HERWIG

Herwig++

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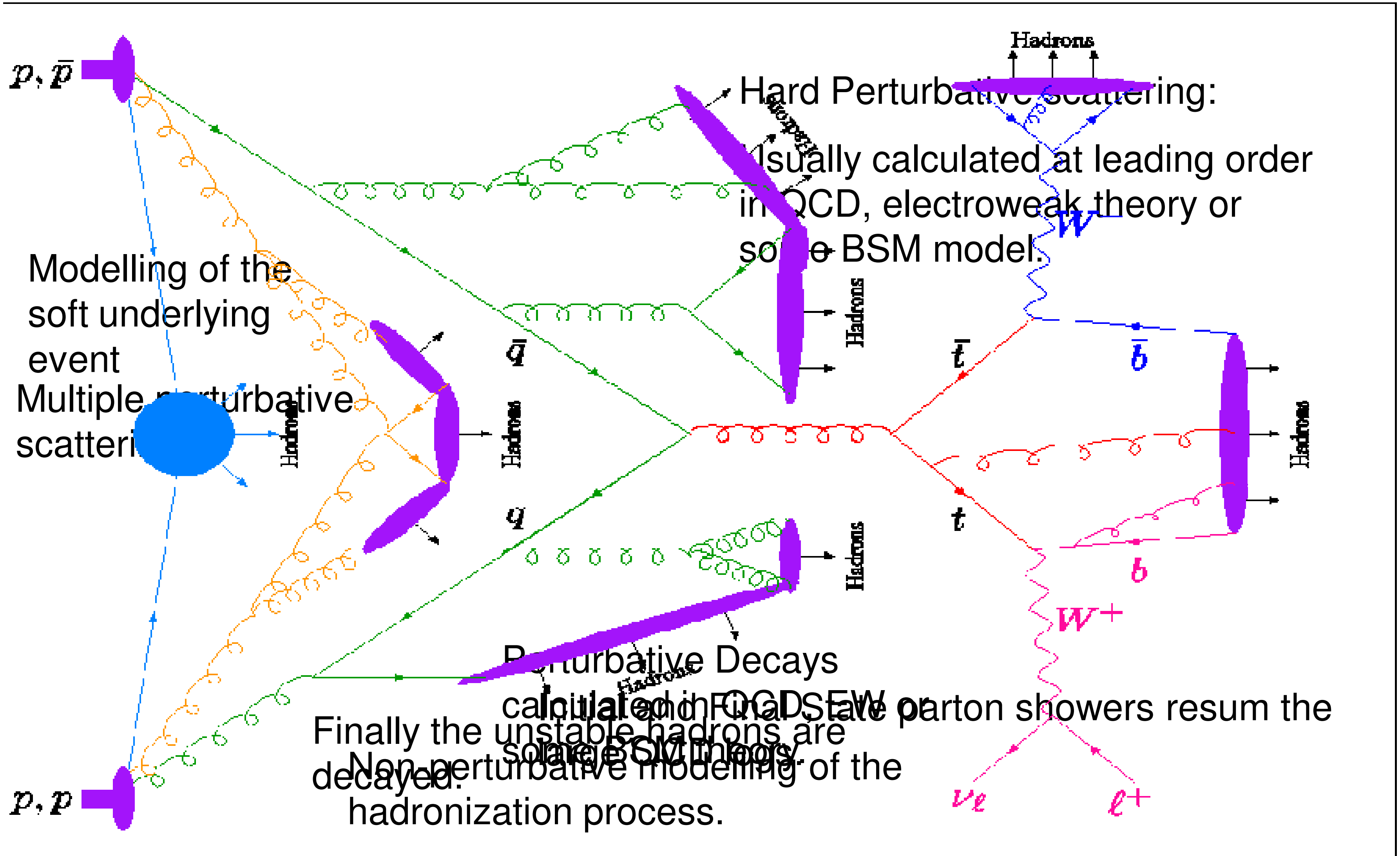
IPPP, Durham University

Summary

- Introduction
- HERWIG 6.5
- Herwig++
  - Parton Shower
  - Underlying Event
  - Hard Radiation and NLO
  - BSM Physics
  - Hadronization
  - Hadron and Tau Decays
- Conclusions

A Monte Carlo Event

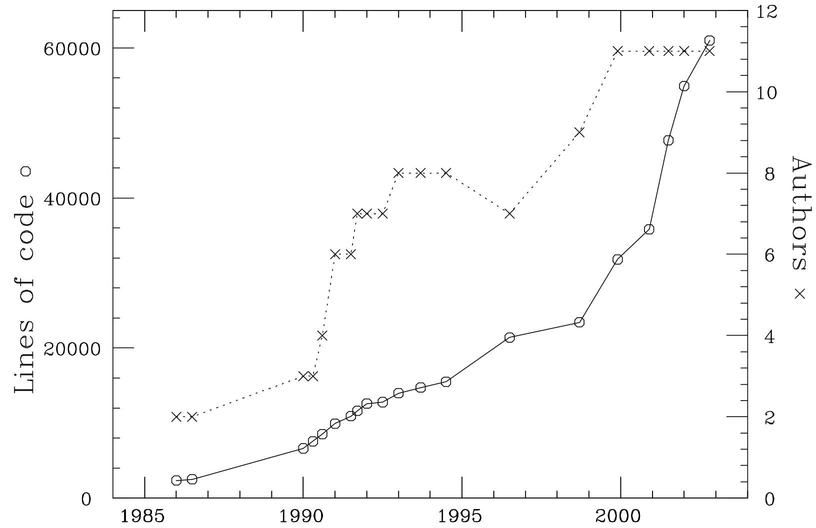


Introduction

- The HERWIG project began 25 years ago and was intended to provide a good description of perturbative QCD.
- Less emphasis on the modelling of non-perturbative physics, with:
  - Angular ordered parton shower;
  - Cluster hadronization model;
  - Soft model of the underlying event.
- Many improvements and developments over the years.

HERWIG 6.5

- The current and last major release of the FORTRAN HERWIG simulation provides a good description of hadron collider physics.



- In 2000 it became clear that the structure of the FORTRAN program was limiting future physics developments.
- Decided to write a new generator using the same physics philosophy but with improved theoretical calculations and models.

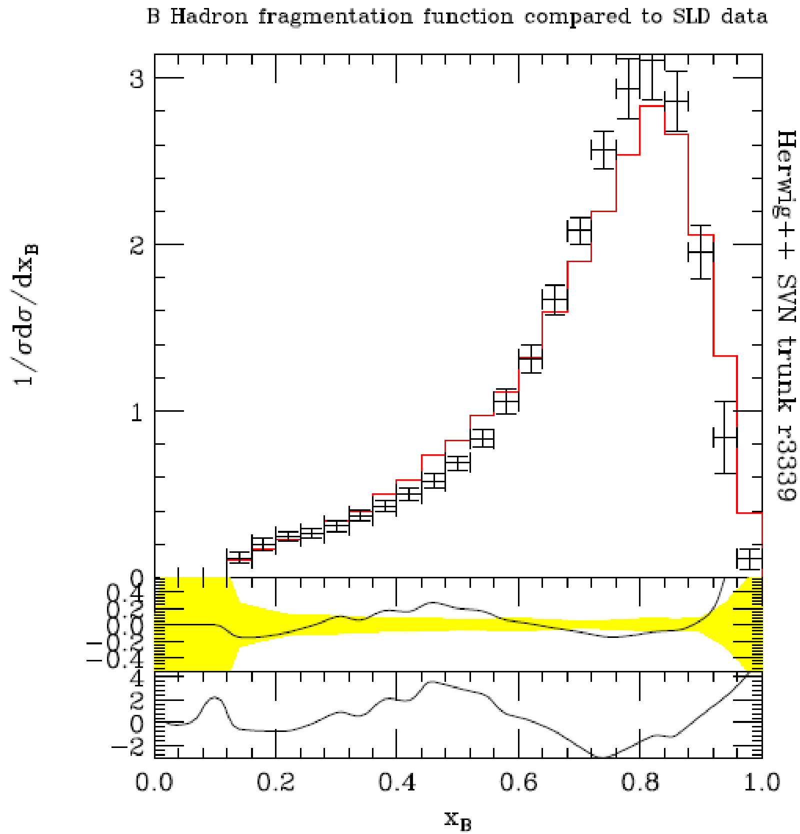
Herwig++

- The new Herwig++ program now provides a full simulation of lepton-lepton, lepton-hadron and hadron-hadron collisions with many improvements over its FORTRAN predecessor:
  - New angular ordered parton shower with better theoretical control and mass treatment;
  - Many processes at NLO in the POWHEG approach;
  - Multiple scattering model of the underlying event;
  - Better treatment of BSM physics models;
  - Improved simulation of tau and hadron decays.

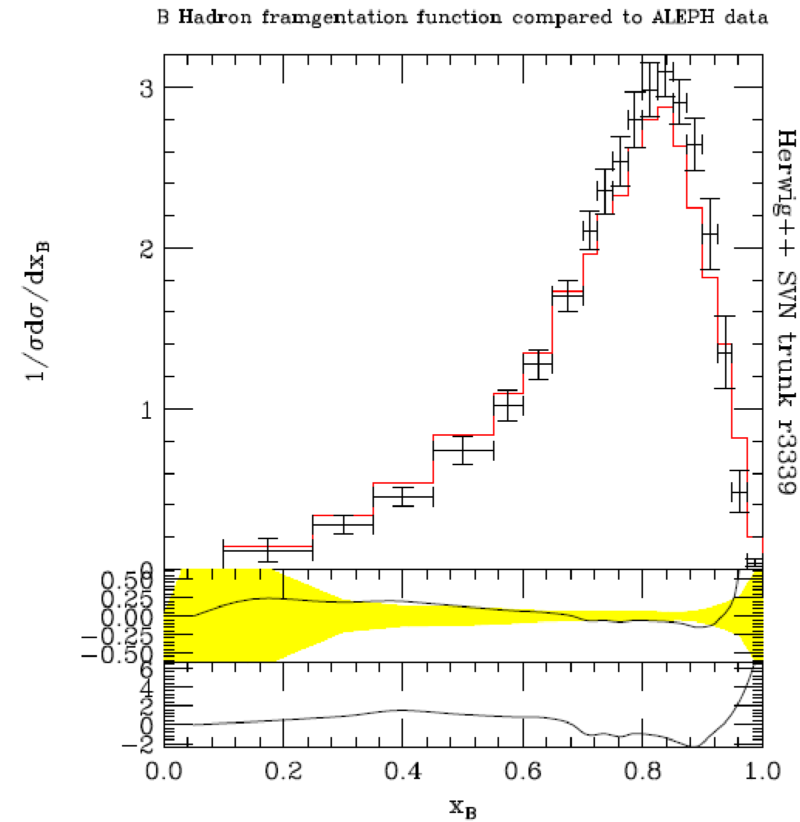
Parton Shower

- The new Herwig++ parton shower is still angular ordered but:
  - Uses quasi-collinear splitting functions to improve the treatment of mass effects;
  - A Sudakov decomposition to give better theoretical control.
- Gieseke, Stephens, Webbers JHEP 0312:045,2003
- Gives better description of B hadron fragmentation functions
- Makes matching the shower to hard matrix elements easier.

