

QCD Simulation for LHC and Herwig++

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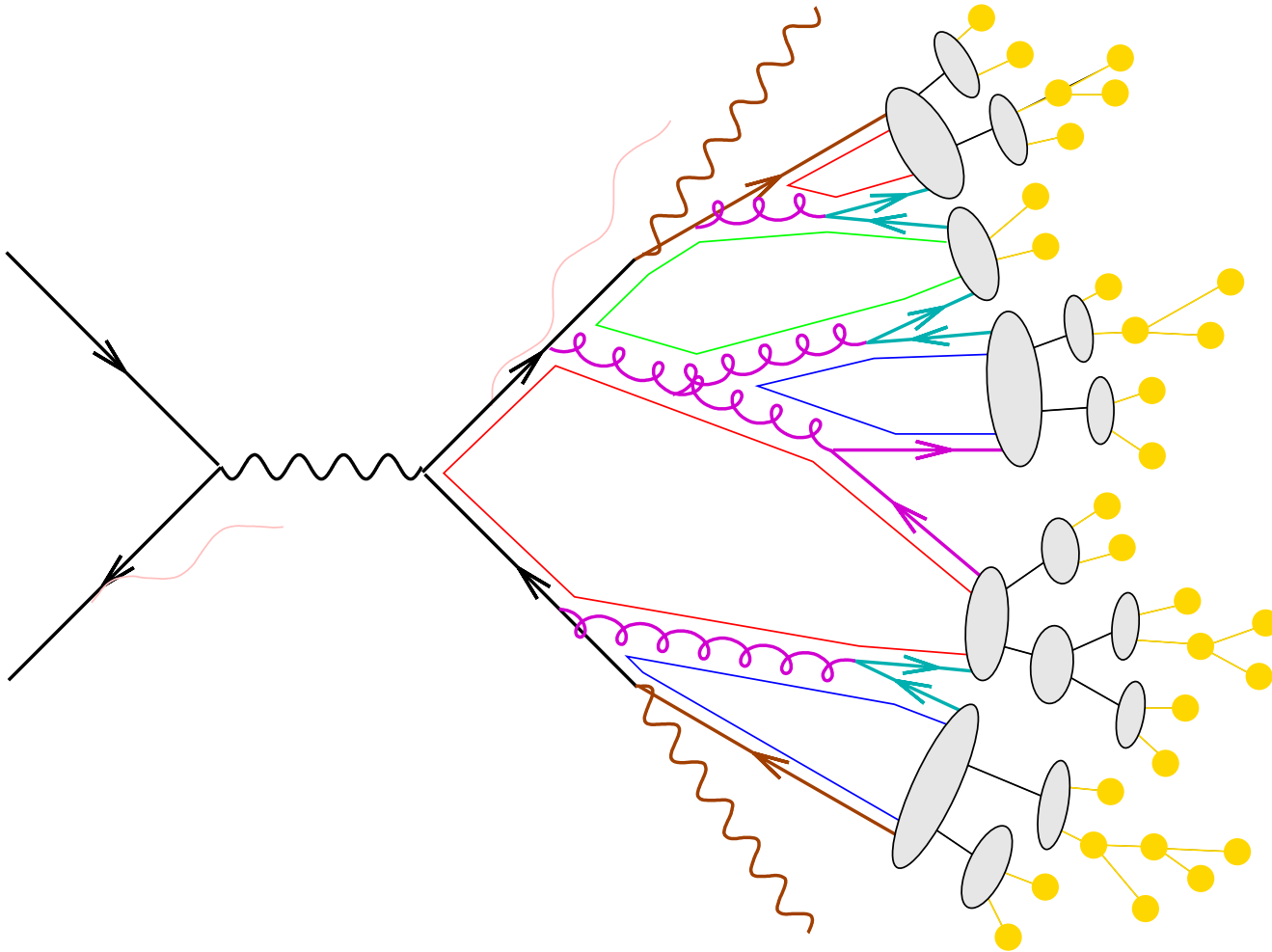
with Stefan Gieseke, Alberto Ribon, Mike Seymour & Phil Stephens (Cambridge, Manchester, CERN)

- Some issues in QCD simulation for LHC
 - Improving shower variables
 - Combining matrix elements and showers
 - Multiscale showering
- Herwig++
 - Overview
 - Hadronization model
 - Results (e^+e^-)
 - Outlook

S. Gieseke, P. Stephens and BW, JHEP **0312** (2003) 045 [hep-ph/0310083]

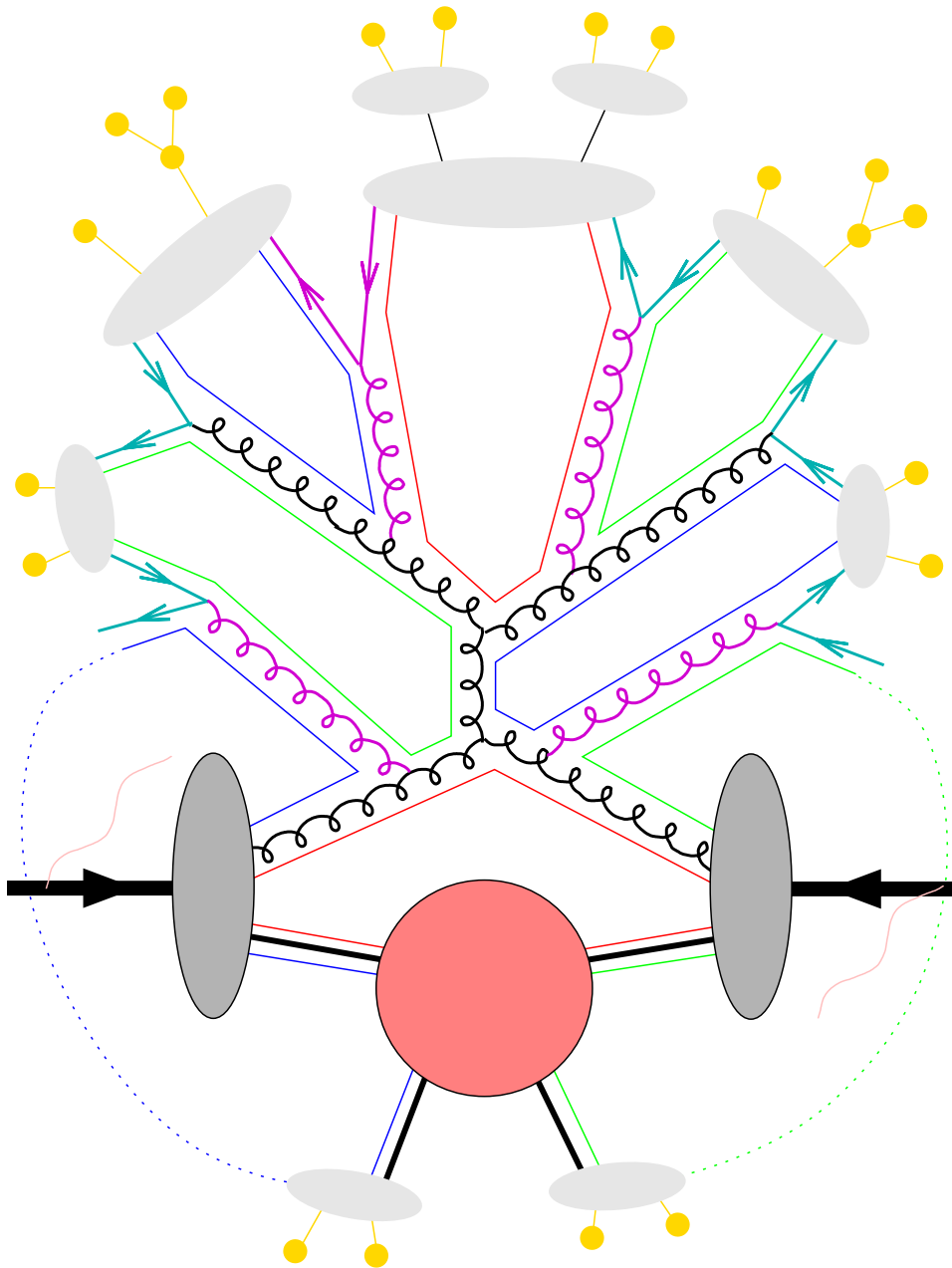
S. Gieseke, A. Ribon, M. H. Seymour, P. Stephens and BW, JHEP **0402** (2003) 005 [hep-ph/0311208]

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

Additional Complications in pp



- backward parton evolution
- underlying event (Odagiri talk)

Collinear Enhancement (Light Partons)

ME involving $q \rightarrow qg$ (or $g \rightarrow gg$) strongly enhanced whenever emitted gluon is almost collinear. Propagator factor

$$\frac{1}{(p_q + p_g)^2} \approx \frac{1}{2E_q E_g (1 - \cos \theta_{qg})}$$

- soft+collinear divergences.
- dominant contribution to the ME.

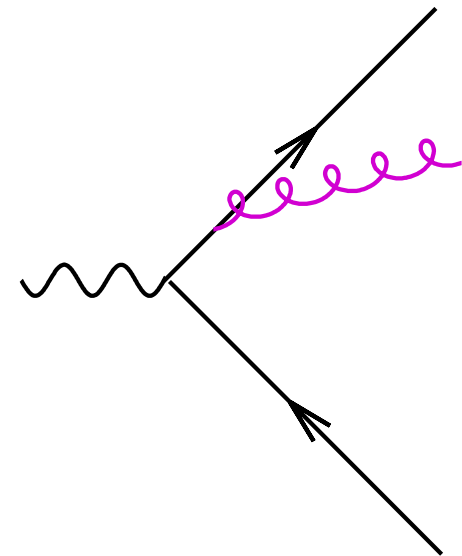
Collinear factorization

$$|M_{p+1}|^2 d\Phi_{p+1} \approx |M_p|^2 d\Phi_p \frac{dt}{t} \frac{\alpha_s}{2\pi} P(z) dz d\phi$$

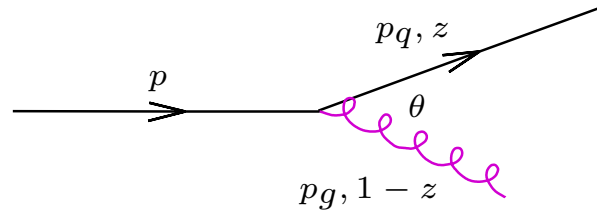
$$P(z) = C_F \frac{1+z^2}{1-z}$$

→ Parton shower MC.

- Shower resums leading logarithmic contributions.



Quasi-Collinear Limit (Heavy Quarks)



- **Sudakov basis** p, n with $p^2 = m^2$ ('forward'), $n^2 = 0$ ('backward'), $p_\perp^2 = -\mathbf{p}_\perp^2$

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

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

- **Quasi-collinear limit** (Catani et al.): for $|\mathbf{p}_\perp| \sim m \ll p_+$

$$\begin{aligned} P_{qq}(z, \mathbf{p}_\perp^2, m^2) &= C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\mathbf{p}_\perp^2 + (1-z)^2 m^2} \right] \\ &\equiv \frac{C_F}{1-z} \left[1+z^2 - \frac{2m^2}{z\tilde{q}^2} \right] \end{aligned}$$

- **Generalised angular variable**: for $m \rightarrow 0$, $\tilde{q} \sim |\mathbf{p}_\perp|/z(1-z) \sim E\theta$
- **Collinear limit**: for $p_\perp \rightarrow 0$, $\tilde{q} \sim m/z$, $P_{qq} \sim C_F(1-z)$

New evolution variables

- Adopt \tilde{q}^2 as new evolution variable: $\tilde{q}^2 = \frac{\mathbf{p}_\perp^2}{z^2(1-z)^2} + \frac{m^2}{z^2}$ for $q \rightarrow qg$
- Argument of running α_S chosen according to

$$\alpha_S \left(z^2(1-z)^2 \tilde{q}^2 = \mathbf{p}_\perp^2 + (1-z)^2 m^2 \right)$$

- Generalized angular ordering in $\tilde{q}_i \rightarrow \tilde{q}_{i+1} + \tilde{k}_{i+1}$:

$$\tilde{q}_{i+1} < z_i \tilde{q}_i \quad \tilde{k}_{i+1} < (1-z_i) \tilde{q}_i$$

- **Reinterpretation** of evolution variables: branching probability for $a \rightarrow bc$ is still

$$dP(a \rightarrow bc) = \frac{d\tilde{q}^2}{\tilde{q}^2} \frac{\alpha_S}{2\pi} P_{ba}(z, \tilde{q}) dz d\phi$$

—→ **Sudakov form factors etc. remain the same!**

- Allows better treatment of heavy particles, avoiding collinear “dead cones” and overlapping regions in phase space, in particular for soft emissions.

Kinematics

- Sudakov basis p, n with $p^2 = m^2, n^2 = 0$,

$$q_i = \alpha_i p + \beta_i n + q_{\perp i}$$

- Longitudinal splitting: $\alpha_i = z_i \alpha_{i-1}$
- Transverse momenta reconstructed from \mathbf{p}_{\perp} ,

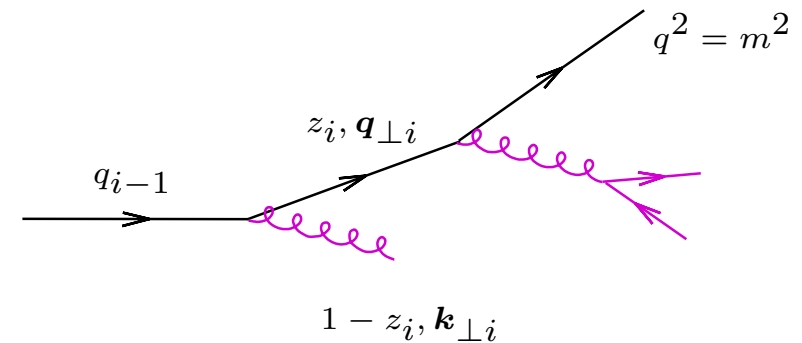
$$\mathbf{q}_{\perp i} = \mathbf{p}_{\perp i} + z_i \mathbf{q}_{\perp, i-1} \quad \mathbf{k}_{\perp i} = -\mathbf{p}_{\perp i} + (1 - z_i) \mathbf{q}_{\perp, i-1}$$

- Recursive reconstruction of virtualities and β_i 's from

$$q_{i-1}^2 = \frac{q_i^2}{z_i} + \frac{k_i^2}{1 - z_i} + \frac{\mathbf{p}_{\perp i}^2}{z_i(1 - z_i)}$$

$$\beta_i = \frac{\mathbf{q}_{\perp i}^2 + q_i^2 - \alpha_i^2 m^2}{2\alpha_i(p \cdot n)}$$

- Azimuthal angle φ chosen randomly (now), or using *azimuthal spin correlations* (planned).



Universal cutoff parameter δ

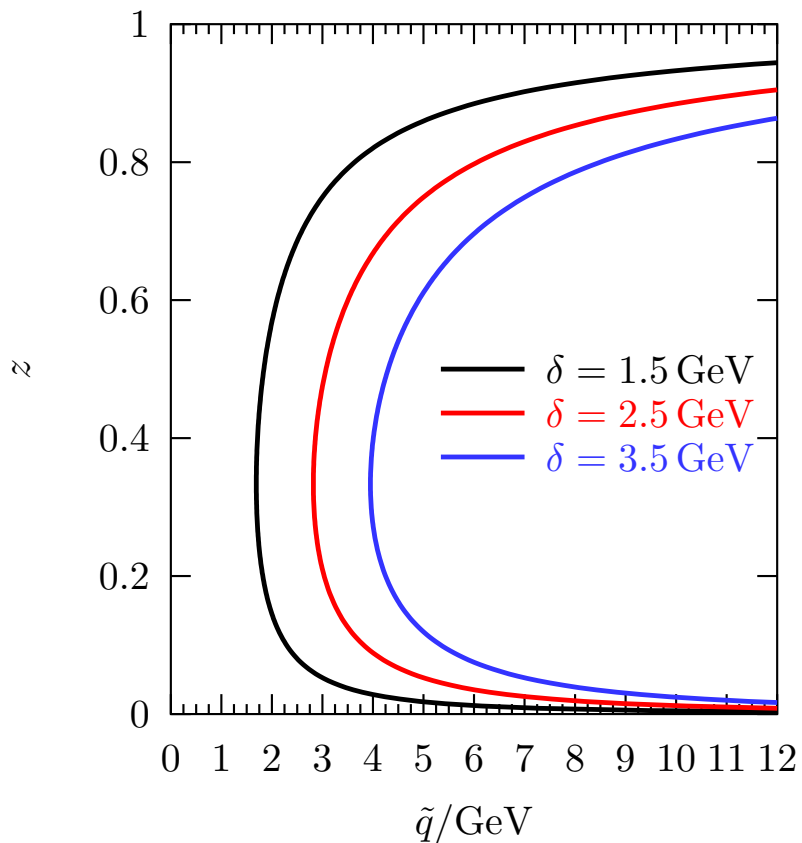
Require threshold in parton shower phase space.

