Polarization of B → VV experimental status

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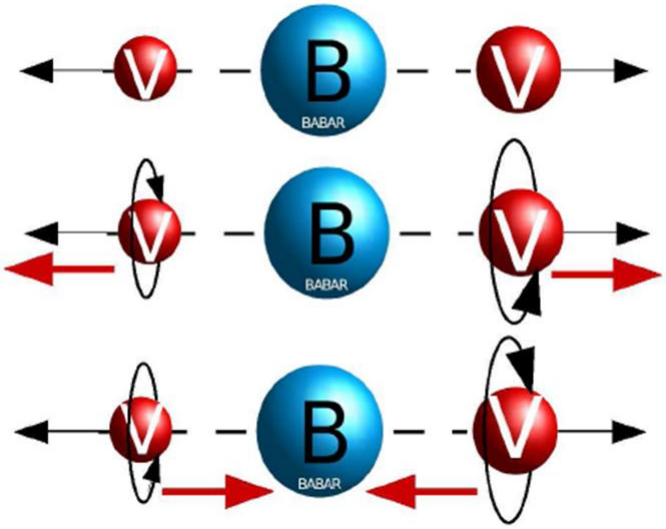
Polarization in B → VV

- Three amplitudes.
- Helicity basis:
  - A_0 (longitudinal: $\lambda_{V1}=\lambda_{V2}= 0$)
  - A_{+1} (transverse: $\lambda_{V1}=\lambda_{V2}= +1$)
  - A_{-1} (transverse: $\lambda_{V1}=\lambda_{V2}= -1$)



- Transversity basis:

$$A_0 \qquad A_{//} = \frac{A_{+1} + A_{-1}}{\sqrt{2}} \qquad A_{\perp} = \frac{A_{+1} - A_{-1}}{\sqrt{2}}$$

CP-even longitudinal CP-even transverse CP-odd transverse

Polarization puzzle

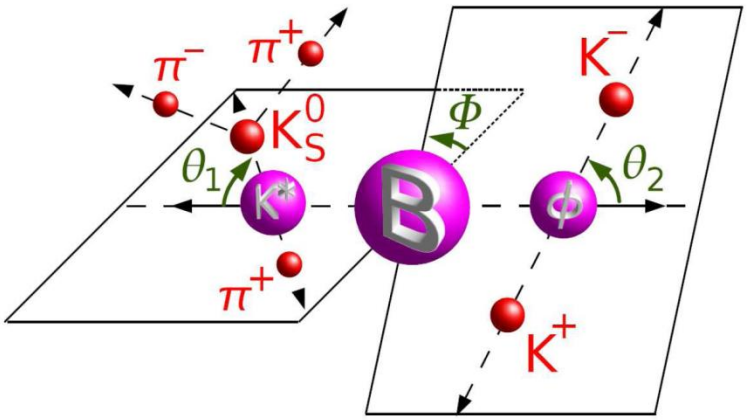
- Naïve expectation:

  $A_0 \sim 1 \gg A_{+1} \sim m_V/m_B \gg A_{-1} \sim m_V^2/m_B^2$

  or $A_0 \sim 1 \gg A_{//} \sim A_\perp \sim m_V/m_B$

- The naïve expectation is not (always) verified experimentally (in penguin dominated decays).
- Several possible explanations *(cf. A. Kagan's talk)*:
  - Within standard model:
    - Penguin annihilation
    - Rescattering
  - Outside standard model.

Angular distribution



- 3 observables: θ_1, θ_2, Φ
- to measure:

$$f_{L,//,\perp} = \frac{\left|A_{0,//,\perp}\right|^2}{\left|A_0\right|^2 + \left|A_{//}\right|^2 + \left|A_\perp\right|^2}$$

$$\phi_{//,\perp} = \arg\left(A_{//,\perp} A_0^{\,*}\right)$$

$$d^3\Gamma / d\cos\theta_1\, d\cos\theta_2\, d\Phi \sim$$

$\alpha_1(f_L)\times$ XAxis $\Rightarrow |A_0|^2$

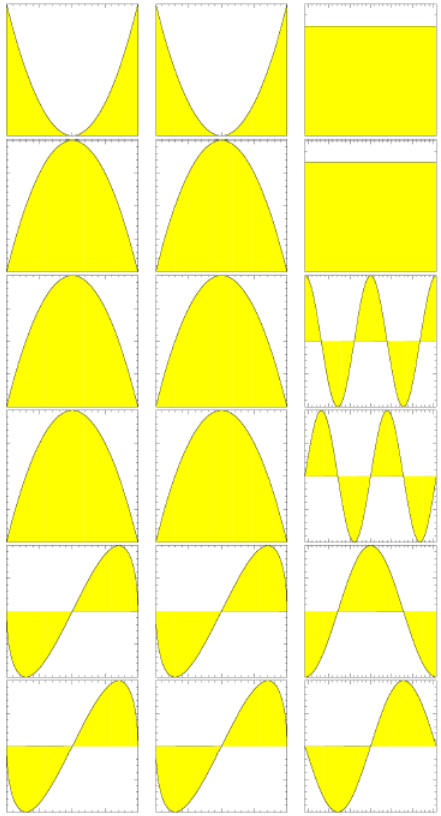
$\alpha_2(f_L)\times \Rightarrow |A_\parallel|^2+|A_\perp|^2$

