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Direct CP violation in B decays

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Introduction

- Direct *CP* violation is decay property
- It is difference of decay width between $B \to f$ and $\overline{B} \to \overline{f}$
- For charged B mesons, only *CP* violation possible
- In decays to flavour eigenstates

$$A_f = \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)}$$

- In case of *CP* eigenstates, need to disentangle *CP* violation caused by mixing from direct *CP* violation

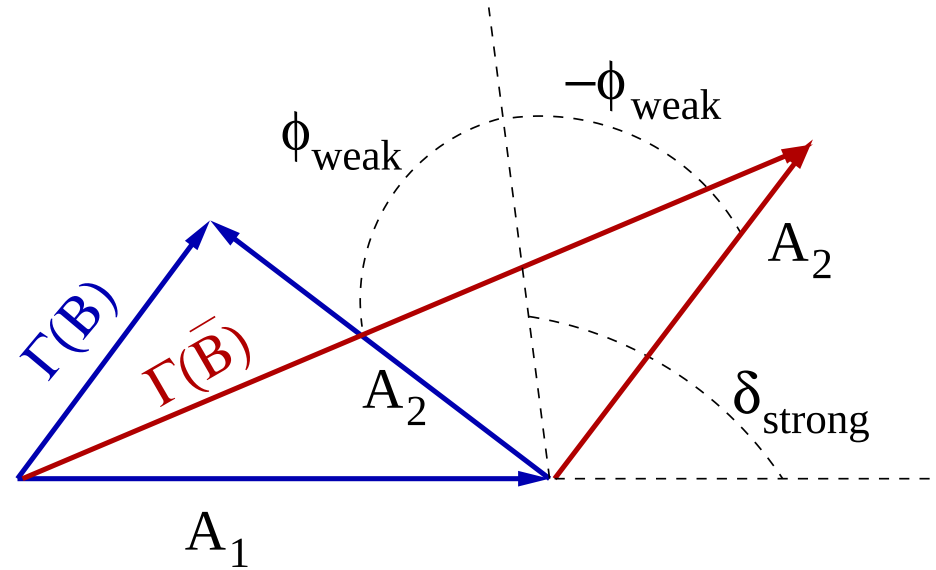
$$A_f(t) = \frac{d\Gamma/dt(\overline{M} \to f) - d\Gamma/dt(M \to f)}{d\Gamma/dt(\overline{M} \to f) + d\Gamma/dt(M \to f)} = \mathcal{S} \sin \Delta m t + \mathcal{A} \cos \Delta m t$$

- Different convention for Belle and *BABAR* $\mathcal{A} = -\mathcal{C}$

Introduction

- For observable direct CPV, necessary requirement is to have at least two interfering decay amplitudes

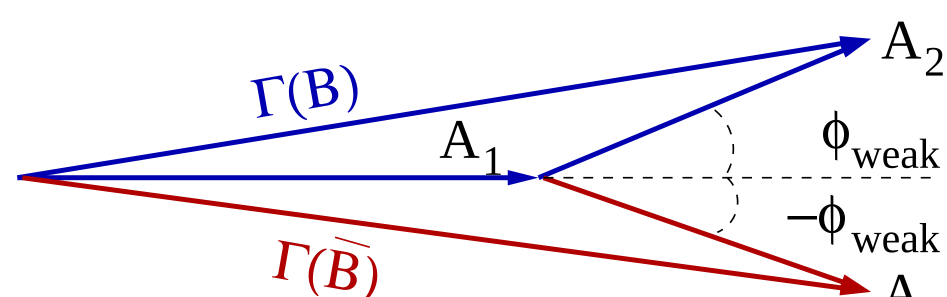
$$\Gamma(B \to f) = |A_1 + A_2 e^{i\phi} e^{i\delta}|^2$$
$$\Gamma(\overline{B} \to \overline{f}) = |A_1 + A_2 e^{-i\phi} e^{i\delta}|^2$$



$$A_f \propto \sin\phi \sin\delta$$

$\Rightarrow$ Need both $\phi \neq 0$ and $\delta \neq 0$

- Theoretical predictions difficult because of need to calculate strong phases



Introduction

- Direct *CP* violation is crucial to determine CKM angle γ, discussed by A. Poluektov
- Largest direct *CP* violation expected with two interfering amplitudes of comparable size

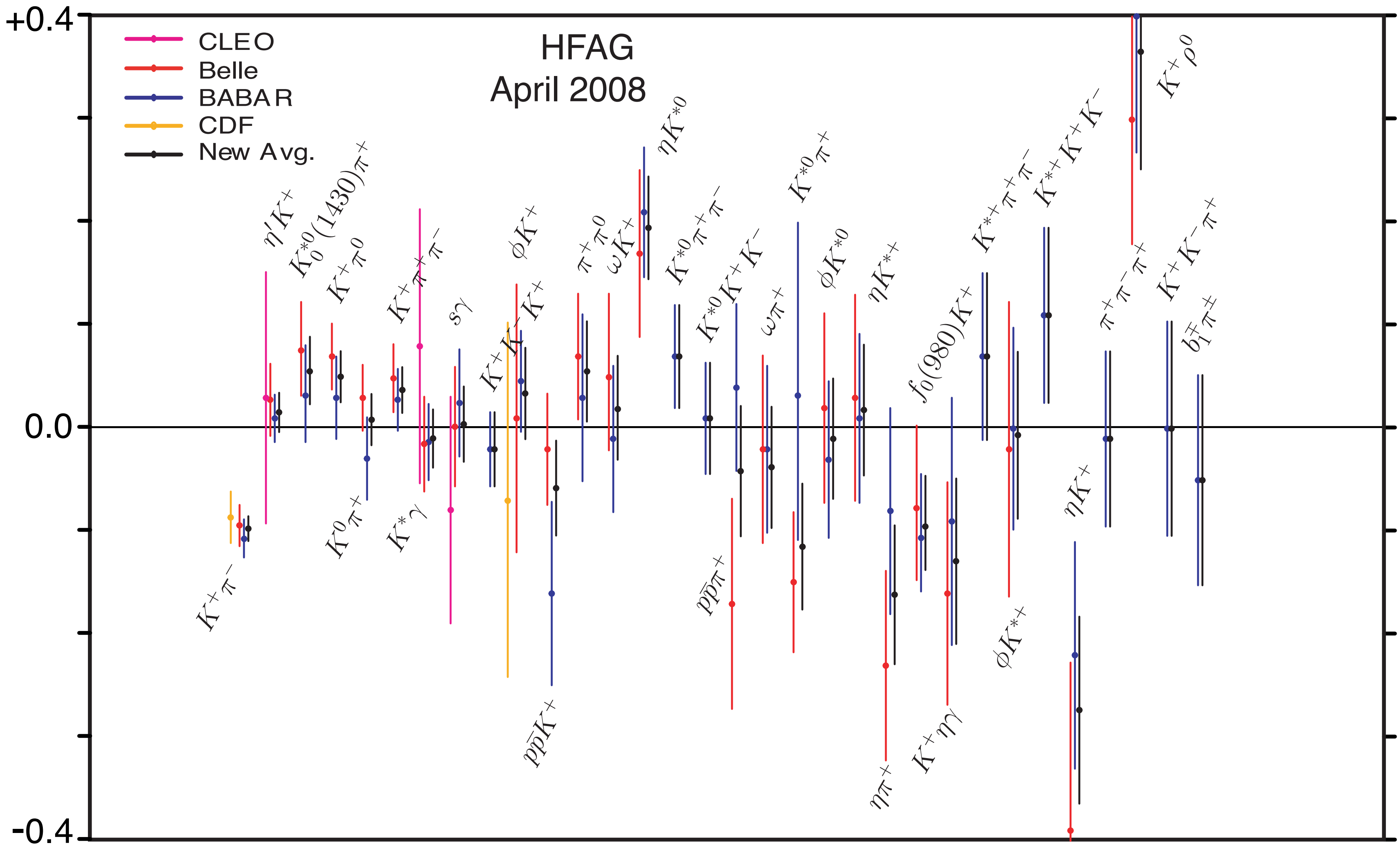
$\longrightarrow$ Test our theoretical tools

- Search for new physics
  - Null tests $\Leftrightarrow$ decays with dominant single amplitude expect negligible direct *CP* violation

  $\longrightarrow$ Nonzero direct *CP* violation implies additional amplitude $\Rightarrow$ new physics