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

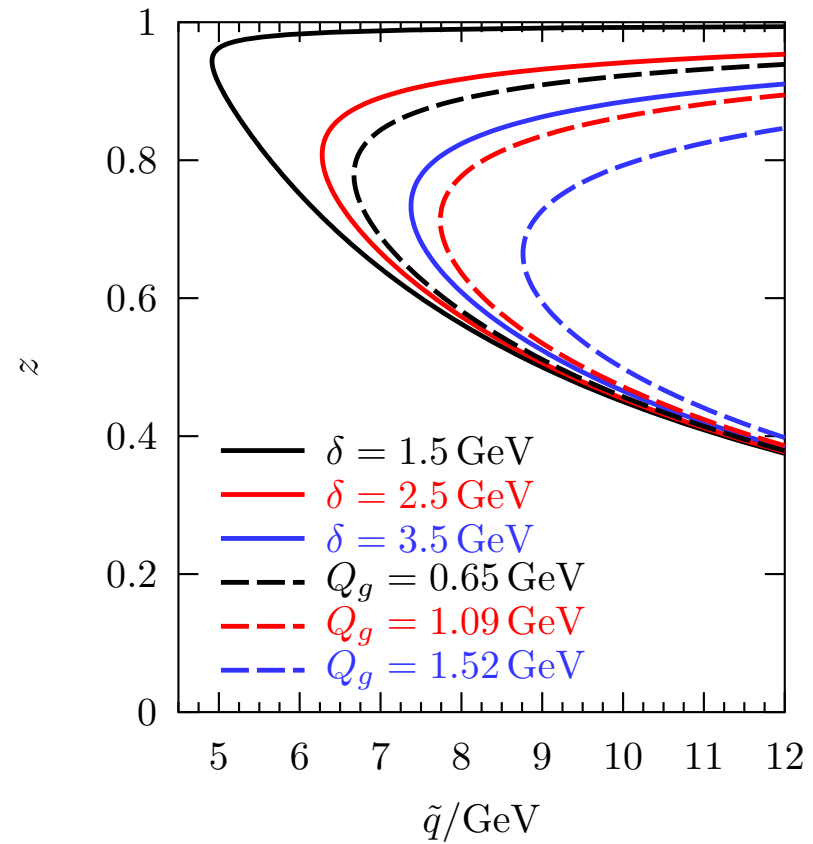
Parametrization of Q_g in terms of δ, m_q

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

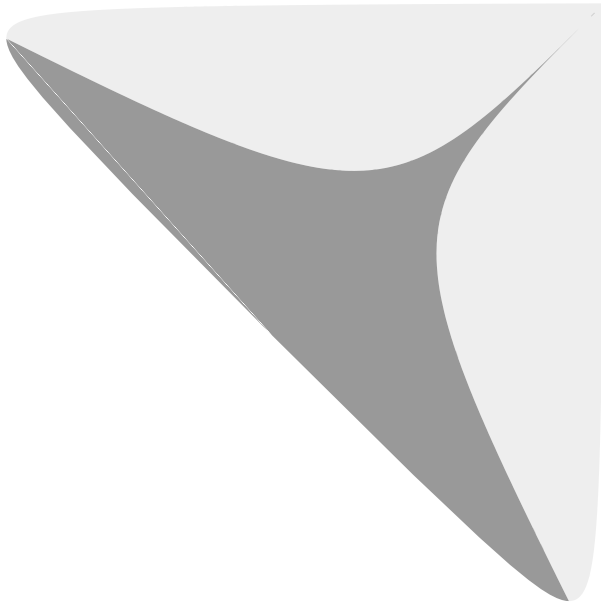
light quarks:



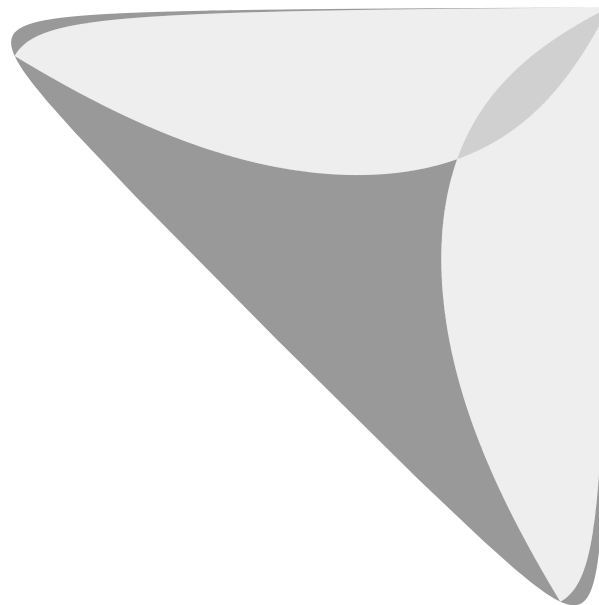
b quarks:



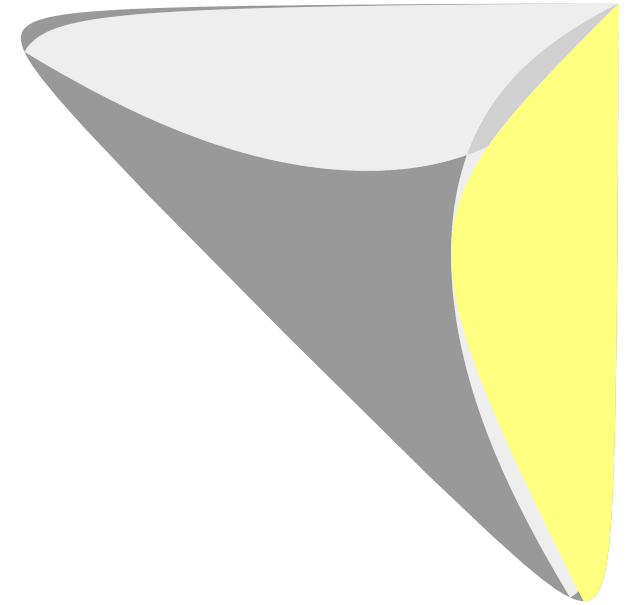
$q\bar{q}g$ phase space: old vs new variables



Herwig++



Fortran HERWIG

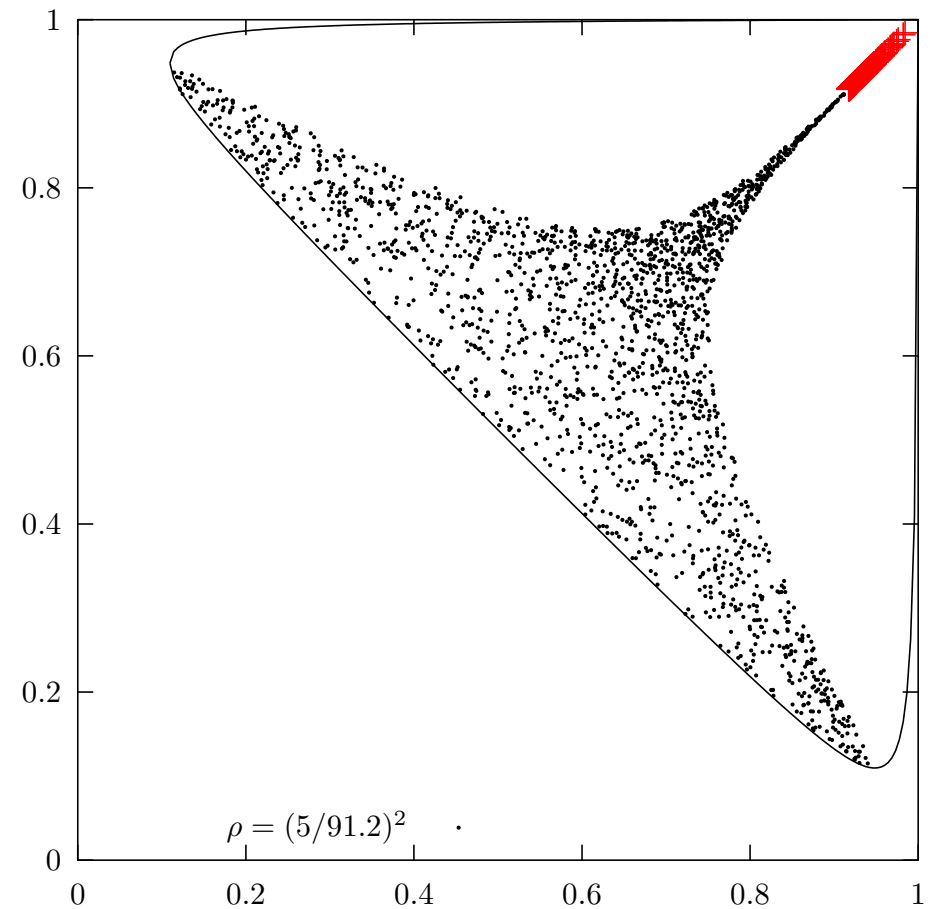


Comparison

- No overlapping regions in phase space.
- Smooth coverage of soft gluon region.
- No collinear dead cones.
- Larger non-collinear dead region.

Hard Matrix Element Corrections

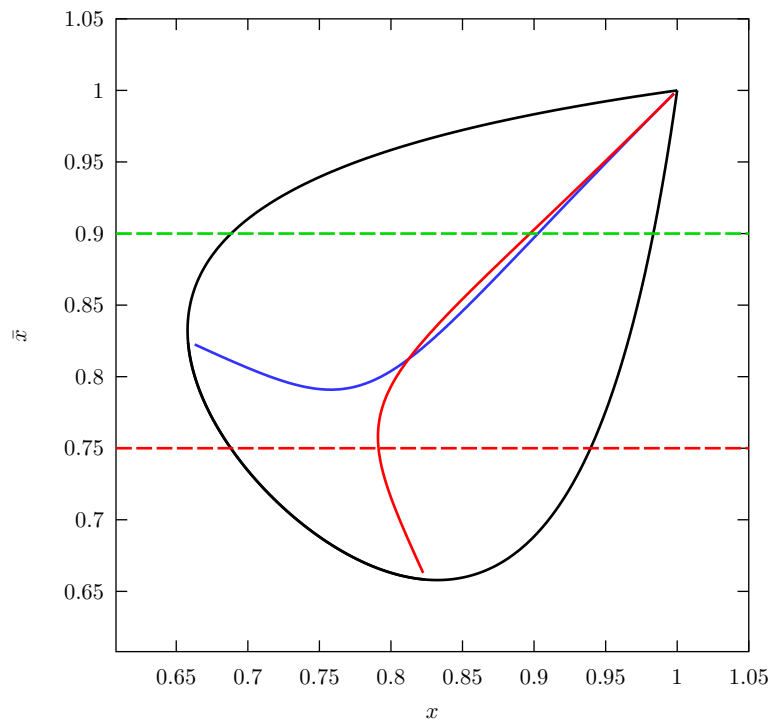
- Points $(x_q, x_{\bar{q}})$ in **dead region** chosen according to LO $q\bar{q}g$ matrix element and accepted according to ME weight.
- About **3%** of all events are actually hard $q\bar{q}g$ events.
- Red points have **weight** > 1 , practically no error by setting weight to one.
- Event **oriented**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



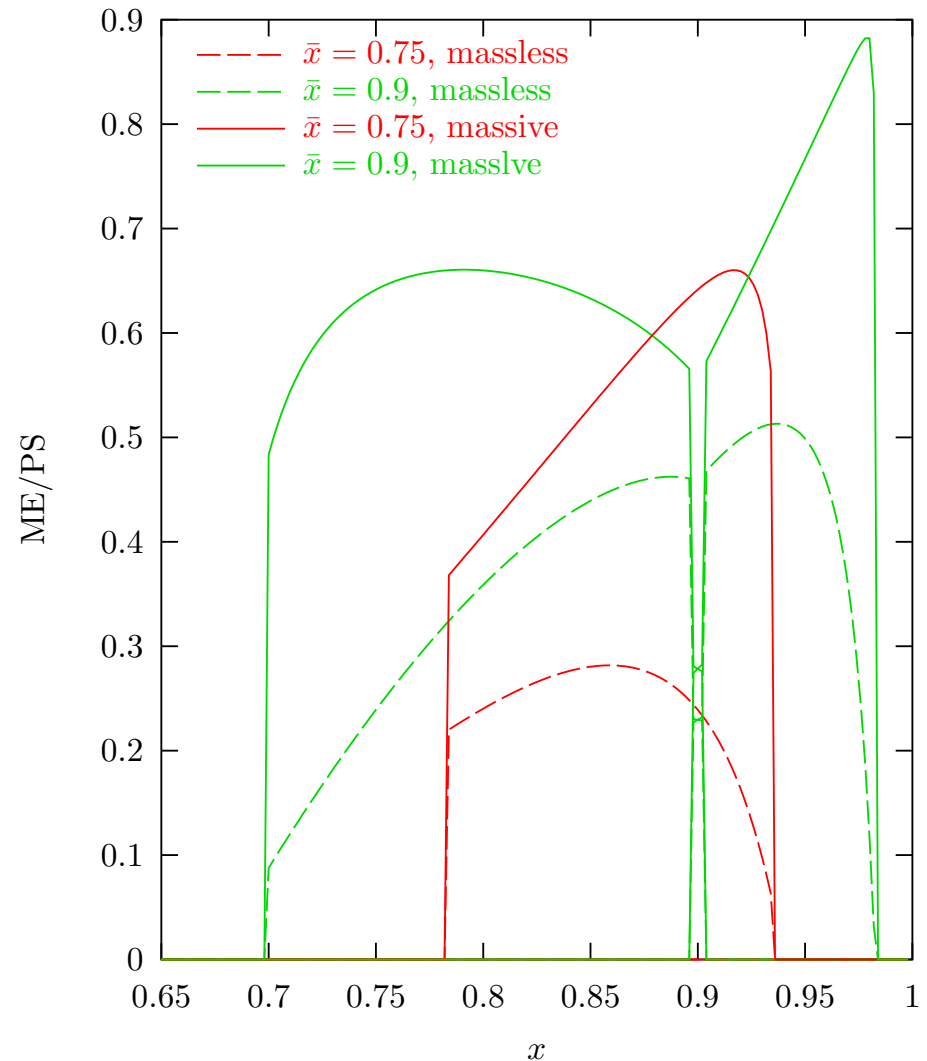
Soft Matrix Element Corrections

- 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, $m^2/Q^2 = 0.1$
 ($\approx t\bar{t}$ at 500 GeV)



Comparison with massless splitting function

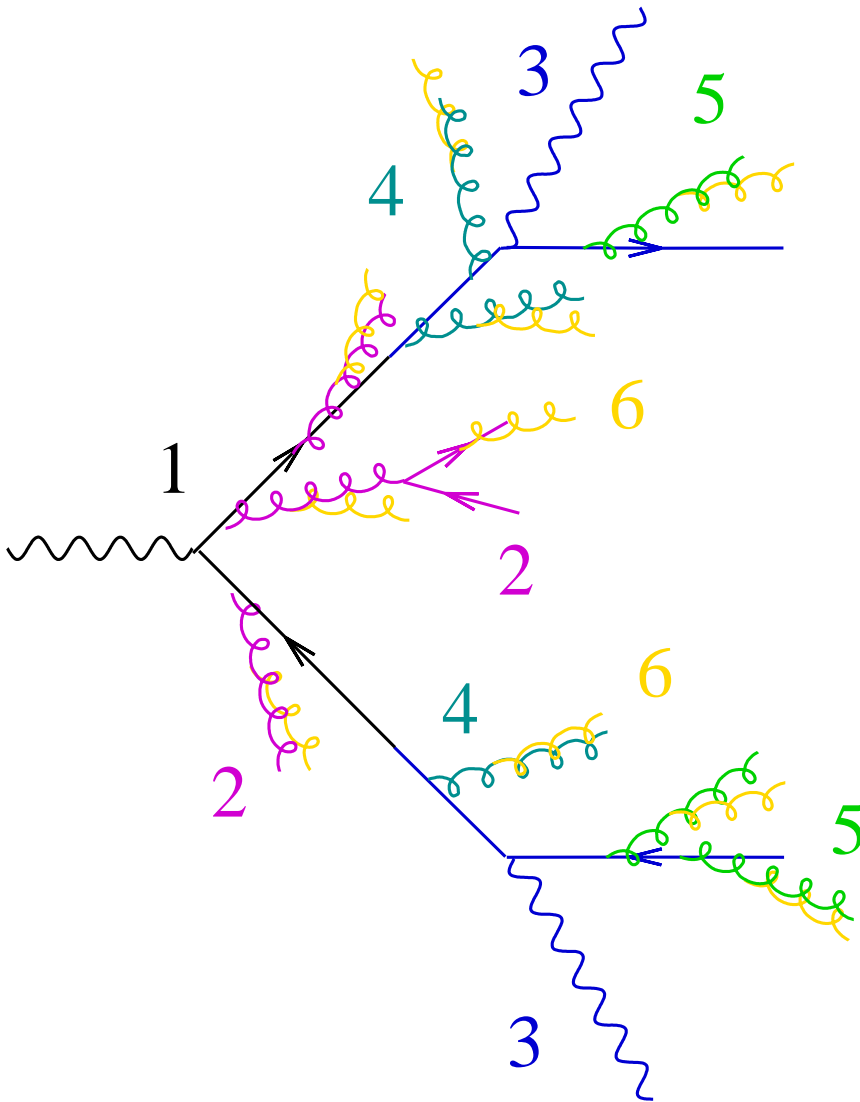


Multiscale Showering

Example: $t\bar{t}$ production & decay

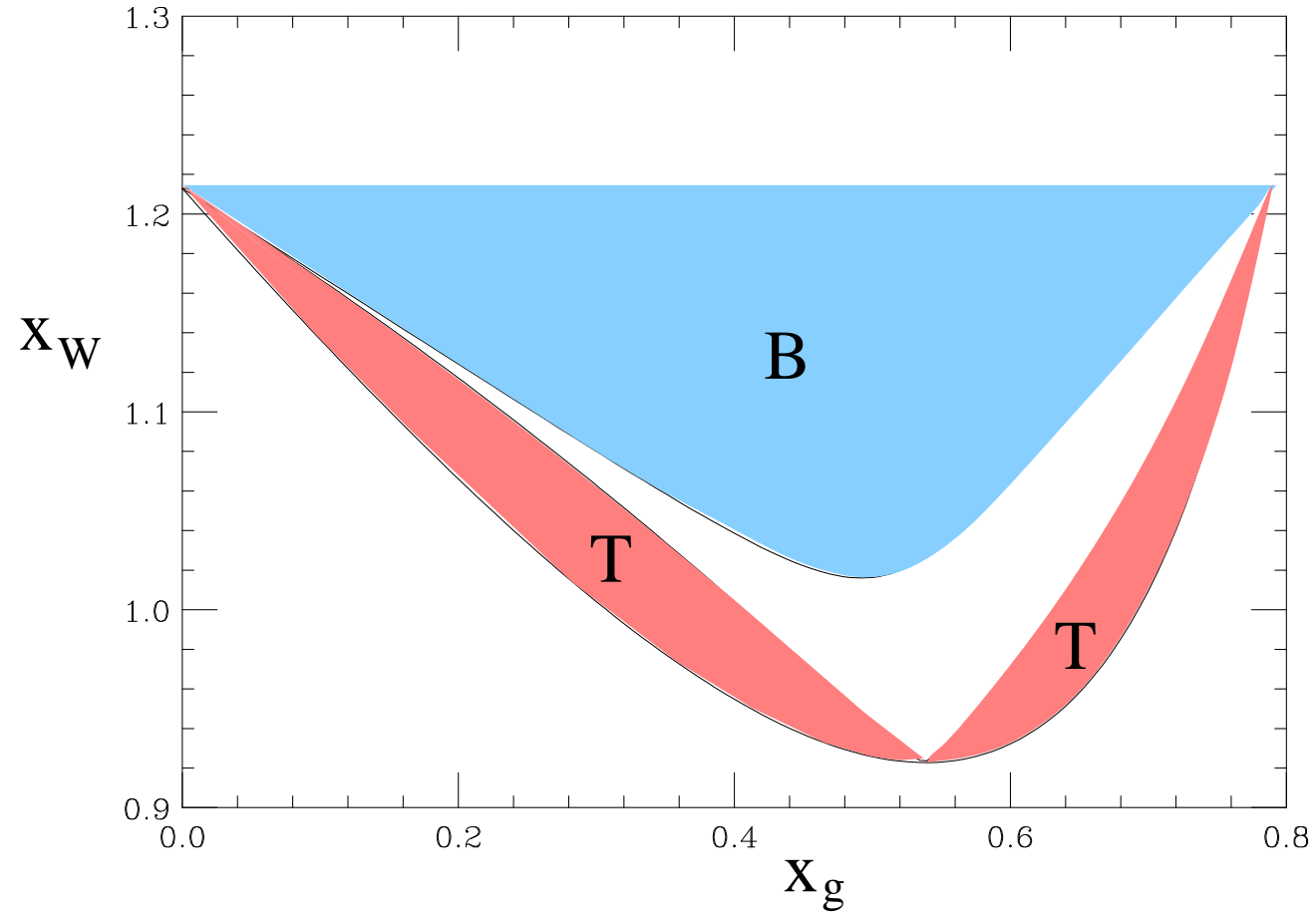
1. Hard process (scale $\sim \hat{s}$)
2. Showers from t, \bar{t} ($\hat{s} \rightarrow \Gamma_t$)
3. Decays $t \rightarrow Wb, \bar{t} \rightarrow W\bar{b}$
4. ISR from t, \bar{t} ($m_t \rightarrow \Gamma_t$)
5. FSR from b, \bar{b} ($m_t \rightarrow \Gamma_t$)
6. Global showering ($\Gamma_t \rightarrow \Gamma_b$)

etc.



Heavy Quark Decay

- In $t \rightarrow Wb$, ISR from t fills soft and collinear regions \rightarrow ME correction is finite.



- In Fortran HERWIG, ISR was missing \rightarrow infrared divergence in ME correction.

