Recent CP violation results from BaBar

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Representing the BaBar Collaboration at

Supersymmetry 2011 (SUSY 2011)

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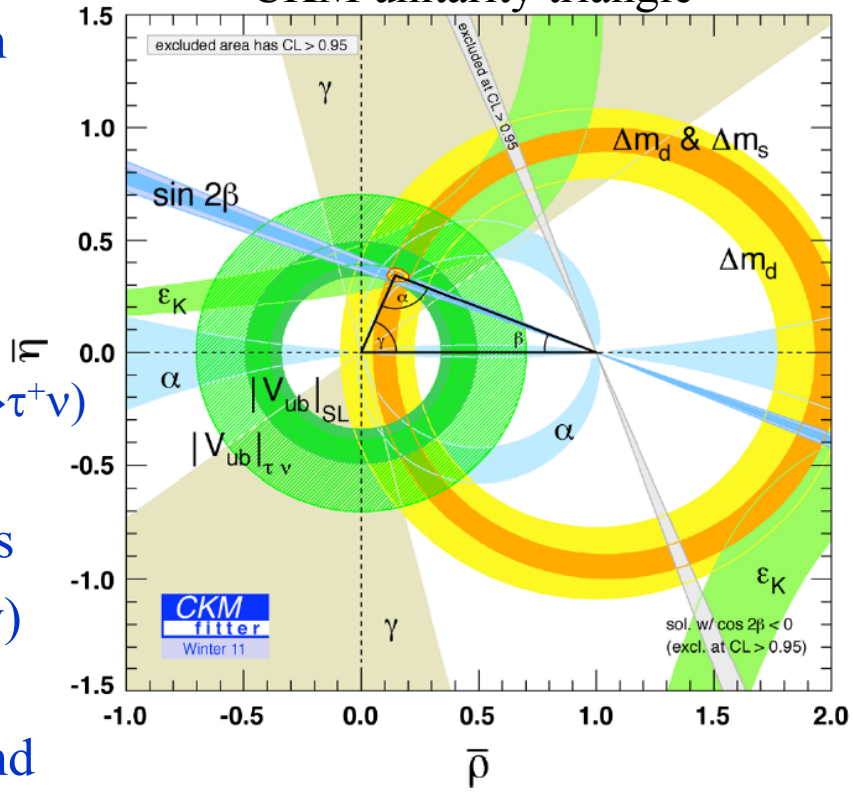
CP violation

- Leading source of quark-sector CP violation established (mostly by BaBar and Belle)
  - CKM mechanism
- Overall good consistency between measurements and predictions within CKM
  - ~2.8σ tension for $\sin 2\beta_{B\to(c\bar{c})K}$ and $BF(B^+\to\tau^+\nu)$
- New physics (NP) can be revealed in low-energy flavor processes…especially in loops
- Particularly fruitful are processes with (very) small effects predicted by the SM
- NP in general induces (additional) FCNC and CP-violating phases

CKM unitarity triangle



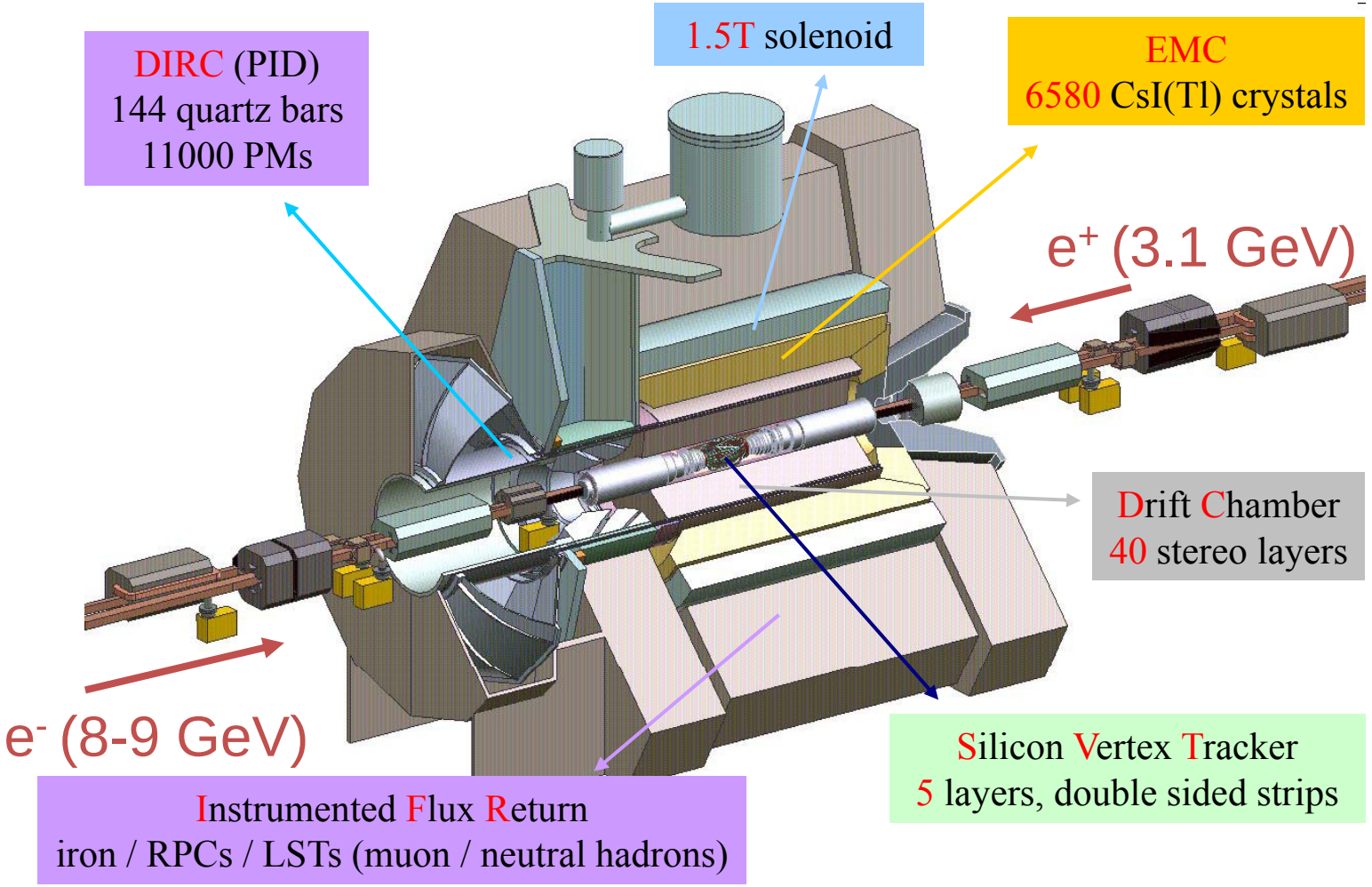
PRD 84, 033005 (2011)

- The particle can be very heavy…can probe NP at the multi-TeV scale, but need huge data sets…Luminosity frontier
- Complementary to direct searches at energy frontier

