

# The new MC event generator Herwig++

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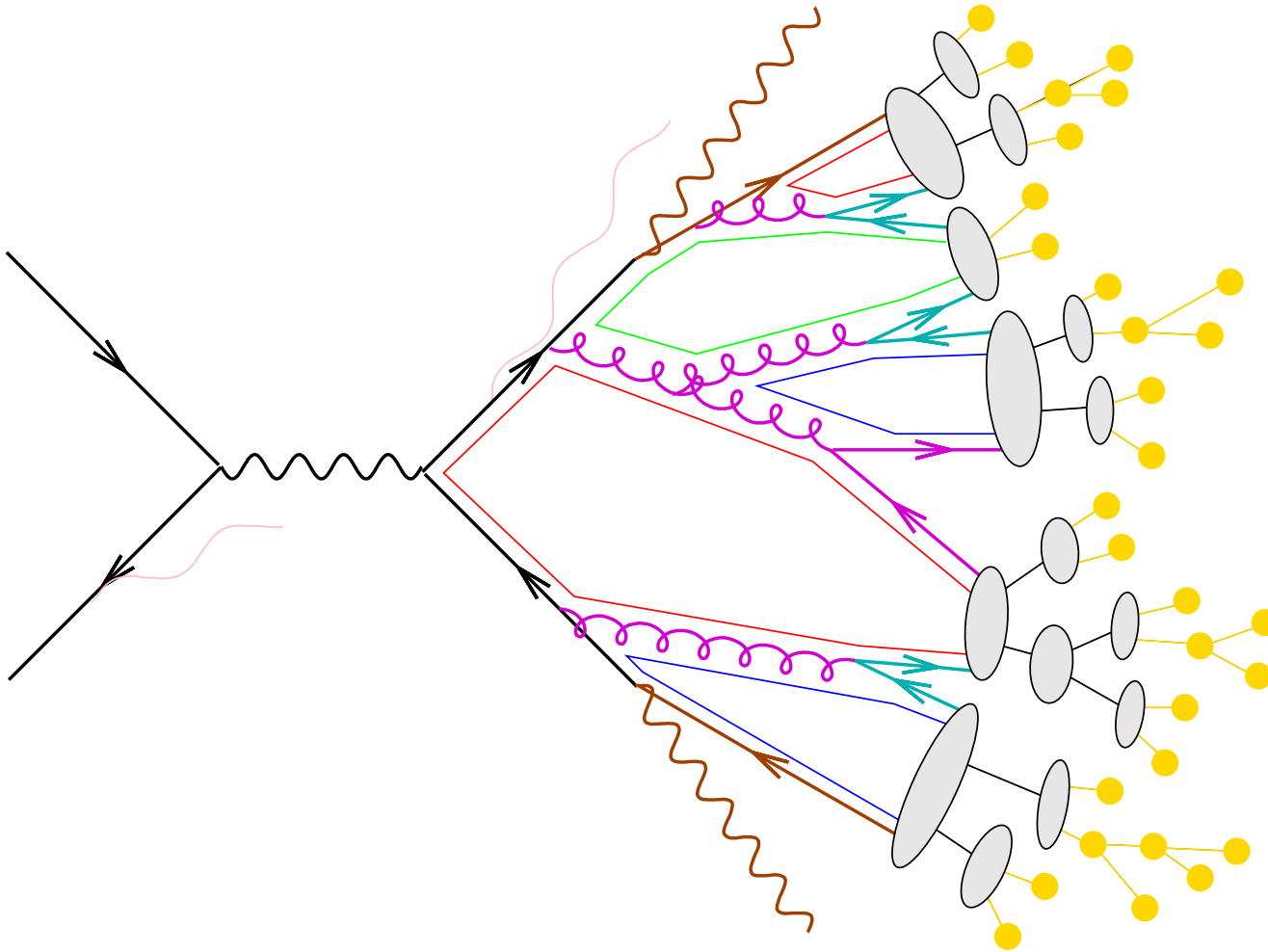
work with A Ribon, MH Seymour, P Stephens, BR Webber (Cambridge, CERN)

- Introduction
- Tour of Herwig++
- Results for  $e^+e^-$  Annihilation
- Outlook

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** (2003) 005 [hep-ph/0311208]

# $e^+e^-$ Event Generator

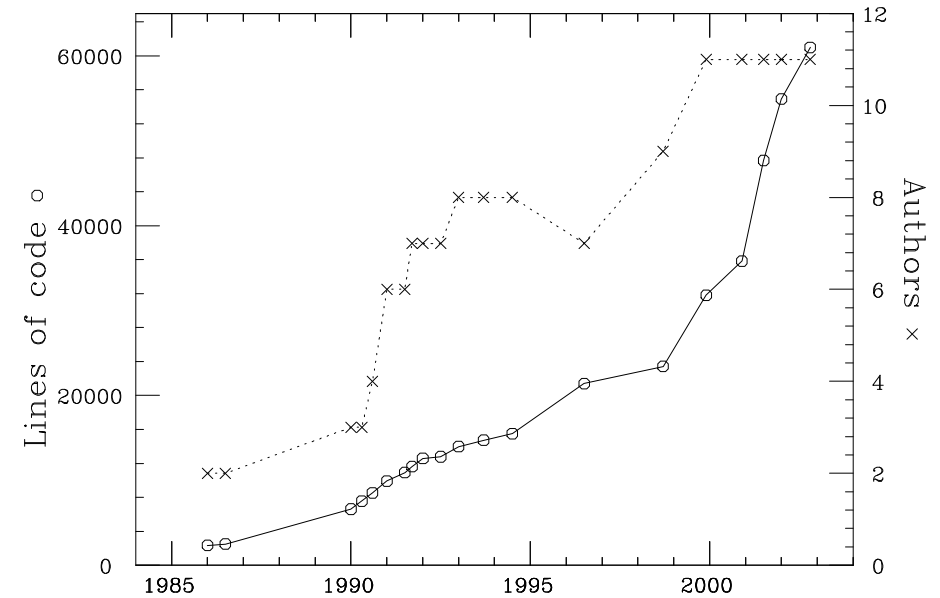


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g.  $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster  $\rightarrow$  hadrons
- hadronic decays

# The new generator Herwig++

*Complete rewrite of HERWIG in C++*

- aiming at full multi-purpose generator for LHC and future colliders.
- Preserve main features of HERWIG such as
  - angular ordered parton shower
  - Cluster Hadronization
- New features and improvements
  - improved parton shower evolution for heavy quarks
  - consistent radiation from unstable particles



HERWIG's growth. . .

# Use of ThePEG in Herwig++

ThePEG = Toolkit for high energy Physics Event Generation



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 possibility 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!

## Hard interactions

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

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

we use them.

- Soft and hard **matrix element corrections** implemented for  $e^+e^- \rightarrow q\bar{q}g$ .
- **AMEGIC++** will provide arbitrary ME's for multiparton final states via **AMEGICInterface**.
- CKKW ME+PS foreseen.
- Other authors can easily include their own matrix elements ( $\rightarrow$  *safety* of OO code)

# Quasi-Collinear Limit (Heavy Quarks)

Sudakov-basis  $p, n$  with  $p^2 = M^2$  ('forward'),  $n^2 = 0$  ('backward'),

$$p_q = zp + \beta_q n - q_\perp$$

$$p_g = (1 - z)p + \beta_g n + q_\perp$$

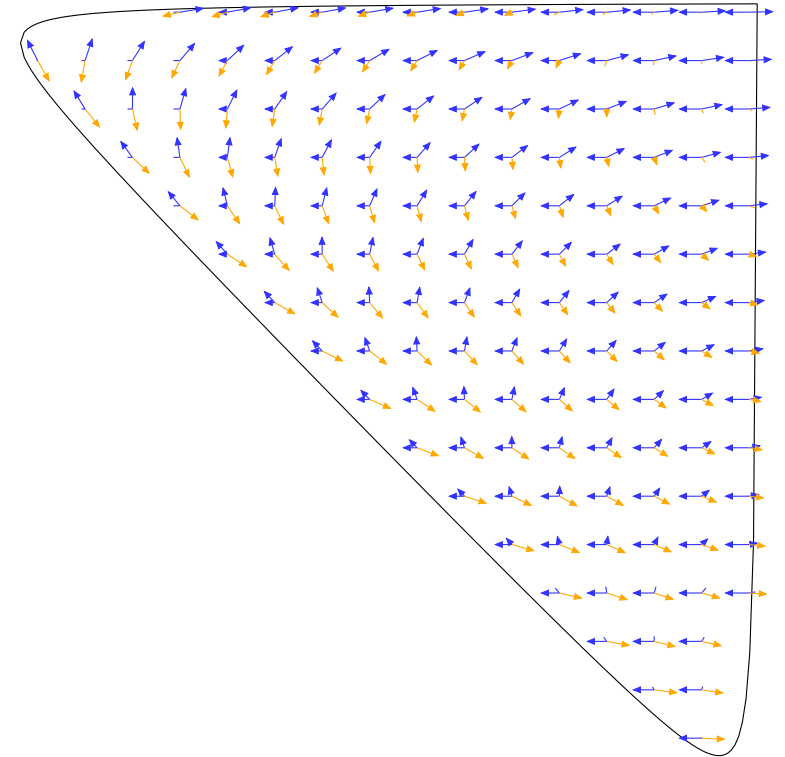
Collinear limit for radiation off heavy quark,

$$P_{gq}(z, \mathbf{q}^2, m^2) = C_F \left[ \frac{1 + z^2}{1 - z} - \frac{2z(1 - z)m^2}{\mathbf{q}^2 + (1 - z)^2 m^2} \right]$$

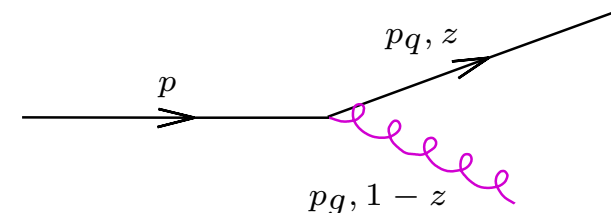
$$= \frac{C_F}{1 - z} \left[ 1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right]$$

→  $\tilde{q}^2 \sim \mathbf{q}^2$  may be used as evolution variable.

$q\bar{q}g$ -Phase space  $(x, \bar{x})$

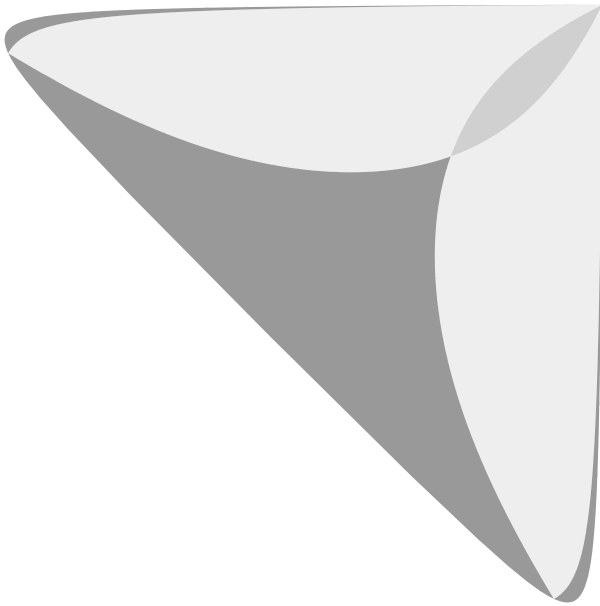


Single emission:

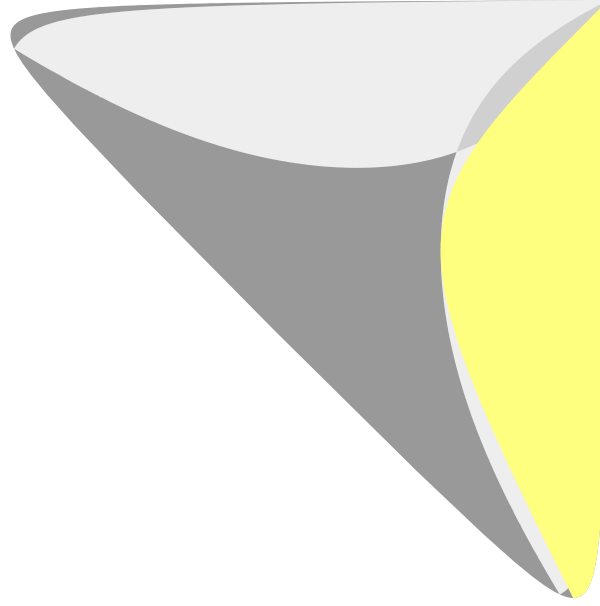


## $q\bar{q}g$ Phase Space old vs new variables

Consider  $(x, \bar{x})$  phase space for  $e^+e^- \rightarrow q\bar{q}g$



HERWIG



Comparison



Herwig++

- ✗ Larger dead region with new variables.
- ✓ Smooth coverage of soft gluon region.
- ✓ No overlapping regions in phase space.

