Vector-Vector(Tensor) B Decays at BABAR

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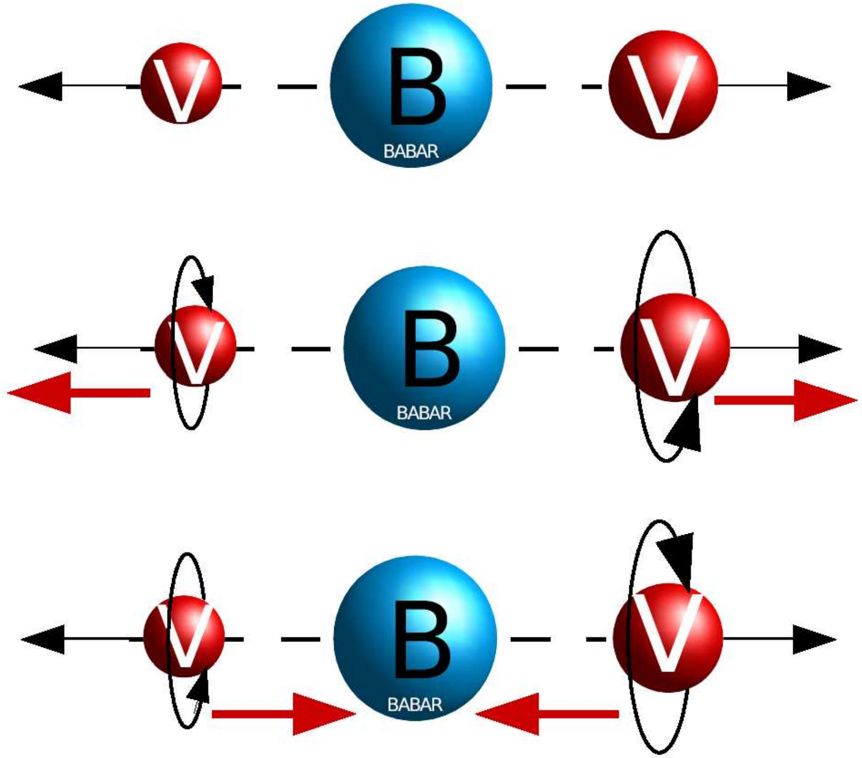
$\boldsymbol{B}$ Decays to Two Mesons with Spin

- Three configurations of spin projections in $B \to VV$:

A_{00}

A_{++}

A_{--}



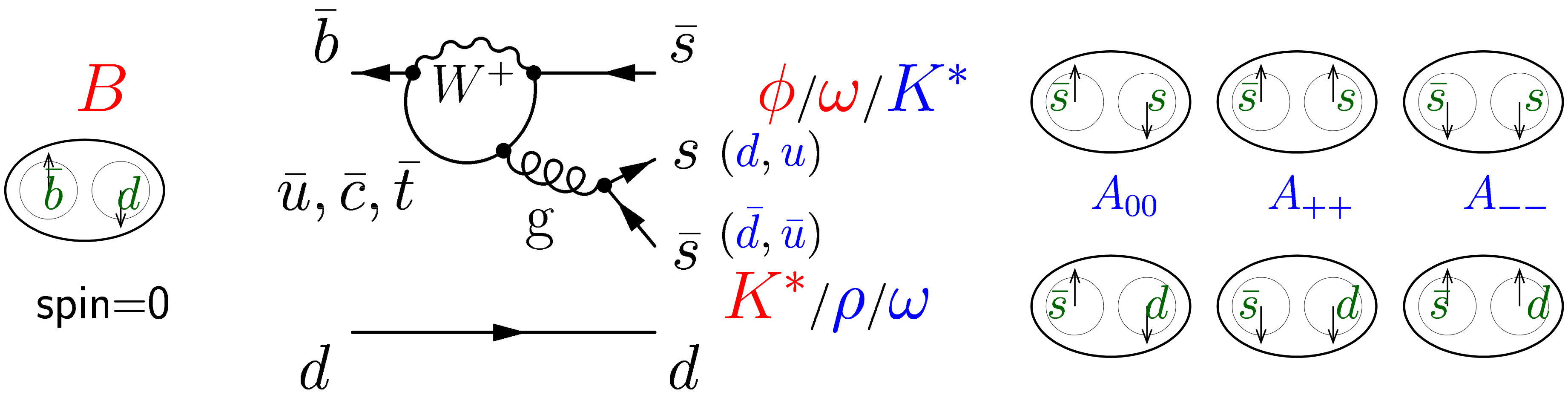
- 12 measurements (!)

complex amplitude $A = \langle V_1 V_2 | \mathcal{H} | B \rangle = A_{00} + A_{++} + A_{--}$

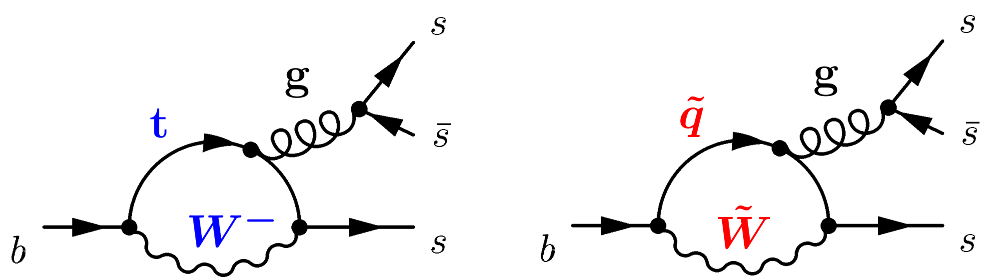
Separate B and $\bar{B}$: 6 $|A_i|$, 5 arg(A_i/A_j), 1 phase

Penguin $B \to VV$ Decays

- Interest in "penguin" dominated modes: $B \to \phi, \omega, \rho + K^*$



- New Physics in loop amplitude: 12 measurements (!)



Compare: $B \to \pi, \eta', \phi, \rho, .. + K^{\pm}$ 2 observables: $|A_0|$, $|\bar{A}_0|$ $\leftarrow \mathcal{A}_{CP}$

$B \to \eta', \phi, \pi^0, \omega, .. + K^0$ 3 obs.: $|A_0|$, $|\bar{A}_0|$, $\arg(A_0/\bar{A}_0)$ $\leftarrow \sin 2\beta_{\rm eff}$

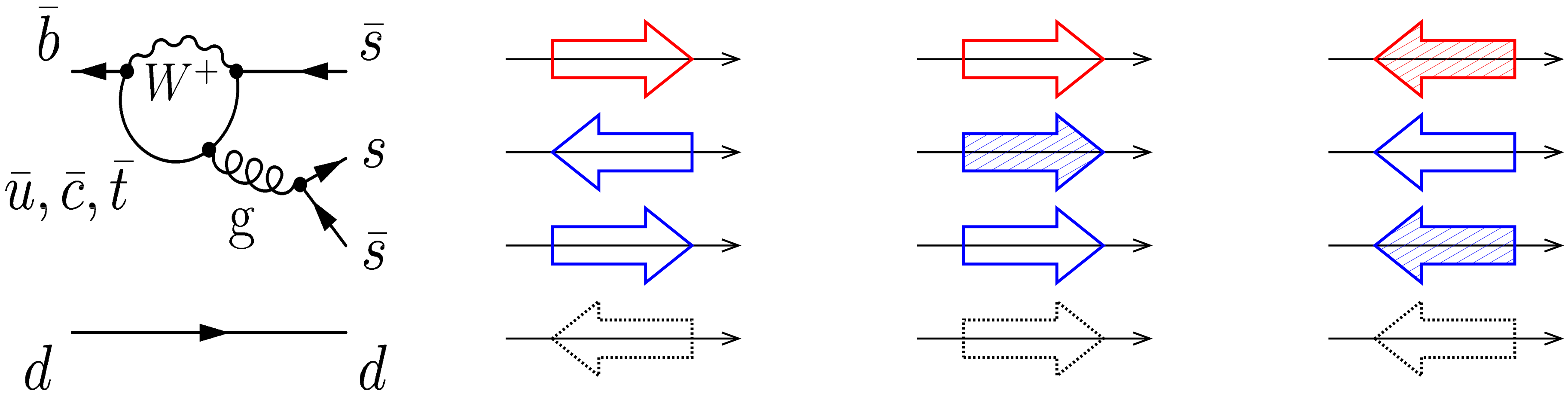
Spin Flip Suppression and Polarization Puzzle

- Standard Model $(V-A)$: left-handed quarks (!)

$$\bar{q}W^+ \to \bar{s} \Rightarrow \lambda_{\bar{s}} = +\tfrac{1}{2} \qquad \mathrm{g} \to s\bar{s} \quad \Rightarrow \lambda_s = \pm\tfrac{1}{2},\ \lambda_{\bar{s}} = \mp\tfrac{1}{2}$$

(A.Ali; M.Suzuki; A.Kagan,..)