Outline

- The BaBar detector & data set
- CP violation in D decays
  - $D^+ \to \pi^+ K^0_s$
  - $D^+_{(s)} \to K^+ K^0_s \pi^+ \pi^-$ and $D^0 \to K^+ K^- \pi^+ \pi^-$
- CP violation in τ decays
  - $\tau^- \to \pi^- K^0_s \nu_\tau$
- CP violation in Charmless B decays
  - $B^+ \to (\rho^0/f_0) K^{*+}$ and $B^0 \to \rho^- K^{*+}$
  - $B^0 \to K^+ \pi^- \pi^0$ and $B^+ \to K^+ \pi^0 \pi^0$
- Conclusions

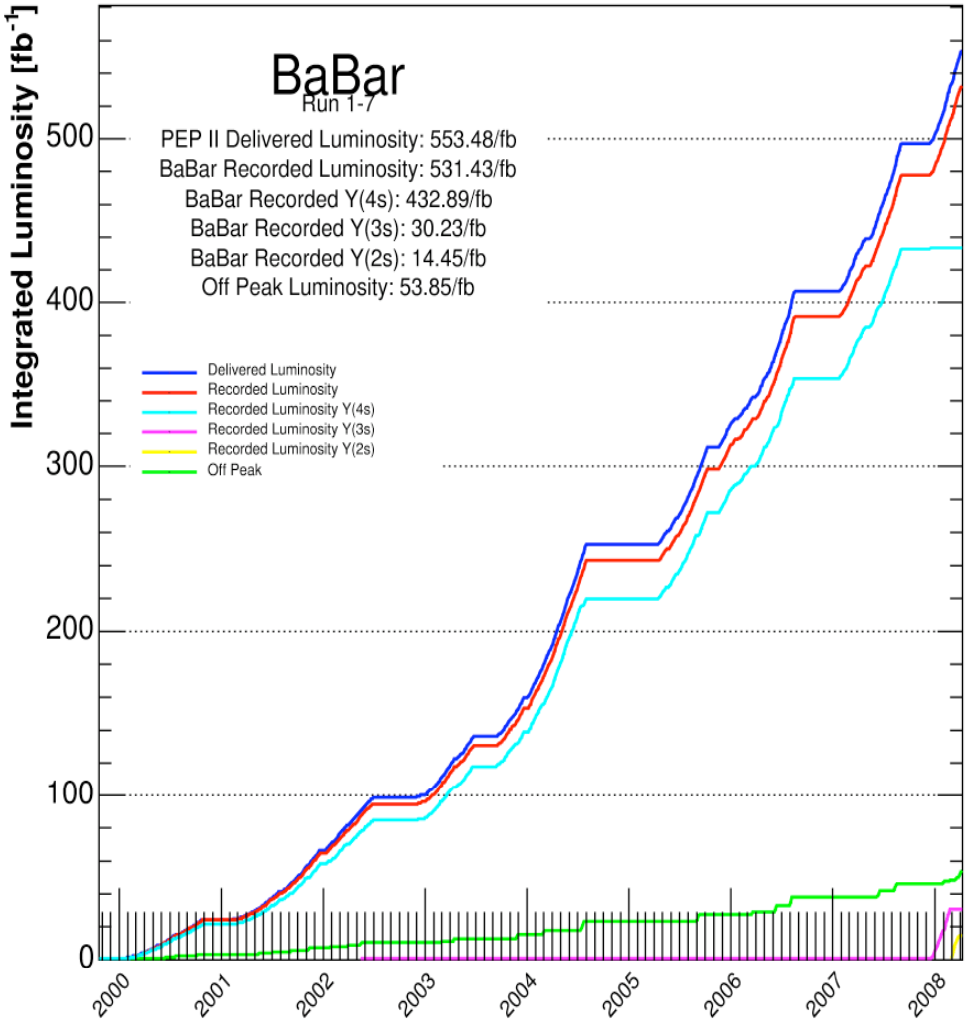
BaBar detector

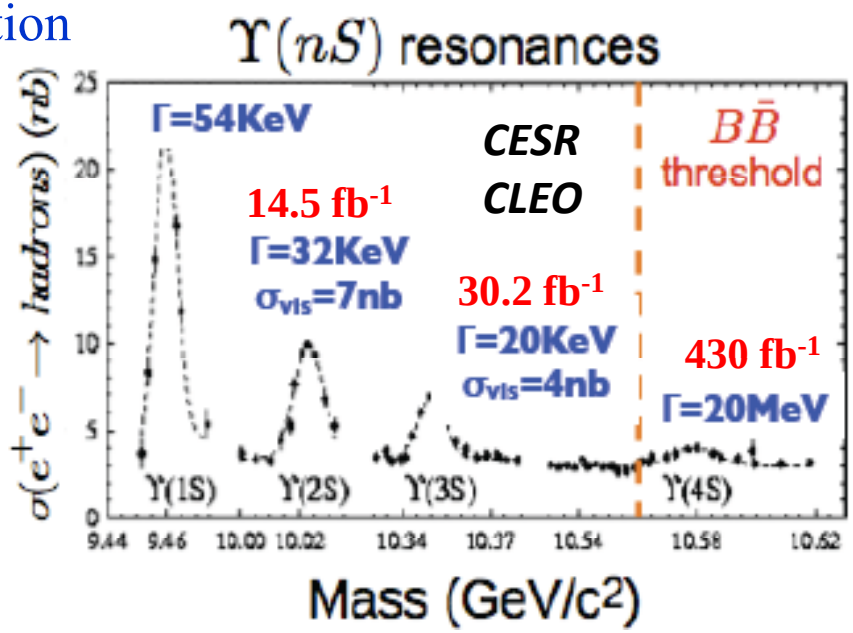


- Asymmetric B-factory: E_{cms} = 10.58 GeV $\quad e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L identification. Very stable over the 9 years of operation

Data set

- 530 fb^{-1} recorded in the 9 years of operation





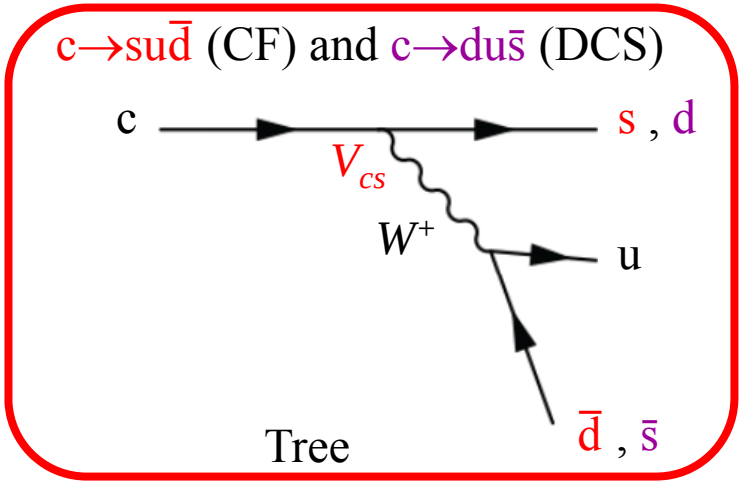
54 fb^{-1} Off-Υ(nS)
4 fb^{-1} above Υ(4S)

