Direct CP and Rare Decays @ *BABAR*

BEAUTY 05 - Assisi

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On behalf of the *BABAR* collaboration

Overview

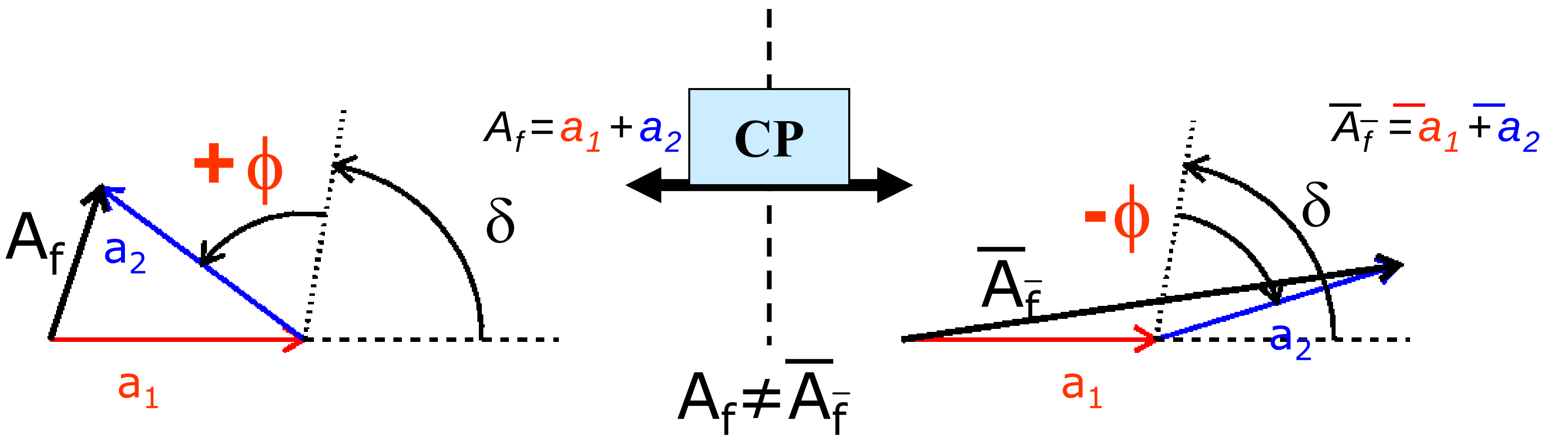
- Direct CP overview
- Analysis techniques
- Experimental results
  - Time integrated
    - $B \rightarrow K^{(*)} \pi$ / $B \rightarrow \eta^{(')} h$ / $B \rightarrow K_S K_S K$
  - Time Dependent
    - $B \rightarrow \pi\pi$ / $B \rightarrow \pi\pi\pi$
- Conclusion

Direct CP violation

- Direct CPV is when the Decay Amplitude for a process is different than the Amplitude of the ***CP*** conjugate process

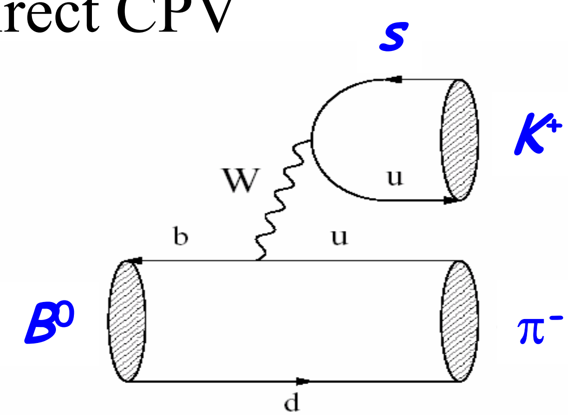
$$A_{CP} \equiv \frac{\left|\bar{A}_{\bar{f}}\right|^2 - \left|A_f\right|^2}{\left|\bar{A}_{\bar{f}}\right|^2 + \left|A_f\right|^2} \neq 0$$

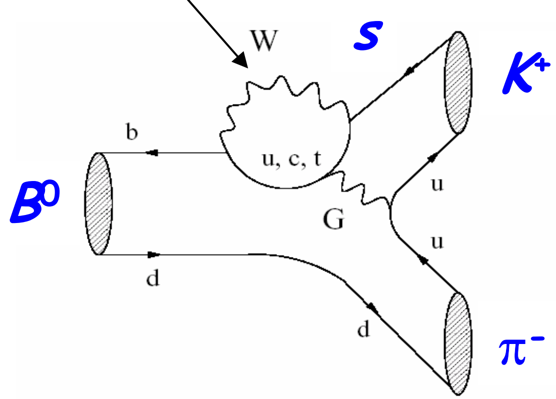
- This can happen if we have ≥ 2 interfering amplitudes with different weak phases (ϕ) and different strong phases (δ) (the weak phase changes sign under ***CP*** whereas the strong phase is unchanged)



Direct CP violation

- For 2 amplitudes: $A_{CP} = \frac{2\sin(\phi_i - \phi_j)\sin(\delta_i - \delta_j)}{R + 1/R + \cos(\phi_i - \phi_j)\cos(\delta_i - \delta_j)}$, $R \equiv \left|\frac{A_i}{A_j}\right|$
- So for large direct CPV we need
  - Two amplitudes to have similar magnitudes $|A_1| \sim |A_2|$
  - Large weak & strong phase differences
- Expected for some charmless B decays where we have a penguin amplitude & (Cabbibo & (sometimes color) suppressed) tree amplitude
- For some modes New Physics in the penguin loop can change the expected direct CPV





Direct CPV: experimental issues

- Can measure time-integrated & time-dependent Direct CPV
- Time Integrated
  - Measure $\mathbf{A_{CP}} \equiv \dfrac{\mathrm{N}(\overline{B}\to\overline{f}) - \mathrm{N}(B\to f)}{\mathrm{N}(\overline{B}\to\overline{f}) + \mathrm{N}(B\to f)}$
  - Experimentally simple for charged B decays or self tagging neutral B decays
- Time dependent asymmetry in $B^0 \to f_{CP}$ given by:

$$A_{CP}(f;t) = \underbrace{\frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}}_{S} \sin\Delta m_d t - \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}_{C} \cos\Delta m_d t$$

$$\lambda_f = e^{-i2\beta}\frac{A(\overline{B}^0 \to f)}{A(B^0 \to f)}$$

  - Direct CPV if $C \neq 0$ ($|\lambda_f| \neq 1$)
  - Experimentally fit to Δt of tagged events

Analysis techniques - Kinematics

Exploit kinematic constraints from beam energies to form 2 kinematic variables.

