to specify the momenta of the partons:

$$q_j = zp + \beta_j n + q_\perp;$$
$$q_k = (1-z)p + \beta_k n - q_\perp.$$

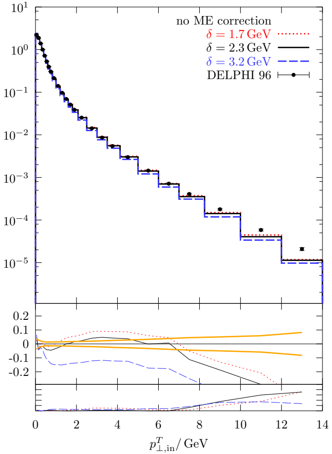
- The transverse momentum is determined from the evolution variable

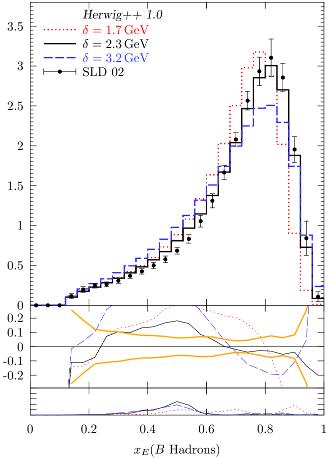
$$z(1-z)\tilde{q}^2 = -m_j^2 + \frac{m_j^2}{z} + \frac{m_k^2}{(1-z)} + \frac{q_\perp^2}{z(1-z)},$$

where the masses include an infrared virtuality cut-off.

- Momentum conservation is enforced after the shower has been generated.
- Improved treatment of mass effects and the soft limit.

Herwig++ 1.0


no ME correction
$\delta = 1.7$ GeV
$\delta = 2.3$ GeV
$\delta = 3.2$ GeV
DELPHI 96
$p^T_{\perp,\mathrm{in}}$/ GeV


Herwig++ 1.0
$\delta = 1.7$ GeV
$\delta = 2.3$ GeV
$\delta = 3.2$ GeV
SLD 02
$x_E(B$ Hadrons)

Herwig++ 2.0

S. Gieseke, D. Grellscheid, K. Hamilton, A. Ribon, P. Richardson, M.H. Seymour, P. Stephens, B.R. Webber

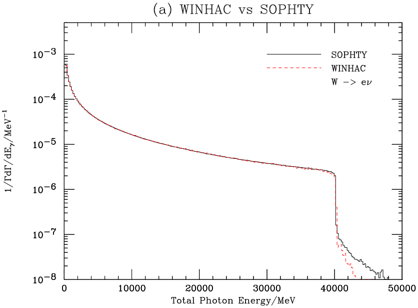
hep-ph/0609306

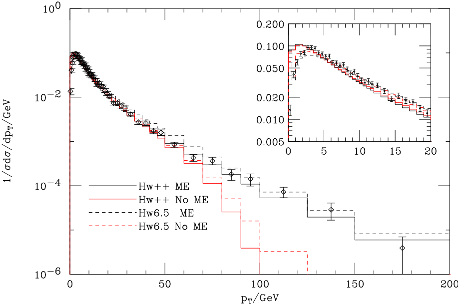
- Inclusion of a much wider range of hard processes.
- Initial-state QCD radiation together with matrix element corrections as in HERWIG
- Using UA5 soft underlying-event model.
- Still no BSM processes.
- Accurate simulation of QED in decays (not present in HERWIG)

