LHC Event Generation with Herwig++

Stefan Gieseke

Universität Karlsruhe (TH)
Institut für Theoretische Physik

- What's inside Herwig++
- Outlook on Higher Order MEs in Herwig++

SG, P. Stephens and B. Webber, JHEP **0312** (2003) 045 [hep-ph/0310083]

SG, A. Ribon, M. H. Seymour, P. Stephens and B. Webber, JHEP **0402** (2004) 005 [hep-ph/0311208]

SG, JHEP **0501** (2005) 058 [hep-ph/0412342]

SG, D. Grellscheid, A. Ribon, P. Richardson, M.H. Seymour, P. Stephens, B.R. Webber hep-ph/0602069

SG, D. Grellscheid, K. Hamilton, A. Ribon, P. Richardson, M.H. Seymour, P. Stephens, B.R. Webber hep-ph/0609306

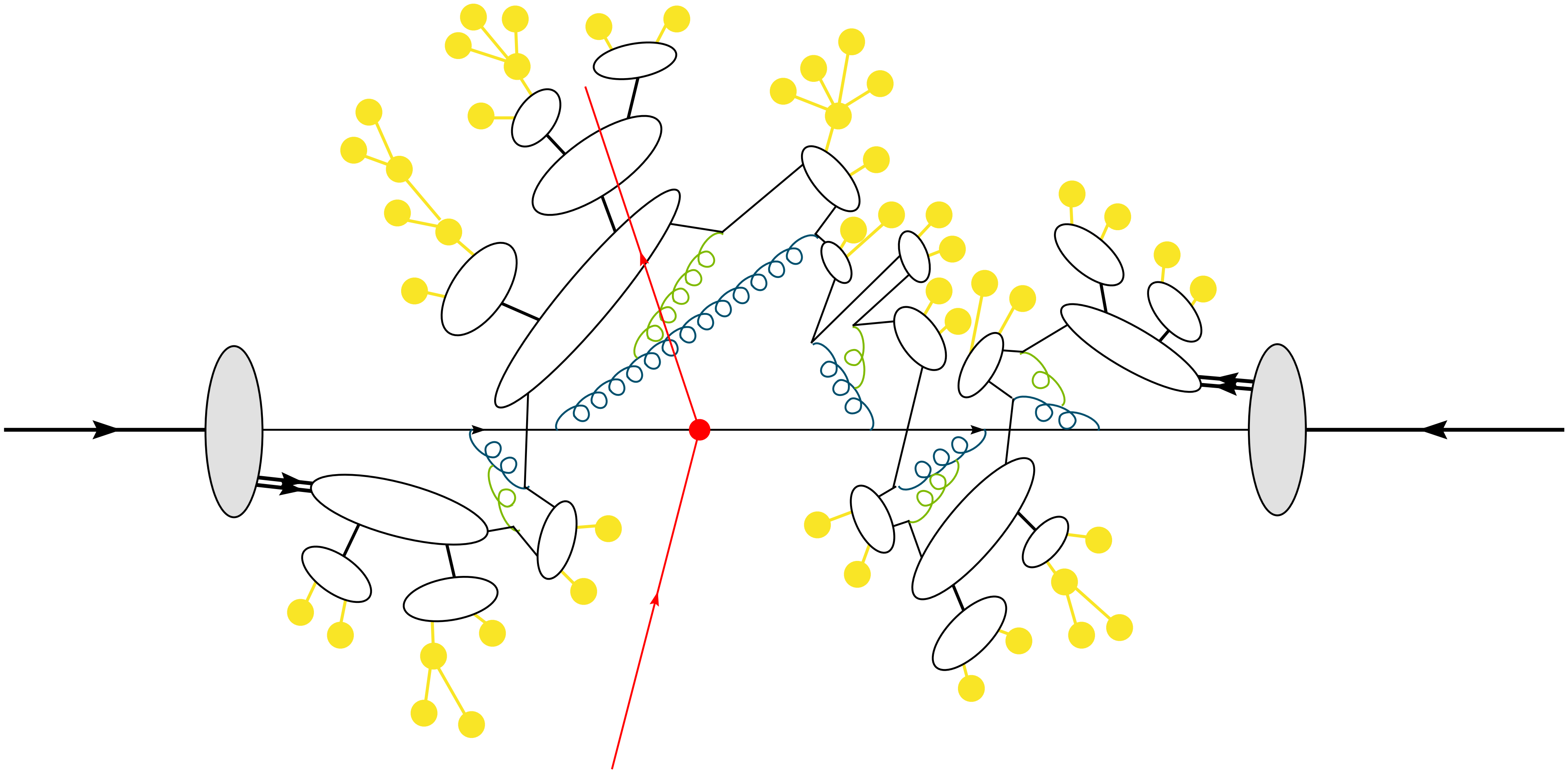
O. Latunde–Dada, SG, B.R. Webber hep-ph/0612281

Who and where we are

- Cambridge
  - Bryan Webber, A. Sherstnev$^\bullet$, Seyi Latunde–Dada*
- CERN
  - Mike Seymour, Alberto Ribon, L. Sonnenschein$^\bullet$
- Durham
  - Peter Richardson, David Grellscheid$^\bullet$, Keith Hamilton$^\bullet$, Martyn Gigg*, Jonathon Tully*
- Karlsruhe
  - SG, Manuel Bähr*, Simon Plätzer*, C. Hackstein$^\circ$
- Kraków
  - Phil Stephens$^\bullet$

$^\bullet$ Postdoc ($\leq$3yr contract)
* PhD Student
$^\circ$ Diploma Student

pp Event Generator



A (simplified) picture of what we are talking about.

Hard interactions in Herwig++

Herwig++ will probably never have a very large library of built–in hard matrix elements.

- Basic ME's included in ThePEG, such as:

$$e^+e^- \to q\bar{q}, \text{ partonic } 2 \to 2.$$

- We provide our own set of basic processeses, currently

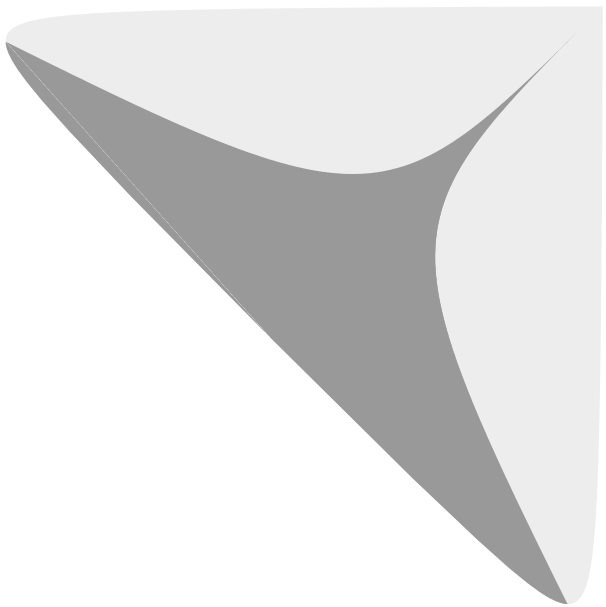
$$e^+e^- \to Z^0,\ e^+e^- \to q\bar{q},$$
$$\text{QCD } 2 \to 2,\ pp \to t\bar{t},$$
$$pp \to (\gamma, Z^0) \to \ell^+\ell^-,\ pp \to W^\pm \to \ell^\pm\nu_\ell,$$
$$pp \to h^0 + \text{jet},\ pp \to \gamma + \text{jet},\ pp \to \gamma\gamma\ .$$

- `LesHouchesFileReader` enables to read in and process *any* hard event generated by parton level event generators (`MadGraph/MadEvent, AlpGen, CompHEP,...`).

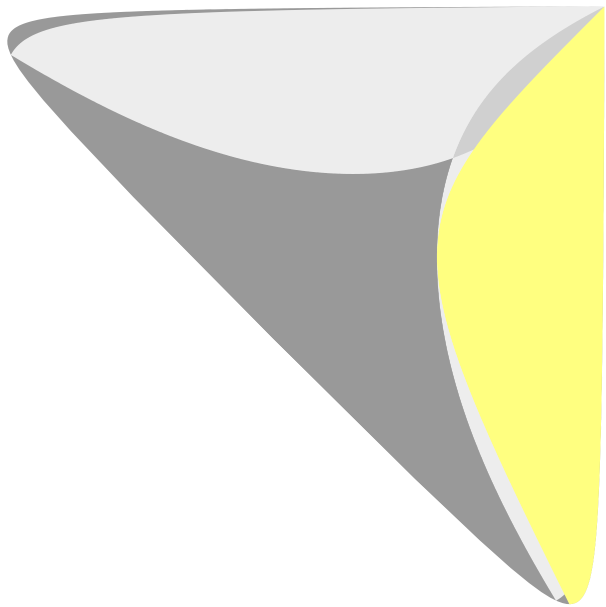
However: HELAS like structures are already implemented for decays and spin correlations $\longrightarrow$ allows us to code simple processes efficiently.

New parton shower variables — HERWIG vs Herwig++

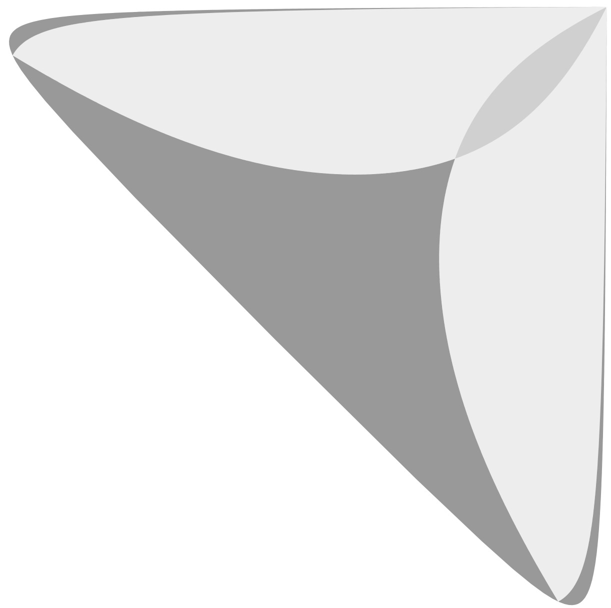
New evolution variables for parton shower evolution in Herwig++ [hep-ph/0311208].
Consider $(x, \bar{x})$ phase space for $e^+e^- \to q\bar{q}g$



Herwig++



Comparison

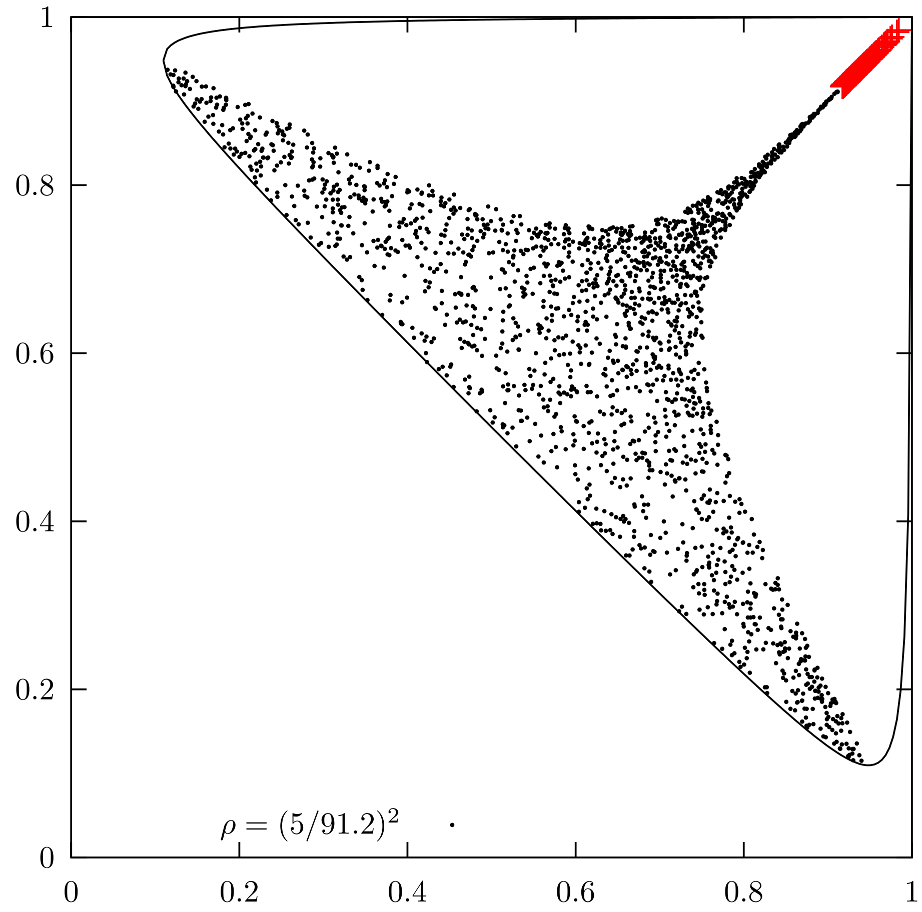


HERWIG

✓ Smooth coverage of soft gluon region.
✓ No overlapping regions in phase space.
✓ Evolution of heavy quarks.

