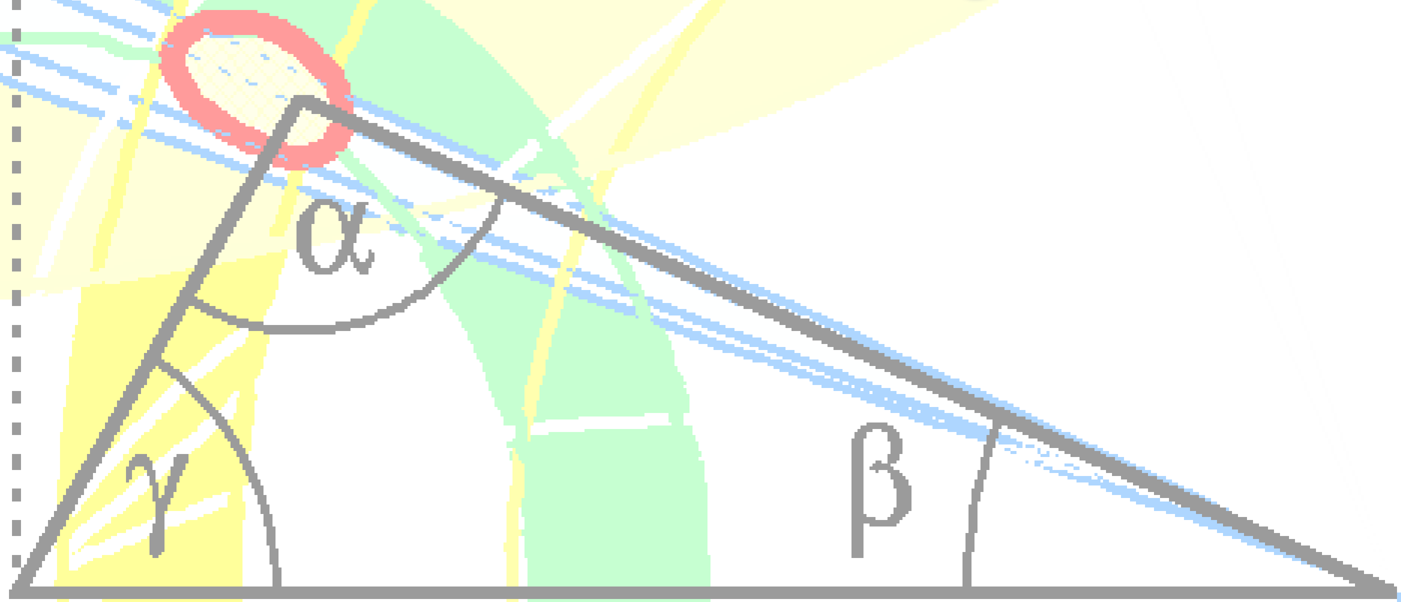
Europhysics Conference On High Energy Physics
July 16-22 2009, Krakow Poland

CP Violation in Hadronic Penguin Modes



Eli Ben-Haïm
LPNHE-IN2P3-
Université Paris VI
On behalf of the ***BABAR*** collaboration

Introduction

- Time Dependent CP Asymmetry
- Technique for Time Dependent Measurements and Flavor Tagging
- $\sin 2\beta$ From $b \rightarrow s$ Penguins

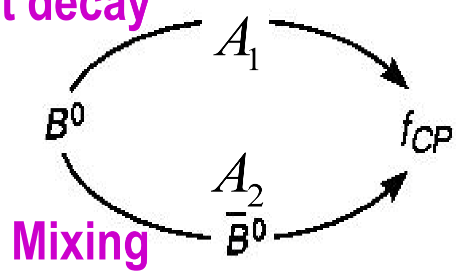
(Will not be included in this introduction:

- PEP-II, the BaBar experiment and Dataset
- Definition of kinematic variables (m_{ES} and ΔE)
- Event shape variables for continuum reduction

$\Big\}$ In previous talks)

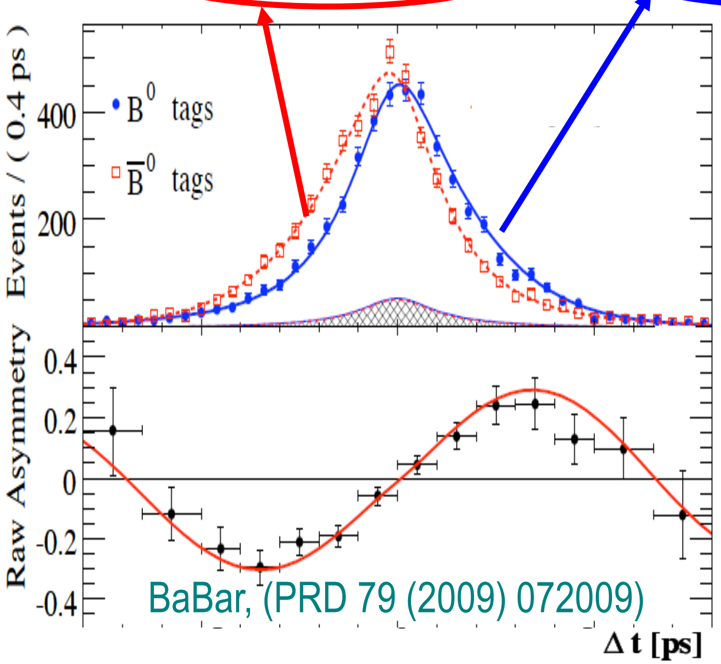
Time Dependent CP Asymmetry

- Can be used for the extraction of sin(2β); interference between decay and mixing

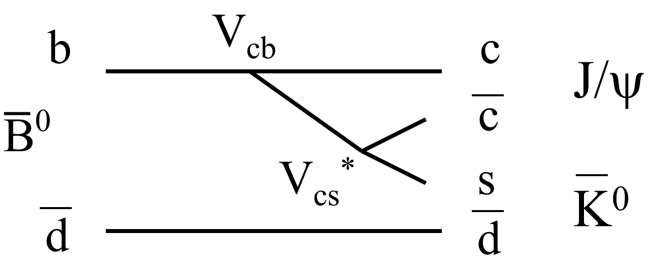


- For example, in the "Golden" b→c$\bar{c}$s mode ($B^0 \rightarrow J/\psi\ K^0_S$):

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0 \rightarrow J/\psi K_S](t) - \Gamma[B^0 \rightarrow J/\psi K_S](t)}{\Gamma[\bar{B}^0 \rightarrow J/\psi K_S](t) + \Gamma[B^0 \rightarrow J/\psi K_S](t)} = \boxed{S}\sin(\Delta m_d t) - C\cos(\Delta m_d t)$$



BaBar, (PRD 79 (2009) 072009)



~ only one amplitude (tree diagram)

$$C = 0$$

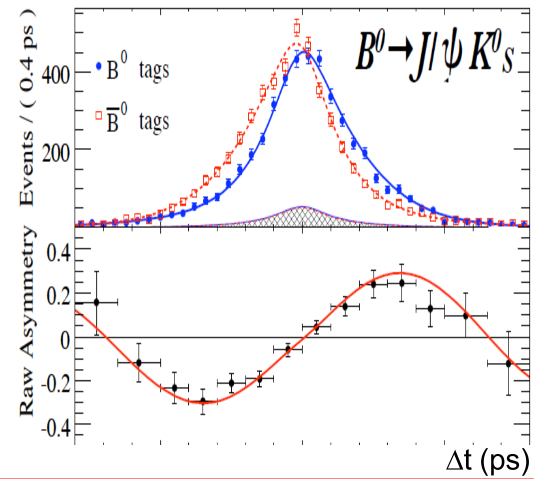
$$S = -\eta_{CP} \sin 2\beta$$

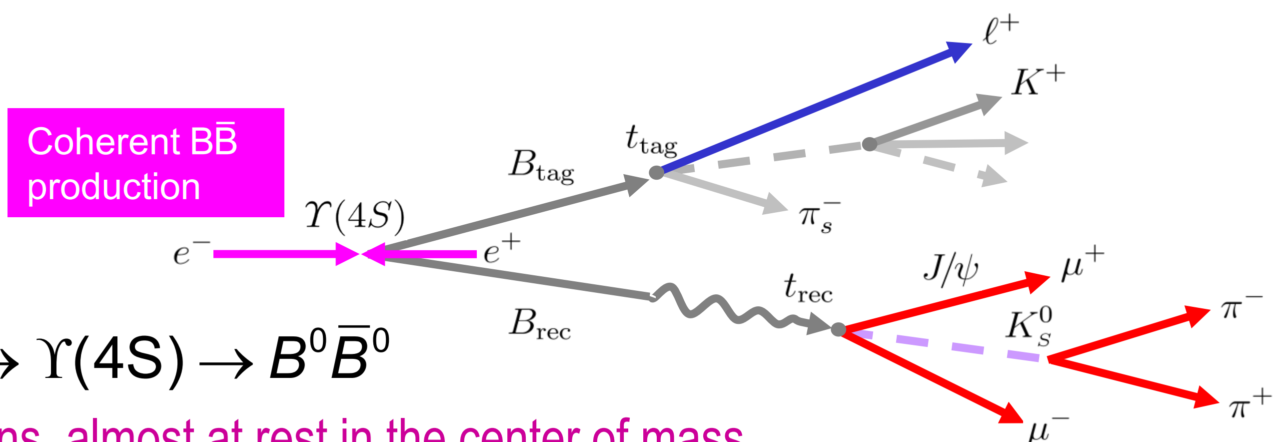
$\Rightarrow$ Extraction of $\sin 2\beta$ from A_{cp}

Time Dependent Measurements, Flavor Tagging

Ingredients:

1. **We need to measure time**
2. If we want to study a decay **$B^0 \to f$**
   where f is also accessible by an anti-B^0 **$\overline{B}^0 \to f$**
   and we want to be sensitive to **$\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to f)$**
   we need to "tag" the B flavor





$$e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0$$

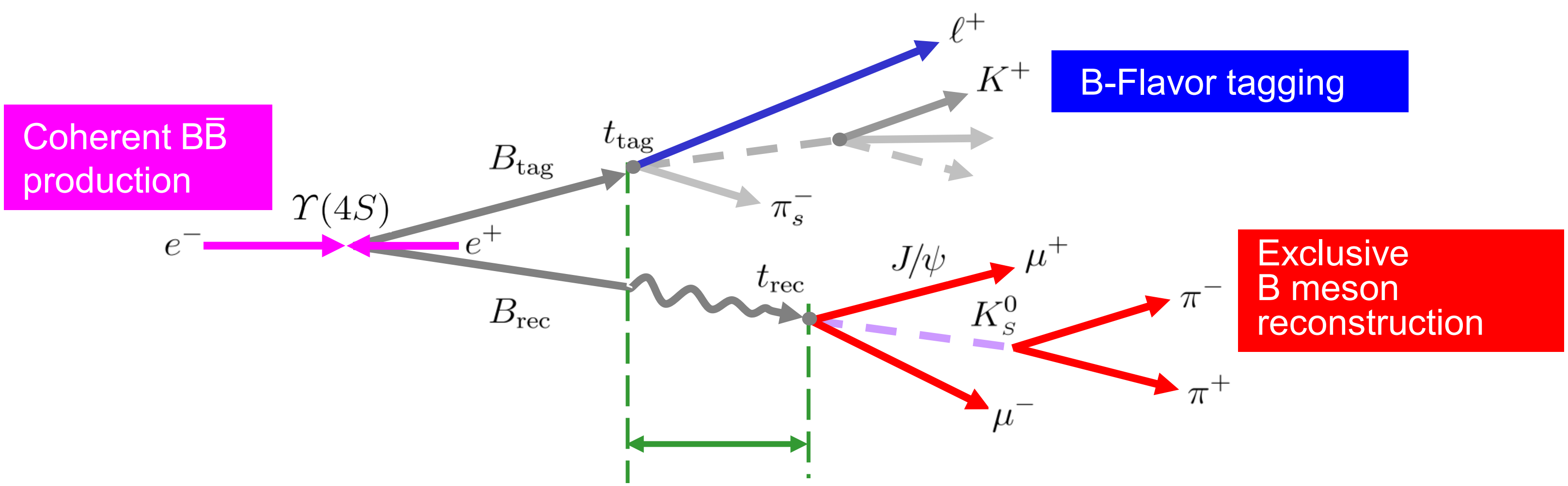
Two B mesons, almost at rest in the center of mass,
boosted in the laboratory, are produced in a coherent state
$\Rightarrow$ until the first B decay, there is exactly one B^0 and one $\overline{B}^0$

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

Time Dependent Measurements, Flavor Tagging

Method:

- **Boost**: Δt measured via space length measurement Δz between B_{tag} and B_{rec}
- **Coherent evolution**:
  - at t_{tag} the flavors of B_{rec} and B_{tag} are opposite
  - flavor of the B_{tag} determined by its decay product (charge of leptons, K, π)
  - flavor of the B_{rec} determined from the flavor of B_{tag} (and Δt)



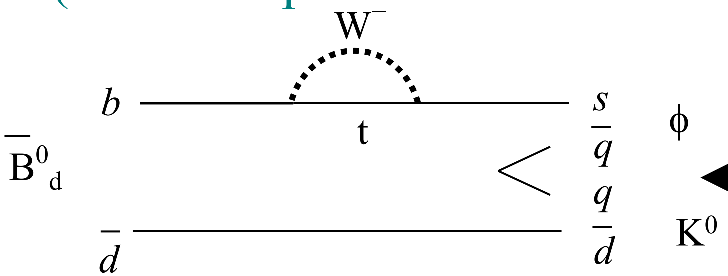
$$\Delta t \equiv t_{rec} - t_{tag} \approx \Delta z / \beta\gamma c$$

sin2β From b→s Penguins (I)

- Within the Standard Model (SM):

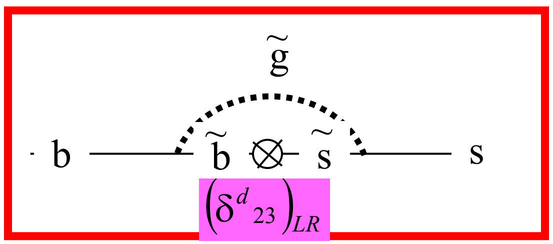
$$S_{c\bar{c}s} = S_{q\bar{q}s} + \Delta S_{SM} = -\eta_{CP} \sin 2\beta$$
$$C_{c\bar{c}s} \approx C_{q\bar{q}s} = 0$$

(dominant phase is the same as in $b \to c\bar{c}s$)



Standard Model contribution

- New physics in the loop may cause deviation in the values of S and C.

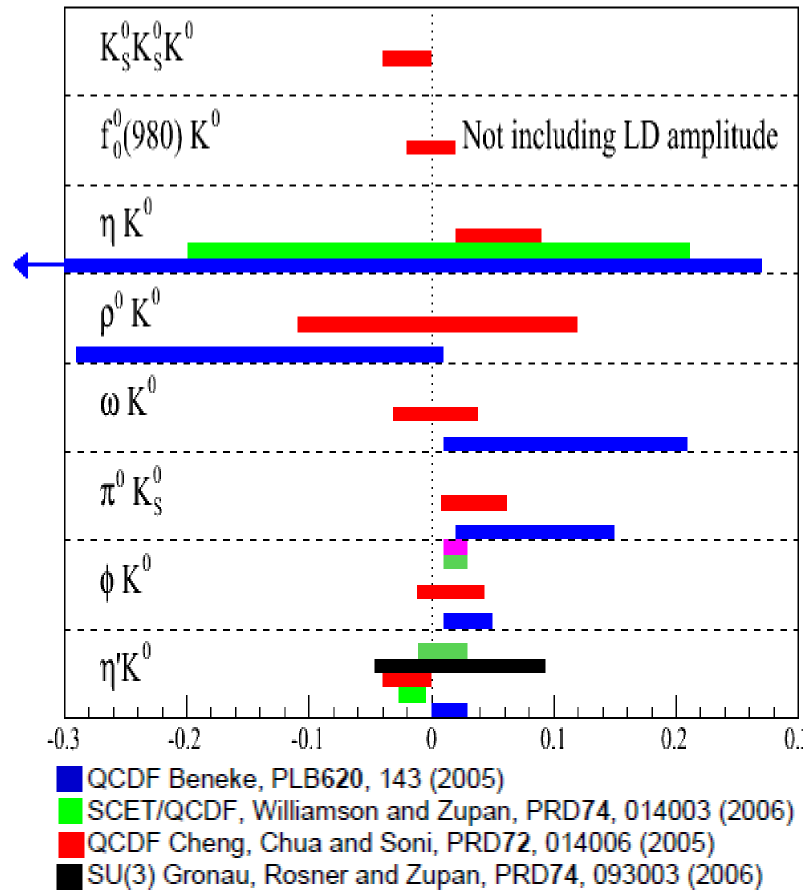


New Physics contribution

- Definitions:

$$\Delta S = S_{c\bar{c}s} - S_{q\bar{q}s}$$
$$\sin 2\beta^{\text{eff}} = -\eta_{CP} S_{q\bar{q}s}$$

Theoretical prediction for ΔS_{SM}



For most of the modes, theory predicts $\Delta S_{SM} > 0$

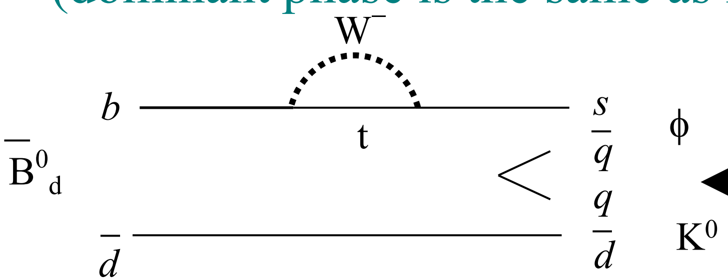
sin2β From b→s Penguins (I)

- Within the Standard Model (SM):

$$S_{c\bar{c}s} = S_{q\bar{q}s} + \Delta S_{SM} = -\eta_{CP}\sin 2\beta$$

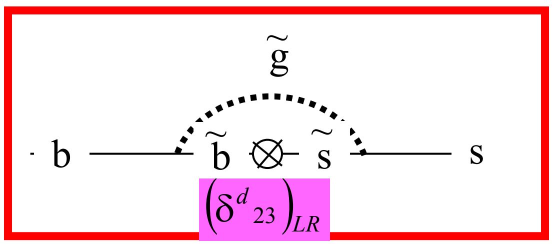
$$C_{c\bar{c}s} \approx C_{q\bar{q}s} = 0$$

(dominant phase is the same as in $b \rightarrow c\bar{c}s$)



Standard Model contribution

- New physics in the loop may cause deviation in the values of S and C.



