

**Measurement of branching fractions,
CP asymmetries and polarizations
in charmless $B \rightarrow VV$ decays.**

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BABAR

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Interests of charmless $B \rightarrow VV$ decay modes

- **Measurement of the CKM angles α and γ :**
 - similarly to $\pi\pi$ and $K\pi$ systems, [Buras *et al*, hep-ph/0402112]
 - see presentation of Haibo Li (constaining α with $B \rightarrow \rho\rho$ decays).
- **Understand $B \rightarrow VV$ decays, search for new physics:**
 - **11 observables:** 6 amplitudes A_λ (λ : helicity) (A_0, A_{+1}, A_{-1}) $\times (B, \bar{B})$,
5 phases,
 - measurement of branching fraction, polarization ($f_L = A_0/A$), ...
 - experiment ahead to theory in $B \rightarrow VV$ (constrain models),
 - solving $K^*\phi$ riddle: expect $f_L(K^*\phi) \sim 1$, \leftarrow confirmed: $\rho^+\rho^-, \rho^+\rho^0, K^{*+}\rho^0$
but measure $f_L(K^*\phi) \sim 0.5 \pm 0.1$.
- **Search for direct CP-violation:**
 - measurement of charge / flavour asymmetries,
 - measurement of vector triple-product asymmetries.

"pure" penguin decay mode

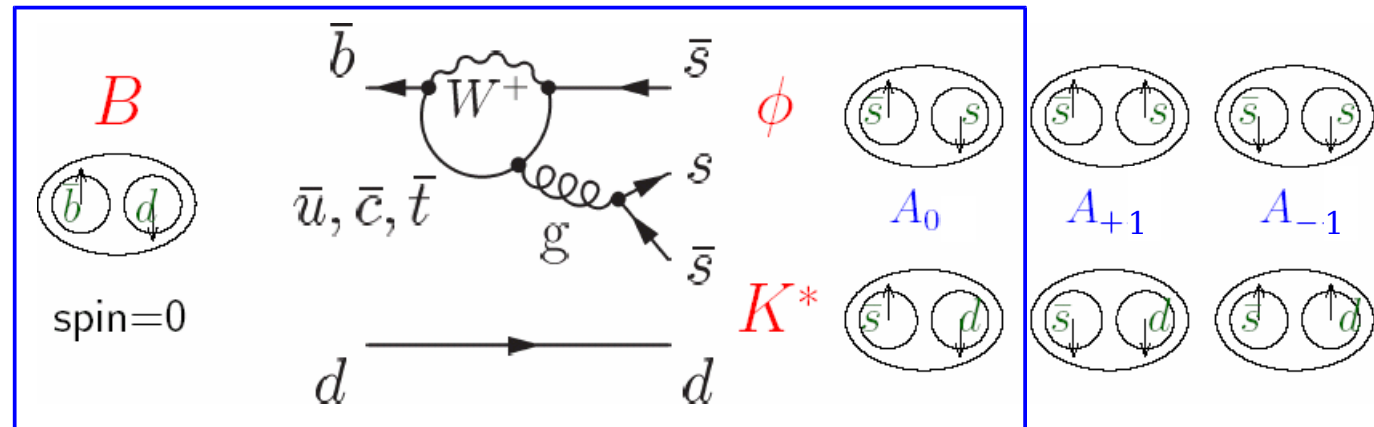
Decay polarization

- 3 helicity amplitudes: A_0, A_{+1}, A_{-1}

- Each spin flip costs $\sim m_V/m_B$

$$A_{+1} \sim A_0 \times (m_V/m_B)$$

$$A_{-1} \sim A_0 \times (m_V/m_B)^2$$



polarization $f_L \sim 1 - O((m_V/m_B)^2)$ expected but $f_L(K^*\phi) \sim 0.5$ observed

- $f_L(K^*\phi) \sim 0.5$ predictable in QCDF by tuning QCD parameters + adding annihilation [Kagan, hep-ph/0405134]
 \Rightarrow predicts: same polarization expected in $B^+ \rightarrow K^{*0} \rho^+$ decays (or maybe not?)

- Polarization also sensitive to FSI and new physics amplitudes:

[Grossman, ph-ph/0310229]

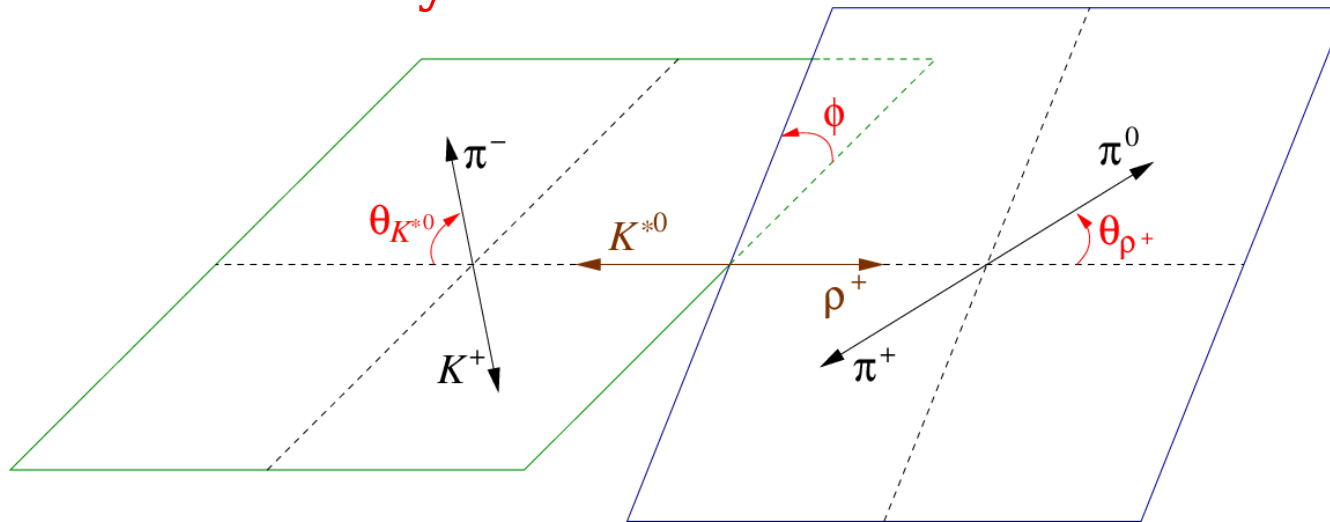
[Hou *et al*, ph-0408007]

[Colangelo *et al*, ph-0406162]

- need broad $B \rightarrow VV$ experimental programme

Angular analysis

- Performed in the helicity frame:

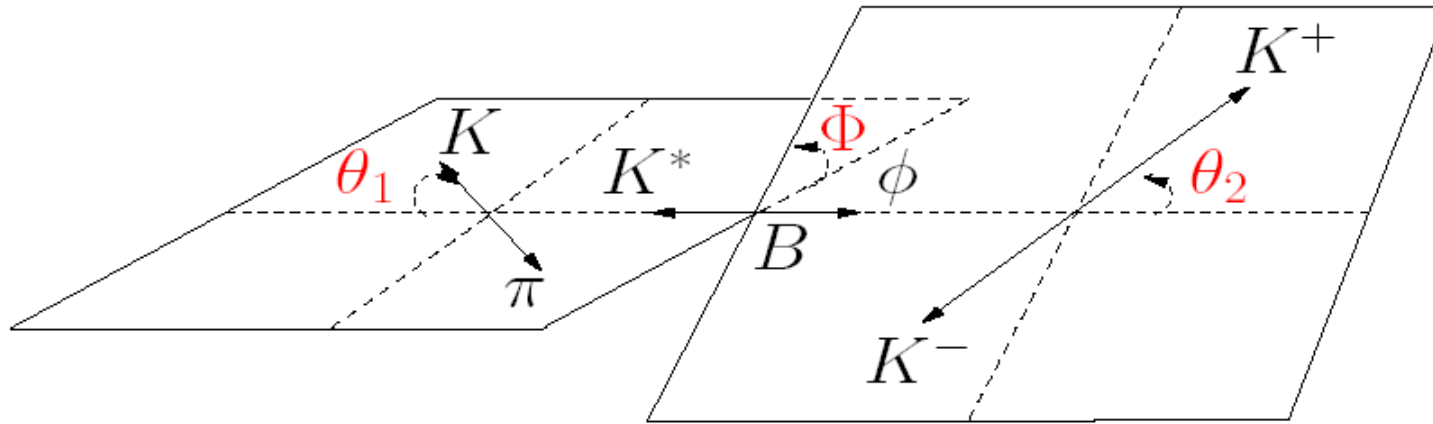


- helicity angle θ_V : between vector meson V and its decay products
- angle Φ : between the 2 decay planes
- Analysis may be simplified by integrating over Φ :
 \Rightarrow differential decay rate for signal:

$$\frac{1}{\Gamma} \frac{d^2\Gamma}{d \cos \theta_1 d \cos \theta_2} \propto \frac{1}{4} (1 - f_L) \sin^2 \theta_1 \sin^2 \theta_2 + \underbrace{f_L}_{\text{longitudinal}} \cos^2 \theta_1 \cos^2 \theta_2 \xrightarrow{\text{polarization}}$$

Full angular analysis

- More observables accessible in a full angular analysis: $B \rightarrow K^* \phi$



$$\frac{d^3\Gamma}{d \cos \theta_1 d \cos \theta_2 d\Phi} \propto \left| \sum_{m=-1,0,1} A_m \times Y_{1,m}(\theta_1, \Phi_1) \times Y_{1,-m}(\theta_2, \Phi_2) \right|^2$$

$$\propto \left\{ \frac{1}{4} \sin^2 \theta_1 \sin^2 \theta_2 (|A_{+1}|^2 + |A_{-1}|^2) + \cos^2 \theta_1 \cos^2 \theta_2 |A_0|^2 \right.$$

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

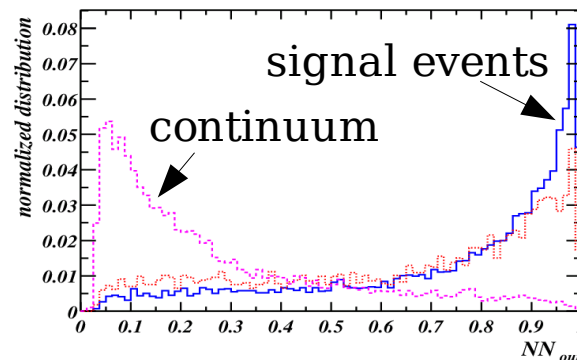
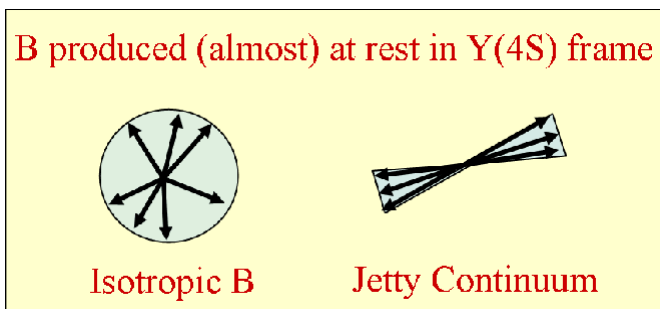
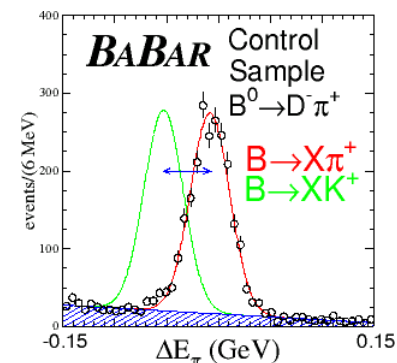
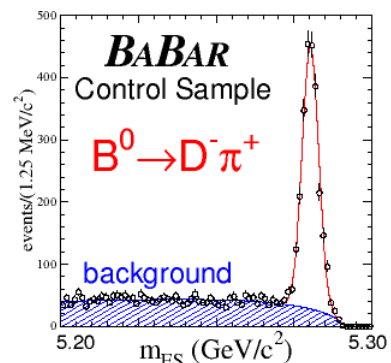
$$\left. + \frac{1}{4} \sin 2\theta_1 \sin 2\theta_2 [\cos \Phi \operatorname{Re}(A_{+1}A_0^* + A_{-1}A_0^*) - \sin \Phi \operatorname{Im}(A_{+1}A_0^* - A_{-1}A_0^*)] \right\}$$

Analysis

- Use of large data samples: **89 to 227 million $B\bar{B}$ pairs** at $\Upsilon(4S)$
- **Candidate reconstruction & selection:**
 - energy & momentum,
 - vertexing,
 - particle identification.
- **Backgrounds** (wide resonances, high f_L , rare decays):
 - mostly: continuum ($q\bar{q}$) decays,
 - also: more challenging: B decays.
- **Discriminating variables:**
 - beam energy substituted B mass:
- **energy difference:**
- **event shape** (neural network or Fisher discriminant):

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

$$\Delta E = E_B^* - E_{beam}^*$$

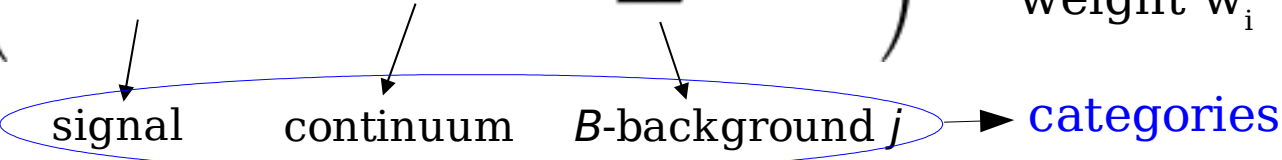


NN_{out} in
 $K^{*0} \rho^+$
analysis

Maximum likelihood method

- Likelihood function:

$$\mathcal{L} = e^{-N'} \prod_{i=1}^N \left(N_S P_{S,i}(f_L) + N_C P_{C,i} + \sum N_j P_{j,i} \right) \times \text{multiplicity weight } w_i$$