Herwig++ 2.0

S. Gieseke, D. Grellscheid, K. Hamilton, A. Ribon, P. Richardson, M.H. Seymour, P. Stephens, B.R. Webber

hep-ph/0609306





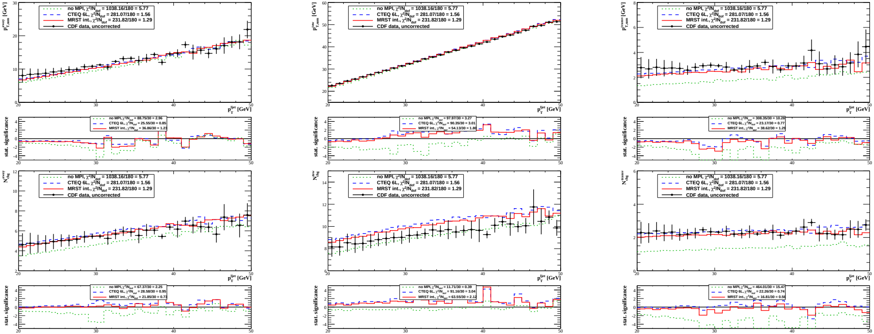
Herwig++ 2.1

M. Bähr, S. Gieseke, M. Gigg, D. Grellscheid, K. Hamilton, O. Latunde-Dada, S. Platzer, P. Richardson, M. H. Seymour, A. Sherstnev, B. R. Webber arXiv:0711.3137

- Multiple Scattering model for the underlying event
- BSM Physics
- New hadronic decay model.

Multiple Parton Interactions

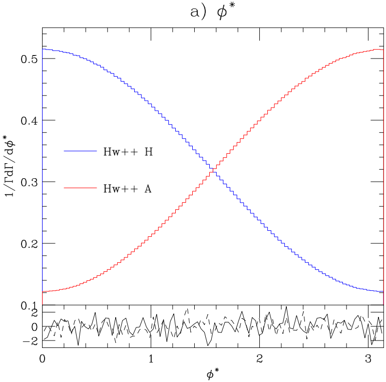
M. Bähr, S. Gieseke, M. Seymour JHEP 0807 (2008) 076

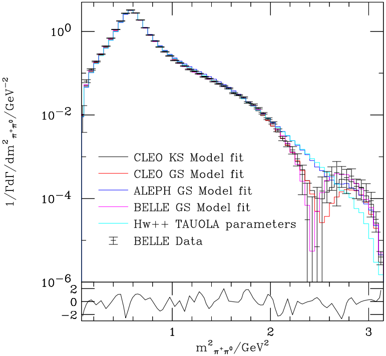


- New model with hard perturbative scatters above $p_{\perp,\mathrm{min}}$.
- and soft non-perturbative scatters below $p_{\perp,\mathrm{min}}$.

Hadron and Tau Decays

D. Grellscheid and P. Richardson





$h^0, A^0 \to \tau^+\tau^- \to \pi^+\bar{\nu}_\tau\pi^-\nu_\tau$

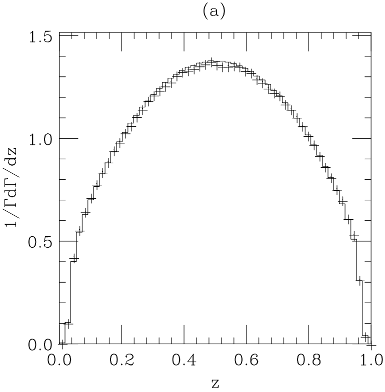
$\tau^- \to \rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau$

- New model matrix element and spin correlations for most

BSM Physics

M. Gigg, D. Grellscheid and P. Richardson

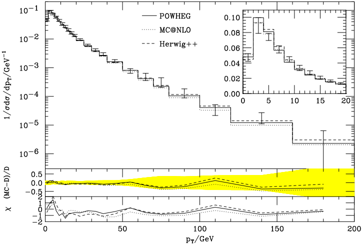
- Inclusion of automatic calculation of BSM with:
  - $1 \to 2$ and $1 \to 3$ decay modes;
  - $2 \to 2$ scattering processes;
- Still needed to code the Feynman rules, but everything is worked out from them.

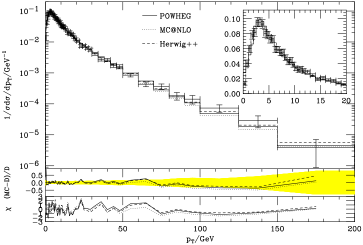


$\tilde{\tau}_L \to \tau^- \tilde{\chi}^0_1 \to \pi^- \pi^0 \nu_\tau \tilde{\chi}^0_1$

POWHEG Process in Herwig++

K. Hamilton, J. Tully, L. d'Errico, P. Richardson





Hard-coded implementations of a number of processes including truncated showers.

