New sources of CP Violation at BaBar (CP violation in τ and 3 body B decays)

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Introduction

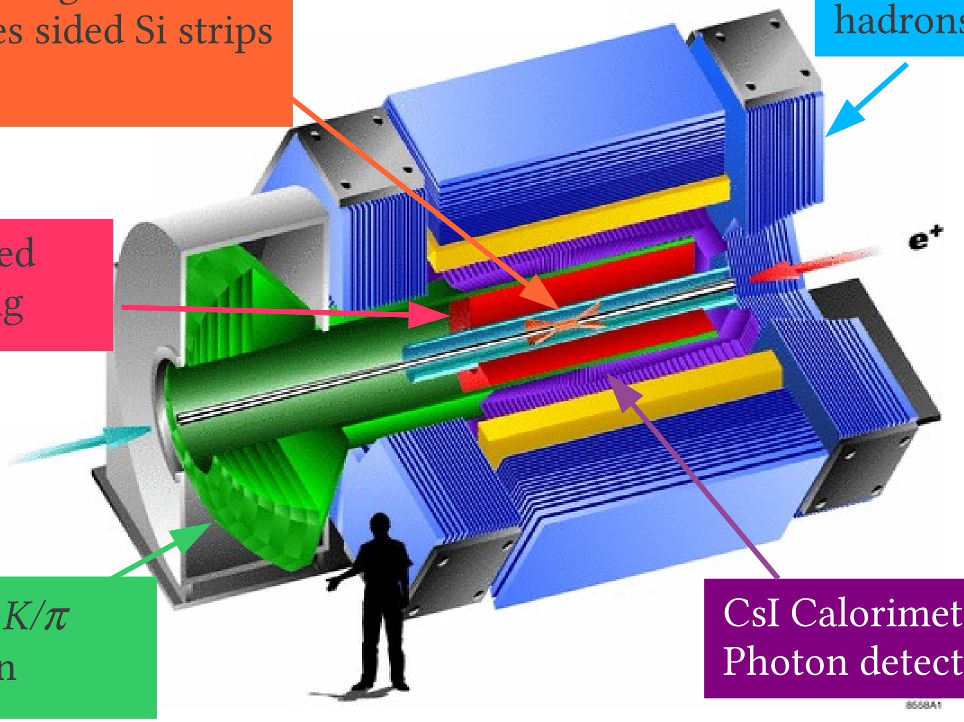
- Flavor physics experiments have measured precisely CP violation and the parameters of the CKM matrix in B and D decays
  - No significant inconsistencies or deviations from SM have been observed
- $\longrightarrow$ The CKM mechanism describe very well the observed pattern of CP violation
  - However ~3 σ tensions in Vub, $B \longrightarrow \tau\nu$, $B \longrightarrow D^{(*)}\tau\nu$, A_{SL}, ΔA_{CP}^{D}
  - Search for CP violation in lepton decays: there is no SM mechanism so the new physics signature is clean.
  - Precisely Measure $\sin 2\beta$ in $b \longrightarrow s q\bar{q}$ decays to see the indirect effect of high mass scale new physics in the $b \longrightarrow s$ loop
  - Search for CPV in $b \longrightarrow s\gamma$, $b \longrightarrow sll$ decays again to see the effect of new physics in the $b \longrightarrow s$ loop and SM can make precise predictions

Synopsis

- $B \to K^{(*)}ll$:
  - Differential BF and direct CP asymmetry [arXiv:1204.3933]
- $B \to K_S K_S K_S$
  - Dalitz Plot <CP>, time dependent CPV <DP>, S~sin2β, C~0 [PRD85, 054 023]
- $B \to KKK$
  - Time dependent CP violation with DP analysis, S~sin2β and C~0 [arXiv:1201.5897]
- $\tau^+ \to K_S \pi^+ \nu$
  - Direct CP violation, A_{CP}~0 (⟵ from τ decay)[Phys.Rev. D85 (2012) 031 102]

BABAR Detector at PEPII

Nucl.Instrum.Meth.A479:1-116,2002



Trigger
L1 ~2KHz, L3 120Hz
Trigger eff. ~98%

Y(4S) C.M.
Energy

Integrated Luminosity 1999 – 2008

On-Peak 424 fb^{-1} ~465 MBB

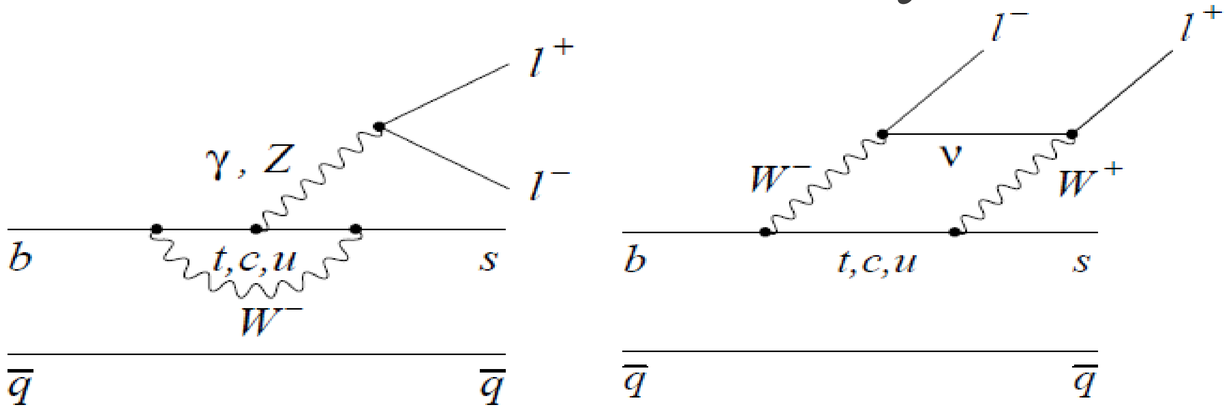
Off-Peak 44 fb^{-1},

100M Υ(2S), 120M Υ(3S), 4fb^{-1} above Υ(4S)

$$M_{ES}=\sqrt{(s/2+\mathbf{p_0 p_B})^2/E_0^2-p_B^2}$$

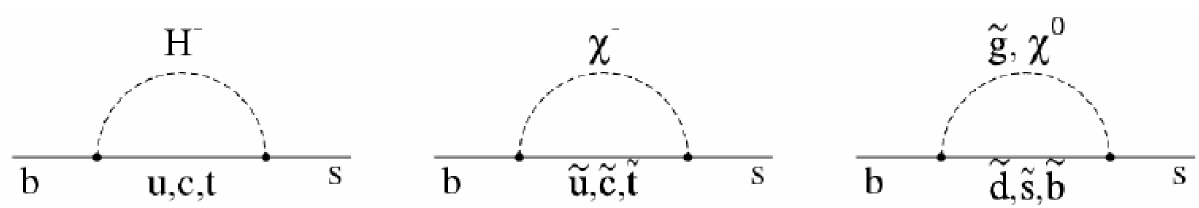
$$\Delta E=E_B^*-\frac{\sqrt{s}}{2}$$

B→K$^{(*)}$ll rates and asymmetries



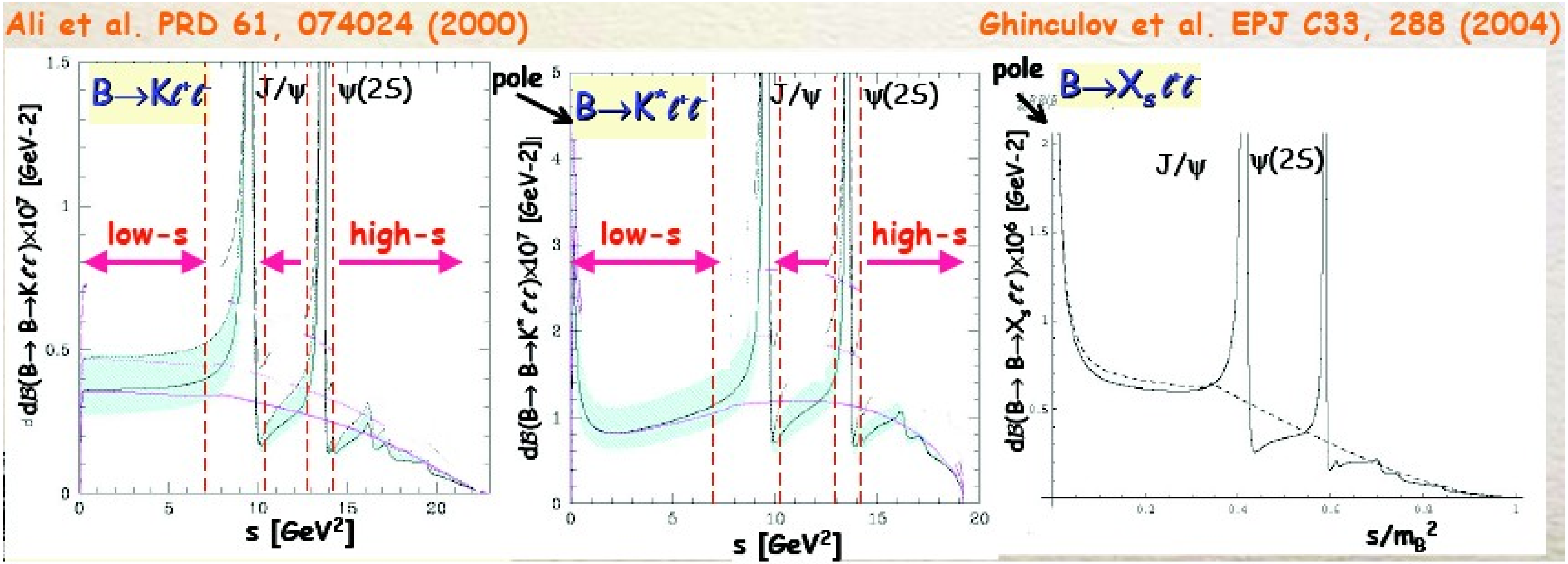
EM penguin encoded in C7, EW penguin & W-box encoded in C9 & C10