LEP Event Shapes



Herwig++ compared to SLD
Phys.Rev.D65:092006,2002

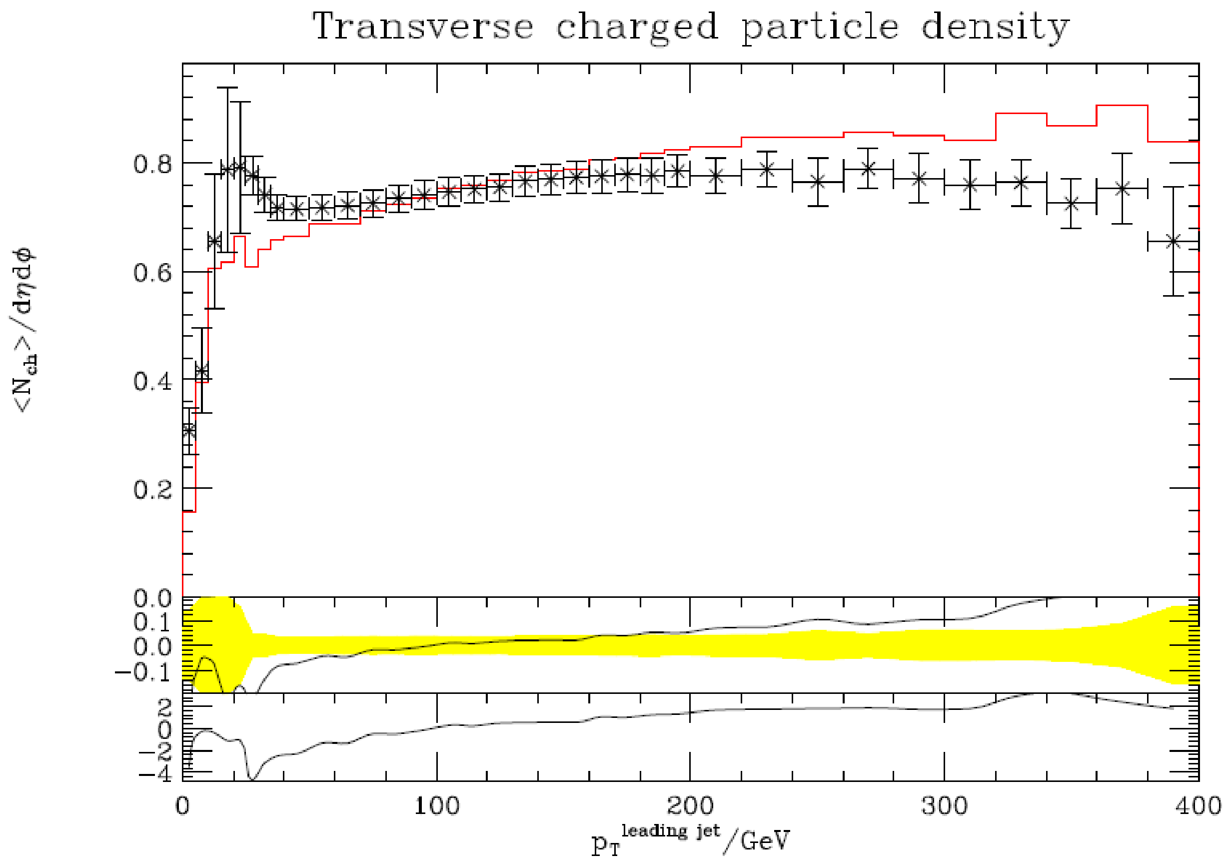


Herwig++ compared to ALEPH
Phys.Lett.B512:30-48,2001

Multiple Scattering

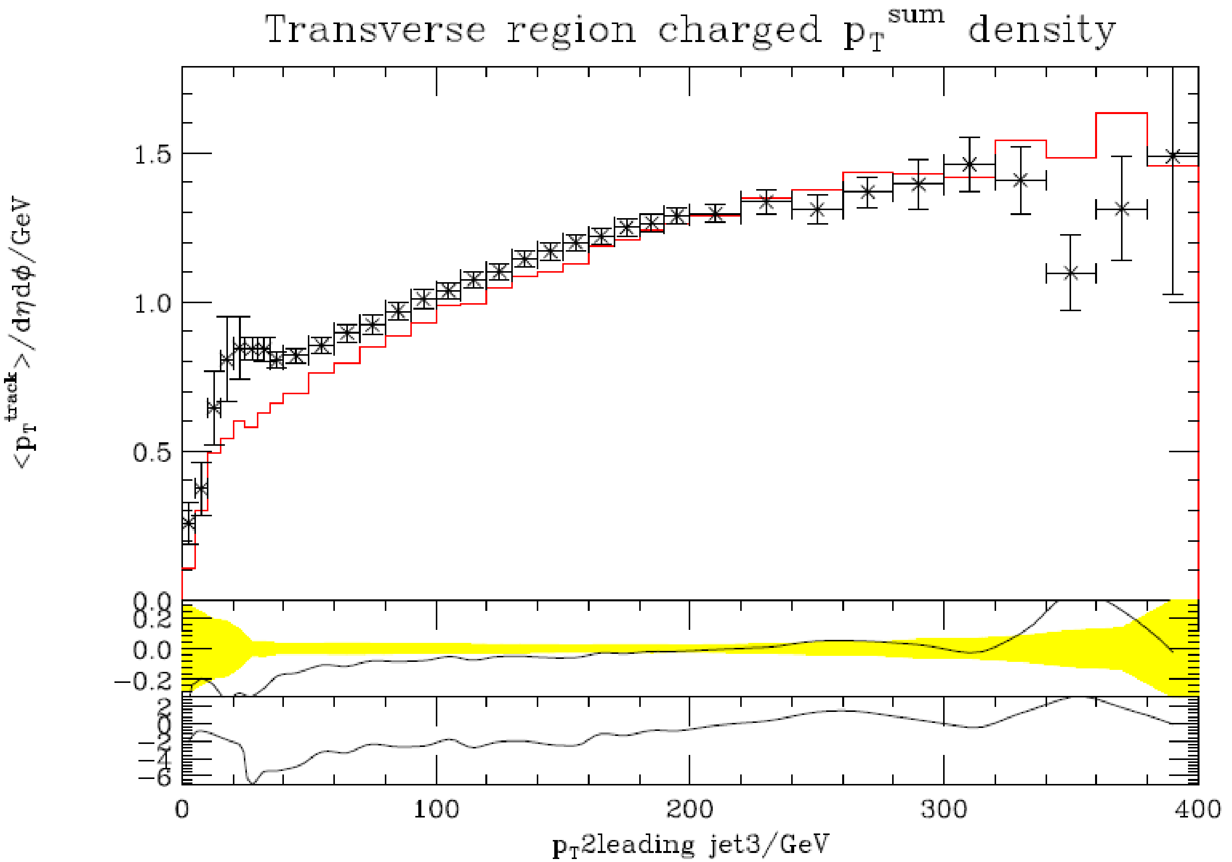
- In FORTRAN HERWIG there was a built in soft model for the underlying event and the option of using the JIMMY multiple parton interaction model.
- In Herwig++ we use a improved version of the JIMMY MPI model including a soft component.
- Bahr, Butterworth, Seymour JHEP 0901:065,2009, Bahr, Gieseke, Seymour JHEP 0807:076,2008

Underlying Event



Herwig++ compared to CDF data

Underlying Event



Herwig++ compared to CDF data

Hard Radiation

- Much of the research in Monte Carlo simulations in recent years has involved matching the parton shower to fixed order matrix elements at both:
  - NLO to improve the overall normalisation and description of the hardest jet in the event;
  - Leading order to matrix elements with higher multiplicities to improve the simulation of events with many hard jets.
- There are many improvements in Herwig++ to include both types of approach.

Hard Radiation

- In the angular ordered parton shower the hardest emission in p_T is not the emission with the largest emission scale.
- In fact the hardest emission is often proceeded by softer wide angle emissions.
- This is a problem if we want to use a fixed order matrix element to describe the hardest emission.
- However work by Nason JHEP 0411:040,2004 showed how to do this.

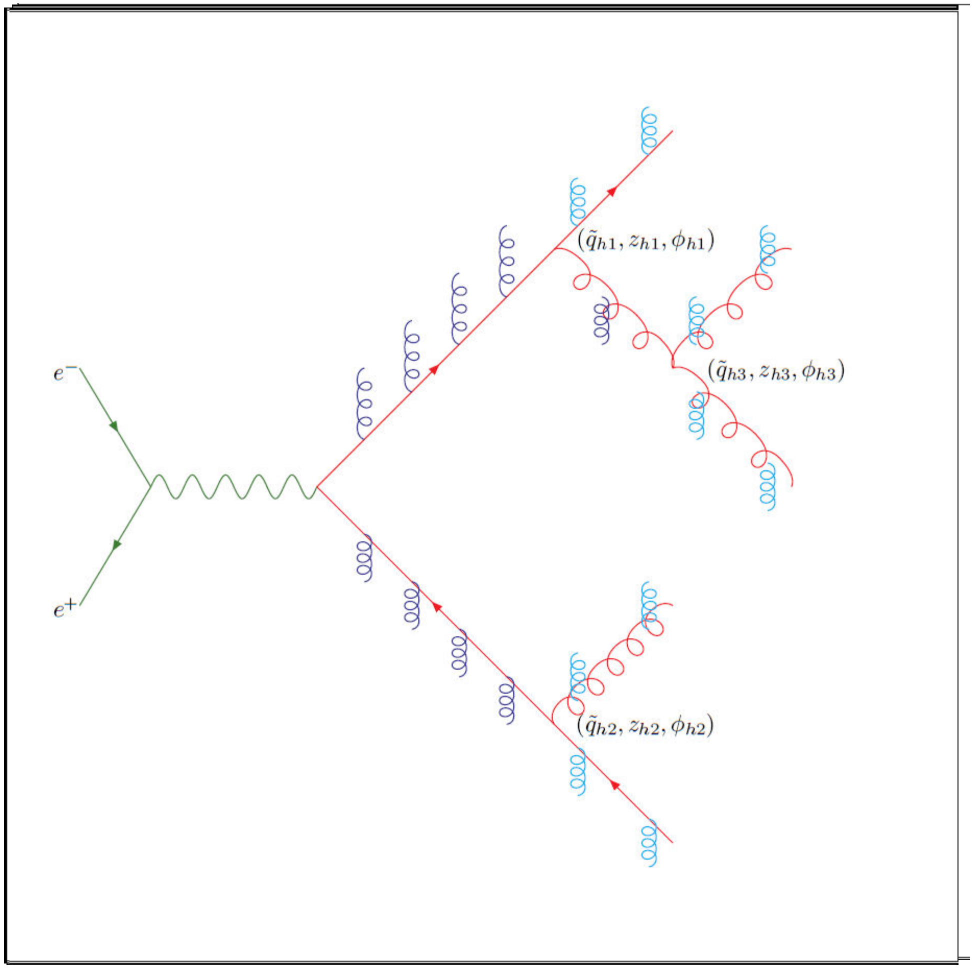
Hard Radiation

- Nason showed that the angular ordered parton shower could be decomposed into:
  - the hardest emission;
  - a truncated shower describing soft wide angle emission at higher evolution scales than the hardest emission;
  - vetoed showers from the partons constrained to only generate emissions softer than the hardest one.
- This allows the hardest emission to be generated separately.
- Problem is how to do it in practice.

Hard Radiation

- In Herwig++ we use a simple approach to implement this procedure:
  - the momenta including the hard emission are generated;
  - work out the shower evolution variables which would give the same momenta;
  - shower the event with some additional vetoes to generate the truncated and vetoed showers inserting the hard emissions at the right scales.
- Can generate the full shower including additional hard radiation in one step.

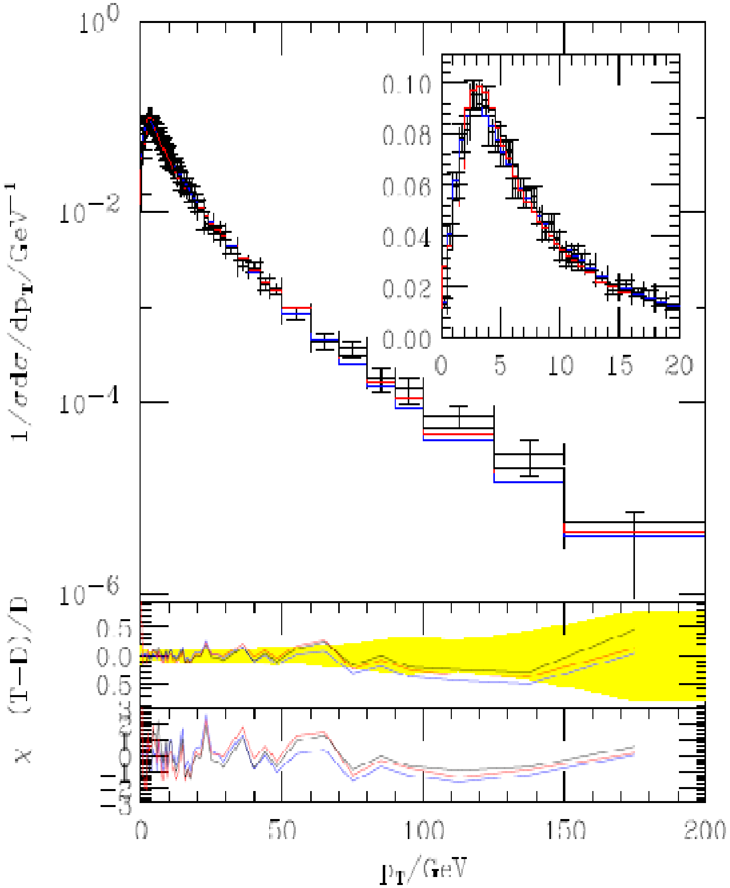
Shower including Hard Radiation



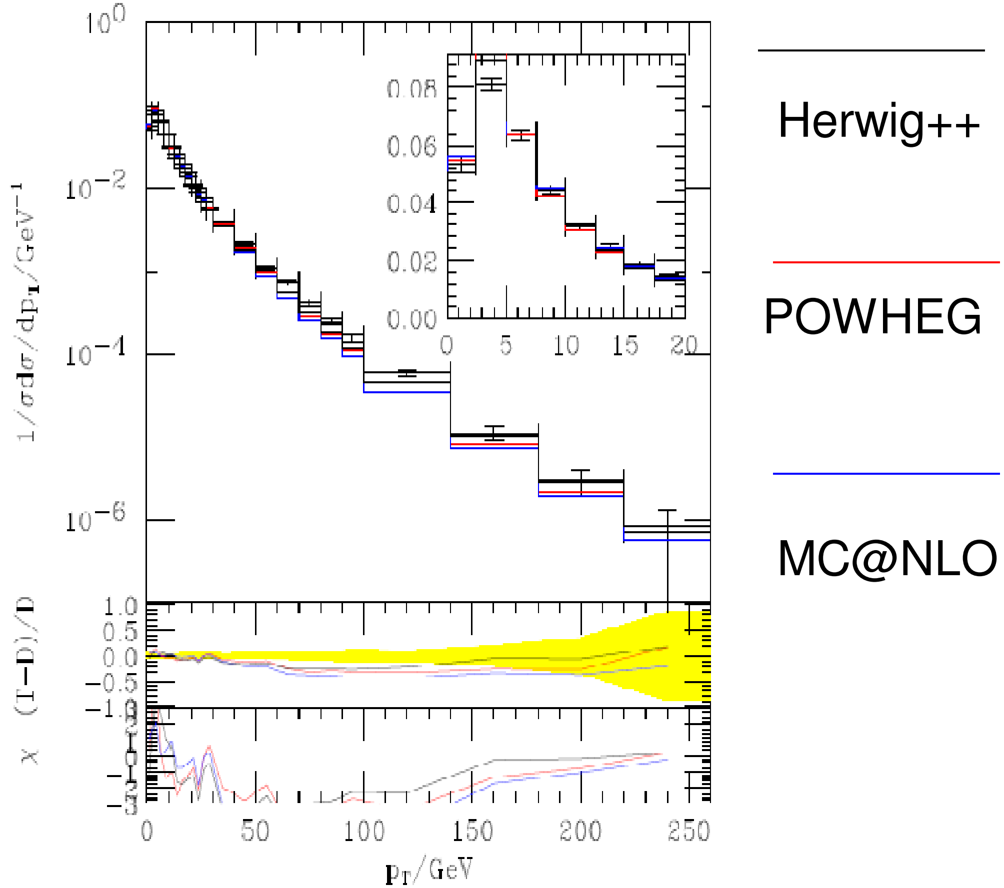
Hard Radiation in the Shower

- This relatively simple approach allows us to improve the simulation of additional hard radiation in the Herwig++ angular ordered parton shower.
- I will now go on and describe how we have done this for a range of processes:
  - Drell-Yan at NLO;
  - Higgs Production at NLO;
  - DIS and VBF at NLO;
  - Vector Boson pairs at NLO;
  - $e^+e^- \rightarrow$hadrons at leading order;
  - Drell-Yan at leading order.

