$B \to VV$ at Super-B

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Super B Factory Workshop in Hawaii

Introduction/Outline

- Rare $B \to VV$ decays ideal for Super-B:
  - deeper reach than e.g. $B \to PP$ or PV
  - need large statistics to fully explore potential

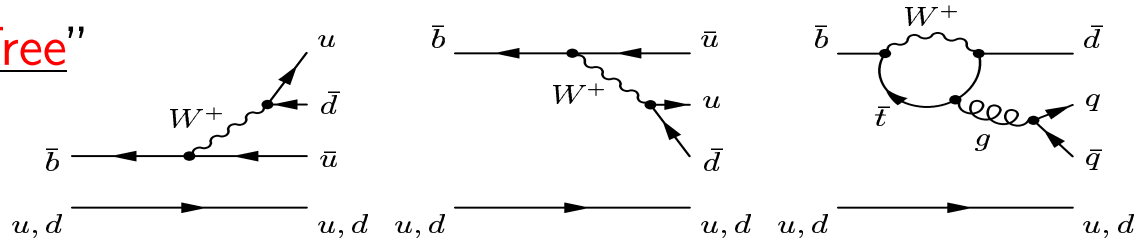
- Major steps in $B \to VV$ at Super-B workshop in May 2003 (*BABAR*):
  1. $B \to \rho^0\rho^0$: $\mathcal{B} < 2 \times 10^{-6} \Rightarrow$ small penguin pollution in $B \to \rho\rho$
  2. $B \to \phi K^*$: $f_L \sim 0.5 \Rightarrow$ polarization puzzle in $b \to s$ "penguin"

- Two Super-B topics covered today:
  1. Unique role of $B \to \rho\rho$ in measuring α in $b \to u$ transition
  2. Unique role of $B \to K^*\phi/\rho/\omega$ in studying $b \to s$ penguins

Part I: "Rare Tree" $B \to VV$ Decays

$\alpha_T \cdot T \quad + \quad \alpha_C \cdot C \quad + \quad \alpha_P \cdot P$

"Tree" "Penguin"



B decay	α_T	α_C	α_P	$\mathcal{B}$ (10^{-6})	$f_L = \lvert A_0\rvert^2/\Sigma\lvert A_m\rvert^2$	$N_{B\bar{B}}$
$\rho^0\rho^0$	0	1	-1	< 1.1 (90%)	–	*BABAR* $(230 \cdot 10^6)$
$\rho^-\rho^+$	$\sqrt{2}$	0	$\sqrt{2}$	$30 \pm 4 \pm 5$	$0.978 \pm 0.014^{+0.021}_{-0.029}$	*BABAR* $(89/230 \cdot 10^6)$
$\rho^0\rho^+$	1	1	0	$23\ ^{+6}_{-5} \pm 6$ $32 \pm 7\ ^{+4}_{-7}$	$0.97^{+0.03}_{-0.07} \pm 0.04$ $0.95 \pm 0.11 \pm 0.02$	*BABAR* $(89 \cdot 10^6)$ BELLE $(85 \cdot 10^6)$
$\omega\rho^+$	-1	-1	2	$12.6\ ^{+3.7}_{-3.3} \pm 1.6$	$0.88^{+0.12}_{-0.15} \pm 0.03$	*BABAR* $(89 \cdot 10^6)$
$\omega\rho^0$	0	0	$-\sqrt{2}$	< 3.3 (90%)	–	*BABAR* $(89 \cdot 10^6)$

- $\rho^-\rho^+$, $\rho^0\rho^+$, $\omega\rho^+$: large decay rate with "tree" (compared to $\pi\pi$)
- Confirm $f_L \sim 1 \Rightarrow CP$-even eigenstate $\rho^-\rho^+$
- $\rho^0\rho^0$, $\omega\rho^0$: small "penguin" $\Rightarrow$ great for Unitarity Triangle α

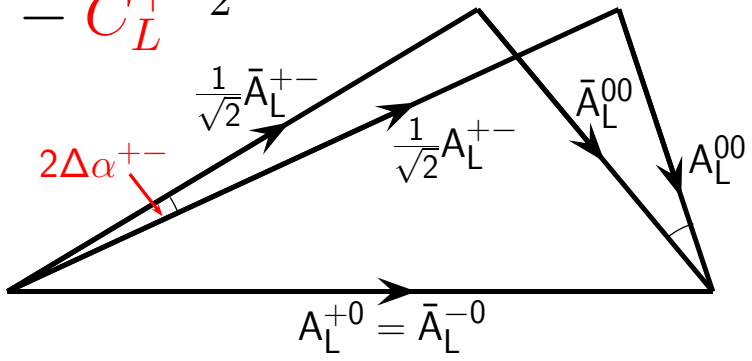
Measuring α with $\rho\rho$ like with $\pi\pi$

- $\mathcal{A}_{\rho^-\rho^+}(t) = C_L^{+-}\cos(\Delta m_B t) - S_L^{+-}\sin(\Delta m_B t)$

$$\sin(2\alpha_{\rm eff}^{+-}) = \mathrm{Im}(\frac{q}{p}\frac{\bar{A}_L^{+-}}{A_L^{+-}})/|\lambda| = S_L^{+-}/\sqrt{1-C_L^{+-2}}$$

