Hadronisation and Decay of Excited Heavy Hadrons in

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This Study

- **Enhancing Herwig's Hadronisation Model**: Aiming to simulate the formation and decay of hadrons more accurately, particularly by transmitting polarization information of heavy quarks to the hadronization handler.
- **Applying Heavy Quark Effective Theory**: Utilizing HQET to systematically describe heavy quark behavior within hadrons, considering heavy quark spin-flavour symmetry for model-independent predictions of heavy hadron properties.
- **Modeling Excited Heavy Hadron Decays**: Refining strong isospin-conserving and isospin-violating as well as electromagnetic decay modes of excited heavy mesons, crucial due to limited experimental data.
- **Kinematics of Cluster splitting**: Introduction of a "dynamic thereshold scheme" for cluster hadronization.
- **General Tuning of Hadronization and Shower Parameters**: For both hadronization and parton shower parameters.

Heavy Quark Effective Theory in Cluster Hadronisation

– Passing through the polarization of heavy hadrons at the end of parton shower.

- For $m_Q \gg \Lambda_{\rm QCD}$, the light degrees of freedom become insensitive to m_Q. For the iso-spin heavy hadron multiplet $(H,\, H^\star)$ we can have:

$$\Gamma(H \to X) \gg \Delta m \gg \gamma(H \to H^\star X)$$

$$\gamma(H^\star \to HX) \propto \Phi^{H^\star \to HX}_{\rm phase-space} \times |\mathcal{M}(H^\star \to HX)|^2 \sim \mathcal{O}(m_q^{-(2+n)}), \quad n \geq 1$$

- Heavy quarks act as non-recoiling sources of color at the end of PS.
- A **spin-flavor symmetry** appears for heavy quarks.
- A net polarization of the initial heavy quark may be detected, either in a polarization of the final ground state or in the decay products of the **excited heavy mesons** and **heavy baryons**.
- **Falk-Peskin "no-win" theorem**: [Falk, Peskin, Phys.Rev.D 49 (1994) 3320-3332]
  No polarization information would be found in non-excited mesons. This could be realized for other possible cases, i.e.

$$\Delta m \gg \Gamma \gg \gamma \qquad \text{or} \qquad \Delta m \gg \gamma \gg \Gamma$$

Polarization of Excited Heavy Mesons

– Considering charm mesons with a left handed c quark, $j_Q = -1/2$.

– Colour magnetic interaction becomes decoupled leaving the spin-orientation of the light degrees independent of the charm quark and distributed uniformly:

$j_q^{(3)}$	-3/2	-1/2	1/2	3/2
Probability	$\frac{1}{2}\omega_{\frac{3}{2}}$	$\frac{1}{2}(1-\omega_{\frac{3}{2}})$	$\frac{1}{2}(1-\omega_{\frac{3}{2}})$	$\frac{1}{2}\omega_{\frac{3}{2}}$

– ω_j is the likelihood of fragmentation leading to a state with maximum value $|j_q^{(3)}|$.

– Coherent linear superposition of the charmed state helicity probablities $P_{H^\star}(j_q + j_Q)$:

$j^{(3)}$	-2	-1	0	$+1$	$+2$
D	–	–	$\frac{1}{4}$	–	–
$D^\star$	–	$\frac{1}{2}$	$\frac{1}{4}$	0	–
D_1	–	$\frac{1}{8}(1-\omega_{\frac{3}{2}})$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{3}{8}(1-\omega_{\frac{3}{2}})$	–
$D_2^\star$	$\frac{1}{2}\omega_{\frac{3}{2}}$	$\frac{3}{8}(1-\omega_{\frac{3}{2}})$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{1}{8}\omega_{\frac{3}{2}}$	0

Polarization of Excited Heavy Mesons

– To evaluate the parameter ω_j:

$$\frac{d\Gamma(H^\star \to H\pi)}{d\cos\theta} \propto \int d\phi \sum_j P_{H^\star}(j) \left|Y_j^\ell(\theta,\phi)\right|^2$$

$$\frac{1}{\Gamma}\frac{d\Gamma(D_2^\star \to D\pi)}{d\cos\theta} = \frac{1}{4}\left[1 + 3\cos^2\theta - 6\omega_{\frac{3}{2}}\left(\cos^2\theta - \frac{1}{3}\right)\right]$$

– Comparing to the avaiable experimental data, $\omega_{\frac{3}{2}} < 0.24$ with in 90% CL.