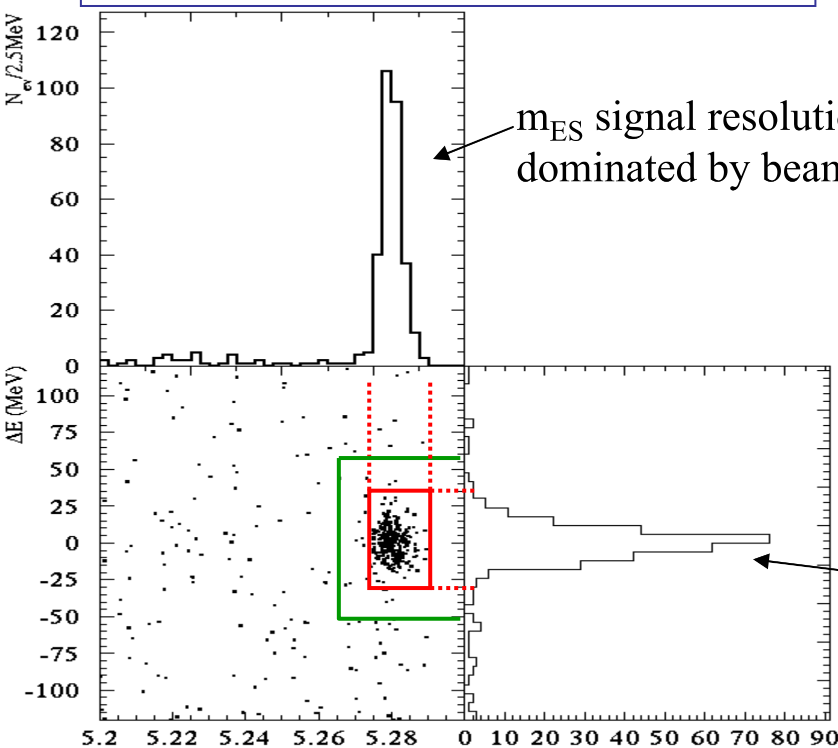
$$m_{ES} = \sqrt{E^{*2}_{BEAM} - p^{*\,2}_{B}}$$

p^*_B is c. m. momentum of B

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

Energy of the B Candidate in c. m. frame

Energy of the beam in c.m. frame



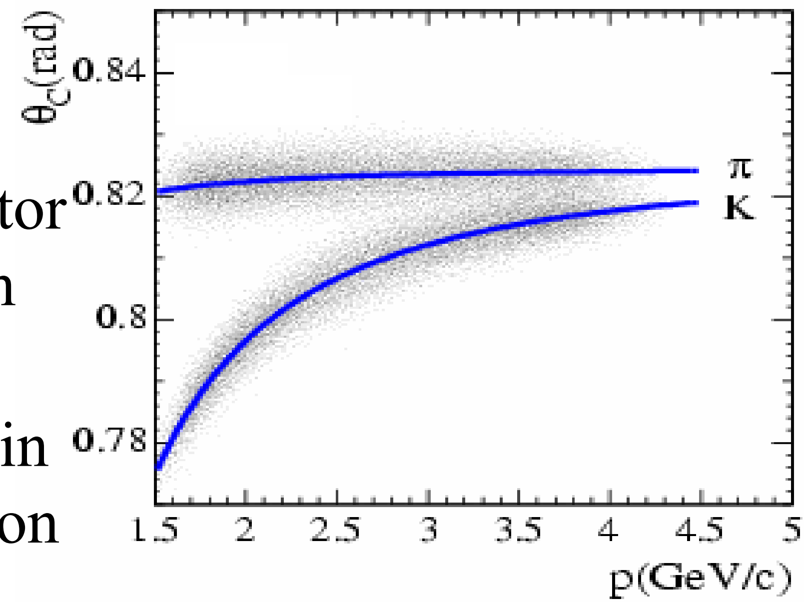
m_{ES} signal resolution ~ 3 MeV/c^2 dominated by beam energy spread

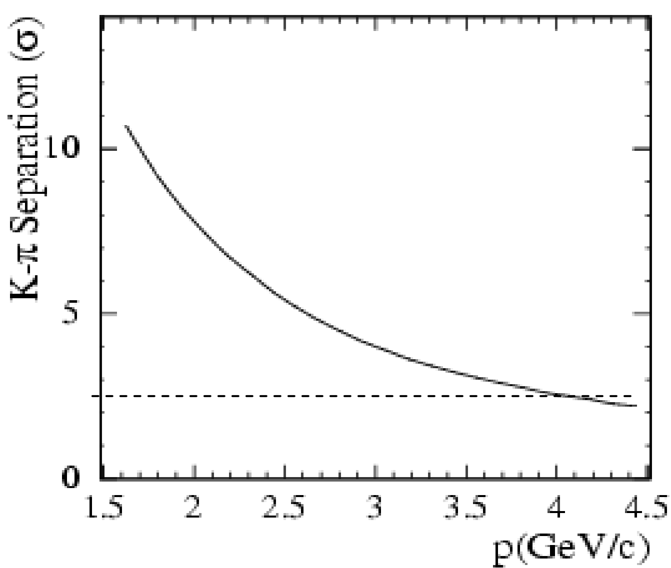
ΔE can also be used for particle id (PID) as calculate with pion mass hypothesis so kaon peak is shifted.

ΔE signal resolution ~ 10-50 MeV depending on number of neutrals in final state

Analysis techniques - Particle Id (PID)

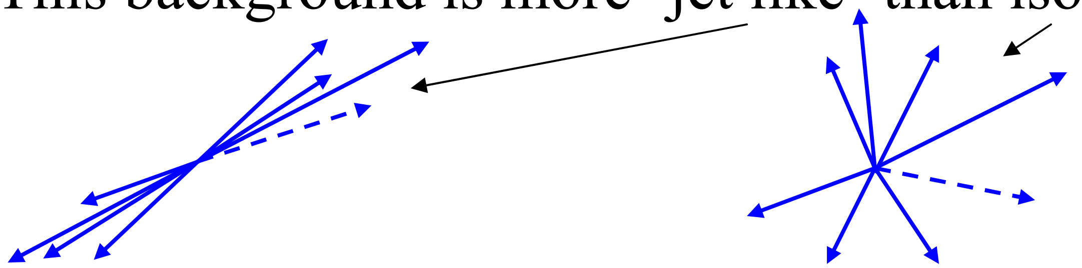
- Good K/π separation (>2.5σ) for momentum < 4 GeV/c
- This comes from Cherenkov detector (DIRC) combined with dE/dX from drift chamber
- Combine sub-detector information in ML fit to give greatest discrimination





Analysis techniques - Backgrounds

- Need to extract a tiny signal (BF~10^{-6}) from a huge background
- Background dominated by light quark continuum (u,d,s,c)
  - This background is more 'jet like' than isotropic B decays



  - Use event shapes (combined with Fisher or Neural Net) to reduce this background
- Also have background from other B decays
- Signal extracted using unbinned maximum likelihood fits to event shape, ΔE, m_{ES}, PID, +…

