News from Herwig++

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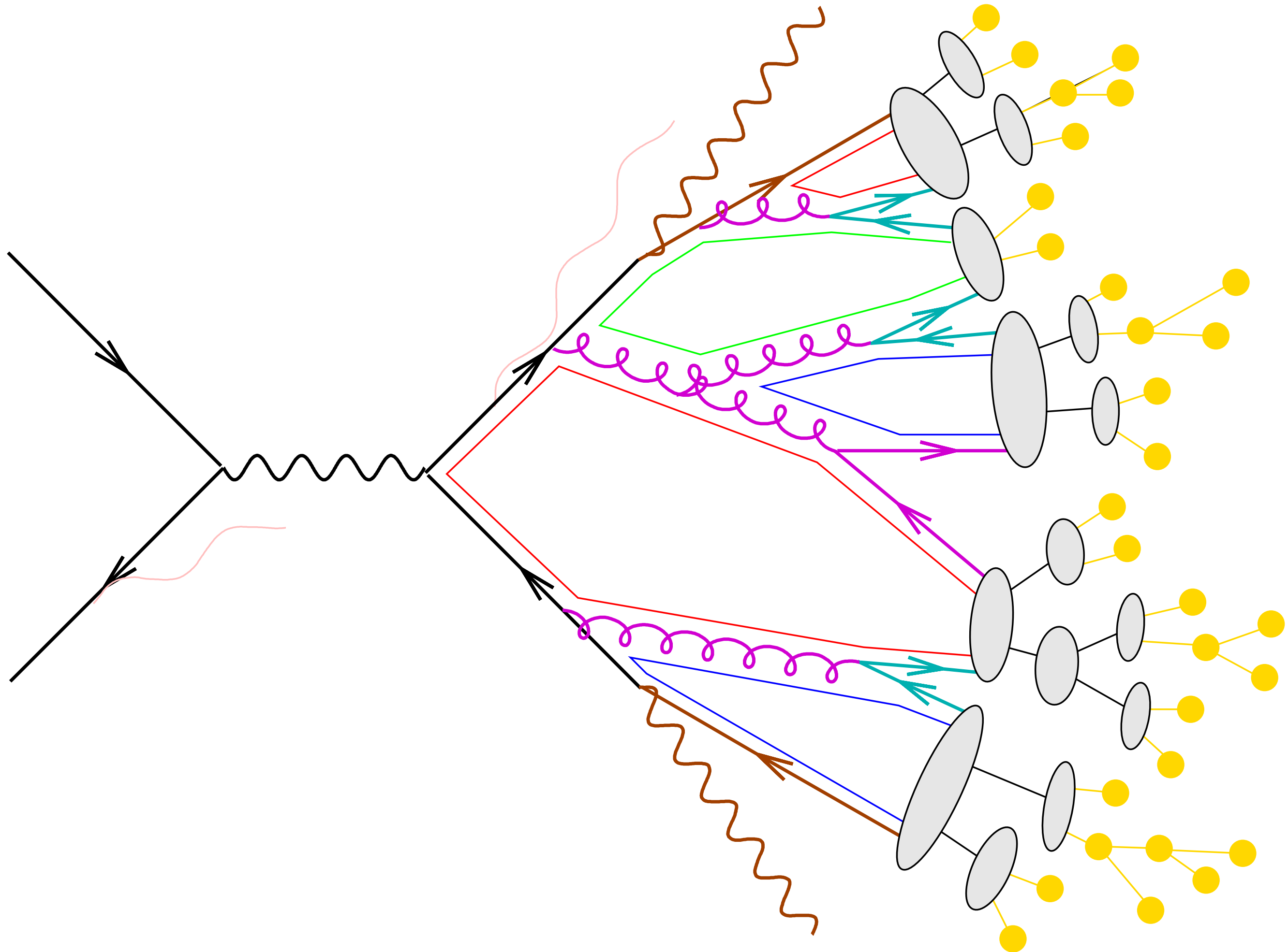
work with A Ribon, P Richardson, MH Seymour, P Stephens, BR Webber (Cambridge, Durham, CERN)

- Quick tour of Herwig++ (mainly e^+e^-)
- Jet physics, results for e^+e^- Annihilation
- Initial state shower — towards a full hadronic event generator
- New Decays
- Summary and Future

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

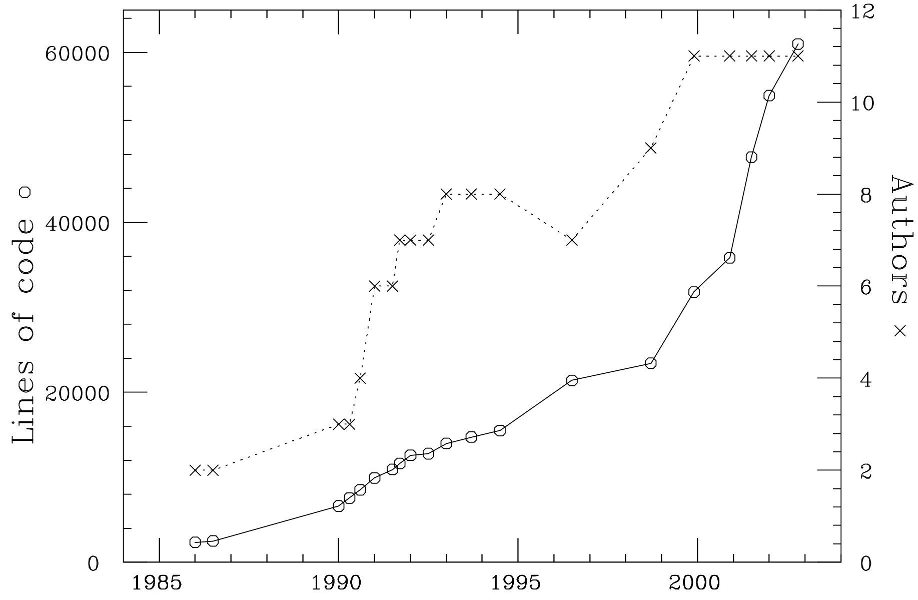


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\to$ hadrons
- hadronic decays

The new generator Herwig++

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

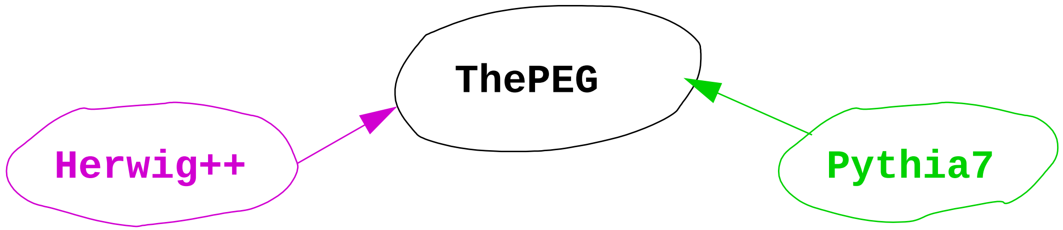
- aiming at full multi–purpose generator for LHC and future colliders.
- Preserve main features of `HERWIG` such as
  - angular ordered parton shower
  - Cluster Hadronization
- New features and improvements
  - improved parton shower evolution for heavy quarks
  - consistent radiation from unstable 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.
- LesHouchesFileReader enables to read in and process *any* hard event generated by parton level event generators (MadGraph/MadEvent, AlpGen, CompHEP,...).
- CKKW ME+PS foreseen.
- Other authors can easily include their own matrix elements ($\rightarrow$ *safety* of OO code)

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

Quasi–Collinear Limit (Heavy Quarks)

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

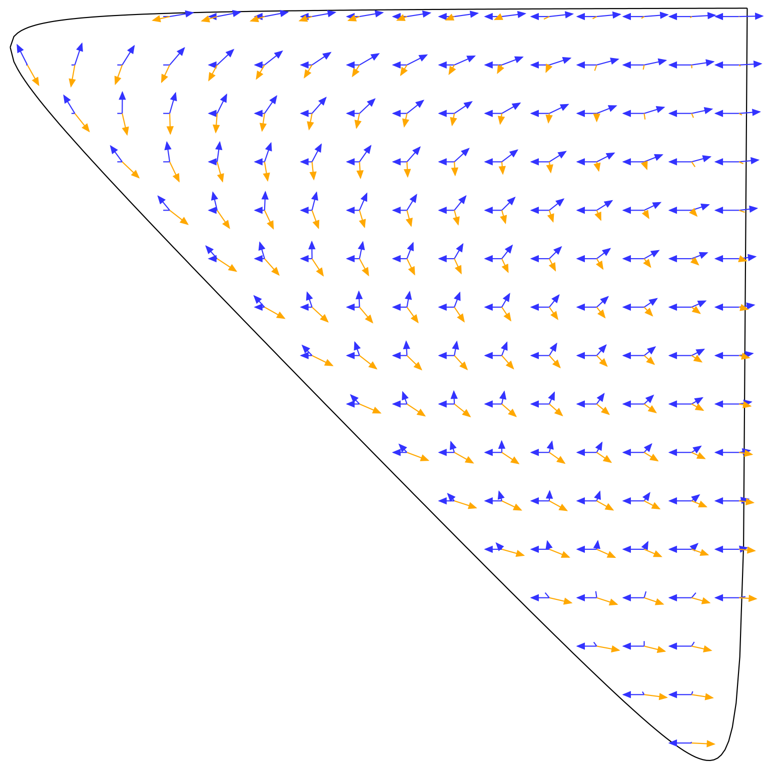
$$
\begin{aligned}
p_q &= zp + \beta_q n - q_\perp \\
p_g &= (1-z)p + \beta_g n + q_\perp
\end{aligned}
$$

Collinear limit for radiation off heavy quark,

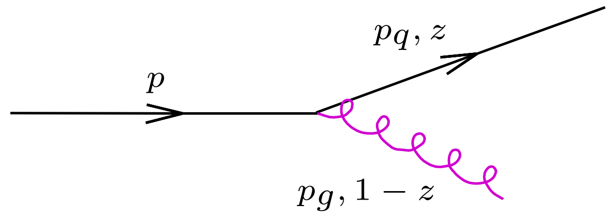
$$
\begin{aligned}
P_{gq}(z, \boldsymbol{q}^2, m^2) &= C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\boldsymbol{q}^2 + (1-z)^2 m^2} \right] \\
&= \frac{C_F}{1-z} \left[1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right]
\end{aligned}
$$

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

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

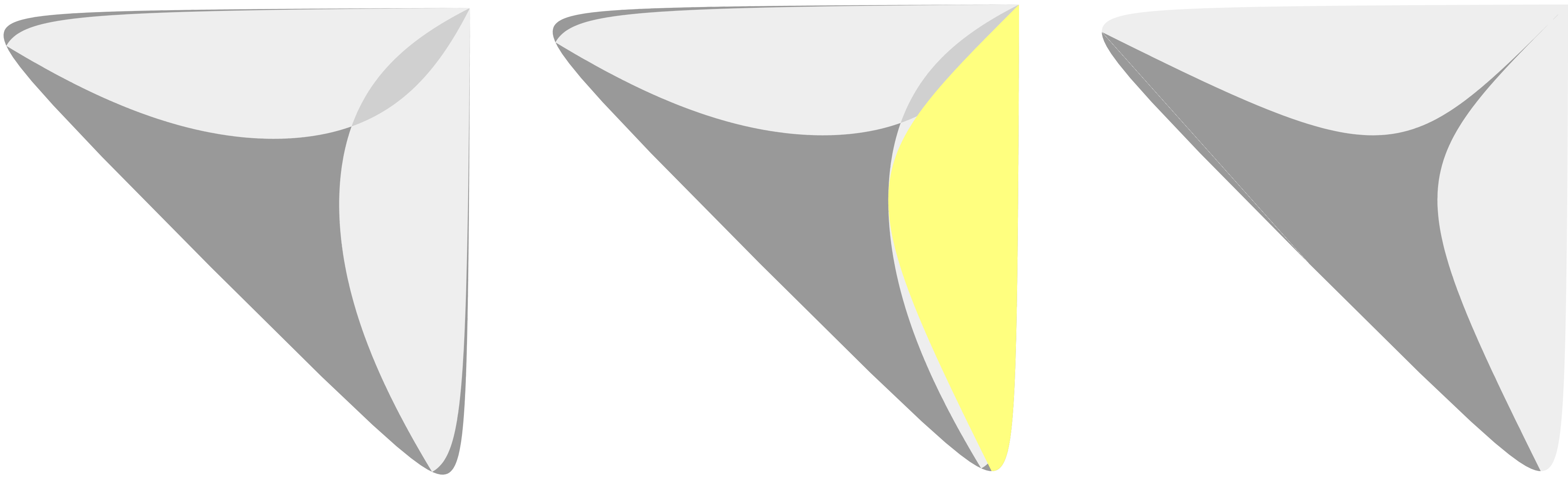


Single emission:



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

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

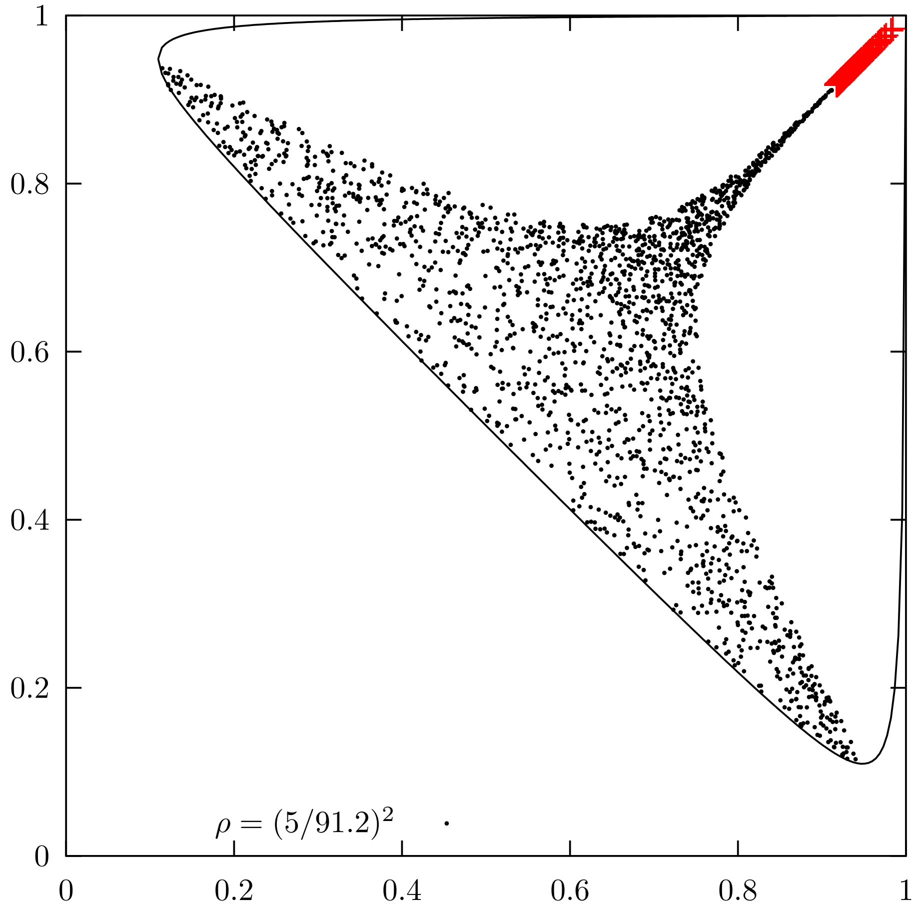


HERWIG Comparison Herwig++

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

Hard Matrix Element Corrections

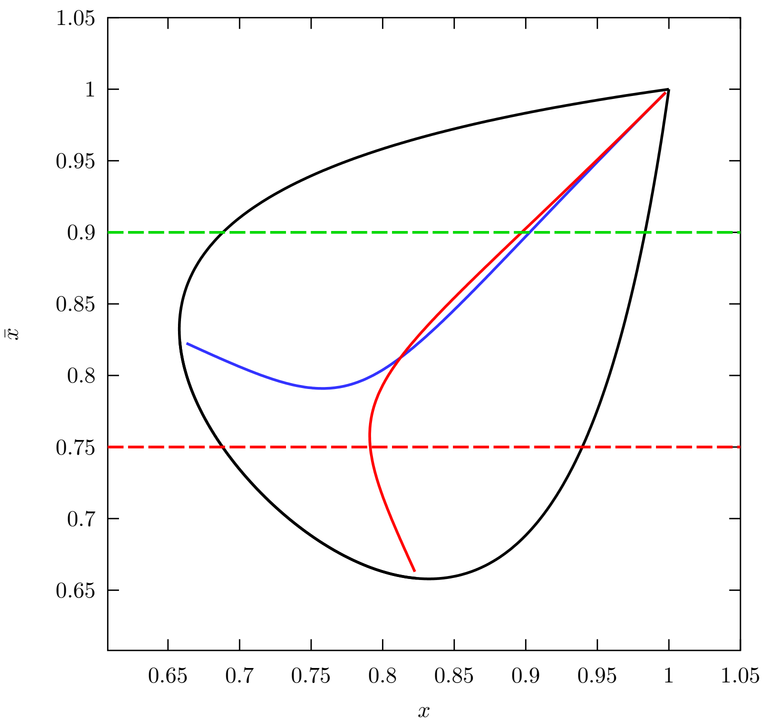
- Points $(x, \bar{x})$ in dead region chosen acc to LO $e^+e^- \to q\bar{q}g$ matrix element and accepted acc to ME weight.
- About 3% of all events are actually hard $q\bar{q}g$ events.
- Red points have weight > 1, practically no error by setting weight to one.
- Event oriented according to given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

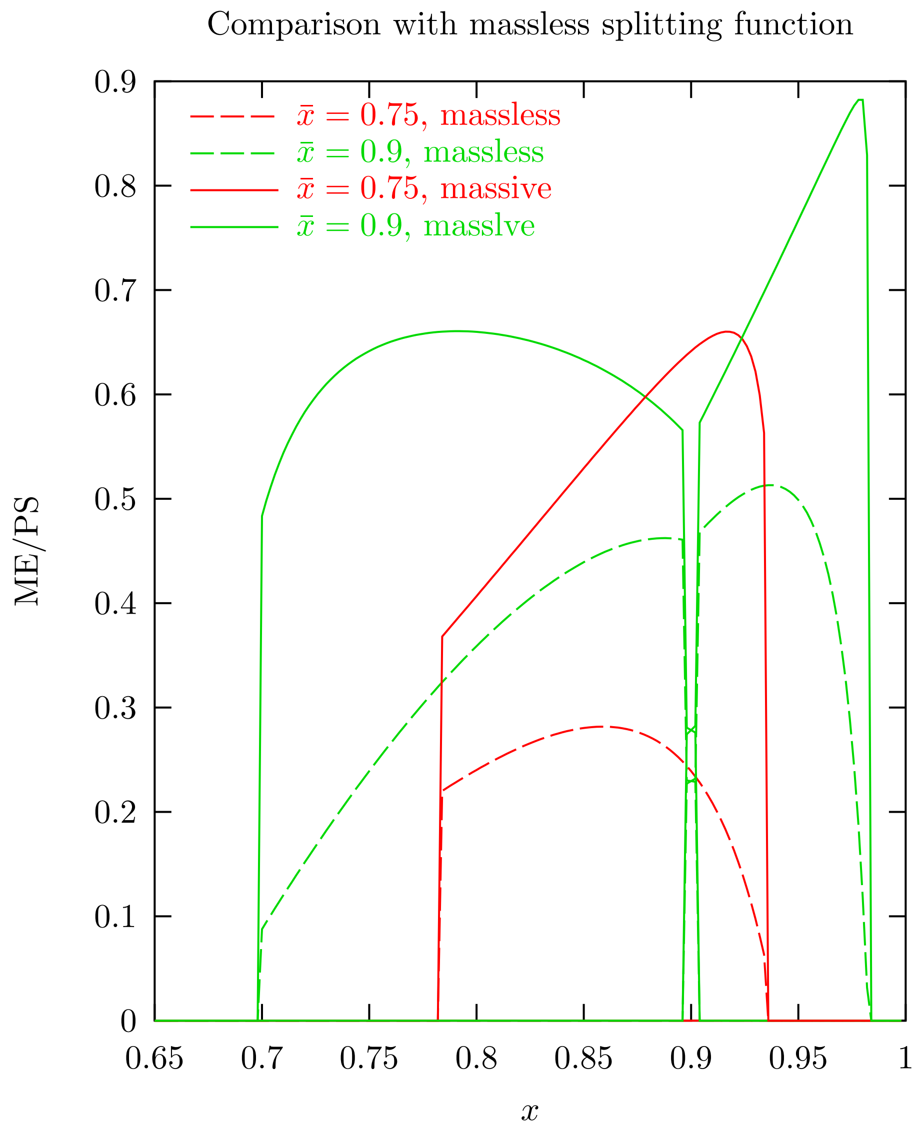


Soft Matrix Element Corrections

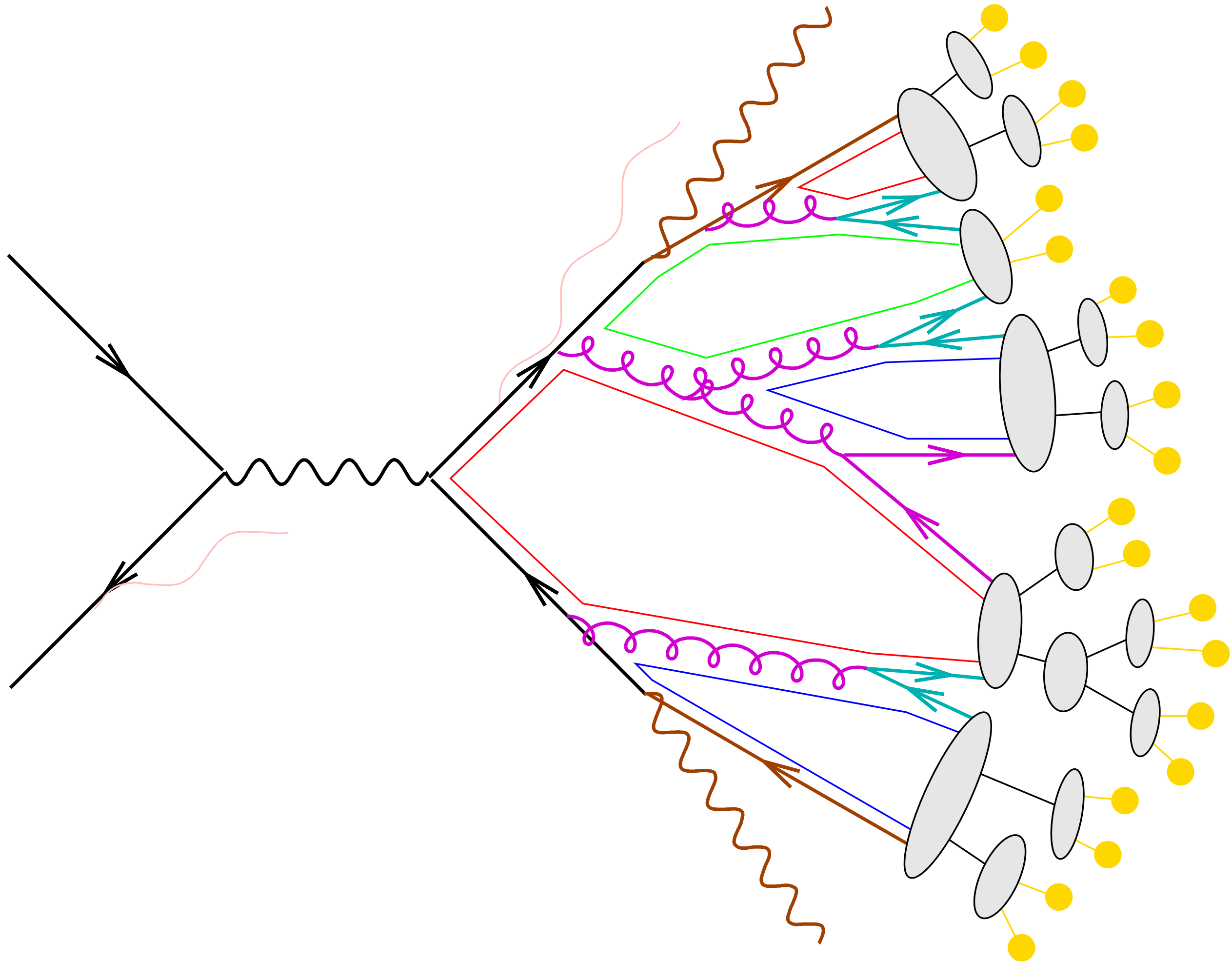
- Ratio ME/PS compares emission with result from true ME if slightly away from soft/collinear region.
- Veto on ‘hardest emission so far’ in $p_\perp$.
- Massive splitting function *very important*!

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





e^+e^- Event Generator



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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

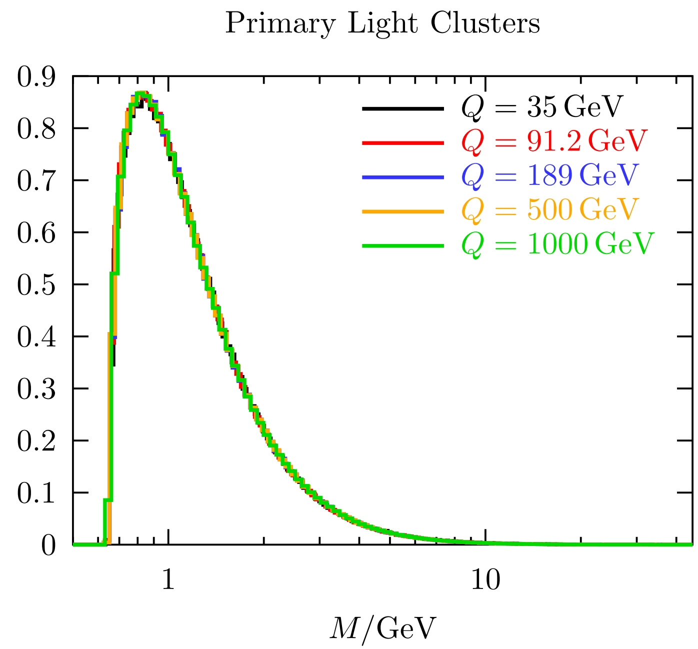
$$M_i = \left[\left(M^P - (m_i + m_3)^P \right) r_i + (m_i + m_3)^P \right]^{1/P},$$

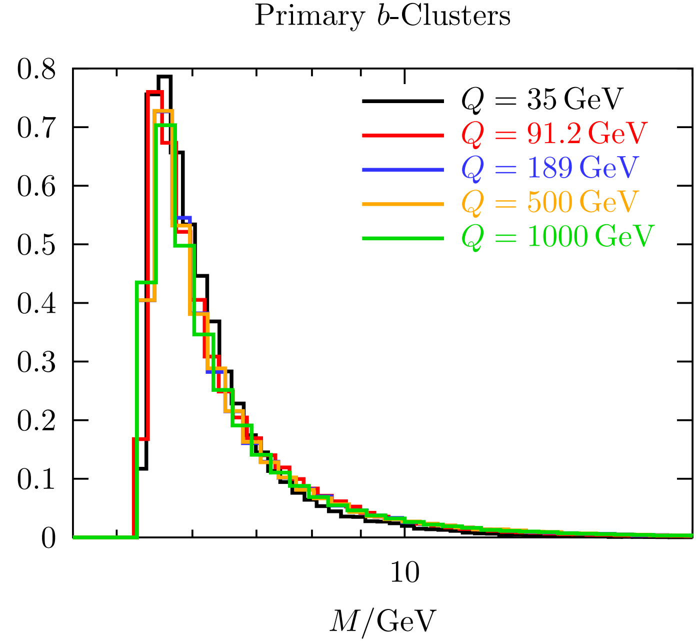
with additional phase space contraints. Constituents keep moving in their original direction.