– Default value in Herwig is set $\omega_{\frac{3}{2}} = 0.20$.

– Generalise for the possible spin polarisations of excited charmed mesons:

$\hat{\rho}$	$\rho_{0,0}$	$\rho_{1,1}$	$\rho_{2,2}$	$\rho_{3,3}$	$\rho_{4,4}$
D	1	–	–	–	–
$D^\star$	$\frac{1}{2}(1-\rho_Q)$	$\frac{1}{2}$	$\frac{1}{2}(1+\rho_Q)$	–	–
D_1	$\frac{1}{16}[1-\rho_Q+\omega_{\frac{3}{2}}(3-5\rho_Q)]$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{1}{16}[1-\rho_Q+\omega_{\frac{3}{2}}(3+5\rho_Q)]$	–	–
$D_2^\star$	$\frac{1}{4}\omega_{\frac{3}{2}}(1-\rho_Q)$	$\frac{3}{16}(1-\rho_Q)-\frac{1}{8}\omega_{\frac{3}{2}}(1-\rho_Q)$	$\frac{1}{4}(1-\omega_{\frac{3}{2}})$	$\frac{3}{16}(1+\rho_Q)-\frac{1}{8}\omega_{\frac{3}{2}}(1+\rho_Q)$	$\frac{1}{4}\omega_{\frac{3}{2}}(1+\rho_Q)$

Polarization of Heavy Baryons

- For ground state heavy baryons, $j_q = 0$ so the initial polarization will be preservated without dilution.
- Considering charm baryons with a left handed c quark, $j_Q = -1/2$.
- $\omega_1 = 2/3$.
- ω_a is the rate of spin-0 to spin-1 diquark producion, which we take to be $\omega_a = 1$.

$j^{(3)}$	$-3/2$	$-1/2$	$+1/2$	$+3/2$
Λ_c	–	$\frac{1}{1+\omega_a}$	0	–
Σ_c	–	$\frac{(1-\omega_1)\omega_a}{3(1+\omega_a)}$	$\frac{\omega_1\omega_a}{3(1+\omega_a)}$	–
$\Sigma_c^\star$	$\frac{\omega_1\omega_a}{2(1+\omega_a)}$	$\frac{2(1-\omega_1)\omega_a}{3(1+\omega_a)}$	$\frac{\omega_1\omega_a}{6(1+\omega_a)}$	0

- Generalise for the possible spin polarisations of charmed baryons:

$\hat{\rho}$	$\rho_{0,0}$	$\rho_{1,1}$	$\rho_{2,2}$	$\rho_{3,3}$
Λ_c	$\frac{1}{2}(1-\rho_Q)$	$\frac{1}{2}(1+\rho_Q)$	–	–
Σ_c	$\frac{1}{2}(1-\rho_Q)+\omega_1\rho_Q$	$\frac{1}{2}(1+\rho_Q)-\omega_1\rho_Q$	–	–
$\Sigma_c^\star$	$\frac{3}{8}\omega_1(1-\rho_Q)$	$\frac{1}{2}(1-\rho_Q)-\frac{1}{8}\omega_1(3-5\rho_Q)$	$\frac{1}{2}(1-\rho_Q)-\frac{1}{8}\omega_1(3+5\rho_Q)$	$\frac{3}{8}\omega_1(1+\rho_Q)$

