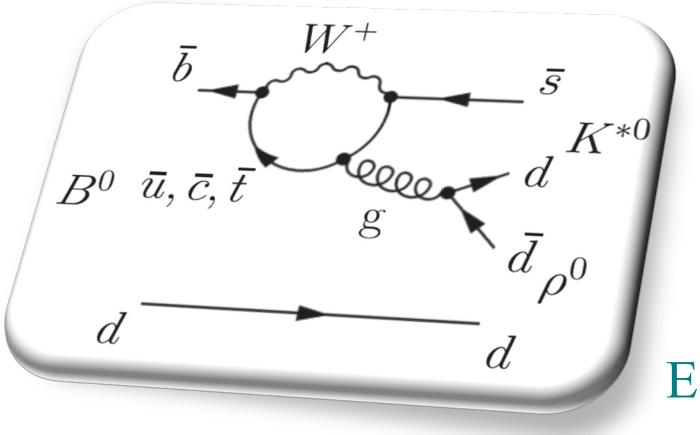
ICHEP 2012
July 4-11, Melbourne, Australia

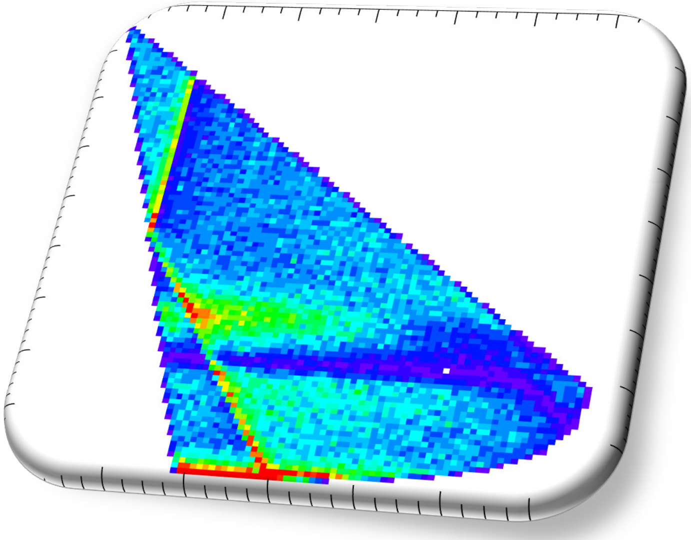
Charmless B decays and CP violation at *BABAR*

Branching fractions, CP asymmetries and polarizations in

$B^0 \rightarrow \rho^0 K^{*0}$, $f_0 K^{*0}$, $\rho^- K^{*+}$

Amplitude analyses and CP violation in B → 3K modes





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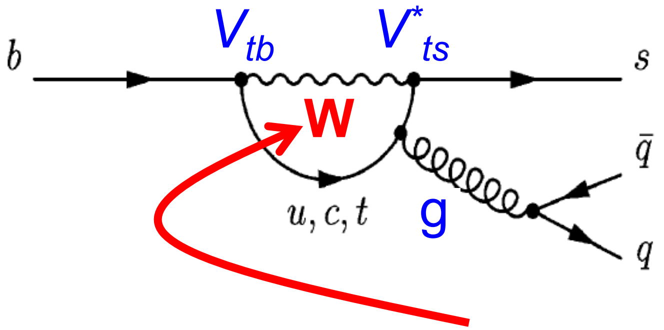
On behalf of the ***BABAR*** collaboration

General introduction

- All the decays presented here are **$b\to q\bar{q}s$ transitions**
- Standard Model (SM): their leading decay amplitude is



$\Rightarrow$ **CP violation (CPV) only by CKM phase**

same as in $b\to c\bar{c}s$ transitions

direct CPV ~ 0, mixing induced CPV ~ sin 2β

- New physics (NP): another virtual particle in the loop (?)
- This can result, e.g., in:
  - **New CP violating phases (?)**

    $\Rightarrow$ **observable through CP asymmetries ($\neq c\bar{c}s$ modes)**
  - Enhanced branching fractions wrt SM expectations
  - Altered polarizations in final state (e.g. in B →VV decays)

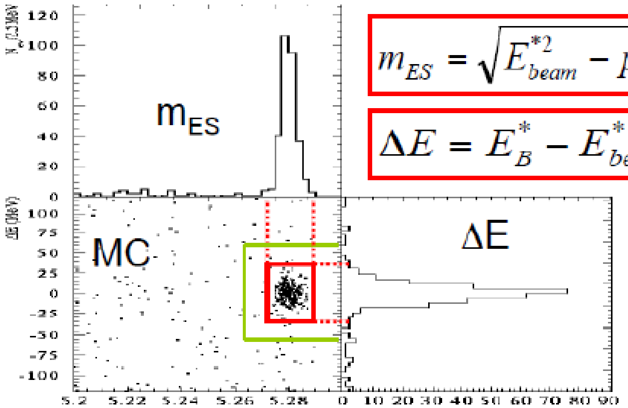
All these observables: probes for new physics!

- But… we observe hadrons and not quarks ⇒ QCD predictions play a crucial role

precise theoretical prediction + precise measurement = powerful test of the SM

Common analysis techniques

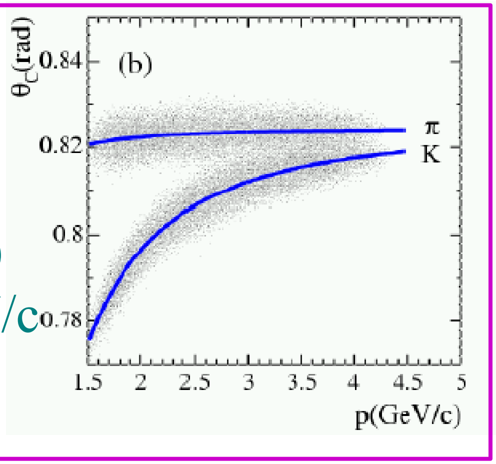
Kinematics of fully reconstructed B



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

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

Good charged particle ID (in particular K/π) up to few GeV/c



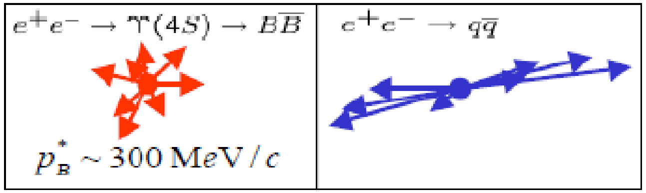
Background characterization:

→ Mainly continuum: $e^+e^- \rightarrow q\bar{q}$ (q = u,d,s,c).

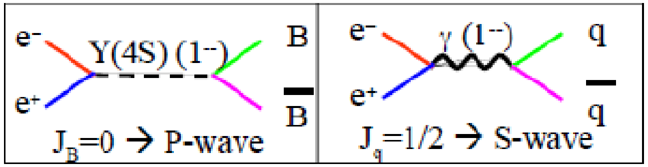
Suppression by multi-variable classifiers based on event-shape variables:

Fisher discriminant, Neural Networks (NN)…

Topology:



Angular distribution:



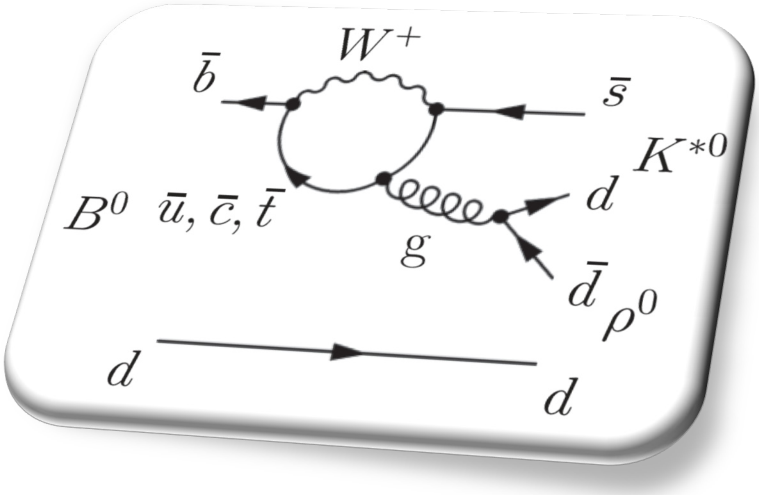
→ Background from B decays: classified by kinematic and topological properties