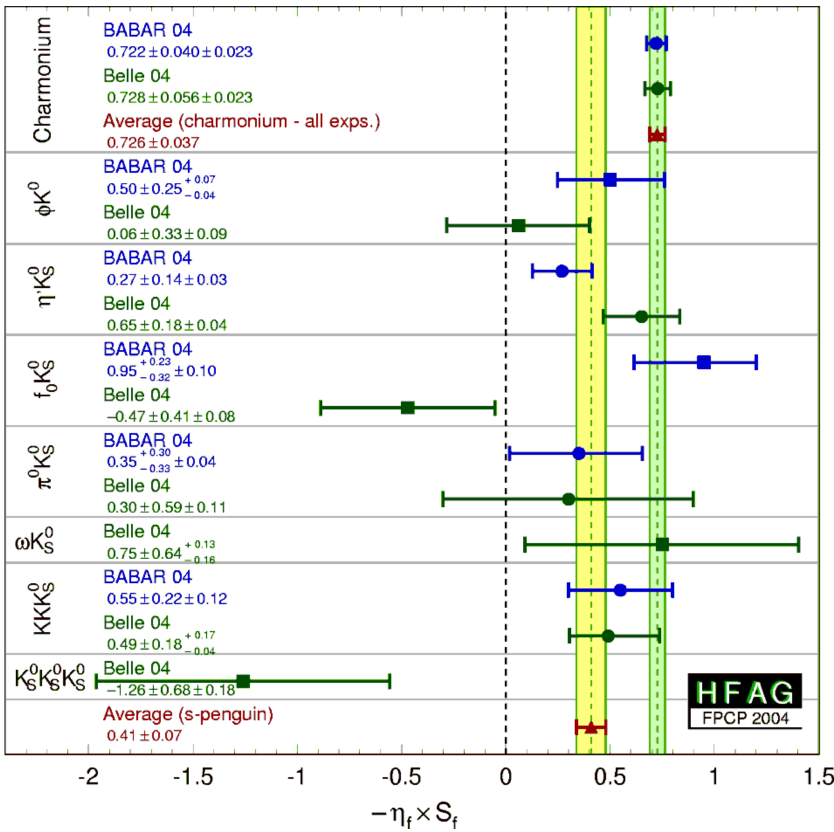
New Physics contribution

- Definitions:

$$\Delta S = S_{c\bar{c}s} - S_{q\bar{q}s}$$

$$\sin 2\beta^{\mathrm{eff}} = -\eta_{CP} S_{q\bar{q}s}$$

In 2004:

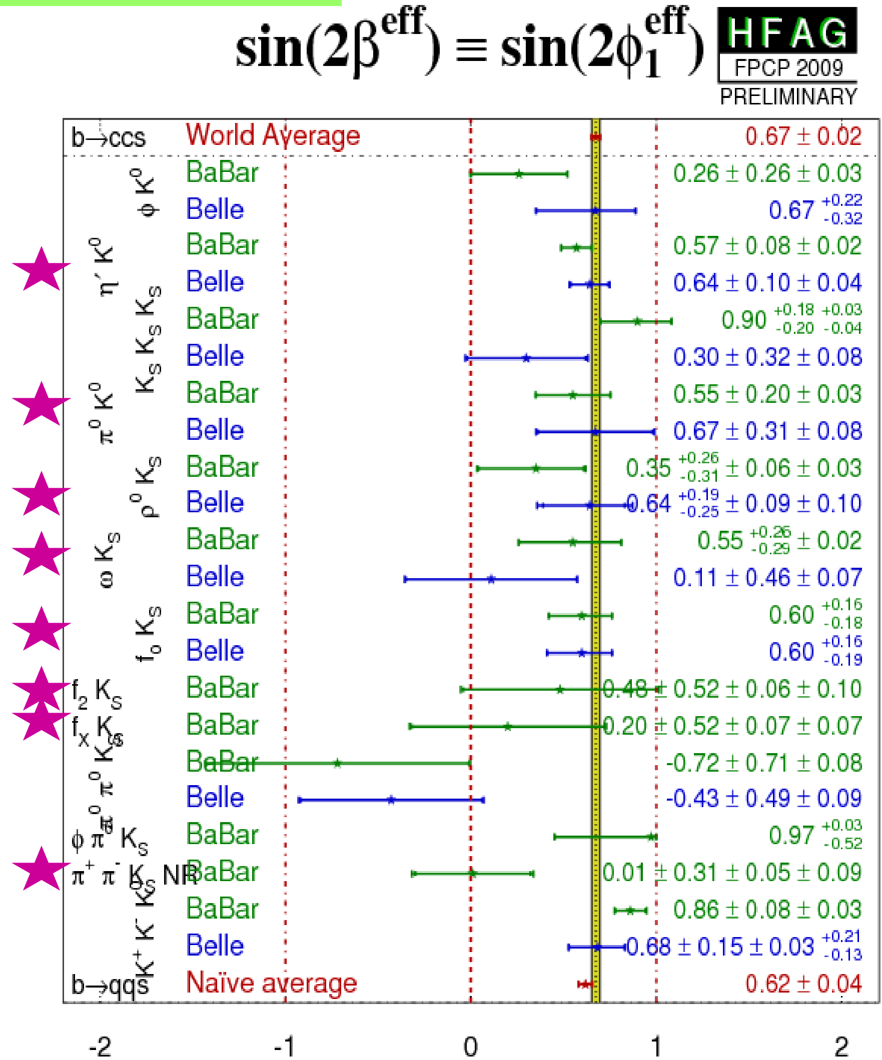


Tensions between sin2β from $b \rightarrow c\bar{c}s$ and $b \rightarrow q\bar{q}s$ (**ΔS < 0**)

sin2β From b→s Penguins (II)

The situation today is quite different

- **Fresh sin*2β* world averages (HFAG):**
  - **b→c$\bar{c}$s: 0.67 ± 0.02**
  - **b→q$\bar{q}$s: 0.62 ± 0.04** (naïve!)
- Improvements:
  - hints of trends/deviations in previous measurements clarified by B factories
  - several results from (Time Dependent) Dalitz Plot analyses
- **Still… some tension persists because of the theoretical prediction $\Delta S_{SM} > 0$**



In the following I will talk about analyses that measure S and C for the modes marked with ★

Analyses and Results

- Time Dependent CP Asymmetry in $B^0 \rightarrow \omega K^0_S$, $\eta' K^0$, $\pi^0 K^0_S$
  arXiv:0809.1174 [hep-ex], Phys.Rev.D79:052003,2009.

- Time Dependent Dalitz-Plot Analysis of $B^0 \rightarrow \pi^+ \pi^- K^0_S$
  arXiv:0905.3615 [hep-ex], submitted to PRD.

Overview

$B^0 \to \omega K^0_S$, $\eta' K^0_S$, $\eta' K^0_L$, $\pi^0 K^0_S$

- The 4 final states are CP eigenstates
- Notably Large BF for $B^0 \to \eta' K^0$

  $BR(\eta' K^0) = 65 \times 10^{-6} \sim 7 \times BR(\pi^0 K^0)$

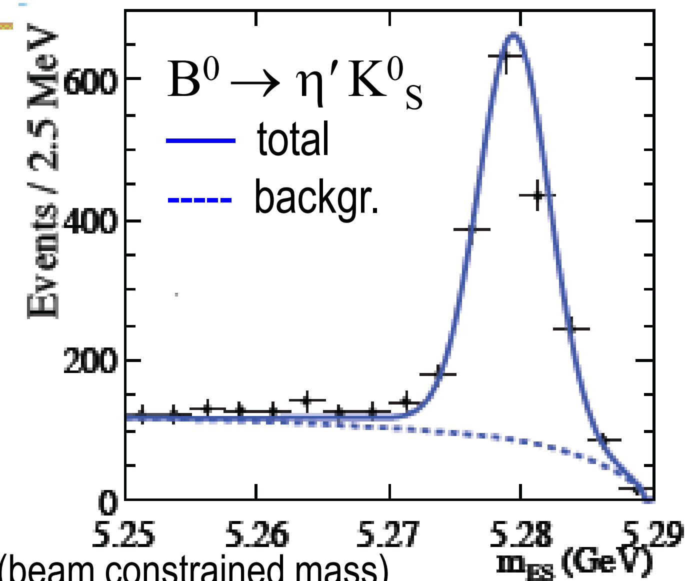
  ("Puzzle of the $B \to \eta' K$ branching ratio")

  → small errors on S and C
- The present analysis:
  - uses full BaBar dataset (467M $B\bar{B}$ pairs)

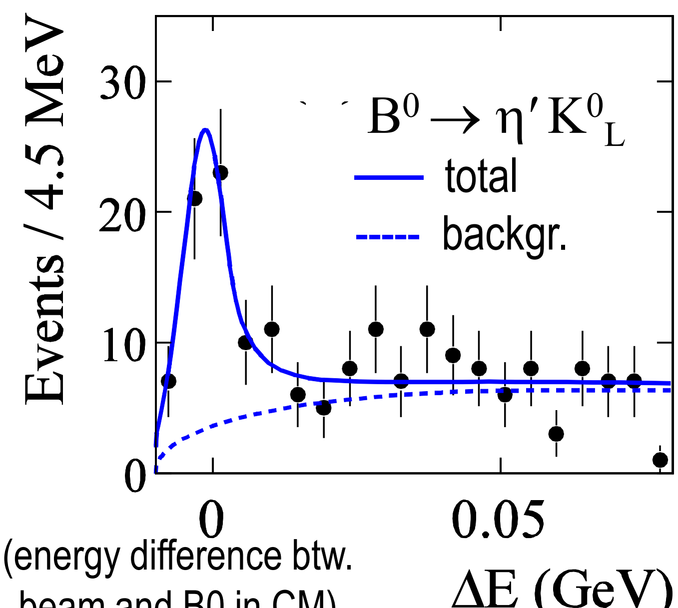
    → 20% increase wrt. previous analysis
  - has an additional η' decay channel in $\eta' K^0_L$
  - decreased errors on S and C for $\eta' K^0$ by 20-25%

Signal yields:

Mode	$\eta' K^0_S$	$\eta' K^0_L$	ωK^0_S	$\pi^0 K^0_S$
Yield	1959±58	556±38	163±18	556±32



(beam constrained mass)



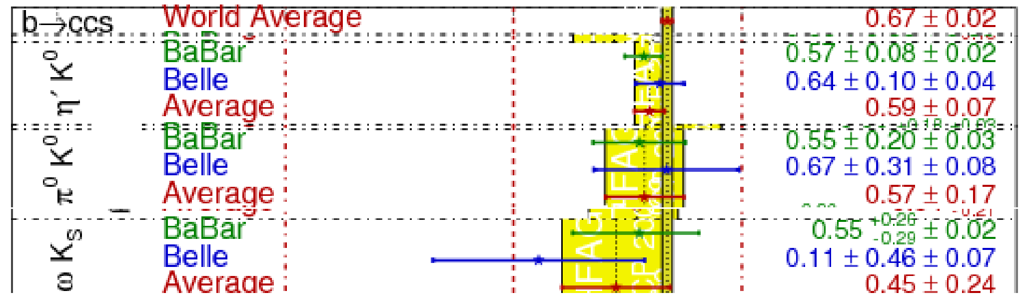
(energy difference btw. beam and B0 in CM)

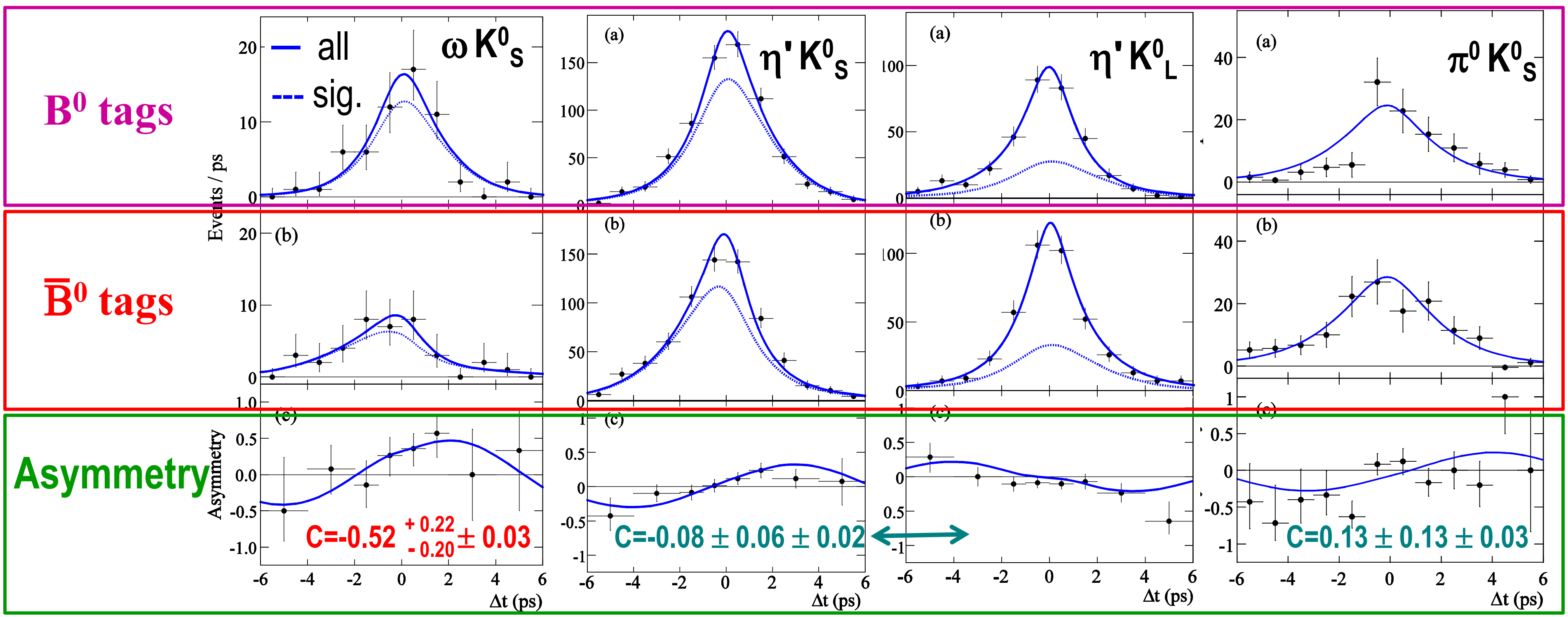
Results

$B^0 \to \omega K^0_S,\ \eta' K^0_S,\ \eta' K^0_L,\ \pi^0 K^0_S$

- $\sin 2\beta^{\rm eff} < \sin 2\beta$ for all these modes
- C compatible with 0 to 1σ, except $C(\omega K^0_S) = -0.52^{+0.22}_{-0.20} \pm 0.03$
- More data is needed to confirm possible deviations

$\sin 2\beta^{\rm eff}$ (HFAG – FPCP 2009)





Analyses and Results

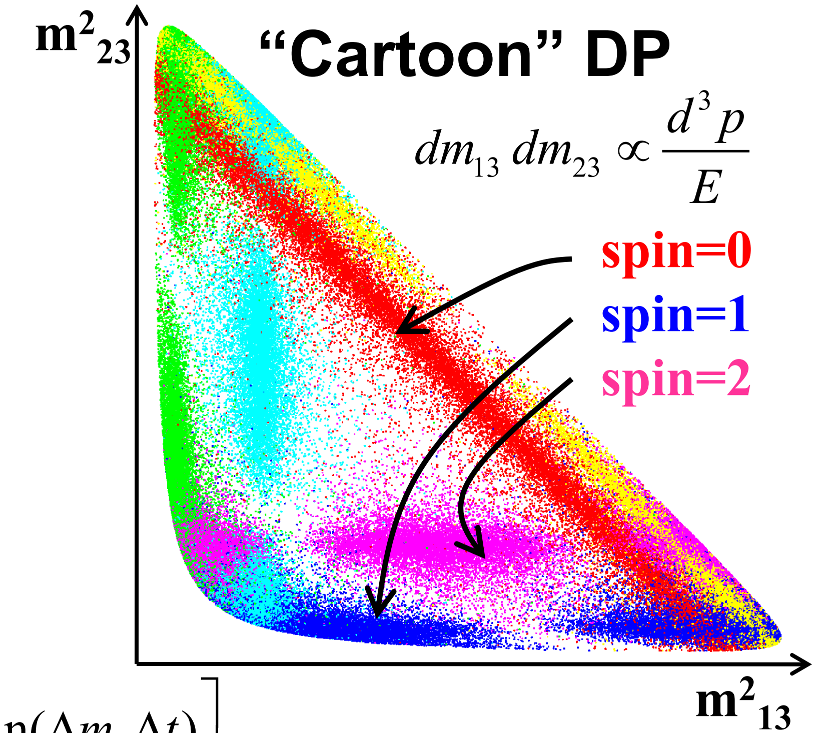
- Time Dependent CP Asymmetry in $B^0 \to \omega K^0_S$, $\eta' K^0_S$, $\pi^0 K^0_S$
  arXiv:0809.1174 [hep-ex], Phys.Rev.D79:052003,2009.