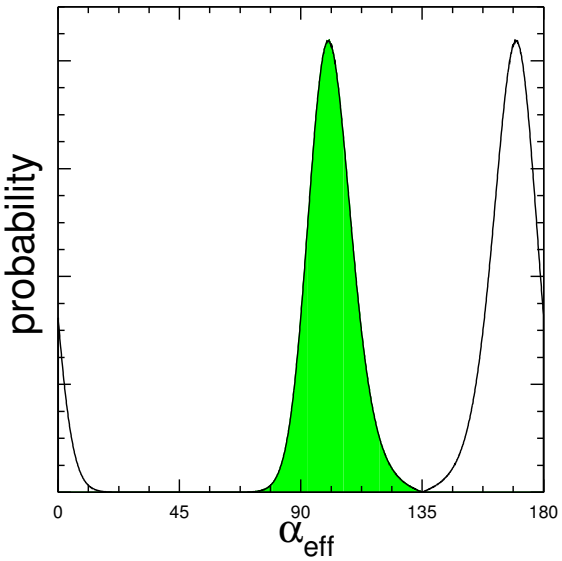
$$2\Delta\alpha^{+-} = \arg(\frac{A_L^{+-}}{A_L^{+0}}) - \arg(\frac{\bar{A}_L^{+-}}{\bar{A}_L^{-0}})$$

$$\alpha = \alpha_{\rm eff}^{+-} + \Delta\alpha^{+-}$$

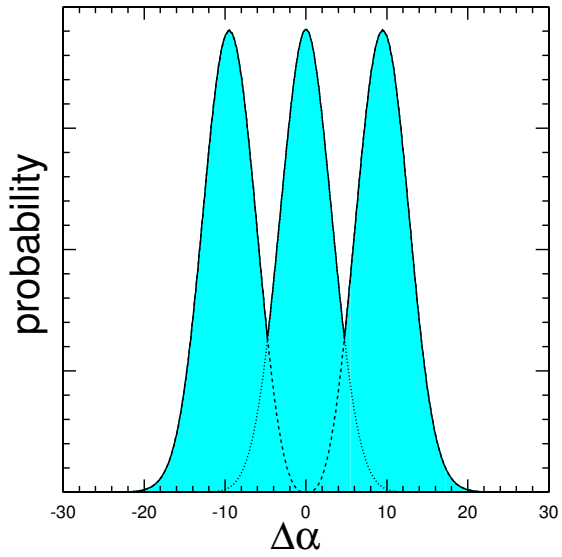


BABAR:

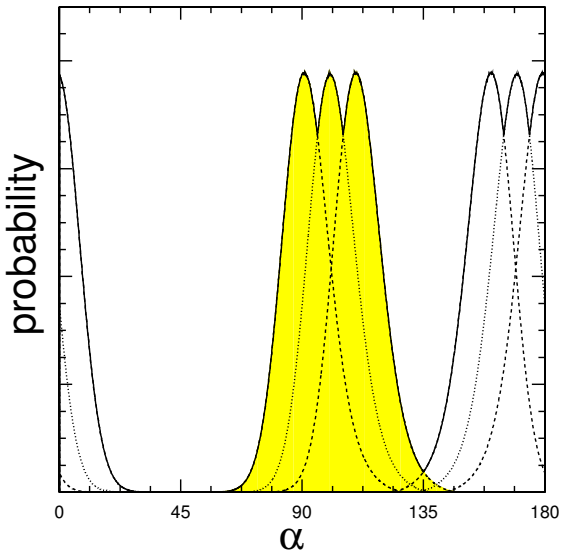
$\alpha_{\rm eff}^{+-} = (100 \pm 9)^\circ$



$\Delta\alpha^{+-} = (0 \pm 11)^\circ$



$\alpha = (100 \pm 14)^\circ$



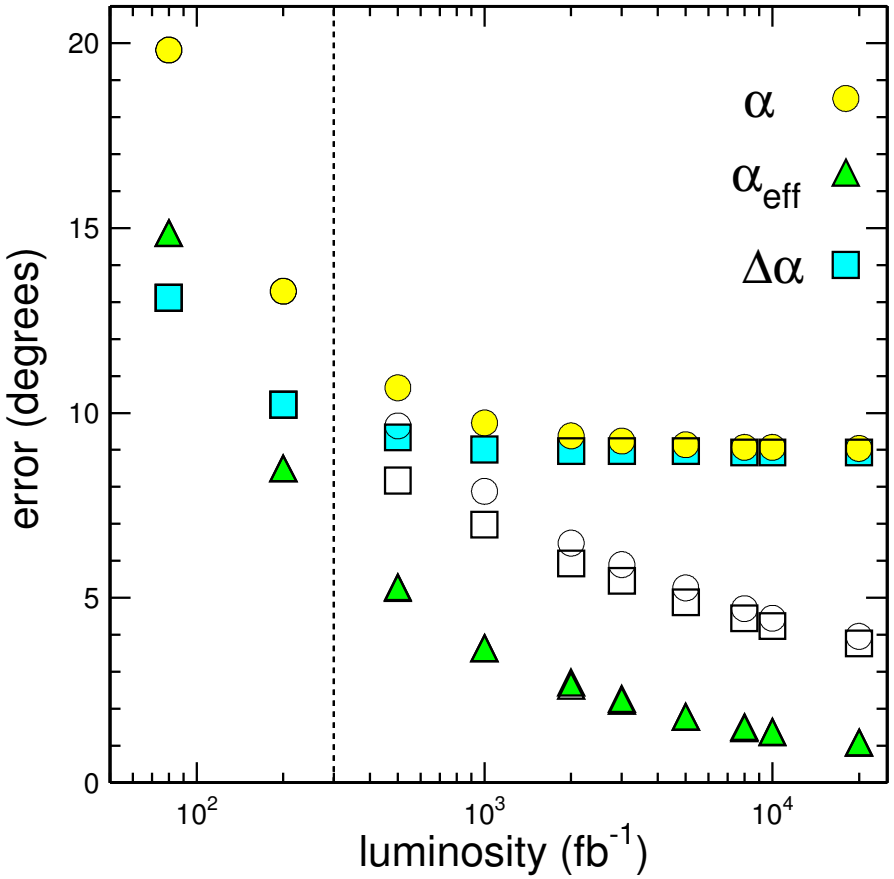
Projection of Current Analysis to 10 ab^{-1}

