Direct CP asymmetries in $B \to K\pi$
Forward-Backward asymmetry in $B \to K^* ll$
D-Mixing
at BABAR

Heiko Lacker

Humboldt University of Berlin

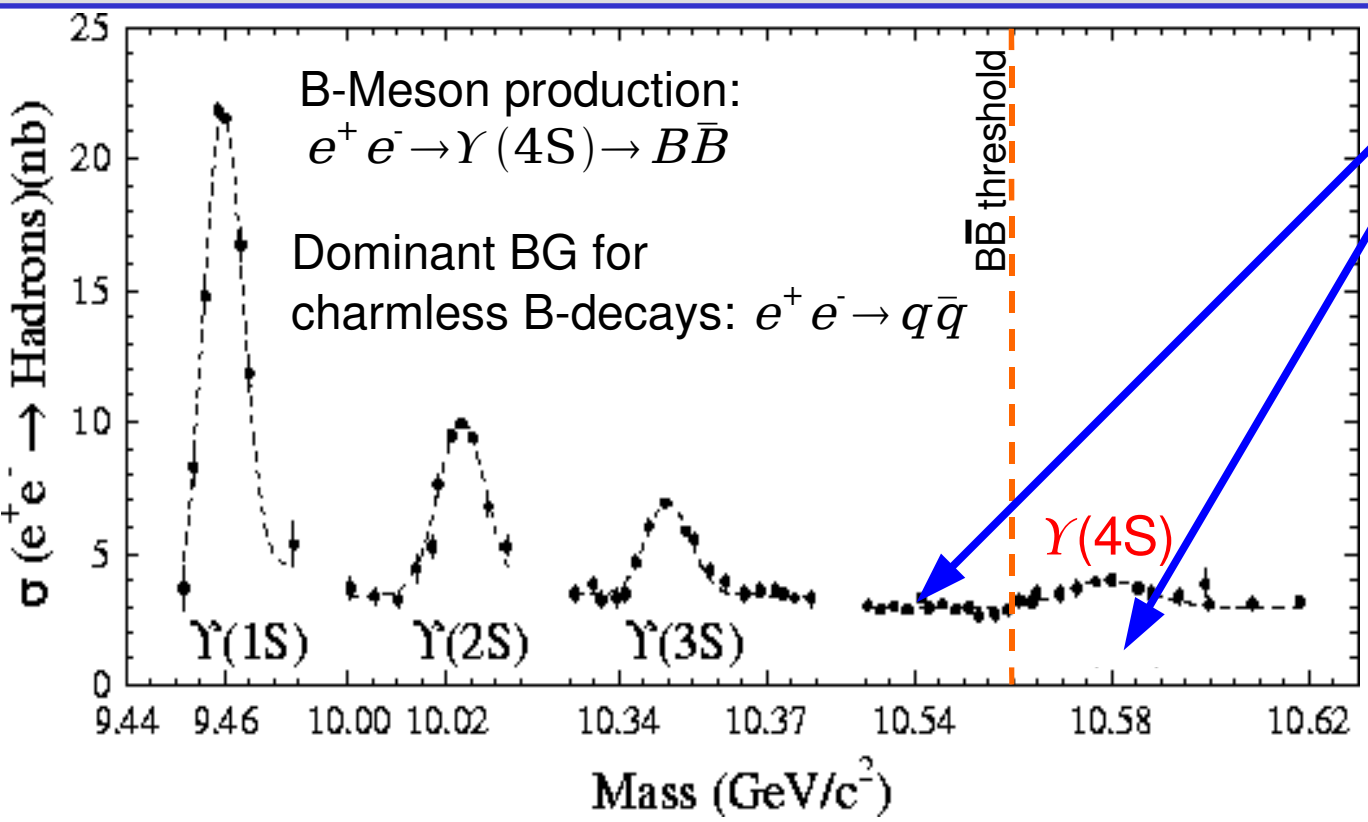
on behalf of the BABAR collaboration

Second Workshop on Beyond 3 Generation Standard Model

--- New Fermions at the Crossroads of Tevatron and LHC

January 14-16, 2009, Taipeh, Taiwan

B-Meson Production at Y(4S)

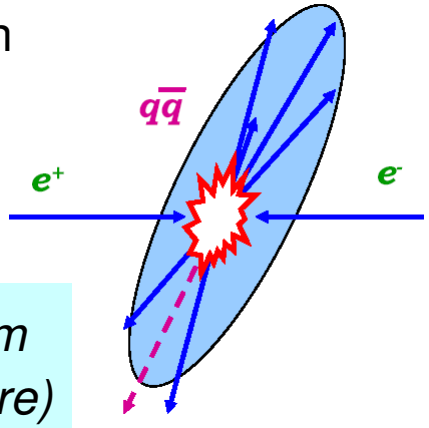


D-Mixing: use Offpeak & Onpeak data

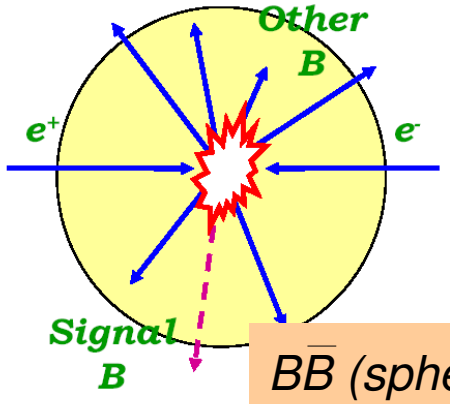
e^+e^-	$\to$	σ
$b\bar{b}$		1.10 nb
$c\bar{c}$		1.30 nb
$s\bar{s}$		0.35 nb
$u\bar{u}$		1.39 nb
$d\bar{d}$		0.35 nb

$$\frac{\sigma(B\bar{B})}{\sigma(hadr)} = 0.28$$

Suppress with event shape variables:



Continuum (jet-structure)



$B\bar{B}$ (spherical)

Often combined in Fisher discriminant or Neural Net

Kinematical constraints for signal reconstruction at the Y(4S)

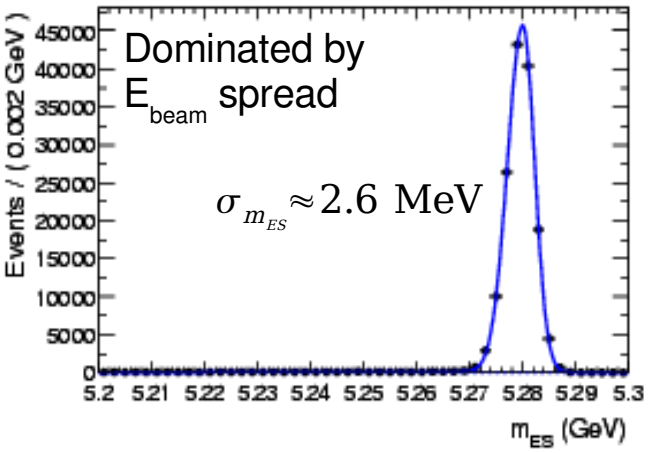
Beam-energy substituted mass

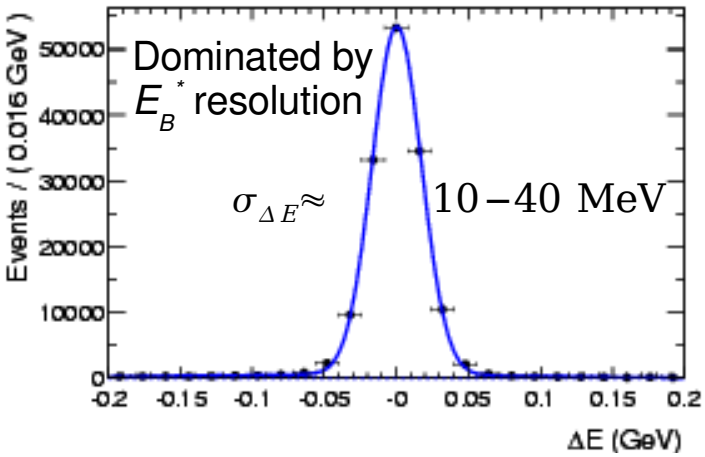
$$m_{ES}=\sqrt{\left(\frac{s}{2}+\left|\vec{p}_{e^+e^-}\right|\right)^2/E^2_{e^+e^-}-\vec{p}_B}$$

