Charmless *B* Decays to Vector-Vector (Tensor)

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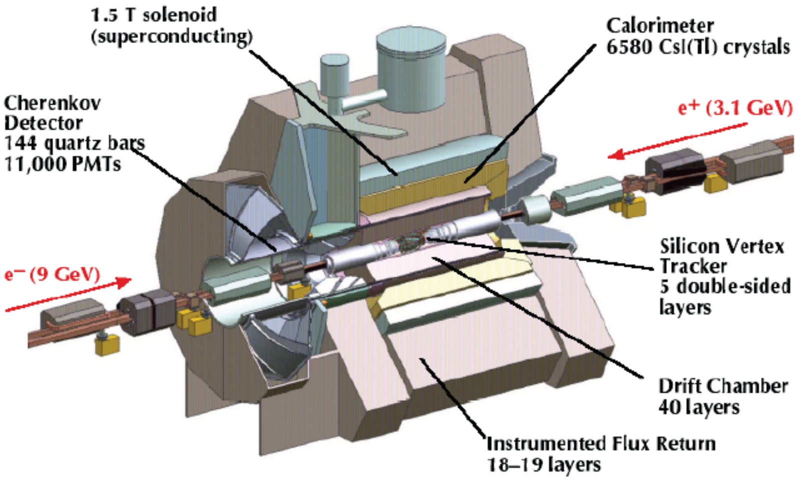
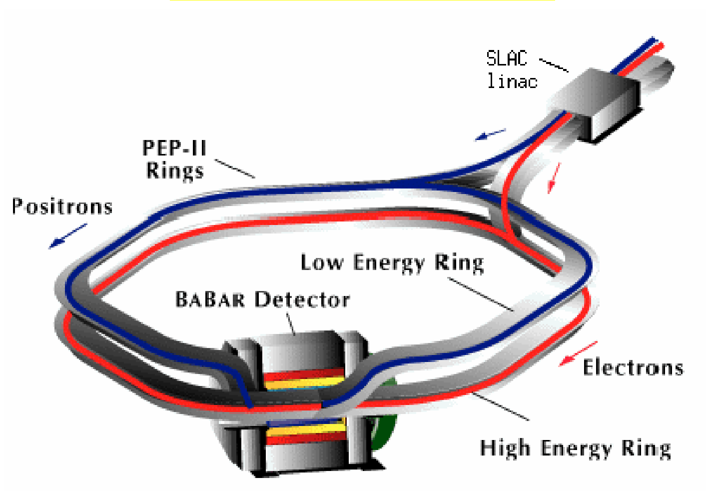
OUTLINE

- Introduction
- Angular Distributions
- $B \to \varphi K^{*0}, \varphi K_2^{*0}, \varphi K^{*+}$
- $B \to K^{*0}\overline{K}^{*0}, K^{*0}K^{*0}$
- Summary