$\alpha_3(f_L, f_\perp)\times \Rightarrow |A_\parallel|^2-|A_\perp|^2$

$\alpha_4(f_L, f_\perp, \phi_\perp, \phi_\parallel)\times \Rightarrow \mathrm{Im}(A_\perp A_\parallel^*)$

$\alpha_5(f_L, f_\perp, \phi_\parallel)\times \Rightarrow \mathrm{Re}(A_\parallel A_0^*)$

$\alpha_6(f_L, f_\perp, \phi_\perp)\times \Rightarrow \mathrm{Im}(A_\perp A_0^*)$



$\cos\theta_1$ $\cos\theta_2$ Φ

Angular analysis

- Partial angular analysis:
  - Integrate over Φ, use only θ_1 and θ_2.
  - Measure f_L.
- Full angular analysis:
  - Use the three observables: θ_1, θ_2, and Φ.
  - Measure f_L, $f_\perp$, $\phi_{//}$, $\phi_\perp$.
  - Other parameters may be measured:
    - overall phase δ_0 .
    - direct CP asymmetries:

      $\mathcal{A}_L$, $\mathcal{A}_\perp$, $\Delta\phi_{//}$, $\Delta\phi_\perp$, $\Delta\delta_0$.

B → ρ ρ

- Tree diagram dominated decays.
  - higher penguin fraction in color suppressed mode $B^0 \to \rho^0 \rho^0$.
- $f_L \sim 1$ as expected for $B^0 \to \rho^+ \rho^-$ and $B^+ \to \rho^+ \rho^0$.

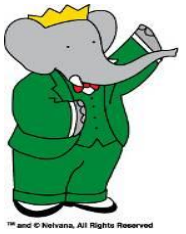
$B(\rho^+\rho^-) = (22.8 \pm 3.8^{+2.3}_{-2.6}) \times 10^{-6}$	$B(\rho^+\rho^-) = (25.5 \pm 2.1^{+3.6}_{-3.9}) \times 10^{-6}$
$f_L(\rho^+\rho^-) = 0.941^{+0.034}_{-0.040} \pm 0.030$	$f_L(\rho^+\rho^-) = 0.992 \pm 0.024^{+0.026}_{-0.013}$
$B(\rho^+\rho^0) = (31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$	$B(\rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$
$f_L(\rho^+\rho^0) = 0.95 \pm 0.11 \pm 0.02$	$f_L(\rho^+\rho^0) = 0.950 \pm 0.015 \pm 0.006$
$B(\rho^0\rho^0) < 1.0 \times 10^{-6}\ (90\%\ CL)$	$B(\rho^0\rho^0) = (0.9 \pm 0.3 \pm 0.1) \times 10^{-6}$
	$f_L(\rho^0\rho^0) = 0.75^{+0.11}_{-0.14} \pm 0.05$

535M BB | 85M BB | 657M BB

383M BB | 465M BB | 465M BB

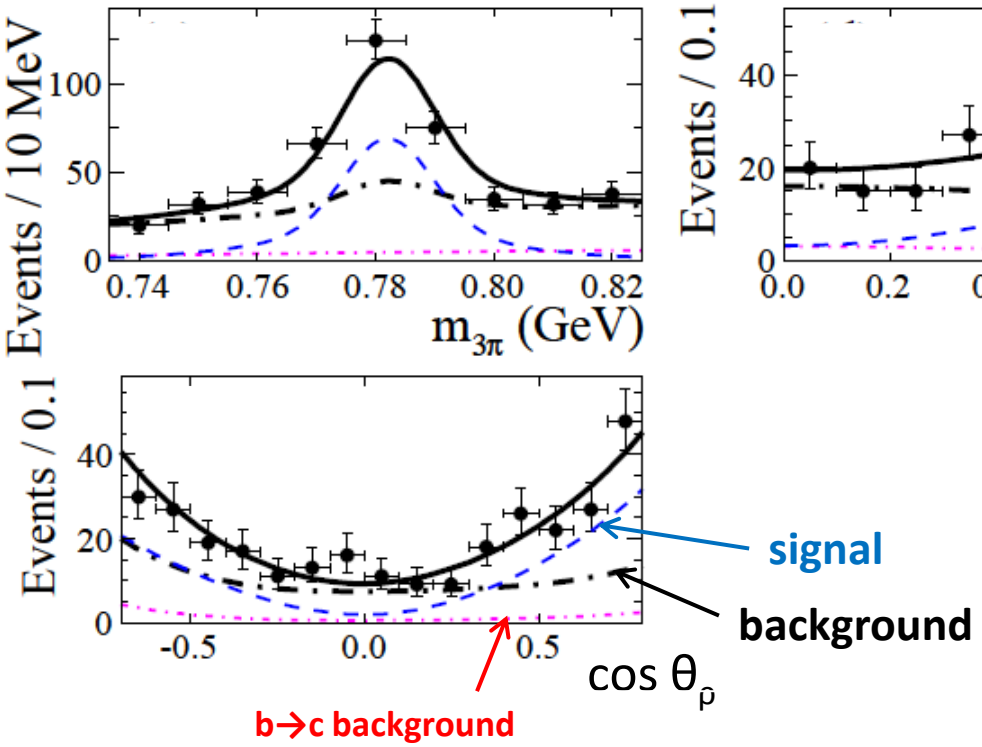
PRL 96, 171801 (2006)
PRL 91, 221801 (2003)
PRD 78, 111102 (2008)

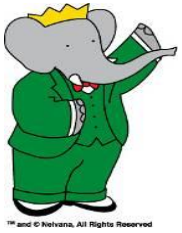
PRD 76, 052007 (2007)
PRL 102, 141802 (2009)
PRD 78, 071104 (2008)



B → ω ρ

- Also tree diagram dominated decay.
- f_L ~ 1 also.