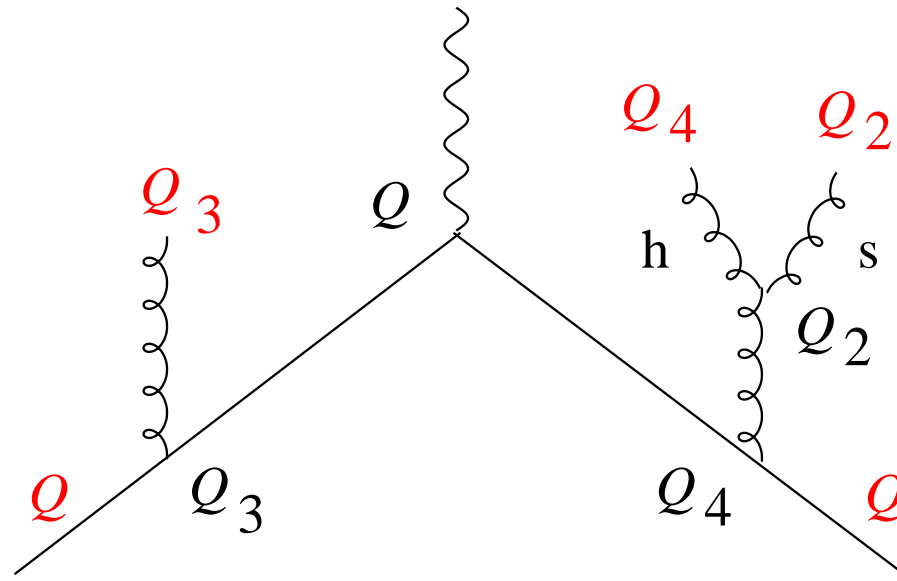
Combining Matrix Elements and Showers

Above method of hard+soft matrix element corrections is difficult to extend to NLO, or to more complicated processes.

- **MC@NLO**: subtract approximate NLO contributions generated by showers from exact NLO matrix elements.
 - Regularizes divergences of NLO ME!
 - All NLO results formally reproduced
 - Shower resums soft & collinear divergences to all orders
 - Frixione talk.
- **CKKW** (+ Krauss, Lönnblad, Mrenna & Richardson): generate ME with k_T -cutoff Q_1 , apply corresponding Sudakov form factors, veto $k_T > Q_1$ in showers.
 - Q_1 dependence cancels to NLL
 - Can combine different multiplicity ME's without double counting jet rates (to NLL)
 - Mrenna, Schumann talks.

Combining ME & PS: Scales

- Coherent branching \longrightarrow evolution in **angle**, not k_T
- k_T -cutoff Q_1 on ME \longrightarrow veto $k_T > Q_1$ in showers
- However, starting scale for showers is **not** $\tilde{q} = Q_1$
 - Showers must “fill in” radiation at larger angles, with $\tilde{q} > Q_1$ but $k_T < Q_1$
- Construct parton “histories” (gauge invariant) from clustering sequence
 - Each parton evolves from the \tilde{q} scale at which it was “created” (shown in **red**)



Combining ME & PS: Kinematics

Formally subleading \longrightarrow important for MC@NLO.

After showering, hard partons have virtualities $q_i^2 \neq m_i^2$

\longrightarrow boost/rescale jets.

Started with

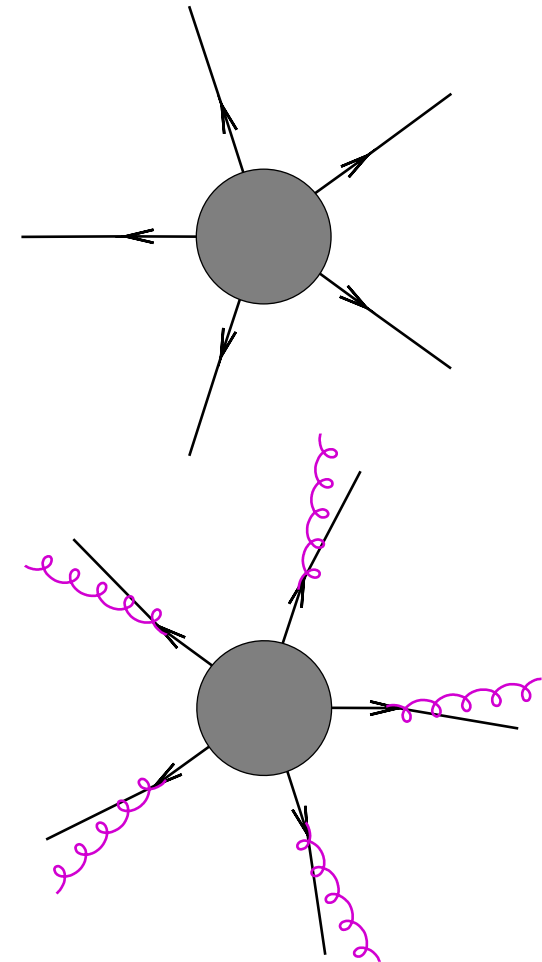
$$\sqrt{s} = \sum_{i=1}^n \sqrt{m_i^2 + \mathbf{p}_i^2}$$

We can **rescale** 3-momenta with common factor K ,

$$\sqrt{s} = \sum_{i=1}^n \sqrt{q_i^2 + K \mathbf{p}_i^2}$$

to preserve overall energy/momentum.

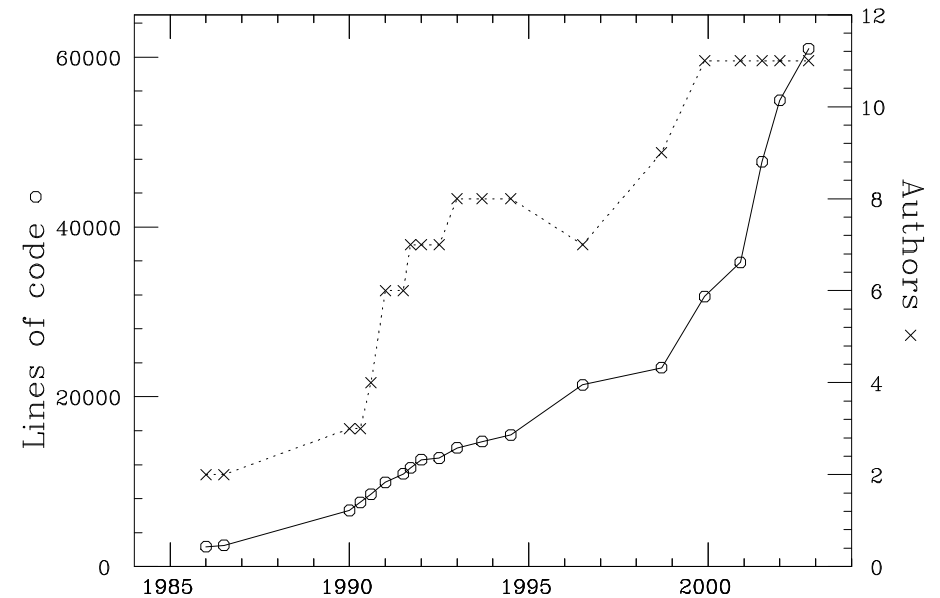
\longrightarrow resulting jets are then **boosted** accordingly.



The new generator Herwig++

A completely new event generator in C++

- Aiming at full multi-purpose generator for LHC and future colliders.
- Preserving main features of HERWIG such as
 - angular ordered parton shower
 - cluster hadronization
- New features and improvements
 - covariant shower formulation
 - improved parton shower evolution for heavy quarks
 - consistent radiation from unstable particles (multiscale evolution)



Growth of Fortran HERWIG

Use of ThePEG in Herwig++

ThePEG = Toolkit for high energy Physics Event Generation

Leif Lönnblad, <http://www.thep.lu.se/ThePEG/>



Share administrative overhead, common to event generators with Pythia7

Independent *physics* implementation

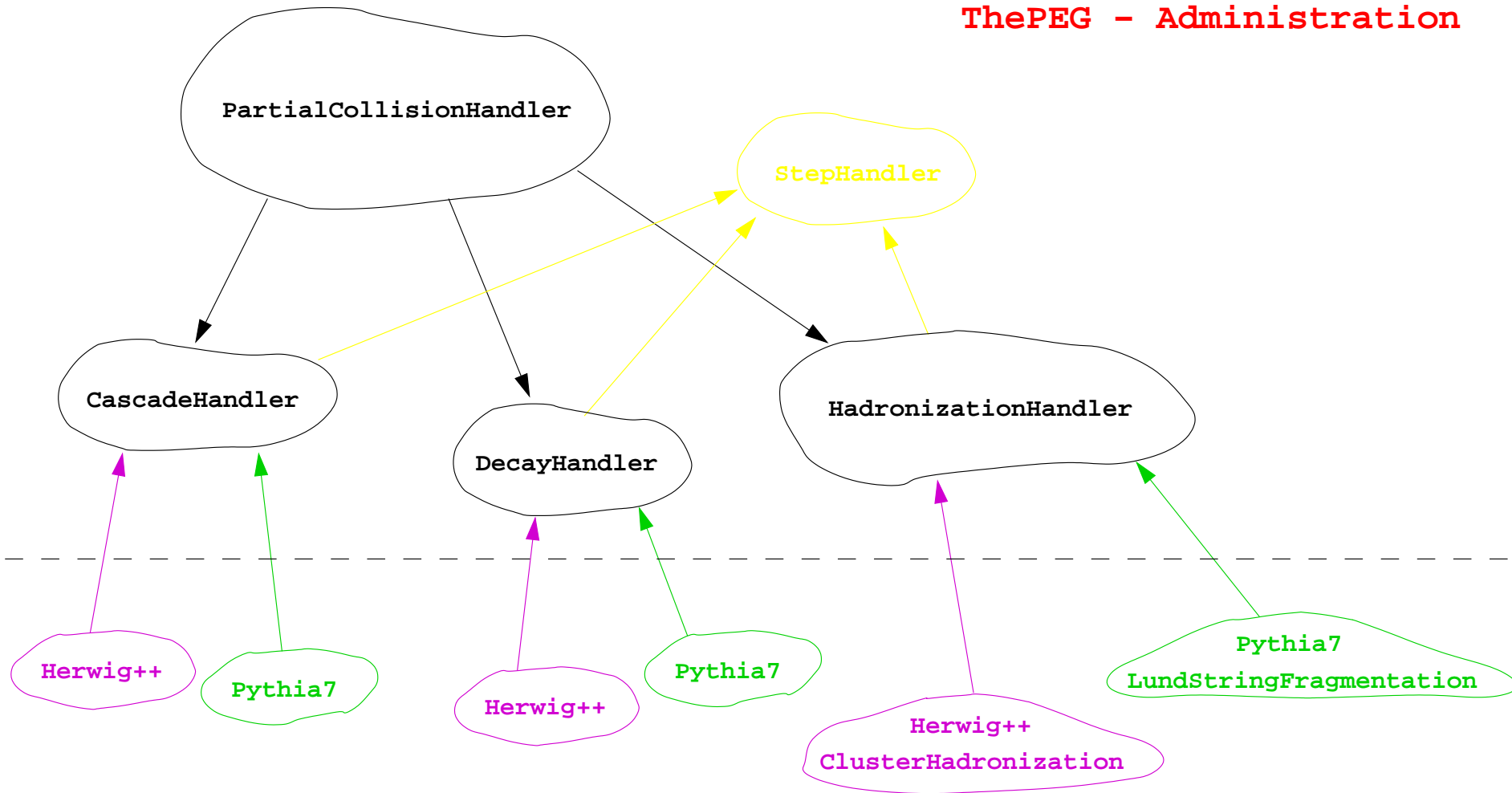
Large but very flexible implementation

Common basis for Pythia7/Herwig++

- Lack of independence.
- Less possibility to test codes against each other.
- Physics is still independent.
- Beneficial for the user to have the same framework.
- Running Herwig++ with Lund String Fragmentation from Pythia7 is very simple!

PartialCollisionHandlers

ThePEG - Administration

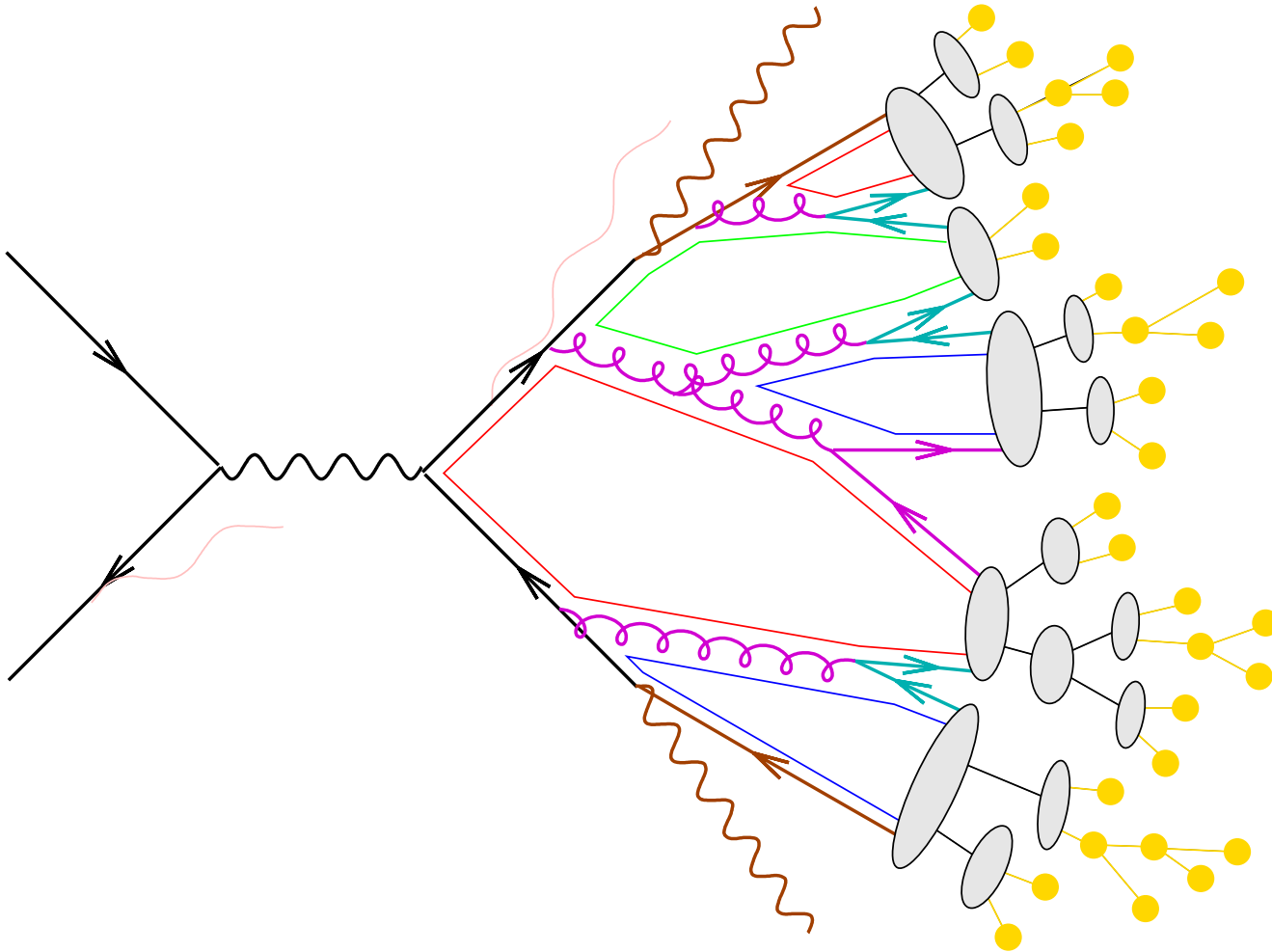


Physics Implementations

Hard interactions

- Basic ME's included in **ThePEG**, such as $e^+e^- \rightarrow q\bar{q}$, QCD $2 \rightarrow 2$: 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)

Cluster Hadronization Model



- 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

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 right)
- Cluster fission until

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

where masses are chosen from

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

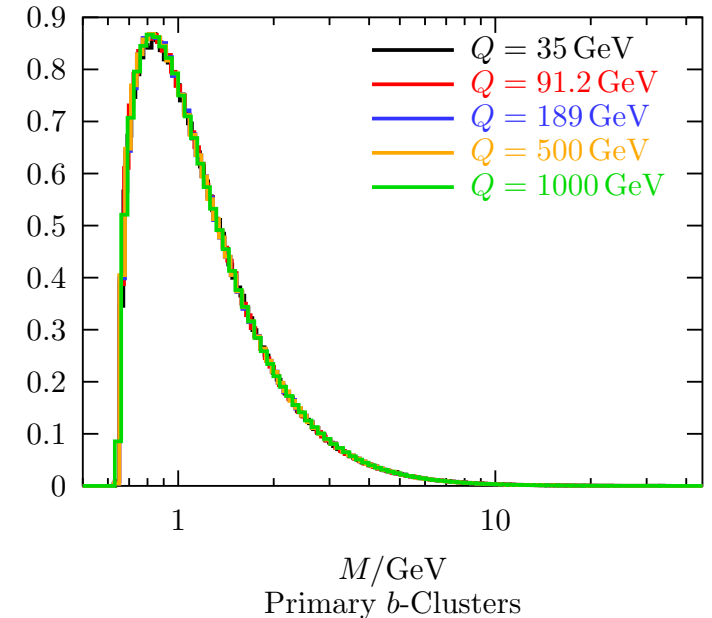
with additional phase space constraints. Constituents keep moving in their original directions.