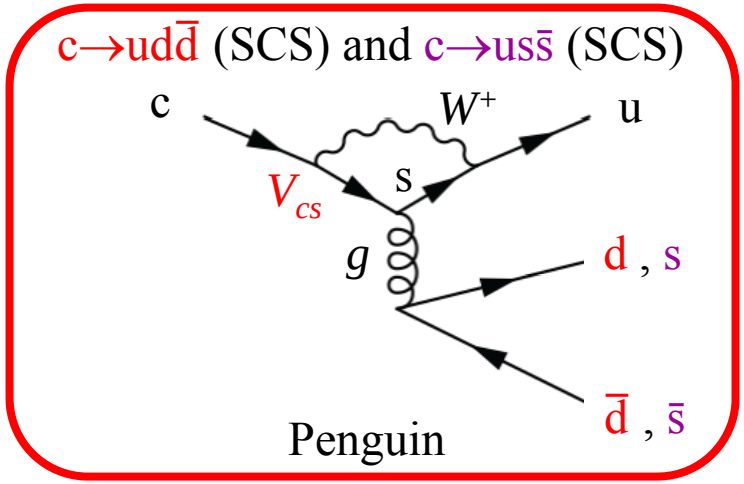
- ≈ 470×10^6 $B\bar{B}$ (0.5×Belle)
- ≈ 690×10^6 $c\bar{c}$
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 1.2×10^8 Υ(3S) (7×Belle+Cleo)
- ≈ 1.0×10^8 Υ(2S) (0.5×Belle+Cleo)

Recent CP violation results: D decays

D decays: motivation

- Direct CP violation in D decays arises through interference between:





- In the SM is CKM suppressed $O(10^{-3})$ or less

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & \boxed{V_{cs}} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{1}{2}i\eta\lambda^2) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - \boxed{i\eta A^2\lambda^4} & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- NP can increase or reduce the effect
  - e.g. additional CP phase from charged Higgs boson
  - SCS decays are more likely to show the effect if present
- Current experimental sensitivity $O(10^{-3})$

PRD 75, 036008 (2007)
hep-ph/0104008 (2001)
PRD 51, 003478 (1995)

$D^+ \to \pi^+ K^0_s$: experimental technique

- Due to CPV in mixing in the kaon sector, the direct CP asymmetry

$$A_{CP} = \frac{\Gamma(D^+ \to \pi^+ K_s^0) - \Gamma(D^- \to \pi^- K_s^0)}{\Gamma(D^+ \to \pi^+ K_s^0) + \Gamma(D^- \to \pi^- K_s^0)}$$

is expected to be $A_{CP}^{SM} = |p|^2 - |q|^2 = (-0.332 \pm 0.006)\%$ hep-ph/0104008 (2001)

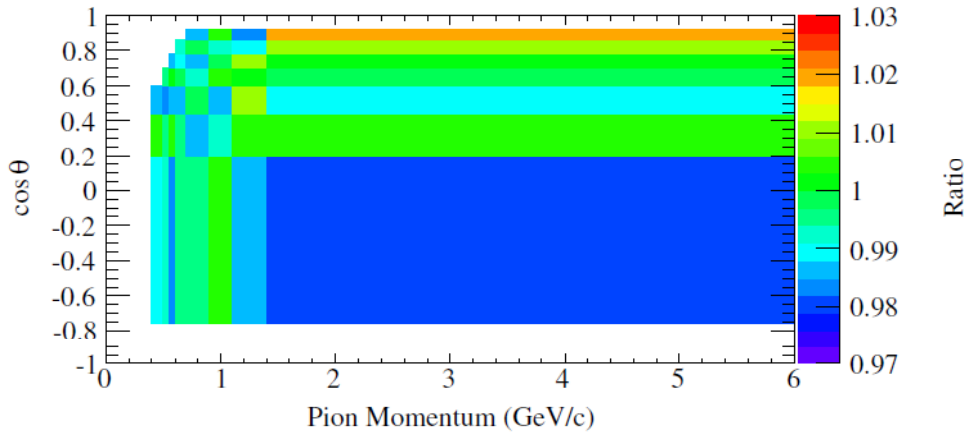
- Signal yields from likelihood fit to $m(\pi^+ K^0_s)$, with selection based on a Boosted Decision Tree with 7 variables: $\tau_T(D^\pm)$, $L_T(D^\pm)$, $p^*(D^\pm)$, $p(K^0_S)$, $p_T(K^0_S)$, $p(\pi^\pm)$, $p_T(\pi^\pm)$
- 807K $D^\pm$ signal events
- Measure

Forward-Backward asymmetry

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}} = A_{CP} + \boxed{A_{FB}} + \boxed{A_\varepsilon}$$

Detector charge asymmetry

- Data-driven method to correct for A_ε
  - Use tracks from $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ decays (isotropic in rest frame) to map the ratio of π^+/π^- detection efficiencies
  - Offset on $A_{CP} \approx +0.05\%$

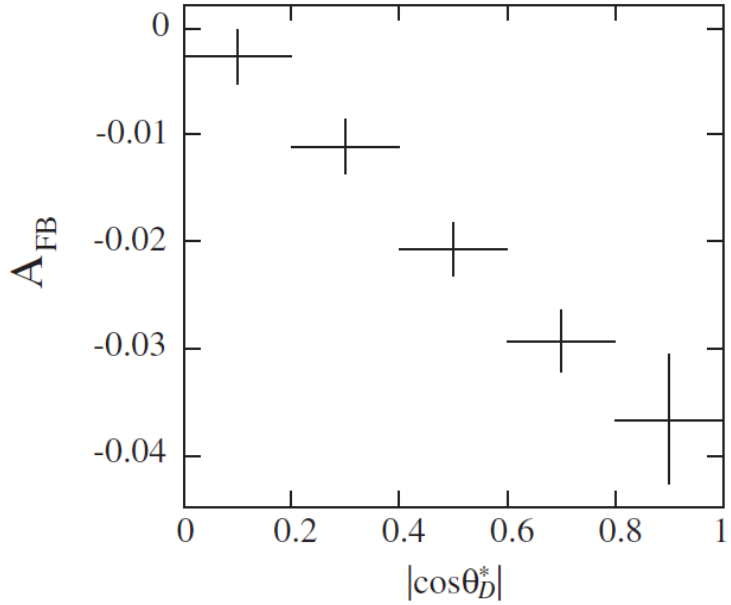


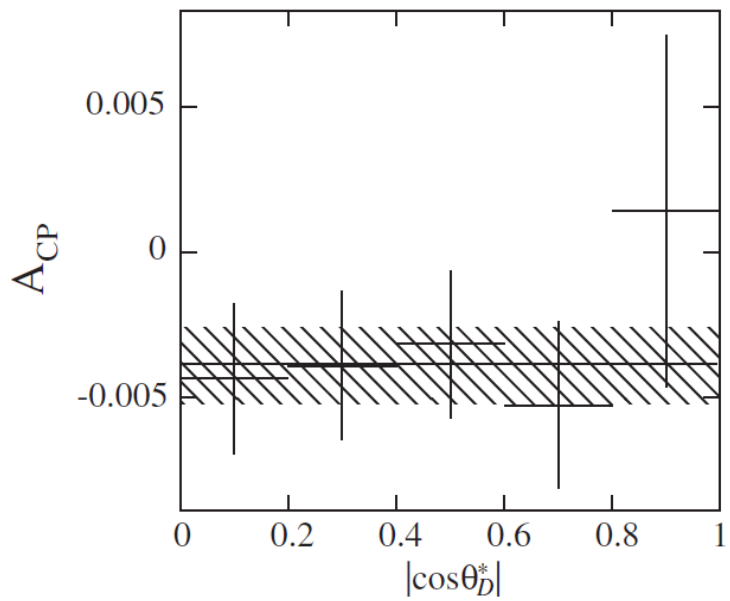
$D^+ \to \pi^+ K^0_S$: results

470 fb^{-1}

- Use data-driven method to extract A_{FB}, and A_{CP} in bins of polar angle

$$A_{FB}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) - A(-|\cos\theta_D^*|)}{2} \qquad A_{CP}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) + A(-|\cos\theta_D^*|)}{2}$$





systematics	
evaluation $A_\epsilon^{\pi^+}$	0.08%
$K^0/\bar{K}^0$ regeneration	0.06%
fit model	0.01%
total	0.10%

