The new MC event generator Herwig++

Stefan Gieseke

University of Cambridge
Cavendish Laboratory

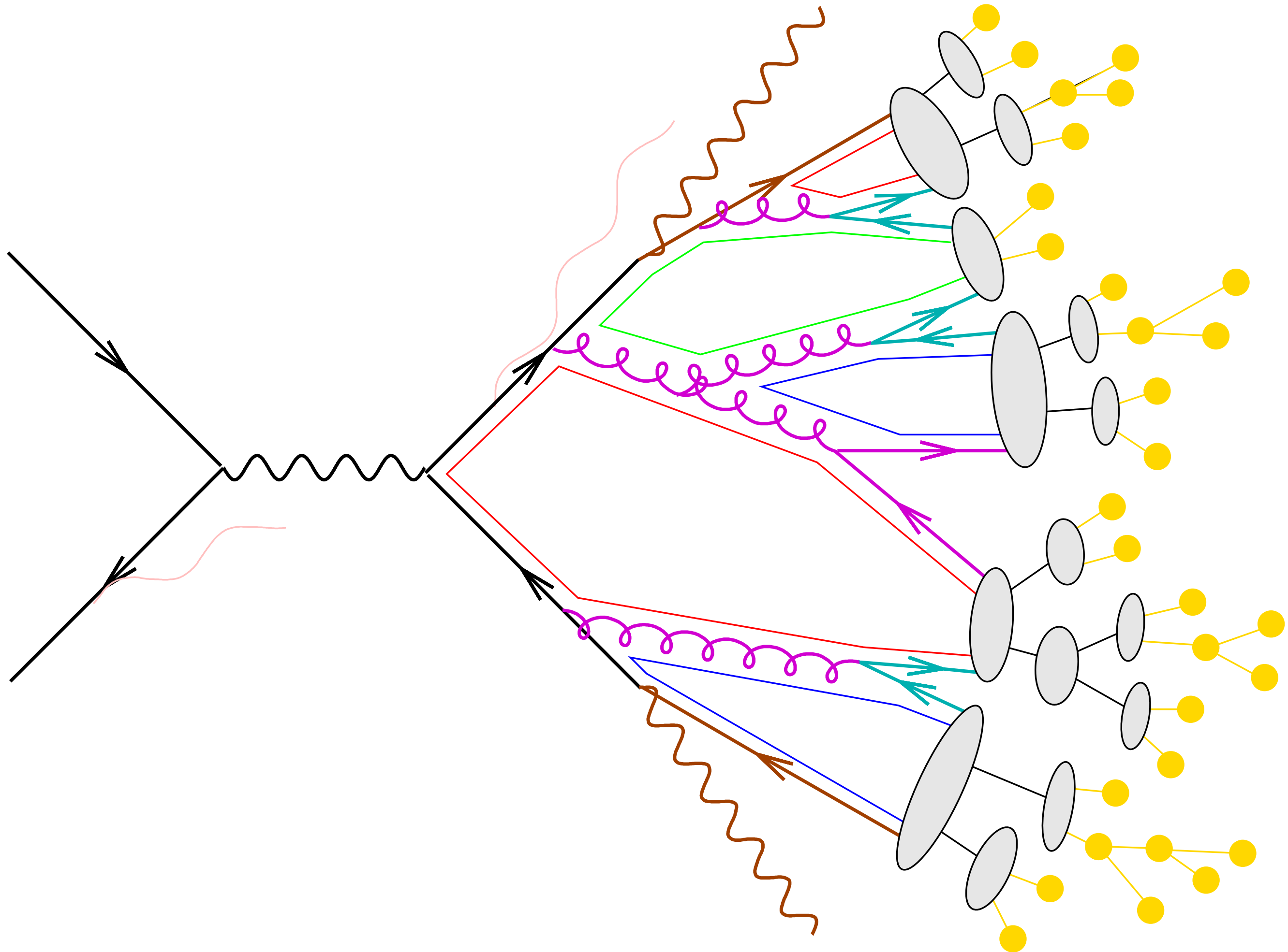
work with A Ribon, MH Seymour, P Stephens, BR Webber (Cambridge, CERN)

- 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

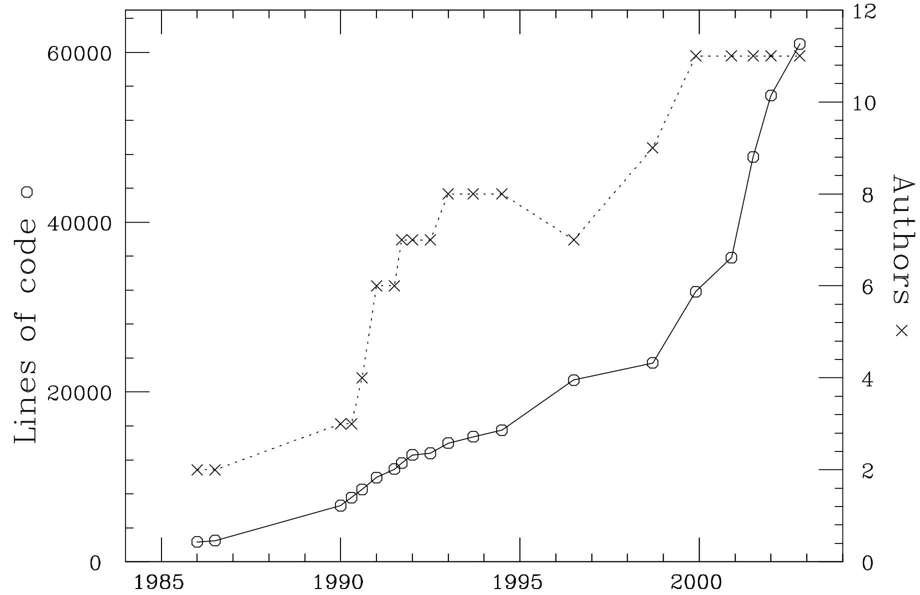


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

The new generator Herwig++

Complete rewrite of `HERWIG` *in C++*

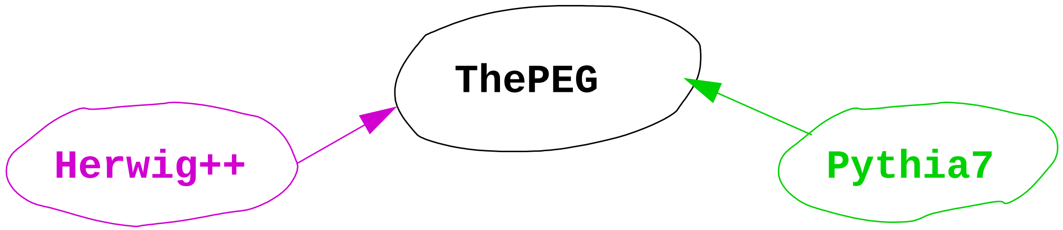
- aiming at full multi–purpose generator for LHC and future colliders.
- Preserve main features of `HERWIG` such as
  - angular ordered parton shower
  - Cluster Hadronization
- New features and improvements
  - improved parton shower evolution for heavy quarks
  - consistent radiation from unstable 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 possiblity to test codes against each other.
- ✓ Physics, however, is still independent.
- ✓ Beneficial for the user to have the same framework.
- ✓ Running Herwig++ with the Lund String Fragmentation from Pythia7 is very simple!

Hard interactions

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

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

  we use them.
- Soft and hard matrix element corrections imlemented for $e^+e^- \longrightarrow q\bar{q}g$.
- 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 ($\longrightarrow$ *safety* of OO code)

Quasi–Collinear Limit (Heavy Quarks)

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

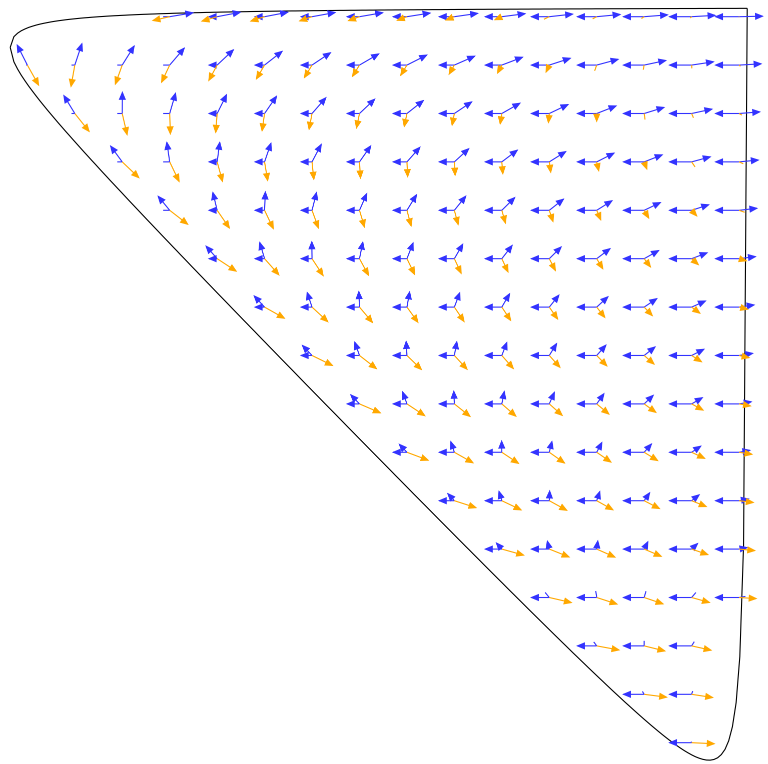
$$
\begin{aligned}
p_q &= zp + \beta_q n - q_\perp \\
p_g &= (1-z)p + \beta_g n + q_\perp
\end{aligned}
$$

Collinear limit for radiation off heavy quark,

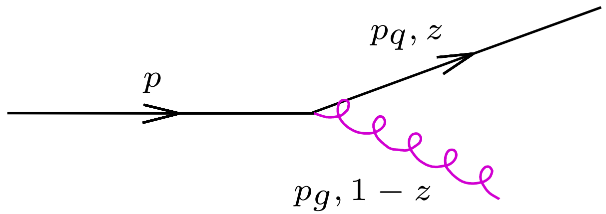
$$
\begin{aligned}
P_{gq}(z, \boldsymbol{q}^2, m^2) &= C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\boldsymbol{q}^2 + (1-z)^2 m^2} \right] \\
&= \frac{C_F}{1-z} \left[1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right]
\end{aligned}
$$

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

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

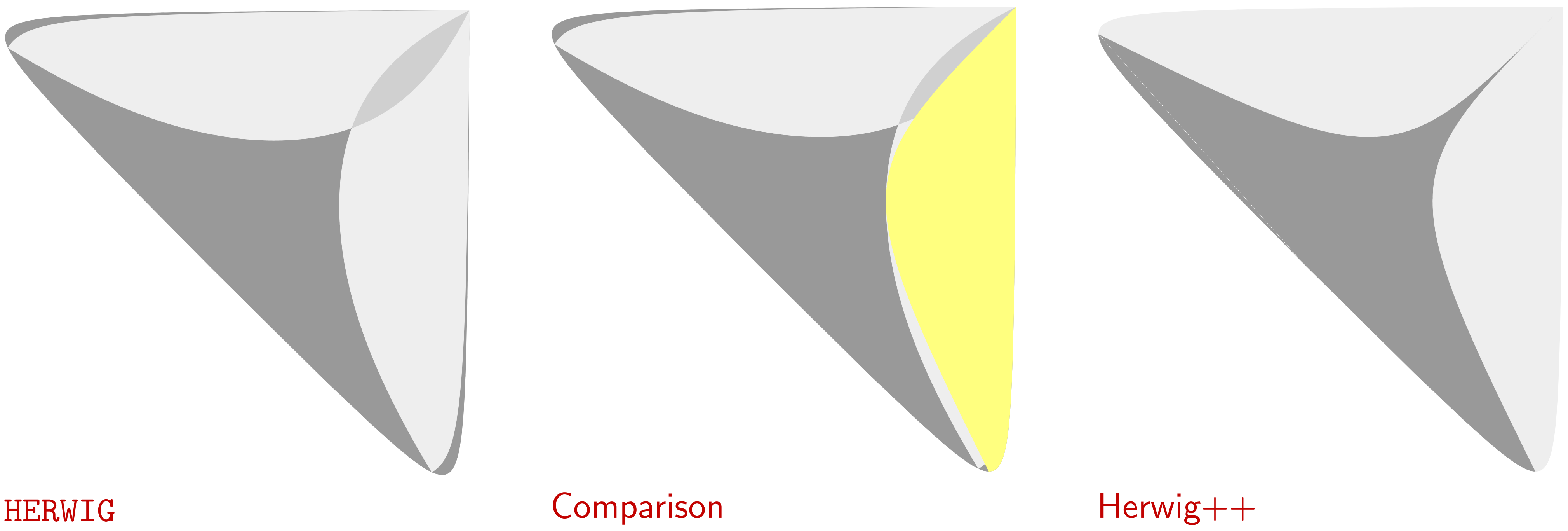


Single emission:



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

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



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

Universal cutoff parameter δ

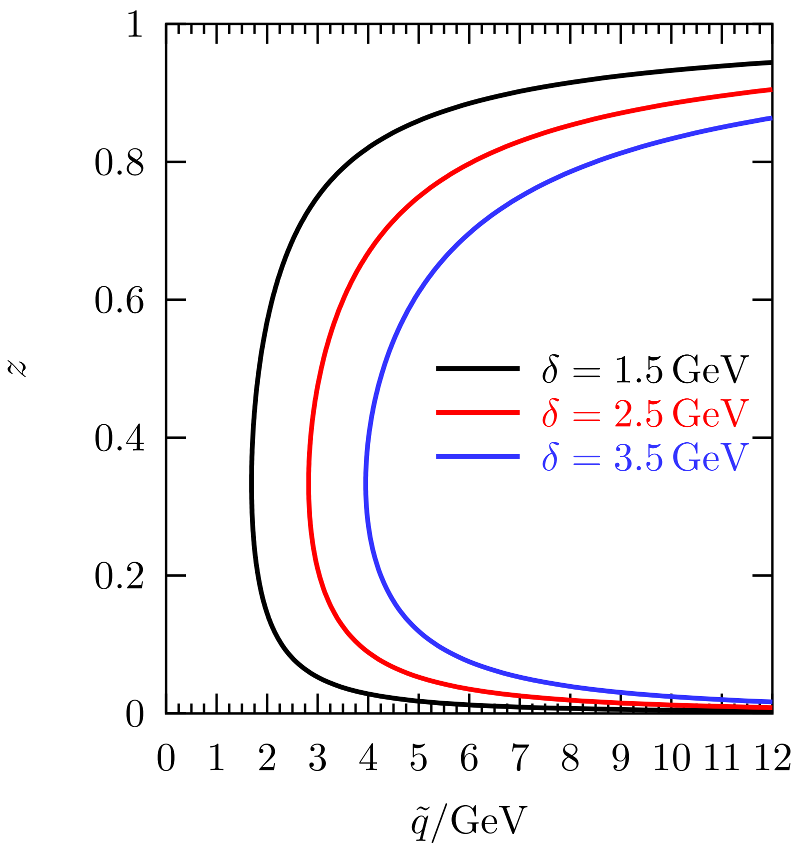
Require threshold in parton shower phase space

$$Q_{\rm thr} = \beta m_q + \delta \qquad (\beta = 0.85)$$

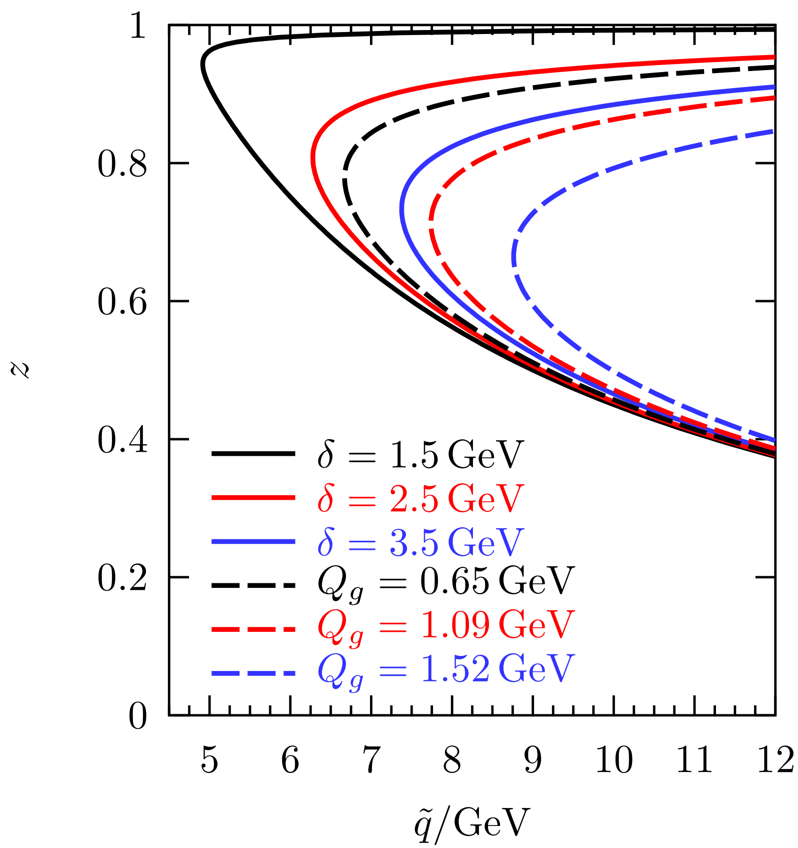
parametrization of Q_g in terms of δ, m_q

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

light quarks:

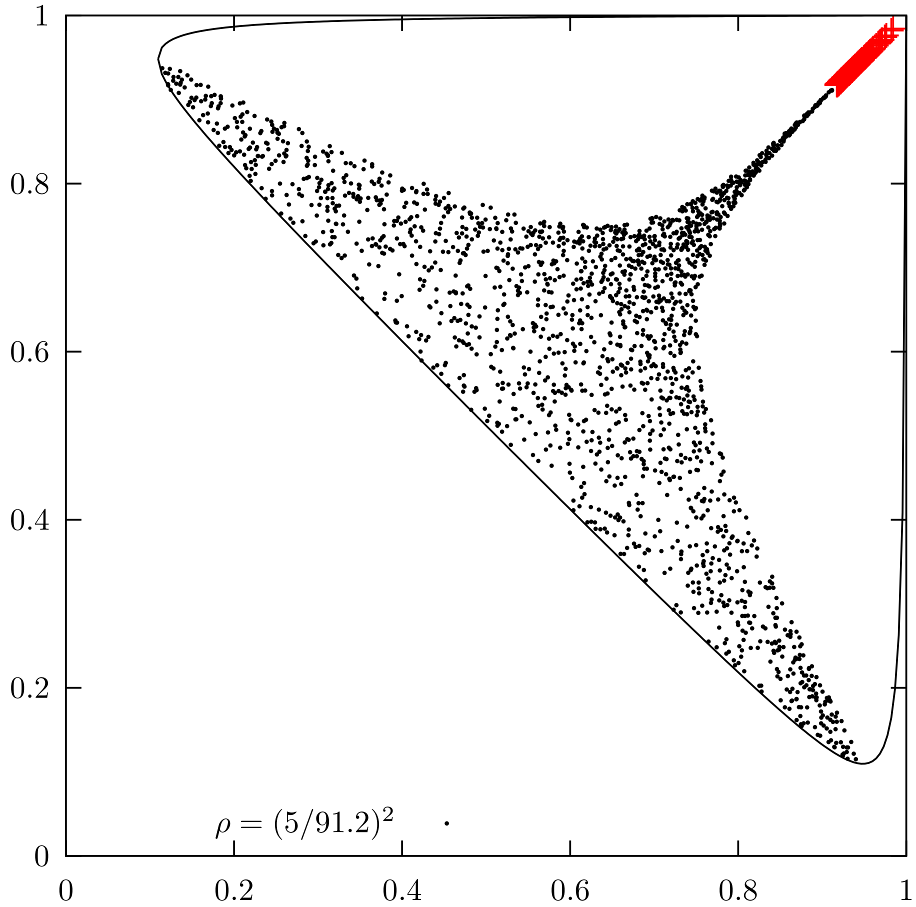


b quarks:



Hard Matrix Element Corrections

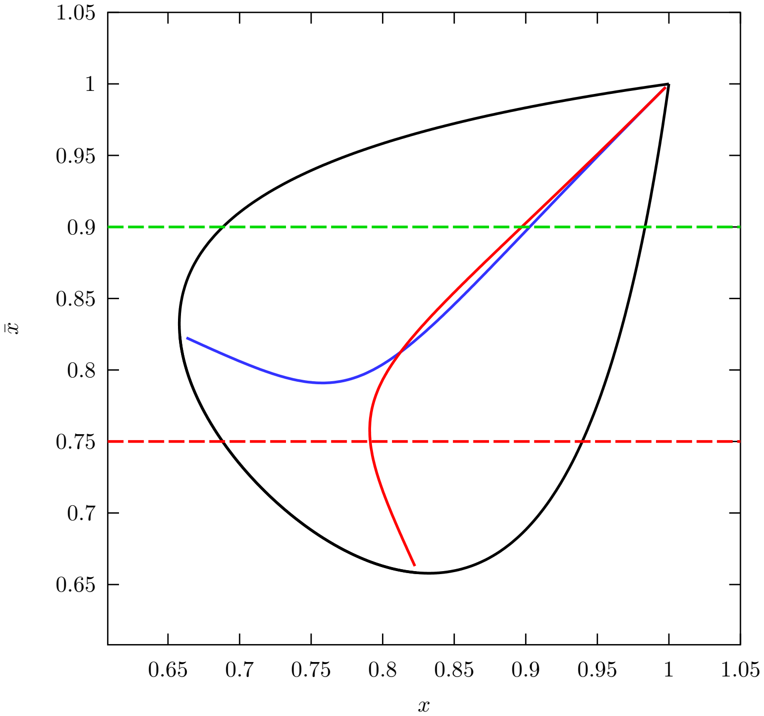
- Points $(x, \bar{x})$ in dead region chosen acc to LO $e^+e^- \to q\bar{q}g$ matrix element and accepted acc to ME weight.
- About 3% of all events are actually hard $q\bar{q}g$ events.
- Red points have weight > 1, practically no error by setting weight to one.
- Event oriented according to given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

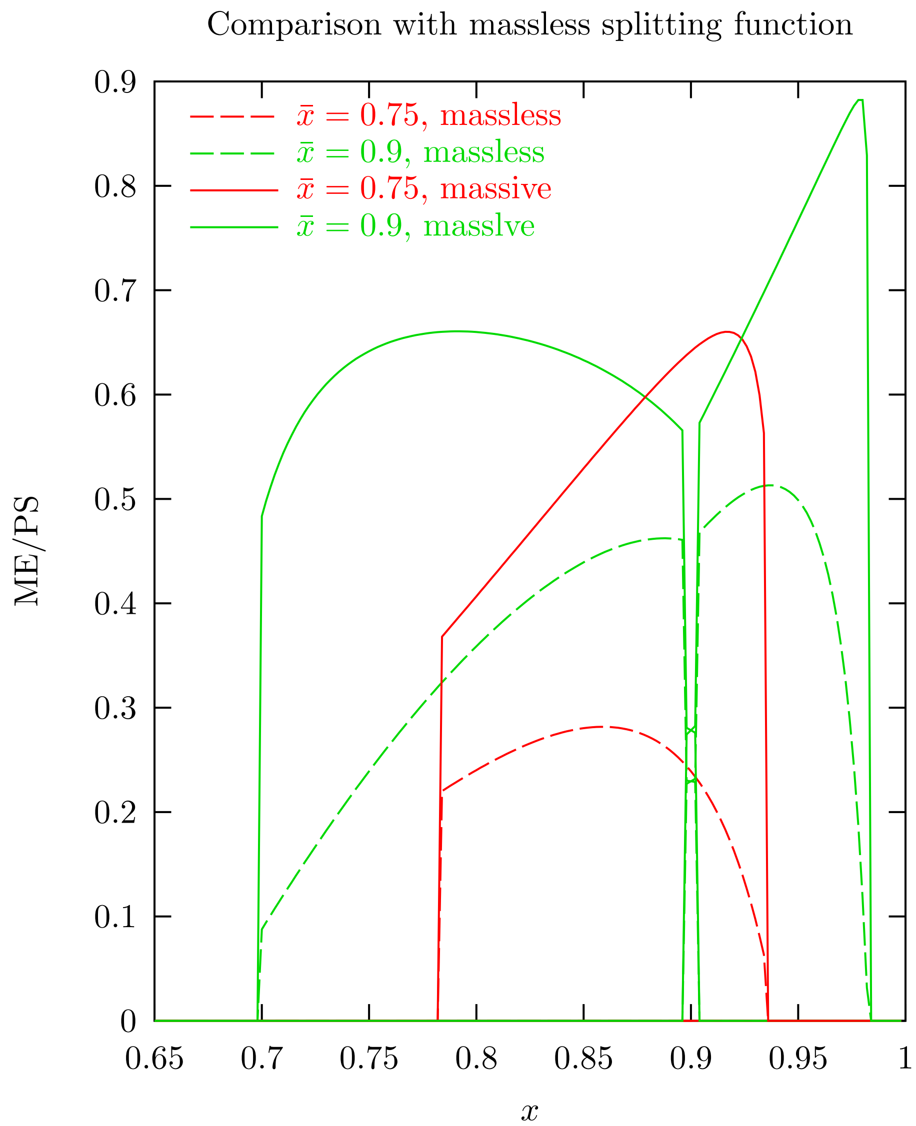


Soft Matrix Element Corrections

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





Cluster hadronization in a nutshell

- Nonperturbative $g \to q\bar{q}$ splitting ($q = uds$) isotropically. Here, $m_g \approx 750$ 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