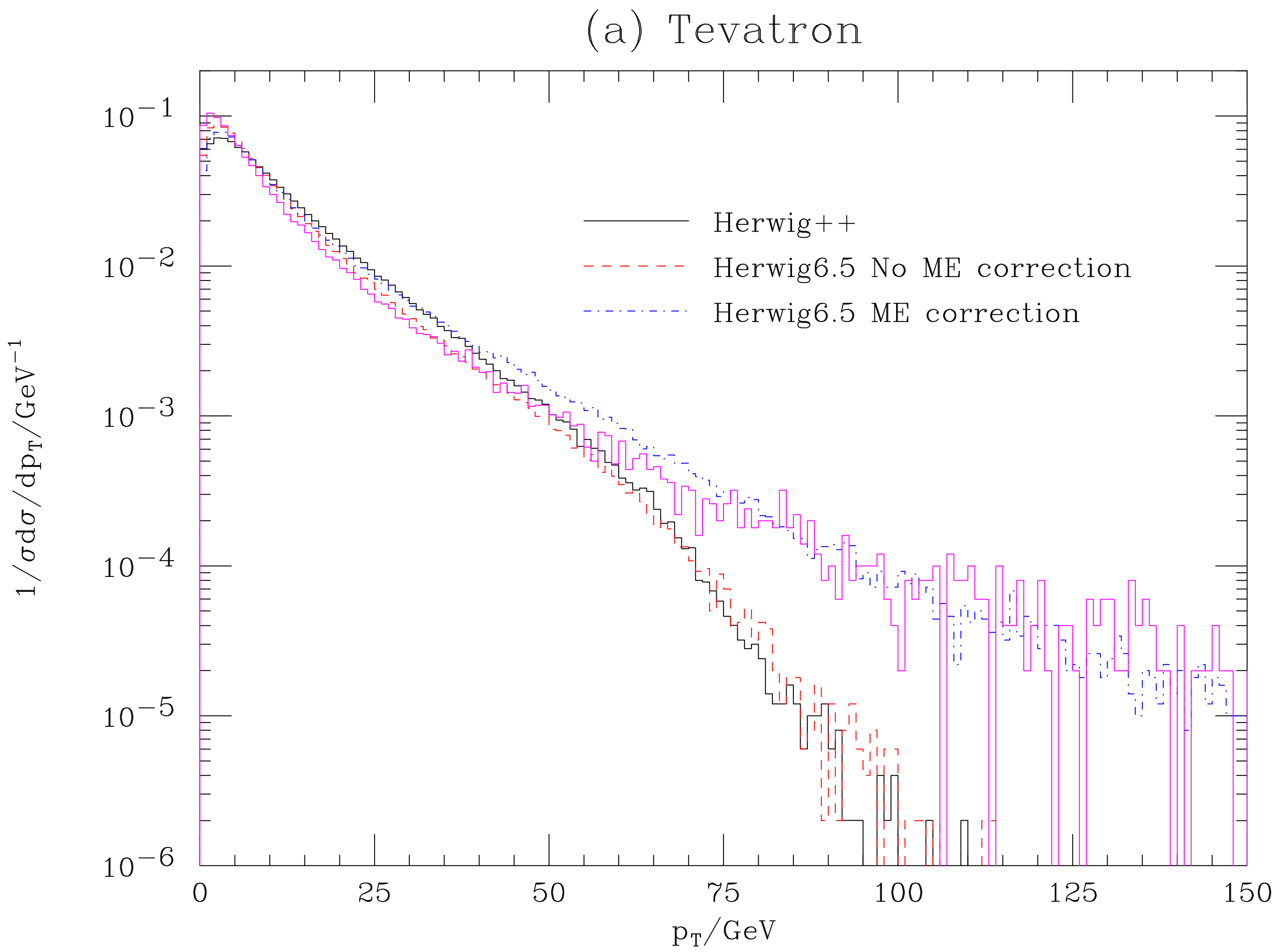
Hard Matrix Element Corrections

- Points $(x, \bar{x})$ in dead region chosen acc to LO $e^+e^- \to q\bar{q}g$ matrix element and accepted acc to ME weight.
- About 3% of all events are actually hard $q\bar{q}g$ events.
- Red points have weight > 1, practically no error by setting weight to one.
- Event oriented according to given $q\bar{q}$ geometry. Quark direction is kept with weight $x^2/(x^2 + \bar{x}^2)$.



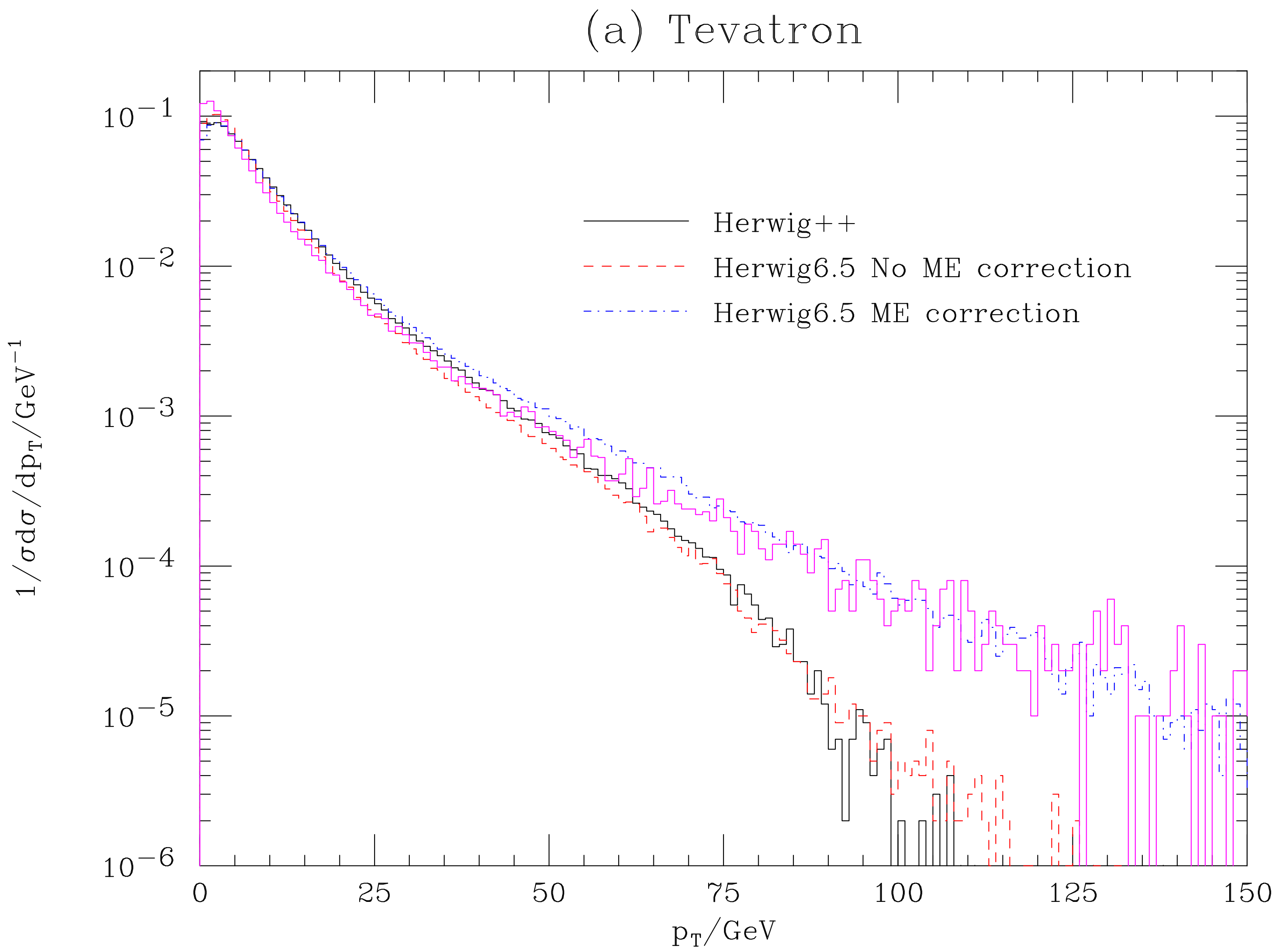
To be complemented by soft ME corrections.

$W^{\pm}$ Boson $p_{\perp}$ distribution



New: Hard ME correction in Herwig++.

Z^0 Boson $p_\perp$ distribution

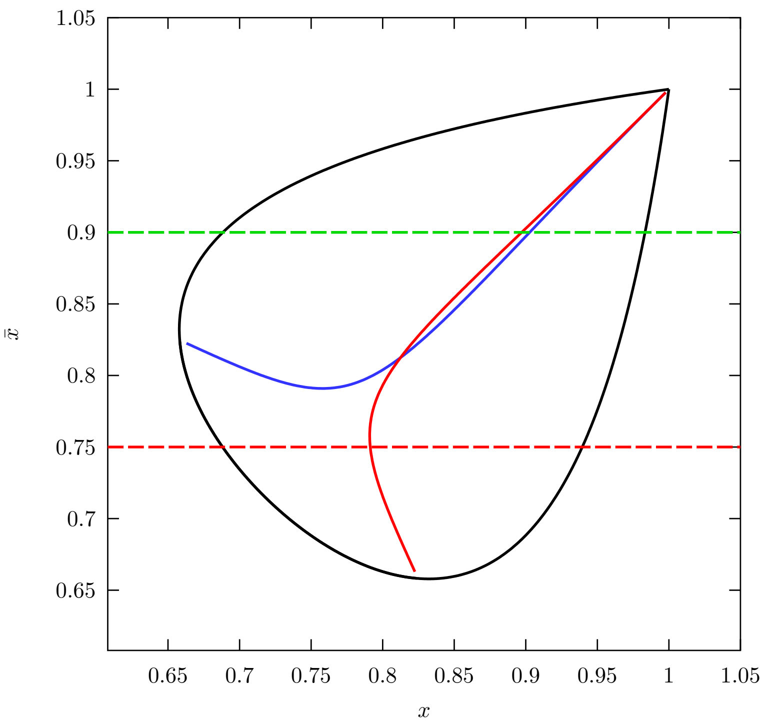


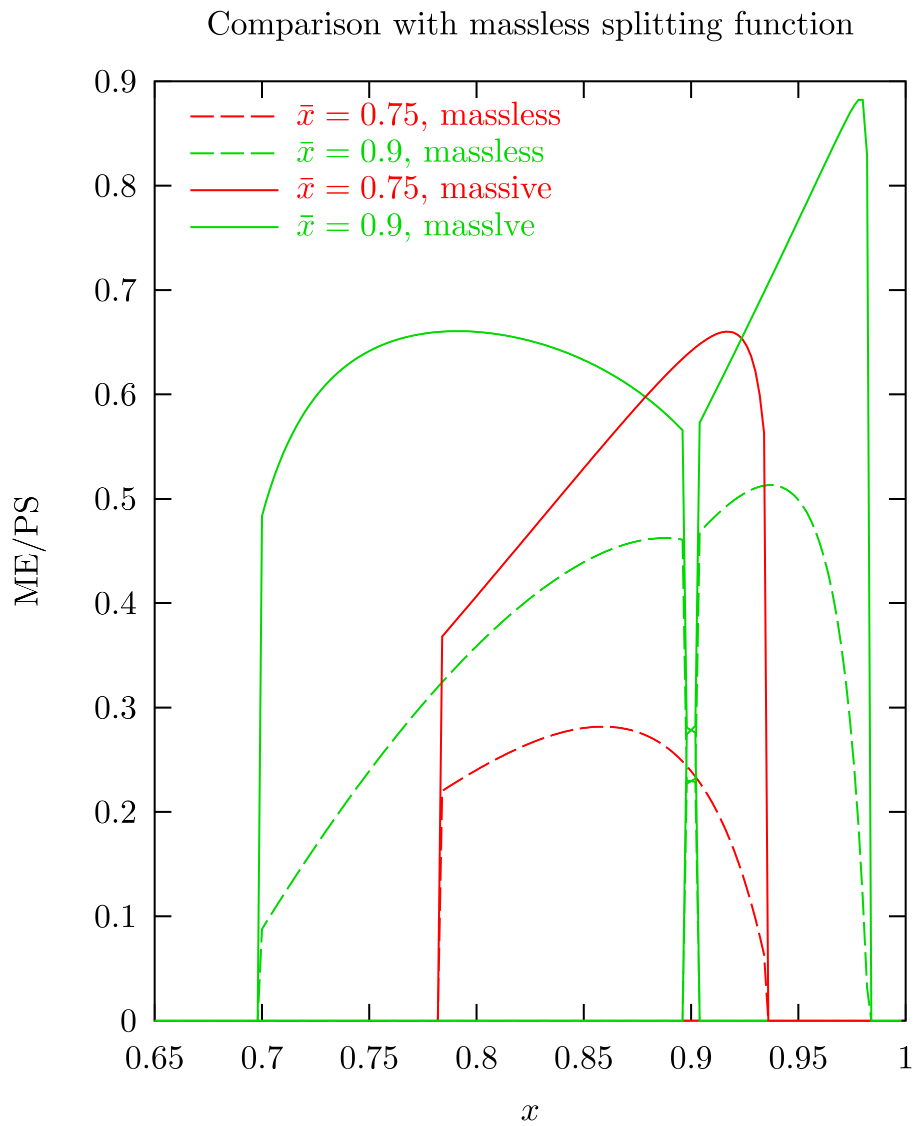
New: Hard ME correction in Herwig++.