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



- Originally pointed for "tree" $B \to VV$ decays, but:
  - extends to "penguins" (above)
  - we can apply to $J_2 > J_1 = 1$ (not discussed before)
- ϕK^{*+} & ϕK^{*0}: $A_0 \sim 50\%$

BABAR at Frontier Science Conf. (Oct.2002)

BABAR, hep-ex/0303020, PRL **91**, 171802 (2003)

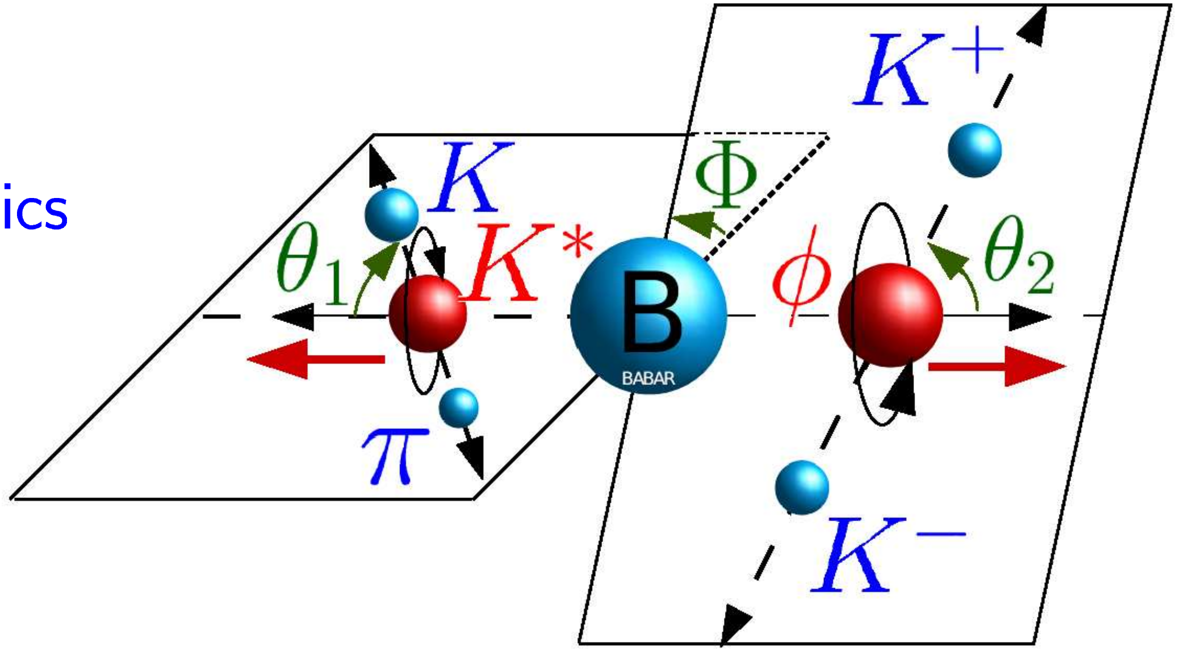
Belle, hep-ex/0307014, PRL **91**, 201801 (2003)

Angular Measurements

- Angular distribution

  from Quantum Mechanics

  $A_{\pm 1} = (A_\parallel \pm A_\perp)/\sqrt{2}$



- For $J_1 = J_2 = 1$:

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto |A_{00} + A_{++} + A_{--}|^2 = \left| \sum_{\lambda=1}^{3} A_\lambda \times Y_{J_1}^{\lambda}(\theta_1, 0) \times Y_{J_2}^{-\lambda}(\pi - \theta_2, -\Phi) \right|^2$$

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

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

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

Angular Observables in Analysis

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

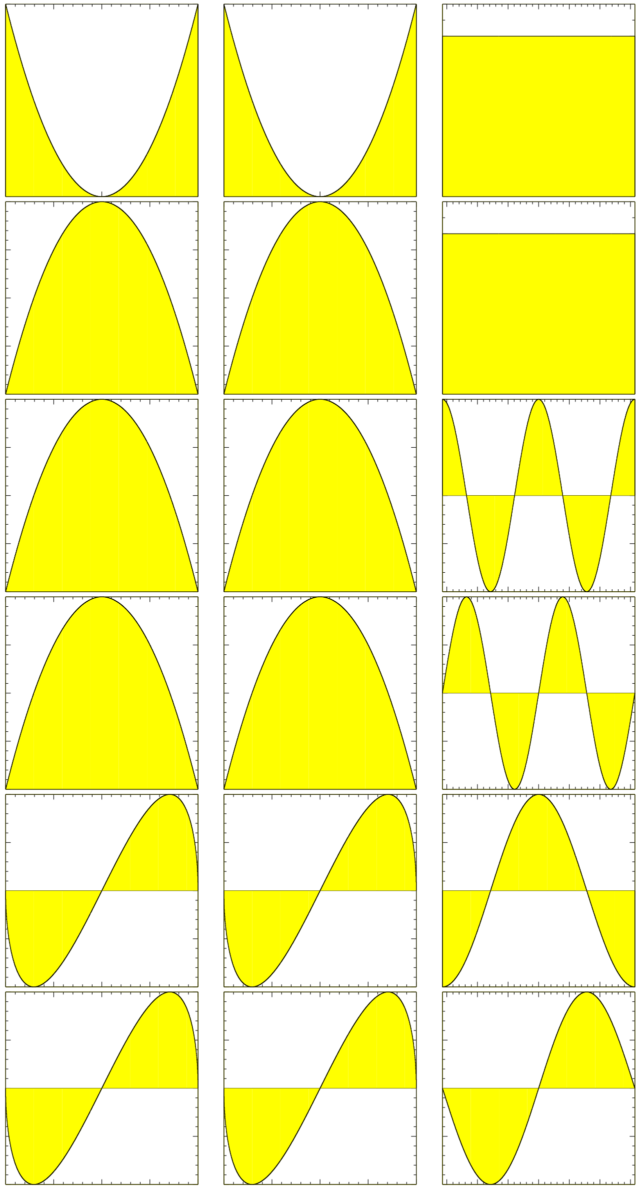
$\alpha_2(f_L)\times$ $\Rightarrow |A_\parallel|^2 + |A_\perp|^2$