POWHEG method for Drell-Yan



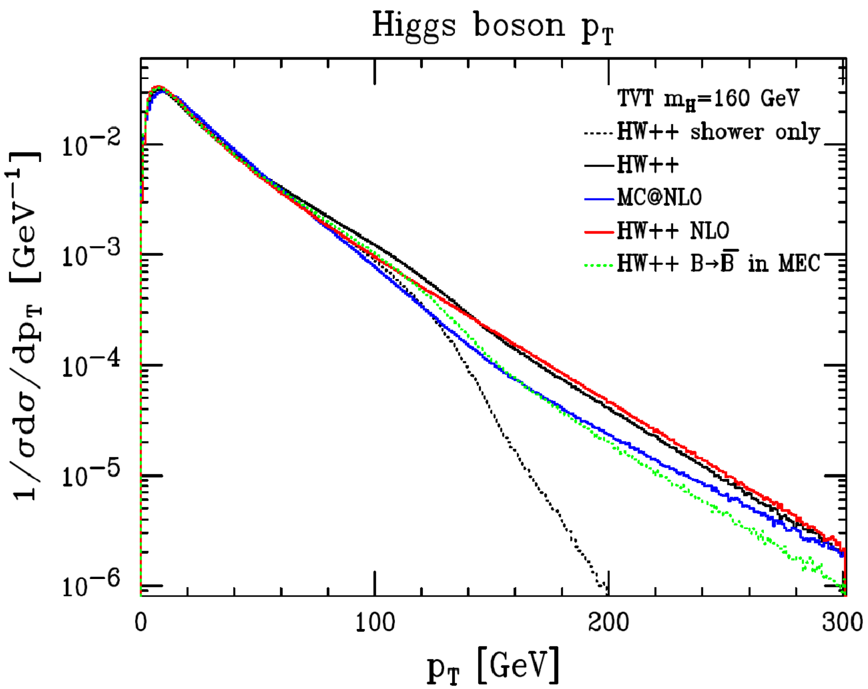
CDF Run I Z p_T



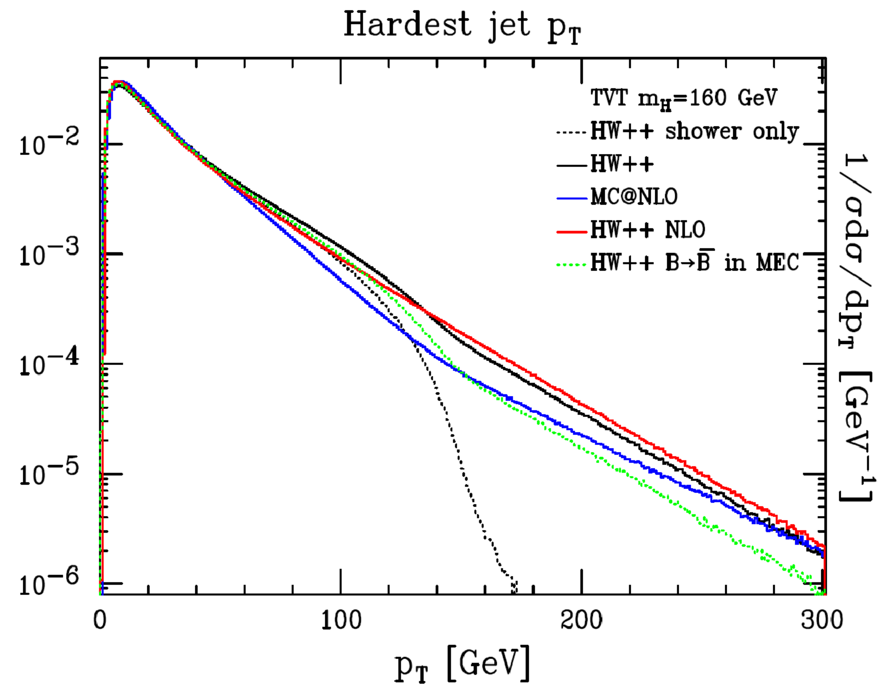
D0 Run II Z p_T

JHEP 0810:015,2008 Hamilton, PR, Tully

POWHEG Method for gg→H



Tevatron



LHC

JHEP 0904:116,2009 Hamilton, PR, Tully

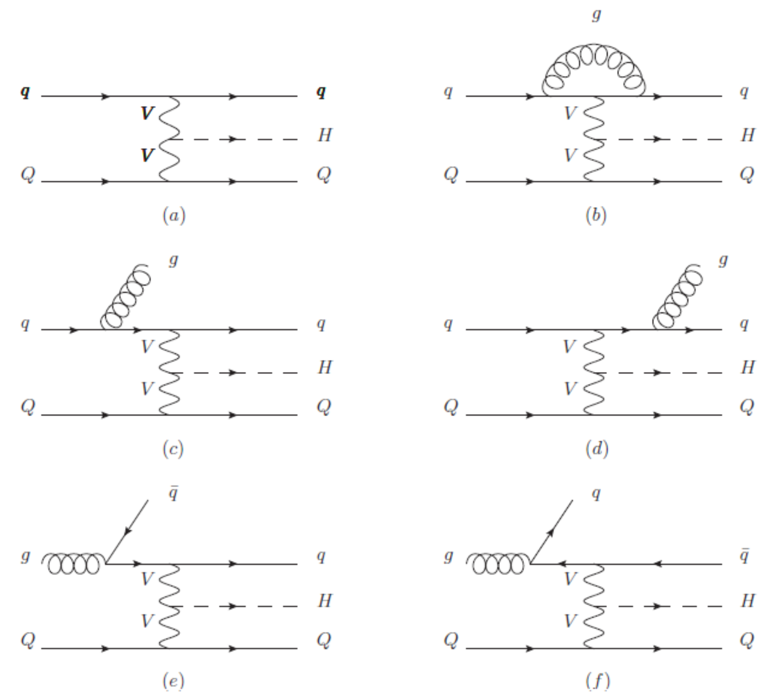
Deep Inelastic Scattering

- In Herwig++ the parton shower conserves the invariant mass of colour singlet systems, i.e.:
  - the final-state quark-antiquark pair in e+e-;
  - the gauge boson in Drell-Yan processes.
- In processes where there's a t-channel vector boson, e.g.:
  - Deep Inelastic scattering (DIS);
  - Higgs production via vector boson fusion,

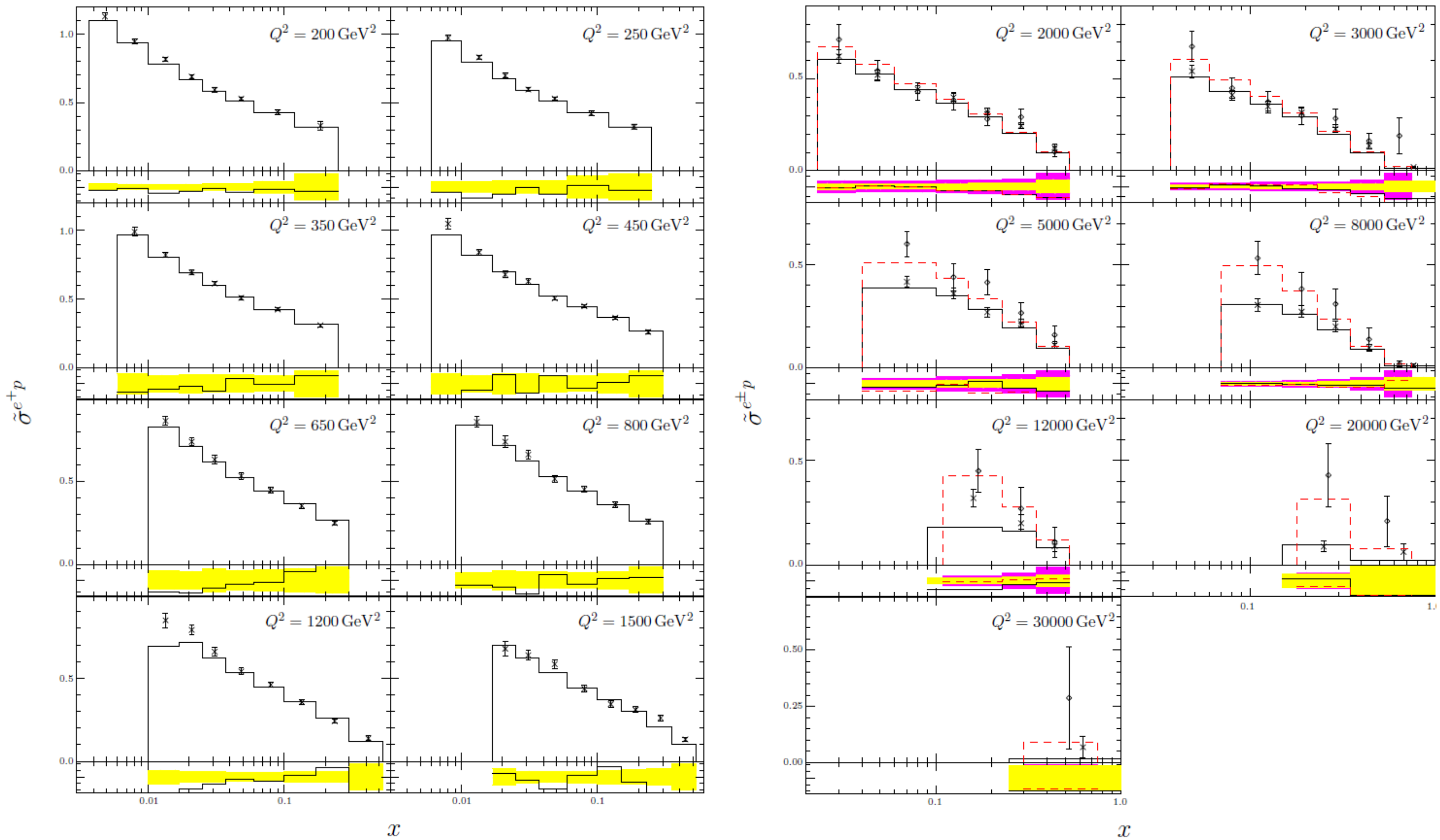
we preserve the momentum of this boson.

Deep Inelastic Scattering

- The QCD corrections to the two processes are also similar.
- DIS is important is its own right for validating and tuning new event generators.
- Also a useful testing ground for our treatment of the VBF process which is important for Higgs boson searches at the LHC.

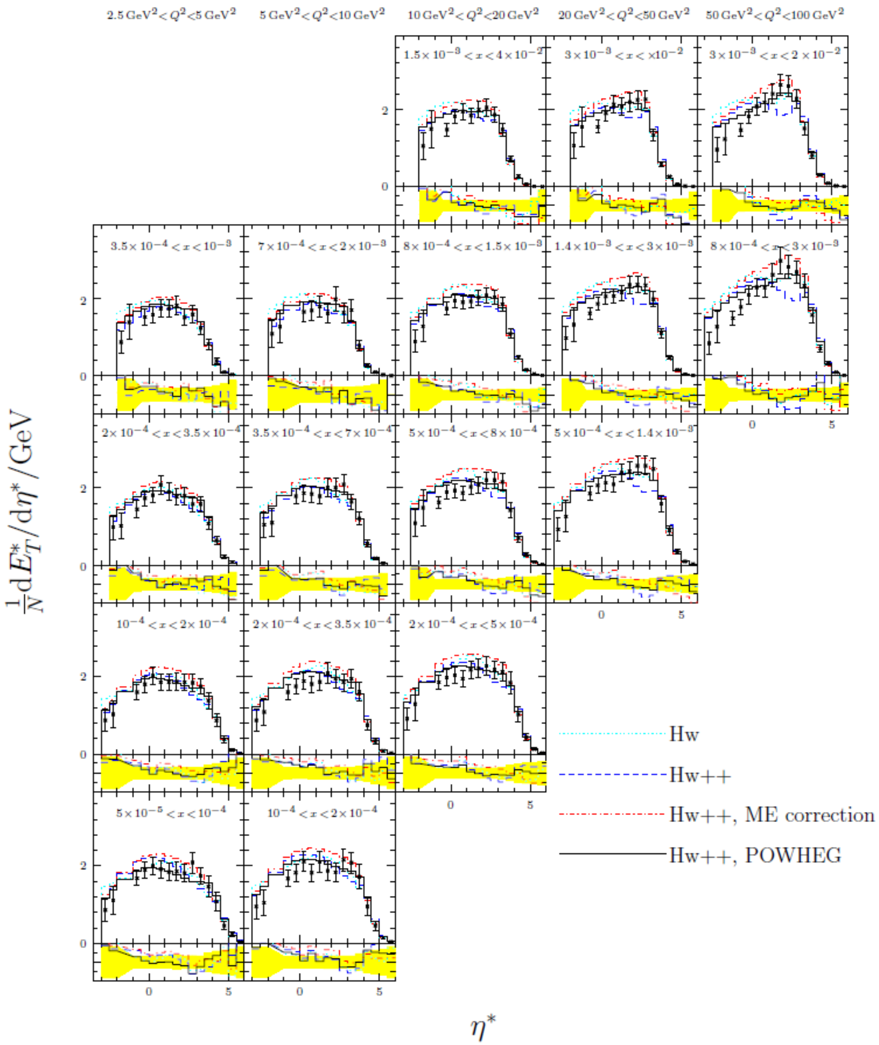


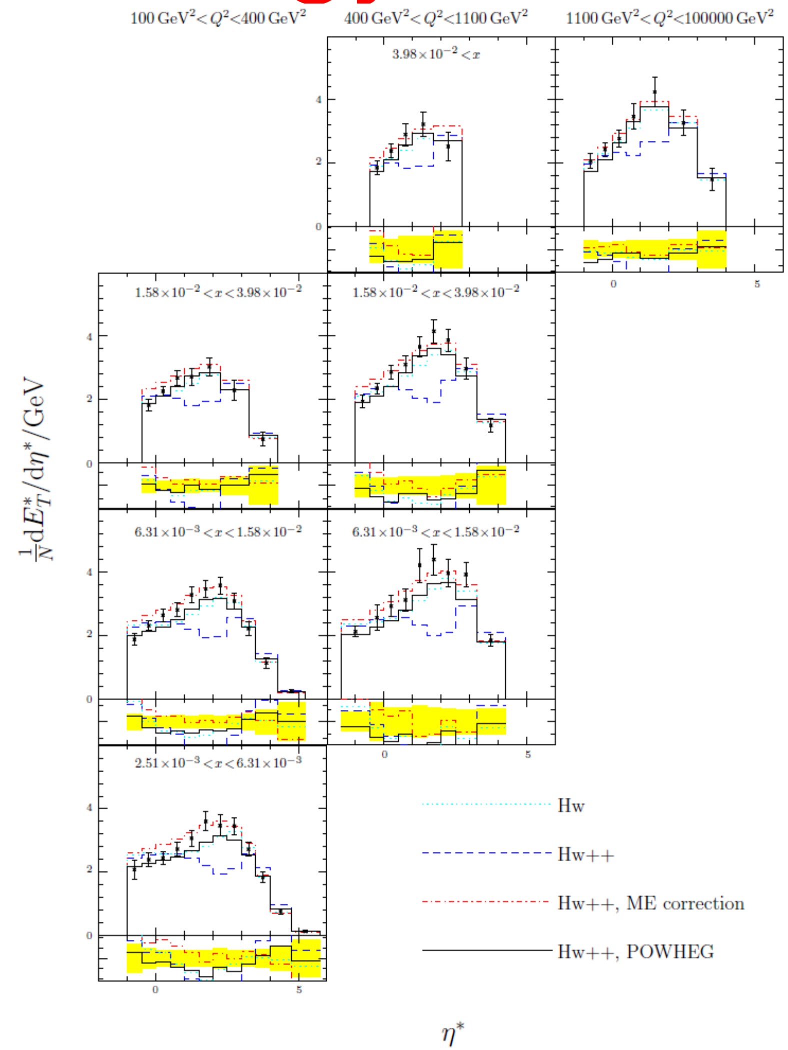
DIS Reduced Cross Section



PR and L d'Errico in preparation Herwig++ compared to ZEUS data Phys.Rev.D70:052001,2004, Eur.Phys.J.C28:175-201,2003

DIS Transverse Energy Flow

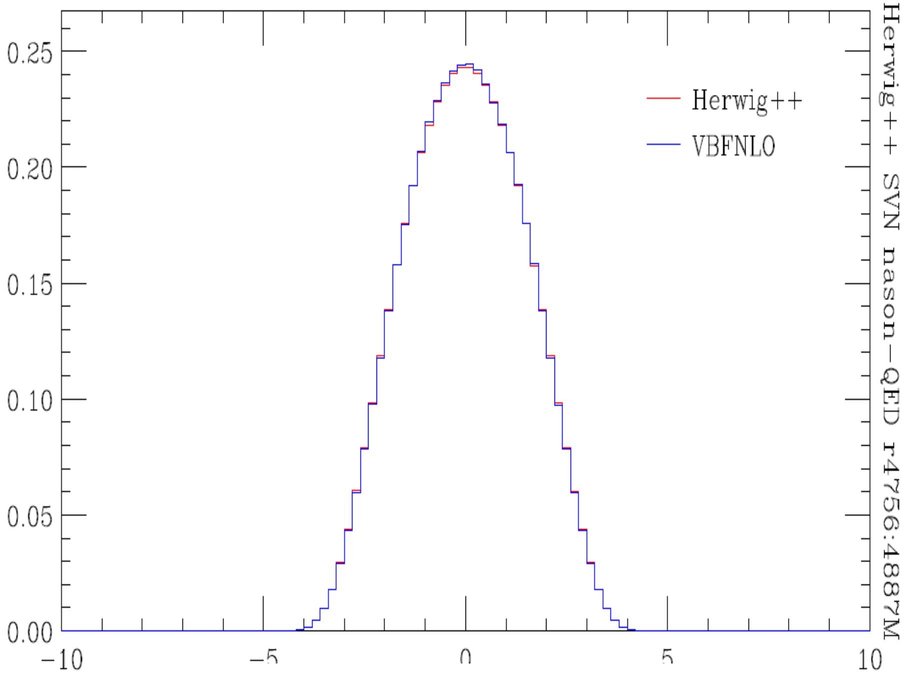




PR and L d'Errico in preparation Herwig++ compared to H1 data Eur.Phys.J.C12:595-607,2000.

