Recent results from *BaBar*

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Moscow, 19th August 2009

Flavour physics

- Understand flavour structure of Standard Model
- Measure properties of weak interaction, i.e. flavour-changing interactions of quarks
  - *CP* violation
  - Test CKM mechanism
  - Over-constrain CKM matrix
- Test Standard Model predictions
- Search for New Physics in deviations from SM predictions

This talk

Concentrate on angles of the Unitarity Triangle

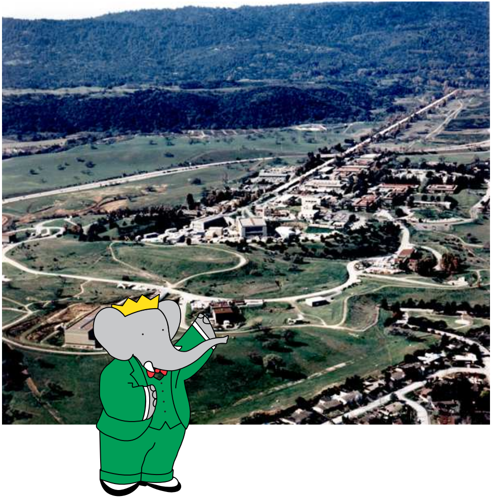
Introduction

- *BABAR*
- *CP* violation

Angles of the Unitarity Triangle

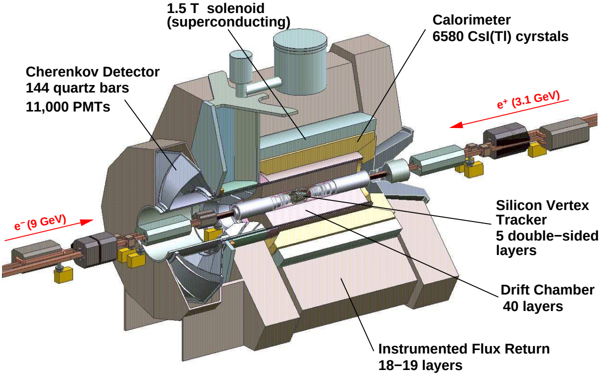
- $\sin 2\beta$
- $b \to sq\overline{q}$ penguins
- α