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%$$

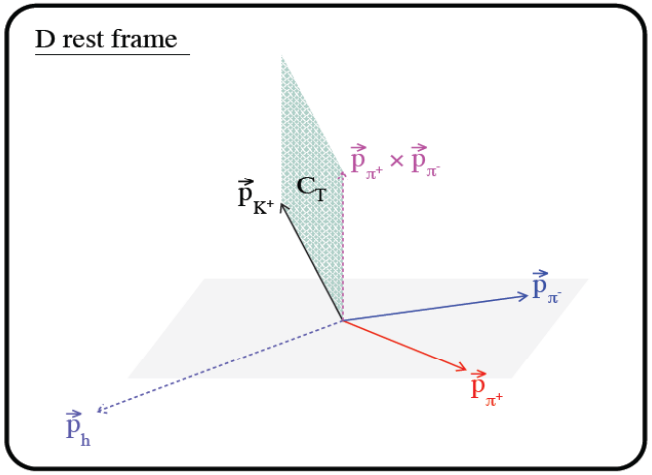
Consistent with SM prediction (–0.332±0.006)%

PRD 83, 071103(R) (2011)

$D^+_{(s)} \to K^+ K^0_s \pi^+ \pi^-$: experimental technique

- Measure a T-odd observable
  - If we assume CPT invariance ⇒ CP violation
- Define T-odd triple products for $D^+_{(s)}$ and $D^-_{(s)}$

$$C_T = \vec{p}_{K^+} \cdot \left(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-} \right) \qquad \overline{C}_T = \vec{p}_{K^-} \cdot \left(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-} \right)$$



- Define the T-odd asymmetries

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) - \Gamma(C_T < 0)} \qquad \overline{A}_T = \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}$$

PRD 66, 094004 (2002)
PRD 64, 116003 (2001)
PLB 538, 309 (2002)
Int.J.M.Phys. A24, 657 (2009)

- FSI could introduce fake T-odd asymmetries.

  To remove, define

$$\mathcal{A}_T = \frac{1}{2}(A_T - \overline{A}_T) \qquad \text{T-violating asymmetry}$$

- Signal selection optimized by means of likelihood ratio with 3 variables:
  - fit probability, fit probability with D vertex constrained to IP, transverse D decay length
- Yields obtained from simultaneous likelihood fit to $m(K^+K_s\pi^+\pi^-)$ distributions for D^+, D^-, D_s^+, D_s^-, for >0 and < 0 triple products

$D^+_{(s)} \to K^+ K^0_s \pi^+ \pi^-$: results

520 fb^{-1}

- ~21K $D^\pm$ and 30K $D_s^\pm$ signal events
- Results

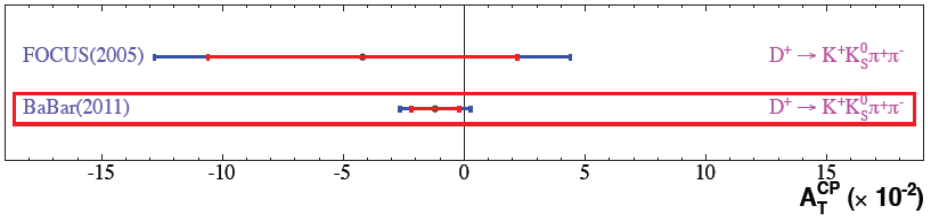
$$A_T(D^+) = (+11.2 \pm 14.1 \pm 5.7) \times 10^{-3} \qquad A_T(D_s^+) = (-99.2 \pm 10.7 \pm 8.3) \times 10^{-3}$$

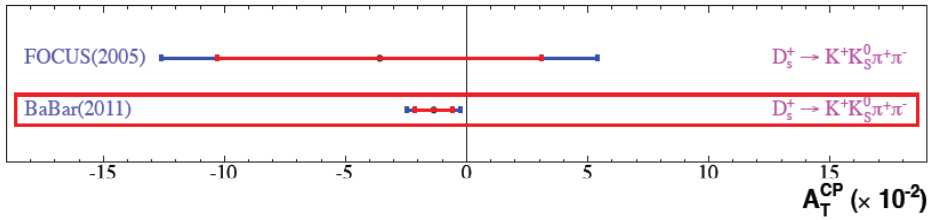
$$\overline{A}_T(D^-) = (+35.1 \pm 14.3 \pm 7.2) \times 10^{-3} \qquad \overline{A}_T(D_s^-) = (-72.1 \pm 10.9 \pm 10.7) \times 10^{-3}$$

FSI seem to be larger in D^+_s than D^+ decays

1107.1232 [hep-ph] (2011)

$$\mathcal{A}_T(D^+) = (-12.0 \pm 10.0 \pm 4.6) \times 10^{-3} \qquad \mathcal{A}_T(D_s^+) = (-13.6 \pm 7.7 \pm 3.4) \times 10^{-3}$$





T-violating asymmetry consistent with 0

×10 improvement wrt previous result

1105.4410 [hep-ex] (2011). Accepted by PRD(RC)

- Similar BaBar analysis using $D^0 \to K^+K^-\pi^+\pi^-$
  - ~47K $D^0/\overline{D}^0$ signal events

$$A_T(D^0) = (-68.5 \pm 7.3 \pm 5.8) \times 10^{-3}$$

$$\overline{A}_T(\overline{D}^0) = (-70.5 \pm 7.3 \pm 3.9) \times 10^{-3}$$

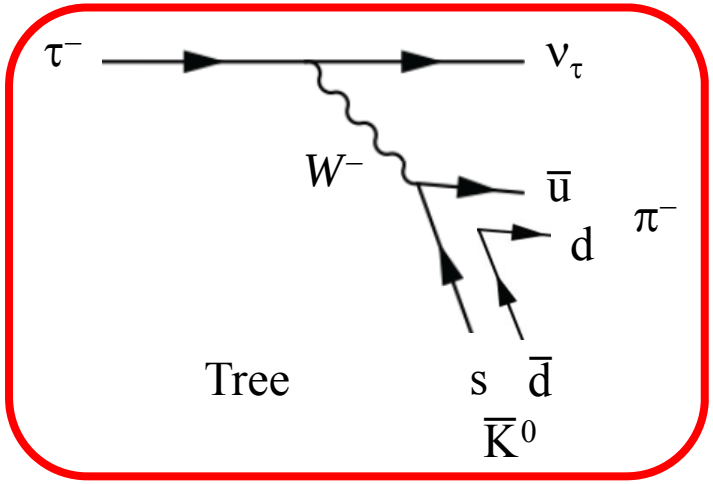
$$\mathcal{A}_T(D^0) = (+1.0 \pm 5.1 \pm 4.4) \times 10^{-3}$$