PRL **93**, 131801 (2004)

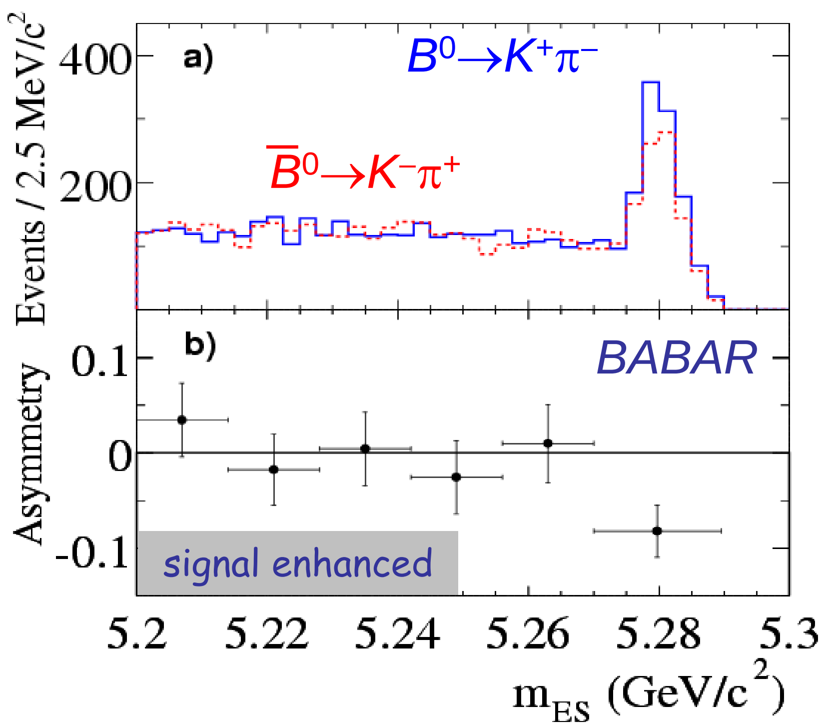
$B^0 \to K^+\pi^-$ (Observation of Direct CPV in B decays)

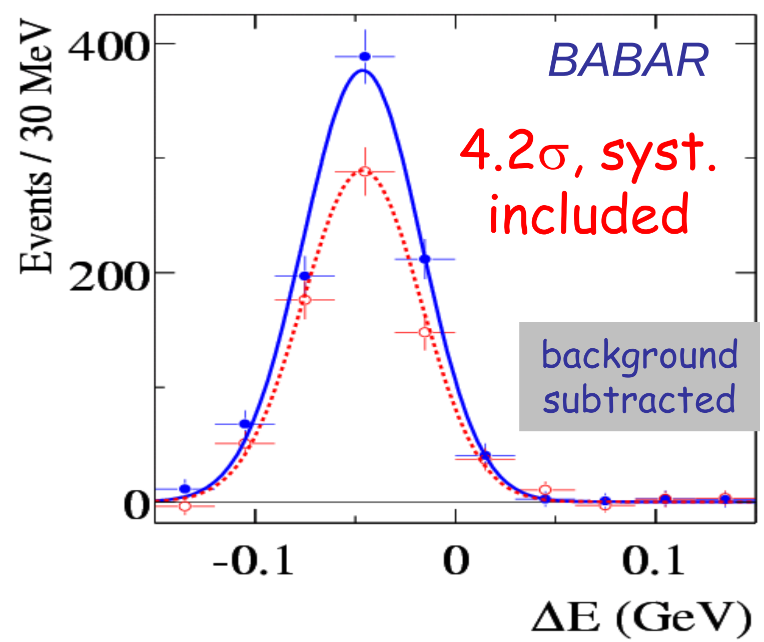
- Self tagging – flavour of the B from the charge of the K
- ML Fit uses input variables m_{ES}, ΔE, Fisher, θ_C^+, θ_C^-
  - θ_c PDFs separately for +ve, -ve tracks from PID D^* control sample
- Fit result $n_{K\pi} = 1606 \pm 51$

$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

Important cross check

$A_{K\pi}^{bkg} = 0.001 \pm 0.008$

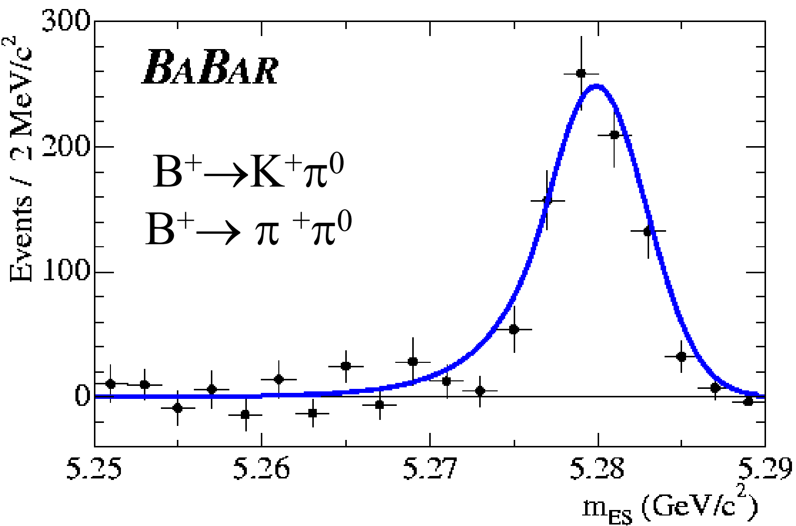


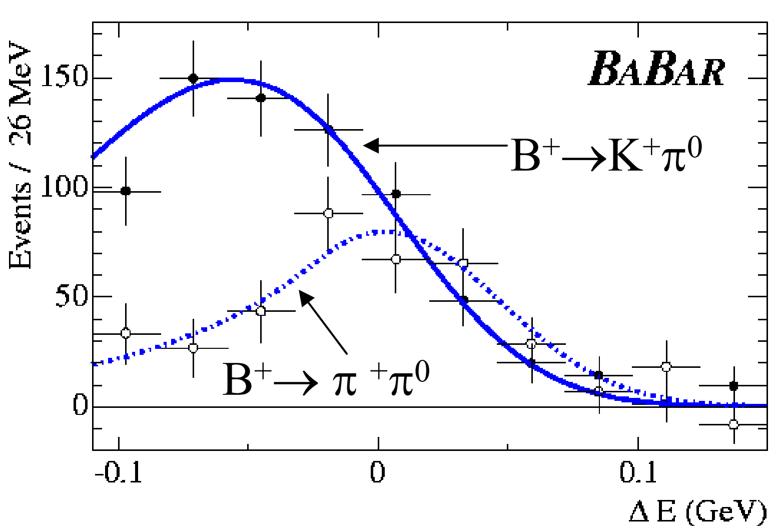


PRL **94**, 181802 (2005)