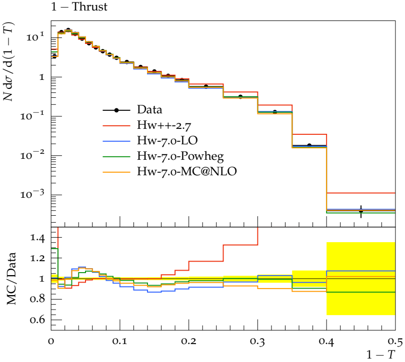
Herwig 7.0 (Herwig++ 3.0)

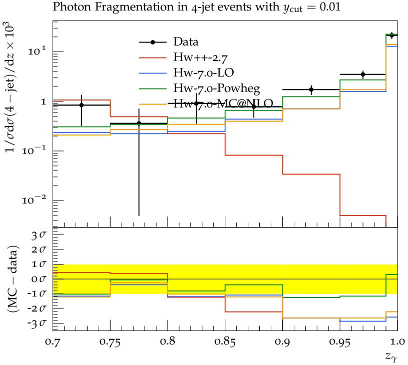
- For the the last 10 years we have been working towards a goal of a release that met a (moving) definition intended fully replace the FORTRAN HERWIG program.
- Over time that has evolved as the needs of the experimental and phenomenological communities have developed over the last ten years.
- Precision is now the key and matching to higher orders absolutely essential.

Herwig 7.0 (Herwig++3.0)

- There will be a new release in the next few weeks that meets these needs.
- Default is to have NLO matrix elements matched to the parton shower.
- Fully automated, so that users can choose their process and everything is set up for them.
- Both POWHEG and MC@NLO type matchings
- Option of two different parton showers, angular-ordered and dipole.
- Much better documentation
- Finally completely replaces FORTRAN HERWIG.

Herwig 7.0 (preliminary)

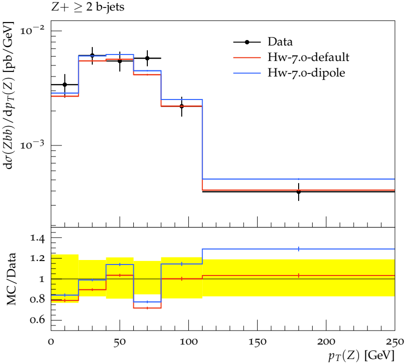


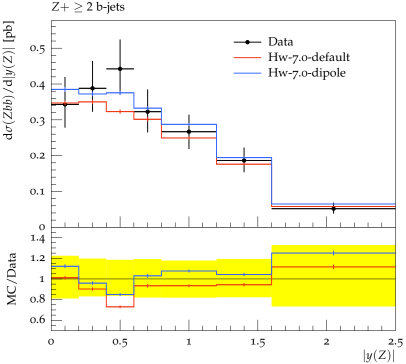


Herwig 7.0 MC@NLO Matching for $e^+e^- \to q\bar{q}$ with matrix element corrections, MC@NLO and Powheg from Z.Phys.C73:11-60,1996 and ALEPH Z.Phys.C69:365-378,1996

Herwig 7.0 NLO (preliminary)