465M BB

$$B(\omega\rho^+) = (15.9 \pm 1.6 \pm 1.4) \times 10^{-6}$$

$$f_L(\omega\rho^+) = 0.90 \pm 0.05 \pm 0.03$$

$$B(\omega\rho^0) < 1.6 \times 10^{-6} (90\%\, CL)$$

PRD 79, 052005 (2009)

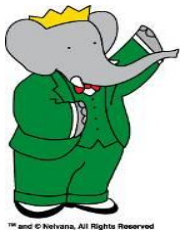
$B^0 \to \phi K^{*0}$

- Penguin diagram dominated decay.
- $f_L \sim 0.5$ and $f_{//} \sim f_\perp$.

275M BB

$$B(\phi K^{*0}) = (10.0^{+1.6+0.7}_{-1.5-0.8}) \times 10^{-6}$$
$$f_L(\phi K^{*0}) = 0.45 \pm 0.05 \pm 0.02$$
$$f_\perp(\phi K^{*0}) = 0.30 \pm 0.06 \pm 0.02$$
$$\phi_{//}(\phi K^{*0}) = 2.39 \pm 0.24 \pm 0.04$$
$$\phi_\perp(\phi K^{*0}) = 2.51 \pm 0.23 \pm 0.04$$
$$A_L(\phi K^{*0}) = 0.13 \pm 0.12 \pm 0.04$$
$$A_\perp(\phi K^{*0}) = -0.20 \pm 0.18 \pm 0.04$$
$$\Delta\phi_{//}(\phi K^{*0}) = -0.32 \pm 0.27 \pm 0.07$$
$$\Delta\phi_\perp(\phi K^{*0}) = -0.30 \pm 0.25 \pm 0.06$$

PRL 94, 221804 (2005)



465M BB

$$B(\phi K^{*0}) = (9.7 \pm 0.5 \pm 0.6) \times 10^{-6}$$
$$f_L(\phi K^{*0}) = 0.49 \pm 0.03 \pm 0.01$$
$$f_\perp(\phi K^{*0}) = 0.21 \pm 0.03 \pm 0.01$$
$$\phi_{//}(\phi K^{*0}) = 2.40 \pm 0.13 \pm 0.08$$
$$\phi_\perp(\phi K^{*0}) = 2.35 \pm 0.13 \pm 0.09$$
$$\delta_0(\phi K^{*0}) = 2.82 \pm 0.15 \pm 0.09$$
$$A_L(\phi K^{*0}) = 0.01 \pm 0.07 \pm 0.02$$
$$A_\perp(\phi K^{*0}) = -0.04 \pm 0.15 \pm 0.06$$
$$\Delta\phi_{//}(\phi K^{*0}) = 0.22 \pm 0.12 \pm 0.08$$
$$\Delta\phi_\perp(\phi K^{*0}) = 0.21 \pm 0.13 \pm 0.08$$
$$\Delta\delta_0(\phi K^{*0}) = 0.27 \pm 0.14 \pm 0.08$$

CP asymmetries

PRD 78, 092008 (2008)

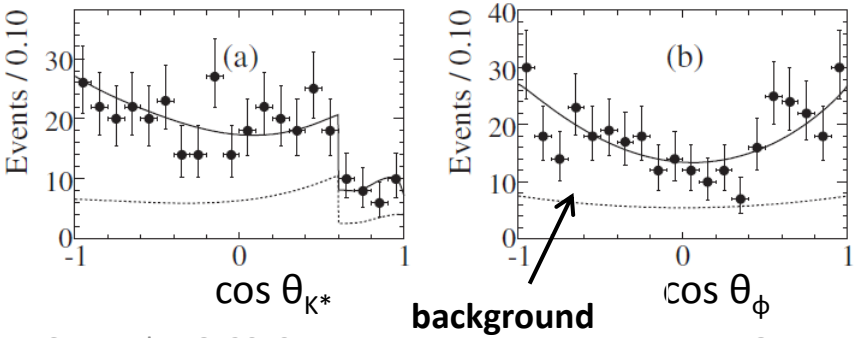
$B^+ \to \phi K^{*+}$

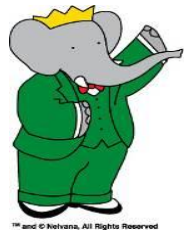
- Penguin diagram dominated decay.
- $f_L \sim 0.5$ and $f_{//} \sim f_\perp$ as for $B^0 \to \phi K^{*0}$.