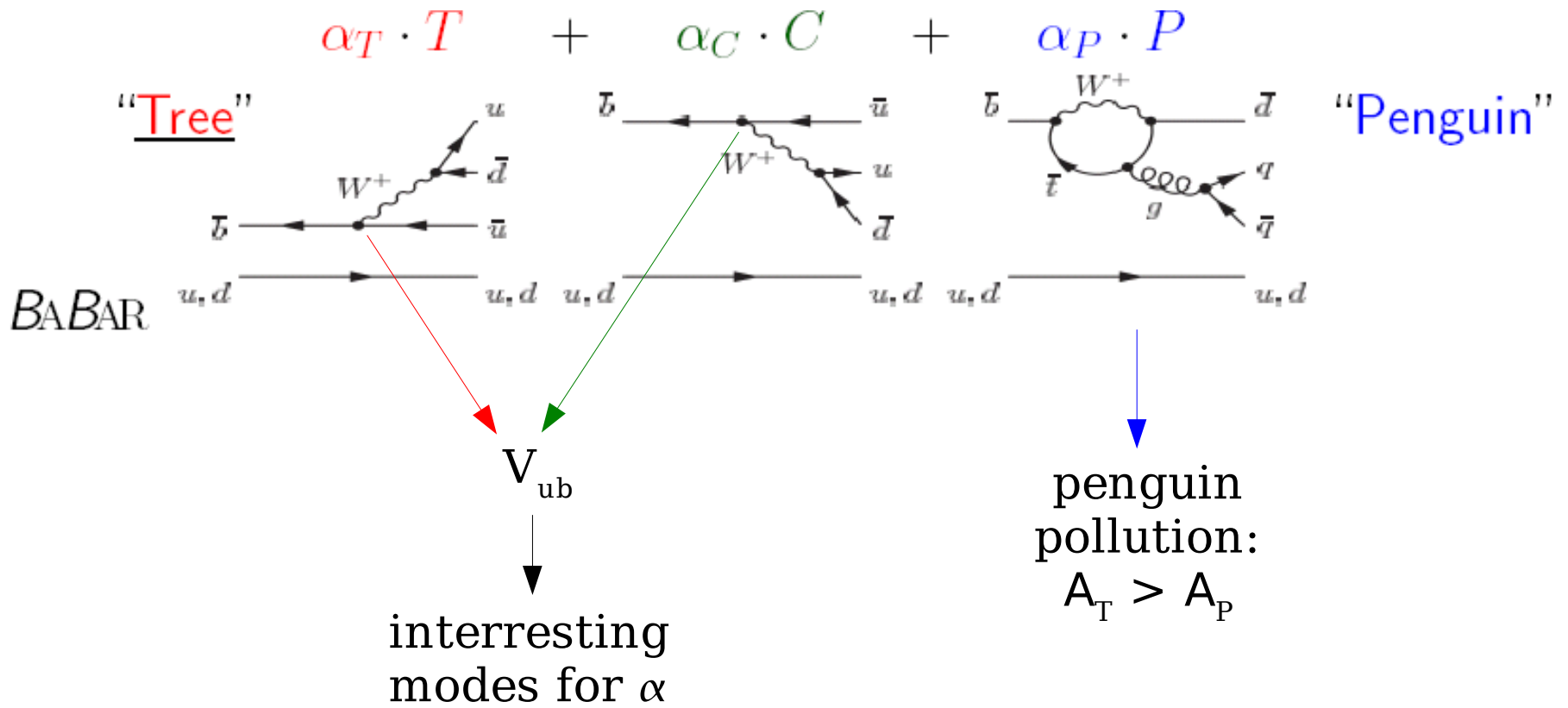
- Variables modeled:

- m_{ES} , ΔE , NN_{out} (or Fisher)
- vector mesons masses: m_{V1} , m_{V2}
- helicities: $\cos \theta_{V1}$, $\cos \theta_{V2}$ (measurement of polarization)
⇒ apply "acceptance correction"
- angle Φ (in full angular analyses)
- B charge / flavour (measurement of asymmetries)

- Measure:

- branching fraction,
- angular observables: polarization f_L , ...
- asymmetries.

Analysis of $\rho\rho$, $\omega\rho$ decays

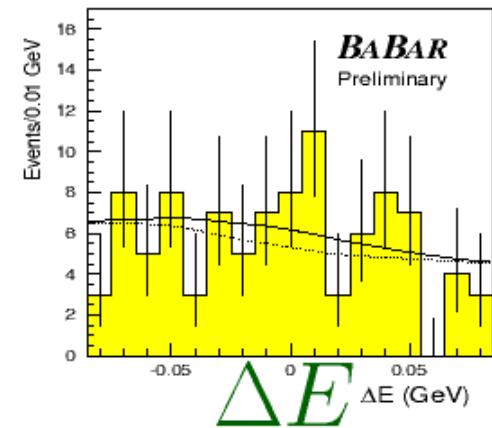
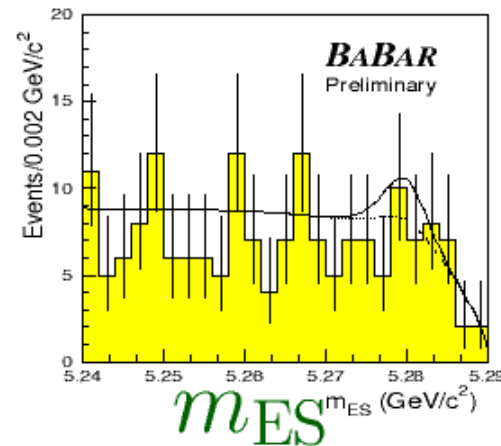


Search for $B \rightarrow \rho^0 \rho^0$ and $B \rightarrow \omega \rho^0$

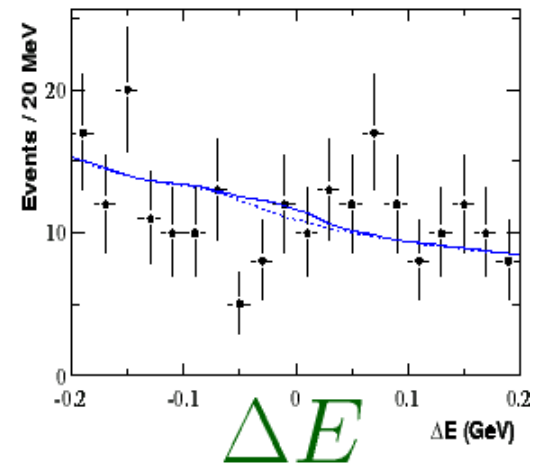
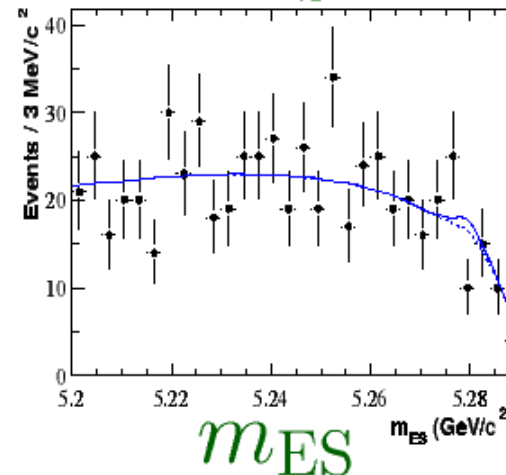
[hep-ph/0408061]

- Now improved $\rho^0 \rho^0$ analysis, sensitivity & statistics

$n_{\text{sig}}(\rho^0 \rho^0)$	33_{-20}^{+22}
UL (90% CL)	$< 1.1 \times 10^{-6}$
$\mathcal{B} (\times 10^{-6})$	$0.54_{-0.32}^{+0.36} \pm 0.19$
$\mathcal{E}ff$	27%
$N_{B\bar{B}}$	227×10^6



$n_{\text{sig}}(\omega \rho^0)$	$4.3_{-9.1}^{+11.0}$
UL (90% CL)	$< 3.3 \times 10^{-6}$
$\mathcal{B} (\times 10^{-6})$	$0.6_{-1.1}^{+1.3} \pm 0.4$
$\mathcal{E}ff$	9.3%
$N_{B\bar{B}}$	89×10^6