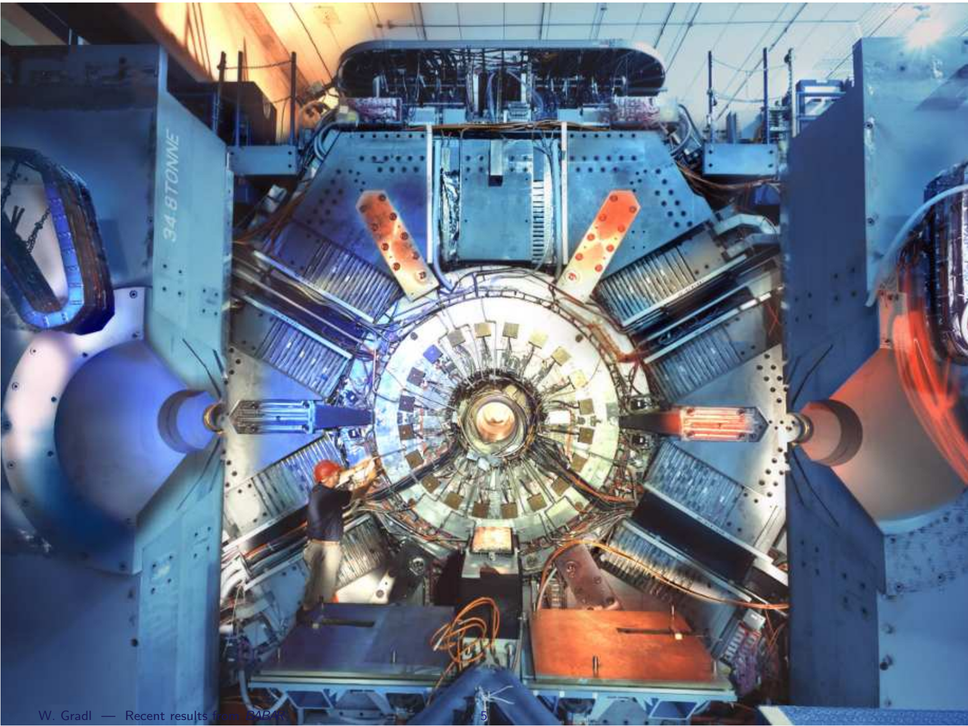
Summary, Outlook



BABAR at the B-factory PEP-II

- e^+e^--collider running primarily at $\sqrt{s} = m(\Upsilon(4S)) = 10.58\,\text{GeV}$
- Asymmetric beam energies, $\beta\gamma \sim 0.56$ to separate B decay vertices
- High luminosity: $\mathcal{L} \sim \mathcal{O}(10^{34})\,\text{cm}^{-2}\text{s}^{-1}$
- Data taking stopped in April 2008
- $\mathcal{L}_{\text{int}} = 531\,\text{fb}^{-1}$
  465 million $B\overline{B}$
  120 million $\Upsilon(3S)$
  100 million $\Upsilon(2S)$
  1.7 billion $e^+e^- \to q\overline{q}$

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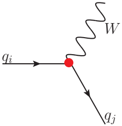
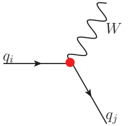
Unitarity Triangle and CP violation



$\sim gV_{ij}$

$$V_{\mathrm{CKM}} \simeq \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity Triangle and *CP* violation



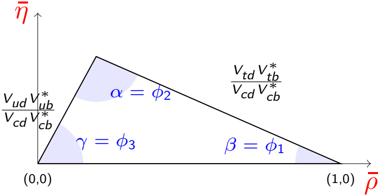
$$\sim gV_{ij} \quad V_{\mathrm{CKM}} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Assuming unitarity of V_{CKM} (universality of weak interaction):

$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0$$

➡ triangle in complex $(\overline{\rho}, \overline{\eta})$ plane
$\overline{\rho} \equiv (1 - \lambda^2/2)\rho$

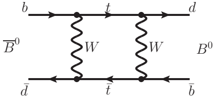
➡ apex at
$\overline{\rho} + i\overline{\eta} \equiv (V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$



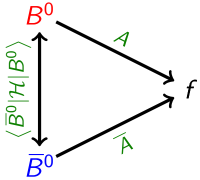
- Kobayashi & Maskawa 1973:
  Non-zero phase in CKM matrix generates *CP* violation:
  $\eta \neq 0 \Leftrightarrow$ Unitarity triangle is not flat
  (Nobel Prize 2008)

Time-dependent CP asymmetries

- Neutral B mesons oscillate between B^0 and $\overline{B}^0$.

$\langle \overline{B}^0 | \mathcal{H} | B^0 \rangle =$  + long distance

- Mass eigenstates $|B_{\mathrm{H,L}}\rangle = p \left|B^0\right\rangle \pm q \left|\overline{B}^0\right\rangle$; $q/p \simeq e^{-2i\beta}$
- Decay into common final state f:

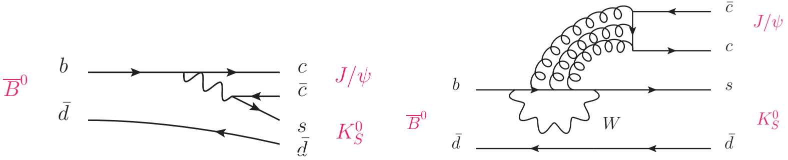


- If f is CP eigenstate:
  interference between two decay paths
- V_{CKM} complex
  ➠ B^0 and $\overline{B}^0$ decays have different weak phase
- Phase difference due to mixing: 2β
- Leads to lifetime dependent differences
  $\Gamma(B^0\big|_{t=0} \to f\big|_t) \neq \Gamma(\overline{B}^0\big|_{t=0} \to f\big|_t)$

$$\mathcal{A}_{cp}(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} = -\eta_f S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t$$

CP violating asymmetry in $B^0 \to (c\overline{c})K^0$

- Measure S and C in $b \to c\overline{c}s$ decays ('Golden mode')
- Experimentally clean ($J/\psi \to \ell\ell$, $K^0_s \to \pi^+\pi^-$)
- Theoretically clean:
  - dominated by single (tree) amplitude
  - gluonic (loop) penguin small & with same weak phase