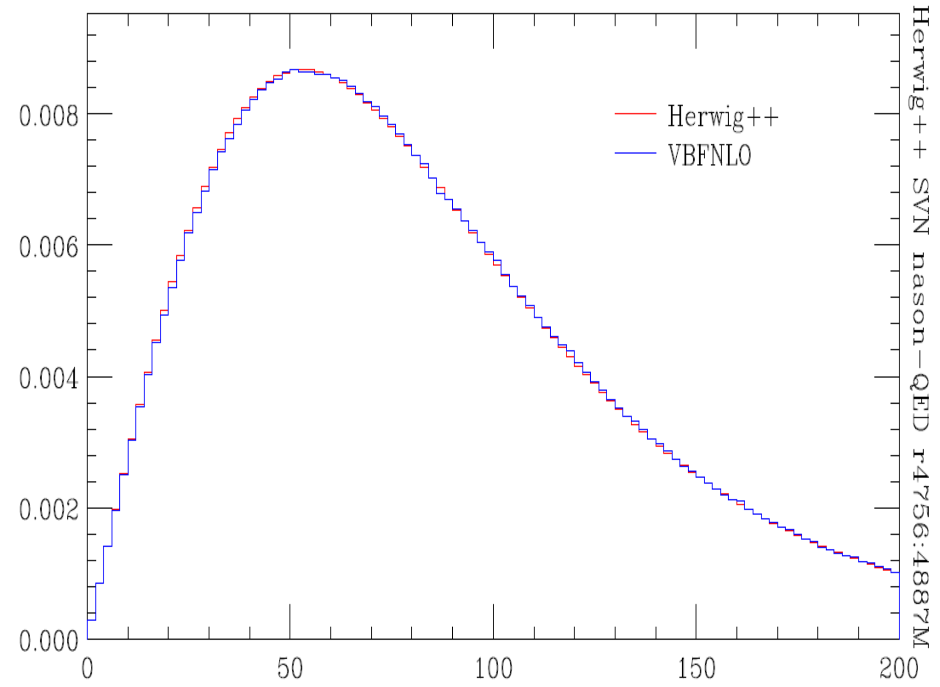
VBF

Higgs Rapidity



y

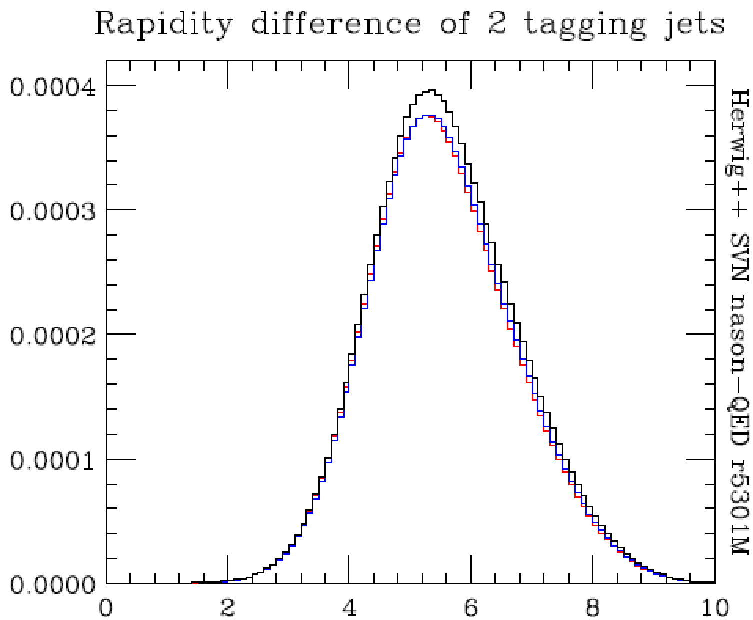
Higgs p_T

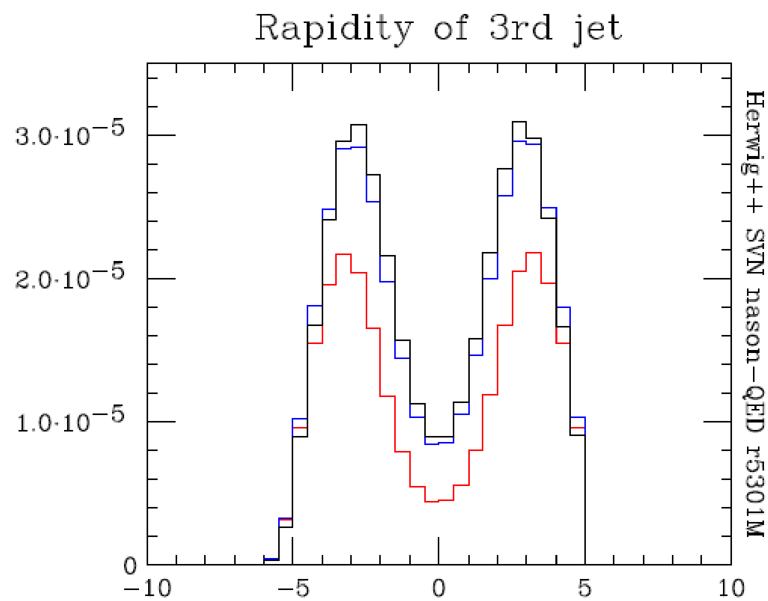


p_T/GeV

PR and L d'Errico in preparation.

VBF





Δy

y_3

Herwig++ POWHEG

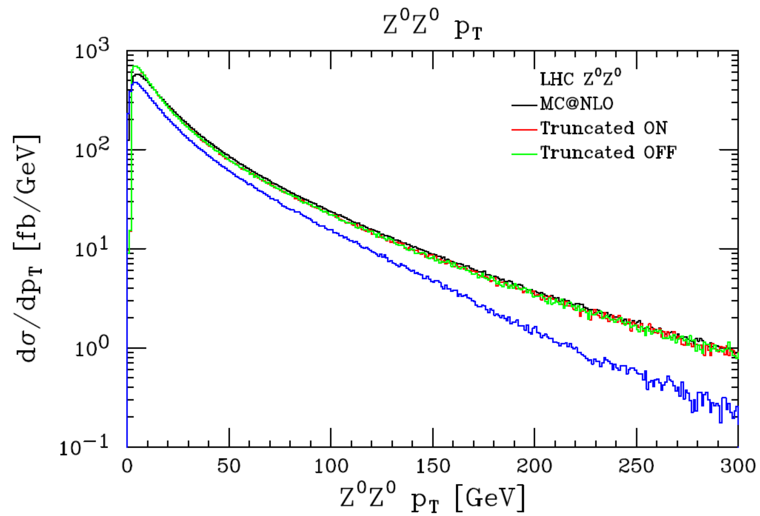
Herwig++ LO

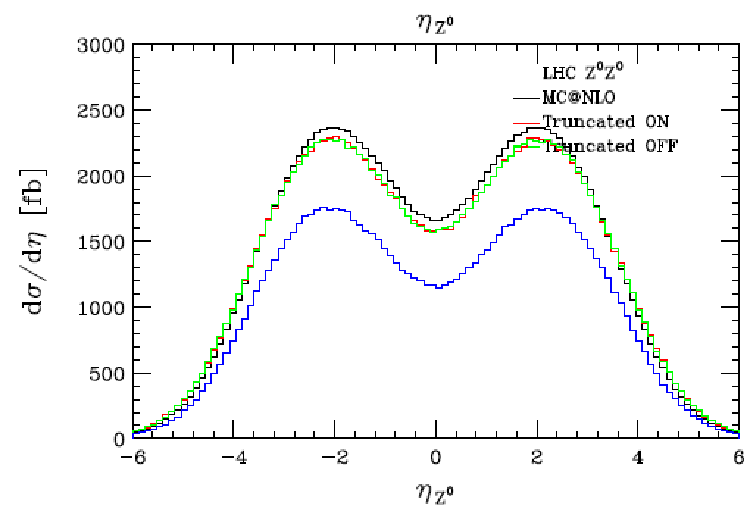
Herwig++ ME correction

Vector Boson Pairs

- The production of pairs of electroweak vector bosons, W^+W^-, Z^0Z^0, $W^{\pm}Z^0$ is both interesting for electroweak physics and as a background to BSM physics processes.
- KH in preparation

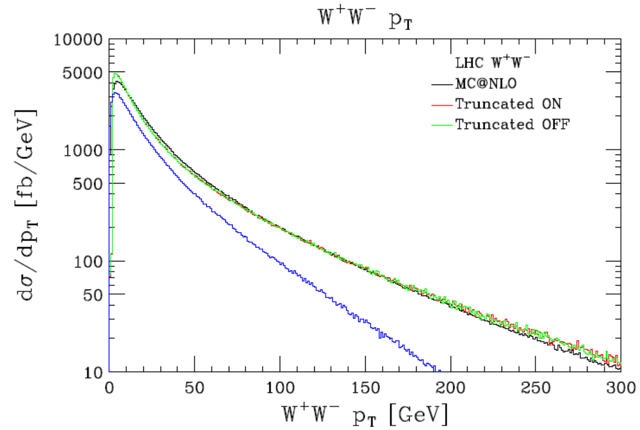
Z^0Z^0

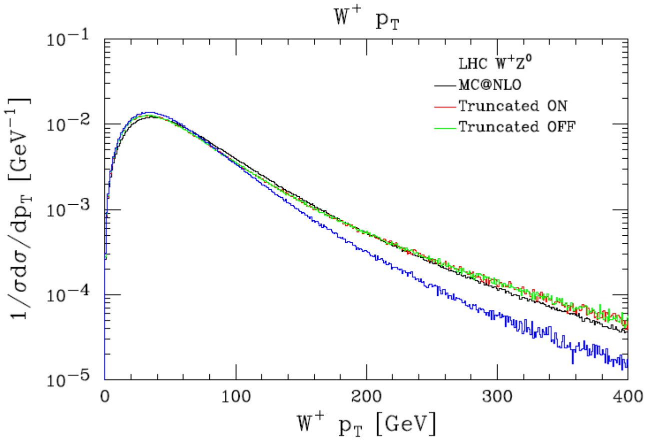


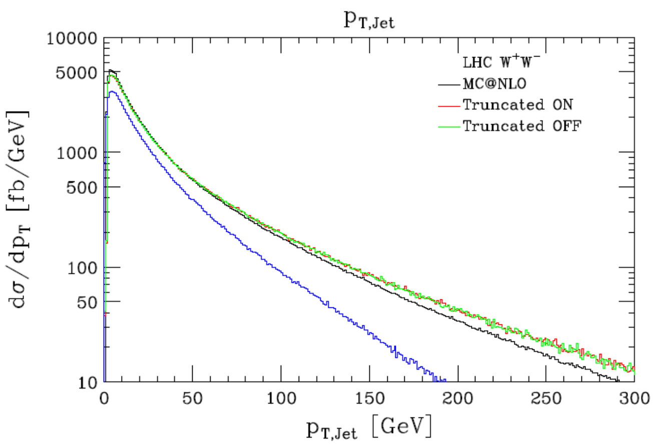


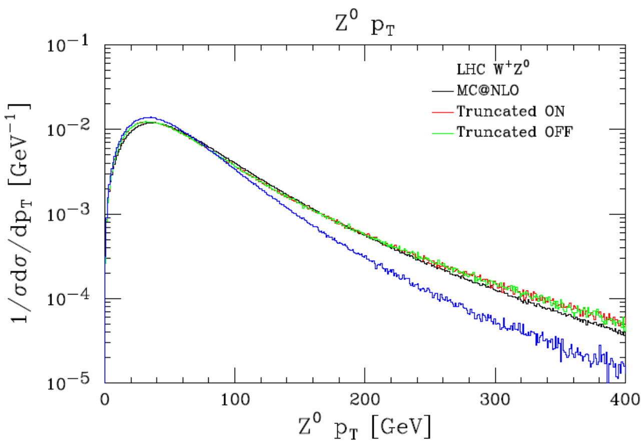
Vector Boson Pairs

W^+W^- | W^+Z^0









KH in preparation

NLO Processes

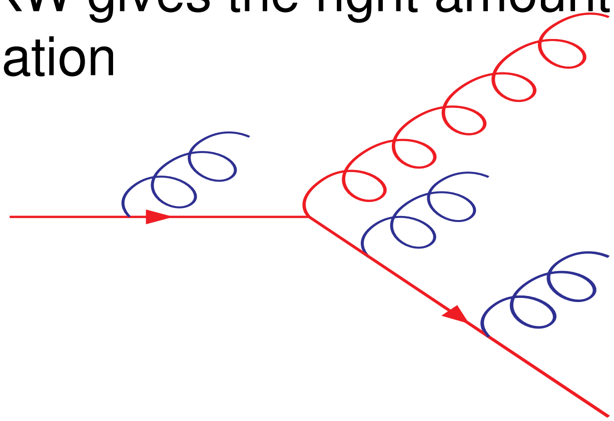
- There are now a range of processes accurate to NLO in current version of Herwig++:
  - W/Z production;
  - $gg \rightarrow h^0$;
  - Higgs production in association with $W^{\pm}$ and Z^0.
- In addition the next version will include:
  - DIS;
  - Higgs production via VBF;
  - Vector Boson pair production.

Multi-Jet Leading Order

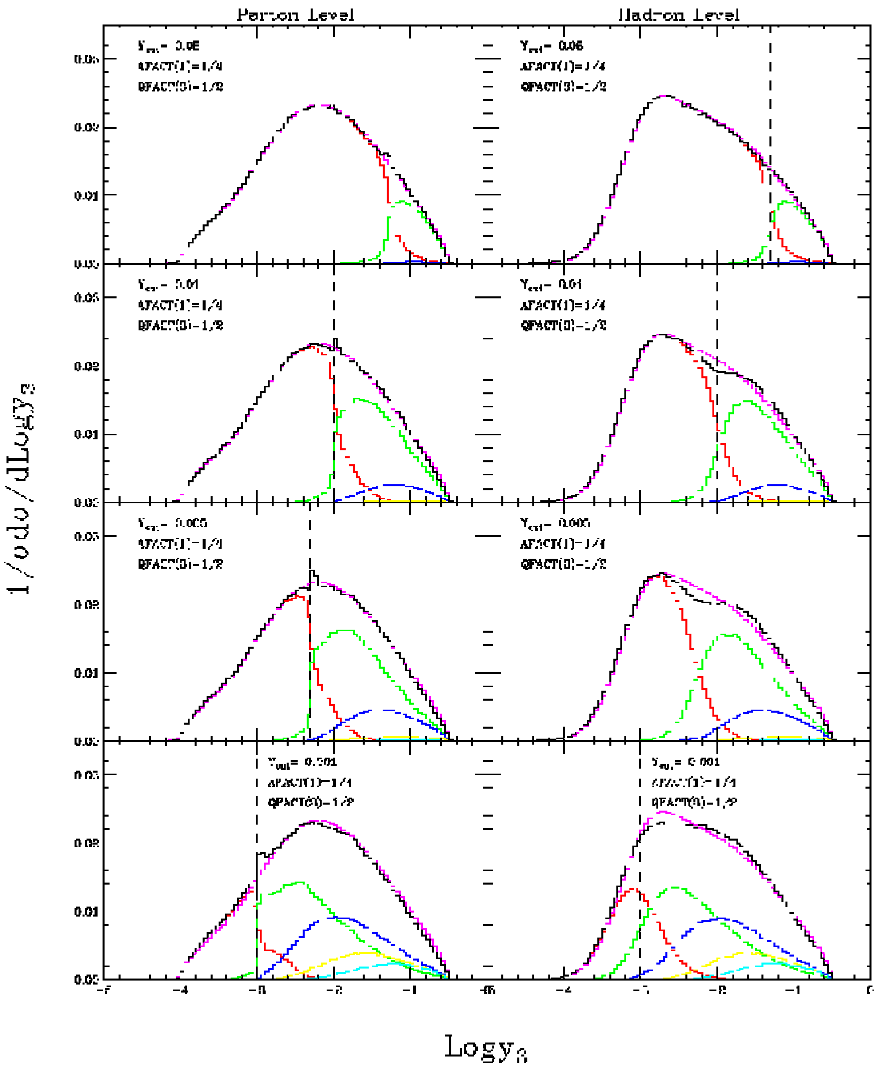
- While the NLO approach is good for one hard additional jet and the overall normalization it cannot be used to give many jets.
- Therefore to simulate these processes use matching at leading order to get many hard emissions correct.
- We use a modified CKKW approach.