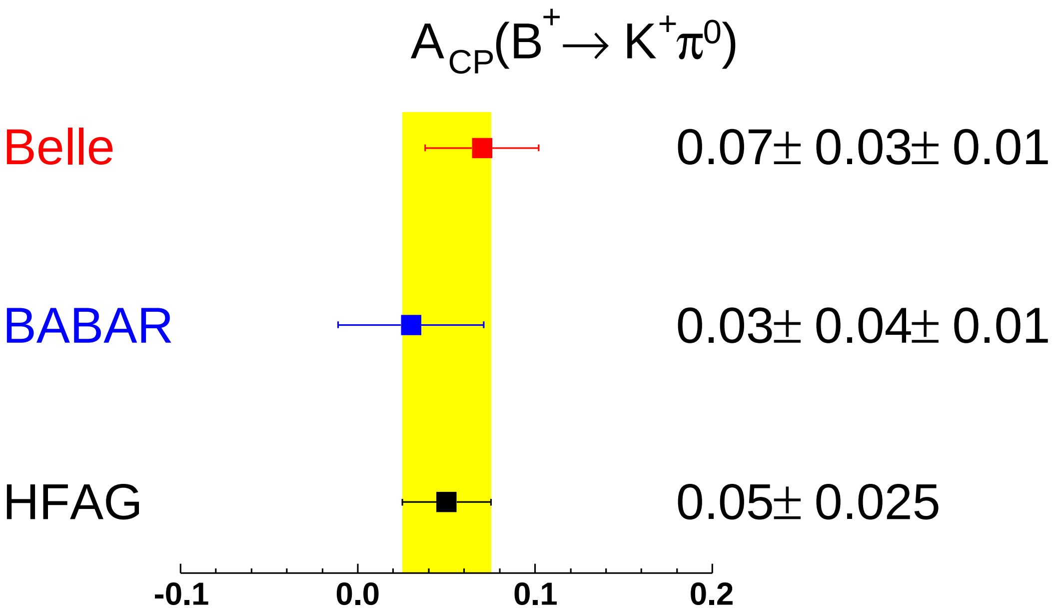
Charmless b-hadron decays

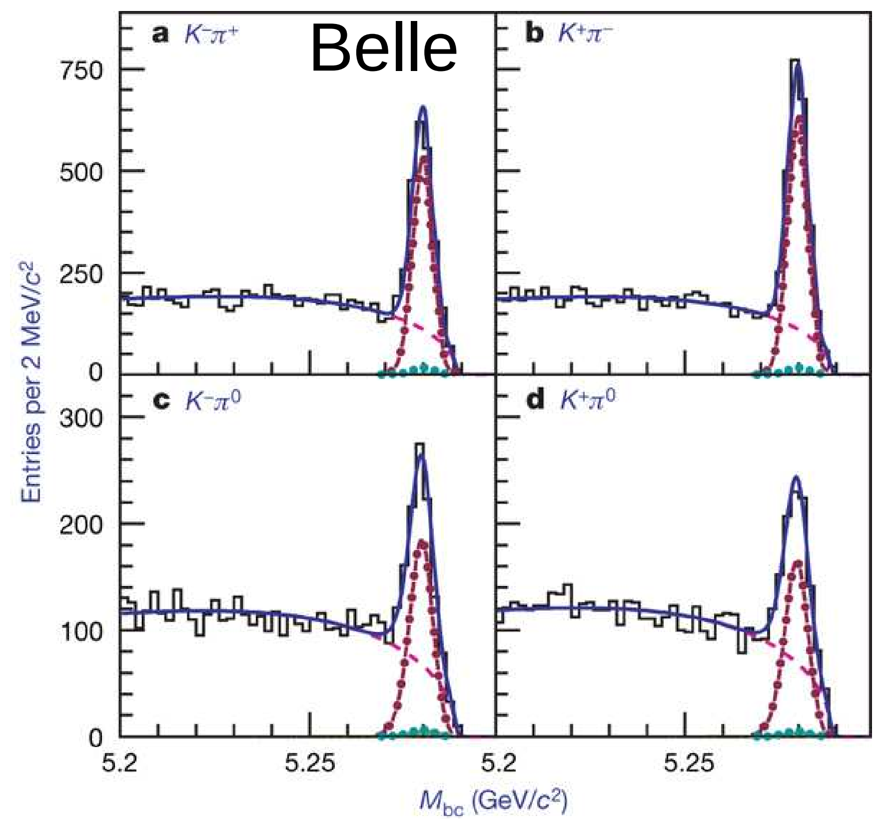
CP Asymmetry in Charmless B Decays



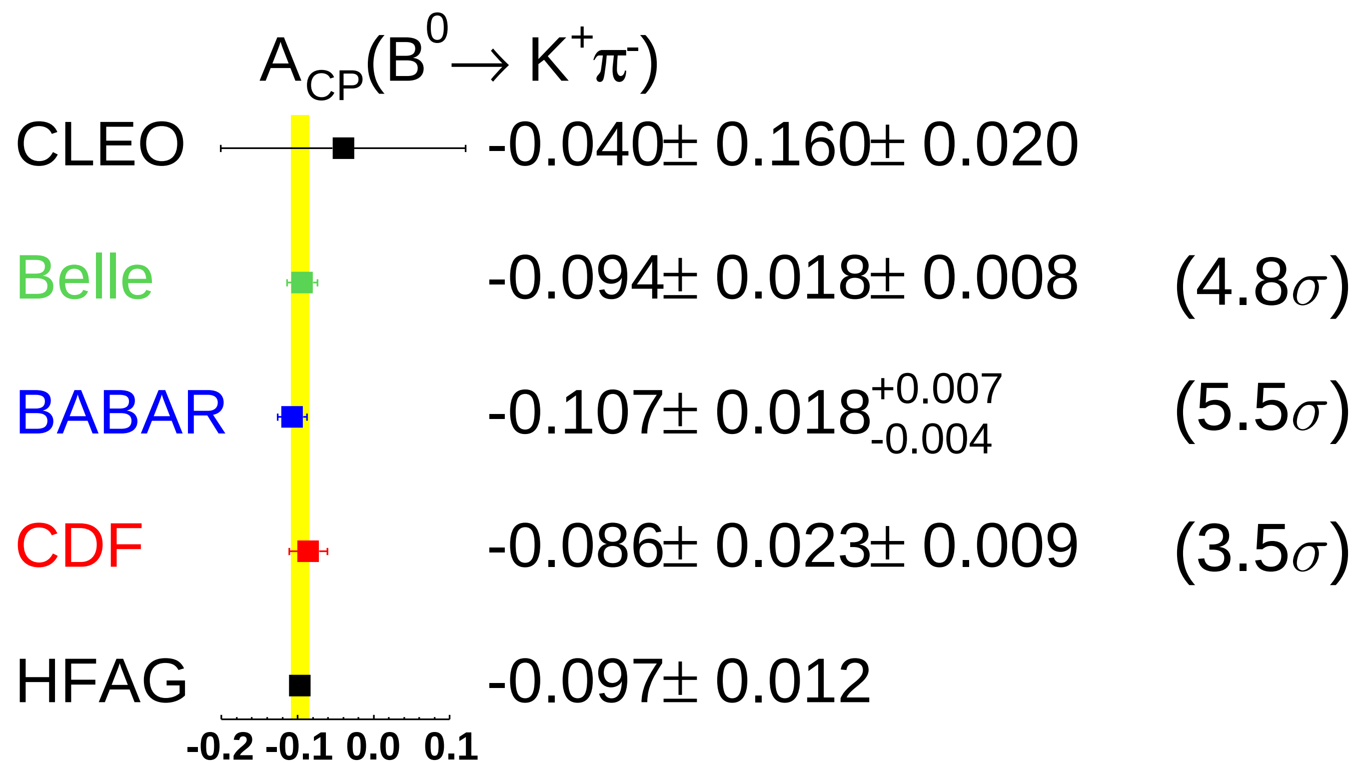
$B^+ \to K^+\pi^0$

- Both Belle and *BABAR* published result on $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$
- Belle uses 535 million $B\overline{B}$ pairs
- *BABAR* uses 383 million $B\overline{B}$ pairs





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



- First $> 5\sigma$ measurement of direct CPV
- Consistent amongst experiments
- Difference between B^+ and B^0 has 5.3σ significance

- Is the difference between B^+ and B^0 sign of new physics?
- Consistent with fourth generation (W.-S. Hou)
- Could be effect of color suppressed tree amplitude (M. Gronau)

$\Rightarrow$ Too early to claim new physics

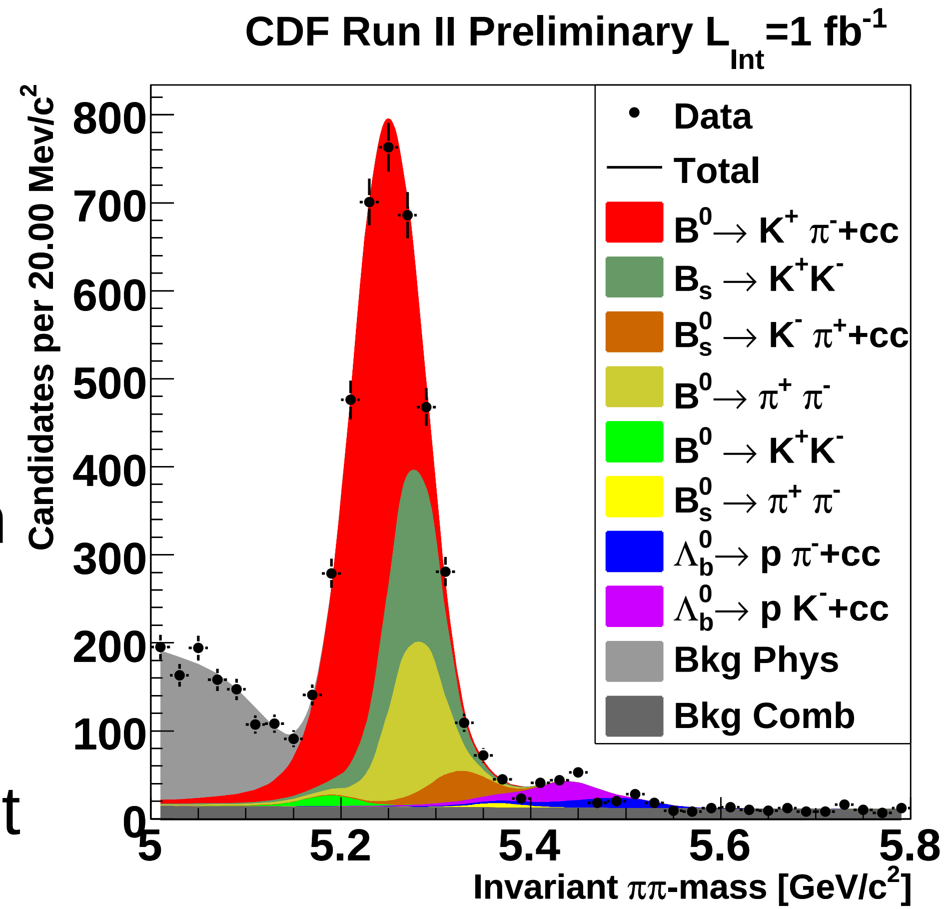
$\mathrm{B_s} \to \mathrm{K}\pi$

- One can use $A_{\mathrm{CP}}(B^0 \to K^+\pi^-)$ to predict

$$A_{\mathrm{CP}}(B_s \to K^-\pi^+) = -A_{\mathrm{CP}}(B^0 \to K^+\pi^-)\frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B_s \to K^-\pi^+)} \cdot \frac{\tau(B^0)}{\tau(B_s)}$$

$\Rightarrow A_{\mathrm{CP}}(B_s \to K^-\pi^+) \approx +37\%$

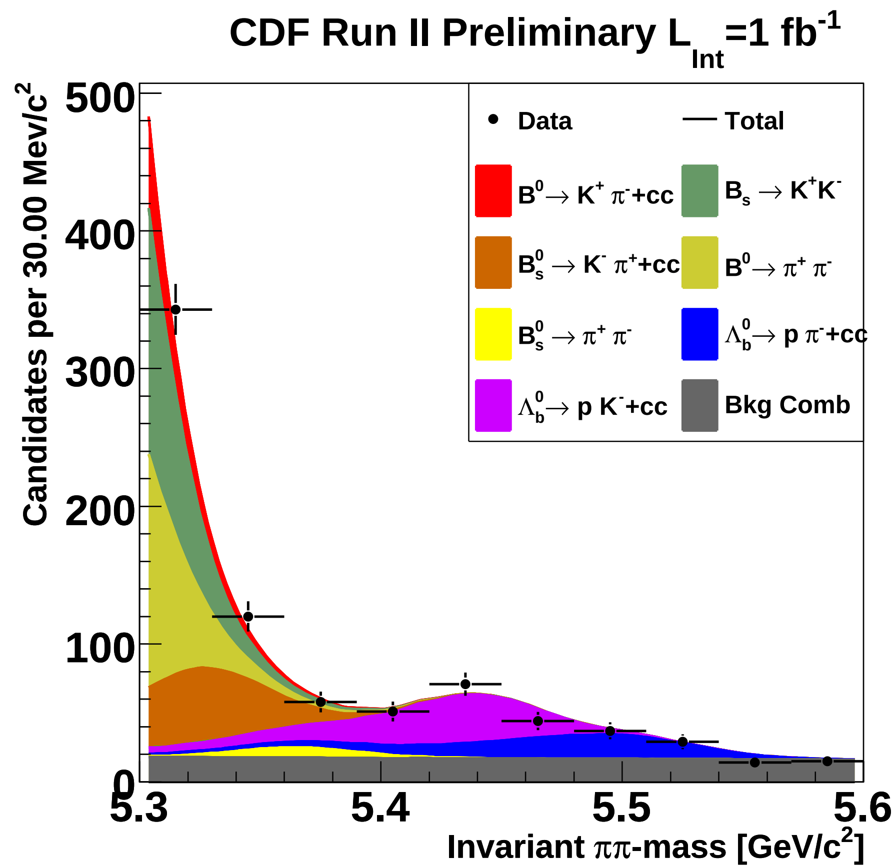
$$\frac{N(\overline{B}_s \to K^+\pi^-) - N(B_s \to K^-\pi^+)}{N(\overline{B}_s \to K^+\pi^-) + N(B_s \to K^-\pi^+)} = +0.39 \pm 0.15 \pm 0.08$$



- Consistent with SM expectation
- 2.5σ significance of being nonzero
- Still only measurement of direct CPV in B_s system

$\Lambda_b \to p\pi$ and $\Lambda_b \to pK$

- Same quark level transition as $B \to K\pi$
- SM expect large direct CPV for $\Lambda_b \to pK$ $[\mathcal{O}(10\%)]$
- Very little know from theory
- Another decay to test SM and search for new physics
- Branching fractions in talk of A. Warburton



$$A_{CP}(\Lambda_b \to p\pi) = 0.03 \pm 0.17 \pm 0.05$$
$$A_{CP}(\Lambda_b \to pK) = 0.37 \pm 0.17 \pm 0.03 \qquad (2.1\sigma)$$

First measurement, consistent with SM expectation

Three body decay Dalitz plot analysis

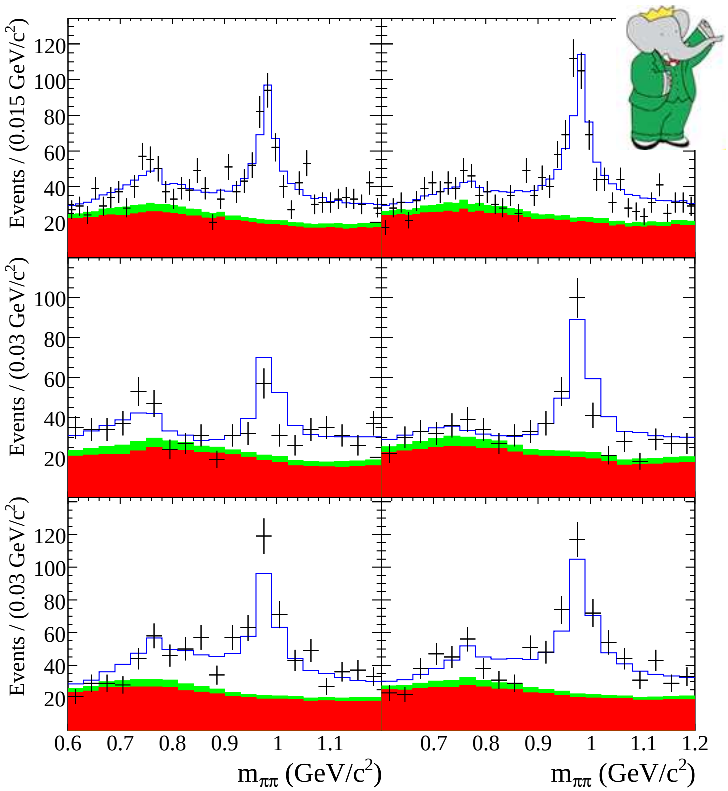
- Dalitz plot analysis only way to cope with broad overlapping resonances
- In single measurement extracts lot of information
- With increasing statistics becomes very sensitive to modeling of Dalitz plot variables
- Many final states analyzed: $K\pi\pi$, $KK\pi$, KKK
- Here results from $B^+ \rightarrow K^+\pi^-\pi^+$
- Some details on Dalitz models, branching fraction etc. in talk of William Ford