Energy difference

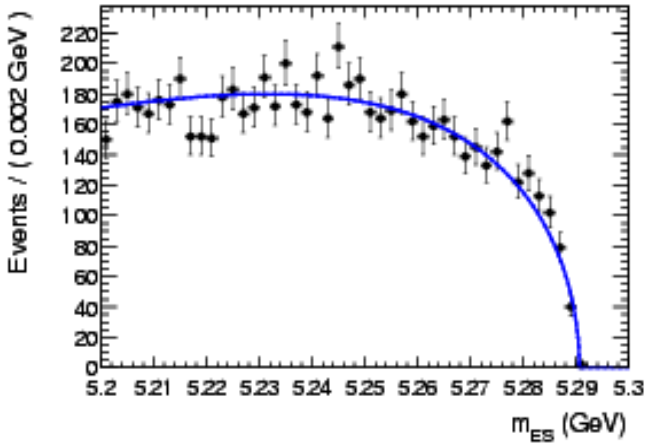
$$\Delta E=E^*_B-E^*_{beam}$$

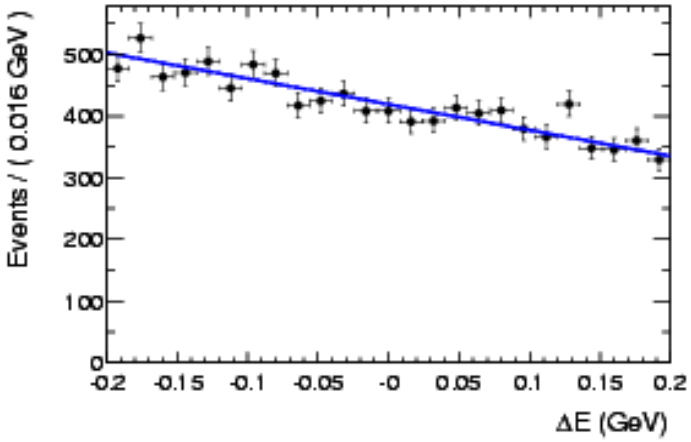
Correctly reconstructed **BB events**



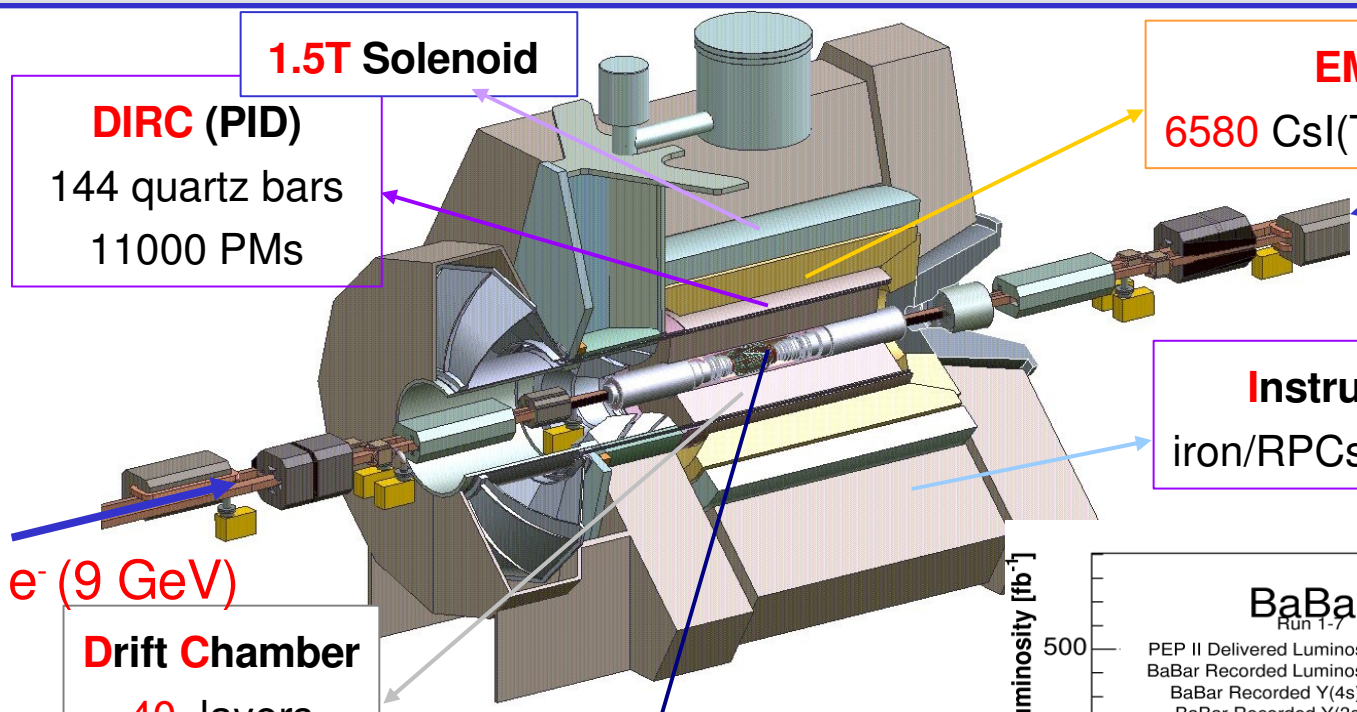


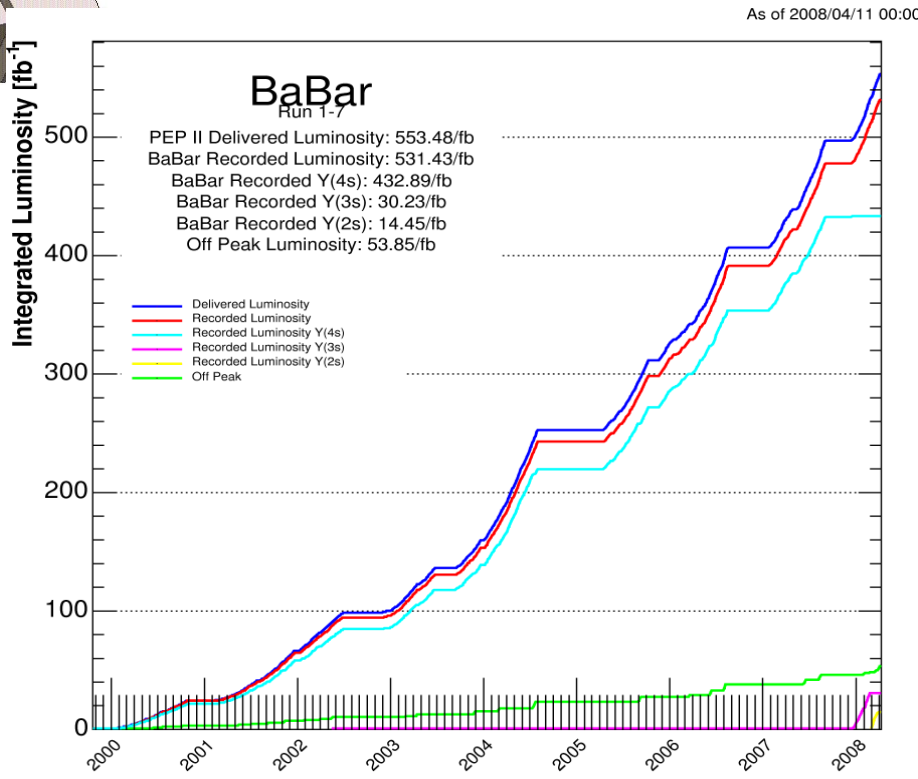
Combinatorial **background**





BABAR and PEP-II



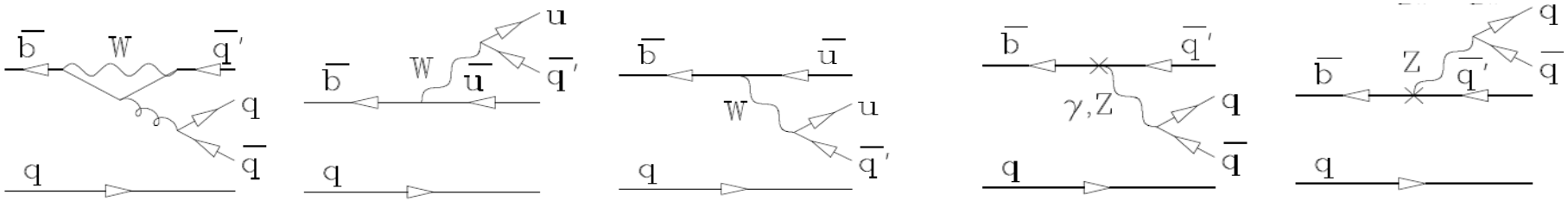


- Full statistics:
  Onpeak: 433 fb^{-1} ≙ 467·10^6 Y(4S)
  Offpeak: 54 fb^{-1}
- Not all published results with full statistics yet

$B \to K\pi$

SM amplitudes ($\lambda_t = V_{ts}V_{tb}^*, \lambda_u = V_{us}V_{ub}^*$, Annihilation (A) not shown):

$\lambda_t P_{tc} + \lambda_u P_{uc}$ $\lambda_u T$ $\lambda_u C$ $\lambda_t P_{EW}^C$ $\lambda_t P_{EW}$



$$-A(K^+\pi^-) = \lambda_u(P_{uc} + T) + \lambda_t(P_{tc} + \frac{2}{3}P_{EW}^C)$$

$$-\sqrt{2}\,A(K^+\pi^0) = \lambda_u(P_{uc} + T + C + A) + \lambda_t(P_{tc} + \frac{2}{3}P_{EW}^C + P_{EW})$$

$$\sqrt{2}\,A(K^0\pi^0) = \lambda_u(P_{uc} - C) + \lambda_t(P_{tc} - \frac{1}{3}P_{EW}^C - P_{EW})$$

$$A(K^0\pi^+) = \lambda_u(P_{uc} + A) + \lambda_t(P_{tc} - \frac{1}{3}P_{EW}^C)$$

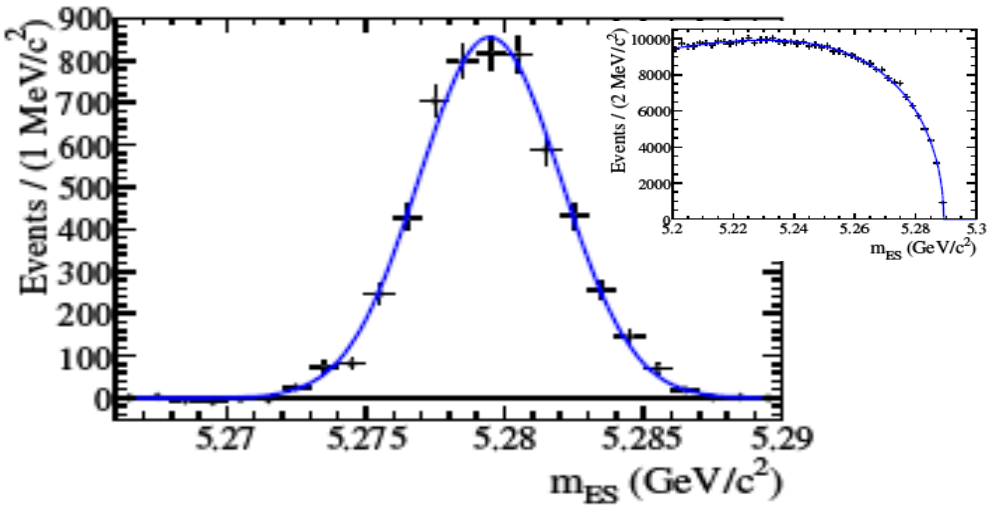
$\left|\frac{\lambda_u}{\lambda_t}\right| \approx \lambda^2 \Rightarrow P_{tc}$ dominant