# Universal cutoff parameter $\delta$

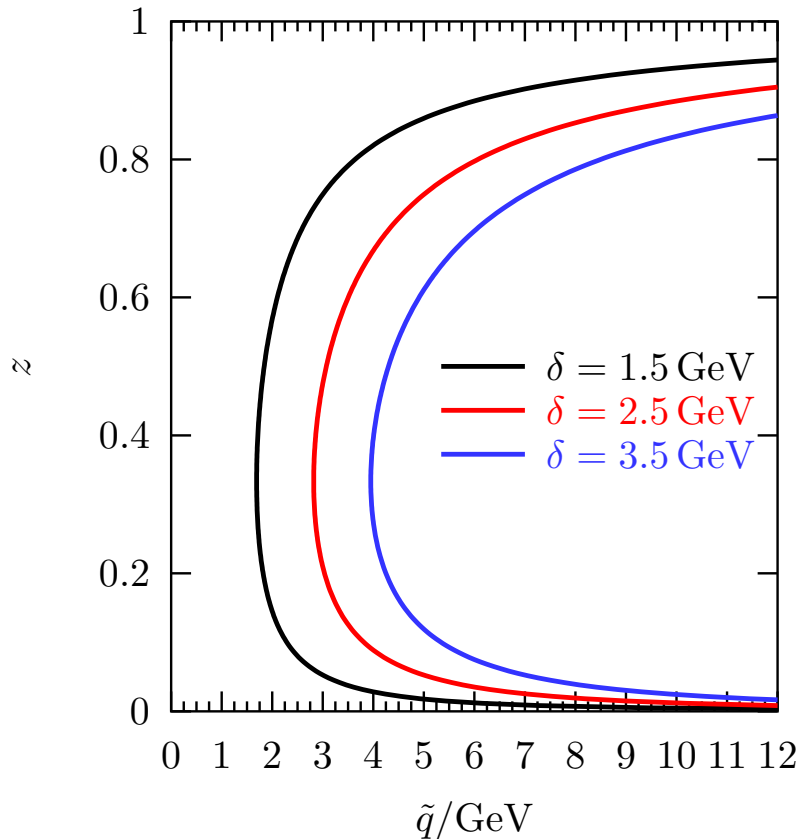
Require threshold in parton shower phase space

$$Q_{\text{thr}} = \beta m_q + \delta \quad (\beta = 0.85)$$

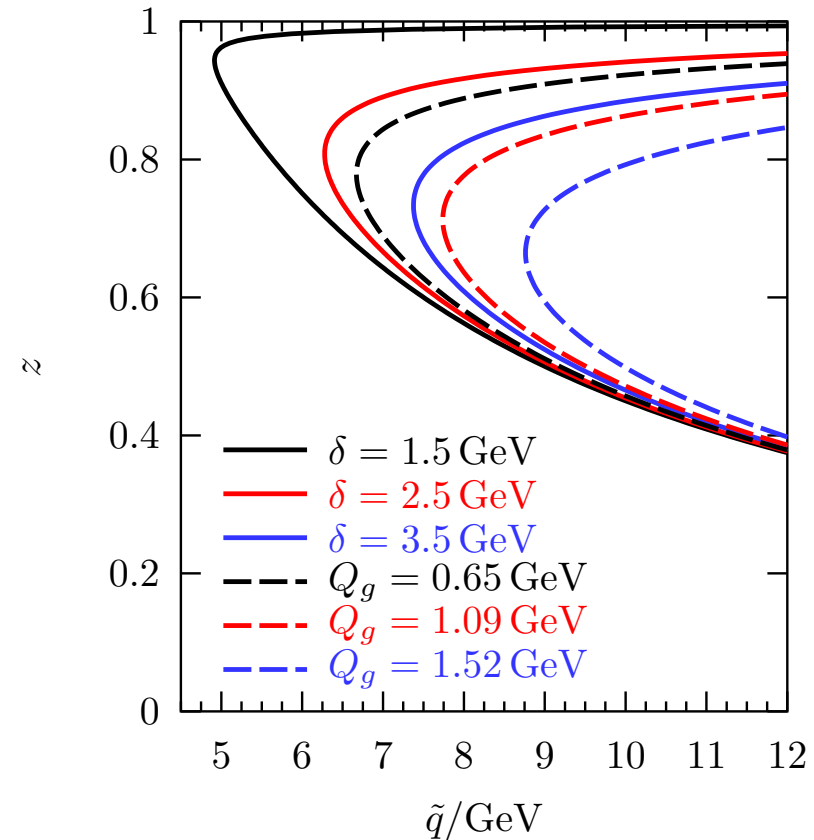
parametrization of  $Q_g$  in terms of  $\delta, m_q$

$$Q_g = \frac{\delta - 0.3m_q}{2.3} .$$

*light quarks:*

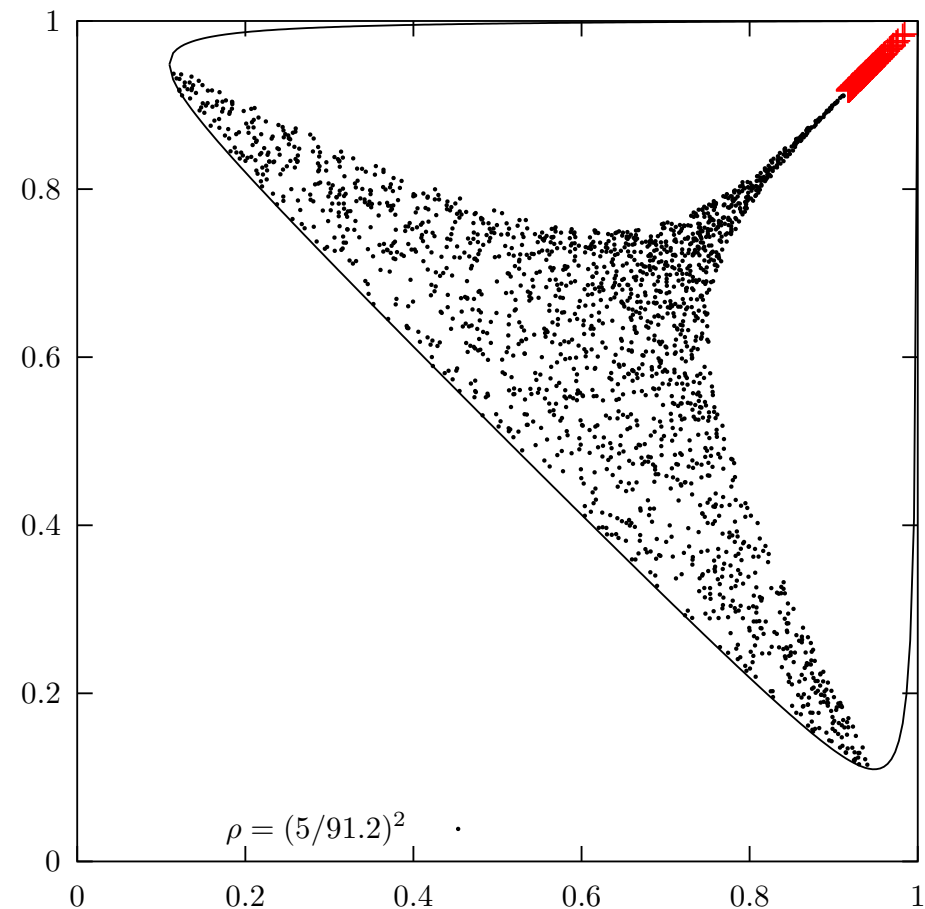


*b quarks:*



## Hard Matrix Element Corrections

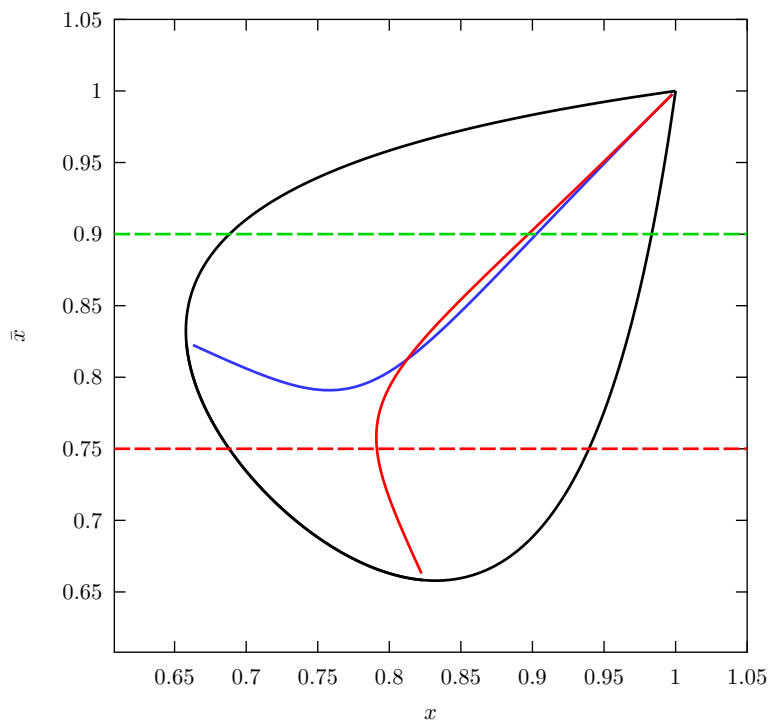
- Points  $(x, \bar{x})$  in **dead region** chosen acc to LO  $e^+e^- \rightarrow q\bar{q}g$  matrix element and accepted acc to ME weight.
- About **3%** of all events are actually hard  $q\bar{q}g$  events.
- Red points have **weight  $> 1$** , practically no error by setting weight to one.
- Event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



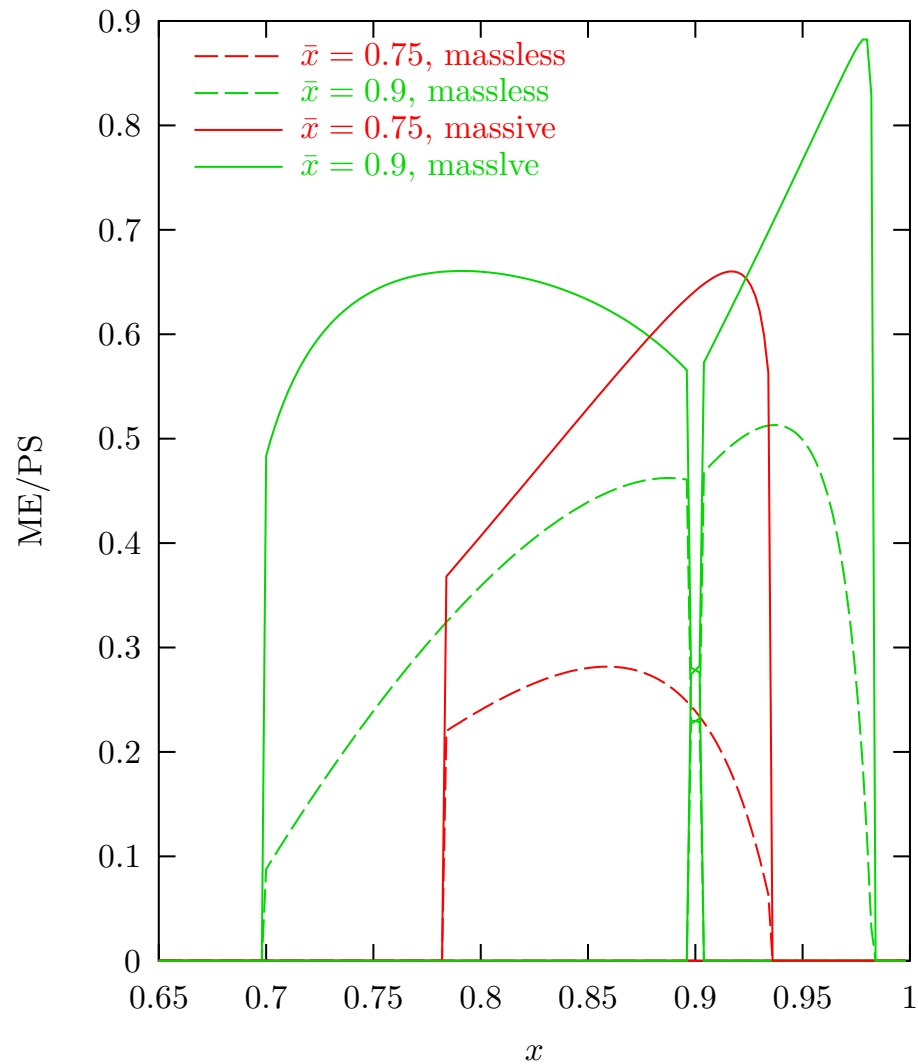
# Soft Matrix Element Corrections

- 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,  $m^2/Q^2 = 0.1$ :



Comparison with massless splitting function



## Cluster hadronization in a nutshell

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

$$M^P < M_{\text{max}}^P + (m_1 + m_2)^P$$

where masses are chosen from

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

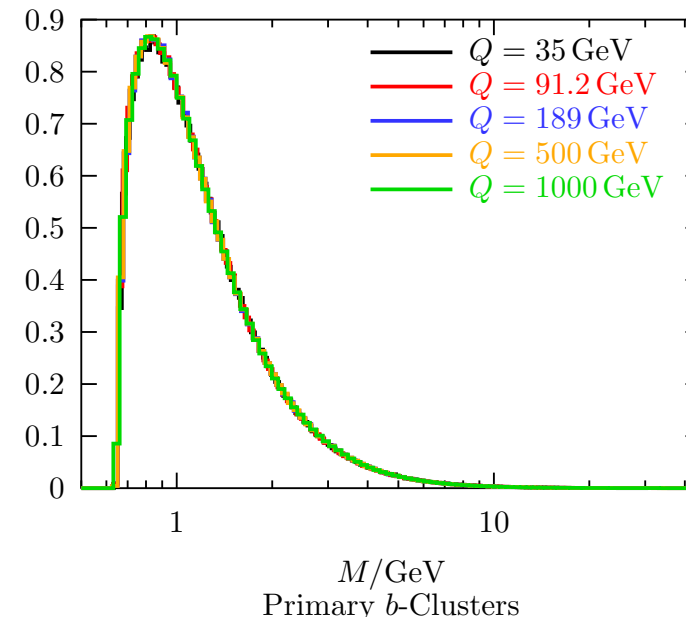
with additional phase space constraints. Constituents keep moving in their original direction.