- Cluster decay

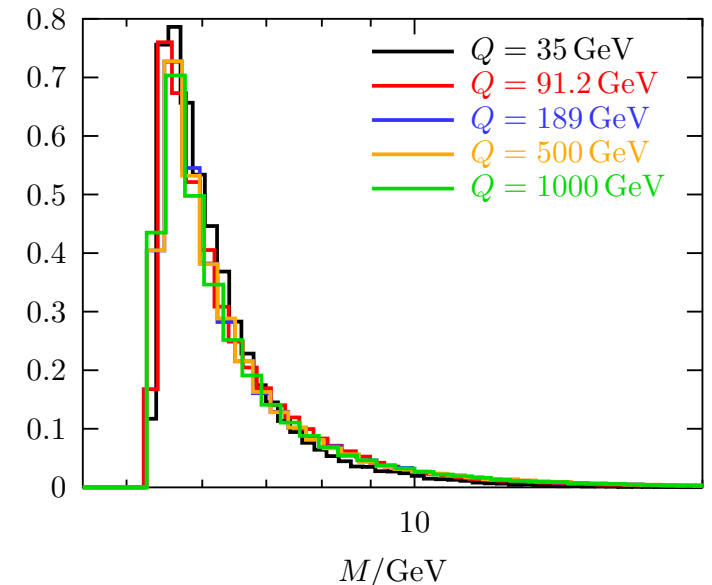
$$P(a_{i,q}, b_{q,j} | i, j) = \frac{W(a_{i,q}, b_{q,j} | i, j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j} | i, j)}.$$

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

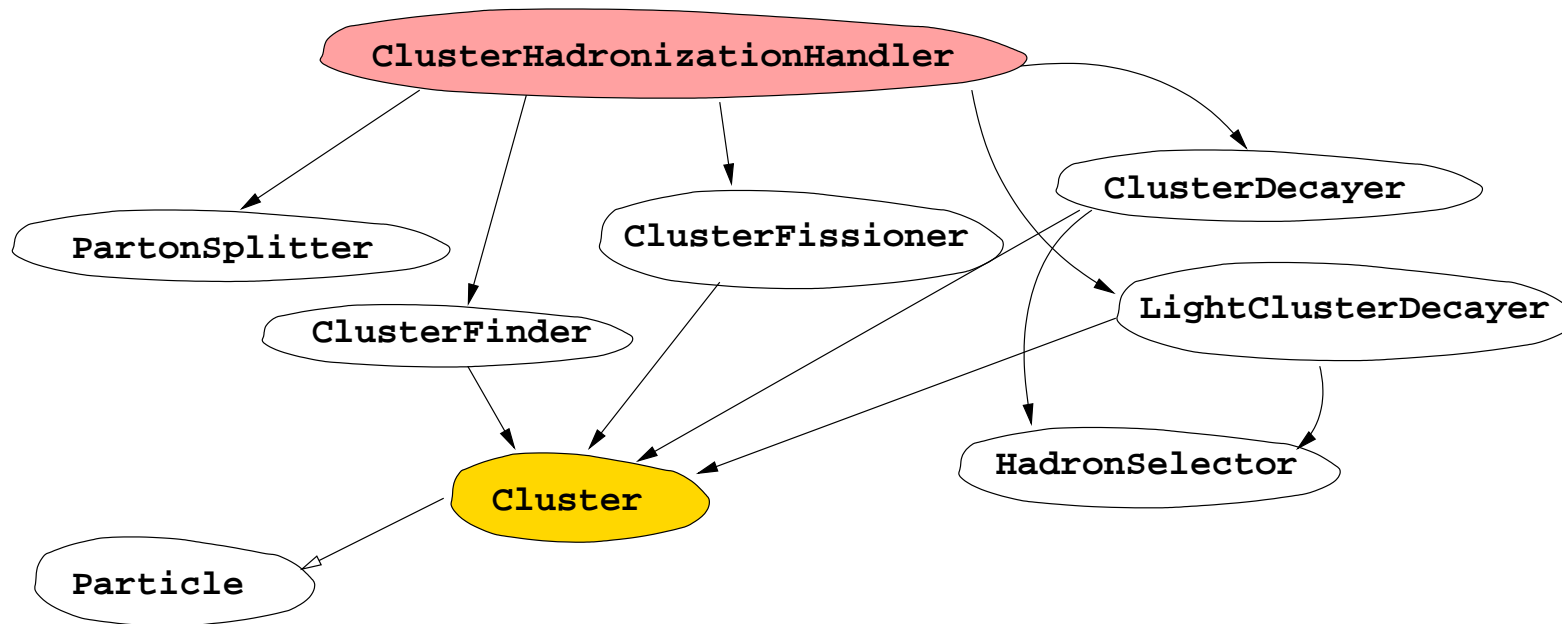
Primary Light Clusters



Primary b-Clusters

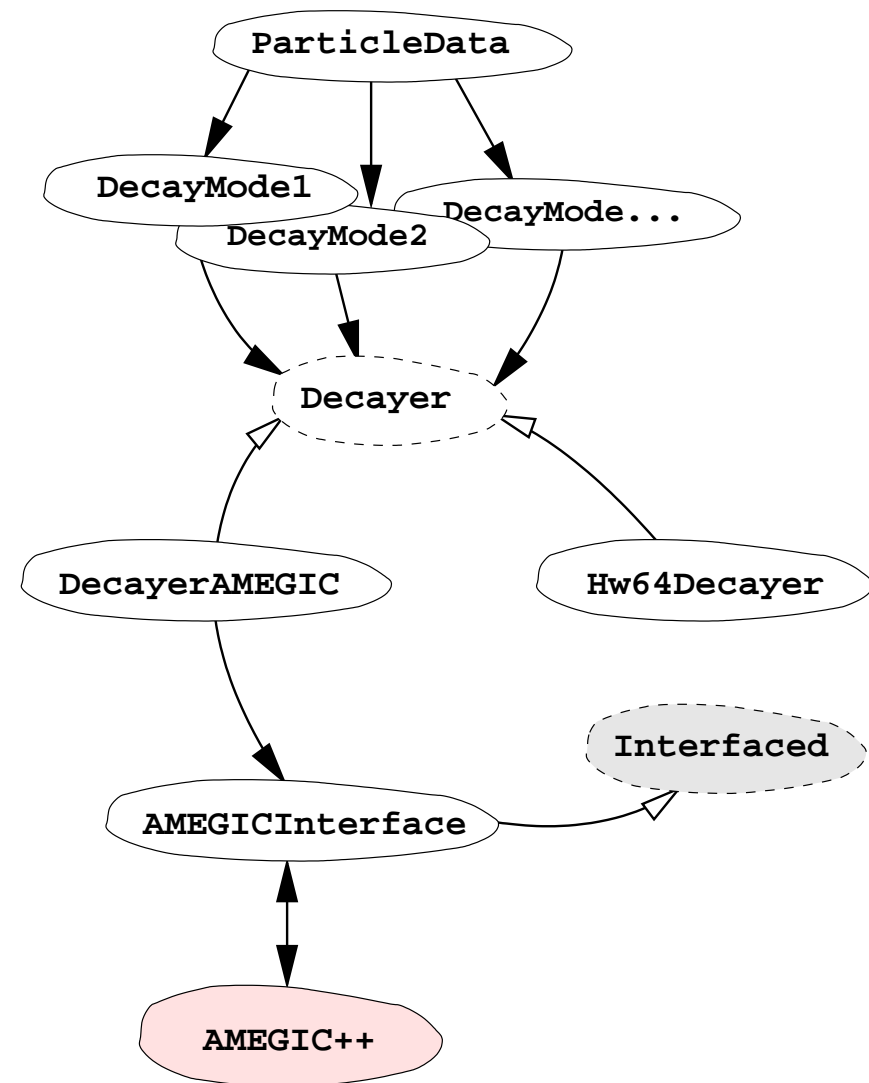


ClusterHadronization



- Cluster hadronization is designed, implemented and debugged.
- **HadronSelector** / **ClusterDecayer** in different ways.
- Tests ongoing.
- Lund string model is implemented already in **Pythia7** and will work together with **Herwig++**.
- This requires that final state gluons are on-shell \longrightarrow foreseen in shower.

Particle Decays



- FORTRAN HERWIG is reproduced with **Hw64Decayer** using the same matrix element codes as before (used for hadronic decays right now).
- **DecayerAMEGIC** gets final states for a decay mode directly from **AMEGIC++**.
- Works fine in principle, further tests required.

$Z^0 \rightarrow$ Hadron Multiplicities

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

$Z^0 \rightarrow$ 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*

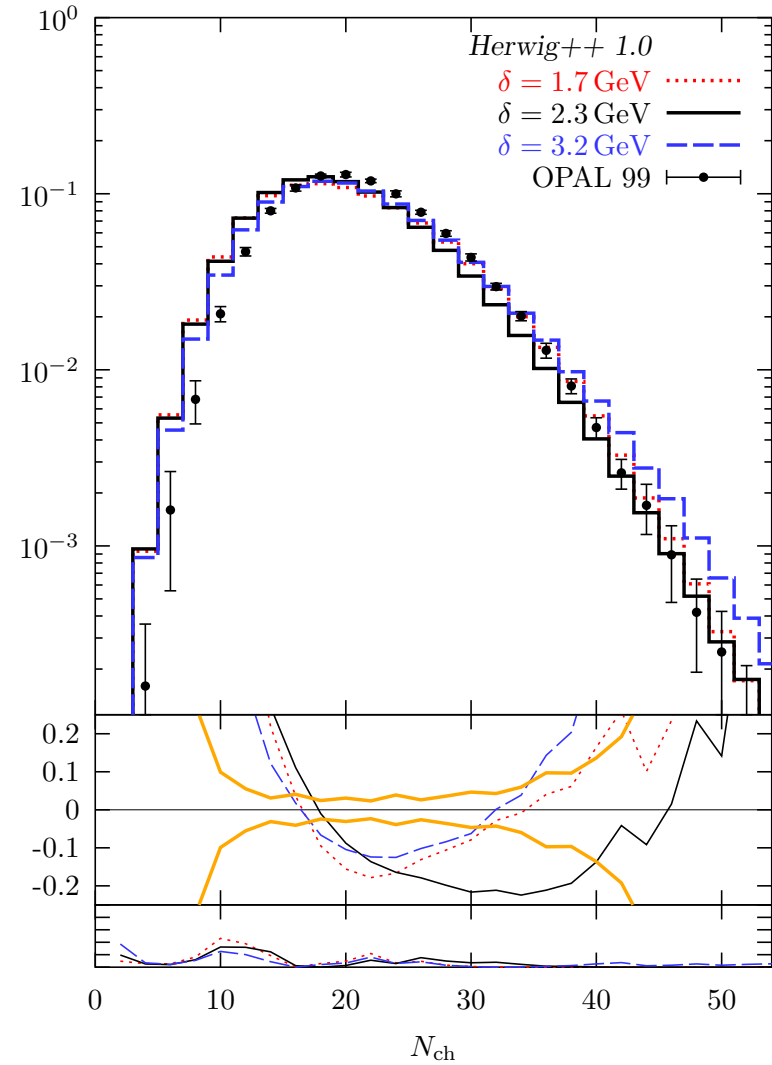
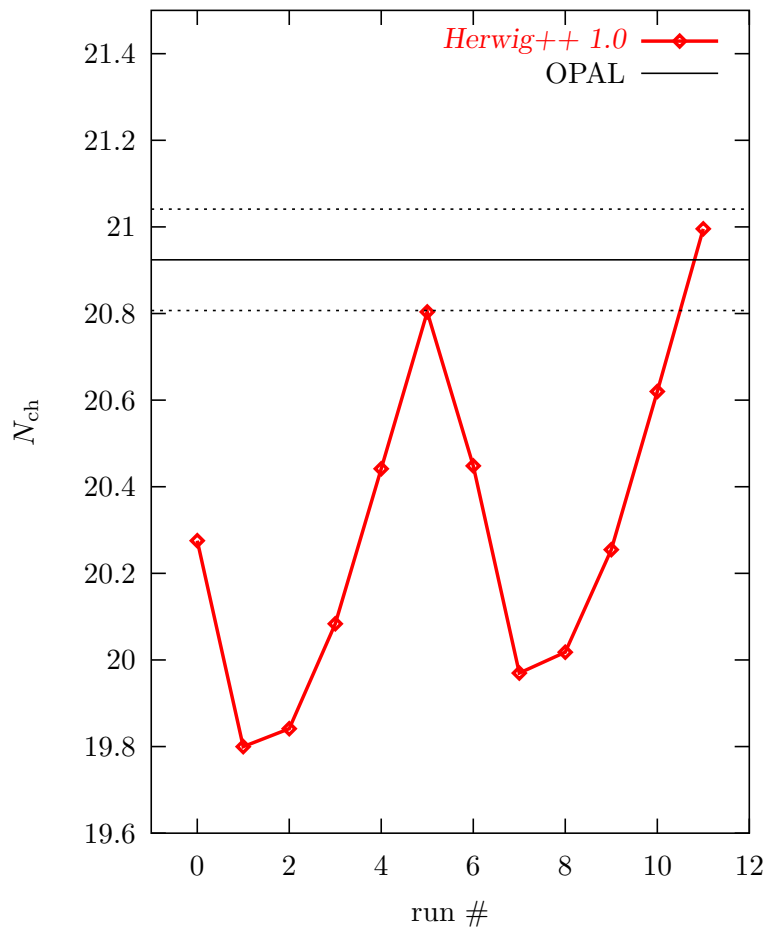
of *'s = observables with more than 3σ deviation:

Old Model : Herwig++ : Fortran = 9 : 7 : 13

N.B. No systematic parameter tuning yet.

Charged Particle Multiplicity

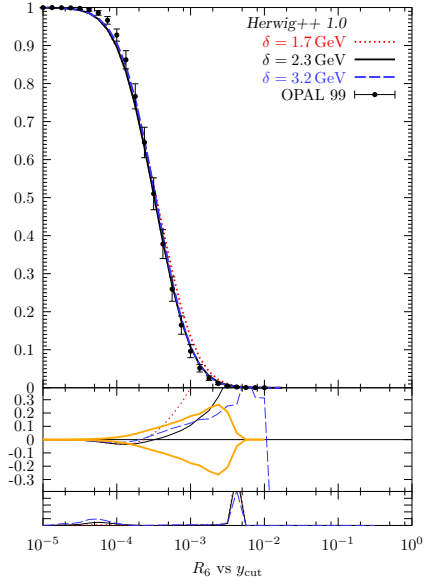
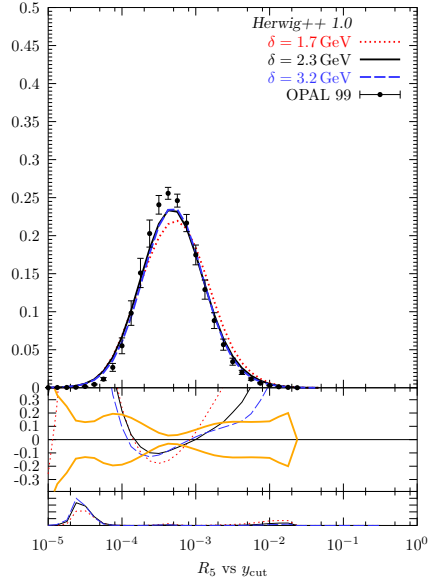
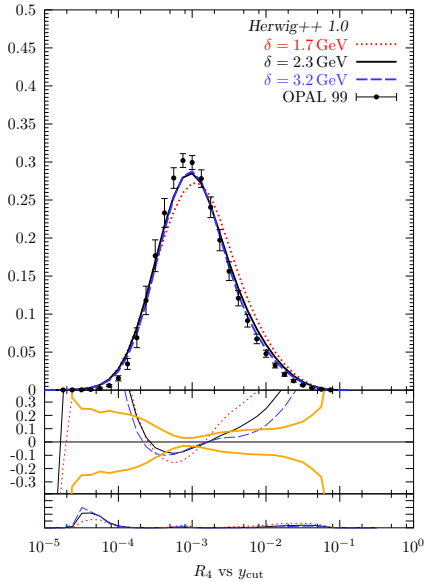
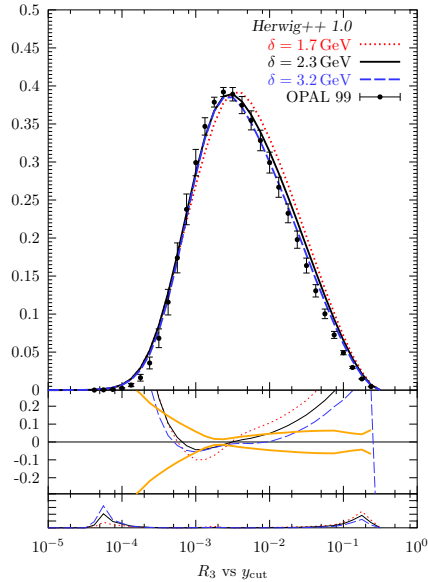
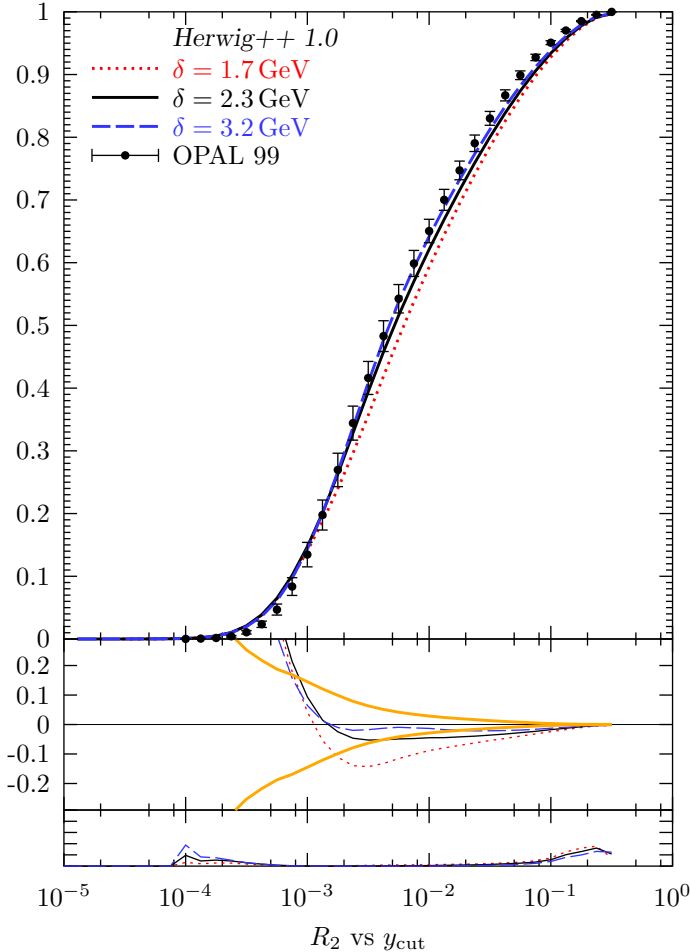
Good indicator for quality of hadronization.
Still very sensitive to shower cutoff:



Jet Rates (Durham/ k_T Algorithm)

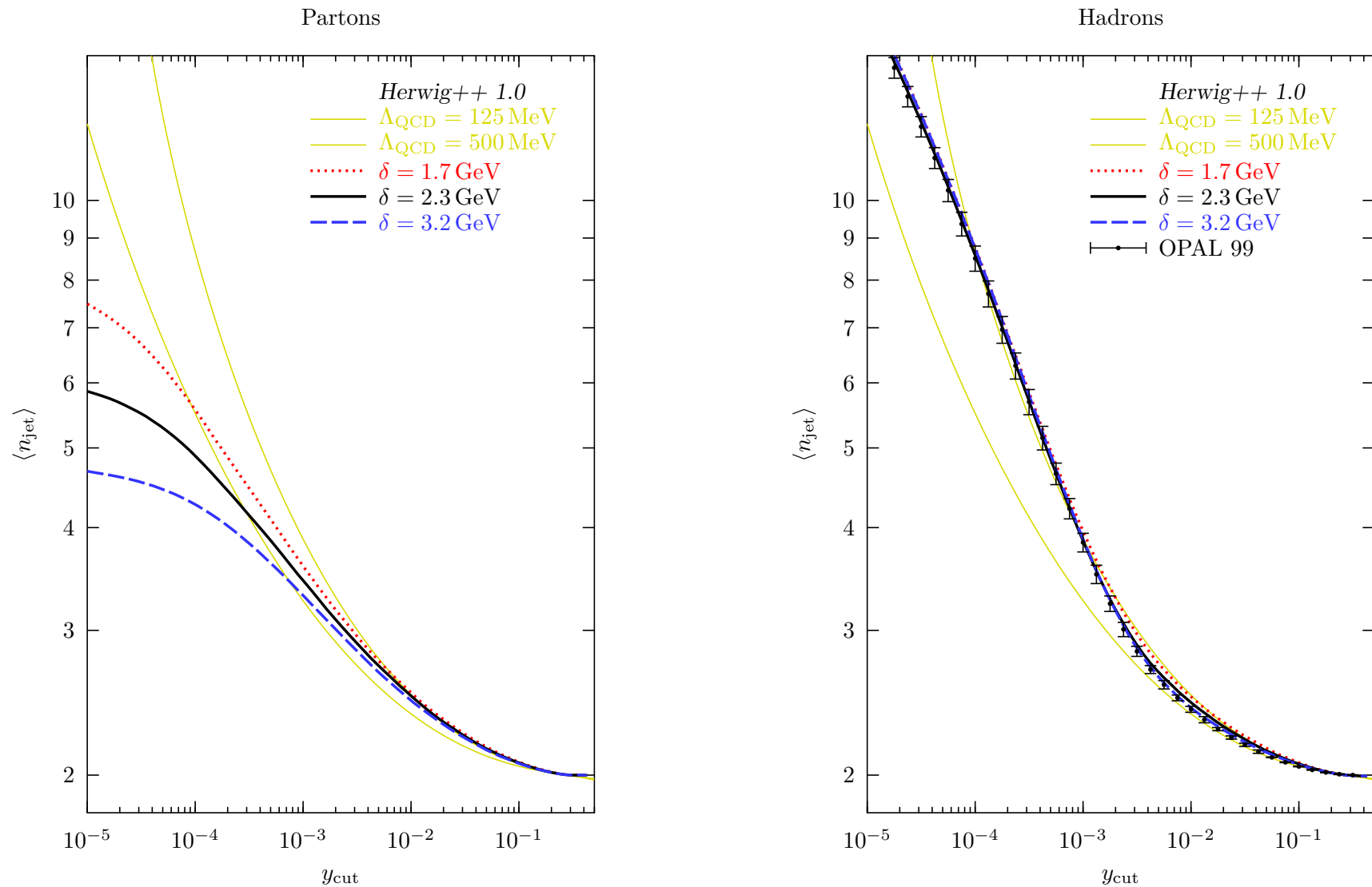
$$R_n = \sigma(n\text{-jets}) / \sigma(\text{jets}) \quad (n = 2..5)$$