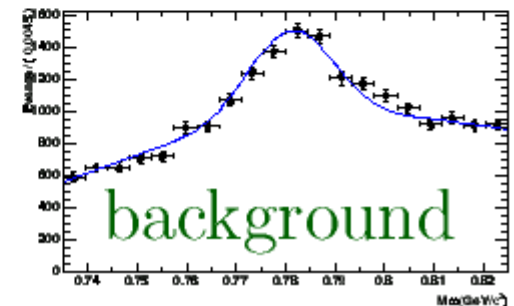
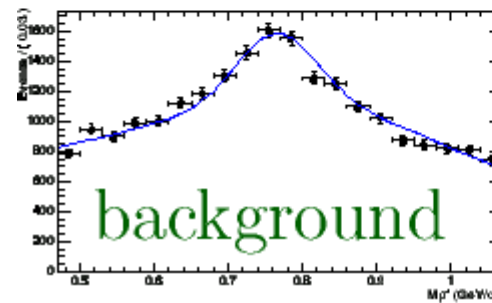
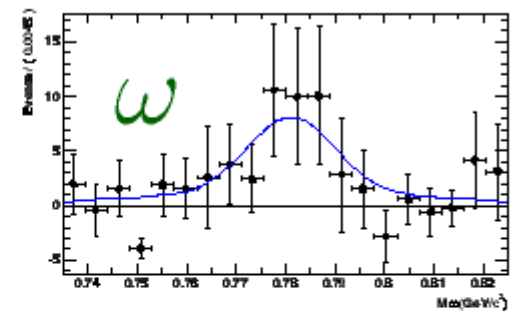
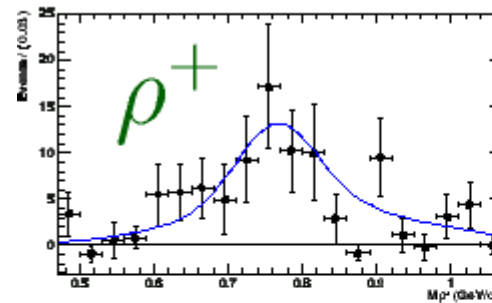
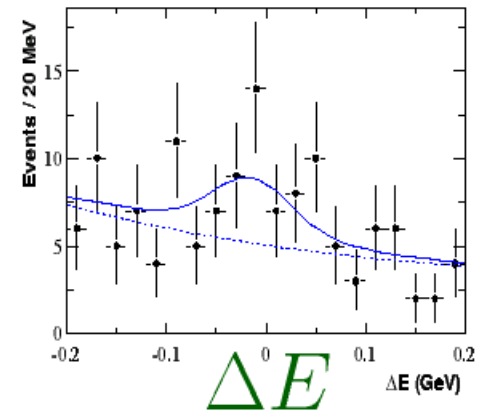
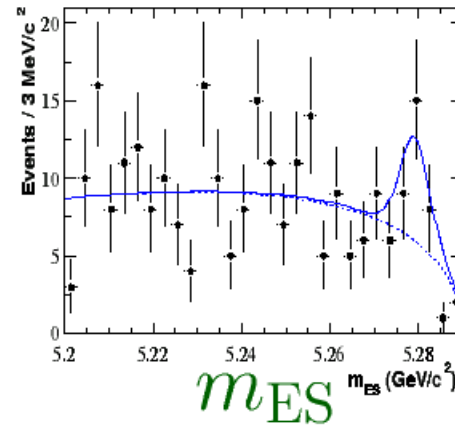


- No evidence of $\rho^0 \rho^0$ and $\omega \rho^0$ decays
 \Rightarrow tight constraints on "penguin pollution"

Observation of $B^+ \rightarrow \omega \rho^+$

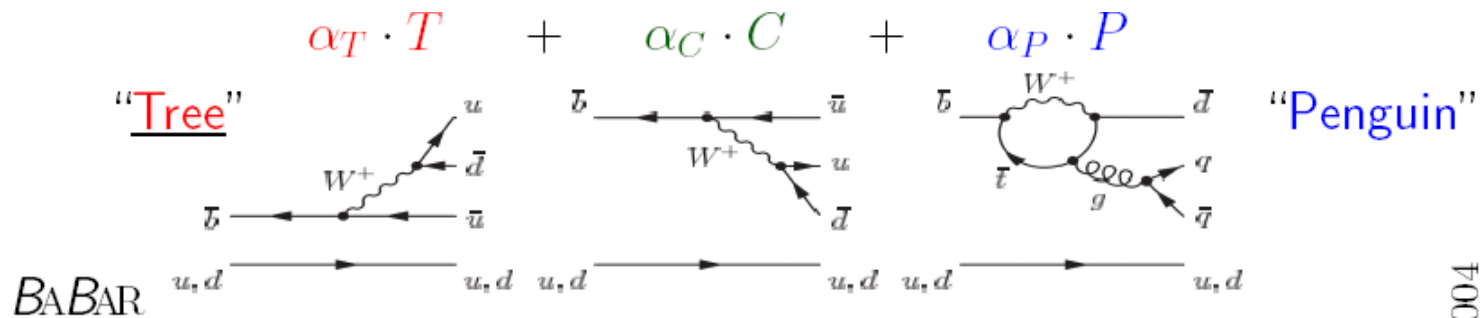
- Measure, with 89 million $B\bar{B}$:

$n_{\text{sig}}(\omega\rho^+)$	$57.7^{+18.5}_{-16.5}$
f_L	$0.88^{+0.12}_{-0.15} \pm 0.03$
signif.	4.7σ
$\mathcal{B}(\times 10^{-6})$	$12.6^{+3.7}_{-3.3} \pm 1.8$
\mathcal{A}_{CP}	$0.05 \pm 0.26 \pm 0.02$
$\mathcal{E}ff$	4.8%
$N_{B\bar{B}}$	89×10^6



- Large BR and f_L in $B^+ \rightarrow \omega\rho^+$ decays
confirms and complements $\rho^+\rho^0$ and $\rho^+\rho$ measurements

Summary of $\rho\rho$, $\omega\rho$, $\phi\phi$ decays

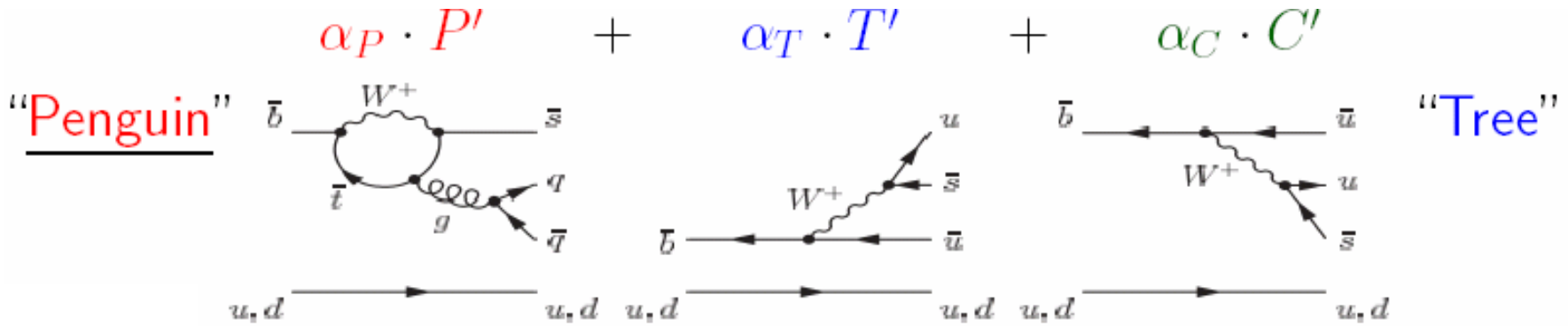


B decay	α_T	α_C	α_P	\mathcal{B} (10^{-6})	f_L	N_{BB} (10^6)
$\rho^- \rho^+$	$\sqrt{2}$	0	$\sqrt{2}$	$30 \pm 4 \pm 5$	$0.99 \pm 0.03^{+0.04}_{-0.03}$	89
$\rho^0 \rho^+$	1	1	0	$23^{+6}_{-5} \pm 6$	$0.97^{+0.03}_{-0.07} \pm 0.04$	89
$\rho^0 \rho^0$	0	1	-1	< 1.1 (90%)	–	227 (new)
$\omega \rho^+$	-1	-1	2	$12.6^{+3.7}_{-3.3} \pm 1.8$	$0.88^{+0.12}_{-0.15} \pm 0.03$	89 (new)
$\omega \rho^0$	0	0	$-\sqrt{2}$	< 3.3 (90%)	–	89 (new)
$\phi\phi$	0	0	0	< 1.5 (90%)	–	89 (new)

