Herwig++ for e^+e^- collisions

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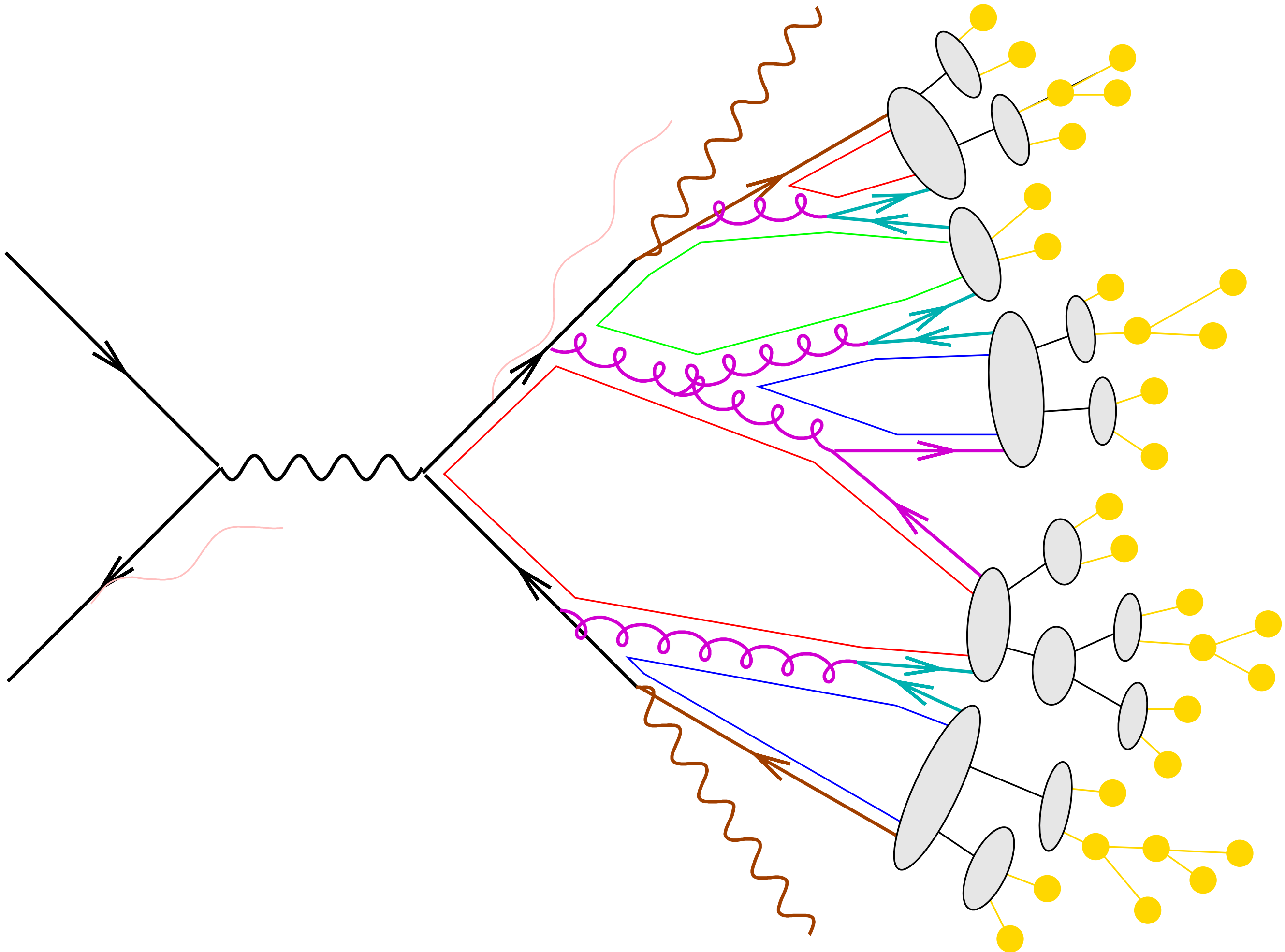
- Introduction/Motivation
- Some features of Herwig++
- Selection of LEP results for e^+e^- Annihilation
- Jet Multiplicity at the Linear Collider
- Outlook

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

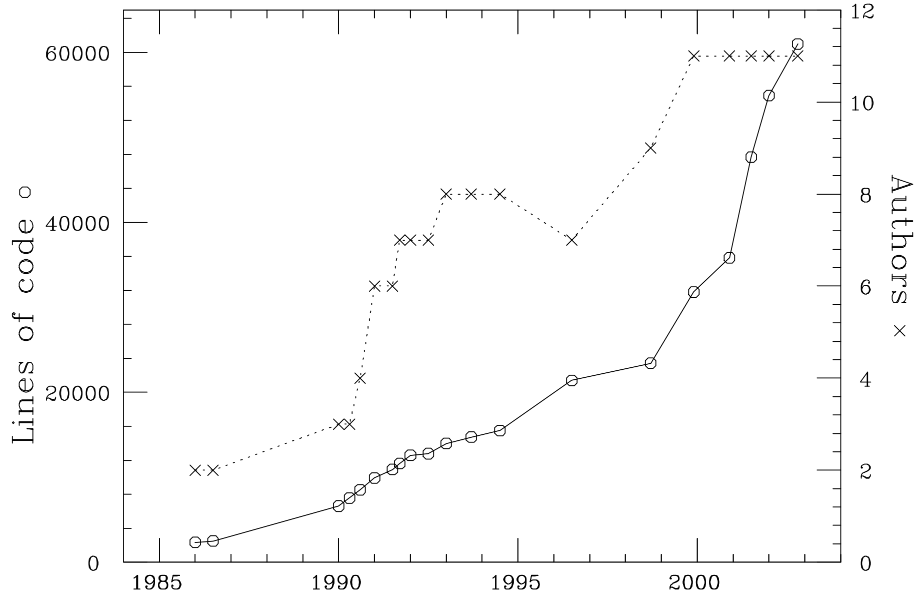


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \longrightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\longrightarrow$ hadrons
- hadronic decays

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. . .

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'),

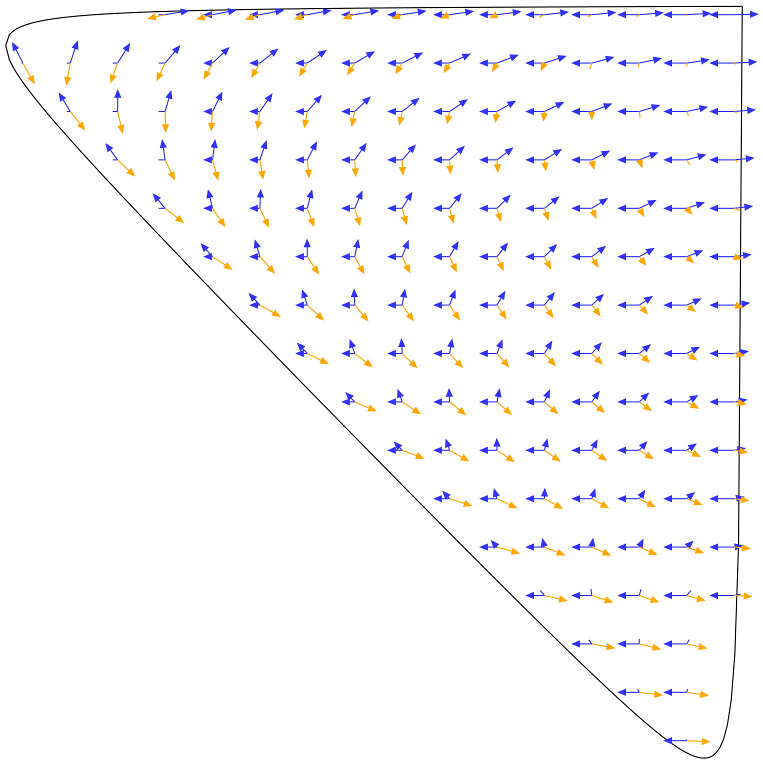
$$\begin{aligned} p_q &= zp + \beta_q n - q_\perp \\ p_g &= (1-z)p + \beta_g n + q_\perp \end{aligned}$$

Collinear limit for radiation off heavy quark,

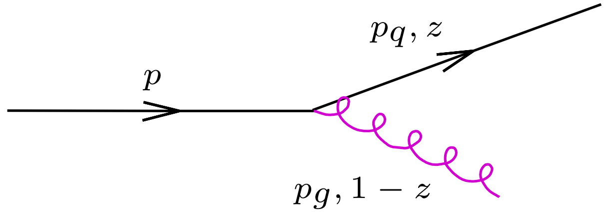
$$\begin{aligned} P_{gq}(z, \boldsymbol{q}^2, m^2) &= C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\boldsymbol{q}^2 + (1-z)^2 m^2} \right] \\ &= \frac{C_F}{1-z} \left[1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right] \end{aligned}$$