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



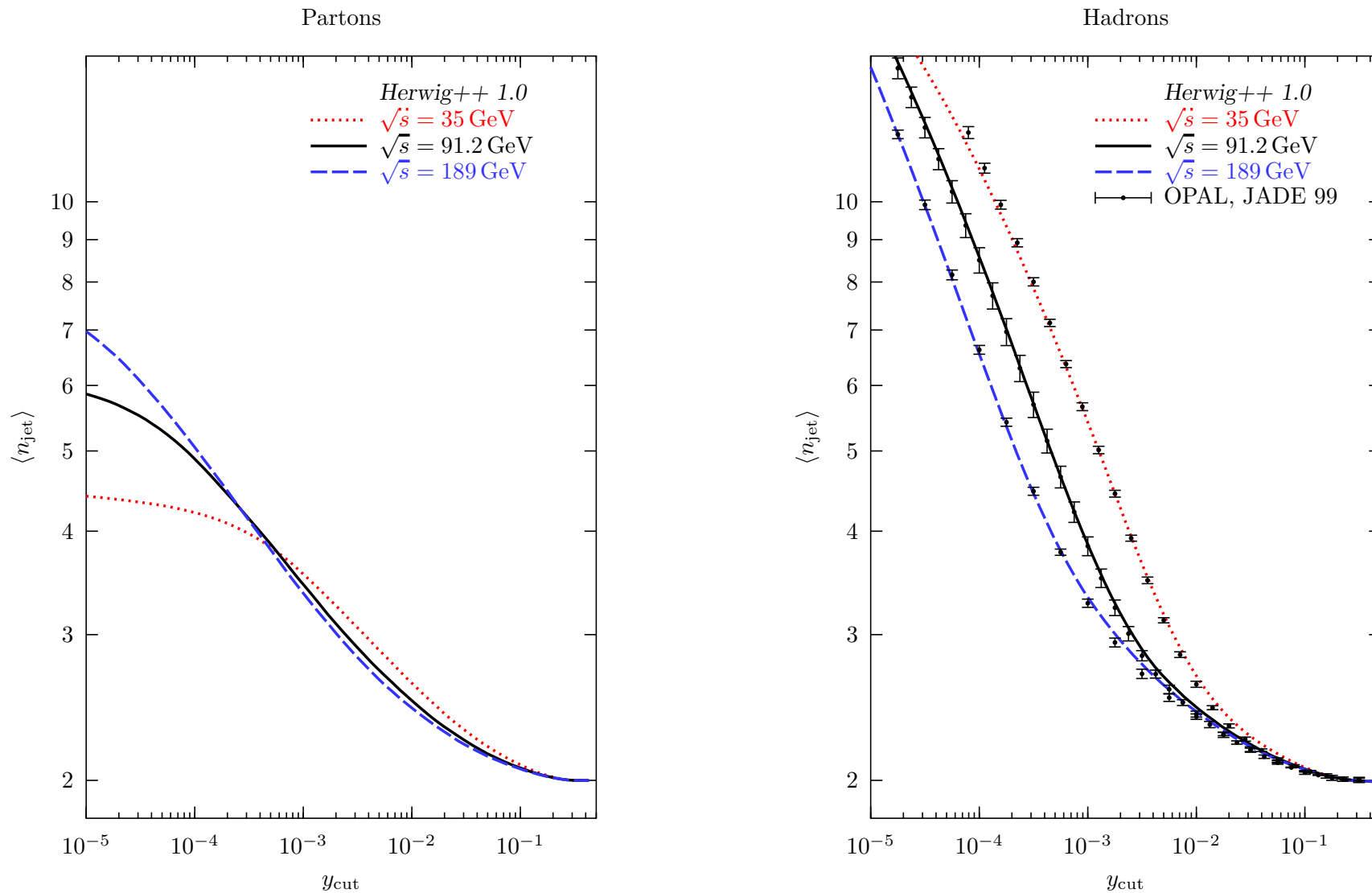
Jet Multiplicity

Cutoff dependence largely cancels 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

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

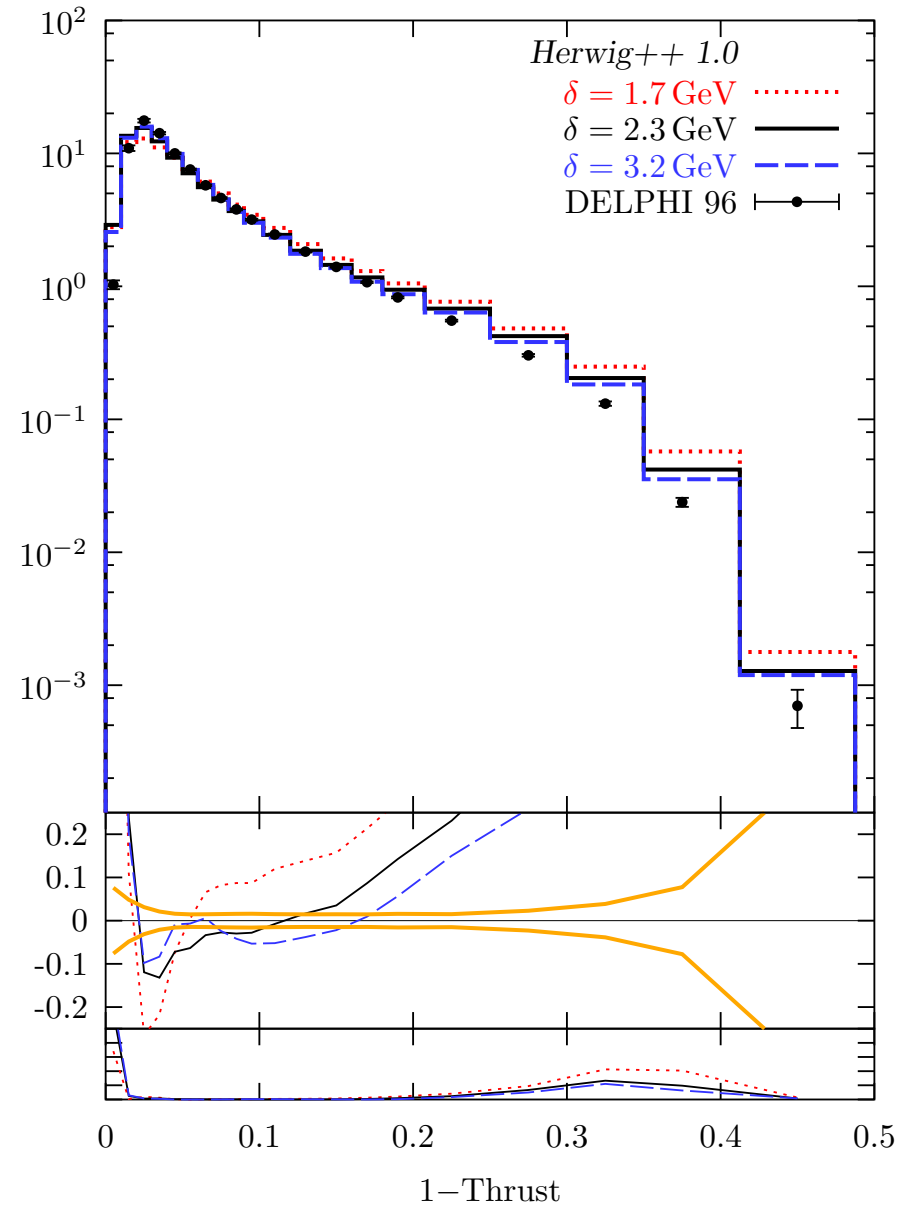
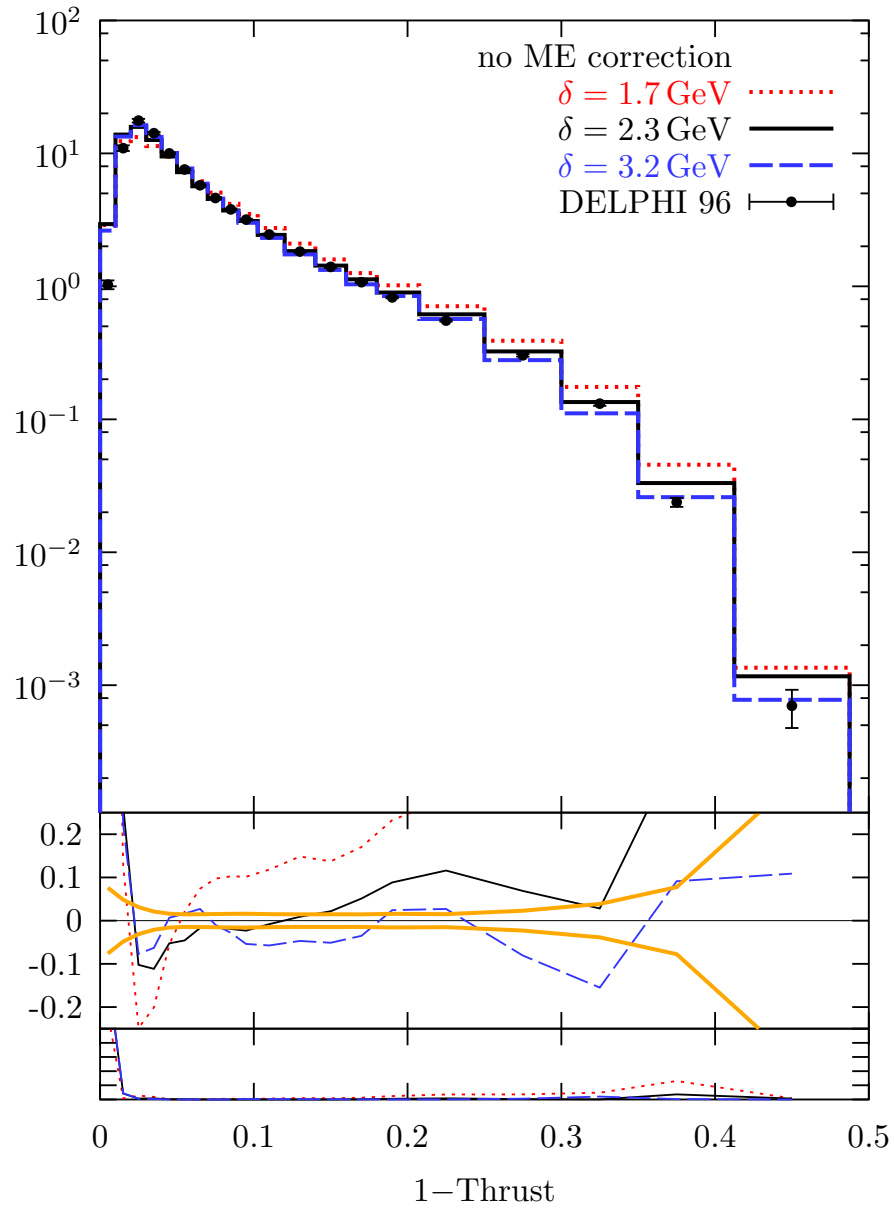
Diagonalize, eigenvalues