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

- Extended ML fit to ~41k $B^\pm \to h^\pm\pi^0$ candidates
- Input m_{ES}, ΔE, Fisher, θ_C, and expected yields and asymmetries for B-backgrounds $B \to \rho\pi$, $B \to \rho K$ & $B \to K^*\pi$
- Preliminary results
  - $B^+ \to K^+\pi^0$ - In SM naively expect $A_{CP}(B^+ \to K^+\pi^0) \sim A_{CP}(B^0 \to K^+\pi^-)$
    - **N = 672 ± 39, BF = (12.0 ± 0.7 ± 0.6)x10^{-6}, A_{CP}= 0.06 ± 0.06 ± 0.01**
  - $B^+ \to \pi^+\pi^0$ - In SM expect $A_{CP}(B^+ \to \pi^+\pi^0) \sim 0$
    - **N=379 ± 41, BF = (5.8 ± 0.6 ± 0.4)x10^{-6}, A_{CP}= -0.01 ± 0.10 ± 0.02**



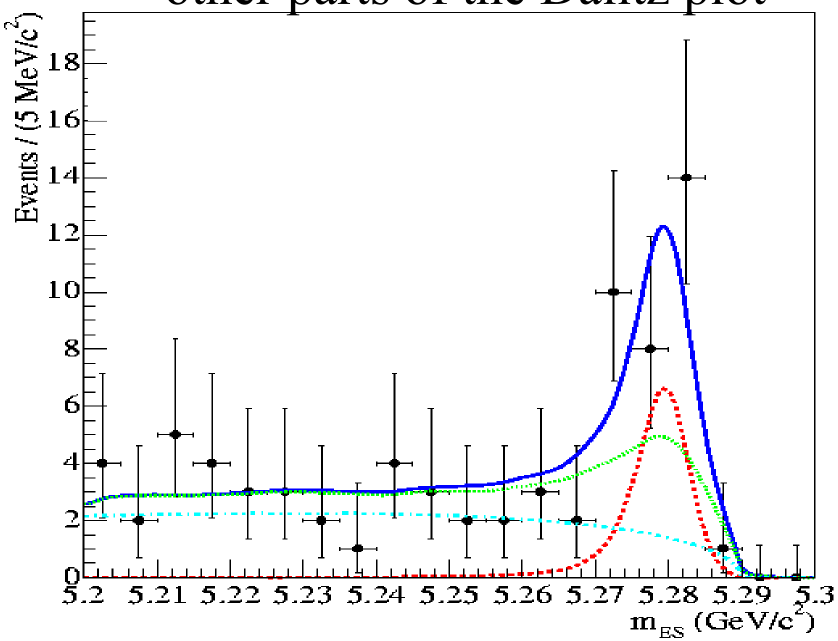


background subtracted

Phys Rev D **71**, 111101(R) (2005)

$B^+ \to K^{*+} \pi^0$

- Large CPV expected from tree/penguin interference
- $B^+ \to K^{*+}\pi^0, K^{*+} \to K^+\pi^0$ (challenging as 2 π^0 in final state)
- Analysis done using a quasi-twobody approximation
  - $0.8 < m_{K\pi} < 1.0$ GeV/c^2
- ML-Fit to m_{ES}, ΔE, $m_{K\pi}$, NN
- Systematics dominated by B backgrounds (higher K* contributions)
- Non-resonant $K^+\pi^0\pi^0$ and higher K* contributions estimated from fits to other parts of the Dalitz plot



Results (230M BB pairs):

$A_{CP} = 0.04 \pm 0.29 \pm 0.05$

BF = $(6.9 \pm 2.0 \pm 1.3)$ x10^{-6} [3.6σ]

Plot made with likelihood ratio cut (likelihood doesn't include plotted variable)

$B^+ \rightarrow \eta\pi^+ / \eta K^+ / \eta'\pi^+ / \eta\rho^+$ & $B^0 \rightarrow \eta K_S / \eta\omega$

- CKM suppressed $b \rightarrow u$ tree amplitudes contribute with $b \rightarrow s$ penguins leading to possible large Direct CPV
  - $B \rightarrow \eta K$ suppressed by destructive interference between penguin diagrams
- Some models predict very large A_{CP} in ηK, $\eta\pi$ (up to 20-50%)

e.g. M. Beneke, M. Neubert, Nucl.Phys. **B675** (2003) 333-415
C.W.Chiang, M.Gronau and J.L.Rosner, Phys. Rev. D **68** (2003) 074012

- $B^+ \rightarrow \eta'\pi^+$ important for understanding sin2β in $B \rightarrow \eta' K_S$
- Reconstruct the following sub decays
  - $\eta \rightarrow \gamma\gamma$ ($\eta_{\gamma\gamma}$), $\eta \rightarrow \pi^+ \pi^- \pi^0$
  - $\eta' \rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-$, $\eta' \rightarrow \rho^0 \gamma$ ($\eta'_{\rho\gamma}$)
  - $\omega \rightarrow \pi^+ \pi^- \pi^0$, $K_S \rightarrow \pi^+ \pi^-$, $\pi^0 \rightarrow \gamma\gamma$
- ML-Fit to m_{ES}, ΔE, Fisher, Particle ID, Helicity angle (ρ, ω)
- B background negligible except for $B^+ \rightarrow \eta_{\gamma\gamma}\pi^+$, $B^+ \rightarrow \eta_{\gamma\gamma} K^+$, $B^+ \rightarrow \eta\rho^+$, $B^+ \rightarrow \eta'_{\rho\gamma}\pi^+$
  - For these modes model B background with MC and add as component in the fit