PRD 81, 111103(R) (2010)

Recent CP violation results: τ decays

$\tau^- \to \pi^- K^0_s \nu_\tau$: motivation

- SM model predicts the decay amplitude $\tau^- \to \pi^- \overline{K}^0 \nu_\tau$ and its CP conjugate to be the same ⇒ no direct CP V is expected
- However, like in $D^+ \to \pi^+ K_s$, due to CPV in the kaon sector, the CP asymmetry



$$A_{CP} = \frac{\Gamma(\tau^+ \to \pi^+ K_s^0 \overline{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_s^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_s^0 \overline{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_s^0 \nu_\tau)}$$

is expected to be $A_{CP}^{SM} = |p|^2 - |q|^2 = (0.332 \pm 0.006)\%$ PLB 625, 47 (2005)

Note: the sign of the asymmetry is opposite to that of $D^+ \to \pi^+ K^0_s$

- A deviation of the measured A_{CP} from A_{CP}^{SM} would be a hint of NP
  - e.g. an additional CP violating phase from an exotic charged Higgs boson

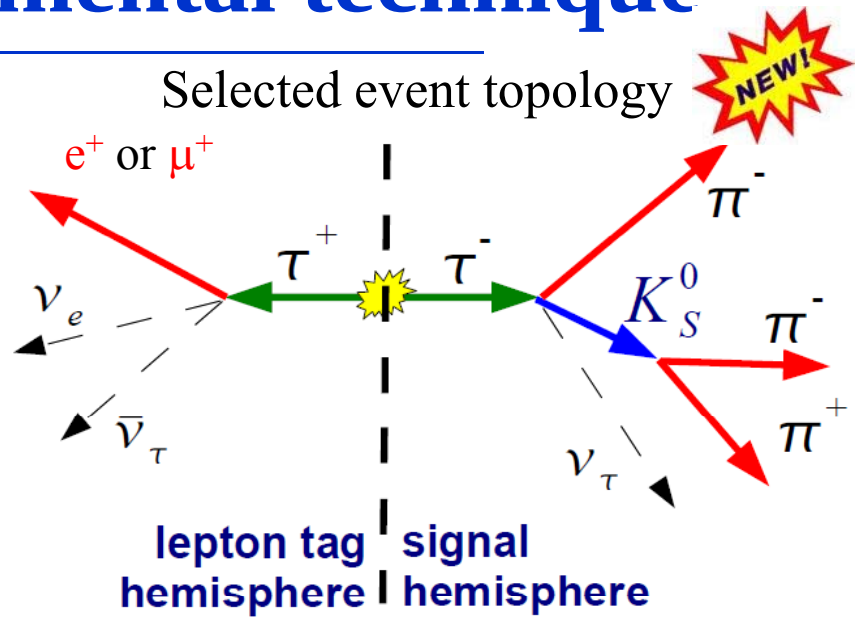
PLB 398, 407 (1997)

- Can consider $\tau^- \to \pi^- K_s^0 (\geq 0\pi^0) \nu_\tau$
  - π^0s are expected not to change the asymmetry

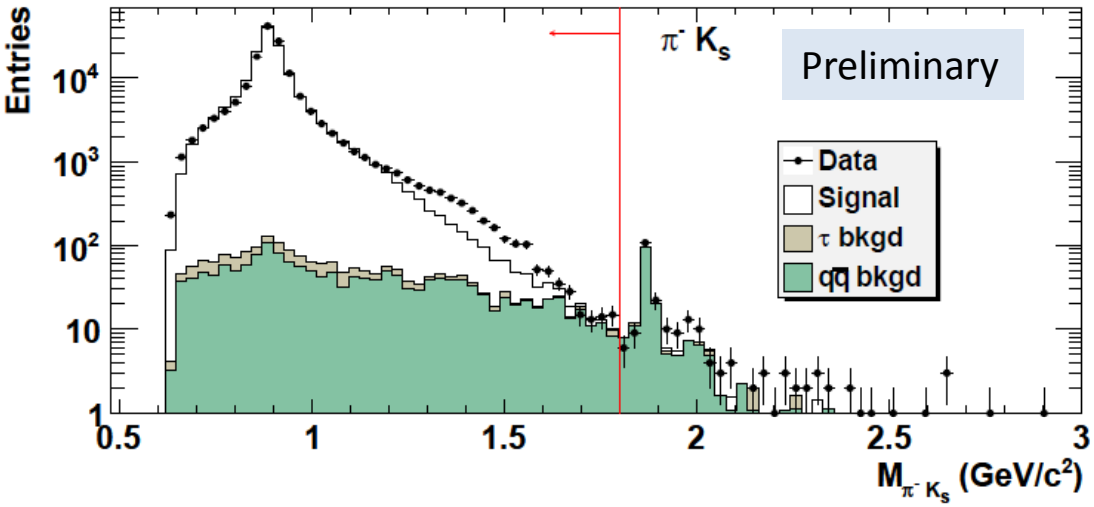
$\tau^- \to \pi^- K^0_s \nu_\tau$: experimental technique

- Reconstruct $\tau^- \to \pi^- K^0_s (\geq 0\pi^0) \nu_\tau$ up to $3\pi^0$s
- Electron and muon tags
  - $p_l^* > 4$ GeV to reduce background from non-τ-pairs
- Reconstructed hadronic mass < 1.8 GeV
  - Rejects $q\bar{q}$ background

Selected event topology



Invariant mass of the hadronic final state ($0\pi^0$s)



- Remaining $q\bar{q}$ and K^0_s background further reduced using likelihood ratio technique
  - Visible energy, number of neutral clusters, thrust, total transverse momentum
  - Displaced vertex, invariant mass, momentum and polar angle of the K^0_s candidate

$\tau^- \to \pi^- K^0_S \nu_\tau$: results

NEW!

437x10^6 $\tau^+\tau^-$ pairs

- Measured raw A_{CP} value (after subtraction of $q\bar{q}$ background and non-K^0_S τ decays) has to be corrected by
  - Different nuclear reaction cross-section of K^0 and $\bar{K}^0$ with material detector
    - (0.14±0.03)% for e-tag, (0.14±0.02)% for μ-tag
    - Errors include uncertainties from kaon-nucleon cross-sections and isospin
  - Dilution from background modes including K^0_S

Source	Fraction e-tag (%)	Fraction μ-tag (%)	SM expected A_{CP}
$\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau$	78.4 ± 4.0	77.4 ± 4.0	(0.33±0.01)%
$\tau^- \to K^- K^0_S(\geq 0\pi^0)\nu_\tau$	4.2 ± 0.3	4.0 ± 0.3	(–0.33±0.01)%
$\tau^- \to \pi^- K^0 \bar{K}^0(\geq 0\pi^0)\nu_\tau$	15.6 ± 3.7	15.7 ± 3.7	0

