Study of $\bar{B}^0 \to D^{*+}\omega\pi$ at Belle

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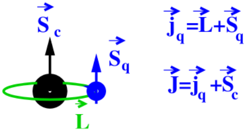
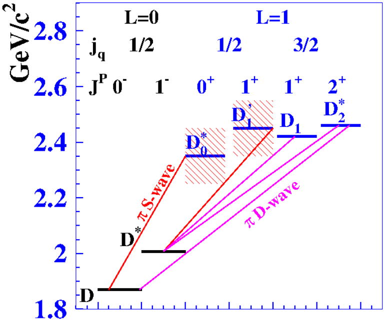
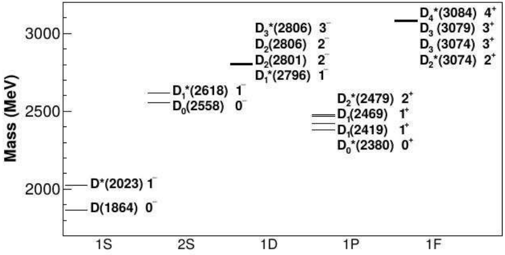
Mini-worshop on $D^{(*)}\tau\bar{\nu}$ and related topics
Nagoya University, March 27-28, 2017

D^{**} spectroscopy

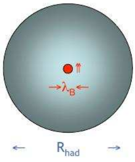


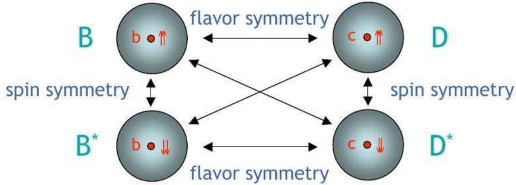


$D_0^* \to$	$D\pi$		in S-wave
$D_1' \to$		$D^*\pi$	in S-wave
$D_1 \to$		$D^*\pi$	in D-wave
$D_2^* \to$	$D\pi$	$D^*\pi$	in D-wave



Spin-flavor symmetry



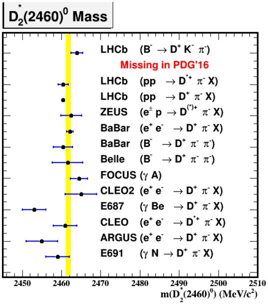


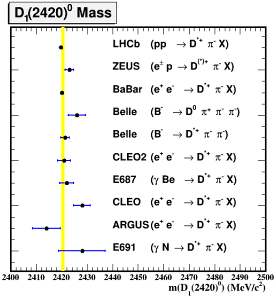
- Binding energy

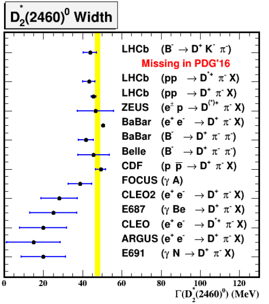
$$M_H = m_Q + \boxed{\bar{\Lambda}} + 1/m_Q \cdot (\lambda_1 + c_s\lambda_2) + O(1/m_Q^2)$$

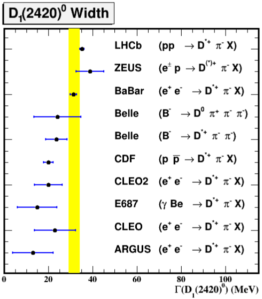
- Power corrections to heavy-quark limit
  - λ_1: spin-independent
  - λ_2: spin-dependent

