Rare Vector-Vector B decays

a New Approach to α and New Physics

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BABAR collaboration

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LBNL

Research Progress Meeting

Reference: *BABAR*-COLL-0028

https://oraweb.slac.stanford.edu:8080/pls/slacquery/babar_documents.startup

Outline of the talk

- Why Study Heavy Flavor Physics
- Interest in Vector-Vector B Decays
- B-Physics Laboratory – *BABAR*
- B-Meson Reconstruction and Analysis
- $B \longrightarrow VV$ Results
  - Pioneering effort
  - Ahead of theory and experimental prejudice
- Latest results from Moriond-2004
  - Success of α from $B \longrightarrow \rho\rho$
  - Puzzle of $B \longrightarrow \phi K^*$

Fundamental Particles (Standard Model)

- Fundamental subject of matter (fermions):

matter					anti-matter			
quarks		leptons			anti-quarks		anti-leptons	
d	u	e	ν_e		$\bar{d}$	$\bar{u}$	$\bar{e}$	$\bar{\nu}_e$
s	c	μ	ν_μ		$\bar{s}$	$\bar{c}$	$\bar{\mu}$	$\bar{\nu}_\mu$
b	t	τ	ν_τ		$\bar{b}$	$\bar{t}$	$\bar{\tau}$	$\bar{\nu}_\tau$
-e/3	2e/3	-e	0	Q	e/3	-2e/3	e	0

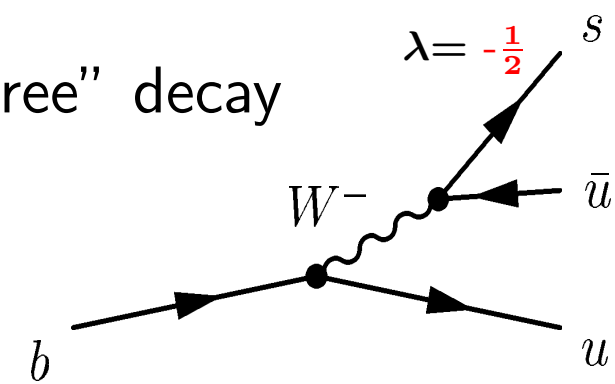
- ... and forces

  Electro-Weak (γ, $W^{\pm}$, Z)

  Strong (gluons)

  Gravity (not in model yet...)

"tree" decay



Fundamental Questions (Beyond SM?)

- Why does Matter dominate (Sakharov):
  - baryon non-conserving interaction
  - Charge-Parity (CP, or Time) asymmetry
  - non-equilibrium
- Need something beyond the Standard Model

SUperSYmmetry (popular model)

quarks (spin$=\frac{1}{2}$) s̃quarks (spin$=0$)

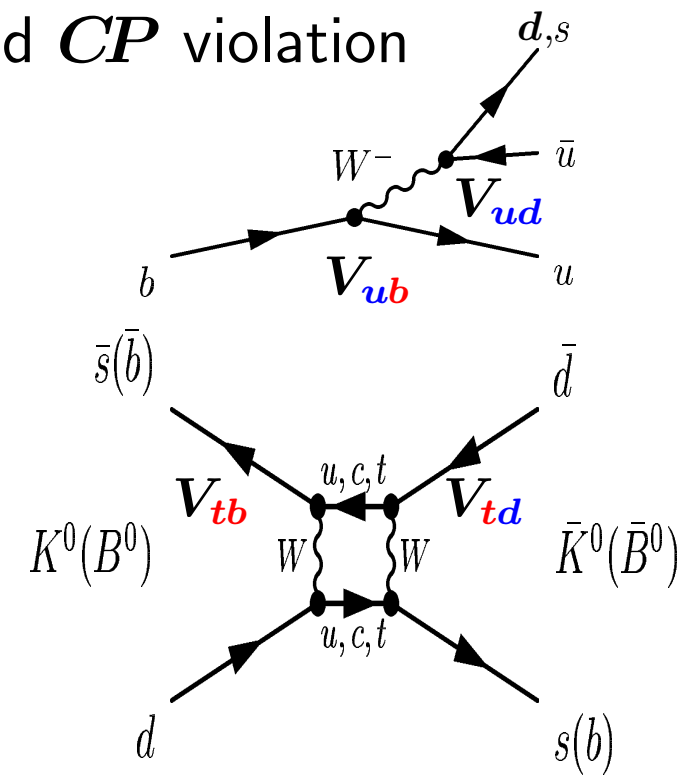
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix} \quad \text{heavy} \longrightarrow \quad \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} \begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \end{pmatrix}$$

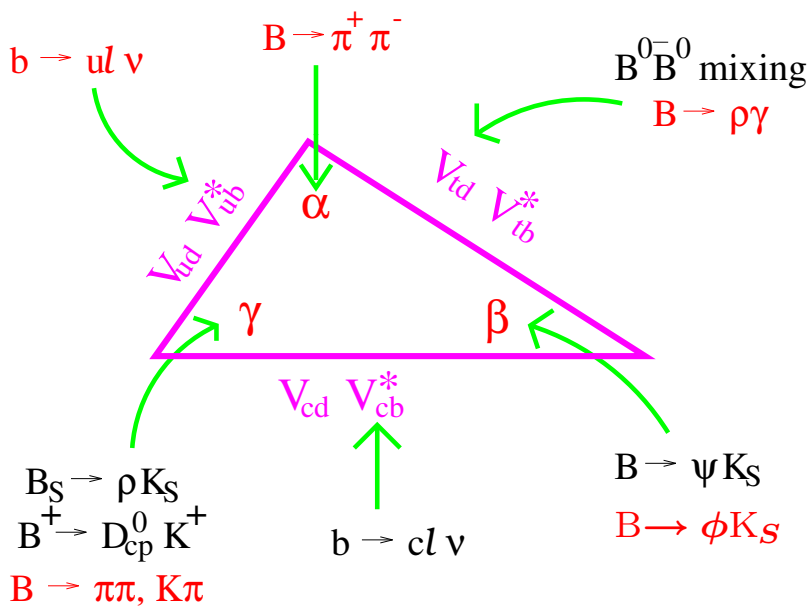
- Experiment: try to reach Beyond

What we are doing on *BABAR*

- Study fundamental EW forces and CP violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$





$\alpha = \arg[-V_{td}V_{tb}{}^*/V_{ud}V_{ub}{}^*]$ with $b \to u\bar{u}d$ ($\pi\pi$, $\rho\rho$, ...)

$\beta = \arg[-V_{cd}V_{cb}{}^*/V_{td}V_{tb}{}^*]$ with $b \to c\bar{c}s$ ($\psi K^{(*)}$); $s\bar{s}s$ ($\phi K^{(*)}$)

Success of sin(2β)

- $\Upsilon(4S) \to B^0{}_{(t_1)}\bar{B}^0{}_{(t_1)}$ coherent P-wave
- Two paths: $B^0{}_{(t_1)} \to B^0{}_{(t_2)} \to f_{CP}$ Ampl$=A_{f_{CP}}$

  $B^0{}_{(t_1)} \to \bar{B}^0{}_{(t_2)} \to f_{CP}$ Ampl$=\bar{A}_{f_{CP}} \times (\frac{q}{p})_{\rm mix}$
- Measure:

$$\Gamma(B^0 \to f, t_2) \propto e^{-|\Delta t|/\tau_B}(1 - \sin(2\beta) \times \sin(\Delta m \Delta t))$$

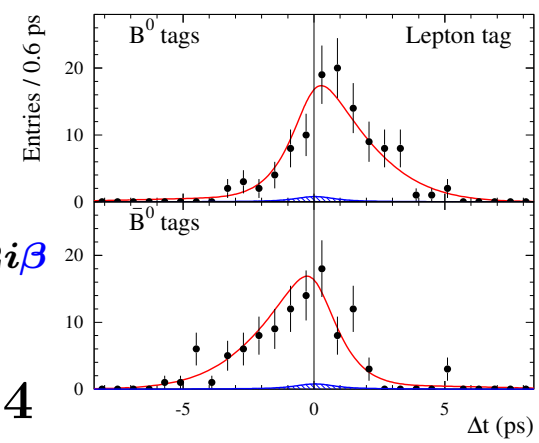
$$\Gamma(\bar{B}^0 \to f, t_2) \propto e^{-|\Delta t|/\tau_B}(1 + \sin(2\beta) \times \sin(\Delta m \Delta t))$$

$$S_{f_{CP}} = \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2} = \sin(2\beta) \qquad \lambda_{f_{CP}} = \pm(\frac{q}{p})_{\rm mix} \times \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

- $B \to \psi K$:

$$\boldsymbol{\lambda = -(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}})(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}})(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}) = e^{2i\beta}}$$

$$\boldsymbol{S = \sin(2\beta) = 0.741 \pm 0.067 \pm 0.034}$$

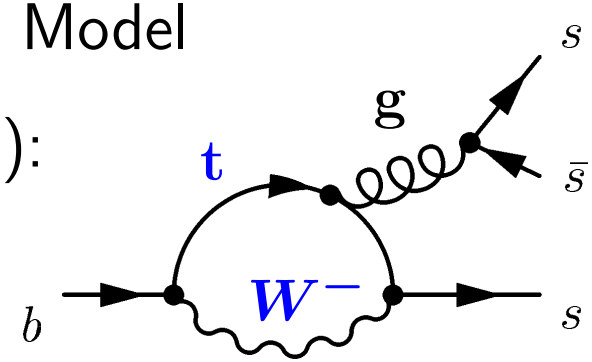


Importance of "Penguin" Loops

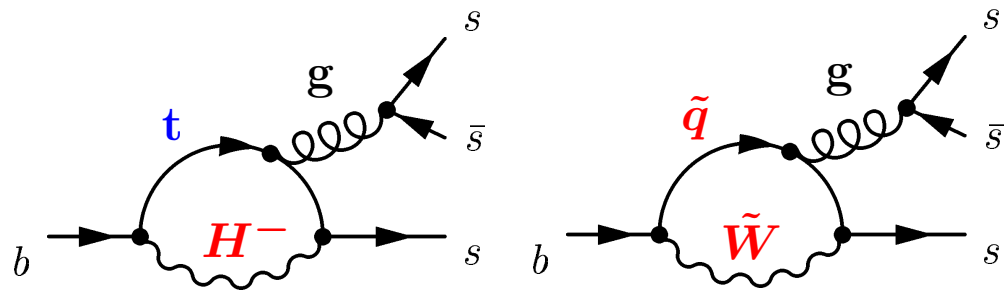
- No FCNC (e.g. $b \to s$) in Standard Model
- Effective transition – loop (penguin):

  heaviest known particles in loops

  t (∼180 GeV) and W (∼80 GeV)



- Sensitive to New Physics (Higgs$^+$, SUSY) to ∼500 GeV



- Observed first gluonic penguins (1996/97):

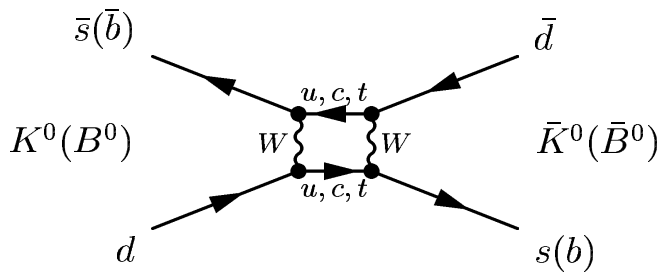
  $B \to \eta' K$, ... (puzzle: large decay rate)

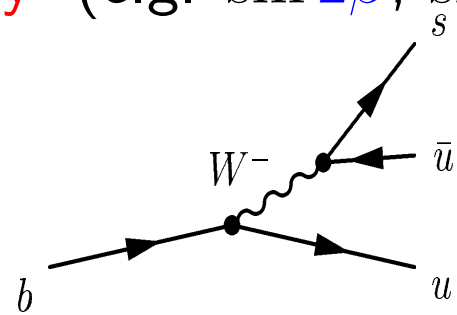
  CLEO, Phys.Rev.Lett 80, 3710 (1998); RPM Spring 2000

  Pointed by Vainshtein *et al* (1975) for $K \to \pi\pi$

Manifestation of CP-violation

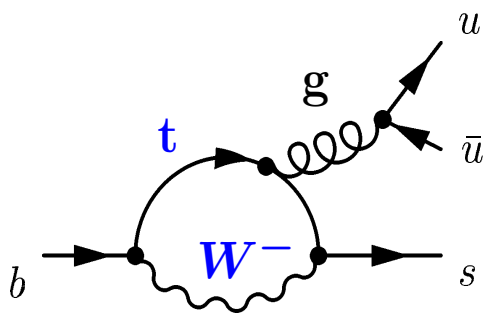
- Interference of mixing and decay (e.g. $\sin 2\beta$, $\sin 2\alpha$)

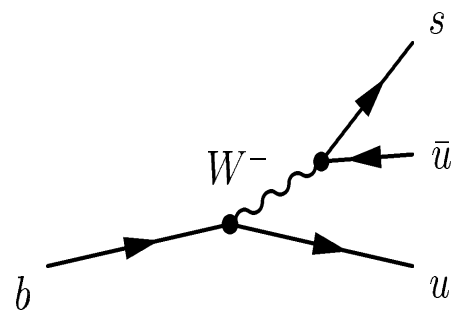




- Direct: $|A| \neq |\bar{A}|$, $\quad |A_1|e^{i(\pm\phi_1+\delta_1)} + |A_2|e^{i(\pm\phi_2+\delta_2)}$