275M BB

$$B(\phi K^{*+}) = (6.7^{+2.1+0.7}_{-1.9-1.0}) \times 10^{-6}$$
$$f_L(\phi K^{*+}) = 0.52 \pm 0.08 \pm 0.03$$
$$f_\perp(\phi K^{*+}) = 0.19 \pm 0.08 \pm 0.02$$
$$\phi_{//}(\phi K^{*+}) = 2.10 \pm 0.28 \pm 0.04$$
$$\phi_\perp(\phi K^{*+}) = 2.31 \pm 0.30 \pm 0.07$$

PRL 94, 221804 (2005)





384M BB

$$B(\phi K^{*+}) = (11.2 \pm 1.0 \pm 0.9) \times 10^{-6}$$
$$f_L(\phi K^{*+}) = 0.49 \pm 0.05 \pm 0.03$$
$$f_\perp(\phi K^{*+}) = 0.21 \pm 0.05 \pm 0.02$$
$$\phi_{//}(\phi K^{*+}) = 2.47 \pm 0.20 \pm 0.07$$
$$\phi_\perp(\phi K^{*+}) = 2.69 \pm 0.20 \pm 0.03$$
$$\delta_0(\phi K^{*+}) = 3.07 \pm 0.18 \pm 0.06$$
$$A_L(\phi K^{*+}) = 0.17 \pm 0.11 \pm 0.02$$
$$A_\perp(\phi K^{*+}) = 0.22 \pm 0.24 \pm 0.08$$
$$\Delta\phi_{//}(\phi K^{*+}) = 0.07 \pm 0.20 \pm 0.05$$
$$\Delta\phi_\perp(\phi K^{*+}) = 0.19 \pm 0.20 \pm 0.07$$
$$\Delta\delta_0(\phi K^{*+}) = 0.20 \pm 0.18 \pm 0.03$$

CP asymmetries

PRL 99, 201802 (2007)

B → K* ρ

- Penguin diagram dominated decays.
- $f_L \sim 0.5$ like ϕ K*.

275M BB

657M BB

$$B(K^{*0}\rho^+) = (8.9 \pm 1.7 \pm 1.2) \times 10^{-6}$$

$$f_L(K^{*0}\rho^+) = 0.43 \pm 0.11^{+0.05}_{-0.02}$$

$$B(K^{*0}\rho^0) < 3.4 \times 10^{-6}\,(90\%\,CL)$$

PRL 95, 141801 (2005)
PRD 80, 051103 (2009)

$$B(K^{*0}\rho^+) = (9.6 \pm 1.7 \pm 1.5) \times 10^{-6}$$

$$f_L(K^{*0}\rho^+) = 0.52 \pm 0.10 \pm 0.04$$

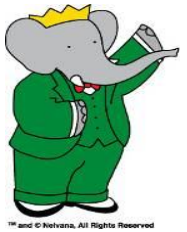
$$B(K^{*0}\rho^0) = (5.6 \pm 0.9 \pm 1.3) \times 10^{-6}$$

$$f_L(K^{*0}\rho^0) = 0.57 \pm 0.09 \pm 0.08$$

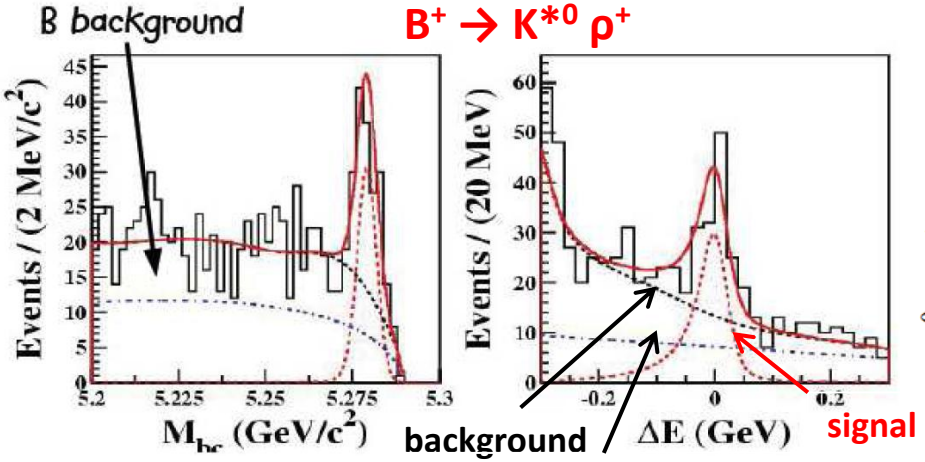
$$B(K^{*+}\rho^0) < 6 \times 10^{-6}\,(90\%\,CL)$$

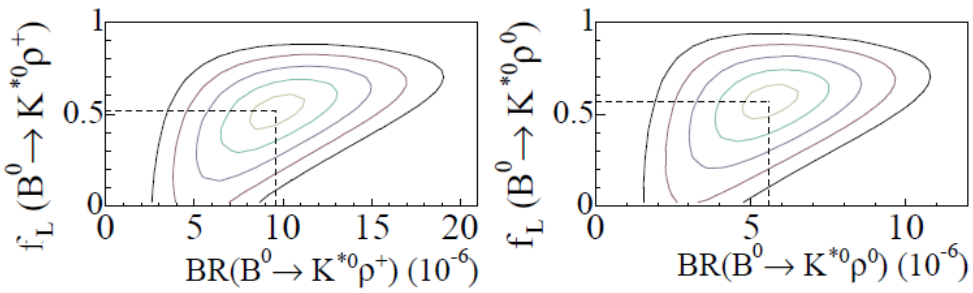
$$B(K^{*+}\rho^-) < 12 \times 10^{-6}\,(90\%\,CL)$$

232M BB



PRL 97, 201801 (2006)





B → ω K*

- Penguin diagram dominated decays.
- $f_L \sim 0.5$ like ϕ K* and ρ K*.