Neutral narrow D^{**} states

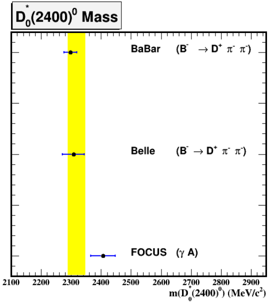


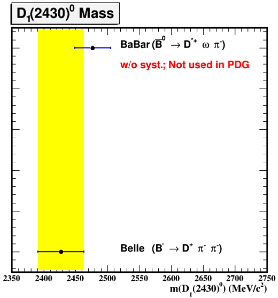


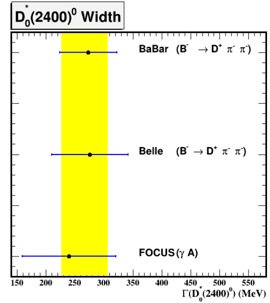


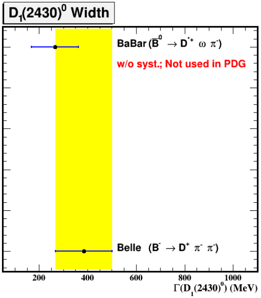


Neutral broad D^{**} states









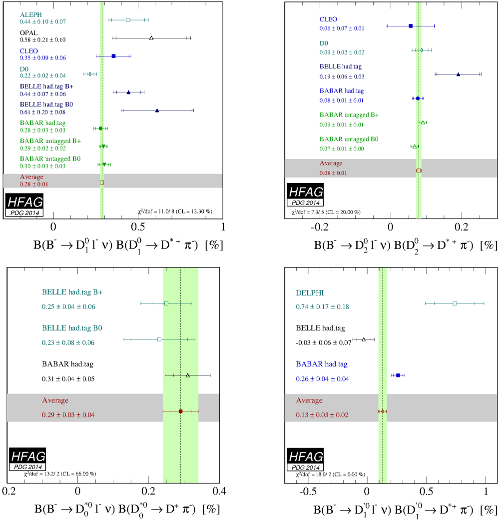
D^{**} mixing

Mixing is suppressed in the heavy quark limit

$$|D_1(2420)^0> = \sin\omega\,|j_q = 1/2> + \cos\omega\, e^{-i\varphi}\,|j_q = 3/2>$$
$$|D_1^*(2430)^0> = \cos\omega\,|j_q = 1/2> - \sin\omega\, e^{i\varphi}\,|j_q = 3/2>$$

$$\left.\begin{aligned}\omega &= (-0.10 \pm 0.03 \pm 0.02 \pm 0.02)\ \mathrm{rad}\\ \varphi &= (+0.05 \pm 0.20 \pm 0.04 \pm 0.06)\ \mathrm{rad}\end{aligned}\right\}\ \text{Belle}\quad (B^- \to D^{*+}\pi^-\pi^-)$$

D^{**} production in semileptonic decays



HQET vs. experiment discrepancy

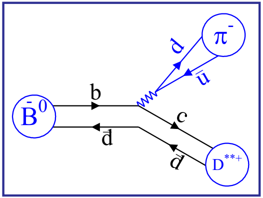
Belle II data could clarify situation

Hadronic dynamics is welcome

D^{**} production in hadronic decays

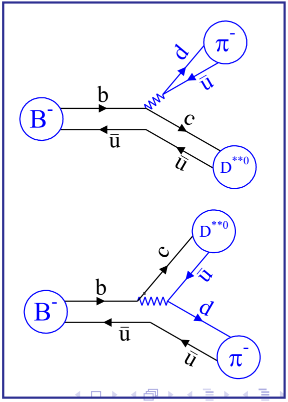
Class I decays

Pion emission: "$B \to D^{**}$" $\times f_\pi$
Isgur-Wise functions: $\tau_{1/2} \ll \tau_{3/2}$
Narrow D^{**}'s dominate



Class III decays

Pion + D^{**} emission:
("$B \to D^{**}$" $\times f_\pi$) + ("$B \to \pi$" $\times f_{D^{**}}$)
Constructive interference
Isgur-Wise functions: $\tau_{1/2} \ll \tau_{3/2}$
D^{**} weak constants: $f_{1/2} > f_{3/2}$
The rates of all D^{**}'s are of the same order