HQET and the Decay Modes of the Excite Heavy Mesons

- Improving the **strong isospin-conserving** decay modes
  - $J^P = 0^-, 1^-$ doublet; D and $D^\star$
  - $J^P = 1^+, 2^+$ doublet; D_1 and $D_2^\star$
  - $J^P = 0^+, 1^+$ doublet; $D_0^\star$ and D_1'
- The **electromagnetic** and **strong isospin-violating** decay modes
  - Particular importance where the strong isospin conserving decays are either **not allowed** or **kinematically suppressed**.
  - D^* and B^* mesons, where the strong decays are kinematically suppressed and radiative modes are important.
  - D_s^{*+}, D_{s0}^{*+} and $D_{s1}^+(2460)$ mesons, where both radiative and isospin-violating decay modes are important as the strong isospin conserving DK modes are kinematically forbidden.
  - the B_s^{*0} where only the radiative mode is kinematically allowed.
  - The D_s system is the most complicated as there are many excited mesons below the strong decay threshold.
- Has been used for heavy baryon decays since Herwig++.

Decay Modes

For 2-body decay modes in HQET: [Falk, M. E. Luke, 1992; Falk, Mehen, 1996]

$$\mathcal{M}(D^\star \to D\pi) = -\frac{2g}{f_\pi}\left(m_D m_{D^\star}\right)^{\frac{1}{2}} p_0 \cdot \epsilon_0$$

$$\mathcal{M}(D_2^\star \to D\pi) = -\frac{2h}{f_\pi \Lambda}\left(m_{D_2} m_D^\star\right)^{\frac{1}{2}} \epsilon_0^{\mu\nu} p_{0,\mu} p_{0,\nu}$$

$$\mathcal{M}(D_2^\star \to D^\star\pi) = -i\frac{2h}{f_\pi \Lambda}\left(\frac{m_{D^\star}}{m_{D_2}}\right)^{\frac{1}{2}} \epsilon^{\alpha\beta\mu\nu}\epsilon^0_{\alpha\gamma} p_0^\gamma p_{0,\mu} p_{1\nu} \epsilon_{1\beta},$$

$$\mathcal{M}(D_1 \to D^\star\pi) = \frac{h}{f_\pi \Lambda}\left(\frac{2}{3} m_{D_1} m_D\right)^{\frac{1}{2}} \left[\epsilon_0 \cdot \epsilon_1 \left(p_0^2 - \left[\frac{p_0 \cdot p_1}{m_0}\right]^2\right) - 3\epsilon_0 \cdot p_0 \epsilon_1 \cdot p_0\right]$$

$$\mathcal{M}(D_0^\star \to D\pi) = \frac{f''}{f_\pi}\left(m_{D_0^\star} m_D\right)^{\frac{1}{2}} p_0 \cdot \left(\frac{p_1}{m_{D_0^\star}} + \frac{p_2}{m_D}\right)$$

$$\mathcal{M}(D_1' \to D^\star\pi) = -\frac{f''}{f_\pi}\left(m_{D_1'} m_D\right)^{\frac{1}{2}} \left[-p_0 \cdot \left(\frac{p_1}{m_{D_0^\star}} + \frac{p_2}{m_D}\right) \epsilon_0 \cdot \epsilon_1 + \frac{1}{m_{D_1'}} \epsilon_1 \cdot p_1 \epsilon_0 \cdot p_0 + \frac{1}{m_D} \epsilon_0 \cdot p_2 \epsilon_1 \cdot p_0\right]$$

Decay Modes

Decay Widths: [Richardson, AM, 2023]

$$\Gamma(D^\star \to D\pi) = \frac{g^2}{6\pi f_\pi^2}\frac{m_D}{m_{D^\star}}p_{\rm cm}^3$$

$$\Gamma(D_2^\star \to D^\star\pi) = \frac{h^2}{15\pi f_\pi^2\Lambda^2}\frac{m_{D^\star}}{m_{D_2^\star}}p_{\rm cm}^5$$

$$\Gamma(D_2^\star \to D\pi) = \frac{h^2}{10\pi f_\pi^2\Lambda^2}\frac{m_D}{m_{D_2^\star}}p_{\rm cm}^5$$

$$\Gamma(D_1 \to D^\star\pi) = \frac{h^2}{144\pi f_\pi^2\Lambda^2}\frac{\left[-2m_{D^1}^2(m_{D^\star}^2-5m_\pi^2)+(m_\pi^2-m_{D^\star}^2)^2+25m_{D^1}^4\right]}{m_{D^\star}m_{D^1}^3}p_{\rm cm}^5$$

$$\Gamma(D_0^\star \to D\pi) = \frac{f''^2}{32f_\pi^2\pi}\frac{\left(m_{D_0^\star}-m_D\right)^2}{m_D m_{D_0^\star}^3}\left[\left(m_{D_0^\star}+m_D\right)^2-m_\pi^2\right]^2 p_{\rm cm}$$