(new) = Preliminary Summer 2004

- large $\rho^+\rho$, $\rho^+\rho^0$, $\omega\rho^+$ BR (compared to related $B \rightarrow PP$ decays)
- small $\rho^0\rho^0$, $\omega\rho^0$ BR \Rightarrow small penguin
- longitudinal polarization dominates (as expected)
 - $\Rightarrow \rho^+\rho$ is almost pure CP -even, interesting modes for measuring α

Analysis of $K^*\phi$, $K^*\rho$, $K^*\omega$ decays



"pure" penguin
 modes:
 $B \rightarrow K^*\phi$,
 $B^+ \rightarrow K^{*0}\rho^+$

Particular interest:
 f_L measurement

CKM suppressed,
 $A_T \sim A_P$

Observation of $B^+ \rightarrow K^{*0} \rho^+$ (1)

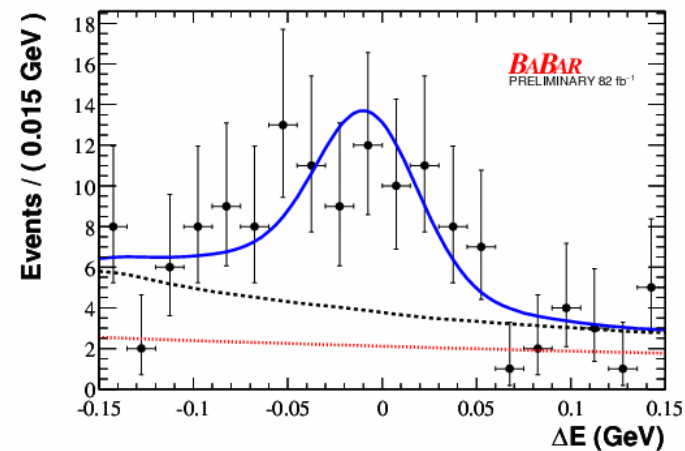
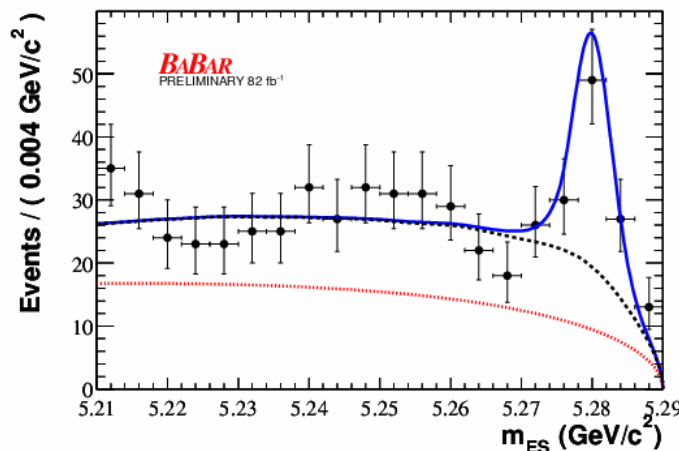
[hep-ph/0408093]

- $B \rightarrow K^{*0} \rho^+$ is a "pure" penguin mode like $K^* \phi$
 \Rightarrow polarization of special interest

- Analysis of 89 million $B\bar{B}$:
 - signal observed at $>5\sigma$
 - dominant systematics:
 - π^0 & tracks reconstruction
 - PDF shapes
 - non-resonant contribution

$n_{\text{sig}}(\rho^+ K^{*0})$	$141.0^{+23.4}_{-22.3}$
f_L	$0.79 \pm 0.08 \pm 0.04 \pm 0.02$
signif.	$>5\sigma$
$\mathcal{B}(\times 10^{-6})$	$17.0 \pm 2.9 \pm 2.0^{+0.0}_{-1.9}$
A_{CP}	$-0.14 \pm 0.17 \pm 0.04$
$\mathcal{E}ff$	9.4%
$N_{B\bar{B}}$	89×10^6

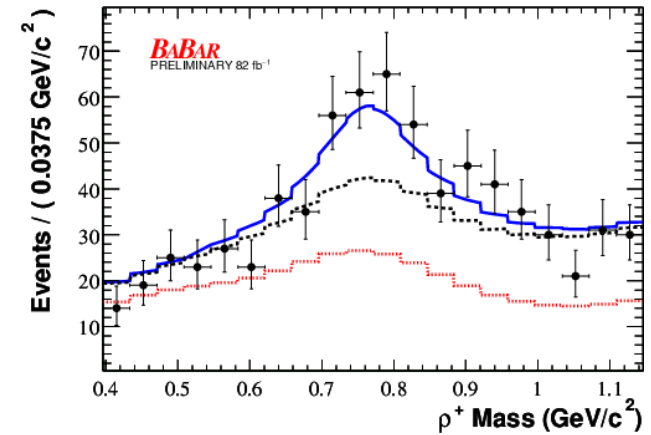
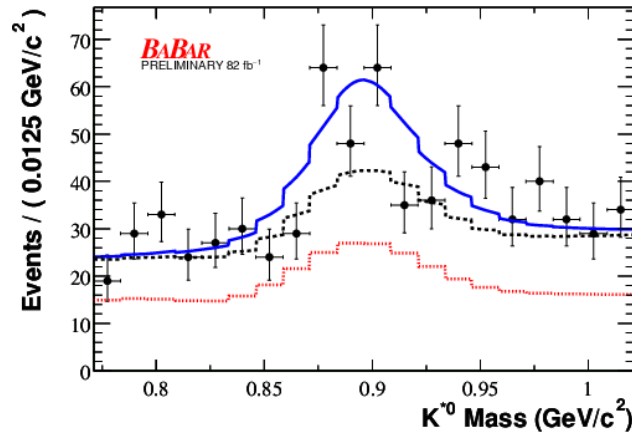
- Signal enriched distributions (cut on $L_{\text{sig}}/L_{\text{bkg}}$ using non-projected variables) + project likelihood function obtained in the data fit



Observation of $B^+ \rightarrow K^{*0} \rho^+$ (2)

Enrichment cut on :

$$\frac{L_{\text{sig}}(\Delta E, m_{\text{ES}}, x_{\text{NN}})}{L_{\text{bkg}}(\Delta E, m_{\text{ES}}, x_{\text{NN}})}$$