- **Cluster Decay**

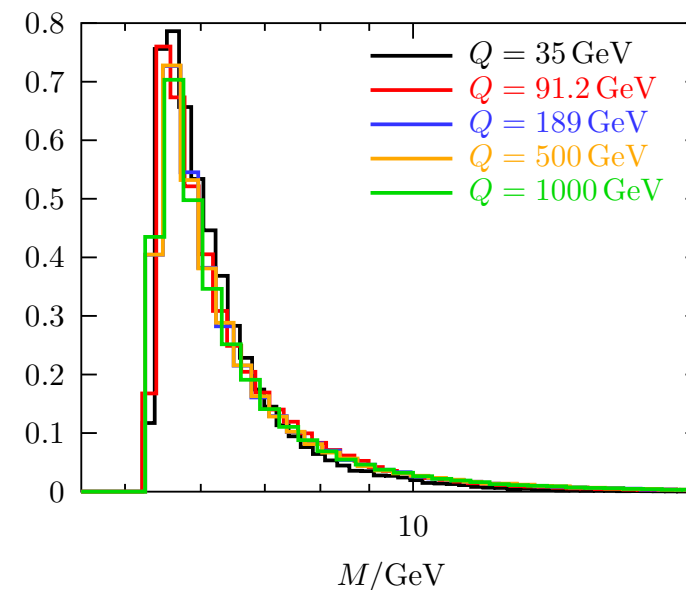
$$P(a_{i,q}, b_{q,j} | i, j) = \frac{W(a_{i,q}, b_{q,j} | i, j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j} | i, j)}.$$

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

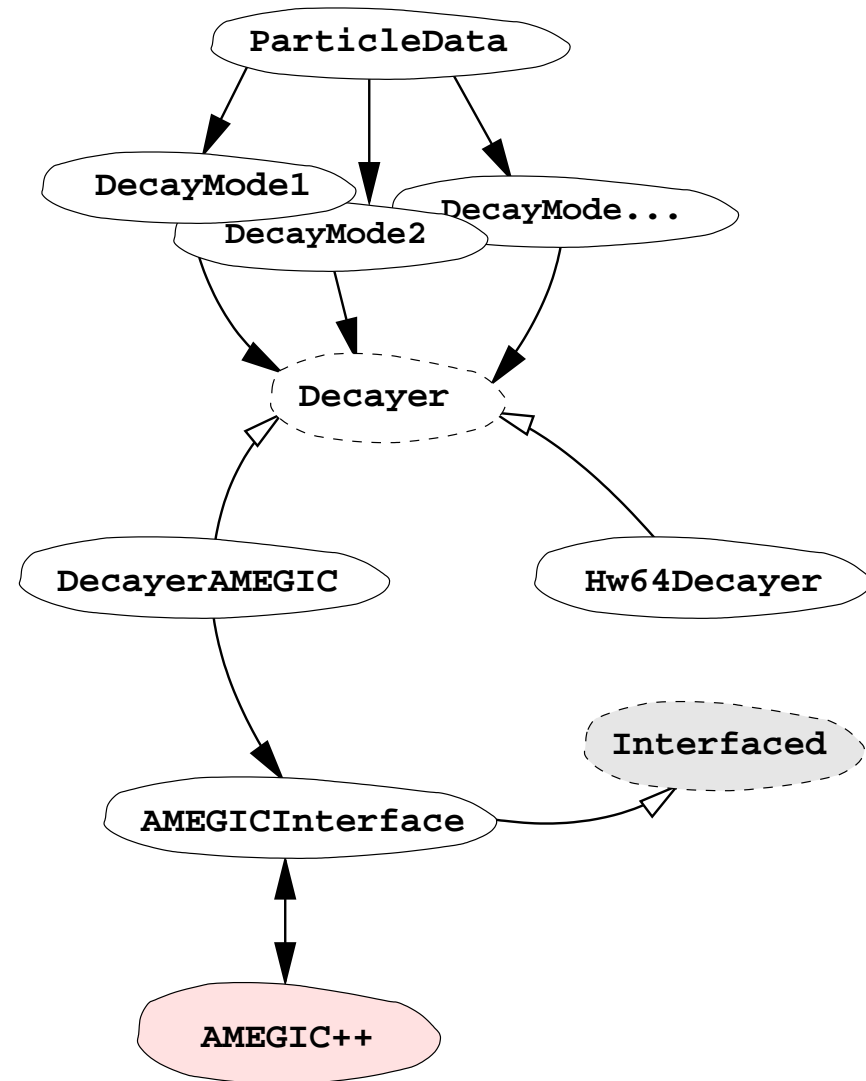
Primary Light Clusters



Primary  $b$ -Clusters



# 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++**
- Room for improvement. . .

# Results

Aim: test new parton shower and its interplay with other parts of the program in great detail.

- $e^+e^- \rightarrow$  jets, mainly at  $Z^0$ .
- hard and soft ME corrections.
- Cutoff parameter  $\delta$  varied.

Analysis:

- Each bin  $i$ : data  $D_i \pm \delta D_i$  and MC result  $M_i \pm \delta D_i$ .
- Normalization  $N$  MC/data not necessarily given.
- $\delta D_i/D_i > 5\%$  to emphasize *global* strategy.
- Then

$$\chi^2 = \sum_i \chi_i^2 = \sum_i \frac{(D_i - N M_i)^2}{\delta D_i^2 + \delta M_i^2}$$
$$R_i = \frac{M_i - D_i}{D_i} \pm \left( \frac{\delta M_i}{D_i} \oplus \frac{M_i \delta D_i}{D_i^2} \right)$$

Most plots in the following include

- Histograms with  $\delta = 1.7, 2.3, 3.2$  GeV and data.
- $R_i$  compared to  $\delta D_i/D_i$  (yellow band).
- $\chi_i^2/\chi^2$  for each bin.

# Hadron Multiplicities

| Particle           | Experiment | Measured              | Old Model | Herwig++ | Fortran |
|--------------------|------------|-----------------------|-----------|----------|---------|
| All Charged        | M,A,D,L,O  | $20.924 \pm 0.117$    | 20.22*    | 20.814   | 20.532* |
| $\gamma$           | A,O        | $21.27 \pm 0.6$       | 23.032    | 22.67    | 20.74   |
| $\pi^0$            | A,D,L,O    | $9.59 \pm 0.33$       | 10.27     | 10.08    | 9.88    |
| $\rho(770)^0$      | A,D        | $1.295 \pm 0.125$     | 1.235     | 1.316    | 1.07    |
| $\pi^\pm$          | A,O        | $17.04 \pm 0.25$      | 16.30     | 16.95    | 16.74   |
| $\rho(770)^\pm$    | O          | $2.4 \pm 0.43$        | 1.99      | 2.14     | 2.06    |
| $\eta$             | A,L,O      | $0.956 \pm 0.049$     | 0.886     | 0.893    | 0.669*  |
| $\omega(782)$      | A,L,O      | $1.083 \pm 0.088$     | 0.859     | 0.916    | 1.044   |
| $\eta'(958)$       | A,L,O      | $0.152 \pm 0.03$      | 0.13      | 0.136    | 0.106   |
| $K^0$              | S,A,D,L,O  | $2.027 \pm 0.025$     | 2.121*    | 2.062    | 2.026   |
| $K^*(892)^0$       | A,D,O      | $0.761 \pm 0.032$     | 0.667     | 0.681    | 0.583*  |
| $K^*(1430)^0$      | D,O        | $0.106 \pm 0.06$      | 0.065     | 0.079    | 0.072   |
| $K^\pm$            | A,D,O      | $2.319 \pm 0.079$     | 2.335     | 2.286    | 2.250   |
| $K^*(892)^\pm$     | A,D,O      | $0.731 \pm 0.058$     | 0.637     | 0.657    | 0.578   |
| $\phi(1020)$       | A,D,O      | $0.097 \pm 0.007$     | 0.107     | 0.114    | 0.134*  |
| $p$                | A,D,O      | $0.991 \pm 0.054$     | 0.981     | 0.947    | 1.027   |
| $\Delta^{++}$      | D,O        | $0.088 \pm 0.034$     | 0.185     | 0.092    | 0.209*  |
| $\Sigma^-$         | O          | $0.083 \pm 0.011$     | 0.063     | 0.071    | 0.071   |
| $\Lambda$          | A,D,L,O    | $0.373 \pm 0.008$     | 0.325*    | 0.384    | 0.347*  |
| $\Sigma^0$         | A,D,O      | $0.074 \pm 0.009$     | 0.078     | 0.091    | 0.063   |
| $\Sigma^+$         | O          | $0.099 \pm 0.015$     | 0.067     | 0.077    | 0.088   |
| $\Sigma(1385)^\pm$ | A,D,O      | $0.0471 \pm 0.0046$   | 0.057     | 0.0312*  | 0.061*  |
| $\Xi^-$            | A,D,O      | $0.0262 \pm 0.001$    | 0.024     | 0.0286   | 0.029   |
| $\Xi(1530)^0$      | A,D,O      | $0.0058 \pm 0.001$    | 0.026*    | 0.0288*  | 0.009*  |
| $\Omega^-$         | A,D,O      | $0.00125 \pm 0.00024$ | 0.001     | 0.00144  | 0.0009  |

## Hadron Multiplicities (ctd')

| Particle        | Experiment | Measured              | Old Model | Herwig++ | Fortran |
|-----------------|------------|-----------------------|-----------|----------|---------|
| $f_2(1270)$     | D,L,O      | $0.168 \pm 0.021$     | 0.113     | 0.150    | 0.173   |
| $f_2'(1525)$    | D          | $0.02 \pm 0.008$      | 0.003     | 0.012    | 0.012   |
| $D^\pm$         | A,D,O      | $0.184 \pm 0.018$     | 0.322*    | 0.319*   | 0.283*  |
| $D^*(2010)^\pm$ | A,D,O      | $0.182 \pm 0.009$     | 0.168     | 0.180    | 0.151*  |
| $D^0$           | A,D,O      | $0.473 \pm 0.026$     | 0.625*    | 0.570*   | 0.501   |
| $D_s^\pm$       | A,O        | $0.129 \pm 0.013$     | 0.218*    | 0.195*   | 0.127   |
| $D_s^{*\pm}$    | O          | $0.096 \pm 0.046$     | 0.082     | 0.066    | 0.043   |
| $J/\Psi$        | A,D,L,O    | $0.00544 \pm 0.00029$ | 0.006     | 0.00361* | 0.002*  |
| $\Lambda_c^+$   | D,O        | $0.077 \pm 0.016$     | 0.006*    | 0.023*   | 0.001*  |
| $\Psi'(3685)$   | D,L,O      | $0.00229 \pm 0.00041$ | 0.001*    | 0.00178  | 0.0008* |

# of \*'s = observables with more than  $3\sigma$  deviation:

OldModel : Herwig++ : Fortran = 9 : 7 : 13

## $k_{\perp}$ Algorithm (“Durham”–Algorithm)

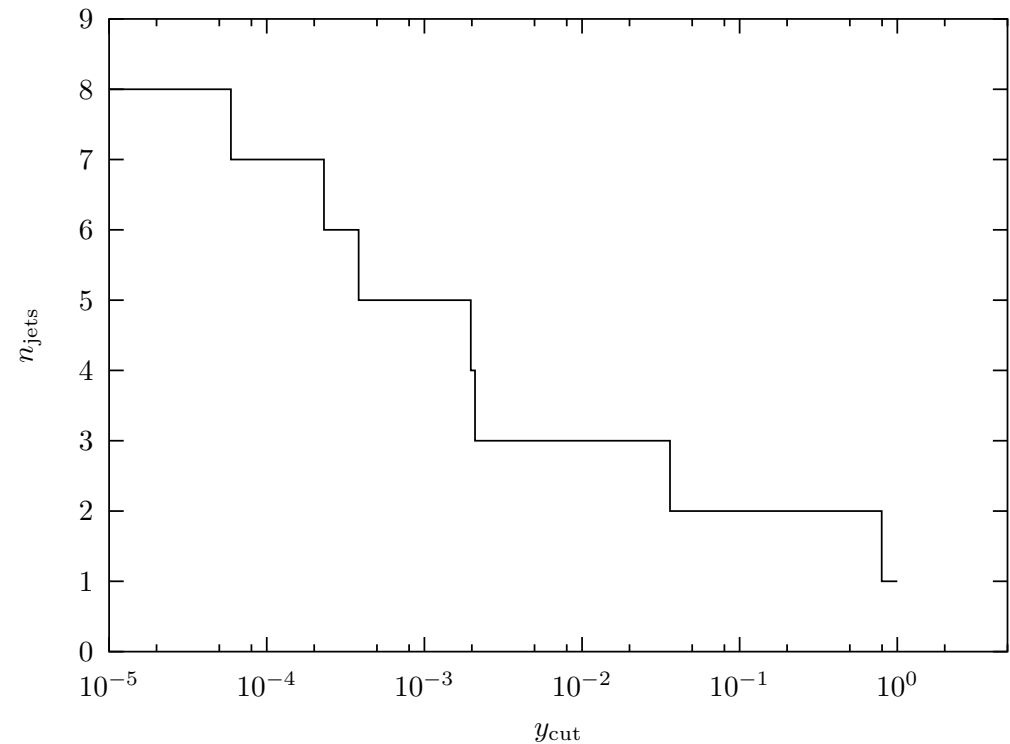
- For each pair  $i, j$  of particles in an event calculate the ‘distance’

$$y_{ij} = \frac{2 \min(E_i^2, E_j^2)}{Q^2} (1 - \cos \theta_{ij}).$$

[resolution scale  $Q_{ij} = Q \sqrt{y_{ij}}$ ]

- The pair with minimum  $y_{ij}$  is **clustered** into a pseudoparticle with momentum  $p = p_i + p_j$ .
- Stop** when all particles are clustered or all  $y_{ij} > y_{\text{cut}}$ .

We have an  $n$ -jet event if  $n$  particles or pseudoparticles are left at a given  $y_{\text{cut}}$ .