Variables are often combined to a likelihood function, used in a maximum likelihood fit for signal/background separation and to measure parameters of interest

Branching fractions, CP asymmetries and polarizations in $B^0 \rightarrow \rho^0 K^{*0}$, $f_0 K^{*0}$ and $\rho^- K^{*+}$ decays

Different K^{*0} states: $K^*(892)$, $(K\pi)^*_0$ s-wave, $K^*_2(1430)^0$

arXiv:1112.3896 [hep-ex], Phys.Rev.D85:072005, 2012.



full BaBar dataset
(467M $B\bar{B}$ pairs)
twice the previous analysis

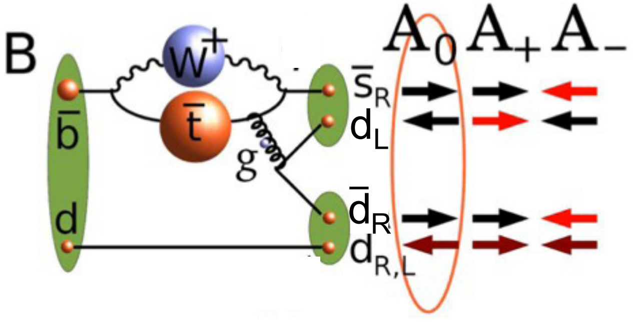
Introduction

- "Polarization puzzle" for B → VV modes

  Naïve expectation from helicity arguments: longitudinal polarization fraction (f_L) ~ 1

  $B \to \rho\rho$ has $f_L > 0.9$

  but other $b \to s$ penguin VV states have $f_L \sim 0.5$



$$|A_{00}|^2 \gg |A_{++}|^2 \gg |A_{--}|^2$$

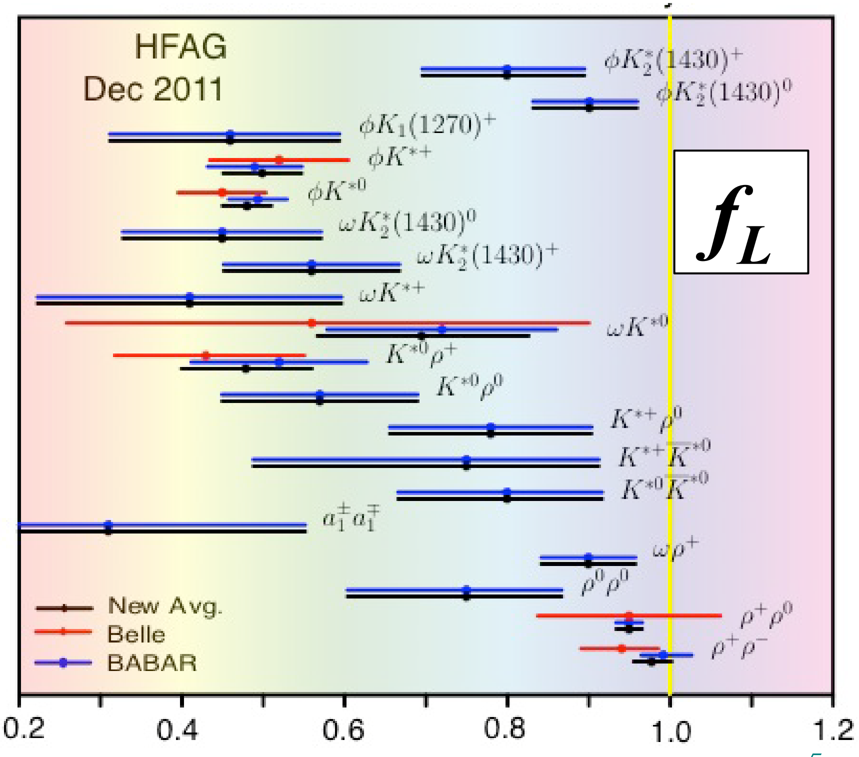
- (partially integrated) decay rate ∝

$$\frac{1-f_L}{4}\sin^2\theta_{K^*}\sin^2\theta_\rho + f_L\cos^2\theta_{K^*}\cos^2\theta_\rho$$

helicity angles in the K*/ρ decay planes

⇒ angles give access to f_L (in VV channels)

- The modes $f_0/\rho^0\,(K\pi)^*_0$ and $f_0K^*_2(1430)^0$ are studied for the first time
- QCDF predicts BF, f_L, and A_{CP} for $B \to \rho K^*$



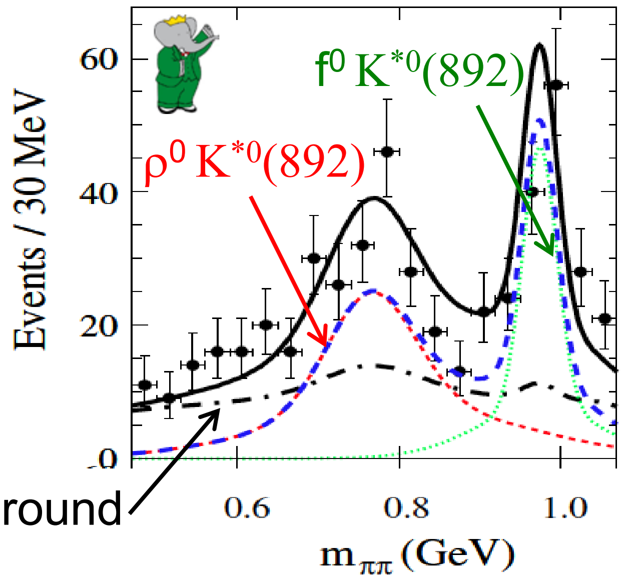
Analysis

$B^0 \to \rho^0/f_0 K^{*0}$ and $\rho^- K^{*+}$

- Reconstruction: $\rho^{0(-)} \to \pi^{+(0)} \pi^-$ and $f_0(980) \to \pi^+ \pi^-$; $K^{*0(+)} \to K^+ \pi^{-(0)}$
- Maximum likelihood fit with 7 variables: m_{ES}, ΔE, Fisher, $m_{\pi\pi}$, $m_{K\pi}$, $\underbrace{\cos\theta_\rho, \cos\theta_{K*}}_{\text{VV modes only}}$
- $m_{K\pi}$ in 2 regions:
  - Low Mass Region [0.75, 1.0], contains $K^*(892)$
  - High Mass Region [1.0, 1.55], contains $(K\pi)^*_0$, $K^*_2(1430)^0$