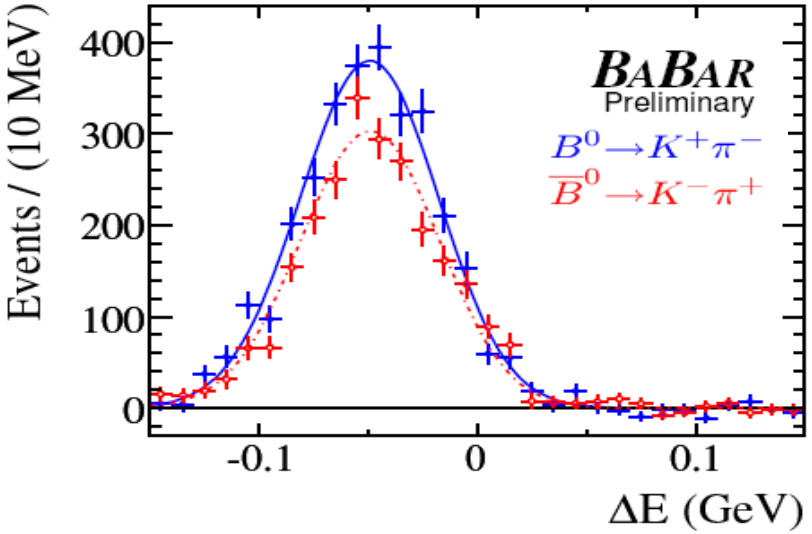
P_{EW} only possible for final states with π^0

- If A & C << T: $\frac{1}{2}BF(B \to K^+\pi^-) \approx BF(B \to K^+\pi^0)$ $\quad \Delta A_{CP} = A_{CP}(B \to K^+\pi^-) - A_{CP}(B \to K^+\pi^0) \approx 0$
- $\Delta A_{CP} \neq 0$ might be interpreted as anomously large P_{EW} => NP (e.g. 4th gen.)
  (Yoshikawa '03; Mishima & Yoshikawa '04; Buras et al '04, '06; Baek & London '07; Hou et al '07; Jung & Mannel '08; Baek et al '09; Li & Mishima '09)
- But: C~T observed in ππ system (e.g. CKMfitter group 2005 and others)
  => $\Delta A_{CP} \neq 0$ possible simply due to failing ability in calculating hadronic SM amplitudes?
  (Chiang et al 2004; Charng, Li, Mishima & Sanda 2005, ... QCDFA, PQCD, SCET)

$B \to K^{\pm} \pi^{\mp}$

- Preliminary result: 467·10^6 Y(4S) (arXiv:0807.4226[hep-ex])
- Unbinned Maximum Likelihood (ML) fit of $\theta_{Cherenkov}$, kinematic & event shape variables
- Kaon charge determines B-meson flavor tag (self-tagging)





Distributions obtained from weighting technique ($_s$*Plots*): Pivk and Le Diberder, NIM A555, 356 (2005)

$$A_{CP}^{BABAR}(B \to K^{\pm}\pi^{\mp}) = \frac{N(\bar{B}) - N(B)}{N(\bar{B}) + N(B)} = -0.107 \pm 0.016^{+0.006}_{-0.004}$$

$$A_{CP}^{Belle}(B \to K^{\pm}\pi^{\mp}) = -0.094 \pm 0.018 \pm 0.008$$

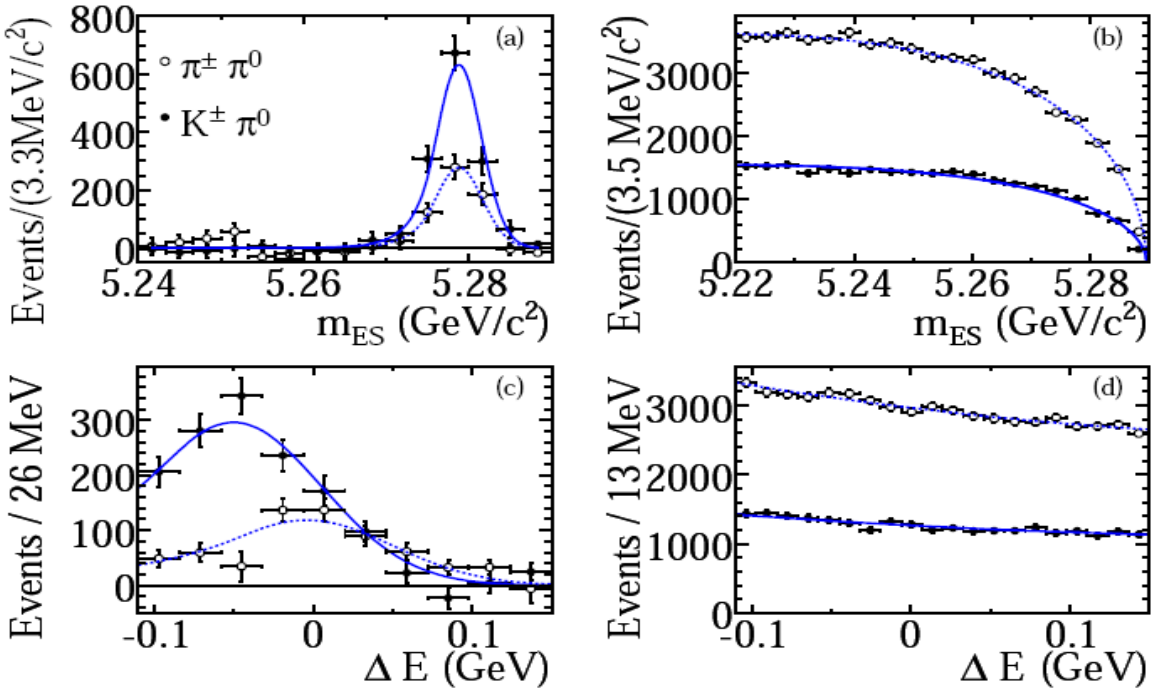
$$A_{CP}^{CDF}(B \to K^{\pm}\pi^{\mp}) = -0.086 \pm 0.023 \pm 0.009$$

$$A_{CP}^{WA}(B \to K^{\pm}\pi^{\mp}) = -0.098^{+0.012}_{-0.011}$$

535·10^6 Y(4S)
Nature 452, 332 (2008)
1.0 fb^{-1}
hep-ex/0612018

$B^{\pm} \to K^{\pm} \pi^{0}$

- Published result: 383·10^6 Y(4S) (PRD-RC 76, 091102 (2007))
- Unbinned ML fit of $\theta_{Cherenkov}$, kinematic & event shape variables



$$A_{CP}^{BABAR}(B^{\pm} \to K^{\pm} \pi^{0}) = +0.030 \pm 0.039 \pm 0.010$$

$$A_{CP}^{Belle}(B^{\pm} \to K^{\pm} \pi^{0}) = +0.07 \pm 0.03 \pm 0.01$$

535·10^6 Y(4S)
Nature 452, 332 (2008)

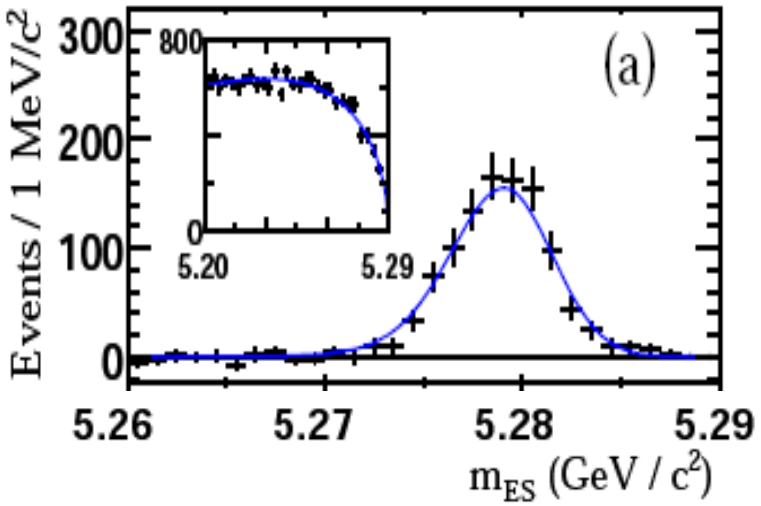
$$A_{CP}^{WA}(B^{\pm} \to K^{\pm} \pi^{0}) = +0.050 \pm 0.025$$

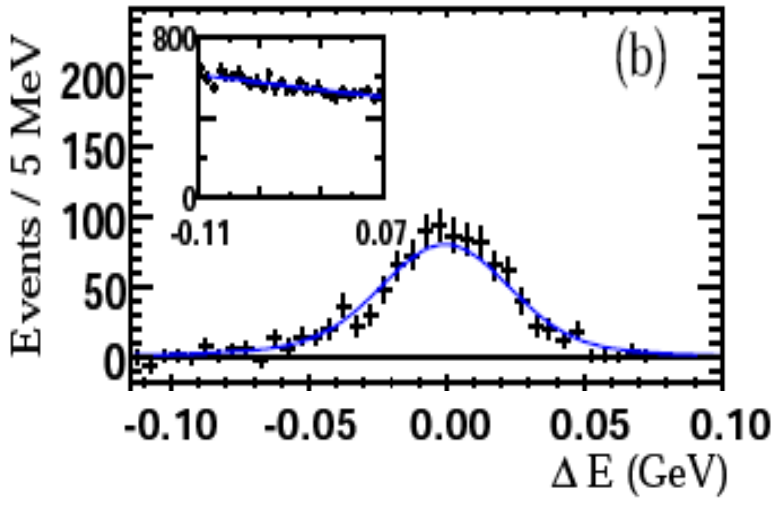
$$\Rightarrow \Delta A_{CP}^{WA} = A_{CP}^{WA}(B \to K^{+} \pi^{-}) - A_{CP}^{WA}(B \to K^{+} \pi^{0}) = -0.148 \pm 0.028 \neq 0 \quad (5.3\sigma)$$

"Kπ puzzle"!?