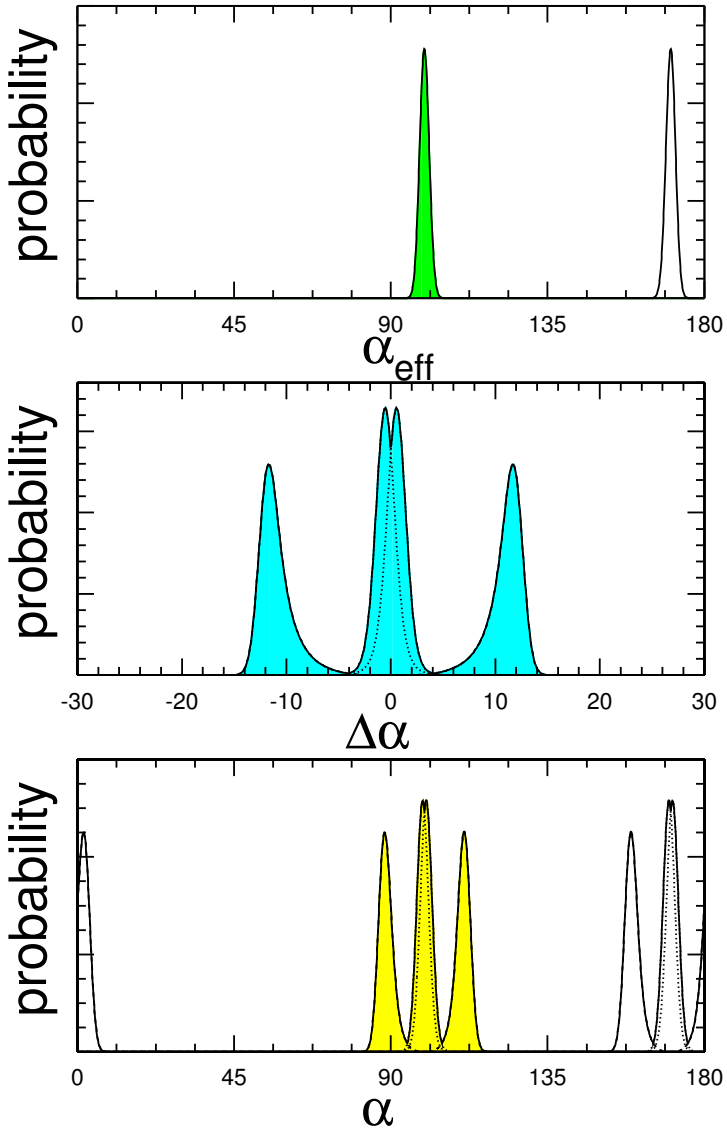
(1) set only limits on $\rho^0\rho^0 \Rightarrow$ straight-forward but unlikely

(2) $\mathcal{B}(\rho^0\rho^0) \sim 0.8 \times 10^{-6}$

not resolved ambiguities (8/180°)

each solution down to few°





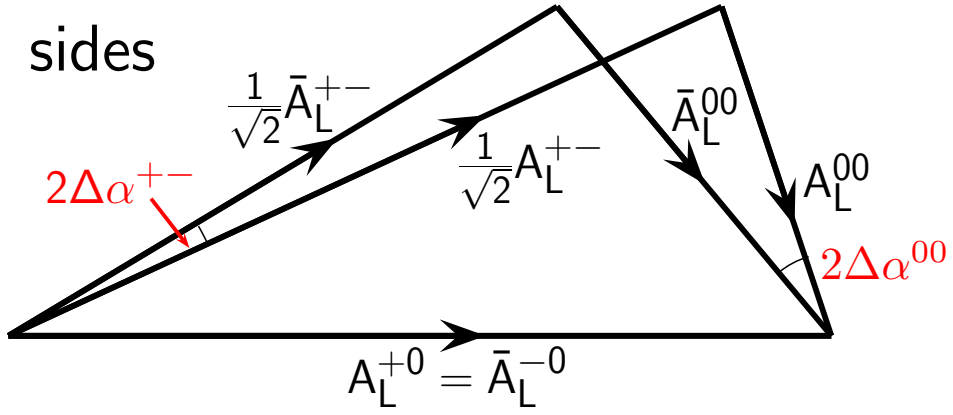
Measuring α with $\rho^0\rho^0$

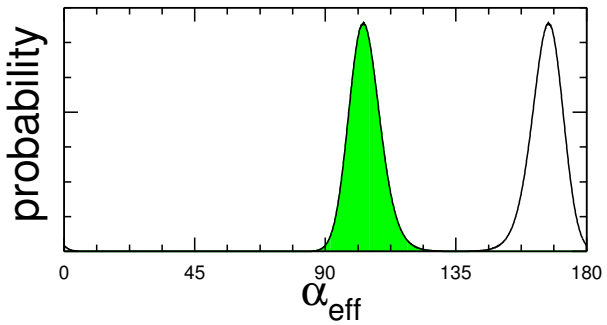
- Unique to $B \to \rho\rho$ (vs. $\pi\pi$): $B^0 \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$
  - measure $\alpha_{\rm eff}^{00}$ with $\mathcal{A}_{\rho^0\rho^0}(t) \Rightarrow$ need Super-B
  - $\Delta\alpha^{00}$ from the same triangle
- Limited α resolution due to "long" sides