- Effective Wilson coeff. (C_i) encode short distance physics, calculated to NNLO in SM to ~5% accuracy
- BF and asymmetries can be studied as a function of m_{ll}^2
- Coefficients can be affected by NP entering at the same order as the SM observables and give a different dependence on m_{ll}^2



$K^{(*)}l^+l^-$: signal extraction

- Reconstruct $B^{+(0)} \rightarrow K^{+(0)}l^+l^-$, $B^{+(0)} \rightarrow K^{*(0)}l^+l^-$, $l=e,\mu$
- Tight particle ID on e,μ,K to reduce fakes
- Neural Net suppression of combinatoric background ($q\underline{q}$ and $B\underline{B}$)
- Veto most peaking background ($J/\psi,\psi(2S),D(K^*\pi)\pi)l^+l^-$
- J/ψ ll used as a control sample.



ArXiv:1204.3933

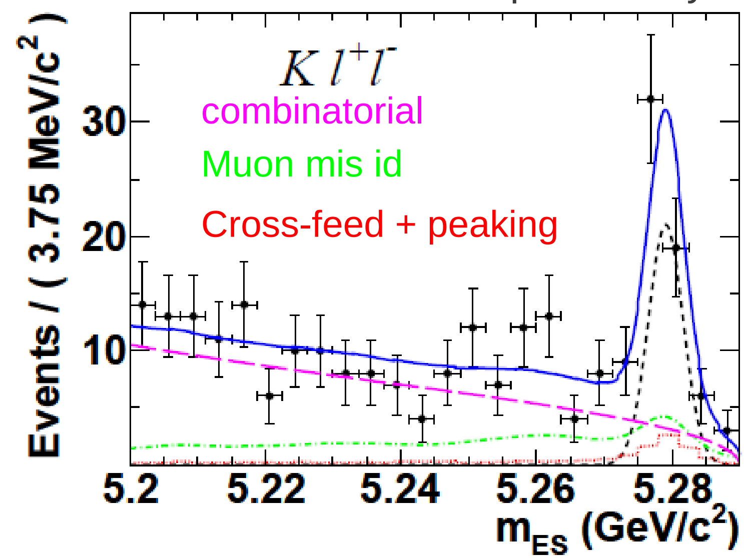
BABAR preliminary

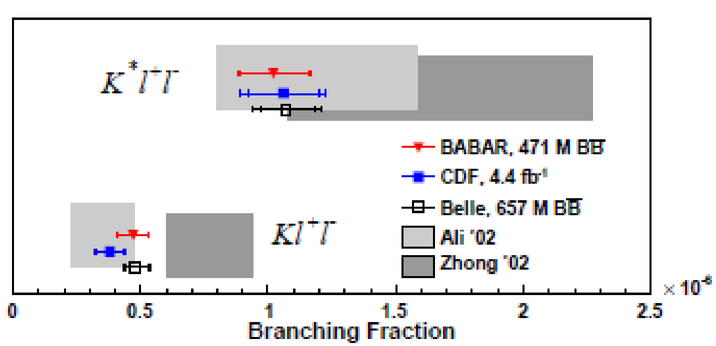
BF results

- Signal extracted from ML fit to M_{ES} and ΔE $M_{ES} = \sqrt{(s/2 + \boldsymbol{p_0 p_B})^2 / E_0^2 - p_B^2}$ $\Delta E = E_B^* - \frac{\sqrt{s}}{2}$
- Total BF

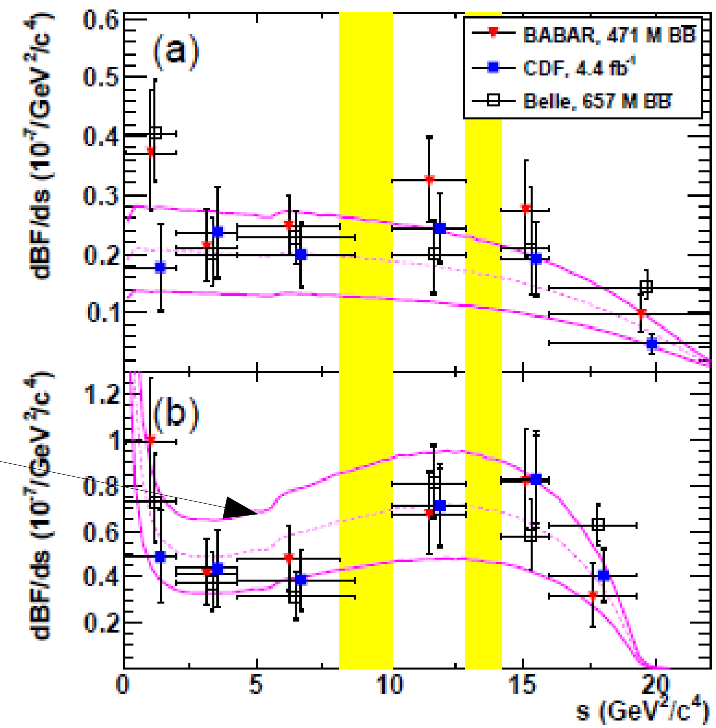
$$\mathcal{B}(B \to K\ell^+\ell^-) = (4.7 \pm 0.6 \pm 0.2) \times 10^{-7},$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (10.2^{+1.4}_{-1.3} \pm 0.5) \times 10^{-7}.$$

- BaBar Belle and CDF [and LHCb] agree with SM prediction





SM Based predictions with uncertainties



K$^{(*)}$ll Isospin asymmetry

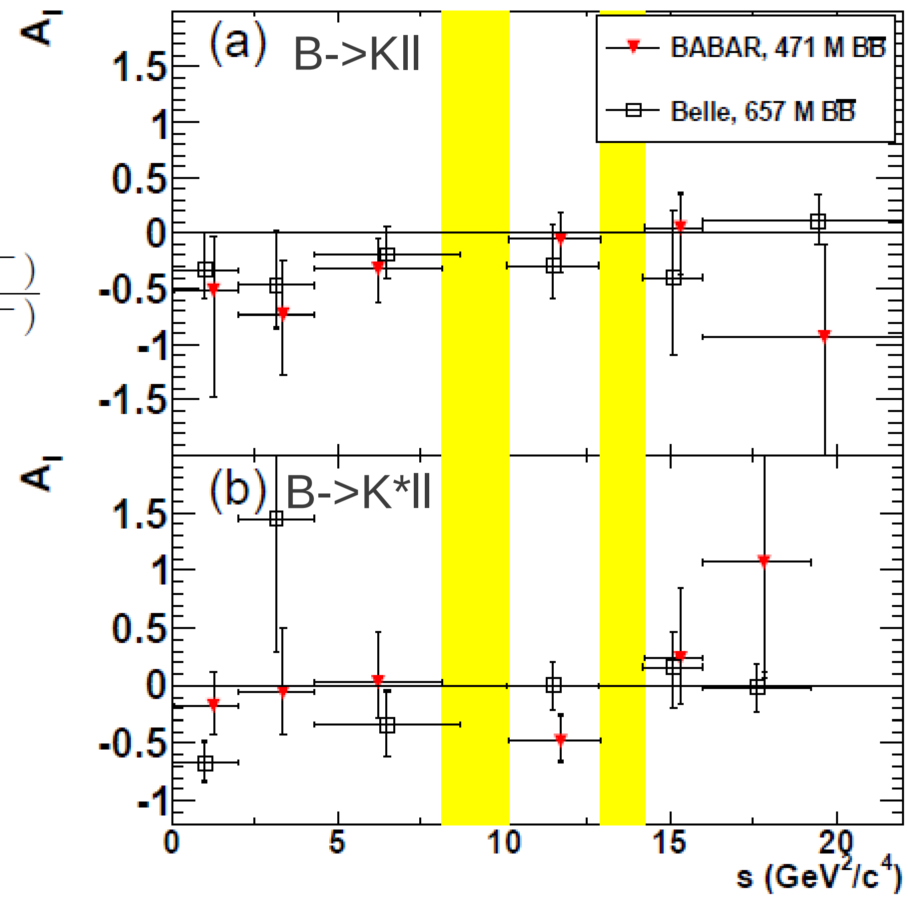
ArXiv:1204.3933
BABAR preliminary

- Isospin asymmetries as the difference between B^0 and $B^{\pm}$

$$\mathcal{A}_I^{K^{(*)}} \equiv \frac{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - r_\tau \mathcal{B}(B^+ \to K^{(*)+}\ell^+\ell^-)}{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + r_\tau \mathcal{B}(B^+ \to K^{(*)+}\ell^+\ell^-)}$$