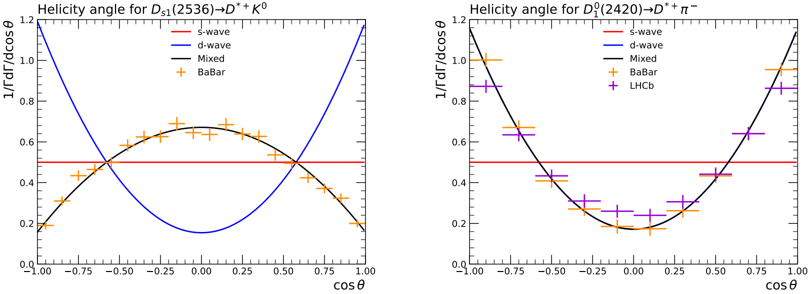
$$\Gamma(D_1' \to D^\star\pi) = \frac{f''^2}{32f_\pi^2\pi}\frac{\left(m_{D_1'}-m_{D^\star}\right)^2}{m_{D^\star} m_{D_1'}^3}\left[\left(m_{D_0'}+m_{D^\star}\right)^2-m_\pi^2\right]^2 p_{\rm cm}$$

Decay Data

Multiplet	State	Meson	Mass [GeV]	Width	Δm
$(0^-, 1^-)$	0^-	D^+	1.8697 ± 0.0001	N/A	4.82 ± 0.07
		D^0	1.8648 ± 0.0001	N/A	0.00 ± 0.00
		D_s^+	1.9683 ± 0.0001	N/A	103.51 ± 0.09
	1^-	D^{*+}	2.0103 ± 0.0001	$(0.0834 \pm 0.0018) \times 10^{-3}$	3.41 ± 0.07
		D^{*0}	2.0069 ± 0.0001	< 0.0021	0.00 ± 0.00
		D_s^{*+}	2.1122 ± 0.0004	< 0.0019	105.35 ± 0.40
$(1^+, 2^+)$	1^+	D_1^+	2.4232 ± 0.0024	0.0250 ± 0.0060	2.40 ± 2.45
		D_1^0	2.4208 ± 0.0005	0.0317 ± 0.0025	0.00 ± 0.00
		D_{s1}^+	2.5351 ± 0.0001	0.0009 ± 0.0001	114.31 ± 0.50
	2^+	D_2^{*+}	2.4654 ± 0.0013	0.0467 ± 0.0012	4.70 ± 1.36
		D_2^{*0}	2.4607 ± 0.0004	0.0475 ± 0.0011	0.00 ± 0.00
		D_{s2}^{*+}	2.5691 ± 0.0008	0.0169 ± 0.0007	108.40 ± 0.89
$(0^+, 1^+)$	0^+	D_0^+	2.3490 ± 0.0070	0.2210 ± 0.0180	49.00 ± 20.25
		D_0^0	2.3000 ± 0.0190	0.2740 ± 0.0400	0.00 ± 0.00
		D_{s0}^+	2.3178 ± 0.0005	< 0.0038	17.80 ± 19.01
	1^+	$D_1'^+$	Not observed		
		$D_1'^0$	2.4270 ± 0.0400	$0.38^{+0.13}_{-0.11}$	0.00 ± 0.00
		$D_{s1}'^+$	2.4595 ± 0.0006	< 0.0035	32.50 ± 40.00