- Time Dependent Dalitz-Plot Analysis of $B^0 \to \pi^+ \pi^- K^0_S$
  arXiv:0905.3615 [hep-ex], submitted to PRD.

Dalitz-Plot (DP) Analysis

- Each intermediate resonance appears as a structure in the DP according to its mass, width and spin
- Resonance parameterization (isobar model):
- $A \sim \Sigma\, \mathbf{C_i}\, \mathbf{F}(m^2_{13}, m^2_{23})$

complex ⇙ ⇘ e.g. Breit-Wigner



- DP and Δt model:

$$\frac{d\Gamma\left(m^2_{13}, m^2_{23}, \Delta t, q_{tag}\right)}{d\Delta t\, dm_{13}\, dm_{23}} \propto e^{-|\Delta t|/\tau_{B^0}} \times \Big[\left(|A|^2 + |\bar{A}|^2\right)$$

$$-q_{tag} \underbrace{\left(|A|^2 - |\bar{A}|^2\right)}_{\sim C} \cos(\Delta m_d \Delta t) + q_{tag} \underbrace{2\,\mathrm{Im}\left(\bar{A}A^* e^{-i \cdot 2\beta}\right)}_{\sim S} \sin(\Delta m_d \Delta t)\Big]$$

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

- Superimposed resonant contributions → interference

→ access to phases with no sin$2\beta^{\text{eff}}$ = sin(180° - $2\beta^{\text{eff}}$) ambiguity!

Dalitz-Plot Signal Model

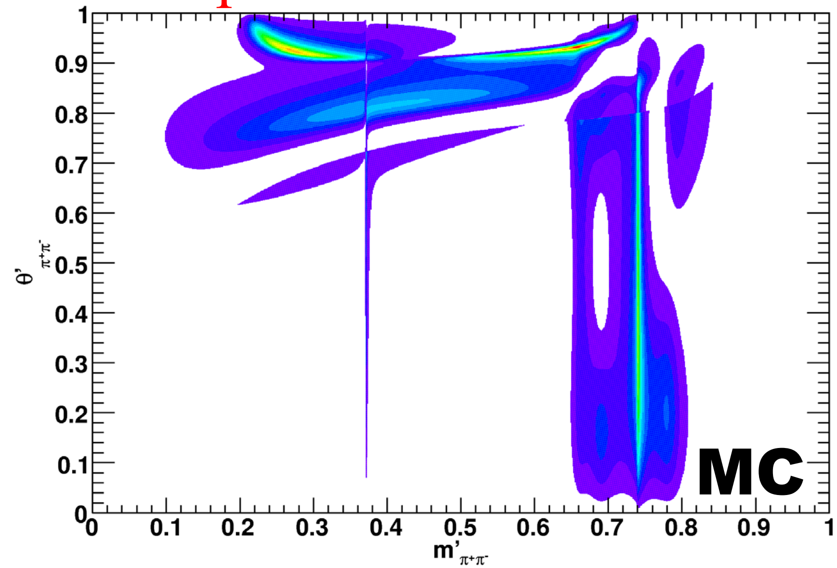
$B^0 \to \pi^+ \pi^- K^0_S$

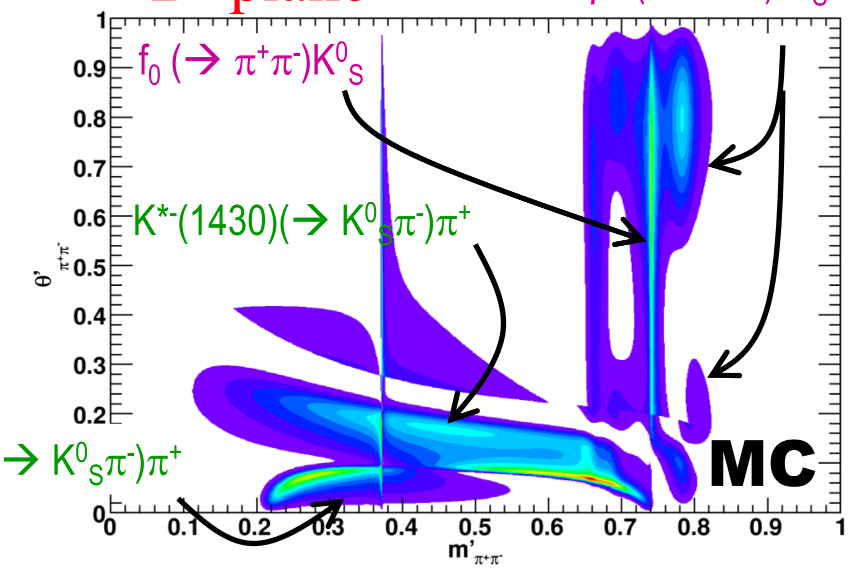
- In Practice, we use a "square DP": a transformation $(m_{13}, m_{23}) \to (m', \theta')$
- Signal components:
  - $B^0 \to \rho^0(770) K^0_S$
  - $B^0 \to f_0(980) K^0_S$
  - $B^0 \to f_X(1300) K^0_S$
  - $B^0 \to f_2(1270) K^0_S$
  - $B^0 \to \chi_{c0} K^0_S$
  - $B^0 \to K^*(892) \pi$
  - $B^0 \to K\pi$ S-wave
  - Non-resonant

  $\pi^+ \pi^-$ resonances

  $K \pi$ resonances

  $\to$ 8x2–1=15 complex isobar amplitudes
- Same signal model as in BaBar $B^+ \to K^+ \pi^- \pi^+$ analysis
- The interference is visible





Motivations

$B^0 \to \pi^+ \pi^- K^0_S$

- From what we have already seen…
  - The signal contains $\rho^0(770)\ K^0_S$ and $f_0(980)\ K^0_S$ intermediate resonant states ($b \to q\bar{q}s$ modes) $\Rightarrow$ measurement of β^{eff}
  - Time dependent DP $\Rightarrow$ no $\sin 2\beta^{eff} = \sin(180° - 2\beta^{eff})$ ambiguity on phases
  - Rich resonance structure $\Rightarrow$ access to many observables!

- Furthermore…
  - Access CKM angle γ from phases related to the $K^*\pi$ intermediate states in $B^0 \to K^+\pi^-\pi^0$ and $B^0 \to K_S\pi^+\pi^-$

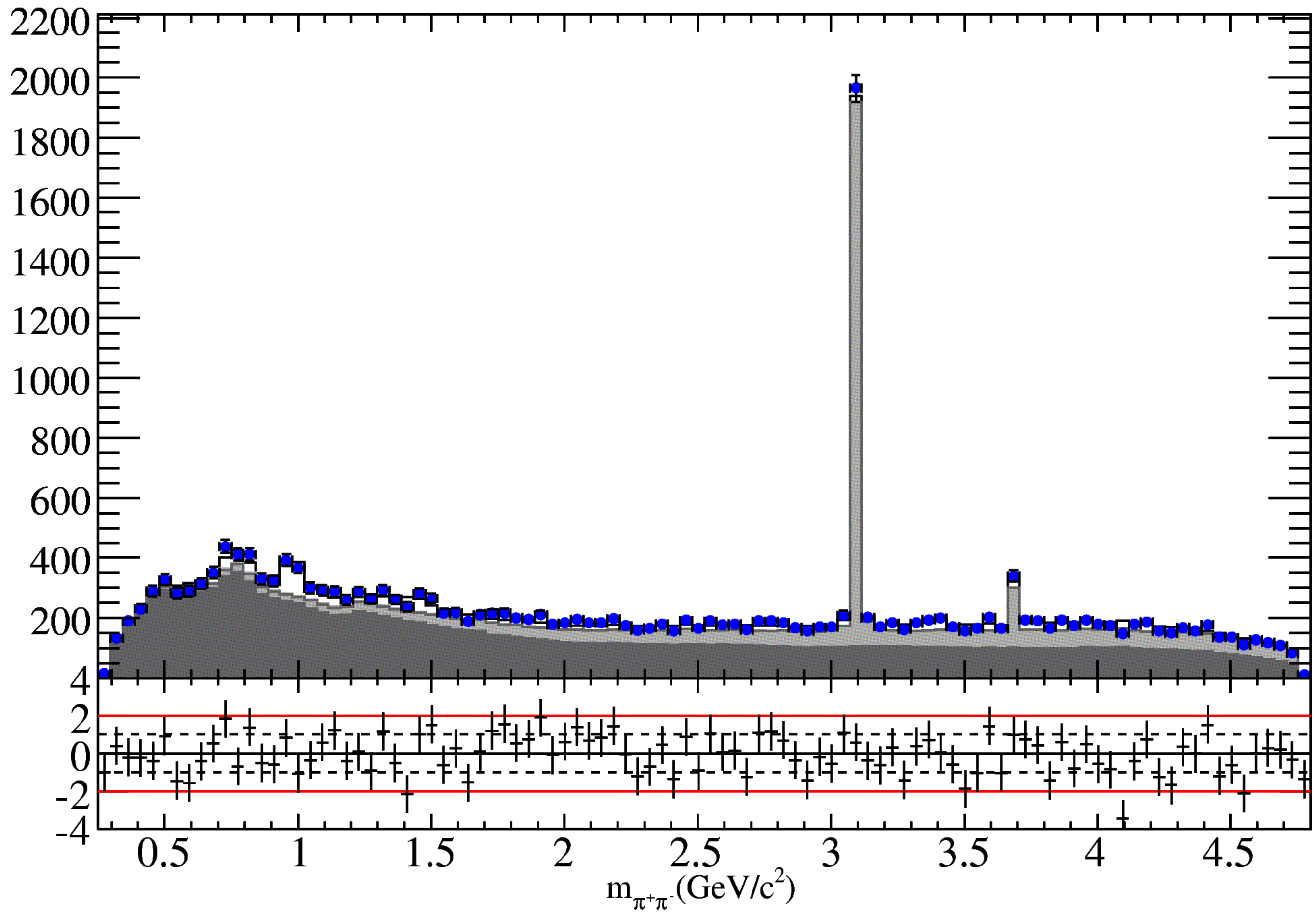
    Ciuchini, Pierini & Silvestrini [PRD74:051301 2006]

    Gronau, Pirjol, Soni & Zupan [PRD75:014002 2007]

Results: goodness of fit – distributions of $m_{\pi\pi}$

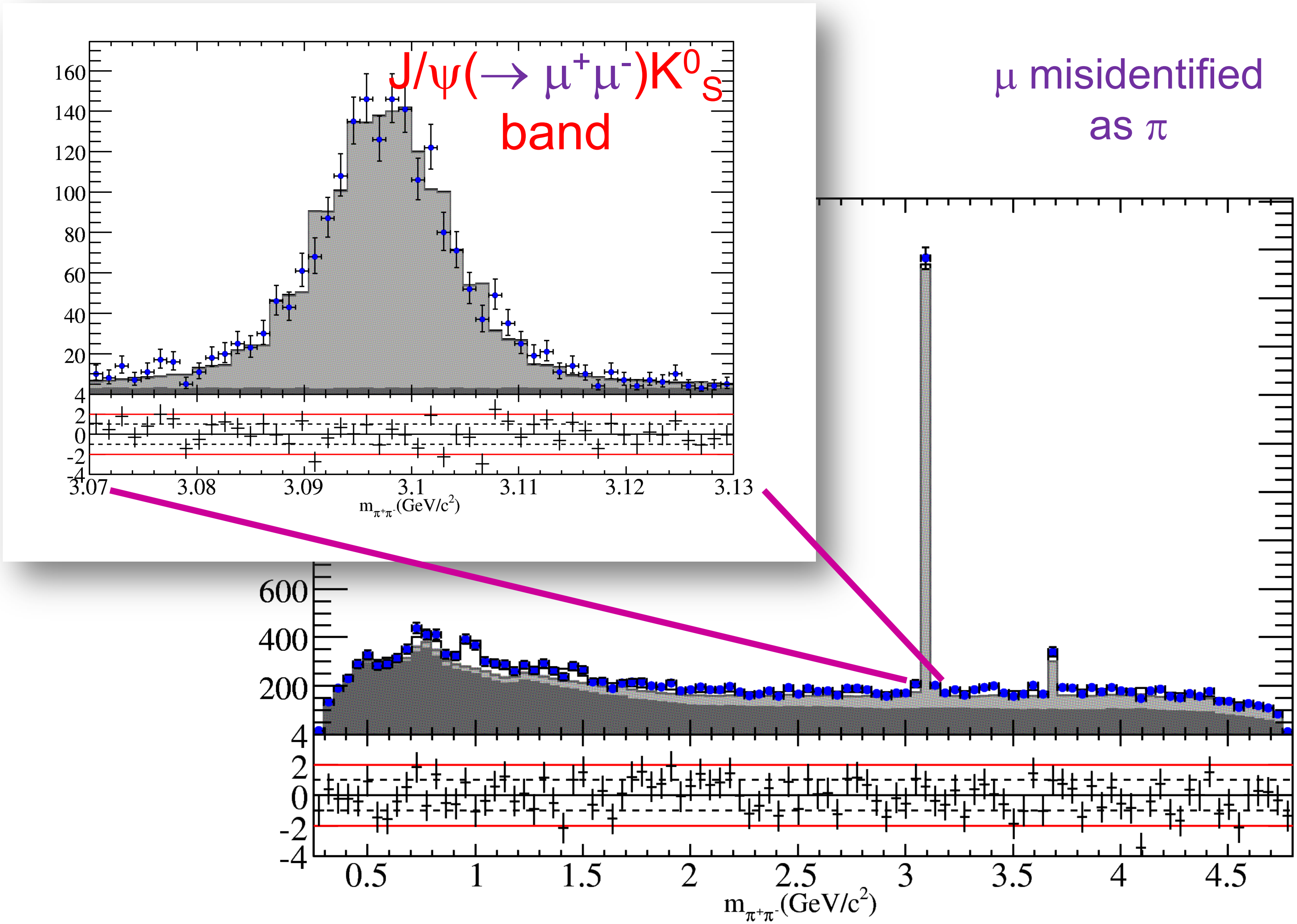
$B^0 \to \pi^+ \pi^- K^0_S$

Invariant mass of the two pions ($m_{\pi\pi}$) for all the events



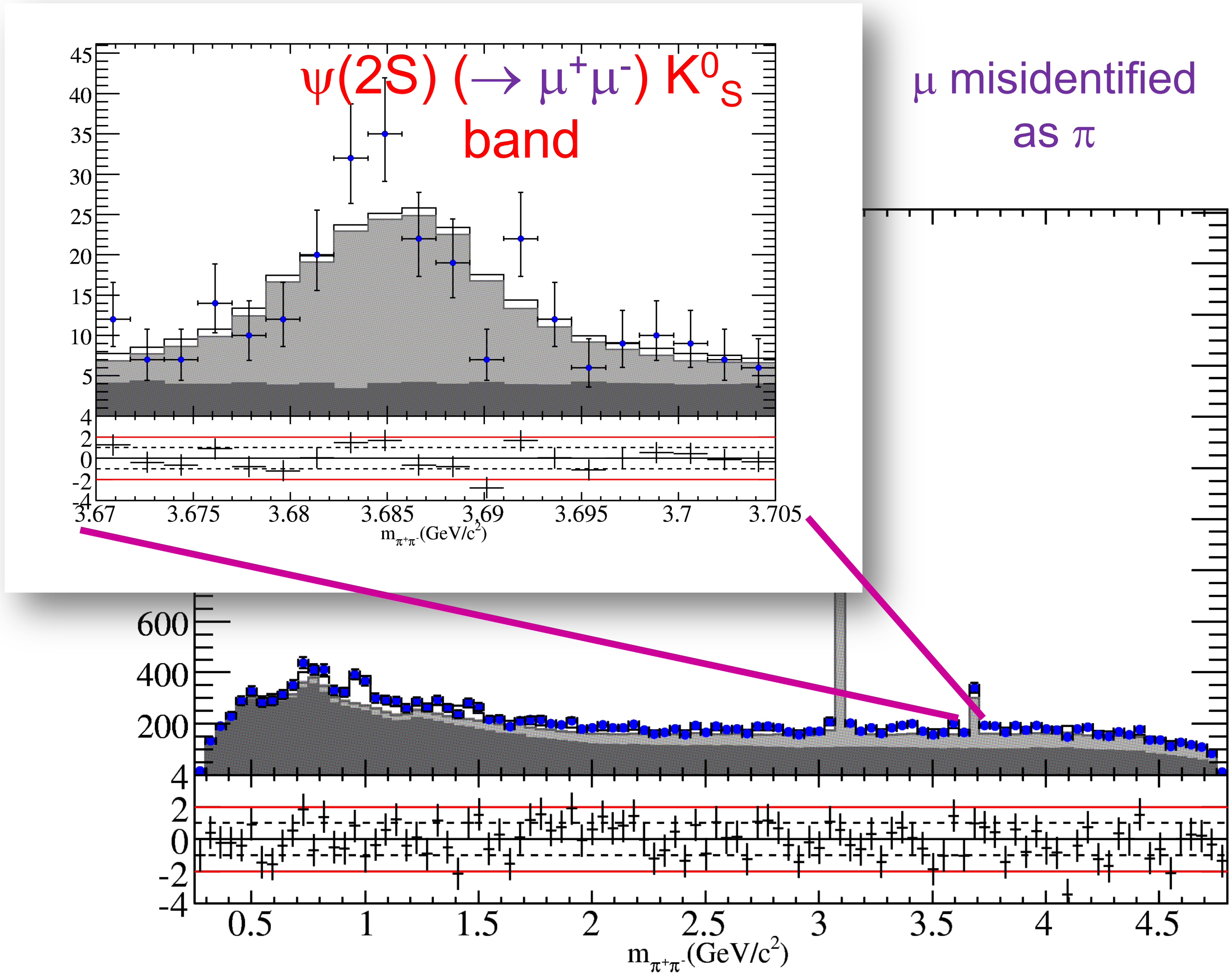
Results: goodness of fit – distributions of $m_{\pi\pi}$