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

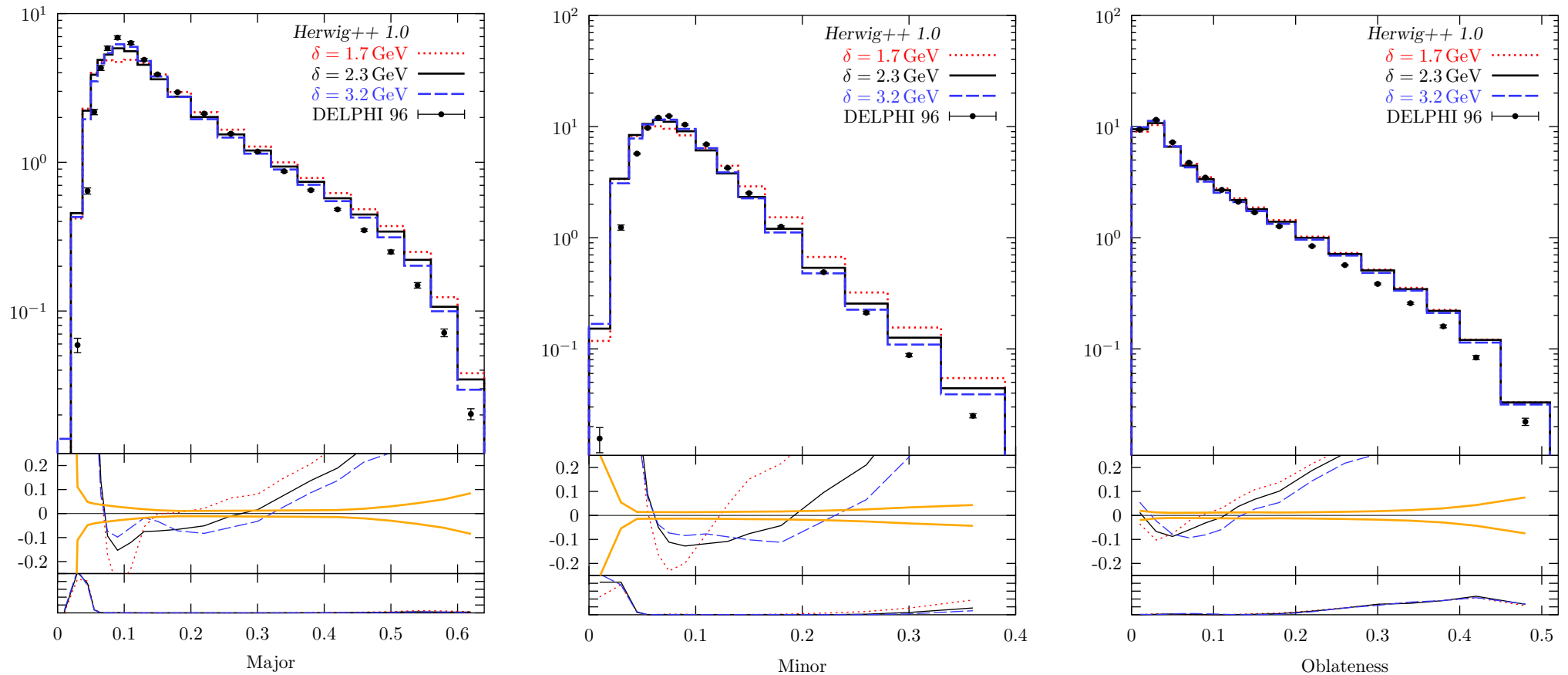
and define

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

Thrust — ME Corrections off/on

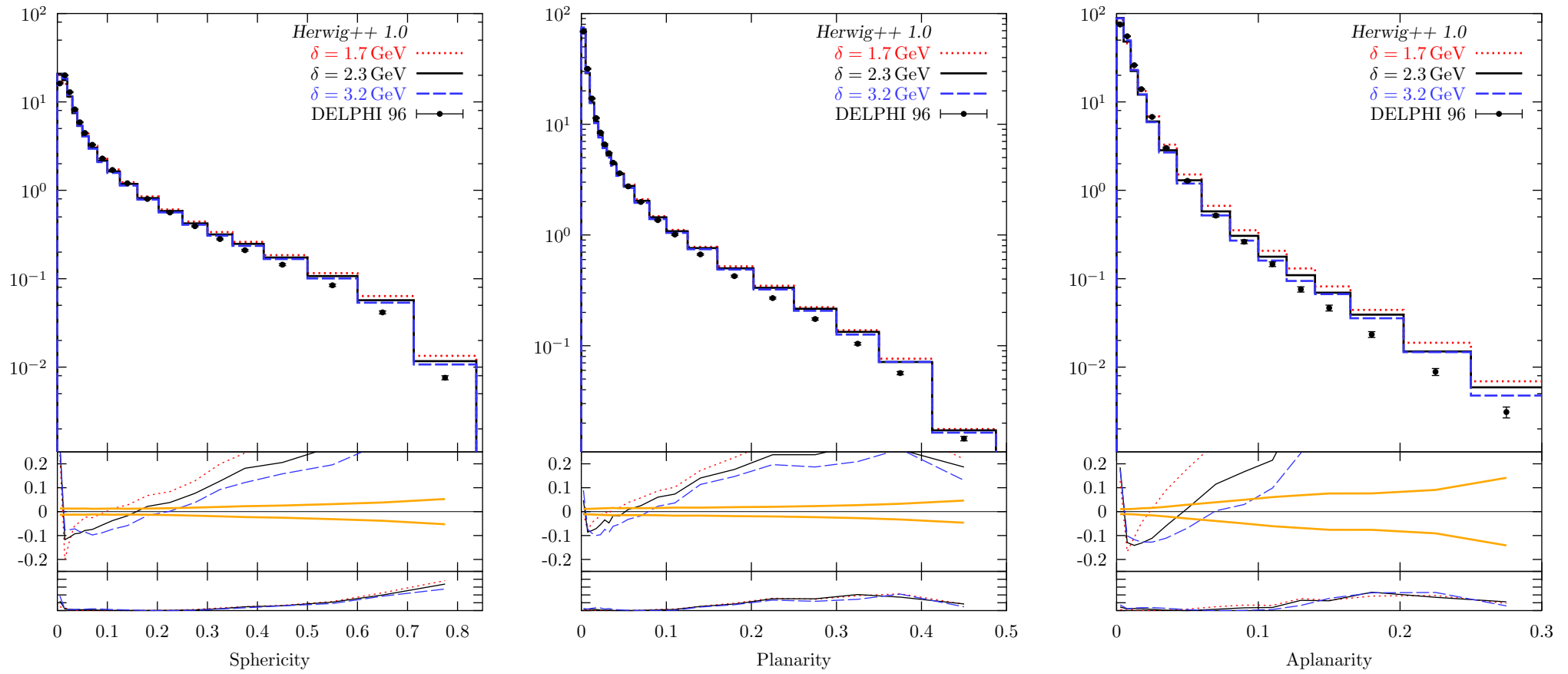


Major, Minor, Oblateness



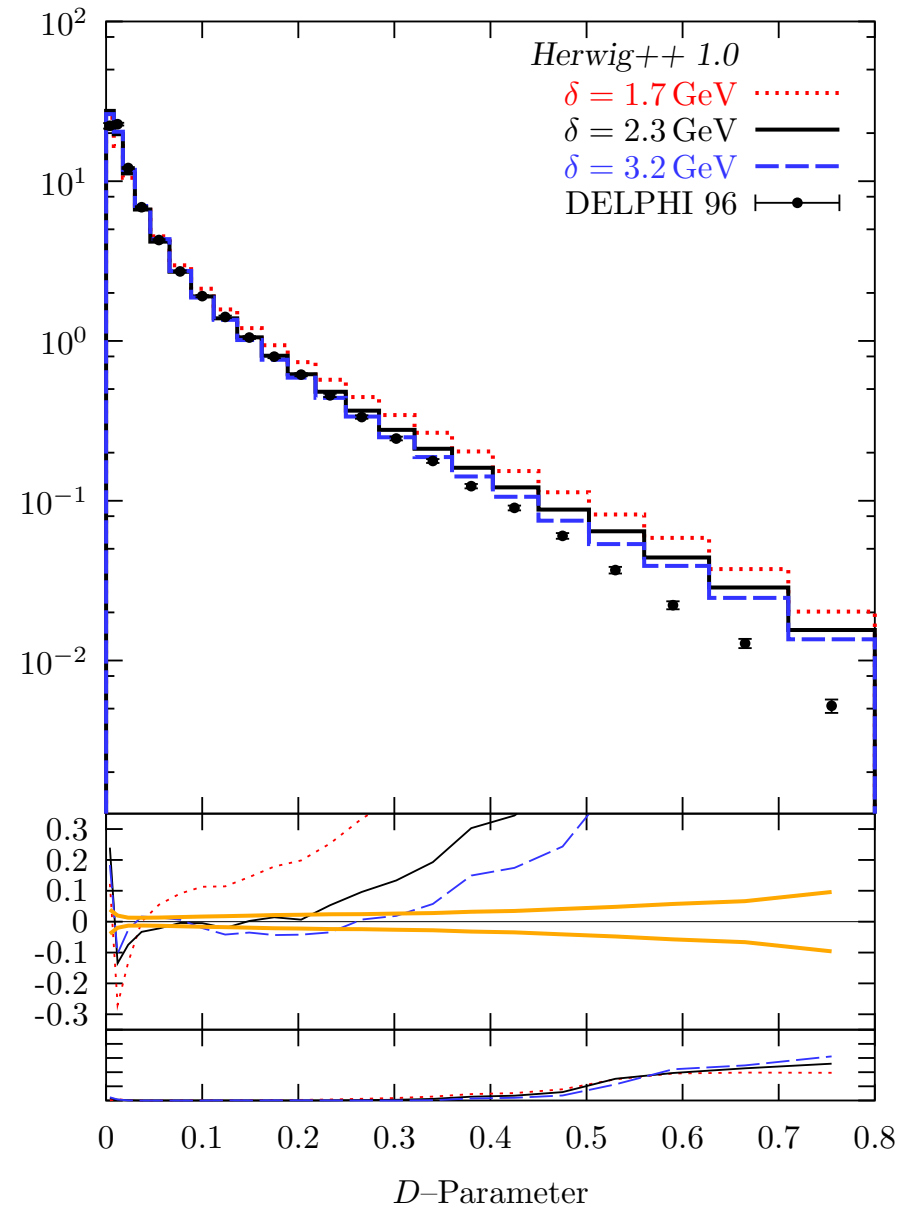
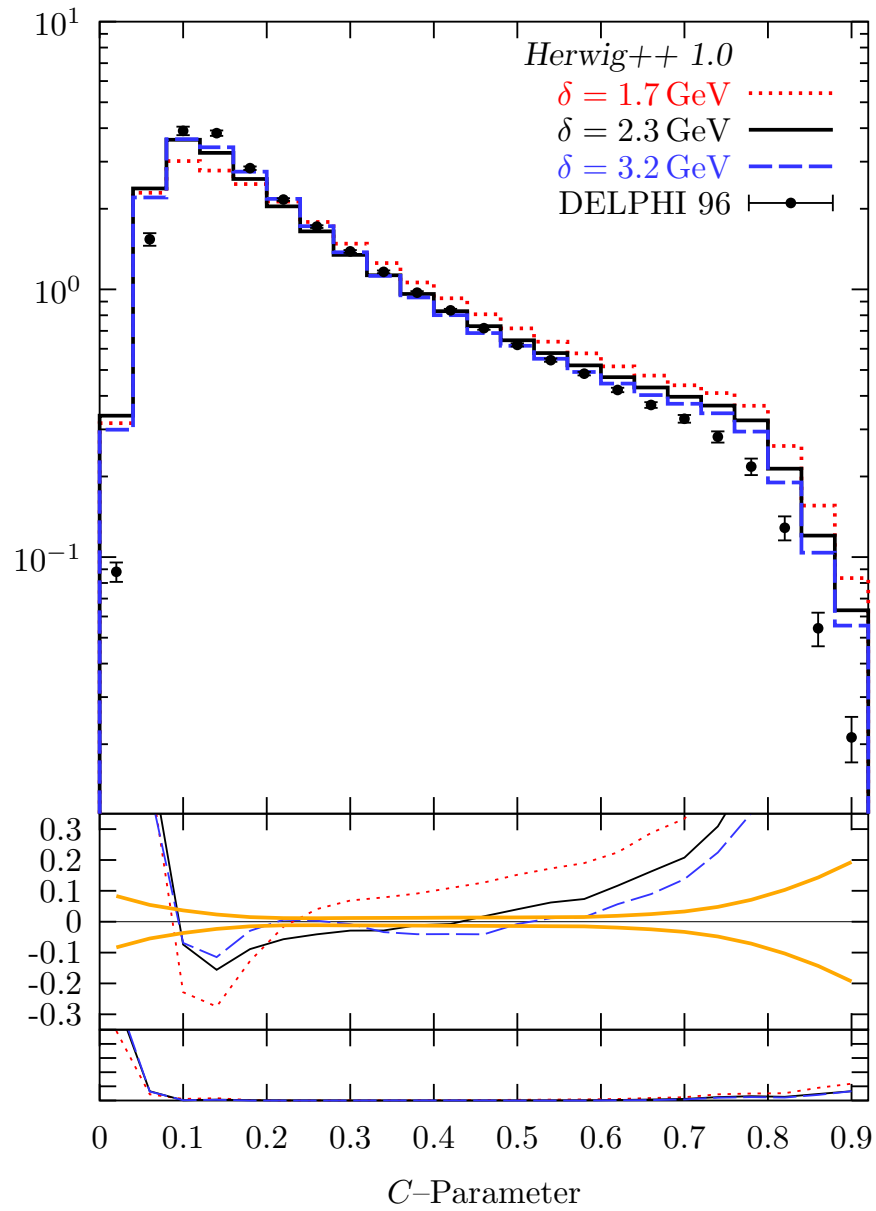
All Thrust-related distributions slightly wide, ie too many 2-jet like on one side and too many spherical events on the other side.

Sphericity, Planarity, Aplanarity



More emphasis on large momenta in quadratic tensor.

C and D parameter



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

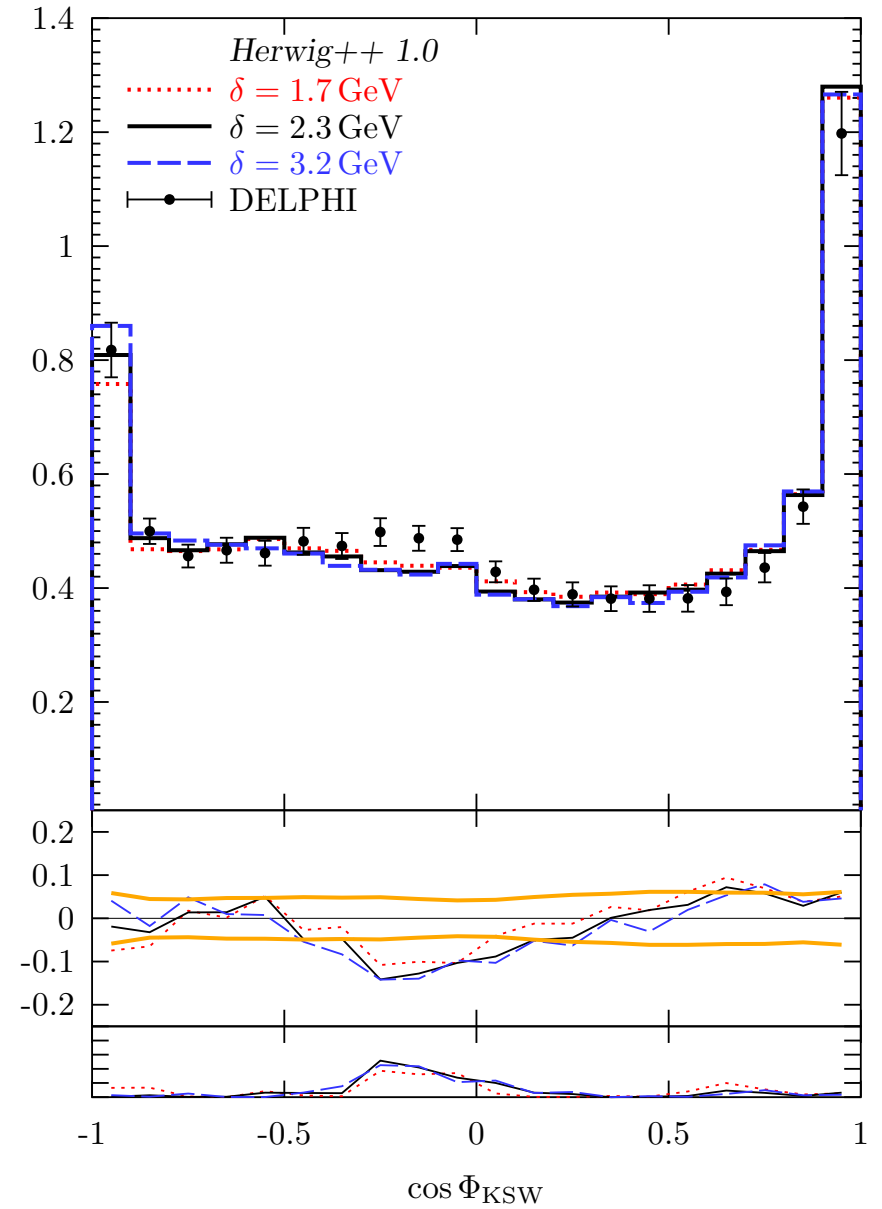
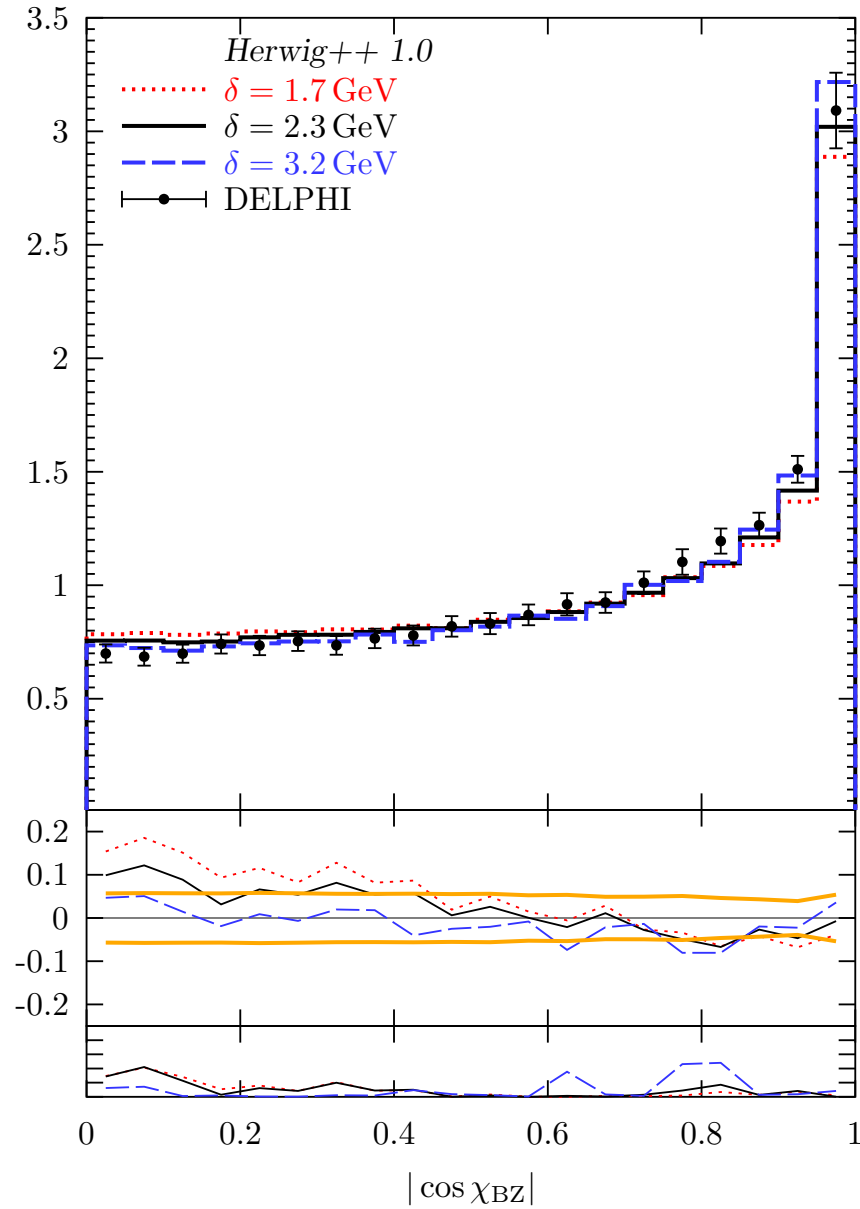
$$\theta_{NR}^* = \angle(\mathbf{p}_1 - \mathbf{p}_2, \mathbf{p}_3 - \mathbf{p}_4)$$

- Angle between softest jets

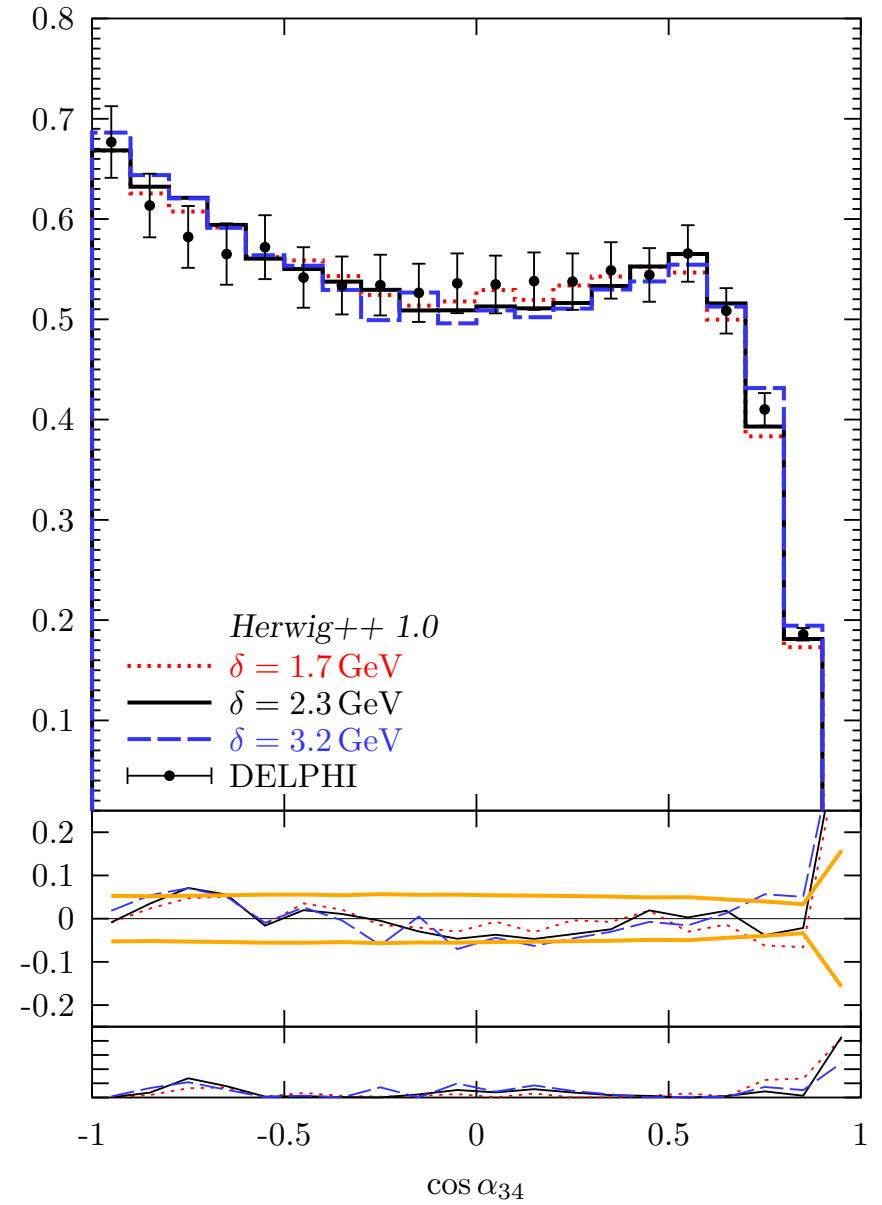
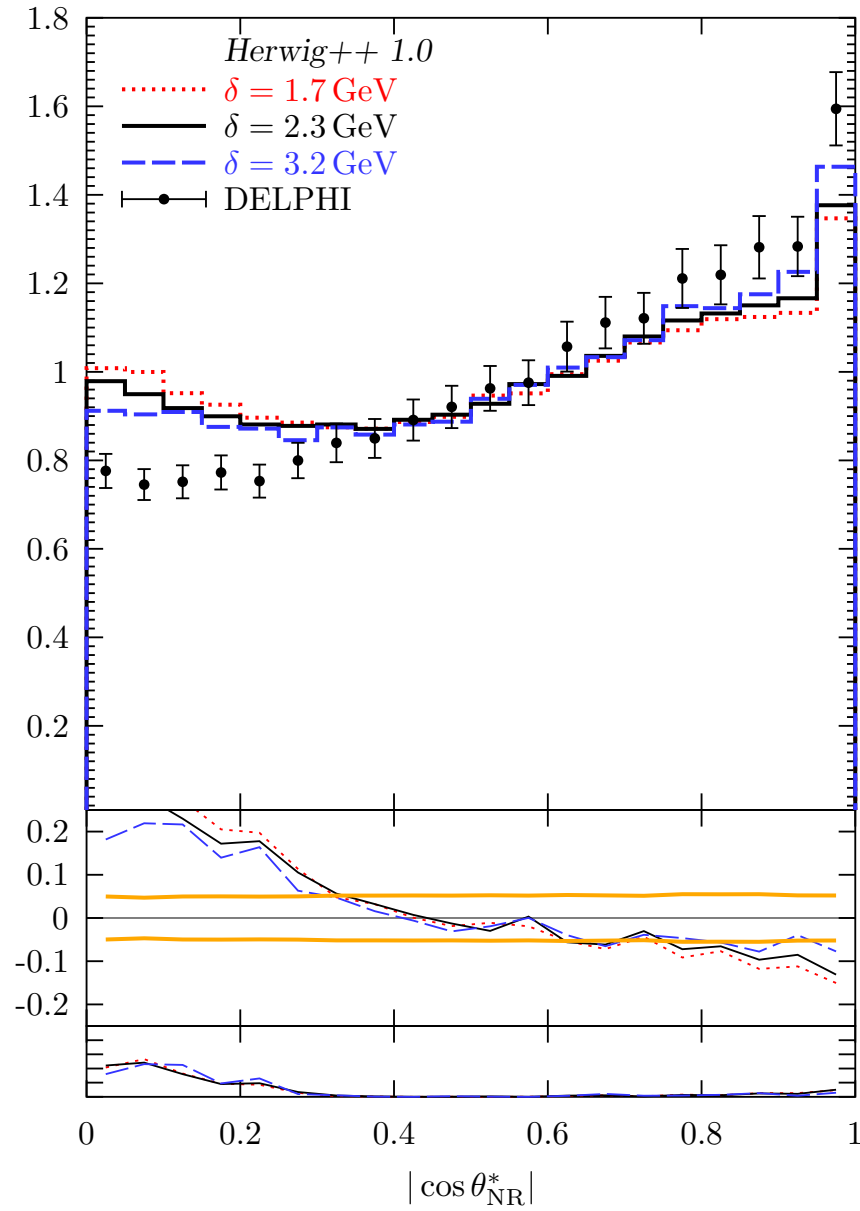
$$\alpha_{34} = \angle(\mathbf{p}_3, \mathbf{p}_4)$$

N.B. No four-parton ME in Herwig++ (yet).