- In SM expect very small asymmetries O(1%)
- Measure the asymmetry below J/ψ (0.1<s<8.12 GeV^2/c^4)

$$\mathcal{A}_I^{\text{low}}(B \to K\ell^+\ell^-) = -0.58^{+0.29}_{-0.37} \pm 0.02 \;\; [2.1\sigma],$$
$$\mathcal{A}_I^{\text{low}}(B \to K^*\ell^+\ell^-) = -0.25^{+0.20}_{-0.17} \pm 0.03 \;\; [1.2\sigma],$$



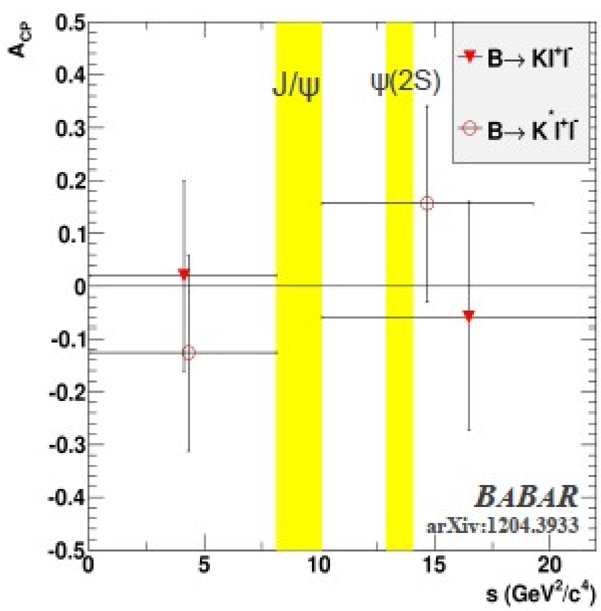
- Consistent with SM predictions at 2σ and agree with Belle results

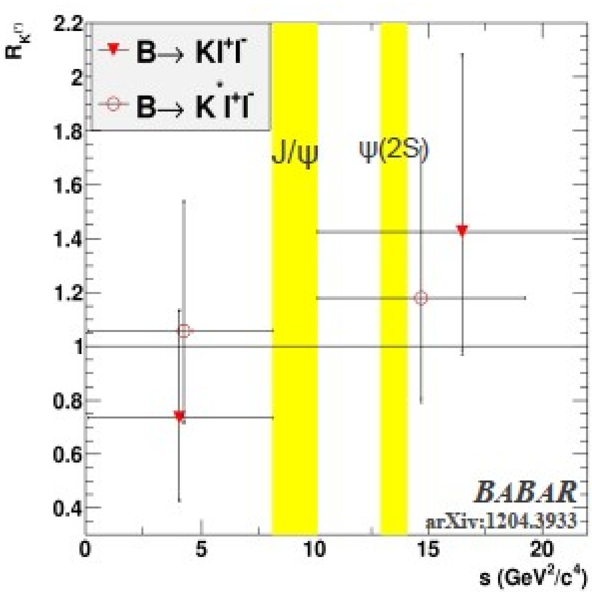
CP Asymmetry

- Direct CP asymmetries agrees with SM expectation (0)
- Lepton flavor ratio agree with unity

s (GeV$^2/c^4$)	$A_{CP}(B^+ \to K^+\ell^+\ell^-)$	$A_{CP}(B \to K^*\ell^+\ell^-)$
All	$-0.03 \pm 0.14 \pm 0.01$	$0.03 \pm 0.13 \pm 0.01$
0.10–8.12	$0.02 \pm 0.18 \pm 0.01$	$-0.13^{+0.18}_{-0.19} \pm 0.01$
>10.11	$-0.06^{+0.22}_{-0.21} \pm 0.01$	$0.16^{+0.18}_{-0.19} \pm 0.01$

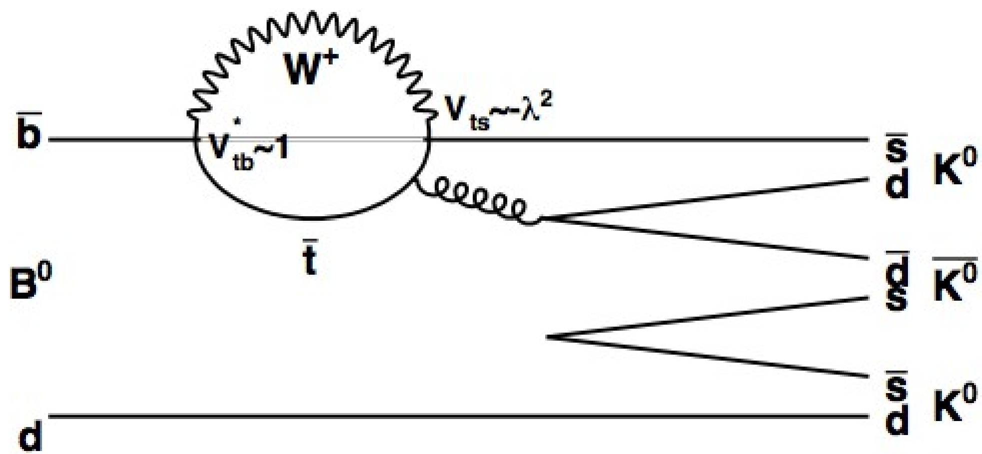
s (GeV$^2/c^4$)	$\mathcal{R}_K$	R_{K^*}
All	$1.00^{+0.31}_{-0.25} \pm 0.07$	$1.13^{+0.34}_{-0.26} \pm 0.10$
0.10–8.12	$0.74^{+0.40}_{-0.31} \pm 0.06$	$1.06^{+0.48}_{-0.33} \pm 0.08$
>10.11	$1.43^{+0.65}_{-0.44} \pm 0.12$	$1.18^{+0.55}_{-0.37} \pm 0.11$





TD CPV in $B^0 \longrightarrow K_S K_S K_S$: motivation

- Penguin loop dominated – NP sensitive at large scales
- CP=+1 => time dependent CPV analysis
- $b \longrightarrow s$ loop diagram has the same weak phase as $b \longrightarrow c\bar{c}\ K^{(*)}$



- However $b \longrightarrow u$ pollution and new physics contributions could depend on the resonance structure -> study Dalitz plot
  - Study the poorly understood $f_x(1500)$

Signal Modeling

- Dalitz Plot: time integrated , CP averaged:
  - 3 identical particles in the final state ⇒ amplitudes are symmetric for exchange of two K_S

$$d\Gamma(B \to K_S^0 K_S^0 K_S^0) = \frac{1}{(2\pi)^3} \frac{|\mathcal{A}|^2}{32 m_{B^0}^3} ds_{\min} ds_{\max},$$

$$s_{\min} = \min(s_{12}, s_{23}, s_{13}),$$
$$s_{\max} = \max(s_{12}, s_{23}, s_{13}).$$
$$s_{ij} = s_{ji} = m^2_{K_S^0(i) K_S^0(j)} = (p_i + p_j)^2,$$