Problems with CKKW

- CKKW uses an enhanced starting scale for the evolution of the partons which is designed to simulate soft, wide angle emission from the internal lines.
- CKKW gives the right amount of radiation



- But puts some of it in the wrong place with the wrong colour flow.

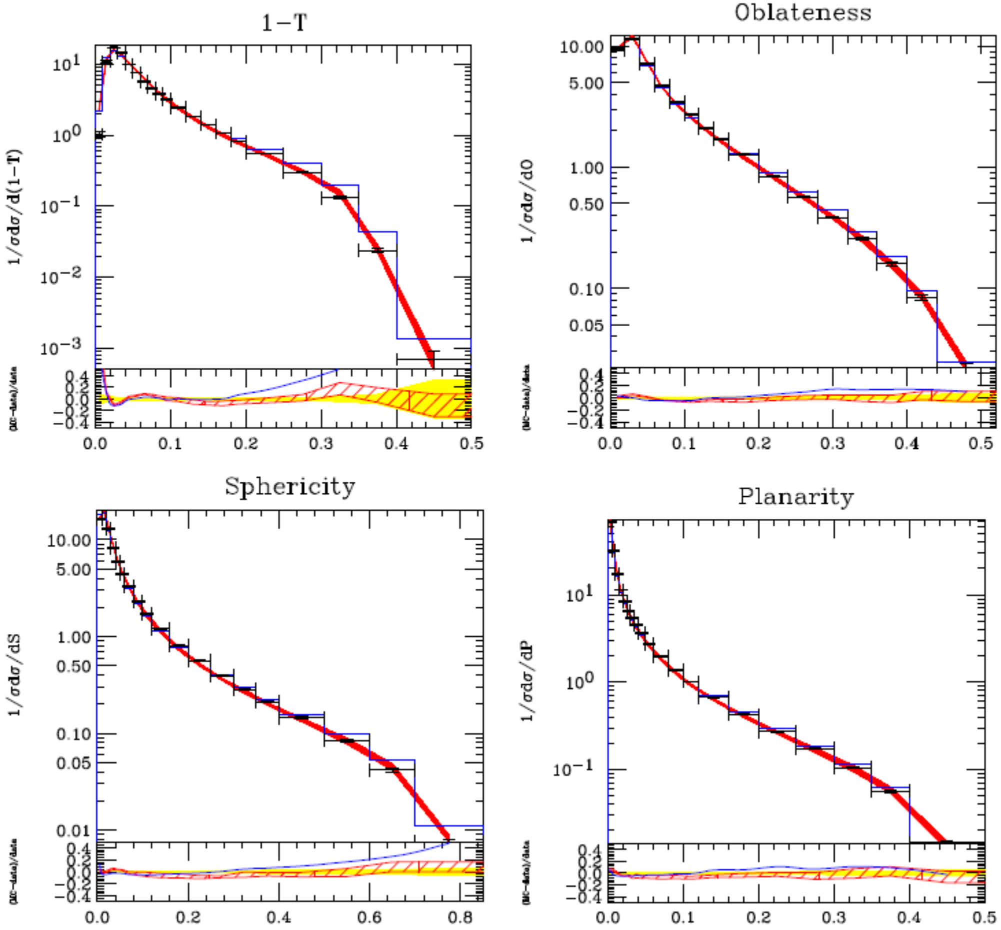


S. Mrenna and PR JHEP 0405: 04 (2004)

Solution

- The solution is that we should use a truncated shower to generate the soft wide angle emission.
- Use the truncated shower rather than enhanced emission scales to generate radiation from internal lines.
- Will be available in the next release.

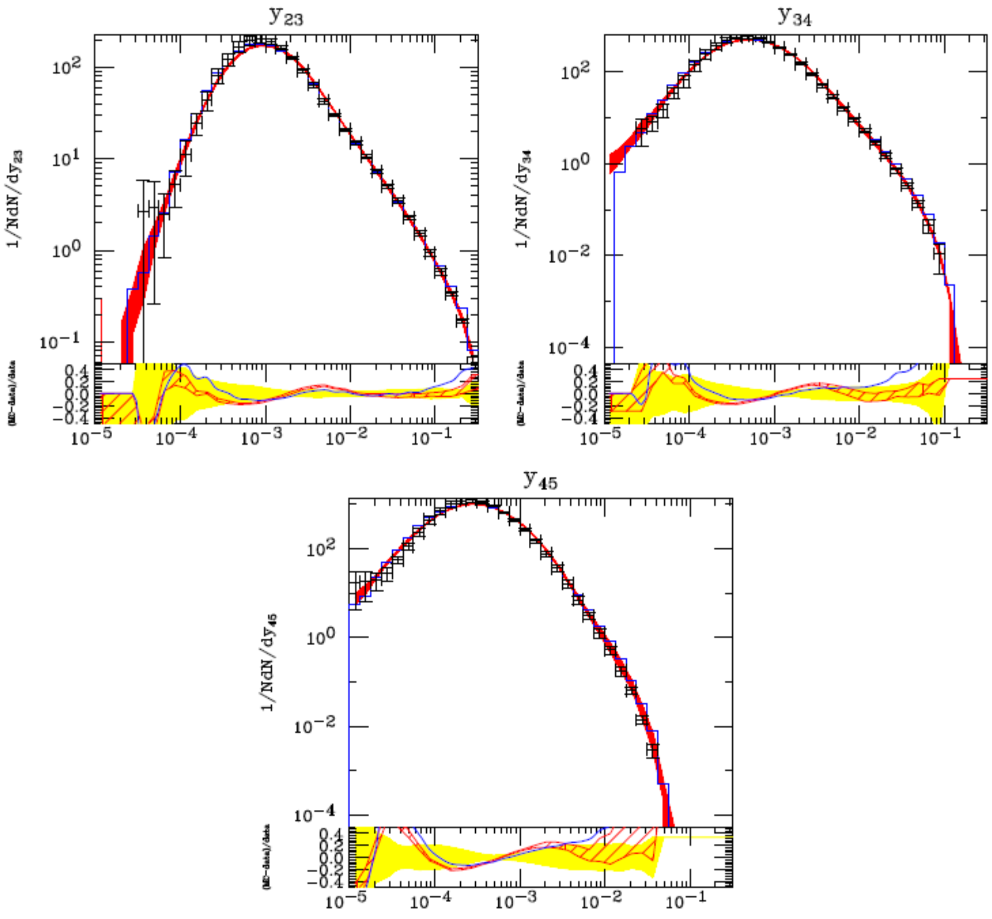
LEP Event Shapes



JHEP 0911:038,2009 Hamilton, PR, Tully

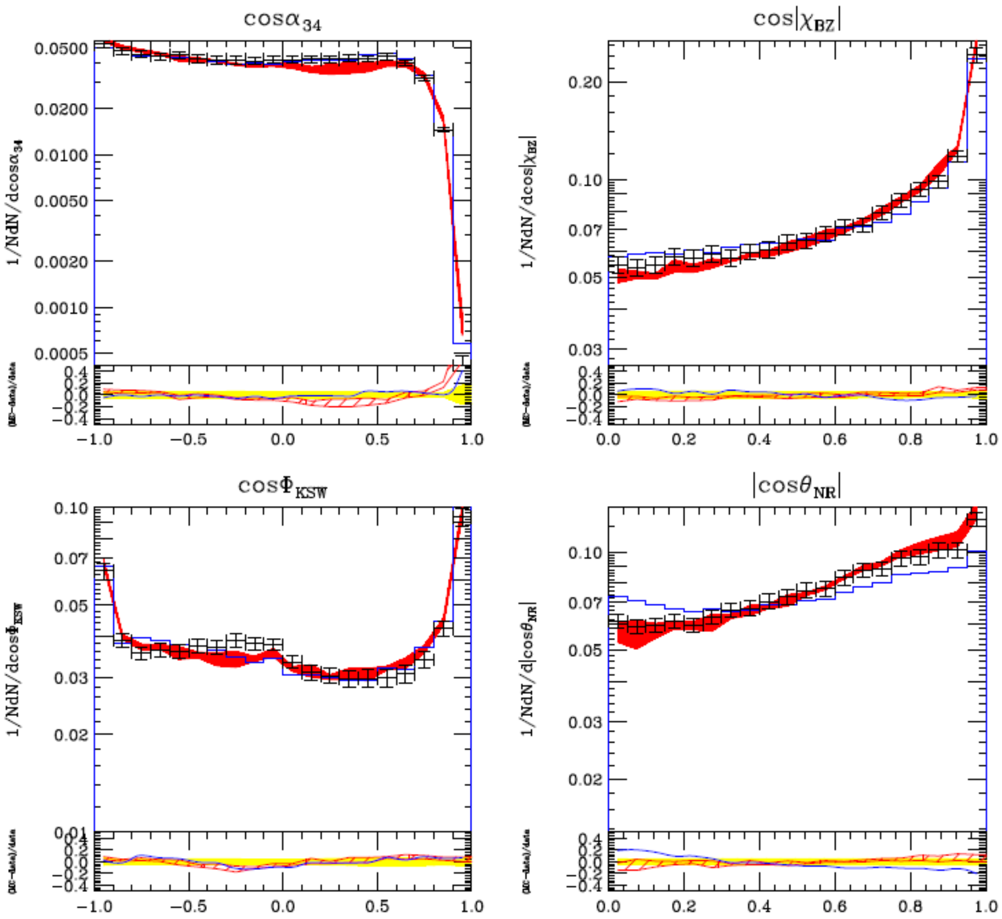
Herwig++ compared to DELPHI, Z.Phys.C73:11-60,1996

LEP Jet Distributions



JHEP 0911:038,2009 Hamilton, PR, Tully
Herwig++ compared to Eur.Phys.J.C17:19-51,2000

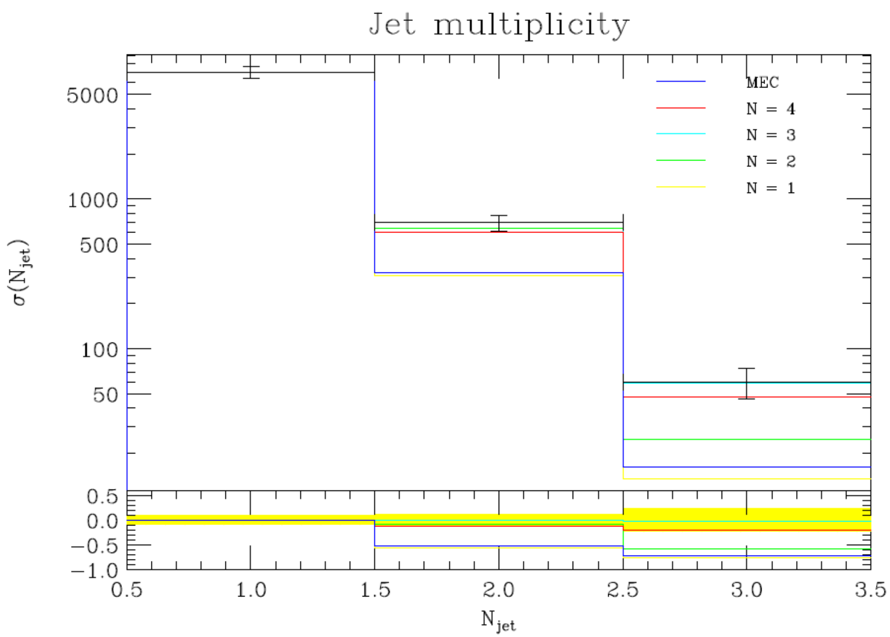
LEP Four Jet Angles

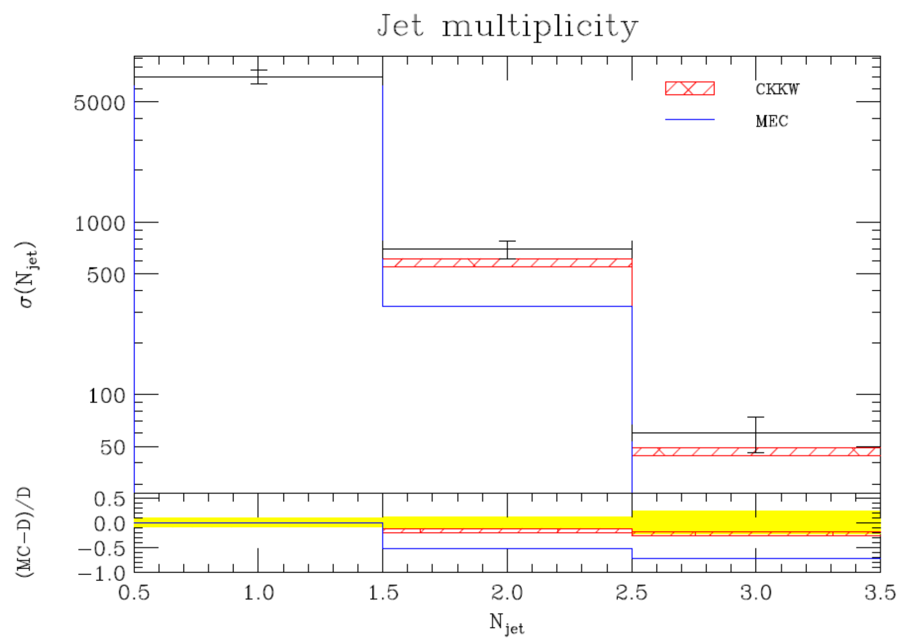


JHEP 0911:038,2009 Hamilton, PR, Tully

Herwig++ compared to Eur.Phys.J.C27:1-17,2003

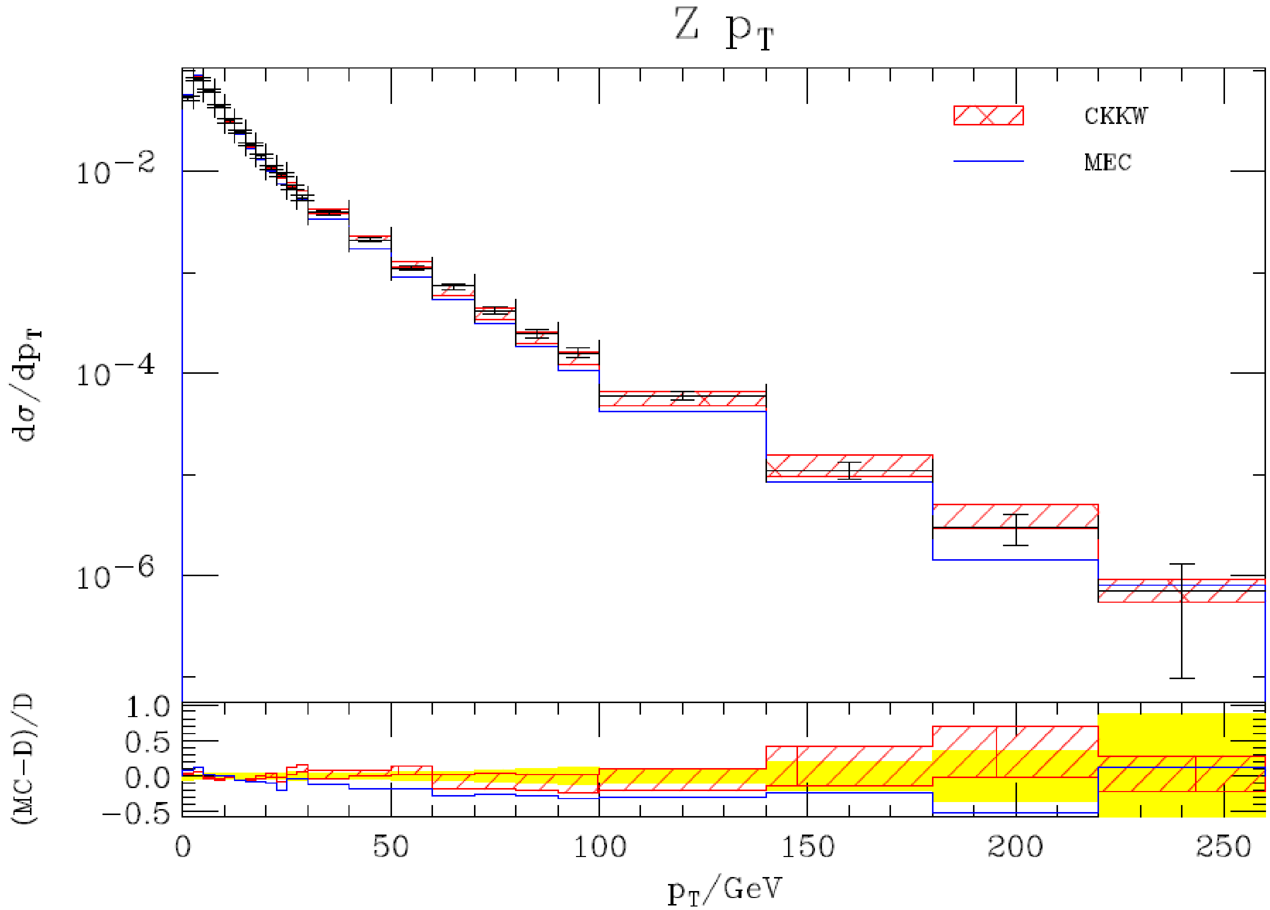
Jet Multiplicity in Z+jets at the Tevatron