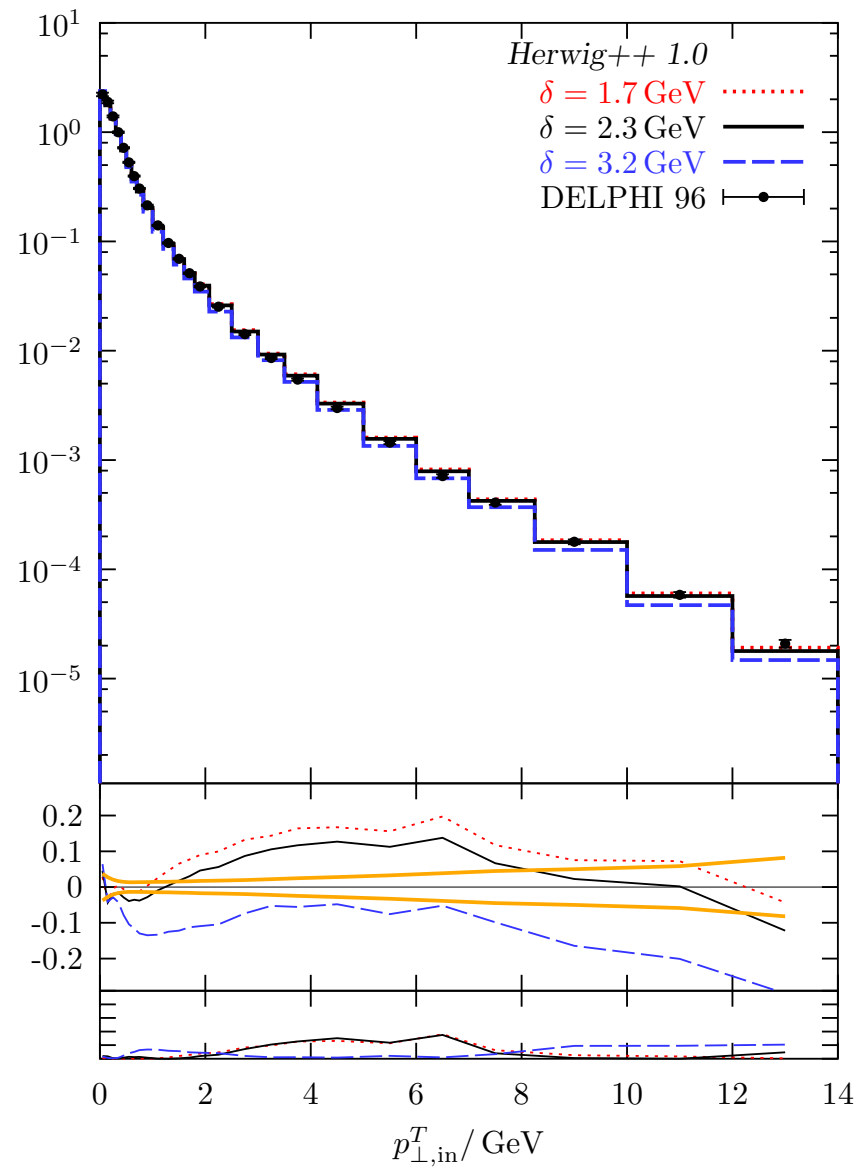
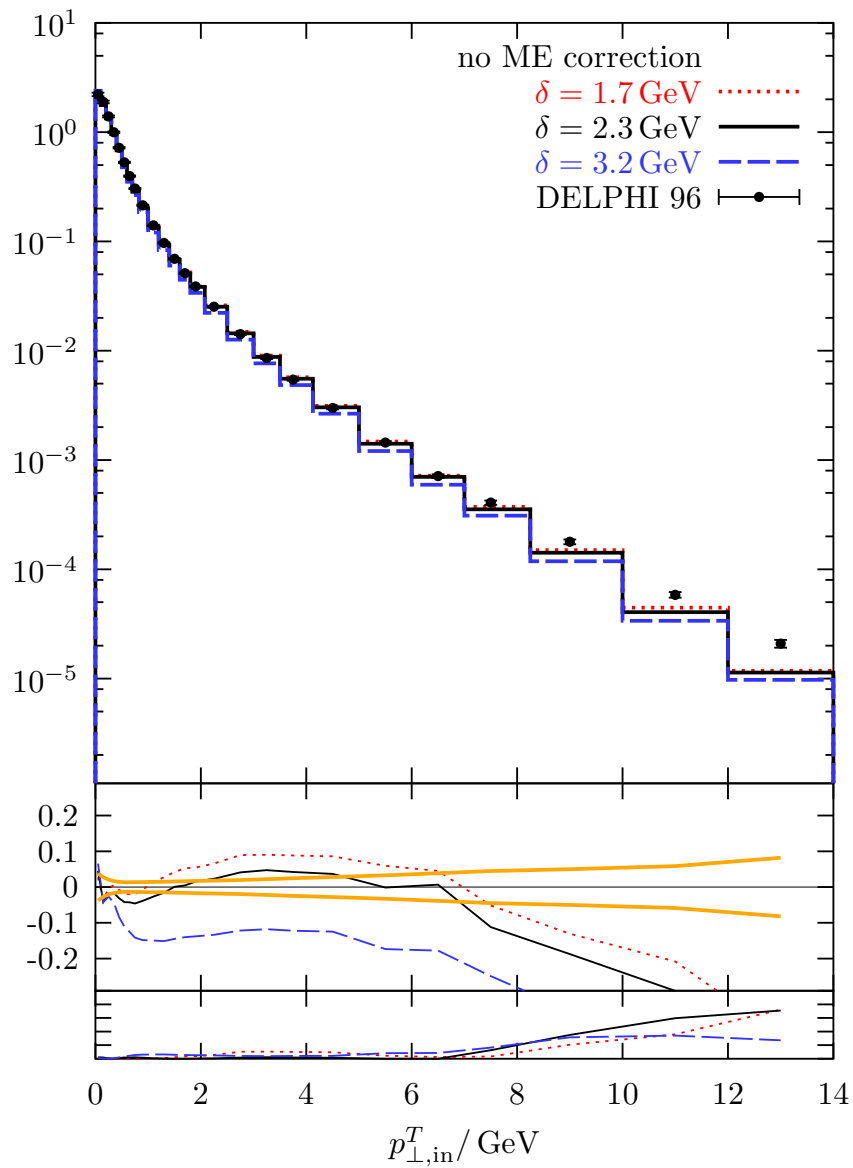
Four-Jet Angles I



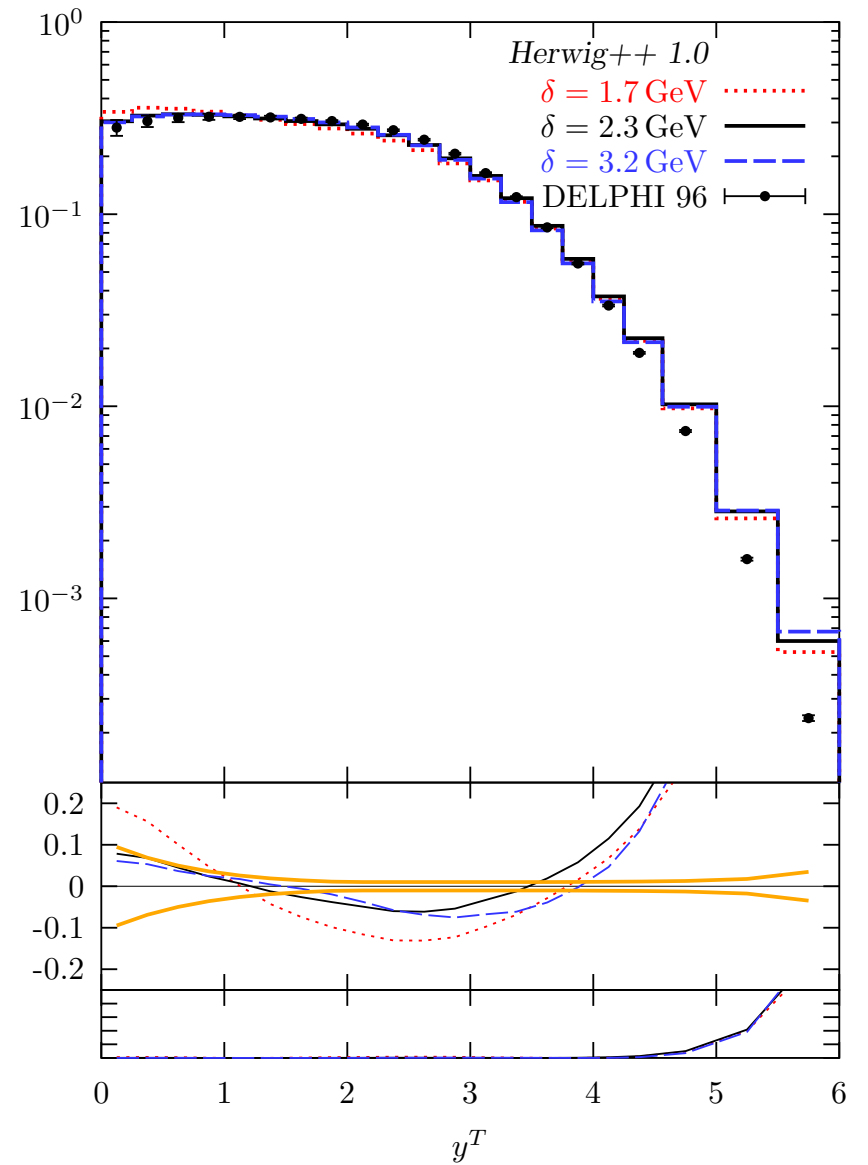
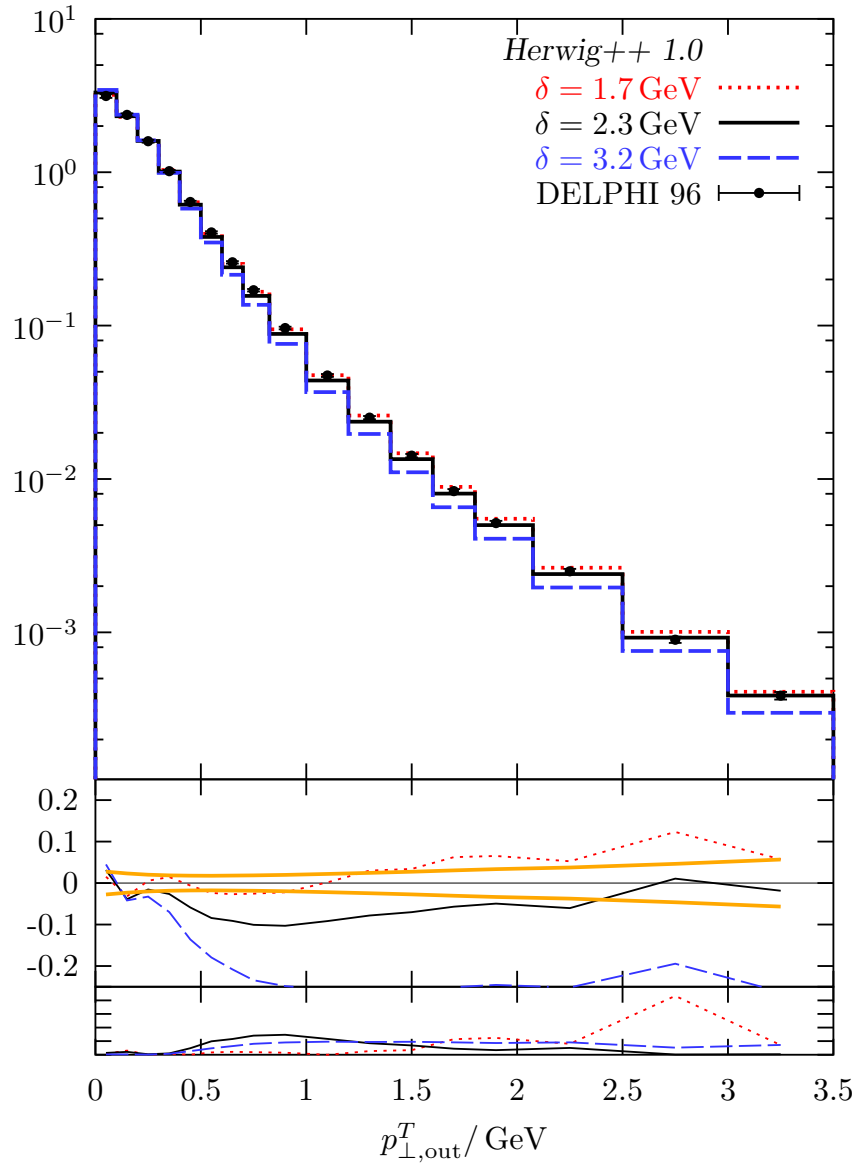
Four-Jet Angles II



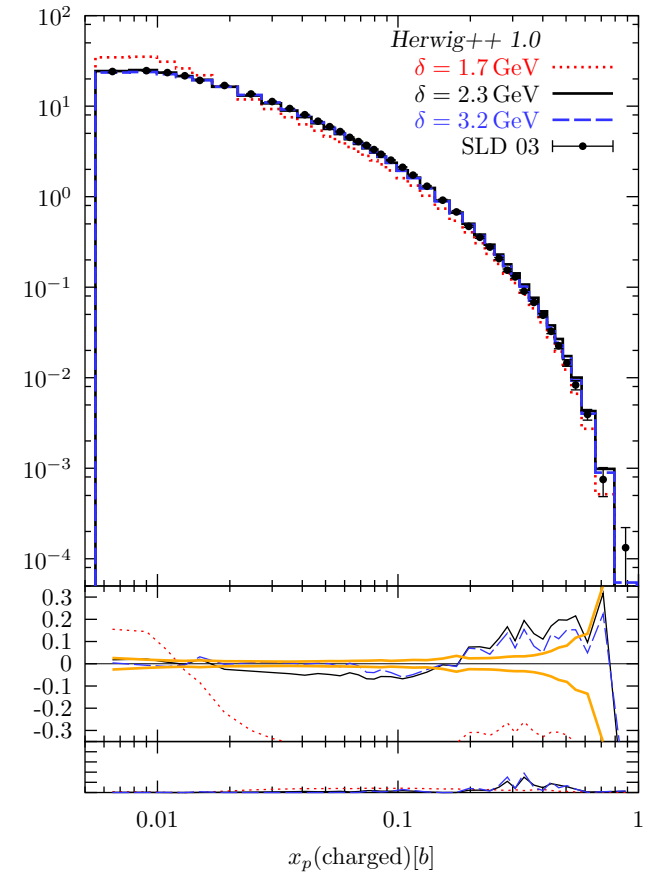
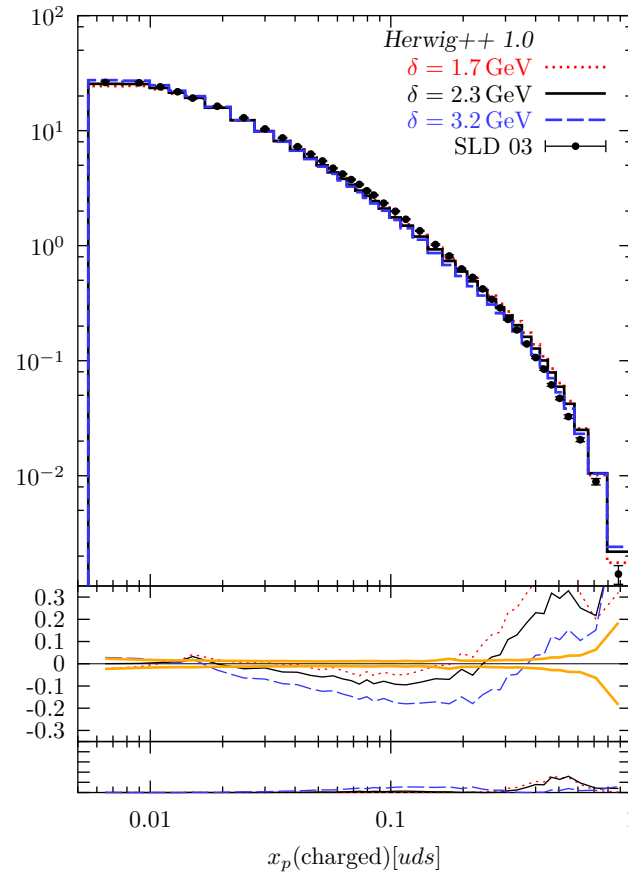
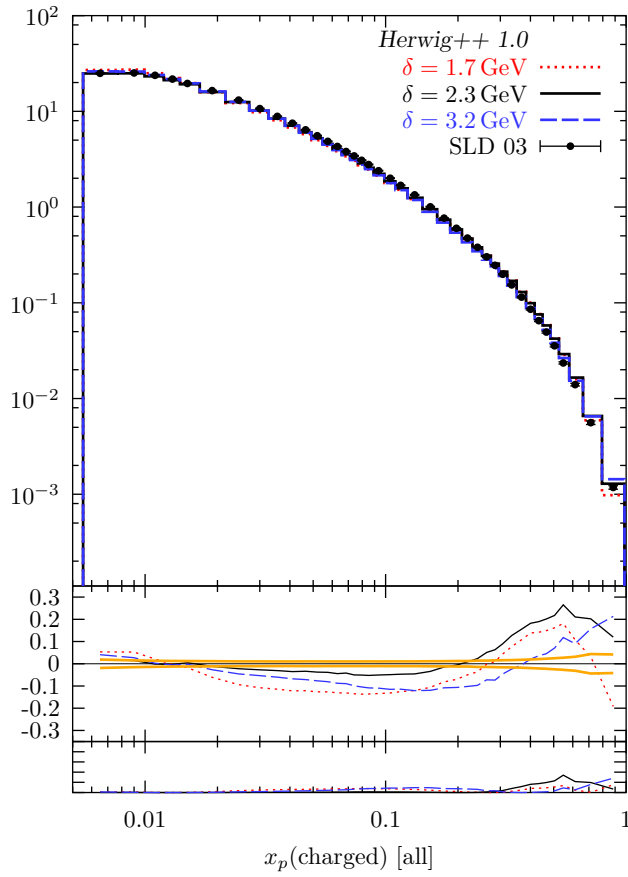
Single particle distributions: $p_{\perp,in}^T$