$B^0 \to \pi^+ \pi^- K^0_S$



Results: goodness of fit – distributions of $m_{\pi\pi}$

$B^0 \to \pi^+ \pi^- K^0_S$

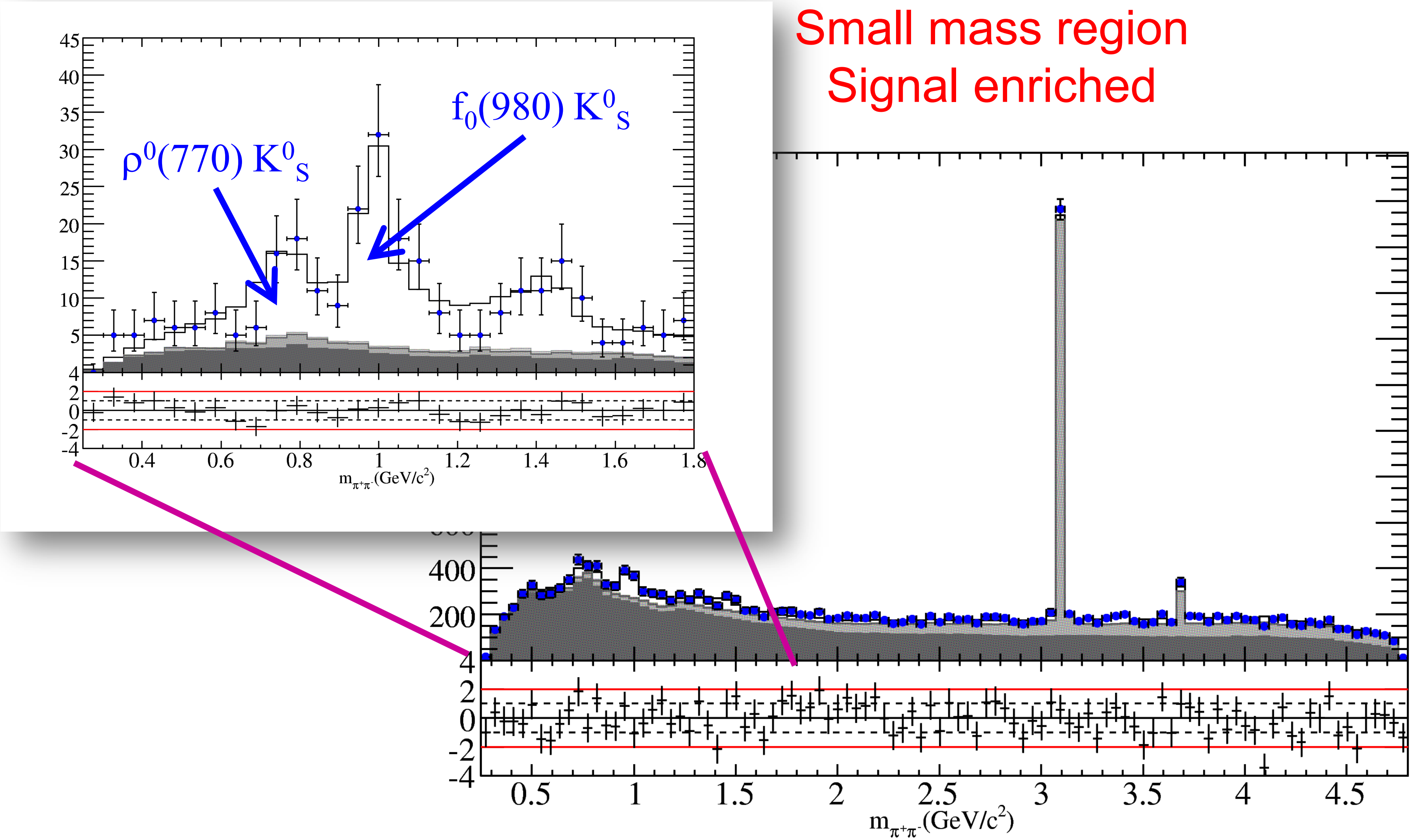


μ misidentified as π

Results: goodness of fit – distributions of $m_{\pi\pi}$

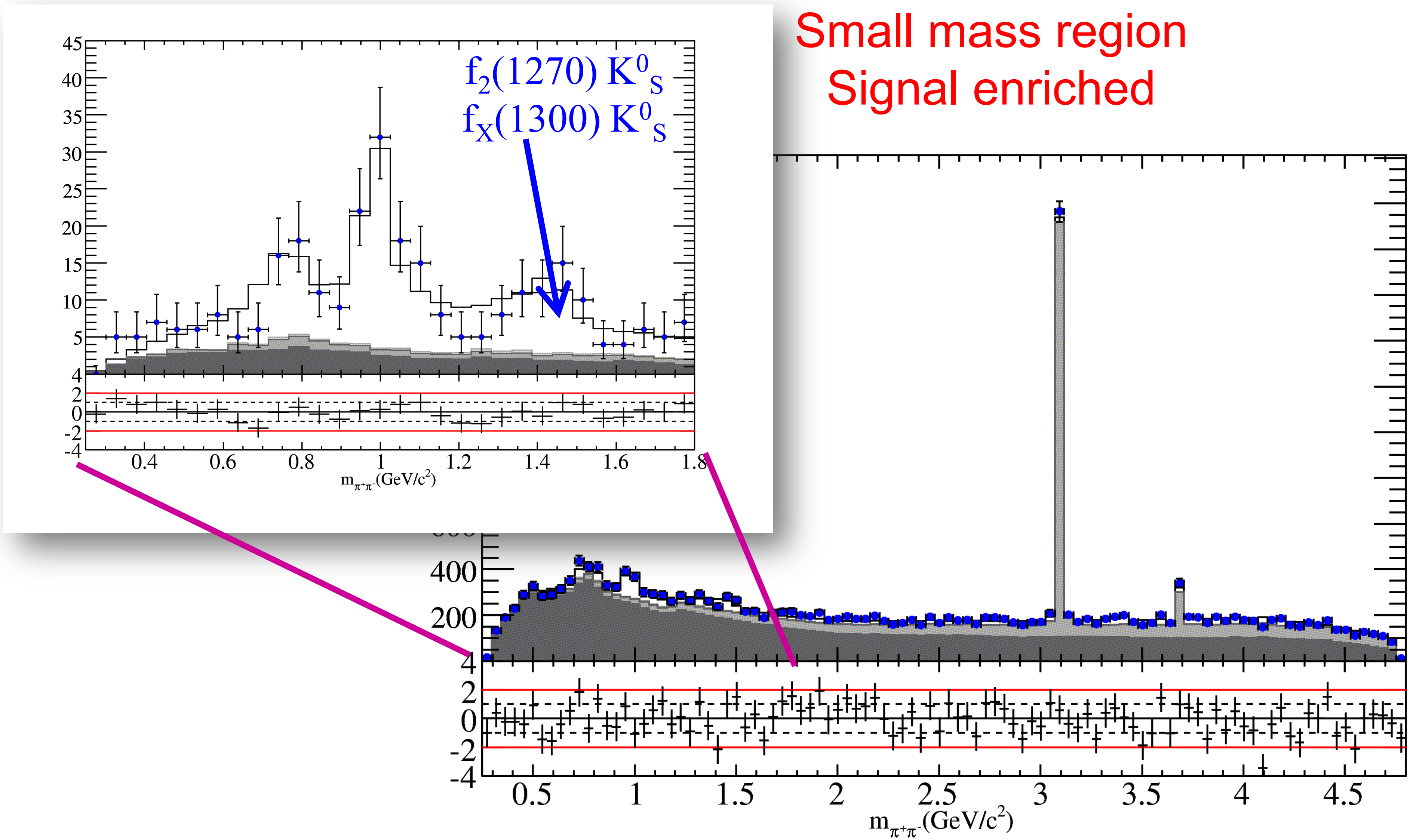
$B^0 \to \pi^+ \pi^- K^0_S$

Small mass region
Signal enriched



Results: goodness of fit – distributions of $m_{\pi\pi}$

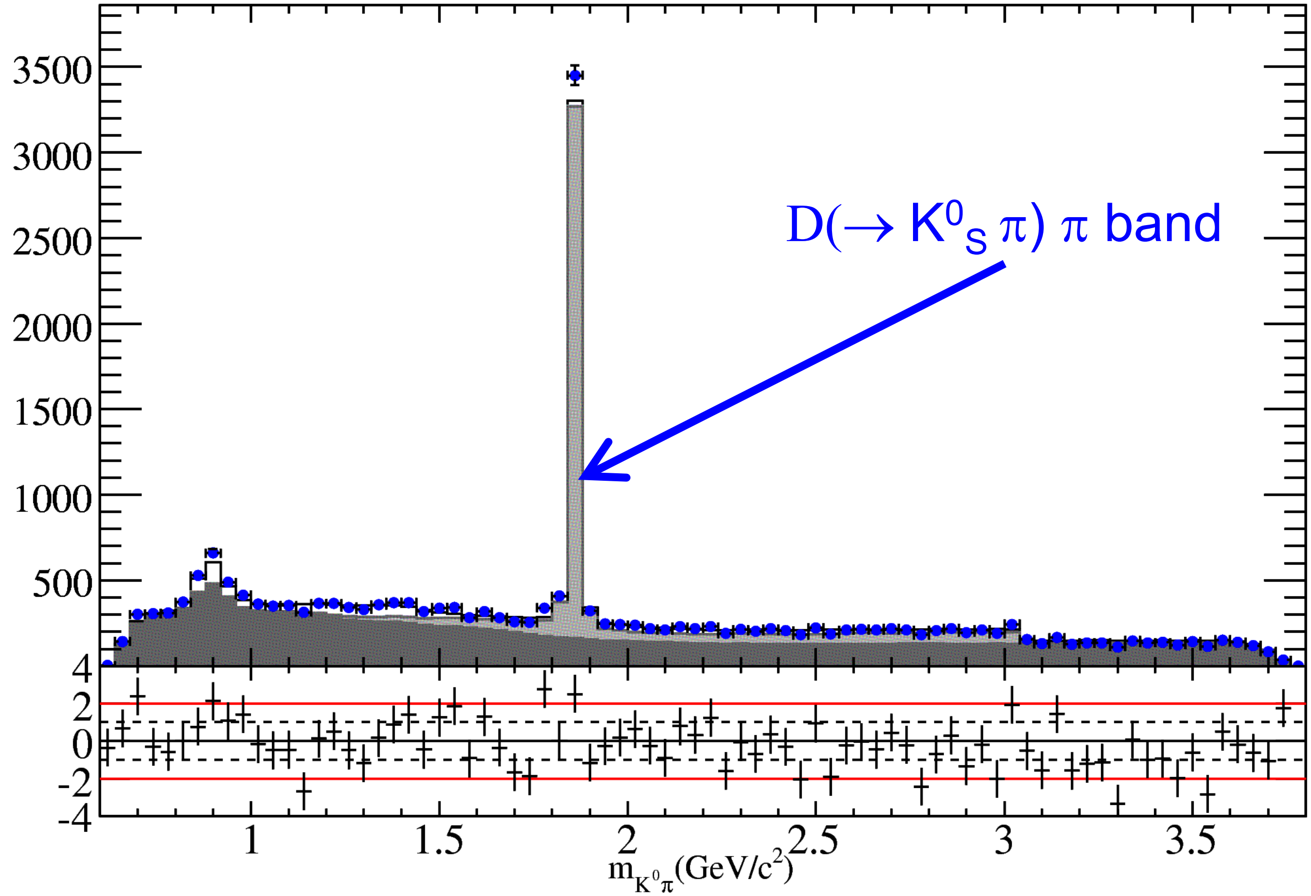
$B^0 \to \pi^+ \pi^- K^0_S$



$B^0 \to \pi^+ \pi^- K^0_S$

Results: goodness of fit – distributions of $m_{K\pi}$

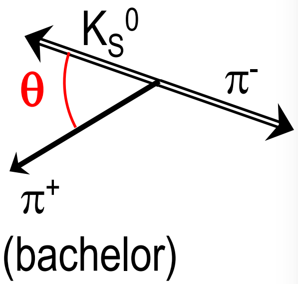
Invariant mass of the K and π system ($m_{K\pi}$) for all the events



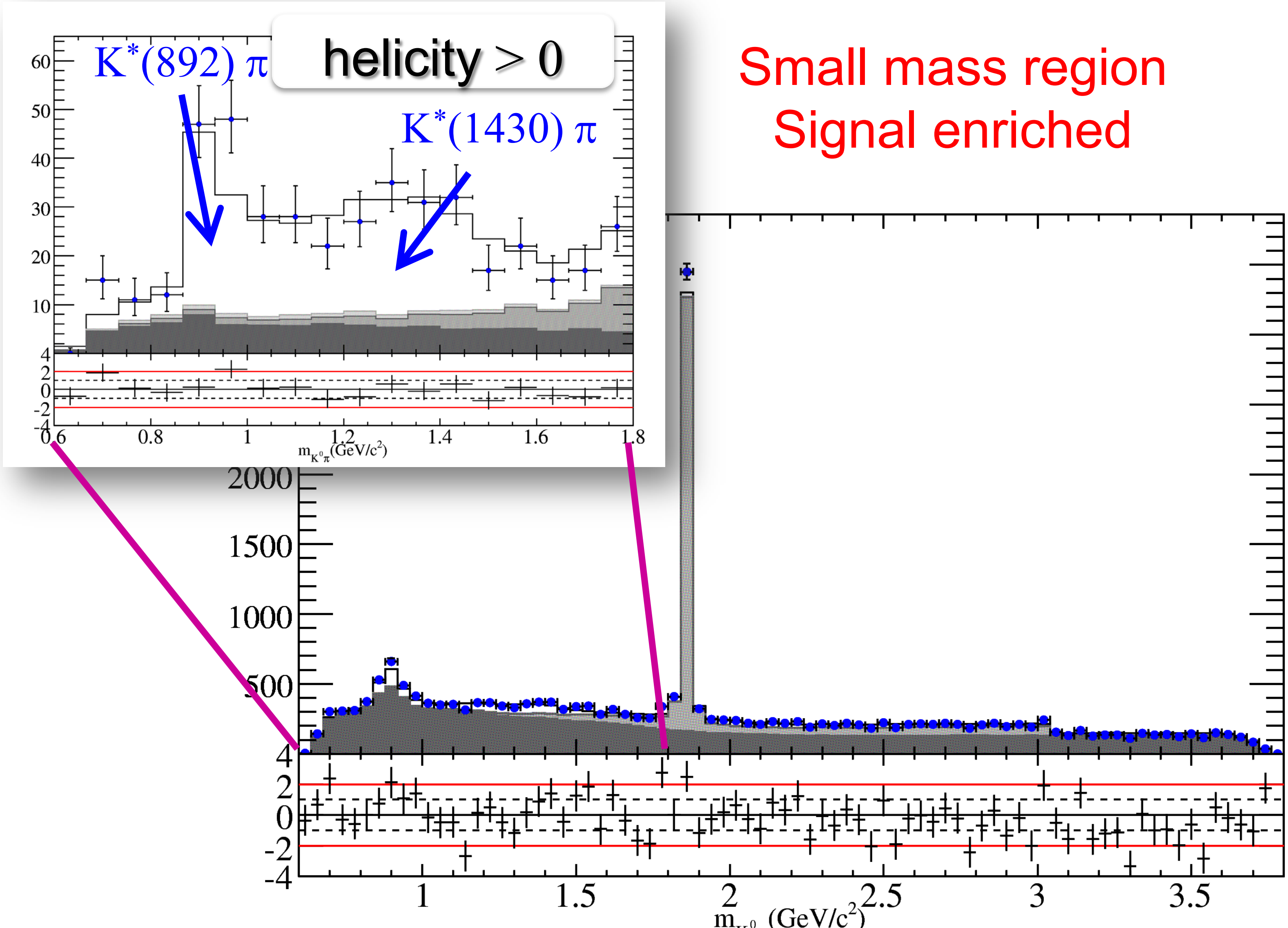
Results: goodness of fit – distributions of $m_{K\pi}$