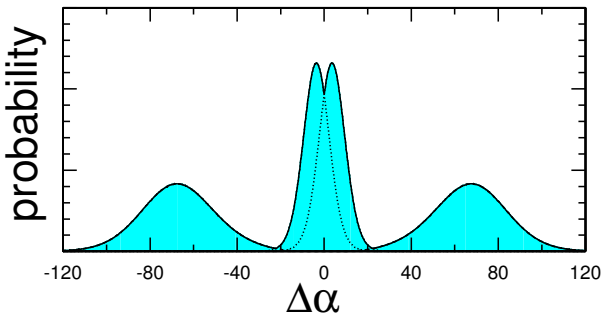
  systematics in $\mathcal{B}^{+-}$ and $\mathcal{B}^{0+}$

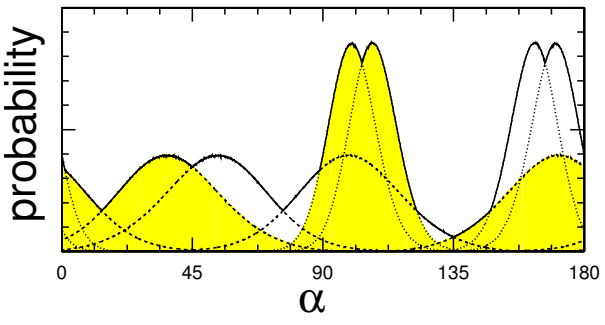
  (assume $\sim 7\%$ here)
- Real advantage:

  resolving triangle ambiguities







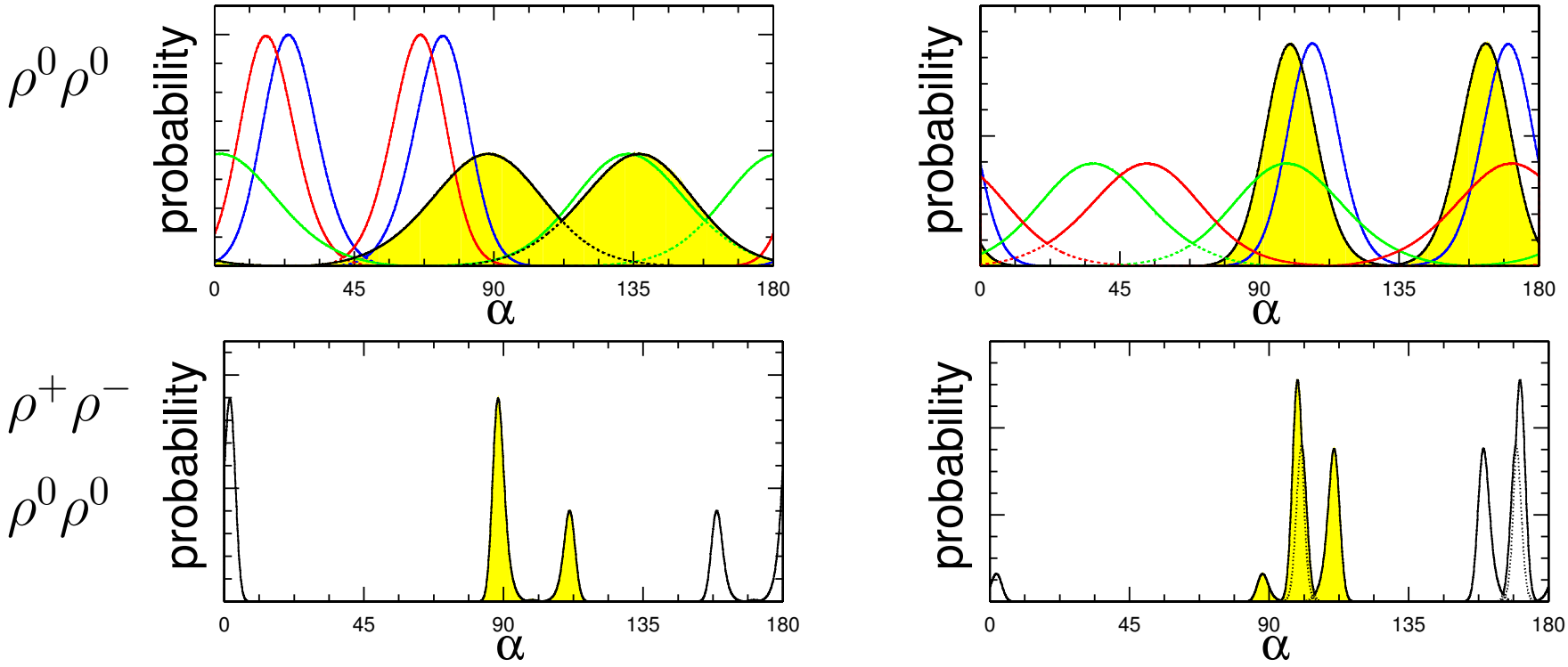


Resolving α Ambiguities with $\rho^0\rho^0$ and $\rho^+\rho^-$

- Triangle orientations should match for $\Delta\alpha^{00}$ and $\Delta\alpha^{+-}$

(A) opposite orientations

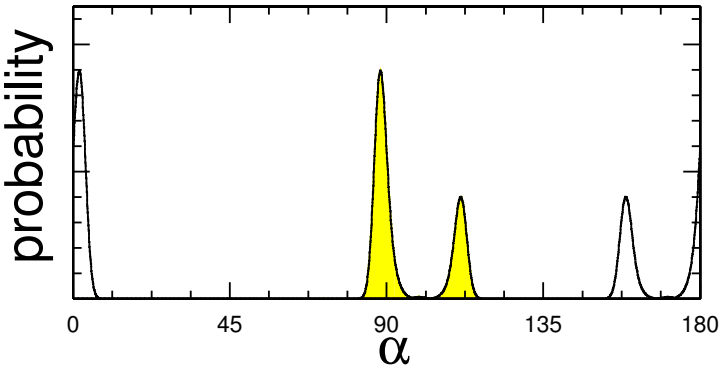
(B) the same orientations



- Super-B can resolve α ambiguities with $\rho^0\rho^0$
  - could completely resolve if $\mathcal{B}$ranching systematics $\sim 1\%$