Soft Matrix Element Corrections

- Ratio ME/PS compares emission with result from true ME if slightly away from soft/collinear region.
- Veto on 'hardest emission so far' in $p_\perp$.
- Massive splitting function *very important*!

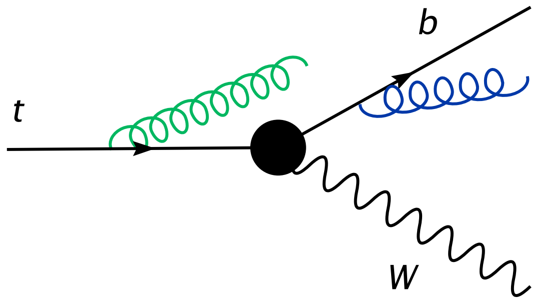
Example with heavy quark, $m^2/Q^2 = 0.1$, ($t\bar{t}$, $Q = 500$ GeV):



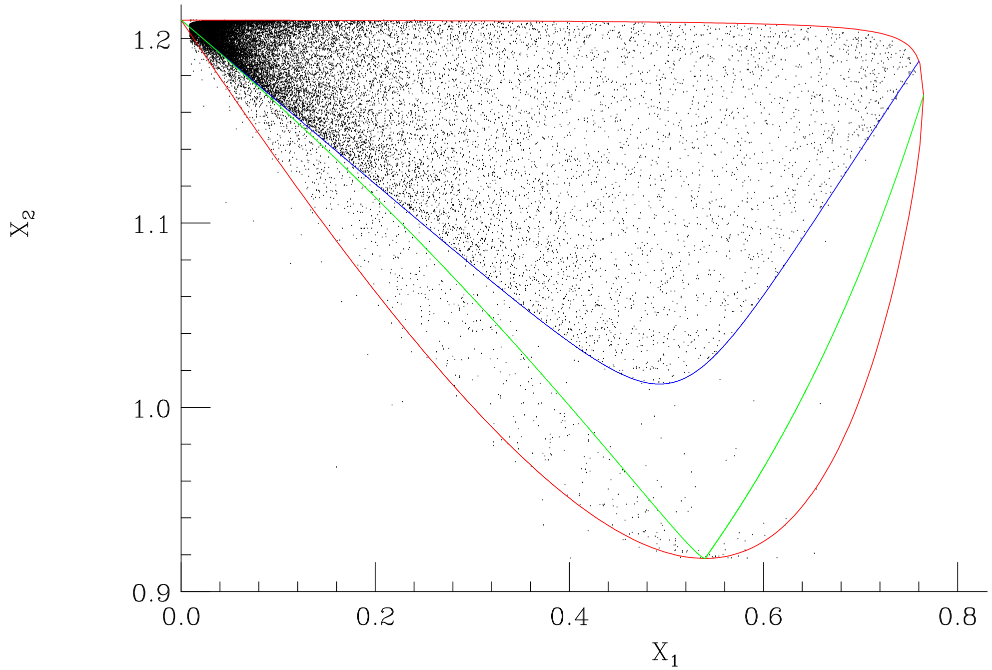


Soft ME Corrections in t Decays

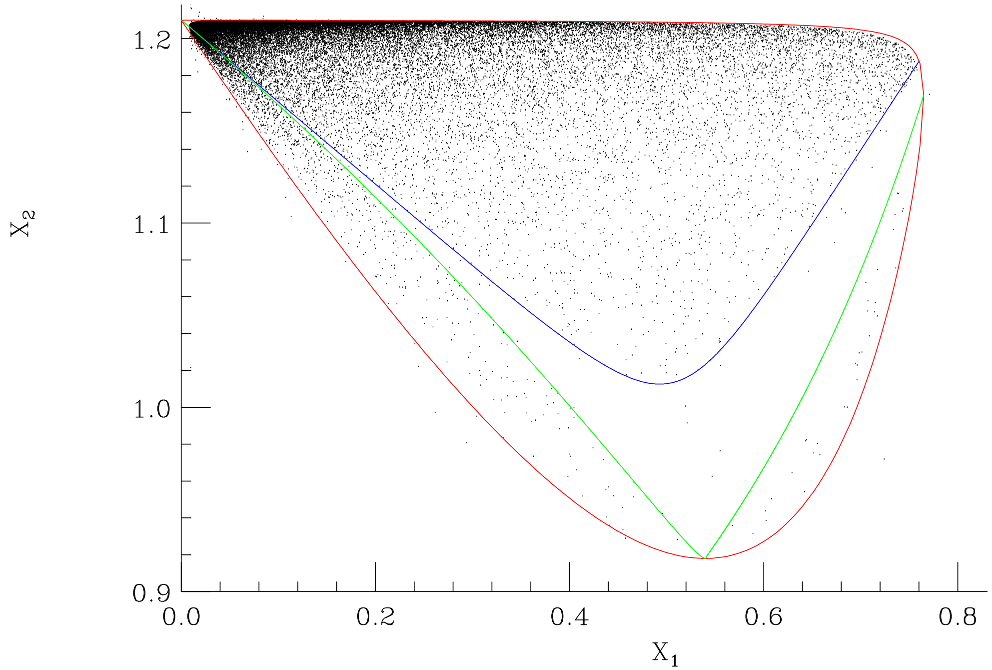
Smooth coverage of soft gluon region from both parton showers.



$$x_1 = \frac{2q_g \cdot p_t}{m_t^2}\ , \quad x_2 = \frac{2q_W \cdot p_t}{m_t^2}$$



w/o soft ME correction



with soft ME correction

Cluster hadronization in a nutshell

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

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

where masses are chosen from

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

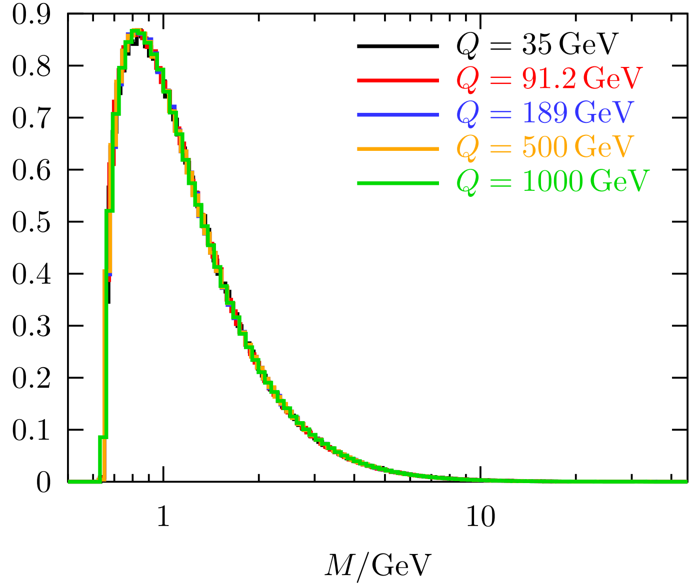
with additional phase space contraints. Constituents keep moving in their original direction.

- Cluster Decay

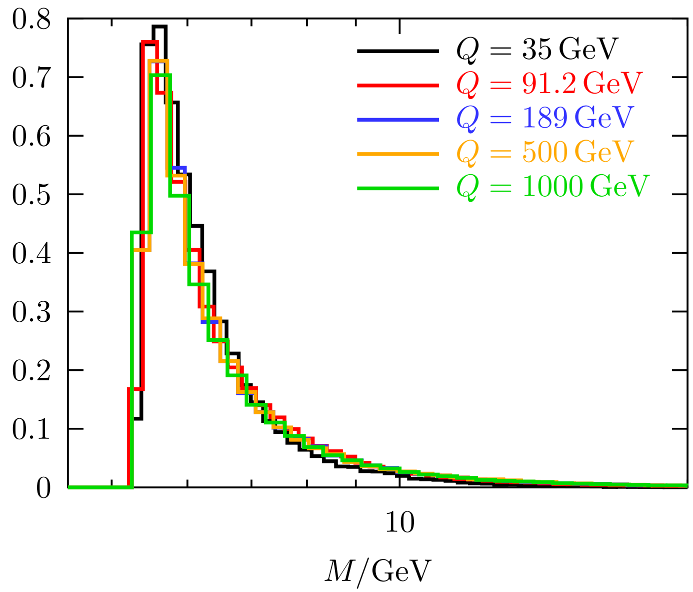
$$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$