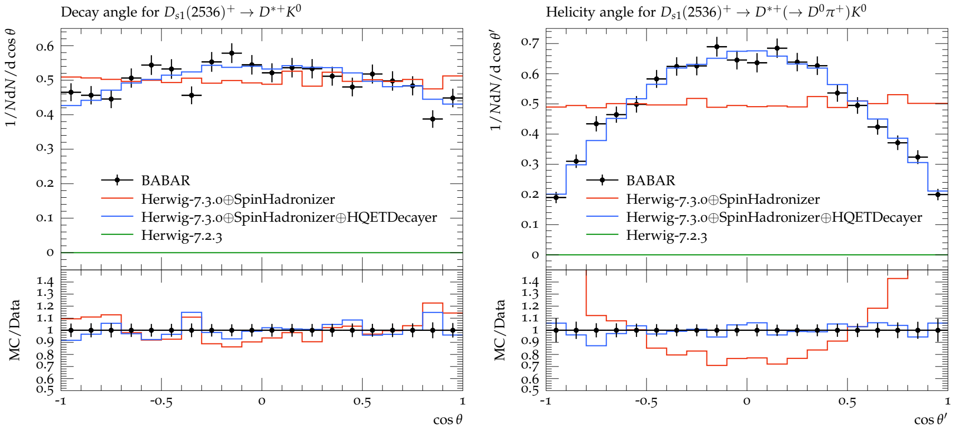
Observed masses and widths of the charm mesons, from BaBar and LHCb.

Fitting HQET Parameters



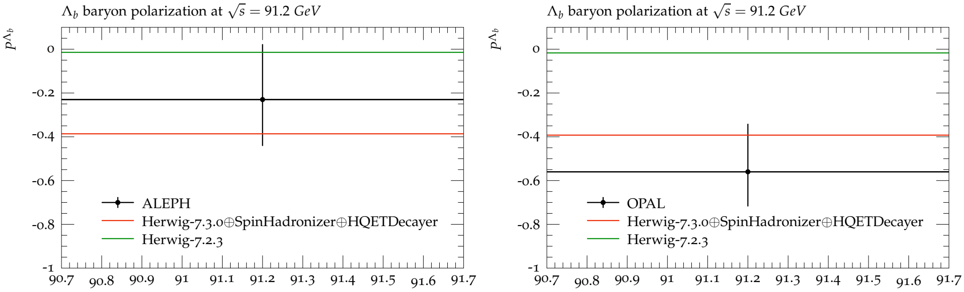
Parameter	f''	f_π	h	Λ	g	$\theta_{u,d}$	θ_s
Fitted Value	-0.465 ± 0.017	0.130 ± 0.001 GeV	0.824 ± 0.007	1.000 ± 0.000 GeV	0.565 ± 0.006	0.000 ± 0.100	-0.047 ± 0.002

HQET in Herwig 7



Efficiency-corrected decay rates of D_{s1}^+ meson.

HQET in Herwig 7



Average polarization of Λ_b baryons in hadronic Z^0 decays at LEP by ALEPH and OPAL.

General Tune for Herwig-7.3.0

- First general tune of Herwig 7.3.0 since the 7.2.0 release.
- Fitting to e^-e^+ mesurments from LEP, PETRA, SLAC, SLC and TRISTAN, for over 9,200 data bins.
- Tune weighted around both light and heavy hadron production rates and multiplicities, prioritising more dominant processes.
- Initial attempts to use Professor II yielded inconsistencies.
- We resorted to a multi-layered, brute-force approach to minimizing the χ^2 parameter.
- 5 consecutive runs, making the parameter range smaller, focusing on the best tune in the previous run. Each run for 5000 samples.
- 2 parton shower parameters and 10 hadronization parameters, including 3 new ones related to the kinematic handling of cluster splittings.