$B^{\pm} \to K_S \pi^{\pm}$

- Published result: 347·10^6 Y(4S) (PRL 97, 171805 (2006))
- ML fit of Cherenkov angle, kinematic and event shape variables





$$A_{CP}^{BABAR}(B^{\pm} \to K^0 \pi^{\pm}) = -0.029 \pm 0.039 \pm 0.010$$

$$A_{CP}^{Belle}(B^{\pm} \to K^0 \pi^{\mp}) = +0.03 \pm 0.03 \pm 0.01$$

449·10^6 Y(4S)
PRL 98, 181804 (2007)

$$A_{CP}^{WA}(B^{\pm} \to K^0 \pi^{\mp}) = +0.009 \pm 0.025$$

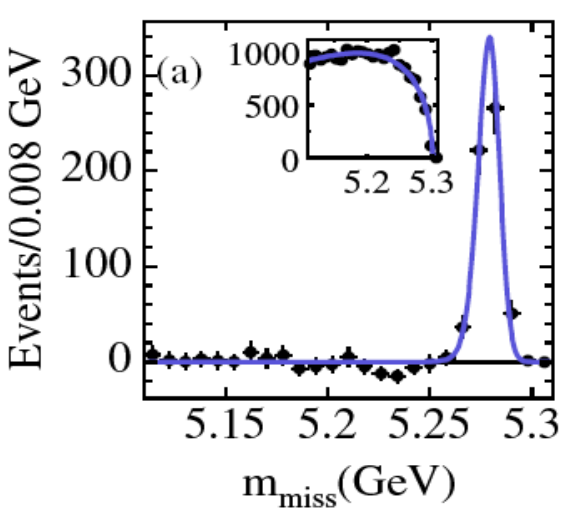
$B \to K_S \pi^0$

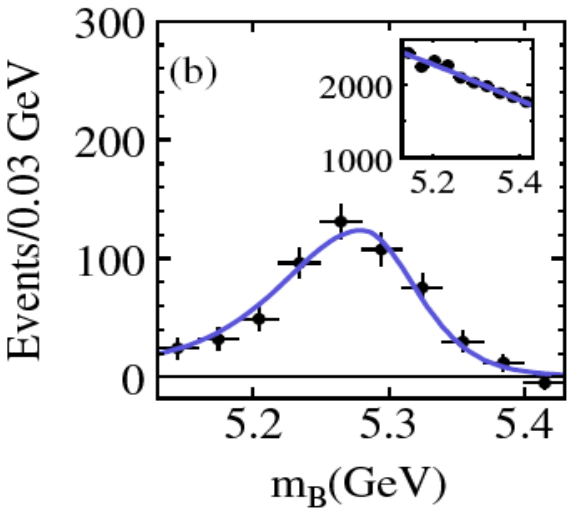
- Published result: 467·10^6 Y(4S) (PRD 79, 052003 (2009))
- ML fit of Cherenkov angle, kinematic and event shape variables, Δt

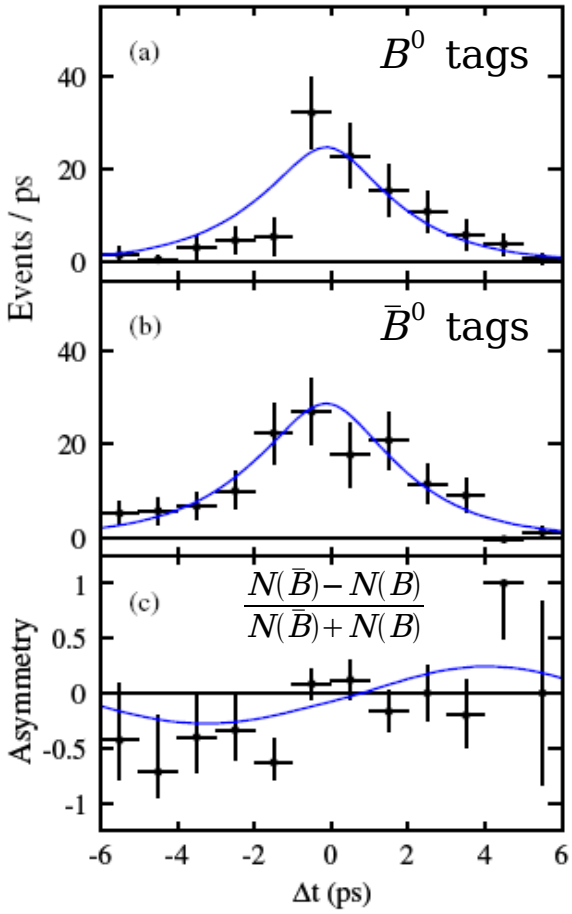
  m_B: M_{inv} of reconstructed B_{CP}-meson

  m_{miss}: M_{inv} of B_{tag} from E_{Beam} & $p(B_{CP})$ with $m(B_{CP})=m_B(PDG)$

  (lower correlation due to π^0 energy resolution wrt m_{ES} & ΔE)
- Δt: B_{CP} vertex from K_S flight direction with beam spot constraint in transverse plane
- Flavour tagging from other B







$S_{CP}^{BABAR}(B^0 \to K_S\pi^0) = +0.55 \pm 0.20 \pm 0.03$

$A_{CP}^{BABAR}(B^0 \to K_S\pi^0) = -0.13 \pm 0.13 \pm 0.03$

$A_{CP}^{Belle}(B^0 \to K_S\pi^0) = +0.14 \pm 0.13 \pm 0.06$

$A_{CP}^{WA}(B^0 \to K_S\pi^0) = -0.01 \pm 0.10$

657·10^6 Y(4S)
0809.4366 [hep-ex]

Summary: B→Kπ

- Isospin sum rule (e.g. no assumption on C<<T):

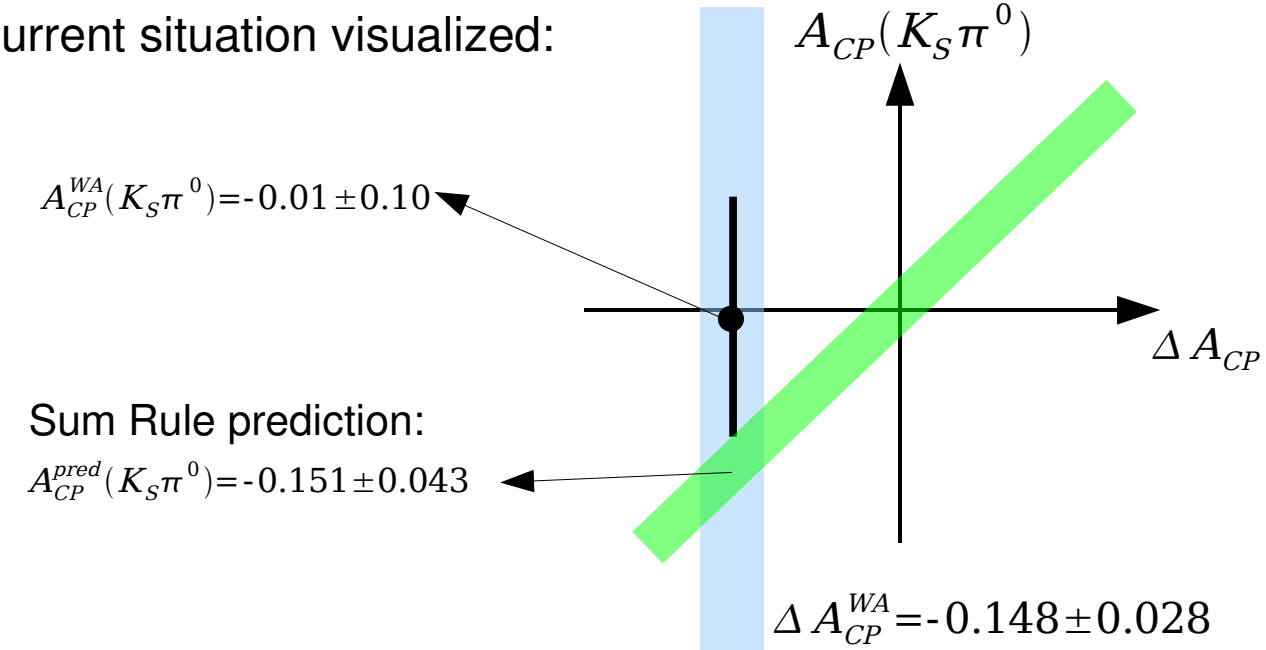
$$A_{CP}(K_S\pi^0)\frac{2\,BF(K^0\pi^0)}{BF(K^+\pi^-)}\frac{\tau_0}{\tau_+}=A_{CP}(K^+\pi^-)-A_{CP}(K^+\pi^0)\frac{2\,BF(K^+\pi^0)}{BF(K^+\pi^-)}\frac{\tau_0}{\tau_+}+A_{CP}(K^0\pi^+)\frac{BF(K^0\pi^+)}{BF(K^+\pi^-)}\frac{\tau_0}{\tau_+}$$

$$A_{CP}(K_S\pi^0)\approx A_{CP}(K^+\pi^-)-A_{CP}(K^+\pi^0)+A_{CP}(K^0\pi^+)\ \text{(Simplified version)}$$

Gronau, PLB 627, 82 (2005); Atwood & Soni, PRD 58, 036005 (1998)
Gronau, Pirjol & Zupan, 1001.0702 [hep-ph]: Violation of sum rule at most -2%

Violation of sum rule beyond this level => Evidence for NP in ΔI=1 trans. (P_{EW}&$P_{EW}{}^C$)