LMR

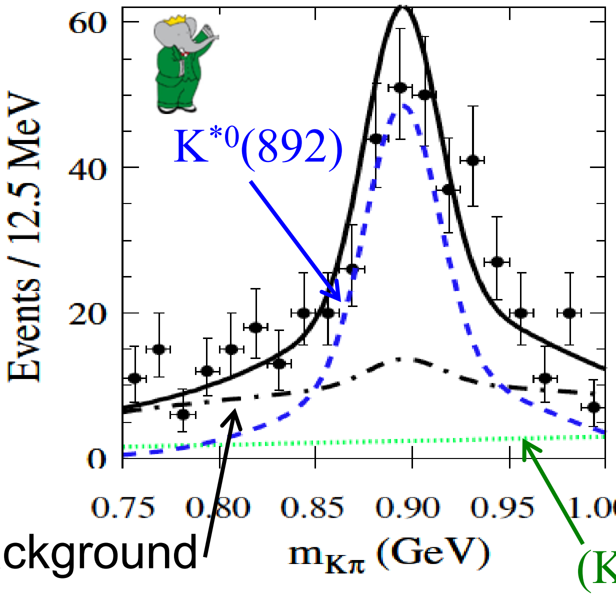
$f^0/\rho^0\, K^{*0}(892)$



$f^0\, K^{*0}(892)$

$\rho^0\, K^{*0}(892)$

background



$K^{*0}(892)$

background

$(K\pi)^*_0$

Analysis

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  - Low Mass Region [0.75, 1.0], contains $K^*(892)$
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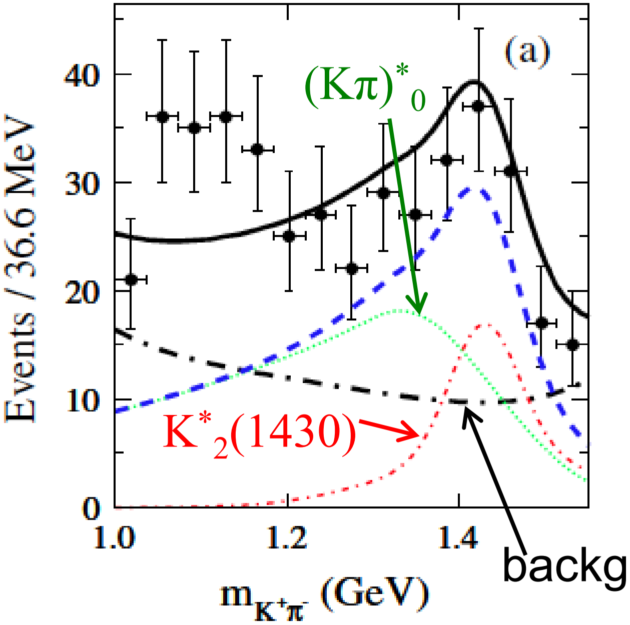
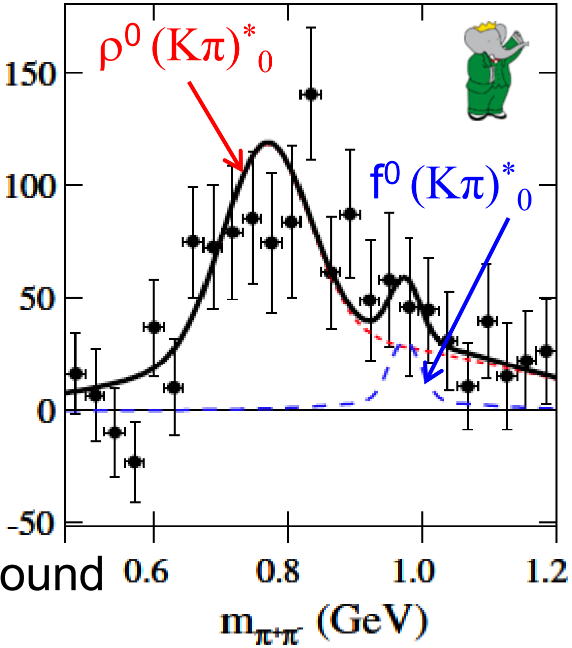
HMR

$f^0/\rho^0\,(K\pi)^*_0$

Two stage fit in HMR: extract **sWeights** for $(K\pi)^*_0$ and $K^*_2(1430)$ then fit $m_{\pi\pi}$ to ρ, f_0





Results

$B^0 \to \rho^0/f_0K^{*0}$ and ρ^-K^{*+}

Mode	Y (events)	S (σ)	$\mathcal{B}$ (10^{-6})	U.L. (10^{-6})	f_L	$\mathcal{A}_{\rm ch}$
$\rho^0K^*(892)^0$	376 ± 37	6.0	$5.1 \pm 0.6^{+0.6}_{-0.8}$	···	$0.40 \pm 0.08 \pm 0.11$	$-0.06 \pm 0.09 \pm 0.02$
$\rho^0(K\pi)^{*0}_0$	$1045 \pm 36 \pm 118$	6.3	$31 \pm 4 \pm 3$	★ ···	···	···
$f_0K^*(892)^0$	220 ± 23	9.8	$5.7 \pm 0.6 \pm 0.4$	★ ···	···	$+0.07 \pm 0.10 \pm 0.02$
$f_0(K\pi)^{*0}_0$	$88 \pm 19 \pm 10$	3.0	$3.1 \pm 0.8 \pm 0.7$	★ ···	···	···
$f_0K^*_2(1430)^0$	$134 \pm 14 \pm 23$	4.3	$8.6 \pm 1.7 \pm 1.0$	★ ···	···	···
$\rho^-K^*(892)^+$	167 ± 27	5.1	$10.3 \pm 2.3 \pm 1.3$	★ ···	$0.38 \pm 0.13 \pm 0.03$	$+0.21 \pm 0.15 \pm 0.02$
$\rho^-(K\pi)^{*+}_0$	221 ± 74	2.8	$32 \pm 10 \pm 6$	<48	···	···

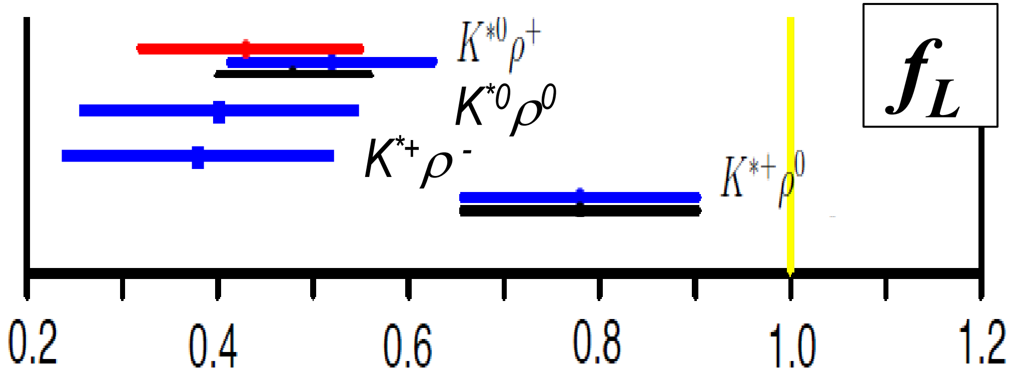
★ 1st observation

★ 1st evidence

consistent with 0.5 and with other penguin modes

(wrt final state $K^{\pm}$) consistent with 0

- Need more data to check consistence of f_L hierarchy with QCDF prediction
- BR of modes with $(K\pi)^*_0$ allow to favor predictions from QCDF over pQCD.