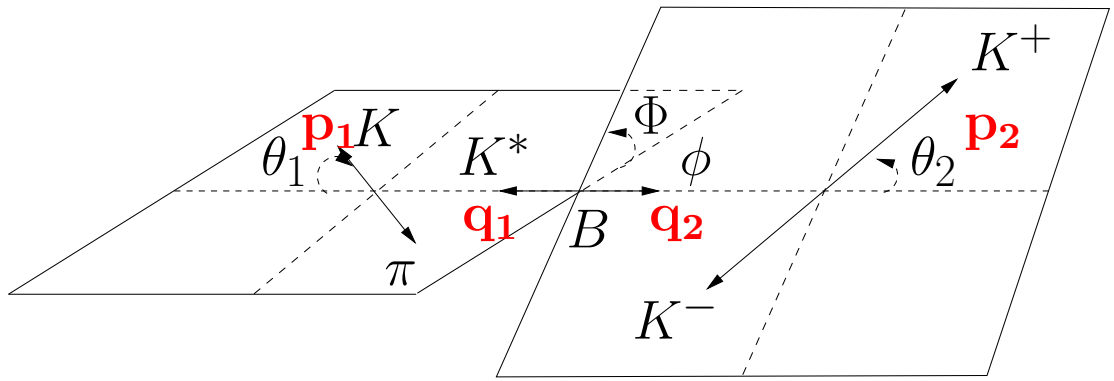
$$\mathcal{A}_{CP} \propto |\bar{A}|^2 - |A|^2 \propto |A_1|\,|A_2|\,\sin\Delta\phi_{\rm EW}\,\sin\Delta\delta_{\rm strong}$$





- New approach in B-physics (special to $B \to VV$)
  - asymmetry in Triple-Products ($\mathbf{p} \cdot \epsilon_1 \times \epsilon_2$), T-odd
  - first applied to $B \to \phi K^*$, Phys.Rev.Lett 91, 171802 (2003)

Triple-Product Asymmetries



- $CP \Rightarrow \mathcal{A}_B = -\mathcal{A}_{\bar{B}}$ in $(\mathbf{q_1}-\mathbf{q_2})\cdot\mathbf{p_1}\times\mathbf{p_2}$ $>$ or < 0
- For S- and P-waves: $S(\bar{S}) = +S_1 e^{i\delta_1^S} e^{\pm i\phi_1^S} + S_2 e^{i\delta_2^S} e^{\pm i\phi_2^S}$

  $P(\bar{P}) = \pm P_1 e^{i\delta_1^P} e^{\pm i\phi_1^P} \pm P_2 e^{i\delta_2^P} e^{\pm i\phi_2^P}$

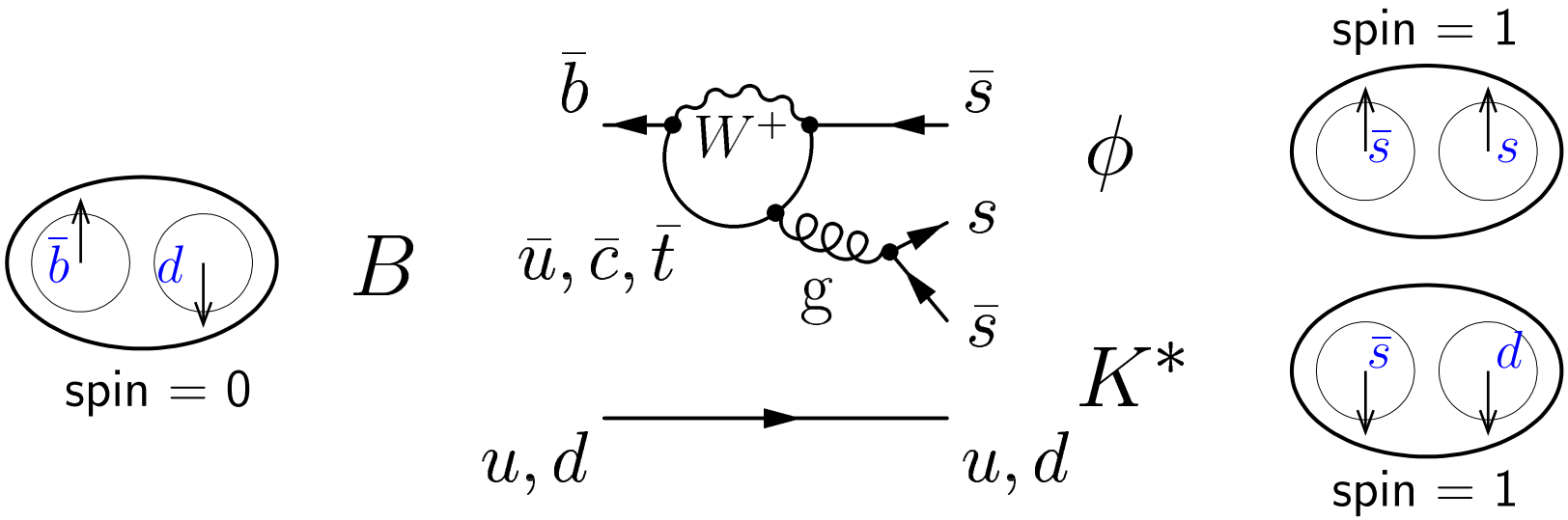
$$(\mathcal{A}_B + \mathcal{A}_{\bar{B}}) \propto \mathrm{Im}(SP^*)+\mathrm{Im}(\bar{S}\bar{P}^*) \propto \cos\Delta\delta \sin\Delta\phi$$

- Familiar from Hyperon decays

$$\Xi^- \to \Lambda\pi^-,\ \Lambda \to \mathrm{p}\pi^- \quad \text{vs.} \quad \Xi^+ \to \bar{\Lambda}\pi^+,\ \bar{\Lambda} \to \bar{\mathrm{p}}\pi^+$$

B-Meson Decays to Two Vector Mesons

- Decays reveal fundamental dynamics:



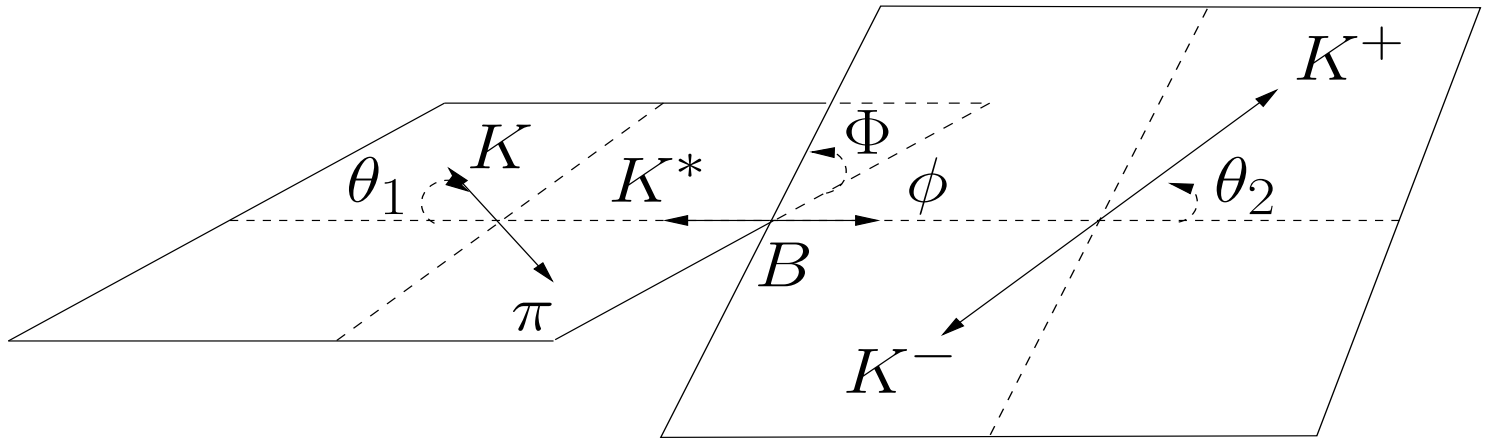
- Conservation of angular momentum:

$S_{\rm tot} = 0$, helicities $(\boldsymbol{s} \cdot \boldsymbol{p})$ $\lambda_\phi = \lambda_{K^*} = 0, +1, -1$,

Decay amplitude: $A = \langle f|\mathcal{H}|i\rangle = A_0 + A_+ + A_-$

11 observables (!) (for B and $\bar{B}$): 6 $|A_i|$, 5 arg(A_i/A_j)

$B \to VV$ Angular Distributions



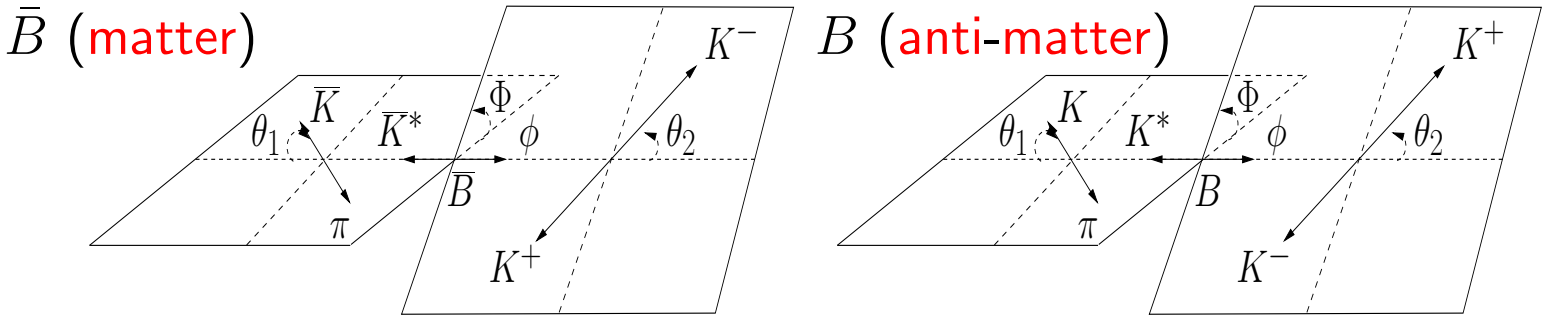
$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_{m=-1,0,1} A_m \times Y_{1,m}(\theta_1,\Phi_1) \times Y_{1,-m}(\theta_2,\Phi_2) \right|^2$$

$$\propto \left\{ \frac{1}{4}\sin^2\theta_1 \sin^2\theta_2 \left(|A_{+1}|^2 + |A_{-1}|^2\right) + \cos^2\theta_1 \cos^2\theta_2 |A_0|^2 \right.$$

$$+\frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \left[\cos 2\Phi \ \mathrm{Re}(A_{+1}A_{-1}^*) - \sin 2\Phi \ \mathrm{Im}(A_{+1}A_{-1}^*)\right]$$

$$\left. +\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 \left[\cos\Phi \ \mathrm{Re}\left(A_{+1}A_0^* + A_{-1}A_0^*\right) - \sin\Phi \ \mathrm{Im}\left(A_{+1}A_0^* - A_{-1}A_0^*\right)\right] \right\}$$

CP Asymmetries in $B \to VV$



- Direct (rate) asymmetries:

$$|A_0|^2 \neq |\bar{A}_0|^2 \quad \text{(longitudinal)}$$
$$|A_\parallel|^2 \neq |\bar{A}_\parallel|^2 \quad \text{(transverse } CP\text{-even)}$$
$$|A_\perp|^2 \neq |\bar{A}_\perp|^2 \quad \text{(transverse } CP\text{-odd)}$$

$$\propto \sin\Delta\delta_{\rm EW} \ \sin\Delta\delta_{\rm strong}$$

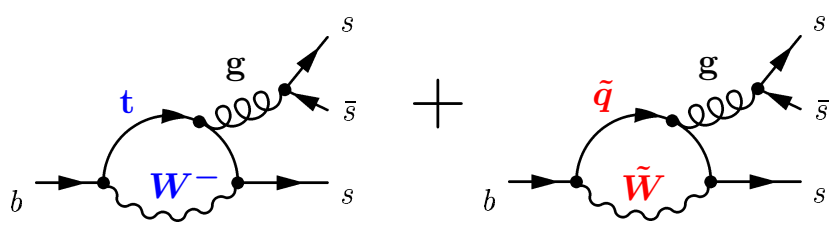
- Triple-product asymmetries

define $A_{\parallel,\perp} = (A_+ \pm A_-)/\sqrt{2}$

$$\propto \sin\Delta\delta_{\rm EW} \ \cos\Delta\delta_{\rm strong}$$

$$\mathrm{Im}(A_\perp A_0^*) \neq -\mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)$$
$$\mathrm{Im}(A_\perp A_\parallel^*) \neq -\mathrm{Im}(\bar{A}_\perp \bar{A}_\parallel^*)$$

$$\Delta\delta_{\rm EW} \neq 0 \quad \Leftrightarrow$$

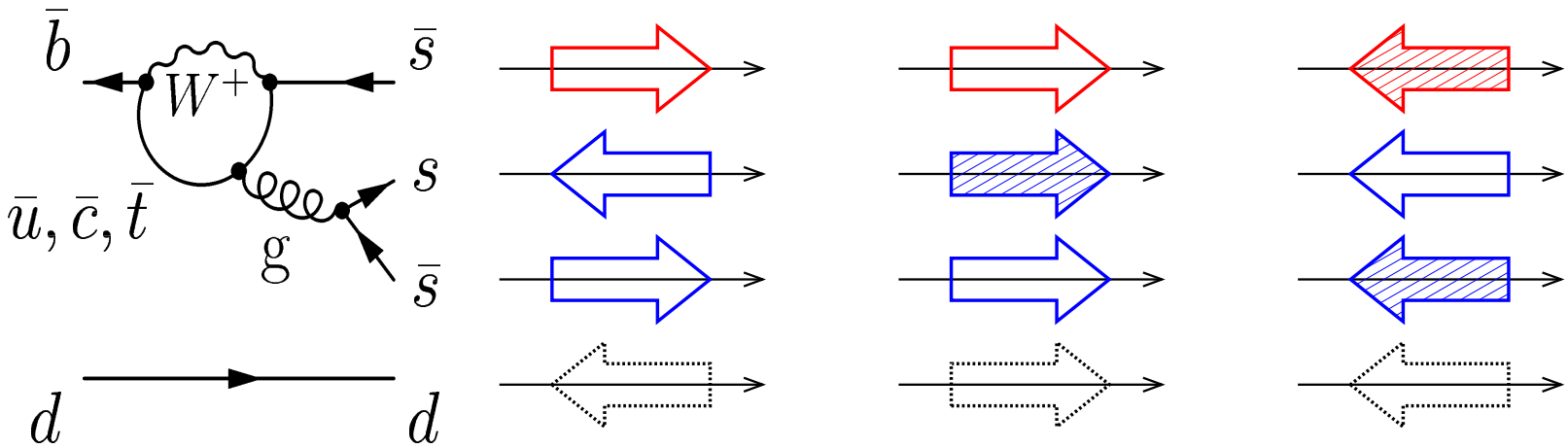


Helicity Hierarchy

- Standard Model: $\bar{q}W^+ \to \bar{s} \Rightarrow \lambda_{\bar{s}} = +\frac{1}{2}$