- SM expectation: Only phase from $B^0 - \overline{B}^0$ mixing

$$C < 10^{-3} \quad \text{(no direct } CPV\text{)}$$
$$S = -\eta_f \sqrt{1-C^2} \sin 2\beta \approx -\eta_f \sin 2\beta$$

$B \to (c\bar{c})K^0$

BABAR's full data sample:

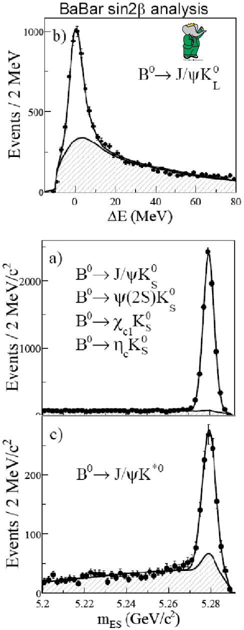
465M $B\bar{B}$ events, Phys. Rev. D **79**, 072009 (2009)

- Reconstruct charmonium $c\bar{c}$ as J/ψ, $\psi(2S)$, χ_{c1}, η_c
- $K^0_S \to \pi^+\pi^-, \pi^0\pi^0$
- K^0_L as neutral cluster, with some quality criteria
- Large, pure samples:
  e.g. $B^0 \to J/\psi\, K^0_S$ with 6750 events
- $K^{*0} \to K^0_S\pi^0$:
  ignore angular information
  ➠ dilution due to mix of *CP*-odd and *CP*-even final states, 'effective' η_f^{eff}

$\eta_f = +1$

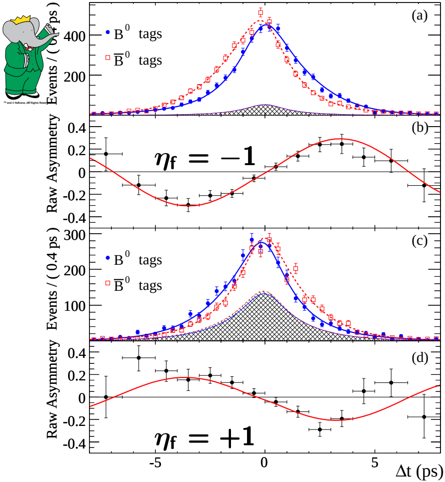
$\eta_f = -1$

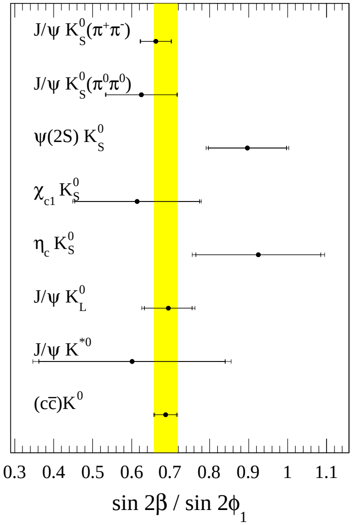
$\eta_f^{\mathrm{eff}} \approx 0.5$



$\sin 2\beta$ from $B^0 \to (c\bar{c})K^0$

$\beta \equiv \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$



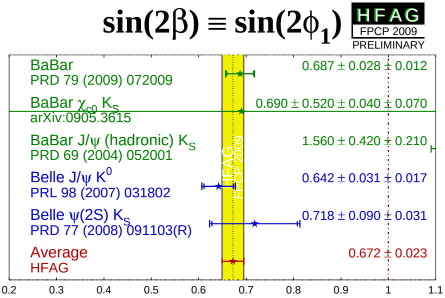


$\sin 2\beta = 0.687 \pm 0.028(stat) \pm 0.012(syst)$

BABAR, 465M $B\bar{B}$ events

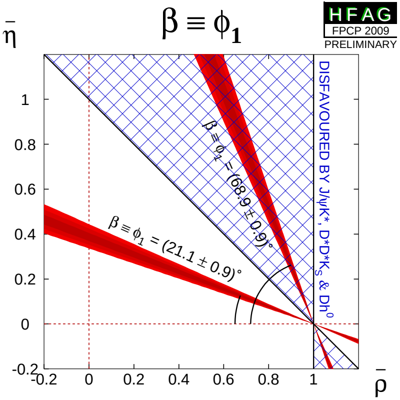
Phys. Rev. D **79**, 072009 (2009)