work led by S Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle

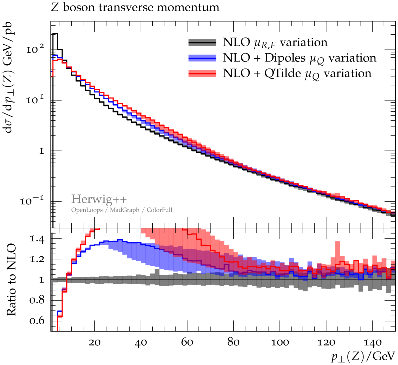


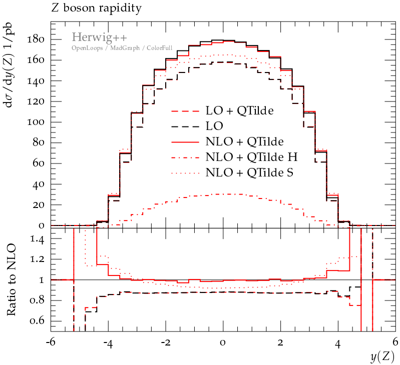


Herwig 7.0 MC@NLO Matching for $Zb\bar{b}$ for the $\tilde{q}$ and dipole showers using Madgraph+OpenLoops for LO and NLO amplitudes, data from ATLAS JHEP 1410 (2014) 141

Herwig 7.0 NLO (preliminary)

work led by S Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle

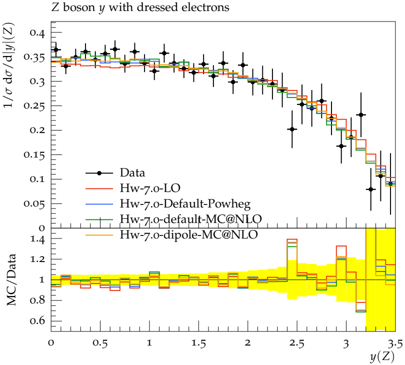


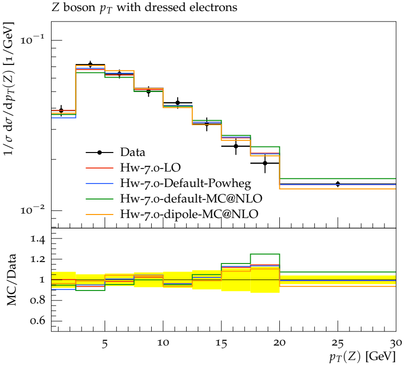


- NLO matching using MATCHBOX and the BLHA

Herwig 7.0 NLO (preliminary)

work led by S Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle

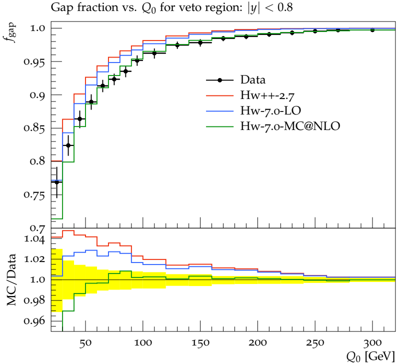


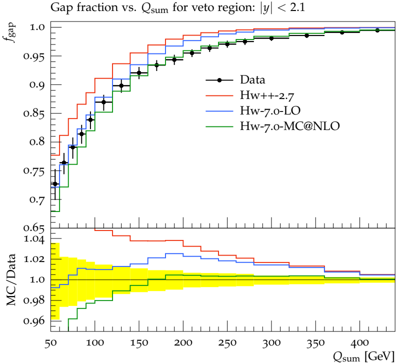


Herwig 7.0 compared to W production from CMS Phys.Rev. D85 (2012) 032002.

Herwig 7.0 NLO (preliminary)

work led by S Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle

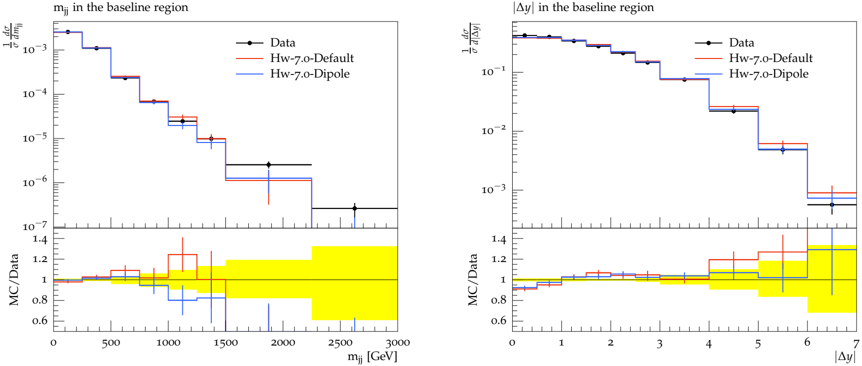




Herwig 7.0 compared to top production with a central jet veto compared to ATLAS Eur.Phys.J. C72 (2012) 2043.