Producing and Detecting B Mesons at BABAR



BABAR Detector

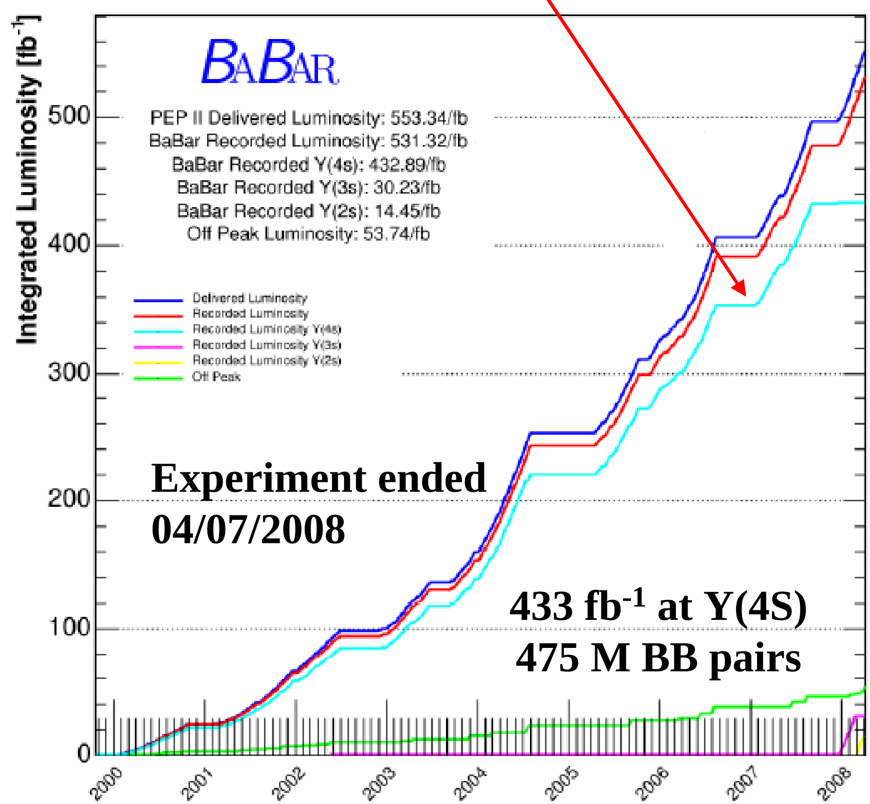


PEP-II

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0,\ B^+B^-$$

$$E_{cm} = 10.58 \text{ GeV}$$

use 384 million $B\bar{B}$ pairs in $B \rightarrow \varphi K^*$ and $K^*\bar{K}^*$ analyses



Why Study B → Vector-Vector Decays

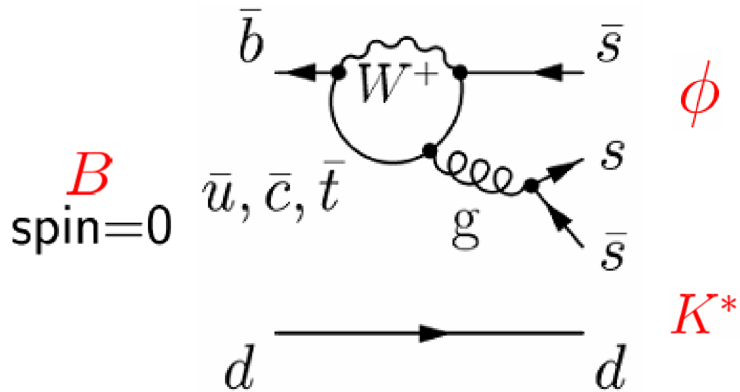
- Interest in "penguin" dominated modes, e.g. $B \to \varphi K^*$

Standard Model (V-A): expected $|A_0| \sim 1 \gg |A_+| \sim \frac{m_V}{m_B} \gg |A_-| \sim \frac{m_V^2}{m_B^2}$

(A.Ali; M.Suzuki; A.Kagan,..) $\lambda=0$ $\lambda=+1$ $\lambda=-1$

$\lambda \equiv$ Vector meson helicity

$b \to s$

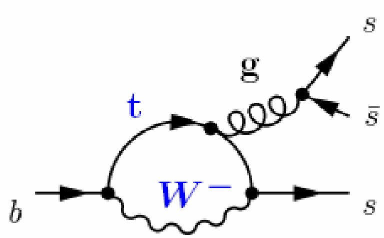


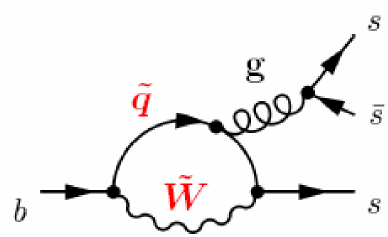
BABAR at Frontier Science (Oct.2002)
hep-ex/0303020, PRL **91**, 171802 (2003)
Belle, PRL **91**, 201801 (2003)
94, 221804 (2005)

Surprise: for φK^{*+} and φK^{*0}, $|A_0|^2 \sim 50\%$

$|A_0| \sim |A_\pm|$, but $|A_+| >> |A_-|$ or $|A_-| >> |A_+|$ (?)

- Possible New Physics in loop amplitude:



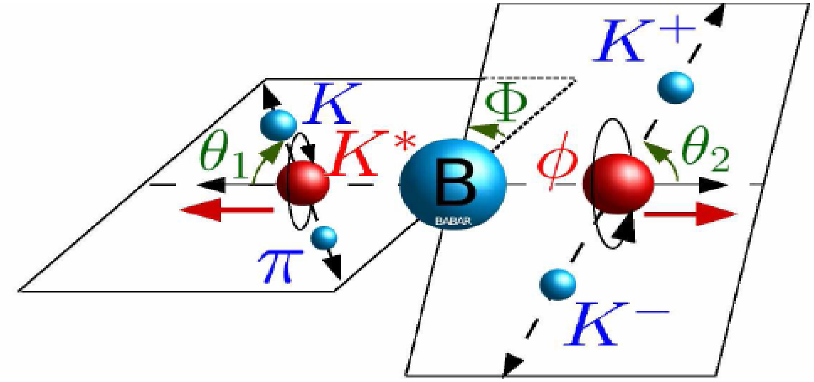


if separate B and $\bar{\text{B}}$:

12 measurements

6 $|A_i|$, 5 $\arg(A_i/A_j)$, 1 phase

V-V ANGULAR DISTRIBUTIONS



$$K^* \xleftarrow{\lambda_{K^*}} \boldsymbol{B} \xrightarrow{\lambda_\phi} \phi$$

B **has spin 0** $\Rightarrow \lambda_{K^*} = \lambda_\phi$

no orbital angular momentum projection

θ_1 **and** θ_2 **are the helicity angles;** Φ **is the angle between the decay plane normals**

- **Measure amplitudes from the full angular dependence;**

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_{\lambda=-,0,+} A_\lambda \times Y_1^\lambda(\theta_1, \Phi) \times Y_1^{-\lambda}(\pi - \theta_2, 0) \right|^2$$

$$\propto \Big\{ \frac{1}{4} \underbrace{\sin^2\theta_1 \sin^2\theta_2 \left(|A_+|^2 + |A_-|^2\right)}_{\text{transverse}} + \underbrace{\cos^2\theta_1 \cos^2\theta_2 |A_0|^2}_{\text{longitudinal}}$$

$$+\frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \left[\cos 2\Phi \ \mathrm{Re}(A_+A_-^*) - \sin 2\Phi \ \mathrm{Im}(A_+A_-^*)\right]$$

$$+\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 \left[\cos\Phi \ \mathrm{Re}\left(A_+A_0^* + A_-A_0^*\right) - \sin\Phi \ \mathrm{Im}\left(A_+A_0^* - A_-A_0^*\right)\right]\Big\}$$

Define Transversity Amplitudes

$$A_{\parallel,\perp} = (A_+ \pm A_-)/\sqrt{2}$$

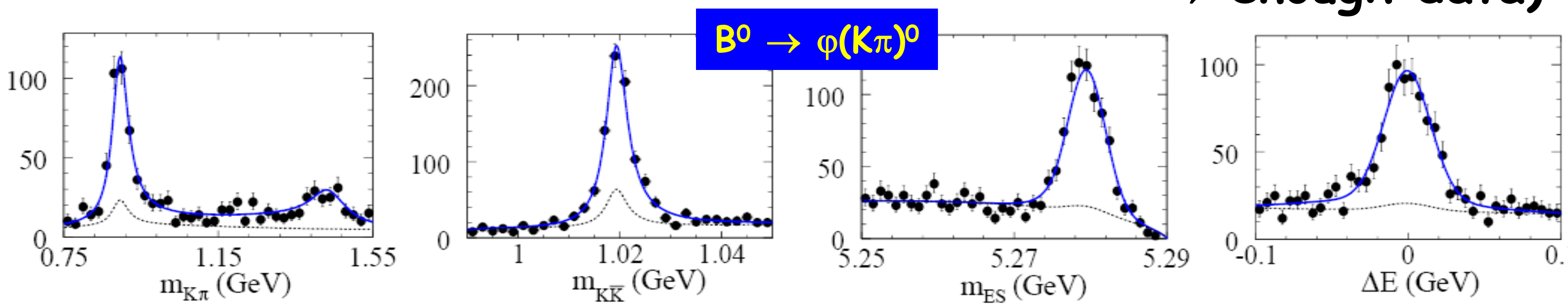
$B \to \varphi K^{*0}$ and φK^{*+}

- Estimate parameters using Maximum Likelihood Fit

$$\vec{x}_j = \{m_{\mathrm{ES}},\ \Delta E,\ \mathcal{F},\ m_1,\ m_{K\pi},\ \theta_1,\ \theta_2,\ \Phi,\ Q_B\}$$

(polarization, strong phase, weak phase difference, …)

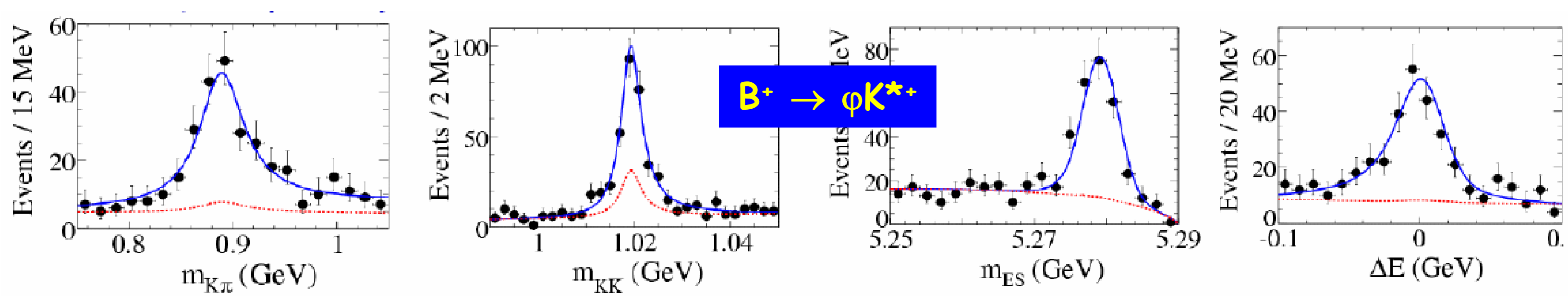
- Full angular analysis in $B \to \varphi K^*$ (possible since high luminosity → enough data)