B → 3K modes

- $B^0 \rightarrow K_S K_S K_S$

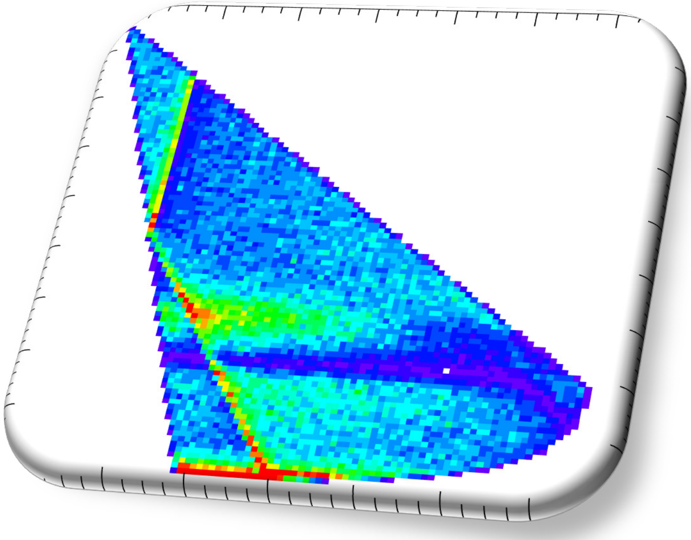
  Amplitude analysis and time dependent CP asymmetry

  arXiv:1111.3636 [hep-ex], Phys.Rev.D85:054023 (2012)

- $B^0 \rightarrow K^+K^-K_S$, $B^+ \rightarrow K^+K^-K^+$ and $B^+ \rightarrow K_S K_S K^+$

  Amplitude analysis and study of CP violation

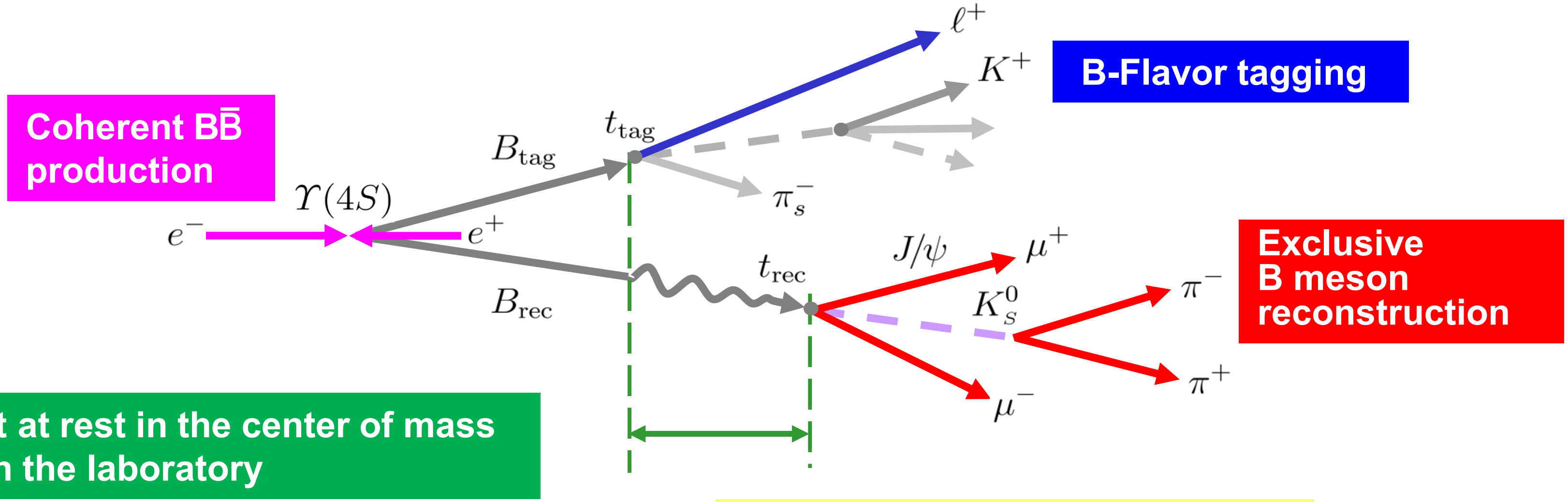
  arXiv:1201.5897 [hep-ex], Phys.Rev.D85:112010 (2012)



full BaBar dataset (467M $B\bar{B}$ pairs)

Time dependent measurements, flavor tagging

Used in $\mathbf{B^0} \rightarrow K_S K_S K_S$ and $\mathbf{B^0} \rightarrow K^+ K^- K_S$



Coherent $B\bar{B}$ production

B-Flavor tagging

Exclusive B meson reconstruction

$B\bar{B}$ Almost at rest in the center of mass
Boosted in the laboratory

$\beta\gamma \sim 0.56$
$\Delta t \sim \tau_B \approx 1.5\text{ps} \Leftrightarrow \Delta z \sim 250\mu\text{m}$

$$\Delta t \equiv t_{rec} - t_{tag} \approx \Delta z / \beta\gamma c$$

Dalitz plot and the isobar model

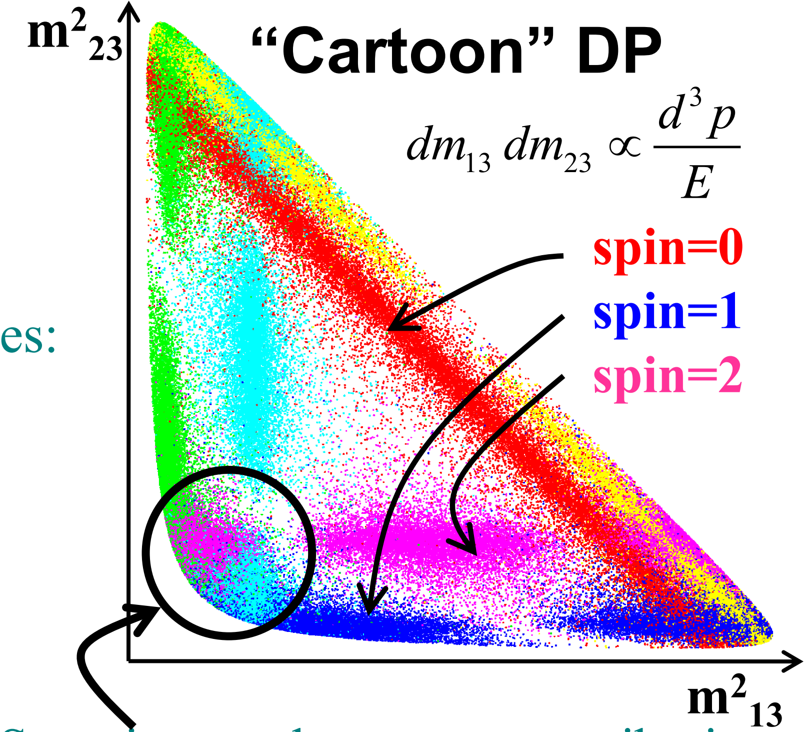
- Each intermediate resonance in P → 1 2 3 appears as a structure in the DP according to its mass, width and spin

- Parameterization of intermediate state amplitudes:

- $A \sim \Sigma\, c_i\, \mathbf{F}(m^2_{13},m^2_{23})$ B decays
  $\bar{A} \sim \Sigma\, \bar{c}_i\, \mathbf{F}(m^2_{13},m^2_{23})$ $\bar{\text{B}}$ decays

complex e.g. Breit-Wigner

Directly extracted parameters:
isobar amplitudes c_i
Other parameters (S, C, A_{CP}, phases, Branching Fractions) are computed from them



$$dm_{13}\, dm_{23} \propto \frac{d^3p}{E}$$

Superimposed resonant contributions
→ Interference
→ access to phases
with no ambiguity such as $\sin 2\beta_{\text{eff}} = \sin(180° - 2\beta_{\text{eff}})$

Complexity of analyses varies: mode, time/ tag dependence…

$B^0 \to K_S K_S K_S$ overview and motivations

- Small theoretical uncertainty ⇒ Comparison with $b \to c\bar{c}s$ is more meaningful
- Low background level (difficult to “imitate” 3 K^0_S)

Inclusive time dependent analysis
to extract CP asymmetries S and C
$B^0 \to 3K^0_S(\pi^+\pi^-)$
$B^0 \to 2K^0_S(\pi^+\pi^-)\ K^0_S(\pi^0\pi^0)$