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

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

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

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



$\cos\theta_1$ $\cos\theta_2$ Φ $\times$acceptance

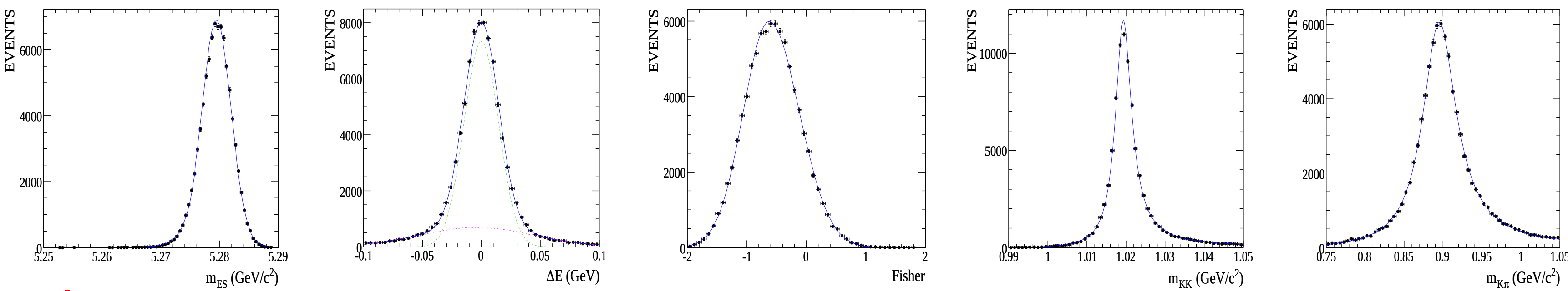
Kinematic Observables in Analysis

- Fully reconstruct $B \to \phi(K^+K^-)K^*(K\pi)$

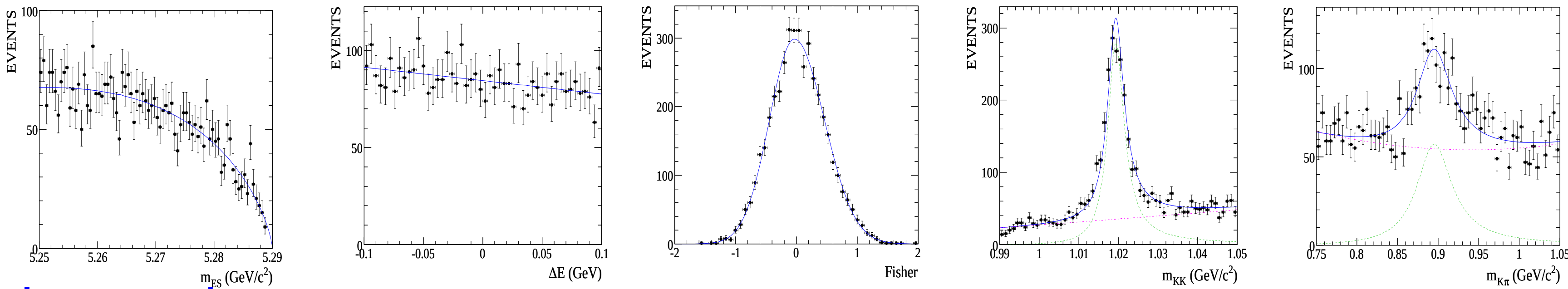
$$B \to \rho(\pi^\pm\pi^{0\mp})\ K^*(K\pi)$$

$$B \to \omega(\pi^+\pi^-\pi^0)K^*(K\pi)$$

m_{ES} | ΔE | $\mathcal{F}$isher | $m_1(\phi)$ | $m_{K\pi}(K^*)$



Signal



Background

- Discrete observables e.g. $Q_B = +/-$: B flavor (charge)

Statistical Methods

- Estimate parameters with N events:

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

likelihood $\mathcal{L} = \exp\left(-\sum_{i,k} n_{ik}\right) \prod_{j=1}^{N} \left(\sum_{i,k} n_{ik} \mathcal{P}_{ik}(\vec{x}_j; \vec{\xi}\,)\right)$ = maximum

$$\mathcal{P}_{i,k}(\vec{x}_j) = \mathcal{P}_{i1}(m_{\mathrm{ES}}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{F}) \cdot \mathcal{P}_{i4}(m_1) \cdot \delta_{kQ} \times$$

$$\times\, \mathcal{P}^{\mathrm{hel}}_{i,k}(m_{K\pi}, \theta_1, \theta_2, \{\Phi\}, {f_L}^k, \{{f_\perp}^k, {\phi_\perp}^k, {\phi_\parallel}^k, {\delta_0}^k\}) \times \mathcal{G}(\theta_1, \theta_2, \Phi)$$

acceptance

- Measure: polarization $f_L = \frac{|A_0|^2}{\Sigma|A_\lambda|^2}$ $\quad f_\perp = \frac{|A_\perp|^2}{\Sigma|A_\lambda|^2}$

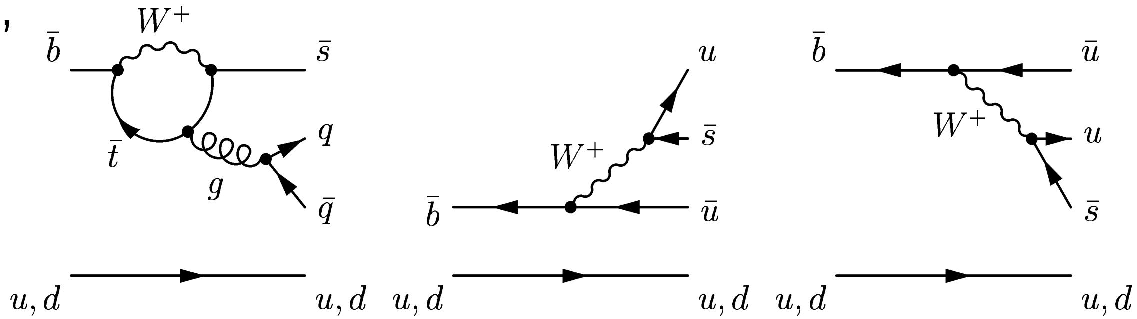
  phases $\phi_\parallel = \arg(\frac{A_\parallel}{A_0})$ $\quad \phi_\perp = \arg(\frac{A_\perp}{A_0})$ $\quad \delta_0 \propto \arg(\frac{A_{\mathrm{LASS}}}{A_0})$

  CP asymmetries

$B \to VV$ "Penguin" Decays

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

"Penguin"



"Tree"

BABAR

	α_P	α_T	α_C	Branching fraction (10^{-6})	$f_L = \lvert A_0\rvert^2/\Sigma\lvert A_\lambda\rvert^2$	$N_{B\bar{B}}$ (10^6)	Ref. (BABAR)
ϕK^{*0}	$\sqrt{2}$	0	0	$9.2 \pm 0.7 \pm 0.6$	$0.506 \pm 0.040 \pm 0.015$	384	hep-ex/0610073
ϕK^{*+}	$\sqrt{2}$	0	0	$12.7\ ^{+2.2}_{-2.0} \pm 1.1$	$0.46 \pm 0.12 \pm 0.03$	89	PRL 91, 171802
$\rho^- K^{*0}$	$\sqrt{2}$	0	0	$9.6 \pm 1.7 \pm 1.5$	$0.52 \pm 0.10 \pm 0.04$	232	hep-ex/0607057
$\rho^- K^{*+}$	-$\sqrt{2}$	-$\sqrt{2}$	0	$< 12.0\ (5.4^{+3.8}_{-3.4} \pm 1.6)$	n/a $(-0.18^{+0.52}_{-1.74})$	232	hep-ex/0607057
$\rho^0 K^{*0}$	1	0	-1	$5.6 \pm 0.9 \pm 1.3$	$0.57 \pm 0.09 \pm 0.08$	232	hep-ex/0607057
$\rho^0 K^{*+}$	-1	-1	-1	$< 6.1\ (3.6^{+1.7}_{-1.6} \pm 0.8)$	n/a (0.9 ± 0.2)	232	hep-ex/0607057
ωK^{*0}	1	0	1	$< 4.2\ (2.4 \pm 1.1 \pm 0.7)$	n/a $(0.71^{+0.27}_{-0.24})$	232	PRD 74, 051102
ωK^{*+}	1	1	1	$< 3.4\ (0.6^{+1.4+1.1}_{-1.2-0.9})$	n/a	232	PRD 74, 051102

Challenges in $B \to \rho K^{*0}$

- Non-resonant
  and other resonances:

$B \to (\pi\pi)_{\mathrm{S-wave}} K^{*0}$

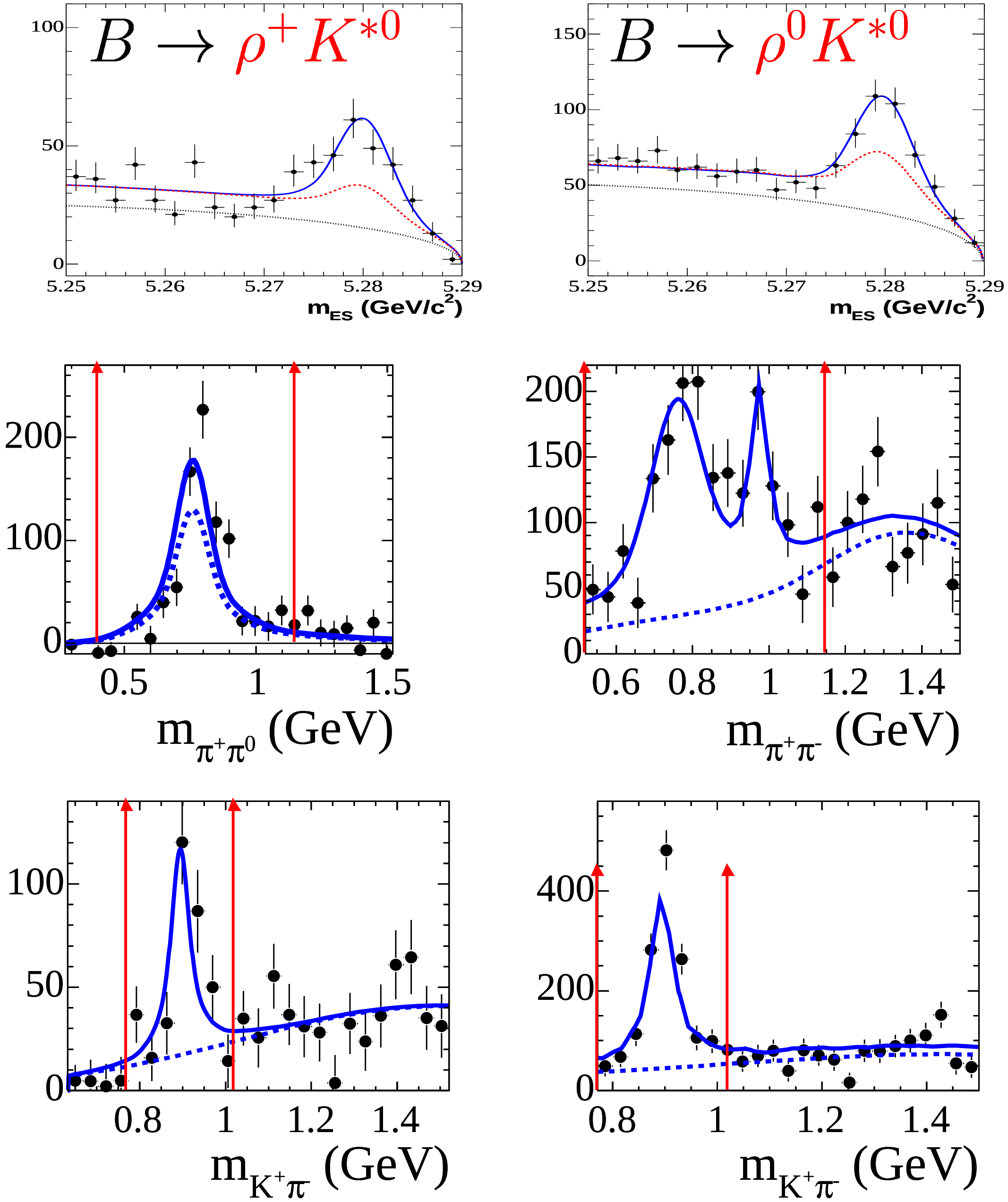
$B \to f_0(980) K^{*0}$

$B \to f_0(1370) K^{*0}$

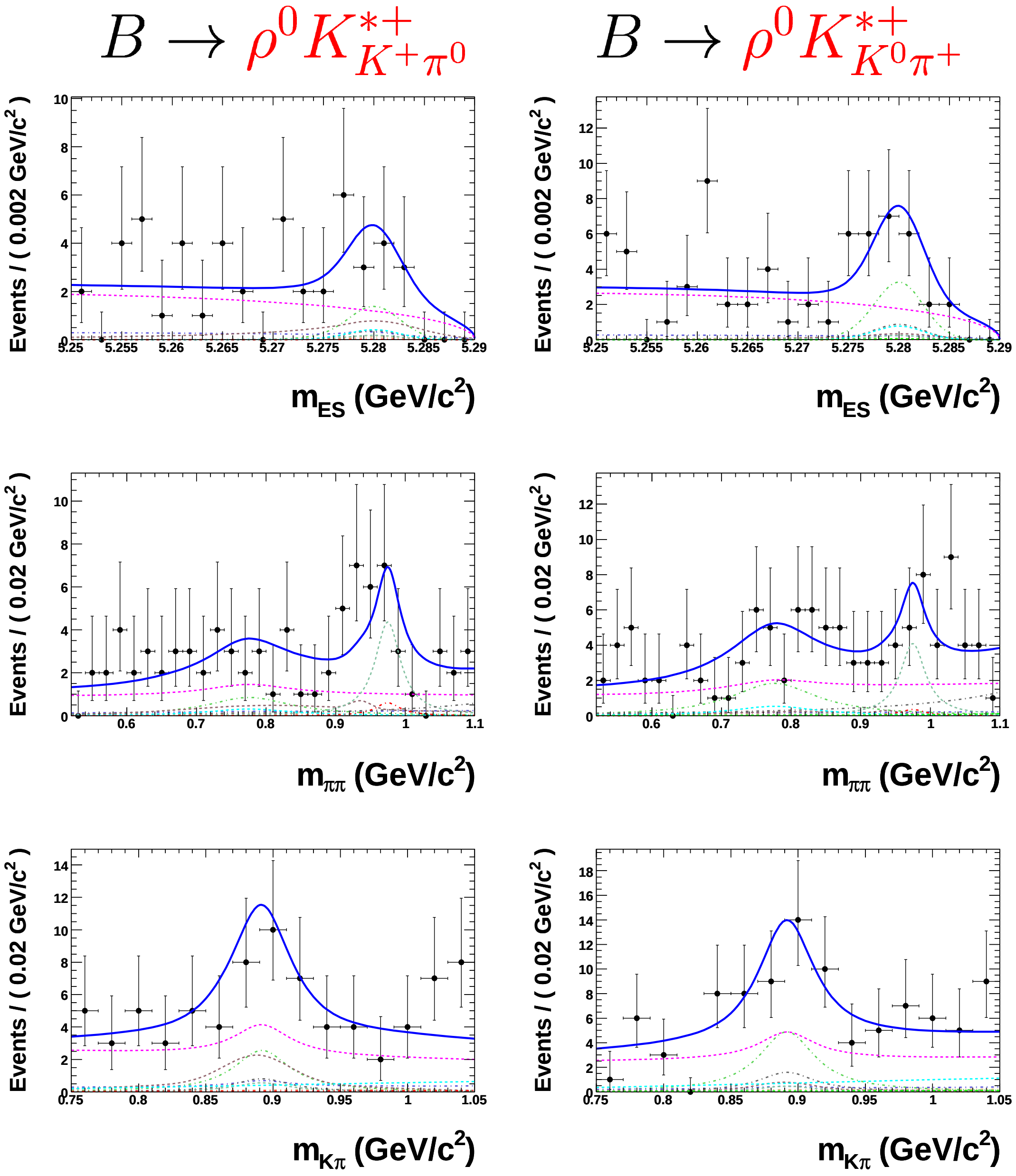
$B \to \rho (K\pi)_{\mathrm{S-wave}}$

$B \to \pi\pi K\pi$

plots with sPlots technique



Challenges in $B \to \rho^0 K^{*+}$



- Non-resonant

  and other resonances:

  $B \to f_0(980) K^{*+}$ (observed)

  $B \to f_0(1370) K^{*+}$

  $B \to (\pi\pi)_{\text{S-wave}} K^{*+}$

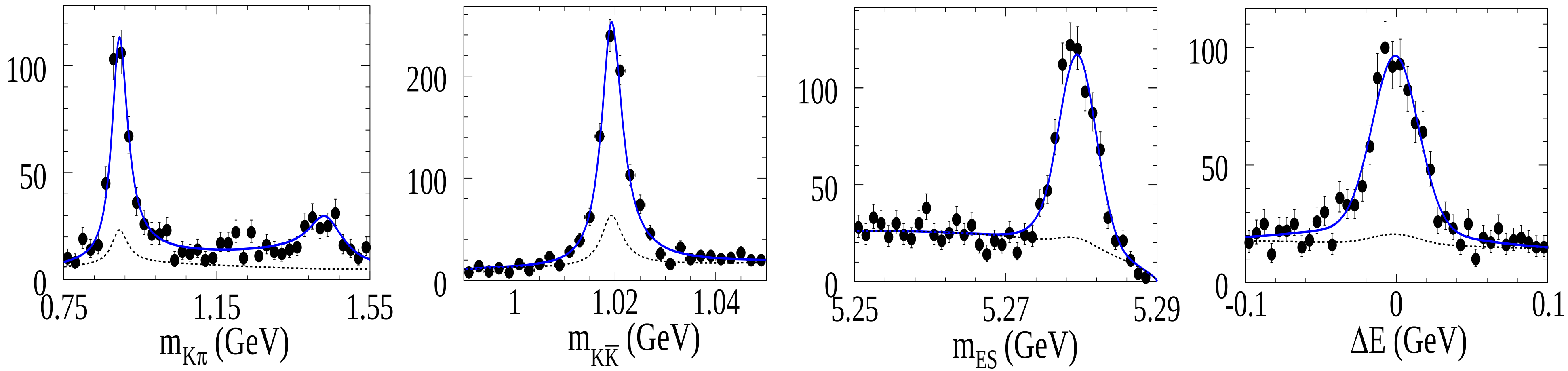
  $B \to \rho(K\pi)_{\text{S-wave}}$

- Previous (PRL 91, 171802)