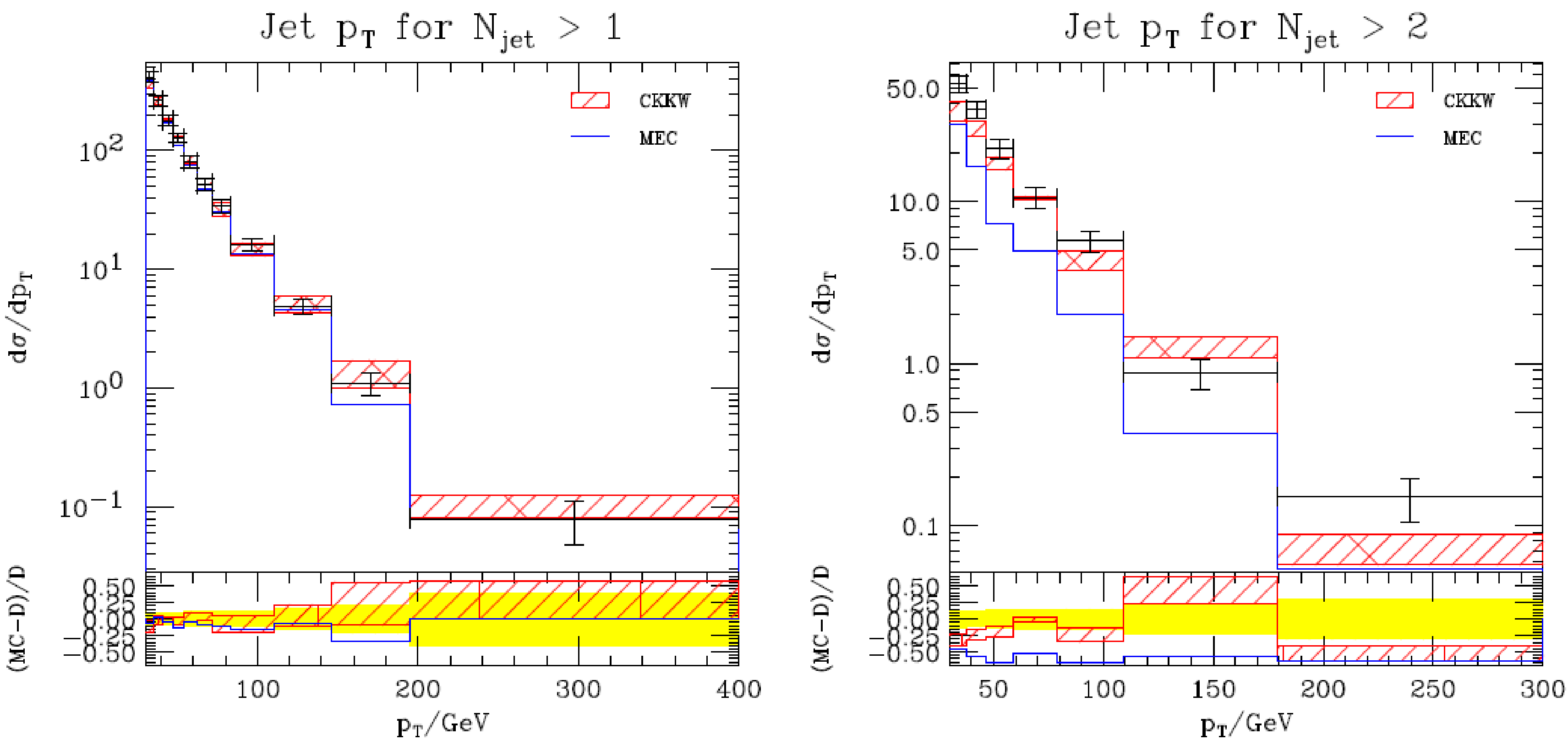
Herwig++ compared to data from CDF
Phys.Rev.Lett.100:102001,2008

p_T of the Z in Z+jets at the Tevatron



Herwig++ compared to data from D0
Phys.Rev.Lett.100:102002,2008

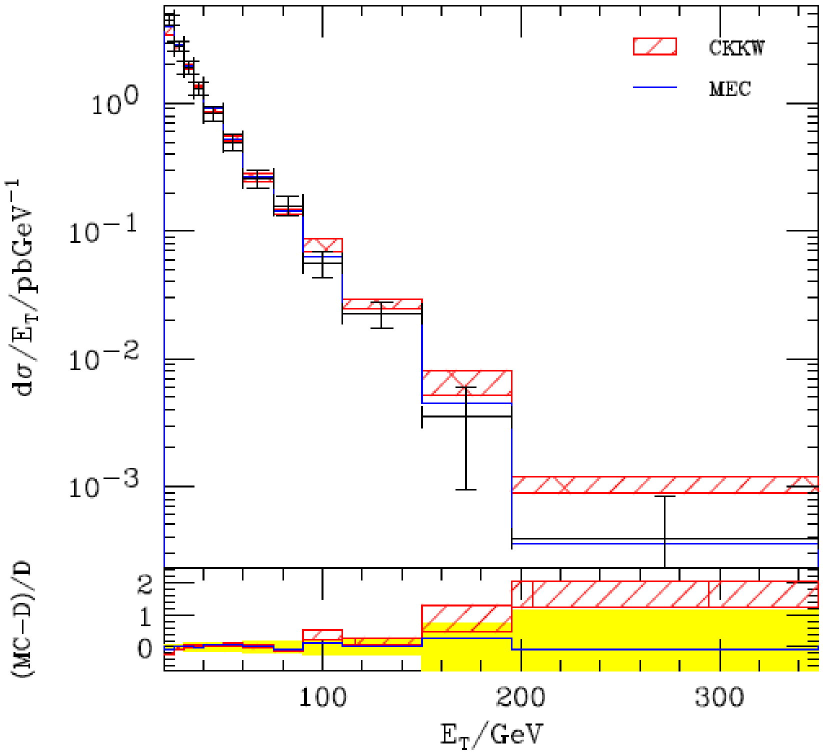
p_T of jets in Z+jets at the Tevatron



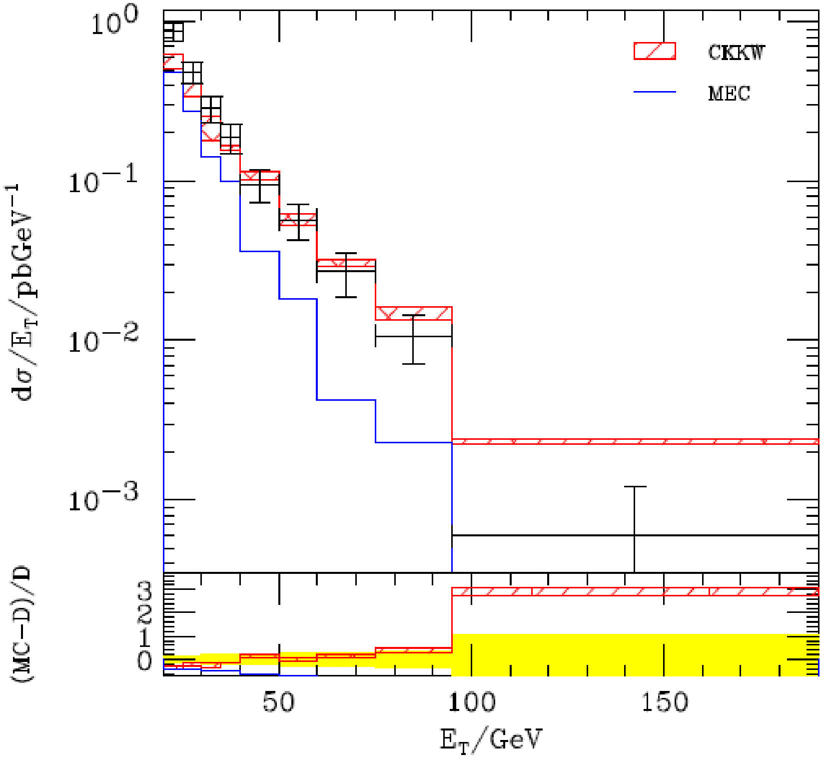
Herwig++ compared to data from CDF
Phys.Rev.Lett.100:102001,2008

p_T of jets in W+jets at the Tevatron

Hardest Jet



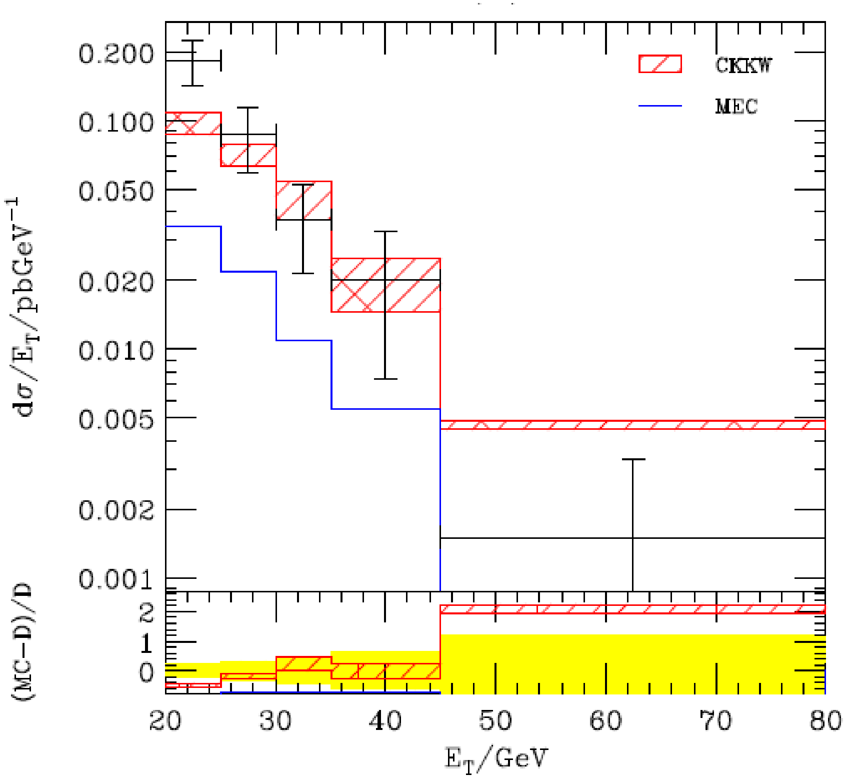
2nd Hardest Jet



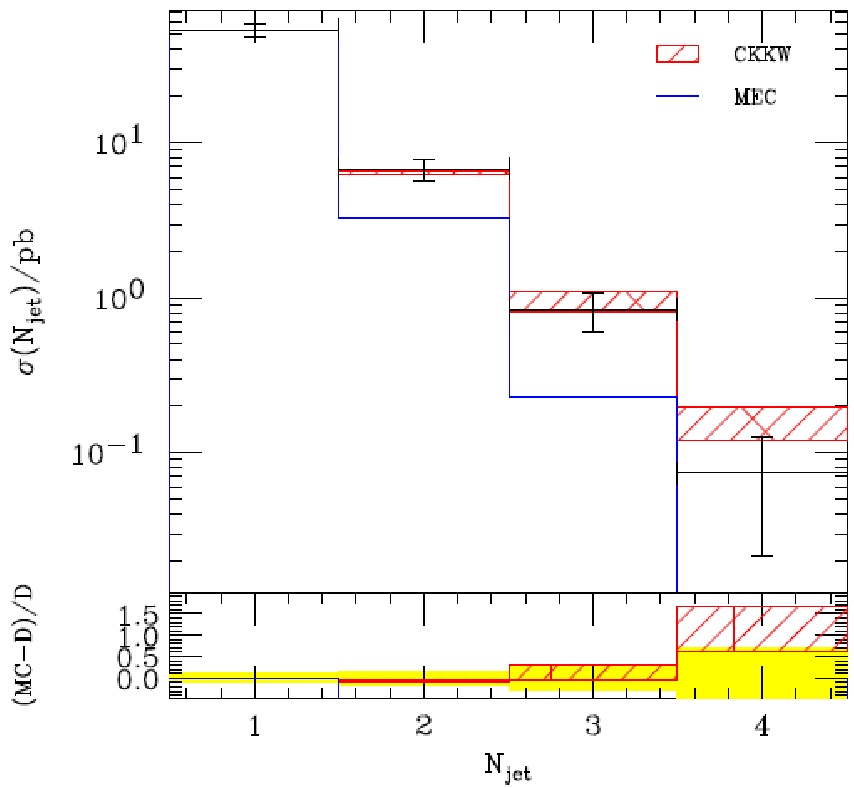
Herwig++ compared to data from CDF
Phys.Rev.D77:011108,2008

p_T of jets in W+jets at the Tevatron

3rd Hardest Jet



All Jets



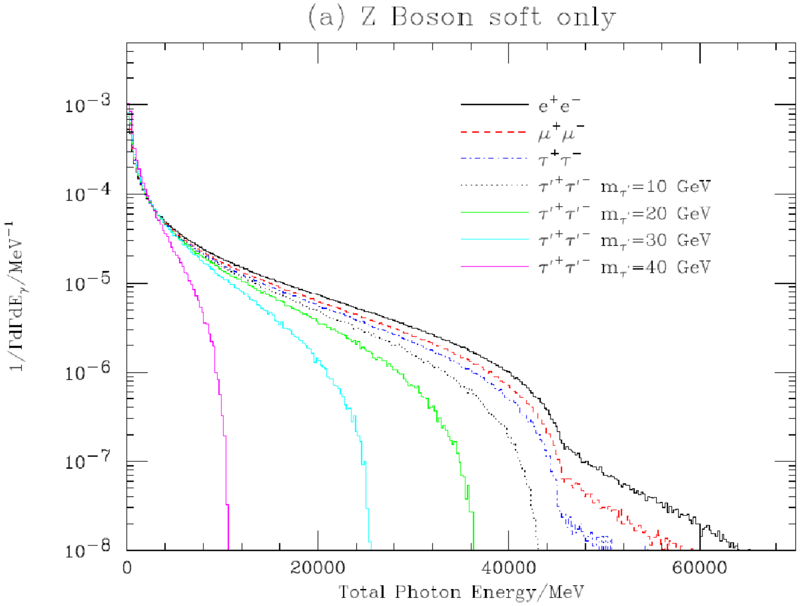
Herwig++ compared to data from CDF
Phys.Rev.D77:011108,2008

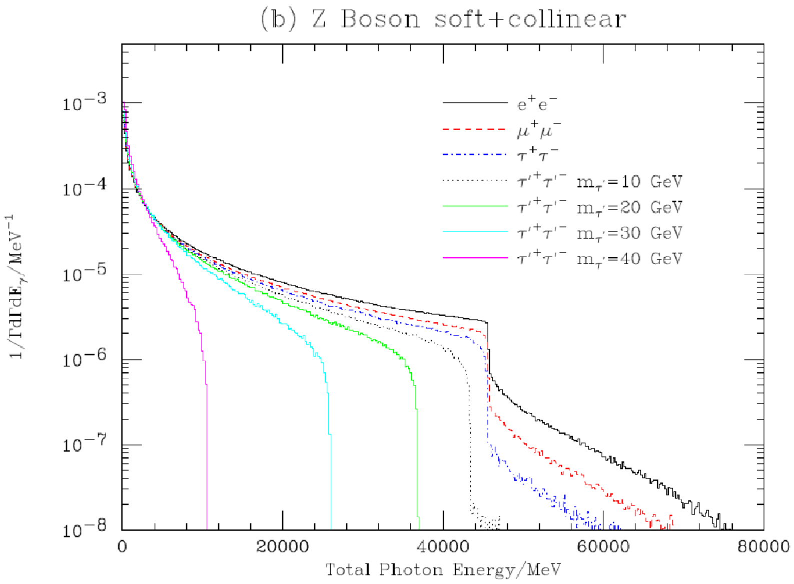
QED Radiation

- FORTRAN HERWIG did not simulate QED radiation from charged leptons
- Important for the simulation of W and Z leptonic decays.
- In Herwig++ we simulate this using the YFS formalism.