Precise measurement of β

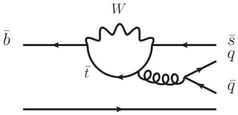


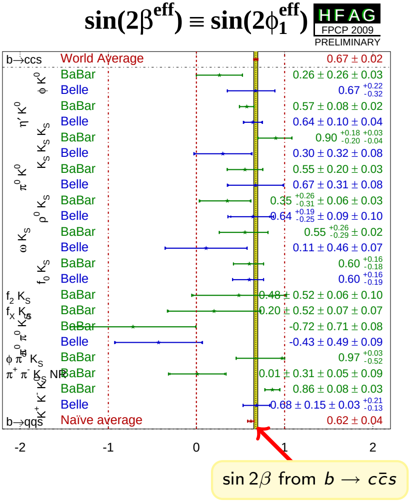
Still limited by statistics

$$\sin 2\beta = 0.672 \pm 0.023$$
$$\beta = (21.1 \pm 0.9)^\circ$$



$\sin 2\beta$ from $b \to q\bar{q}s$ penguins





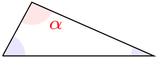
- Standard model and penguin only:

$$S_f = -\eta_f \sin 2\beta$$

- Sensitive to New Physics in loop
- 'Golden mode' $B^0 \to \phi K_S^0$
- Need SM correction to naïve expectation mode by mode
- Theory prefers $\Delta S > 0$
- Experiments seem to favour $\Delta S < 0$

- Was more exciting 2 years ago
- Limited by statistics; needs next-generation experiments

Measuring $\alpha \equiv \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$

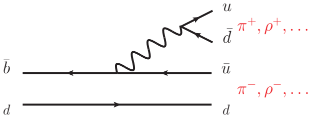


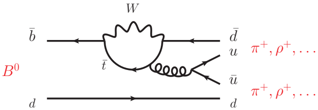
- Process involving both B-mixing (β) and $b \to u$ transition (γ):

$$\alpha = \pi - \beta - \gamma.$$

e.g. $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^+\rho^-$

- Complication: penguin amplitudes not negligible, different weak phase and (unknown) relative strong phase δ





$\delta = \delta_P - \delta_T$, P/T different for each final state

➠ Measure effective $\alpha_{\rm eff}$, and

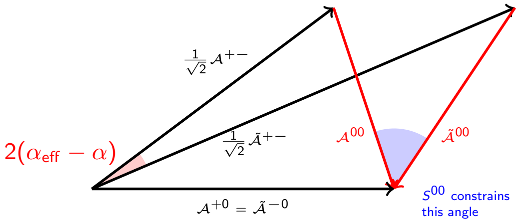
$$C_{hh} \propto \sin\delta; \qquad S_{hh} = \sqrt{1 - C_{hh}^2}\,\sin 2\alpha_{\rm eff}$$

- Need to constrain $|\alpha_{\rm eff} - \alpha|$

Isospin analysis to constrain $\alpha_{\text{eff}} - \alpha$

- Time dependent $\pi^+\pi^-$ or $\rho^+\rho^-$ *CP* asymmetry ➠ measure α_{eff}
- Use SU(2) isospin to relate amplitudes of all $\pi\pi$ ($\rho\rho$) modes and constrain $\alpha_{\text{eff}} - \alpha$ Gronau & London, Phys. Rev. Lett. **65**, 3381

$$\frac{\mathcal{A}^{+-}}{\sqrt{2}} + \mathcal{A}^{00} = \mathcal{A}^{+0} = e^{2i\gamma}\overline{\mathcal{A}}^{-0}$$



$$\begin{aligned}
\mathcal{A}^{+-} &= \mathcal{A}(B^0 \to h^+ h^-) \\
\mathcal{A}^{+0} &= \mathcal{A}(B^+ \to h^+ h^0) \\
\mathcal{A}^{00} &= \mathcal{A}(B^0 \to h^0 h^0)
\end{aligned}$$

$$\tilde{\mathcal{A}} \equiv e^{2i\gamma}\overline{\mathcal{A}}$$

If only $\mathcal{B}$ are measured: 4-fold ambiguity for $2(\alpha_{\text{eff}} - \alpha)$