  $> 4\sigma$ was model-dependent

  (included $\rho K\pi$ and $\pi\pi K^{*+}$)

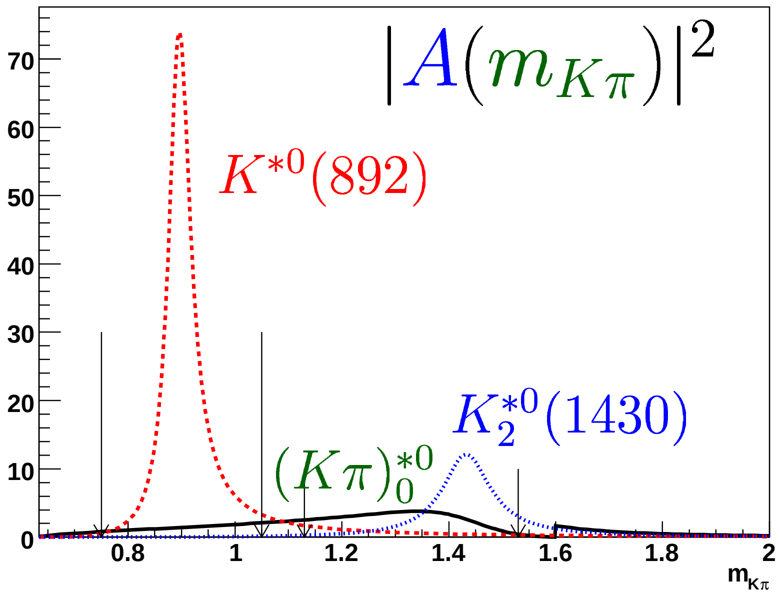
Clean Environment: $B^0 \to \phi(K\pi)^0$

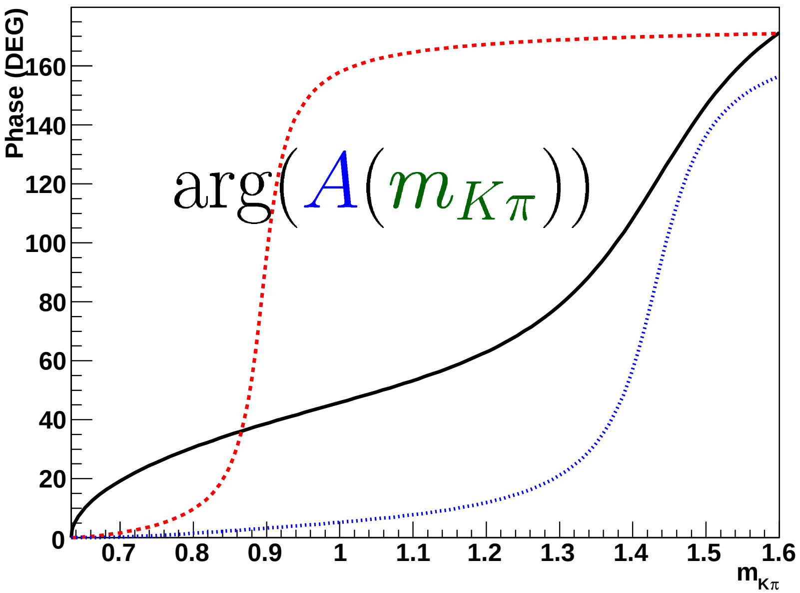


Mode	$m_{K\pi}$	$n_{\rm sig}$ (events)	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$
$\phi K^*(892)^0$	BW	$406 \pm 29 \pm 15$	$9.2 \pm 0.7 \pm 0.6$	$-0.03 \pm 0.07 \pm 0.03$
$\phi K_2^*(1430)^0$	BW	$133 \pm 19 \pm 7$	$7.8 \pm 1.1 \pm 0.6$	$-0.12 \pm 0.14 \pm 0.04$
$\phi(K\pi)_0^{*0}$	LASS	$147 \pm 23 \pm 7$	$5.0 \pm 0.8 \pm 0.3$	$+0.17 \pm 0.15 \pm 0.03$

- Significant $(K\pi)_0^{*0}$: $J^P = 0^+$ $K\pi$ component
  - inludes $K_0^*(1430)^0$ and non-resonant
  - interference $\Rightarrow$ resolve $(2\pi - \phi_\parallel, \pi - \phi_\perp)$ ambiguity (like $B^0 \to J/\psi(K\pi)_0^{*0}$)

Interference in $B^0 \to \phi(K\pi)$





$$\mathcal{P}(\theta_1, \theta_2, \Phi, m_{K\pi}) = f \cdot |A_{VV}|^2 + (1-f) \cdot |A_{VS}|^2 + \sqrt{f(1-f)} \cdot 2\mathcal{R}\mathrm{e}(A_{VV} A_{VS}^*)$$

$$A_{VV} = \sqrt{\tfrac{9}{8\pi}}[A_0 \cos\theta_1 \cos\theta_2 + \tfrac{1}{2}\sin\theta_1 \sin\theta_2 (A_{+1}e^{i\Phi} + A_{-1}e^{-i\Phi})] A_{\mathrm{BW}}(m_{K\pi})$$

$$A_{VS} = \sqrt{\tfrac{3}{8\pi}} A \cos\theta_2 A_{\mathrm{LASS}}(m_{K\pi}) \times e^{i\delta_0}$$

- Approach validated in $B^0 \to J/\psi(K\pi)_0^{*0}$

$$\delta_0 \sim \pi \Leftrightarrow e^{i\delta_0} = -1$$

Resolve Phase Ambiguity in $B^0 \to \phi K^*(892)^0$

- Strong phases:

$$\phi_{\parallel} = \arg(A_{\parallel}/A_0) = 2.31 \pm 0.14 \pm 0.08 \neq \pi, 0$$

$$\phi_{\perp} = \arg(A_{\perp}/A_0) = 2.24 \pm 0.15 \pm 0.09 \neq \pi, 0$$

without interf.: $\{\phi_{\parallel}, \phi_{\perp}\} \leftrightarrow \{2\pi - \phi_{\parallel}, \pi - \phi_{\perp}\}$

preserve $\sin(\phi_{\perp} - \phi_{\parallel})$, $\cos(\phi_{\parallel})$, $\sin(\phi_{\perp})$

- With interference new terms:

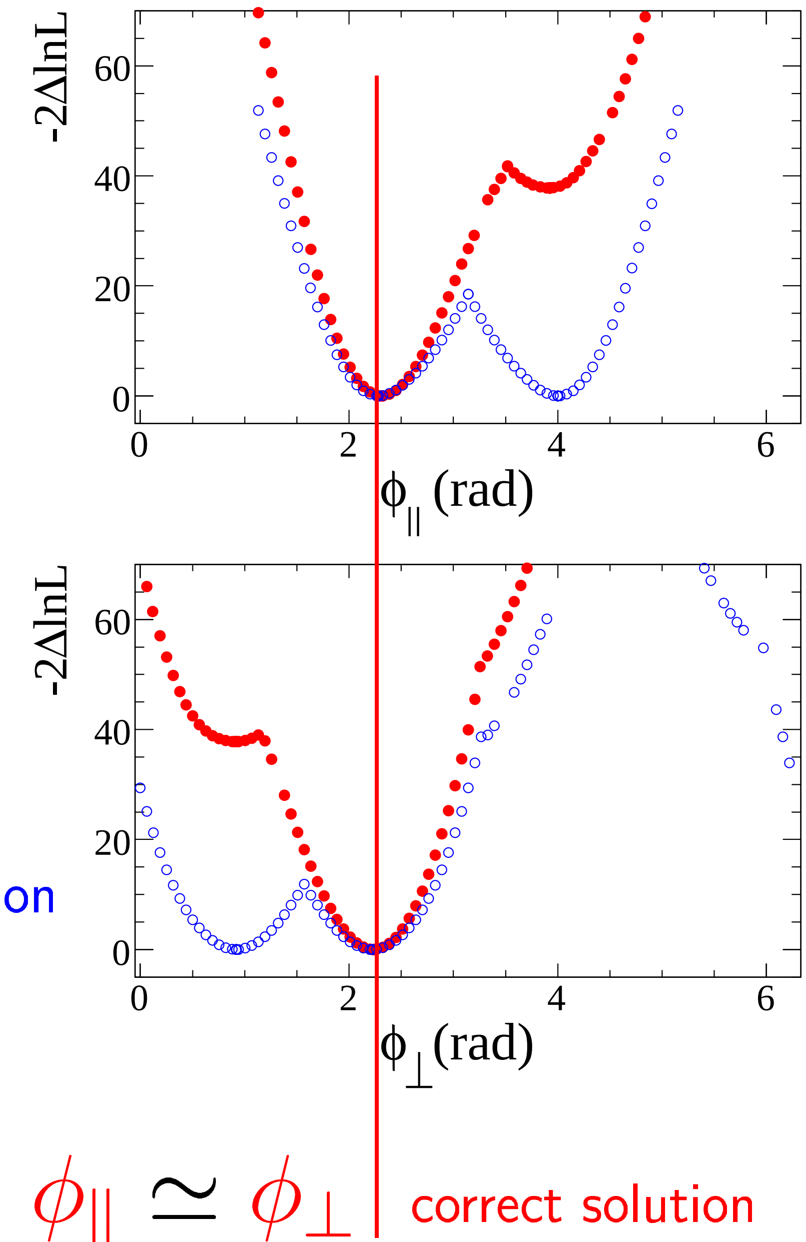
$\cos(\phi_{\perp} + \delta(m_{K\pi}) - \delta_0)$

$\sin(\phi_{\perp} + \delta(m_{K\pi}) - \delta_0)$,......

$\Longrightarrow$ reject wrong solution

$$\delta_0 = 2.78 \pm 0.17 \pm 0.09 \sim \pi$$

illustration plots with stat. only
and small CP-v. $|\Delta\phi_{\parallel,\perp}| < 0.5$



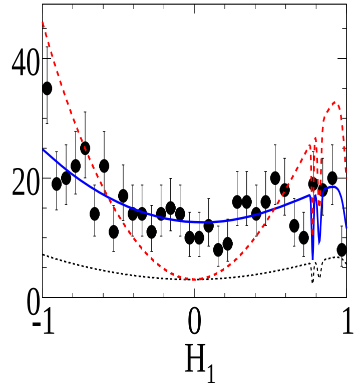
$\phi_{\parallel} \simeq \phi_{\perp}$ correct solution

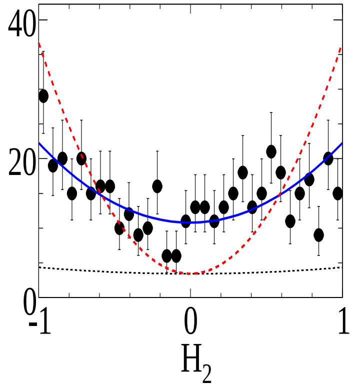
Angular Projections in $B^0 \to \phi K^*(892)^0$

(1) $\mathcal{H}_{1,2} = \cos\theta_{1,2}$

$$(|A_\perp|^2 + |A_\parallel|^2)\ (1 - \cos^2\theta_i) \Rightarrow \text{large}$$

$$f_L = 0.506 \pm 0.040 \pm 0.015$$

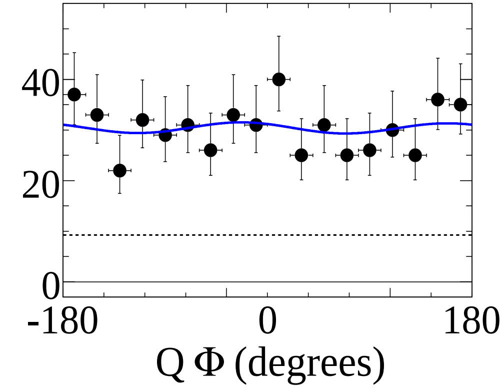




(2) Φ, small terms:

$$(|A_\parallel|^2 - |A_\perp|^2)\ \cos 2\Phi \quad \& \quad \mathrm{Im}(A_\perp A_\parallel{}^*)\ \sin 2\Phi$$

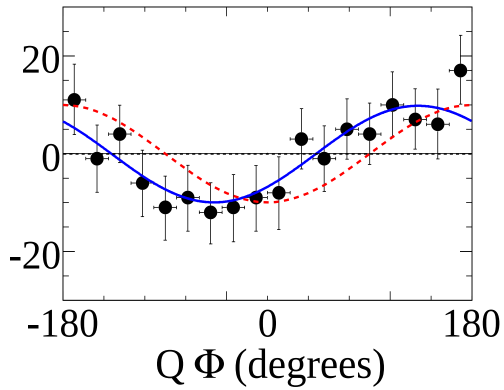
$$f_\perp = 0.227 \pm 0.038 \pm 0.013 \sim (1 - f_L)/2$$



(3) $\Phi\ (\cos\theta_1 \cos\theta_2 > 0)$ – $\Phi\ (\cos\theta_1 \cos\theta_2 < 0)$

$$\mathrm{Re}(A_\parallel A_0{}^*)\ \cos\Phi \quad \& \quad \mathrm{Im}(A_\perp A_0{}^*)\ \sin\Phi \Rightarrow \text{large}$$

$$\phi_\parallel \simeq \phi_\perp \neq \pi \text{ or } 0 \quad \Rightarrow \quad \text{FSI}$$



Polarization and CP Results in $B^0 \to \phi K^*(892)^0$

f_L	$0.506 \pm 0.040 \pm 0.015$
$f_\perp$	$0.227 \pm 0.038 \pm 0.013$
$\phi_\parallel$ (rad)	$2.31 \pm 0.14 \pm 0.08$
$\phi_\perp$ (rad)	$2.24 \pm 0.15 \pm 0.09$
δ_0 (rad)	$2.78 \pm 0.17 \pm 0.09$
$\mathcal{A}_{CP}$	$-0.03 \pm 0.07 \pm 0.03$
$\mathcal{A}^0_{CP}$	$-0.03 \pm 0.08 \pm 0.02$
$\mathcal{A}^\perp_{CP}$	$-0.03 \pm 0.16 \pm 0.05$
$\Delta\phi_\parallel$	$+0.24 \pm 0.14 \pm 0.08$
$\Delta\phi_\perp$	$+0.19 \pm 0.15 \pm 0.08$
$\Delta\delta_0$	$+0.21 \pm 0.17 \pm 0.08$

f_L and $f_\perp$ confirmed and improved (puzzle)

$\phi_\parallel$ and $\phi_\perp$ away from π $>5\sigma$ (FSI)

δ_0 close to π (similar to $B \to J/\psi K^*$)

CP asymmetries consistent with 0

watch for $\Delta\phi_\perp$ $(\beta_{\rm eff}^{\rm P-odd} - \beta_{\rm eff}^{\rm P-even})$