Conclusion on $\rho\rho$ and Open Issues

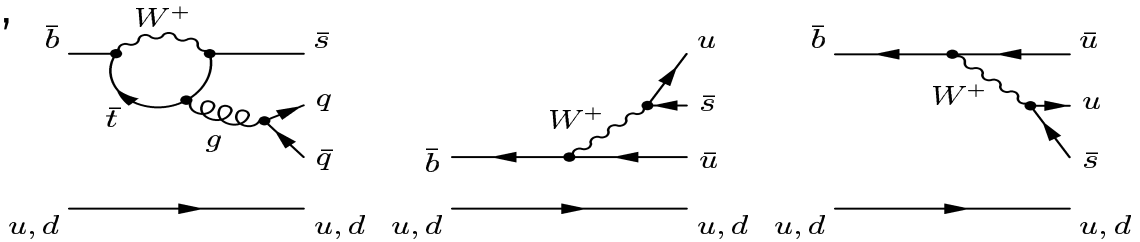
- $B \to \rho^0\rho^0$ unique, may allow α precision few° together with $\rho^+\rho^{-0}$



- Challenges:
  - broad $\rho \Rightarrow$ I=1 contribution, isospin-breaking, interference
  - high background and B cross-feed
  - branching $\mathcal{B}^{+0}$ and $\mathcal{B}^{+-}$ systematics down to few %
  - even relative $\Upsilon(4S) \to B^+B^-$ vs. $B^0\bar{B}^0$ matters for $\mathcal{B}^{+0}/\mathcal{B}^{+-}$
  - assume $f_L(\rho^0\rho^0) = 1$, lesson of ϕK^*: other contributions to $\rho\rho$?
- We learn to deal with challenges as we accumulate statistics

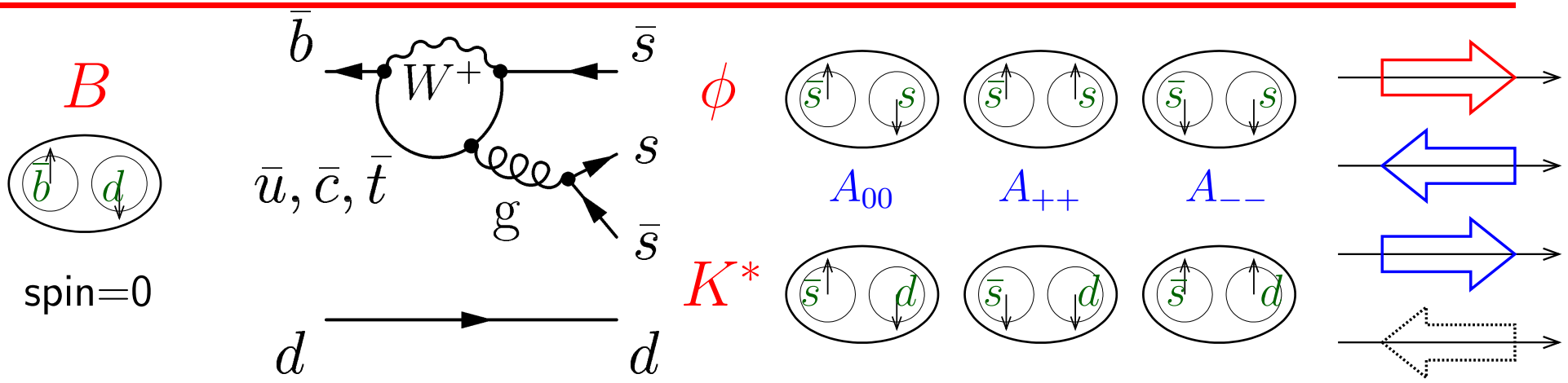
Part II: "Penguin" $B \to VV$ Decays

"Penguin" $\alpha_P \cdot P'$ + $\alpha_T \cdot T'$ + $\alpha_C \cdot C'$ "Tree"



B decay	α_P	α_T	α_C	$\mathcal{B}(10^{-6})$	$f_L = \lvert A_0\rvert^2/\Sigma\lvert A_m\rvert^2$	$N_{B\bar{B}}$
ϕK^{*0}	$\sqrt{2}$	0	0	$9.2 \pm 0.9 \pm 0.5$ $10.0^{+1.6+0.7}_{-1.5-0.8}$	$0.52 \pm 0.05 \pm 0.02$ $0.45 \pm 0.05 \pm 0.02$	*BABAR* $(227 \cdot 10^6)$ BELLE $(86/275 \cdot 10^6)$
ϕK^{*+}	$\sqrt{2}$	0	0	$12.7\ ^{+2.2}_{-2.0} \pm 1.1$ $6.7^{+2.1+0.7}_{-1.9-1.0}$	$0.46 \pm 0.12 \pm 0.03$ $0.52 \pm 0.08 \pm 0.03$	*BABAR* $(89 \cdot 10^6)$ BELLE $(86/275 \cdot 10^6)$
$\rho^0 K^{*0}$	1	0	-1	< 2.6 (90%)	–	BELLE $(152 \cdot 10^6)$
$\rho^0 K^{*+}$	-1	-1	-1	$10.6\ ^{+3.0}_{-2.6} \pm 2.4$	$0.96^{+0.04}_{-0.15} \pm 0.04$	*BABAR* $(89 \cdot 10^6)$
$\rho^- K^{*0}$	$\sqrt{2}$	0	0	$17.0 \pm 2.9^{+2.0}_{-2.8}$ $8.9 \pm 1.7 \pm 1.0$	$0.79 \pm 0.08 \pm 0.04$ $0.43 \pm 0.11^{+0.05}_{-0.02}$	*BABAR* $(89 \cdot 10^6)$ BELLE $(275 \cdot 10^6)$
$\rho^- K^{*+}$	$-\sqrt{2}$	$-\sqrt{2}$	0	< 24 (90%)	–	*BABAR* $(123 \cdot 10^6)$
ωK^{*0}	1	0	1	< 6.1 (90%)	–	*BABAR* $(89 \cdot 10^6)$
ωK^{*+}	1	1	1	< 7.4 (90%)	–	*BABAR* $(89 \cdot 10^6)$