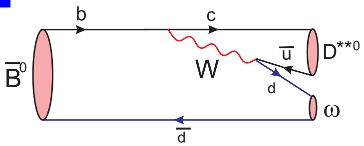
D^{**} production in hadronic decays

Class I & Class III BF products (PDG'16)	Value
$\mathcal{B}(\bar{B}^0 \to D_0^*(2400)^+\pi^-) \times \mathcal{B}(D_0^*(2400)^+ \to D^0\pi^+)$	$(6.0 \pm 3.0) \times 10^{-5}$
$\mathcal{B}(\bar{B}^0 \to D_1(2430)^+\pi^-) \times \mathcal{B}(D_1(2430)^+ \to D^{*0}\pi^+)$	$< 7 \times 10^{-5}$
$\mathcal{B}(\bar{B}^0 \to D_1(2420)^+\pi^-) \times \mathcal{B}(D_1(2420)^+ \to D^{*0}\pi^+)$	$(3.7 \pm 0.9) \times 10^{-4}$
$\mathcal{B}(\bar{B}^0 \to D_2^*(2460)^+\pi^-) \times \mathcal{B}(D_2^*(2460)^+ \to D^0\pi^+)$	$(2.2 \pm 0.4) \times 10^{-4}$
$\mathcal{B}(\bar{B}^0 \to D_2^*(2460)^+\pi^-) \times \mathcal{B}(D_2^*(2460)^+ \to D^{*0}\pi^+)$	$(2.5 \pm 0.6) \times 10^{-4}$
$\mathcal{B}(\bar{B}^- \to D_0^*(2400)^0\pi^-) \times \mathcal{B}(D_0^*(2400)^0 \to D^-\pi^+)$	$(6.4 \pm 1.4) \times 10^{-4}$
$\mathcal{B}(\bar{B}^- \to D_1(2430)^0\pi^-) \times \mathcal{B}(D_1(2430)^0 \to D^{*-}\pi^+)$	$(5.0 \pm 1.3) \times 10^{-4}$
$\mathcal{B}(\bar{B}^- \to D_1(2420)^0\pi^-) \times \mathcal{B}(D_1(2420)^0 \to D^{*-}\pi^+)$	$(6.8 \pm 1.5) \times 10^{-4}$
$\mathcal{B}(\bar{B}^- \to D_2^*(2460)^0\pi^-) \times \mathcal{B}(D_2^*(2460)^0 \to D^-\pi^+)$	$(3.5 \pm 0.4) \times 10^{-4}$
$\mathcal{B}(\bar{B}^- \to D_2^*(2460)^0\pi^-) \times \mathcal{B}(D_2^*(2460)^0 \to D^{*-}\pi^+)$	$(2.2 \pm 1.1) \times 10^{-4}$

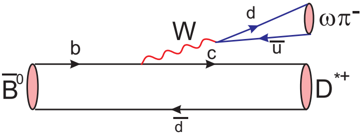
Class I & III data confirm the theoretical expectations

Class II data are needed

$\bar{B}^0 \to D^{**}\omega \to (D^{*+}\pi^-)\omega$ decays



Class II decays

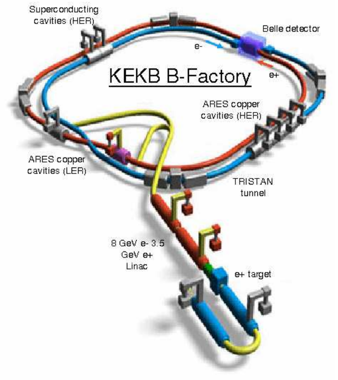


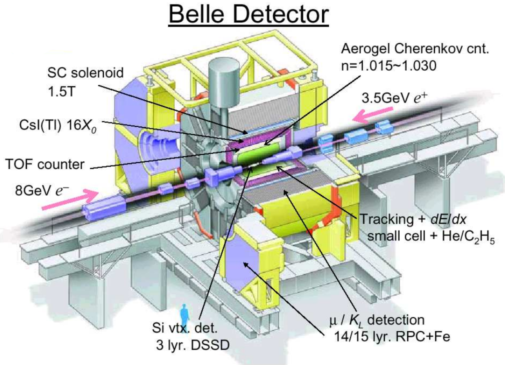
- 1. What are the $j = 1/2$ and $j = 3/2$ rates in class II decays?
- 2. What is the tensor $j = 3/2$ rate in class II decays?
  Soft Collinear Effective Theory (SCET) (Phys. Rev. D **70**, 114006 (2004))
  predicts equal rates and strong phases for $D_1(2420)$ and $D_2^*(2460)$ $(j = 3/2)$
  in the $\bar{B}^0 \to D^{**0}M$ decays, $M = \pi, \rho, K$ or $M = K^*$ with long. polarization.
  SCET vs naive factorization (?)