$\Delta\delta_0 = \frac{1}{2}(\delta_0^+ - \delta_0^-)$ is a new approach to CP

In short: $|A_0| \simeq |A_{+1}| \gg |A_{-1}|$

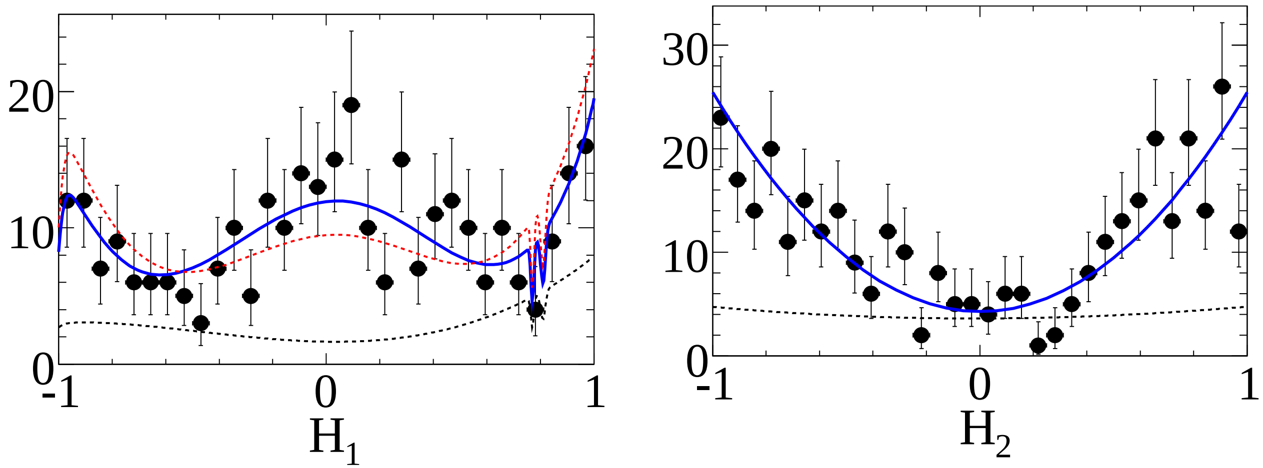
$\arg(A_0) \neq \arg(A_{+1})$

because: $A_{\pm1} = (A_\parallel \pm A_\perp)/\sqrt{2}$

Polarization and CP in $B^0 \to \phi K_2^*(1430)^0 / (K\pi)_0^{*0}$

f_L	$0.853^{+0.061}_{-0.069} \pm 0.036$
$f_\perp$	$0.045^{+0.049}_{-0.040} \pm 0.013$
$\phi_\parallel$ (rad)	$2.90 \pm 0.39 \pm 0.06$
$\phi_\perp$ (rad)	$5.72^{+0.55}_{-0.87} \pm 0.11$
δ_0 (rad)	$3.54^{+0.12}_{-0.14} \pm 0.06$
$\mathcal{A}_{CP}(\phi K_2^*)$	$-0.12 \pm 0.14 \pm 0.04$
$\mathcal{A}_{CP}(\phi K_0^*)$	$+0.17 \pm 0.15 \pm 0.03$

no other CP-violation terms



$f_L(\phi K_2^*) \sim 1 \Rightarrow \propto \cos^2\theta_2$ (like ϕK_0^*)

$\Rightarrow \propto (3\cos^2\theta_1 - 1)^2$ ("flat" ϕK_0^*)

$2\mathcal{R}\mathrm{e}(A_1 A_2^*) \Rightarrow \propto (1 - 3\cos^2\theta_1)$

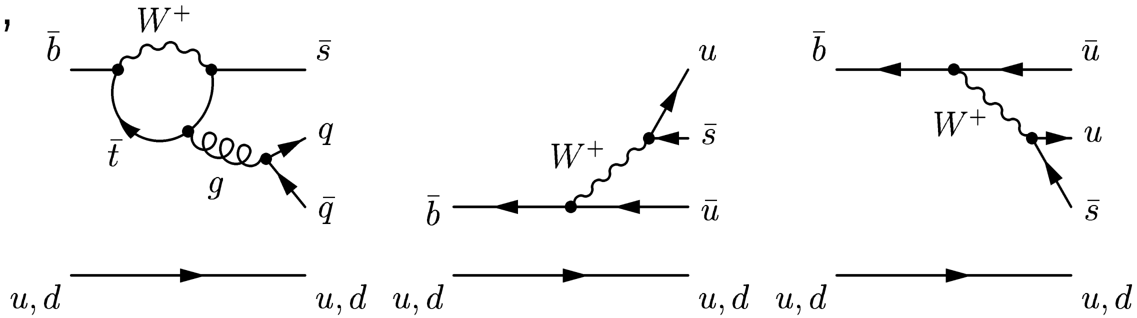
again $\delta_0 \sim \pi$

- Weak constraints on $\phi_\parallel$ (2.9σ) and $\phi_\perp$ (1.6σ)
- In short $|A_0| \gg |A_\pm|$, why in $B \to VT$ not VV (?)

$B \to VV$ and VT "Penguin" Summary

"Penguin"

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



"Tree"

BABAR

B decay	α_P	α_T	α_C	$\mathcal{B}(10^{-6})$	f_L	$N_{B\bar{B}}(10^6)$
ϕK_2^{*0}	$\sqrt{2}$	0	0	$7.8 \pm 1.1 \pm 0.6$	$0.853^{+0.061}_{-0.069} \pm 0.036$	384
ϕK^{*0}	$\sqrt{2}$	0	0	$9.2 \pm 0.7 \pm 0.6$	$0.506 \pm 0.040 \pm 0.015$	384
ϕK^{*+}	$\sqrt{2}$	0	0	$12.7\ ^{+2.2}_{-2.0} \pm 1.1$	$0.46 \pm 0.12 \pm 0.03$	89
$\rho^- K^{*0}$	$\sqrt{2}$	0	0	$9.6 \pm 1.7 \pm 1.5$	$0.52 \pm 0.10 \pm 0.04$	232
$\rho^- K^{*+}$	$-\sqrt{2}$	$-\sqrt{2}$	0	$< 12.0\ (5.4^{+3.8}_{-3.4} \pm 1.6)$	n/a $(-0.18^{+0.52}_{-1.74})$	232
$\rho^0 K^{*0}$	1	0	-1	$5.6 \pm 0.9 \pm 1.3$	$0.57 \pm 0.09 \pm 0.08$	232
$\rho^0 K^{*+}$	-1	-1	-1	$< 6.1\ (3.6^{+1.7}_{-1.6} \pm 0.8)$	n/a (0.9 ± 0.2)	232
ωK^{*0}	1	0	1	$< 4.2\ (2.4 \pm 1.1 \pm 0.7)$	n/a $(0.71^{+0.27}_{-0.24})$	232
ωK^{*+}	1	1	1	$< 3.4\ (0.6^{+1.4+1.1}_{-1.2-0.9})$	n/a	232

Summary

- Polarization puzzle: strong or weak interaction effect (?)

  $|A_0| \simeq |A_+| \gg |A_-|$ in $B \to \phi K^*(892)^0$ (puzzle)

  $|A_0| \simeq |A_\pm|$ in $B \to \rho K^*(892)^0$, $\phi K^*(892)^+$ (consistent with above)

  $|A_0| \gg |A_\pm|$ in $B \to \phi K_2^*(1430)^0$ (not consistent with above)

- Effects of strong interactions:

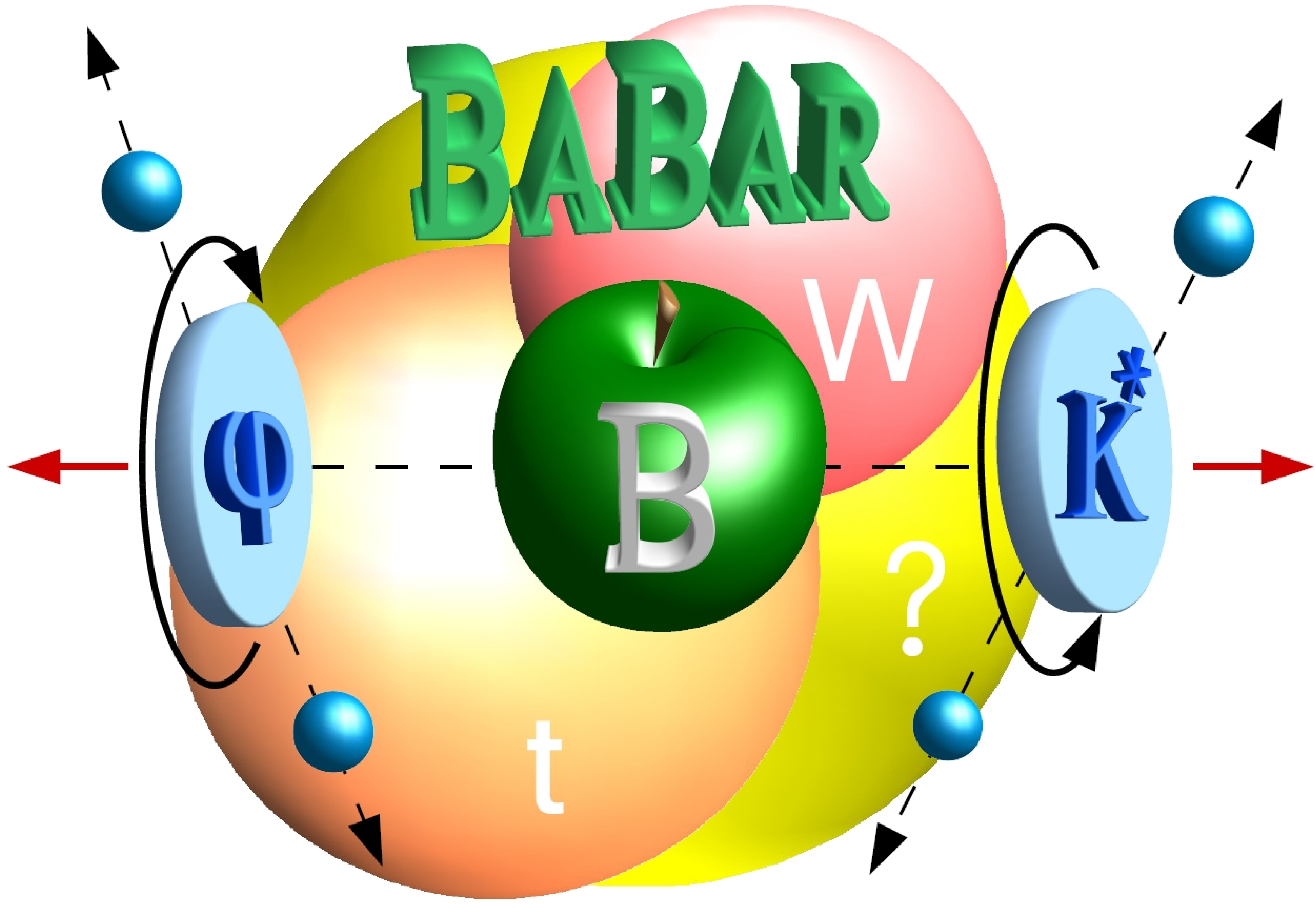
  $\arg(A_0) \neq \arg(A_+)$ in $B \to \phi K^*(892)^0$

  $\arg(A_0) \sim \pi$ in $B \to VT$ and VV relative to VS

- CP-parameters include clean weak interaction observables:

  $\Delta\phi_\perp$, $\Delta\phi_\parallel$, $\Delta\delta_0$ equivalent to $\sin 2\beta_{\rm eff}$

  also three direct-CP parameters $\mathcal{A}_{CP}^{\rm x}$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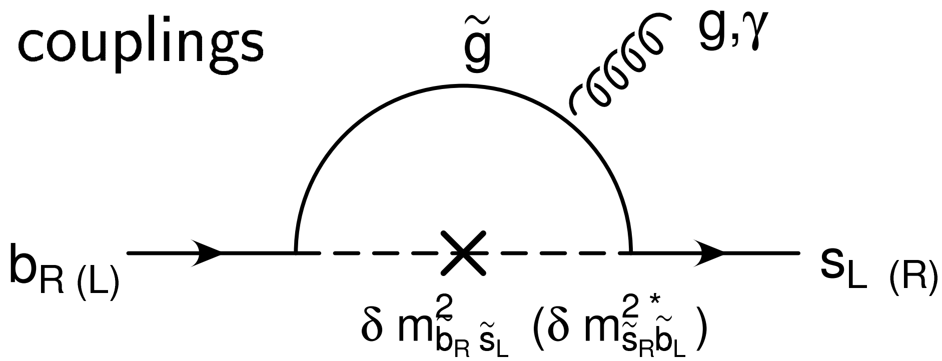
BACKUP SLIDES

New Physics in Penguins?

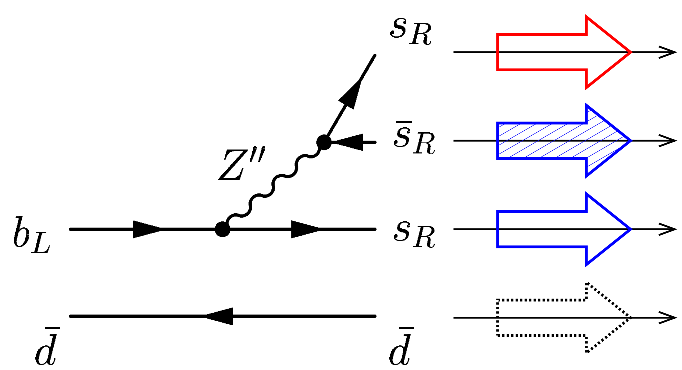
- Loops could reveal Right-Handed couplings
  - popular model of "$\sin(2\beta_{\rm eff})$"
  - $B \to VV$ ideal test

  (Kagan/Grossman/Alvarez/Yang/Giri/Das/*et al.*)

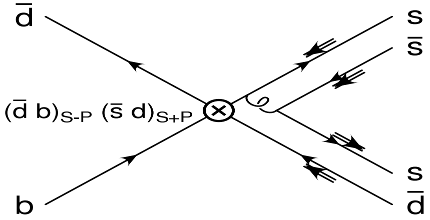


model	current	A_0	A_+	A_-
SM	$\bar{s}\gamma^\mu(1-\gamma_5)b\bar{s}\gamma_\mu(1\pm\gamma_5)s$	~ 1	$\sim \frac{m_V}{m_B}$	$\sim (\frac{m_V}{m_B})^2$
RH vector	$\bar{s}\gamma^\mu(1+\gamma_5)b\bar{s}\gamma_\mu(1\pm\gamma_5)s$	~ 1	$\sim (\frac{m_V}{m_B})^2$	$\sim \frac{m_V}{m_B}$
Tensor/scalar	$\bar{s}\sigma^{\mu\nu}(1+\gamma_5)b\bar{s}\sigma_{\mu\nu}(1+\gamma_5)s$	$\sim \frac{m_V}{m_B}$	~ 1	$\sim (\frac{m_V}{m_B})^2$
Tensor/scalar	$\bar{s}\sigma^{\mu\nu}(1-\gamma_5)b\bar{s}\sigma_{\mu\nu}(1-\gamma_5)s$	$\sim \frac{m_V}{m_B}$	$\sim (\frac{m_V}{m_B})^2$	~ 1

- Our observation: $|A_0| \simeq |A_+| \gg |A_-|$
  - tune SM + RH interference
  - SM + Tensor "exotic"

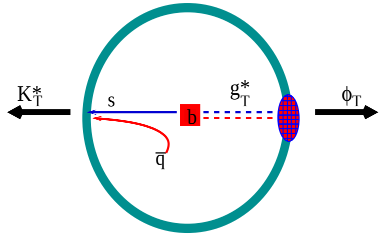


Polarization Anomaly: Some Ad hoc Models in SM



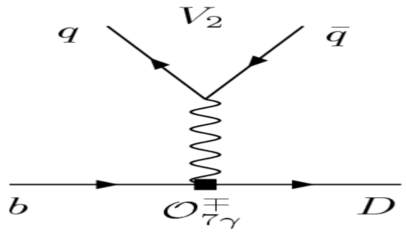
- **Annihilation diagram** (hep-ph/0405134)

  formally suppressed $1/m_b$
  not conclusive (vary free parameters)



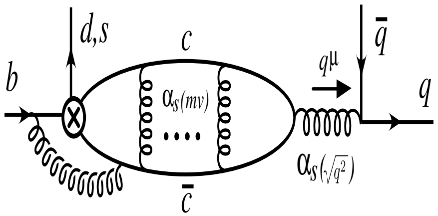
- **Transverse gluon from $b \to sg$** (hep-ph/0408007)

  analogy with γ from $B \to K^*\gamma$
  seems to be suppressed, not conclusive



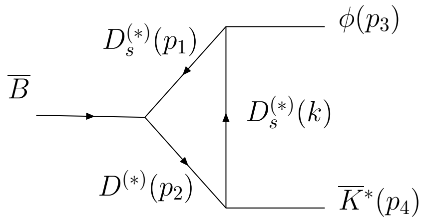
- **EM penguin** (hep-ph/0512258)

  similar polarization to $B \to K^*\gamma$
  appears only for neutral vector mesons



- **Charming penguins** (hep-ph/0401188)

  rely on free parameters, not conclusive



- **Long-distance rescattering** (hep-ph/0409317)

  model-dependent, constrained by other data
  expect $f_L \sim f_{||} \gg f_\perp$ (?)