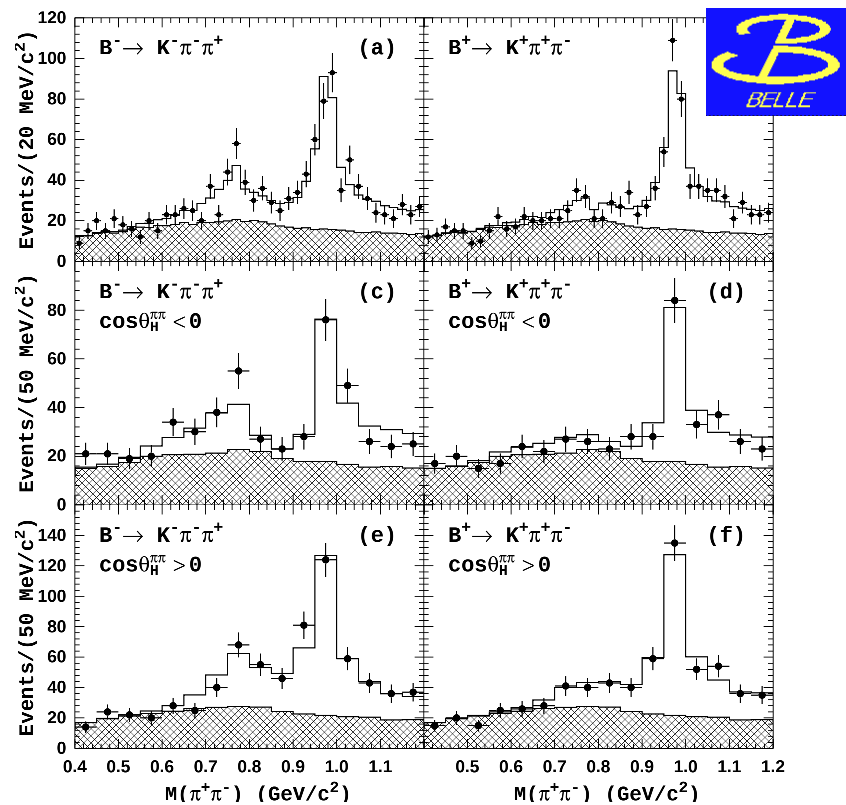
$B^+ \to K^+\pi^-\pi^+$

- 383 million $B\overline{B}$ pairs
- $K^+\rho^0$: $0.44 \pm 0.10^{+0.06}_{-0.14}$ significance 3.7σ
- K^+f_2: $-0.85 \pm 0.22^{+0.26}_{-0.13}$

- 386 million $B\overline{B}$ pairs
- $K^+\rho^0$: $0.30 \pm 0.11^{+0.11}_{-0.05}$ significance 3.9σ
- K^+f_2: $-0.59 \pm 0.22 \pm 0.04$

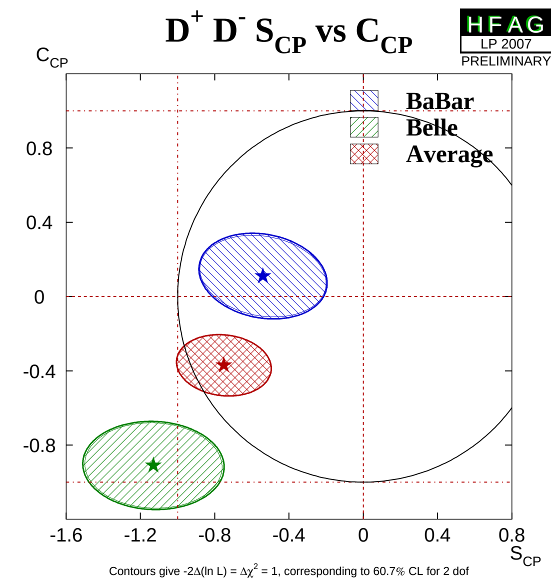
First evidence for direct CPV in B^+ decays

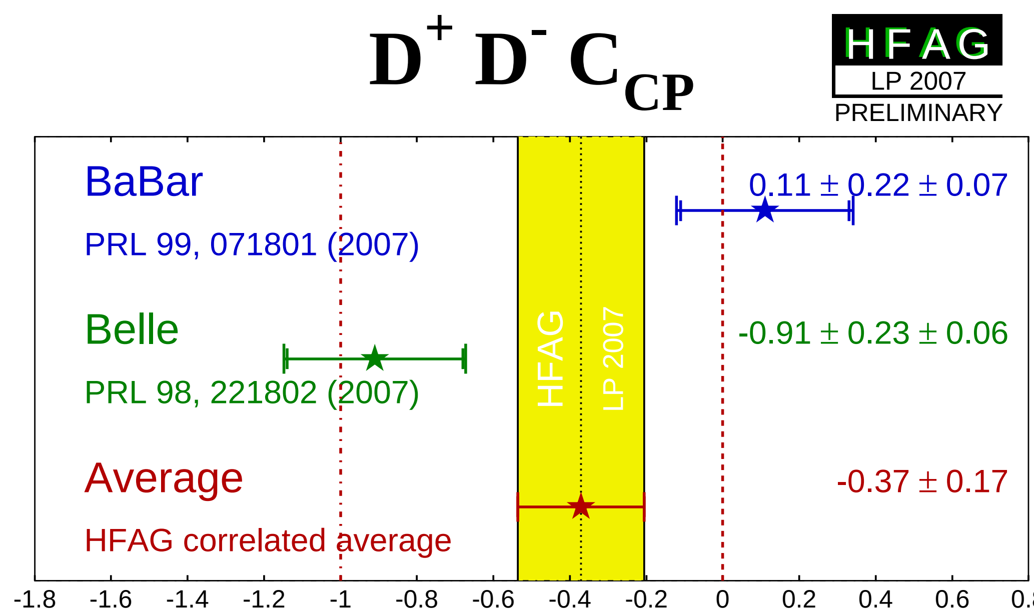




$B \to D^{(*)}D^{(*)}$

- Probing $b \to c\bar{c}d$ transition
- Expect no direct CPV in SM
- First analysis by Belle (535 mil. $B\bar{B}$) showed unusually high direct CPV
- Result from *BABAR* (383 mil. $B\bar{B}$) consistent with zero
- After one year discrepancy remains
- Effort mainly to final states with D^*D^*, which has same quark level transition

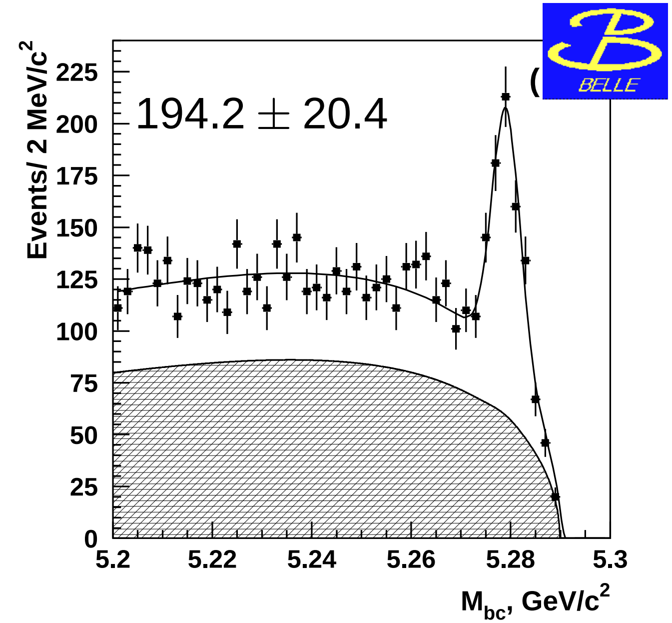


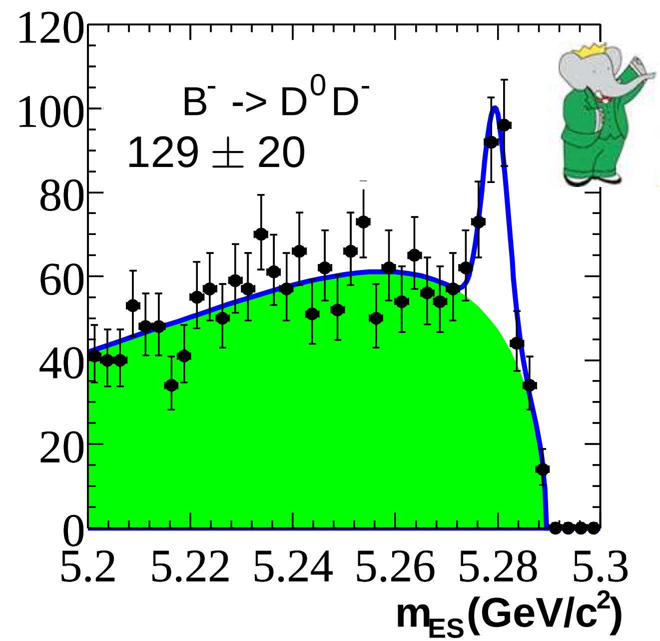


$B^+ \to D^+\overline{D}^0$

- Similar decay as $B^0 \to D^+D^-$
  – Weak exchange and annihilation diagrams not present
- Belle: 657 mil. $B\overline{B}$
  $A_{CP} = 0.00 \pm 0.08 \pm 0.02$
- *BABAR* : 231 mil. $B\overline{B}$
  $A_{CP} = -0.13 \pm 0.14 \pm 0.02$
- Both experiments consistent with each other
- A_{CP} consistent with no direct CPV
- *BABAR* measurement extracts also A_{CP} for $B^+ \to D^{*+}\overline{D}^{*0}$, $B^+ \to D^{*+}\overline{D}^0$, $B^+ \to D^+\overline{D}^{*0}$

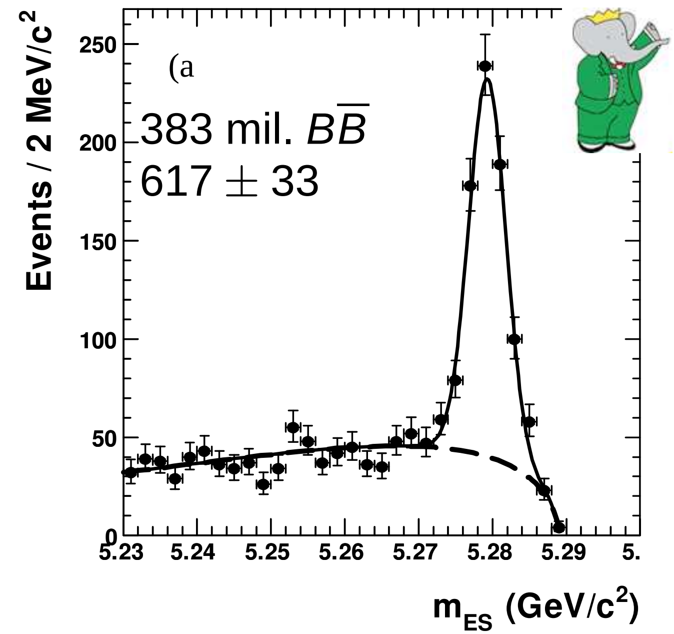
$\rightarrow$ All consistent with no direct CPV