Advantage of $\bar{B}^0 \to D^{**}\omega$ study

- Lower fractions of $q\bar{q}$ continuum and combinatorial $B\bar{B}$ backgrounds than in $B \to D^{**0}\pi^0$.
- Possibility to measure the polarizations and partial-wave fractions of D^{**}-states.
- Possibility to perform the coherent study of $\rho(770)$, $\rho(1450)$ and $\rho(1700)$ in the $\omega\pi$ final state.

Belle experiment





- Asymmetric beam energies: $E_{e^-} = 8\,\text{GeV}$, $E_{e^+} = 3.5\,\text{GeV}$
- Peak luminosity: $\mathcal{L} = 2.1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
- $B\bar{B}$ luminosity: $\int \mathcal{L}\, dt \approx 711\,\text{fb}^{-1}$ corresponds to $(772 \pm 11) \times 10^6$ $B\bar{B}$ pairs produced.
- Reported analysis uses the full $B\bar{B}$ data sample collected at Belle.

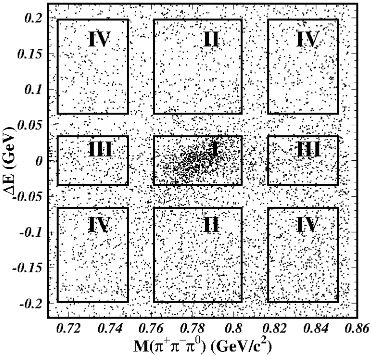
$\bar{B}^0 \to D^{**+}\omega\pi^-$ analysis strategy

$$M_{\rm bc} = \sqrt{(E_{\rm beam}^{\rm CMS})^2/c^4 - |\sum_i \mathbf{p}_{\rm i}^{\rm CMS}|^2/c^2}$$

$$\Delta E = \sqrt{|\mathbf{p}_{\rm i}^{\rm CMS}|^2 c^2 + m_i^2 c^4} - E_{\rm beam}^{\rm CMS}$$

$$5.2725\,{\rm GeV}/c^2 < M_{\rm bc} < 5.2845\,{\rm GeV}/c^2$$

Region I — signal
Regions II, III, IV — sidebands

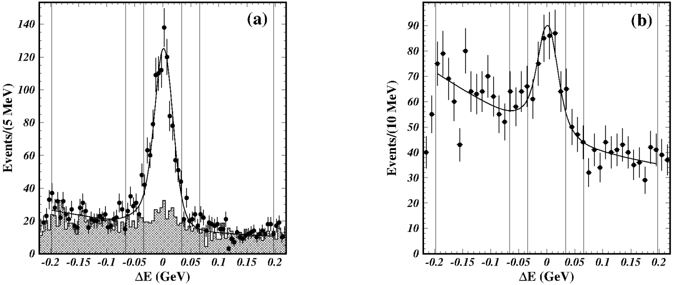


Multidimensional amplitude analysis

- Amplitude analysis as an efficient tool for distinguishing the contributions of narrow & broad D^{**} states.
- Unbinned likelihood fit in the decay kinematic phase space.
- Likelihood function constructed from the background and signal PDF functions.

Total branching fraction

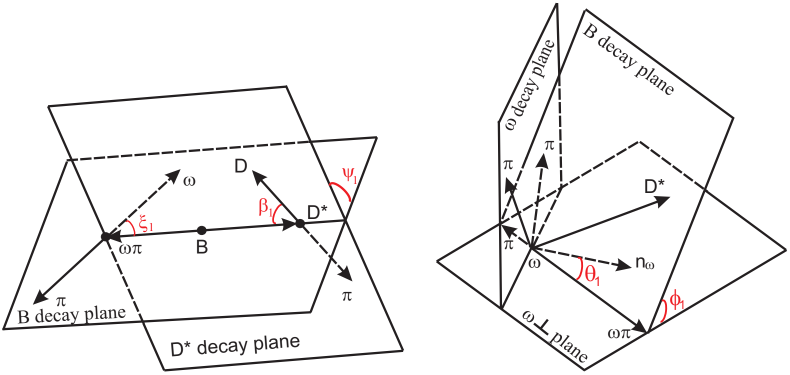
Peaking bkg from $\bar{B}^0 \to D^{*+}\pi^+\pi^-\pi^0\pi^-$