α from $B \to \rho\rho$

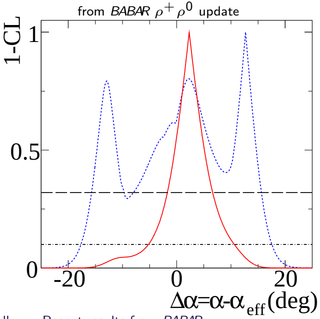
BaBar Phys. Rev. D **78** 071104 (2008)
$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$

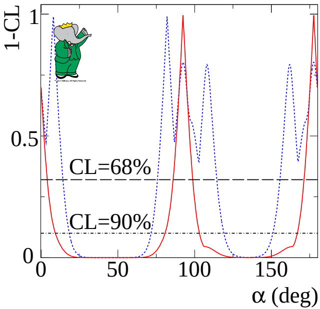
$f_L = 0.75^{+0.11}_{-0.14} \pm 0.14$
$S_L^{00} = 0.3 \pm 0.7 \pm 0.2,\ C_L^{00} = 0.2 \pm 0.8 \pm 0.3$

Belle Phys. Rev. D **78** 111102 (2008)
$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.4 \pm 0.4^{+0.2}_{-0.3}) \times 10^{-6}$
$< 1.0 \times 10^{-6}$ @90% $C.L.$

BaBar, 424 fb^{-1}, Phys. Rev. Lett. **102**, 141802
$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$

$B^0 \to \rho^0\rho^0$ small
➠ isospin triangle flattened,
decreases ambiguity due to $\alpha_{\text{eff}} - \alpha$





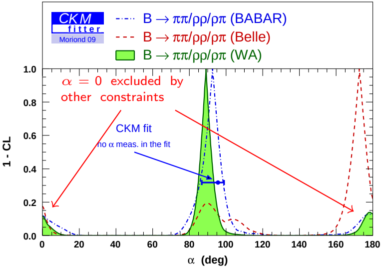
α from $B \to a_1\pi$

- Measure $\alpha_{\rm eff}$ in $B^0 \to a_1(1260)^{\pm}\pi^{\pm}$: $\alpha_{\rm eff}(a_1\pi) = 79^\circ \pm 7^\circ$
  BABAR, Phys. Rev. Lett. **98**, 181803 (2007)
- Use $SU(3)$-flavour symmetry to constrain penguin contribution P/T and obtain bound on $|\alpha_{\rm eff} - \alpha|$
  Gronau & Zupan, Phys. Rev. D **73**, 057502
- Need branching fractions for all decays in the same $SU(3)$ flavour multiplet with $J^{PC} = 1^{++}$:
  - $B \to a_1\pi$ ✓ (BABAR, Belle)
  - $B \to a_1 K$ ✓ (BABAR)
  - $B \to K_{1A}\pi$ (BABAR preliminary)
- Derive bound on $|\alpha_{\rm eff} - \alpha| < 11^\circ (68\% C.L.)$
- Using solution near 90°, α from $B \to a_1\pi$:

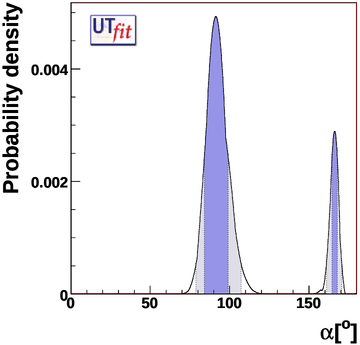
$$\alpha_{a_1\pi} = (79 \pm 7 \pm 11)^\circ$$

Summary on α

Combine measurements from *CP* violation in $B^0 \to \pi\pi, \rho\rho, (\rho\pi)^0$.
$a_1\pi$ not yet included.

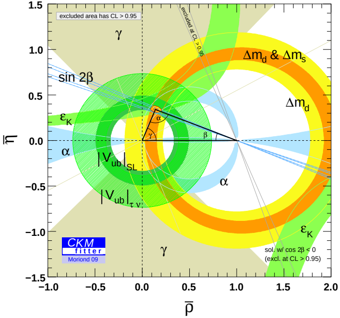


$\alpha = (89.0^{+4.4}_{-4.2})^\circ$ (68% C.L.)