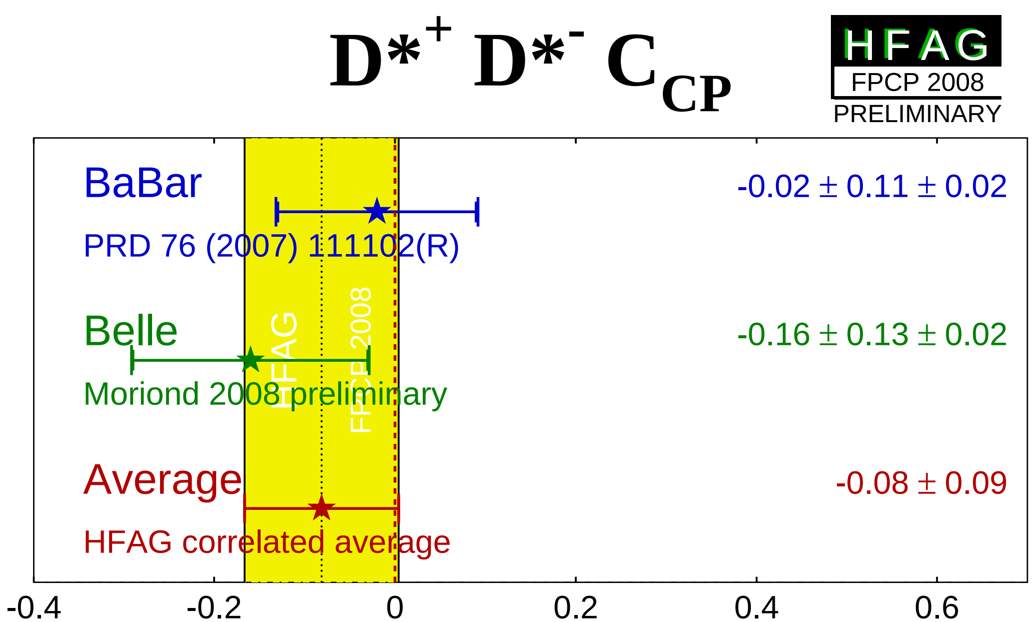


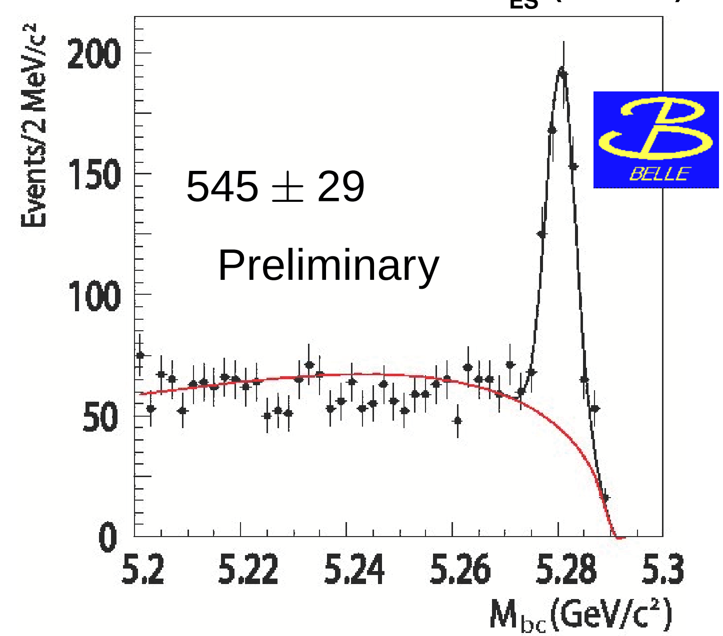


$B^0 \to D^{*+}D^{*-}$

- Mixture of *CP*-even and *CP*-odd state
- 1D angular analysis in transversity framework
- *CP*-odd fraction is
  $(14.3 \pm 3.4 \pm 0.8)\%$ (*BABAR*)
  $(11.6 \pm 4.2 \pm 0.4)\%$ (Belle)

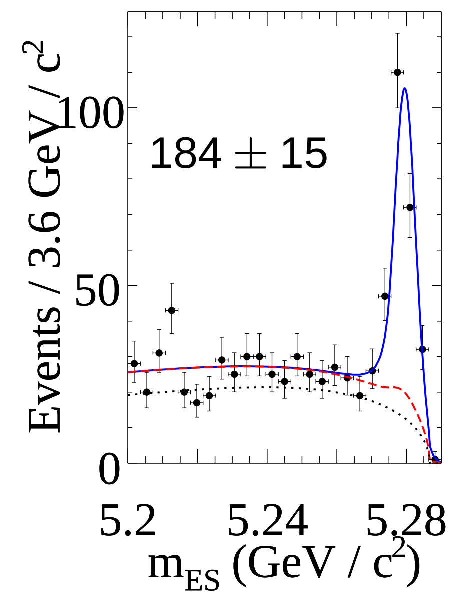


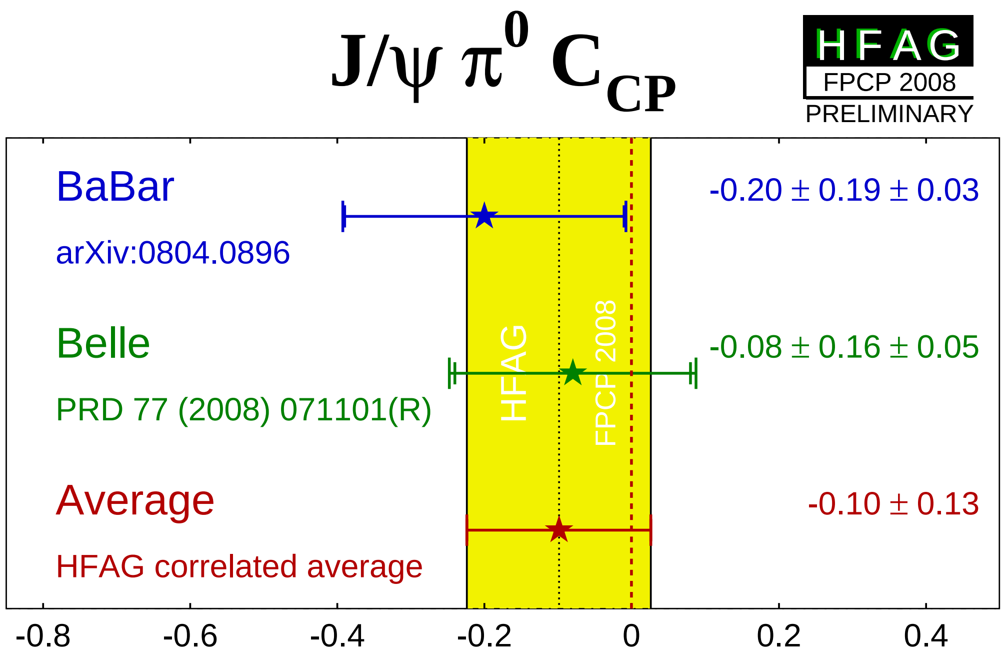


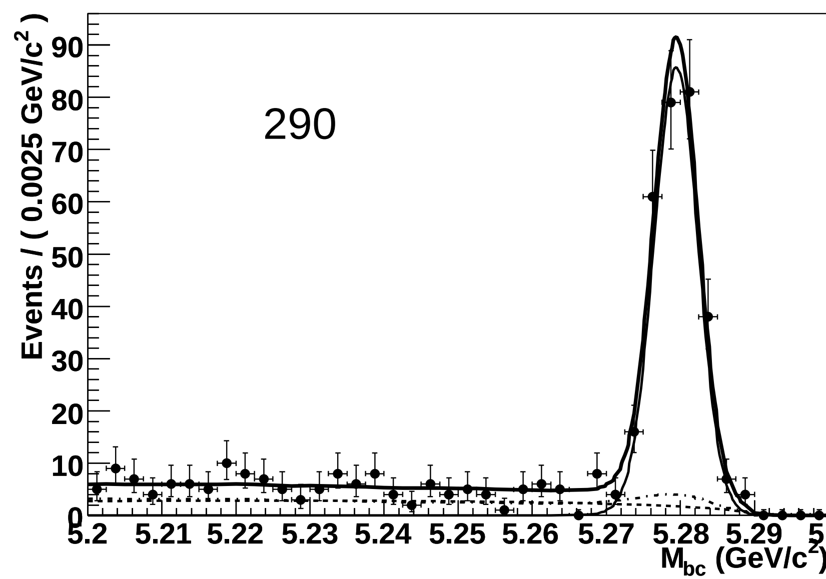


$B^0 \rightarrow J/\psi\pi^0$

- Tree diagram CKM-suppressed
- With other contributions neglected same as $b \rightarrow c\bar{c}s$ transition
- Useful for experimental control over penguin contributions
- 466 (*BABAR*), 535 (Belle) mil. $B\bar{B}$ pairs

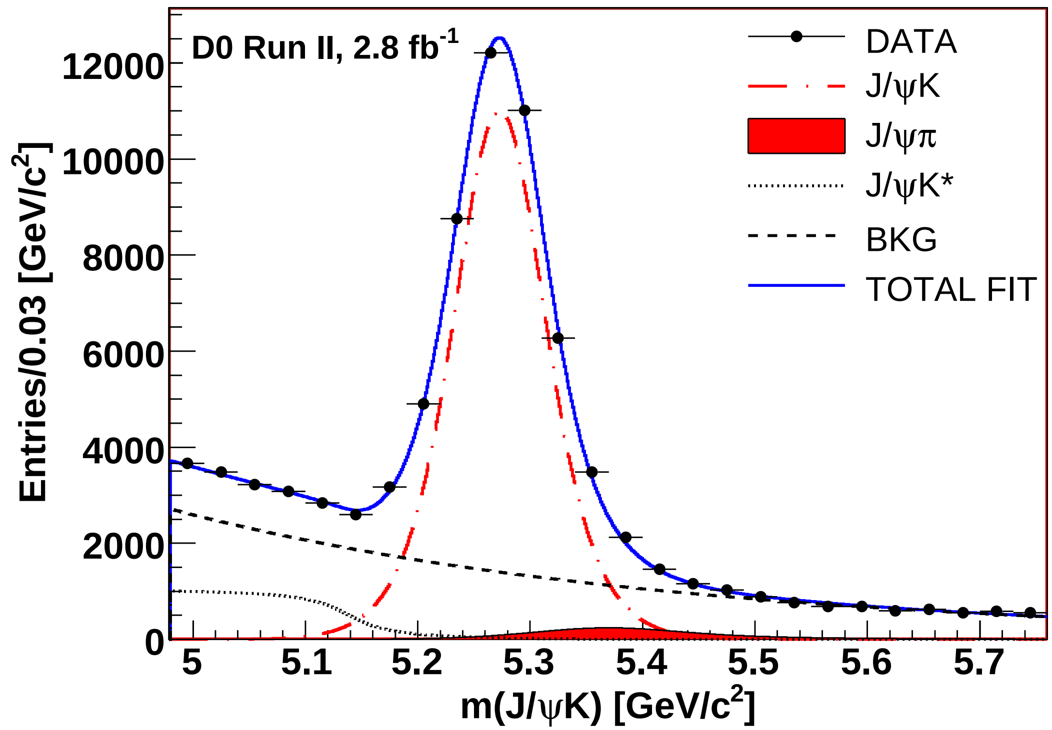






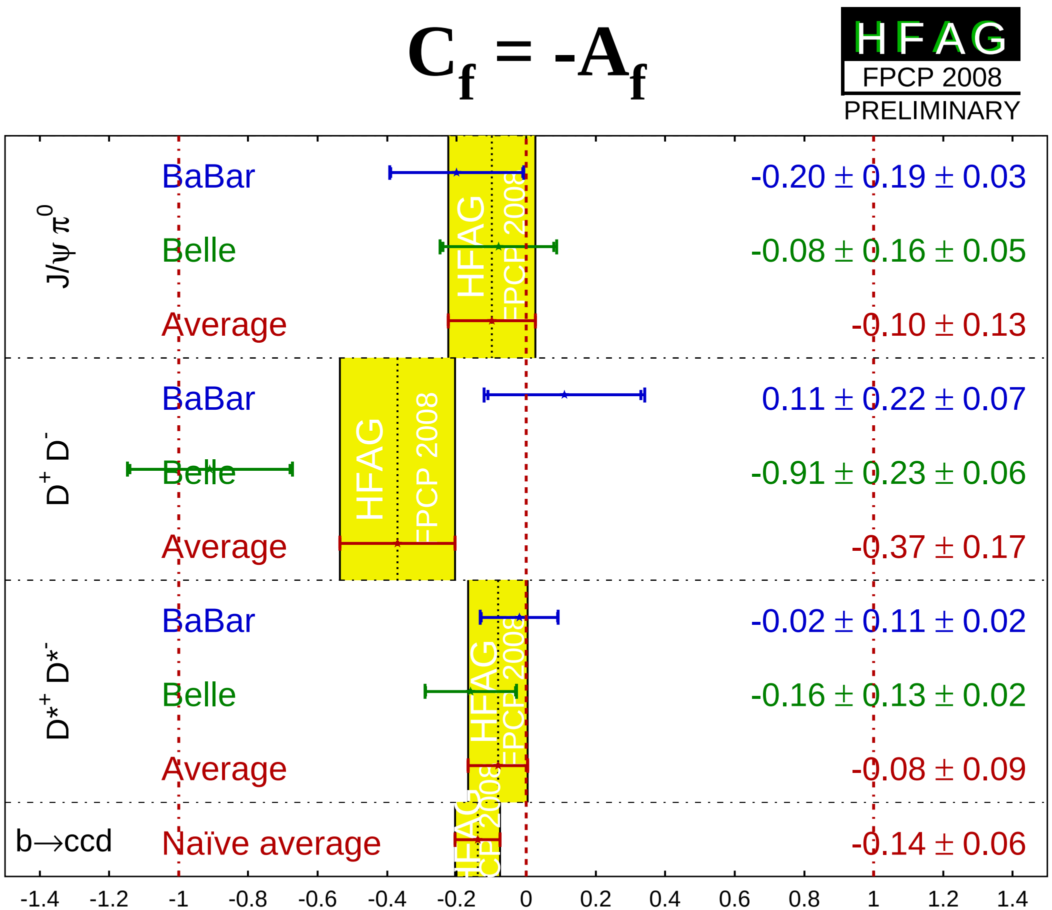
$B^+ \to J/\psi K^+$

- Probes $b \to c\bar{c}s$ transition
- SM expects $A_{CP} \approx 0.003$
- NP can enhance it up to 0.01