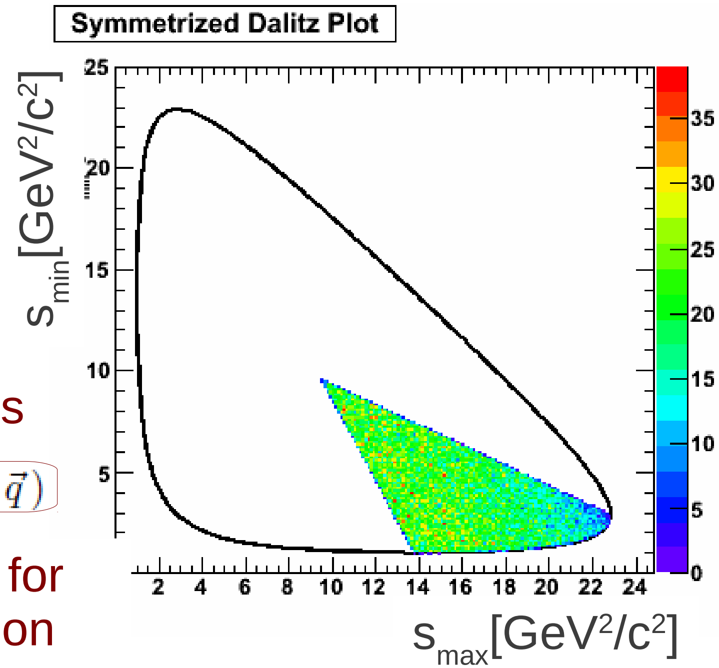
  - Distribution in s_{min} s_{max} populates only 1/6 of the phase space
  - Isobar approximation:

$$\mathcal{A}(s_{\min}, s_{\max}) = \sum_{j=1}^{N} c_j F_j(s_{\min}, s_{\max}).$$

$$F_j(s_{\min}, s_{\max}, L) = R_j(m) X_L(|\vec{p}^\star| r') X_L(|\vec{q}| r) T_j(L, \vec{p}, \vec{q})$$

Centrifugal barrier for tensors

L≠1 lineshape Zemach tensors for angular distribution

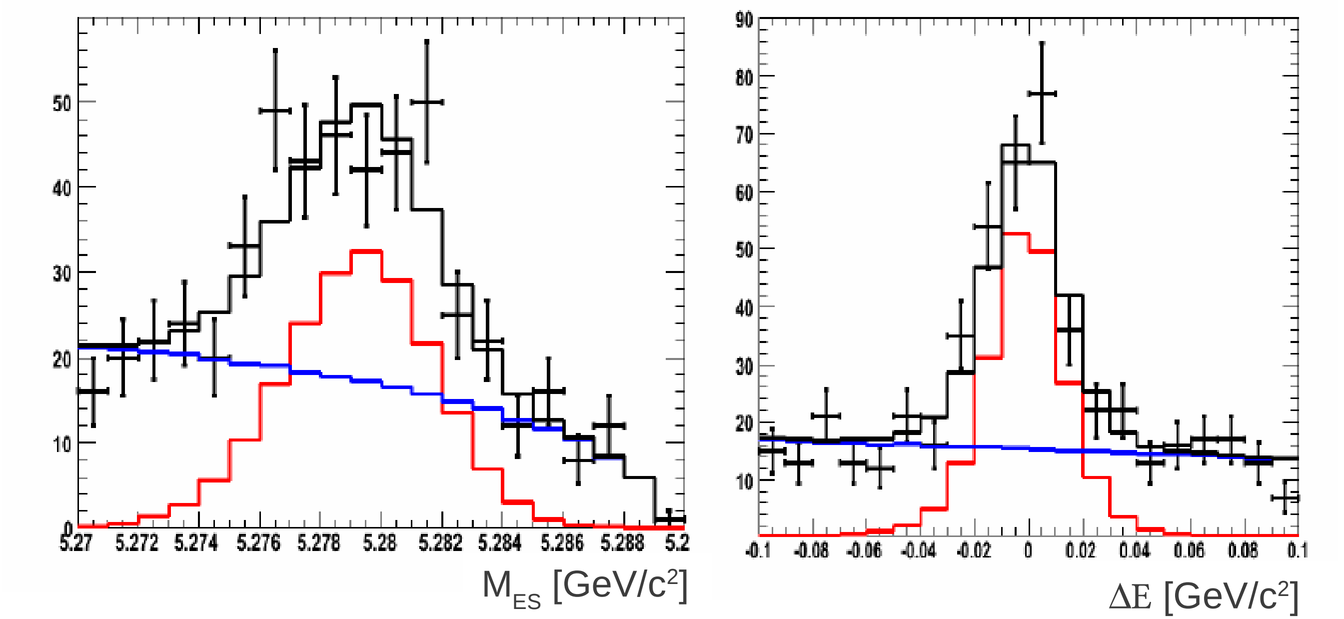


Signal extraction

- Discriminating variables
  - M_{ES}, ΔE, Neural Network($\cos\theta^*$,$\cos\theta_B$,L_2,L_0), Dalitz plot
  - Signal extracted from unbinned ML fit signal and sidebands region

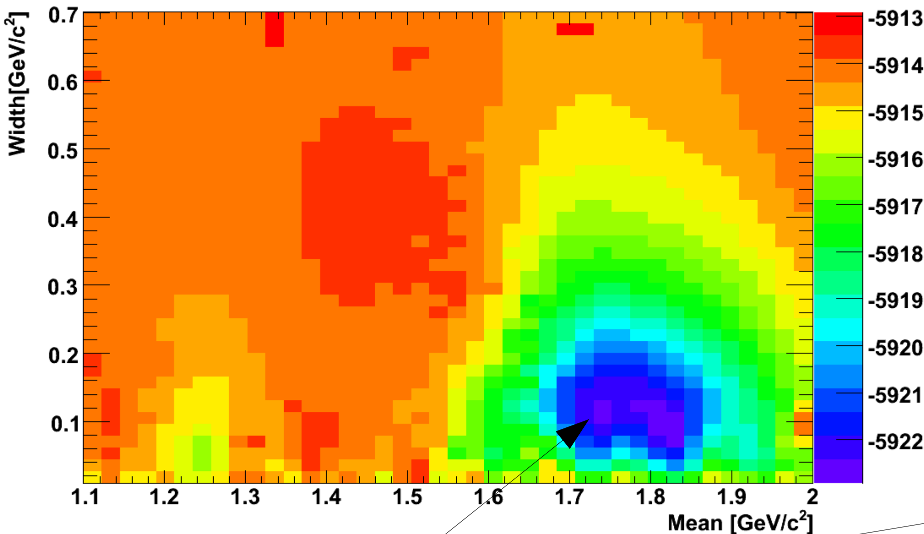
$$\mathcal{L}_i = \sum_j N_j \mathcal{P}_j^i(m_{\rm ES}, \Delta E, {\rm NN}, h_{\rm min}, h_{\rm max}),$$

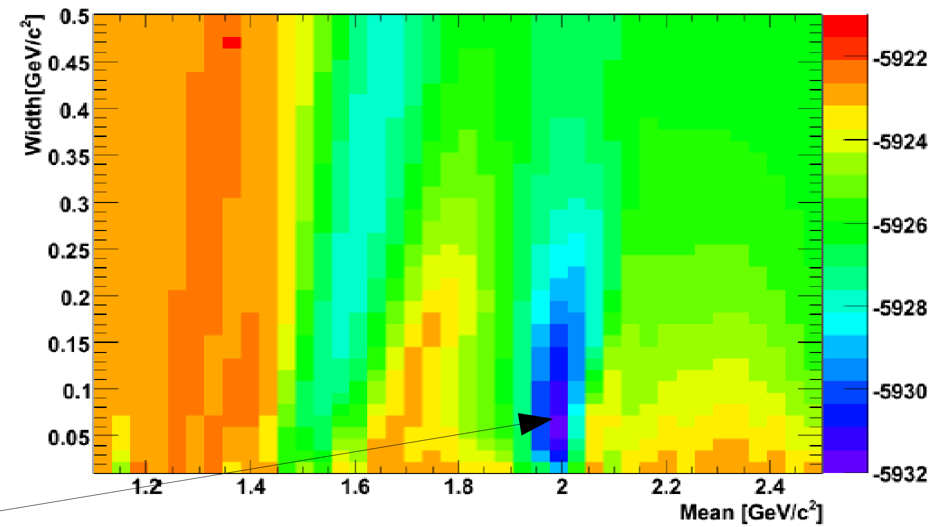
  - ε computed as function of Dalitz plot position to improve sensitivity
    - <ε>=6.6%
  - Background mainly from continuum events
- S=200 ± 15
- S/B=65%



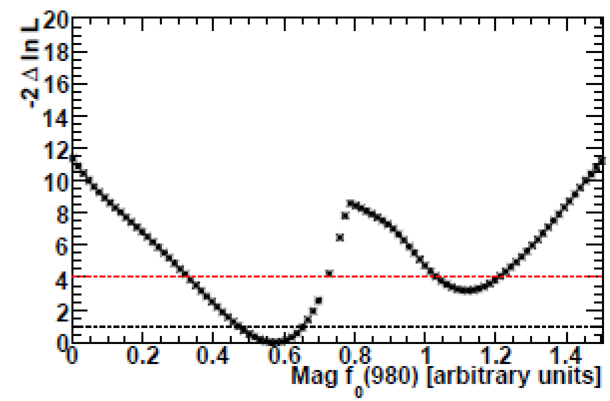
Dalitz Model

- Start with a basic model $f_0(980)$[flatte'], χ_{c0}[RBW],NR[$e^{\alpha m^2}$]