657M BB

$$B(\omega K^{*0}) = (1.8 \pm 0.7^{+0.3}_{-0.2}) \times 10^{-6}$$

$$f_L(\omega K^{*0}) = 0.56 \pm 0.29^{+0.18}_{-0.08}$$

PRL 101, 231801 (2008)

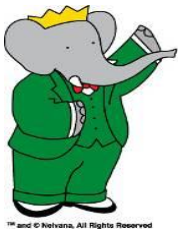
$$B(\omega K^{*0}) = (2.2 \pm 0.6 \pm 0.2) \times 10^{-6}$$

$$f_L(\omega K^{*0}) = 0.72 \pm 0.14 \pm 0.02$$

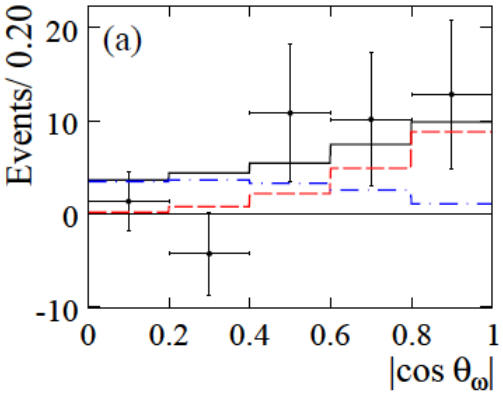
$$B(\omega K^{*+}) = (2.4 \pm 1.0 \pm 0.2) \times 10^{-6}$$

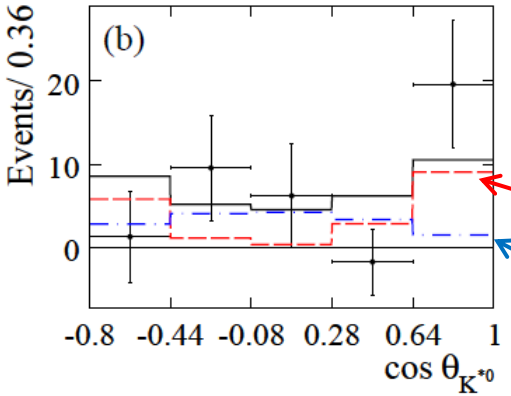
$$f_L(\omega K^{*+}) = 0.41 \pm 0.18 \pm 0.05$$

465M BB



PRD 79, 052005 (2009)



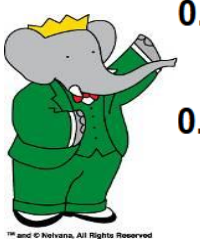


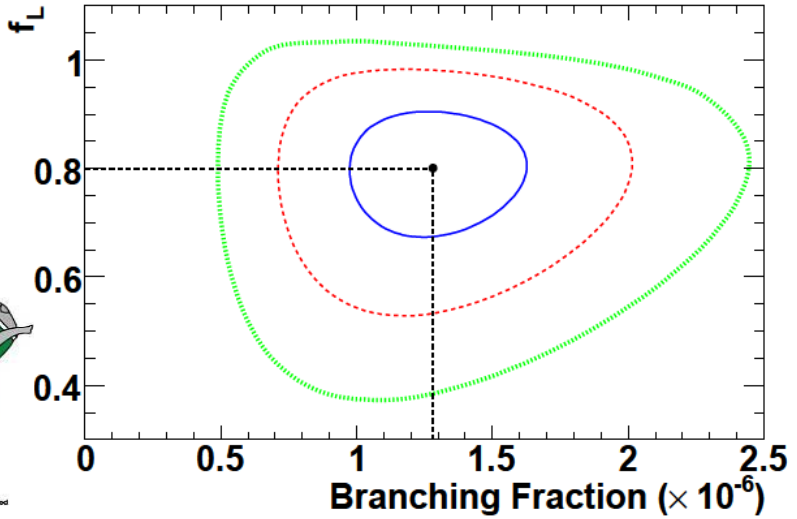
transverse

longitudinal

B → K*K*

- b to d penguin.
- Seen by BABAR but not by Belle.
- f_L larger than in b to s penguin modes.





$$B(K^{*0}\overline{K}^{*0}) < 0.8\times10^{-6}\,(90\%\,CL)$$

657M BB

PRD 81, 071101 (2010)

$$B(K^{*0}\overline{K}^{*0}) = (1.3\pm0.3\pm0.1)\times10^{-6}$$

$$f_L(K^{*0}\overline{K}^{*0}) = 0.80^{+0.10}_{-0.12}\pm0.06$$

383M BB

$$B(K^{*+}\overline{K}^{*0}) = (1.2\pm0.5\pm0.1)\times10^{-6}$$

$$f_L(K^{*+}\overline{K}^{*0}) = 0.75^{+0.16}_{-0.26}\pm0.03$$

467M BB

PRL 100, 081801 (2008)
PRD 79, 051102 (2009)