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

Primary Light Clusters

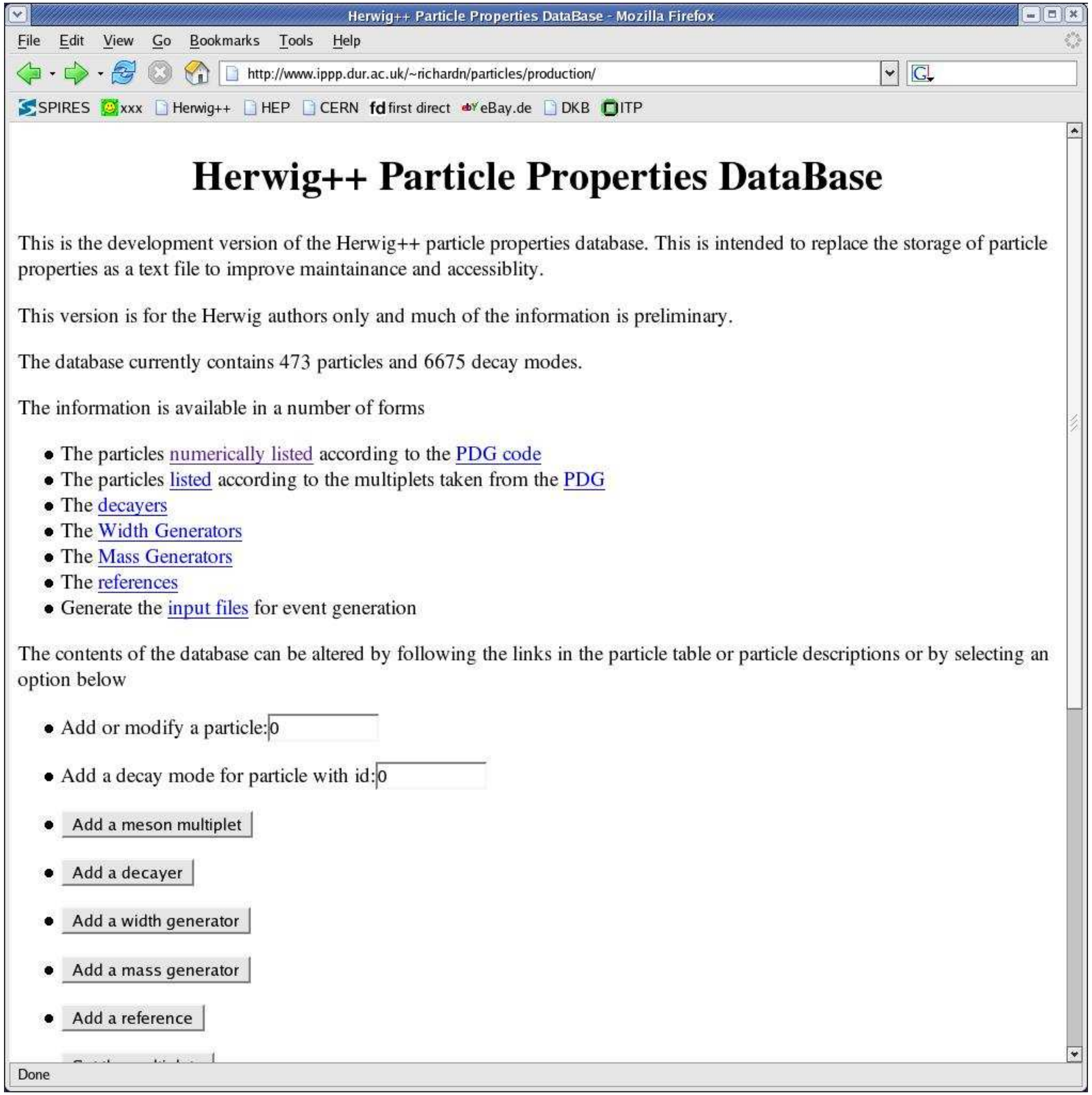


Primary b-Clusters



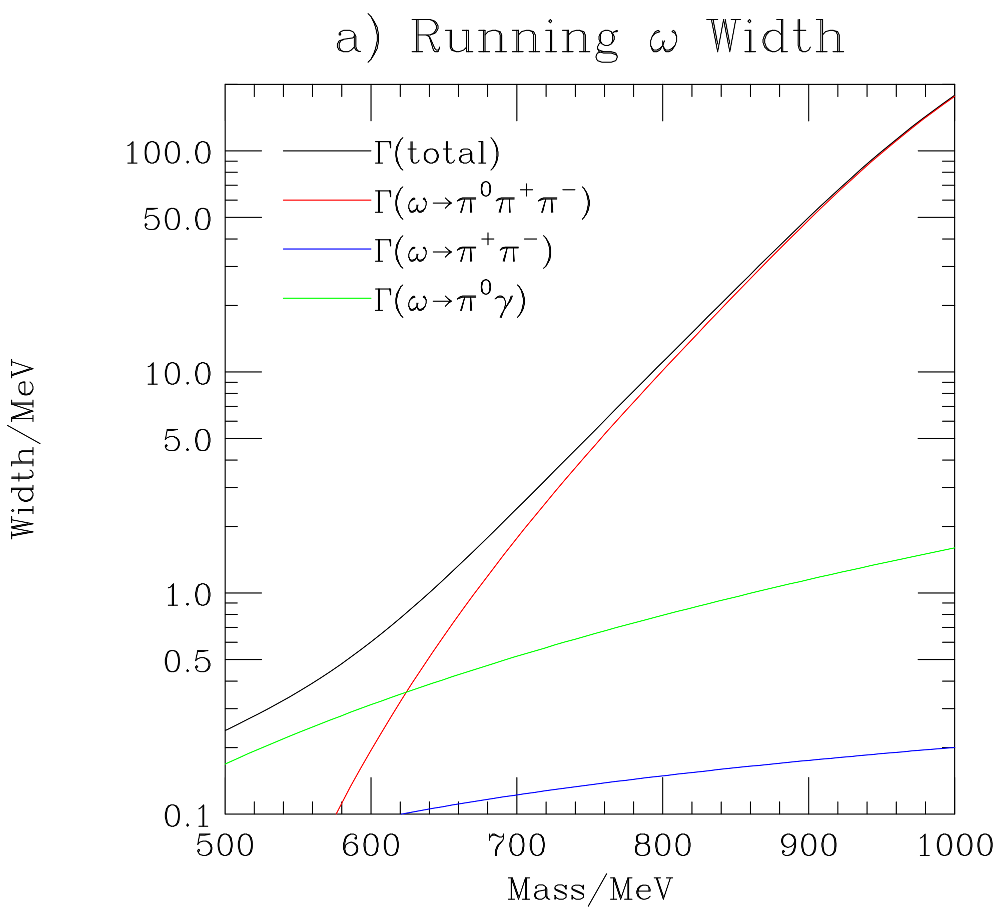
Hadronic Decays

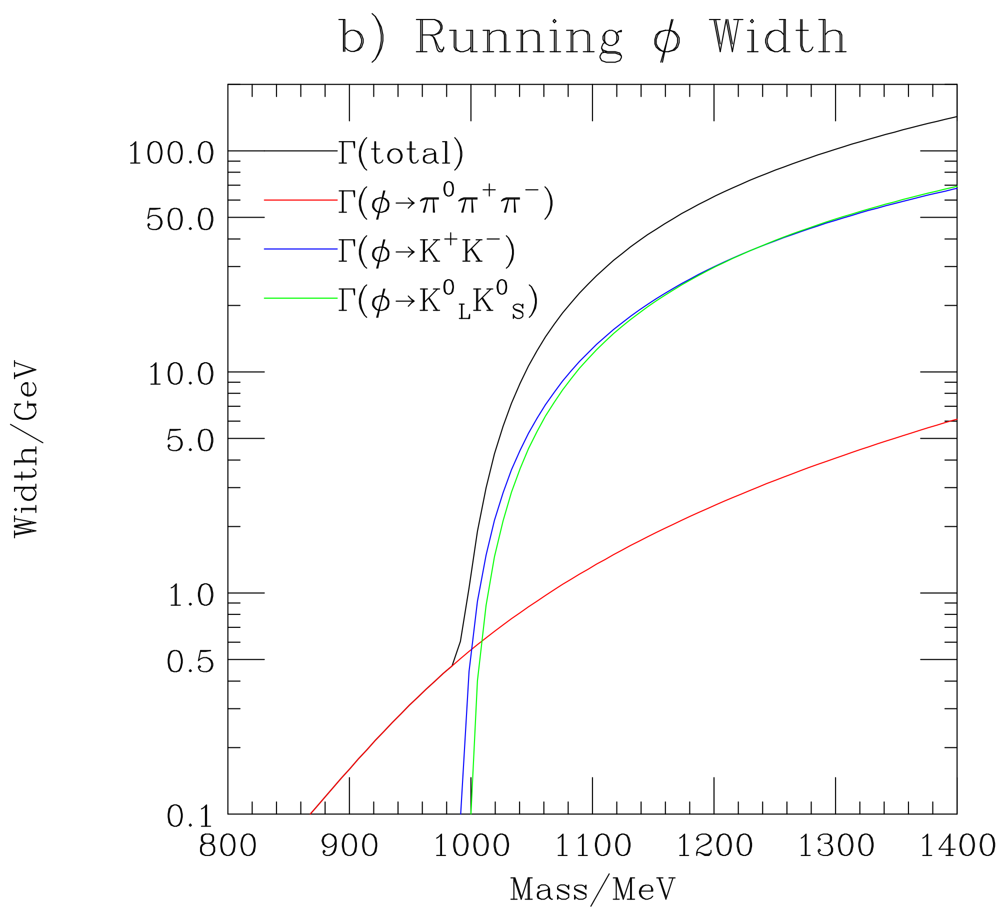
- FORTRAN HERWIG is reproduced with Hw64Decayer using the same Matrix element codes as before.
- Works fine. Still default.
- *New!* Better decayers are being developed for almost all decay modes.
- $\to B$ decays.
- Spin correlations will be included.
- Major effort ongoing
  - a universal database is set up.
  - contains 473 particles and 6675 decay modes at present.
  - possibility to generate configuration files for different generators.



Running Widths

Masses are generated acc to Breit–Wigner like distribution. Subsequent decays will depend on that.

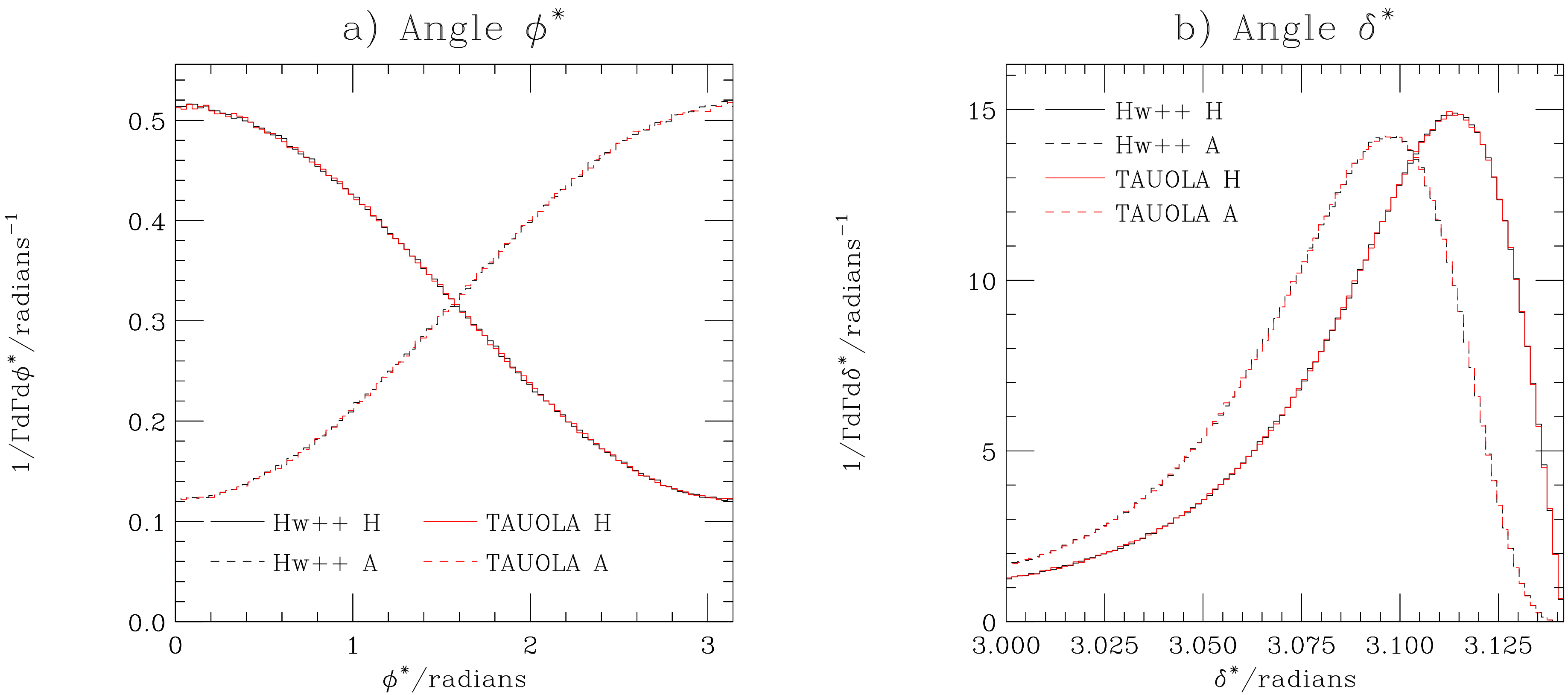




Important for spin correlation algorithm.

Spin Correlations

Use narrow–width approximation for cascade decays. Spin correlations are restored, based upon PR's algorithm.

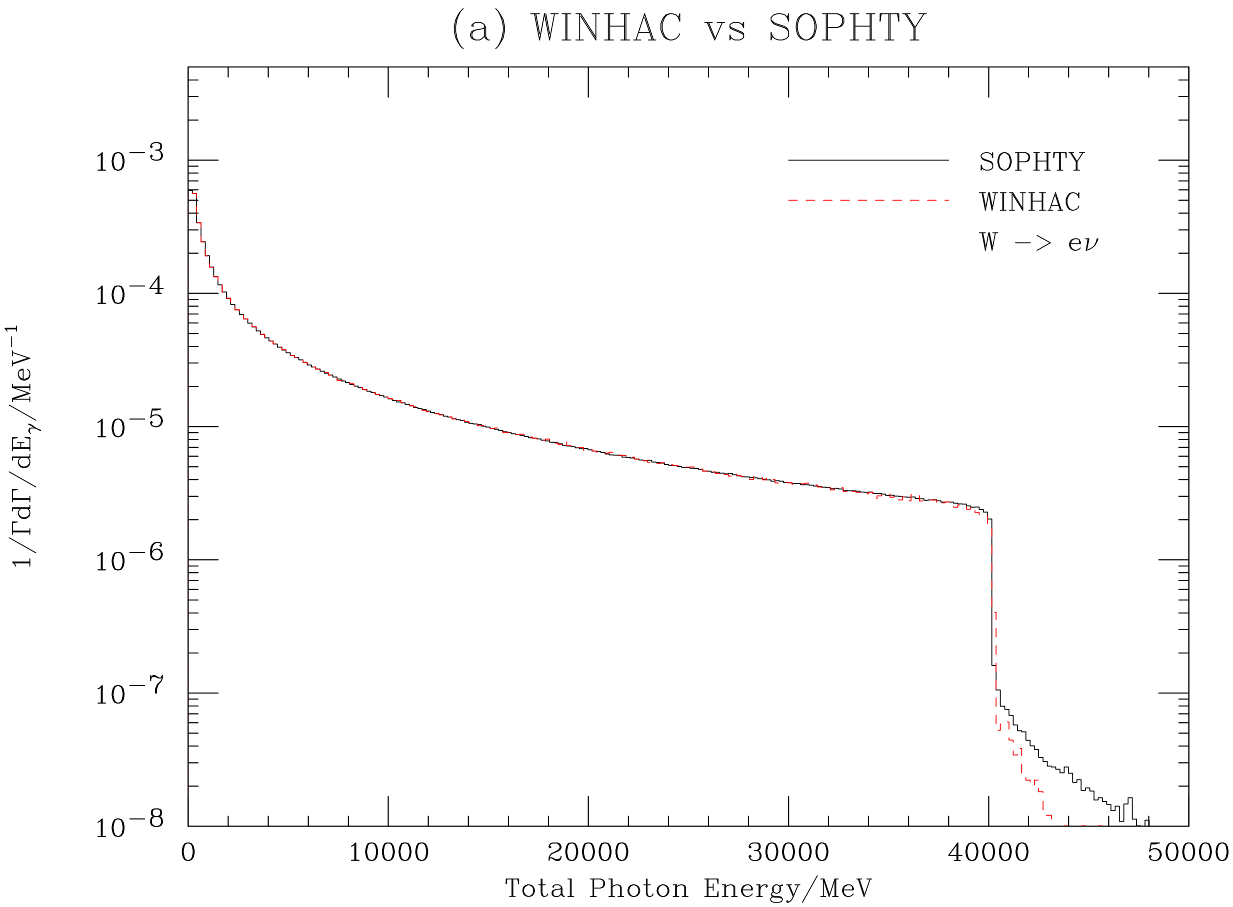


$H, A \to \tau^+\tau^-$, followed by $\tau^\pm \to \pi^\pm\nu_\tau$.

ϕ^* = angle between decay planes of τ's. δ^* = angle between π's in rf of H/A.

Photon Radiation in Decays

New package SOPHTY included in Herwig++. YFS multiple photon radiation with some hard component.