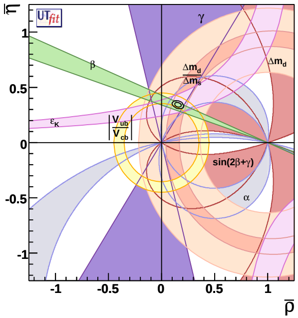
SM solution: $\alpha = (90 \pm 9)^\circ$

Testing the Standard Model



$$\bar{\rho} = 0.139^{+0.025}_{-0.027}$$
$$\bar{\eta} = 0.341^{+0.016}_{-0.015}$$
$$\sin 2\beta = 0.684^{+0.023}_{-0.021}$$

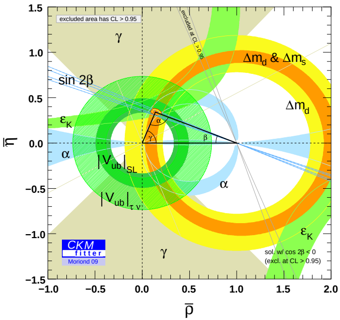
http://ckmfitter.in2p3.fr

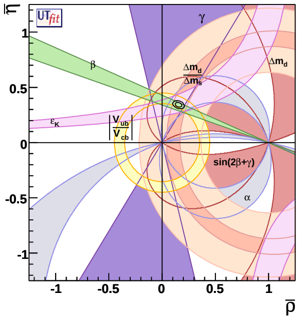


$$\bar{\rho} = 0.154 \pm 0.022$$
$$\bar{\eta} = 0.342 \pm 0.014$$
$$\sin 2\beta = 0.695 \pm 0.020$$

http://www.utfit.org

Testing the Standard Model





- α and β constrain Unitarity Triangle to 5°
- Poor precision on over-constraint:

$$\alpha + \beta + \gamma = (180^{+27}_{-30})^{\circ}/(191 \pm 14)^{\circ}$$

- CKM describes measurements well
- Still plenty of room for New Physics

Conclusions and summary

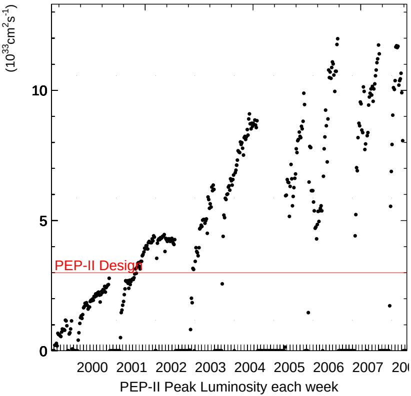
- CKM picture of *CP* violation seems to describe data well
- Most measurements limited by statistics
  need next-generation Flavour facility (LHCb, SuperB / Belle-II)
- Some tensions, but all below 3σ
- Still room for new physics,
  but effects likely to be subtle

- *BABAR* data taking ended, strong analysis effort ongoing
- More *BABAR* (and Belle) results on Monday