Significant $(K\pi)_0^{*0}$: $K\pi$ S-wave (includes $K^*_0(1430)^0$ & non-resonant)

- interference ⇒ resolve ($\phi_{||}$, $\phi_{\perp}$) mathematical ambiguity

cf. $B \to J/\psi K\pi$ (*BABAR*) PRD 71, 032005 (2005)



Polarization and CP Results in $B \to \varphi K^{*0}$ and φK^{*+}

parameter	definition	$\varphi K^*(892)^0$	$\varphi K^*(892)^+$
$\mathcal{B}$	$\Gamma/\Gamma_{\rm total}$	$(9.2 \pm 0.7 \pm 0.6) \times 10^{-6}$	$(11.2 \pm 1.0 \pm 0.9) \times 10^{-6}$
f_L	$\lvert A_0\rvert^2/\Sigma\lvert A_\lambda\rvert^2$	$0.506 \pm 0.040 \pm 0.015$	$0.49 \pm 0.05 \pm 0.03$
$f_\perp$	$\lvert A_\perp\rvert^2/\Sigma\lvert A_\lambda\rvert^2$	$0.227 \pm 0.038 \pm 0.013$	$0.21 \pm 0.05 \pm 0.02$
$\phi_\parallel - \pi$	$\arg(A_\parallel/A_0) - \pi$	$-0.82 \pm 0.14 \pm 0.08$ (rad)	$-0.67 \pm 0.20 \pm 0.07$ (rad)
$\phi_\perp - \pi$	$\arg(A_\perp/A_0) - \pi$	$-0.90 \pm 0.15 \pm 0.09$ (rad)	$-0.45 \pm 0.20 \pm 0.03$ (rad)
$\delta_0 - \pi$	$\arg(A_{\rm LASS}/A_0) - \pi$	$-0.36 \pm 0.17 \pm 0.09$ (rad)	$-0.07 \pm 0.18 \pm 0.06$ (rad)
$\mathcal{A}_{CP}$	$(\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$	$-0.03 \pm 0.07 \pm 0.03$	$0.00 \pm 0.09 \pm 0.04$
$\mathcal{A}^0_{CP}$	$(f_L^- - f_L^+)/(f_L^- + f_L^+)$	$-0.03 \pm 0.08 \pm 0.02$	$+0.17 \pm 0.11 \pm 0.02$
$\mathcal{A}^\perp_{CP}$	$(f_\perp^- - f_\perp^+)/(f_\perp^- + f_\perp^+)$	$-0.03 \pm 0.16 \pm 0.05$	$+0.22 \pm 0.24 \pm 0.08$
$\Delta\phi_\parallel$	$(\phi_\parallel^- - \phi_\parallel^+)/2$	$+0.24 \pm 0.14 \pm 0.08$	$+0.07 \pm 0.20 \pm 0.05$
$\Delta\phi_\perp$	$(\phi_\perp^- - \phi_\perp^+ - \pi)/2$	$+0.19 \pm 0.15 \pm 0.08$	$+0.19 \pm 0.20 \pm 0.07$
$\Delta\delta_0$	$(\delta_0^- - \delta_0^+)/2$	$+0.21 \pm 0.17 \pm 0.08$	$+0.20 \pm 0.18 \pm 0.03$

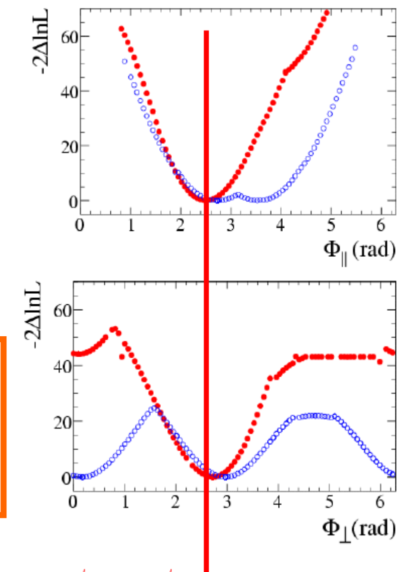
PRL 98, 051801(2007), PRL 99, 201802(2007)

$$\Rightarrow \lvert A_0\rvert^2 \simeq \lvert A_+\rvert^2 + \lvert A_-\rvert^2$$