[K. Hamilton, P. Richardson, hep-ph/0603034]

Validation: Herwig++ 1.0

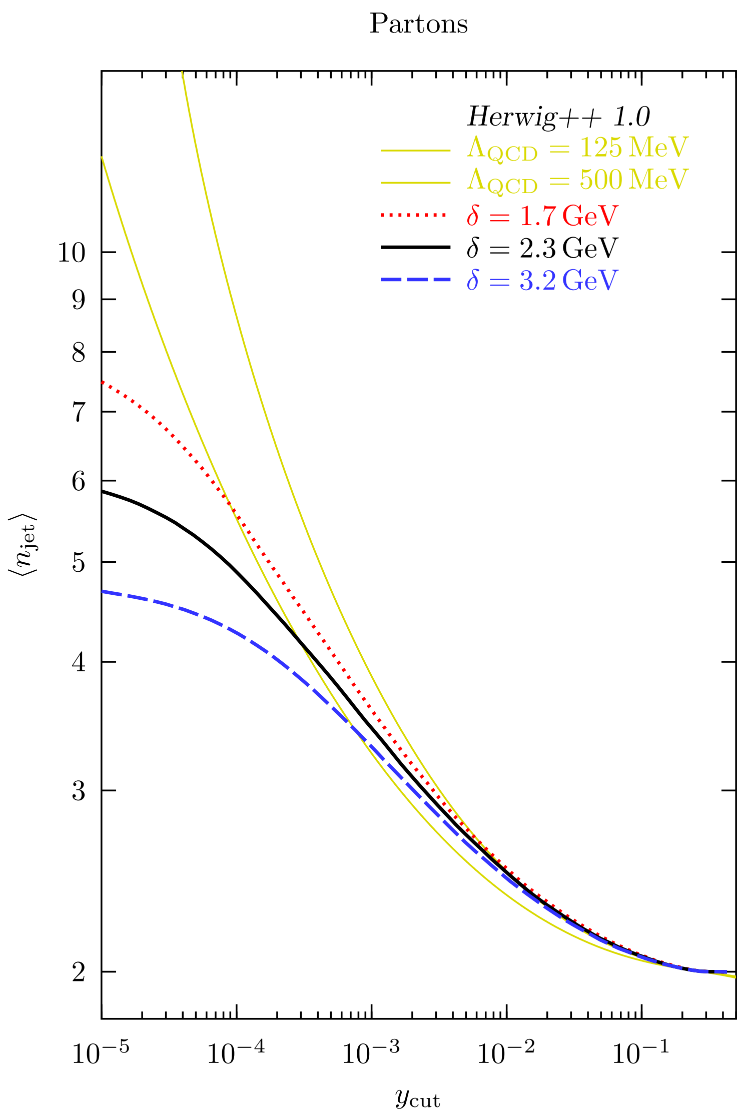
Tested parton shower and hadronization against LEP in great detail [hep-ph/0311208].

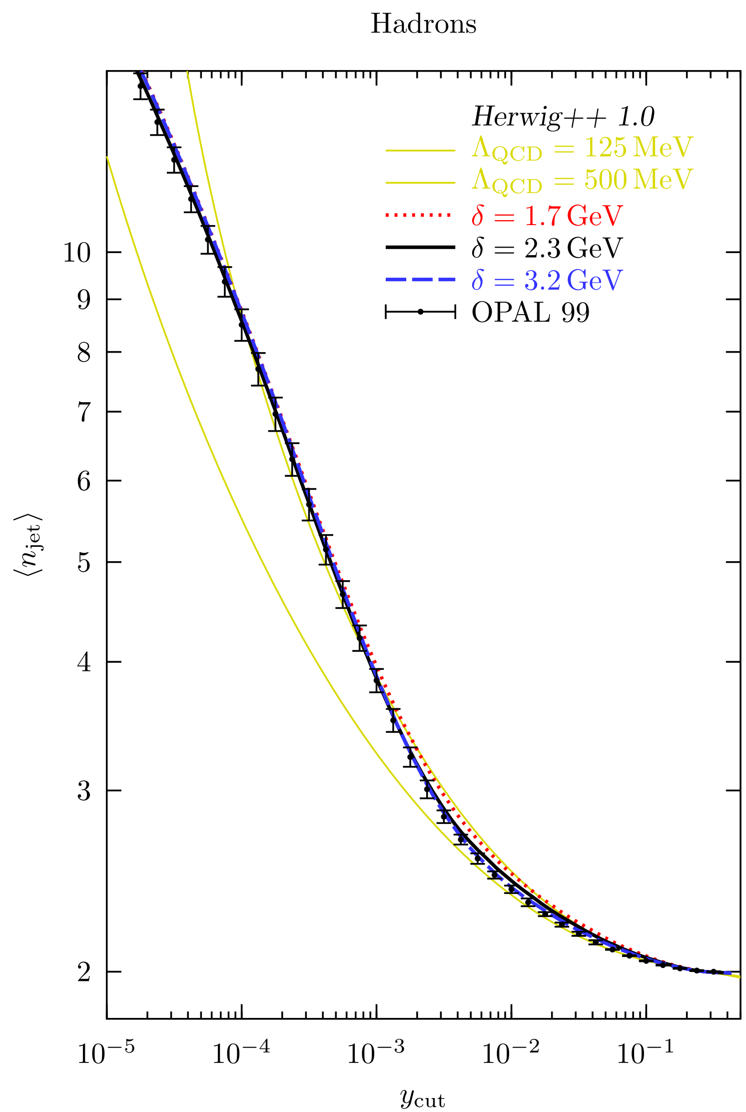
- Hadronization against hadron multiplicities. Find some improvements wrt HERWIG.
- Single particle distributions $\longrightarrow$ hadronization and shower.
- jets, jets, jets.
- Event shapes.
- B fragmentation funcion (new parton shower).

Only small fraction shown here.

Jet Multiplicity

Durham algorithm. Smooth interplay between shower and hadronization.

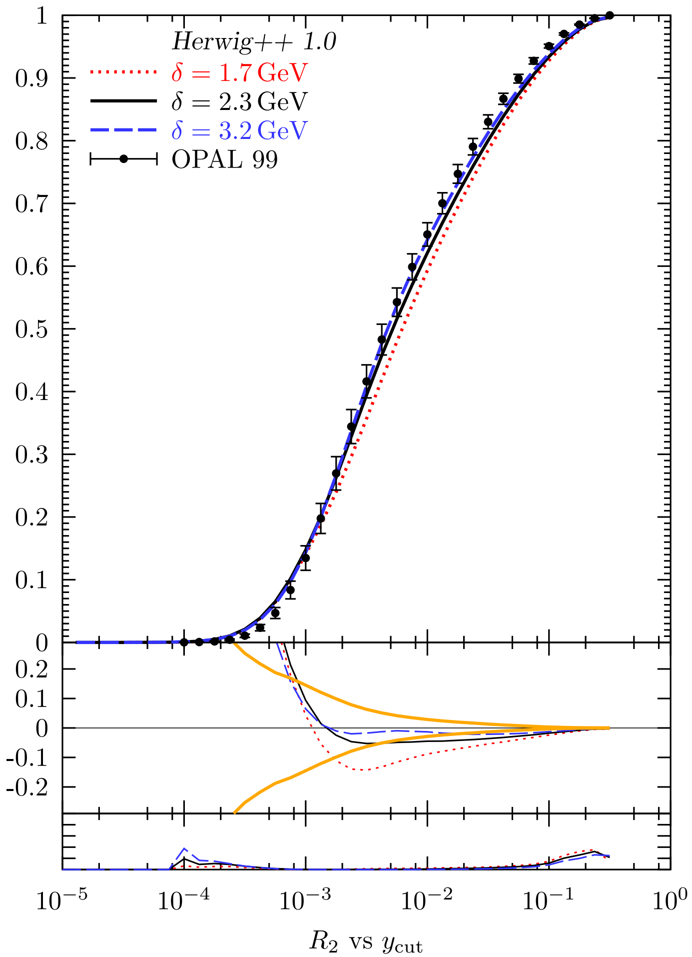


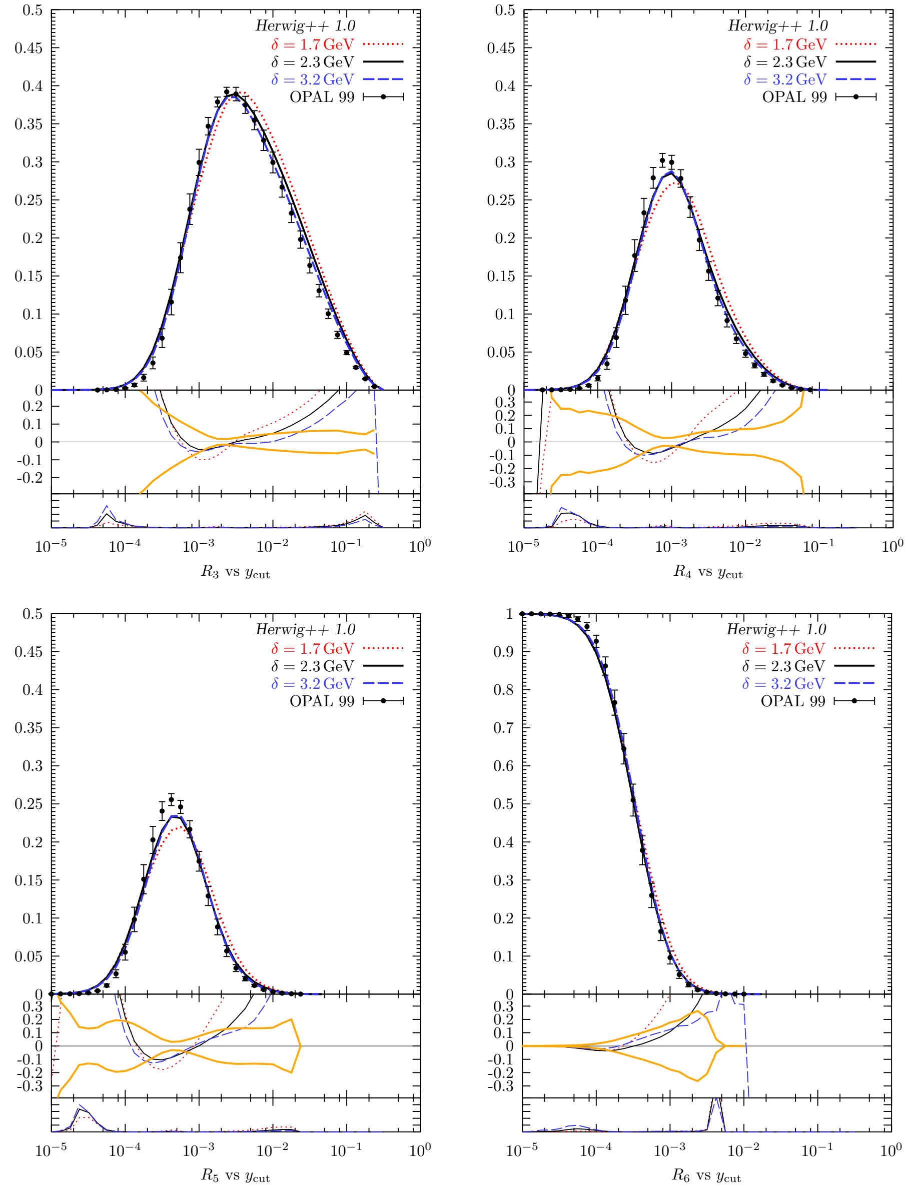


Jet Rates

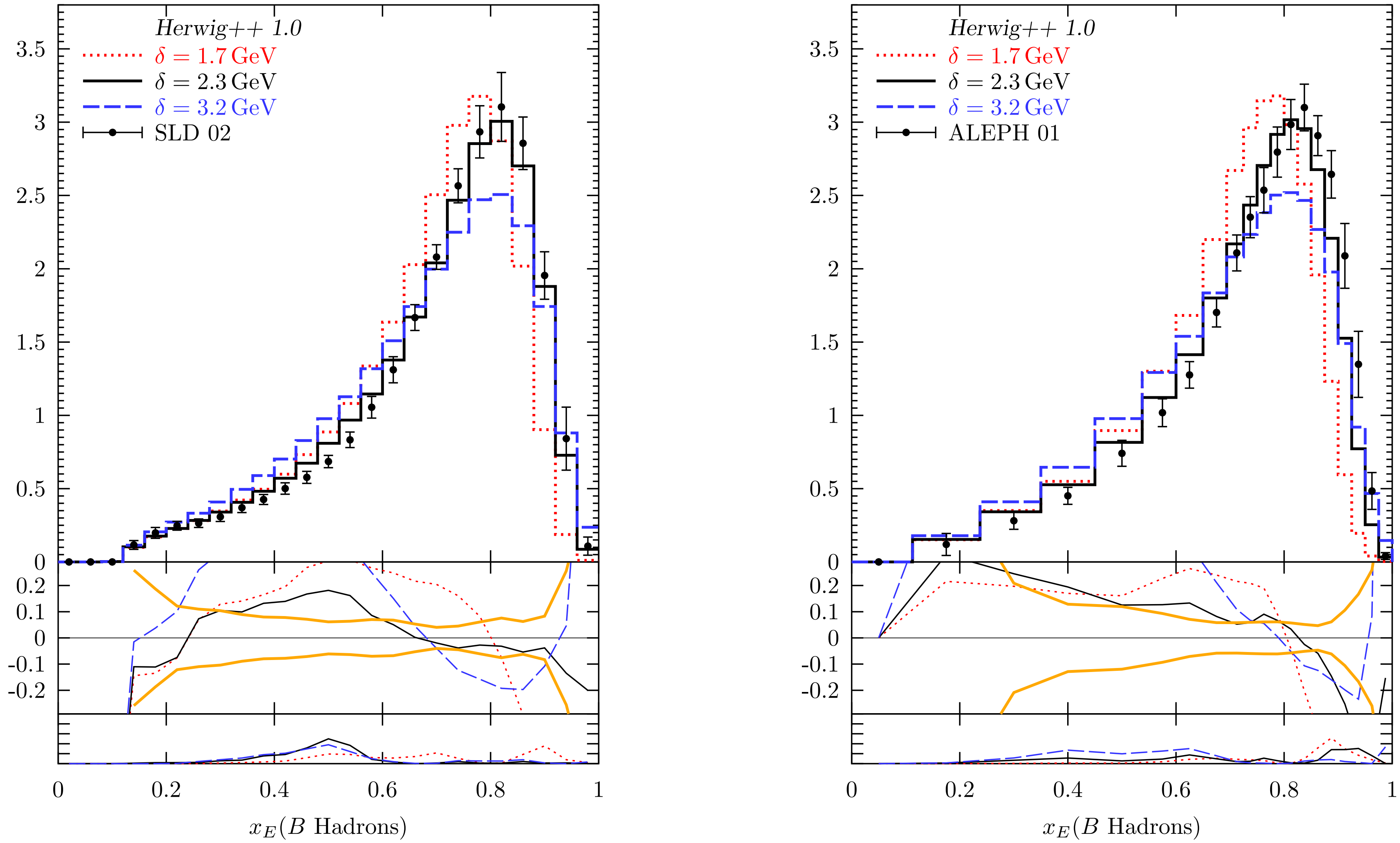
$R_n = \sigma(n\text{–jets})/\sigma(\text{jets}) \qquad (n = 2..5)$