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

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

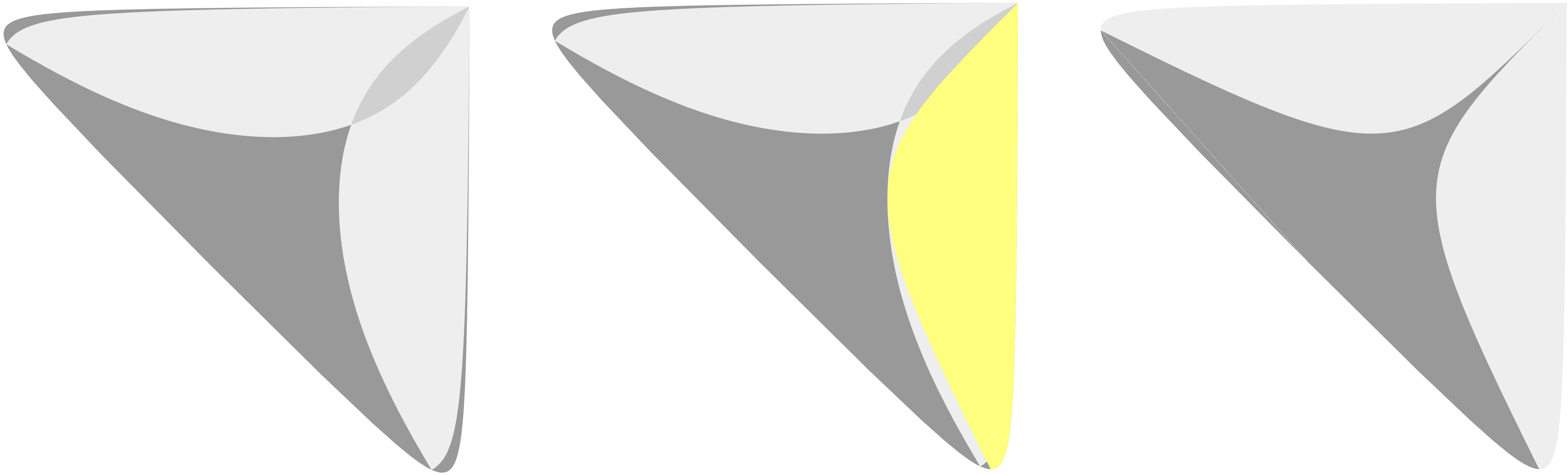


Single emission:



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

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

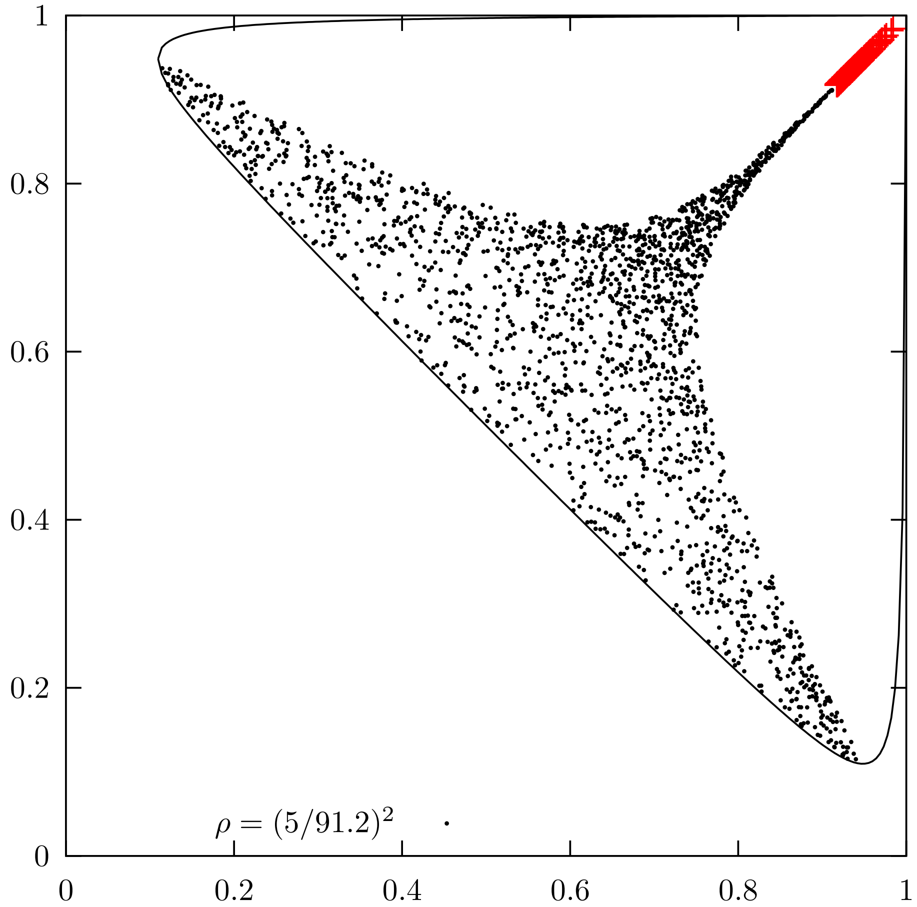


HERWIG   Comparison   Herwig++

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

Hard Matrix Element Corrections

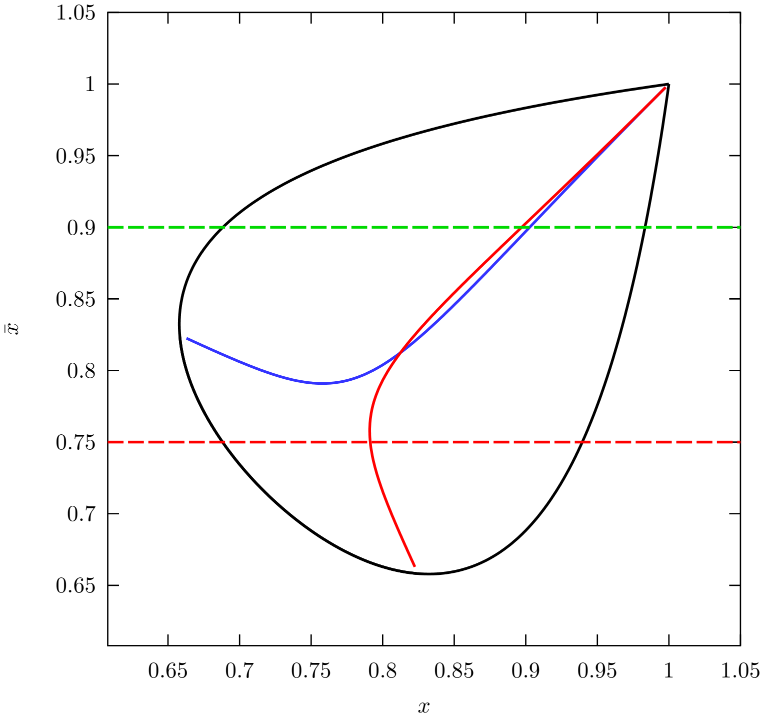
- Points $(x, \bar{x})$ in dead region chosen acc to LO $e^+e^- \to q\bar{q}g$ matrix element and accepted acc to ME weight.
- About 3% of all events are actually hard $q\bar{q}g$ events.
- Red points have weight > 1, practically no error by setting weight to one.
- Event oriented according to given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