K. Hamilton and PR hep-ph/0603034, JHEP 0607:010, 2006.

QED Radiation





BSM Physics

- FORTRAN HERWIG was the only Monte Carlo event generator to include spin correlations between particles production and decay in SUSY models.
- Important for the study of spin effects.
- The problem was that it was very hard to include these effects for new models due to the structure of the code.

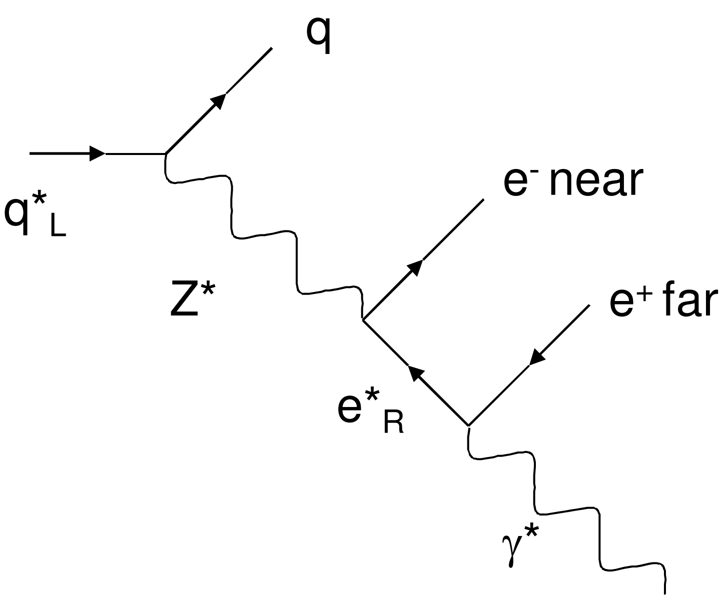
BSM Physics

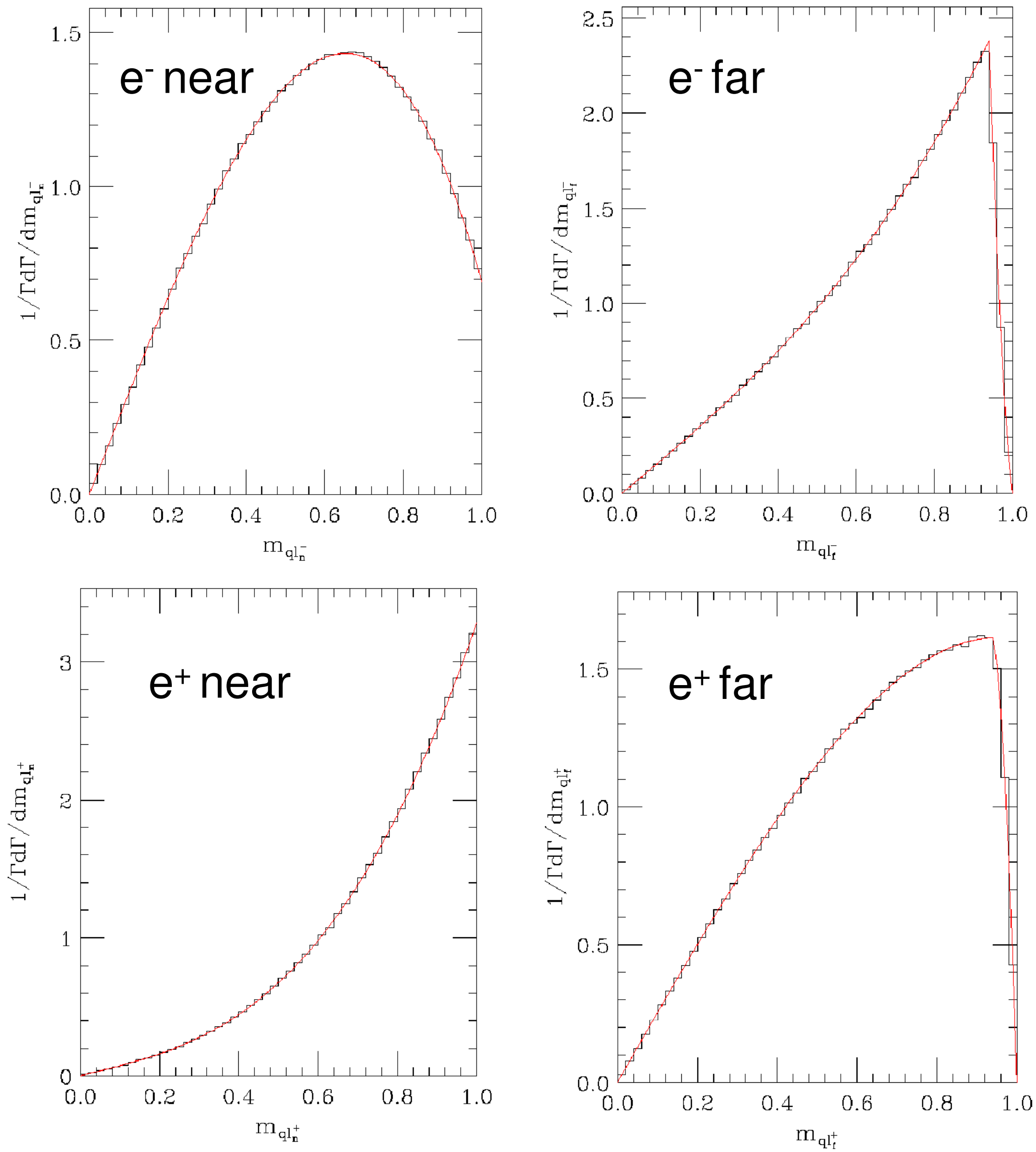
- In Herwig++ use a different approach so only the Feynman rules for a new model need to be coded.
- Automatically calculates the $2 \rightarrow 2$ scattering processes, $1 \rightarrow 2$ and $1 \rightarrow 3$ decays and generates all the spin correlations.
- Currently in addition to the SM the
  - MSSM
  - Minimal UED model
  - RS model

  are available.

UED

Look at the decay

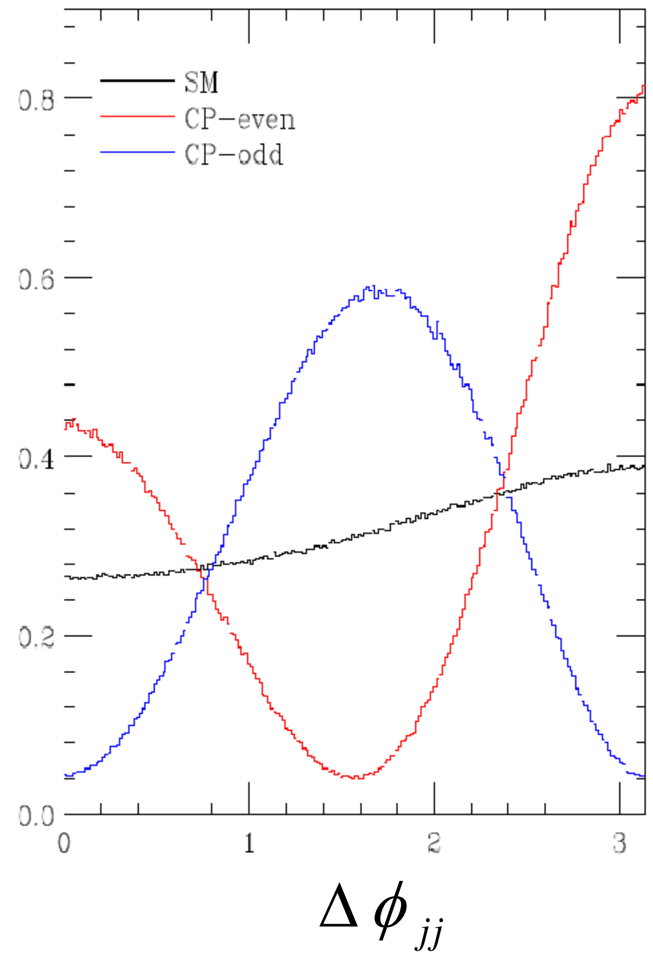




Herwig++ compared to hep-ph/0507170 Smillie and Webber

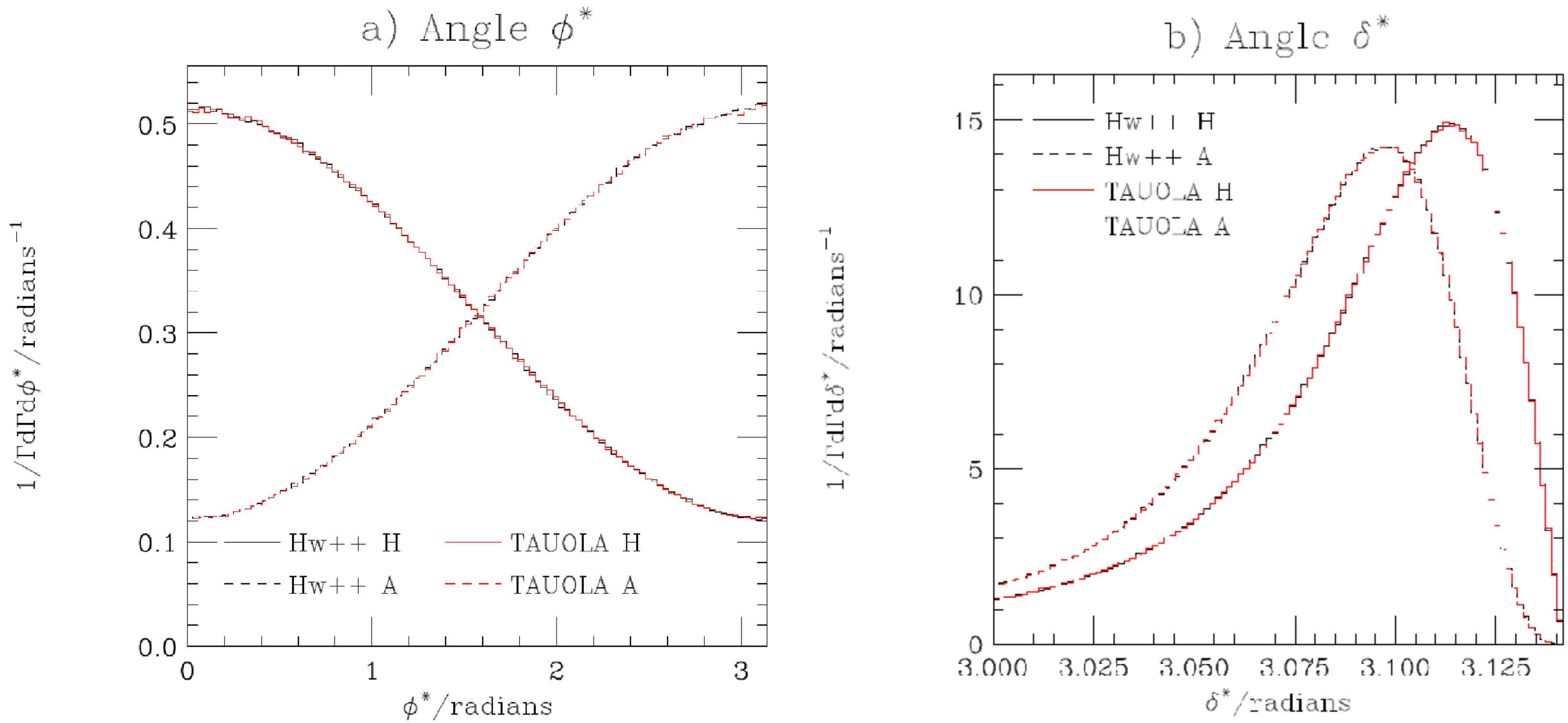
VBF Higgs Production

- Much easier to make changes,
- To explore the CP structure of the Higgs can implement a new CP-even and CP-odd operators.
- Rest of the structure can then be used to calculate scattering processes and decays.



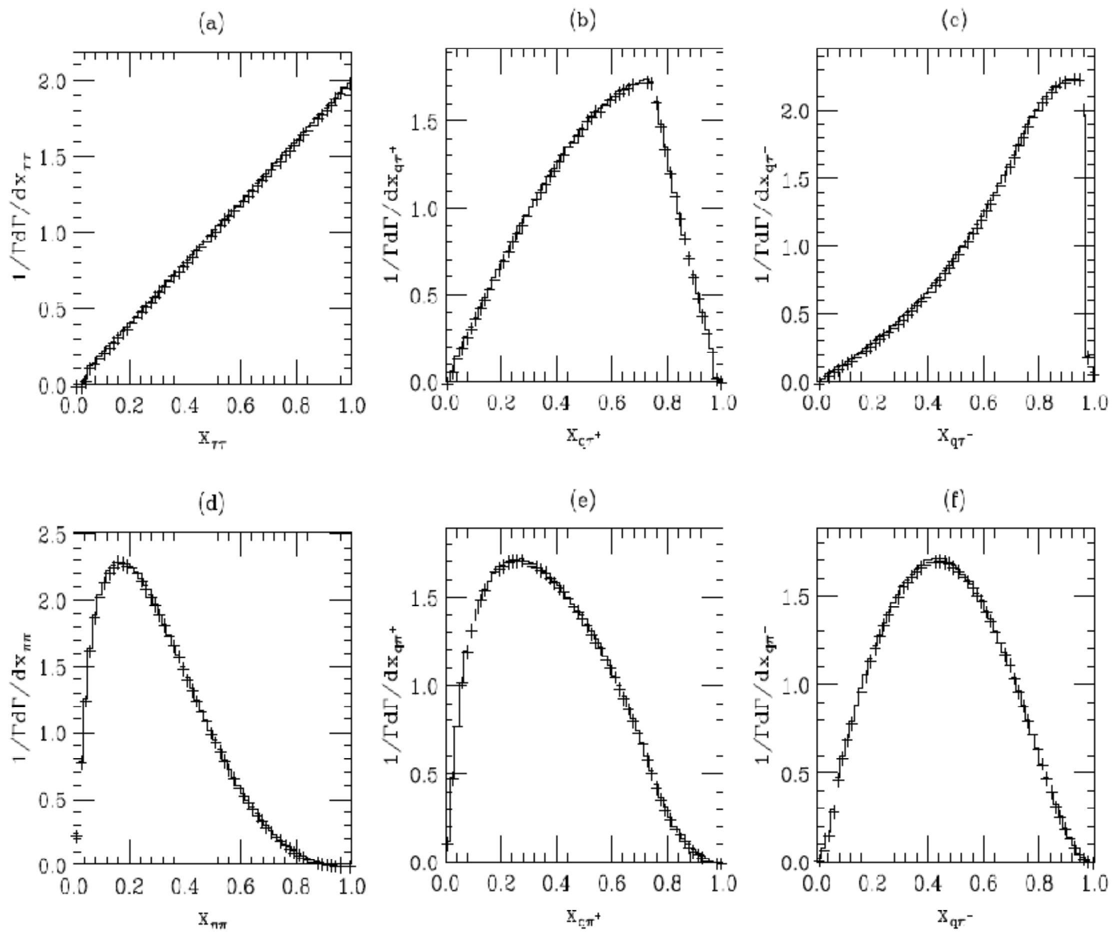
Based on hep-ph/0105325 Plehn et. al

Higgs Decays



- Spin correlations are also included.
- In the decay $H \to \tau^+\tau^- \to \bar{\nu}_\tau \pi^+ \nu_\tau \pi^-$ the angle between the tau decay planes, ϕ^*, and between the pions, δ^*, depends on whether the parity of the Higgs boson.