$R_6 = \sigma(> 5\text{–jets})/\sigma(\text{jets})$





B-fragmentation function

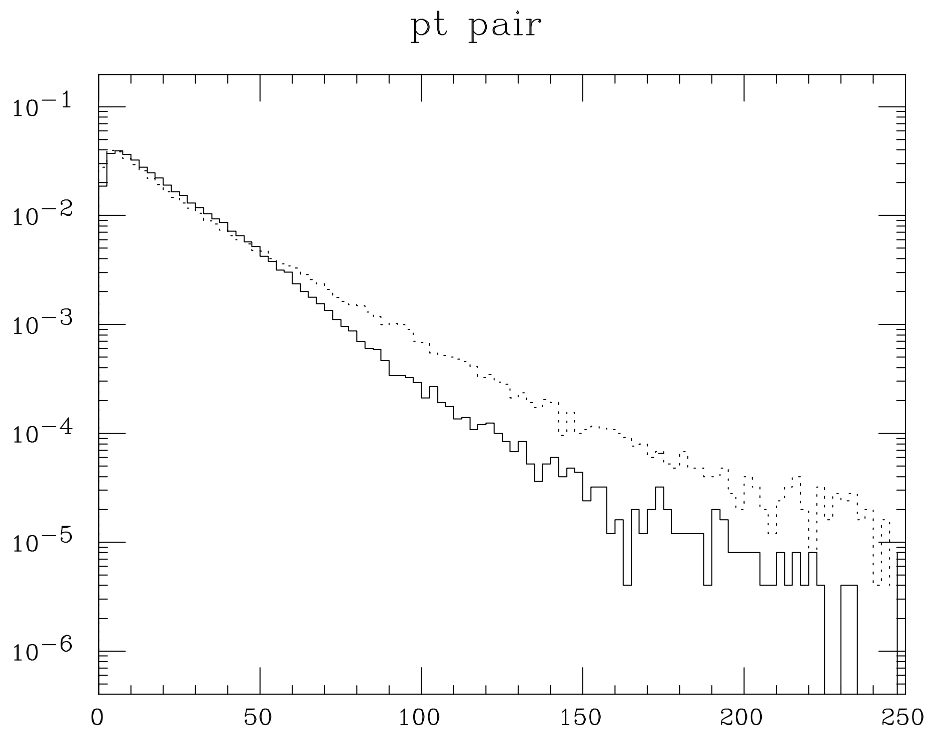


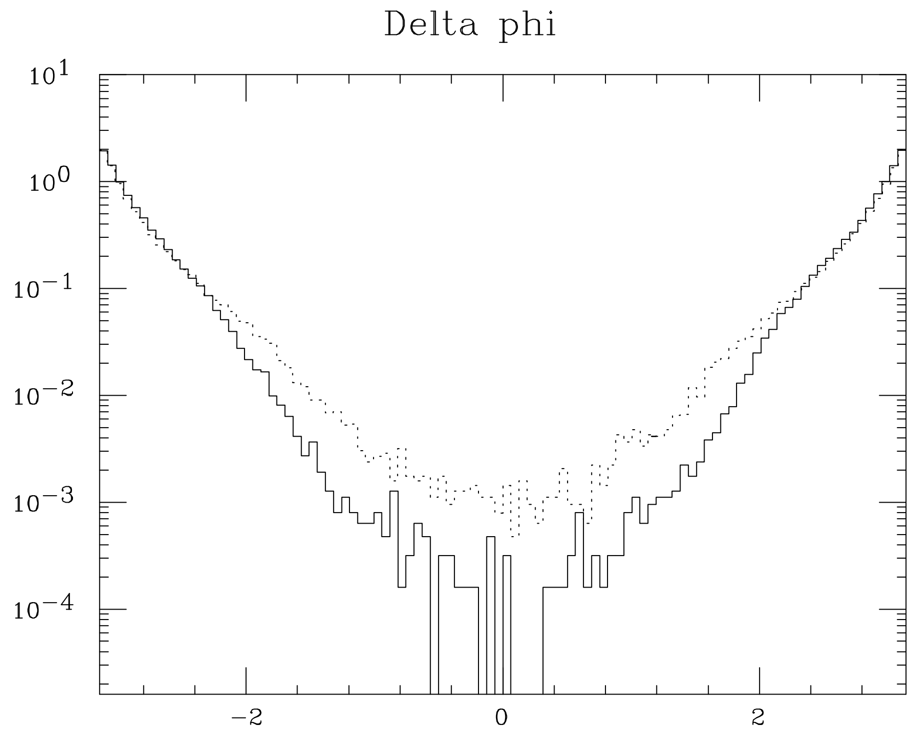
Only parton shower parameters varied

Strong improvement wrt `HERWIG`, due to new parton shower in Herwig++.

Testing against fHERWIG

Eg γ–pair production. Observables sensitive to shower. $p_\perp/\,\mathrm{GeV}$ of the γ–pair and the azimuthal difference $\Delta\phi$. Very useful cross check.





Solid: fHERWIG. Dotted: Herwig++. Herwig++ shower somewhat harder.

This is *only* internal validation. No replacement for validation/tuning efforts by experiments!

Currently

Main goal: LHC physics.

From version 2.0β

- $W^{\pm}$, Z^0 production.
- Backward evolution.
- New hadronic decays.

[hep-ph/0602069]

From full version 2.0:

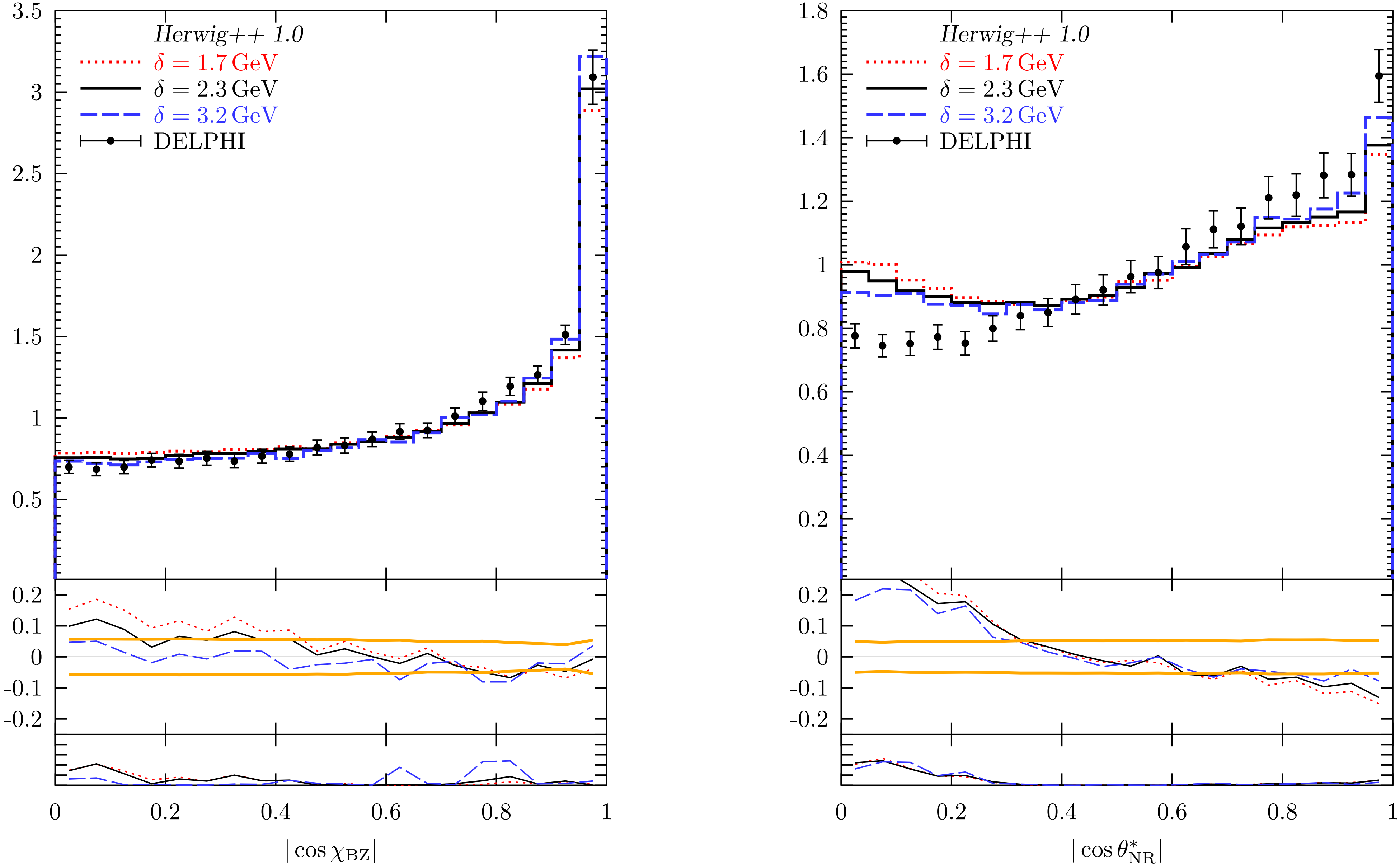
- Full timelike showers
- UA5 type underlying event
- Jet production, more hard processes
- ME correction to DY
- γ radiation in decays
- *Everything you need to simulate LHC final states*

[hep-ph/0609306]

Current version is 2.0.1.

- Bugfixes
- 30% performance boost!

Four Jet Angles



CKKW basics

Consider n–jet rates (resolvable at $Q_{\rm ini}$), computed from Sudakov FF's $\Delta_i(Q,q)$, like

$$R_2(Q_{\rm ini}) = \Delta_q(E, Q_{\rm ini})^2$$

$$R_3(Q_{\rm ini}) = 2\Delta_q(E, Q_{\rm ini}) \int {\rm d}q\, \Gamma_q(E,q) \frac{\Delta_q(E, Q_{\rm ini})}{\Delta_q(E,q)} \Delta_q(q, Q_{\rm ini}) \Delta_g(q, Q_{\rm ini})$$

Necessary input is NLL soft+collinear factorisation (Γ_i is integrated DGLAP splitting–kernel):

$${\rm d}\sigma_3(E) \approx {\rm d}\sigma_2 {\rm d}\Gamma(E, Q_{\rm ini}) \ .$$

Idea: turn the approximation your way

$${\rm d}\Gamma(E, Q_{\rm ini}){\rm d}\sigma_2 \approx {\rm d}\sigma_3(E) \ .$$

- Lhs and rhs both contain the full kinematic information.
- Using full ME rather than coll approximation is still a valid approximation.
- Now compute same jet rates with more accurate phase space population.
- Attach *vetoed* parton shower in order to (formally) get rid of residual $Q_{\rm ini}$ dependence.

$\longrightarrow$ CKKW algorithm [Catani, Krauss, Kuhn, Webber, hep-ph/0109231; Krauss, hep-ph/0205283].