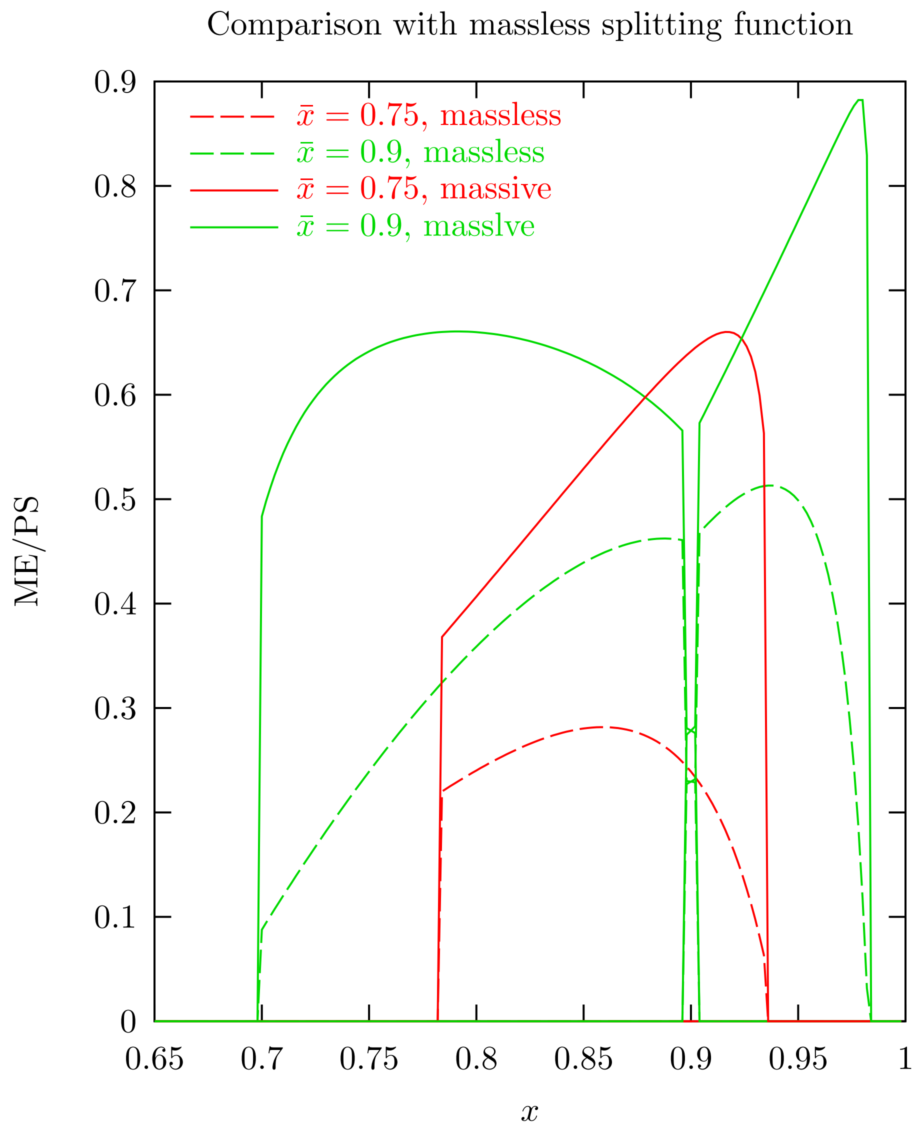


Soft Matrix Element Corrections

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





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 $\pm$ 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/Ψ	A,D,L,O	0.00544 $\pm$ 0.00029	0.006	0.00361^*	0.002^*
Λ_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 3σ deviation:

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

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

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

thrust major

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

thrust minor

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

Sphericity

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

Diagonalize, eigenvalues

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

Then

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

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

C, D parameter

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

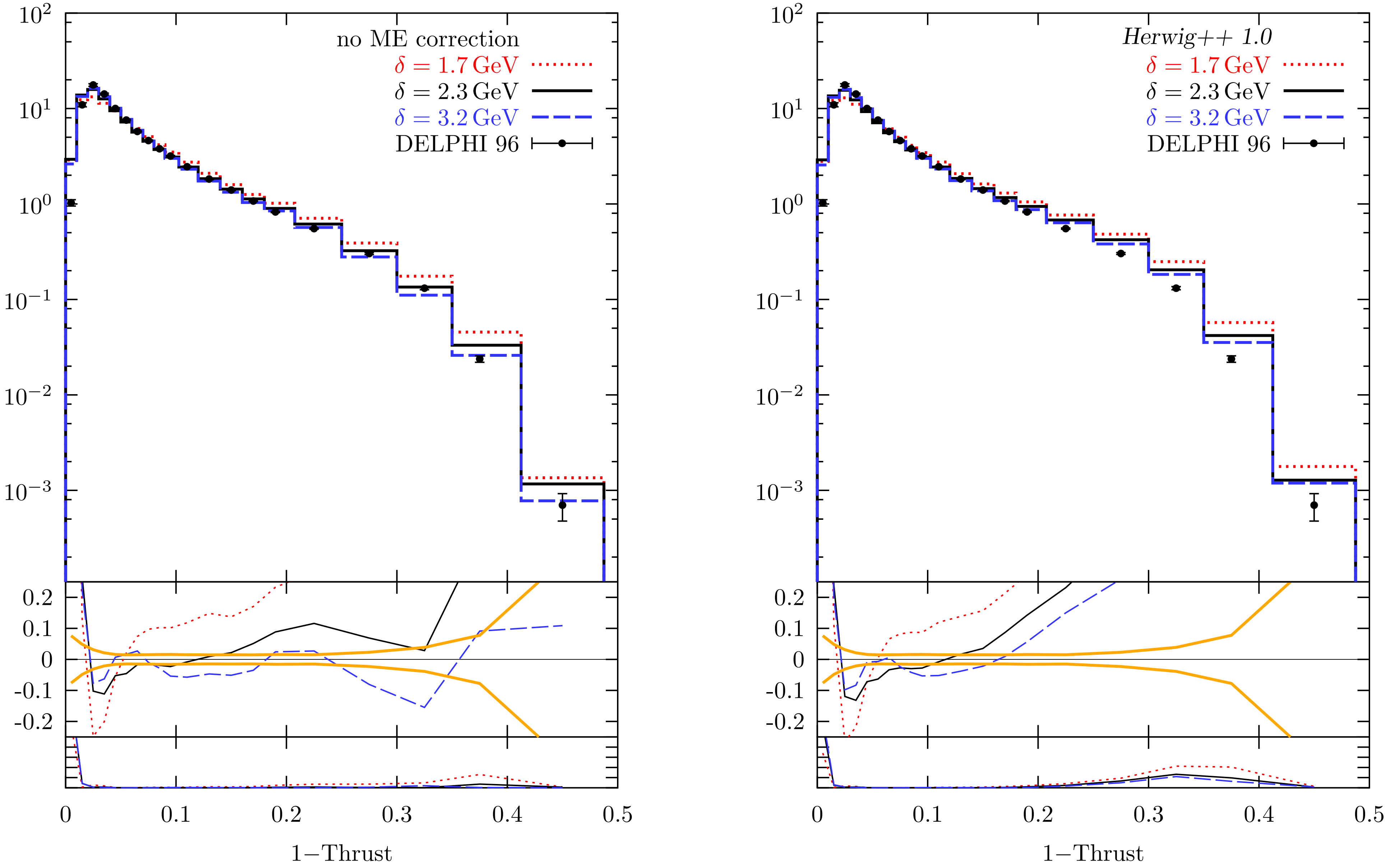
Diagonalize, eigenvalues

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

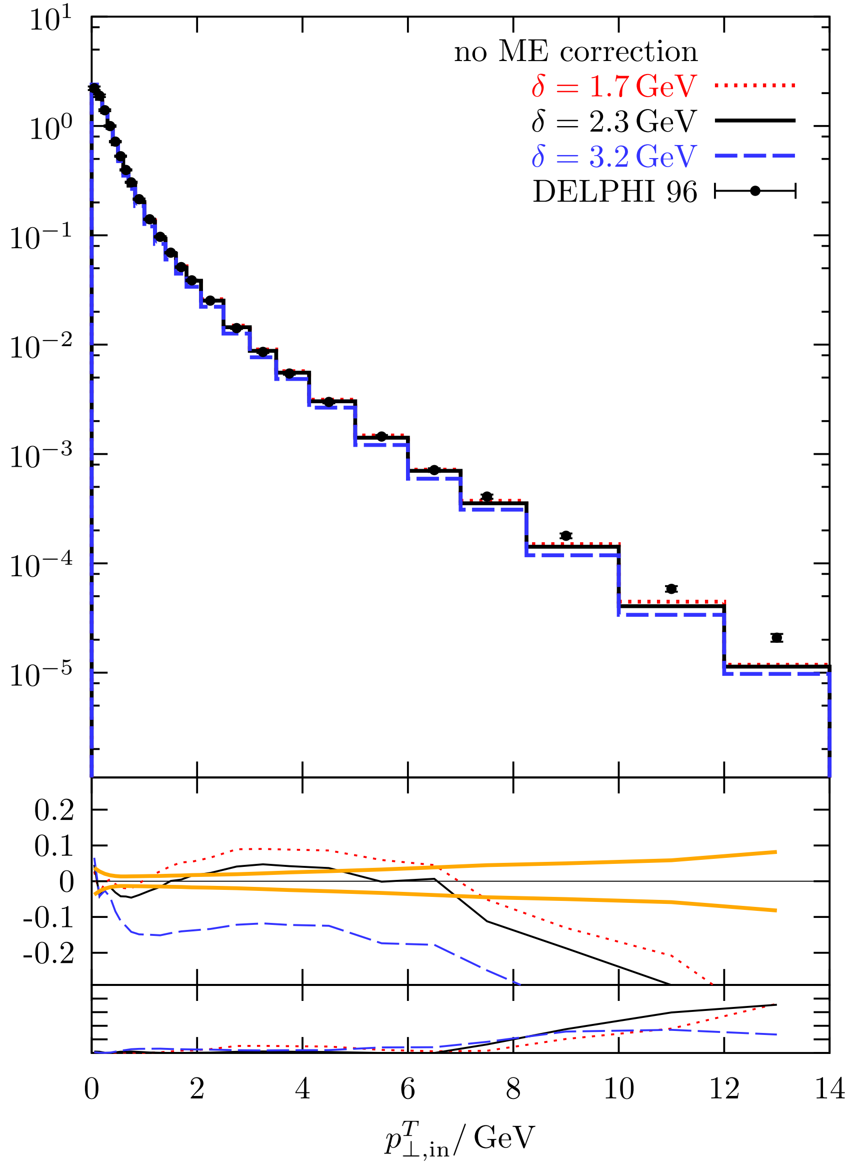
and define

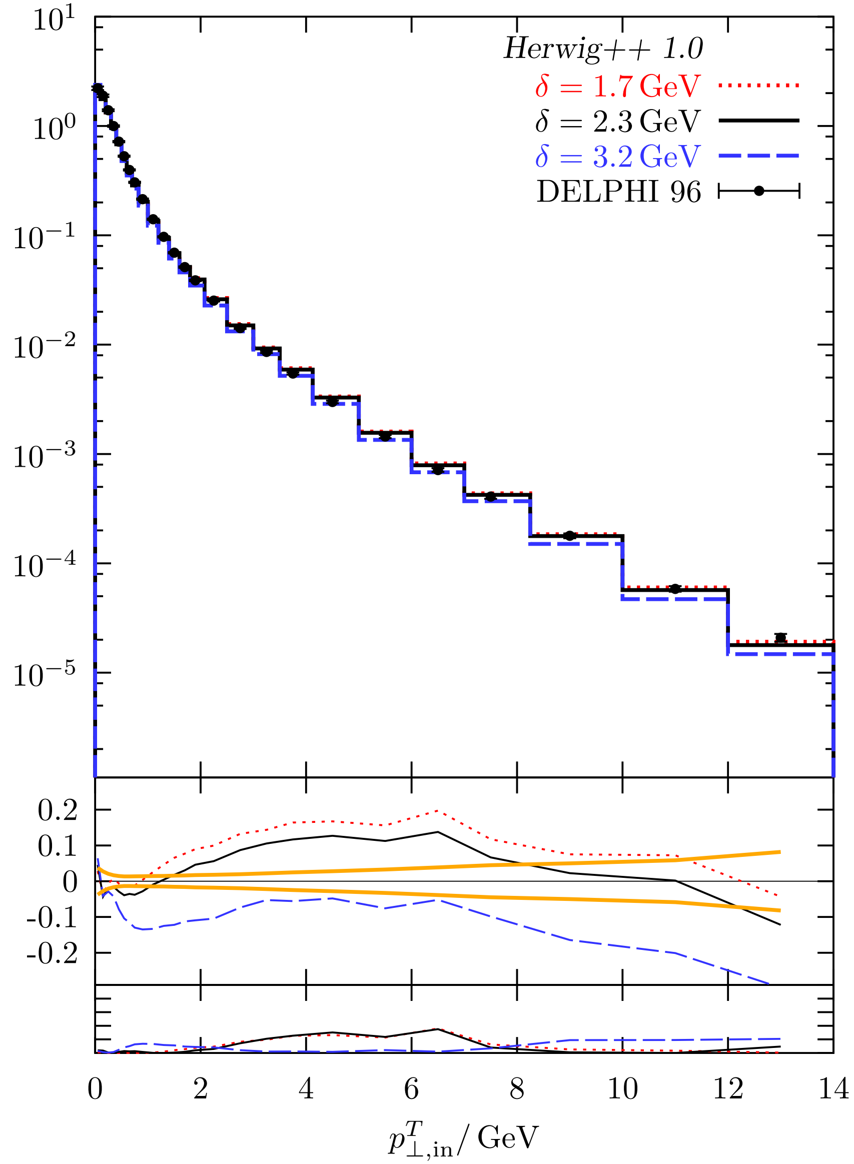
$$\begin{aligned} C &= 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1) \\ D &= 27\lambda_1\lambda_2\lambda_3 \end{aligned}$$

Thrust — ME Corrections off/on

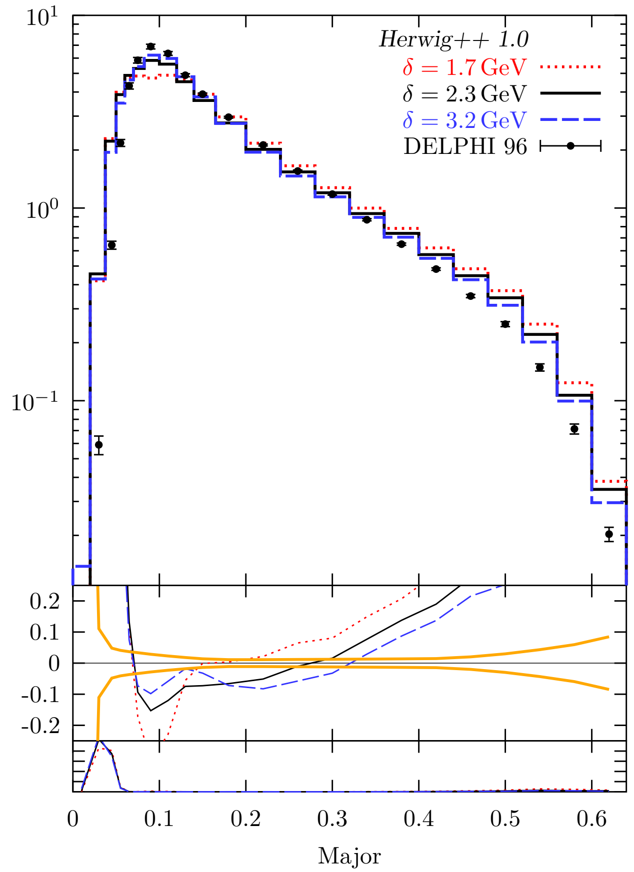


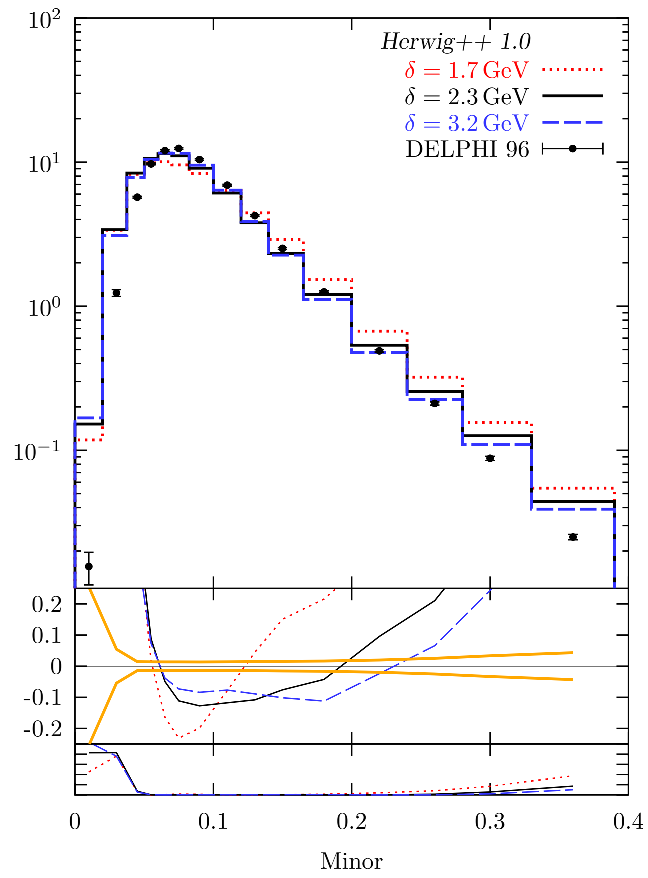
$p^T_{\perp,\mathrm{in}}$ — ME corrections off/on