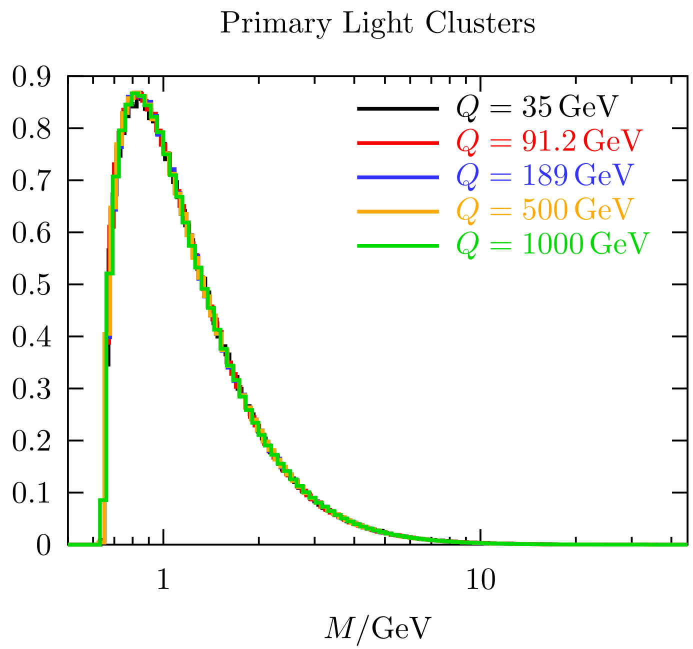
$$M_i = \left[\left(M^P - (m_i + m_3)^P \right) r_i + (m_i + m_3)^P \right]^{1/P},$$

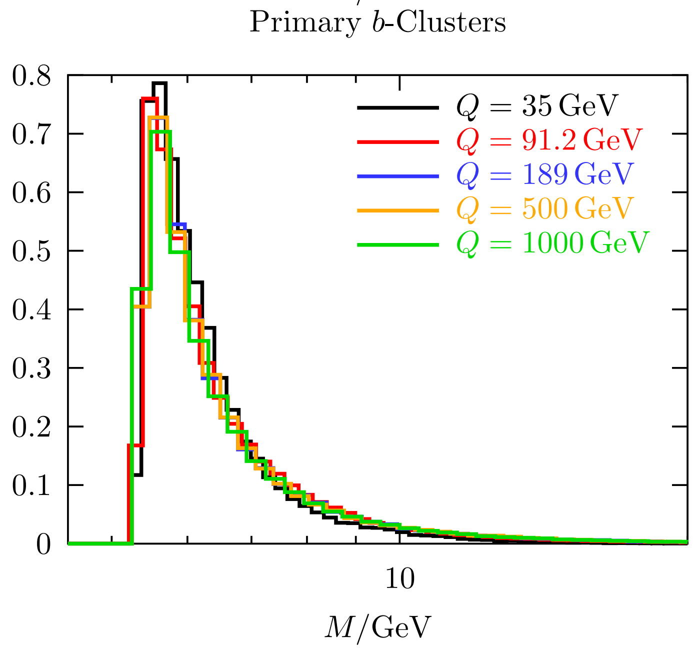
with additional phase space contraints. Constituents keep moving in their original direction.

- Cluster Decay

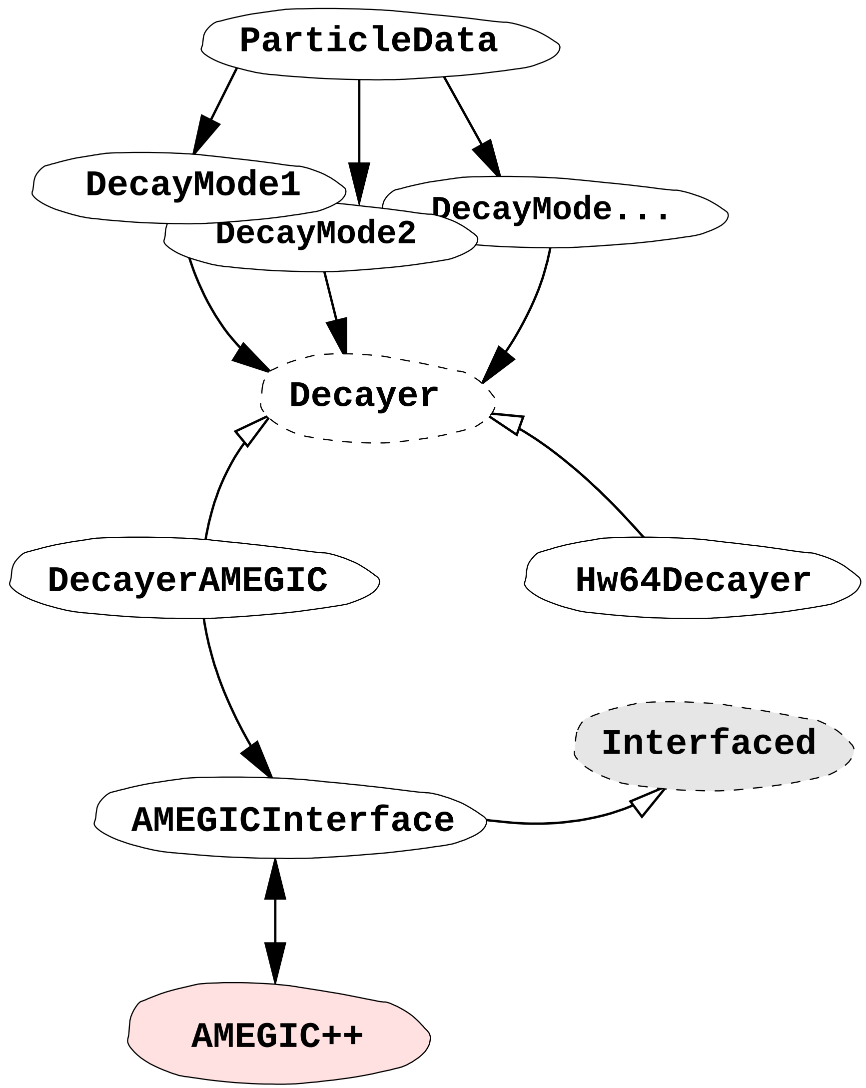
$$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$

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





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.

- $e^+e^- \to$ jets, mainly at Z^0.
- hard and soft ME corrections.
- Cutoff parameter δ 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).
- χ_i^2 / χ^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*
γ	A,O	21.27 $\pm$ 0.6	23.032	22.67	20.74
π^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
η	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
Δ^{++}	D,O	0.088 $\pm$ 0.034	0.185	0.092	0.209*
Σ^-	O	0.083 $\pm$ 0.011	0.063	0.071	0.071
Λ	A,D,L,O	0.373 $\pm$ 0.008	0.325*	0.384	0.347*
Σ^0	A,D,O	0.074 $\pm$ 0.009	0.078	0.091	0.063
Σ^+	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*
Ξ^-	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*
Ω^-	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 ± 0.021	0.113	0.150	0.173
$f_2'(1525)$	D	0.02 ± 0.008	0.003	0.012	0.012
$D^{\pm}$	A,D,O	0.184 ± 0.018	0.322^{*}	0.319^{*}	0.283^{*}
$D^{*}(2010)^{\pm}$	A,D,O	0.182 ± 0.009	0.168	0.180	0.151^{*}
D^{0}	A,D,O	0.473 ± 0.026	0.625^{*}	0.570^{*}	0.501
$D_s^{\pm}$	A,O	0.129 ± 0.013	0.218^{*}	0.195^{*}	0.127
$D_s^{*\pm}$	O	0.096 ± 0.046	0.082	0.066	0.043
J/Ψ	A,D,L,O	0.00544 ± 0.00029	0.006	0.00361^{*}	0.002^{*}
Λ_c^{+}	D,O	0.077 ± 0.016	0.006^{*}	0.023^{*}	0.001^{*}
$\Psi'(3685)$	D,L,O	0.00229 ± 0.00041	0.001^{*}	0.00178	0.0008^{*}

of $*$'s = observables with more than 3σ deviation:

$$\mathrm{OldModel} : \text{Herwig++} : \mathrm{Fortran} = 9 : 7 : 13$$

$k_\perp$ Algorithm ("Durham"–Algorithm)

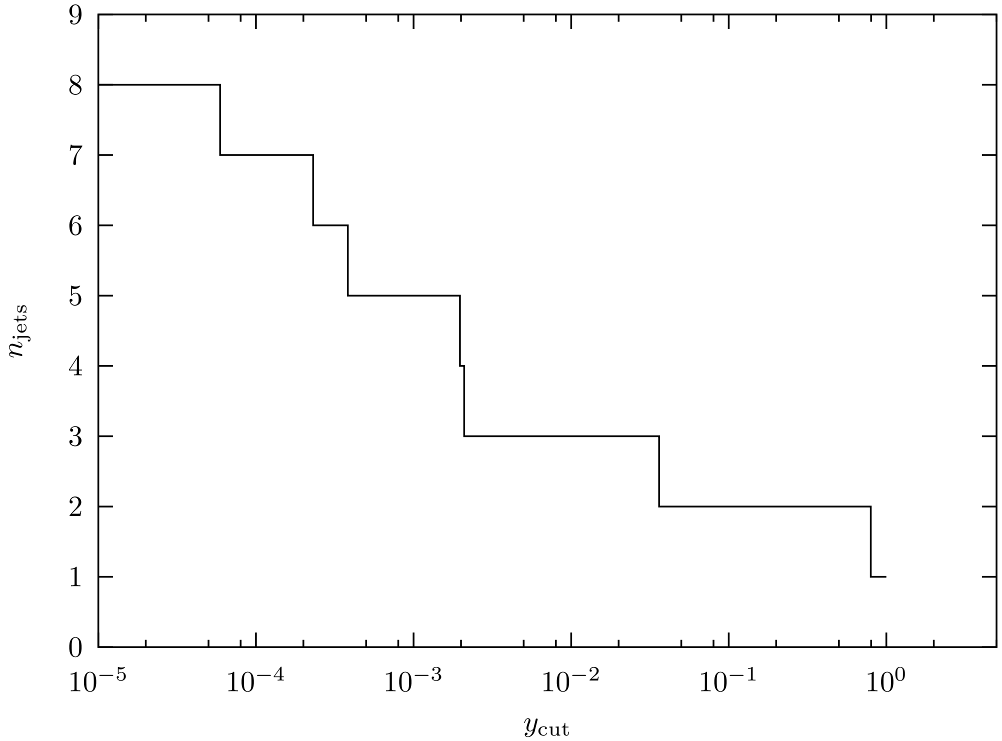
- For each pair i, j of particles in an event calculate the 'distance'

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

[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 $y_{ij} > y_{\rm cut}$.