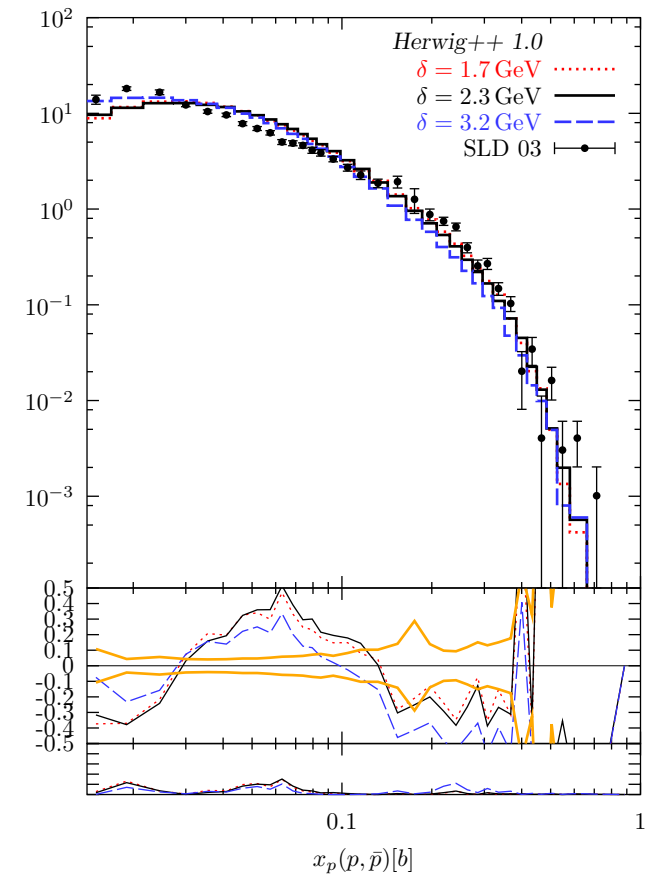
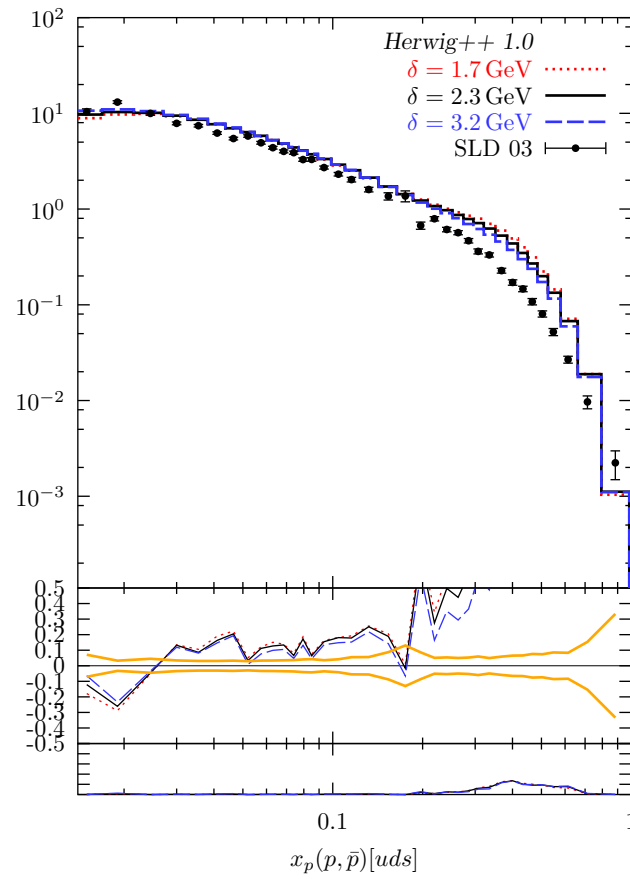
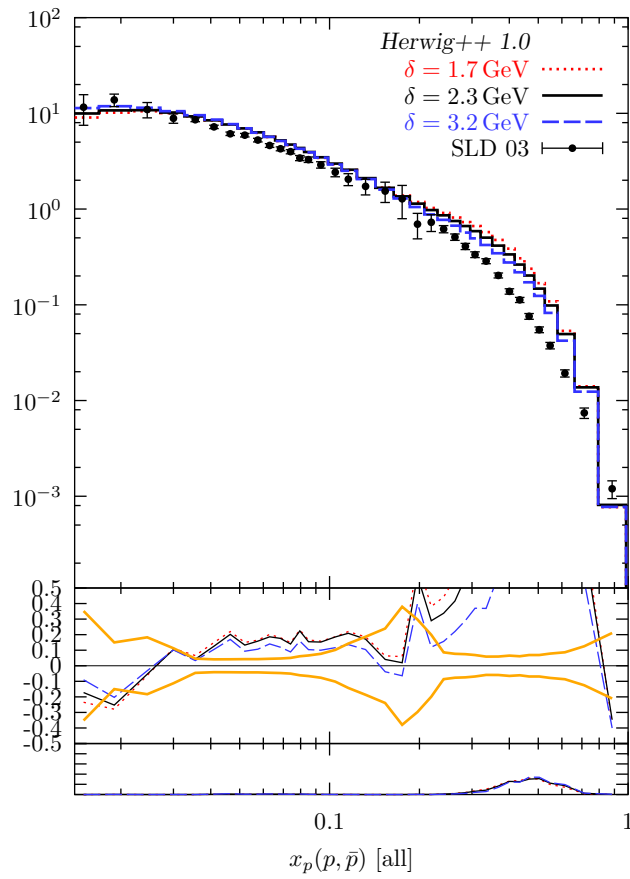
$p_{\perp, \text{out}}^T$ and y^T



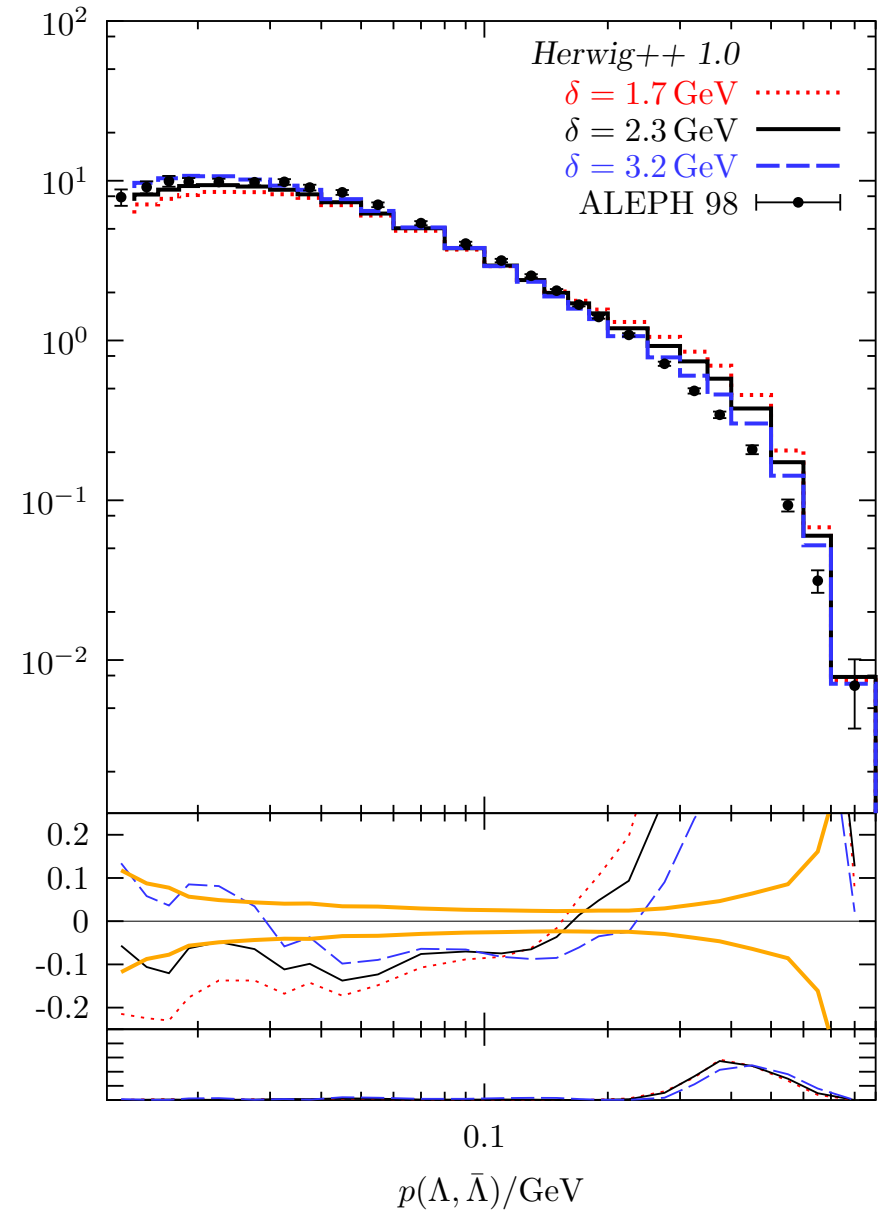
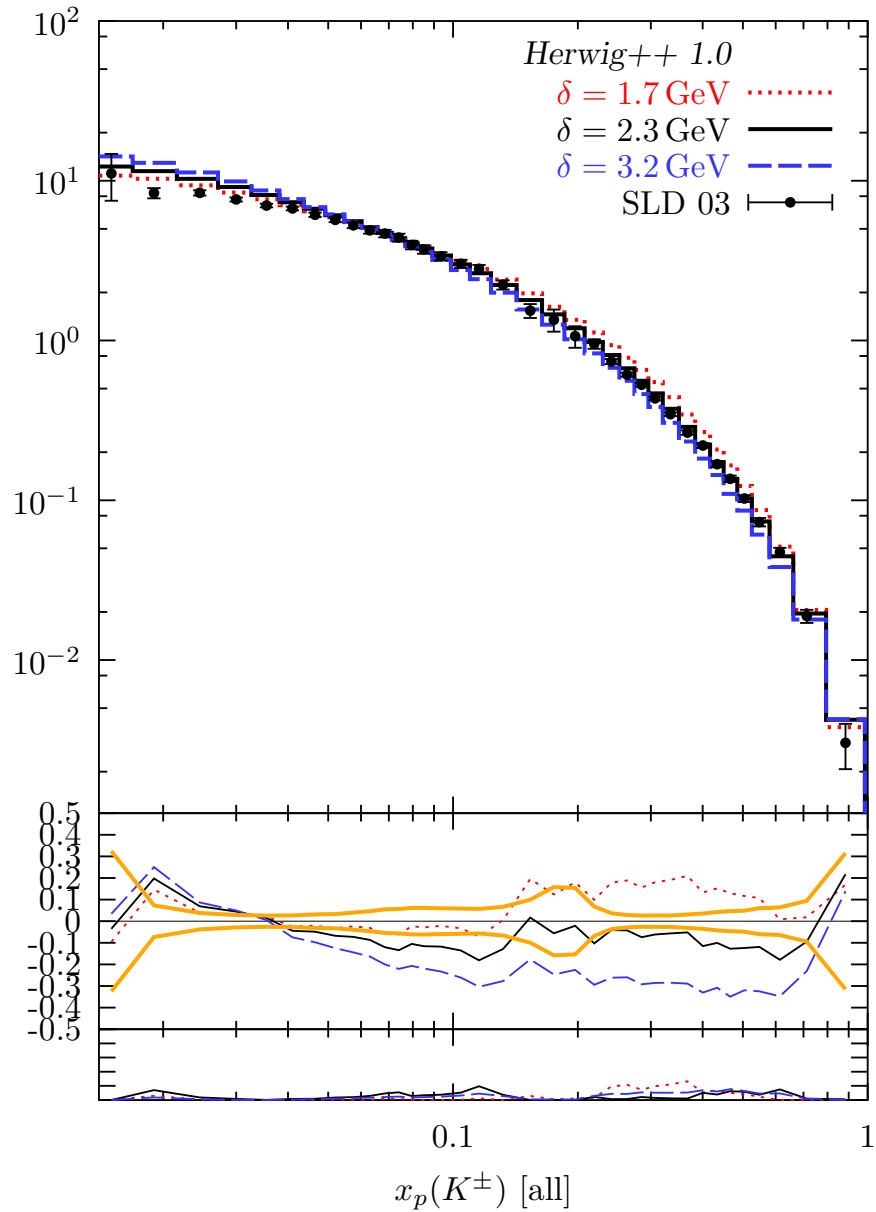
Scaled momentum (all, uds , b)



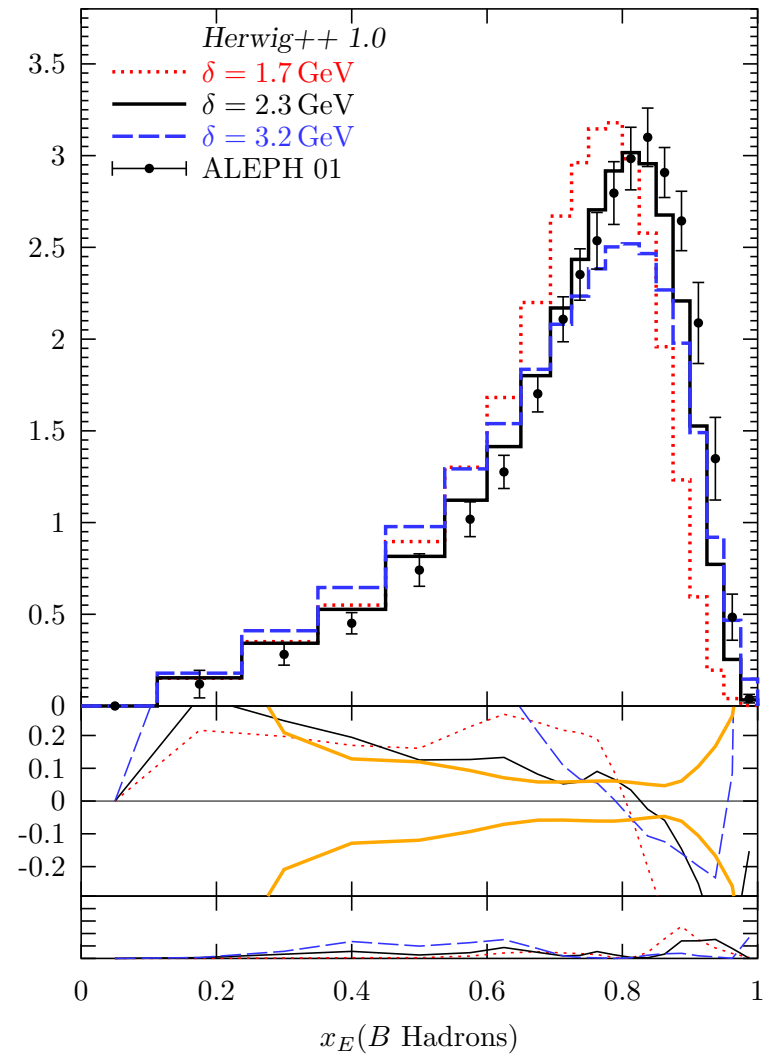
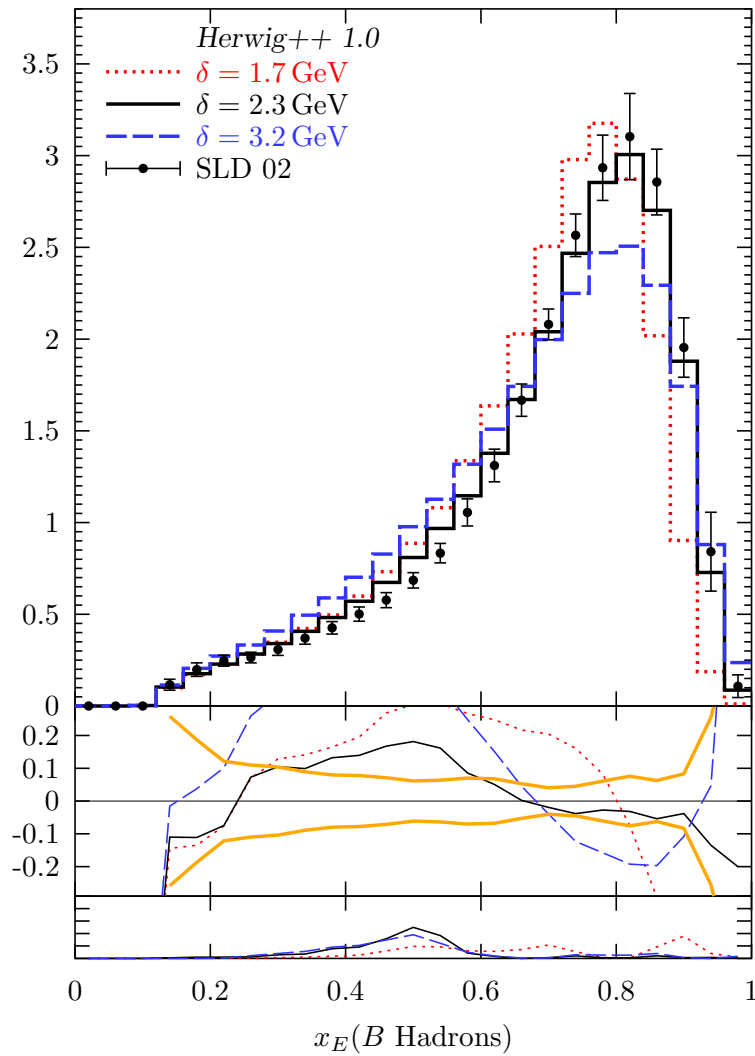
Proton momentum (all, uds , b)



$K^\pm, (\Lambda, \bar{\Lambda})$ momentum



B -fragmentation function



Only parton shower parameters varied!

Recommended parameters

No systematic parameter tuning yet.

- 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_n .
- 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 $\alpha_s(Q_{\min})$	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 _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

Status of Herwig++

S. Gieseke, A. Ribon, M.H. Seymour, P. Stephens, B.R. Webber
(Cambridge, Manchester, CERN)

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

Hard Matrix Elements

- Only simple $2 \rightarrow 2$ ME so far.
- Hard and soft ME corrections for $e^+e^- \rightarrow q\bar{q}g$.
- We have a working interface to AMEGIC++. For e^+e^- this will do the job for up to 6 jets.
- CKKW ME+PS matching algorithm will be implemented.
- More processes straightforward.
- Users can easily and safely include their own matrix elements.

Parton Shower

- New parton shower developed.
- Multiscale shower designed for treatment of unstable particles (no physics implementation yet).
- New evolution variables for better treatment of heavy quarks and smooth coverage of phase space.
- Extension to spacelike shower for pp and ep ongoing.

Status of Herwig++ (ctnd')

Hadronization

- Cluster hadronization is designed and implemented completely.
- Improved cluster decays implemented and tested.
- Works very well, further thorough tests ongoing.
- Lund string fragmentation model implemented in Pythia7 will work together with Herwig++.

Decays

- Fortran HERWIG decays are reproduced with class `Hw64Decayer` using the same ME's as before.
- `DecayerAMEGIC` gets final states for decays (eg. t decay, SUSY in future) directly from AMEGIC++
- Works very well, further thorough tests required.
- More to come (`EvtGen`,. . .)?

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:
 - Can start to test Drell–Yan and jets in pp collisions.
 - Cross-check with Tevatron data and finally make predictions for the LHC.
- Underlying event.
- Hadronic decays: *NEW!* τ -decays, spin correlations (P Richardson).
- New ideas: NLO, multiscale, SUSY

Schedule?

- Ready for LHC!