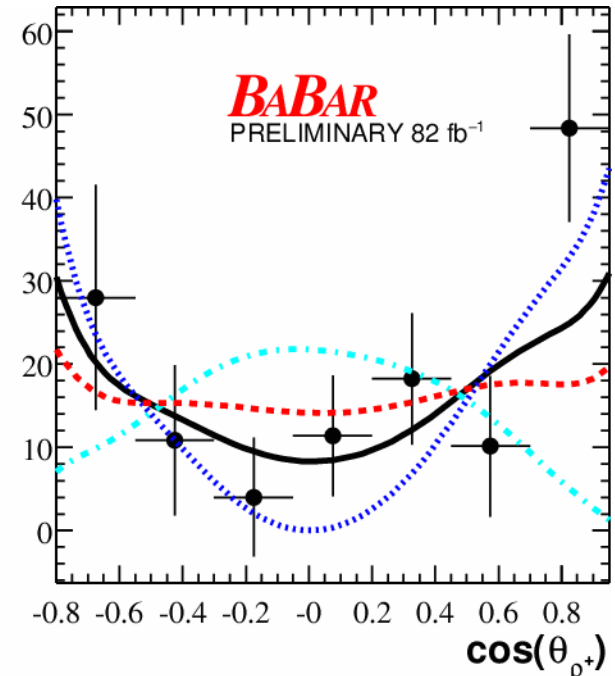
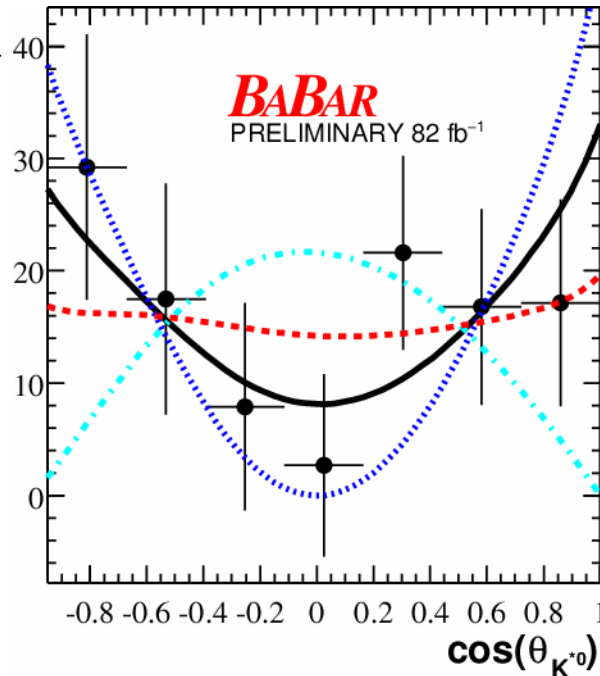


100 % longitudinal

79 % long. (data)

50 % longitudinal

100 % transverse



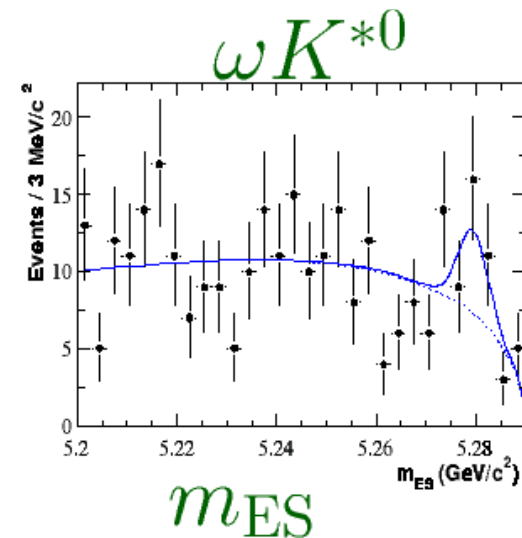
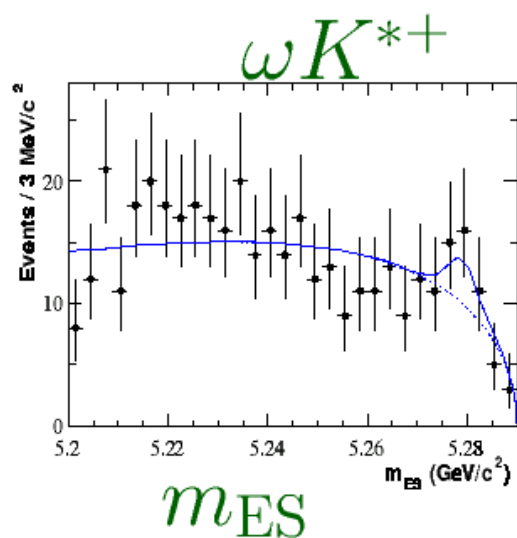
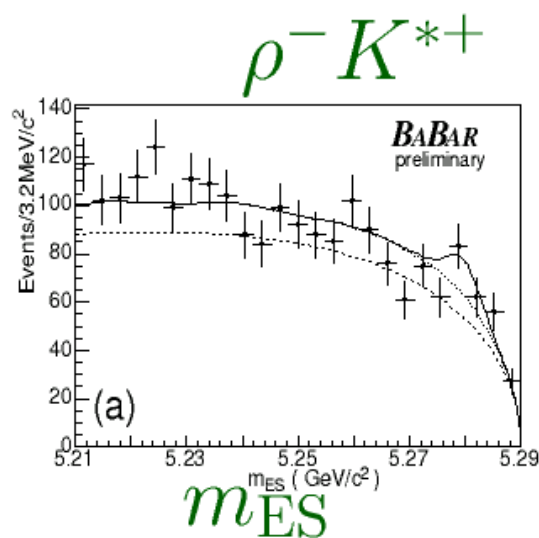
We measure: $f_L = 0.79 \pm 0.08$ (stat) ± 0.04 (syst) ± 0.02 (non-res)

Search for $B^+ \rightarrow K^{*+} \rho$, $B \rightarrow K^{*+} \omega$, $B \rightarrow K^{*0} \omega$

[hep-ph/0408063]

- Setting interesting limits; some signal emerges:

B decay	$\rho^- K^{*+}_{K+\pi^0}$	$\omega K^{*+}_{K+\pi^0 \text{ \& } K^0\pi^+}$	ωK^{*0}
n_{sig}	58 ± 19	$5.4^{+6.0}_{-4.2}$ & $11.6^{+8.7}_{-7.2}$	$26.1^{+12.1}_{-10.8}$
UL (90% CL)	$< 24 \times 10^{-6}$	$< 7.4 \times 10^{-6}$	$< 6.1 \times 10^{-6}$
$\mathcal{B}(\times 10^{-6})$	$16.3 \pm 5.4 \pm 2.3^{+0.0}_{-6.3}$	$3.5^{+2.5}_{-2.0} \pm 0.7$	$3.4^{+1.7}_{-1.6} \pm 0.4$
$\mathcal{E}ff$	2.9%	4.7%	7.8%
UL with $f_L =$	0.7	0.9	0.9
$N_{B\bar{B}}$	123×10^6	89×10^6	89×10^6

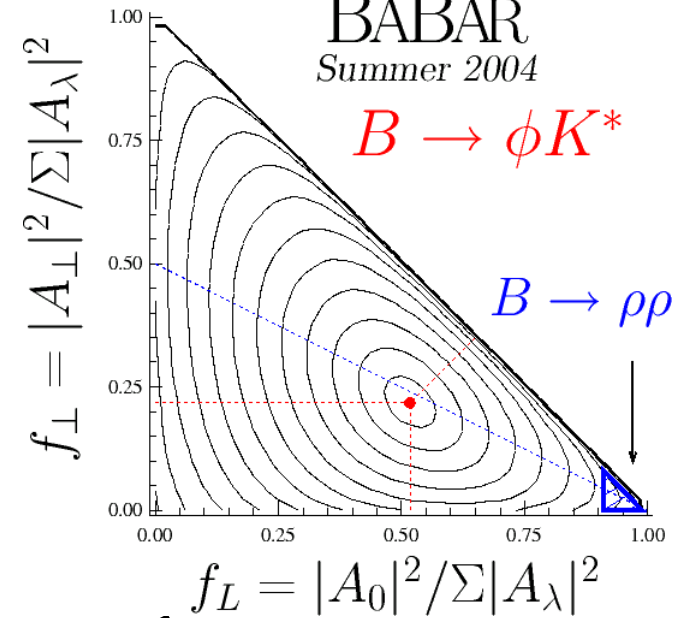


New results for $B^0 \rightarrow K^{*0} \phi$

[hep-ph/04080617]