  (limit $m_s \ll m_b$) $\quad g \to s\bar{s} \quad \Rightarrow \lambda_s = \pm\frac{1}{2},\ \lambda_{\bar{s}} = \mp\frac{1}{2}$

$$\underset{\lambda_\phi = \lambda_{K^*} = 0}{A_0} \gg \underset{\lambda_\phi = \lambda_{K^*} = +1}{A_+} \gg \underset{\lambda_\phi = \lambda_{K^*} = -1}{A_-}$$



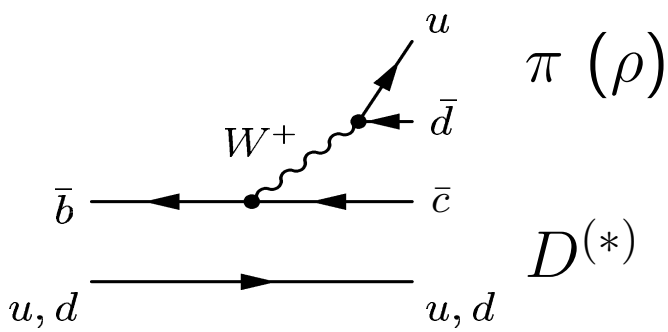
flip suppression: $\sim 1 \qquad \left|\frac{m_V}{m_B}\right|^2 \sim 0.04 \qquad \left|\frac{m_V}{m_B}\right|^4 \sim 0.001$

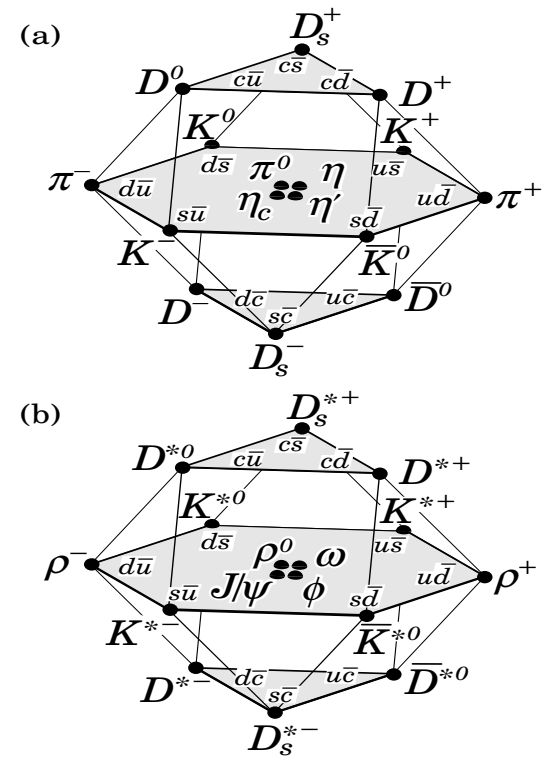
violation: (1) Long-distance FSI (re-scattering ?) $\Rightarrow$ large phases

(2) New Physics (?)

Rare Vector-Vector B Decays

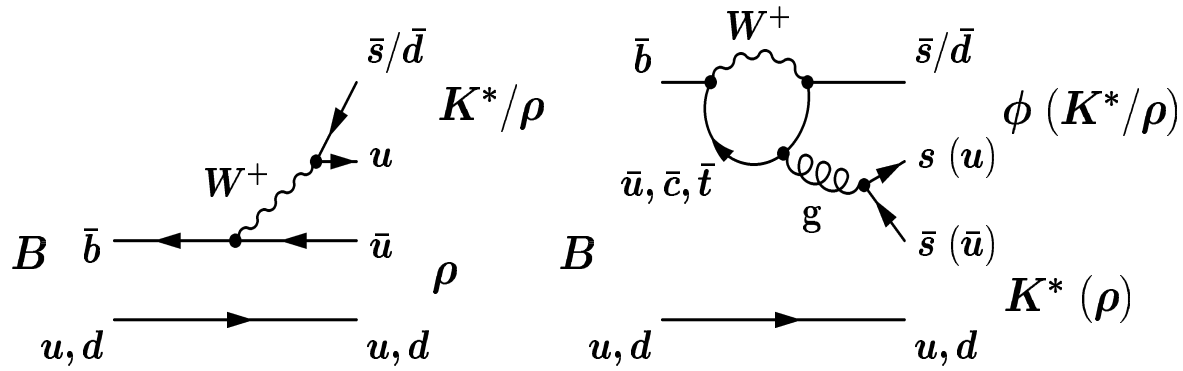
- Dominant B decays $\bar{b} \to \bar{c}$





- Study $B \to \rho\rho$, ϕK^*, ρK^*, $K^* \bar{K}^*$...

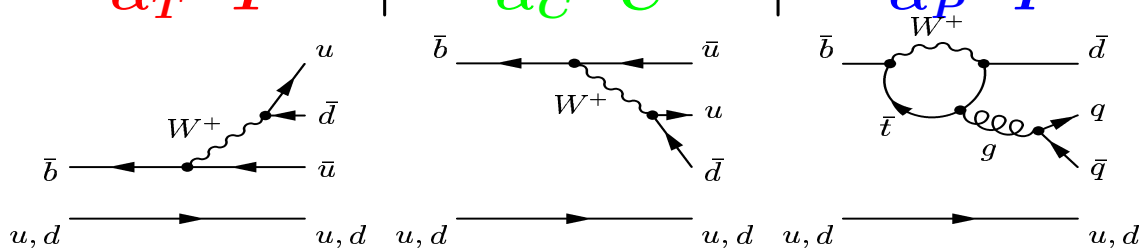
  Rare $\bar{b} \to \bar{u}, \bar{d}, \bar{s}$ ($\mathcal{B} \sim 10^{-5}$)



Why Rare Vector-Vector B Decays

- Despite – not much attention from theory
  – experimental prejudice (difficult)
- Because – rich physics and potential
  – all results are first discoveries
- Example with $B \to \rho\rho$ (was not favored for $\sin 2\alpha$)
  – however $B \to \pi\pi$ suffer from penguin "pollution"
  – $B \to \rho^0\rho^0 \to 4\pi^\pm$ is the key over $\pi^0\pi^0 \to 4\gamma$

$\alpha_T \cdot T \quad + \quad \alpha_C \cdot C \quad + \quad \alpha_P \cdot P$



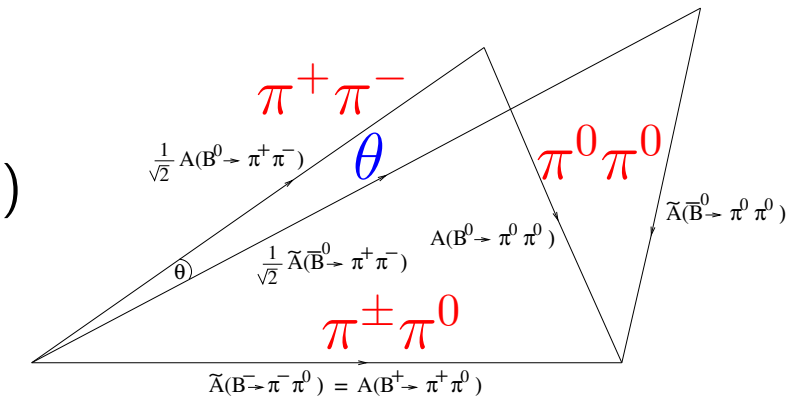
B decay mode		α_T	α_C	α_P	$\mathcal{B}(10^{-6})$ $\pi\pi$	$\mathcal{B}(10^{-6})$ $\rho\rho$
$\pi^-\pi^+$	$\rho^-\rho^+$	$\sqrt{2}$	0	$\sqrt{2}$	$4.7 \pm 0.6 \pm 0.2$	< 2200 (?)
$\pi^0\pi^+$	$\rho^0\rho^+$	1	1	0	$5.5\ ^{+1.0}_{-0.9} \pm 0.6$	< 1000 (?)
$\pi^0\pi^0$	$\rho^0\rho^0$	0	1	-1	$2.1 \pm 0.6 \pm 0.3$	< 18 (?)

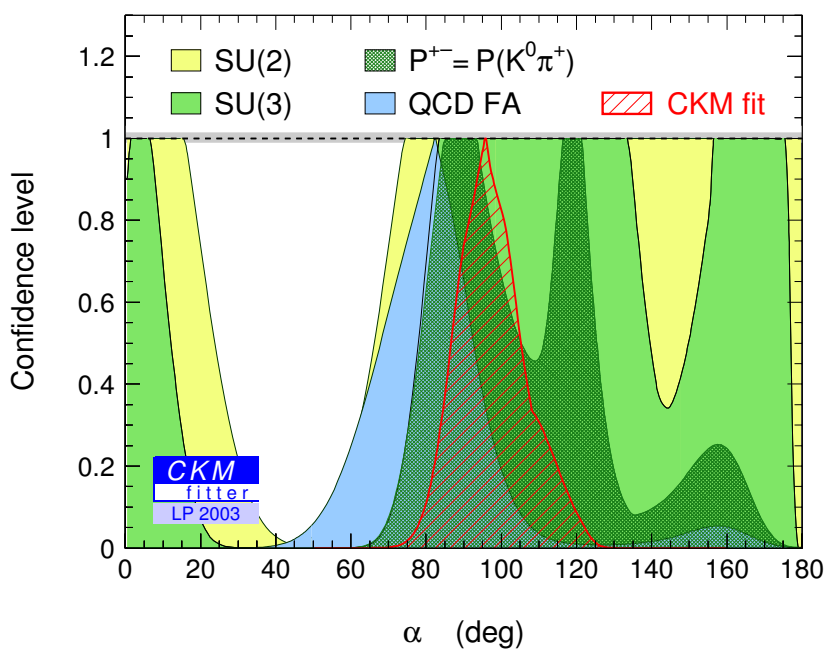
Measuring α with $B \to \pi\pi$

- $\Gamma(B^0 \to \pi^+\pi^-, \Delta t) \propto e^{-|\Delta t|/\tau_B}(1 + C_{\pi\pi}\cos(\Delta m \Delta t) - S_{\pi\pi}\sin(\Delta m \Delta t))$

– $S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}{}^2}\sin(2\alpha_{\rm eff})$

- Isospin: $2\alpha_{\rm eff} = 2\alpha + \theta$ (penguin)





$S_{BABAR} = -0.40 \pm 0.22 \pm 0.03$
$C_{BABAR} = -0.19 \pm 0.19 \pm 0.05$

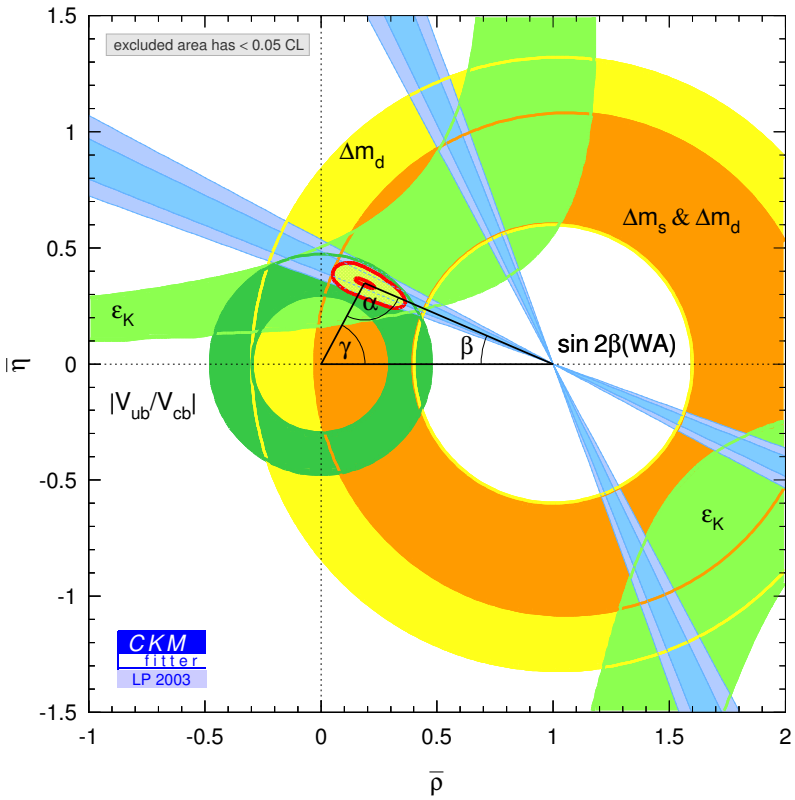
$S_{BELLE} = -1.00 \pm 0.21 \pm 0.07$
$C_{BELLE} = -0.58 \pm 0.15 \pm 0.07$