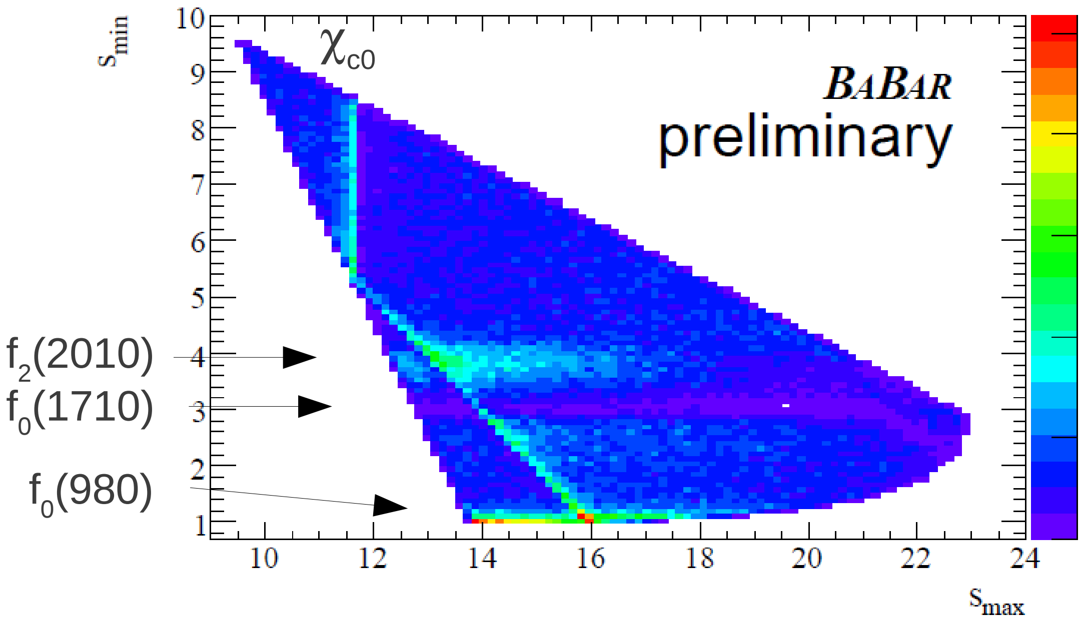


- Add $f_0(1710)$[RBW], $f_2(2010)$[RBW] by scanning the likelihood
- No need for $f_X(1500)$
- Two solutions found for $f_0(980)$:
  - large f0 component with small NR
  - small f0 with large NR



Fit results

Distribution generated using the fitted values



Mode	Parameter	Solution 1	Solution 2
$f_0(980)K_S^0$	FF	$0.44^{+0.20}_{-0.19}$	$1.03^{+0.22}_{-0.17}$
	Phase [rad]	0.09 ± 0.16	1.26 ± 0.17
	$-2\Delta\ln\mathcal{L}$	11.7	-
	Significance [σ]	3.0	-
$f_0(1710)K_S^0$	FF	$0.07^{+0.07}_{-0.03}$	$0.09^{+0.05}_{-0.02}$
	Phase [rad]	1.11 ± 0.23	0.36 ± 0.20
	$-2\Delta\ln\mathcal{L}$	14.2	-
	Significance [σ]	3.3	-
$f_2(2010)K_S^0$	FF	$0.09^{+0.03}_{-0.03}$	0.10 ± 0.02
	Phase [rad]	2.50 ± 0.20	1.58 ± 0.22
	$-2\Delta\ln\mathcal{L}$	14.0	-
	Significance [σ]	3.3	-
NR	FF	$2.16^{+0.36}_{-0.37}$	$1.37^{+0.26}_{-0.21}$
	Phase [rad]	0.0	0.0
	$-2\Delta\ln\mathcal{L}$	68.1	-
	Significance [σ]	8.0	-
$\chi_{c0}K_S^0$	FF	$0.07^{+0.04}_{-0.02}$	0.07 ± 0.02
	Phase [rad]	0.63 ± 0.47	-0.24 ± 0.52
	$-2\Delta\ln\mathcal{L}$	18.5	-
	Significance [σ]	3.9	-
	Total FF	$2.84^{+0.71}_{-0.66}$	$2.66^{+0.35}_{-0.27}$

Time dependent CP violation

- DP result useful to predict the deviation of $\sin 2\beta_{eff}$ from $\sin 2\beta$
- Integrate over Dalitz plot and fit the time distribution with

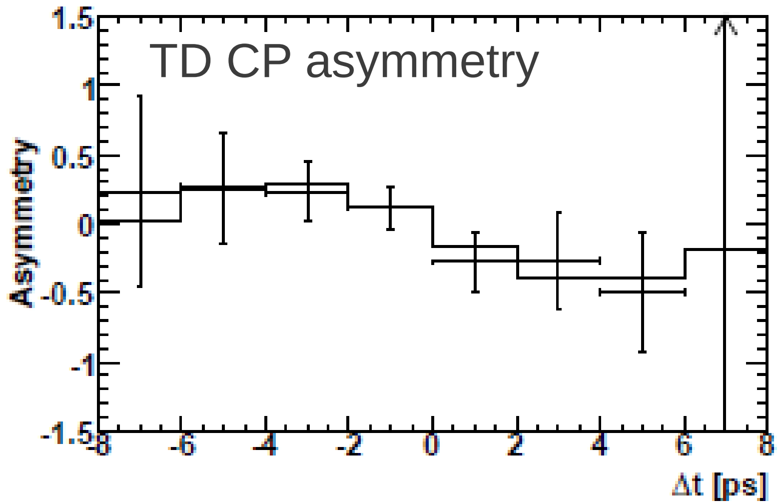
$$\mathcal{P}^i_{sig}(\Delta t, \sigma_{\Delta t}; q_{tag}, c) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 + q_{tag}\frac{\Delta D_c}{2} + q_{tag}\langle D\rangle_c \Big[\mathcal{S}\sin(\Delta m_d \Delta t) - \mathcal{C}\cos(\Delta m_d \Delta t) \Big] \otimes \mathcal{R}_{sig}(\Delta t, \sigma_{\Delta t}),$$

- TD determines also the weak and strong phases
- Use also $K_s \to \pi^0\pi^0$ to improve sensitivity

Species	$3K^0_S(\pi^+\pi^-)$	$2K^0_S(\pi^+\pi^-)K^0_S(\pi^0\pi^0)$
Signal	201^{+16}_{-15}	62^{+13}_{-12}
Continuum	3086^{+56}_{-54}	7086^{+85}_{-83}
B^+B^- bkg	-54^{+29}_{-24}	45^{+34}_{-30}
$B^0\overline{B}^0$ bkg	9^{+31}_{-30}	4^{+38}_{-29}

$$\mathcal{S} = -0.94^{+0.24}_{-0.21},$$
$$\mathcal{C} = -0.17 \pm 0.18,$$

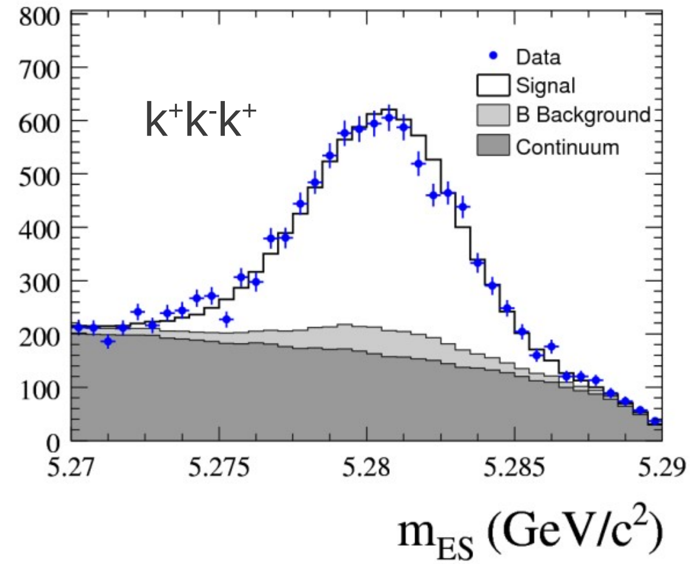
CPV observed at 3.8σ



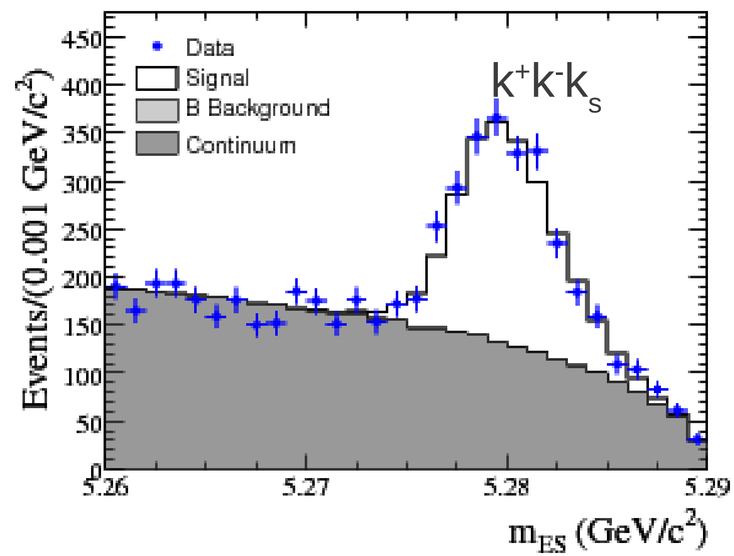
$B \to KKK$ (excl. $K_S K_S K_S$)