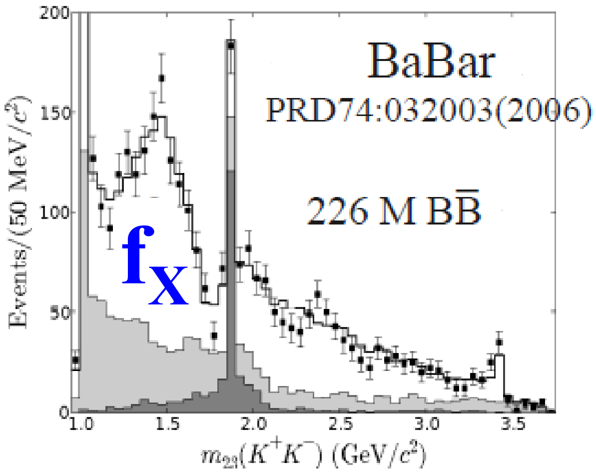
Dalitz plot analysis
(time integrated, tag averaged)
to extract intermediate-states composition
$B^0 \to 3K^0_S(\pi^+\pi^-)$

CP=+1 eigenstate ⇒ possible

!

first time ever

Simplest
Only ~200 sig. events **!!!**



3 identical bosons
Symmetrized amplitude
even-spin resonances only (**f_X(1500) ???**)

↑
Broad structure seen in past analyses, not confirmed

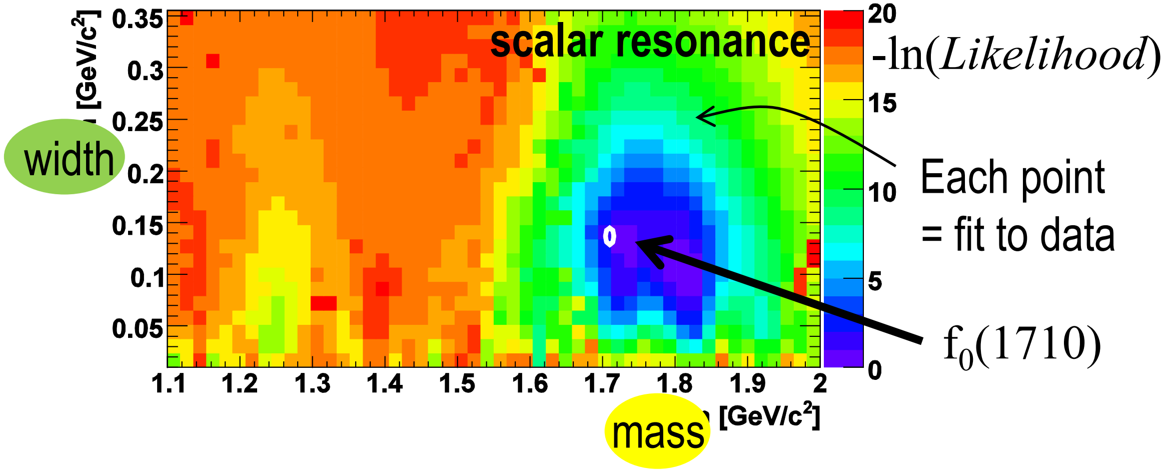
$B^0 \to K_S K_S K_S$

Determining the signal model

Start from a “baseline” model inspired from $K^+K^-K_S$ ($f_0(980)$, χ_{C0}, exponential nonresonant)

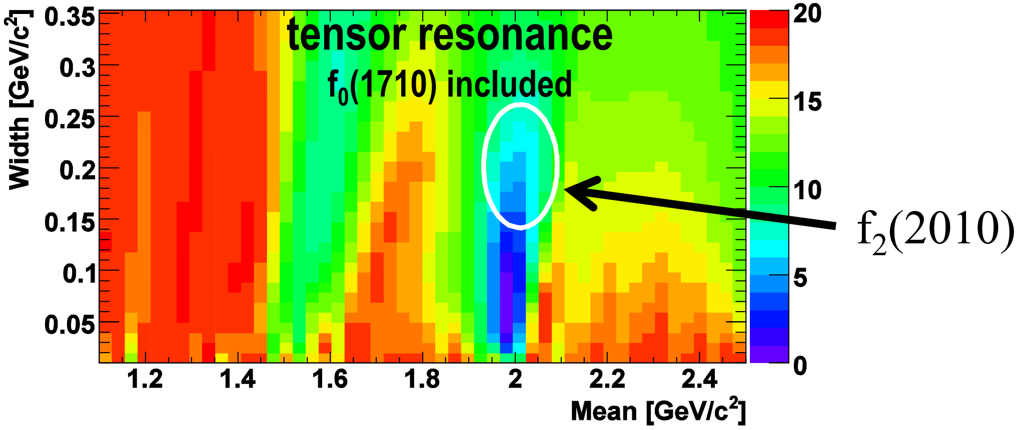
“Ask the data” for the rest:

→ Likelihood projection as a function of the mass and width of additional generic resonance



Each point = fit to data

$f_0(1710)$



$f_2(2010)$

Signal components:

- $B^0 \to f_0(980)\,K^0_S$
- $B^0 \to f_0(1710)\,K^0_S$
- $B^0 \to f_2(2010)\,K^0_S$
- $B^0 \to \chi_{c0}\,K^0_S$
- Non-resonant

→ 5x1–1=4 complex isobar amplitudes

No $f_X(1500)$

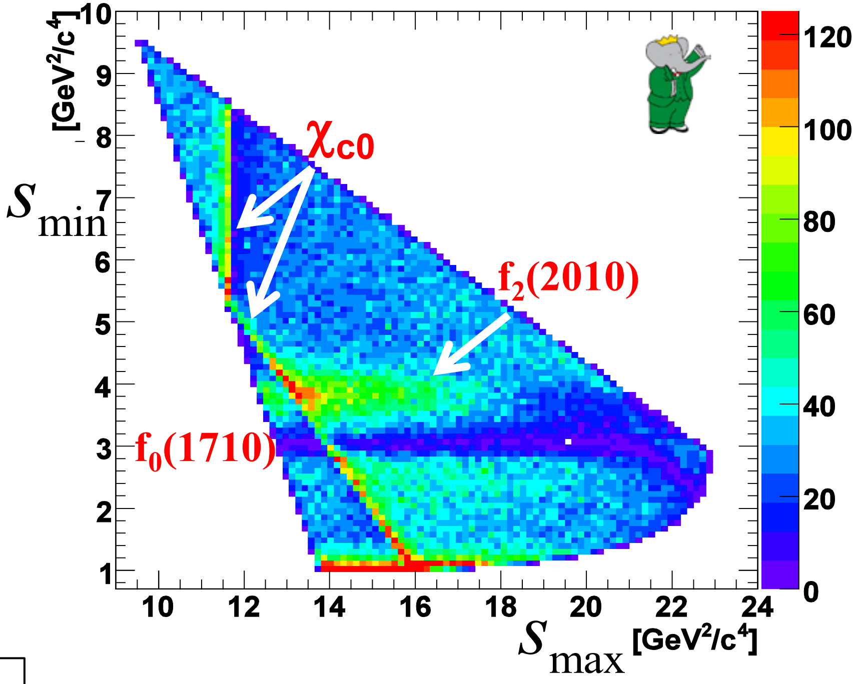
Results of the amplitude analysis

$B^0 \to K_S K_S K_S$

$f_0(980)K^0_S$	Fit Fraction (FF)	$0.44^{+0.20}_{-0.19}$
	Significance [σ]	3.0
$f_0(1710)K^0_S$	FF	$0.07^{+0.07}_{-0.03}$
	Significance [σ]	3.3
$f_2(2010)K^0_S$	FF	$0.09^{+0.03}_{-0.03}$
	Significance [σ]	3.3
NR	FF	$2.16^{+0.36}_{-0.37}$
	Significance [σ]	8.0
$\chi_{c0}K^0_S$	FF	$0.07^{+0.04}_{-0.02}$
	Significance [σ]	3.9
	Total FF	$2.84^{+0.71}_{-0.66}$

Huge destructive interference

!