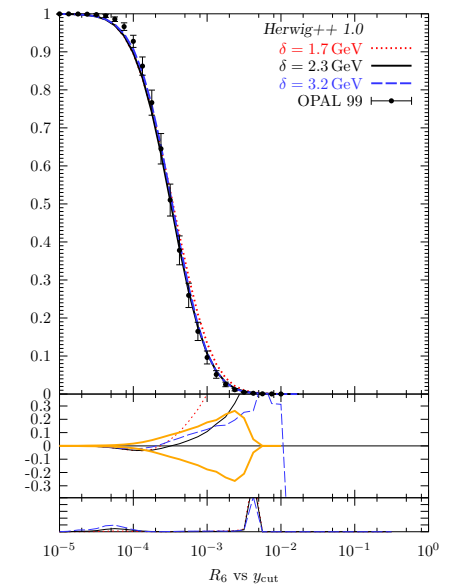
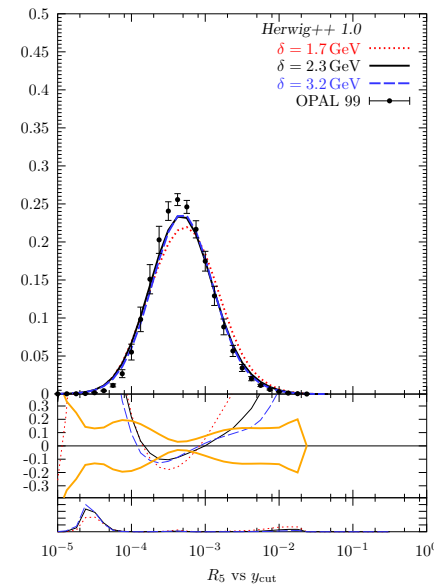
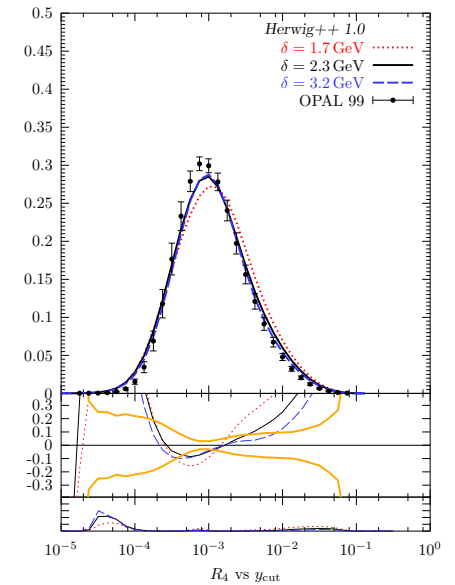
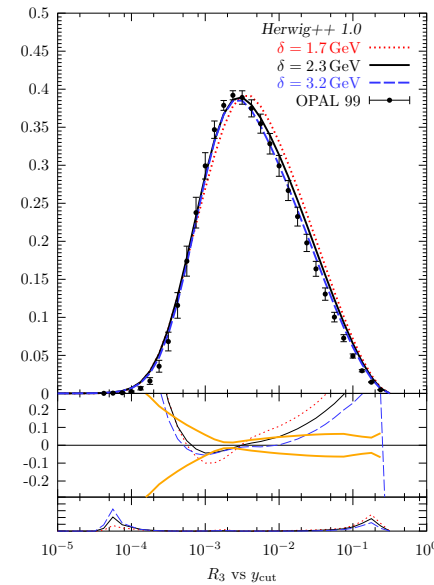
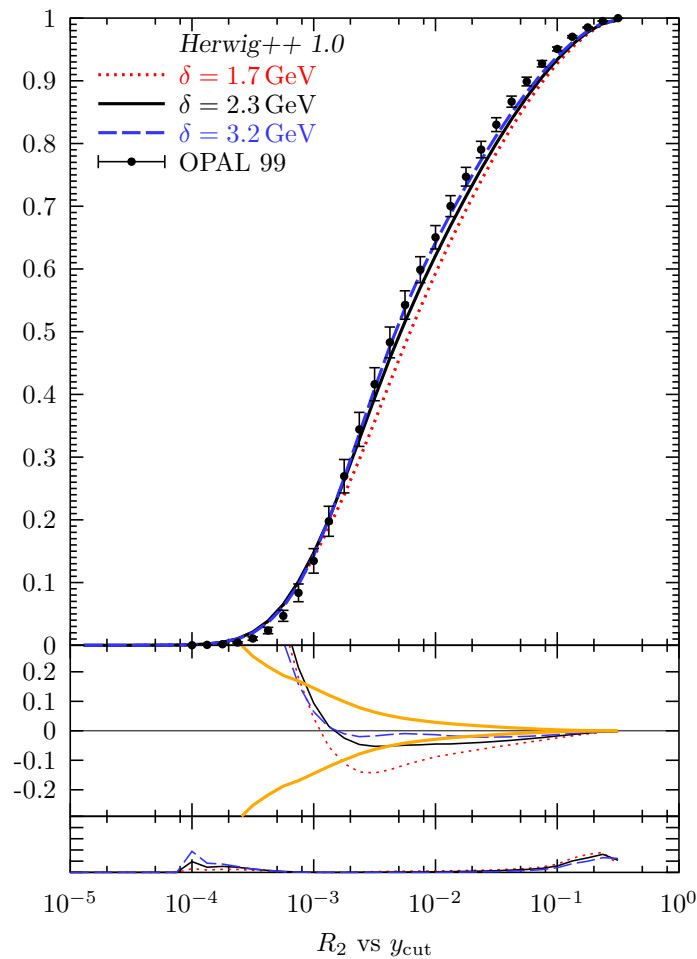


There are other jet algorithms with a different distance measure (JADE) or recombination scheme. We have interfaced the KtJet package for jet clustering.

# Jet Rates

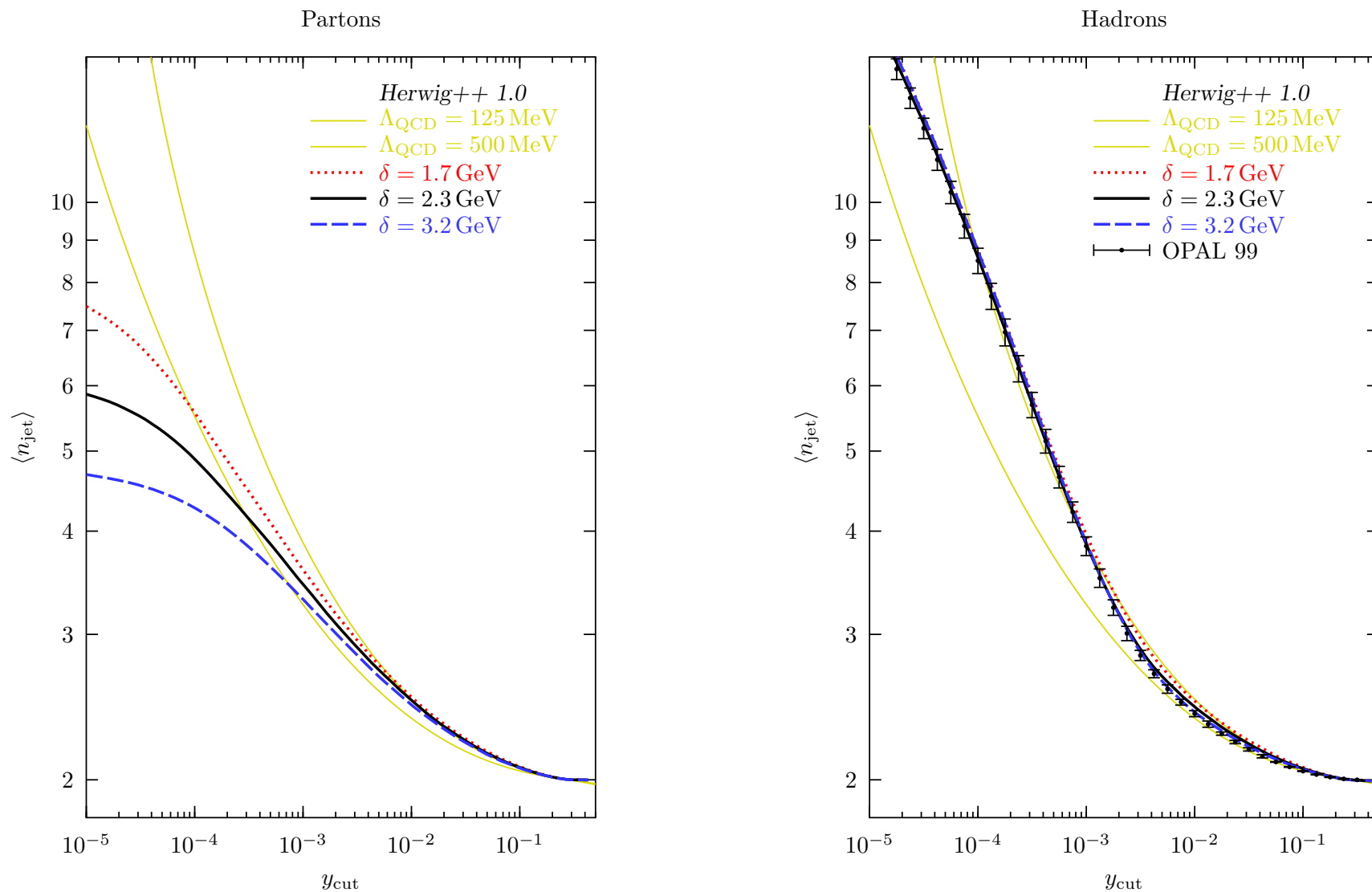
$$R_n = \sigma(n\text{-jets})/\sigma(\text{jets}) \quad (n = 2..5)$$

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



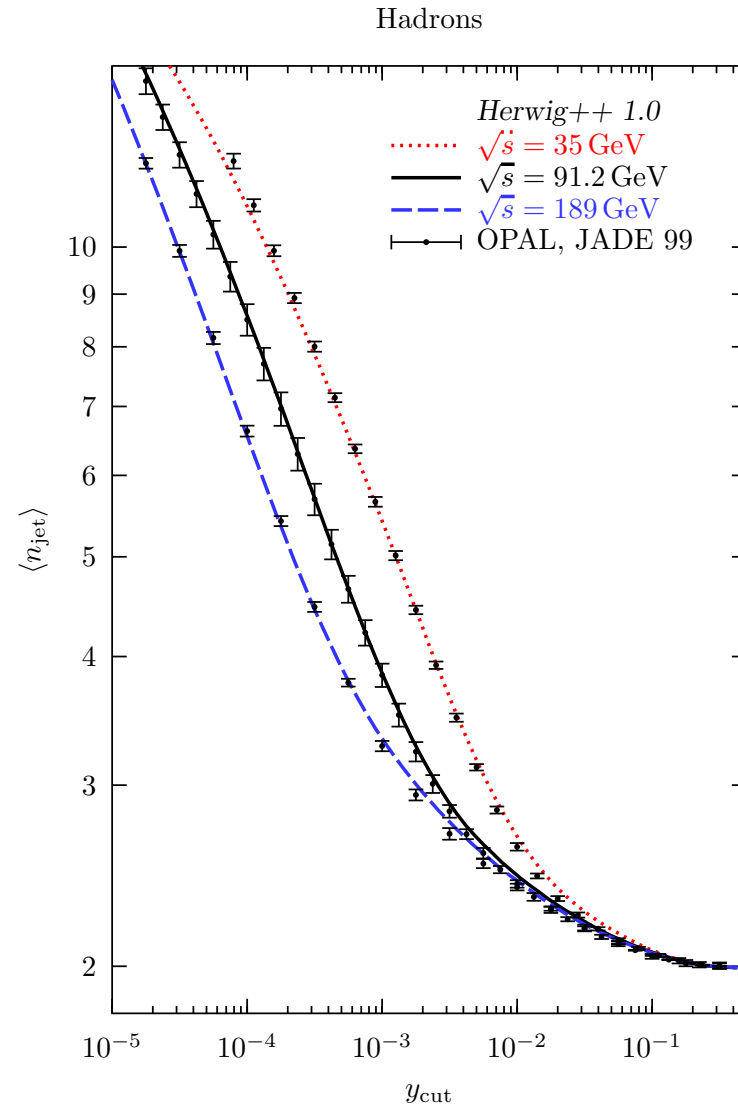
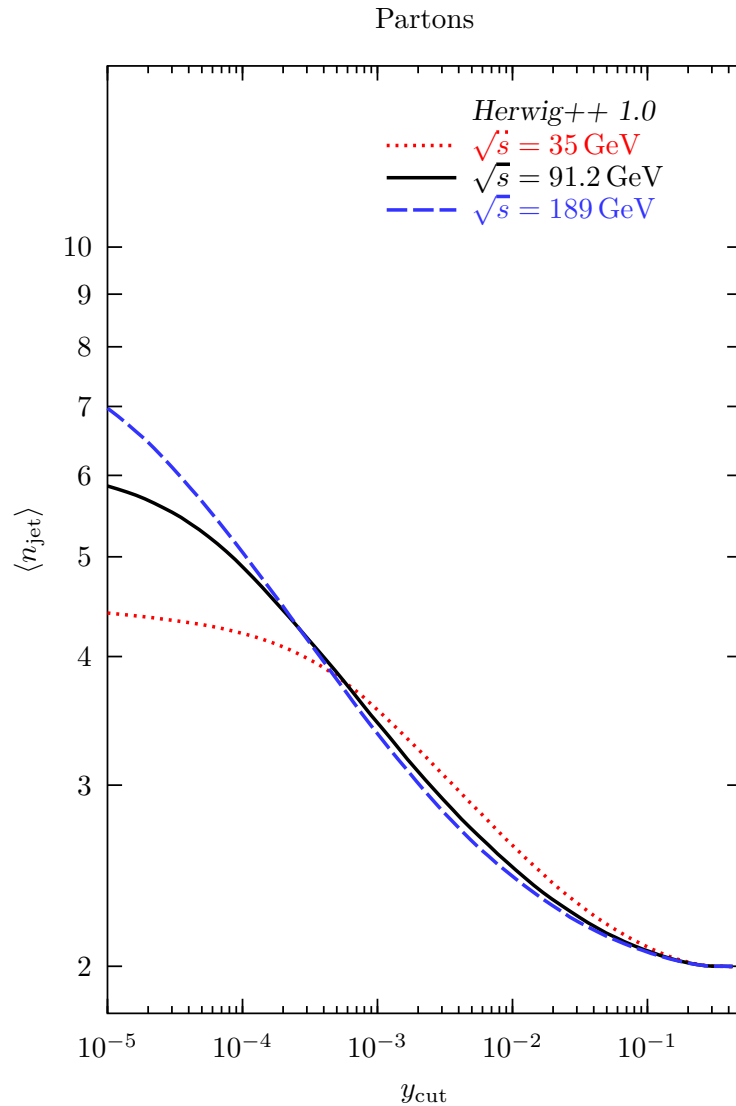
# Jet Multiplicity

Durham algorithm. Smooth interplay between shower and hadronization.