- Also in this case $b \to s$ loop diagram has the same weak phase as $b \to c\bar{c}\, K^{(*)}$ transitions and $b \to u$ tree diagrams can change this by $\sin 2\beta_{eff} - \sin 2\beta = [-1\%, 4\%]$ PLB620, 143; PRD72, 014 006
- However $K^+K^-K_S$ is not guaranteed to be a CP eigenstate
  - interference of resonances $\Rightarrow$ $\sin 2\beta_{eff}$ extracted from a Dalitz plot, time dependent analysis
- Interference allows to resolve the ambiguity on the sign of $\cos 2\beta_{eff}$ (β, $90^o - \beta$ ambiguity) . Can measure β_{eff} for other resonances
- A_{CP} in $B \to \phi(K^+K^-)K^+$ is well predicted in SM ~ $0\% < A_{CP} < 4.7\%$ PRD 74, 094020
- Study the poorly understood $f_x(1500)$ with the high statistics $B^+ \to K^+K^-K^+$ sample and $B^+ \to K^+K_SK_S$ (L=even)

Selection



- Background mostly from b⟶c transitions, fight with NN($\cos\theta_T$, $\cos\theta_B$, L2/L0, $\Delta t/\sigma_{\Delta t}$, tagging)
  - $K^+K^-K^+$: sig: 5300, S/B=78%
  - $K_SK_SK^+$: sig 600, S/B=24%
  - $K^+K^-K_S(\pi^+\pi^-)$: sig: 1400, S/B=34%
- Dalitz plot
  - Isobar model



$$\mathcal{A} \equiv \mathcal{A}(B^+ \to K^+K^+K^-; m_{12}, m_{23}) = \sum_j a_j f_j(m_{12}, m_{23})$$

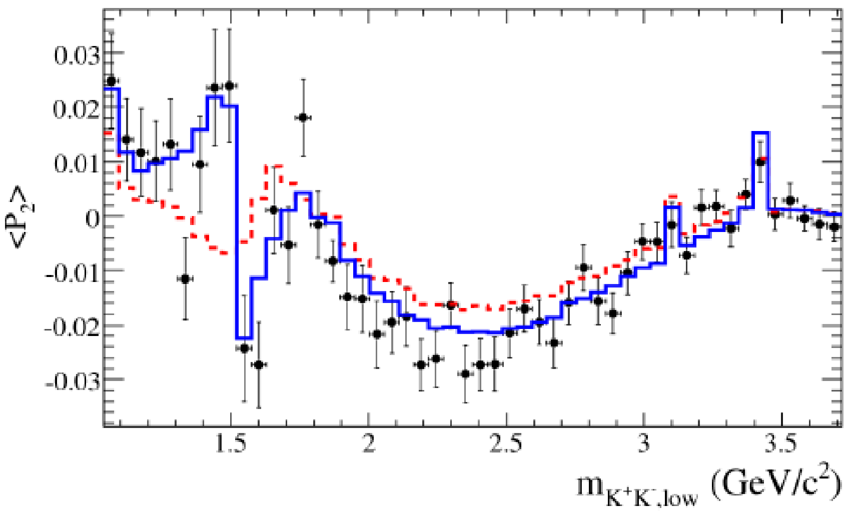
$$\begin{aligned} a_j &= c_j(1+b_j)e^{i(\phi_j+\delta_j)} \\ \bar{a}_j &= c_j(1-b_j)e^{i(\phi_j-\delta_j)} \end{aligned}$$

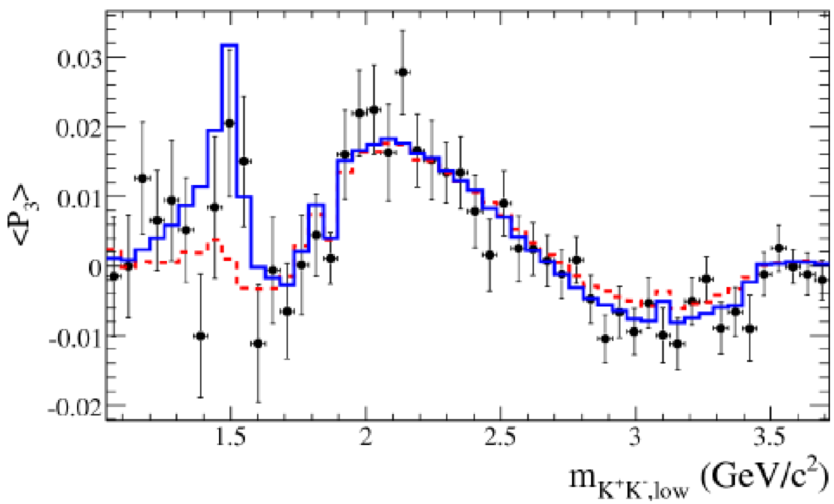
A_{CP} (= -2b/(1+b2)), β_{eff} (= β + δ)

$B \to KKK$ Dalitz model

- No need for $f_X(1500)$
- NR contribution better described by polynomial
- CPV parameters set to nominal ones
- Best fit with ϕ(1020), f0(980), f0(1500), f2′(1525), f0(1710), χc0, polynomial NR.
- Angular moments used to compare data and fit

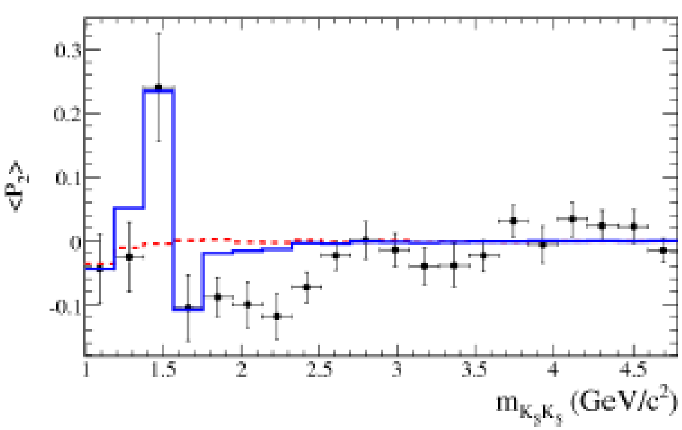
$$\langle P_l \rangle = \int_{-1}^{1} |\mathcal{A}(m_{KK}, \cos\theta)|^2 P_l(\cos\theta) d\cos\theta$$

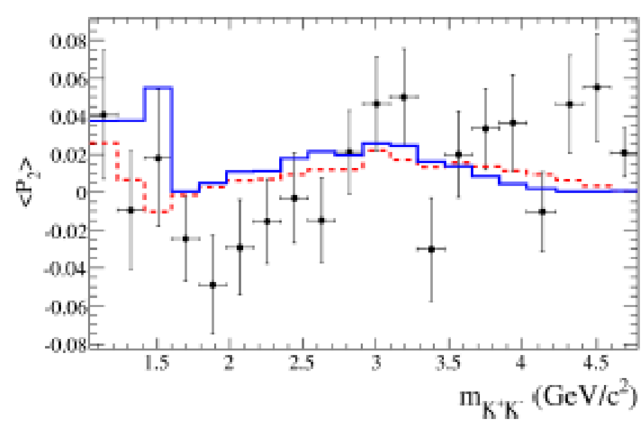




B ⟶ KKK Dalitz model (II)