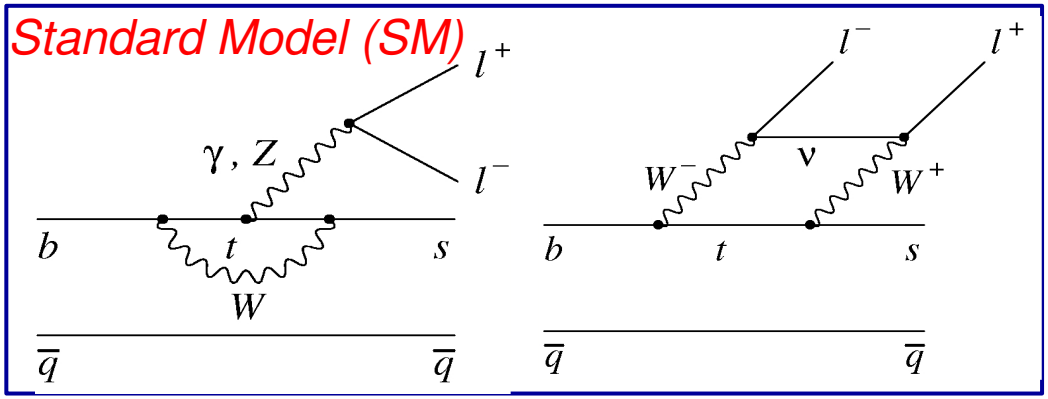
- Current situation visualized:



Clarification possible @ Super-B (π^0 reconstruction difficult @LHCb)

$b \to s\,ll$ Decays: Standard Model and New Physics

- SM: $b \to s\,ll$ forbidden @ tree level
- Sensitive to New Physics



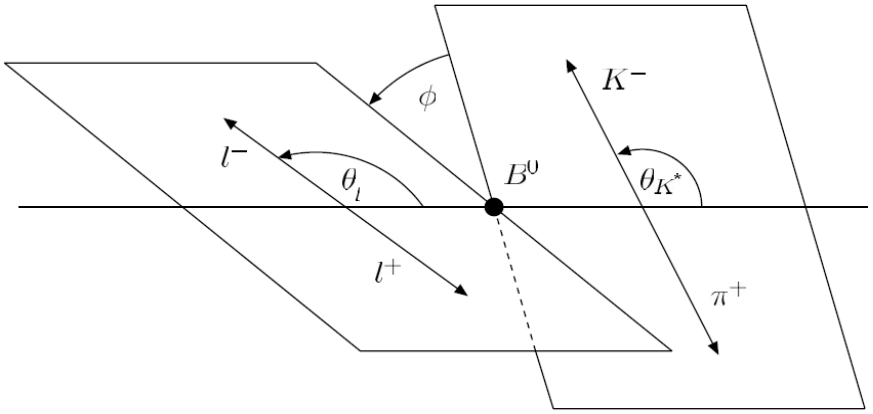
Three Wilson coefficients:

- C_7^{eff} from photon penguin: - BR($b \to s\gamma$) sensitive to $|C_7^{eff}|$
  - $b \to sll$ sensitive to Sign(C_7^{eff})
- C_9^{eff}(C_{10}^{eff}) from vector (axial-vector) contributions of Z,W box diagrams

- NP could modify C_i's or contribute additional scalar and pseudo-scalar terms

- Inclusive $b \to sll$: - Theoretical calculation good to ~10%
  - Experimentally difficult
- Exclusive $b \to sll$: - Large theoretical uncertainties in BRs (~30%)
  Uncertainties cancel partly in angular distributions & asymmetries
  - Experimentally much easier

$B \to K^* l^+ l^-$ Decay Angle Distributions



- $B \to K^* ll$ kinematics: q^2, θ_l, θ_{K^*}, ϕ

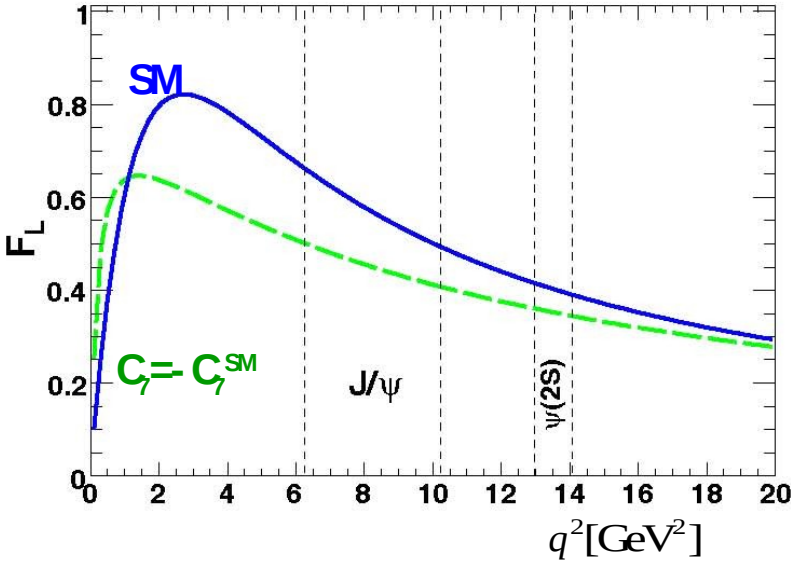
4-dim. fit difficult with small statistics => Fit for

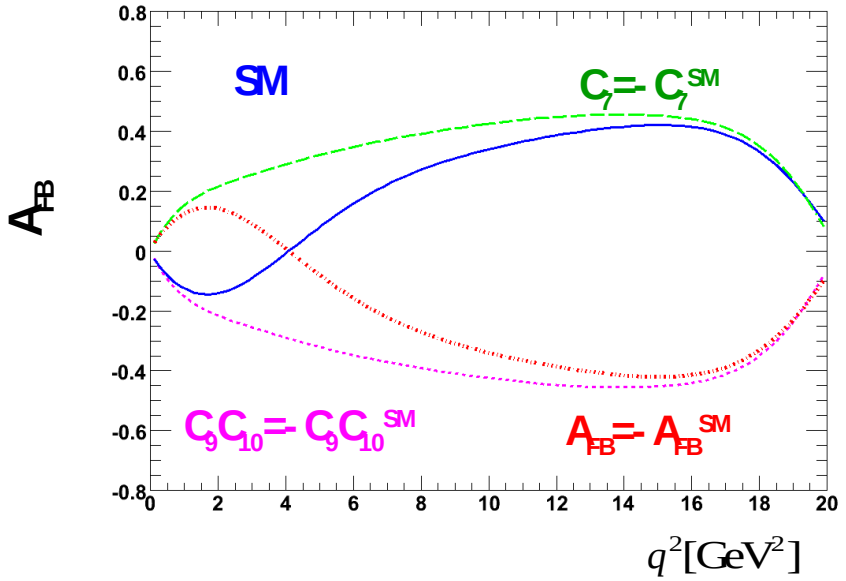
K* longitudinal polarization F_L &

lepton forward- backward asymmetry A_{FB} in Bins of q^2

$$\frac{d\Gamma}{d\cos\theta_{K^*}} = \frac{3}{2}F_L\cos^2\theta_{K^*} + \frac{3}{4}(1-F_L)(1-\cos^2\theta_{K^*})$$

$$\frac{d\Gamma}{d\cos\theta_l} = A_{FB}\cos\theta_l + \frac{3}{4}F_L(1-\cos^2\theta_l) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l)$$





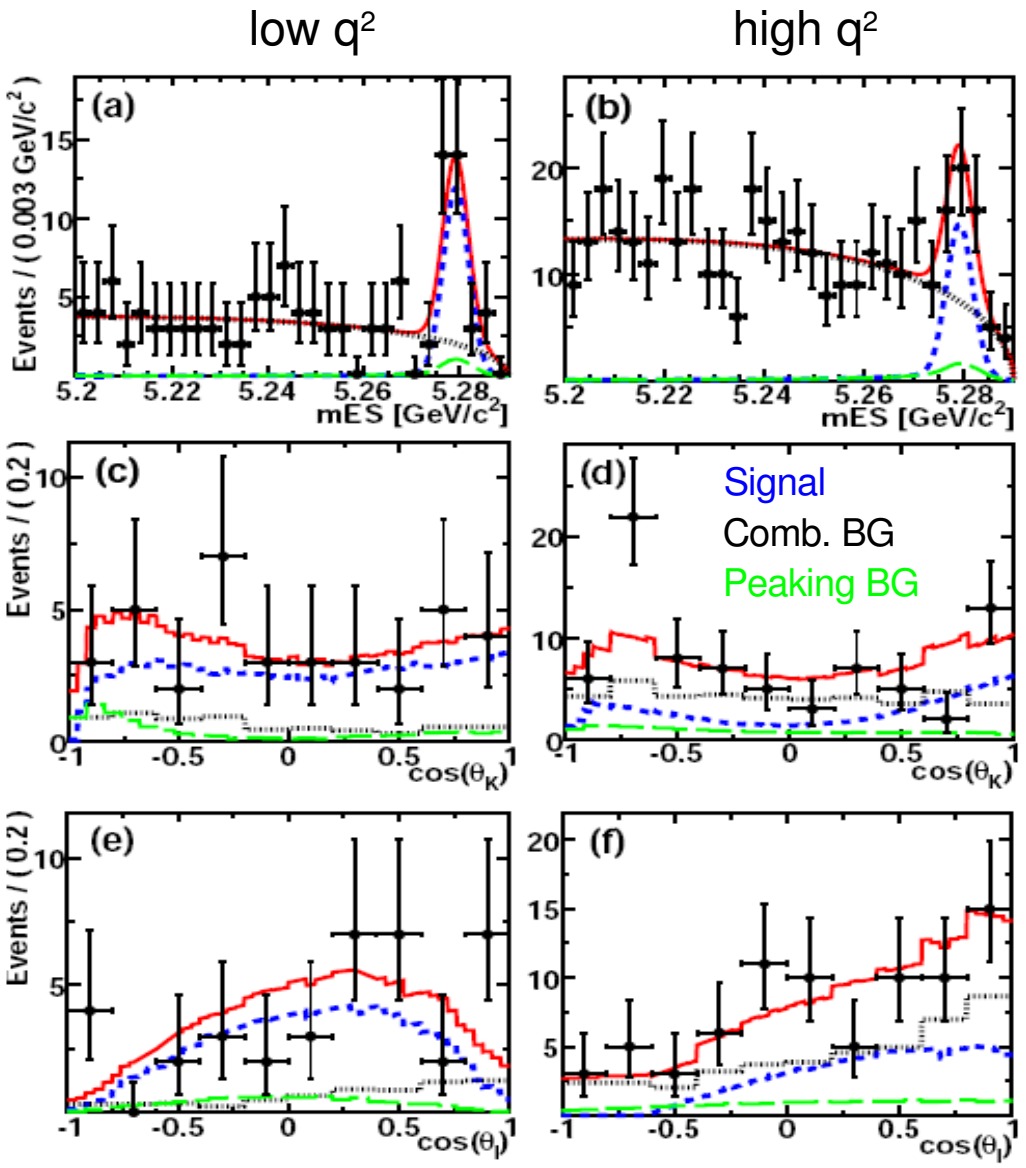
$B \to K^* l^+ l^-$ reconstruction and event yields