# Jet Multiplicity (PETRA, LEP, LEP II)

$$\sqrt{s} = \{35, 91.2, 189\} \text{ GeV}$$



## Event Shape Variables, Definition

Thrust

$$F(\mathbf{n}) = \frac{\sum_{\alpha} |\mathbf{p}_{\alpha} \cdot \mathbf{n}|}{\sum_{\alpha} |\mathbf{p}_{\alpha}|}$$

Find  $\mathbf{n}$ , such that thrust

$$\begin{aligned} T &= \max_{\mathbf{n}} F(\mathbf{n}) \\ &= F(\mathbf{n}_T) , \end{aligned}$$

thrust major

$$\begin{aligned} M &= \max_{\mathbf{n} \perp \mathbf{n}_T} F(\mathbf{n}) \\ &= F(\mathbf{n}_M) , \end{aligned}$$

thrust minor

$$\begin{aligned} \mathbf{n}_m &= \mathbf{n}_T \times \mathbf{n}_M \\ m &= F(\mathbf{n}_m) \end{aligned}$$

Sphericity

$$Q_{ij} = \frac{\sum_{\alpha} (\mathbf{p}_{\alpha})_i (\mathbf{p}_{\alpha})_j}{\sum_{\alpha} \mathbf{p}_{\alpha}^2}$$

Diagonalize, eigenvalues

$$\begin{aligned} \lambda_1 &> \lambda_2 > \lambda_3 \\ \lambda_1 + \lambda_2 + \lambda_3 &= 1 \end{aligned}$$

Then

$$\begin{aligned} S &= \frac{3}{2}(\lambda_2 + \lambda_3) \\ P &= \lambda_2 - \lambda_3 \\ A &= \frac{3}{2}\lambda_3 \end{aligned}$$

Eigenvector  $\mathbf{n}_S$  sphericity axis  
etc.

$C, D$  parameter

$$L_{ij} = \frac{\sum_{\alpha} (\mathbf{p}_{\alpha})_i (\mathbf{p}_{\alpha})_j / |\mathbf{p}_{\alpha}|}{\sum_{\alpha} |\mathbf{p}_{\alpha}|}$$

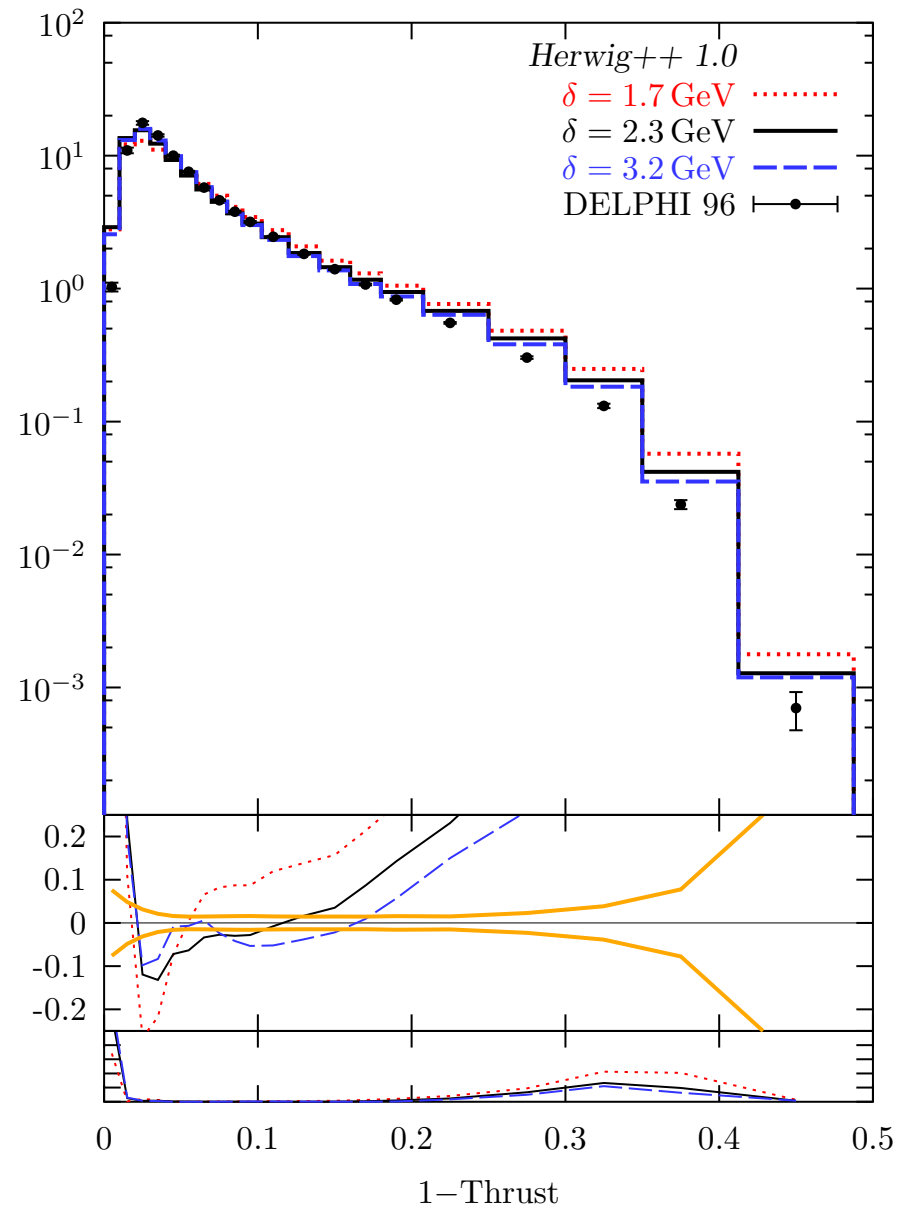
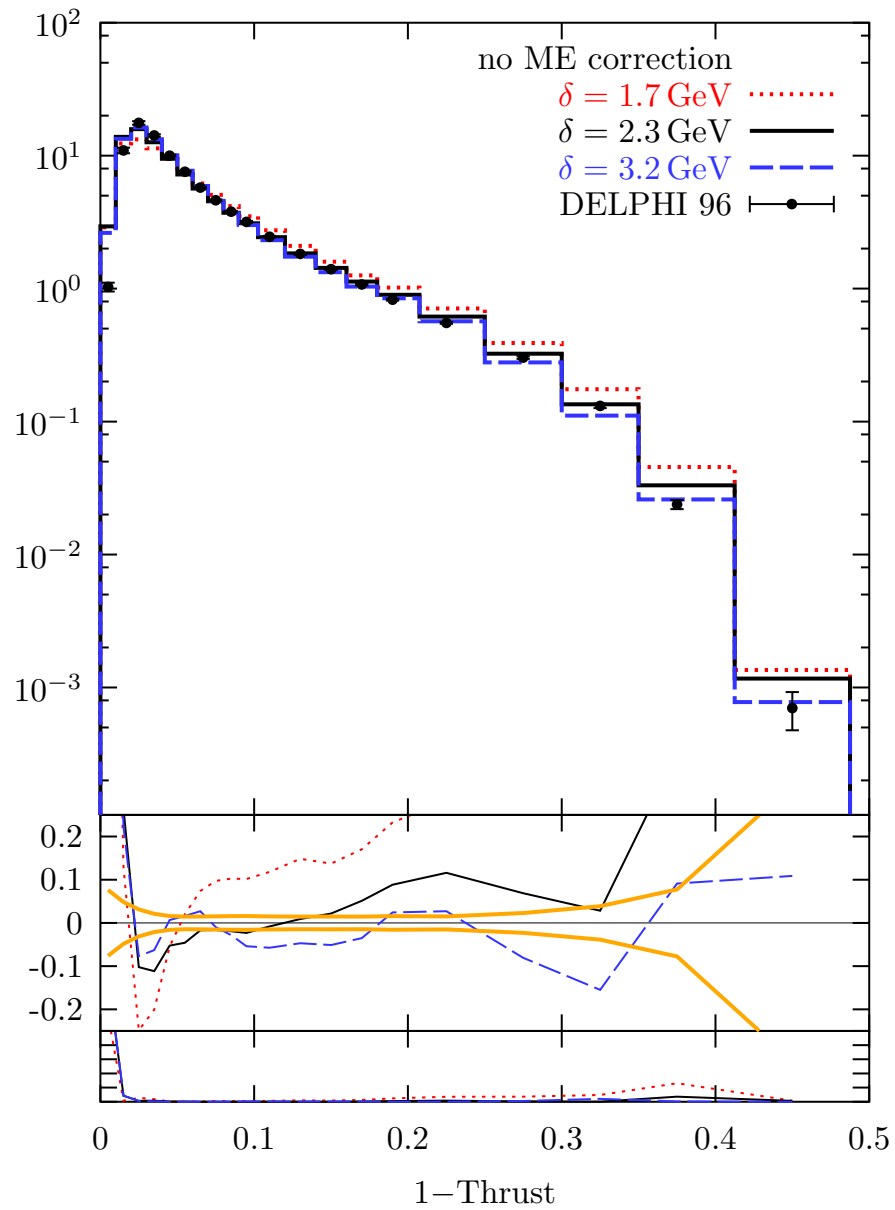
Diagonalize, eigenvalues

$$\lambda_1 + \lambda_2 + \lambda_3 = 1$$

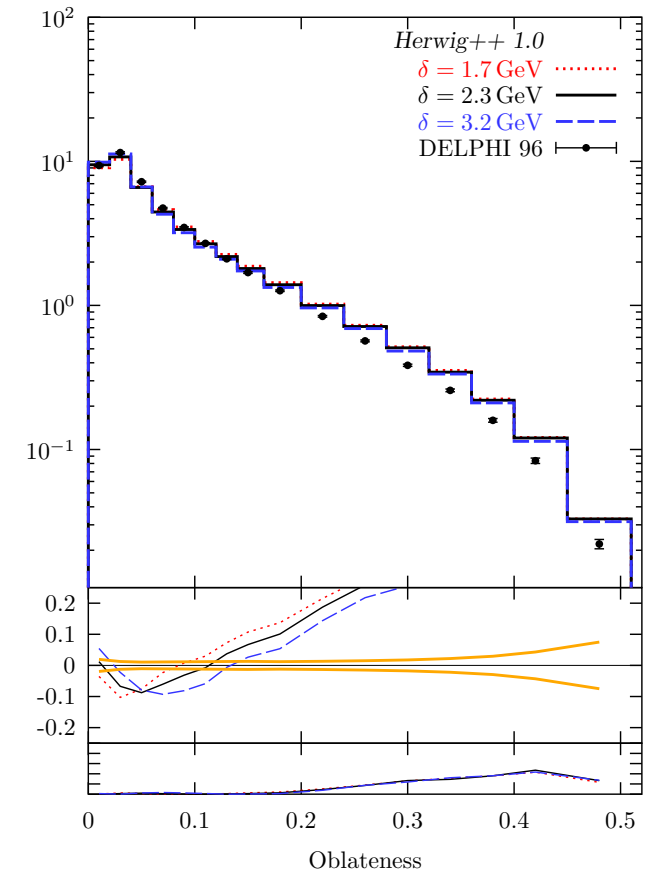
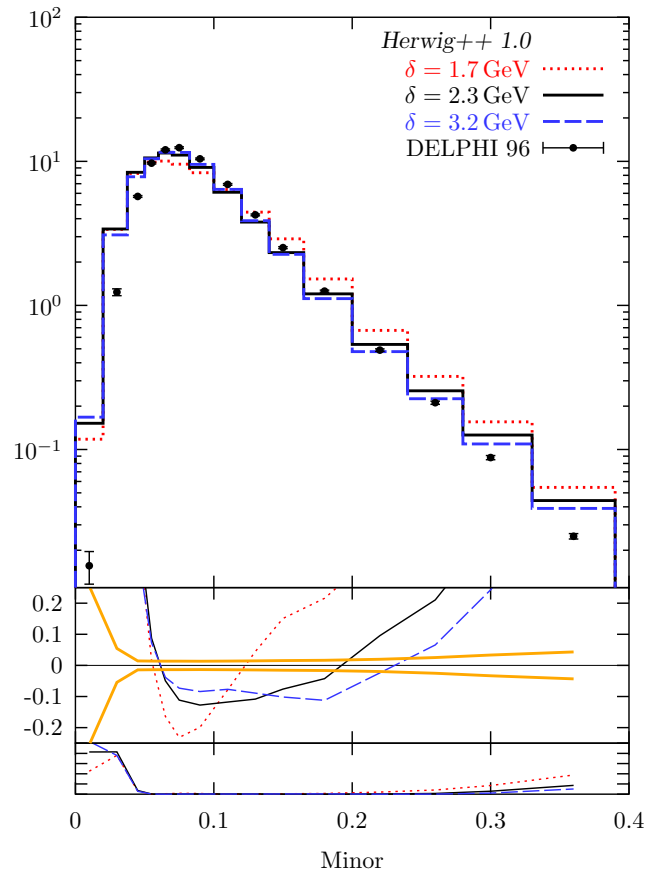
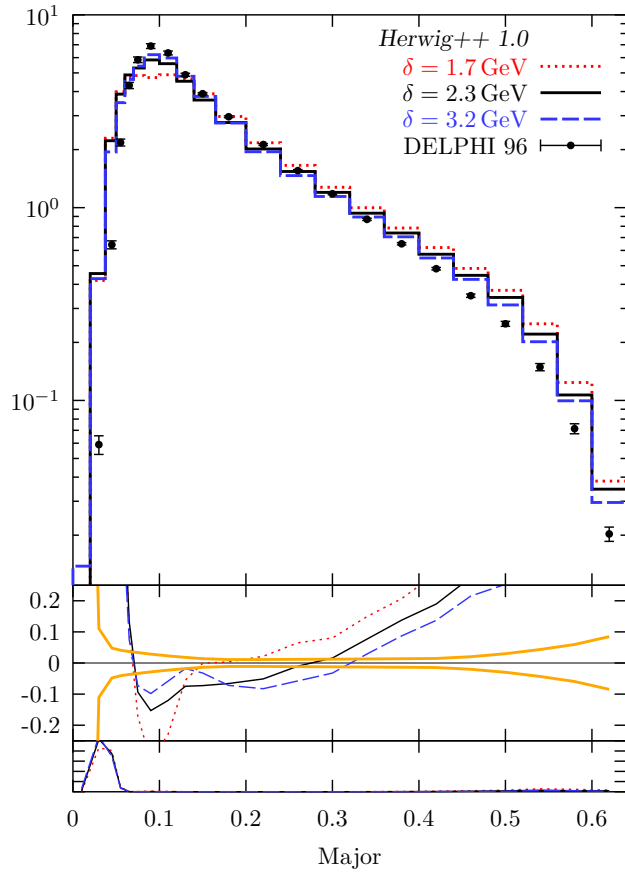
and define

$$\begin{aligned} C &= 3(\lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_3 \lambda_1) \\ D &= 27 \lambda_1 \lambda_2 \lambda_3 \end{aligned}$$

# Thrust — ME Corrections off/on



# Major, Minor, Oblateness



All Thrust-related distributions slightly wide, ie too many 2-jet like on one side and too many spherical events on the other side.