- Cluster Decay

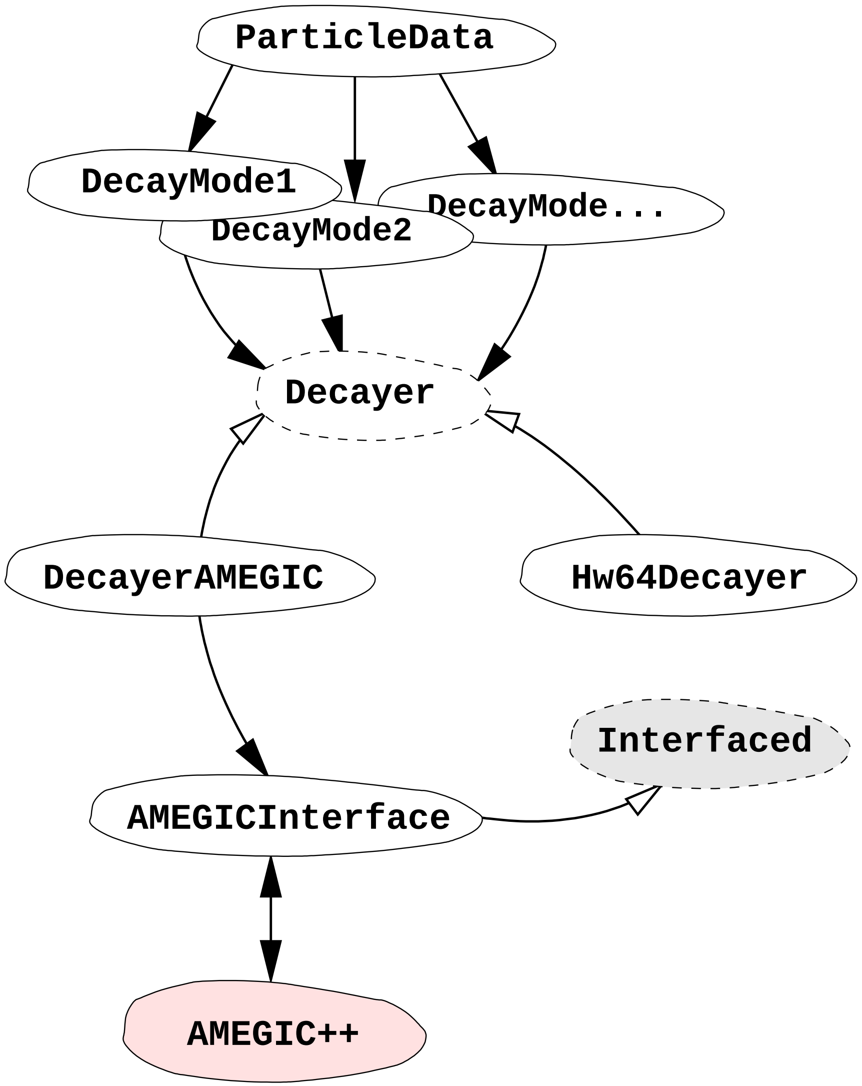
$$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$

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





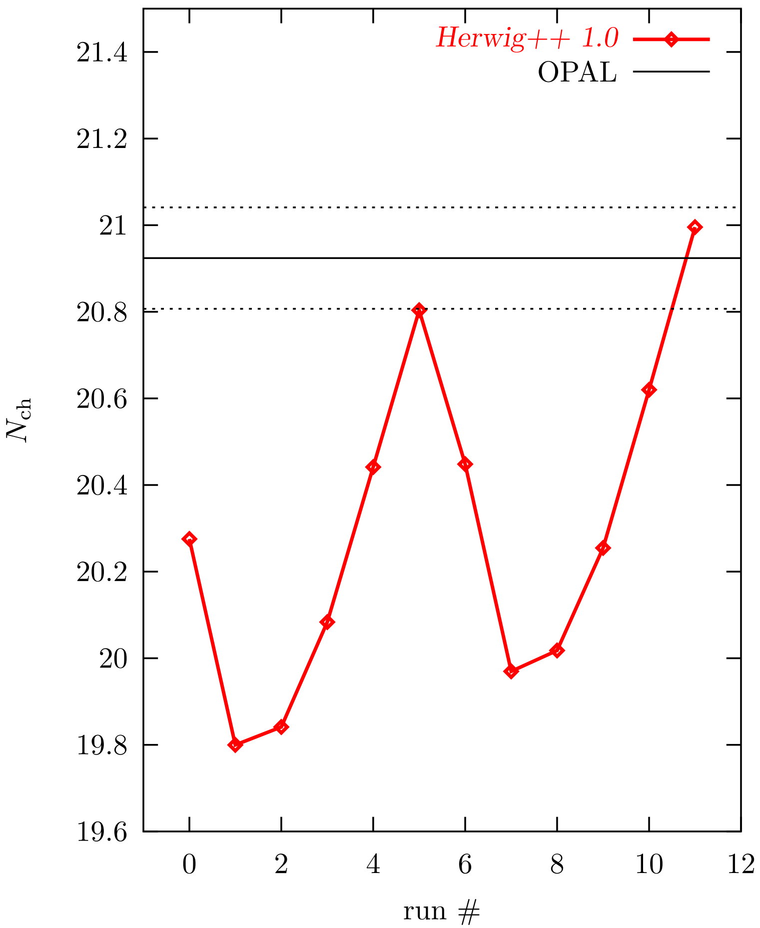
Decays

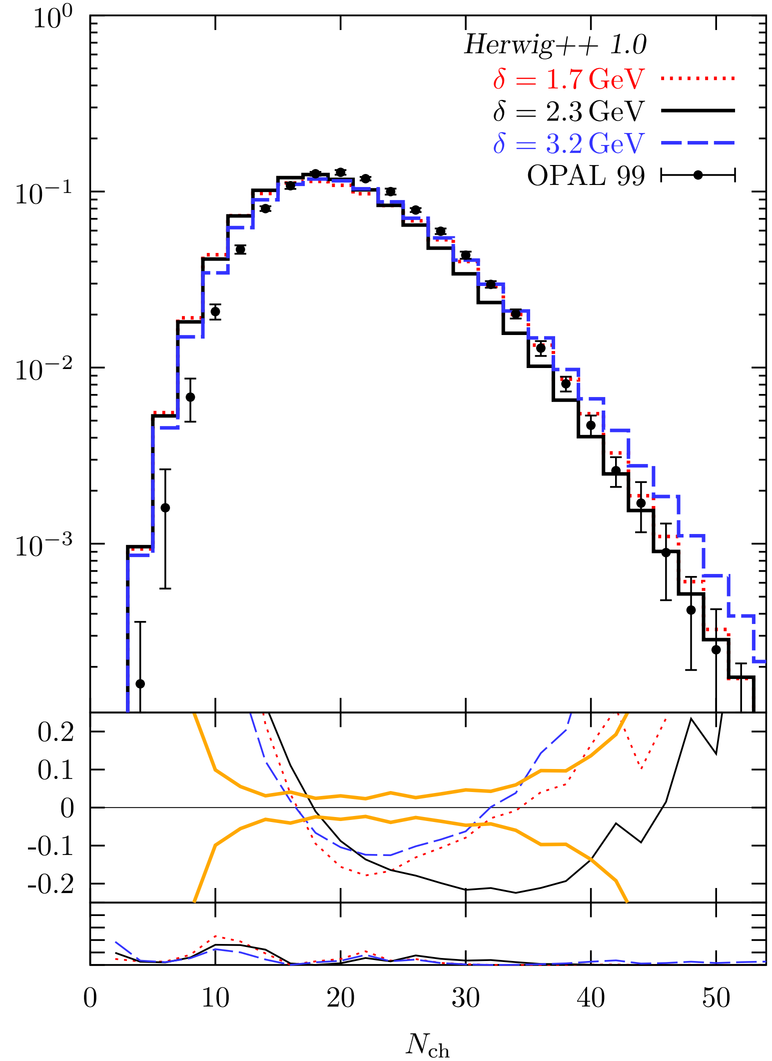


- FORTRAN HERWIG is reproduced with Hw64Decayer using the same Matrix element codes as before (will be used for hadronic decays right now)
- DecayerAMEGIC gets final states for a decay mode directly from AMEGIC++

Charged Particle Multiplicity

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





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
$\pi^\pm$	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

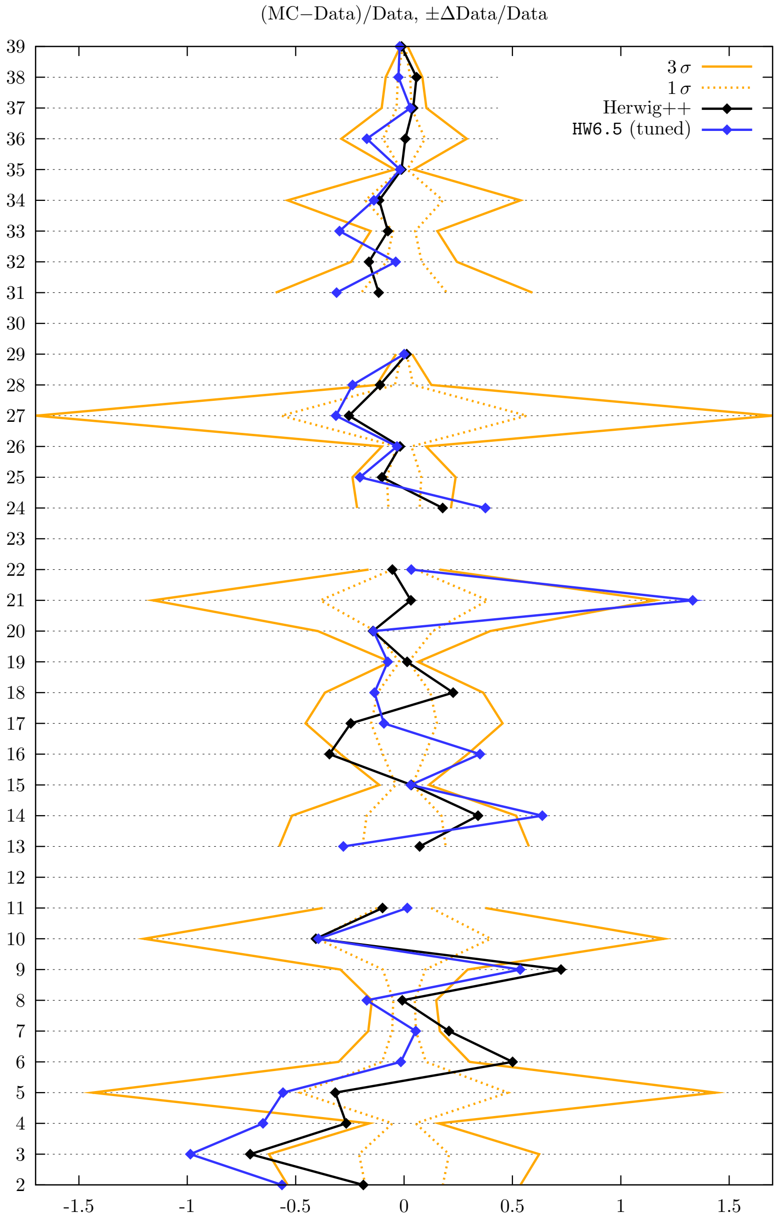
Hadron Multiplicities (ctd')

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:

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

Hadron Multiplicities (ctd')