$$\boxed{\mathcal{B}(\bar{B}^0 \to D^{*+}\omega\pi^-) = (2.31 \pm 0.11\,(\text{stat.}) \pm 0.14\,(\text{syst.})) \times 10^{-3}}$$

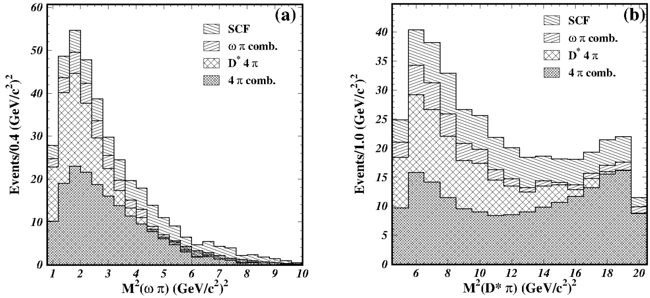
BF consistent with CLEO and BaBar but has higher precision.

Angular variables

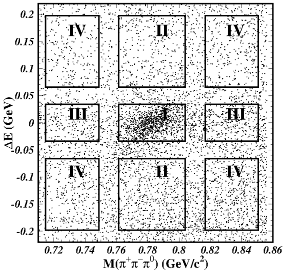


- 5 angles + q^2 = 6 variables
- Two different bases for $\omega\pi$ and D^{**}
- Full angular analysis for all intermediate states

Background description



- SCF (Self Cross-Feed) (regions I, II, III and IV) — misreconstruction of true signal
- $\omega\pi$ comb. (regions I and III) — combinatorial $B\bar{B}$ bkg w/ correctly reconstructed ω
- $D^{*}4\pi$ (regions I and II) — peaking bkg from $\bar{B}^0 \to D^{*+}\pi^+\pi^-\pi^0\pi^-$ w/o ω contribution (basically $\bar{B}^0 \to D^{*+}a_1(1260)\pi$)
- 4π comb. (regions I, II, III and IV) — combinatorial $B\bar{B}$ bkg w/ misreconstructed ω



Signal description

- Sum of quasi-two-body resonant amplitudes:
  $\mathcal{M} = \sum_{i=R} a_R e^{i\phi_R} \mathcal{M}_R$
- Partial-wave formalism for each amplitude:
  $\mathcal{M}_R \sim \frac{1}{\mathcal{D}_R(q^2)} \sum_{L_1} f_{L_1} \sum_{L_2} \mathcal{A}_{L_1,L_2}; \;\; L_1 = L(D^{**}\omega), \; L_2 = L(D^*\pi)$
- Relativistic Breit-Wigner function with q^2-dependent width for all resonances:
  $\mathcal{D}_R(q^2) = q^2 - m_R^2 + i m_R \Gamma_R(q^2)$
- Angular distributions in terms of defined variables:

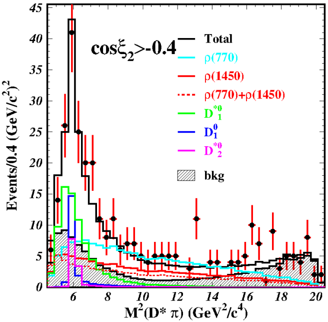
$$\begin{aligned} \mathcal{A}_{L_1=S,L_2=P} &= -s_\theta s_\phi c_\beta s_\xi + s_\theta c_\phi s_\beta s_\psi - s_\theta s_\phi s_\beta c_\psi c_\xi \\ \mathcal{A}_{L_1,L_2} &= \cdots \end{aligned}$$