- DØ has around 40 000 $B^+ \to J/\psi K^+$ signal events
- Main effort to understand detector asymmetry (uses $D^{*+} \to D^0\pi^+$ with $D^0 \to \mu^+\nu_\mu K^-$)
- $A_{CP}(B^+ \to J/\psi K^+) = 0.0075 \pm 0.0061 \pm 0.0027$
  $A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08 \pm 0.03$

$b \to c\bar{c}d$ Summary



- Only discrepancy in $B^0 \to D^+D^-$ from Belle
- Each mode consistent with no direct CPV
- Naïve average 2.3σ from zero

Conclusions

- Many new results on direct CPV during last year
- *BABAR* , Belle, CDF and DØ experiments contributed
- $B^0 \to K\pi$ most precisely measured
- Intriguing difference between $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$
- First measurement in B_s using $B_s \to K^-\pi^+$ decays
- First measurement of direct CPV in *b*-baryon decays $\Lambda_b \to pK$ and $\Lambda_b \to p\pi$
- First evidence for direct CPV in B^+ sector in decay to ρK
- Discrepancy in $B^0 \to D^+D^-$ remains with no new results
- Several other results on $b \to c\bar{c}d$ transition with all measurements consistent with no direct CPV

Backup

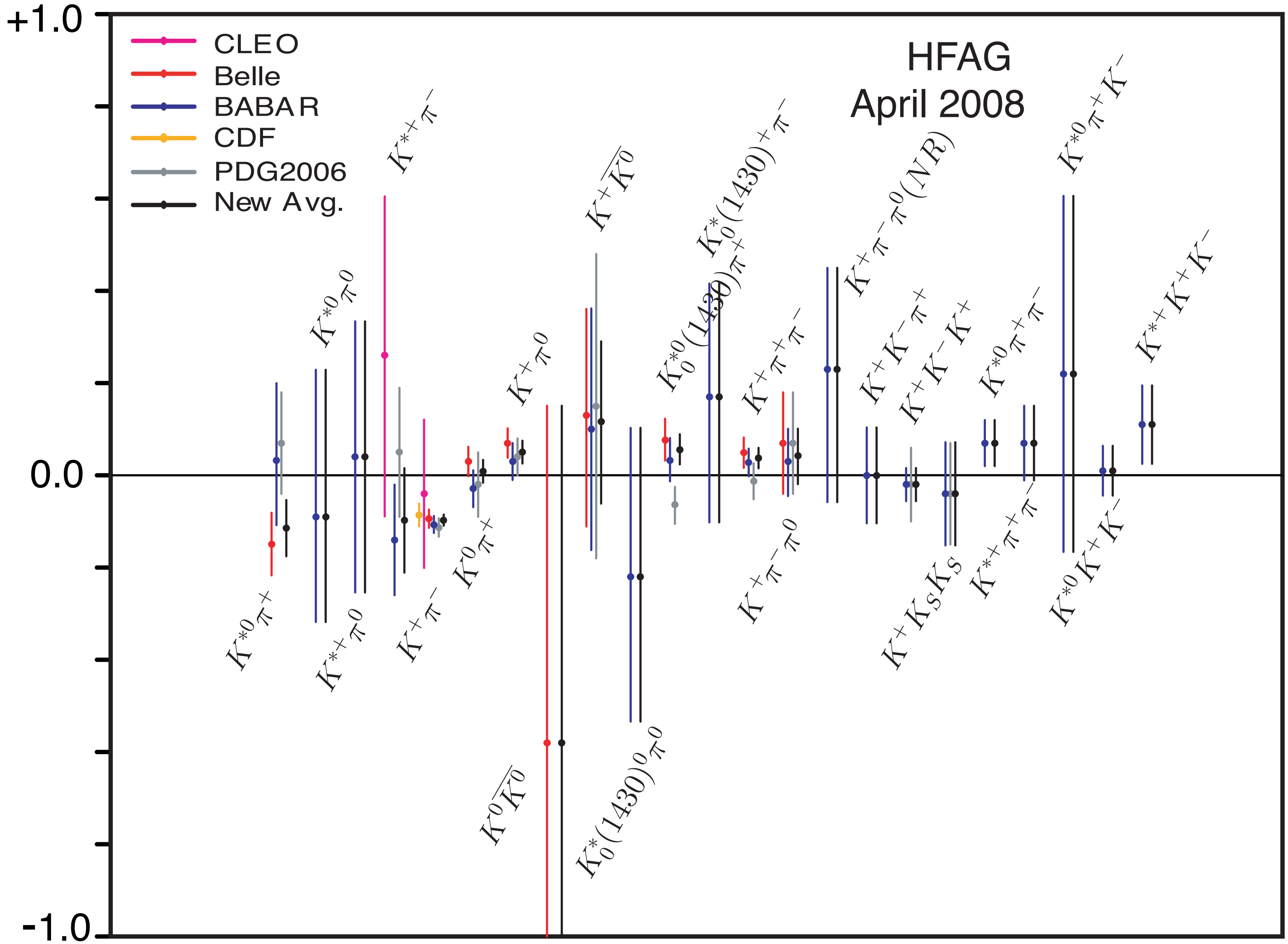
References

- $B \to K\pi$, $B_s \to K\pi$
  - Belle: Nature 452, 332 (2008)
  - *BABAR* : PRL 99, 021603 (2007), PRL 94, 181802 (2005)
  - CDF: CDF Public Note 8579
- $\Lambda_b \to pK$ and $\Lambda_b \to p\pi$
  - CDF: CDF Public Note 9092
- $B^0 \to K^+\pi^-\pi^0$
  - Belle: Phys.Lett.B599:148-158,2004
  - *BABAR* : arXiv:0711.4417 [hep-ex]
- $B^+ \to K^+\pi^-\pi^+$
  - Belle: Phys.Rev.Lett.96:251803,2006
  - *BABAR* : arXiv:0803.4451 [hep-ex]

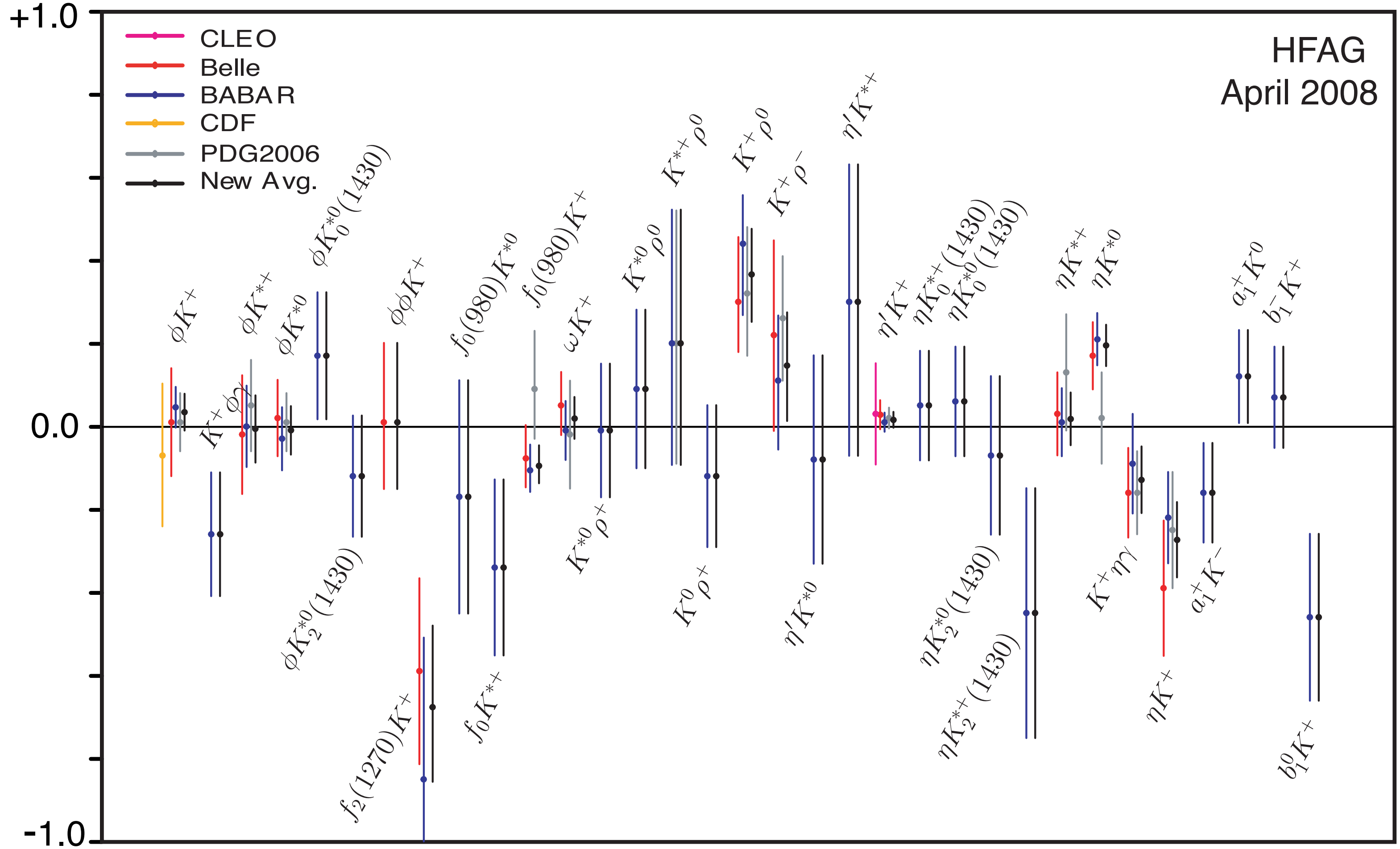
References

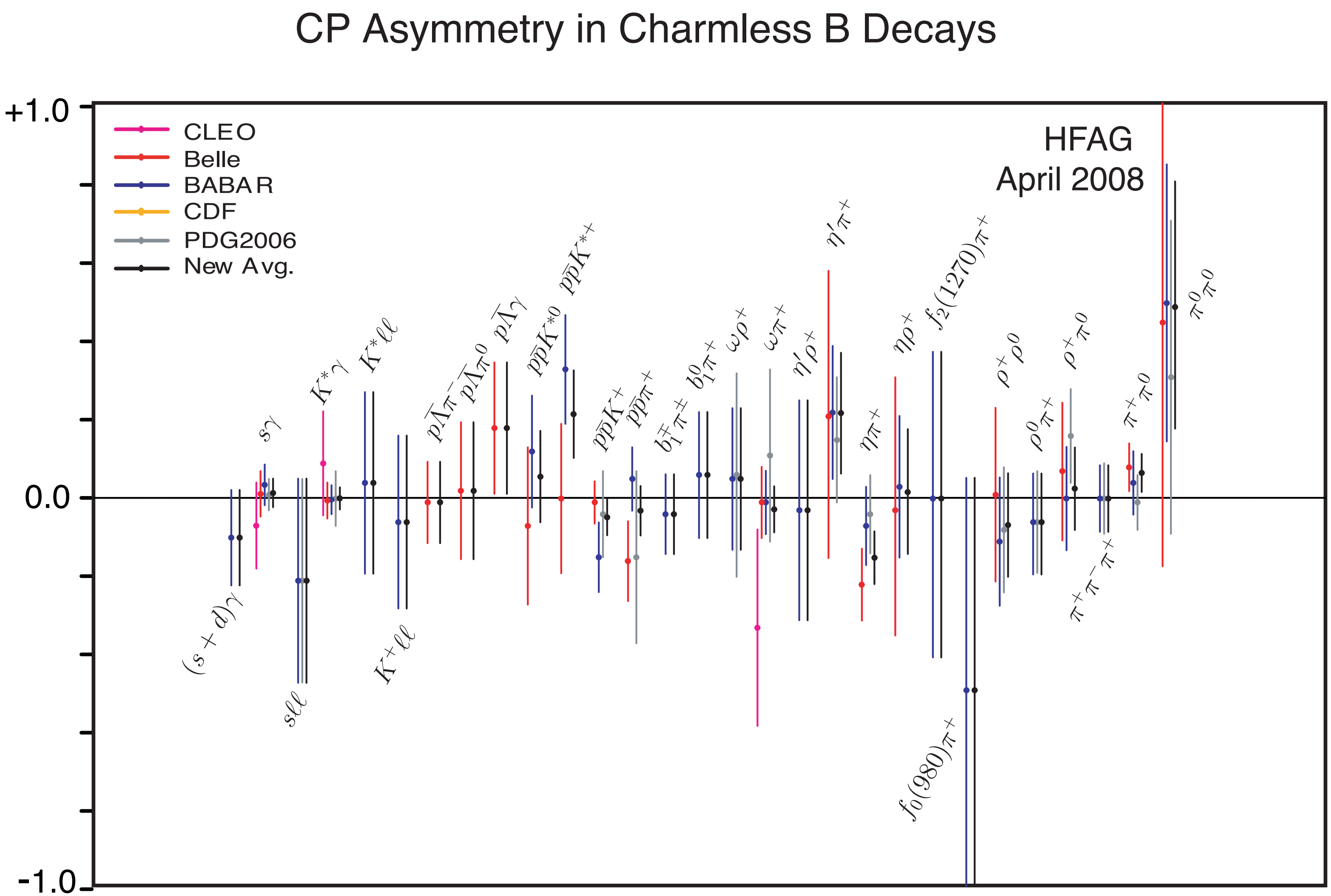
- $B \rightarrow DD$
  - *BABAR* : Phys.Rev.Lett.99:071801,2007; Phys.Rev.D73:112004,2006; Phys.Rev.Lett.99:071801,2007; Phys.Rev.D76:111102,2007
  - Belle: Phys.Rev.Lett.98:221802,2007; arXiv:0802.2988 [hep-ex]; Phys.Rev.Lett.93:201802,2004; Tagir Aushev at Moriond EW 2008
- $B^0 \rightarrow J/\psi\pi^0$
  - *BABAR* : arXiv:0804.0896 [hep-ex]
  - Belle: arXiv:0708.0304 [hep-ex]
- $B^+ \rightarrow J/\psi\pi^+$
  - DØ: arXiv:0802.3299 [hep-ex]