Penguin B Decays to Vector Mesons



- 11 measurements (!) to look for New Physics: 6 $|A_i|$, 5 arg(A_i/A_j)

(1) amplitude hierarchy: $|A_0| \gg |A_+| \gg |A_-|$, phases

(2) direct asymmetries (rate) $\propto \sin\Delta\delta_{\rm weak}\ \sin\Delta\delta_{\rm strong}$

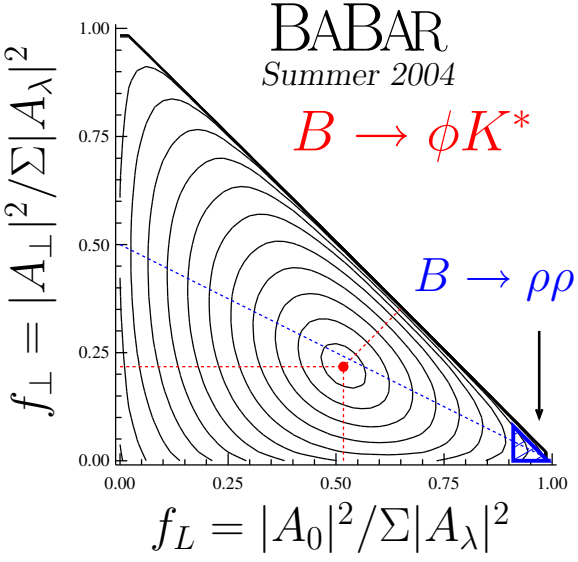
$$|A_0|^2 \neq |\bar{A}_0|^2, \qquad |A_\parallel|^2 \neq |\bar{A}_\parallel|^2, \qquad |A_\perp{}^2| \neq |\bar{A}_\perp|^2$$

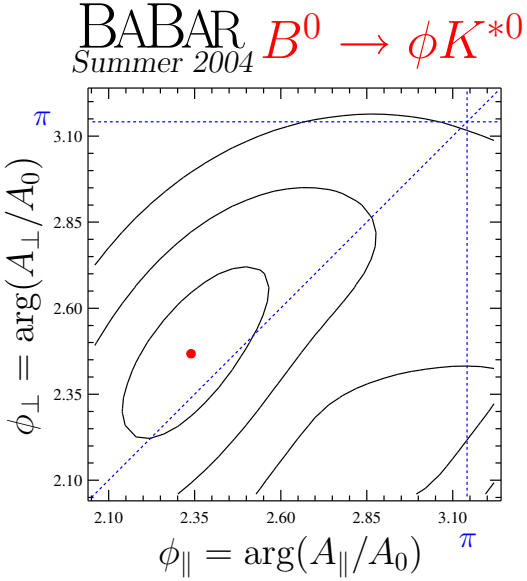
(3) triple-product asymmetries $\propto \sin\Delta\delta_{\rm weak}\ \cos\Delta\delta_{\rm strong}$

$$\mathrm{Im}(A_\perp A_0^*) \neq -\mathrm{Im}(\bar{A}_\perp \bar{A}_0^*) \qquad \mathrm{Im}(A_\perp A_\parallel^*) \neq -\mathrm{Im}(\bar{A}_\perp \bar{A}_\parallel^*)$$

(4) mixing-induced asymmetry: $\mathrm{Im}(\frac{q}{p}\bar{A}_0/A_0) \neq \sin 2\beta$

Full Angular Analysis





- Example of $B^0 \to \phi K^{*0}$

	BABAR	BELLE	average
f_L	$0.52 \pm 0.05 \pm 0.02$	$0.45 \pm 0.05 \pm 0.02$	0.49 ± 0.04
$f_\perp$	$0.22 \pm 0.05 \pm 0.02$	$0.31^{+0.06}_{-0.05} \pm 0.02$	0.27 ± 0.04
$\phi_\parallel$	$2.34^{+0.23}_{-0.20} \pm 0.05$	$2.40^{+0.28}_{-0.24} \pm 0.07$	$2.37^{+0.18}_{-0.16}$
$\phi_\perp$	$2.47 \pm 0.25 \pm 0.05$	$2.51 \pm 0.25 \pm 0.06$	2.49 ± 0.18
A_{CP}	$-0.01 \pm 0.09 \pm 0.02$	$0.02 \pm 0.09 \pm 0.02$	0.01 ± 0.07
A^0_{CP}	$-0.06 \pm 0.10 \pm 0.01$	$0.13 \pm 0.12 \pm 0.04$	0.01 ± 0.08
$A^\perp_{CP}$	$-0.10 \pm 0.24 \pm 0.05$	$-0.20 \pm 0.18 \pm 0.04$	-0.16 ± 0.15
$\Delta\phi_\parallel$	$0.27^{+0.20}_{-0.23} \pm 0.05$	$-0.32 \pm 0.27 \pm 0.07$	0.00 ± 0.17
$\Delta\phi_\perp$	$0.36 \pm 0.25 \pm 0.05$	$-0.30 \pm 0.25 \pm 0.06$	0.02 ± 0.18