$B^0 \to \pi^+ \pi^- K^0_S$

helicity = cosθ



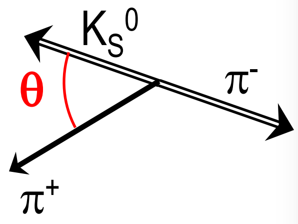
Small mass region
Signal enriched

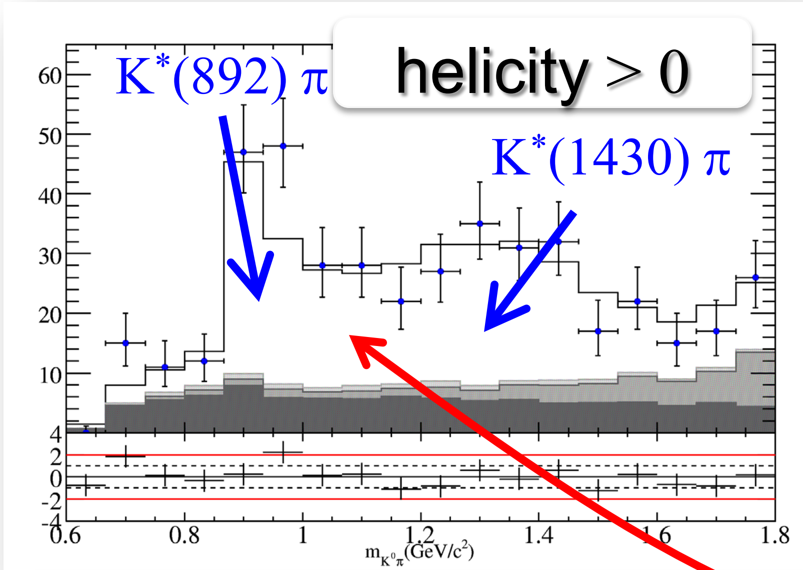


Results: goodness of fit – distributions of $m_{K\pi}$

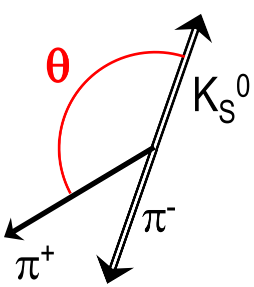
$B^0 \to \pi^+ \pi^- K^0_S$

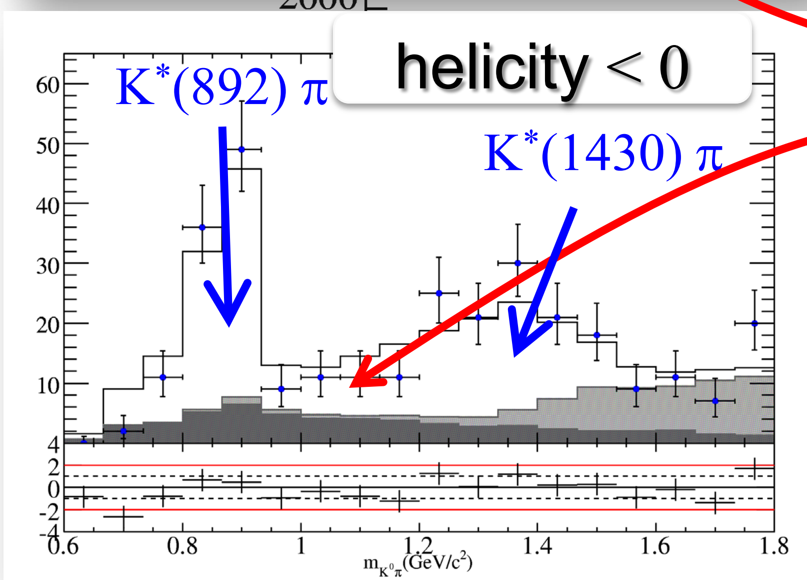
helicity = $\cos\theta$

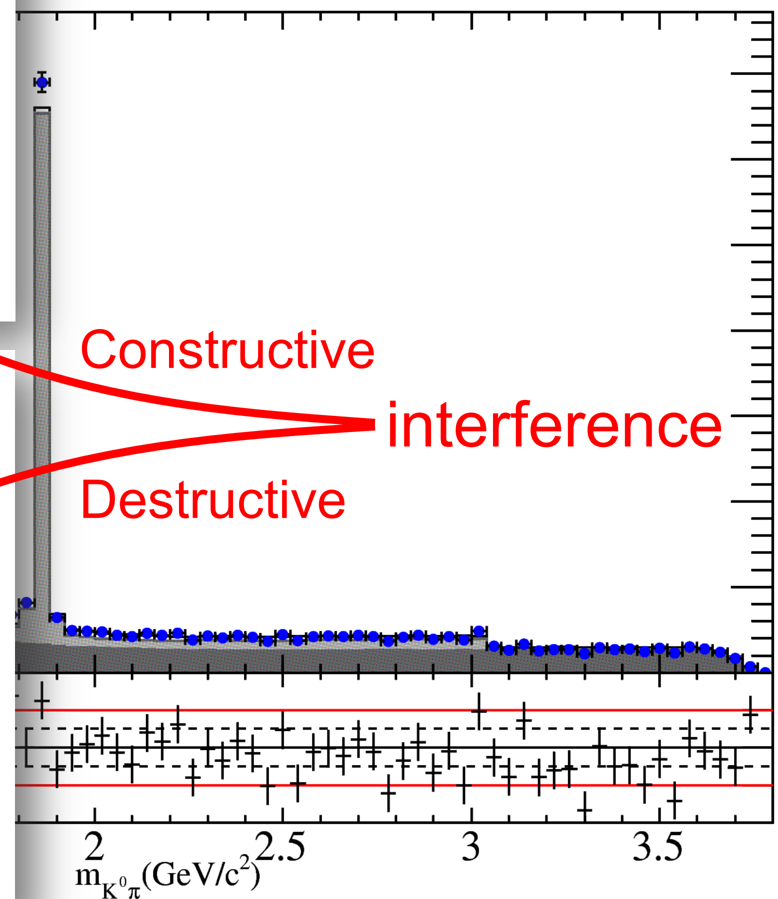




Small mass region
Signal enriched







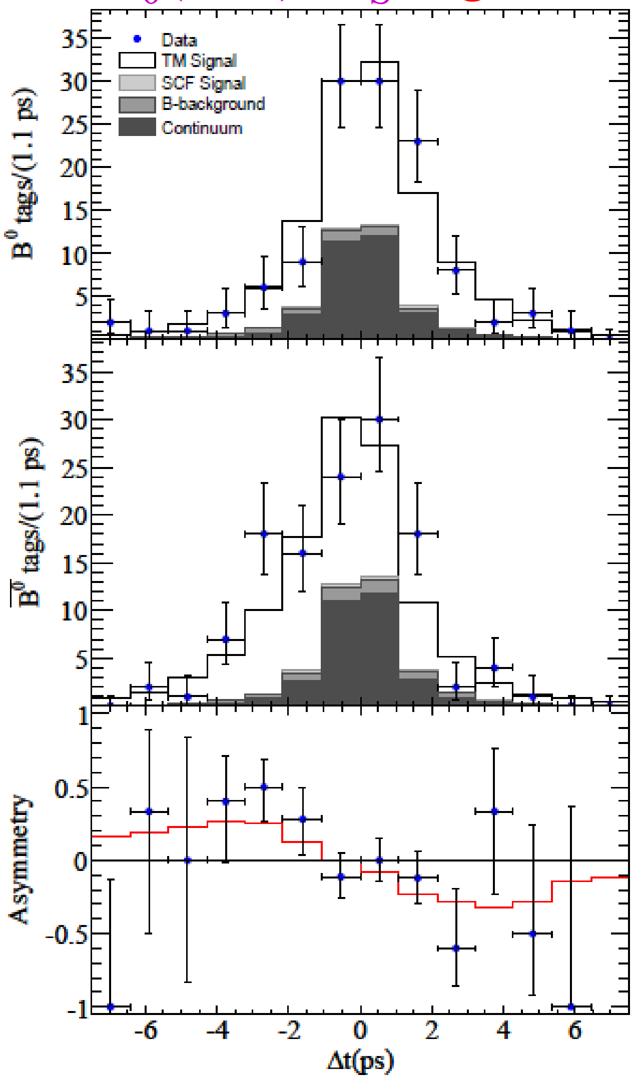
Constructive
interference
Destructive

Results: Δt and asymmetry for $f_0(980)\ K^0_S$

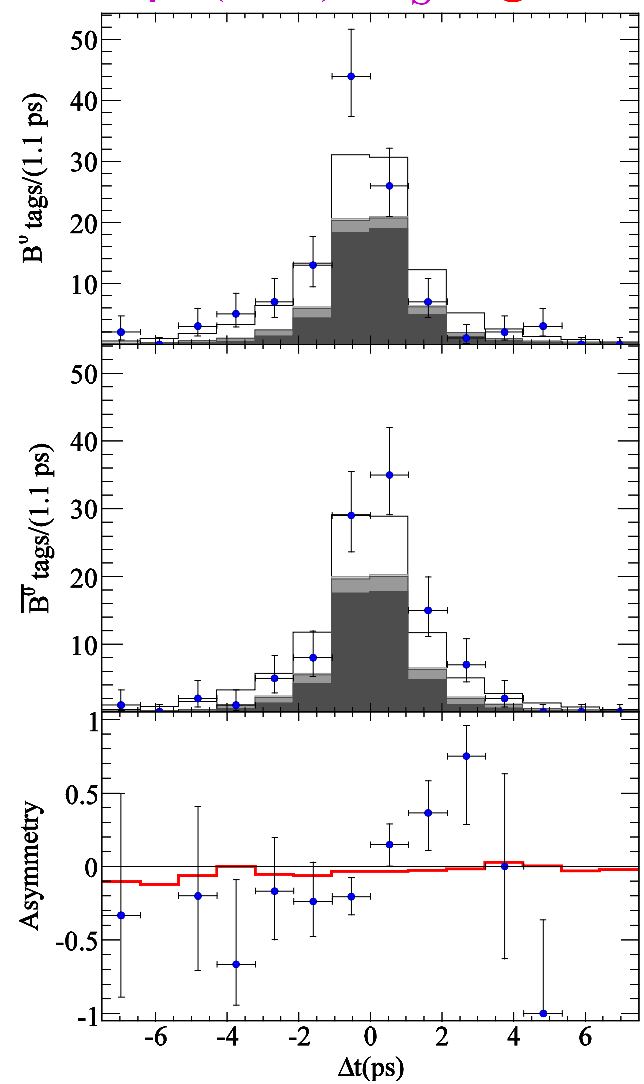
$B^0 \rightarrow \pi^+ \pi^- K^0_S$

Signal enriched sample

$f_0(980)K^0_S$ region



$\rho^0(770)K^0_S$ region



B^0 tagged events

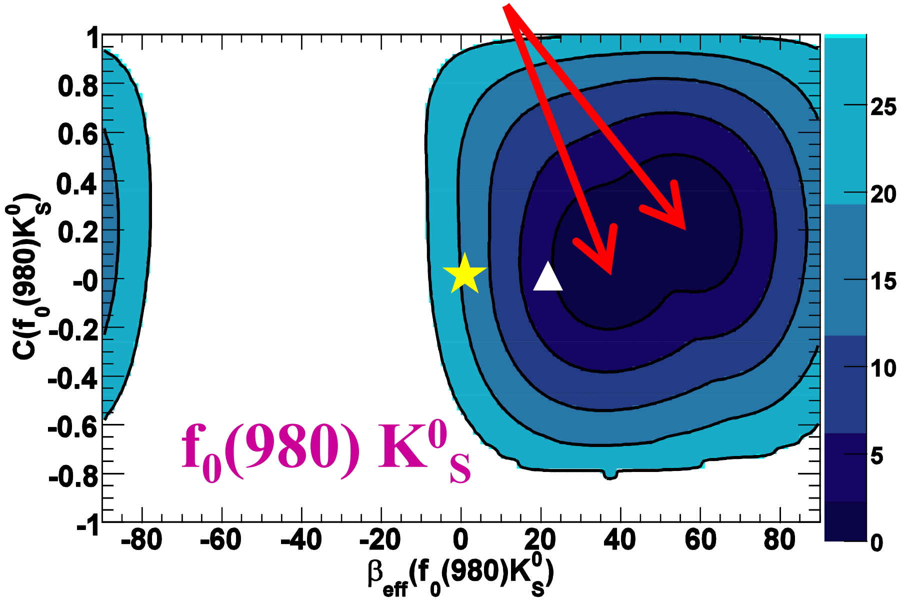
$\bar{B}^0$ tagged events

Asymmetry

$B^0 \rightarrow \pi^+ \pi^- K^0_S$

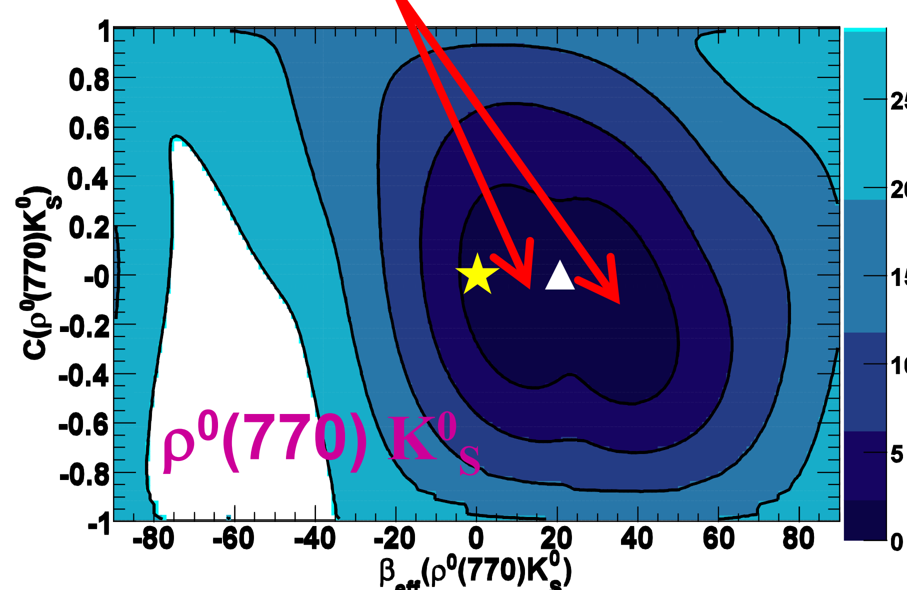
Results: CP parameters - C and β^{eff}

- Projections of the likelihood function (including systematic uncertainties) on the C - β^{eff} plan for $f_0(980)\ K^0_S$ and $\rho^0(770)\ K^0_S$.
- Contours represent the 1 to 5σ (Gaussian standard deviations) regions
- We have two solutions, almost degenerate in likelihood.