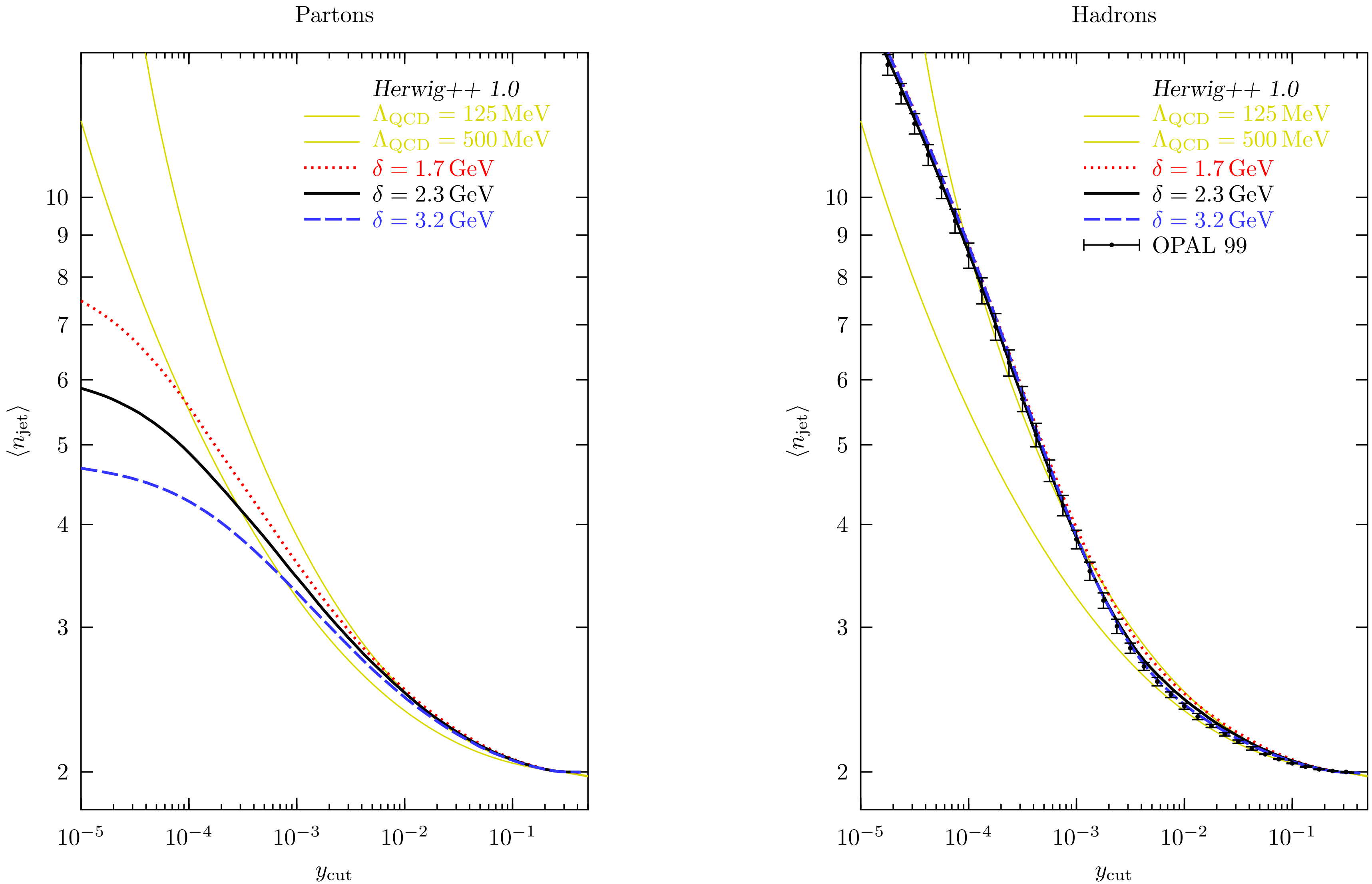


We can compare χ^2's:

model	$\sum \chi^2/\text{dof} =$	
DKMode 0:	$543.84/35 =$	15.54
DKMode 1:	$3644.33/35 =$	104.12
Herwig++:	$277.16/35 =$	7.92
no $D^{\pm}$:	$=$	6.54
HW65d:	$7151.13/35 =$	204.32
HW65t:	$490.52/35 =$	14.01
no J/ψ:	$=$	4.38

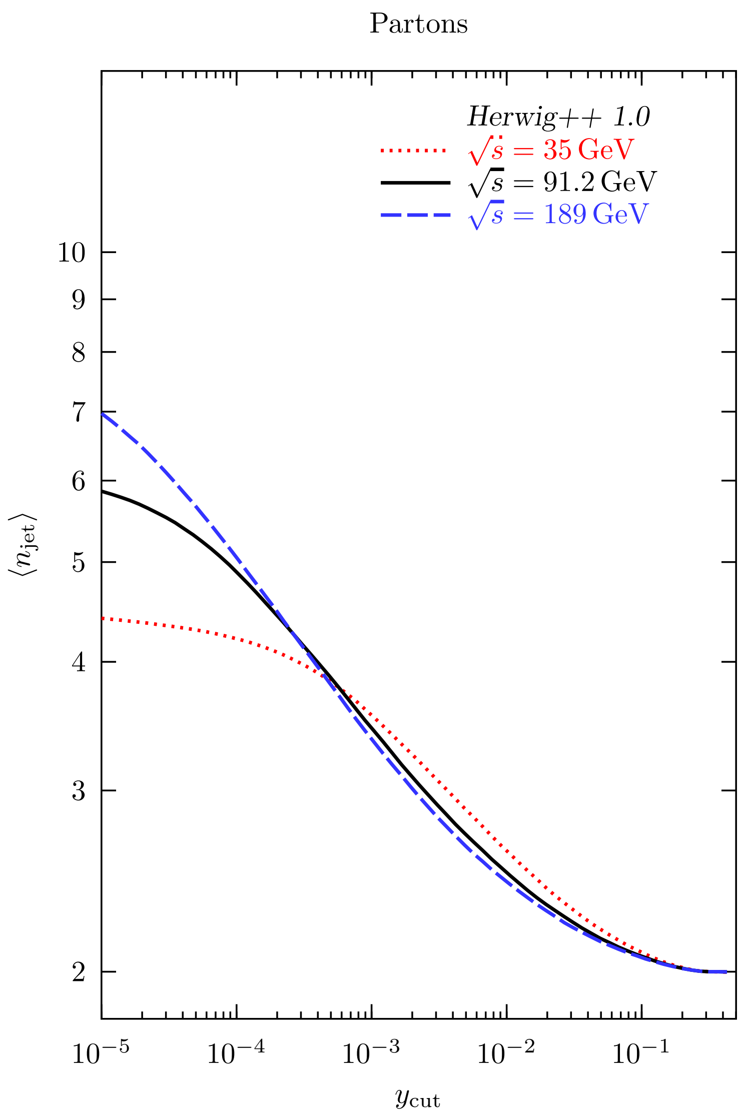
Jet Multiplicity

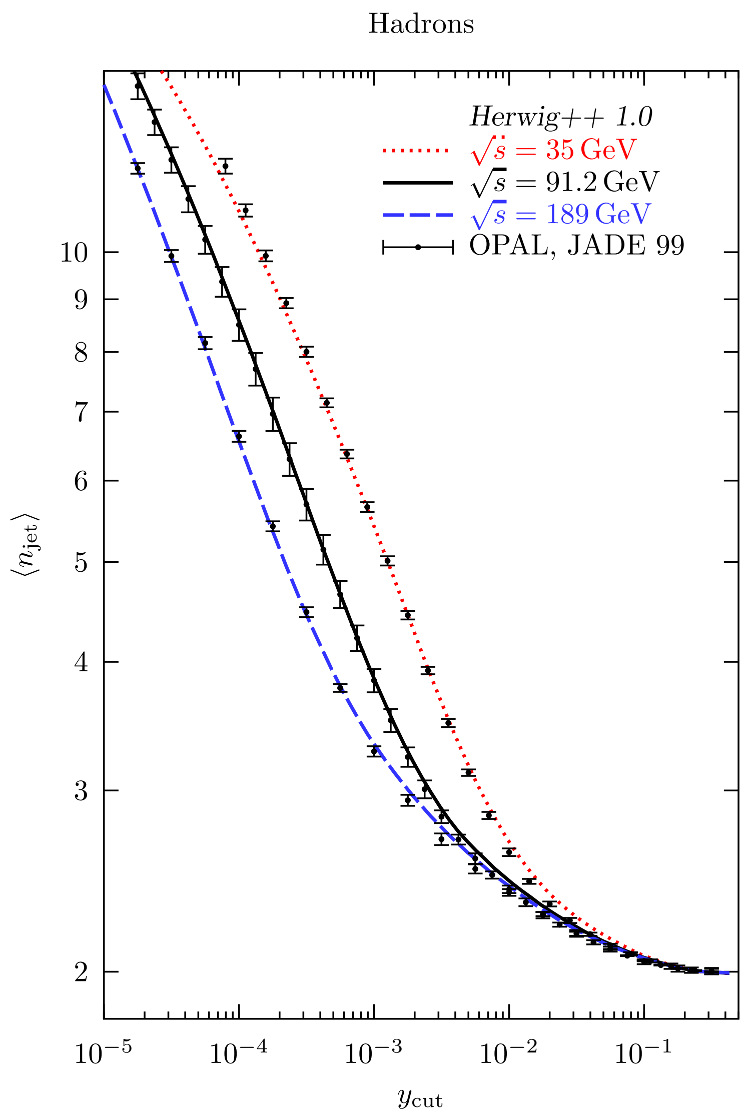
Durham algorithm. Smooth interplay between shower and hadronization.



Jet Multiplicity (PETRA, LEP, LEPII)