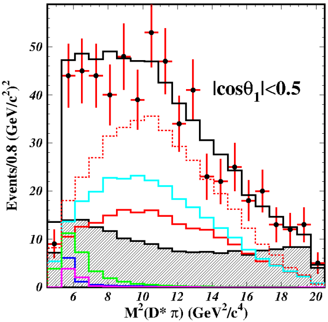
- Blatt-Weisskopf factor for each partial wave: $f_{L_1}(q^2) \sim B_{L_1}(q^2)$
- Mixing between $j_q = 1/2$ and $j_q = 3/2$

$D_1(2430)^0$ resonance

No significant mixing observed:

$$\omega = -0.03 \pm 0.02\,(\text{stat.}),$$
$$\varphi = -0.27 \pm 0.75\,(\text{stat.})$$



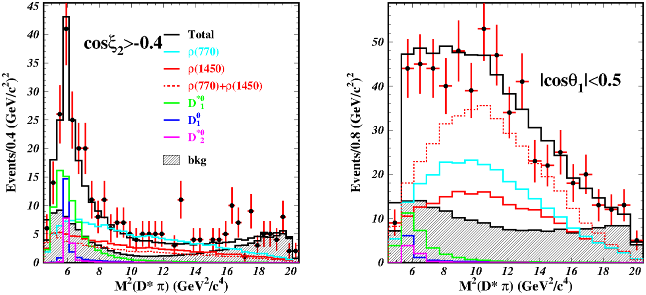


$$\boxed{\mathcal{B}_{D_1(2430)^0} = (2.5 \pm 0.4\,(\text{stat.})\,^{+0.7}_{-0.2}\,(\text{syst.})\,^{+0.4}_{-0.1}\,(\text{model})) \times 10^{-4}}$$

$$\boxed{\delta = 8.6\sigma}$$

- Consistent with HQET $\Longrightarrow \mathcal{B}_{D_1(2430)^0} \simeq 3.5 \times 10^{-4}$

$D_1(2420)^0$ & $D_2^*(2460)^0$ resonances



$$\mathcal{B}_{D_1(2420)^0} = (0.7 \pm 0.2\,(\text{stat.})\,^{+0.1}_{-0.0}\,(\text{syst.}) \pm 0.1\,(\text{model})) \times 10^{-4}$$ $\delta = 5.5\sigma$

$$\mathcal{B}_{D_2^*(2460)^0} = (0.4 \pm 0.1\,(\text{stat.})\,^{+0.0}_{-0.1}\,(\text{syst.}) \pm 0.1\,(\text{model})) \times 10^{-4}$$ $\delta = 5.0\sigma$

- Narrow D^{**} are suppressed according to HQET
- SCET prediction could be reasonable
  $\mathcal{B}(\bar{B}^0 \to D_1(2420)^0\omega_\parallel) = \mathcal{B}(\bar{B}^0 \to D_2^*(2460)^0\omega_\parallel)$
  (but only for the longitudinal component)

D^{**} polarizations & partial waves

D^{**} longitudinal polarizations
Long-distance QCD effects could be essential

$$\mathcal{P}_{D_1(2430)^0} = (63.0 \pm 9.1\,(\text{stat.}) \pm 4.6\,(\text{syst.})\,^{+4.6}_{-3.9}(\text{model}))\%$$

$$\mathcal{P}_{D_1(2420)^0} = (67.1 \pm 11.7\,(\text{stat.})\,^{+0.0}_{-4.2}\,(\text{syst.})\,^{+2.3}_{-2.8}(\text{model}))\%$$

$$\mathcal{P}_{D_2^*(2460)^0} = (76.0\,^{+18.3}_{-8.5}\,(\text{stat.}) \pm 2.0\,(\text{syst.})\,^{+2.9}_{-2.0}(\text{model}))\%$$

$$\mathcal{P}_{D^{*0}} = (66.5 \pm 4.7(\text{stat.}) \pm 1.5\,(\text{syst.}))\%$$ $\Longleftarrow$ BaBar ($\bar{B}^0 \to D^{*0}\omega$)