α limited by "penguin pollution"

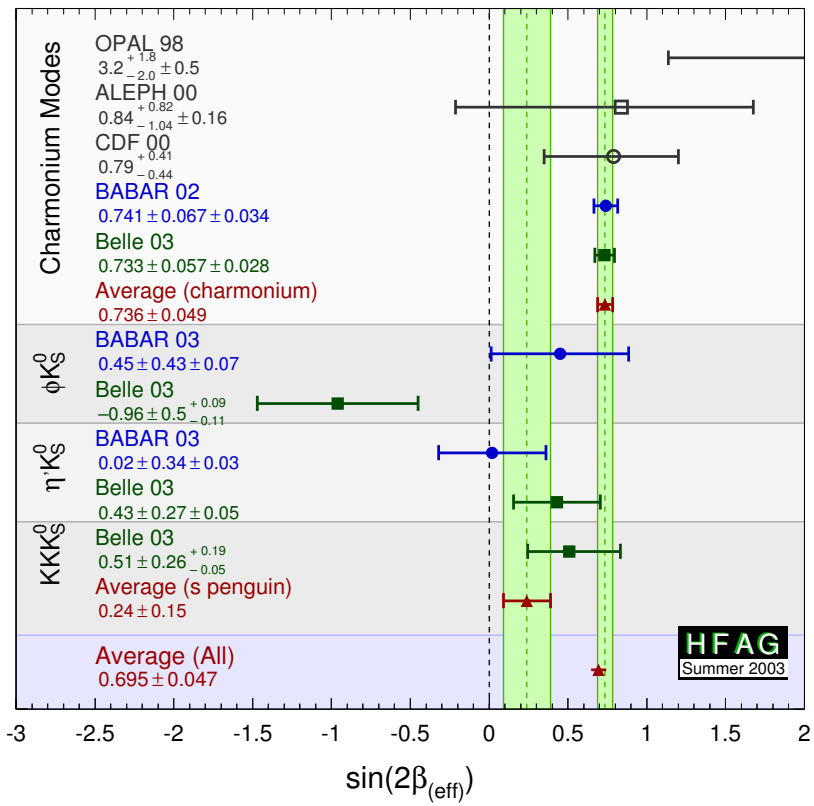
- $B \to \rho^+\rho^-$, if A_0 dominates:
  – CP eigenstate
  – the same isospin $\rho\rho$ triangle

Heavy Flavor Physics Highlights-2003

CKM constraints meet



Deviations with $B \to \phi K^0$



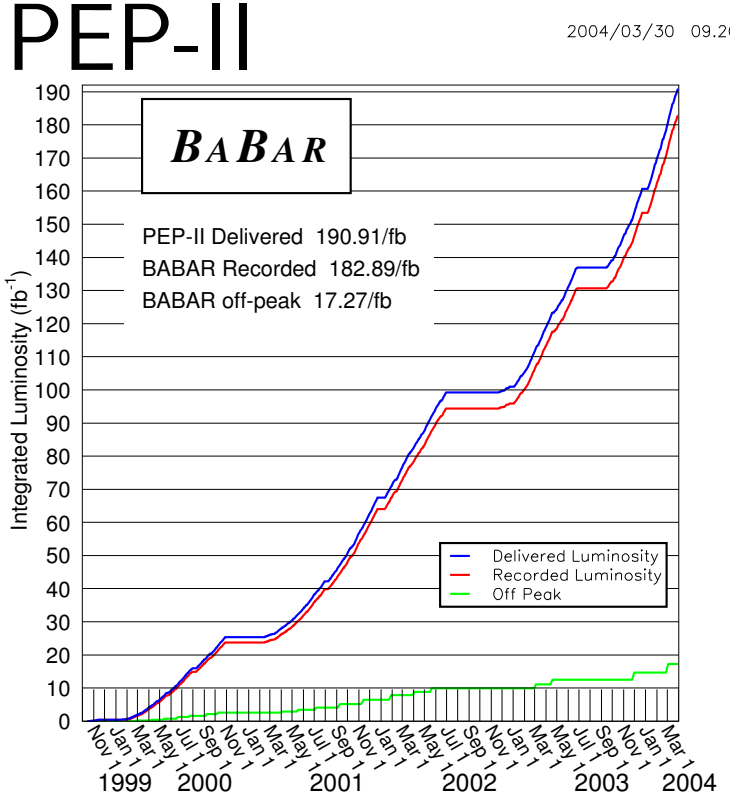
- Try to answer questions:

(1) other CKM constraints (α) $B \to \rho\rho$

(2) do we understand penguins $B \to \phi K^*$

BABAR Experiment

PEP-II

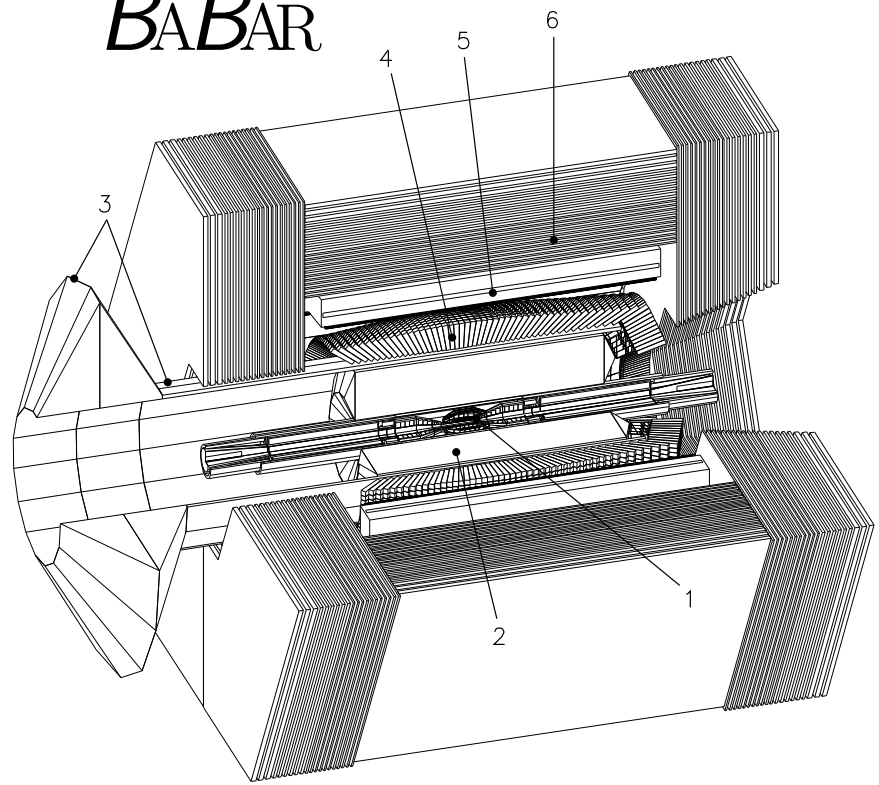


$$e^+e^- \longrightarrow \Upsilon(4S) \longrightarrow B\bar{B}$$

$$e^+e^- \longrightarrow q\bar{q} \longrightarrow \text{“jets”}$$

$$N_{B\bar{B}} \sim 200 \times 10^6$$

BABAR



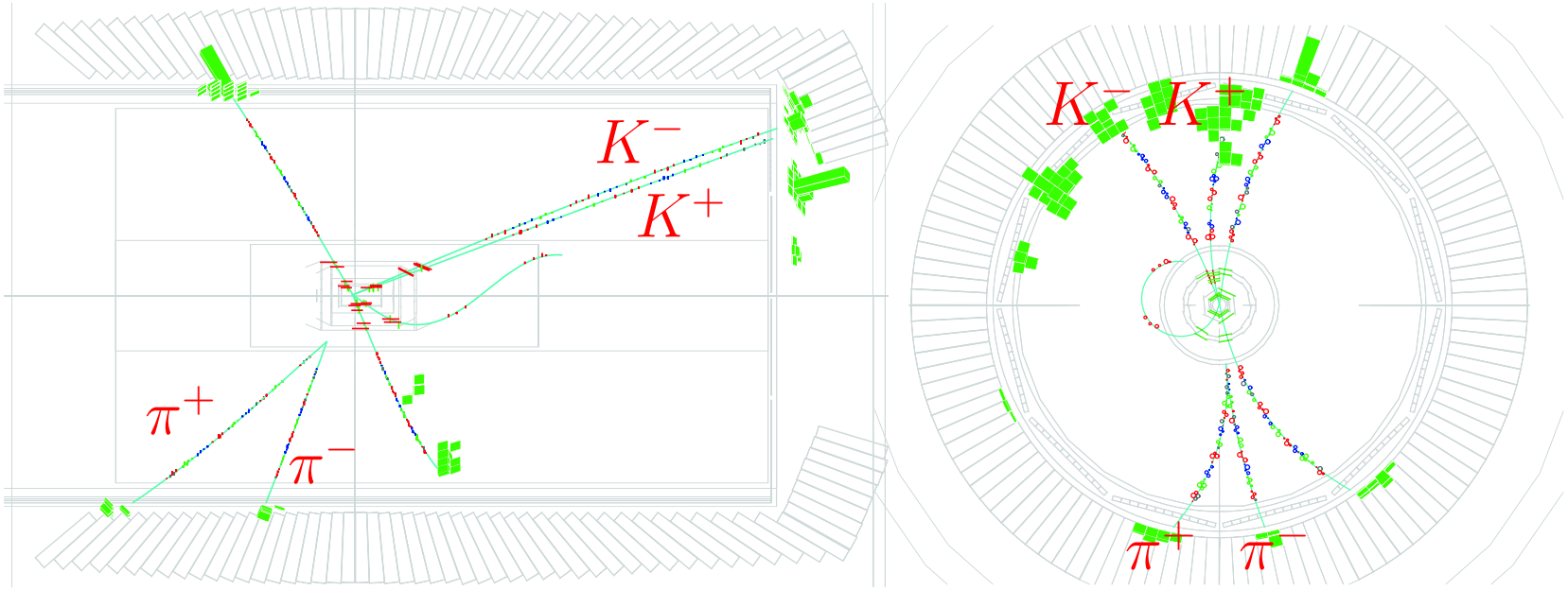
- Silicon Vertex Tracker (SVT)
- Drift Chamber (DCH)
- Cherenkov Detector (DIRC)
- EM Calorimeter (EMC)
- Instr. Flux Return (IFR)

BABAR Event Reconstruction

- Fully reconstruct B decay products

  e.g. $B^0 \to \phi K^0 \to (K^+K^-)(\pi^+\pi^-)$

  similar $B^0 \to \phi K^{*0} \to (K^+K^-)(K^+\pi^-)$, etc



B-decay Analysis at $\Upsilon(4S)$

Fully reconstruct e.g. $B \to \rho^+\rho^- \to \pi^+\pi^-(\gamma\gamma)(\gamma\gamma)$

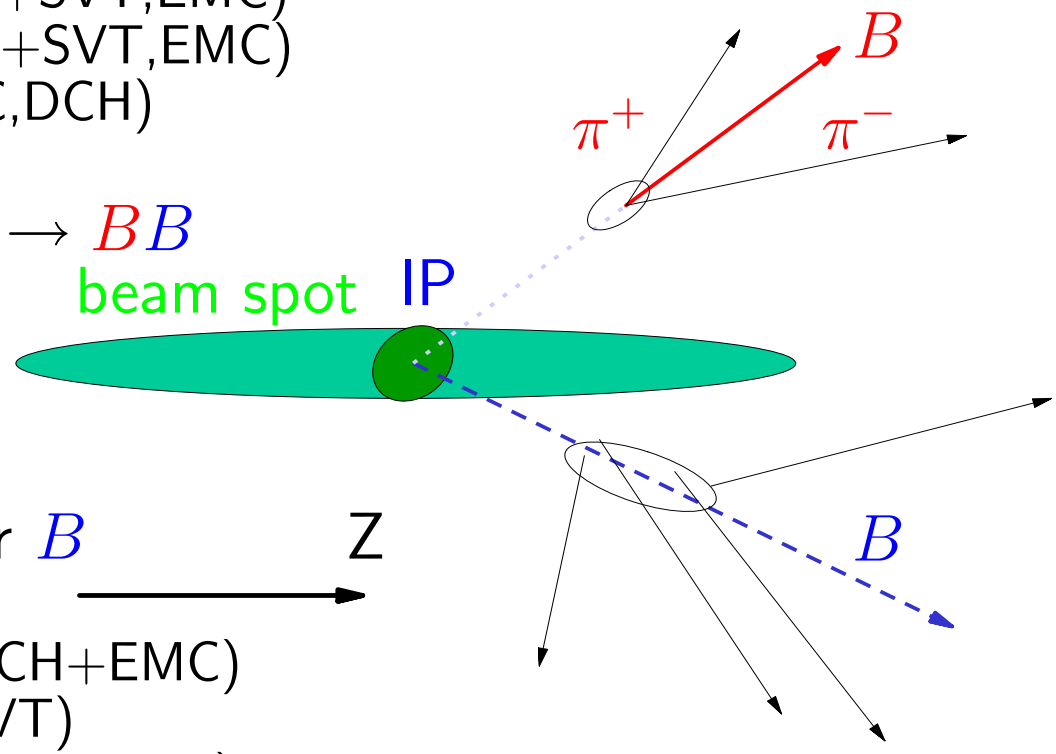
- Vertex (SVT)
- Momentum (DCH+SVT,EMC)
- Energy (DCH+SVT,EMC)
- Particle ID (DIRC,DCH)