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

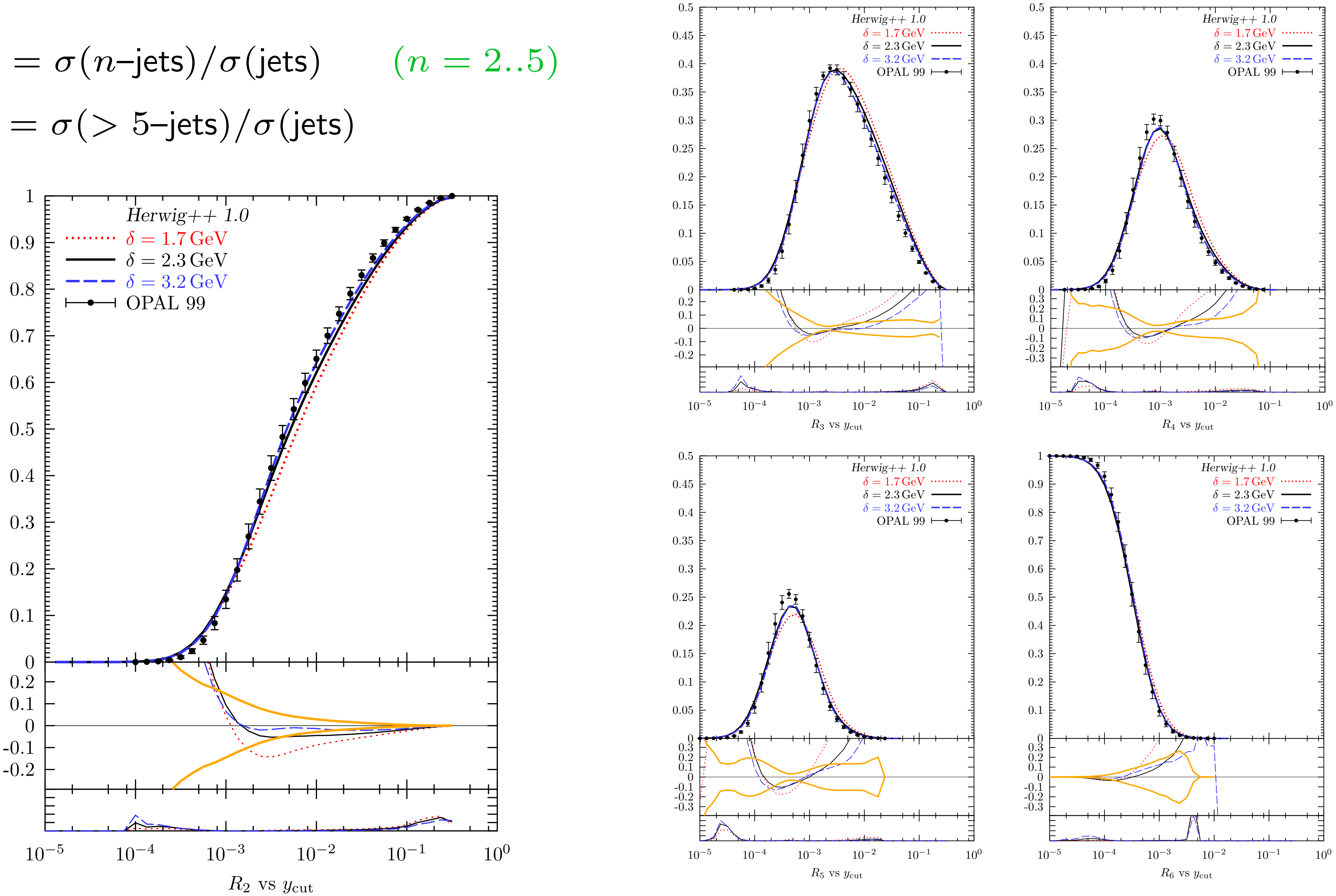


There are other jet algorithms with a different distance measure (JADE) or recombination scheme. We have interfaced the `KtJet` package for jet clustering.

Jet Rates

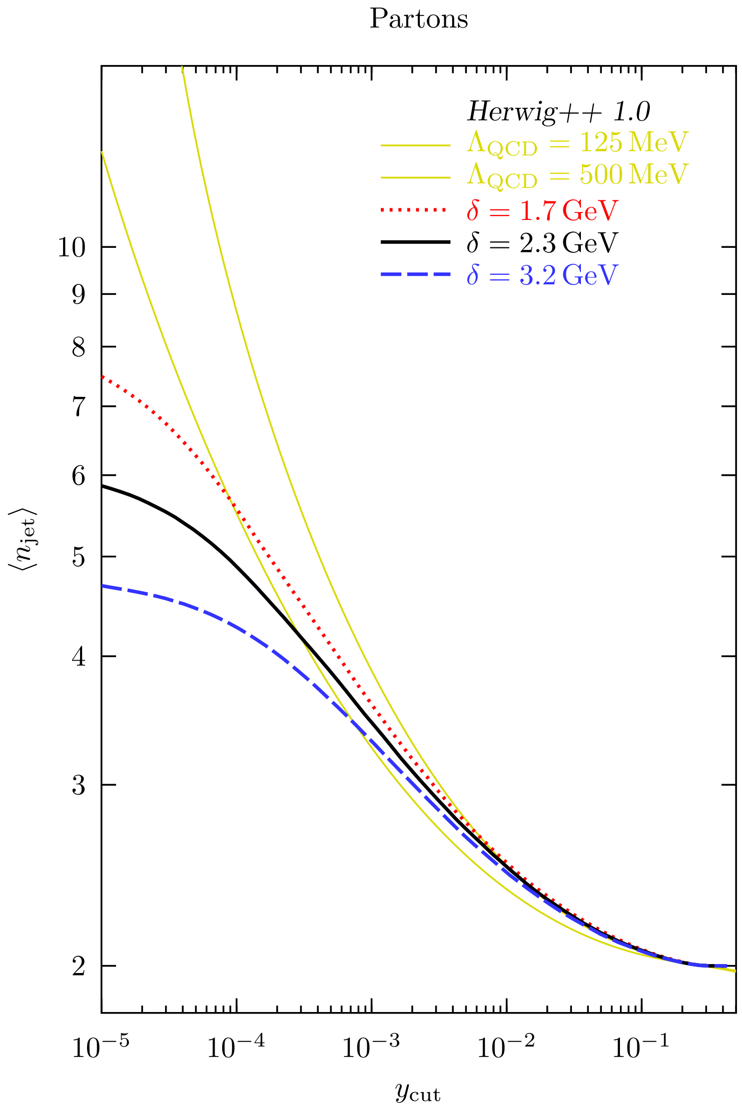
$$R_n = \sigma(n\text{–jets})/\sigma(\text{jets}) \qquad (n = 2..5)$$

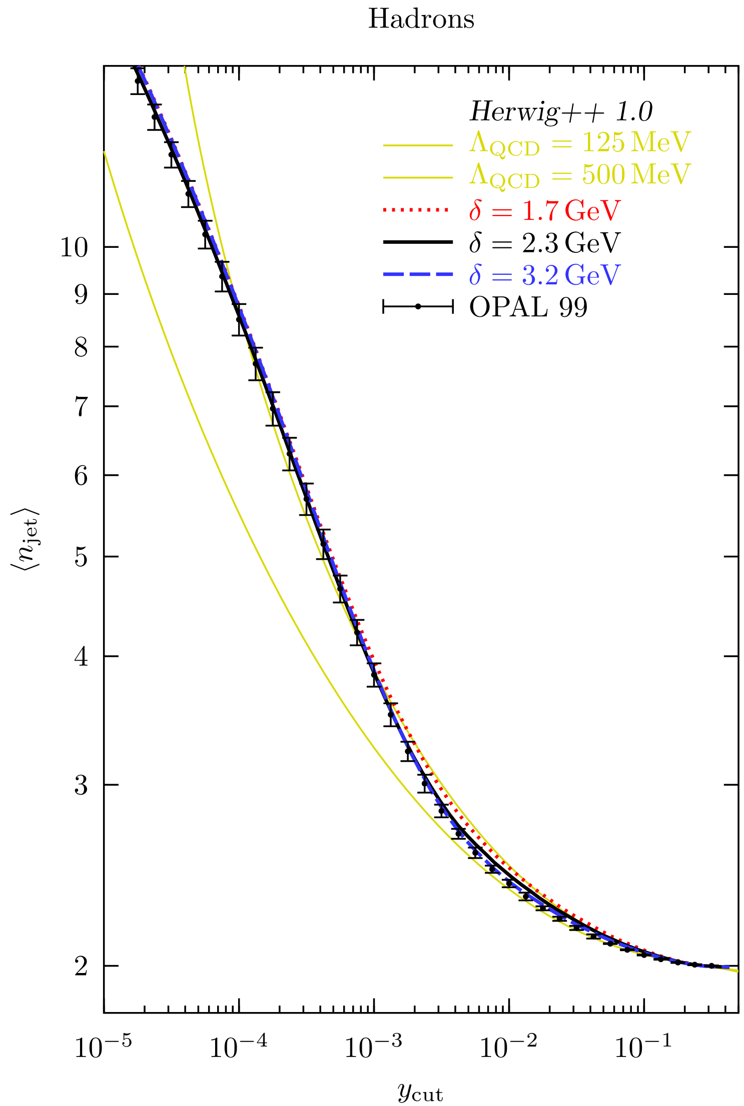
$$R_6 = \sigma(> 5\text{–jets})/\sigma(\text{jets})$$



Jet Multiplicity

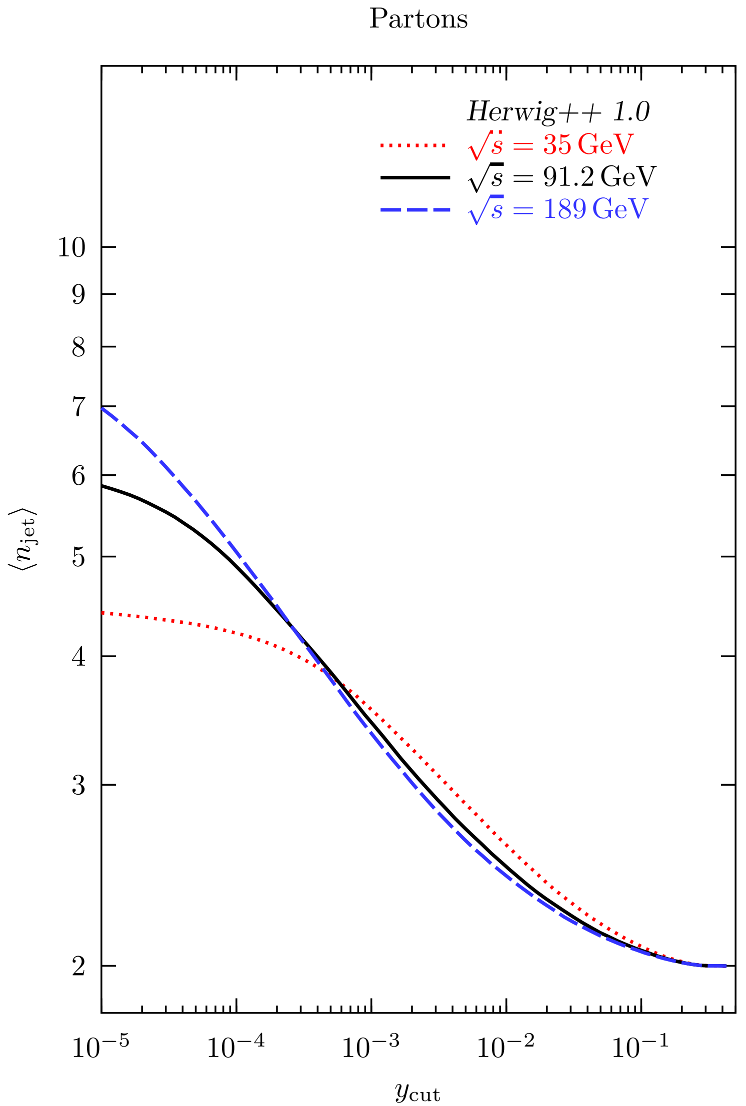
Durham algorithm. Smooth interplay between shower and hadronization.