- At Super-B:
  - precision CP measurements
  - full analysis of all $B \to VV$ modes

Triple-Product Asymmetries

- "Triple-products" new in B-physics $(\mathbf{q_1}-\mathbf{q_2}) \cdot \mathbf{p_1} \times \mathbf{p_2}$

  would be evidence of CP-violation and new amplitude

$$\mathcal{A}_T^{0,\parallel} = \mathrm{Im}(A_\perp A_{0,\parallel}^*)/(2\Sigma|A_m|^2) + \mathrm{Im}(\bar{A}_\perp \bar{A}_{0,\parallel}^*)/(2\Sigma|\bar{A}_m|^2)$$

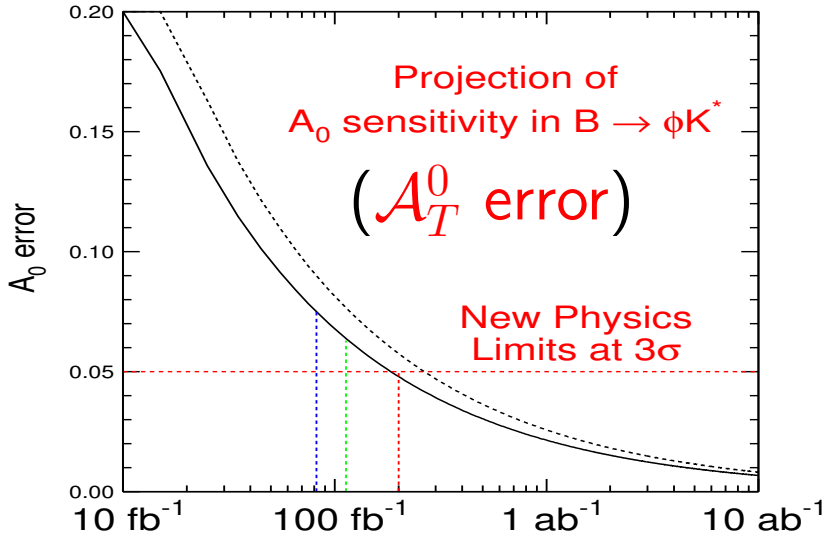
  – New Physics $\mathcal{A}_T^{0,\parallel} \neq 0$, e.g. $\mathcal{A}_T^0 \sim 0.15$ with NP (Datta/London)

- Precision measurement at Super-B

  projection from 2003 still valid:

BABAR $\mathcal{A}_T^0 = +0.11 \pm 0.05 \pm 0.01$

BELLE $\mathcal{A}_T^0 = -0.08 \pm 0.08 \pm 0.02$



$B^0 \to \phi K^{*0}(K^0_S\pi^0)$

- Separate CP eigenstates through angular analysis $\Rightarrow$ "$\sin 2\beta_{\rm eff}$"
- Different NP effect CP-odd and CP-even (more info than ϕK^0_S):

  $\sin 2\beta_0$, $\sin 2\beta_\perp$, $\sin 2\beta_\parallel$ $\neq$ $\sin 2\beta$ with NP

- Effectively one parameter due to TP constraint

  naive projection based on *BABAR* data:

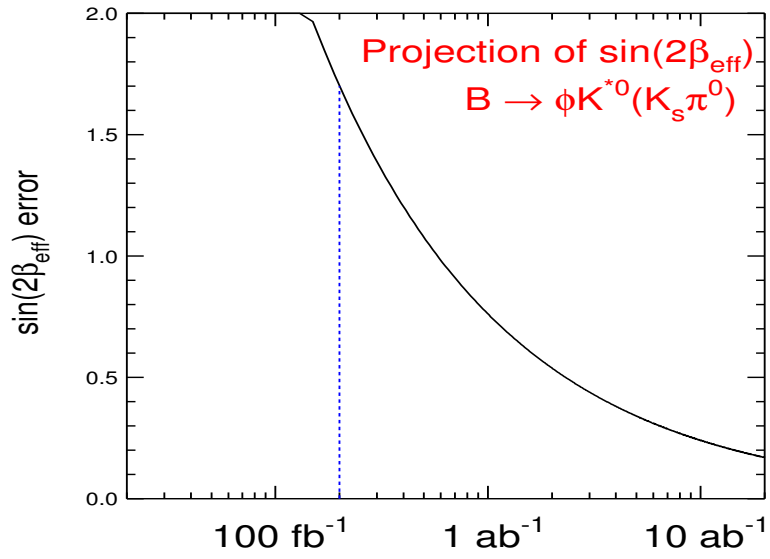
  $B^0 \to \phi K^{*0}(K^0_S\pi^0)$

  event yield $\sim 6\%$ of $\phi K^{*0}(K^+\pi^-)$

  $B^0 \to J/\psi K^{*0}(K^0_S\pi^0)$

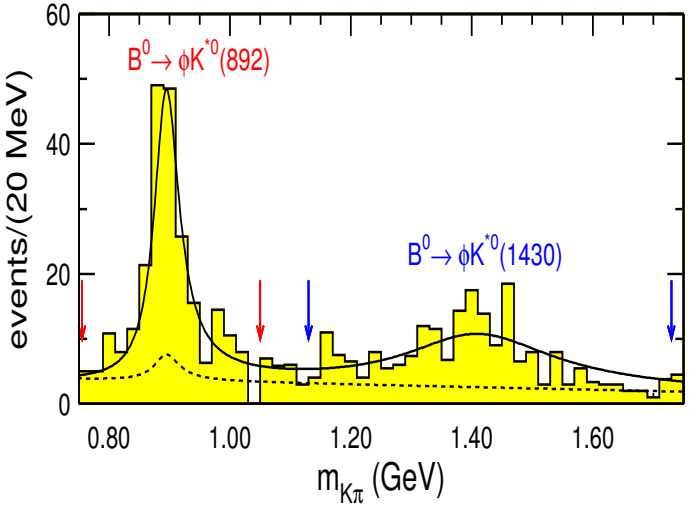
  angular CP(t) analysis

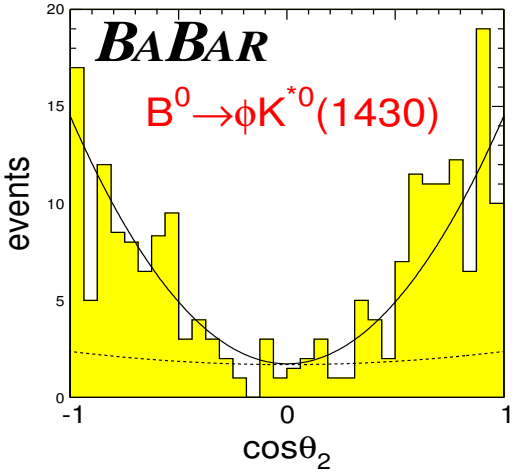
- Interesting precision at Super-B

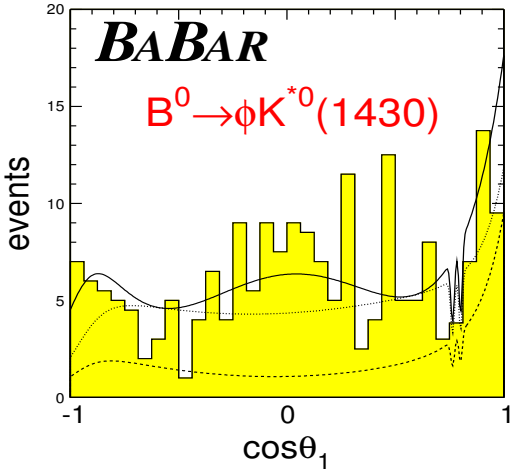


Polarization in $B \to VT$

- $B \to \phi K_J^{*0}(1430)$, Tensor ($J$=2) or Scalar ($J$=0)



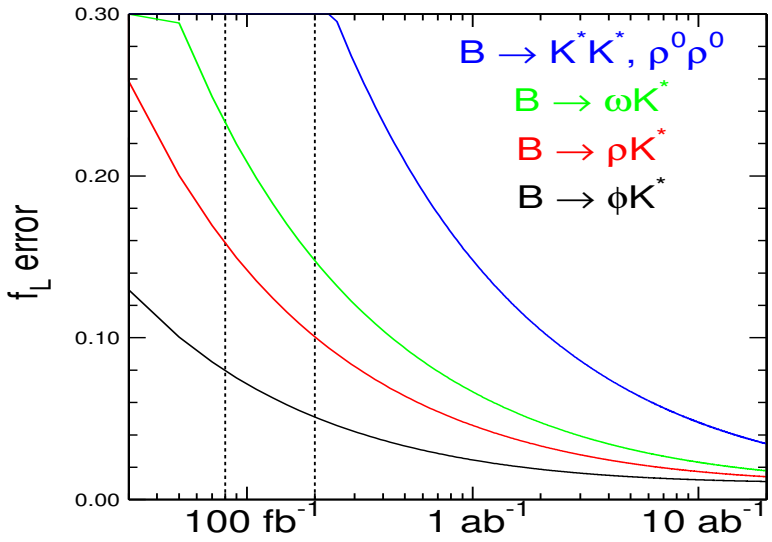




- Scalar dominates, but
  - 3σ evidence for Tensor
  - if $|A_0| \gg |A_\pm|$ holds for $B \to VT$, reject many $B \to VV$ models
- Super-B:
  - precise angular analysis of $B \to VT$

Approaching Polarization Anomaly

- Resolving $B \to \phi K^*$ polarization anomaly:
  - resolve polarization of $B \to \rho K^*$
  - observation and polarization of $B \to \omega K^*$
  - observation and polarization of $B \to \bar{K}^* K^*$ and $\rho^0 \rho^0$
  - resolve $|A_+| \gg |A_-|$ vs. $|A_+| \ll |A_-|$ like in $J/\psi K^*$
  - full angular analysis of $B \to VT$
- Need Super-B statistics
  for many of these



Conclusion

- $B \to \rho^0\rho^0$
  - key mode in α constraints and resolving ambiguities at Super-B

- $B \to VV$ deep understanding of weak and strong dynamics:
  (1) polarization: $|A_0|$ vs. $|A_\parallel|$ vs. $|A_\perp|$
  (2) FSI: $arg(A_0/A_\parallel)$ and $arg(A_0/A_\perp)$
  (3) direct-CP: $|A_0|/|\bar{A}_0|$, $|A_\parallel|/|\bar{A}_\parallel|$, $|A_\perp|/|\bar{A}_\perp|$
  (4) CP phases: $arg(A_0/\bar{A}_0)$, $arg(A_\parallel/\bar{A}_\parallel)$, $arg(A_\perp/\bar{A}_\perp)$

- Only Super-B statistics will allow to explore all of the above
  - could reveal New Physics if indeed hidden in the penguin loop