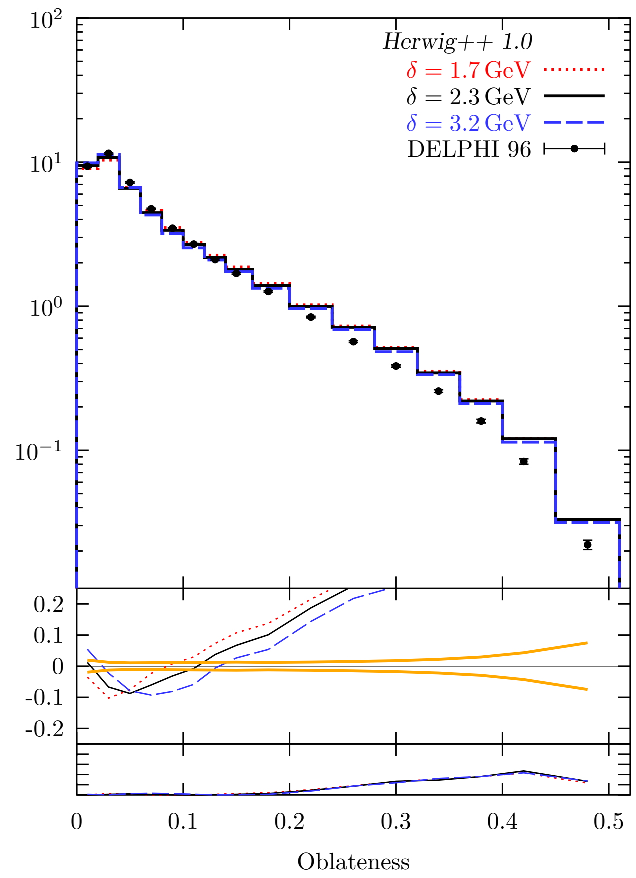




Major, Minor, Oblateness

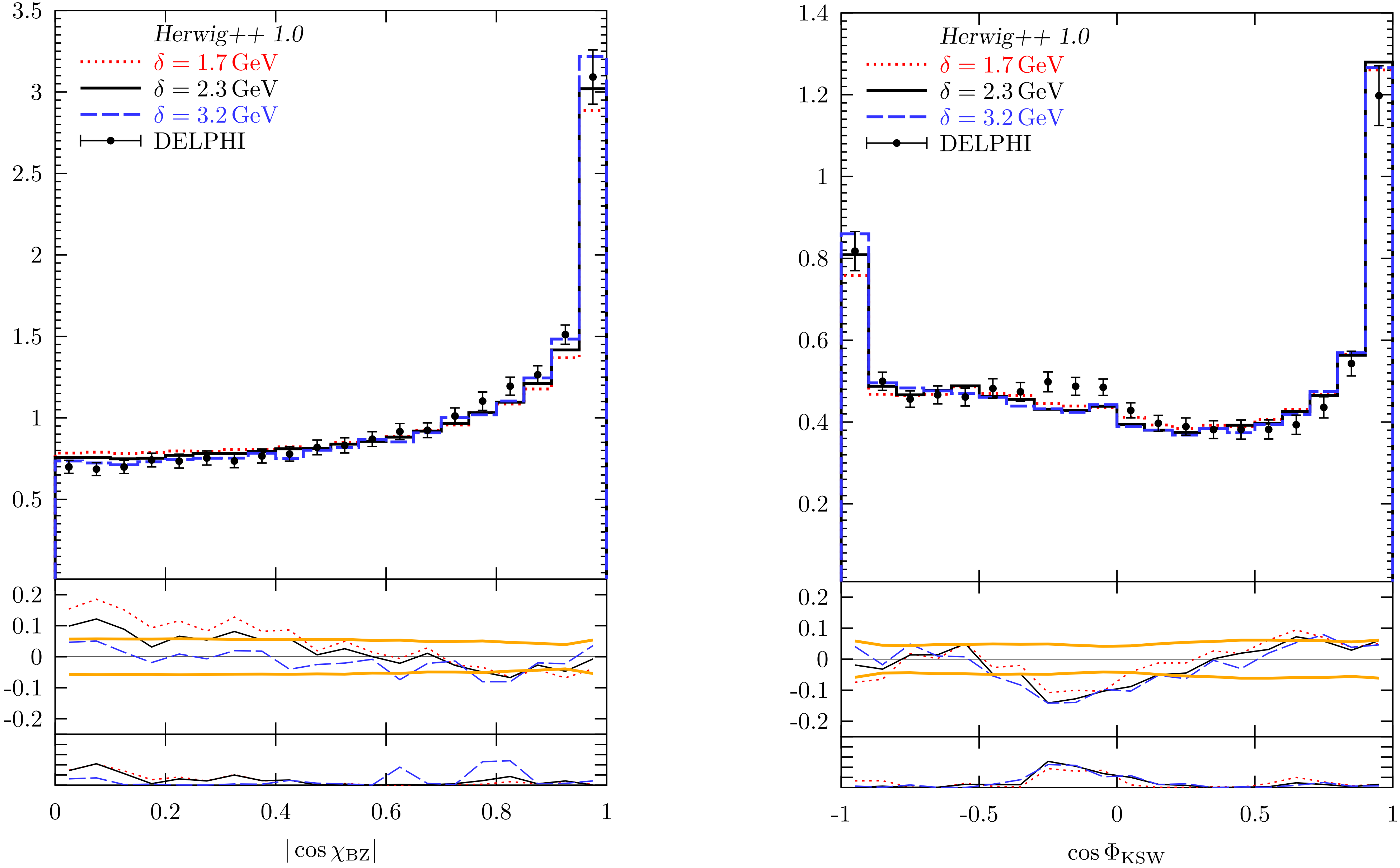




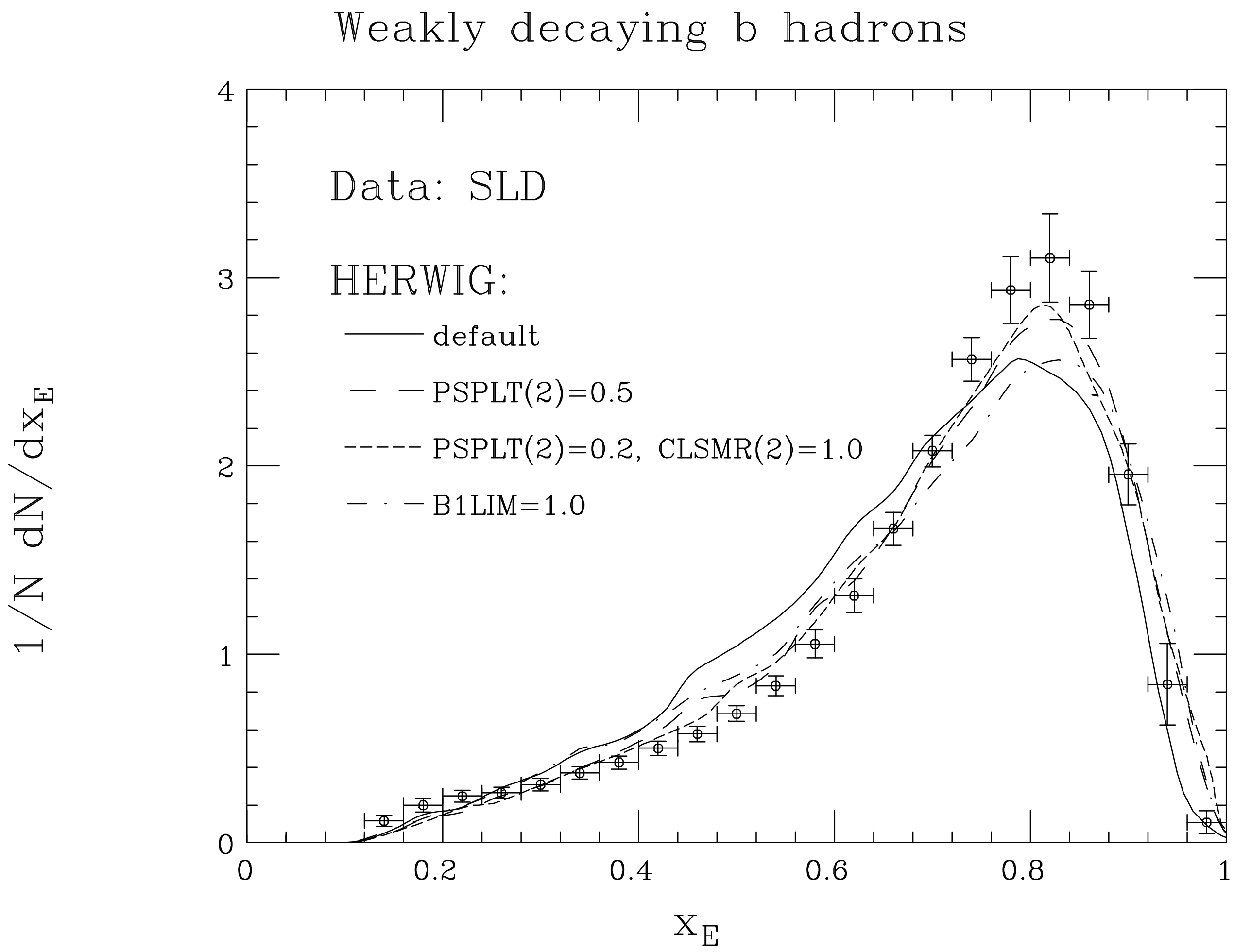


All Thrust–related distributions slightly wide, ie too many 2-jet like on one side and too many spherical events on the other side.