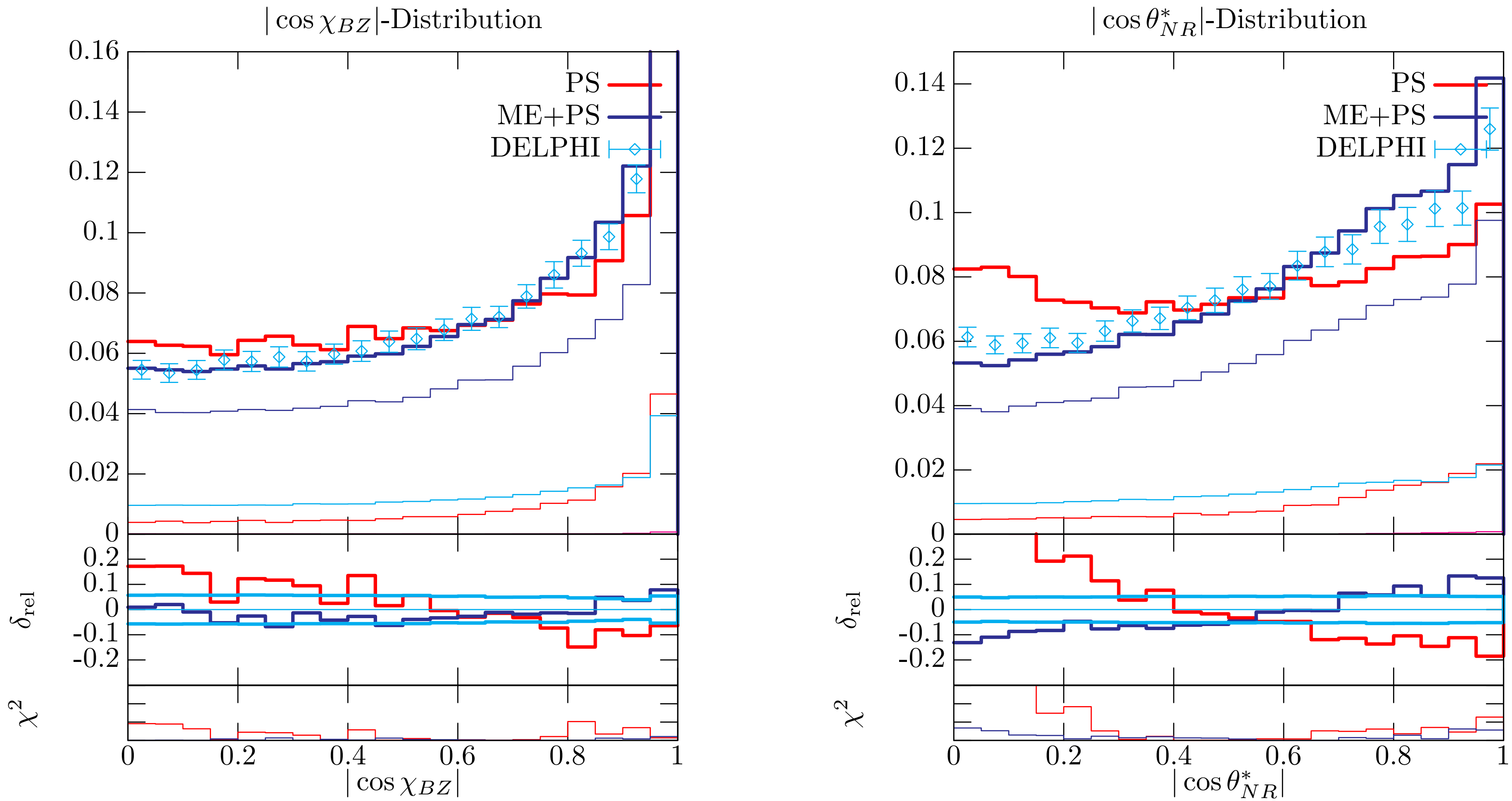
Matching of Matrix elements and parton showers in Herwig++

- Matching algorithm á la CKKW.
- Requires new resolution criteria for Herwig++ specific parton shower evolution.
- Angular ordering is usually not $\sim k_\perp$ ordering.
- Use full tree level matrix elements for additional jets.
- Use full same Sudakovs (including terms beyond NLL) as the parton shower.
- Rates still accurate to NLL, like parton shower.
- Better description of interjet correlations due to full ME.

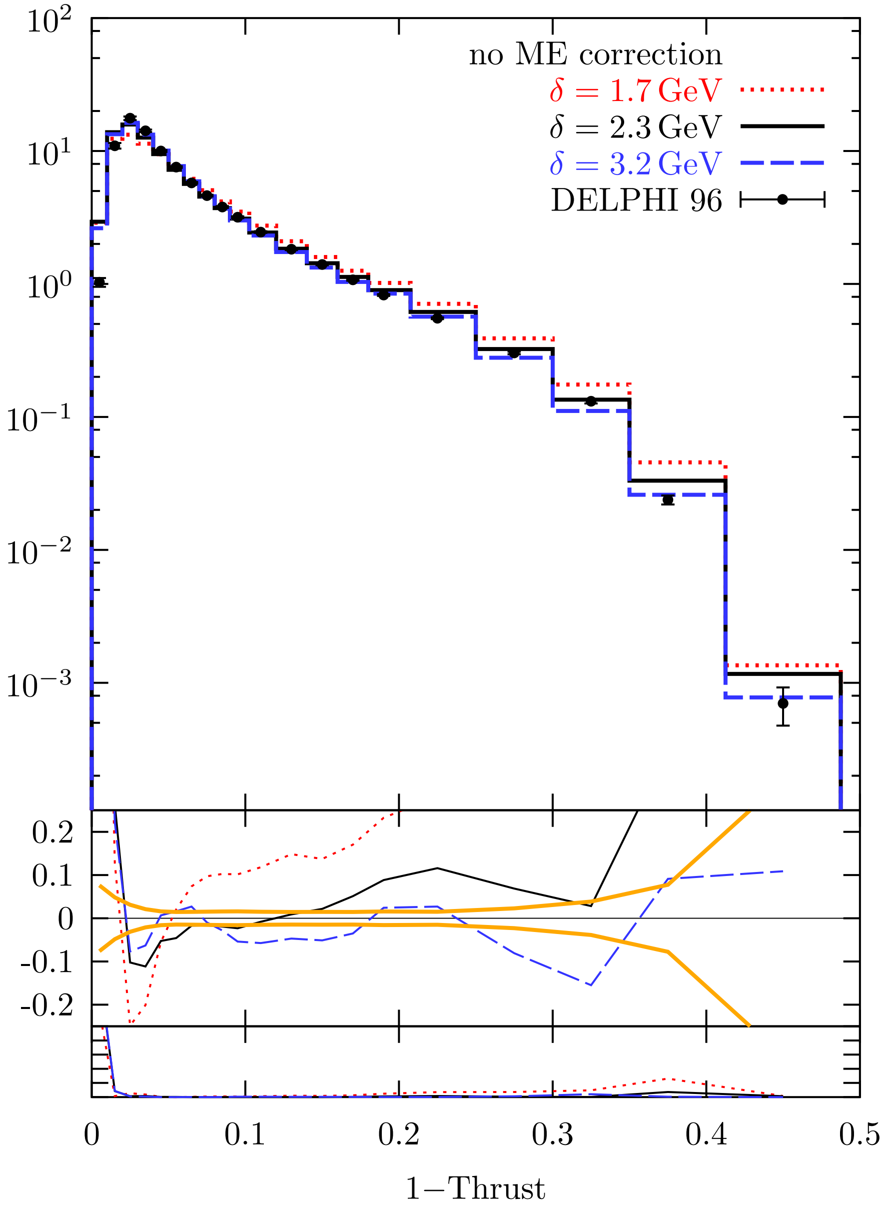
- Currently developed for $e^+e^- \to$ jets.
- Implented with hadronic interactions in mind.

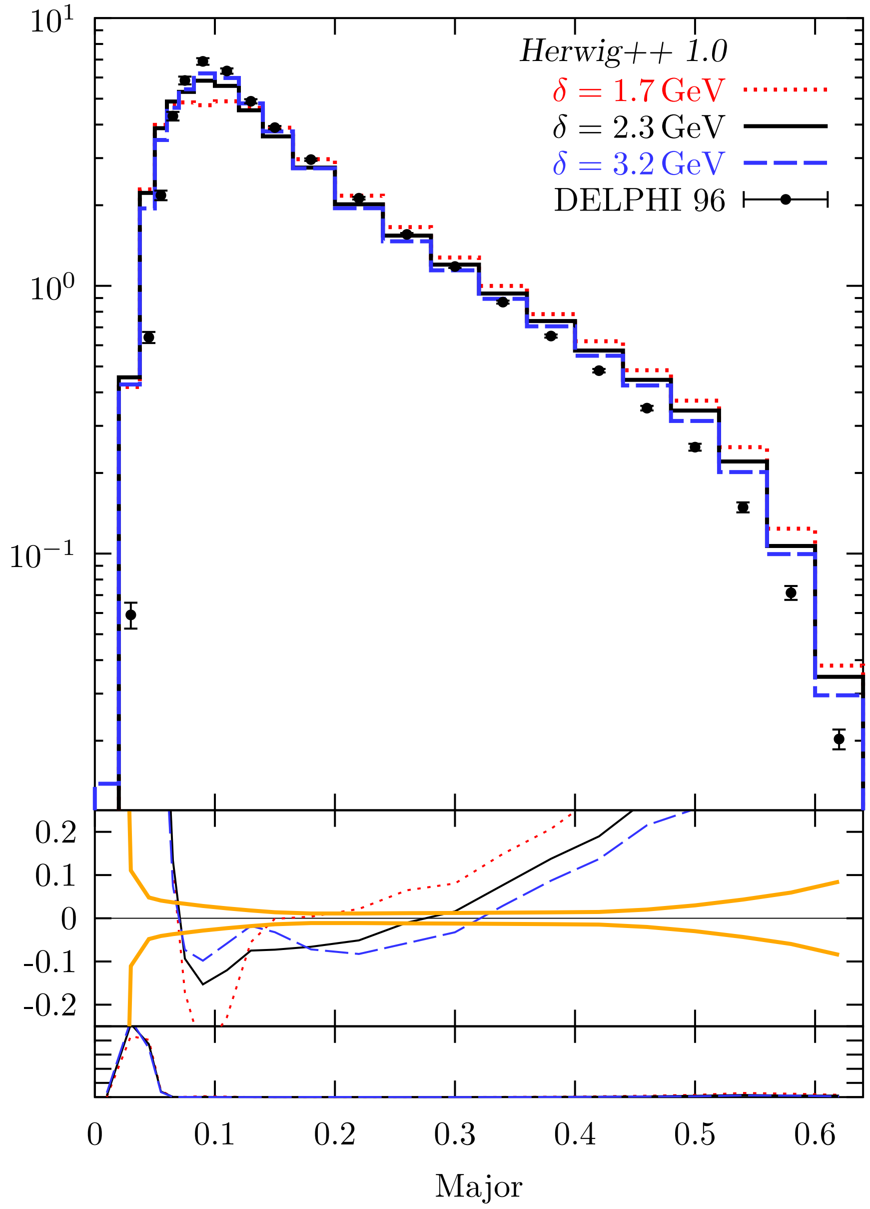
Four Jet Angles with ME+PS matching

Preliminary results from our ME+PS implementation



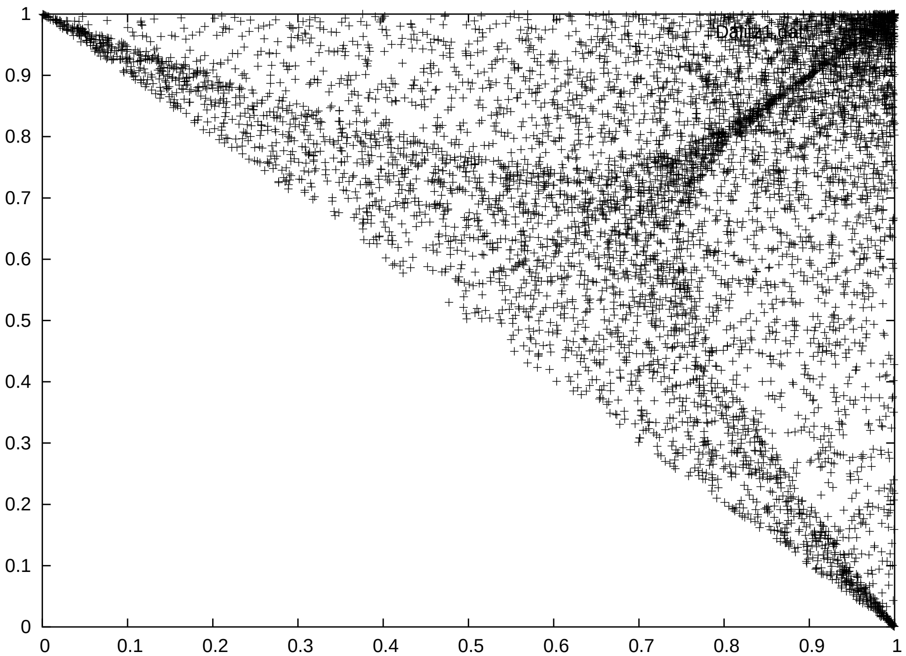
Thrust, Thrust Major

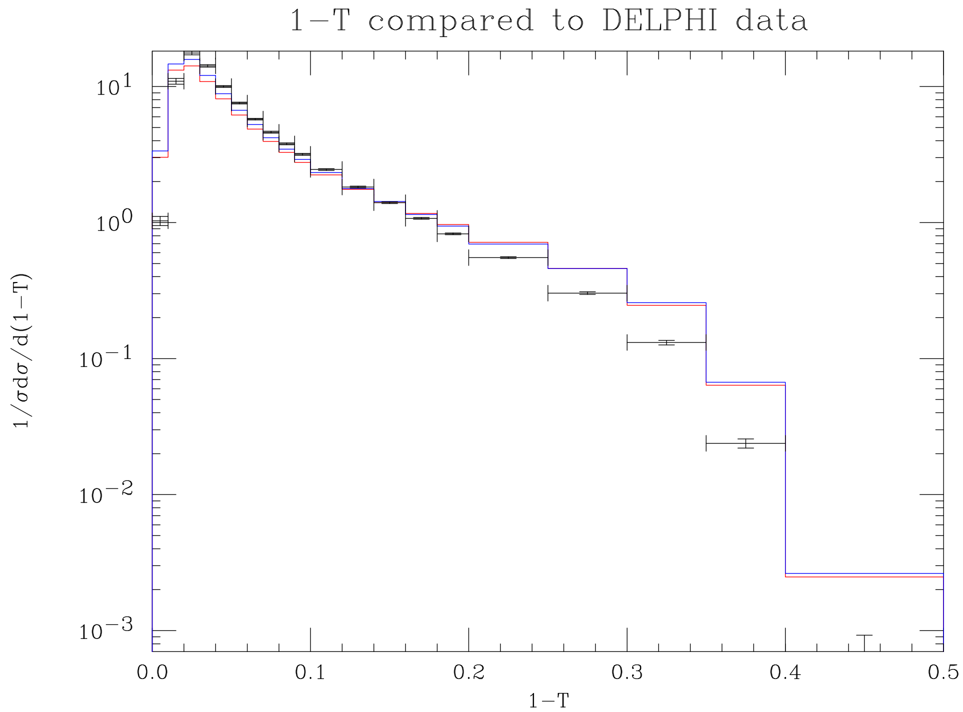




MC@NLO with Herwig++

Dalitz plot for $e^+e^- \longrightarrow q\bar{q}g$ events.
Unweighted events in 'dead region' $(w = 1)$, counter events $(w = -1)$ in shower region.