5 (+inclusive) Branching fractions (*B*)

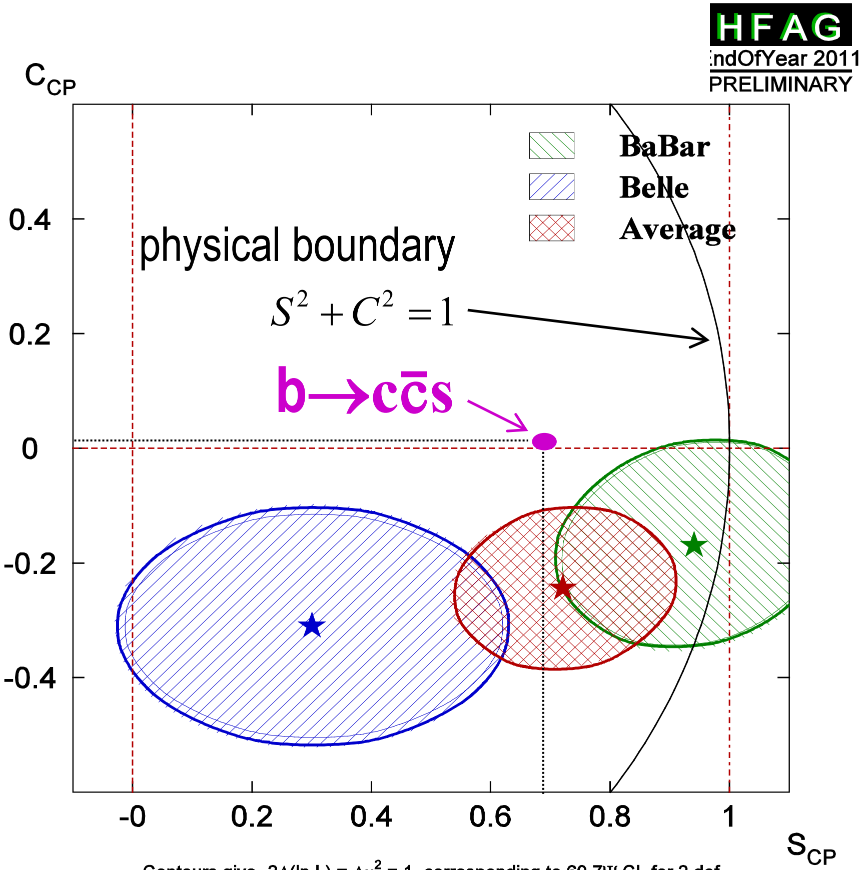
Mode	$\mathcal{B}$ [$\times 10^{-6}$]
Inclusive $B^0 \to K^0_S K^0_S K^0_S$	$6.19 \pm 0.48 \pm 0.15 \pm 0.12$
$f_0(980)K^0_S$, $f_0(980) \to K^0_S K^0_S$	$2.7^{+1.3}_{-1.2} \pm 0.4 \pm 1.2$
$f_0(1710)K^0_S$, $f_0(1710) \to K^0_S K^0_S$	$0.50^{+0.46}_{-0.24} \pm 0.04 \pm 0.10$
$f_2(2010)K^0_S$, $f_2(2010) \to K^0_S K^0_S$	$0.54^{+0.21}_{-0.20} \pm 0.03 \pm 0.52$
NR, $K^0_S K^0_S K^0_S$	$13.3^{+2.2}_{-2.3} \pm 0.6 \pm 2.1$
$\chi_{c0}K^0_S$, $\chi_{c0} \to K^0_S K^0_S$	$0.46^{+0.25}_{-0.17} \pm 0.02 \pm 0.21$

PDG:
$6.2 \pm^{1.2}_{1.1}$

Consistent with other measurements

Results of the time dependent analysis

$B^0 \to K_S K_S K_S$



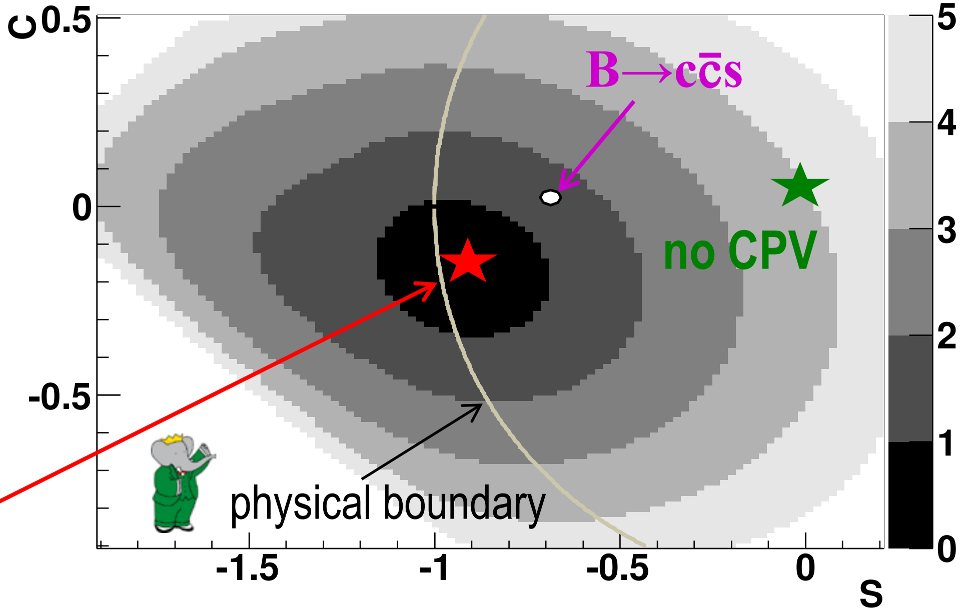
Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7Ψ CL for 2 dof

Signal yields:

$201 \pm^{16}_{15}$ $B^0 \to 3K^0_S(\pi^+\pi^-)$ (Purity = 40%)

$62 \pm^{13}_{12}$ $B^0 \to 2K^0_S(\pi^+\pi^-)\,K^0_S(\pi^0\pi^0)$

Confidence level contours (*C*, *S*)



$$S = -0.94 \pm^{0.24}_{0.21}\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$

$$C = -0.17 \pm 0.18\,(\text{stat.}) \pm 0.04\,(\text{syst.})$$

First evidence of CPV (at 3.8σ)

Other $B \to KKK$ modes

overview and motivations

$B^+ \to K^+K^-K^+$ $B^+ \to K_SK_SK^+$ $B^0 \to K^+K^-K_S$

- In general: rich resonance structure ⇒ access to many observables:
  - A_{CP}
  - Branching Fraction

  } For each component
  - relative phases between components

  which can be used to set non-trivial constraints on the CKM parameters $(\bar{\rho}, \bar{\eta})$

- Time dependent analysis to measure the effective β in $B^0 \to K^+K^-K_S$

  → not a CP eigenstate! CP content depends on the intermediate state

  → includes ϕK_S (small theoretical uncertainty)

- DP structure of $B^+ \to K^+K^-K^+$ and $B^+ \to K_SK_SK^+$ useful for $B^0 \to K^+K^-K_S$

  → 2 K_S in the final state: helpful to study the nature of broad $f_X(1500)$

Determining the signal model

Other B → 3K modes

- Prior to fitting CPV parameters, the nominal DP models are established

  → CPV parameters set to the SM ones

  → angular moments vs invariant masses are used to compare data and fit

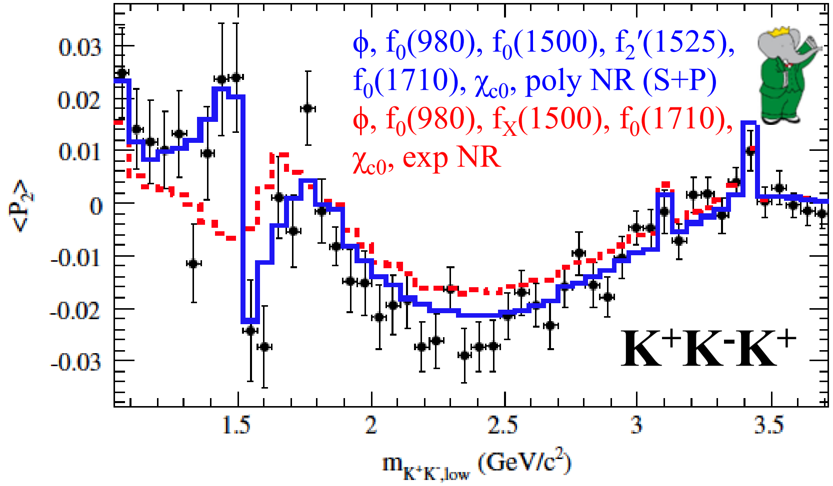
$$\langle P_\ell(\cos\theta_3)\rangle \equiv \int_{-1}^{1} d\Gamma P_\ell(\cos\theta_3) d\cos\theta_3$$