B → ϕ K*$_2$(1430), ϕ K$_1$(1270)

- B → V T decays (ϕ K*$_2$(1430)):
  - f_L~0.9 and f~0.0 unlike ϕ K*.
- B → V A decays (ϕ K$_1$(1270)):
  - f_L~0.5 like ϕ K*.

$$B(\phi K_2^{*0}) = (7.5 \pm 0.9 \pm 0.5) \times 10^{-6}$$

$$f_L(\phi K_2^{*0}) = 0.90^{+0.05}_{-0.06} \pm 0.04$$

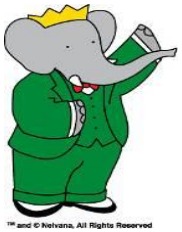
$$f_\perp(\phi K_2^{*0}) = 0.00^{+0.02}_{-0.00} \pm 0.03$$

$$B(\phi K_2^{*+}) = (8.4 \pm 1.8 \pm 1.0) \times 10^{-6}$$

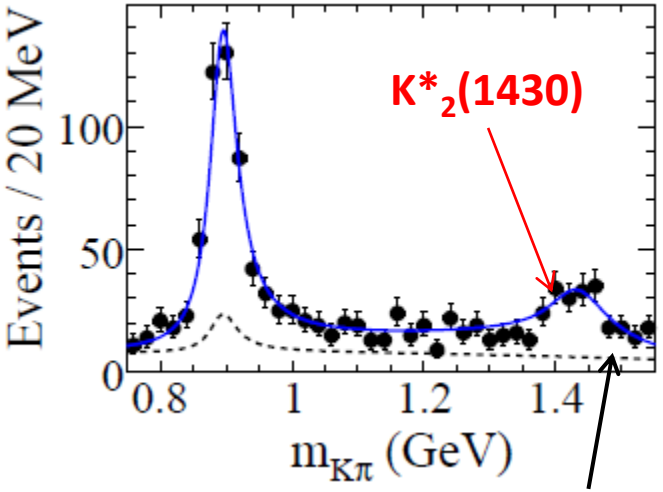
$$f_L(\phi K_2^{*+}) = 0.80^{+0.09}_{-0.10} \pm 0.03$$

$$B(\phi K_1^{+}) = (6.1 \pm 1.6 \pm 1.1) \times 10^{-6}$$

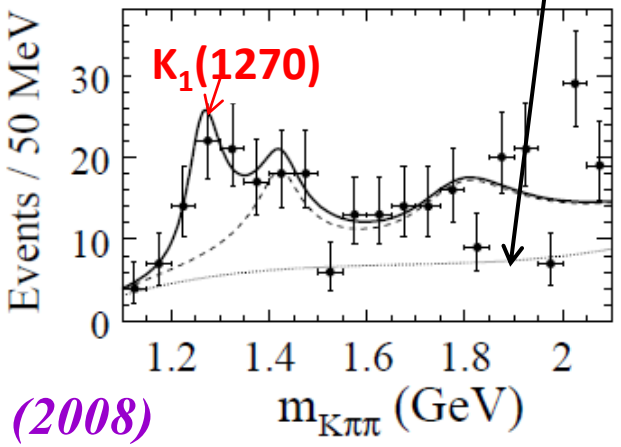
$$f_L(\phi K_1^{+}) = 0.46^{+0.12+0.06}_{-0.13-0.07}$$