Constrain $\Upsilon(4S) \to BB$

- Beam momenta
- Beam spot

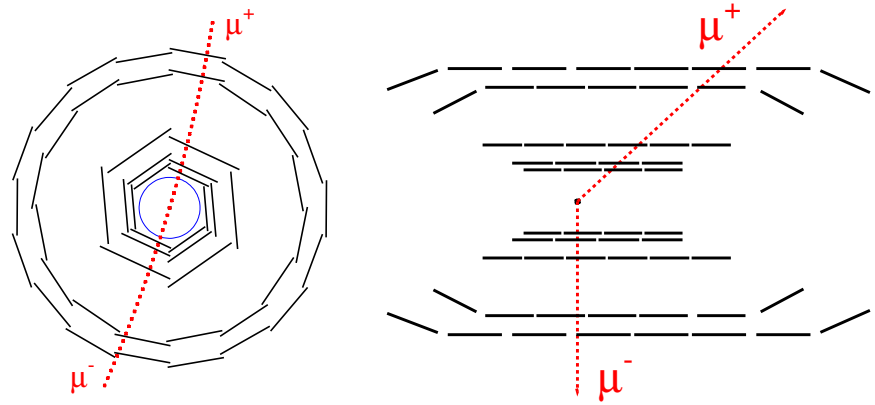
Look at the other B

- Event shape (DCH+EMC)
- Vertex (SVT)
- Flavor tagging (full BABAR)

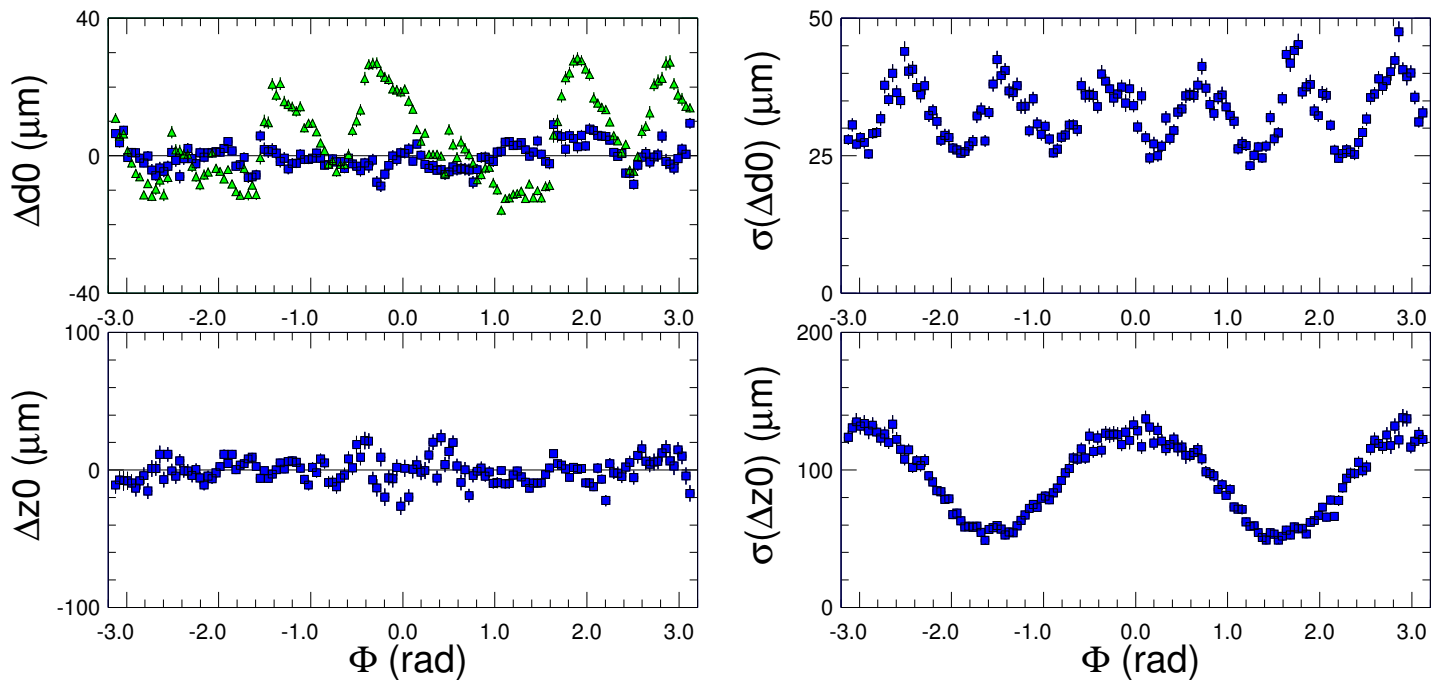


Position Resolution with the SVT

- Impact parameter (high p_T) $\sim$ 30μm
- Beam-spot σ(x,y,z) $\sim$(150, 5, 10000)μm



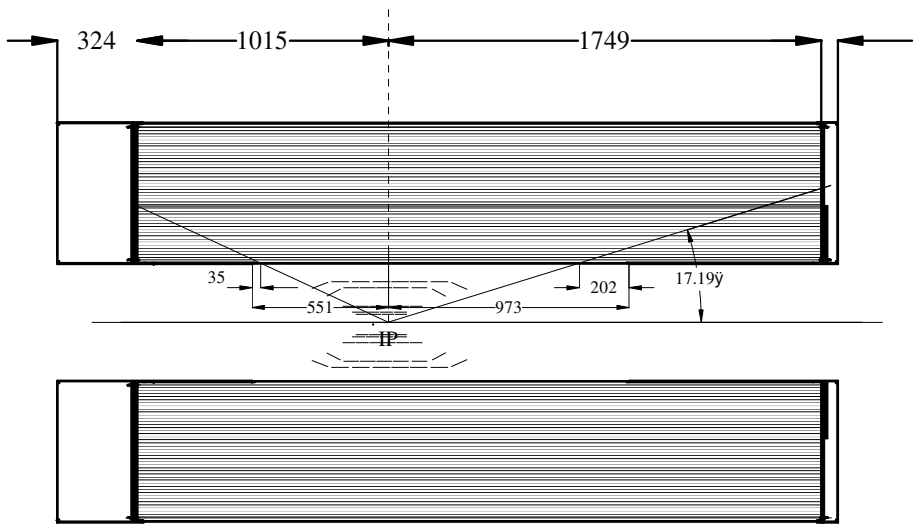
compare $\sigma_{\Delta Z_B}$ $\sim$180μm, $\beta\gamma c\tau_B$ $\sim$250μm

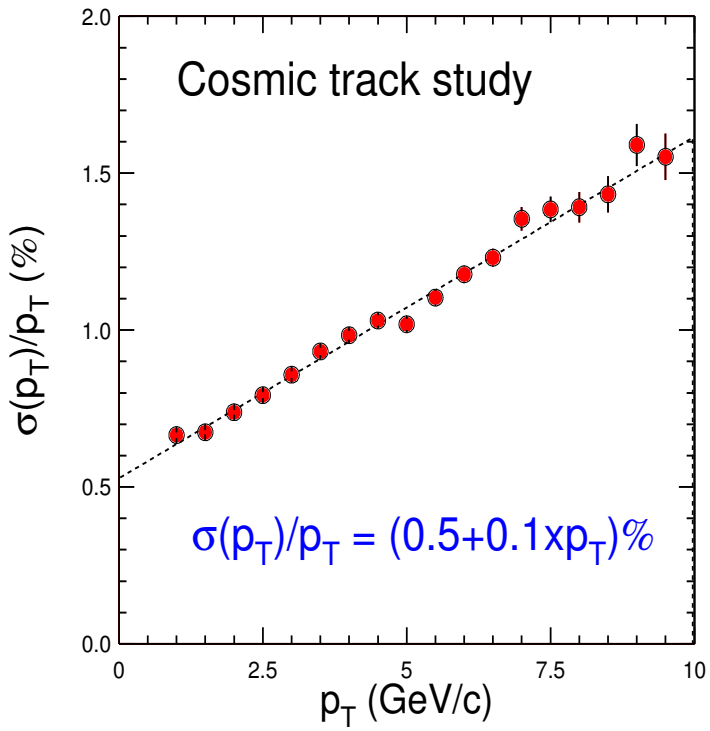


BABAR Tracking System

- DCH + SVT $\Rightarrow$ tracking
  - SVT dominates position and angular at IP
  - DCH curvature (momentum) measurements
  - also dE/dx for Particle ID

$p_T \sim 1.5$GeV, $\sigma_{p_T} \sim 10$MeV





Momentum Constraint

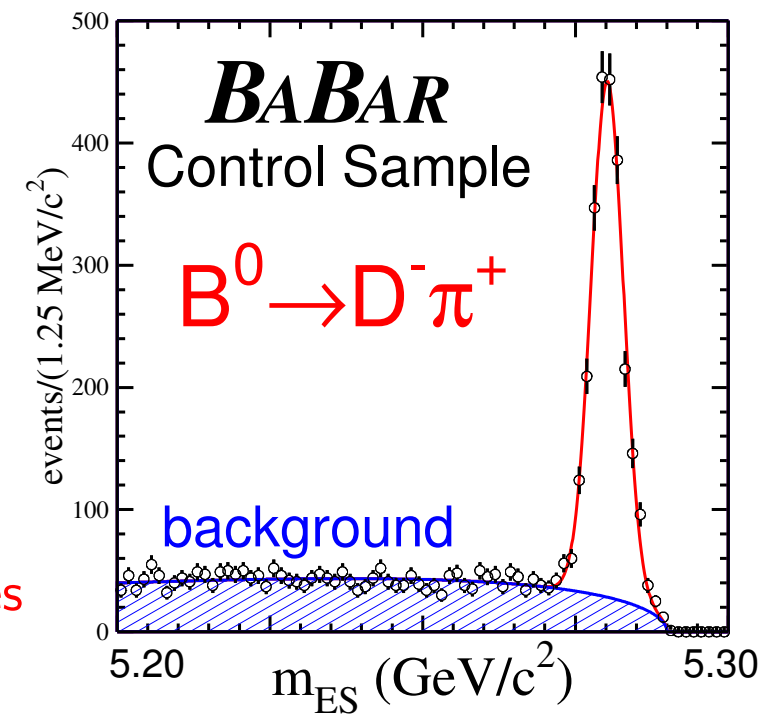
- Fully reconstruct e.g. $B \to \phi K^{*0} \to (K^+K^-)(K^+\pi^-)$
  - invariant masses of the resonances (m_{KK}, $m_{K\pi}$)
- Energy-substituted B mass $(e^+e^- \to \Upsilon(4S) \to B\bar{B})$

$$m_{\rm ES} = \sqrt{E_{\rm b}^2 - \vec{p}_B^{\,2}}$$

  - $\sigma \sim 2.6$ MeV ($E_{\rm beam}$ dominated)
  - B almost at rest (in $\Upsilon(4S)$ cm)

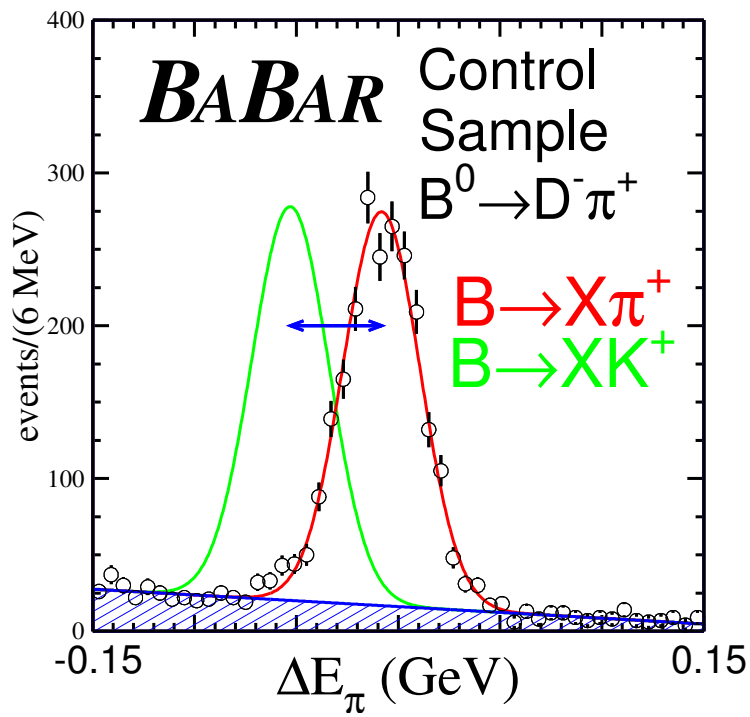
$$E_{\rm beam}^{\rm cm} = 5.29 \text{ GeV}$$
$$m_B = 5.28 \text{ GeV}$$