~~$\phi_\perp \simeq \phi_\parallel - \pi$~~
~~$A_\perp \simeq -A_\parallel$~~
~~$\lvert A_+\rvert^2 \ll \lvert A_-\rvert^2$~~

$\Updownarrow$

$\phi_\perp \simeq \phi_\parallel$
$A_\perp \simeq A_\parallel$
$\lvert A_+\rvert^2 \gg \lvert A_-\rvert^2$



$\phi_\parallel \simeq \phi_\perp$ **correct solution**

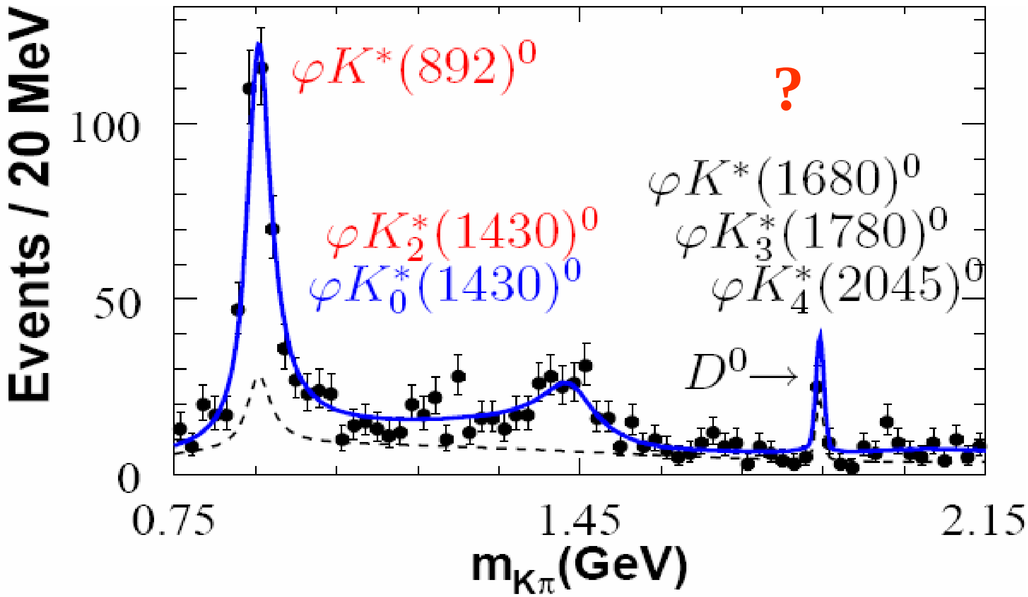
- **12 measurements**
- **6 CP-asymmetries consistent with 0 new approach to CP (weak phase of A^+)**

$$\lvert A_0\rvert \simeq \lvert A_+\rvert \gg \lvert A_-\rvert$$
$$\arg(A_+) \neq \arg(\pm A_0)$$

$$A_\pm = (A_\parallel \pm A_\perp)/\sqrt{2}$$

reject ambiguous solution using the $K\pi$ mass dependence of the S-A_0 relative phase (Wigner Causality)

Vector-Tensor and Spectroscopy in $B^0 \to \varphi(K\pi)^0$



PRL 98, 051801 (2007)
PRD 76, 051103 (2007)

BABAR

Vector-Tensor puzzle:

$f_L(\varphi K^*_2) \sim 1$

Vector-Vector:

$|A_0| \simeq |A_+| \gg |A_-|$

Vector-Tensor:

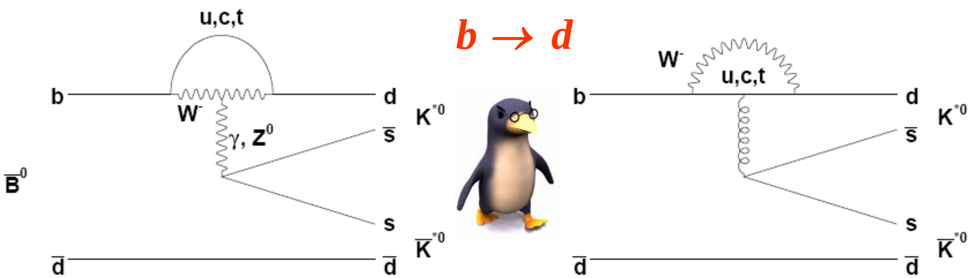
$|A_0| \gg \sqrt{|A_+|^2 + |A_-|^2}$

J^P	mode $B \to$	Branching Fraction (10^{-6})	f_L
0^+	$\varphi K_0^*(1430)^0$	$4.6 \pm 0.7 \pm 0.6$	
1^-	$\varphi K^*(892)^0$	$9.2 \pm 0.7 \pm 0.6$	$0.51 \pm 0.04 \pm 0.02$
1^-	$\varphi K^*(892)^+$	$11.2 \pm 1.0 \pm 0.9$	$0.49 \pm 0.05 \pm 0.03$
1^-	$\varphi K^*(1680)^0$	$< 3.5 \quad (0.7^{+1.0}_{-0.7} \pm 1.1)$	–
2^+	$\varphi K_2^*(1430)^0$	$7.8 \pm 1.1 \pm 0.6$	$0.85^{+0.06}_{-0.07} \pm 0.04$
3^-	$\varphi K_3^*(1780)^0$	$< 2.7 \quad (-0.9 \pm 1.4 \pm 1.1)$	–
4^+	$\varphi K_4^*(2045)^0$	$< 15.3 \quad (6.0^{+4.8}_{-4.0} \pm 4.1)$	–

Observation of $B^0 \to K^{*0}\bar{K}^{*0}$ and Search for $B^0 \to K^{*0}K^{*0}$

- Charmless penguin decay $B^0 \to K^{*0}\bar{K}^{*0}$

$b \to d$



electroweak gluonic

- provide insight into the polarization puzzle
- test factorization models
- could be used to help constrain the angles α and γ

- Previous experimental results (BF): < 22×10^{-6}
  (CLEO2, PRL 88, 021802)
- BF theoretical predictions $(0.16 - 0.96)\times 10^{-6}$
- Longitudinal polarization predictions

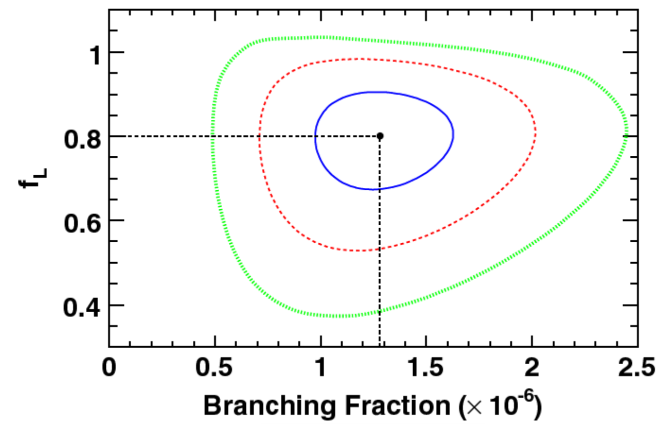
$$f_L = 0.69^{+0.34}_{-0.27}\ (\text{Beneke}\ et\ al.)$$ **NPB 774, 64 (2007)**

- $B^0 \to K^{*0}K^{*0}$: SM suppressed decay
  BF < 37×10^{-6} **(CLEO2, PRL 88, 021802)**

Channel	$K^{*0}\bar{K}^{*0}$	$K^{*0}K^{*0}$
$n_{\rm sig}$	$33.5^{+9.1}_{-8.1}$	2.7 ± 3.3
$n_{B\bar{B}}$	19 ± 12	68 ± 29
ε (%)	6.8	6.4
$S(\sigma)$	6	0.9
$\mathcal{B}(10^{-6})$	$1.28^{+0.35}_{-0.30} \pm 0.11$	$0.11^{+0.16}_{-0.11} \pm 0.04$
UL $\mathcal{B}(10^{-6})$	$\cdots$	0.41
f_L	$0.80^{+0.10}_{-0.12} \pm 0.06$	1.0 ± 1.0

low statistics $\Rightarrow$ measure f_L only

***BABAR* PRL 100, 081801 (2008)**



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

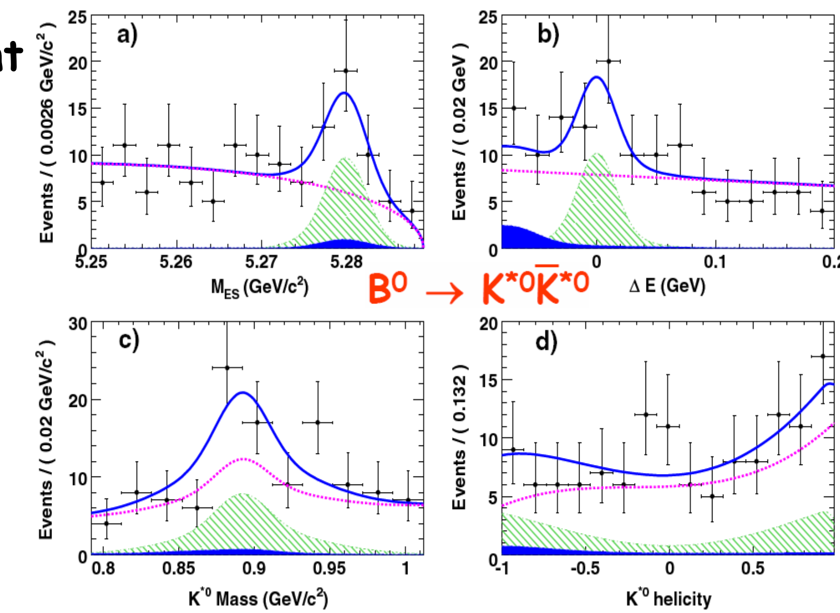
- $B^0 \to K^{*0}\bar{K}^{*0}$: Beneke et al. consistent