465M BB

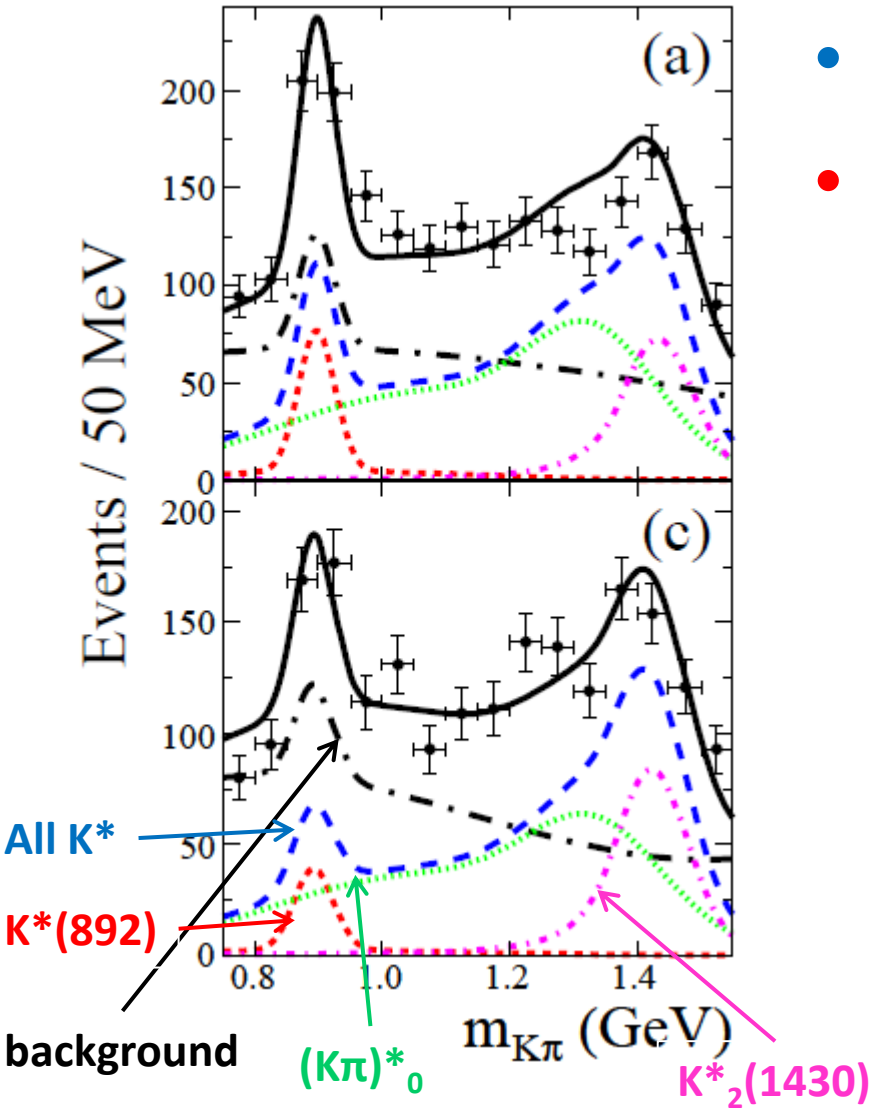


background

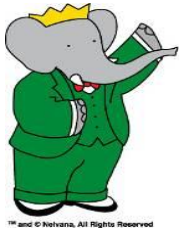


PRD 78, 092008 (2008)
PRL 101, 161801 (2008)

B → ω $K^*_2(1430)$



- B → V T decays.
- f_L~0.5
  - like ϕ K*, ρ K*, ω K*.
  - but unlike ϕ K^*_2.



$$B(\omega K_2^{*0}) = (10.1 \pm 2.0 \pm 1.1) \times 10^{-6}$$

$$f_L(\omega K_2^{*0}) = 0.45 \pm 0.12 \pm 0.02$$

$$B(\omega K_2^{*+}) = (21.5 \pm 3.6 \pm 2.4) \times 10^{-6}$$

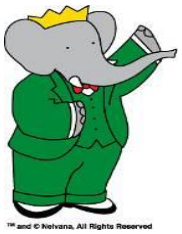
$$f_L(\omega K_2^{*+}) = 0.56 \pm 0.10 \pm 0.04$$

465M BB

PRD 79, 052005 (2009)

$B \rightarrow a_1\, a_1$

- Important to study also A V and A A modes.
- $B^0 \rightarrow a_1^+\, a_1^-$ is the first A A mode to be measured.