## Four Jet Angles — Definitions

Bengtsson–Zerwas angle

$$\chi_{BZ} = \angle(\mathbf{p}_1 \times \mathbf{p}_2, \mathbf{p}_3 \times \mathbf{p}_4)$$

Körner–Schierholz–Willrodt angle

$$\Phi_{KSW} = \frac{1}{2} [\angle(\mathbf{p}_1 \times \mathbf{p}_3, \mathbf{p}_2 \times \mathbf{p}_4) + \angle(\mathbf{p}_1 \times \mathbf{p}_4, \mathbf{p}_2 \times \mathbf{p}_3)]$$

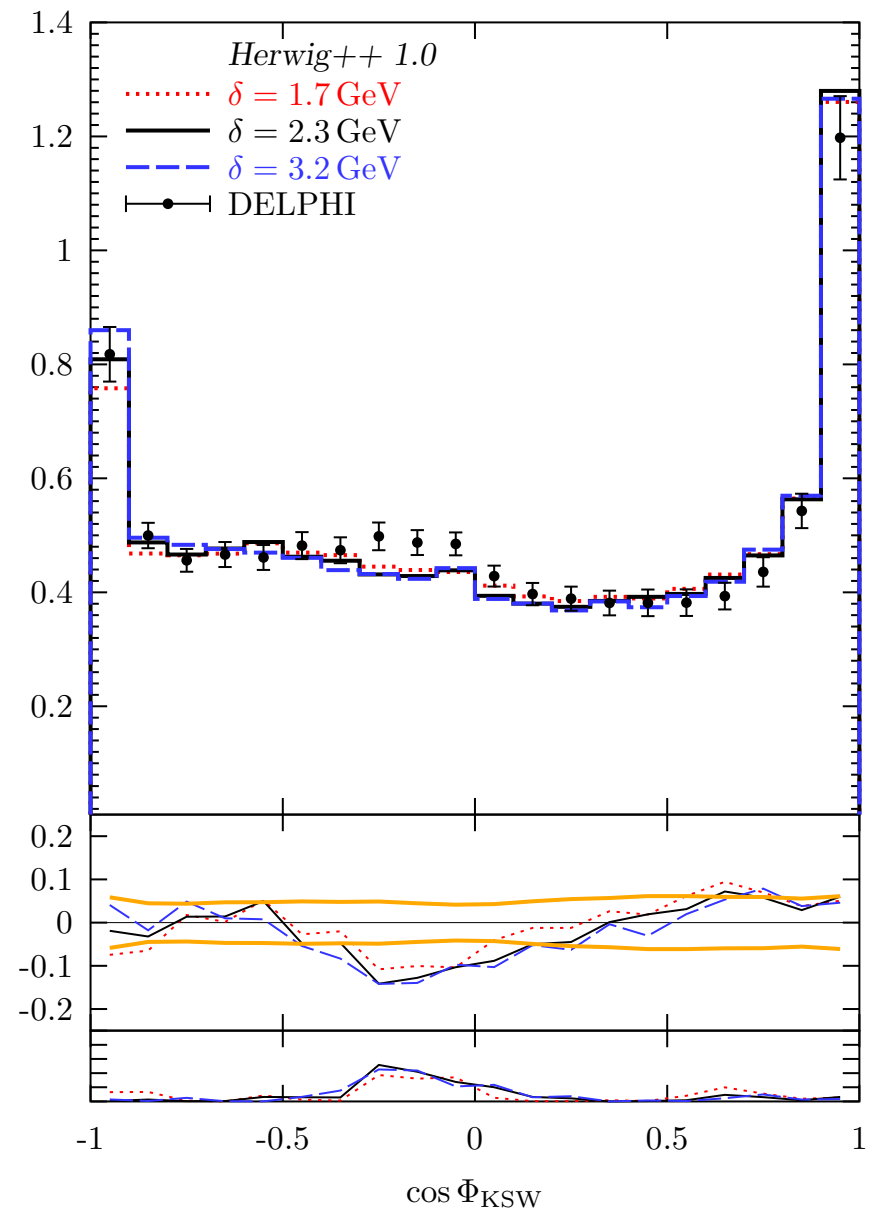
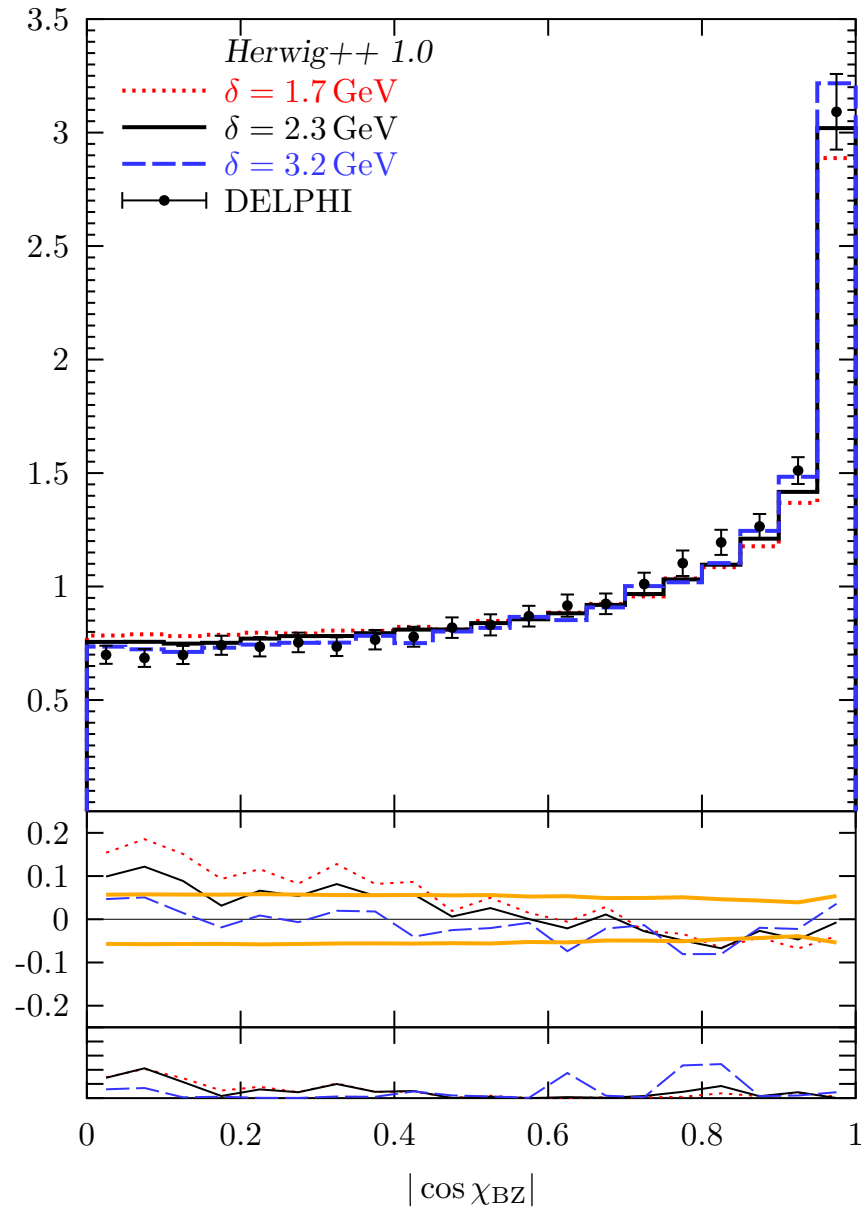
(modified) Nachtmann–Reiter angle

$$\theta_{NR}^* = \angle(\mathbf{p}_1 - \mathbf{p}_2, \mathbf{p}_3 - \mathbf{p}_4)$$

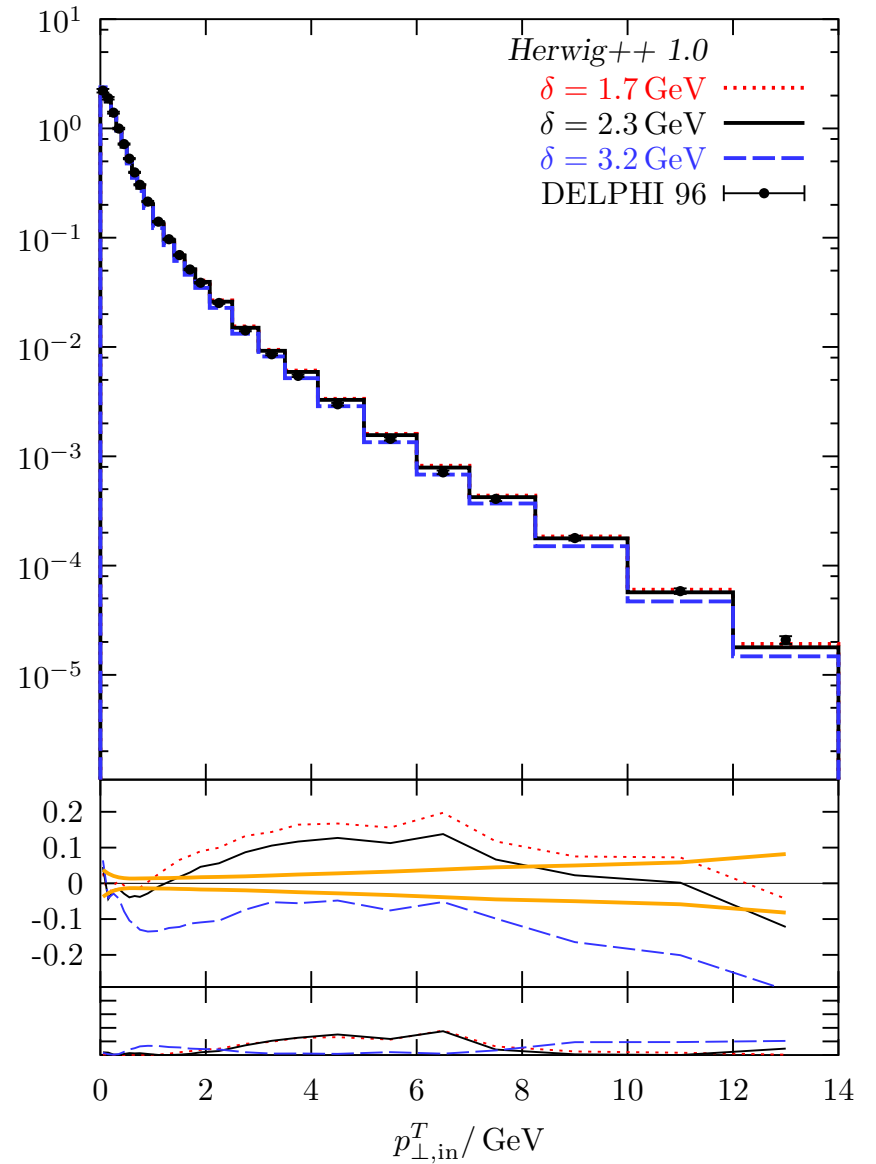
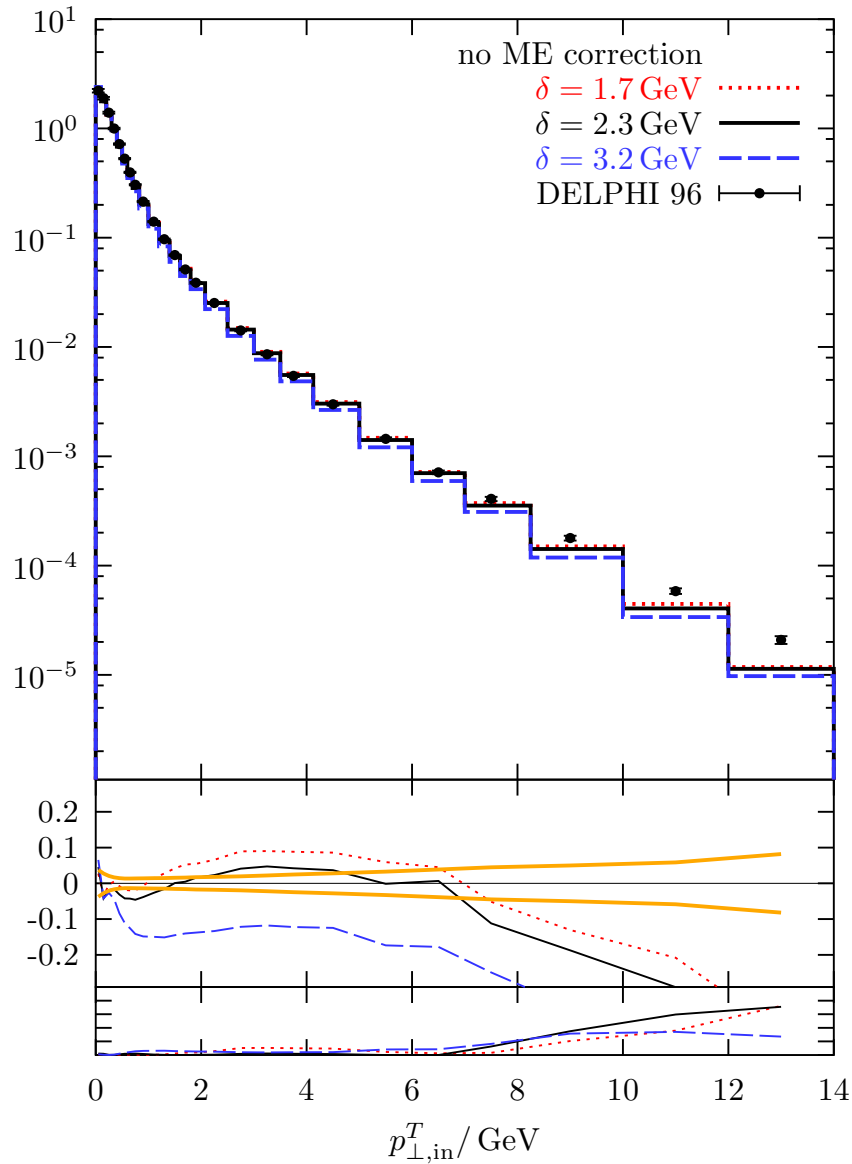
$\alpha_{34}$ :