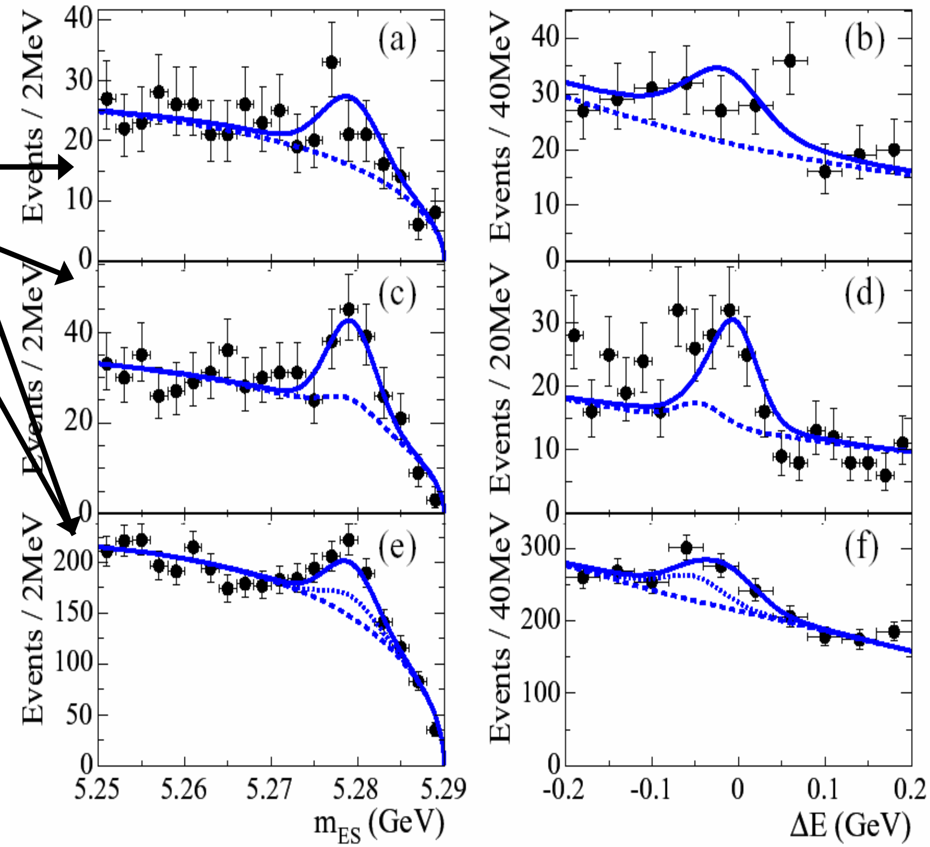
hep-ex/0503035 - Submitted to PRL

$B^+ \to \eta\pi^+ / \eta K^+ / \eta'\pi^+ / \eta\rho^+$ & $B^0 \to \eta K_S / \eta\omega$

- Results from 230 M BB pairs

Mode	BABAR BF ($\times 10^{-6}$)	A_{CP} BABAR	A_{CP} BELLE (Moriond'05)
$\eta\ \rho^+$	8.4 ± 1.9 ± 1.1	0.02 ± 0.18 ± 0.02	-0.17 ± 0.31± 0.02
$\eta'\ \pi^+$	4.0 ± 0.8 ± 0.4	0.14 ± 0.16 ± 0.01	
$\eta\ \pi^+$	5.1 ± 0.6 ± 0.3	-0.13 ± 0.12 ± 0.01	0.07 ± 0.15 ± 0.03
$\eta\ K^+$	3.3 ± 0.6 ± 0.3	-0.20 ± 0.15 ± 0.01	-0.49 ± 0.31 ± 0.07
$\eta\ K^0$	1.5 ± 0.7 ± 0.1 (< 2.5*)		
$\eta\ \omega$	1.0 ± 0.5 ± 0.2 (< 1.9*)		

* = @ 90% CL



- Charge asymmetries all consistent with zero
- All branching fractions consistent with previous theoretical predictions

$B^+ \to \eta\ \rho^+$ observed at 4.7σ

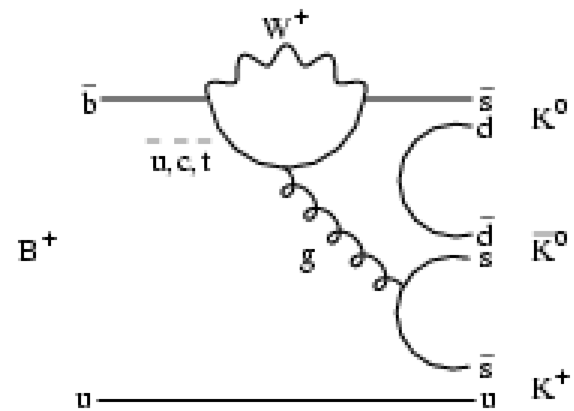
$B^+ \to \eta'\ \pi^+$ observed at 5.4σ

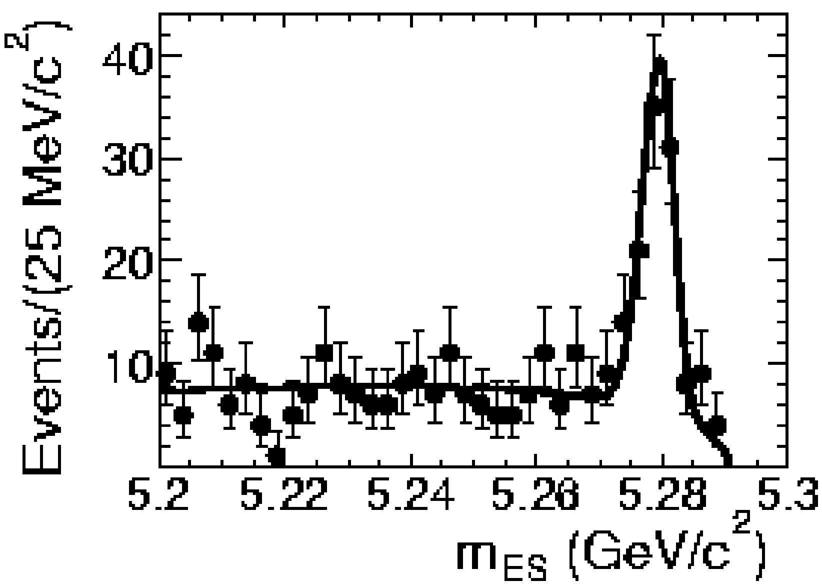
Plots made with likelihood ratio cut (likelihood doesn't include plotted variable)

PRL **93**, 181805 (2004)

$B^+ \to K_S K_S K^+$

- Standard Model A_{CP} expected to be 0
- Sensitive to new physics in the penguin loop
- ML-Fit to {m_{ES}, ΔE, Fisher} on dataset of 122 Million BB pairs
- Systematic on A_{CP} due to charge asymmetry in track finding and identification = 0.02





Result: $A_{CP} = -0.04 \pm 0.11 \pm 0.02$

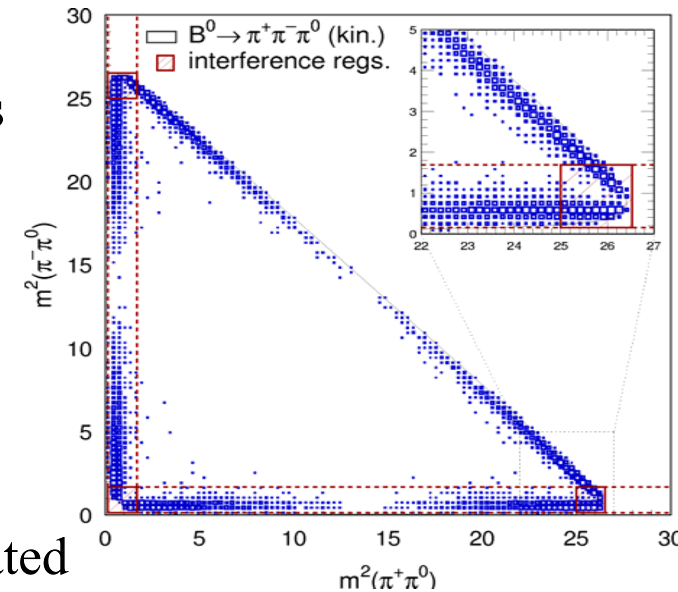
$[-0.23, 0.15]$ @ 90% CL

$BF = (10.7 \pm 1.2 \pm 1.0) \times 10^{-6}$

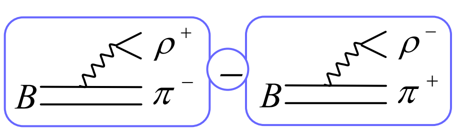
Plot made with likelihood ratio cut (likelihood doesn't include plotted variable)