Correlations in Tau Decays



$$\tilde{q}_\alpha \to q\chi_2^0 \to \tau_{near}^{\perp}\tilde{\tau}_1^{\mp} \to \tau_{far}^{\mp}\chi_1^0$$

- Based on hep-ph/0612237 Choi et al.

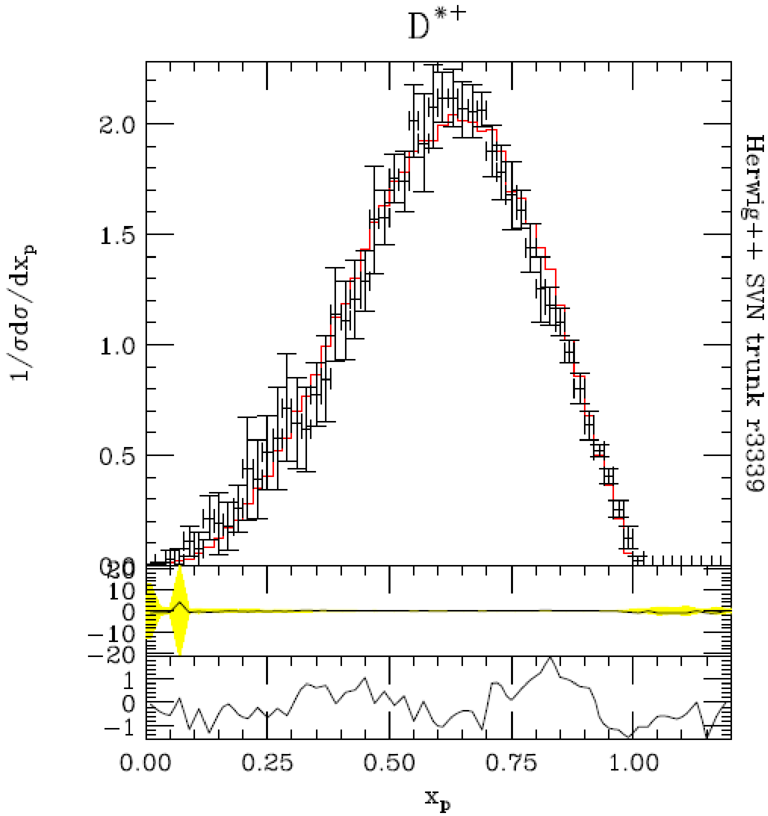
BSM Physics

- The NMSSM and anomalous gauge boson couplings will be available in the next release.
- In the near future we will shift to an interfere to FeynRules to make adding new models even easier.

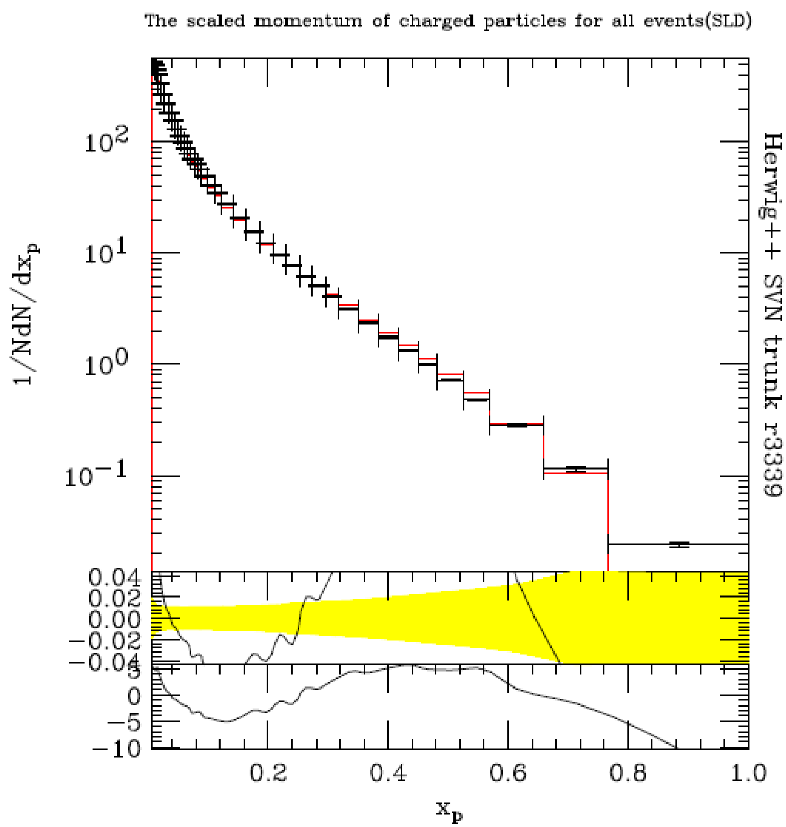
Hadronization

- The main improvements in the hadronization are designed to improve the simulation of
  - the production of bottom and charm hadrons
  - Baryons
- Mainly through the introduction of flavour specific parameters in the hadronization model.

Hadronization



Herwig++ compared to BELLE
Phys.Rev.D73:032002,2006

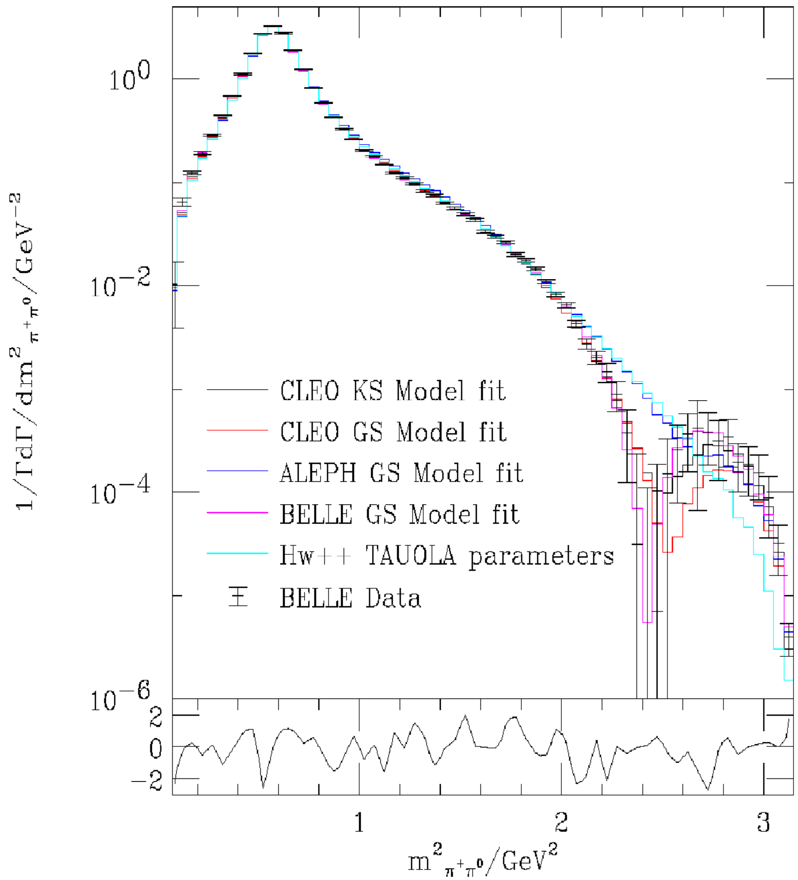


Herwig++ compared to SLD
Phys.Rev.D59:052001,1999

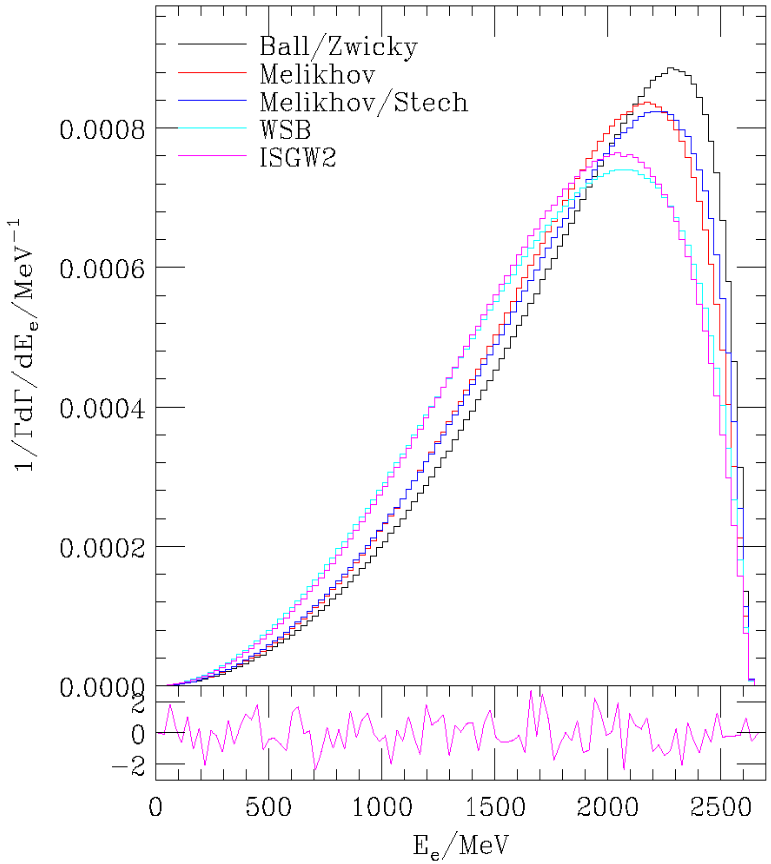
Hadron and Tau Decays

- Herwig++ includes a sophisticated simulation of non-perturbative hadron and tau decays.
- Main concentration on
  - Tau Decays
  - Light mesons and baryons
  - General properties of heavy meson and baryon decays rather the rare B decays and mixing.
- Includes correlations and allows communication with the perturbative stage of the event for tau decays.

Hadron Decays

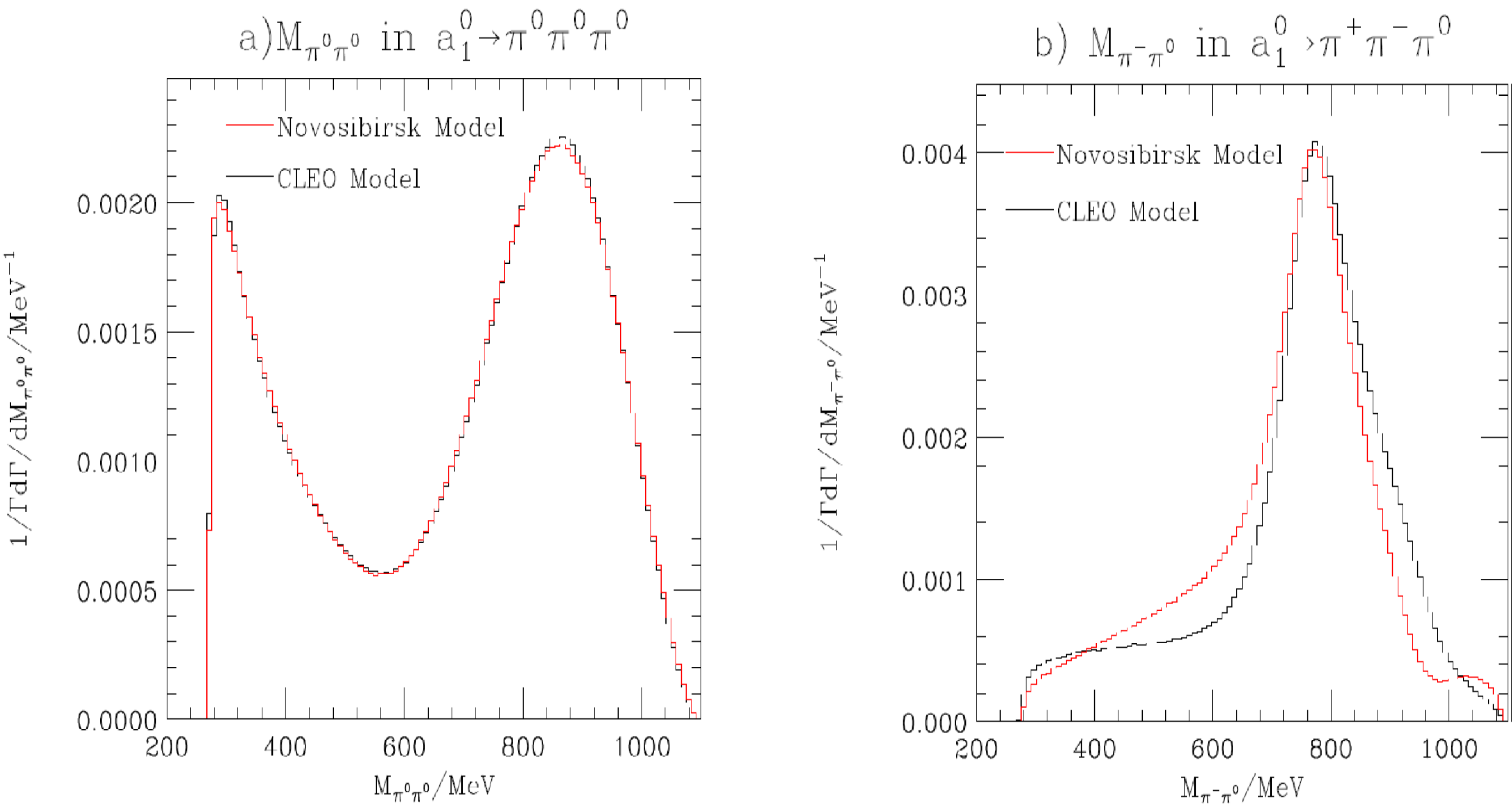


Tau Decays, $\tau \to \rho \nu_\tau$



$B \to \pi e \nu$

Hadron Decays



- The simulation includes detailed modelling of many decays.

Summary

- Herwig++ is now provides a sophisticated simulation of hadron collisions.
- The current version has NLO simulations of W and Z production, gg→H, W/Z+H.
- The next release will include
  – NLO simulations of DIS, VBF and gauge boson pair production.
  – An improved CKKW approach for the simulation of many hard jets.
  – More BSM models.