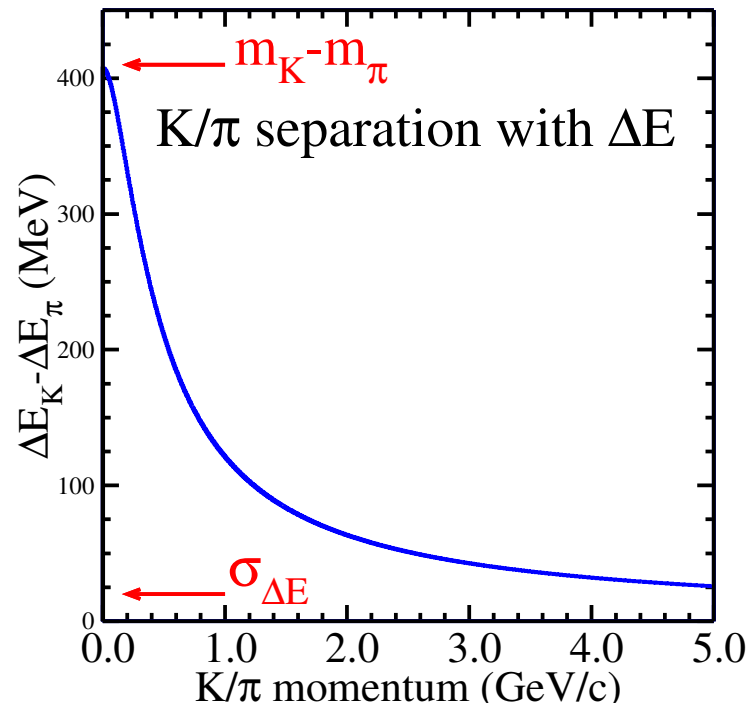
- Signal parameterization:
  - from Monte Carlo/control samples



Energy Constraint

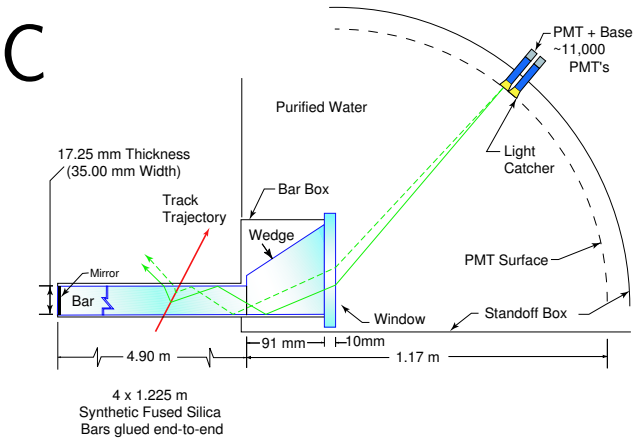
- Energy Constraint: $\Delta E = E_B^{\rm cm} - E_{\rm beam}^{\rm cm}$
  - background suppression; $\sigma \sim 20$ MeV (mom resolution)
  - kinematic K/π separation: momentum correlation
  - boost $\Rightarrow$ broad momentum spectrum

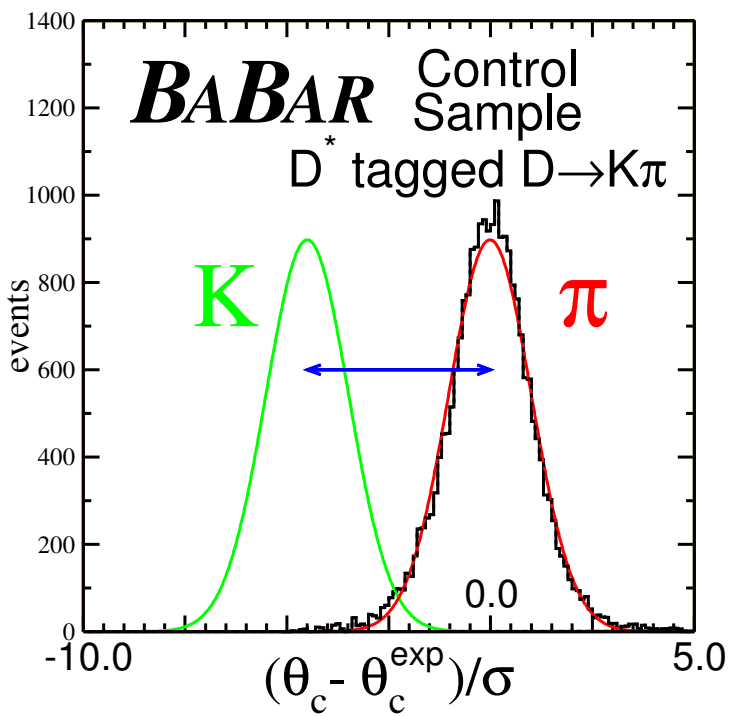


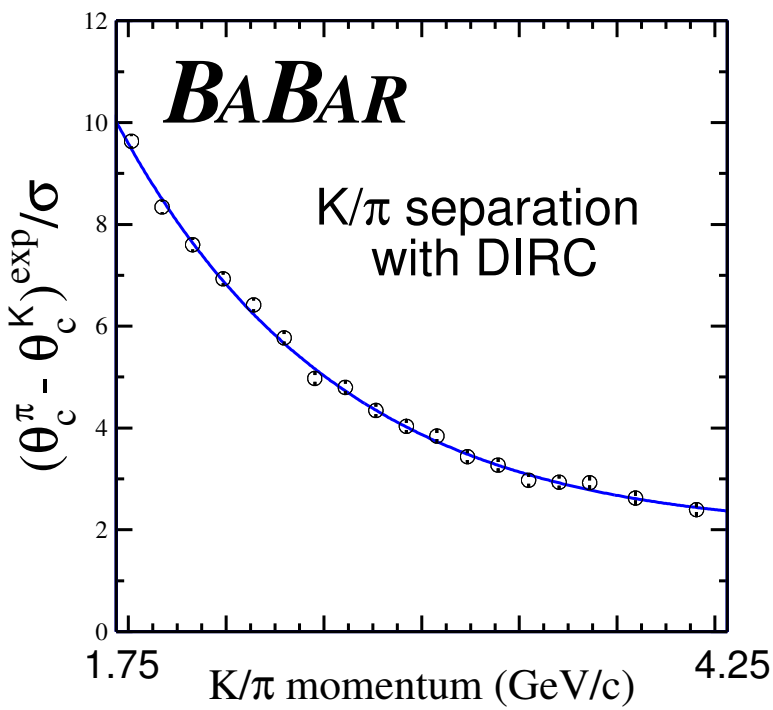


Particle Identification

- Cherenkov angle θ_c from DIRC
  - primary K/π separation
    $\cos(\theta_c) = 1/\beta n$, $\theta_c = f(p, \mathrm{mass})$
  - from 2.5 to $\sim 10\sigma$ separation
  - selector combined with $\mathrm{d}E/\mathrm{d}x$





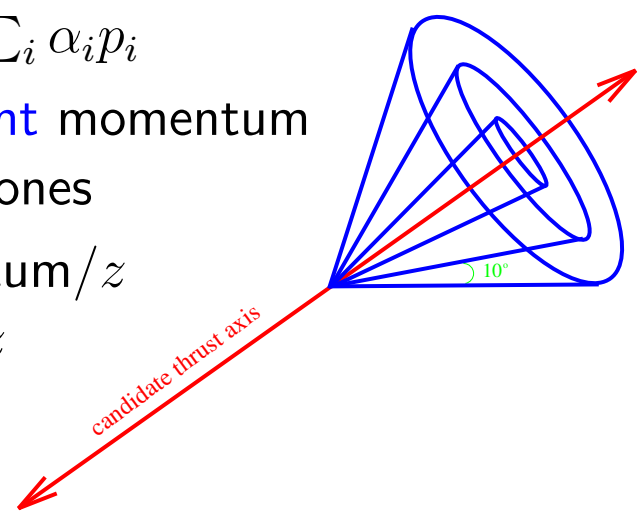


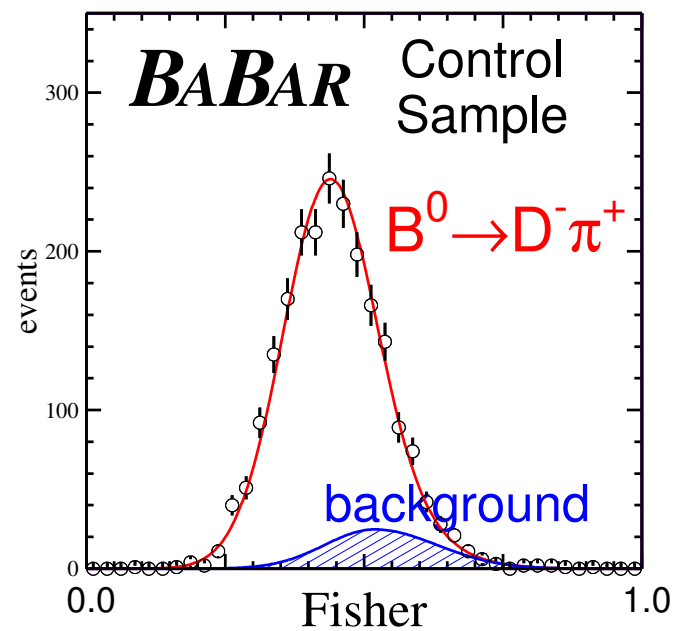
Event Shape

- Suppress background:

  $e^+e^- \to q\bar{q} \to$ "jets" (signal "spherical" $e^+e^- \to \Upsilon(4S) \to B\bar{B}$)

- Define in the $\Upsilon(4S)$ cm frame:
  - thrust axes B/(rest-of-event) angle θ_T
    $\cos(\theta_T) \leq 0.8$; reject $\sim$5/6 background, 1/5 signal
  - $\mathcal{F}$isher$=\sum_i \alpha_i p_i$
    rest-of-event momentum flow in 9 cones
    B momentum/z
    B thrust/z





Tagging and Δt

- Tag the other $B \to K^+, \mu^+$, etc

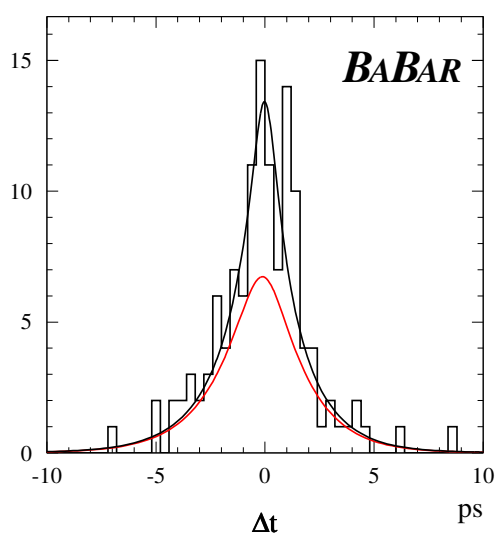
  $Q = \Sigma \epsilon_i (1\text{-}2w_i)^2 \simeq 28\%$

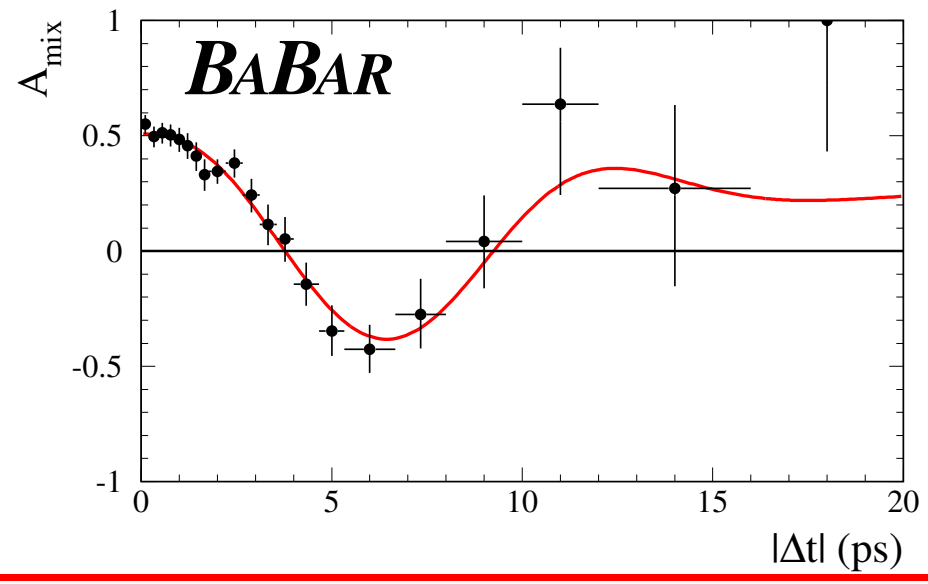
- Resolution $f_{CP}(\Delta t) = \mathcal{R}_{\rm sig}(\Delta t, \Delta t') \otimes [e^{-|\Delta t'|/\tau_B}$