CP Asymmetry in Charmless B Decays



CP Asymmetry in Charmless B Decays

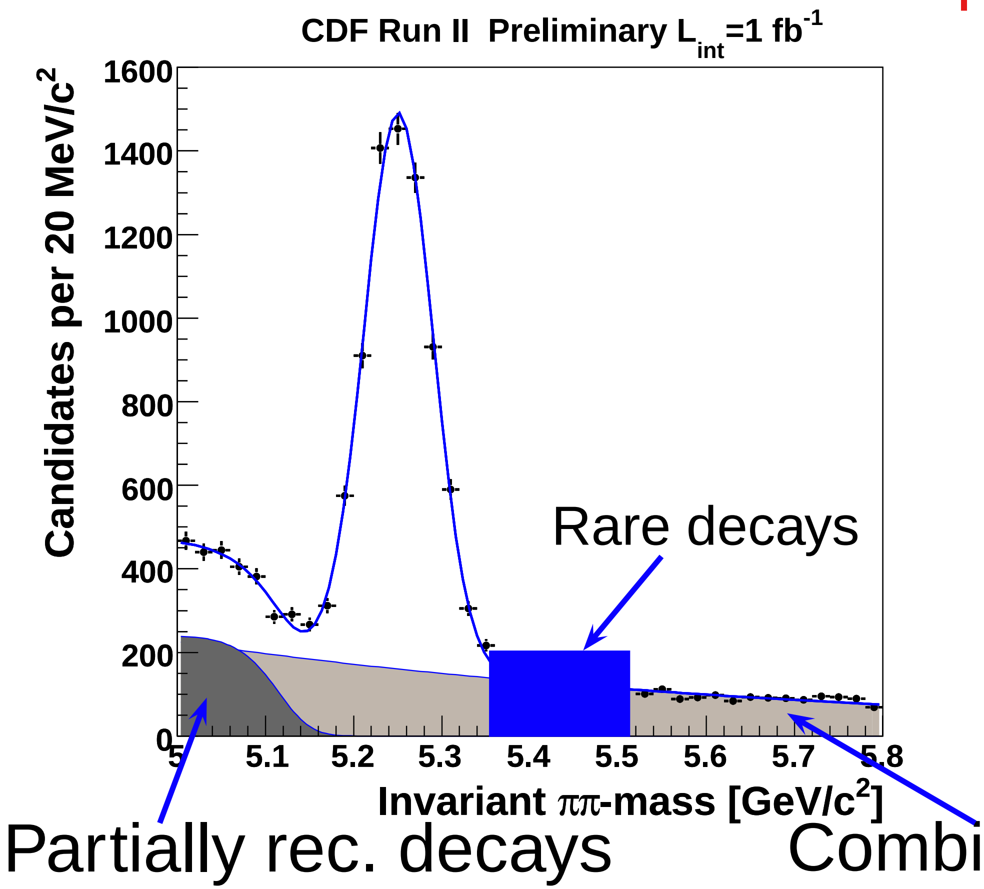


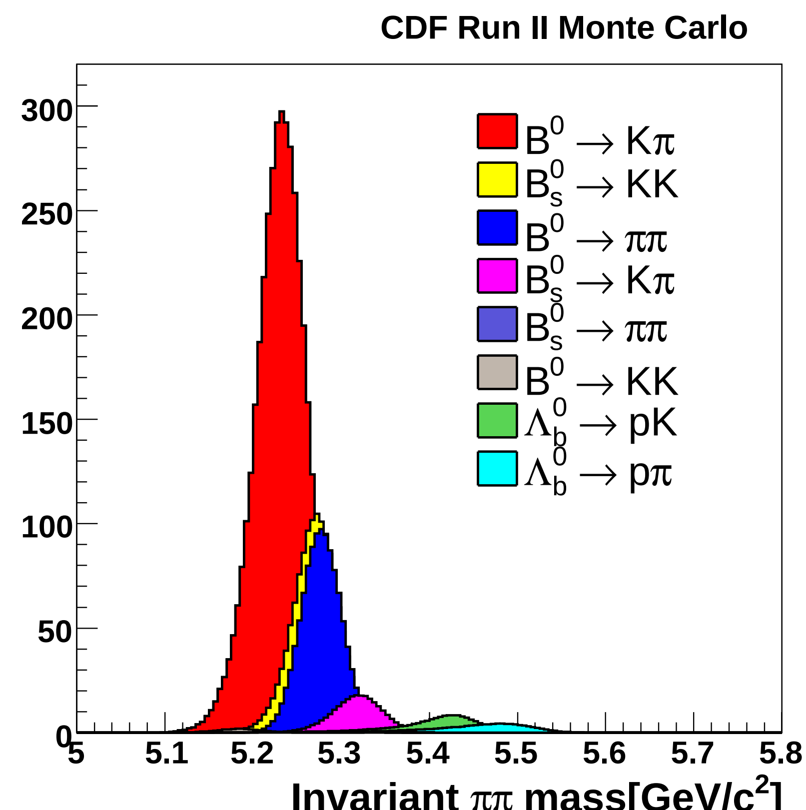

CP Asymmetry in Charmless B Decays
+1.0
0.0
-1.0
CLEO
Belle
BABAR
CDF
PDG2006
New Avg.
HFAG
April 2008

Disentangling modes

- Despite excellent mass resolution ($\approx 22\text{MeV}/c^2$) different decays overlaps
- Event-by-event particle ID not sufficient to separate modes

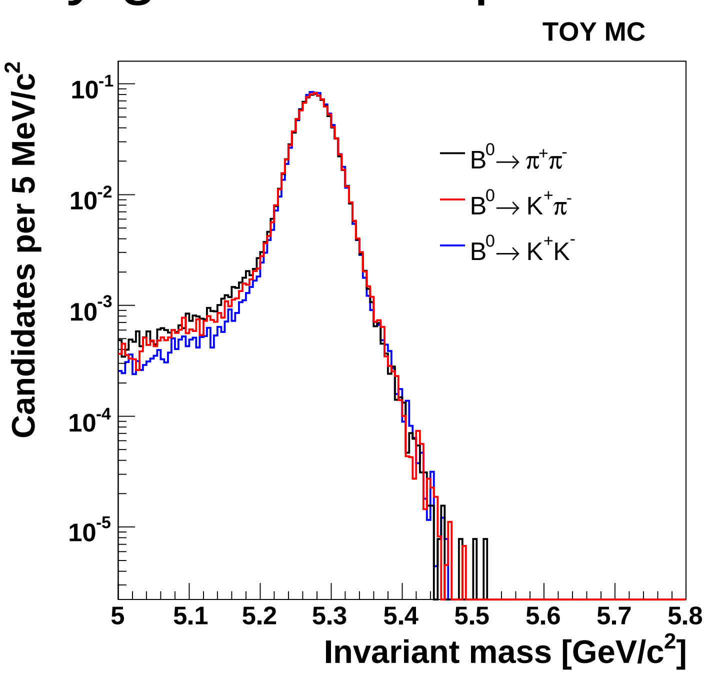
$\Rightarrow$ Combined kinematics and particle ID fit

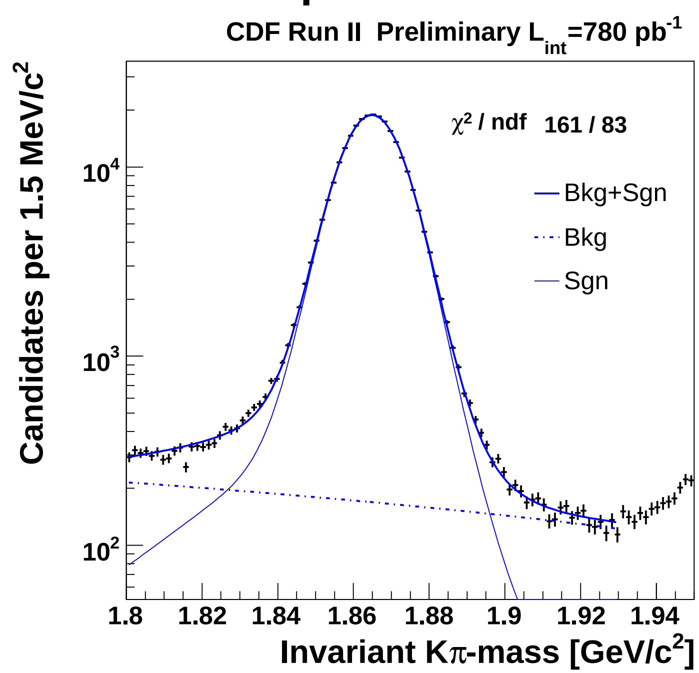




Mass description

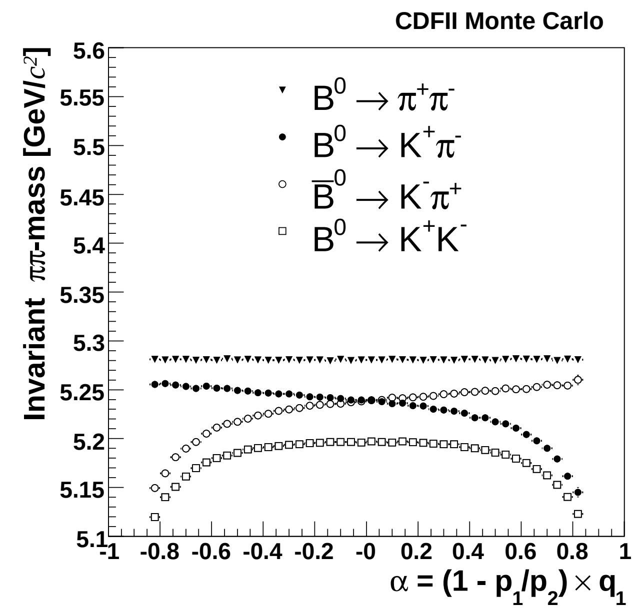
- Need very precise description
  - tails of final state radiation
  - non-Gaussian resolutions tails
- $D^0 \to K\pi$ from D^* provides clean, high statistics control sample
- Very good description of control D^0 sample

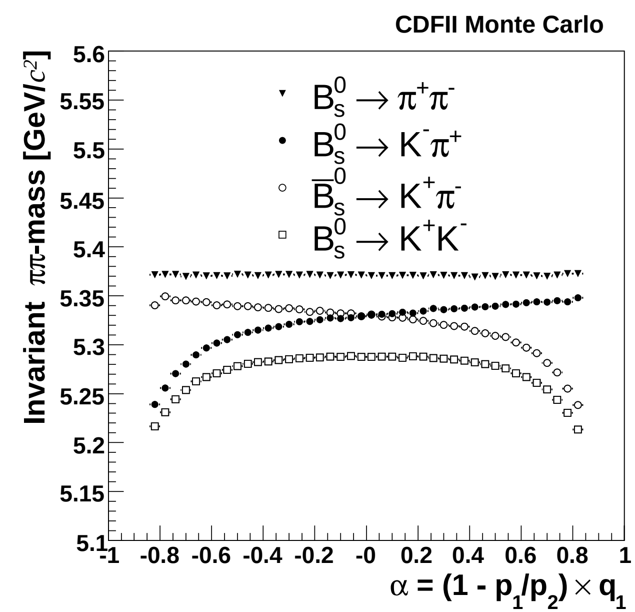




Momentum

- Pion mass used to calculate two track invariant mass $M_{\pi\pi}$
- Unique transformation from $M_{\pi\pi}$ to any $M_{hh'}$ if momentum of tracks known
- Use variables:
  - $M_{\pi\pi}$ - invariant $\pi\pi$-mass
  - $\alpha = (1 - p_1^{\text{min}}/p_2^{\text{max}})q_1^{\text{min}}$ - signed momentum imbalance
  - $p_{\text{tot}} = p_1^{\text{min}} + p_2^{\text{max}}$ - scalar sum of momenta