  $f_L = 0.80^{+0.10}_{-0.12} \pm 0.06$

  BF in reasonable agreement with theoretical predictions

- $B^0 \to K^{*0}K^{*0}$:

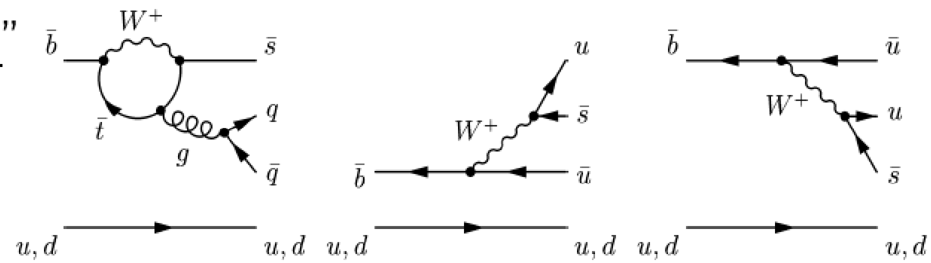
  UL < 0.41×10^{-6} (@90% CL)
  2 orders of magnitude more stringent than previous measmt.



$B \to VK^*$: Experiment-Theory Comparison

"Penguin"

$\alpha_P \cdot P' + \alpha_T \cdot T' + \alpha_C \cdot C'$



"Tree"

	α_P	α_T (SU$_3$)	α_C	$\mathcal{B}$ranching fraction (10^{-6}) BABAR	$f_L = \lvert A_0\rvert^2/\Sigma\lvert A_\lambda\rvert^2$ BABAR	$\mathcal{B}$ (Theory)* (10^{-6})	f_L (Theory)*
ϕK_2^{*0}	$\sqrt{2}$	0	0	$7.8 \pm 1.1 \pm 0.6$	$0.853^{+0.061}_{-0.069} \pm 0.036$	—	—
ϕK^{*0}	$\sqrt{2}$	0	0	$9.2 \pm 0.7 \pm 0.6$	$0.506 \pm 0.040 \pm 0.015$	$9.3^{+11.4}_{-6.5}$	$0.44^{+0.59}_{-0.36}$
ϕK^{*+}	$\sqrt{2}$	0	0	$11.2 \pm 1.0 \pm 0.6$	$0.49 \pm 0.05 \pm 0.03$	$10.1^{+12.2}_{-7.1}$	$0.45^{+0.58}_{-0.36}$
$\rho^- K^{*0}$	$\sqrt{2}$	0	0	$9.6 \pm 1.7 \pm 1.5$	$0.52 \pm 0.10 \pm 0.04$	$5.9^{+6.9}_{-3.7}$	$0.56^{+0.48}_{-0.30}$
$\rho^- K^{*+}$	$-\sqrt{2}$	$-\sqrt{2}$	0	< 12.0 ($5.4^{+3.8}_{-3.4} \pm 1.6$)	n/a ($-0.18^{+0.52}_{-1.74}$)	$5.5^{+5.9}_{-3.3}$	$0.61^{+0.38}_{-0.29}$
$\rho^0 K^{*0}$	1	0	-1	$5.6 \pm 0.9 \pm 1.3$	$0.57 \pm 0.09 \pm 0.08$	$2.4^{+3.5}_{-2.0}$	$0.22^{+0.53}_{-0.14}$
$\rho^0 K^{*+}$	-1	-1	-1	< 6.1 ($3.6^{+1.7}_{-1.6} \pm 0.8$)	n/a (0.9 ± 0.2)	$4.5^{+3.4}_{-1.9}$	$0.84^{+0.16}_{-0.25}$
ωK^{*0}	1	0	1	< 4.2 ($2.4 \pm 1.1 \pm 0.7$)	n/a ($0.71^{+0.27}_{-0.24}$)	$2.0^{+3.1}_{-1.4}$	$0.40^{+0.77}_{-0.43}$
ωK^{*+}	1	1	1	< 3.4 ($0.6^{+1.4+1.1}_{-1.2-0.9}$)	n/a	$2.4^{+3.0}_{-1.5}$	$0.53^{+0.58}_{-0.41}$
$K^{*0}\bar{K}^{*0}$	$\frac{V_{td}}{V_{ts}}\sqrt{2}$	0	0	$1.28^{+0.35}_{-0.30} \pm 0.11$	$0.80^{+0.10}_{-0.12} \pm 0.06$	$0.6^{+0.5}_{-0.3}$	$0.69^{+0.34}_{-0.27}$