Herwig 7.0 NLO (preliminary)

work led by S Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle



Herwig 7.0 MC@NLO Matching for Z+ dijets for the default and dipole showers compared to ATLAS JHEP 1404 (2014) 031.

Monte Carlo Developments: Perturbative QCD

- The last fifteen years have seen major developments in Monte Carlo event generation:

  2000 leading-order matching for some processes;
  2001 leading-order multi-jet matching for some processes;
  2002 MC@NLO matching for some processes;
  2004 Powheg matching for some processes;
  2010 NLO multi-jet matching for some processes;
  2015 automated NLO matching and multi-jet matching;
  2015 NNLO matching for some processes;

- There has been a major effort to develop the tools needed for the LHC and it has deliver way beyond what could have been foreseen 15 years ago.

Monte Carlo Related Developments: BSM Physics

- The last fifteen also seen major developments in simulating BSM physics:

  2000 hand-coded implementations of some models, several man-years of work per model;

  2007 Automatic simulation given the Feynman rules, usually in the specific format of the event generator;

  2012 automatic simulation from the Lagrangian.

Monte Carlo Developments

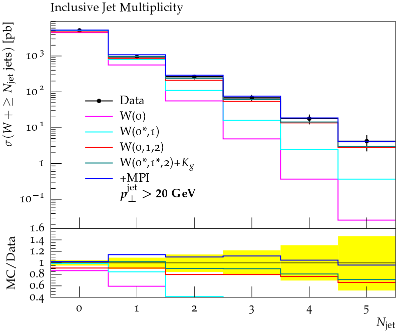
- The last ten years have also seen major developments in areas closely related to Monte Carlo event generators:
  - comparison with data RIVET;
  - tuning event generators to experimental results Professor.
- Rivet and Professor have both been strongly supported by STFC and both MCnet Marie Curie networks.
- It is noticeable that the first Herwig++ tunes were done using analyses code by Herwig++ authors using crude parameter scanning.
- The tunes to the latest versions were done, much systematically and efficiently using RIVET to compare with the data and Professor to tune the parameters.

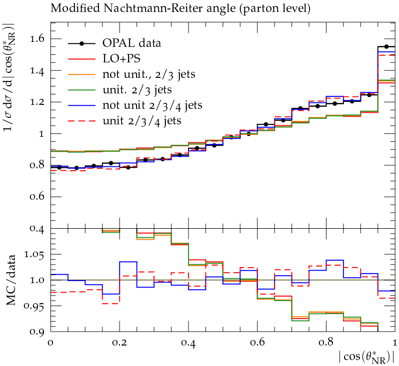
Future of Herwig: Medium Term ($\sim$ 1 year)

- Following the release we hope to produce a release including merging multiple higher-order matrix elements in near future building on the work of S. Plätzer & J. Bellm.
- Minor improvements in other areas which were not quite ready for the Herwig7.0 release.
- Given the amount of time taken to develop the simulations it is important that we exploit it to do as much phenomenology as we can during the second run of the LHC.

Herwig: Multi-Jet Merging

J. Bellm & S. Plätzer & S. Gieseke

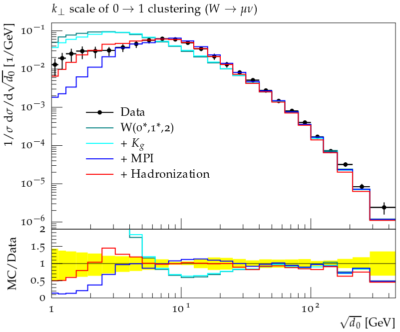


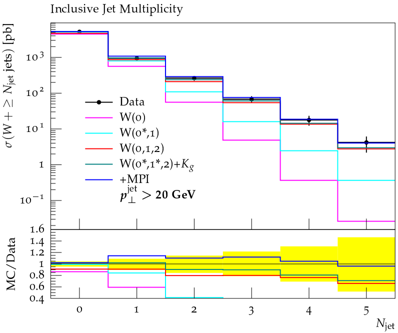


- Multi-jet NLO merging using MATCHBOX and the BLHA.