$18° < \beta^{eff}\ [f_0(980)\ K^0_S] < 76°$ (95% CL)

CP conservation (☆)excluded at 3.5σ
Agreement with $b \rightarrow c\bar{c}s$ value [β,0] (Δ) at 1.1σ



$-9° < \beta^{eff}\ [\rho^0(770)\ K^0_S] < 57°$ (95% CL)

Agrees both with CP conservation (☆) and with $b \rightarrow c\bar{c}s$ value [β,0] (Δ)

Results: information for the extraction of γ

$B^0 \to \pi^+ \pi^- K^0_S$

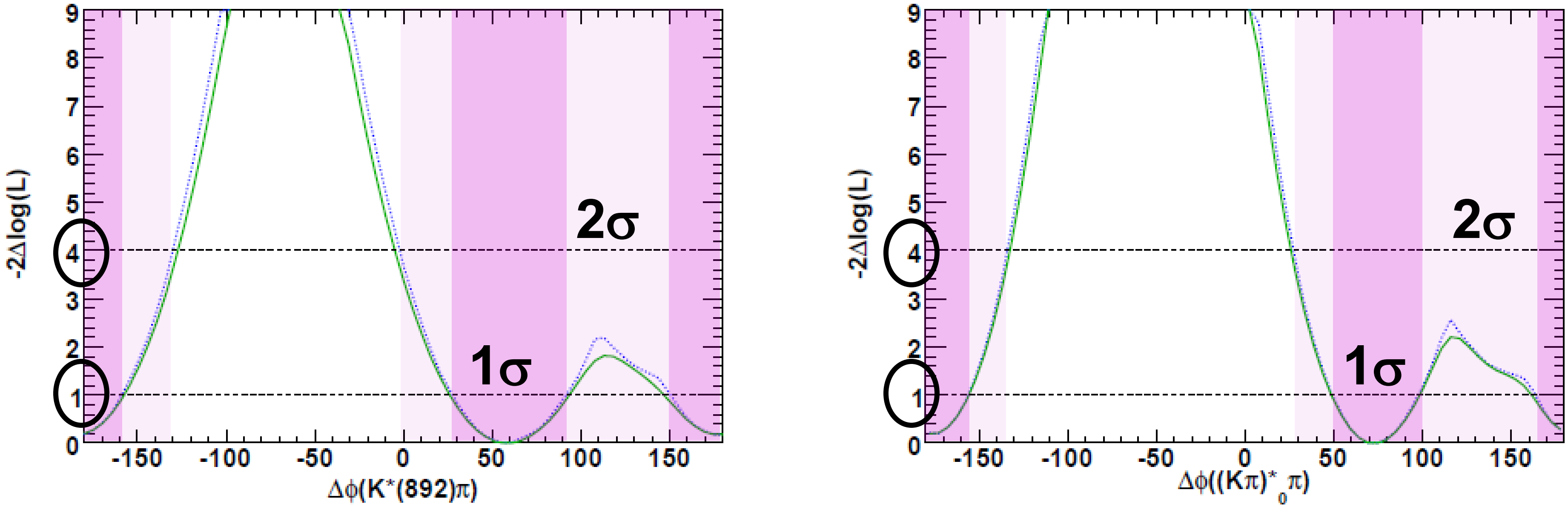
- CPS [PRD74:051301] and GPSZ [PRD75:014002] use the phase differences:

$$\Delta\Phi(K^*(892)\pi) \equiv \arg(C_{K^{*+}(892)\pi^-}) - \arg(C_{K^{*-}(892)\pi^+})$$

and $\Delta\Phi((K\pi)_{\text{S-wave}}\pi)$ to extract **information about the CKM angle γ**

(together with information from K^{*+} / K^{*0} from $K^+ \pi^- \pi^0$)

- The likelihood projection (including systematic uncertainties) on these parameters:



- The constraint obtained here is statistically limited

  e.g. -137° < Δφ [K*(892) π] < -5° excluded at 95% CL

- We also measure:

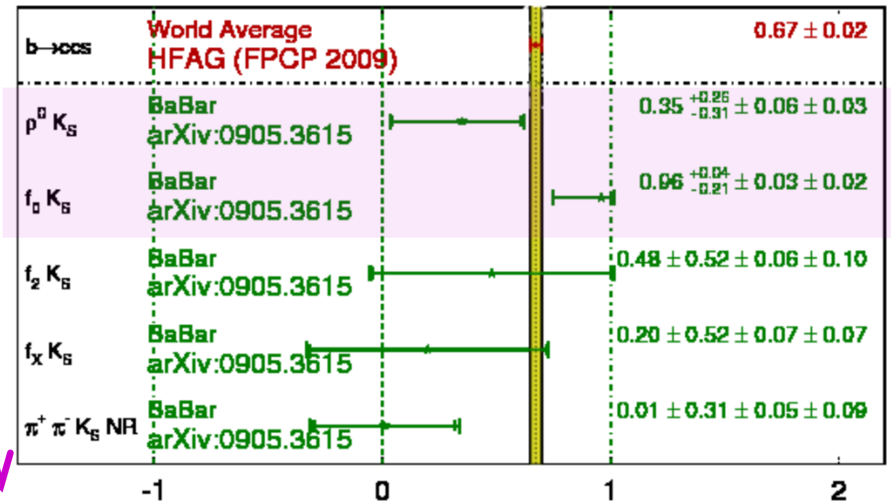
  $A_{CP}[K^*(892)\,\pi] = -0.21 \pm 0.10 \pm 0.01 \pm 0.02$; $A_{CP}[(K\pi)_{\text{S-wave}}\,\pi] = 0.09 \pm 0.07 \pm 0.02 \pm 0.02$

Results: summary and perspectives

$B^0 \to \pi^+ \pi^- K^0_S$

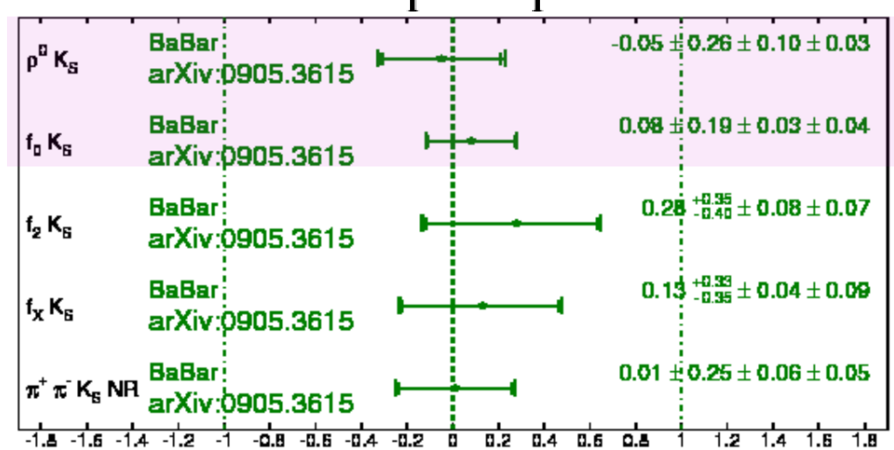
- Using 383M $B\bar{B}$ decays we measured 15 relative isobar magnitudes & phases
  - ⇒ 9 Branching Ratios
  - ⇒ 9 CP Asymmetries
  - ⇒ S and C for 5 modes
- A joint/combined Dalitz plot analysis with the Belle and BaBar likelihood functions is planned for this channel, using the full datasets. The joint analysis, apart from getting the best from the B-factory data might help to solve the multiple solution problem and provide more information about the f_X resonance. We plan to perform as a first step a common fit of the $B^+ \to K^+ \pi^- \pi^+$ channel that provides information about the signal model for the present one.

$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$



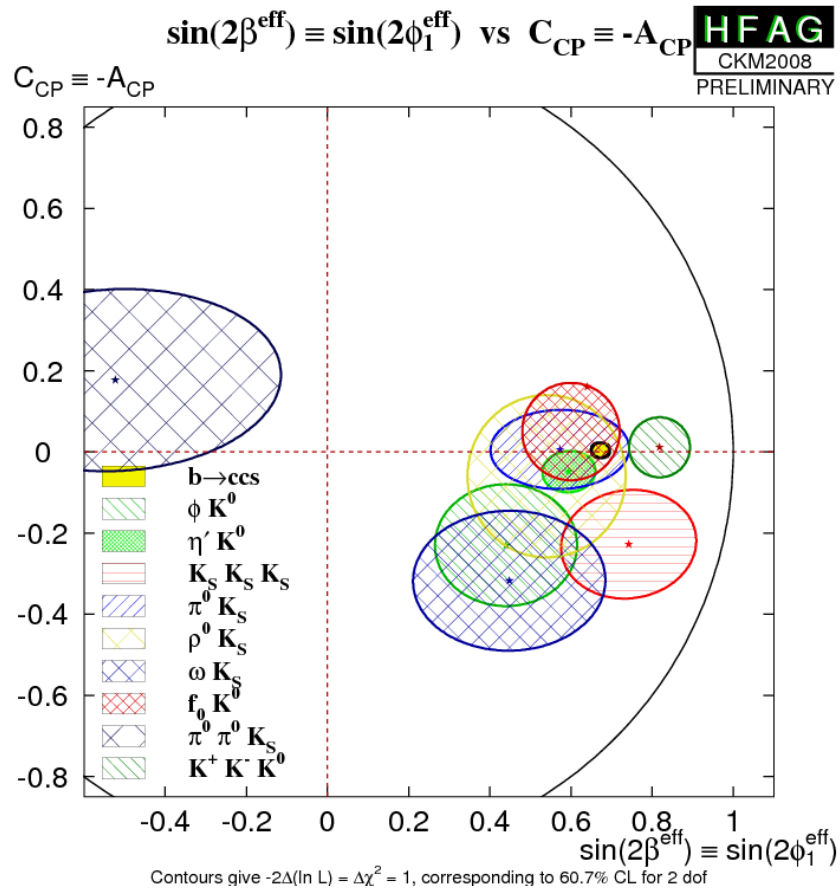
Only from the present analysis

$C_f = -A_f$



Summary and Conclusions

- BaBar is adding more information on sin2β and using more sophisticated analysis techniques to improve the precision of measurement in hadronic penguin modes
- Measurements of decay amplitudes in DP analyses can be used to set non-trivial constraints on the CKM parameters $(\bar{\rho}, \bar{\eta})$
- Overall, we observe an agreement between sin$2\beta^{(\mathrm{eff})}$ in $b\to c\bar{c}s$ and $b\to q\bar{q}s$
- Most of the b $\to$ s penguins still have $\sin 2\beta^{\mathrm{eff}} < \sin 2\beta$
- The actual statistics is not sufficient to tell whether or not this could be an indication for new physics.



This plot does not show all the measurements presented here, but is included for illustration of the general situation

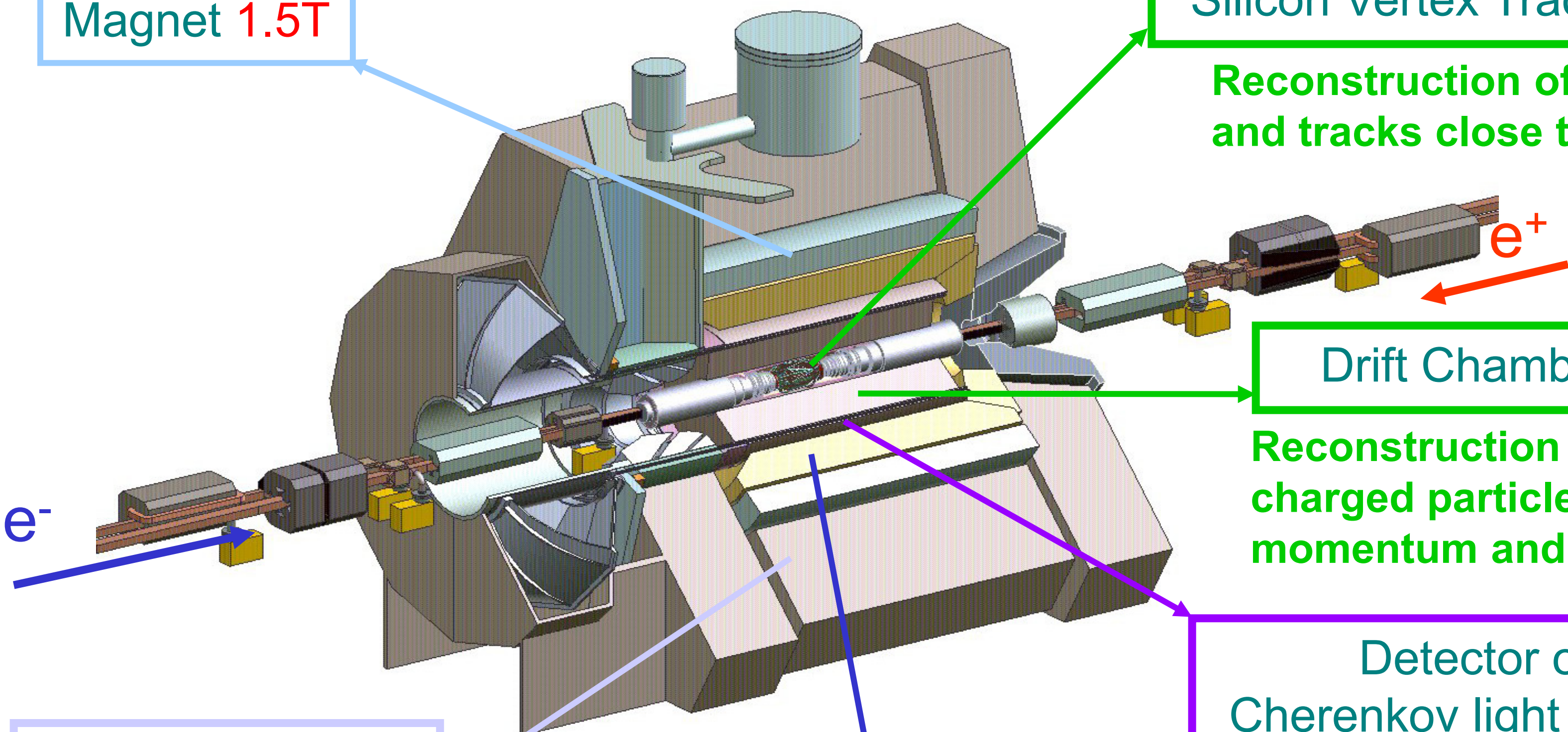
Backup

The BaBar Detector

Magnet 1.5T

Silicon Vertex Tracker (SVT)

Reconstruction of decay vertex and tracks close to the IP



Drift Chamber (DCH)

Reconstruction of deviated charged particles tracks: momentum and angles

Detector of Cherenkov light (DIRC)

Identification of charged particles
Separation $K/\pi > 2.5\sigma$ up to 4 GeV/c

Intrumented flux return (IFR)

Identification of $\mu^{+/-}$

Electromagnetic calorimeter (EMC)

Detection of γ, e^- identification
Reconstruction of $\pi^0 \to \gamma\gamma$, Energy measurement

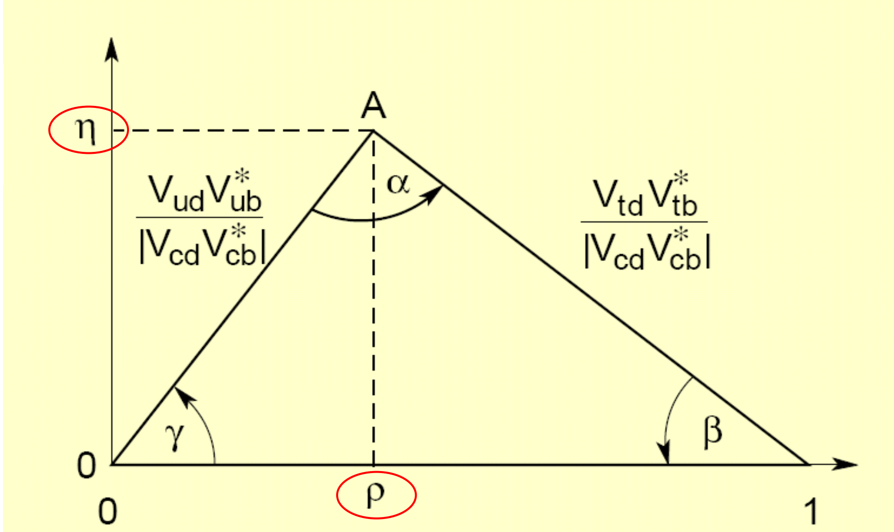
Quick Reminder of Basics

CKM matrix — Wolfenstein parameterization:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

V_{CKM} Unitarity $\Rightarrow$

$$\underbrace{V_{ud}V_{ub}^*}_{\propto\lambda^3} + \underbrace{V_{cd}V_{cb}^*}_{\propto\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{\propto\lambda^3} = 0$$



In other unitarity conditions (triangles) sides are very different.