- Result

$$A_{CP} = (-0.45 \pm 0.24 \pm 0.11)\%$$

≈3σ from the SM prediction

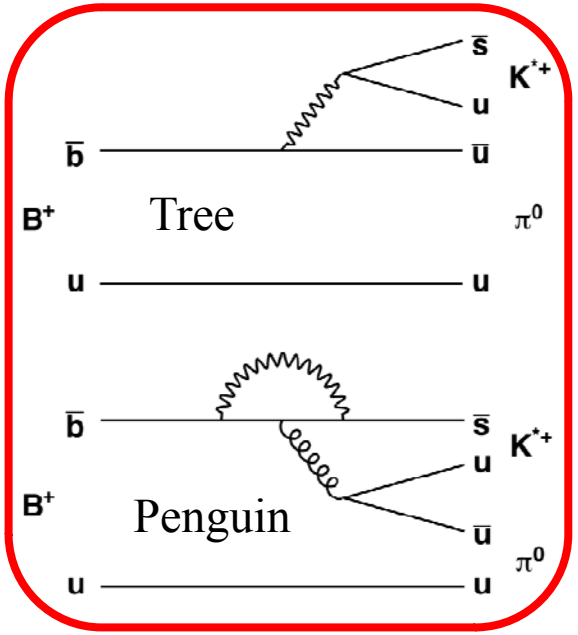
Preliminary. To be submitted to PRD(RC)

Systematic uncertainties	e-tag	μ-tag
Detector and selection bias	0.12%	0.08%
Background subtraction	0.05%	0.06%
$K^0/\bar{K}^0$ interaction	0.03%	0.02%
Total	0.13%	0.10%

Recent CP violation results: Charmless B decays

Charmless B decays

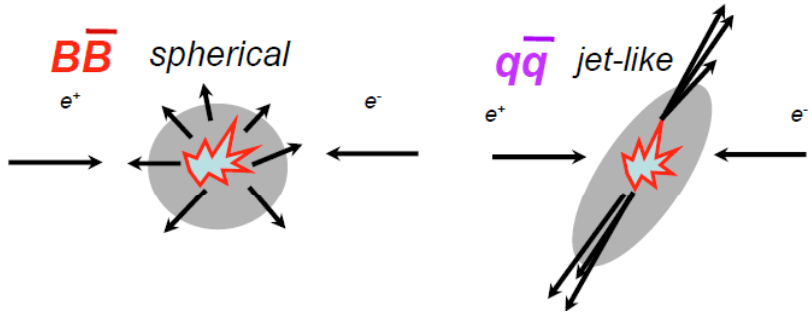
- Many such decays are dominated by b→s penguins
  - Tree amplitudes subdominant in SM
  - Time-dependence and FSI (intermediate states) allow to measure the CKM angles
- NP can change CP asymmetries, branching fractions and polarizations in B→VV decays



- Use kinematic constraints from beam energies

$$m_{ES} = \sqrt{\left(\sqrt{s}/2\right)^2 - p_B^{*2}} \qquad \Delta E = E_B^* - \sqrt{s}/2$$

- Event shape variables combined into a linear (Fisher) or non linear (NN) combination. Tagging (other "B") information often used



  - Apply selection to reject continuum
  - As variable in ML fit

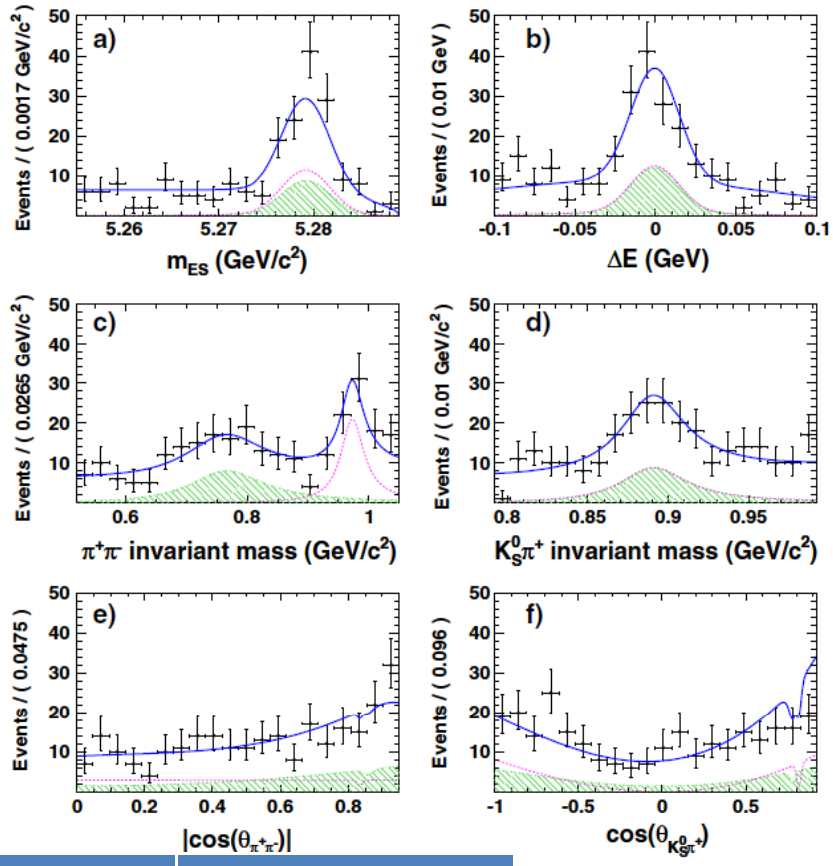
$B^+ \to \rho^0 K^{*+}$ and $B^+ \to f_0 K^{*+}$

467x10⁶ $B\bar{B}$ pairs

- $B^+ \to \rho^0 K^{*+}$ is a VV decay. QCDF
  - Predicts longitudinal polarization $f_L \sim 0.9$
  - Works for $B \to \rho\rho$, not for other VV decays where $f_L \sim 0.5$ ("polarization puzzle")
- Reconstruct $\rho^0/f_0 \to \pi^+\pi^-$, $K^{*+} \to K_s\pi^+, K^+\pi^0$
- ML fit with 7 variables: m_{ES}, ΔE, NN, invariant masses, $\cos\theta$
- Measure simultaneously BF, A_{CP}, f_L
  - First observation of $B^+ \to \rho^0 K^{*+}$ with 5.3σ
  - Consistent with QCDF, BF $\approx (5\pm1)\times10^{-6}$

NPB 774, 64 (2007) | PRD 79, 039903 (2009)

- f_L compatible with other $b \to s$ decays



Decay	N_{signal}	BF($\times10^{-6}$)	A_{CP}	f_L
$B^+ \to \rho^0 K^{*+}$	85±24 ($K_s\pi^+$) 67±31 ($K^+\pi^0$)	4.6±1.0±0.4	0.31±0.13±0.03	0.78±0.12±0.03
$B^+ \to f_0(\to\pi^+\pi^-)K^{*+}$	69±14 ($K_s\pi^+$) 91±20 ($K^+\pi^0$)	4.2±0.6±0.3	−0.15±0.12±0.03	…