Time dependent Direct CPV: $B^0 \to (\rho\pi)^0$

- Time dependent analysis of full Dalitz plot
- Interference taken into account between 3 ρ mesons based on Snyder-Quinn, PRD **48**, 2139 (1993)
- QCD factorization expects direct CPV to be zero
  M. Beneke, M. Neubert, Nucl.Phys. B675 (2003) 333-415
- ML-Fit on dataset of 213 M BB pairs yields 1184 ± 58 $B^0 \to (\rho\pi)^0$ events
- Final states not CP eigenstates (4 flavour charge configurations) so interpretation of results complicated
  - $\frac{1}{2}[A_{CP}(B^0 \to \rho^+\pi^-) + A_{CP}(B^0 \to \rho^-\pi^+)] = 0.34 \pm 0.11 \pm 0.05$

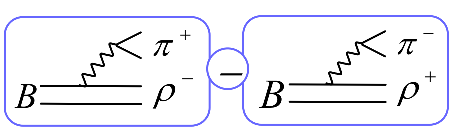


$A_{\rho\pi}^{+-} \cong$

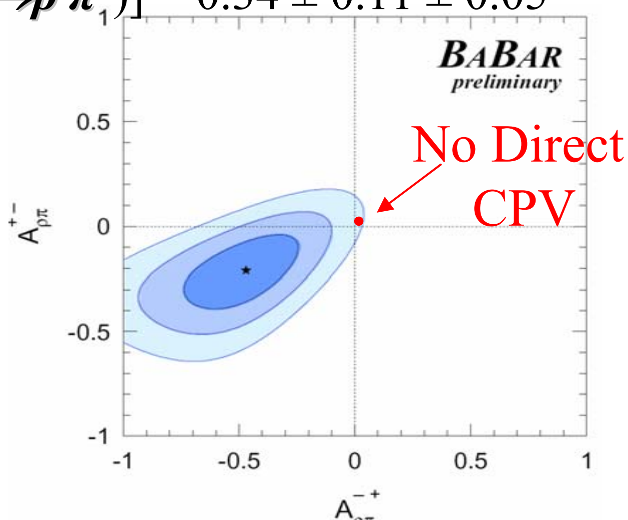


$= -0.21 \pm 0.11 \pm 0.04$

$A_{\rho\pi}^{-+} \cong$



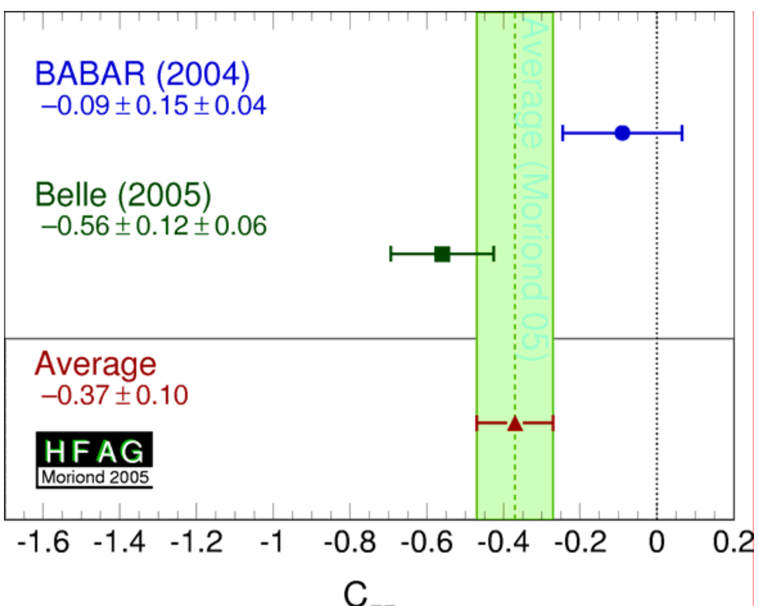
$= -0.47^{+0.14}_{-0.15} \pm 0.06$

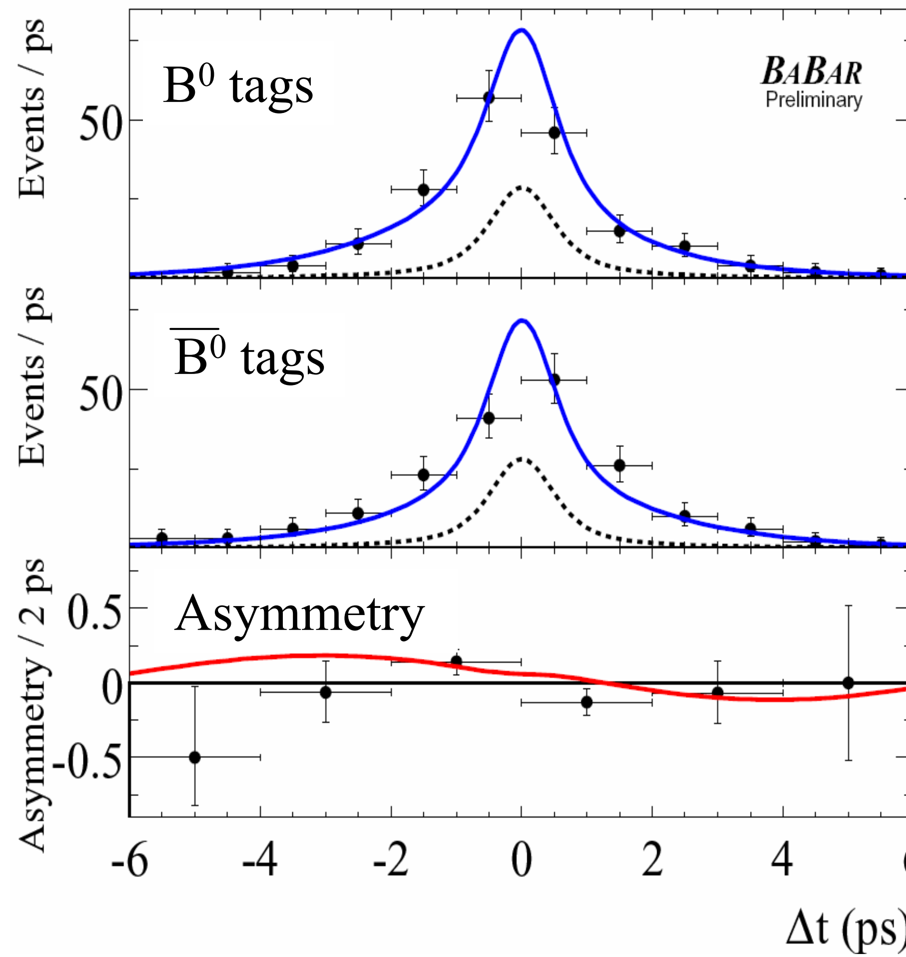


Evidence for direct *CP*: 2.9σ

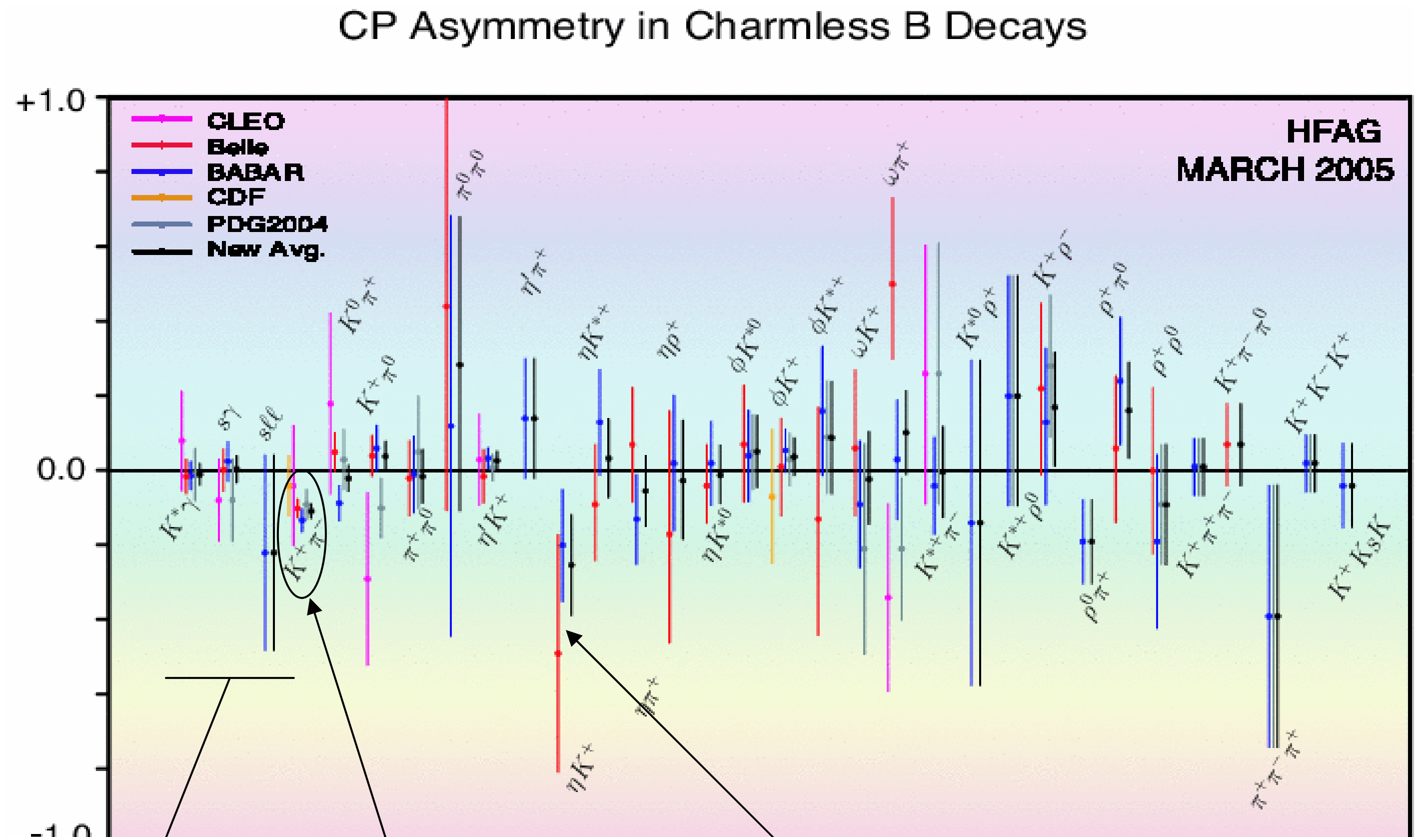
Time dependent Direct CPV: $B^0 \rightarrow \pi^+\pi^-$

- Time dependent analysis using 227M BB pairs
- ML fit to gives
  - $N_{\pi\pi} = 467 \pm 33$
  - $S = -0.30 \pm 0.17 \pm 0.03$
  - $C = -0.09 \pm 0.15 \pm 0.04$
- So no evidence for Direct CPV here
- Belle do see evidence for this
- BaBar/Belle consistent at 2.3 σ level





Summary of Direct CP Violation results



Radiative penguin A_{CP} in Francesca's talk on Thursday

Only statistically significant result so far…

One to watch

Summary

- Direct CP violation observed in time integrated decay:

$B^0 \to K^+\pi^-$ $\quad A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$

- Direct CP looked for in many other charmless modes.
  - No significant signals (yet – need more data!)

- Direct CP in time dependent analyses
  - Evidence for Direct CPV in $B^0 \to (\rho\pi)^0$ (2.9σ)
  - Not observed in $B^0 \to \pi^+\pi^-$

- Large Direct CPV expected in some channels – continuously improving our experimental errors so should start probing these predictions very soon