Results for various events shapes are available. DY also done.
Effect similar to ME correction but histograms normalized to unity (no cross sections).

[Seyi Latunde–Dada]

Hardest Emission First

- Alternative Method to match NLO computations with parton shower Monte Carlos proposed by P. Nason.
- Introduces Modified Sudakov FF for first emission, full NLO recovered upon expansion in α_S.
- Problem in `Herwig++`: Angular ordered Parton Shower first emits fairly soft, large angle gluons, then high p_T.
- *Truncated Shower* adds in this radiation afterwards.
- Finally evolution with 'ordinary' Parton Shower.

Method avoids Phase Space division into hard/soft region. First emission may also be soft/collinear.

[Nason, hep-ph/0409146; Nason, Ridolfi hep-ph/0606275]

Hardest Emission First (ctd')

Use full real ME for hardest emission,

$$R(x,y) = \sigma_B W(x,y) = \sigma_B \frac{2\alpha_s}{3\pi} \frac{x^2+y^2}{(1-x)(1-y)}$$

Using

$$\bar{B}(v) = B(v) + V(v) + \int (R(v,r) - C(v,r)) d\Phi_r \ .$$

we may write the differential cross section as

$$d\sigma = \sum \bar{B}(v) d\Phi_v \left[\Delta_R^{(NLO)}(0) + \Delta_R^{(NLO)}(p_T) \frac{R(v,r)}{B(v)} d\Phi_r \right]$$

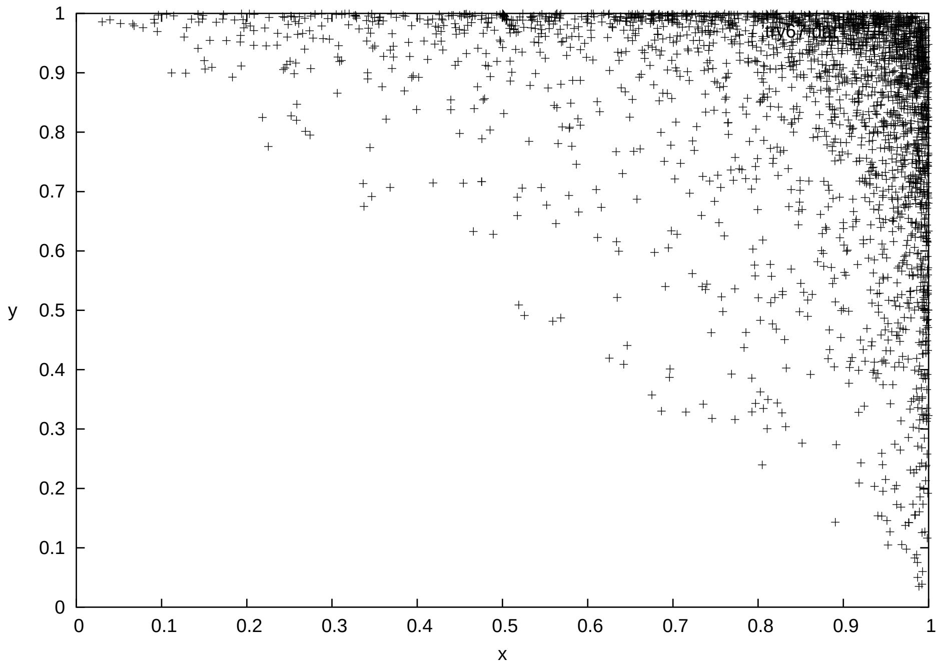
where we have introduced the modified Sudakov form factor $\Delta_R^{NLO}(p_T)$ for the hardest emission with transverse momentum p_T,

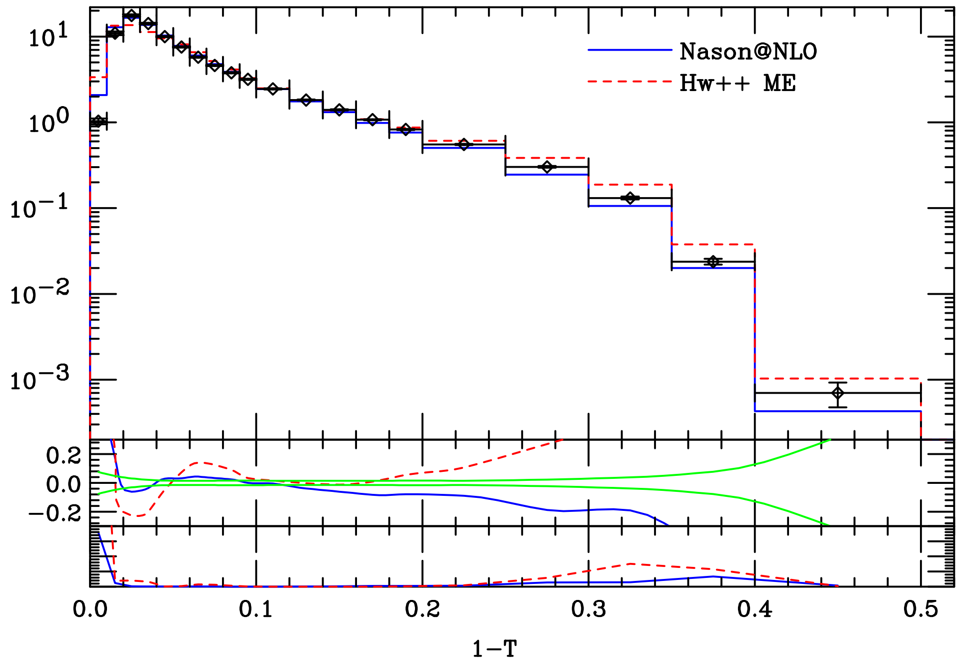
$$\Delta_R^{NLO}(p_T) = \exp\left[-\int d\Phi r \frac{R(v,r)}{B(v)} \Theta(k_T(v,r) - p_T) \right]$$

$$= \exp\left[-\int dx\, dy \frac{2\alpha_s}{3\pi} \frac{x^2+y^2}{(1-x)(1-y)} \Theta(k_T(x,y)) - p_T) \right] \ .$$

Nason–Method in Herwig++

Phase space for first emission populated smoothly.





Many observables for e^+e^- annihilation studied. Better agreement in hard emission region.

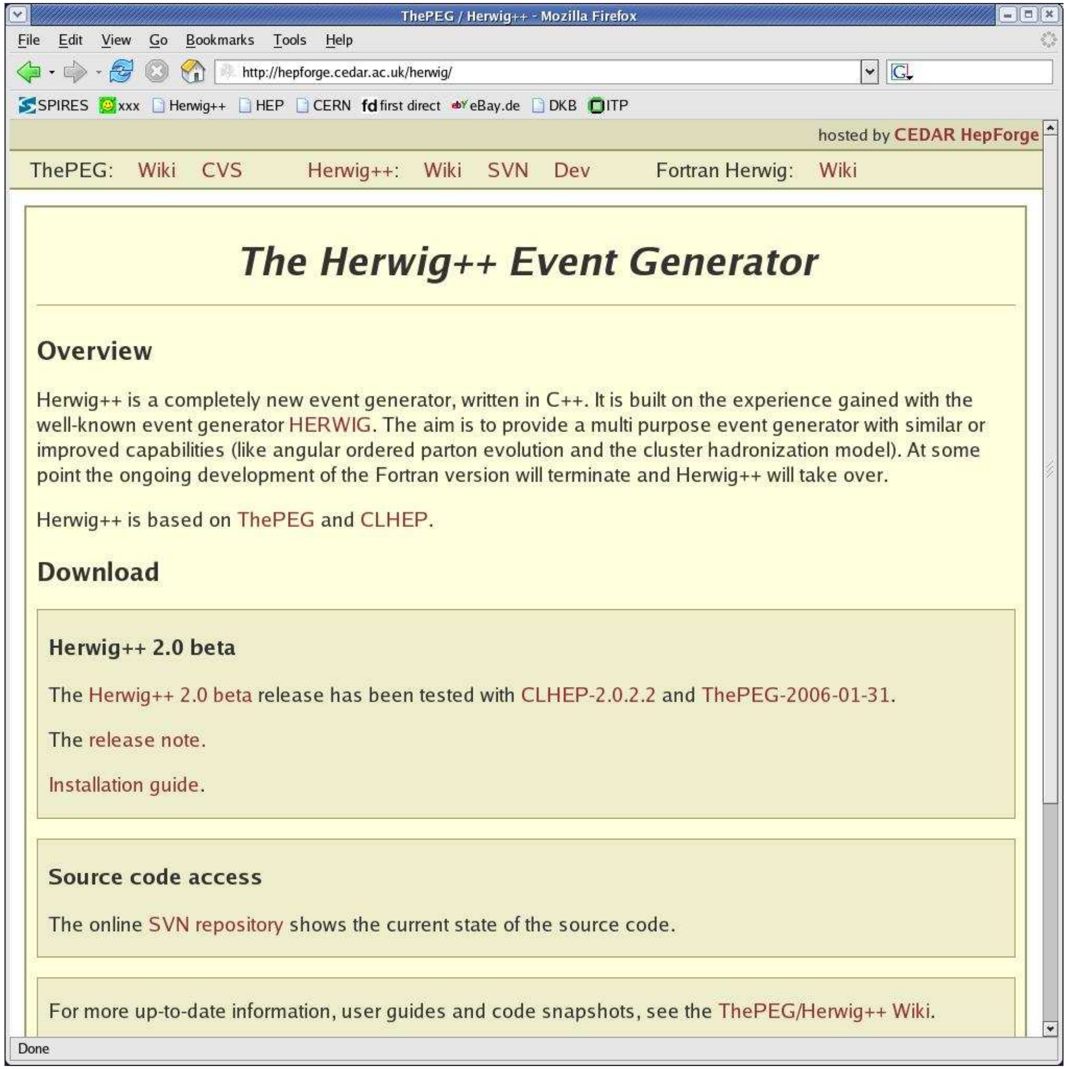
Most striking improvement for C–Parameter:

$$\chi^2(\text{Nason})/\text{bin} : \chi^2(\text{ME correction})/\text{bin} \approx 0.1 \ .$$

[O. Latunde–Dada, SG, B. Webber, hep-ph/0612281]

News, Wiki, downloads. . .

http://hepforge.cedar.ac.uk/herwig/



Current version is 2.0.1.

- Need `CLHEP` and `ThePEG`.
- Builds with `autotools`.
- `./configure`, `make`, `make install`.
- Successfully built with gcc's from 3.2.x to 4.1.1.
- Also on OS X.

Summary

- Some useful hard processes available. All the rest as well via LH interface.
- New parton shower working in IS, FS, t–decays, (SUSY particles).
- ME corrections in $e^+e^- \to q\bar{q}g$, DY, t–decay.
- ME+PS matching a la CKKW for $e^+e^- \to \text{jets}$.
- MC@NLO type matching for $e^+e^- \to \text{jets}$.
- pp simulations now possible in Herwig++. Many new features wrt old `HERWIG`.
- Hadronization ready.
- Much improved hadronic decayers.
- Spin correlations.
- Photon radiation in decays.
- First BSM (mostly MSSM) physics included.
- UA5 model for (simple) Underlying Event simulation.

Near Future of Herwig++

- ME+PS matching for hadronic interactions.
- NLO matching(s).
- More sophisticated Underlying event simulation.
- More BSM physics.
- More validation: Tevatron data (HERA photopruduction data?).