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

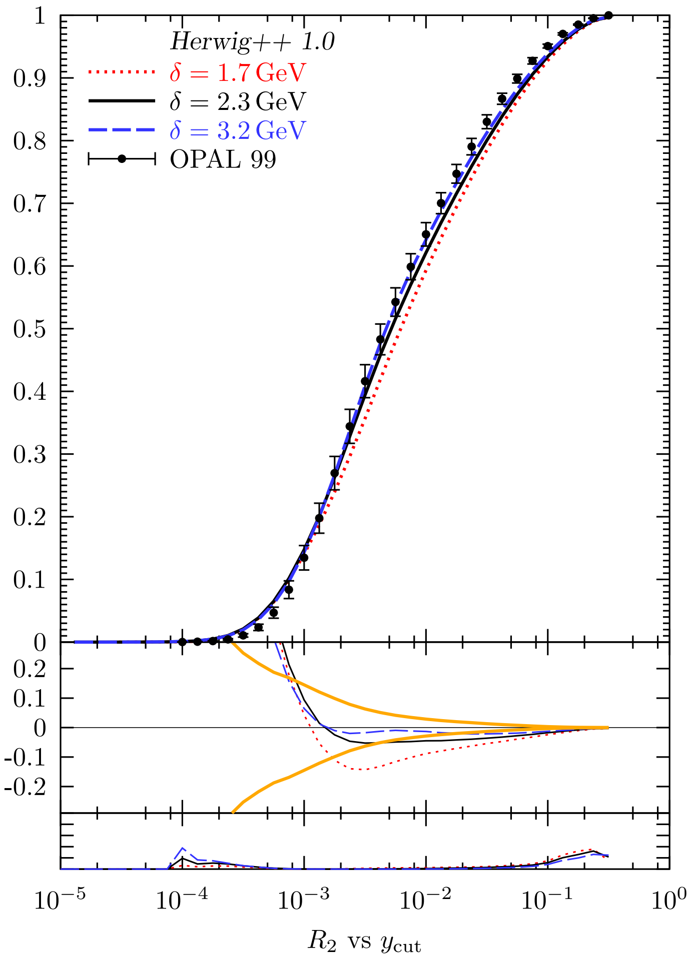


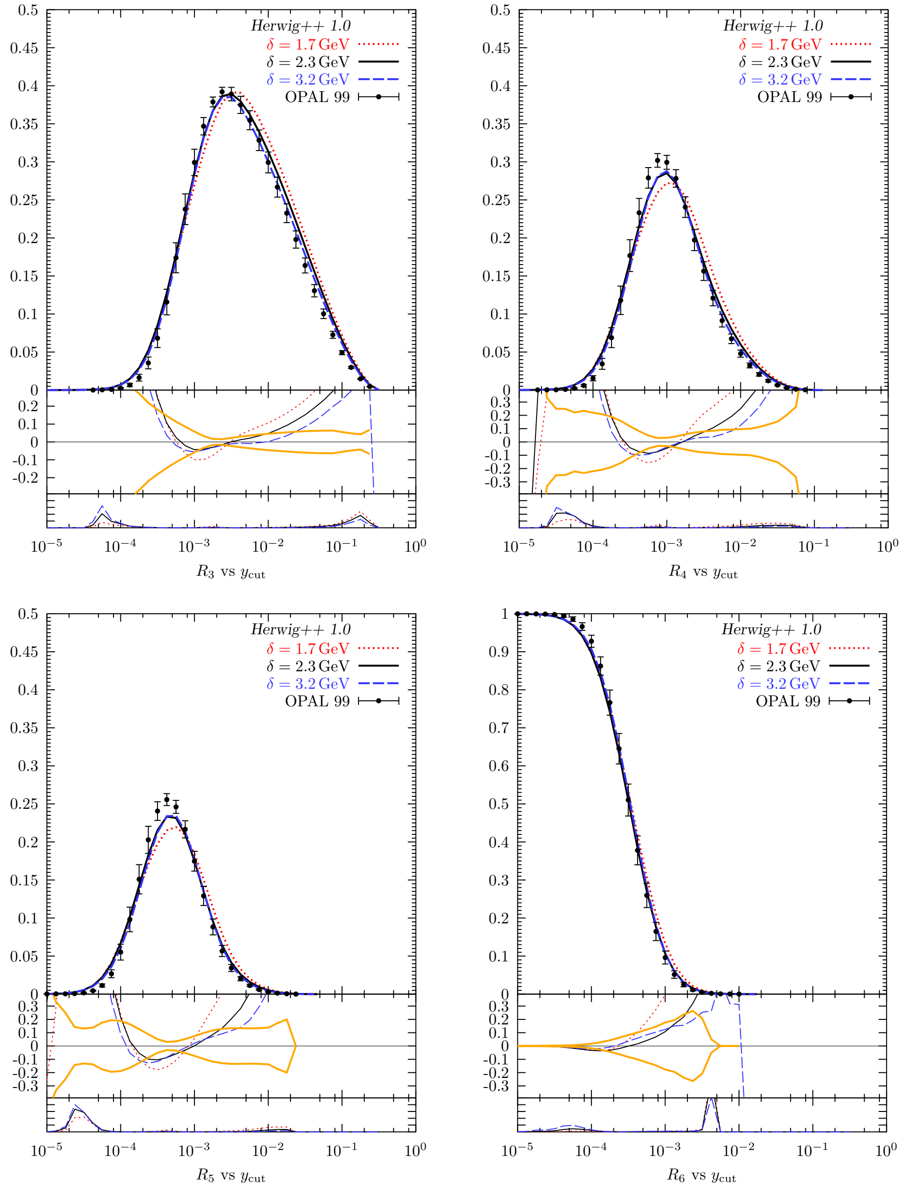


Jet Rates

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

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





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

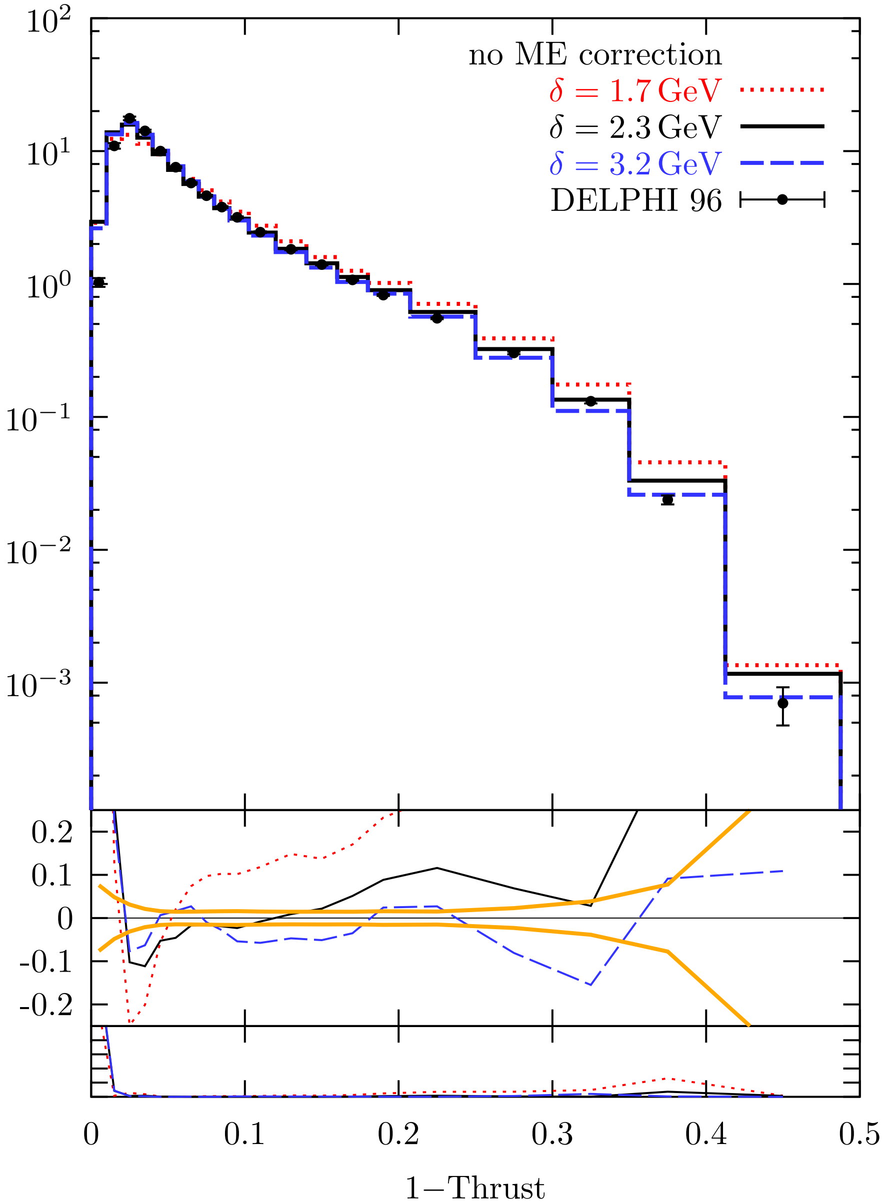
$$\lambda_1 + \lambda_2 + \lambda_3 = 1$$