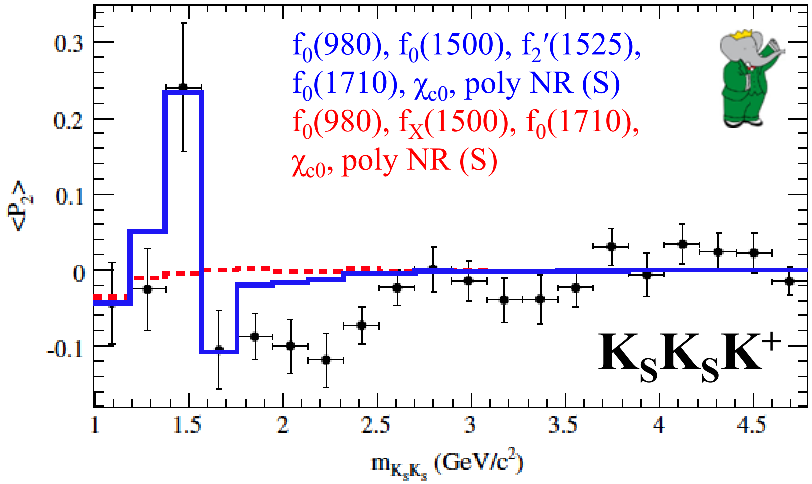
- **$K^+K^-K^+$**: $\phi(1020)$, $f_0(980)$, $f_0(1500)$, $f_2'(1525)$, $f_0(1710)$, χ_{c0}, poly. NR
- **$K_SK_SK^+$:** , $f_0(980)$, $f_0(1500)$, $f_2'(1525)$, $f_0(1710)$, χ_{c0}, poly. NR

} Best fits

In the 3 modes: no need for the $f_X(1500)$

good description with $f_0(1500)$, $f_2'(1525)$, $f_0(1710)$)





Results ($B^+ \to K^+K^-K^+$; $K_SK_SK^+$)

Other B → 3K modes

$K^+K^-K^+$

N_{sig} = **5269±84** (Purity = **43%**)

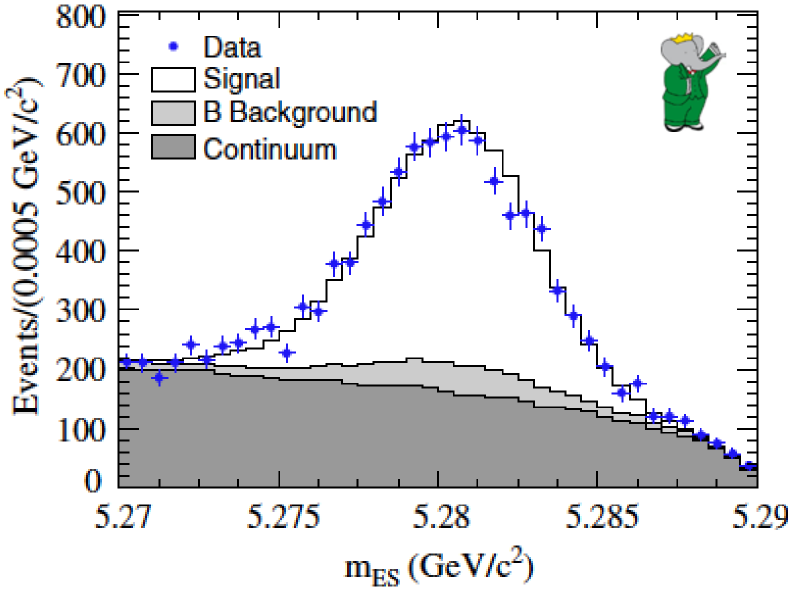
A_{CP}(inclusive) = $(-1.7^{+1.9}_{-1.4} \pm 1.4)\%$

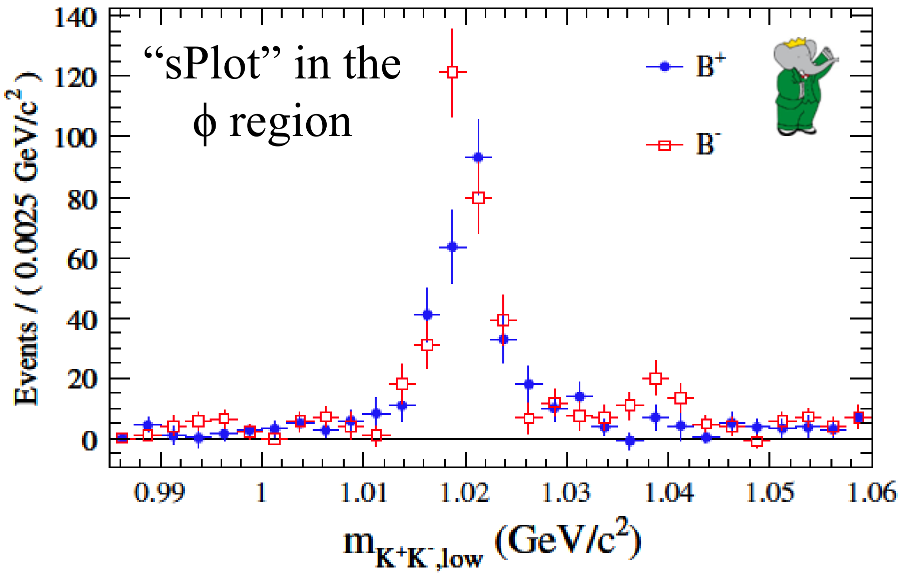
BF = $(33.4 \pm 0.5 \pm 0.9) \times 10^{-6}$ [$\chi_{c0}K$ excluded]

$A_{CP}(\phi K) = (12.8 \pm 4.4 \pm 1.3)\%$

(**2.8σ from 0**, SM: ~ 0 - 4.7%)

Beneke, Neubert, Nucl.Phys B675,333 (QCDF) ; Li, Mishima, PRD 74, 094020 (pQCD)





$K_SK_SK^+$

N_{sig} = 632±28 (Purity = 20%)

A_{CP} = (4±5±2)%

BF = $(10.1 \pm 0.5 \pm 0.3) \times 10^{-6}$ [$\chi_{c0}K$ excluded]

Results ($B^0 \to K^+K^-K_S$)

N_{sig} = 1579±46 (Purity = 18%)