Four Jet Angles

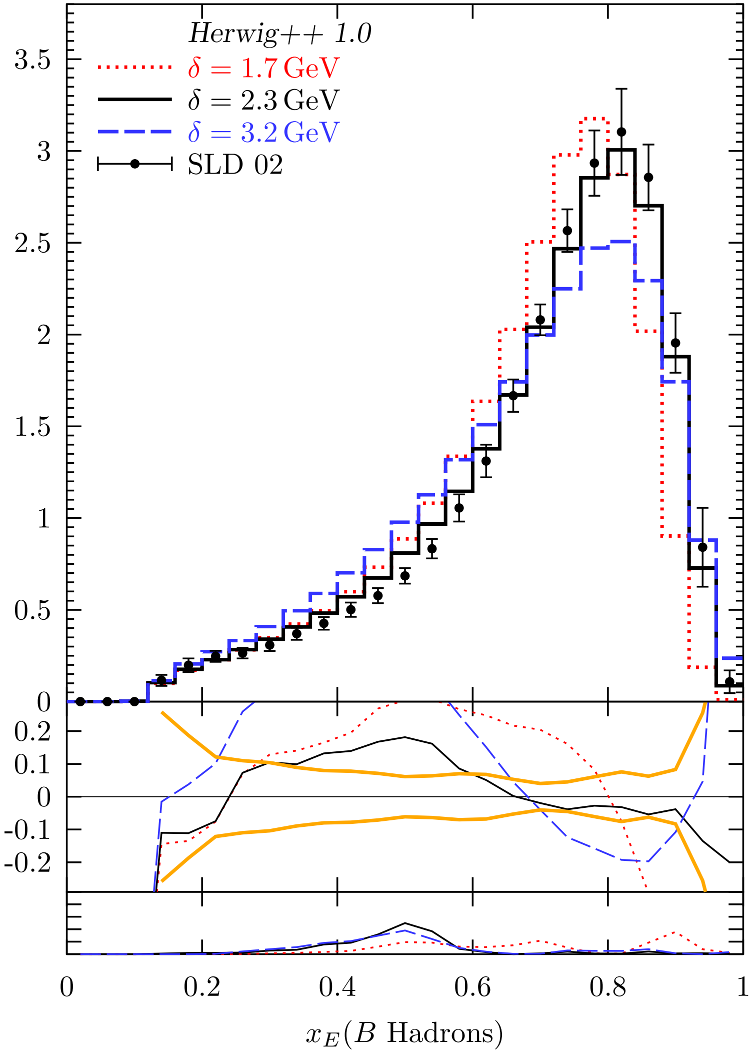


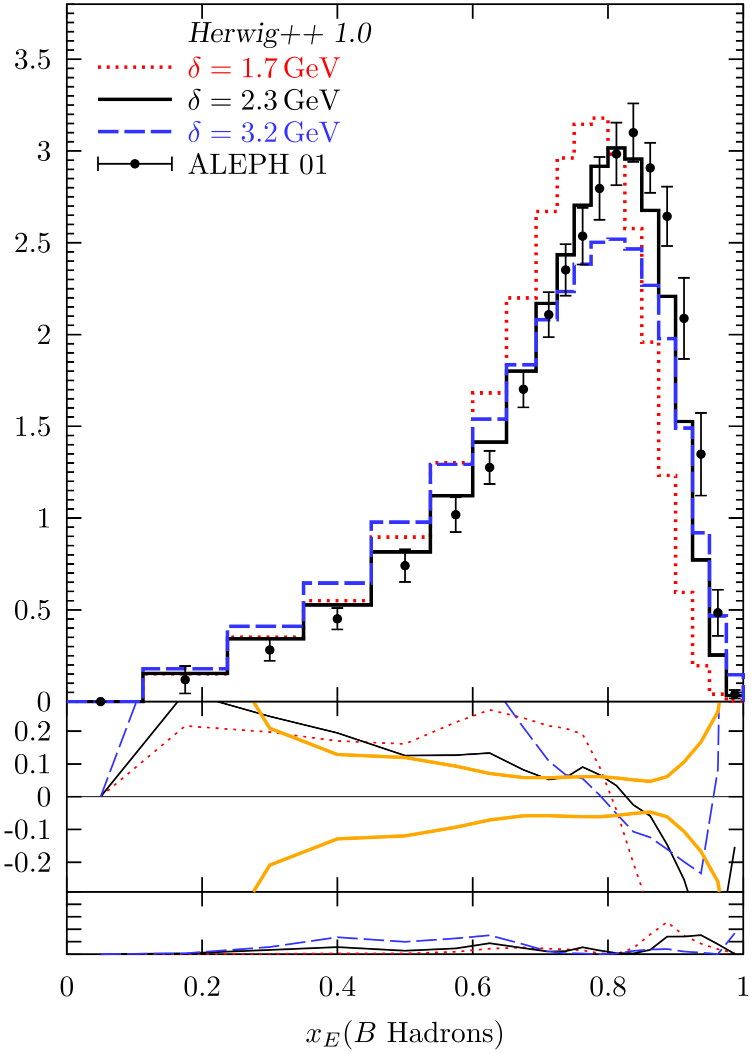
B-fragmentation function



HERWIG 6.4, very sensitive on hadronization!