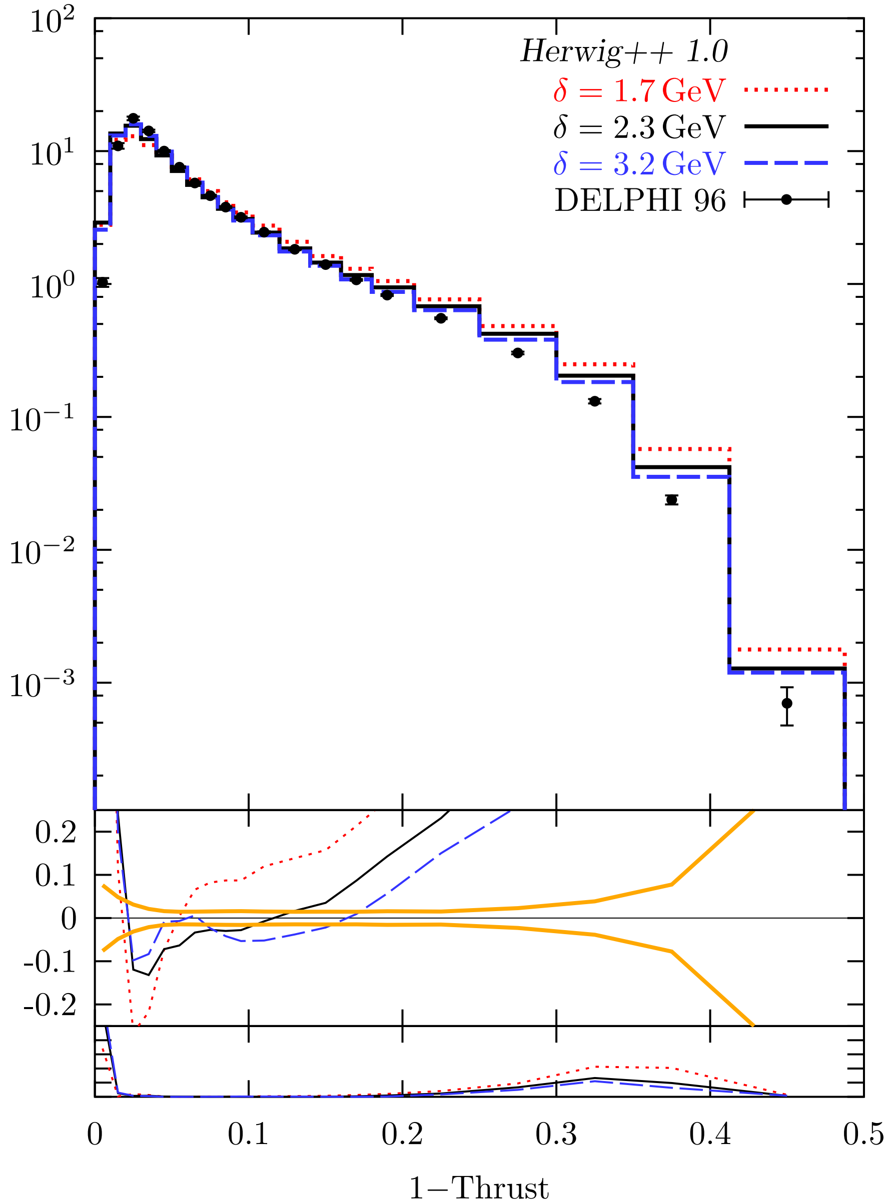
and define

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

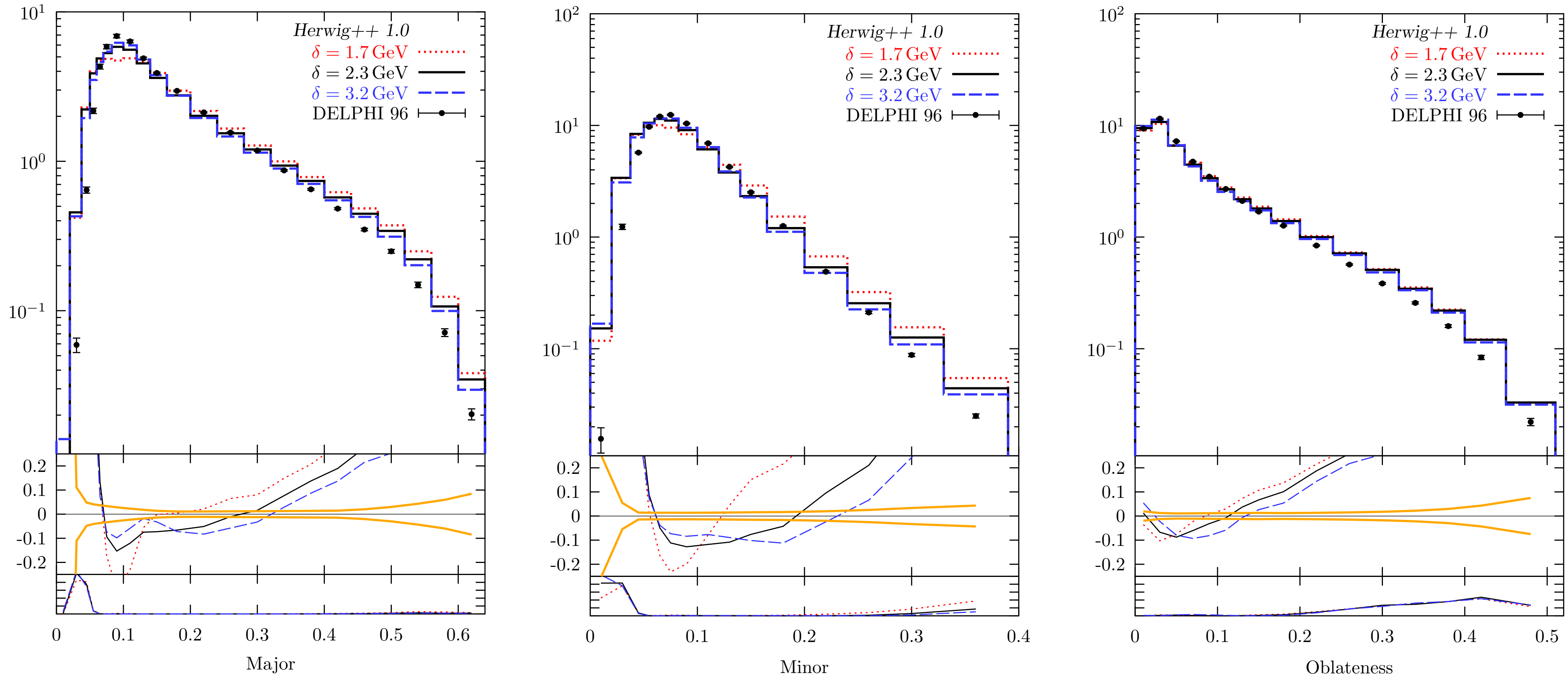
$$D = 27\lambda_1\lambda_2\lambda_3$$

Thrust — ME Corrections off/on



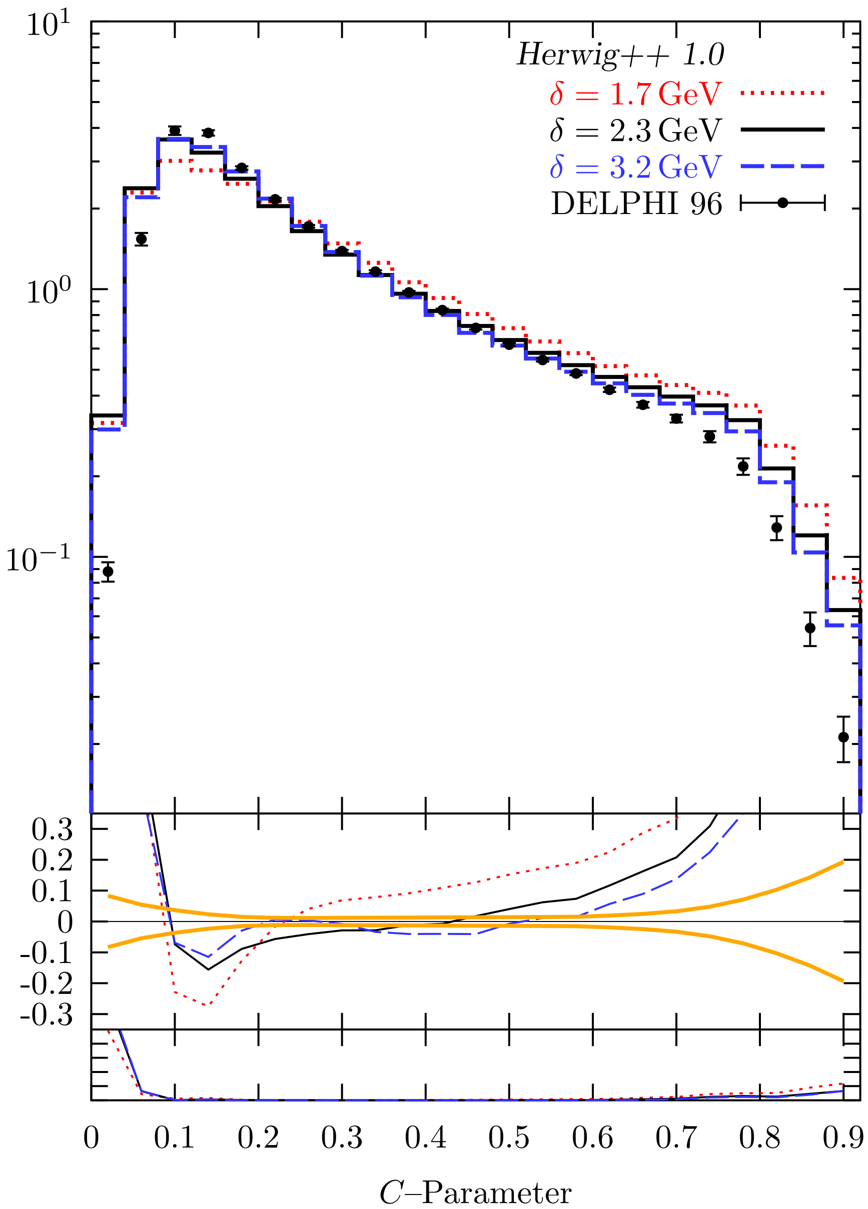


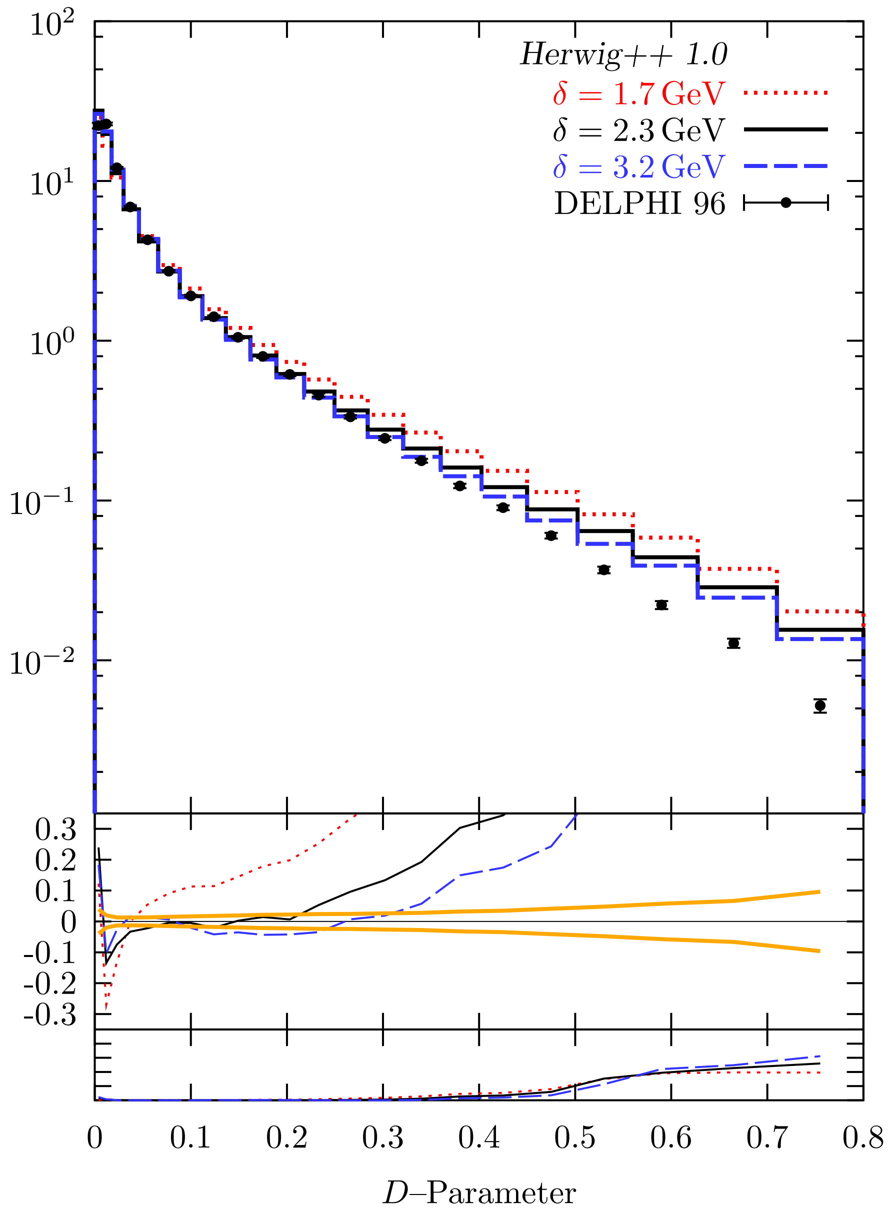
Major, Minor, Oblateness



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

C and D parameter





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

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

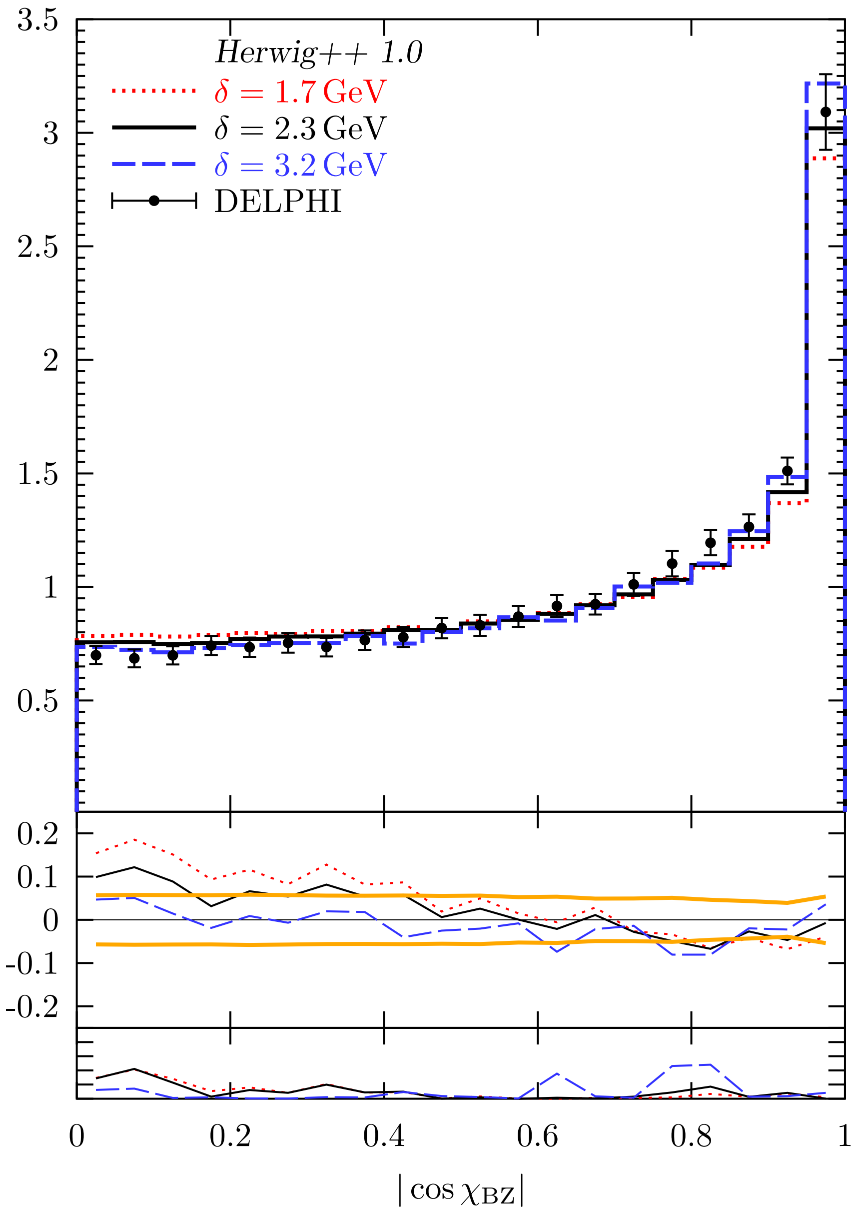
(modified) Nachtmann–Reiter angle

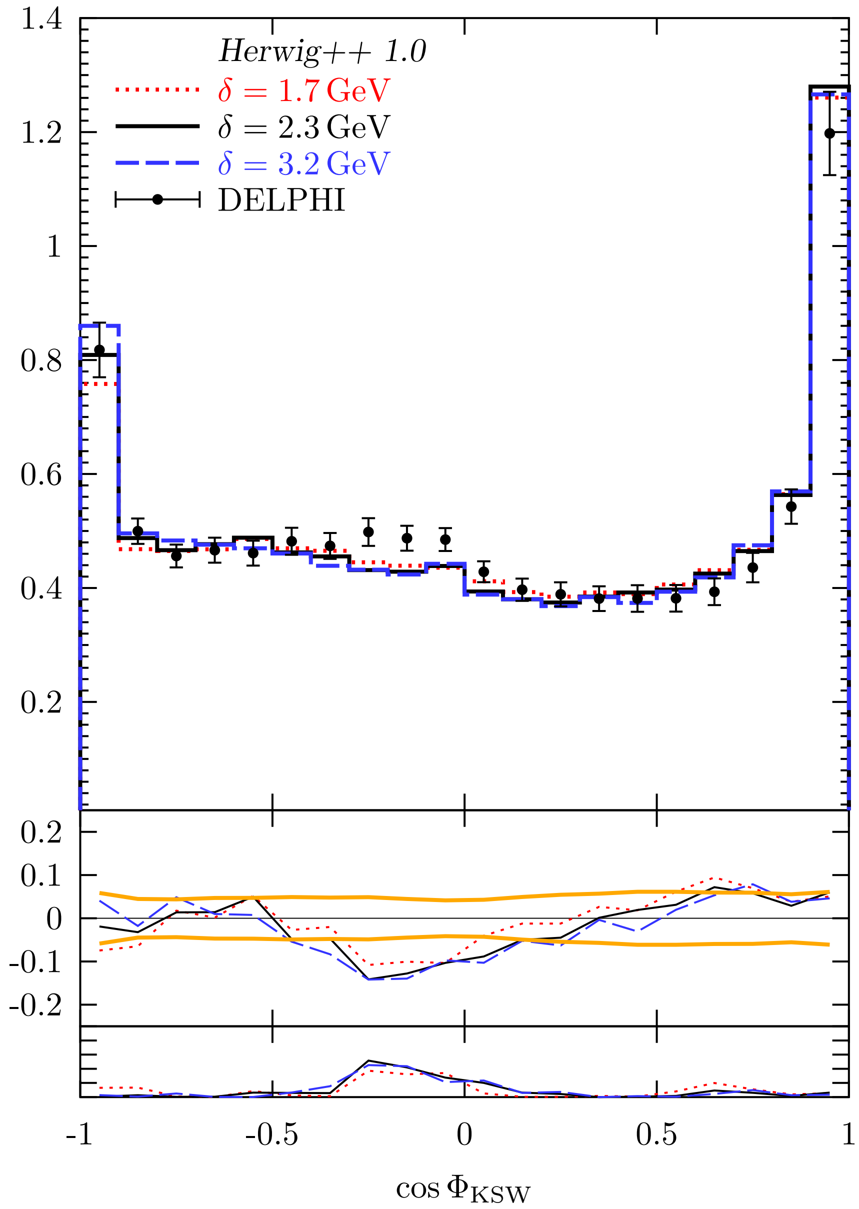
$$\theta^*_{NR} = \angle(\boldsymbol{p}_1 - \boldsymbol{p}_2, \boldsymbol{p}_3 - \boldsymbol{p}_4)$$

α_{34}:

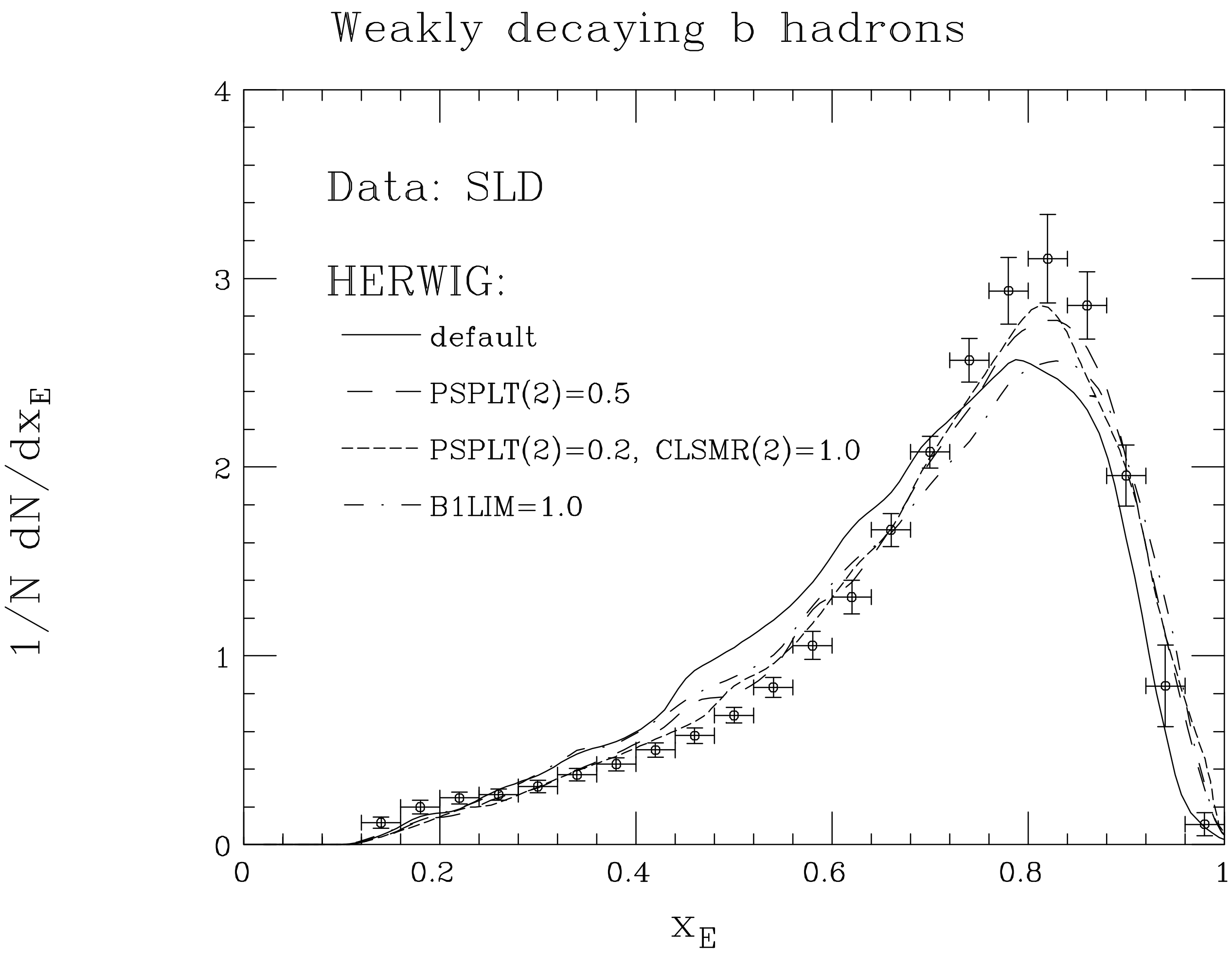
$$\alpha_{34} = \angle(\boldsymbol{p}_3, \boldsymbol{p}_4)$$