  $\times (1 \pm S(1\text{-}2w)\sin(\Delta m_d \Delta t') \mp C(1\text{-}2w)\cos(\Delta m_d \Delta t'))]$

- Study with $B \to D^{(*)-}\pi^+/\rho^+/a_1^+,\ J/\psi K^{*0}(K^+\pi^-)$

$$\mathcal{A}_{\rm mix} = \frac{N_{\rm unmix} - N_{\rm mix}}{N_{\rm unmix} + N_{\rm mix}} = (1\text{-}2w)\cos(\Delta m_d \Delta t)$$





Selection for Analysis

- BaBar - largest database $\sim$Petabyte (10^{15} bytes, 10^6 Gigabytes)

(1) Skim (manage large amount of data) $< 1\%$ in each topology

– stream out any $B \to h_1 h_2 h_3 h_4$ $\quad (\pi^{\pm}, K^{\pm}, K_S^0, \pi^0, \eta)$

– $|\Delta E| \le 0.3$ GeV, $\quad m_{\rm ES} \ge 5.2$ GeV, $\quad |\cos\theta_T| \le 0.8$

– cover all final states (and more):

B^+, B^- / $B^0, \bar{B}^0$ $\longrightarrow$ (K^{*0}, K^{*+}, ϕ, ρ^-, ρ^0, ρ^+, K^{*-}, $\bar{K}^{*0}$) $+$ (K^{*0}, K^{*+}, ϕ, ρ^-, ρ^0, ρ^+, K^{*-}, $\bar{K}^{*0}$)

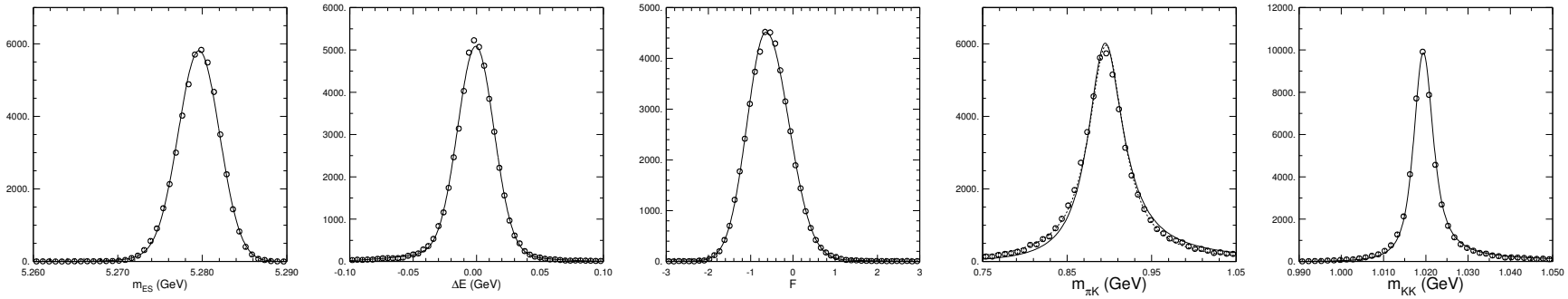
(2) More detailed study in analysis (fit to $\sim 10^4$ events):

– ΔE, $m_{\rm ES}$, $\mathcal{F}$isher, m_{hh}, $\mathcal{H}$elicity, Particle ID, Vertex, etc

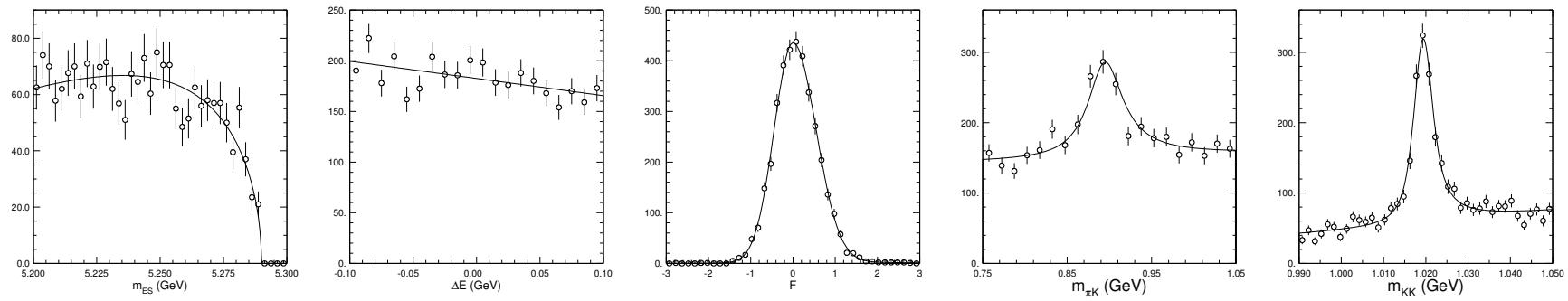
Kinematic Observables in Analysis

- Example of observables for $B^0 \to \phi K^{*0}(K^+\pi^-)$

$m_{\rm ES}$ ΔE $\mathcal{F}$isher $\mathcal{M}_{\pi K}(K^*)$ $\mathcal{M}_{KK}(\phi)$



signal (Monte Carlo)



background (side-bands)

- Observable $Q = +/-$: B flavor (charge)

Maximum Likelihood Method

- Estimate parameters (e.g. $n_{\rm sig}$) with N observations:

$$\vec{x}_j = \{m_{\rm ES},\ \Delta E,\ \mathcal{F},\ m_1,\ m_2,\ \theta_1,\ \theta_2,\ \Phi,\ Q\ \}.$$

$$\mathcal{L} = \exp\left(-\sum_{i,k} n_{ik}\right) \prod_{j=1}^{N_{\rm comb}} \exp\left(\frac{1}{N_j} \ln\left(\sum_{i,k} n_{ik}\, \mathcal{P}_{ik}(\vec{x}_j;\vec{\alpha})\right)\right) = \max.$$

- PDF:

$$\mathcal{P}_{i,k}(\vec{x}_j) = \mathcal{P}_{i1}(m_{\rm ES}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{F}) \cdot \mathcal{P}_{i4}(m_1) \cdot \mathcal{P}_{i5}(m_2) \cdot \delta_{kQ}$$

and angular part with acceptance $\mathcal{G}$

$$\times\, \mathcal{P}^{\rm hel}_{i,k}(\theta_1, \theta_2, \Phi, {f_L}^k, {f_\perp}^k, {\phi_\perp}^k, {\phi_\parallel}^k) \times \mathcal{G}(\theta_1, \theta_2, \Phi)$$

- Measure: ${f_L}^\pm = |{A_0}^\pm|^2$ ${f_\perp}^\pm = |{A_\perp}^\pm|^2$

${\phi_\parallel}^\pm = \arg({A_\parallel}^\pm)$ ${\phi_\perp}^\pm = \arg({A_\perp}^\pm)$

construct asymmetries $\mathcal{A}^i_{CP}$

Angular Observables in Analysis

$\alpha_1(f_L)\times$

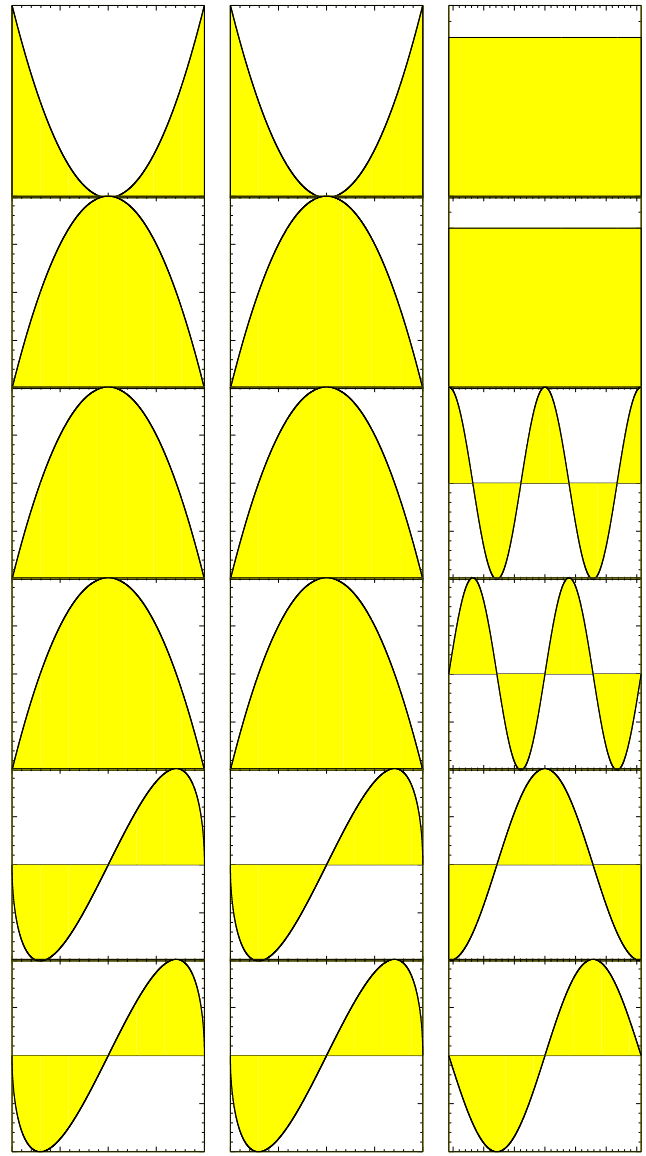
$\alpha_2(f_L)\times$

$\alpha_3(f_L, f_\perp)\times$

$\alpha_4(f_L, f_\perp, \phi_\perp, \phi_\parallel)\times$

$\alpha_5(f_L, f_\perp, \phi_\parallel)\times$

$\alpha_6(f_L, f_\perp, \phi_\perp)\times$



$\Rightarrow |A_0|^2$

$|A_\parallel|^2+|A_\perp|^2$

$|A_\parallel|^2-|A_\perp|^2$

$\Rightarrow \mathrm{Im}(A_\perp A_\parallel^*)$

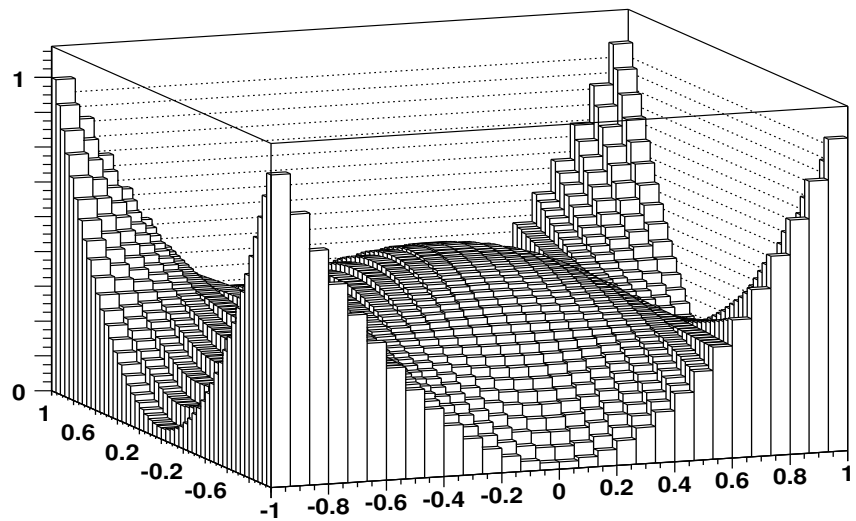
$\Rightarrow \mathrm{Re}(A_\parallel A_0^*)$

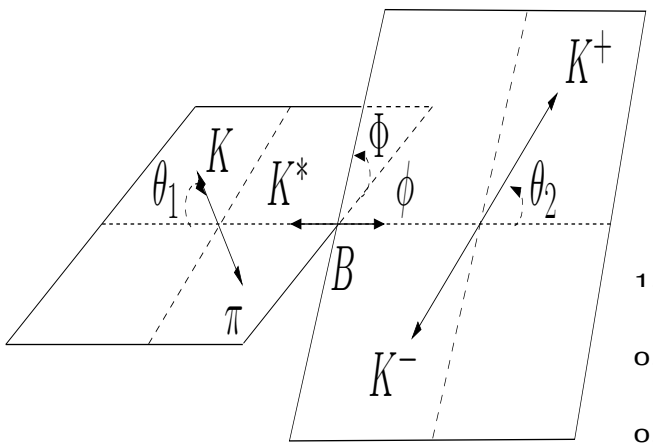
$\Rightarrow \mathrm{Im}(A_\perp A_0^*)$