Herwig: Multi-Jet Merging

J. Bellm & S. Plätzer & S. Gieseke

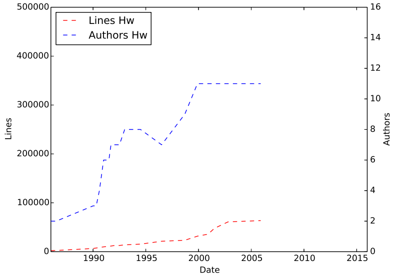




- Multi-jet NLO merging using MATCHBOX and the BLHA.

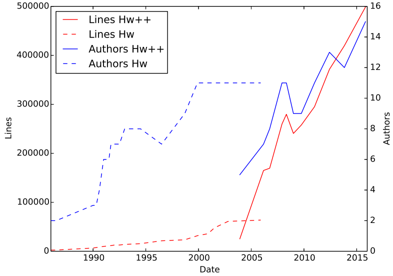
Long Term future

- We are now as far from the start of the redevelopment of Herwig as that was from the start of the project.



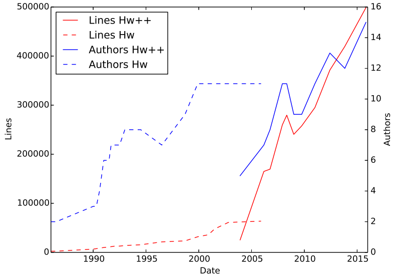
Long Term future

- We are now as far from the start of the redevelopment of Herwig as that was from the start of the project.
- The number of lines is again about a factor of 10 more than when the framework was designed.



Long Term future

- We are now as far from the start of the redevelopment of Herwig as that was from the start of the project.
- The number of lines is again about a factor of 10 more than when the framework was designed.



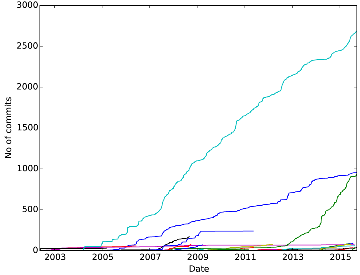
- Not as bad as for FORTRAN as the structure was better in the first place but clearly for the next stage of development some significant restructuring of parts of the code will be required.

Large theory collaborations

- With such a large collaboration there are a lot of issues in ensuring everyone gets a fair amount of credit for their work on the project.
- Clear not everyone make the same contribution.
- Amount of code/unit time $\approx$ constant, and the number of authors clear grows linear with time.
- Can't be that the amount of work done/unit time is independent of the number of people doing it!

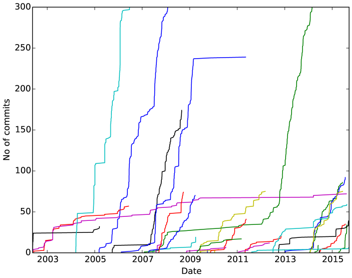
Large theory collaborations

- As in experiments some people have carried out the majority of the core infrastructure development, maintenance support, in the case of Herwig David Grellscheid, and that contribution has to be recognised just like detector builders.



Large theory collaborations

- As in experiments some people have carried out the majority of the core infrastructure development, maintenance support, in the case of Herwig David Grellscheid, and that contribution has to be recognised just like detector builders.



Conclusions

- The HERWIG project has taken over 30 years to reach the current state-of-the-art.
- It has been a constant series of incremental developments combined with occasional major changes in how we simulate events such as the move to NLO.
- Hopefully the next thirty years will see as much development.