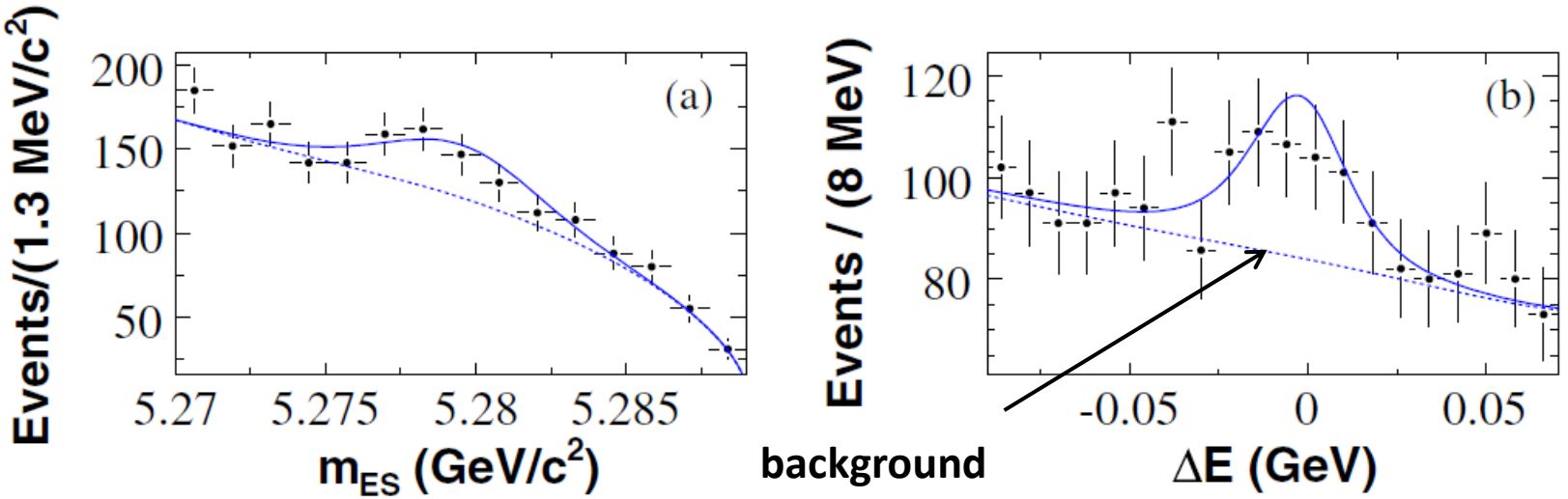


465M BB

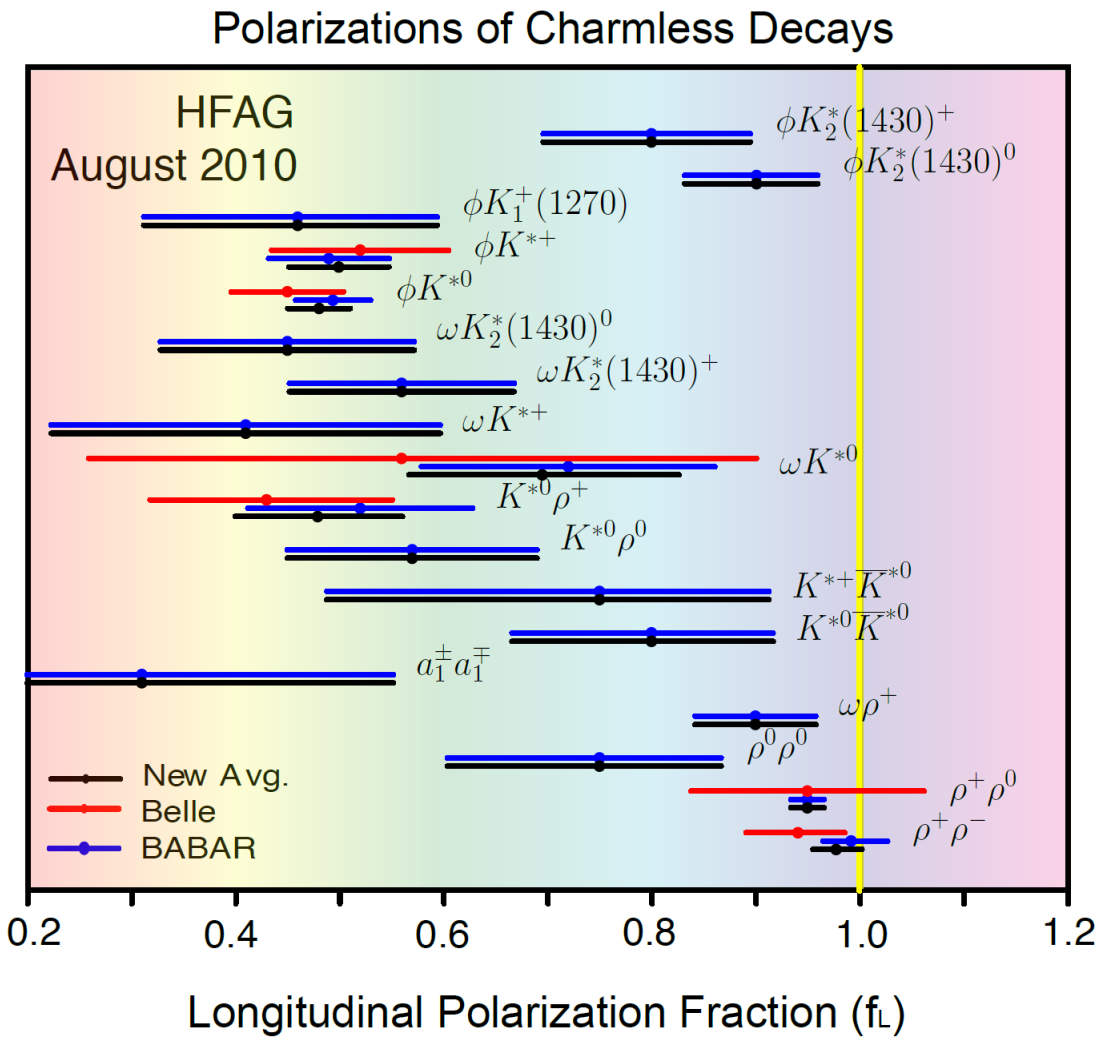
$$B(a_1^+ a_1^-) = (47.3 \pm 10.5 \pm 6.3) \times 10^{-6}$$

$$f_L(a_1^+ a_1^-) = 0.31 \pm 0.22 \pm 0.10$$

PRD 80, 092007 (2009)



Summary



- f_L large (~ 1)
  - ρ ρ, ω ρ (tree VV),
  - K* K* (b→d penguin VV),
  - ϕ K^*_2 (V T).
- f_L smaller (~ 0.5)
  - ϕ K*, ρ K*, ω K* (b→s penguin V V),
  - ω K^*_2 (V T),
  - ϕ K_1 (V A),
  - a_1 a_1 (A A).

Conclusion

- Many V V channels have been measured.
  - Also measured V T, A V, and A A modes.
  - Full angular analysis for ϕ K*.
- There are still several polarization puzzles.
- Future:
  - $B_s \rightarrow$ V V decay modes (Tevatron, LHCb).
  - very rare VV modes like B $\rightarrow \phi \phi$, $\phi \rho$, … (super flavour factory).