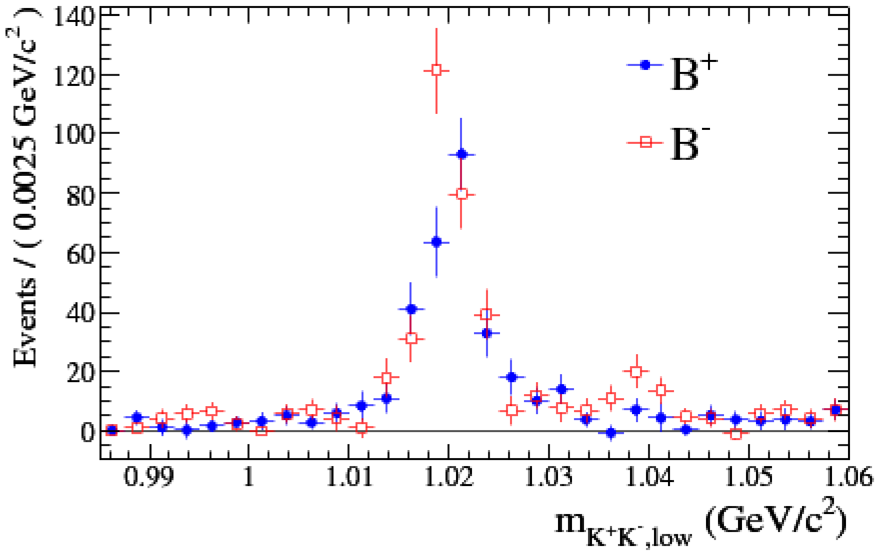
- $K_S K_S K^+$: best fit with $f_0(980)$, $f_0(1500)$, $f_2'(1525)$, $f_0(1710)$, χ_{c0}, polynomial NR. First ever DP analysis
- $K^+K^-K_S$: best fit with $\phi(1020)$, $f_0(980)$, $f_0(1500)$, $f_2'(1525)$, $f_0(1710)$, χ_{c0}, best fit with $f_0(980)$, $f_0(1500)$, $f_2'(1525)$, f0(1710), χc0, polynomial NR.
- In all 3 channels: no need for broad $f_X(1500)$ [not yet established, used to explain some older data]
- f_x ⟶ f0(1500), f2'(1525), f0(1710)



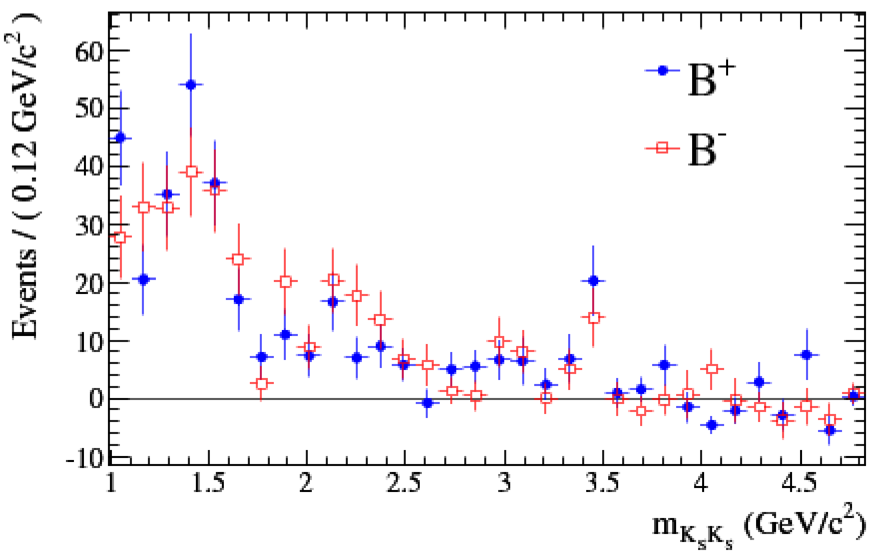


B⟶KKK CP violation results

- $K^+K^-K^+$
  - BF=$(33.4\pm0.5\pm0.9)\times10^{-6}$ [χ_{c0}K excluded]
  - A_{CP}(overall) = $(-1.7+1.9-1.4\pm1.4)\%$
  - $A_{CP}(\phi K) = (12.8\pm4.4\pm1.3)\%$ (2.8σ from 0, SM:~0-4.7%)



- $K_SK_SK^+$
  - BF=$(10.1\pm0.5\pm0.3)\times10^{-6}$ [χ_{c0}K excluded]
  - A_{CP} = $(4\pm5\pm2)\%$



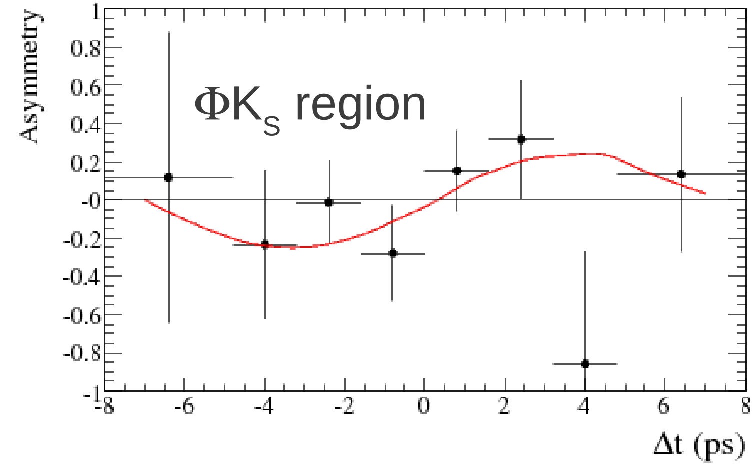
B⟶KKK CP violation results (II)

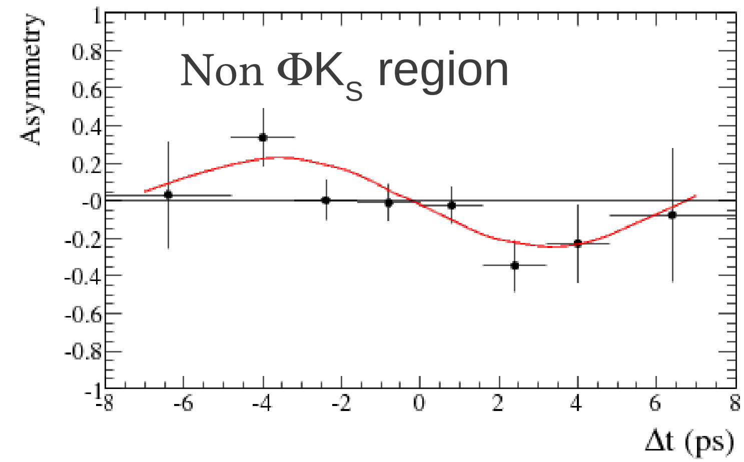
- $K^+K^-K_S$:
  - BF=(25.4±0.9±0.8)×10^{-6} [χ_{c0}K excluded]
  - $\beta_{eff}(\phi K_S)$ = (21±6±2)°, excellent agreement with SM
  - β_{eff}(non-ϕ, non-f_0) = (20.3±4.3±1.2)°, agrees with SM
  - 90°-β_{eff} excluded at 4.8σ (ambiguity in $J/\psi K_S$)
- Constraints on new physics: assume
  - Isospin symmetry [$A(\phi K^+)=A(\phi K_S)$]
  - 2nd amplitude with different phases w.r.t. penguin

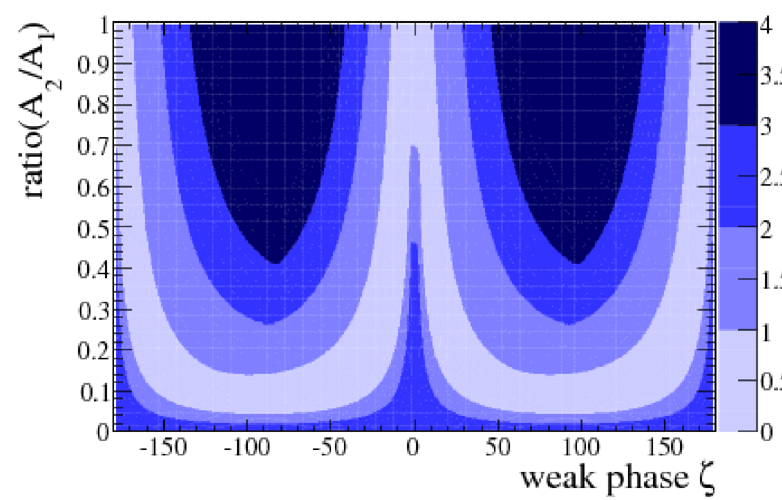
$$\mathcal{A} = \mathcal{A}_1(1 + re^{i(\eta+\zeta)}),$$
$$\bar{\mathcal{A}} = \mathcal{A}_1(1 + re^{i(\eta-\zeta)}),$$

r~10% due to $A(\phi K^+)$

η: 0 and 180 disfavored







CP violation in τ lepton decays

- No CKM type mechanism exists in charged leptons.
- CP asymmetry in leptons has not yet been observed
- Tau is the only lepton that can decay to hadrons, which provides an opportunity for observing non-SM type CP violation.
- Search for time integrated rate asymmetry for $\tau^- \longrightarrow K_S\pi^- (\geq 0\ \pi^0)\nu_\tau$ in $e^+e^- \longrightarrow \tau^+\tau^-$ events

$$A_\tau \equiv \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \nu_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \nu_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