B-fragmentation function

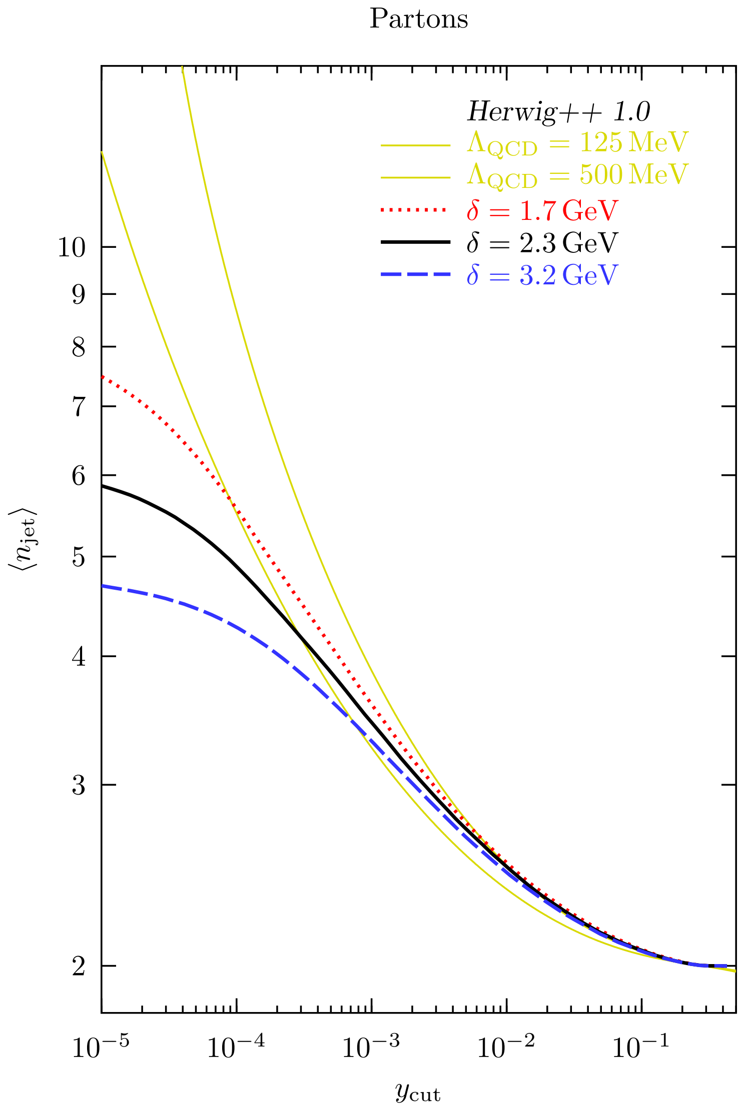


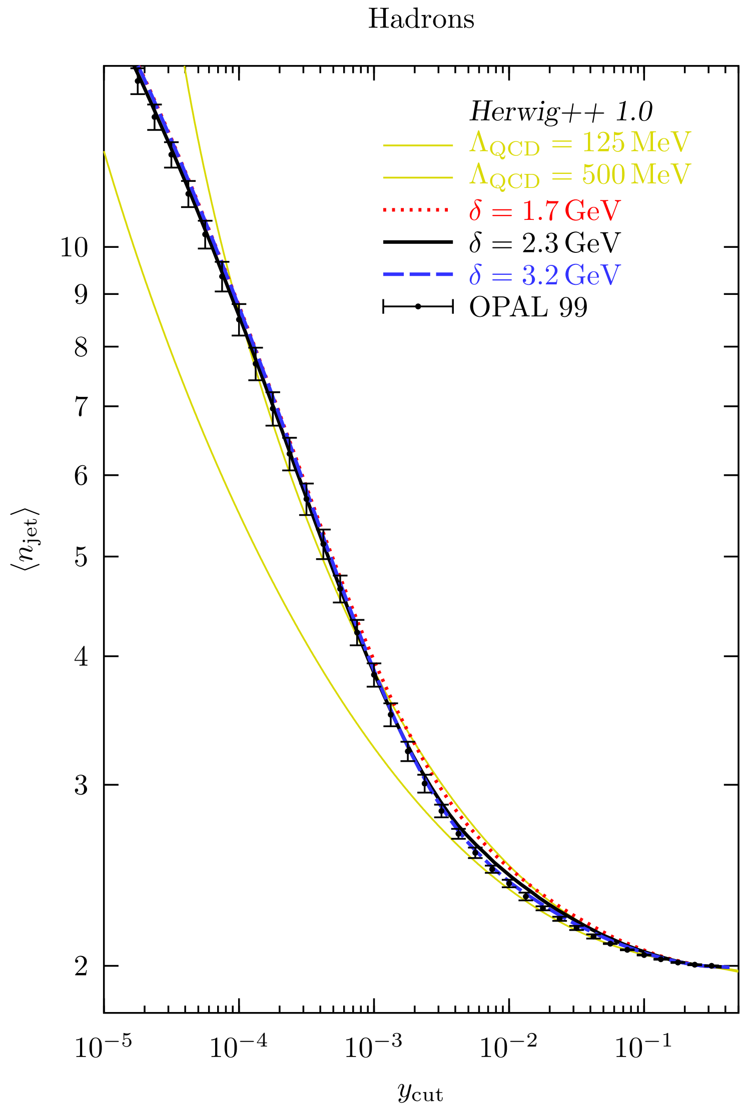


Only parton shower parameters varied!

Jet Multiplicity

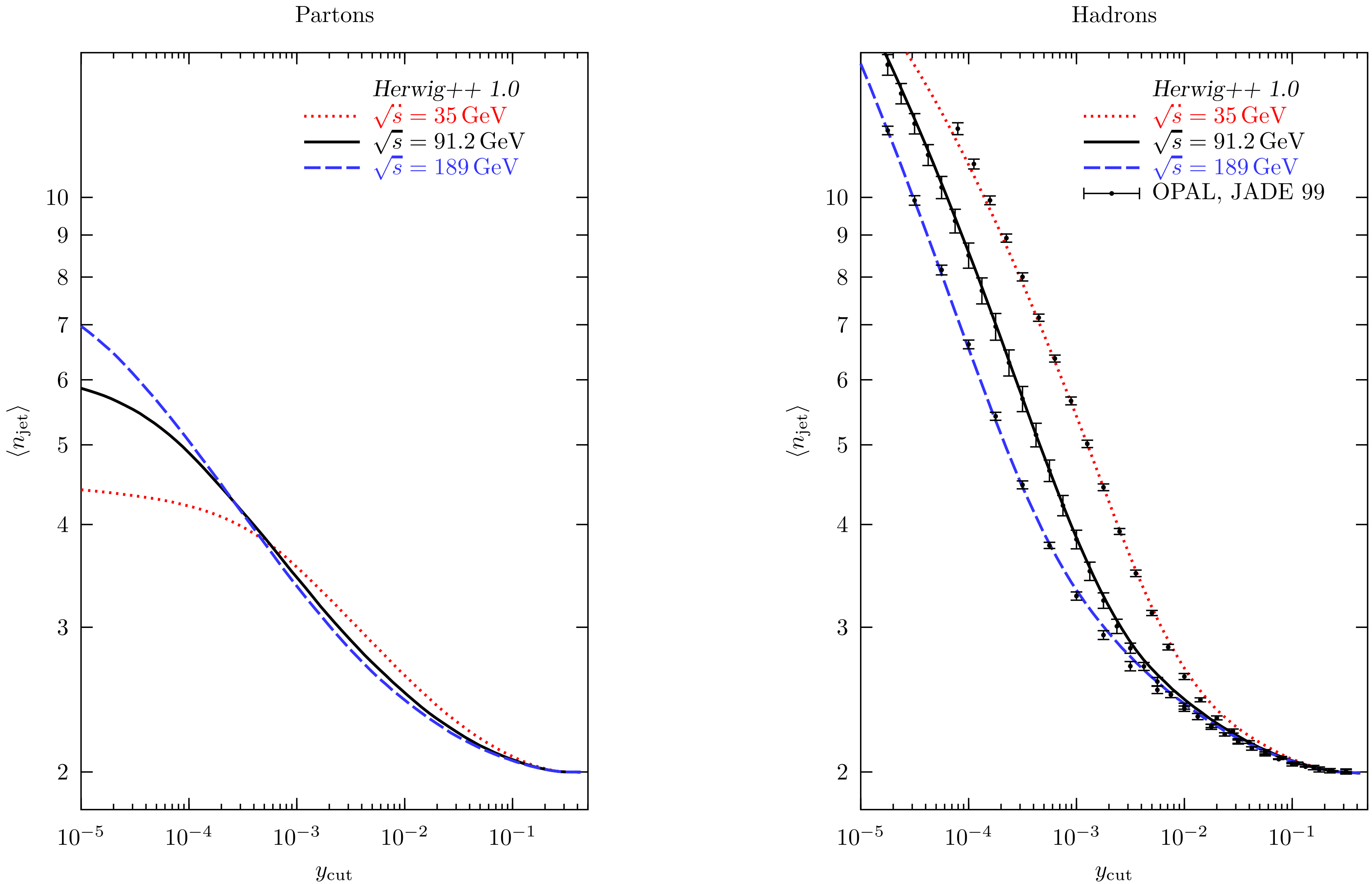
Durham algorithm. Smooth interplay between shower and hadronization.





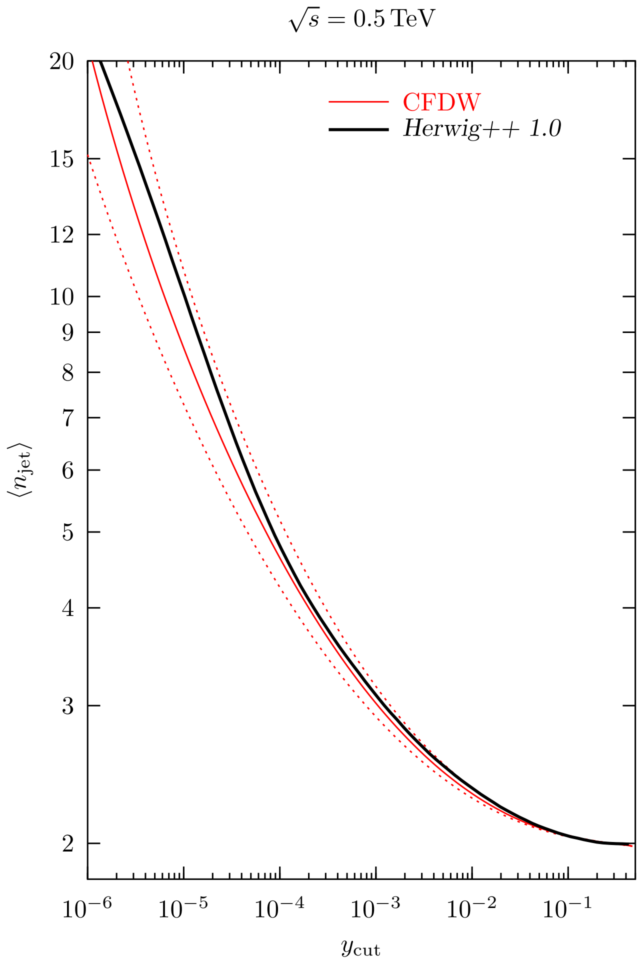
Jet Multiplicity (PETRA, LEP, LEPII)