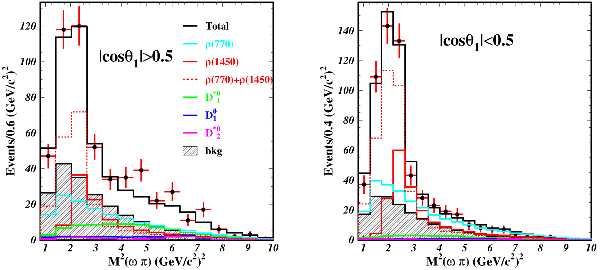
S-, P-, D-wave rates for $D_1(2430)^0$

$$f_S = (38.9 \pm 10.8\,(\text{stat.})\,^{+4.3}_{-0.7}\,(\text{syst,})\,^{+1.2}_{-1.1}\,(\text{model}))\%$$

$$f_P = (33.1 \pm 9.5\,(\text{stat.})\,^{+2.4}_{-5.5}\,(\text{syst,})\,^{+3.0}_{-4.0}\,(\text{model}))\%$$

$$f_D = (28.3 \pm 8.9\,(\text{stat.})\,^{+3.0}_{-0.8}\,(\text{syst,})\,^{+3.9}_{-2.9}\,(\text{model}))\%$$

Other results



$$\mathcal{B}_{\rho(770)^-} = (1.48 \pm 0.27\,(\text{stat.})\,^{+0.15}_{-0.09}\,(\text{syst.})\,^{+0.21}_{-0.56}\,(\text{model})) \times 10^{-3} \qquad \delta = 10.5\sigma$$

$$\mathcal{B}_{\rho(1450)^-} = (1.07\,^{+0.15}_{-0.31}\,(\text{stat.})\,^{+0.06}_{-0.13}\,(\text{syst.})\,^{+0.40}_{-0.02}\,(\text{model})) \times 10^{-3} \qquad \delta = 15.0\sigma$$

$$\mathcal{B}_{\sum\rho} = (1.90 \pm 0.11\,(\text{stat.})\,^{+0.11}_{-0.13}\,(\text{syst.})\,^{+0.02}_{-0.06}\,(\text{model})) \times 10^{-3} \qquad \delta = 29.8\sigma$$

$$\mathcal{B}_{b_1(1235)} < 0.7 \times 10^{-4}\ (90\%\ \text{C.L.})$$

$$\mathcal{P}_{\rho(1450)} = (66.5 \pm 0.6\,(\text{stat.})\,^{+0.1}_{-0.3}\,(\text{syst.})\,^{+1.2}_{-0.8}\,(\text{model}))\%$$

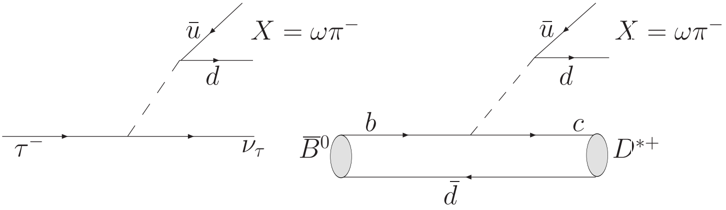
HQET & factorization prediction based on SL data $\Longrightarrow (68.4 \pm 0.9)\%$

Conclusion

- $\bar{B}^0 \to D^{*+}\omega\pi^-$ decay rate is consistent with the CLEO and BaBar measurements but it has higher precision (7.7%).
- Broad $D_1(2430)^0$ production is consistent with HQET.
- Narrow $D_1(2420)$ and $D_2^*(2460)$ productions are suppressed as predicted in HQET
- Significant tensor $D_2^*(2460)$ production is observed.
- D^{**} longitudinal polarizations and partial-wave rates are measured.
- The consistent study of the ρ-meson-like states is performed.

These results could be useful for SL studies

Backup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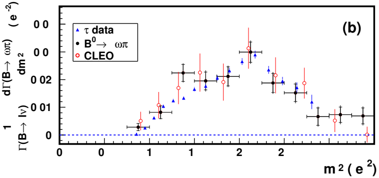
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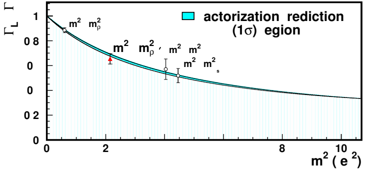
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