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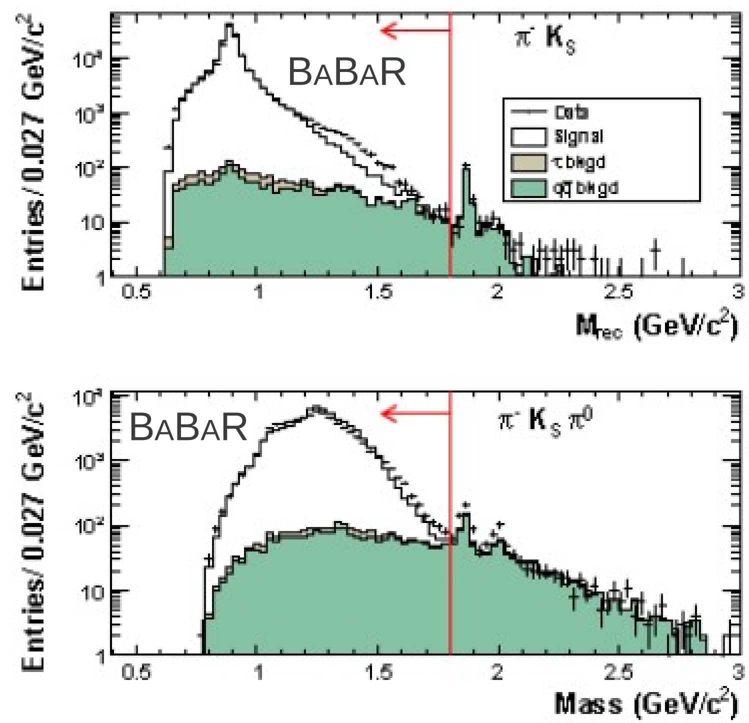
Signal Selection

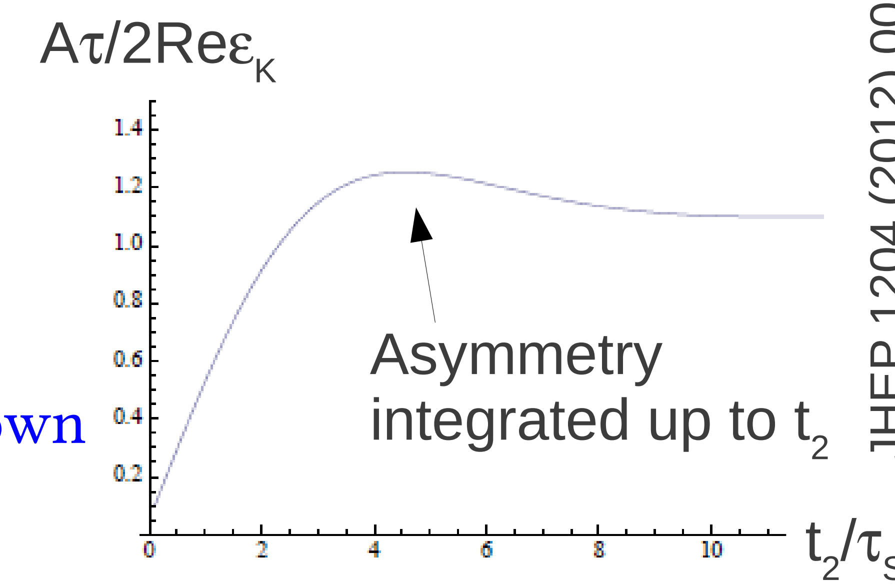


- Signal side.
  - $1K_S^0$
  - 1-prong (not identified as kaon)
  - Any number of π^0
- Tag-side
  - Electron or muon
- Likelihood cuts to reduce qq background and Select good K_S^0
  - Bkg: number of neutral clusters, thrust, visible energy, pt
  - K_S: decay vertex, mass, polar angle
- Yield: 170k events each for τ^+ and τ^-
- 15% background dominated by $\tau^- \to K^- K^0_S (\geq 0\pi^0)\nu_\tau$ and $\tau^- \to \pi^- K^0 \overline{K}^0 \nu_\tau$

Rate asymmetry

- Arec=-0.32% (e tag) , −0.05% (μ tag)
- The asymmetry in reconstructed events has several contributions Arec = (A_{CP}*D_{bkg} + A_ε + A_D)
- A_ε: Control sample $\tau \longrightarrow$ 3-prong
  - No charge asymmetry expected in control sample ⟶ extract detector asymmetry consistent with zeo, included in sys (~0.10%)
- A_D: Kaon interaction asymmetry
  - A_D=(+0.07±0.01)%
- D_{bkg}: background
  - Dilution due to τ background: D_{bkg}=0.75
- Result: A_{CP}=(−0.36 ±0.23±0.11)%

SM expectation



- No CP violation in tau decay but known CP violation effects in Kaon decays
- $\tau^+ \longrightarrow K^0$, $\tau^- \longrightarrow \overline{K^0}$, $|K^0\rangle = (|K_S\rangle + |K_L\rangle)/2p$, $|\overline{K^0}\rangle = (|K_S\rangle - |K_L\rangle)/2q$
- Bigi and Sanda [Phys.Lett. B625(2005)47] predict an asymmetry due to CPV in the K sector equal to $2\mathrm{Re}\varepsilon_K \approx 3.3\ 10^{-3}$

$$A_\tau \equiv \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \nu_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \nu_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)} = +0.33\%$$

Phys.Lett. B625(2005)47

- Not end of story: $K_S \longrightarrow \pi\pi$ and $K_L \longrightarrow \pi\pi$ amplitudes interference generates a time dependence of the asymmetry [Grossman and Nir JHEP 1204 (2012) 002]

Comparison with SM

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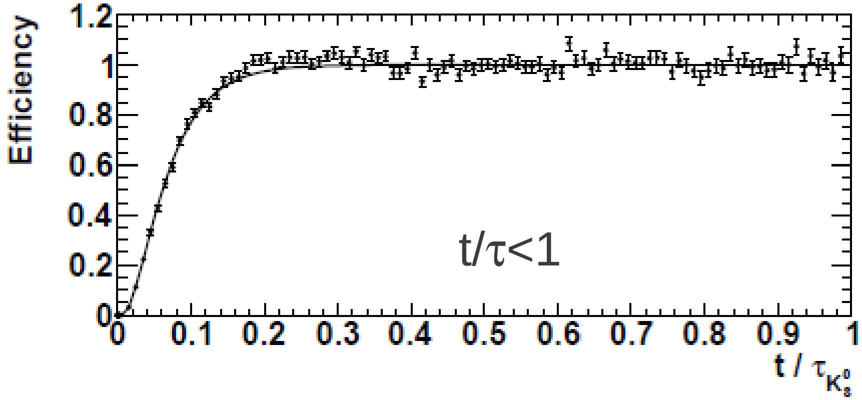
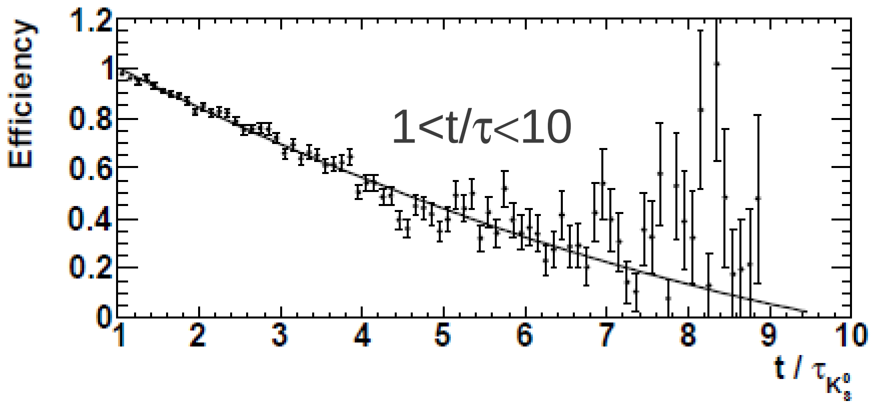
- Experimental detection of K0 $\rightarrow \pi\pi$ has an efficiency dependent on the decay length
- $\Rightarrow$ Correction factor of 1.08
- $\Rightarrow$ SM prediction = +0.36%
- Result : A_τ=(−0.36 ±0.23±0.11)% . 2.8σ deviation from SM
- Similar situation in $D^+ \to K_S\pi^+$ but
  - $D^+ \rightarrow \overline{K}^0$, $D^- \rightarrow K^0$ => $A_D = -A_\tau$
  - Exp. Result A_D=-0.44±0.13±0.10

Incompatible with the τ measurement!





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Summary

- BF and CP asymmetry in $B \to K^{(*)}ll$ consistent with SM
  - Negative Isospin asymmetry at the 2σ level
- Observation of CP violation in $B \to K_S K_S K_S$ consistent with $\sin 2\beta$
- Observation of direct CP violation in $B^+ \to \phi K^+$ 2.8σ from zero
- Improved understanding of the resonance structure of $B \to 3K$: no need for broad $f_x(1500)$, first ever DP analysis of $B^+ \to K_S K_S K^+$
- Measured direct CP asymmetry in tau decays, inconsistent with the SM (after correction for KS decay) and with direct cp violation in D decays.

Backup