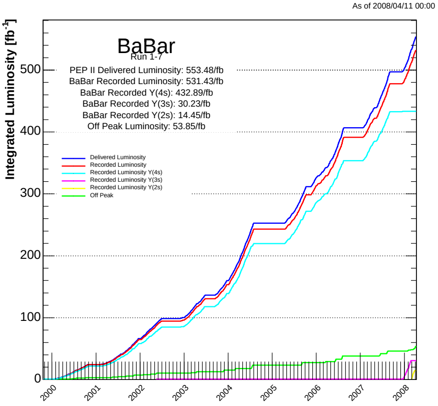
Extra slides

PEP-II performance and the *BABAR* data sample

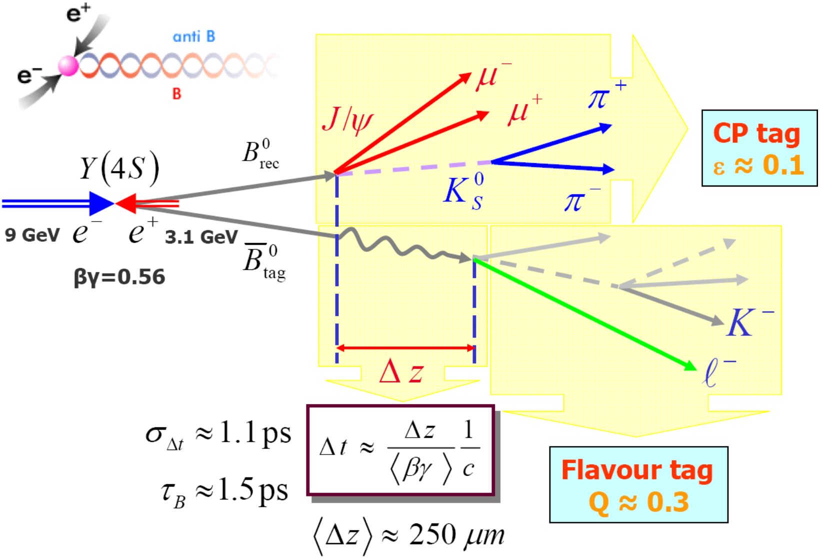
- peak luminosity
  $12.069 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



- data taking stopped 8 April 2008
- integrated luminosity 531 fb^{-1}

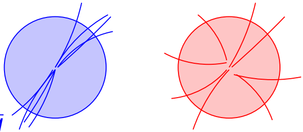


Measuring Δt



Detecting a signal

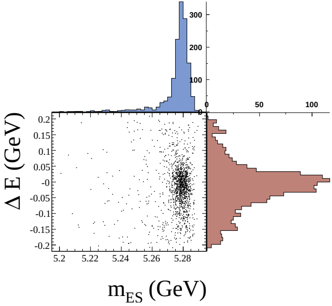
- Largest backgrounds from $e^+e^- \to q\overline{q}$
- Use event shape for background suppression:



- Kinematic variables identify B:

$$\Delta E = E_B^* - E_{\mathrm{beam}}^* \sim 0$$

$$m_{\mathrm{ES}} = \sqrt{{E_{\mathrm{beam}}^*}^2 - {p_B^*}^2} \sim m_B$$



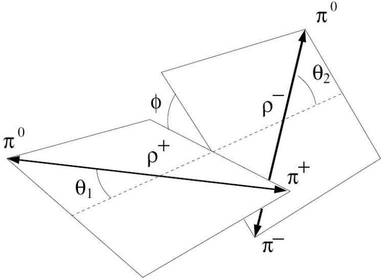
Angular analysis: $B \to VV$

- J^P: $0^- \to 1^- 1^-$
- With enough statistics, full angular analysis possible:

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \propto \left| \sum_{m=-1,0,1} H_m Y_{1,m}(\theta_1,\phi) Y_{1,-m}(\theta_2,\phi) \right|^2$$

- Fraction of longitudinally polarised events

$$f_L \equiv \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}$$



- In transversity basis:

$$A_0 = H_0$$ CP even

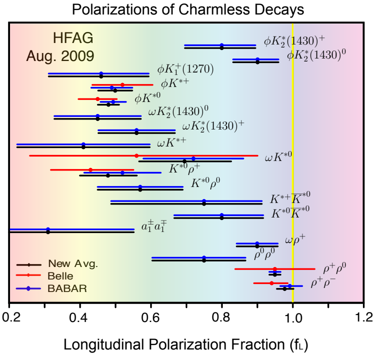
$$A_\parallel = \frac{1}{\sqrt{2}}(H_{+1} + H_{-1})$$

$$A_\perp = \frac{1}{\sqrt{2}}(H_{+1} - H_{-1})$$ CP odd

$A_0 \gg A_\parallel \gg A_\perp$

Polarisation puzzle

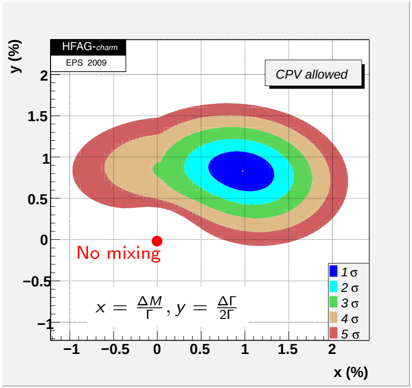
- Expectation vor $B \to VV$ decays:
  $f_L = 1 - \frac{m_V^2}{m_B^2} \sim 1$