Second and third columns: flat triangle for B_S

CP Violation is possible in the Standard Model only if

V_{CKM} is complex $\Leftrightarrow$ $\eta \neq 0$ $\Leftrightarrow$ Unitarity Triangle is not flat

We want to determine ρ and η experimentally

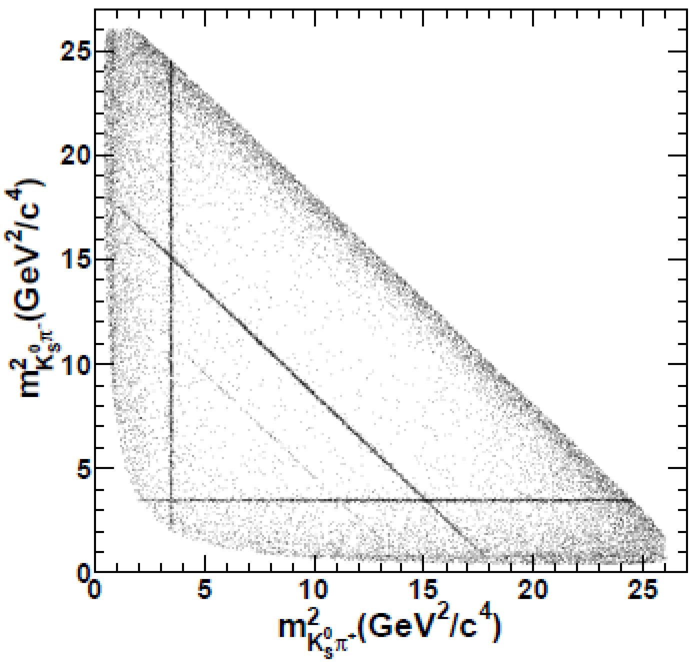
Systematic Uncertainties

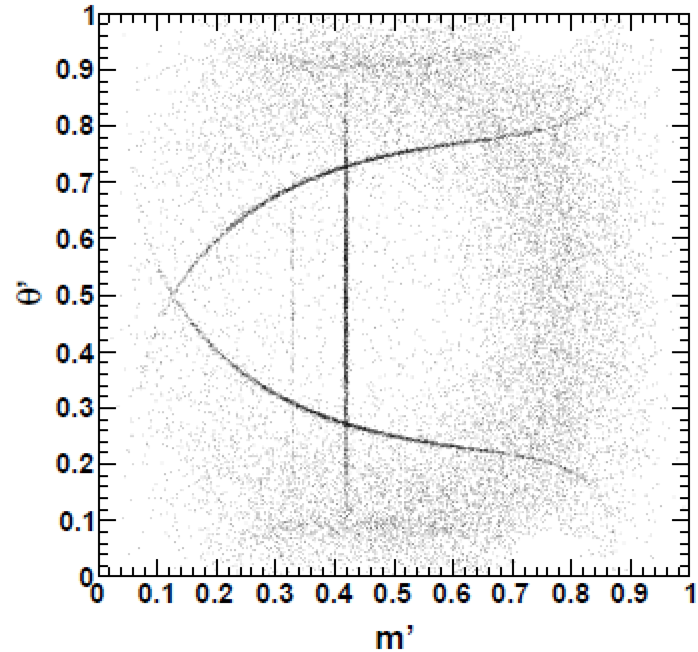
$B^0 \to \omega K^0_S, \eta' K^0_S, \eta' K^0_L, \pi^0 K^0_S$

Source	$S_{\omega K^0_S}$	$C_{\omega K^0_S}$	$S_{\eta' K^0_S}$	$C_{\eta' K^0_S}$	$S_{\eta' K^0_L}$	$C_{\eta' K^0_L}$	$S_{\pi^0 K^0_S}$	$C_{\pi^0 K^0_S}$
Variation of PDF parameters	0.012	0.019	0.006	0.009	0.009	0.007	0.010	0.012
Bias correction	0.010	0.007	0.006	0.005	0.014	0.009	0.011	0.001
Interference from DCSD on tag side	0.001	0.015	0.001	0.015	0.001	0.015	0.001	0.015
$B\overline{B}$ background	0.009	0.010	0.009	0.005	-	-	0.005	0.001
Signal Δt parameters from B_{flav}	0.002	0.001	0.009	0.015	0.004	0.008	0.016	0.011
SVT alignment	0.011	0.003	0.002	0.003	0.004	0.004	0.009	0.009
Beam-spot position and size	0.000	0.000	0.002	0.001	0.004	0.003	0.004	0.002
Vertexing method	-	-	-	-	-	-	0.008	0.016
Self-crossfeed	-	-	0.004	0.001	0.001	0.004	-	-
Total	0.021	0.028	0.016	0.024	0.018	0.021	0.025	0.028

Dataset and Square DP

$B^0 \to \pi^+ \pi^- K^0_S$





$$m' \equiv \frac{1}{\pi}\arccos\left(2\frac{m_0 - m_0^{\min}}{m_0^{\max} - m_0^{\min}} - 1\right), \quad \theta' \equiv \frac{1}{\pi}\theta_0$$

Total: 22525 candidates

Yields

Signal: 2182±64

Continuum : 14240±126

D pi: 3361 ± 60

J/psi Ks1804 ± 44

The Likelihood function

$$
\begin{aligned}
\mathcal{P}_i^c \;\equiv\; & N_{\rm sig} f_{\rm sig}^c \left[(1-\overline{f}^c_{\rm SCF}) \mathcal{P}^c_{{\rm sig-TM},i} + \overline{f}^c_{\rm SCF} \mathcal{P}^c_{{\rm sig-SCF},i} \right] \\
& + N^c_{q\bar{q}} \frac{1}{2} (1 + q_{{\rm tag},i} A_{q\bar{q}}) \, \mathcal{P}^c_{q\bar{q},i} \\
& + N_{B^+} f^c_{B^+} \frac{1}{2} (1 + q_{{\rm tag},i} A_{B^+}) \, \mathcal{P}^c_{B^+,i} \\
& + \sum_{j=1}^{N^{B^0}_{\rm class}} N_{B^0 j} f^c_{B^0 j} \mathcal{P}^c_{B^0,ij} \; .
\end{aligned}
$$

$$
\mathcal{P}^c_{X,i(j)} \;\equiv\; \prod_{k=1}^{4} P^c_{X,i(j)}(x_k)
$$

$$
X = \{ {\rm sig-TM},\ {\rm sig-SCF},\ q\bar{q},\ B^+,\ B^0 \}
$$

$$
\left.\begin{array}{l}
x_1 = m_{\rm ES},\ x_2 = \Delta E,\ x_3 = {\rm NN} \\
x_4 = \{ m', \theta', \Delta t \}:
\end{array}\right\} \text{Fit variables}
$$

Extracted Isobar Parameters

$B^0 \to \pi^+ \pi^- K^0_S$

	Solution I		Solution II	
Isobar Amplitude	Magnitude	Phase (°)	Magnitude	Phase (°)
$c_{f_0(980)K^0_S}$	4.0	0.0	4.0	0.0
$\bar{c}_{f_0(980)K^0_S}$	3.7 ± 0.4	-73.9 ± 19.6	3.2 ± 0.6	-112.3 ± 20.9
$c_{\rho(770)K^0_S}$	0.10 ± 0.02	35.6 ± 14.9	0.09 ± 0.02	66.7 ± 18.3
$\bar{c}_{\rho(770)K^0_S}$	0.11 ± 0.02	15.3 ± 20.0	0.10 ± 0.03	-0.1 ± 18.2
$c_{K^{*+}(892)\pi^-}$	0.154 ± 0.016	-138.7 ± 25.7	0.145 ± 0.017	-107.0 ± 24.1
$\bar{c}_{K^{*-}(892)\pi^+}$	0.125 ± 0.015	163.1 ± 23.0	0.119 ± 0.015	76.4 ± 23.0
$c_{(K\pi)^{*+}_0\pi^-}$	6.9 ± 0.6	-151.7 ± 19.7	6.5 ± 0.6	-122.5 ± 20.3
$\bar{c}_{(K\pi)^{*-}_0\pi^+}$	7.6 ± 0.6	136.2 ± 19.8	7.3 ± 0.7	52.6 ± 20.3
$c_{f_2(1270)K^0_S}$	0.014 ± 0.002	5.8 ± 19.2	0.012 ± 0.003	23.9 ± 22.7
$\bar{c}_{f_2(1270)K^0_S}$	0.011 ± 0.003	-24.0 ± 28.0	0.011 ± 0.003	-83.3 ± 24.3
$c_{f_X(1300)K^0_S}$	1.41 ± 0.23	43.2 ± 22.0	1.40 ± 0.28	85.9 ± 24.8
$\bar{c}_{f_X(1300)K^0_S}$	1.24 ± 0.27	31.6 ± 23.0	1.02 ± 0.33	-67.9 ± 22.1
c_{NR}	2.6 ± 0.5	35.3 ± 16.4	1.9 ± 0.7	56.7 ± 23.6
$\bar{c}_{NR}$	2.7 ± 0.6	36.1 ± 18.3	3.1 ± 0.6	-45.2 ± 17.8
$c_{\chi_{c0}K^0_S}$	0.33 ± 0.15	61.4 ± 44.5	0.28 ± 0.16	51.9 ± 38.4
$\bar{c}_{\chi_{c0}K^0_S}$	0.44 ± 0.09	15.1 ± 30.0	0.43 ± 0.08	-58.5 ± 27.9

Definition of Physical Parameters

$$\beta_{\rm eff}(k) = \frac{1}{2}\arg(c_k \bar{c}_k^*)$$

$$C(k) = \frac{|c_k|^2 - |\bar{c}_k|^2}{|c_k|^2 + |\bar{c}_k|^2}$$

$$S(k) = \frac{2\,\mathcal{I}m(\bar{c}_k c_k^*)}{|c_k|^2 + |\bar{c}_k|^2}$$

$$A_{CP}(k) = \frac{|\bar{c}_{\bar{k}}|^2 - |c_k|^2}{|\bar{c}_{\bar{k}}|^2 + |c_k|^2}$$

$$\phi(k,k') = \arg(c_k c_{k'}^*)$$

$$\bar{\phi}(k,k') = \arg(\bar{c}_k \bar{c}_{k'}^*)$$

$$\Delta\Phi(k) = \arg(c_k \bar{c}_k^*)$$

$$FF(k) = \frac{(|c_k|^2 + |\bar{c}_k|^2)\langle F_k F_k^* \rangle}{\sum_{\mu\nu}(c_\mu c_\nu^* + \bar{c}_\mu \bar{c}_\nu^*)\langle F_\mu F_\nu^* \rangle},$$

where the terms

$$\langle F_\mu F_\nu^* \rangle = \iint F_\mu F_\nu^* ds_+ ds_-$$

$$BF(k) = FF(k) \times \mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)$$

$$A_{CP}^{incl} = \frac{\iint \left(|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2\right) ds_+ ds_-}{\iint \left(|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2\right) ds_+ ds_-}$$

$B^0 \to \pi^+ \pi^- K^0_S$

Physical Parameters (I)

Parameter	Solution I	Solution II
$C(f_0(980)K^0_S)$	$0.08 \pm 0.19 \pm 0.03 \pm 0.04$	$0.23 \pm 0.19 \pm 0.03 \pm 0.04$
$\beta_{\rm eff}(f_0(980)K^0_S)$	$36.0 \pm 9.8 \pm 2.1 \pm 2.1$	$56.2 \pm 10.4 \pm 2.1 \pm 2.1$
$S(f_0(980)K^0_S)$	$-0.96^{+0.21}_{-0.04} \pm 0.03 \pm 0.02$	$-0.90^{+0.26}_{-0.08} \pm 0.03 \pm 0.02$
$\mathrm{Corr}[\beta_{\rm eff}(f_0(980)K^0_S), C(f_0(980)K^0_S)]$	-3.1%	-17.0%
$\mathrm{Corr}[S(f_0(980)K^0_S), C(f_0(980)K^0_S)]$	19.7%	12.5%
$FF(f_0(980)K^0_S)$	$13.8^{+1.5}_{-1.4} \pm 0.8 \pm 0.6$	$13.5^{+1.4}_{-1.3} \pm 0.8 \pm 0.6$
$C(\rho^0(770)K^0_S)$	$-0.05 \pm 0.26 \pm 0.10 \pm 0.03$	$-0.14 \pm 0.26 \pm 0.10 \pm 0.03$
$\beta_{\rm eff}(\rho^0(770)K^0_S)$	$10.2 \pm 8.9 \pm 3.0 \pm 1.9$	$33.4 \pm 10.4 \pm 3.0 \pm 1.9$
$S(\rho^0(770)K^0_S)$	$0.35^{+0.26}_{-0.31} \pm 0.06 \pm 0.03$	$0.91^{+0.07}_{-0.19} \pm 0.06 \pm 0.03$
$\mathrm{Corr}[\beta_{\rm eff}(\rho^0(770)K^0_S), C(\rho^0(770)K^0_S)]$	-23.0%	-34.0%
$\mathrm{Corr}[S(\rho^0(770)K^0_S), C(\rho^0(770)K^0_S)]$	-21.3%	-10.4%
$FF(\rho^0(770)K^0_S)$	$8.6^{+1.4}_{-1.3} \pm 0.5 \pm 0.2$	$8.5^{+1.3}_{-1.2} \pm 0.5 \pm 0.2$
$A_{CP}(K^*(892)\pi)$	$-0.21 \pm 0.10 \pm 0.01 \pm 0.02$	$-0.19^{+0.10}_{-0.11} \pm 0.01 \pm 0.02$
$\Delta\Phi(K^*(892)\pi)$	$58.3 \pm 32.7 \pm 4.6 \pm 8.1$	$176.6 \pm 28.8 \pm 4.6 \pm 8.1$
$FF(K^*(892)\pi)$	$11.0^{+1.2}_{-1.0} \pm 0.6 \pm 0.8$	$10.9^{+1.2}_{-1.0} \pm 0.6 \pm 0.8$
$A_{CP}((K\pi)^*_0\pi)$	$0.09 \pm 0.07 \pm 0.02 \pm 0.02$	$0.12^{+0.07}_{-0.06} \pm 0.02 \pm 0.02$
$\Delta\Phi((K\pi)^*_0\pi)$	$72.2 \pm 24.6 \pm 4.1 \pm 4.4$	$-175.1 \pm 22.6 \pm 4.1 \pm 4.4$
$FF((K\pi)^*_0\pi)$	$45.2 \pm 2.3 \pm 1.9 \pm 0.9$	$46.1 \pm 2.4 \pm 1.9 \pm 0.9$
$C(f_2(1270)K^0_S)$	$0.28^{+0.35}_{-0.40} \pm 0.08 \pm 0.07$	$0.09 \pm 0.46 \pm 0.08 \pm 0.07$
$\beta_{\rm eff}(f_2(1270)K^0_S)$	$14.9 \pm 17.9 \pm 3.1 \pm 5.2$	$53.6 \pm 16.7 \pm 3.1 \pm 5.2$
$S(f_2(1270)K^0_S)$	$-0.48 \pm 0.52 \pm 0.06 \pm 0.10$	$-0.95 \pm 0.17 \pm 0.06 \pm 0.10$
$\mathrm{Corr}[\beta_{\rm eff}(f_2(1270)K^0_S), C(f_2(1270)K^0_S)]$	11.5%	-2.8%
$\mathrm{Corr}[S(f_2(1270)K^0_S), C(f_2(1270)K^0_S)]$	0.9%	21.2%
$FF(f_2(1270)K^0_S)$	$2.3^{+0.8}_{-0.7} \pm 0.2 \pm 0.7$	$2.3^{+0.9}_{-0.7} \pm 0.2 \pm 0.7$

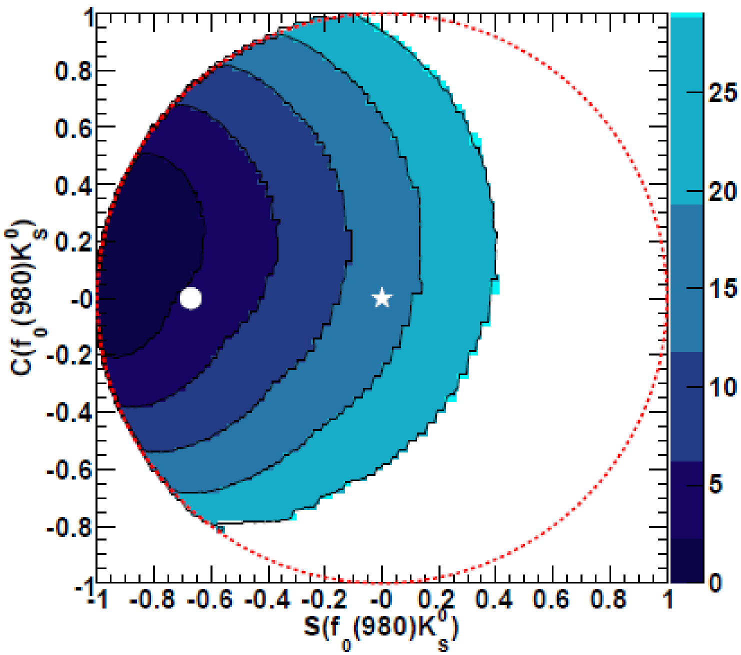
Physical Parameters (II)