Four Jet Angles I



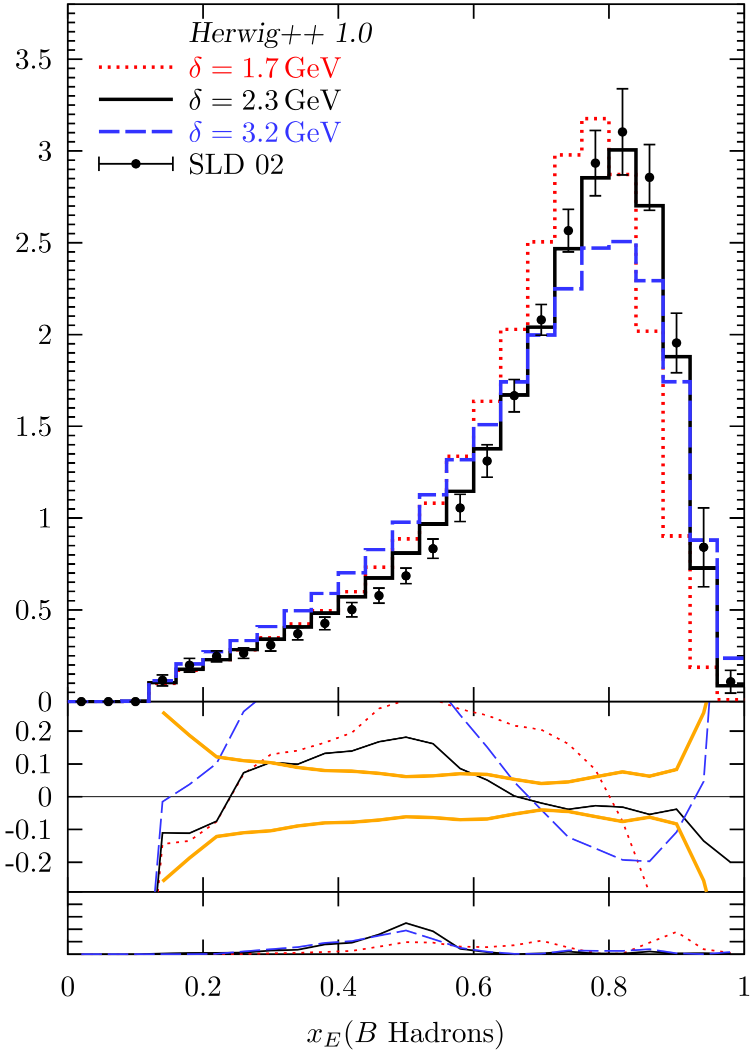


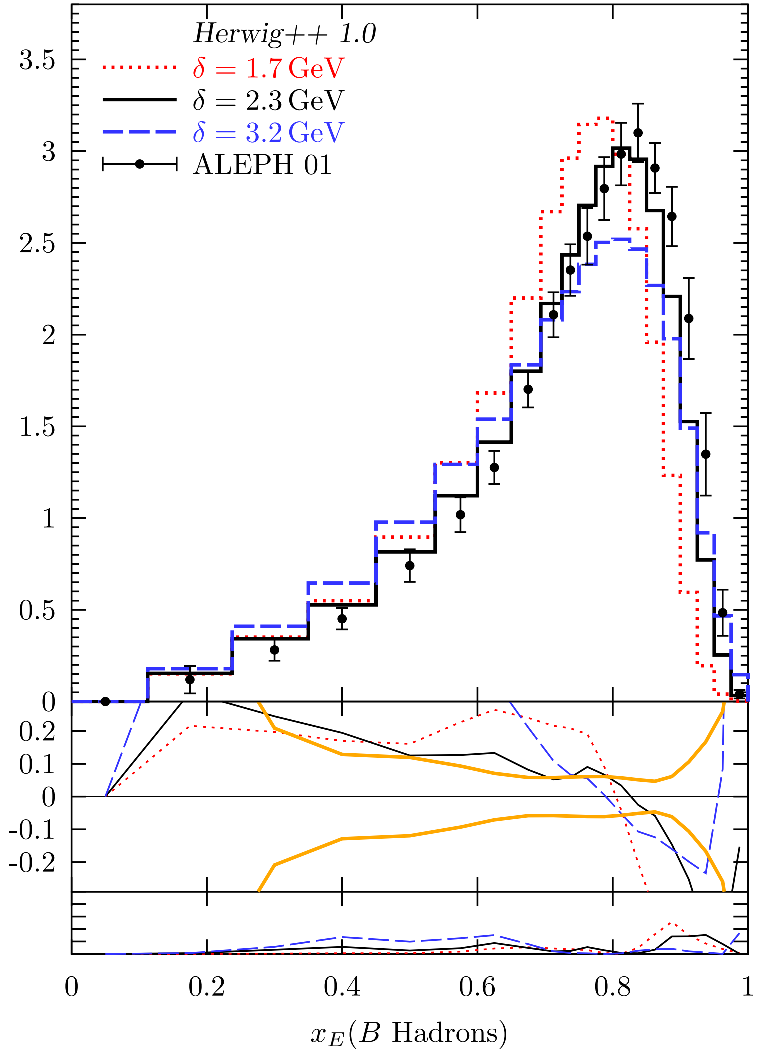
B-fragmentation function



HERWIG 6.4, B specific hadronization parameters needed!

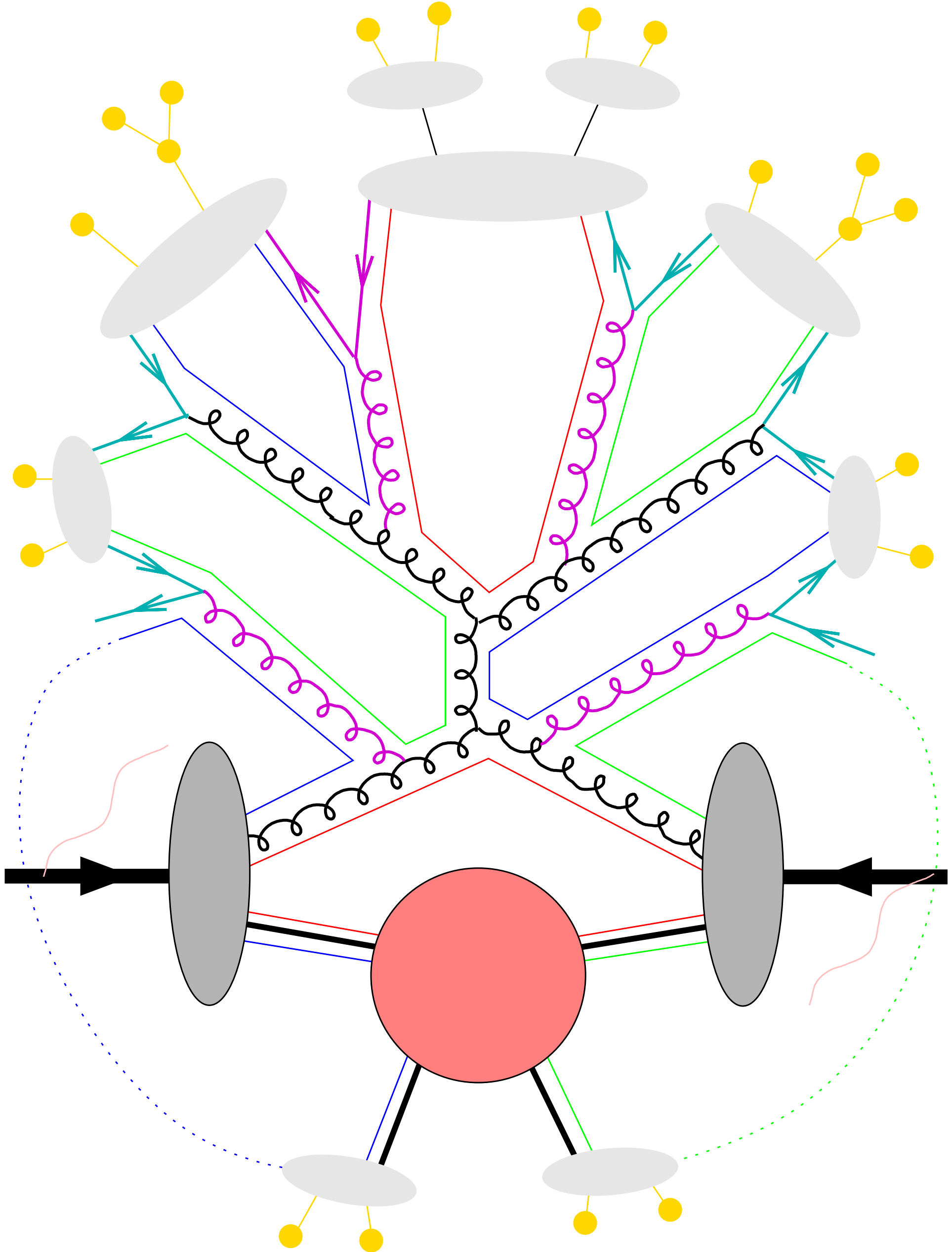
B-fragmentation function





Only parton shower parameters varied!

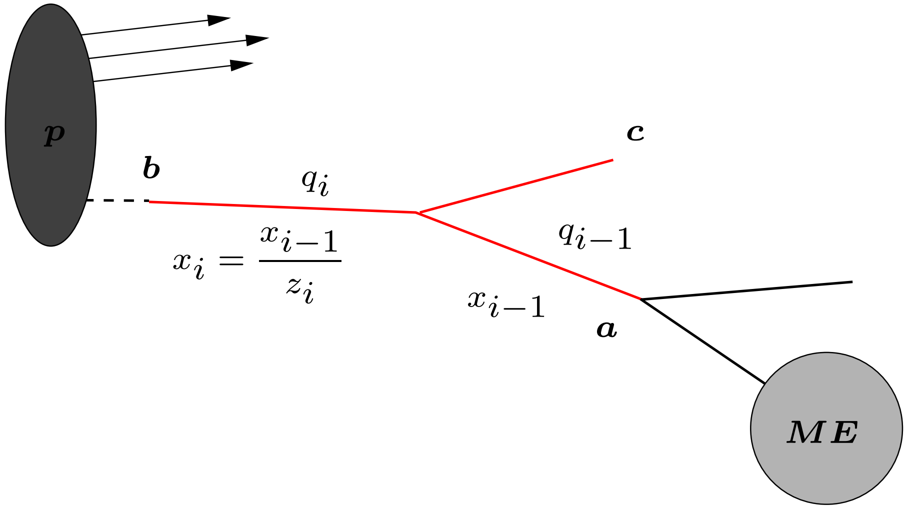
Additional Complications in $pp/p\bar{p}$



+ backward parton evolution
+ underlying event

Backward branching kinematics in Herwig++

Consider only single branching $b \to ac$:



Sudakov decomposition $q_i = \alpha_i p + \beta_i n + q_{\perp i}$. Basis $(p, n) \|$ proton direction. Kinematics of shower reconstructed from

$$\alpha_i = \frac{\alpha_{i-1}}{z}, \qquad \boldsymbol{q}_{\perp i} = \frac{\boldsymbol{q}_{\perp i-1} - \boldsymbol{p}_{\perp i}}{z_i} \; .$$

$$\boldsymbol{p}^2_{\perp i} = (1 - z_i)^2 \tilde{q}_i^2 - z_i Q_g^2 \; .$$

Q_g closely related to parton shower cutoff.

Sudakov form factor for space–like branchings

The Sudakov form factor for spacelike backward evolution of a parton a from the hard scale $\tilde{q}_{\rm max}$ down to some scale $\tilde{q}$,

$$S_a(\tilde{q}, \tilde{q}_{\rm max}; x, \tilde{q}_0) = \exp\left[-\sum_b \mathcal{I}_{ba}(\tilde{q}, \tilde{q}_{\rm max}; x, \tilde{q}_0)\right] \ . \qquad (1)$$

The sum on the right hand side (rhs) is over all possible splittings into partons of type b and

$$\mathcal{I}_{ba}(\tilde{q}, \tilde{q}_{\rm max}; x, \tilde{q}_0) = \int_{\tilde{q}^2}^{\tilde{q}^2_{\rm max}} \frac{d\tilde{q}^2}{\tilde{q}^2} \int_{z_0}^{z_1} dz \frac{\alpha_s(z, \tilde{q}^2)}{2\pi} \frac{x' f_b(x', \tilde{q}^2)}{x f_a(x, \tilde{q}^2)} P_{ba}(z, \tilde{q}^2) \ . \qquad (2)$$

Choosing the argument of $\alpha_s(Q)$ as $Q = (1-z_i)\tilde{q}_i$ we may now rewrite the integral (2) as

$$\mathcal{I}_{ba}(\tilde{q}, \tilde{q}_{\rm max}; x, Q_g) = \int_{\tilde{q}^2}^{\tilde{q}^2_{\rm max}} \frac{d\tilde{q}^2}{\tilde{q}^2} \int_0^1 dz \frac{\alpha_s[(1-z)\tilde{q}]}{2\pi} \frac{x' f_b(x', \tilde{q}^2)}{x f_a(x, \tilde{q}^2)} P_{ba}(z, \tilde{q}^2) \Theta(\mathrm{P.S.}) \ . \qquad (3)$$