$\rho^0 K^{*+}$ signal

$f_0 K^{*+}$ signal

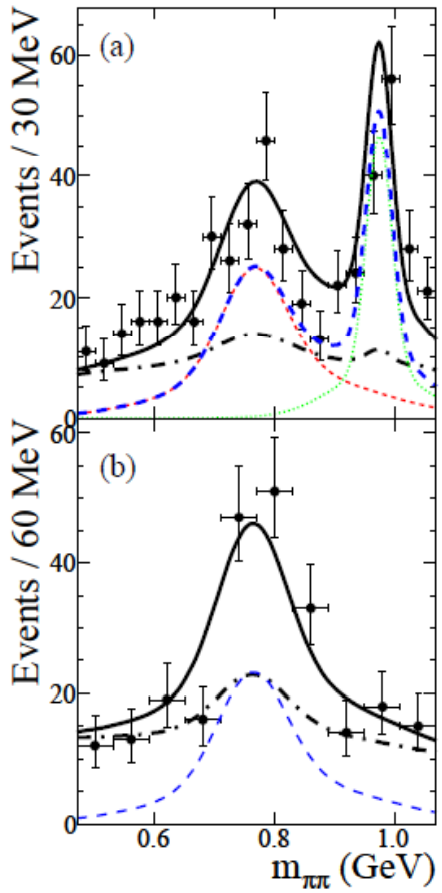
PRD 83, 051101 (2011)

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

471x10⁶ $B\bar{B}$ pairs

- Very similar to previous analysis
- $f_2(1270)K^{*0}$ events extrapolated from $m_{\pi\pi}$ sideband
- First 5σ observations of $B^0 \to \rho^- K^{*+}$ and $B^0 \to f_0 K^{*0}$

Decay	N_{signal}	BF($\times 10^{-6}$)	A_{CP}	f_L
$B^0 \to \rho^0 K^{*0}$	365±37	$5.1 \pm 0.6^{+0.6}_{-0.8}$	−0.06±0.09±0.02	0.40±0.08±0.11
$B^0 \to \rho^- K^{*+}$	167±27	10.3±2.3±1.3	+0.21±0.15±0.02	0.38±0.13±0.03
$B^0 \to f_0 K^{*0}$	220±23	5.7±0.6±0.3	+0.07±0.10±0.02	…



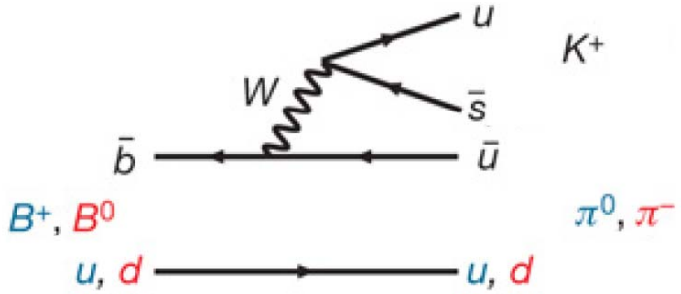
- BF consistent with QCDF, BF ≈ 5×10^{-6}
- f_L inconsistent with QCDF, but consistent with experimental results from other b→s decays

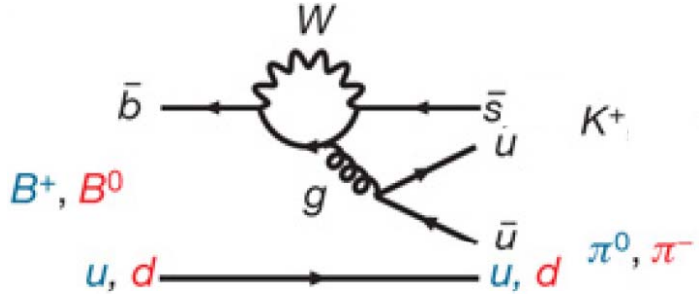
- Also measure scalar $(K\pi)^*_0$ and tensor $K^*_2(1430)$ states in a $(K\pi)$ "high-mass" region (not shown here)

Preliminary

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

- We expect $A_{CP}(B^0 \to K^+\pi^-) \approx A_{CP}(B^+ \to K^+\pi^0)$

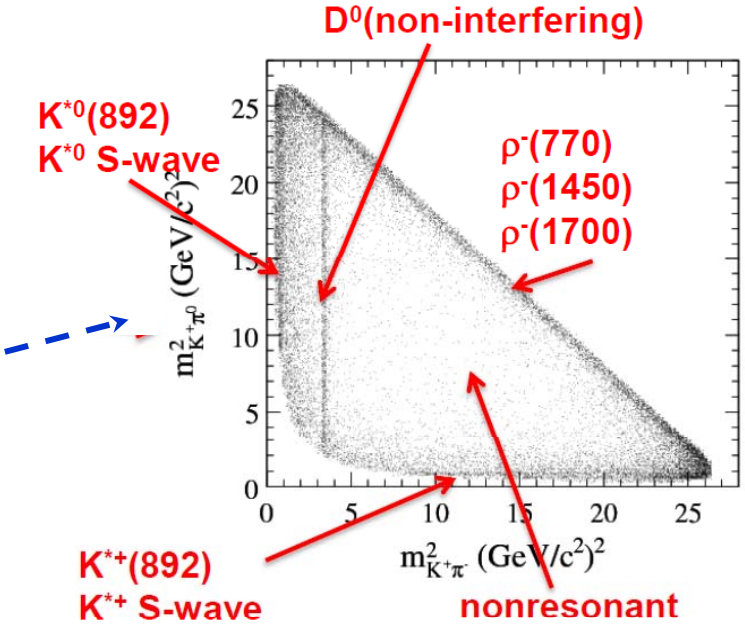




5σ difference

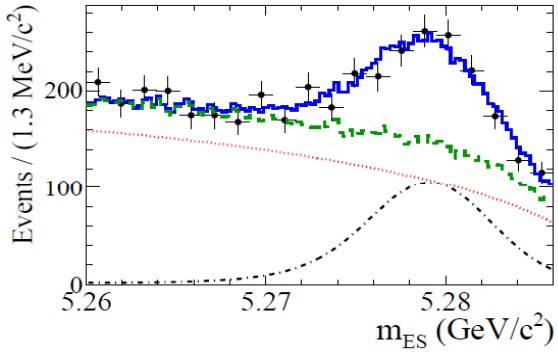
Mod.Phys.Lett.A 24, 1983 (2009)

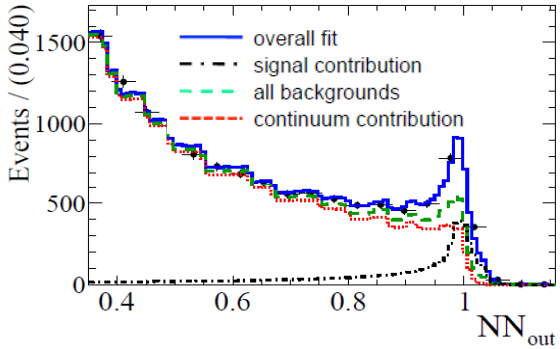
- Experimentally SM or NP? "Kπ puzzle"
  - $A_{CP}(B^+ \to K^+\pi^0) = +0.050 \pm 0.025$
  - $A_{CP}(B^0 \to K^+\pi^-) = -0.098 \pm 0.012$
- Is there a similar $K^*\pi$ puzzle?
- Have to measure $B^0 \to K^{*+}\pi^-$ and $B^+ \to K^{*+}\pi^0$
  - P/T predicted to be 2-3 larger than in Kπ
- Many resonances interfere
  $\Rightarrow$ full amplitude (Dalitz plot) analysis
- Large backgrounds
  - $q\bar{q}$ + many different $B\bar{B}$ categories + large amount of signal misreconstructed (especially for $K^+\pi^0\pi^0$), all accounted for