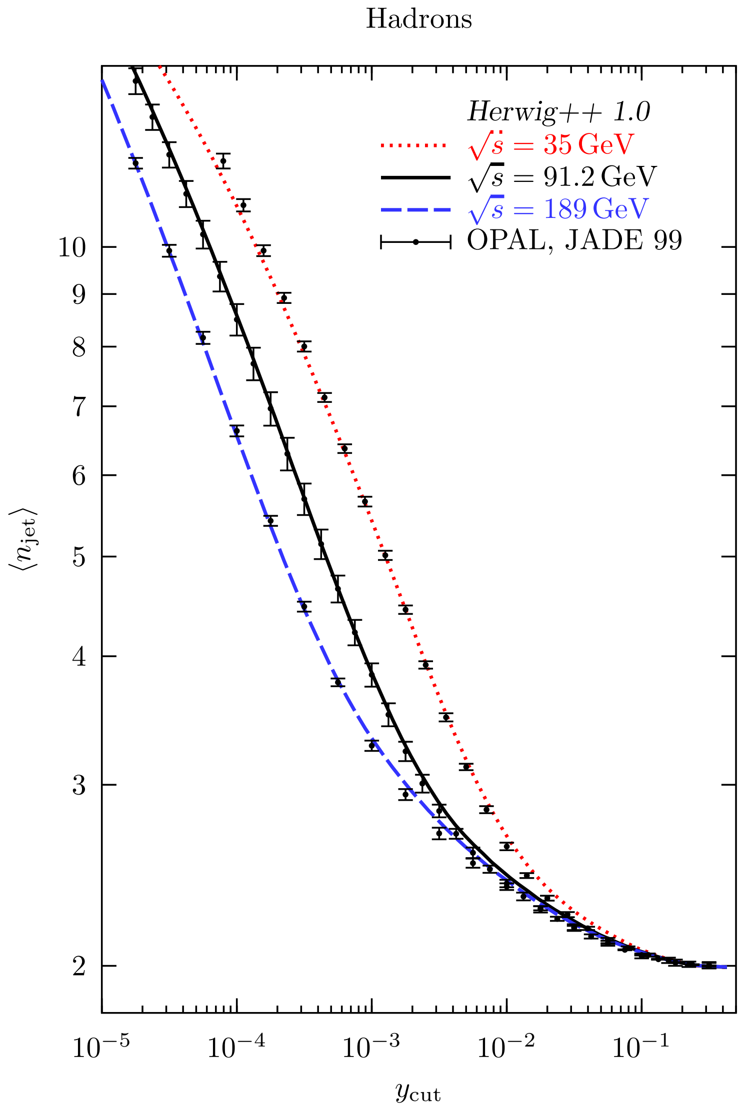




Jet Multiplicity (PETRA, LEP, LEPII)

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





Event Shape Variables, Definition

Thrust

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

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

$$T = \max_{\boldsymbol{n}} F(\boldsymbol{n}) = F(\boldsymbol{n}_T) ,$$

thrust major

$$M = \max_{\boldsymbol{n}\perp\boldsymbol{n}_T} F(\boldsymbol{n}) = F(\boldsymbol{n}_M) ,$$

thrust minor

$$\boldsymbol{n}_m = \boldsymbol{n}_T \times \boldsymbol{n}_M$$

$$m = F(\boldsymbol{n}_m)$$

Sphericity

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

Diagonalize, eigenvalues

$$\lambda_1 > \lambda_2 > \lambda_3$$

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

Then

$$S = \tfrac{3}{2}(\lambda_2 + \lambda_3)$$

$$P = \lambda_2 - \lambda_3$$

$$A = \tfrac{3}{2}\lambda_3$$

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

C, D parameter

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

Diagonalize, eigenvalues

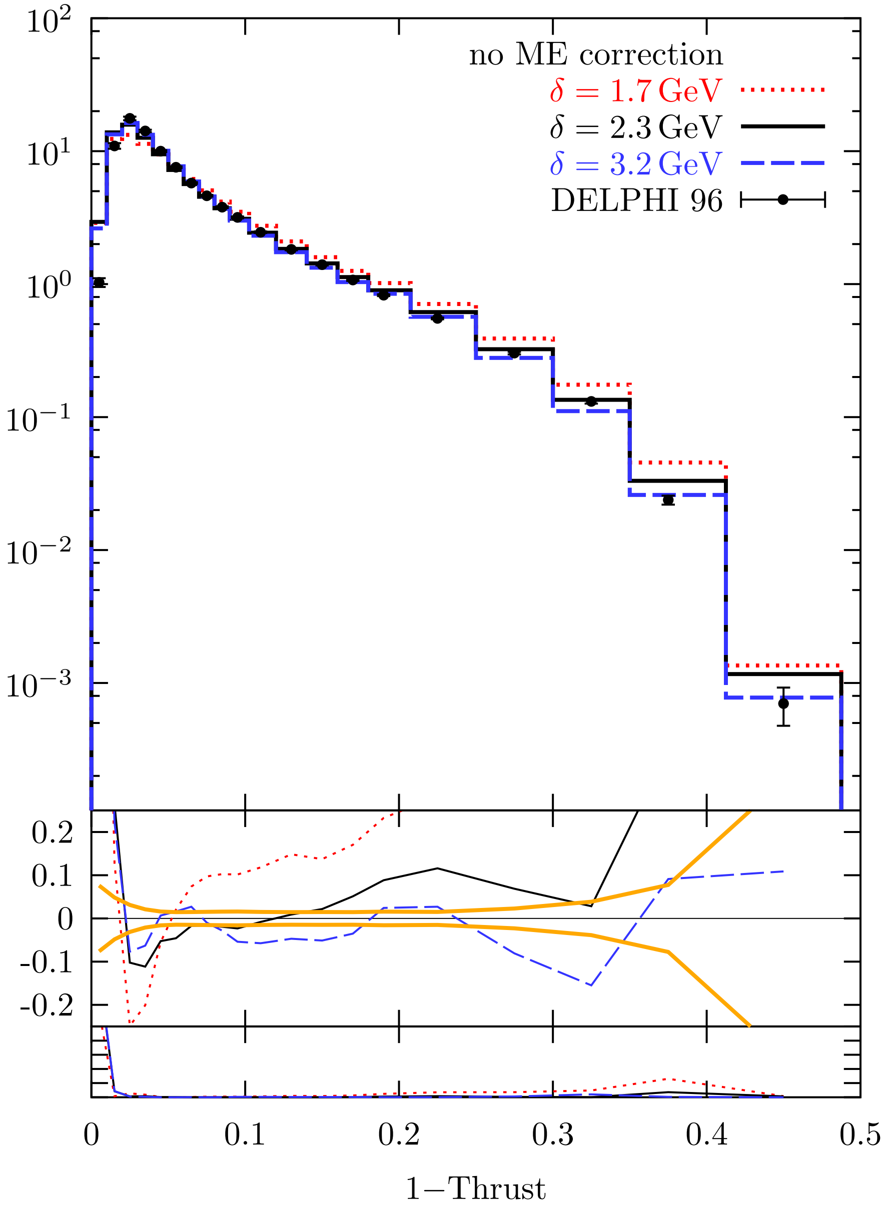
$$\lambda_1 + \lambda_2 + \lambda_3 = 1$$