$$\alpha_{34} = \angle(\mathbf{p}_3, \mathbf{p}_4)$$

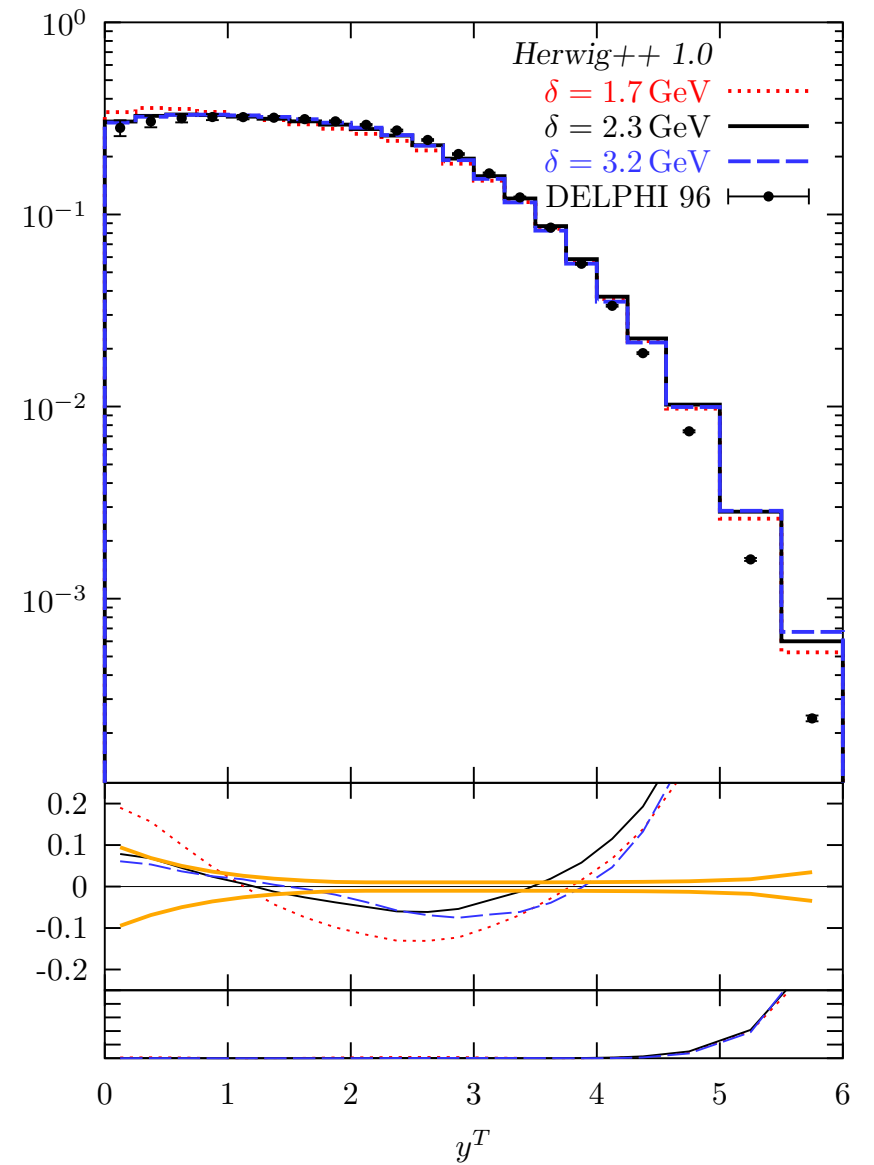
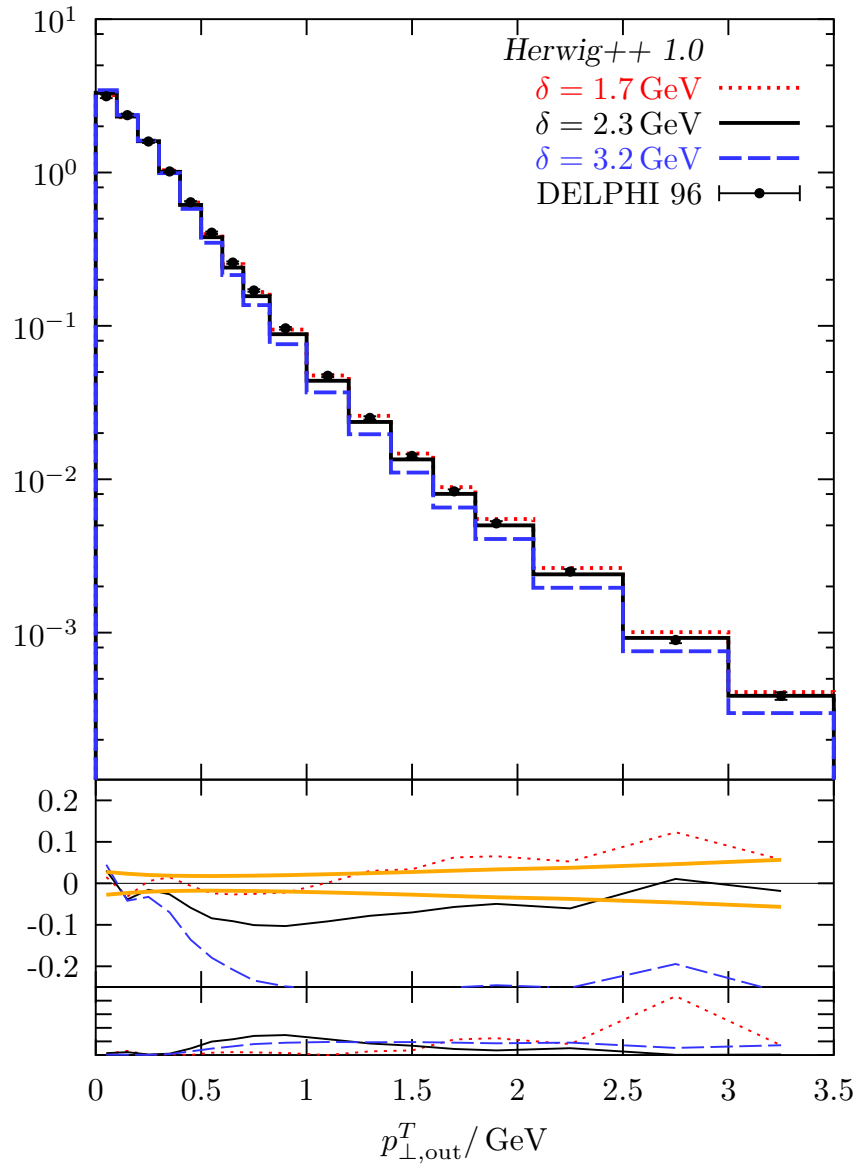
# Four Jet Angles



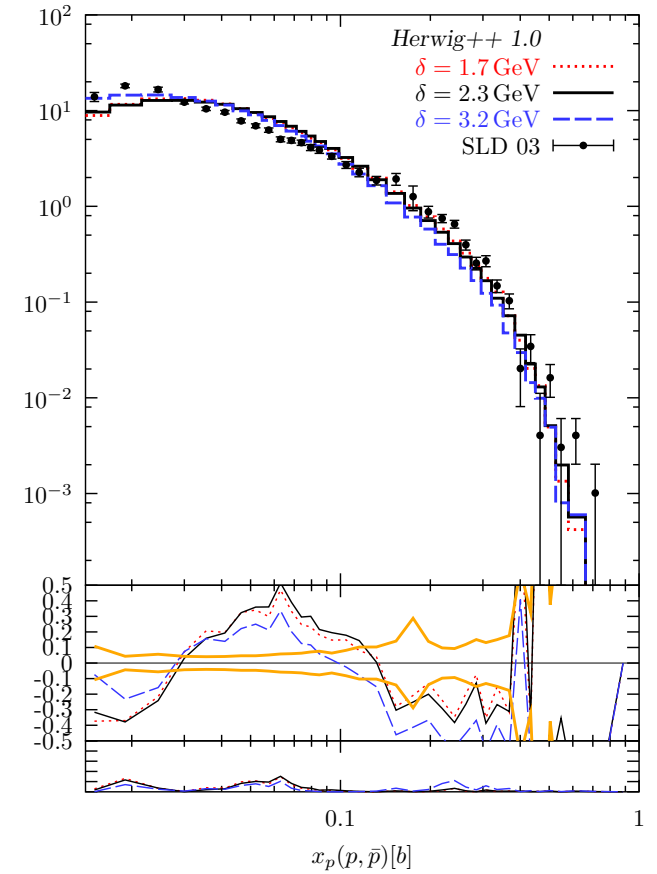
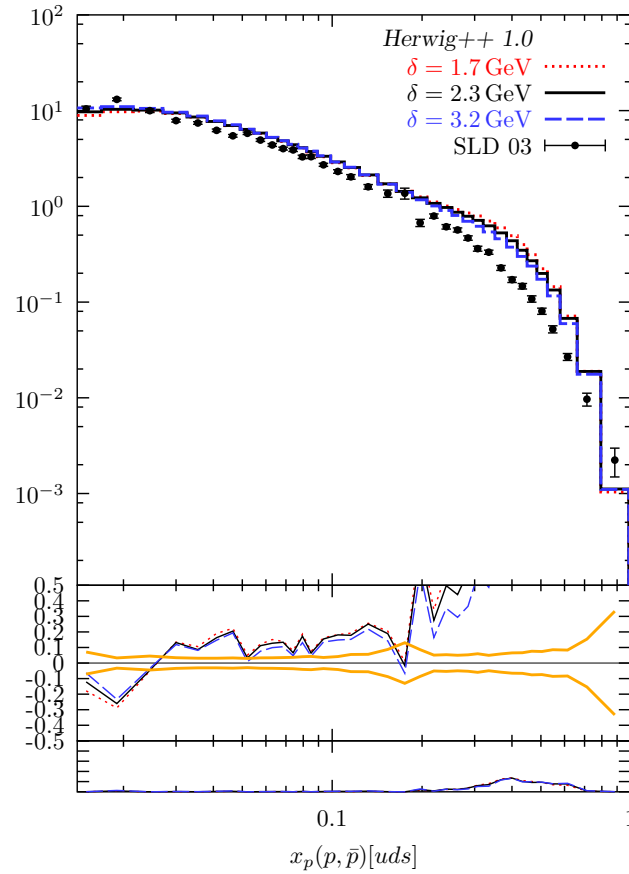
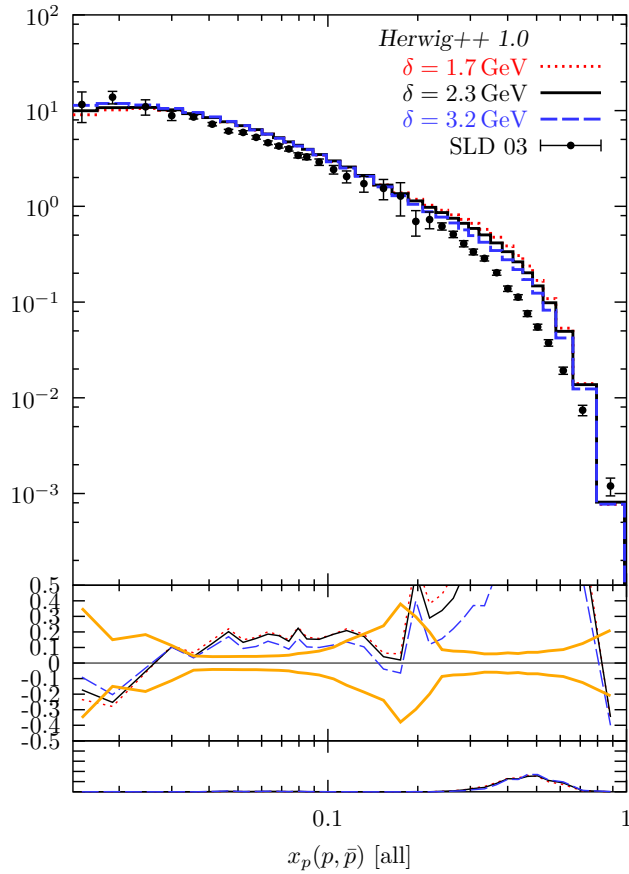
# $p_{\perp, \text{in}}^T$ — ME corrections off/on