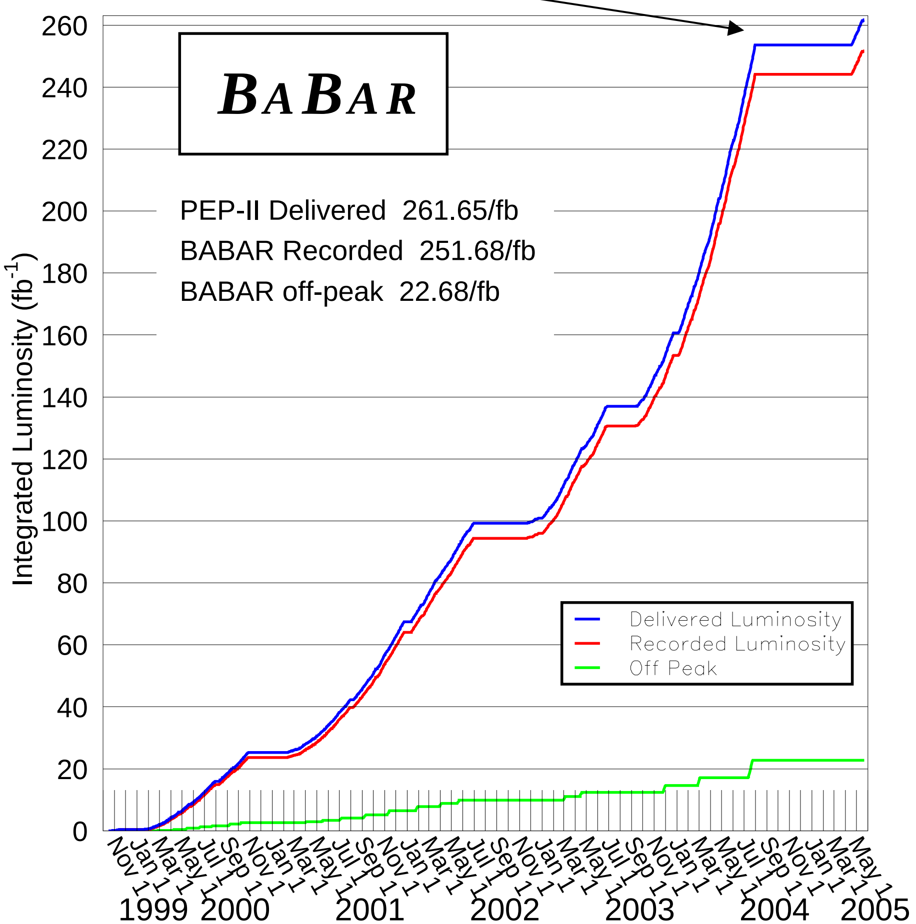
BACKUP SLIDES

ML Fit / Charge asymmetry systematics

- Include big sideband regions in fit to allow background parameters to be floated in the fit
- Toy MC experiments
  - Check for fit bias
  - Include correlations between variables
  - Check Likelihood of data fit compares with Toy test values
- Use data control samples with signal MC to obtain signal PDFs
- Cross check analysis results with simple cut&count analysis
- Charge Asymmetry systematic studies
  - Charge asymmetry in Monte Carlo
  - Charge asymmetry in data control sample
    - $D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^+\pi^-)\ \pi^+$ for PID asymmetry
    - Tau 1-3 decays for tracking efficiency asymmetry

BaBar Dataset

- BaBar has started taking data again after an extended downtime
- New data taking April 2005
- All results presented in this talk used 1999-2004 data
- Plan to collect 500fb^{-1} by summer 2006



Nucl. Instrum. Meth A**479** (2002) 1 479

BaBar experiment

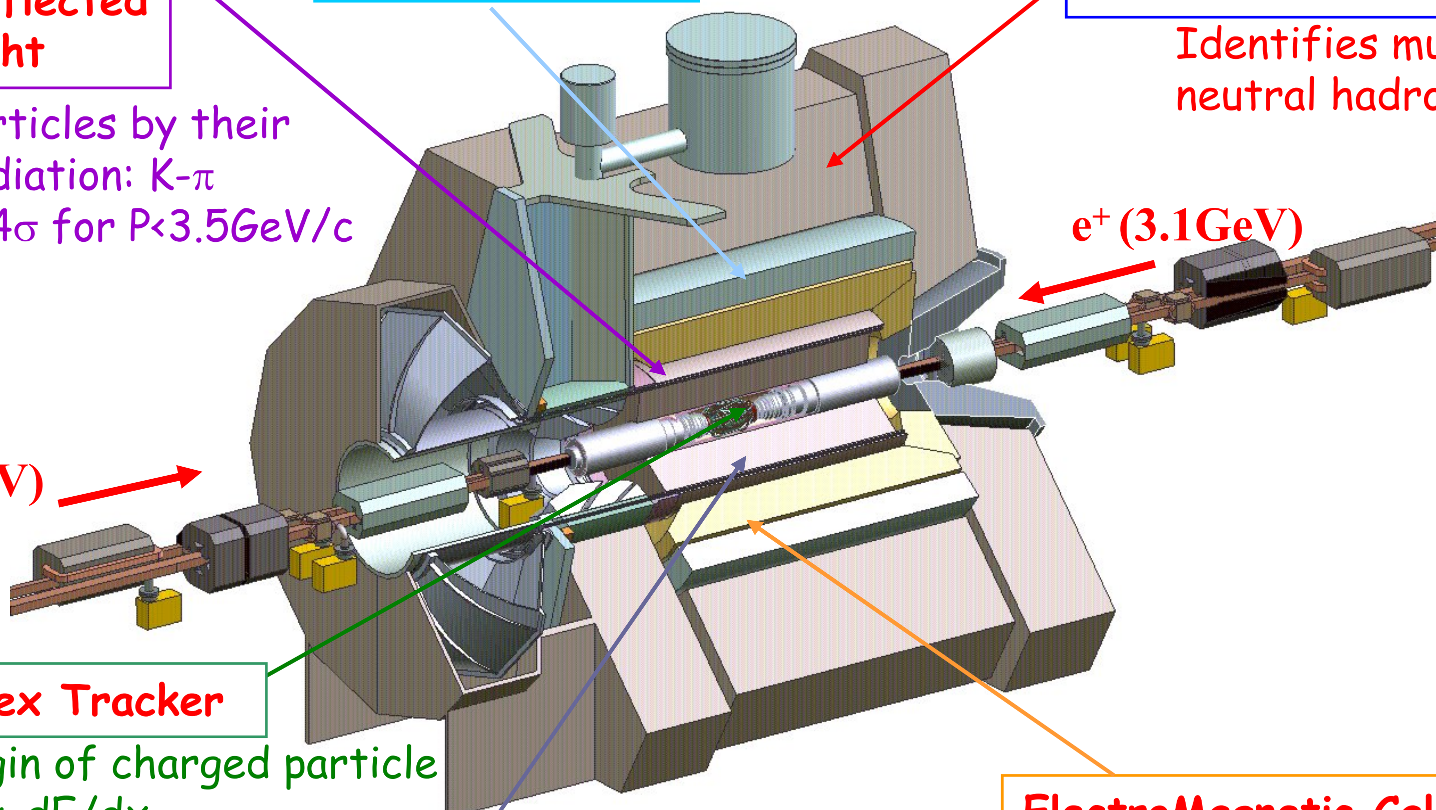
Detector of Internally Reflected Cherenkov light

Identifies particles by their Cherenkov radiation: K-π separation>3.4σ for P<3.5GeV/c

1.5T solenoid

Instrumented Flux Return

Identifies muons and neutral hadrons



e$^+$ (3.1GeV)

e$^-$ (9GeV)

Silicon Vertex Tracker

Measures origin of charged particle Trajectories + dE/dx 97% efficiency

Drift CHamber

Measures momentum of charged particles + dE/dx $\sigma(p_T)/P_T$=0.13%$P_T \oplus$0.45%

ElectroMagnetic Calorimeter

Measures energy of electrons and photons $\sigma(E)/E$=1.33%$E^{-1/4} \oplus$2.1%