Kinematic Optimization in Cluster Hadronisation

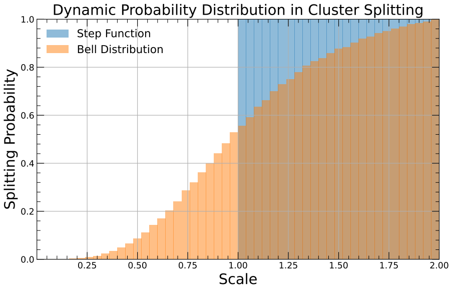
`Static` vs `Dynamic` kinematic thersholds in cluster splitting:

$$\texttt{Static}: \quad M > M_1 + M_2, \quad M_1 > m + m_1, \quad M_2 > m + m_2$$

$$\texttt{Dynamic}: \quad M^2 > M_1^2 + M_2^2, \quad M_1^2 > m^2 + m_1^2 + \delta_{\text{th}}, \quad M_2^2 > m^2 + m_2^2 + \delta_{\text{th}}$$

Probability of cluster splittings for heavy clusters:

$$P_{\text{cluster}} = \frac{1}{1 + \left| \frac{M - \delta}{M_{\text{th}}} \right|^r} > \text{Rand}(0, 1)$$

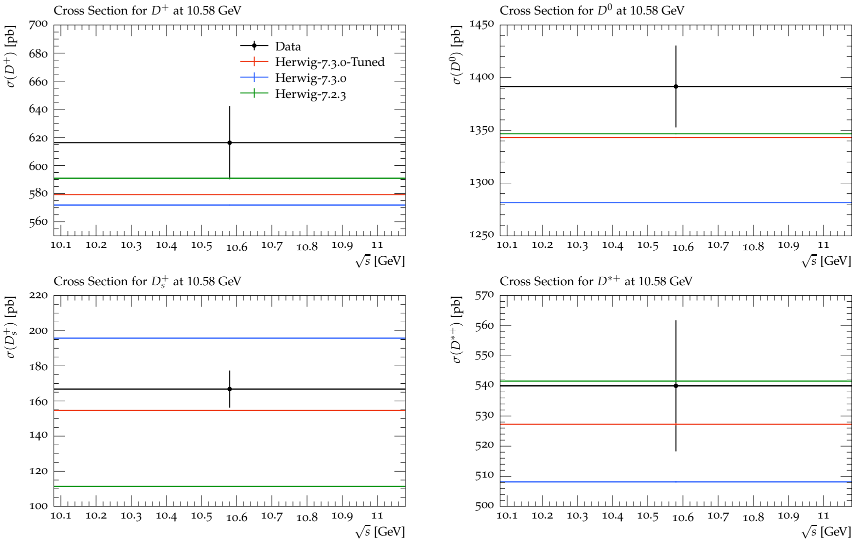


General Tune for Herwig-7.3.0

- The values of tuned parameters in Herwig-7.3.0 compared to Herwig-7.2.0.

Tuned Parameter	Herwig-7.3.0	Herwig-7.2.0
ClMaxLight [GeV]	3.529	3.649
ClPowLight	1.849	2.780
PSplitLight	0.914	0.899
PwtSquark	0.374	0.292
PwtDIquark	0.331	0.298
SngWt	0.891	0.740
DecWt	0.416	0.620
ProbabilityPowerFactor	6.486	–
ProbabilityShift	-0.879	–
KineticThresholdShift [GeV]	0.088	–
AlphaIn	0.102	0.126
pTmin [GeV]	0.655	0.958

- χ^2 improved by 12.76% (compared to Herwig 7.2.0 tune).
- χ^2 improved by 50.75% (compared to the untuned Herwig-7.3.0).



Comparison of heavy meson production rates at LEP, from various experimental data sets.

Summary

- Integration of HQET and spin-flavour symmetry in Herwig 7's cluster hadronization, via SpinHadronizer.
- Introduction of HQETStrongDecayer and HQETRadiativeDecayer for improved heavy meson and baryon decay handling.
- New kinematic regime for cluster splitting, enhancing model accuracy.
- Dynamic probability function for smoother cluster splitting distributions.
- Brute-force, multilayered approach to minimize χ^2.
- Tuning of 12 parameters, including parton shower-related ones.
- Substantial improvement in predictive capabilities for heavy hadron production.

Conclusion: "The integration of HQET and spin-flavour symmetry into Herwig 7 marks a major step forward in predictive modelling of heavy hadron production. The forthcoming Herwig-7.3.0 will offer a powerful tool for precise investigations in this field."

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std::cout«"Thank You!"«"\n";
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