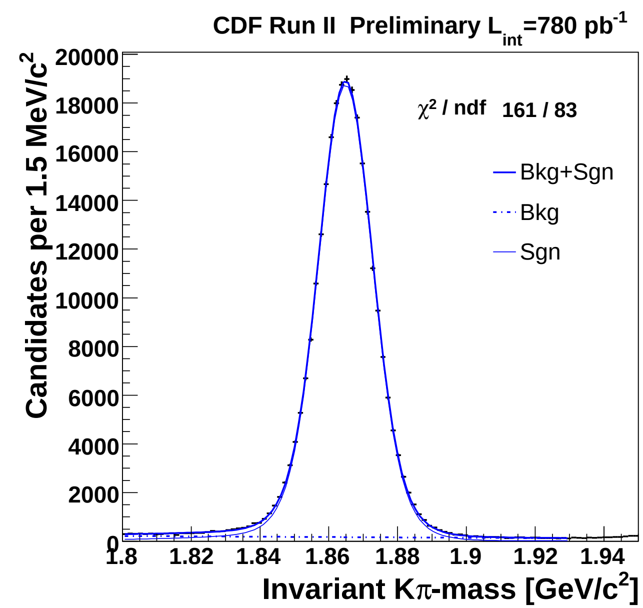


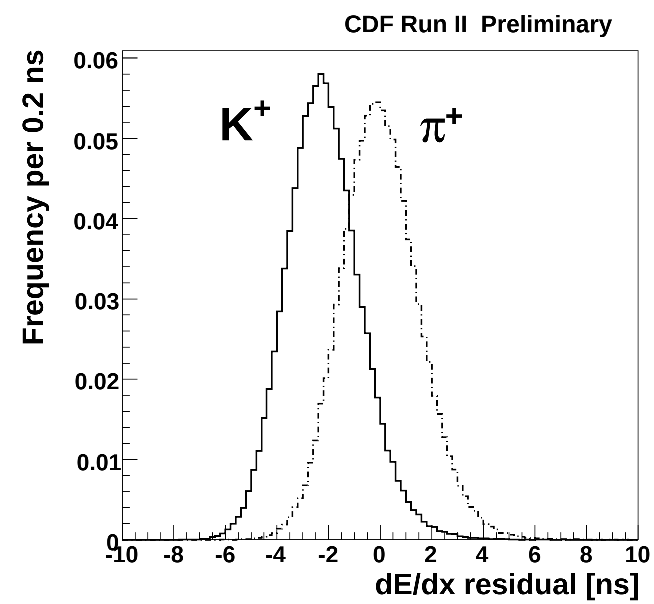
Particle ID

- Use dE/dx measurement in COT
- High statistics, high purity sample of D^0 from D^* available for calibration
- In likelihood use

$$\text{ID} = \frac{dE/dx(\text{meas}) - dE/dx(\pi)}{dE/dx(K) - dE/dx(\pi)}$$

- around 1.4σ separation between K and π for $p > 2\text{GeV}$
- Complements kinematics





$\mathbf{A_{CP}(B_s \to K^+\pi^-)}$ vs. $\mathbf{A_{CP}(B^0 \to K^+\pi^-)}$

SM (Lipkin, Phys. Lett. B621, 126; Gronau, Rosner, Phys. Rev. D71, 074019) predicts

$$\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) = \Gamma(B_s \to K^-\pi^+) - \Gamma(\overline{B}_s \to K^+\pi^-)$$

$\longrightarrow$ Provides model independent test for new physics

Can be used to predict $A_{CP}(B_s \to K^-\pi^+)$ from other measurements

$$A_{CP}(B_s \to K^-\pi^+) = -A_{CP}(B^0 \to K^+\pi^-)\frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B_s \to K^-\pi^+)} \cdot \frac{\tau(B^0)}{\tau(B_s)}$$

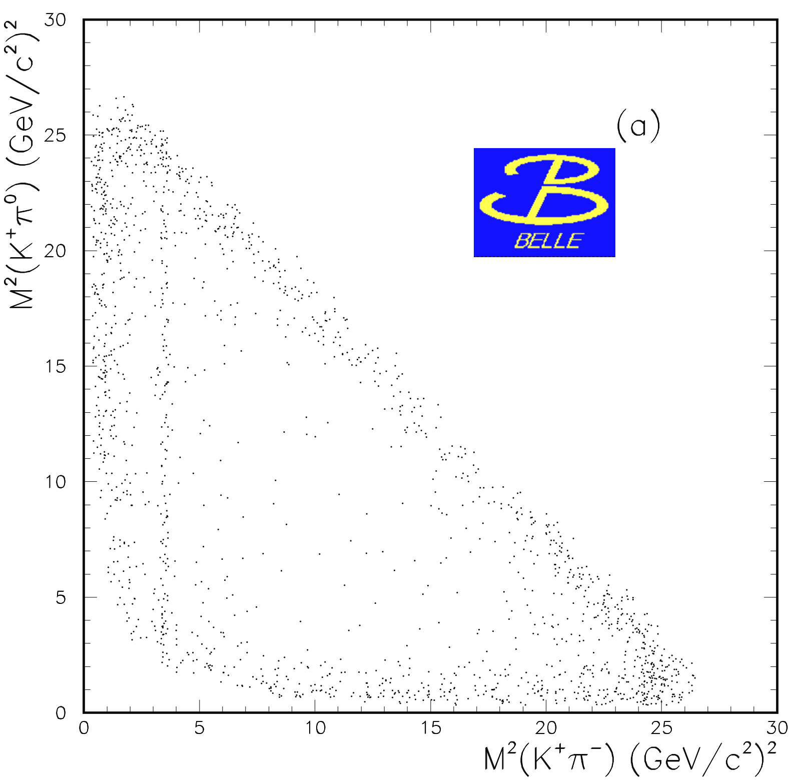
Plugging in numbers

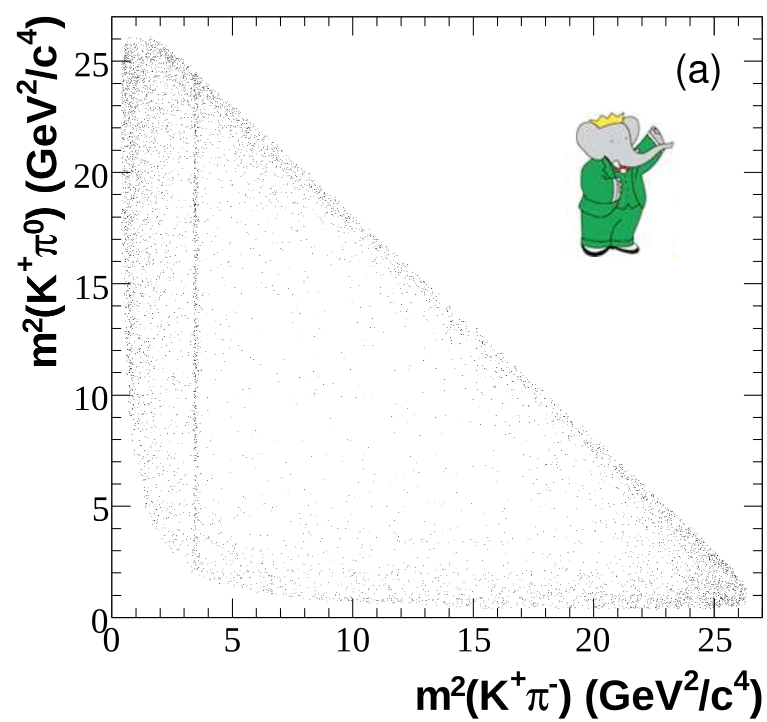
$$\Rightarrow A_{CP}(B_s \to K^-\pi^+) \approx +37\%$$

$\mathbf{B^0 \to K^+\pi^-\pi^0}$

- 85 million $B\overline{B}$ pairs
- $A_{CP}(K^+\rho^-) = 0.22^{+0.22+0.06}_{-0.23-0.02}$

- 232 million $B\overline{B}$ pairs
- $A_{CP}(K^+\rho^-) = 0.11^{+0.14}_{-0.15} \pm 0.07$
- $A_{CP}(K^{*+}\pi^-) = -0.19^{+0.20}_{-0.15} \pm 0.04$
- $A_{CP}(K^{*0}\pi^0) = -0.09^{+0.21}_{-0.24} \pm 0.09$





BABAR $B^+ \to K\pi\pi$ Result

Mode	Fit Fraction (%)	$\mathcal{B}(B^+ \to \text{Mode})(10^{-6})$
$K^+\pi^-\pi^+$ Total		$54.4 \pm 1.1 \pm 4.5 \pm 0.7$
$K^{*0}(892)\pi^+$	$13.3 \pm 0.7 \pm 0.7\,^{+0.4}_{-0.9}$	$7.2 \pm 0.4 \pm 0.7\,^{+0.3}_{-0.5}$
$(K\pi)^{*0}_0\pi^+$	$45.0 \pm 1.4 \pm 1.2\,^{+12.9}_{-0.2}$	$24.5 \pm 0.9 \pm 2.1\,^{+7.0}_{-1.1}$
$\rho^0(770)K^+$	$6.54 \pm 0.81 \pm 0.58\,^{+0.69}_{-0.26}$	$3.56 \pm 0.45 \pm 0.43\,^{+0.38}_{-0.15}$
$f_0(980)K^+$	$18.9 \pm 0.9 \pm 1.7\,^{+2.8}_{-0.6}$	$10.3 \pm 0.5 \pm 1.3\,^{+1.5}_{-0.4}$
$\chi_{c0}K^+$	$1.29 \pm 0.19 \pm 0.15\,^{+0.12}_{-0.03}$	$0.70 \pm 0.10 \pm 0.10\,^{+0.06}_{-0.02}$
nonresonant	$4.5 \pm 0.9 \pm 2.4\,^{+0.6}_{-1.5}$	$2.4 \pm 0.5 \pm 1.3\,^{+0.3}_{-0.8}$
$K_2^{*0}(1430)\pi^+$	$3.40 \pm 0.75 \pm 0.42\,^{+0.99}_{-0.13}$	$1.85 \pm 0.41 \pm 0.28\,^{+0.54}_{-0.08}$
$\omega(782)K^+$	$0.17 \pm 0.24 \pm 0.03\,^{+0.05}_{-0.08}$	$0.09 \pm 0.13 \pm 0.02\,^{+0.03}_{-0.04}$
$f_2(1270)K^+$	$0.91 \pm 0.27 \pm 0.11\,^{+0.24}_{-0.17}$	$0.50 \pm 0.15 \pm 0.07\,^{+0.13}_{-0.09}$
$f_X(1300)K^+$	$1.33 \pm 0.38 \pm 0.86\,^{+0.04}_{-0.14}$	$0.73 \pm 0.21 \pm 0.47\,^{+0.02}_{-0.08}$

BABAR $B^+ \to K\pi\pi$ Result

Mode	A_{CP} (%)	DCPV Sig.
$K^+\pi^-\pi^+$ Total	$2.8 \pm 2.0 \pm 2.0 \pm 1.2$	
$K^{*0}(892)\pi^+$	$+3.2 \pm 5.2 \pm 1.1\,^{+1.2}_{-0.7}$	0.9σ
$(K\pi)_0^{*0}\pi^+$	$+3.2 \pm 3.5 \pm 2.0\,^{+2.7}_{-1.9}$	1.2σ
$\rho^0(770)K^+$	$+44 \pm 10 \pm 4\,^{+5}_{-13}$	3.7σ
$f_0(980)K^+$	$-10.6 \pm 5.0 \pm 1.1\,^{+3.4}_{-1.0}$	1.8σ
$\chi_{c0}K^+$	$-14 \pm 15 \pm 3\,^{+1}_{-5}$	0.5σ
nonresonant	—	—
$K_2^{*0}(1430)\pi^+$	$+5 \pm 23 \pm 4\,^{+18}_{-7}$	0.2σ
$\omega(782)K^+$	—	—
$f_2(1270)K^+$	$-85 \pm 22 \pm 13\,^{+22}_{-2}$	3.5σ
$f_X(1300)K^+$	$+28 \pm 26 \pm 13\,^{+7}_{-5}$	0.6σ