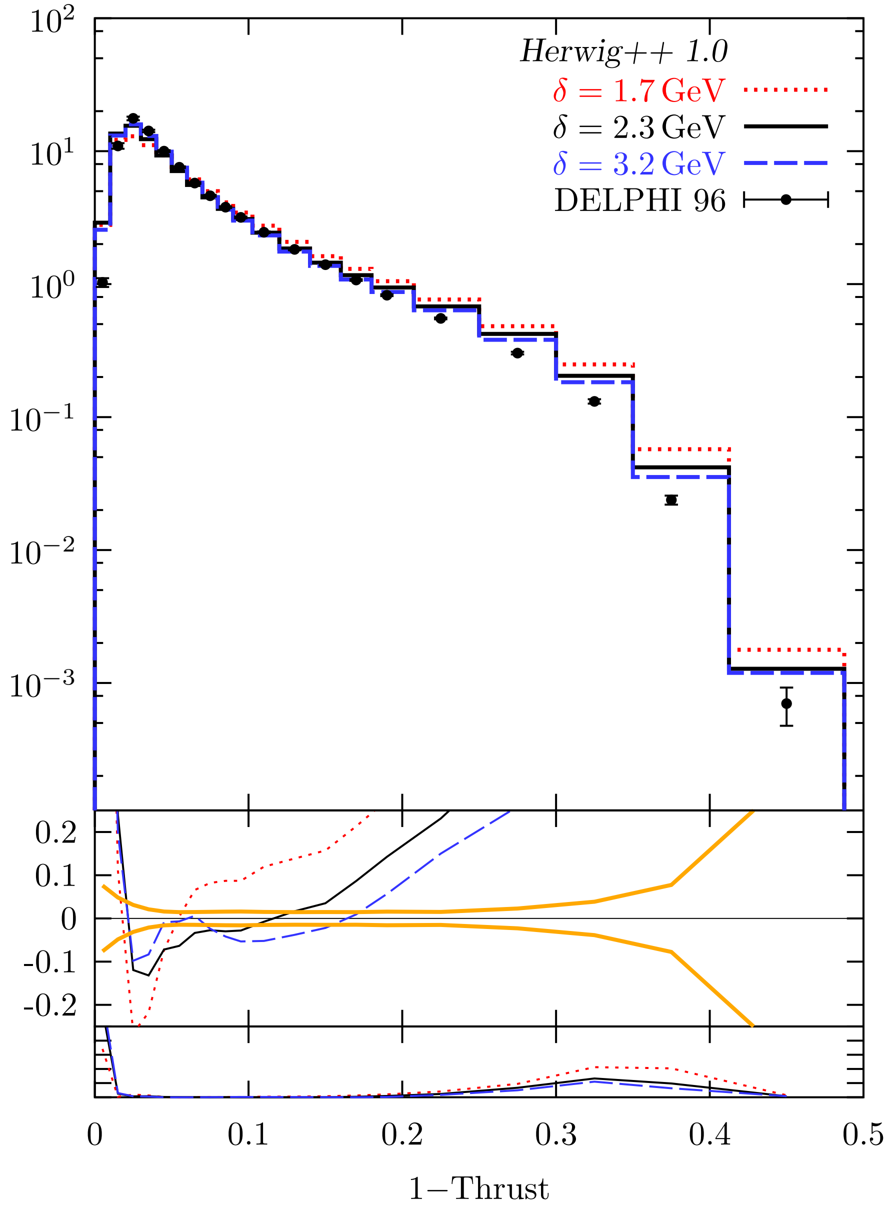
and define

$$C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$$

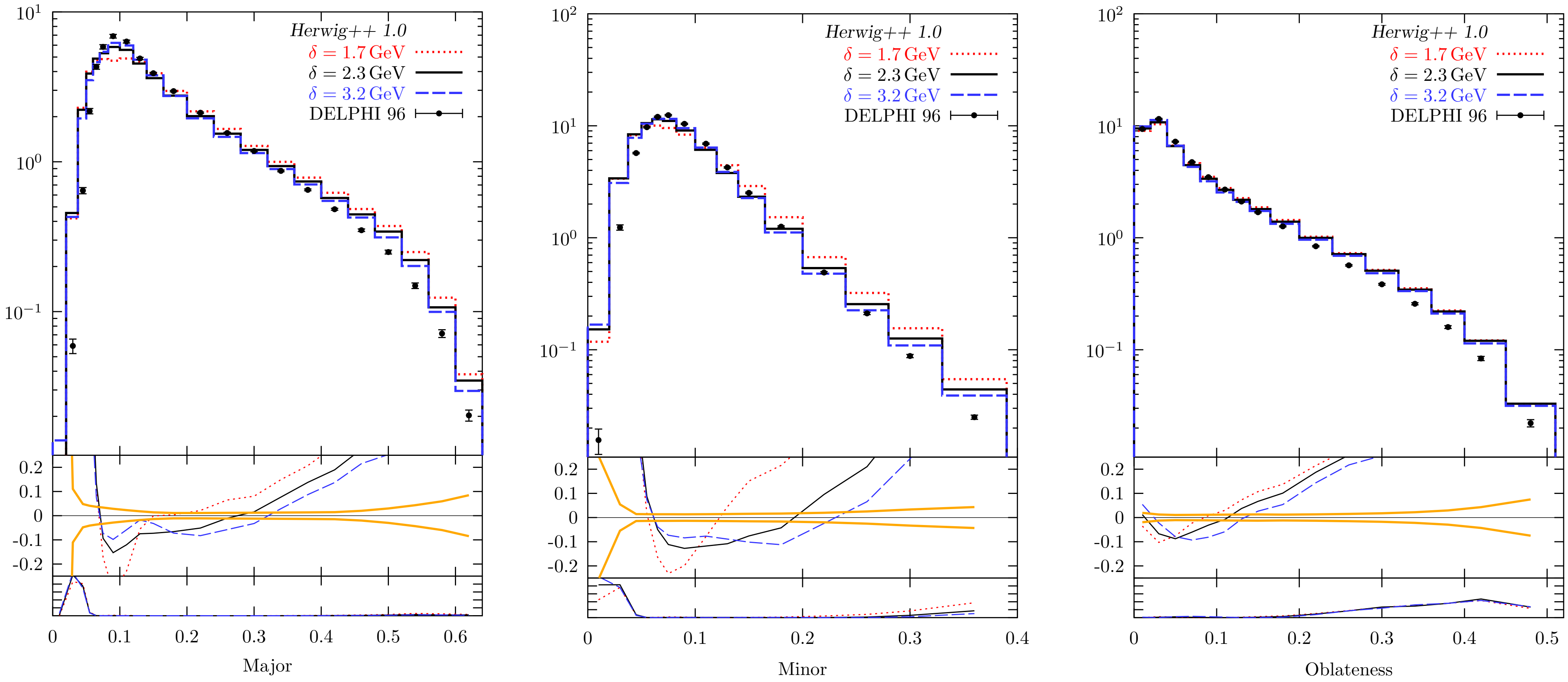
$$D = 27\lambda_1\lambda_2\lambda_3$$

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

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

Körner–Schierholz–Willrodt angle

$$\Phi_{KSW} = \tfrac{1}{2}\left[\angle(\boldsymbol{p}_1 \times \boldsymbol{p}_3, \boldsymbol{p}_2 \times \boldsymbol{p}_4) + \angle(\boldsymbol{p}_1 \times \boldsymbol{p}_4, \boldsymbol{p}_2 \times \boldsymbol{p}_3)\right]$$

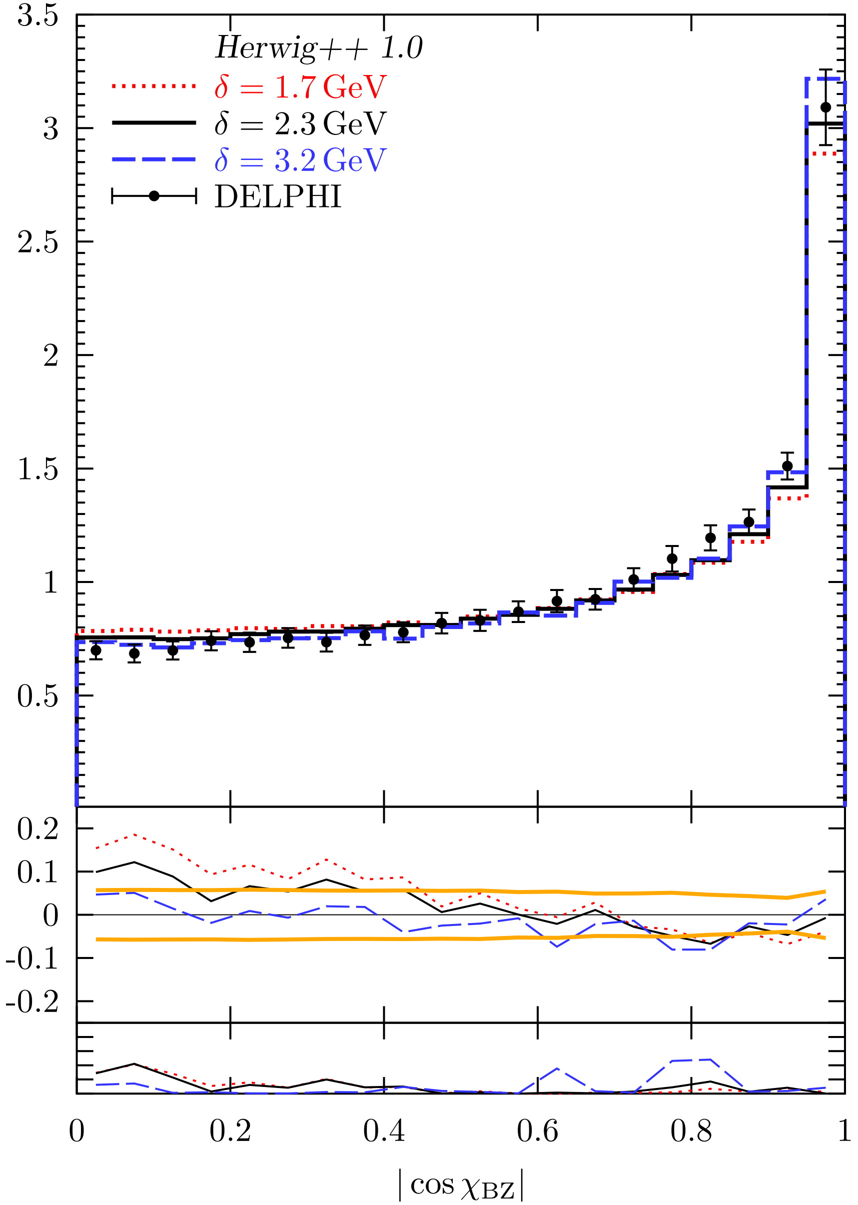
(modified) Nachtmann–Reiter angle

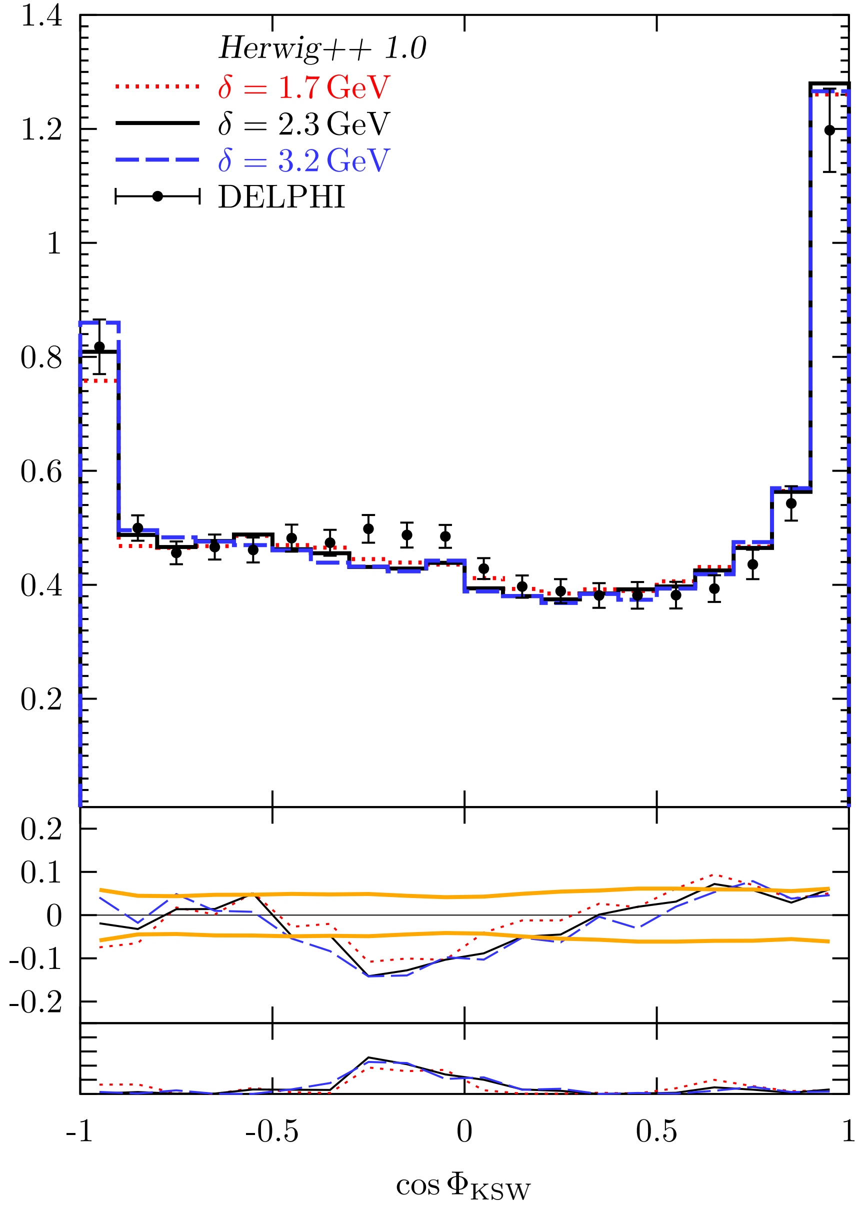
$$\theta^*_{NR} = \angle(\boldsymbol{p}_1 - \boldsymbol{p}_2, \boldsymbol{p}_3 - \boldsymbol{p}_4)$$

α_{34}:

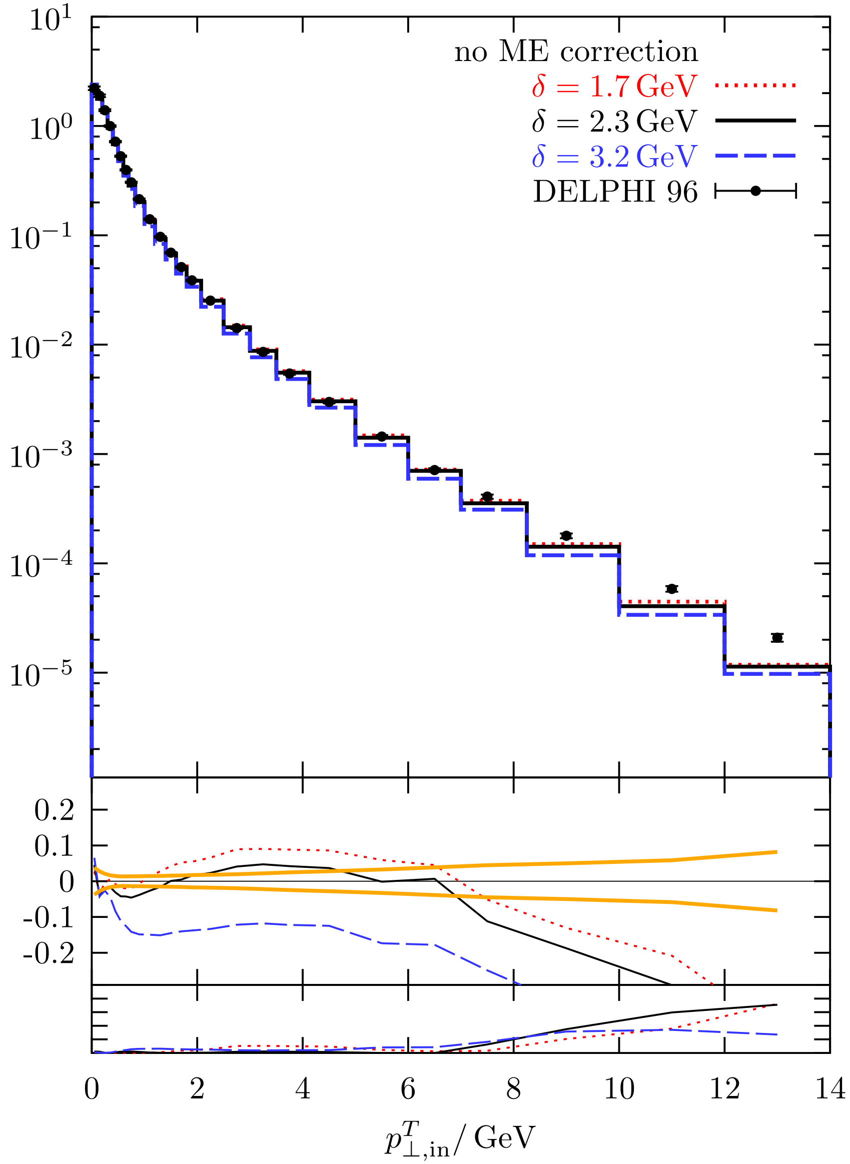
$$\alpha_{34} = \angle(\boldsymbol{p}_3, \boldsymbol{p}_4)$$