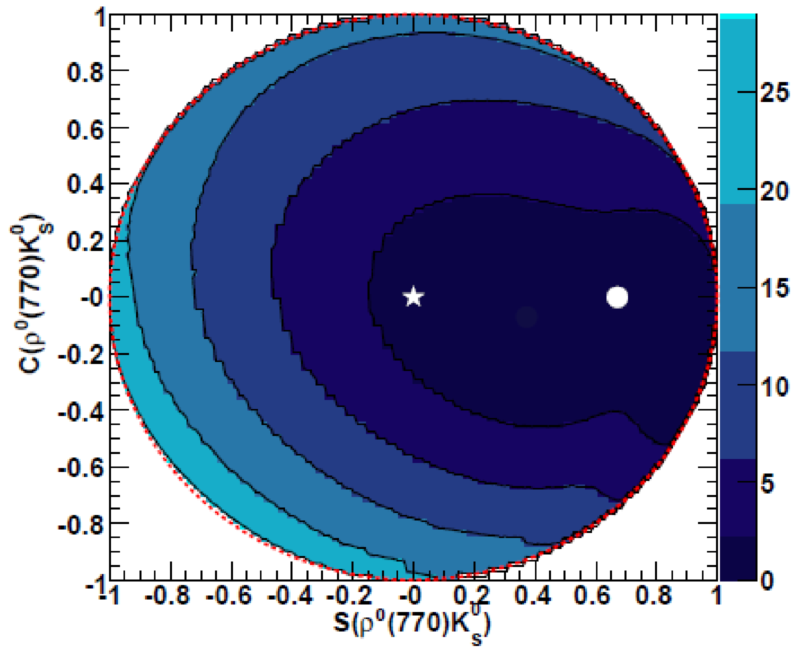
$B^0 \to \pi^+ \pi^- K^0_S$

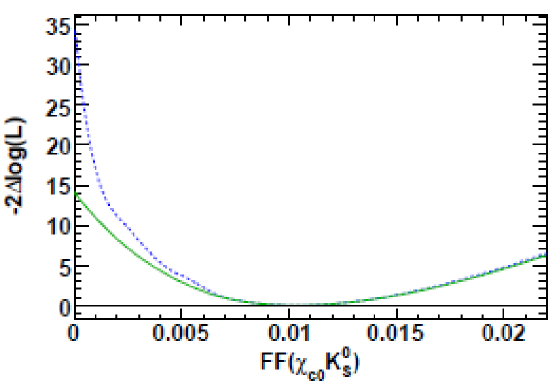
Parameter	Solution I	Solution II
$C(f_X(1300)K^0_S)$	$0.13^{+0.33}_{-0.35} \pm 0.04 \pm 0.09$	$0.30^{+0.34}_{-0.41} \pm 0.04 \pm 0.09$
$\beta_{\rm eff}(f_X(1300)K^0_S)$	$5.8 \pm 15.2 \pm 2.2 \pm 2.3$	$76.9 \pm 13.8 \pm 2.2 \pm 2.3$
$S(f_X(1300)K^0_S)$	$-0.20 \pm 0.52 \pm 0.07 \pm 0.07$	$-0.42 \pm 0.41 \pm 0.07 \pm 0.07$
$\mathrm{Corr}[\beta_{\rm eff}(f_X(1300)K^0_S), C(f_X(1300)K^0_S)]$	-27.0%	-9.3%
$\mathrm{Corr}[S(f_X(1300)K^0_S), C(f_X(1300)K^0_S)]$	28.5%	6.1%
$FF(f_X(1300)K^0_S)$	$3.6^{+1.0}_{-0.9} \pm 0.3 \pm 0.9$	$3.5^{+1.0}_{-0.8} \pm 0.3 \pm 0.9$
$C(NR)$	$0.01 \pm 0.25 \pm 0.06 \pm 0.05$	$-0.45^{+0.28}_{-0.24} \pm 0.06 \pm 0.05$
$\beta_{\rm eff}(NR)$	$0.4 \pm 8.8 \pm 1.9 \pm 3.8$	$51.0 \pm 13.3 \pm 1.9 \pm 3.8$
$S(NR)$	$-0.01 \pm 0.31 \pm 0.05 \pm 0.09$	$-0.87 \pm 0.18 \pm 0.05 \pm 0.09$
$\mathrm{Corr}[\beta_{\rm eff}(NR), C(NR)]$	-10.6%	-37.9%
$\mathrm{Corr}[S(NR), C(NR)]$	10.6%	-91.5%
$FF(NR)$	$11.5 \pm 2.0 \pm 1.0 \pm 0.6$	$12.6 \pm 2.0 \pm 1.0 \pm 0.6$
$C(\chi_{c0}K^0_S)$	$-0.29^{+0.53}_{-0.44} \pm 0.03 \pm 0.05$	$-0.41^{+0.54}_{-0.42} \pm 0.03 \pm 0.05$
$\beta_{\rm eff}(\chi_{c0}K^0_S)$	$23.2 \pm 22.4 \pm 2.3 \pm 4.2$	$55.2 \pm 23.3 \pm 2.3 \pm 4.2$
$S(\chi_{c0}K^0_S)$	$-0.69 \pm 0.52 \pm 0.04 \pm 0.07$	$-0.85 \pm 0.34 \pm 0.04 \pm 0.07$
$\mathrm{Corr}[\beta_{\rm eff}(\chi_{c0}K^0_S), C(\chi_{c0}K^0_S)]$	-5.8%	-5.8%
$\mathrm{Corr}[S(\chi_{c0}K^0_S), C(\chi_{c0}K^0_S)]$	-19.1%	-74.2%
$FF(\chi_{c0}K^0_S)$	$1.04^{+0.41}_{-0.33} \pm 0.04 \pm 0.11$	$0.99^{+0.37}_{-0.30} \pm 0.04 \pm 0.11$
total FF	$97.2^{+1.7}_{-1.3} \pm 2.1 \pm 1.15$	$98.3^{+1.5}_{-1.3} \pm 2.1 \pm 1.15$
A_{CP}^{incl}	$-0.01 \pm 0.05 \pm 0.01 \pm 0.01$	$0.01 \pm 0.05 \pm 0.01 \pm 0.01$
$\phi(f^0(980)K^0_S, \rho(770)K^0_S)$	$-35.6 \pm 14.9 \pm 6.1 \pm 4.4$	$-66.7 \pm 18.3 \pm 6.1 \pm 4.4$
$\phi(K^*(892)\pi, (K\pi)^*_0\pi)$	$13.0 \pm 10.9 \pm 4.6 \pm 4.7$	$15.5 \pm 10.2 \pm 4.6 \pm 4.7$
$\phi(\rho(770)K^0_S, K^*(892)\pi)$	$174.3 \pm 28.0 \pm 8.7 \pm 12.7$	$-173.7 \pm 29.8 \pm 8.7 \pm 12.7$
$\phi(\rho(770)K^0_S, (K\pi)^*_0\pi)$	$-172.8 \pm 22.6 \pm 10.1 \pm 8.7$	$-170.8 \pm 26.8 \pm 10.1 \pm 8.7$
$\bar{\phi}(f^0(980)K^0_S, \rho(770)K^0_S)$	$-89.2 \pm 17.1 \pm 8.5 \pm 7.2$	$-112.2 \pm 17.8 \pm 8.5 \pm 7.2$
$\bar{\phi}(K^*(892)\pi, (K\pi)^*_0\pi)$	$26.9 \pm 9.2 \pm 4.9 \pm 6.1$	$23.8 \pm 9.1 \pm 4.9 \pm 6.1$
$\bar{\phi}(\rho(770)K^0_S, K^*(892)\pi)$	$-147.8 \pm 24.7 \pm 11.3 \pm 11.9$	$-76.5 \pm 24.0 \pm 11.3 \pm 11.9$
$\bar{\phi}(\rho(770)K^0_S, (K\pi)^*_0\pi)$	$-120.9 \pm 21.6 \pm 8.7 \pm 7.3$	$-52.7 \pm 21.4 \pm 8.7 \pm 7.3$

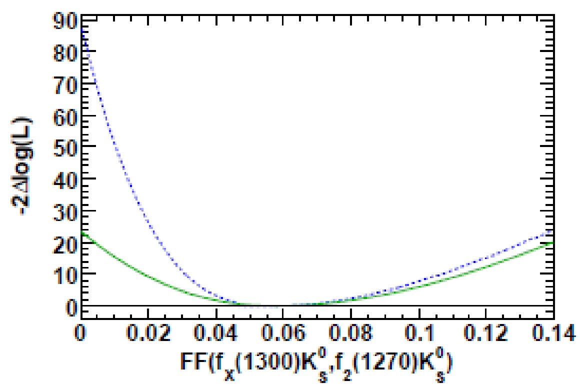
More Likelihood Projection Plots

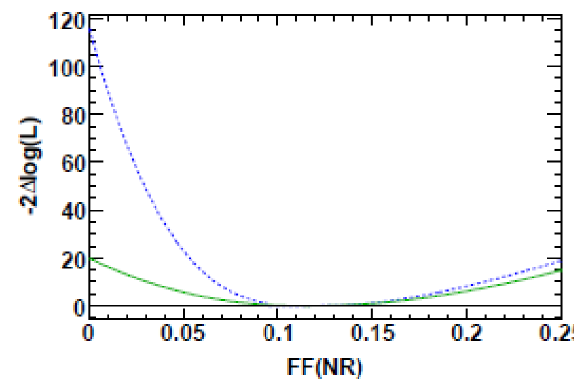
$B^0 \to \pi^+ \pi^- K^0_S$











Branching Fractions

$B^0 \to \pi^+ \pi^- K^0_S$

Mode	$\mathcal{B}(B^0 \to \text{Mode}) \times \mathcal{B}(R \to hh) \times 10^{-6}$	$\mathcal{B}(B^0 \to \text{Mode}) \times 10^{-6}$
Inclusive $B^0 \to K^0\pi^+\pi^-$	$\cdots$	$50.15 \pm 1.47 \pm 1.60 \pm 0.73$
$f_0(980)K^0$	$6.92 \pm 0.77 \pm 0.46 \pm 0.32$	$\cdots$
$\rho^0(770)K^0$	$4.31^{+0.70}_{-0.61} \pm 0.29 \pm 0.12$	$4.36^{+0.71}_{-0.62} \pm 0.29 \pm 0.12 \pm 0.01$
$K^{*+}(892)\pi^-$	$5.52^{+0.61}_{-0.54} \pm 0.35 \pm 0.41$	$8.29^{+0.92}_{-0.81} \pm 0.53 \pm 0.62$
$(K\pi)^{*+}_0\pi^-$	$22.7^{+1.7}_{-1.3} \pm 1.2 \pm 0.6$	$\cdots$
$f_2(1270)K^0$	$1.15^{+0.42}_{-0.35} \pm 0.11 \pm 0.35$	$2.71^{+0.99}_{-0.83} \pm 0.26 \pm 0.83^{+0.08}_{-0.04}$
$f_X(1300)K^0$	$1.81^{+0.55}_{-0.45} \pm 0.16 \pm 0.45$	$\cdots$
flat NR	$\cdots$	$5.77^{+1.61}_{-1.00} \pm 0.53 \pm 0.31$
$\chi_{c0}K^0$	$0.52^{+0.20}_{-0.16} \pm 0.03 \pm 0.06$	$142^{+55}_{-44} \pm 8 \pm 16 \pm 12$

Systematic Uncertainties

$B^0 \to \pi^+ \pi^- K^0_S$

Parameter	DP Model	Lineshape	Fit Bias	B Background	Other	Total
$C(f_0(980)K^0_S)$	0.04	0.02	<0.01	0.01	0.02	0.05
$FF(f_0(980)K^0_S)$	0.6	0.69	0.5	0.07	<0.01	1.03
$\beta_{\rm eff}(f_0(980)K^0_S)$	2.1	1.9	<0.1	0.2	0.3	2.9
$C(\rho^0(770)K^0_S)$	0.03	0.04	<0.01	0.06	0.06	0.10
$FF(\rho^0(770)K^0_S)$	0.23	0.31	0.3	0.09	0.15	0.52
$\beta_{\rm eff}(\rho^0(770)K^0_S)$	1.8	2.2	<0.1	1.2	1.7	3.5
$A_{CP}(K^*(892)\pi)$	0.02	<0.01	<0.01	<0.01	<0.01	0.02
$FF(K^*(892)\pi)$	0.8	0.13	0.4	0.03	0.43	1.00
$\Delta\Phi(K^*(892)\pi)$	8.1	2.8	<0.1	1.4	3.3	9.3
$A_{CP}((K\pi)^*_0\pi)$	0.02	<0.01	<0.01	<0.01	0.02	0.03
$FF((K\pi)^*_0\pi)$	0.90	0.39	1.8	0.12	0.33	2.08
$\Delta\Phi((K\pi)^*_0\pi)$	4.4	2.4	<0.1	1.3	3.0	6.0
$C(f_2(1270)K^0_S)$	0.07	0.04	<0.01	0.05	0.06	0.11
$FF(f_2(1270)K^0_S)$	0.69	0.16	0.09	0.02	0.19	0.74
$C(f_X(1300)K^0_S)$	0.09	0.03	<0.01	0.01	0.03	0.10
$FF(f_X(1300)K^0_S)$	0.87	0.28	0.14	0.02	0.17	0.94
$C(NR)$	0.04	0.01	<0.01	0.01	0.07	0.08
$FF(NR)$	0.60	0.86	0.5	0.12	1.62	2.00
$C(\chi_{c0}K^0_S)$	0.05	0.02	<0.01	0.01	0.02	0.06
$FF(\chi_{c0}K^0_S)$	0.09	0.06	0.04	<0.01	<0.01	0.11
A_{CP}^{incl}	<0.01	<0.01	<0.01	<0.01	0.01	0.01
FF_{Tot}	1.15	0.55	2.0	0.08	0.36	2.40
$\phi(f_0(980)K^0_S, \rho^0(770)K^0_S)$	4.4	2.6	<0.1	3.4	4.3	7.5
$\phi(\rho^0(770)K^0_S, K^*(892)\pi)$	12.7	3.0	<0.1	3.6	7.3	15.4
$\phi(\rho^0(770)K^0_S, (K\pi)^*_0\pi)$	8.7	8.5	<0.1	3.9	3.7	13.3
$\phi(K^*(892)\pi, (K\pi)^*_0\pi)$	4.7	0.7	<0.1	0.3	4.6	6.6
Signal Yield	31.7	5.8	14.0	3.3	23.0	42.1

Extraction of CKM Angle γ

$K^*\pi$ Isospin relations:

$$A(B^0\to K^{*+}\pi^-) = V_{us}V^*_{ub}T^{+-} + V_{ts}V^*_{tb}P^{+-}$$

$$A(B^+\to K^{*0}\pi^+) = V_{us}V^*_{ub}N^{0+} + V_{ts}V^*_{tb}(-P^{+-}+P^C_{EW})$$

$$A(B^+\to K^{*+}\pi^0) = V_{us}V^*_{ub}(T^{+-}+T^{00}-N^{0+}) + V_{ts}V^*_{tb}(P^{+-}-P^C_{EW}+P_{EW})$$

$$\sqrt{2}A(B^0\to K^{*0}\pi^0) = V_{us}V^*_{ub}T^{00} + V_{ts}V^*_{tb}(-P^{+-}+P_{EW})$$

No other hypothesis than Isospin is used

Taking the $B^0\to K^{*+}\pi^-$ and $B^0\to K^{*0}\pi^0$ subsystem

Neglecting P_{EW}, the amplitude combinations:

$$3A_{3/2} = A(B^0\to K^{*+}\pi^-) + \sqrt{2}.A(B^0\to K^{*0}\pi^0) = V_{us}V^*_{ub}(T^{+-}+T^{00})$$

$$3\overline{A}_{3/2} = \overline{A}(\overline{B^0}\to K^{*-}\pi^+) + \sqrt{2}.\overline{A}(\overline{B^0}\to \overline{K^{*0}}\pi^0) = V^*_{us}V_{ub}(T^{+-}+T^{00})$$

Gives: $R_{3/2} = (3A_{3/2})/(3\overline{A}_{3/2}) = e^{-2i\gamma}$

CPS PRD74:051301
GPSZ PRD75:014002

Direct access to γ CKM angle

Extraction of CKM Angle γ

From experiment:

Measurable from $K^+\pi^-\pi^0$ and $K^0_S\pi^+\pi^-$

- $|A(B^0\to K^{*+}\pi^-)|$ and $|A(B^0\to K^{*0}\pi^0)|$
- $|\bar{A}(B^0\to \bar{K}^{*-}\pi^+)|$ and $|\bar{A}(\bar{B}^0\to \bar{K}^{*0}\pi^0)|$

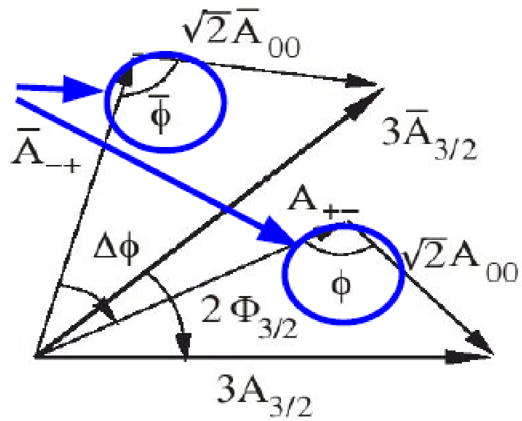
Through BRs and A_{CP}

Measurable from $K^+\pi^-\pi^0$

$\phi = \arg(A(B^0\to K^{*+}\pi^-)A^*(B^0\to K^{*0}\pi^0))$

$\bar{\phi} = \arg(\bar{A}(\bar{B}^0\to K^{*-}\pi^+)\bar{A}^*(\bar{B}^0\to \bar{K}^{*0}\pi^0))$

Through interference in the same DP B^0(B^0-bar) plane



Measurable from $K^0_S\pi^+\pi^-$

$\Delta\phi = \arg(\bar{A}(\bar{B}^0\to K^{*-}\pi^+)A^*(B^0\to K^{*+}\pi^-))$

Through interference with other components