BABAR
Summer 2004

$B \rightarrow \phi K^*$



$B \rightarrow \rho\rho$

• Results with a sample of 227 million $B\bar{B}$:

Fit parameter	Fit result
n_{sig} (events)	$201 \pm 20 \pm 6$
f_L	$0.52 \pm 0.05 \pm 0.02$
f_{\perp}	$0.22 \pm 0.05 \pm 0.02$
ϕ_{\parallel} (rad)	$2.34^{+0.23}_{-0.20} \pm 0.05$
ϕ_{\perp} (rad)	$2.47 \pm 0.25 \pm 0.05$
\mathcal{A}_{CP}	$-0.01 \pm 0.09 \pm 0.02$
\mathcal{A}_{CP}^0	$-0.06 \pm 0.10 \pm 0.01$
\mathcal{A}_{CP}^{\perp}	$-0.10 \pm 0.24 \pm 0.05$
$\Delta\phi_{\parallel}$ (rad)	$0.27^{+0.20}_{-0.23} \pm 0.05$
$\Delta\phi_{\perp}$ (rad)	$0.36 \pm 0.25 \pm 0.05$
ϵ (%)	9.7 ± 0.5
\mathcal{B}	$(9.2 \pm 0.9 \pm 0.5) \times 10^{-6}$
$\mathcal{A}_T^{\parallel}$	$-0.02 \pm 0.04 \pm 0.01$
\mathcal{A}_T^0	$+0.11 \pm 0.05 \pm 0.01$

stat. significance
 $> 10\sigma$

confirm
low f_L

observe FSI
 $> 3\sigma$

no evidence of \mathcal{CP}

(expected negligible
if only 1 diagramme)

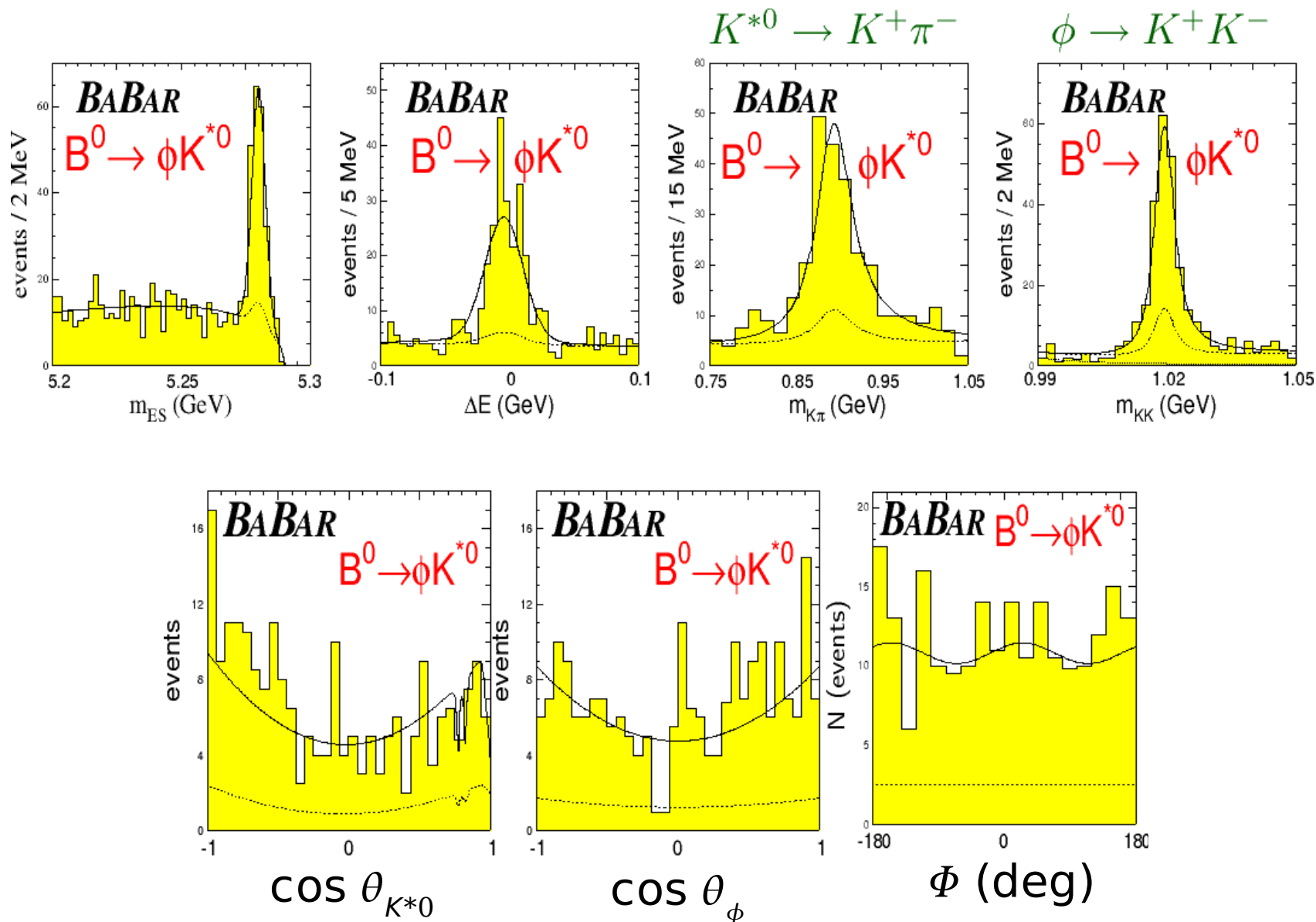
weak phase difference (B^0/\bar{B}^0 decays)

Triple-product asymmetries (\mathcal{A}_T)

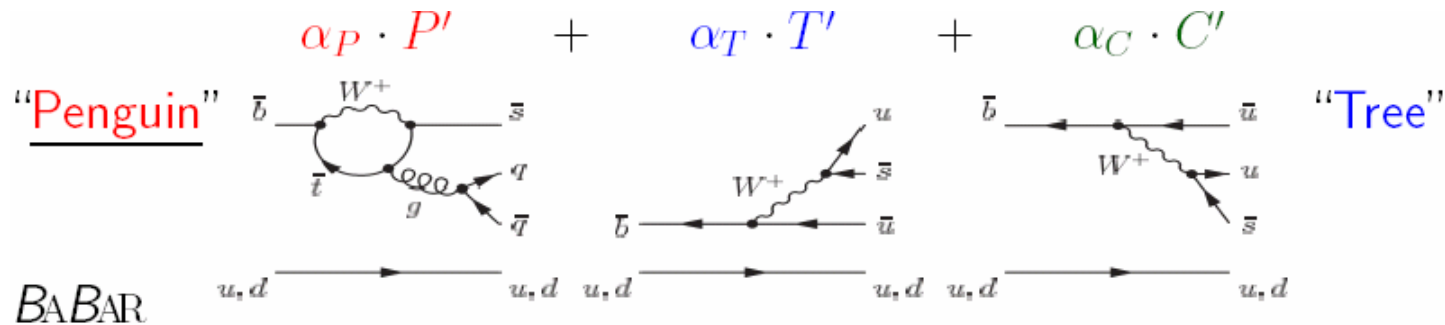
$\mathcal{A}_T^0 \sim 0.15$ with NP [Datta/London]

$$\mathcal{A}_T^{\parallel,0} = \frac{1}{2} \left(\frac{\text{Im}(A_{\perp}^+ A_{\parallel,0}^{+*})}{\sum |A_m^+|^2} + \frac{\text{Im}(A_{\perp}^- A_{\parallel,0}^{-*})}{\sum |A_m^-|^2} \right)$$