Numerical study

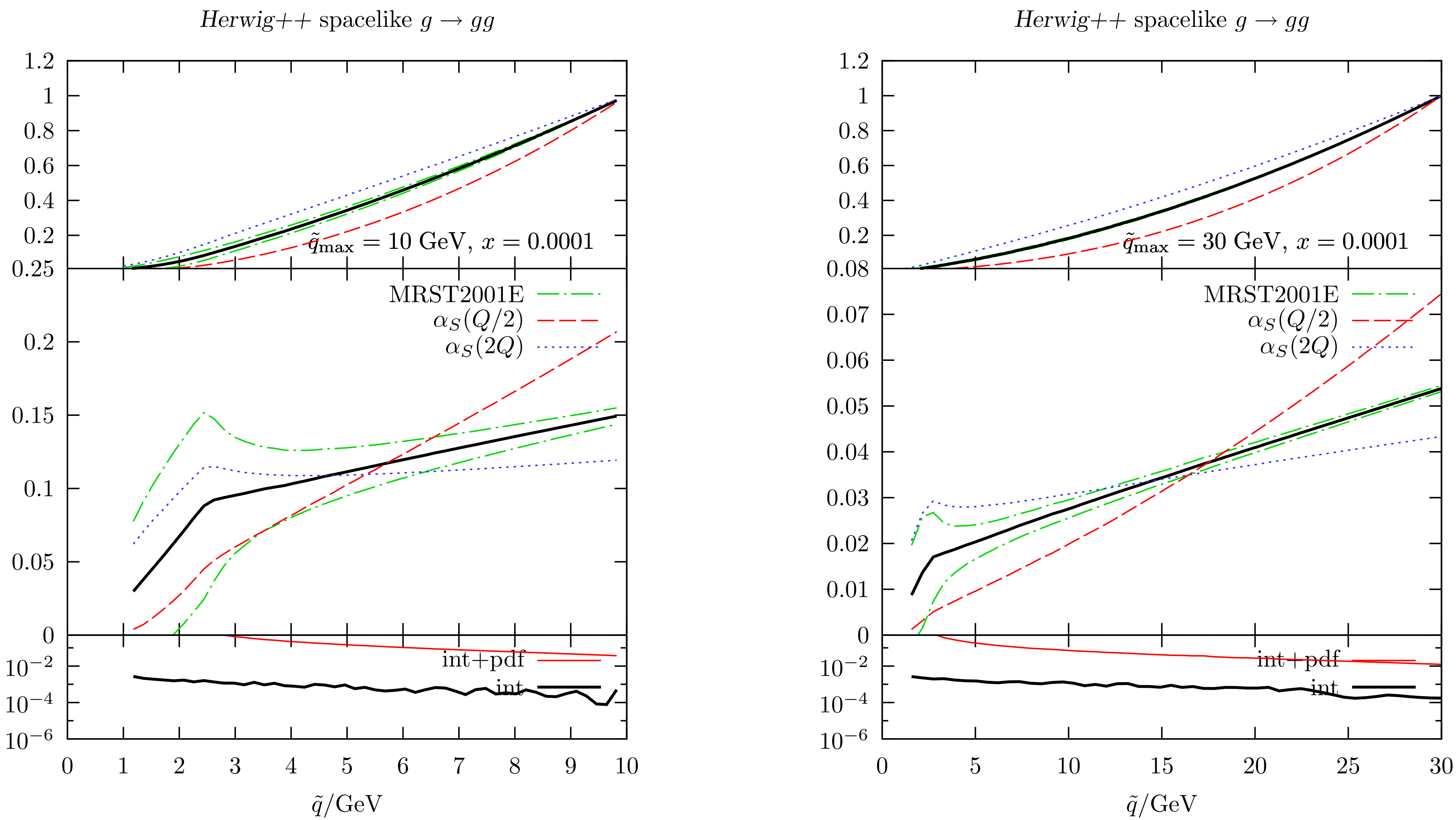
We consider

- different types of splittings.
- low and high x and $\tilde{q}_{\max}$.
- pdf errors from MRST/CTEQ,
- $\alpha_s(Q)$ errors from scale variation in comparison.
- NP treatment of $\alpha_s(Q)$.
- no study of effects beyond NLL.
- no kinematics from other generators
- strictly only first emission (vetos. . .)

We always show

- Sudakov form factor (top panel)
- Branching probability density (middle panel)
- Error information (bottom panel)

$g \to gg$, lower x, higher $\tilde{q}_{\max}$



Quite sizable at very small x. Shrinks again for larger $\tilde{q}_{\max}$.

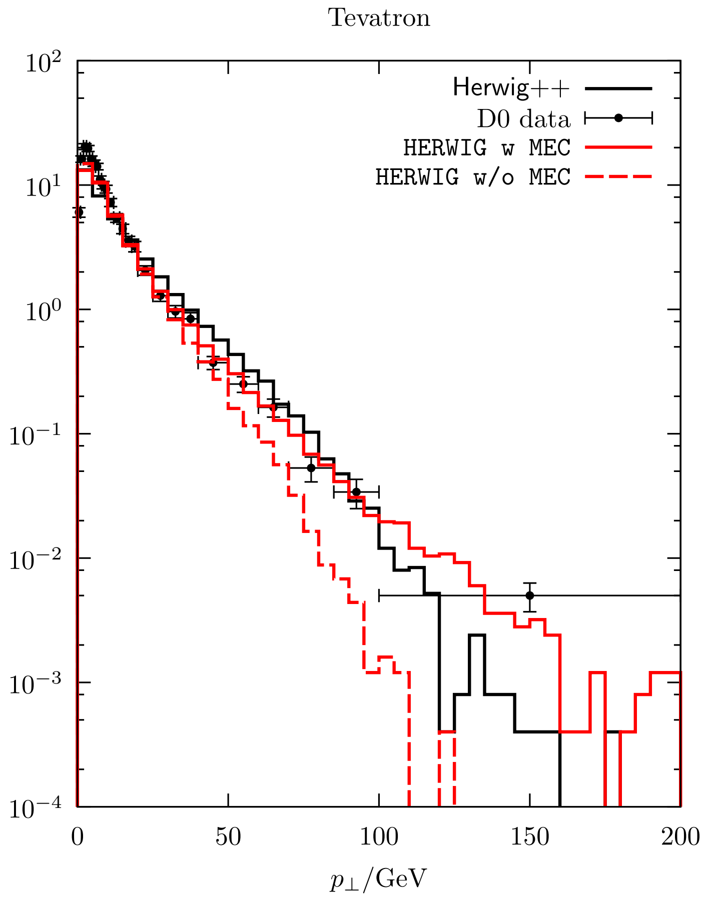
Some remarks

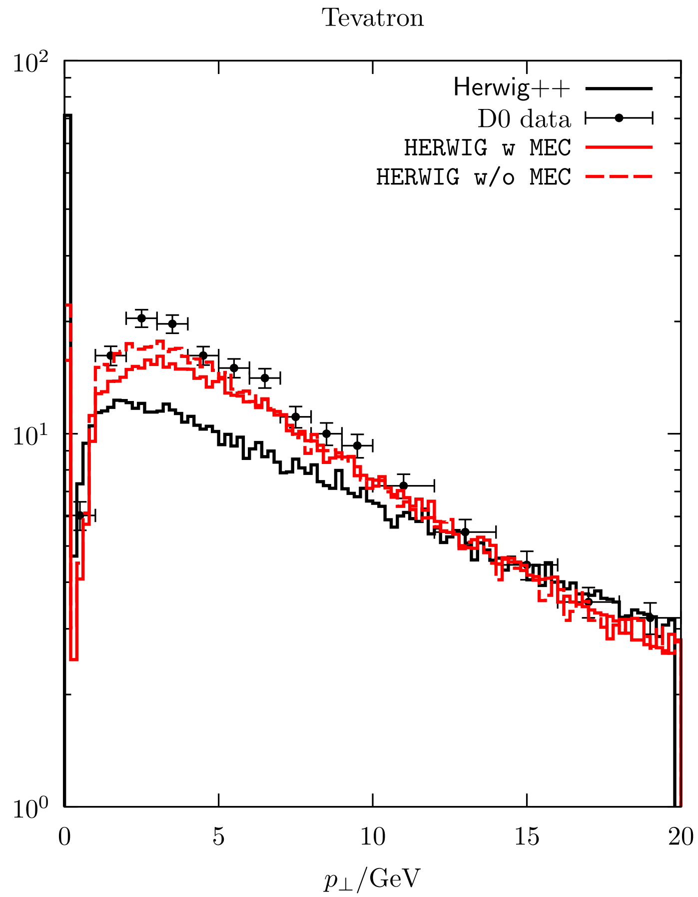
- Sudakov FF can be a useful tool for understanding certain effects.
- effect of pdf errors mostly small.
- *BUT* can be large in places ☛ $t\bar{t}$?
- all compared to α_s scale uncertainties.
- very sensitive to non–perturbative α_s and scale variations in general (used for tuning. . .).
- NLL effects may be interesting to look at in greater detail?!

⟶*talk at parallel session*

Currently working on initial state shower. . .

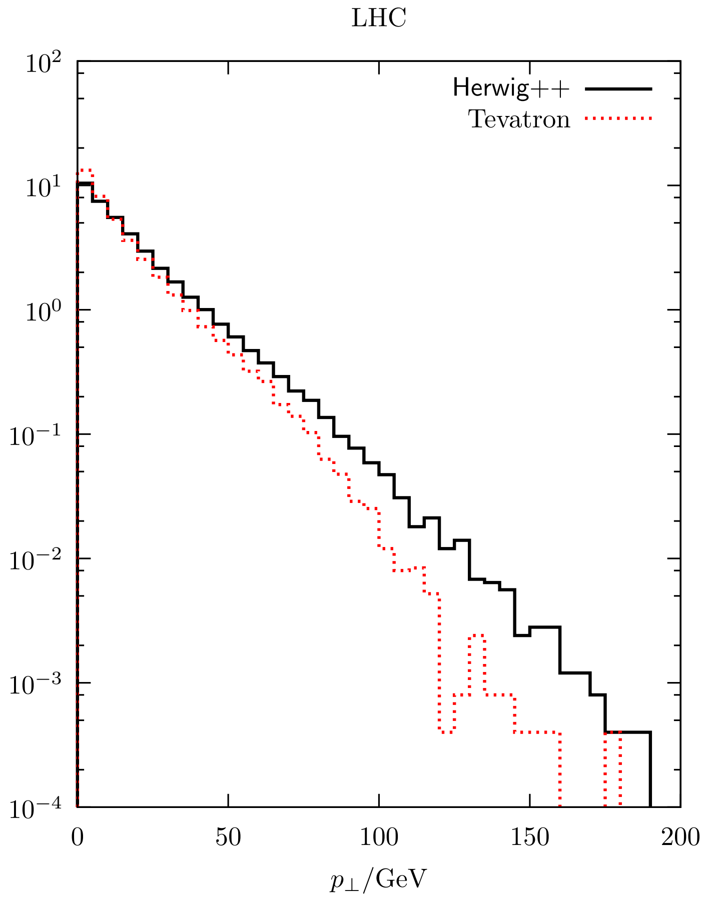
- Parton shower implementations of evolution in our 'new variables' (hep-ph/0310083) ongoing.
- First results for Drell–Yan coming up.
- Decays.

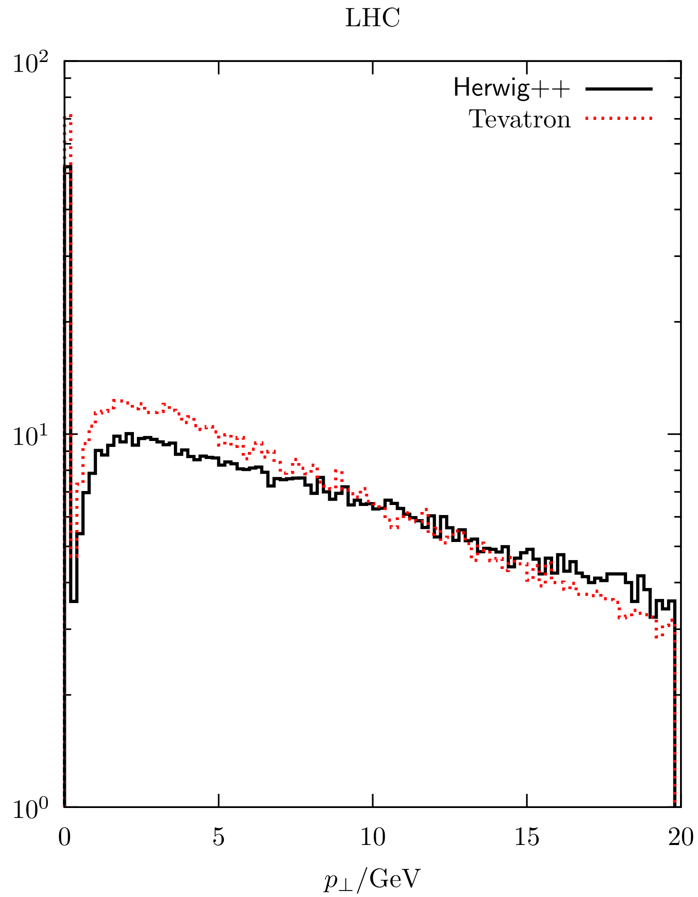




Currently working on initial state shower. . .

- same for LHC, compared to Tevatron.





New Decays!

- Better decayers are being developed for almost all decay modes.
- $\longrightarrow B$ decays.
- Spin correlations will be included.
- Major effort ongoing
  - a universal database is being set up.
  - contains 448 particles and 2607 decay modes at present.
  - possibility to generate configuration files for different generators (they need to write their own code however. . .).
- Particle data book as guideline.

$\longrightarrow$*look at examples. . .*

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.
- ★ Underlying Event.
- ★ Hadronic Decays: *NEW!* many new decayers, τ–decays, Spin correlations (P Richardson).
- ★ New Ideas: soft gluons, improved shower algorithm, NLO, . . .

Schedule?

- Ready for LHC!