# $p_{\perp, \text{out}}^T, y^T$

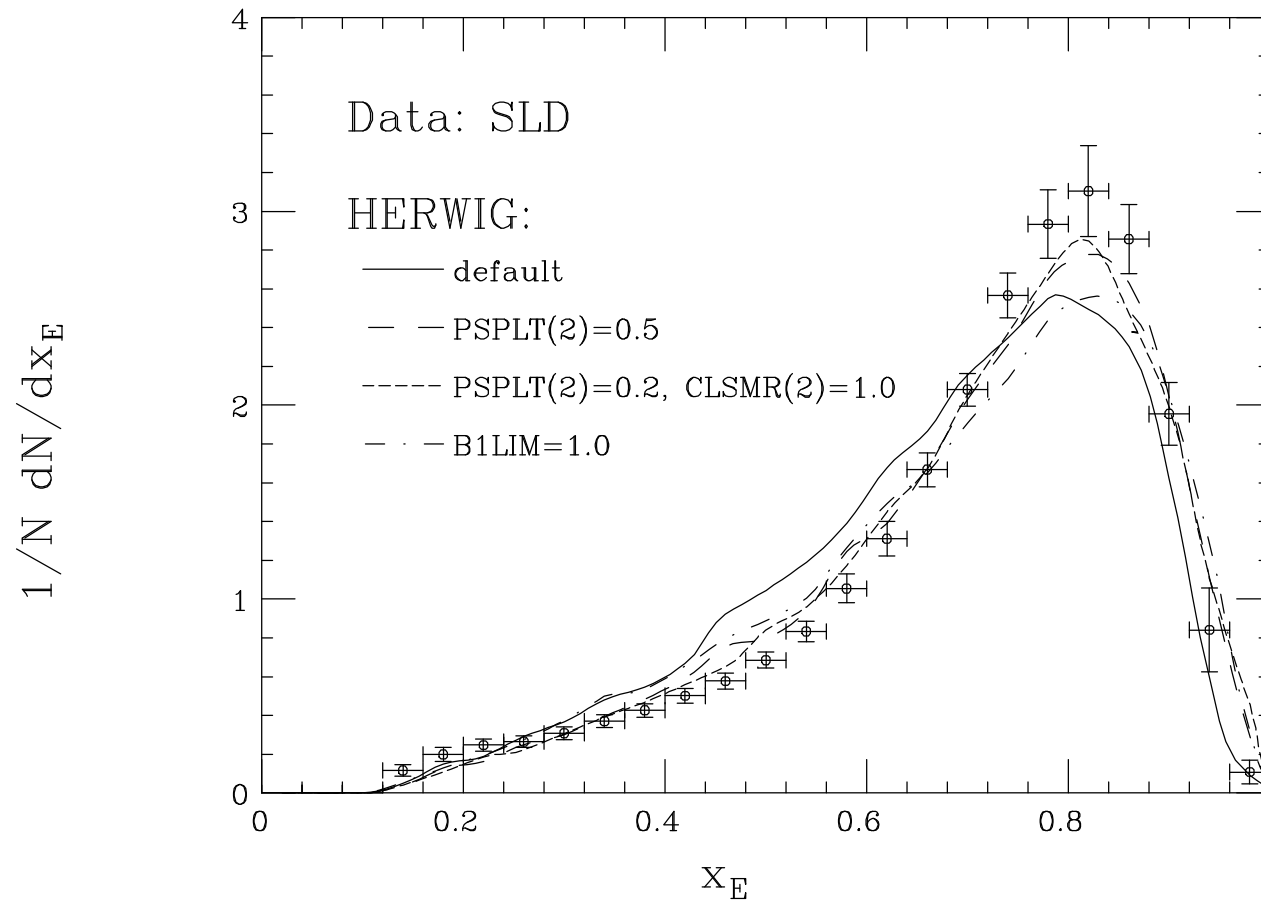


# Proton Momentum (all, $uds$ , $b$ )



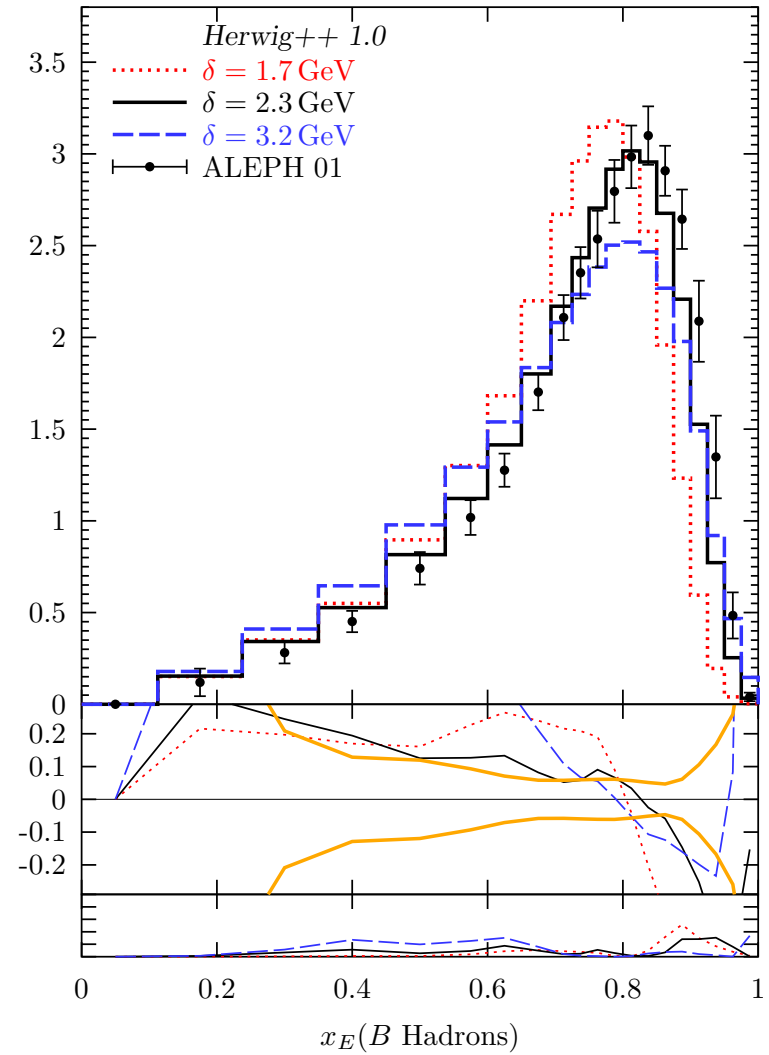
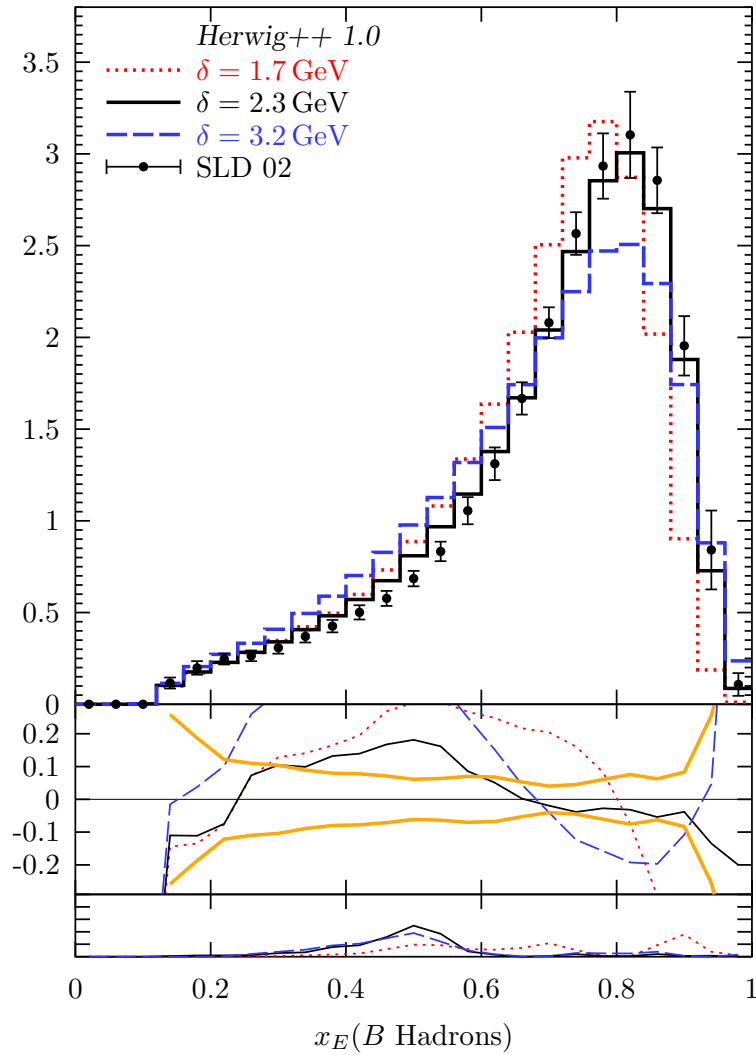
# *B*-fragmentation function

Weakly decaying b hadrons



HERWIG 6.4, very sensitive on hadronization!

# B-fragmentation function



Only parton shower parameters varied!

## Recommendation

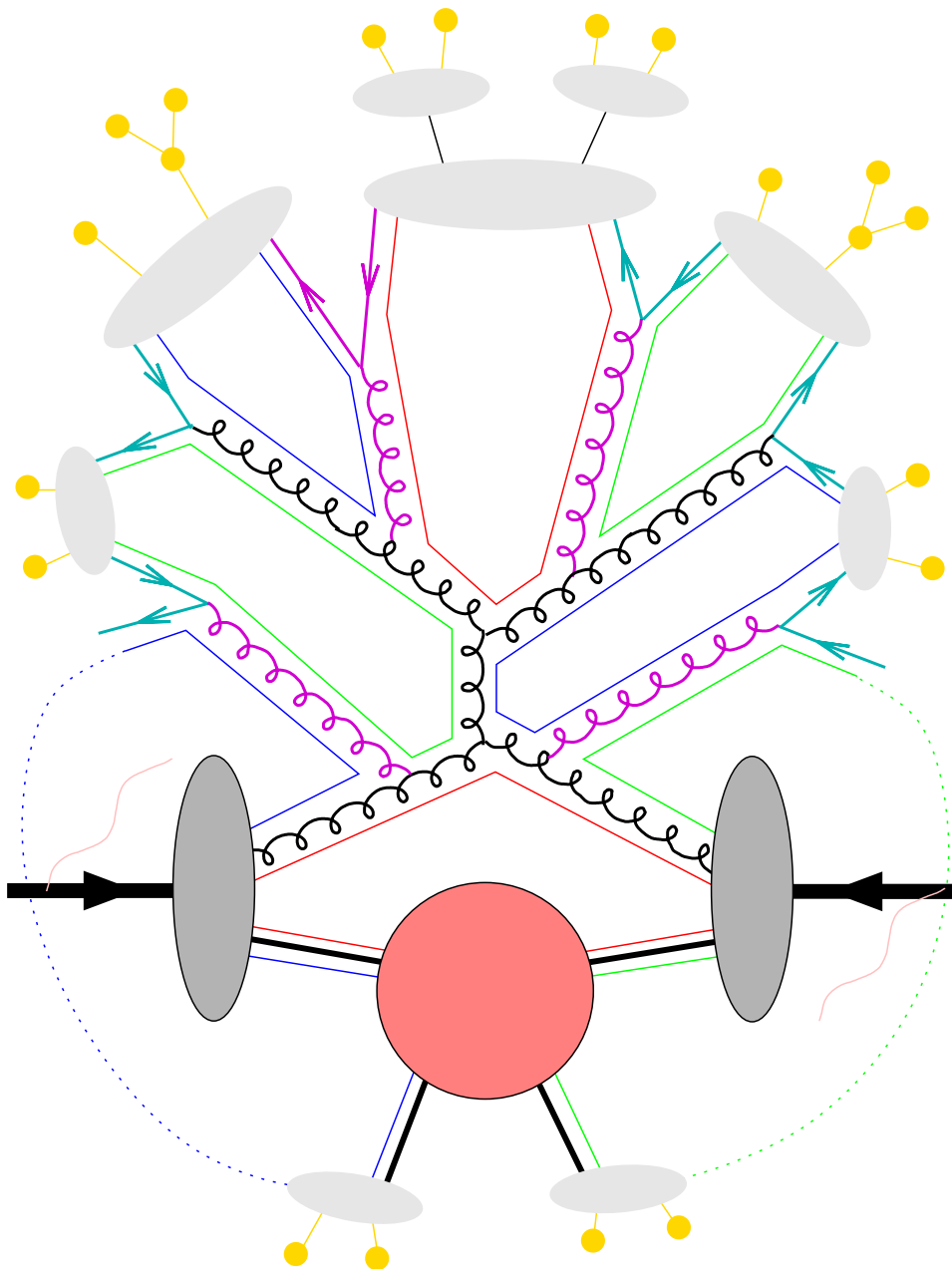
. . . However, the different observables have to be weighted sensibly.

- Low cutoff preferred by event shapes, jet rates, differential jet rates.
- High cutoff preferred by Single Particle distributions along thrust or sphericity axis.
- Either high or low cutoff for  $y_{nm}$ .
- High cutoff preferred by Identified particle spectra, particularly for heavy flavour events.
- Intermediate cutoff preferred by  $B$  fragmentation function.

We recommend the intermediate value.

| Parameter                                     | Default | Initial |
|---|---------|---------|
| $\alpha_s(M_Z)$                               | 0.118   | 0.114   |
| $\delta/\text{GeV}$                           | 2.3     | —       |
| $m_g/\text{GeV}$                              | 0.750   | —       |
| $Q_{\min}/\text{GeV}$ in $\alpha_s(Q_{\min})$ | 0.631   | —       |
| CIMax/GeV                                     | 3.2     | 3.35    |
| CIPow   | 2.0     | —       |
| PSplt1  | 1       | —       |
| PSplt2  | 0.33    | —       |
| B1Lim   | 0.0     | —       |
| CIDir1  | 1       | —       |
| CIDir2  | 1       | —       |
| CISmr1  | 0.40    | —       |
| CISmr2  | 0.0     | —       |
| Pwt <sub>d</sub>                              | 1.0     | —       |
| Pwt <sub>u</sub>                              | 1.0     | —       |
| Pwt <sub>s</sub>                              | 0.85    | 1.0     |
| Pwt <sub>c</sub>                              | 1.0     | —       |
| Pwt <sub>b</sub>                              | 1.0     | —       |
| Pwt <sub>di</sub>                             | 0.55    | 1.0     |
| Singlet Weight                                | 1.0     | —       |
| Decuplet Weight                               | 0.7     | 1.0     |

## Additional Complications in $pp$



- + backward parton evolution
- + soft underlying event

# What's next?

## 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.
  - Study of **DIS** possible.
- ★ Underlying Event.
- ★ Hadronic Decays: **NEW!**  $\tau$ -decays, Spin correlations (P Richardson).
- ★ **New Ideas:** soft gluons, improved shower algorithm, NLO, . . .

## Schedule?

- Ready for LHC!

## Conclusion

We have completed a new event generator for  $e^+e^-$  Annihilation:

**Herwig++ 1.0**

<http://www.hep.phy.cam.ac.uk/theory/Herwig++>