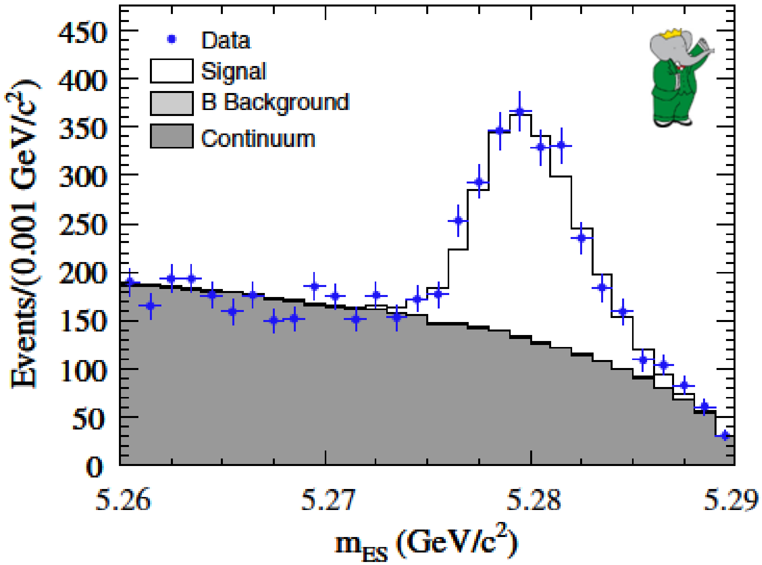
BF = $(25.4\pm0.9\pm0.8)\times10^{-6}$ [$\chi_{c0}K$ excluded]

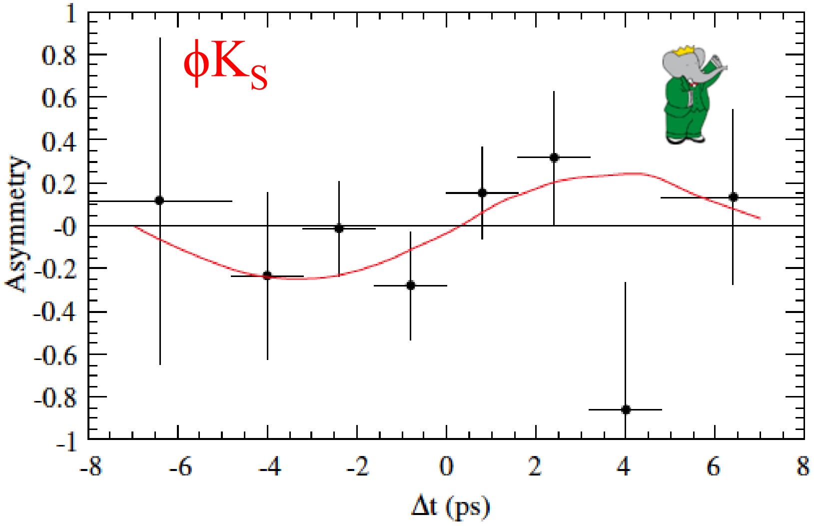
$\beta_{eff}(\phi K_S) = (21\pm6\pm2)°$ ← most precise

β_{eff}(non-φ, non-f_0) = $(20.3\pm4.3\pm1.2)°$

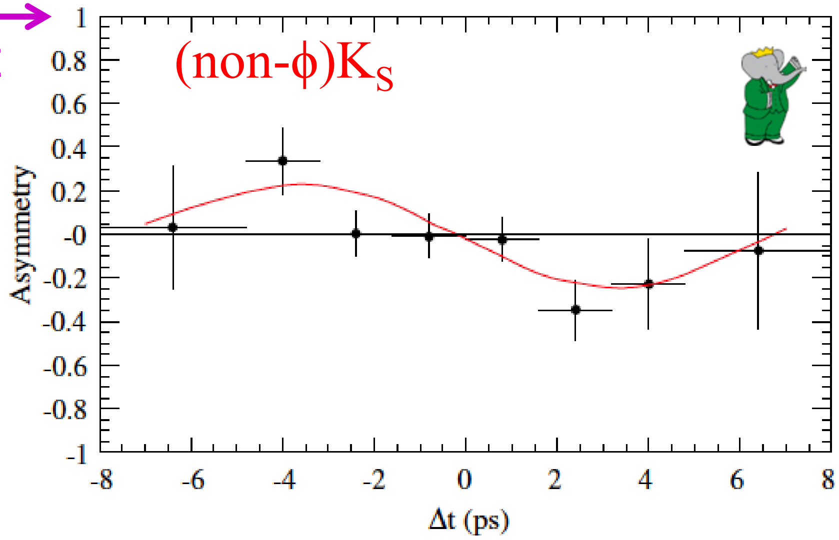
90°-β_{eff} excluded at 4.8σ (ambiguity in $J/\psi K_S$)

Agree with SM





different CP content



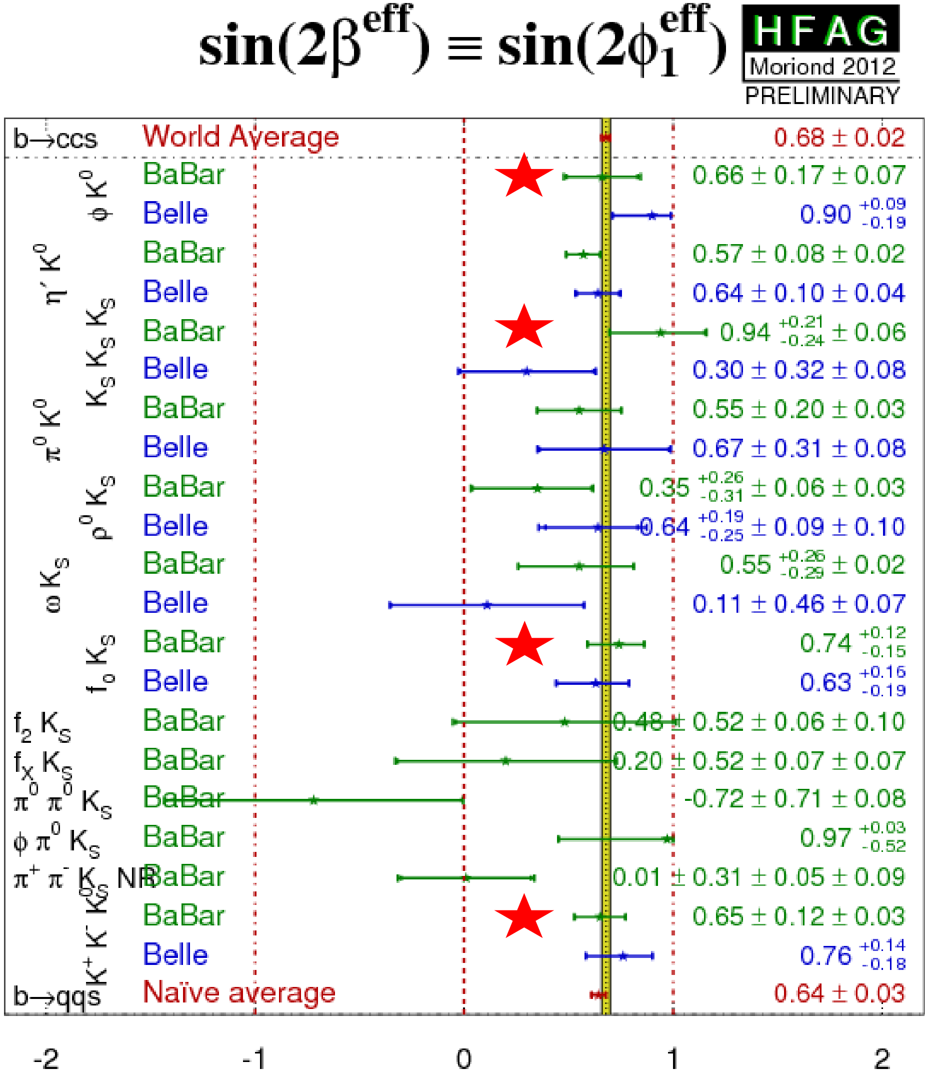
Summary and Conclusions

- BaBar continues to produce physics results, adding more information and using more sophisticated analysis techniques to improve the precision of measurement in hadronic B decays

- All measurements agree with the standard model predictions, though a few tensions and puzzles still exist

- The actual statistics is not sufficient to tell whether or not these could be indications for new physics.

To find new physics in hadronic modes…



★ contribution from analyses shown here