- 10 reconstructed final states: $K^+\pi^-$, $K^+\pi^0$, $K^0_S\pi^+$ and e^+e^-, $\mu^+\mu^-$
- Neural networks suppress BG from continuum and B/D semilep. decays
- Vetoes for $B \to D(K^{(*)}\pi)\pi$ & $B \to K^{(*)} J/\psi\,(\psi(2S))$
- Cut on ΔE, signal yield from fit to m_{ES}
- Signal & BG yield fixed and fit for F_L in θ_{K^*} distribution
- Fix F_L and fit for A_{FB} in θ_l distribution

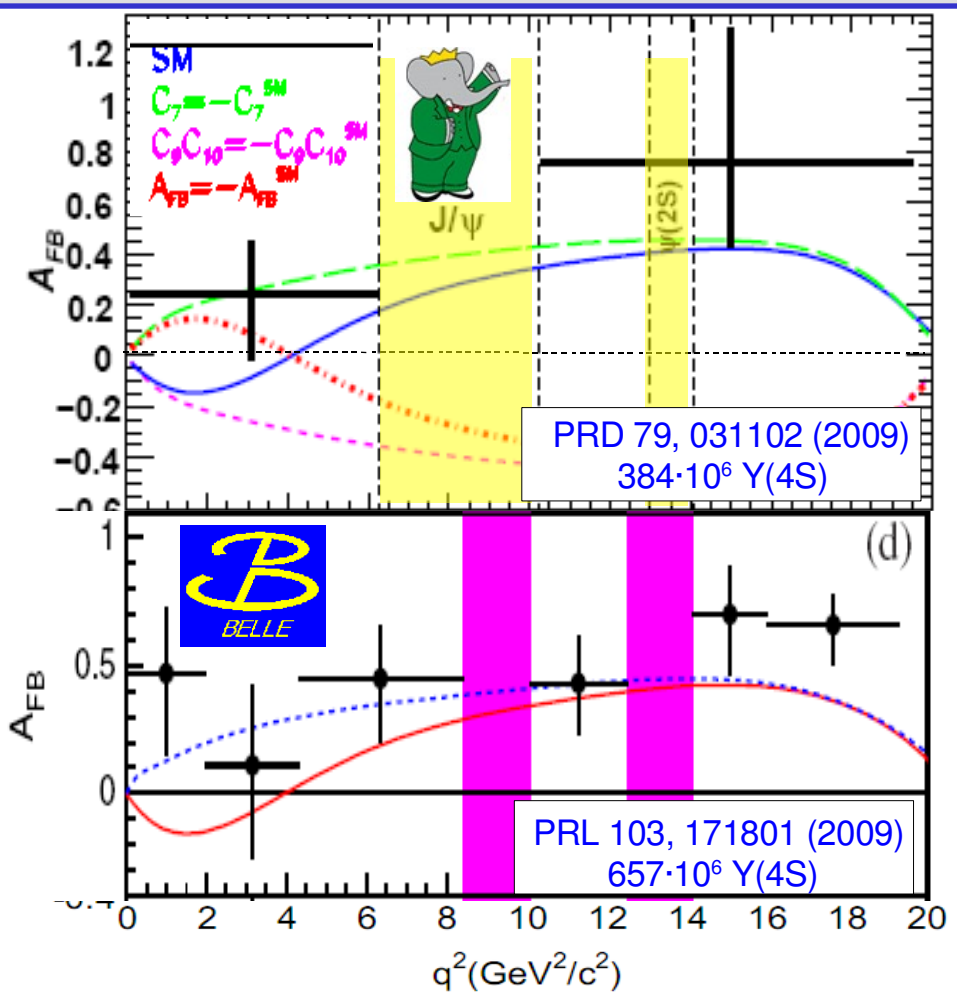
BaBar: $384 \cdot 10^6$ Y(4S)

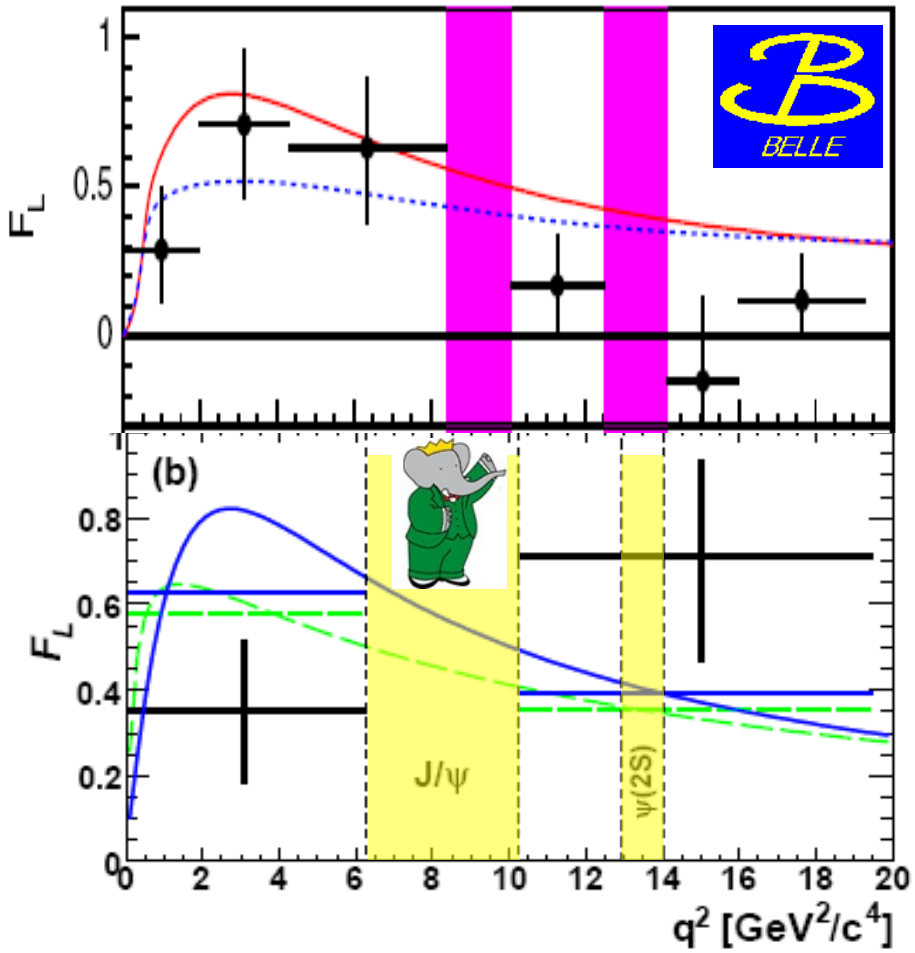
PRL 102, 091803 (2009)

PRD-RC 79, 031102 (2009)



K* Longitudinal Polarization F_L and lepton A_{FB}





* Good agreement between BaBar & Belle
* $-C_9C_{10}^{SM}$ disfavored
* Data above SM pred. (more data needed)
* Need theory error; treatment of resonances?

* Good agreement between BaBar & Belle @low q^2, but deviation of 2.5σ @high q^2
* Reasonable agreement between data & SM

D-Mixing

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \tfrac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Mass eigenstates:

$$|D_1> = p|D^0> + q|\bar{D}^0>$$
$$|D_2> = p|D^0> - q|\bar{D}^0>$$

with Eigenvalues: $m_{1,2} + i\,\Gamma_{1,2}/2 \quad (m=(m_1+m_2)/2,\ \Gamma=(\Gamma_1+\Gamma_2)/2)$

Mixing parameters: $x = \dfrac{m_1 - m_2}{\Gamma}$ $y = \dfrac{\Gamma_1 - \Gamma_2}{2\Gamma}$ $\left|\dfrac{q}{p}\right|$ $\Phi_M = Arg\left(\dfrac{q}{p}\right)$

$D^0 \to \bar{D}^0 \quad \bar{A}_f(\bar{D}^0 \to f)$

D^0  f

$A_f(D^0 \to f)$

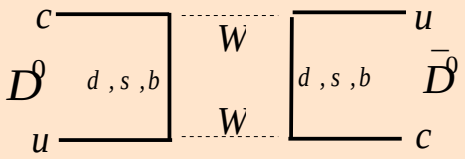
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \propto e^{i(\delta^f_{Strong} + \phi^f_{weak} + \phi_M)}$$

CPV in decay

CPV in mixing: $\left|\dfrac{q}{p}\right| \neq 1$

CPV in interference between decay with and w/o mixing

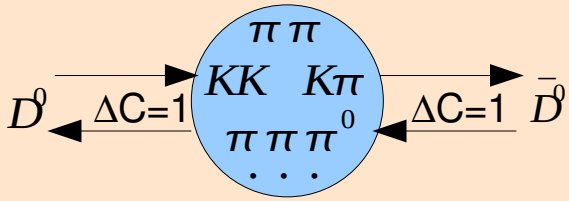
ΔC=2 (short distance) contributing mainly to x



b : CKM-suppressed $((V_{ub}V^*_{cb})^2)$

d, s : GIM-suppressed $((m_s^2 - m_d)^2/m_c^2) \sim 10^{-5}$

Hadronic intermediate states (long distance)



Recent predictions:

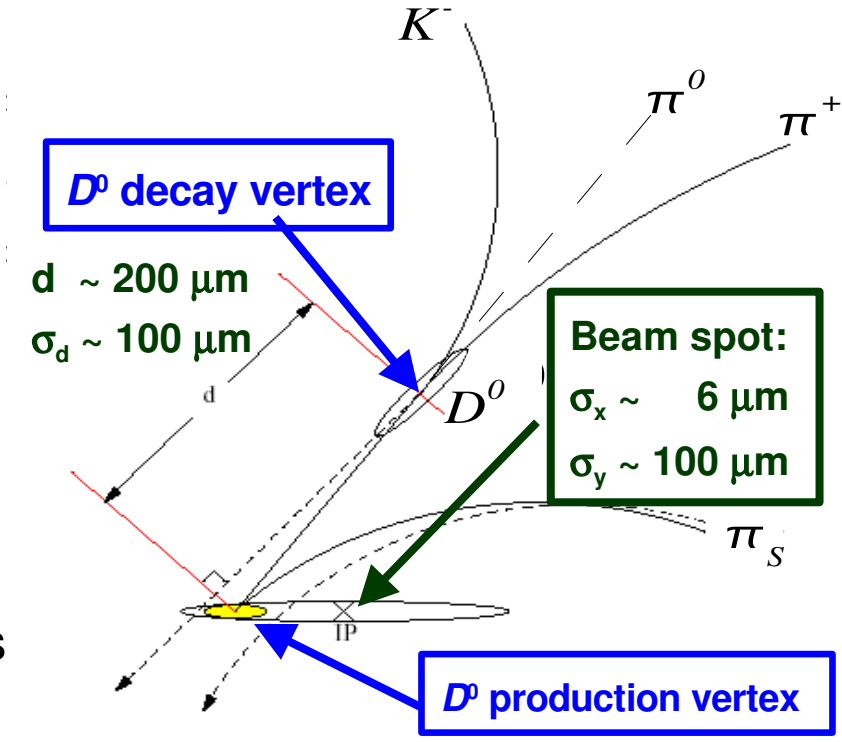
$|x| \leq 1\%$ $|y| \leq 1\%$

Signals for NP:

* $|x| >> |y|$
* *Evidence for CPV*

D-Mixing at BABAR

- Good vertex resolution
  => time-dependence of D^0 decays
- Eliminate D's from B's by cutting out low-momentum D's:
  better S/B & avoids bias in vertexing
- Excellent K/π separation (DIRC, dE/dx)
- Clean D sample from $D^{*+} \rightarrow D^0 \pi_s^+$
- Tag flavour of D^0 at production from π_s charge
- Untagged events for CP-conserving quantities

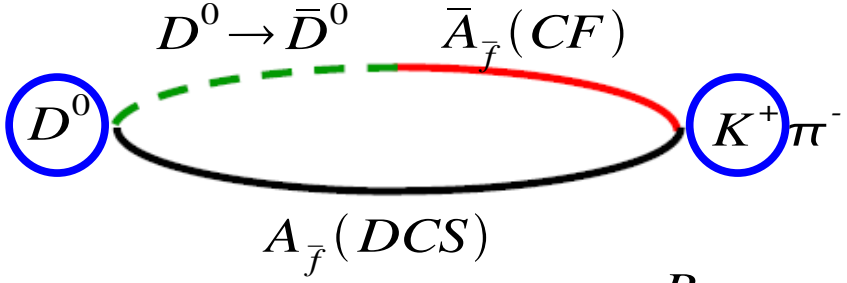


- Analyses:

Mixing	CPV
$D^0 \rightarrow K\pi$	$D^0 \rightarrow KK, \pi\pi$
$D^0 \rightarrow KK, \pi\pi$	$D^0 \rightarrow \pi\pi\pi^0$
$D^0 \rightarrow K\pi\pi^0$	$D^0 \rightarrow KK\pi^0$
$D^0 \rightarrow K^{(*)} l \nu$	
$D^0 \rightarrow K_S \pi\pi$	

Hadronic Decays accessible to both D-Mesons

Tag D^0 and reconstruct "wrong sign" (WS) kaon final state $K\pi$:



$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

Strong phase δ *unknown in this case*

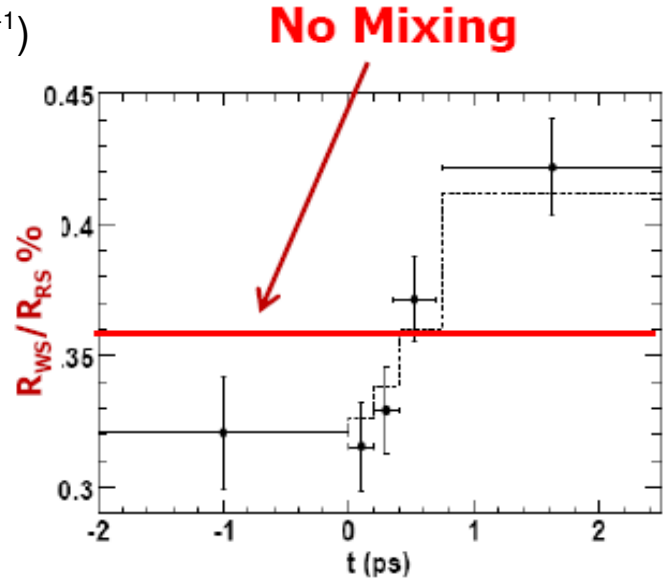
WS decay rate for |x|, |y|<<1:

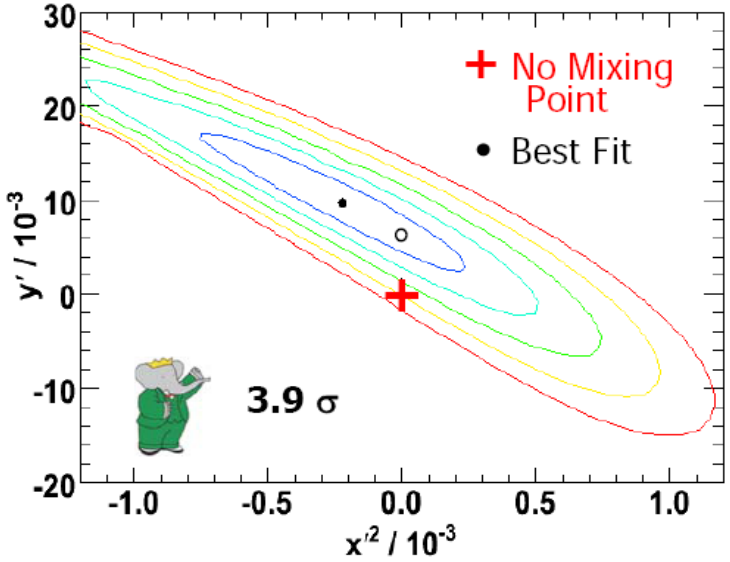
$$\frac{R_{WS}}{e^{-\Gamma t}} \propto \left|A_{\bar{f}}\right|^2 + y'\left|A_{\bar{f}}\right|\left|\bar{A}_{\bar{f}}\right|\cdot\Gamma\cdot t + \frac{x'^2+y'^2}{4}\left|\bar{A}_{\bar{f}}\right|^2\cdot(\Gamma\cdot t)^2$$

DCS rate — DCS-Mixing interference — Mixing rate

"Right Sign" (RS) rate dominated by A_f => $R_{WS}(D^0 \to K^-\pi^+) \propto e^{-\Gamma t}$

Tagged analysis (384 fb^{-1})
PRL 98, 211802 (2007):



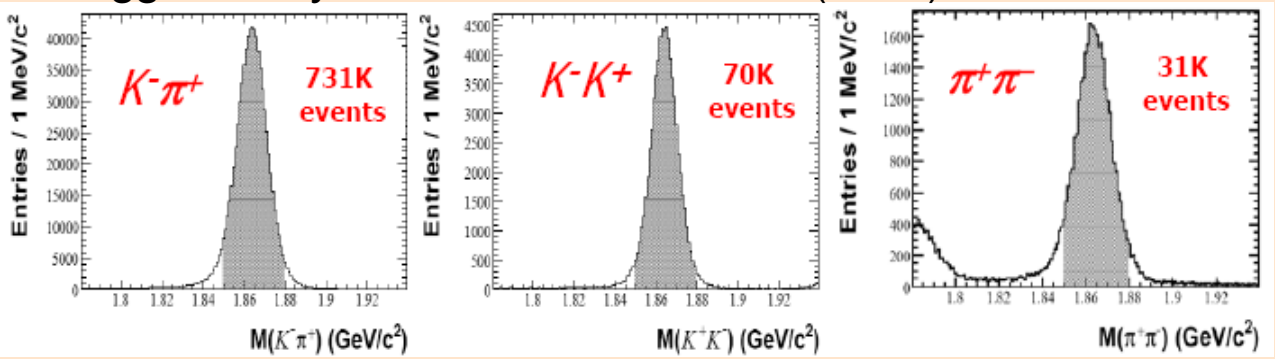


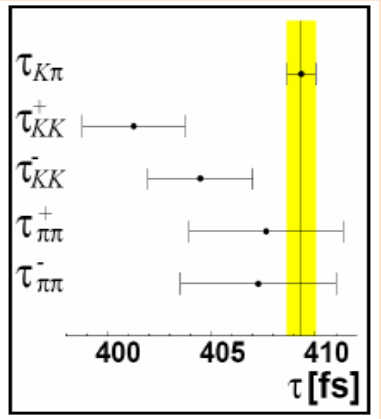
Lifetime difference

No CPV => D_1 CP-even, D_2 CP-odd => $y = y_{CP} = \frac{<\tau_{K\pi}>}{<\tau_{hh}>} - 1$, $<\tau_{hh}> = \frac{(\tau^-(D^0 \to hh) + \tau^+(\bar{D}^0 \to hh))}{2}$