$B^0 \to K^+\pi^-\pi^0$ and $B^+ \to K^+\pi^0\pi^0$: results

- Perform ML fit with m_{ES} and NN, and for $K^+\pi^-\pi^0$ only, also ΔE and DP
- For $B^0 \to K^+\pi^-\pi^0$ PRD 83, 112010 (2011) **454x10⁶ $B\bar{B}$ pairs**
  - $BF(B^0 \to K^+\pi^-\pi^0) = (38.5 \pm 1.0 \pm 3.9)\times 10^{-6}$
  - $A_{CP}(K^{*+}\pi^-) = -0.29 \pm 0.11 \pm 0.02$ 3.1σ evidence for direct CPV
  - When combined with $B^0 \to K_s\pi^+\pi^-$: $A_{CP}(K^{*+}\pi^-) = -0.24 \pm 0.07 \pm 0.02$
- For $B^+ \to K^+\pi^0\pi^0$
  - First inclusive measurement
  - Measure resonances in a two-body fashion





Decay	N_{signal}	BF($\times 10^{-6}$)	A_{CP}
$B^+ \to K^+\pi^0\pi^0$	7427±518	16.2±1.2±1.5	−0.06±0.06±0.04
$B^+ \to K^{*+}\pi^0$	1078±197	8.2±1.5±1.1	**−0.06±0.24±0.04**
$B^+ \to f_0(\to\pi^0\pi^0)K^+$	1186±241	2.8±0.6±0.5	+0.18±0.18±0.04
$B^+ \to \chi_{c0}K^+$	245±105	182±78±32±8	−0.96±0.37±0.04

471x10⁶ $B\bar{B}$ pairs

10σ significance

To be compared to $-0.24 \pm 0.07 \pm 0.02$

Preliminary

- More statistics is needed to better test $A_{CP}(K^{*+}\pi^-) \approx A_{CP}(K^{*+}\pi^0)$

Conclusions

- ended data-taking in 2008 but continues to produce many new physics results on CP violation in D, τ and B decays

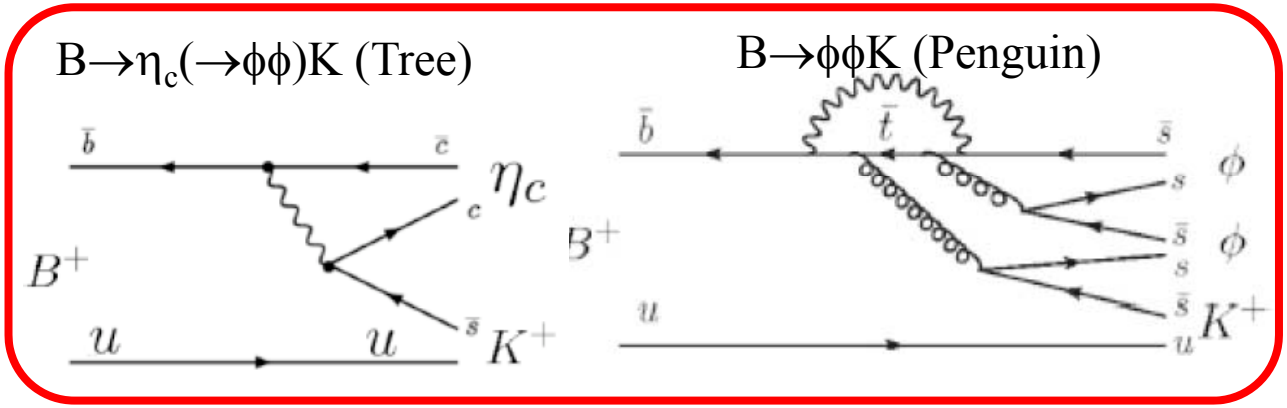
- Only the most recent new results shown in this talk

- Most results agree with SM predictions but some puzzles remain
  - Charmless $B \to VV$ "polarization" puzzle
  - "$K\pi$" puzzle
- …and a 3σ effect has just appeared
  - Direct CP violation in $\tau^- \to \pi^- K^0_s \nu_\tau$

- A larger data sample is required to perform stringent tests and searches
- We look forward for many interesting flavor results from present and future flavor facilities

Bonus slides

B→ϕϕK



- Interference at $m_{\phi\phi} \sim m_{\eta c}$
- SM tree and penguin have ≈ the same weak phase
- NP in the penguin could induce large direct CPV

PLB 583, 285 (2004)

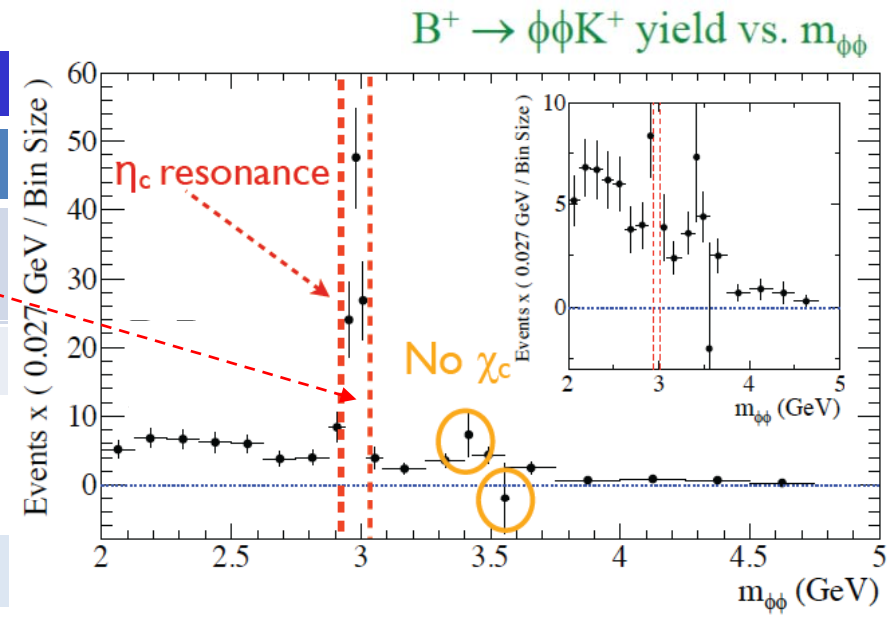
- ML fit in m_{ES}, ΔE, Fisher (and 2 ϕ masses for BF)
- Use ($m_{\phi 1}$,$m_{\phi 2}$) sidebands to extract peaking backgrounds from B→ϕKKK, 5K, f_0ϕK, f_0KKK decays

$m_{\phi\phi}$<2.85 GeV region

464x10^6 B$\bar{B}$ pairs

Decay	N_{signal}	BF(×10^{-6})	A_{CP}
$B^+ \to \phi\phi K^+$	178±15	5.6±0.5±0.3	+0.10±0.08±0.02 −0.09±0.10±0.02
$B^0 \to \phi\phi K^0$	40±7	4.5±0.8±0.3	…

First 5σ observation of $B^0 \to \phi\phi K^0$

A_{CP} consistent with 0 (SM expectation)

PRD 84, 012001 (2011)