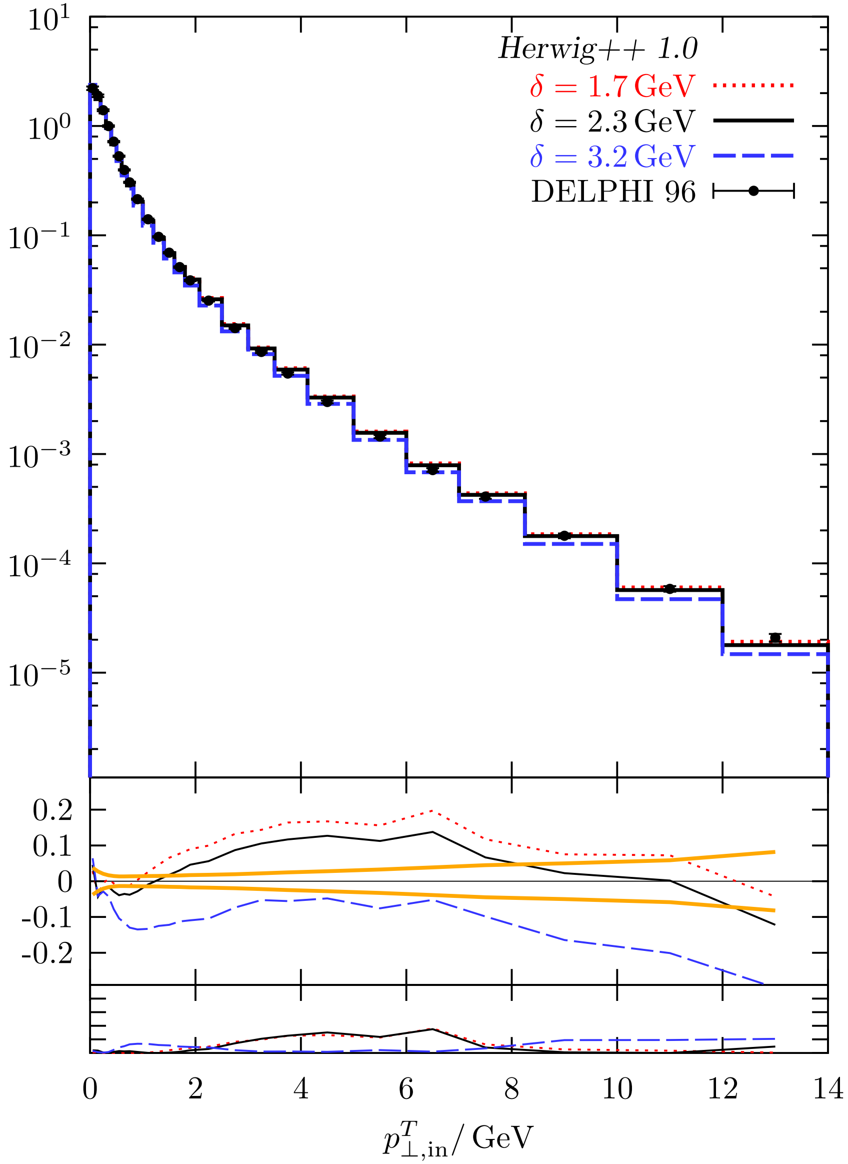
Four Jet Angles



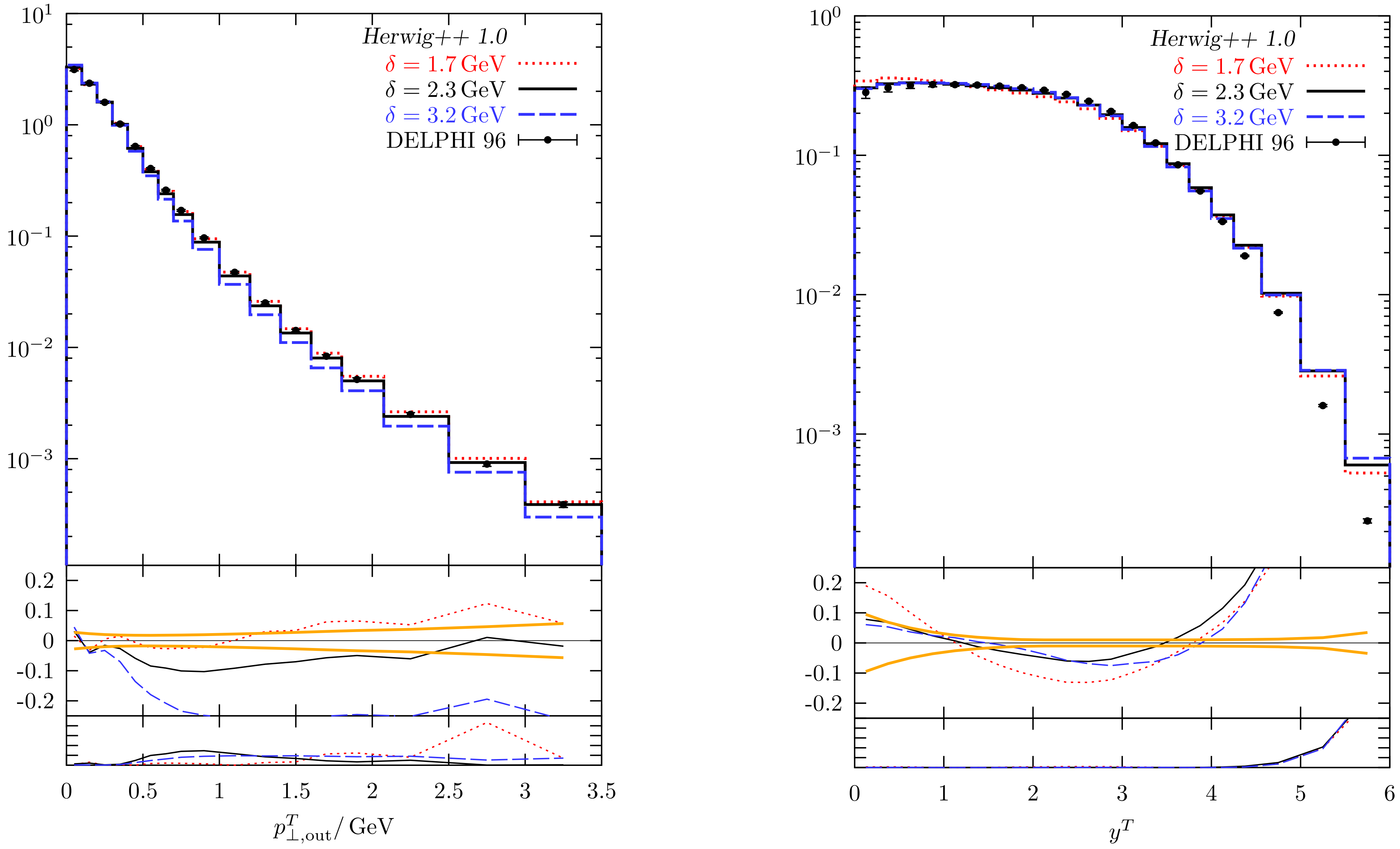


$p^T_{\perp,\mathrm{in}}$ — ME corrections off/on

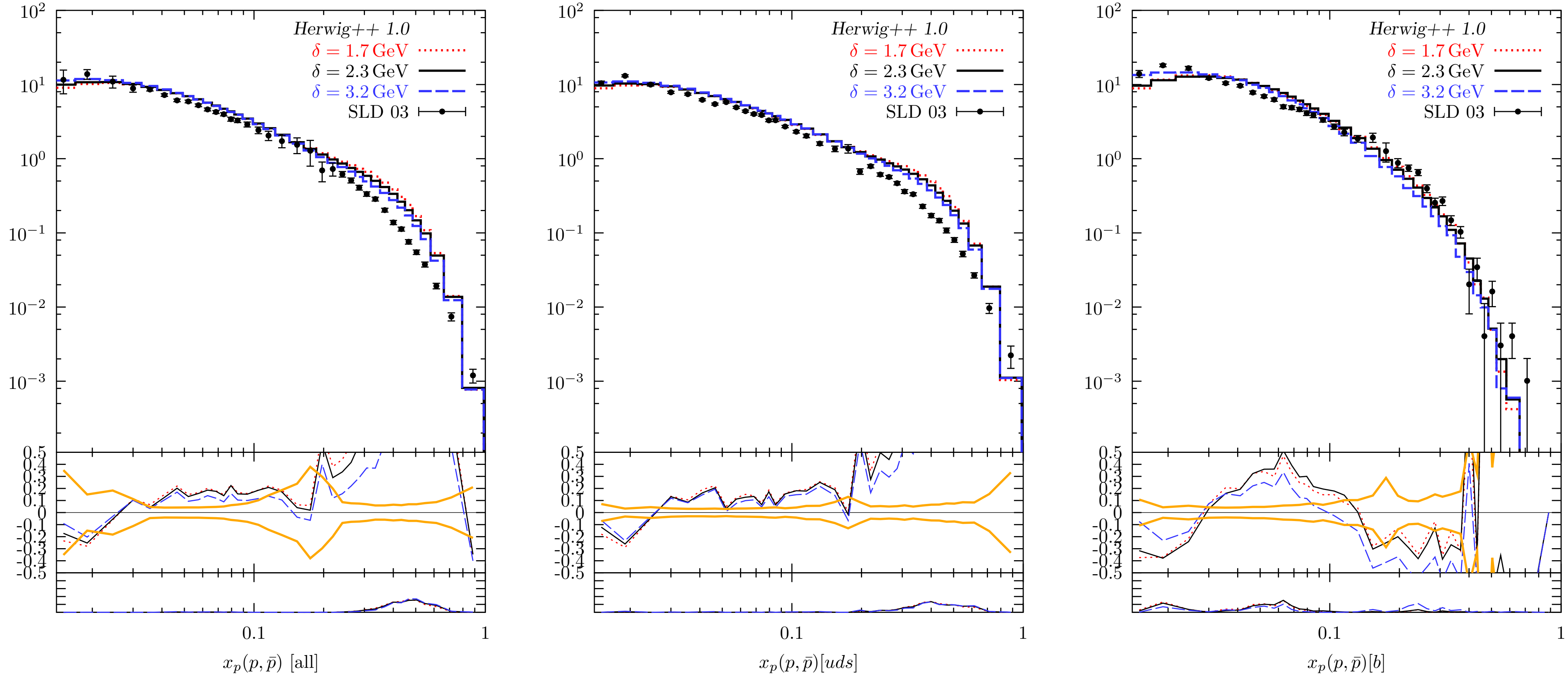




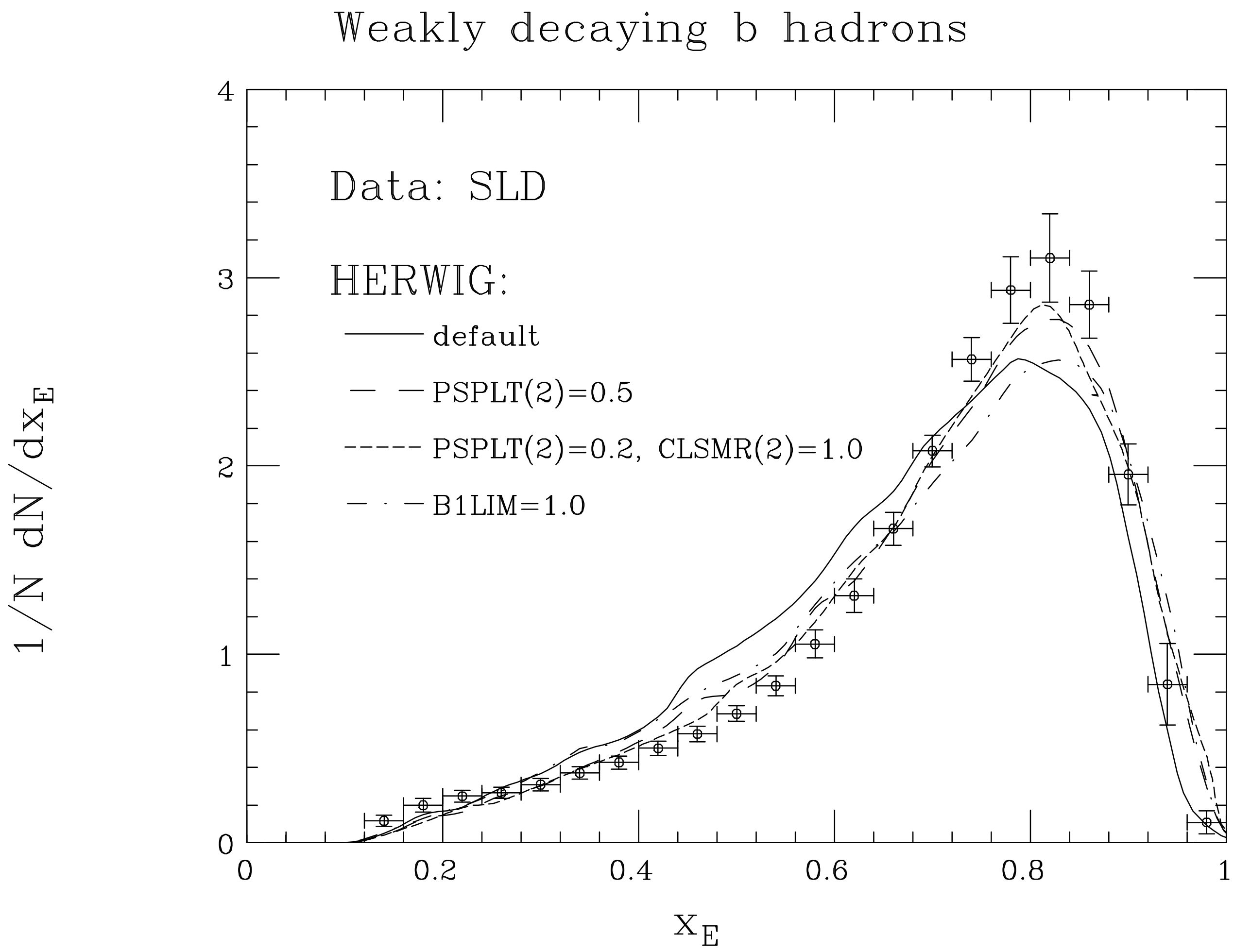
$p^T_{\perp,\mathrm{out}}$, y^T



Proton Momentum (all, *uds*, *b*)

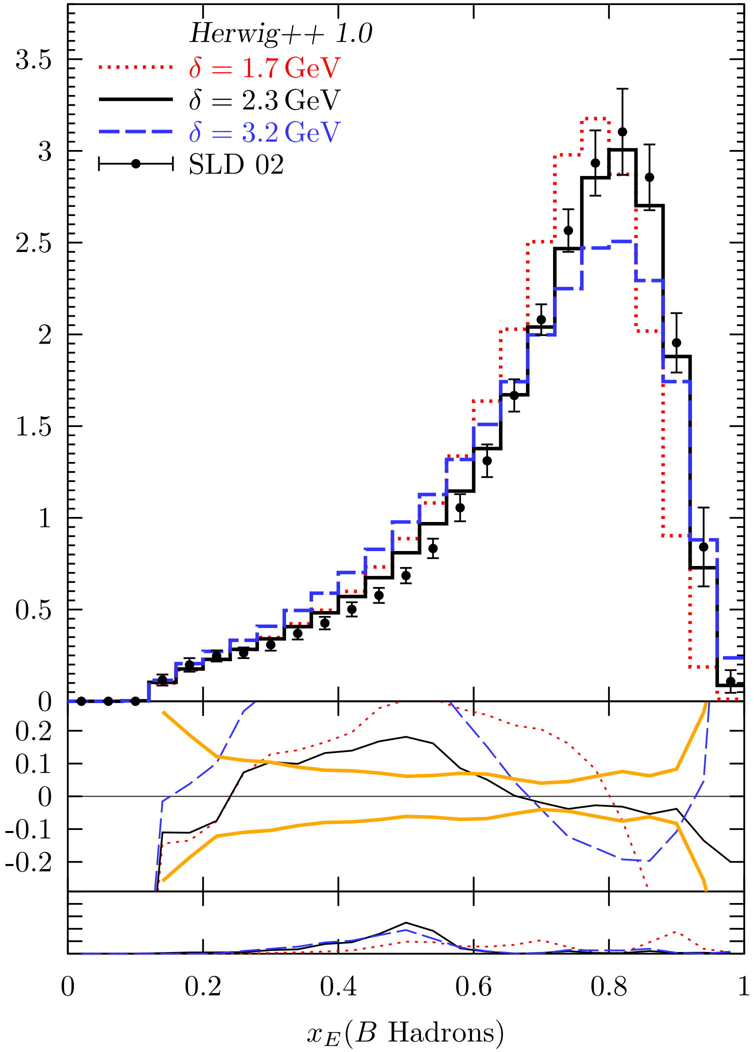


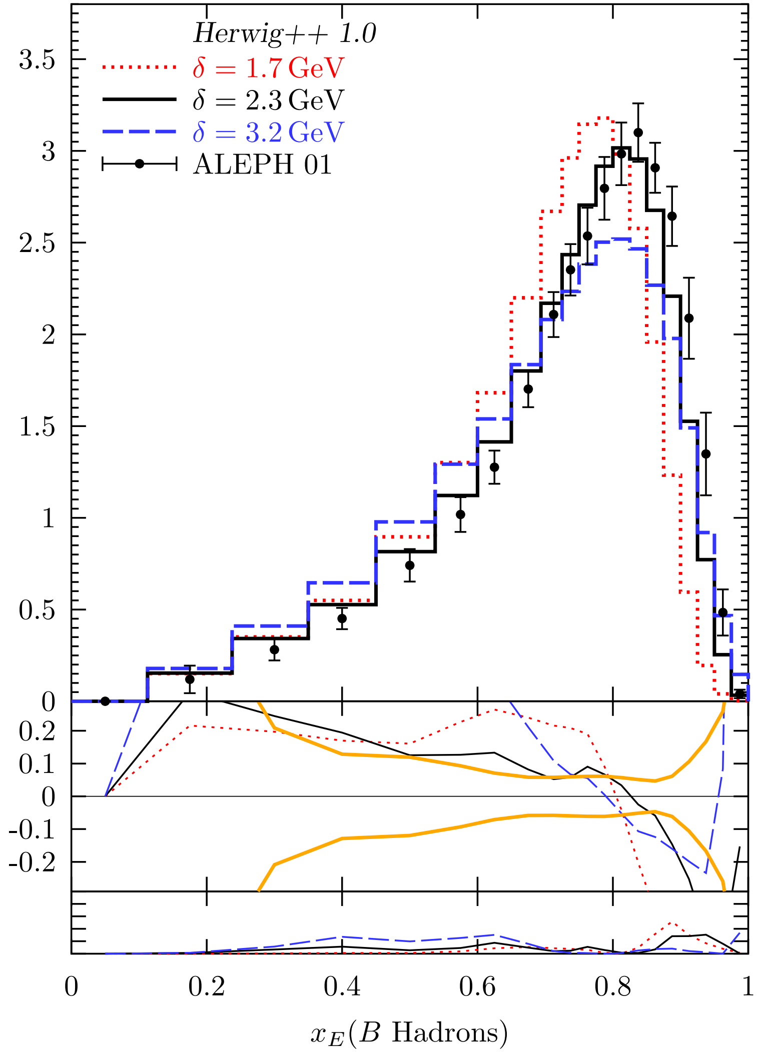
B-fragmentation function



HERWIG 6.4, very sensitive on hadronization!

B-fragmentation function





Only parton shower parameters varied!

Recommendation