Possible CPV: $\Delta Y = \frac{\tau_{K\pi}}{<\tau_{hh}>} A_\tau$ *with* $A_\tau = \frac{\tau^-(\bar{D}^0 \to h^+h^-) - \tau^+(D^0 \to h^+h^-)}{\tau^-(\bar{D}^0 \to h^+h^-) + \tau^+(D^0 \to h^+h^-)}$

Tagged analysis: PRD 78, 011105 (2008) – 384 fb^{-1}

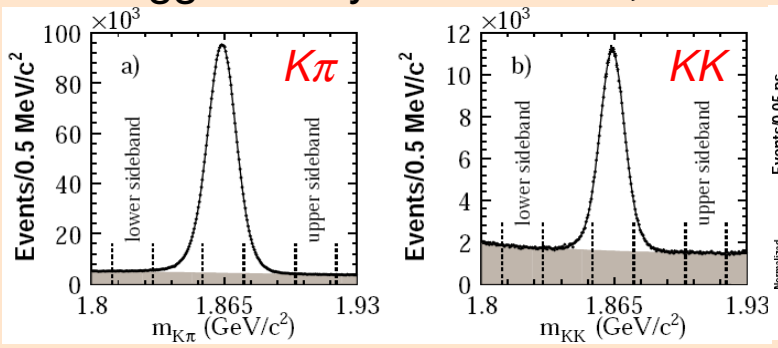


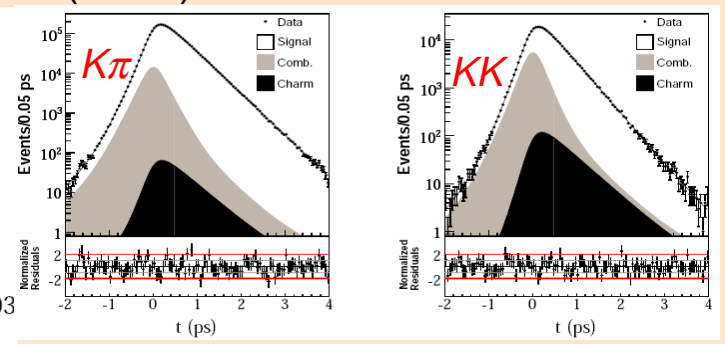


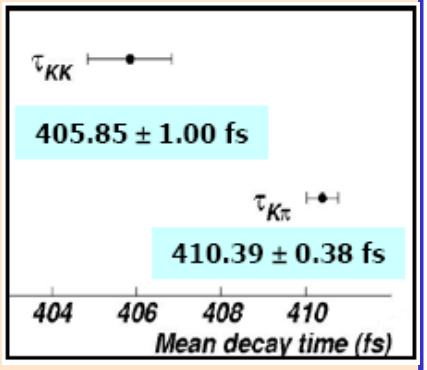
No-mixing excluded @ 3.0σ

No sign of CPV

Untagged analysis: PRL 103, 211801 (2009) – 384 fb^{-1}







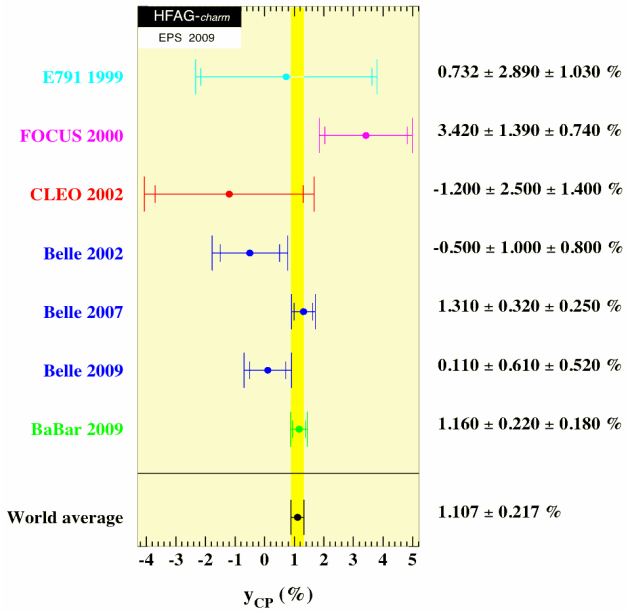
$$y_{CP}^{untagged} = (1.12 \pm 0.26(stat.) \pm 0.22(sys.))\% \quad (3.3\sigma)$$

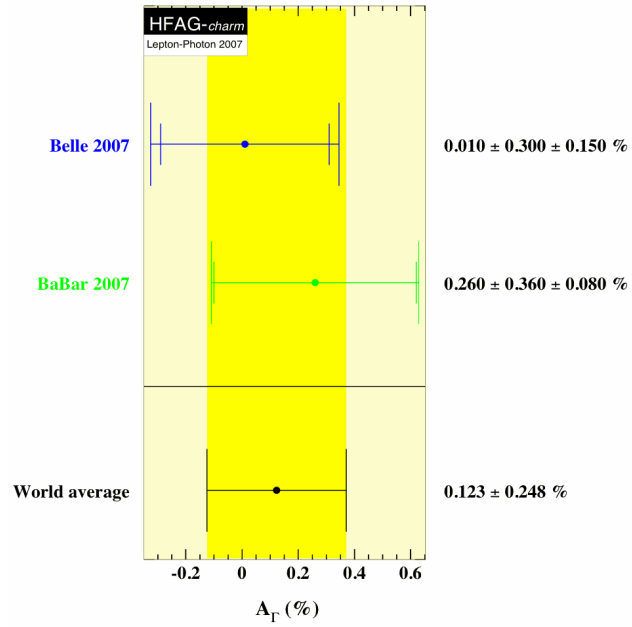
$$y_{CP}^{tagged} = (1.24 \pm 0.39(stat.) \pm 0.13(sys.))\% \quad (3.0\sigma)$$

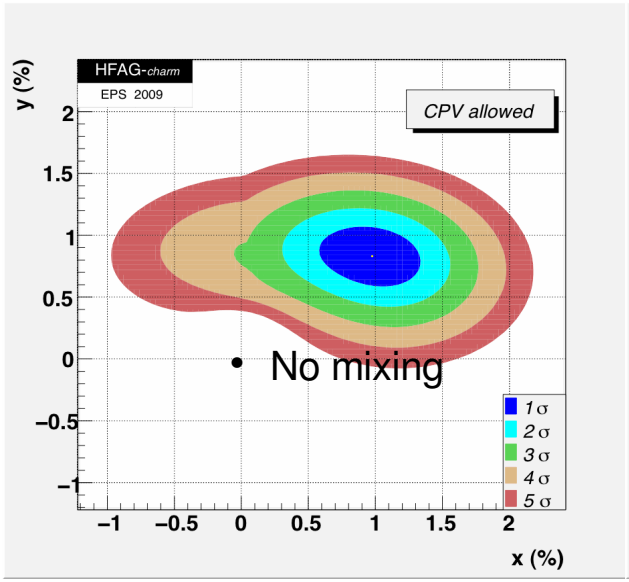
$$\Rightarrow y_{CP} = (1.16 \pm 0.22(stat.) \pm 0.18(sys.))\% \quad (4.1\sigma)$$

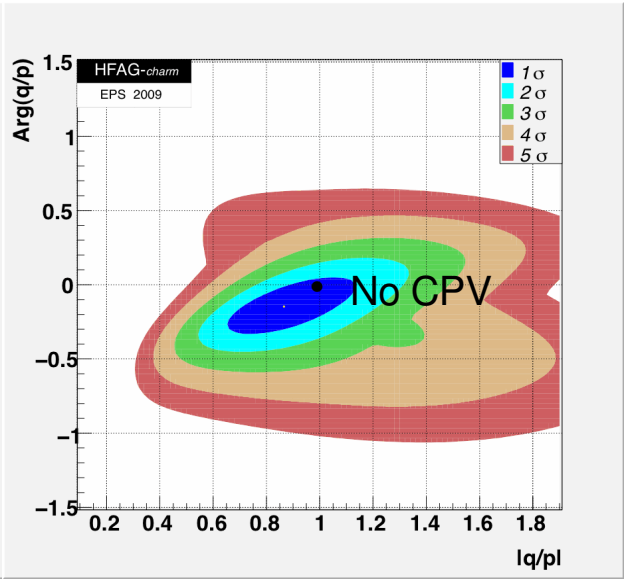
(Stat. errors: uncorr., sys. errors: 100% corr.)

D-Mixing: Summary









x	$=$	$(0.98^{+0.24}_{-0.26})$ %	y	$=$	(0.83 ± 0.16) %
$\lvert q/p \rvert$	$=$	$0.87^{+0.17}_{-0.15}$	ϕ_M	$=$	$(-8.5^{+7.4}_{-7.0})$ degrees
$\delta_{K\pi}$	$=$	$(26.4^{+9.6}_{-9.9})$ degrees	$\delta_{K\pi\pi}$	$=$	$(14.8^{+20.2}_{-22.1})$ degrees
R_D	$=$	(0.337 ± 0.009) %	A_D	$=$	(-2.2 ± 2.4) %

- No-mixing hypthesis excluded @10.2σ
- x ~ y ~ 1%
- No CPV at current precision which would mean NP

Summary

- All loop flavour observables sensitive to 4th generation t' with one exception:
  D-system (e.g. mixing): only flavour observables sensitive to b'

- B→Kπ: Strikingly large ΔA_{CP} but only conclusive once isospin sum rule tested with much higher precision since C~T could very well drive large ΔA_{CP} and not P_{EW} → Super-B ($K_S\pi^0$)

- B→K*ll: Interesting effects seen in A_{FB}/F_L but not conclusive yet
  BABAR: less precision (less statistics, ε_μ, 1D-ML fit) than Belle
  → LHCb, Super-B
  Besides more statistics also more work on theory errors needed

- D-Mixing: Very nice success for B-factories, CLEO-C, FOCUS, etc.
  More to come from BES-III (Super-B?)
  Constraint on $|V_{cb'}V_{ub'}^*|<0.002$ for $m_{b'} > 200$ GeV (theory error?)
  (Golowich et al., PRD76:095009, (2007))

- Some slight improvements still possible from B-factories in these areas