Belle $B^+ \to K\pi\pi$ Result

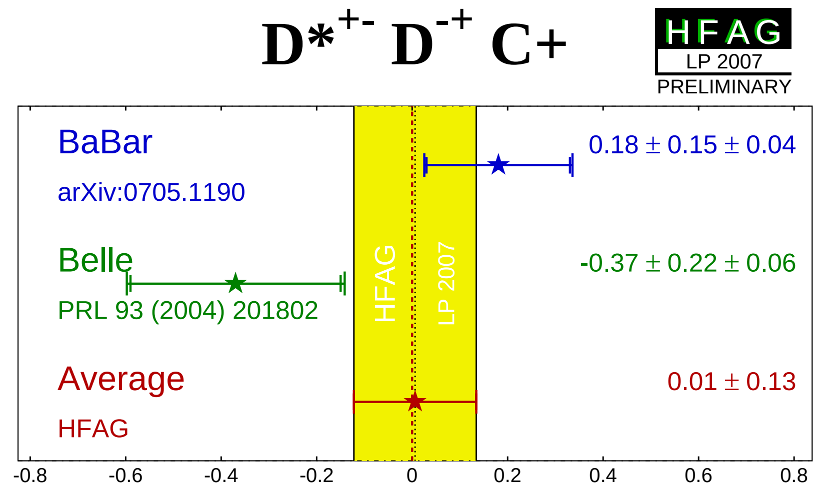
Mode	$\mathcal{B}(B^\pm \to Rh^\pm \to K^+\pi^-\pi^+) \times 10^6$
$K^+\pi^-\pi^+$ Charmless	$48.8 \pm 1.1 \pm 3.6$
$K^*(892)[K^\pm\pi^\mp]\pi^\pm$	$6.45 \pm 0.43 \pm 0.48^{+0.25}_{-0.35}$
$K_0^*(1430)[K^\pm\pi^\mp]\pi^\pm$	$32.0 \pm 1.0 \pm 2.4^{+1.1}_{-1.9}$
$\rho(770)^0[\pi^+\pi^-]K^\pm$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$
$f_0(980)[\pi^+\pi^-]K^\pm$	$8.78 \pm 0.82 \pm 0.65^{+0.55}_{-1.64}$
$f_2(1270)[\pi^+\pi^-]K^\pm$	$0.75 \pm 0.17 \pm 0.06^{+0.11}_{-0.18}$
Non-resonant	–
$\chi_c[\pi^+\pi^-]K^\pm$	$0.56 \pm 0.06 \pm 0.04^{+0.12}_{-0.04}$

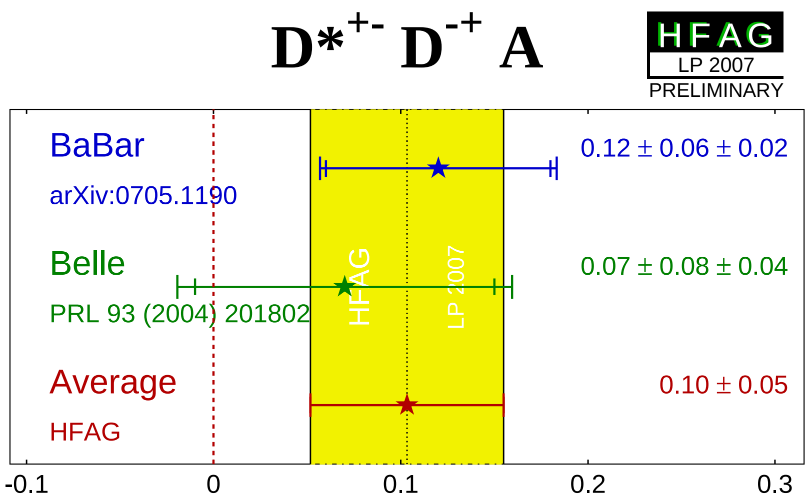
Belle $B^+ \to K\pi\pi$ Result

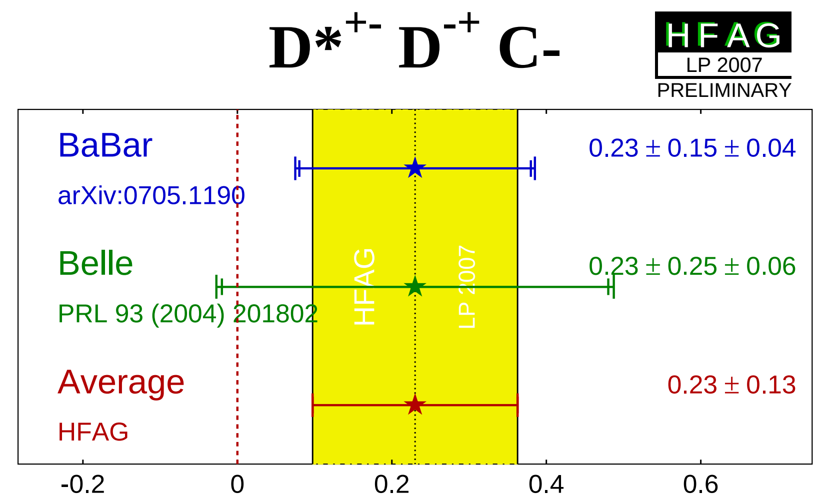
Mode	A_{CP} (%)
$K^+\pi^-\pi^+$ Charmless	$+4.9 \pm 2.6 \pm 2.0$
$K^*(892)[K^\pm\pi^\mp]\pi^\pm$	$-14.9 \pm 6.4 \pm 2.0^{+0.8}_{-0.8}$
$K_0^*(1430)[K^\pm\pi^\mp]\pi^\pm$	$+7.6 \pm 3.8 \pm 2.0^{+2.0}_{-0.9}$
$\rho(770)^0[\pi^+\pi^-]K^\pm$	$+30 \pm 11 \pm 2.0^{+11}_{-4}$
$f_0(980)[\pi^+\pi^-]K^\pm$	$-7.7 \pm 6.5 \pm 2.0^{+4.1}_{-1.6}$
$f_2(1270)[\pi^+\pi^-]K^\pm$	$-59 \pm 22 \pm 2.0^{+3}_{-3}$
Non-resonant	–
$\chi_c[\pi^+\pi^-]K^\pm$	$-6.5 \pm 20 \pm 2.0^{+2.9}_{-1.4}$

$B^0 \to D^{*+}D^-$

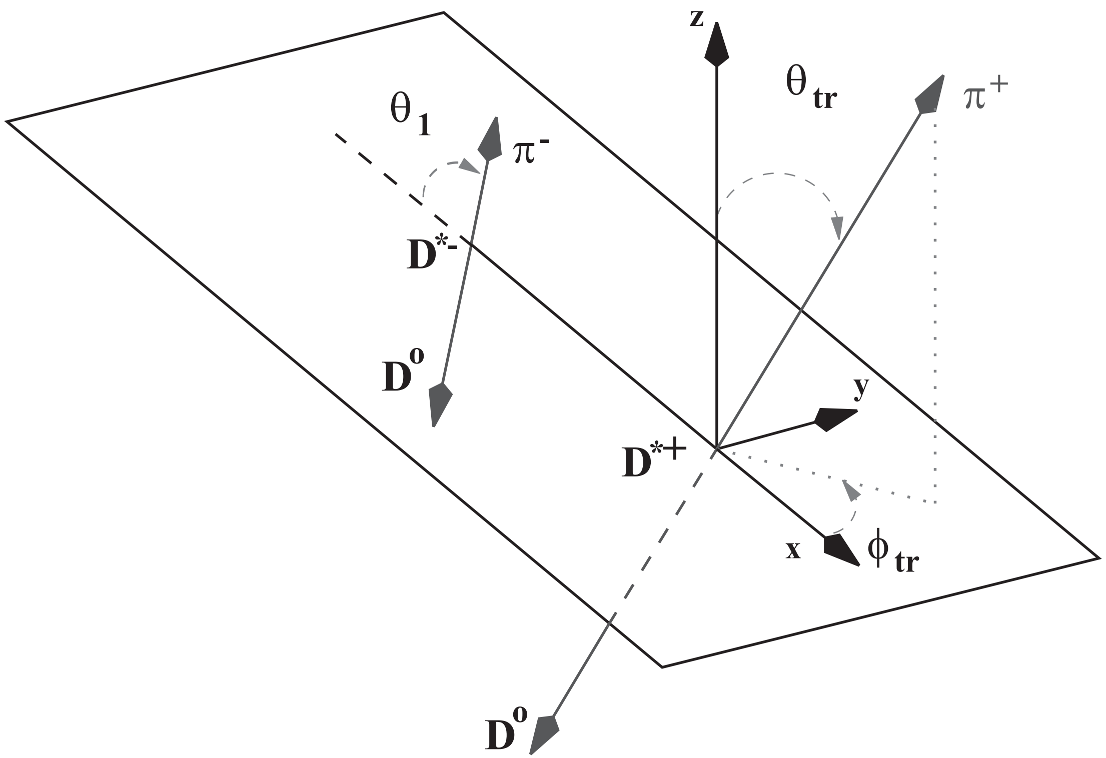
- $D^{*+}D^-$ and $D^{*-}D^+$ not CP eigenstates
- Have tree asymmetries:
  - $C_+(D^{*+}D^-)$
  - $C_-(D^{*-}D^+)$
  - Time integrated $A(D^{*+}D^- - D^{*-}D^+)$



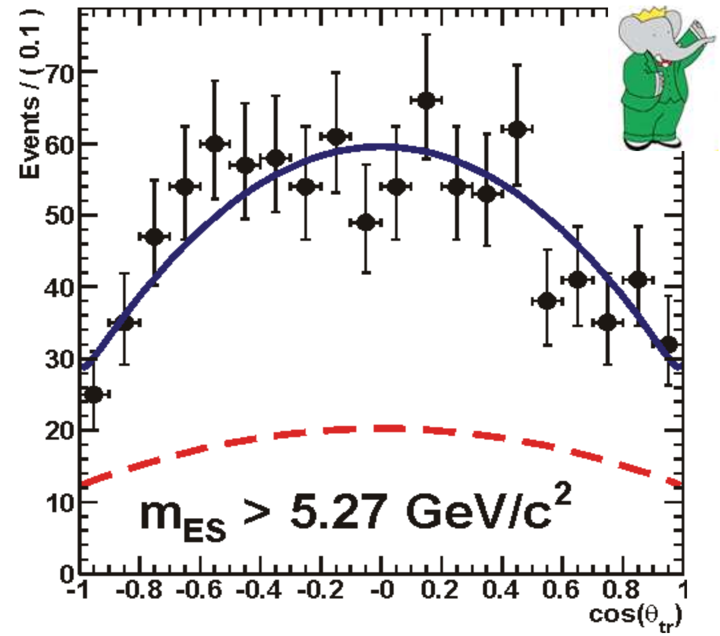




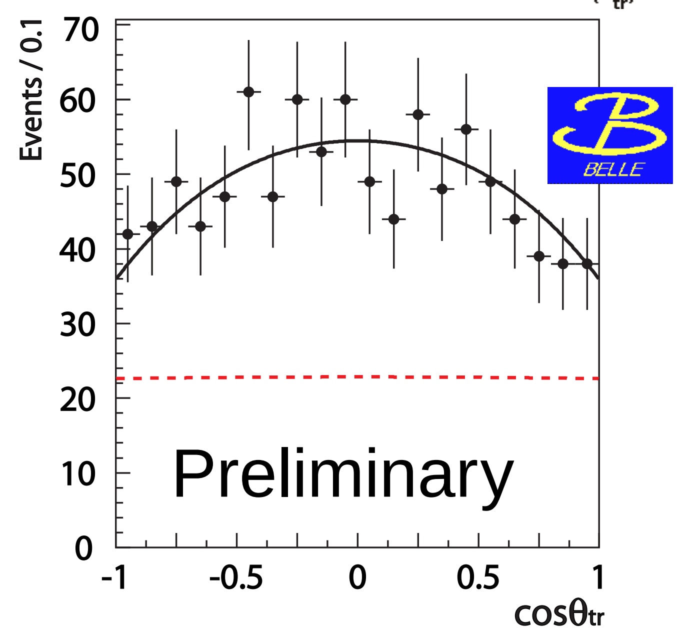
$B^0 \to D^{*+}D^{*-}$



z
θ tr
π+
θ 1
π-
D*-
D°
y
D*+
x
φ tr
D°



Events / (0.1)
m_ES > 5.27 GeV/c^2
cos(θ_tr)



Events / 0.1
Preliminary
BELLE
cosθtr