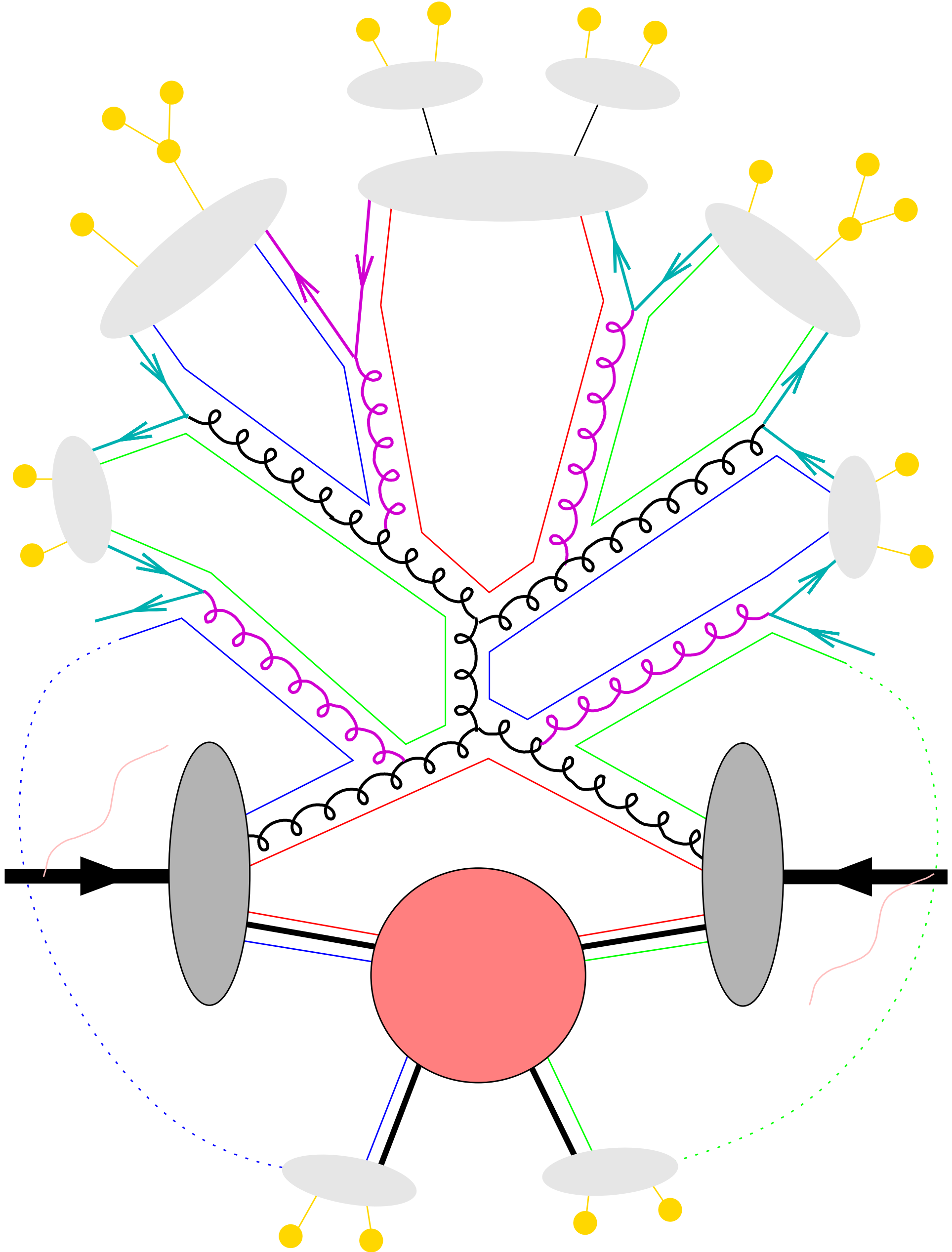
... However, the different observables have to be weighted sensibly.

- 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
δ/GeV	2.3	—
m_g/GeV	0.750	—
Q_{min}/GeV in $\alpha_s(Q_{\mathrm{min}})$	0.631	—
ClMax/GeV	3.2	3.35
ClPow	2.0	—
PSplt1	1	—
PSplt2	0.33	—
B1Lim	0.0	—
ClDir1	1	—
ClDir2	1	—
ClSmr1	0.40	—
ClSmr2	0.0	—
Pwt_d	1.0	—
Pwt_u	1.0	—
Pwt_s	0.85	1.0
Pwt_c	1.0	—
Pwt_b	1.0	—
Pwt_{di}	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!* τ–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++