Projections in $B^0 \rightarrow K^{*0} \phi$ analysis



Analysis of $K^*\phi$, $K^*\rho$, $K^*\omega$ decays



B decay	α_P	α_T	α_C	$\mathcal{B}(10^{-6})$	f_L	$N_{BB}(10^6)$
ϕK^{*0}	$\sqrt{2}$	0	0	$9.2 \pm 0.9 \pm 0.5$	$0.52 \pm 0.05 \pm 0.02$	227 (new)
ϕK^{*+}	$\sqrt{2}$	0	0	$12.7^{+2.2}_{-2.0} \pm 1.1$	$0.46 \pm 0.12 \pm 0.03$	89
$\rho^0 K^{*0}$	1	0	-1	—	—	—
$\rho^0 K^{*+}$	-1	-1	-1	$10.6^{+3.0}_{-2.6} \pm 2.4$	$0.96^{+0.04}_{-0.15} \pm 0.04$	89
$\rho^- K^{*0}$	$\sqrt{2}$	0	0	$17.0 \pm 2.9 \pm 2.0^{+0.0}_{-1.9}$	$0.79 \pm 0.08 \pm 0.04 \pm 0.02$	89 (new)
$\rho^- K^{*+}$	$-\sqrt{2}$	$-\sqrt{2}$	0	< 24 (90%)	—	123 (new)
ωK^{*0}	1	0	1	< 6.1 (90%)	—	89 (new)
ωK^{*+}	1	1	1	< 7.4 (90%)	—	89 (new)

(new) = Preliminary Summer 2004

- **polarization puzzle in $B \rightarrow K^*\phi$ decays** ($f_L \sim 0.5$)
- $B \rightarrow K^*\rho$ decays need further studies:
 - BABAR+Belle [hep-ph/0408102]: $f_L < 1$ likely in $K^{*0}\rho^+$
- searches for $K^{*+}\rho^-$ and $K^*\omega$ decays

Non resonant contributions (decays such as $B \rightarrow K^*\pi\pi$)

Conclusion

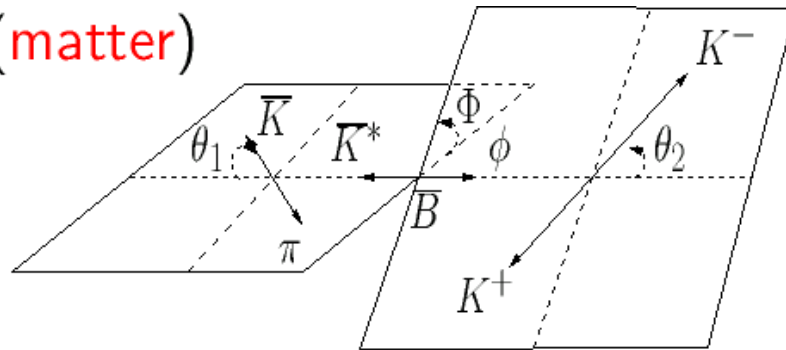
- ♦ **Study of $B \rightarrow VV$ at BABAR:**
 - ♦ modes with a large physics potential,
 - ♦ polarization anomaly in $B \rightarrow K^* \phi$ decays remains (since 2002),
 - ♦ important progress in $K^{*0} \phi$ analysis:
 - ♦ 6 amplitudes, 4 phases (10 measurements),
 - ♦ derived CP and triple-product asymmetries,
 - ♦ evidence of $B \rightarrow VT$ decay: $B^0 \rightarrow \phi K_2^{*0}(1430)$.
 - ♦ more $B \rightarrow VV$ modes have been studied:
 - ♦ challenging analyses,
 - ♦ many observables:
 - ♦ available information only partially exploited,
 - ♦ more measurements in progress,
 - ♦ errors will improve:
 - ♦ dominating statistical errors,
 - ♦ better understanding of systematic effects.

⇒ stay tuned to future progresses!

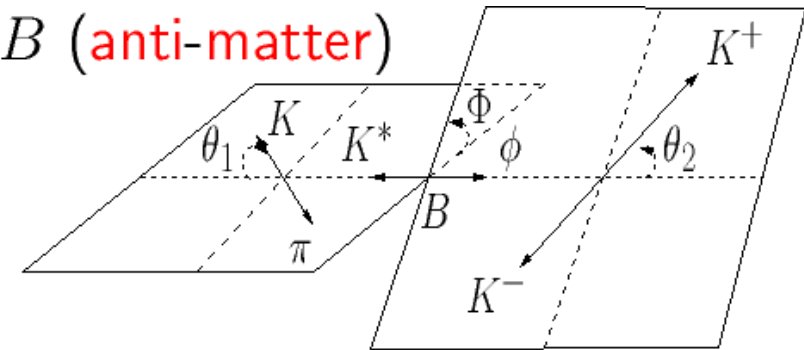
BACKUP TRANSPARENCIES

CP asymmetries in $B \rightarrow WW$

\bar{B} (matter)



B (anti-matter)



- Direct asymmetries (rate):

$$\propto \sin \Delta \delta_{EW} \sin \Delta \delta_{strong}$$

$$|A_0|^2 \neq |\bar{A}_0|^2$$

$$|A_{\parallel}|^2 \neq |\bar{A}_{\parallel}|^2$$

$$|A_{\perp}|^2 \neq |\bar{A}_{\perp}|^2$$

$$A_{\parallel} = \frac{A_{+1} + A_{-1}}{\sqrt{2}}$$

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

- “Triple-product” asymm.

G. Valencia, Phys. Rev. D **39**, 3339 (1989)

A. Datta, D. London, Int. J. Mod. Phys. A **19**, 2505 (2004)

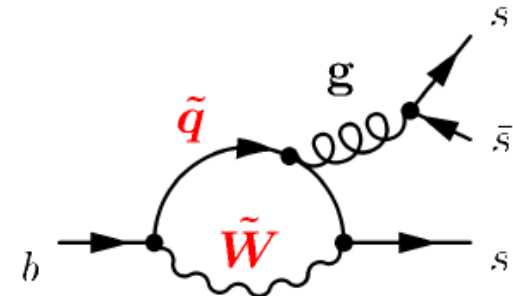
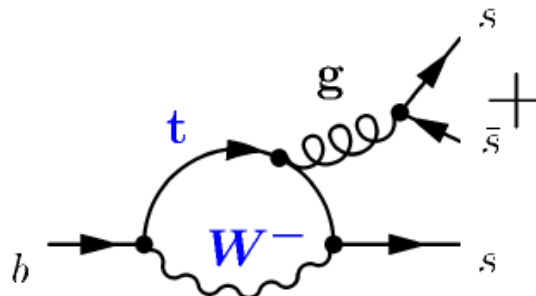
$$\propto \sin \Delta \delta_{EW} \cos \Delta \delta_{strong}$$

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

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

$$\Delta \delta_{EW} \neq 0$$

\Leftrightarrow



Observation of $B \rightarrow \phi K_j^{*0}(1430)$

- Observe 181 ± 17 events of $B \rightarrow \phi K_j^{*0}(1430)$ ($>10\sigma$)
- **Tensor** ($J=2$) or **Scalar** ($J=0$)
 - mass and angles \Rightarrow not pure Tensor $\phi K_0^{*0}(1430)$ ($>10\sigma$)
 - angular distribution evidence for $\phi K_2^{*0}(1430)$ ($>3\sigma$)
- Polarization **longitudinal** (ϕ helicity)
 - obvious for $B \rightarrow VS$
 - if holds for $B \rightarrow VT$ would reject many $B \rightarrow VV$ models