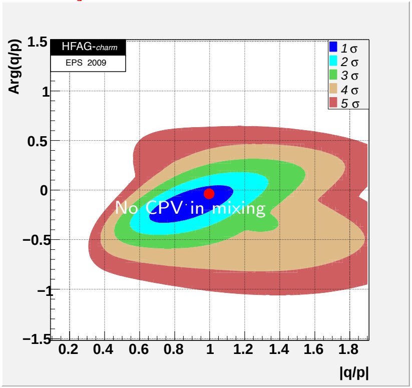


- $B \to \rho\rho$ seem to fit
- $b \to s$ penguin dominated modes ϕK^* and $K^{*0}\rho^+$ show $f_L \sim 0.5$
- So: tree-dominated $f_L \sim 1$ penguin-dominated $f_L \sim 0.5$?
- VT decays add confusion
- $f_L(B \to a_1^+ a_1^-) = 0.31 \pm 0.24$
  BABAR, arXiv:0907.1776
- Mechanism creating this behaviour?

Charm mixing and *CP* violation

HFAG preliminary





- Mixing established at $> 10\sigma$, combining all measurements
- Individual measurements $\sim 4\sigma$

- No evidence of CPV in mixing
- Data consistent with $\frac{q}{p} = 1$

Lifetime ratio: y_{CP}

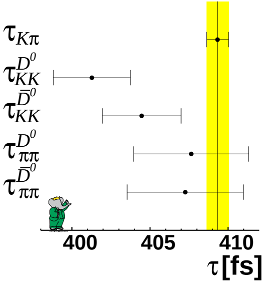
- Compare τ for Cabbibo-favoured $D^0 \to K\pi$ and Cabbibo-suppressed $D^0 \to h^+h^-$ decays

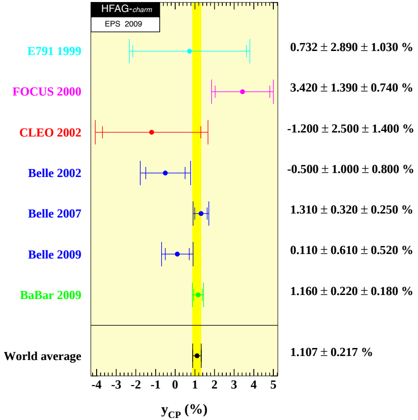
$$y_{CP} = \frac{\tau_{K\pi}}{\tau_{hh}} - 1$$

$$\Delta y = \frac{\tau_{K\pi}}{\tau_{hh}} \left(\frac{\tau_{hh}^{D^0} - \tau_{hh}^{\bar{D}^0}}{\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0}} \right)$$

BABAR tagged analysis:

Phys. Rev. D **78**,011105 (2008)

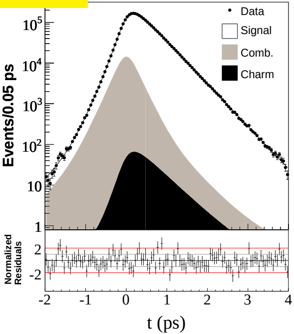




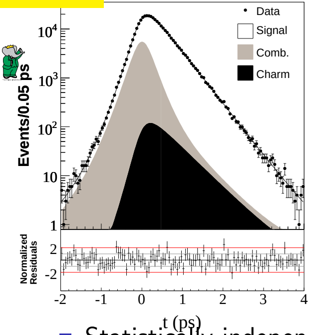
Lifetime ratio: *BABAR* untagged

- Do not tag flavour of D^0: larger signal, more background $\Rightarrow$ comparable sensitivity

$D^0 \rightarrow K\pi$



$D^0 \rightarrow KK$



- $\tau_{K\pi} = 410.39 \pm 0.38_{\text{stat}}$ fs
  $\tau_{KK} = 405.85 \pm 1.00_{\text{stat}}$ fs
- $y_{CP} = [1.12 \pm 0.26_{\text{stat}} \pm 0.22_{\text{sys}}]\%$

BABAR 384 fb^{-1}, arXiv:0908.0761, submitted to PRD-RC

- Statistically independent of previous tagged *BABAR* analysis
- Combined:

  $y_{CP} = [1.16 \pm 0.22_{\text{stat}} \pm 0.18_{\text{sys}}]\%$

  Excludes no-mixing hypothesis at 4.1σ