* **B**eneke, **R**ohrer, and **Y**ang, NPB 774, 64 (2007)

SUMMARY

- Polarization Puzzle: strong or weak interaction effect ?

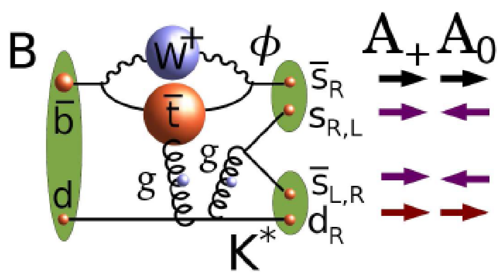
$|A_0| \simeq |A_+| \gg |A_-|$ in $B \to \varphi K^{*0}$, φK^{*+} (puzzle)

$|A_0| \simeq \sqrt{|A_+|^2 + |A_-|^2}$ in $B \to \rho K^{*0}$ ($|A_+| >> |A_-|$ or $|A_-| >> |A_+|$ (?))

$|A_0| \gg \sqrt{|A_+|^2 + |A_-|^2}$ in $B \to \varphi K_2^*(1430)^0$, $K^{*0}\overline{K}^{*0}$

(not consistent with above)

- Possible Solutions to Explain A_+



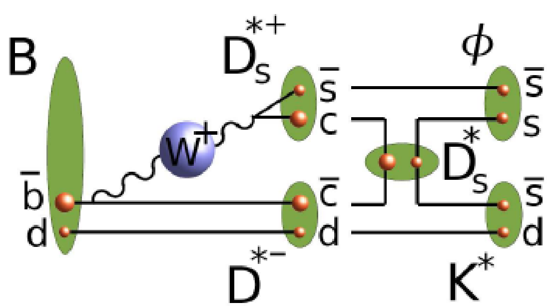
gluon to other quark

suppressed $\sim 1/m_B$

cancel A_0 from usual penguin

Annihilation mechanism

Rescattering mechanism (FSI)



spin-flip heavy $> 2\text{GeV}$ states

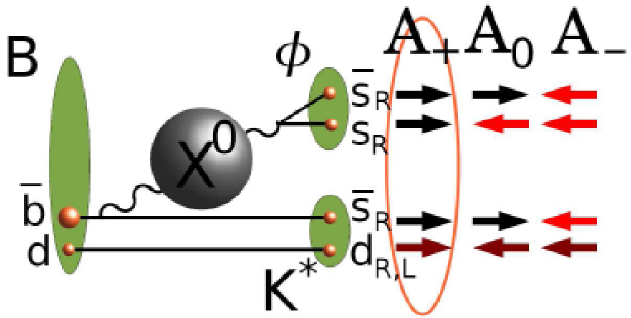
violates both $|A_0|^2 \gg |A_\pm|^2$

and $|A_+|^2 \gg |A_-|^2$

no generally accepted solution

Possible New Physics in Polarization

Scalar interaction



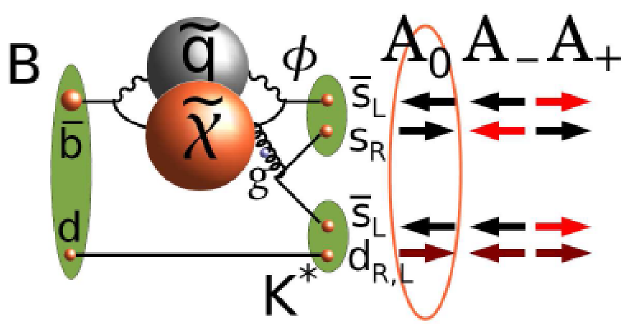
violate $|A_0|^2 \gg |A_+|^2 \gg |A_-|^2$

$\bar{q}\gamma^\mu(1-\gamma^5)q$

$|A_+|^2 \gg |A_0|^2 \gg |A_-|^2$

$\bar{q}(1+\gamma^5)q$

Supersymmetry



$|A_0|^2 \gg |A_-|^2 \gg |A_+|^2$

$\bar{q}\gamma^\mu(1+\gamma^5)q$