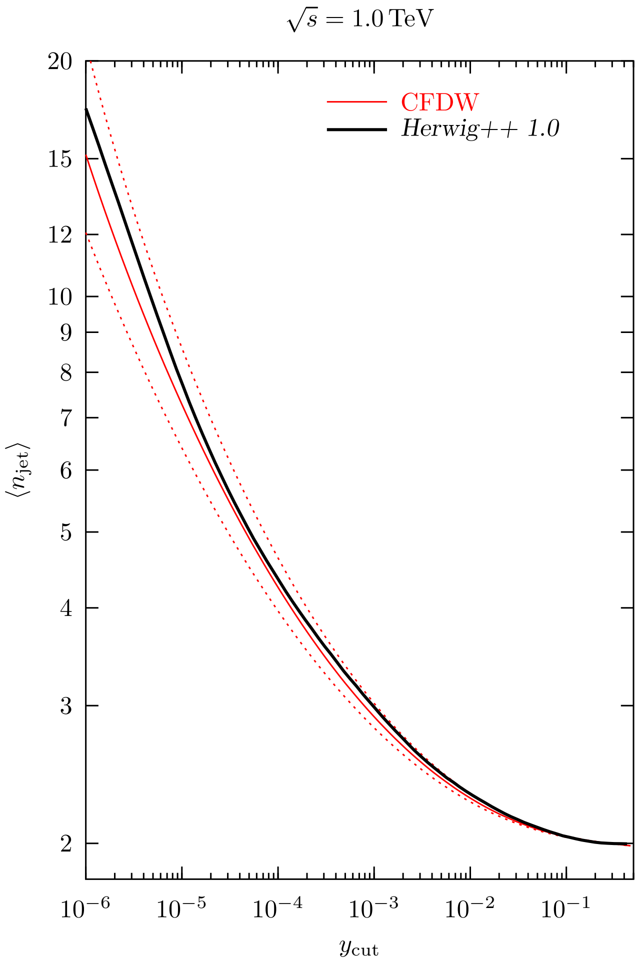
$\sqrt{s} = \{35, 91.2, 189\}\,\mathrm{GeV}$

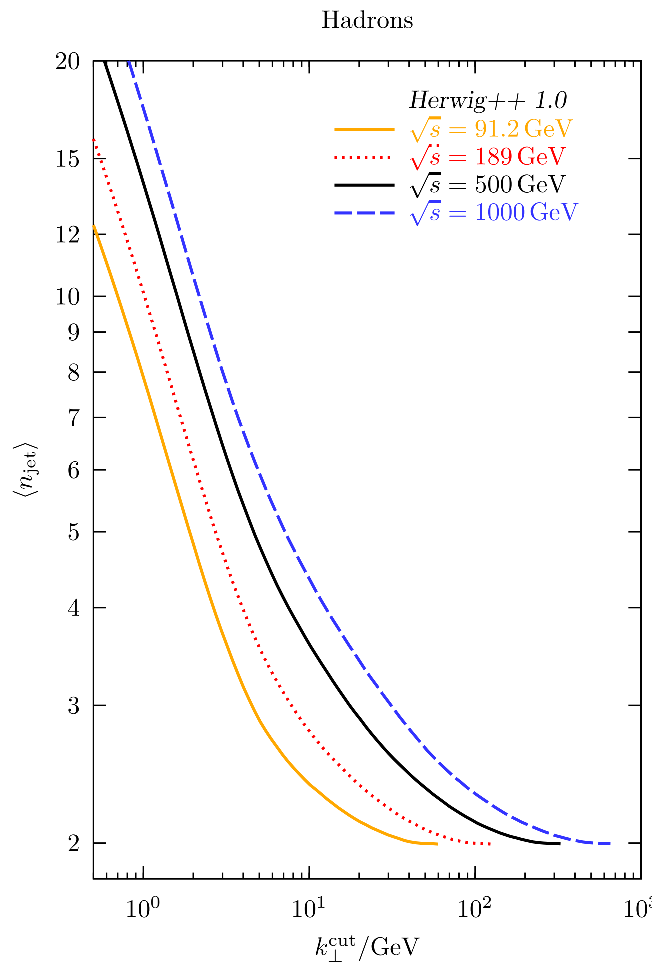


Jet Multiplicity @ Next Linear Collider

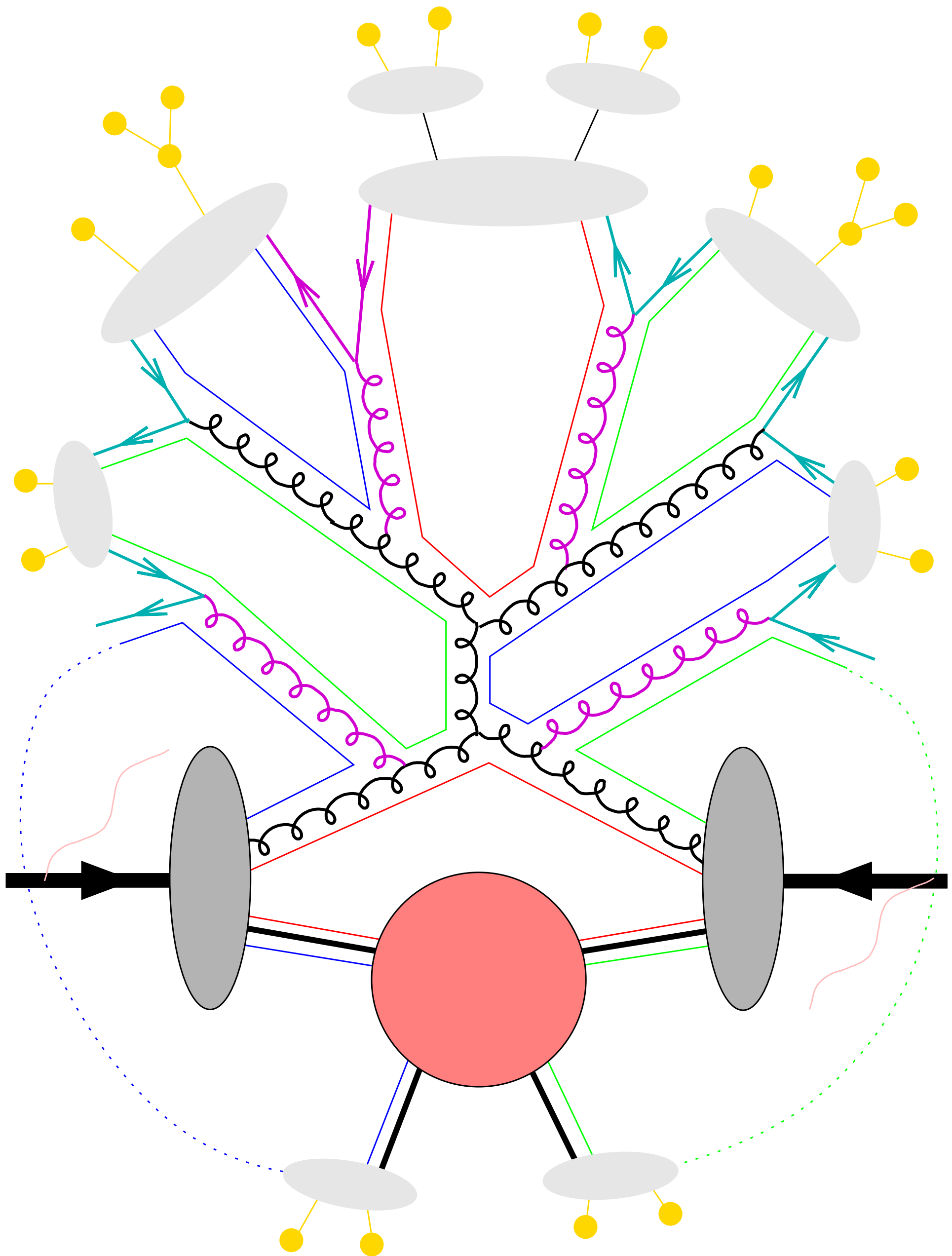
Herwig++ and NLLA pQCD (Catani, Fiorani, Dokshitzer, Webber, 1992); jet events with $n_f = 5$.







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 Future Colliders!

Conclusion

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

Herwig++ 1.0

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