$\cos\theta_1$ $\cos\theta_2$ Φ $\times$acceptance

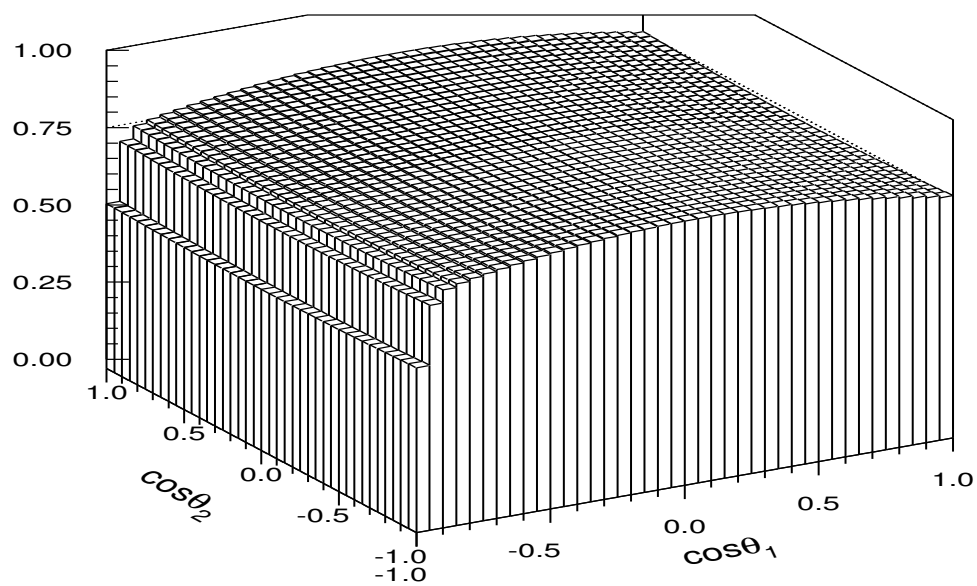
Examples of Angular Distributions

- Example of ideal 2D PDF



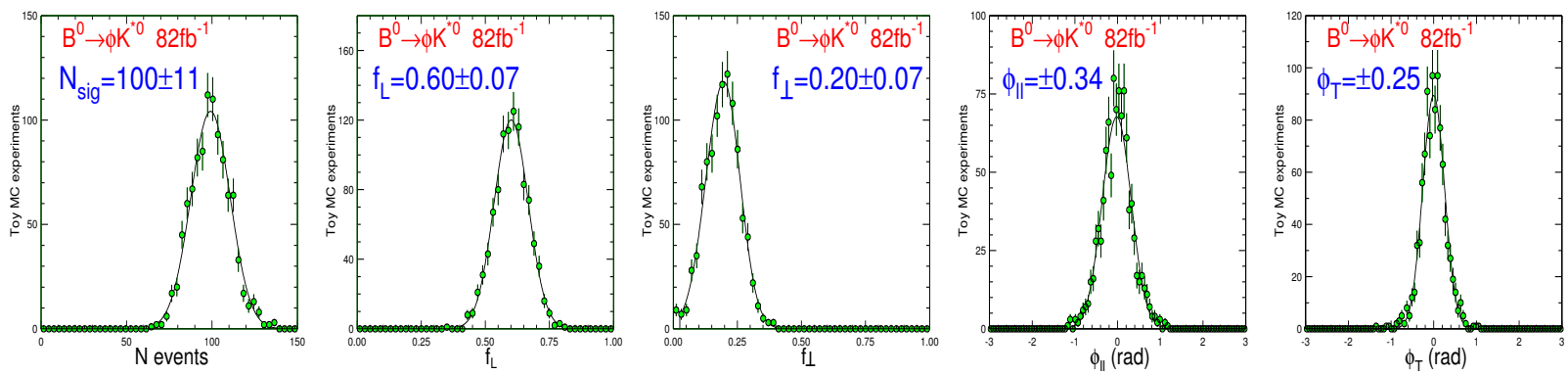


- Non-uniform acceptance with particle momenta



Analysis Validation

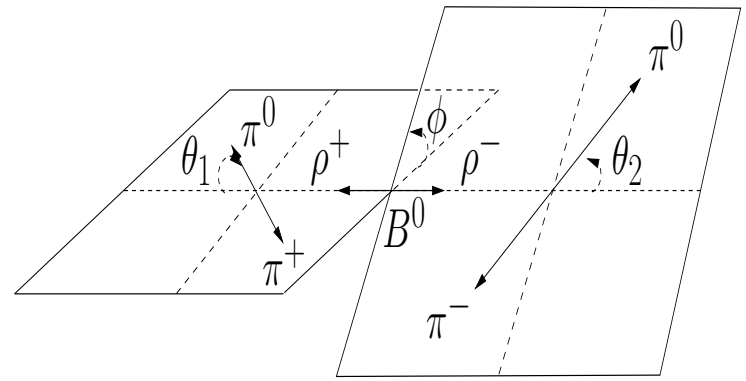
- Blind technique until finalize analysis
  - prove that it is unbiased and presize
- Monte Carlo studies (high statistics):
  - full detector simulation of signal, embed into background
  - reproduce input values and errors
- Example with $B^0 \to \phi K^{*0}$:



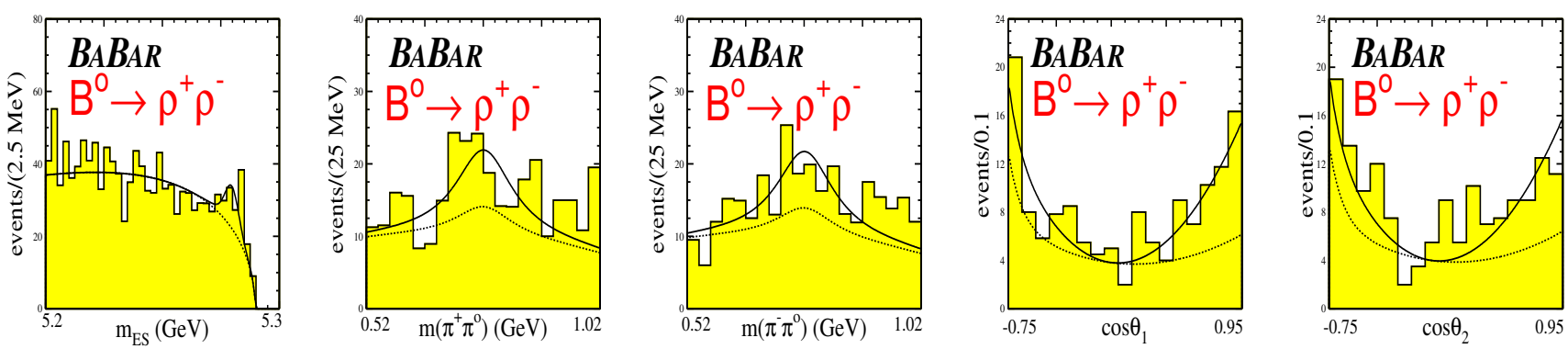
- Many details not discussed:
  - systematic uncertainties (usually with control samples)
  - detailed background understanding

First Observation of $B^0(\bar{B}^0) \to \rho^+\rho^-$

- Ideal mode for $\sin(2\alpha)$
  - Rate larger than $B \to \pi\pi$
  - $|A_0|$ dominates (CP-even)
  - small penguin "pollution" ($\rho^0\rho^0/\rho^+\rho^0$)



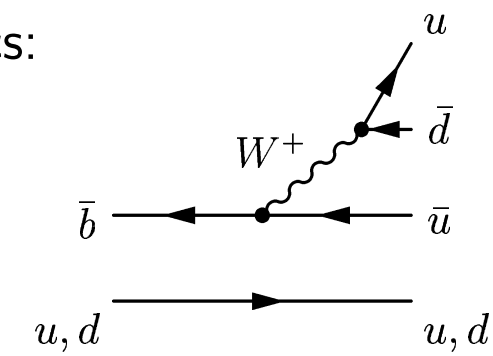
Mode	ε (%)	$n_{\rm sig}$	$\mathcal{B}$	f_L
$\rho^+\rho^-$	3.9	$88^{+23}_{-21} \pm 9$	$25^{+7}_{-6}{}^{+5}_{-6} \times 10^{-6}$	$0.98^{+0.02}_{-0.08} \pm 0.03$



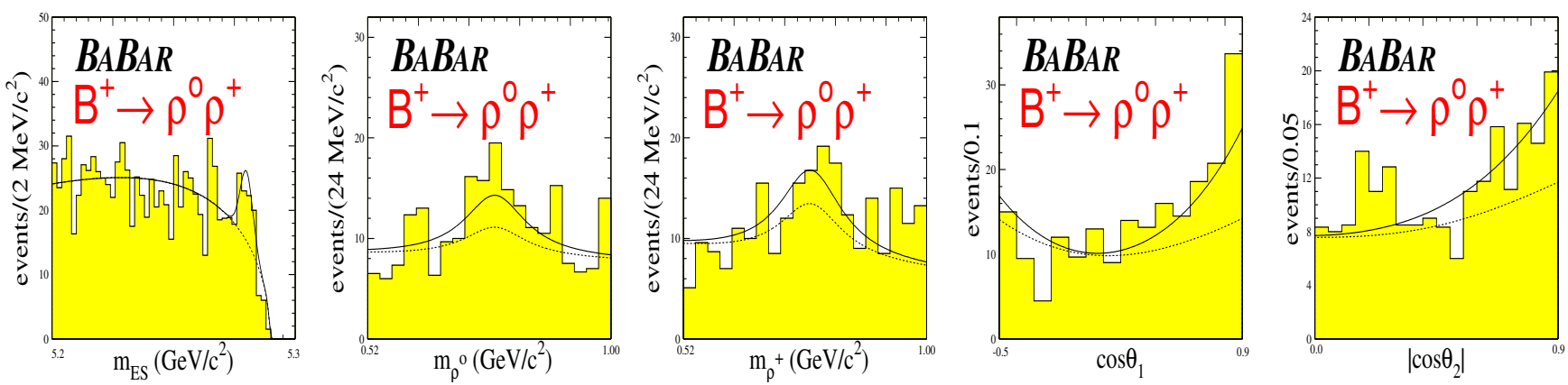
http://arxiv.org/abs/hep-ex/0308024, Phys.Rev.D 69, 031102 (2004)

Observation of $B^{\pm} \longrightarrow \rho^0 \rho^{\pm}$

- Need to understand $B \longrightarrow \rho\rho$ dynamics:
  - $|A_0|$ dominates
  - measurement of the pure "tree"



Mode	ε (%)	$n_{\rm sig}$	$\mathcal{B}$ ($\times 10^{-6}$)	f_L	$\mathcal{A}_{CP}$
$\rho^0\rho^+$	4.6	$93^{+24}_{-22} \pm 10$	$22.5^{+5.7}_{-5.4} \pm 5.8$	$0.97^{+0.03}_{-0.07} \pm 0.04$	$-0.19 \pm 0.23 \pm 0.03$

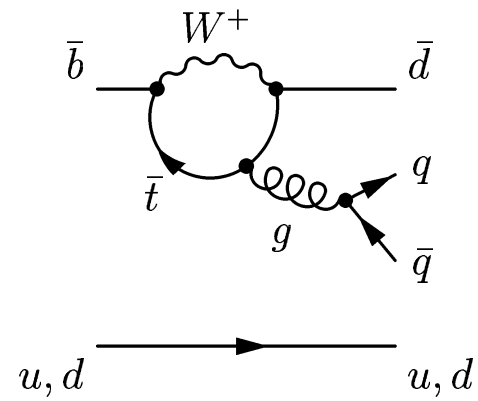


Phys.Rev.Lett 91, 171802 (2003)

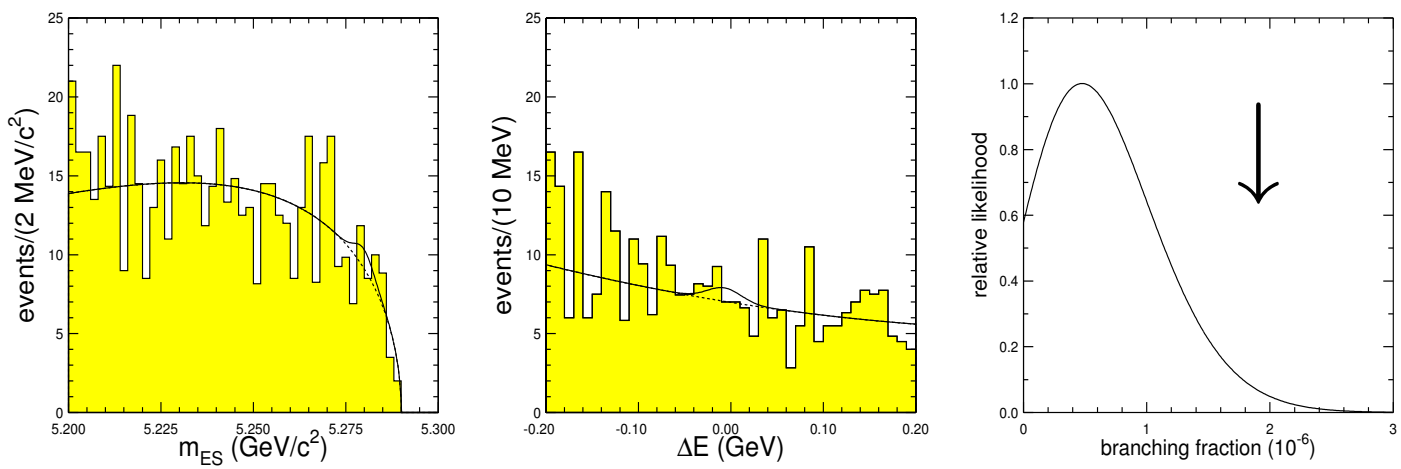
Search for $B^0 \to \rho^0\rho^0$

- Set tight limit on $B \to \rho^0\rho^0$:
  - constrain "penguin"

$$\frac{\mathcal{B}(\rho^0\rho^0) \times f_L(\rho^0\rho^0)}{\mathcal{B}(\rho^0\rho^+) \times f_L(\rho^0\rho^+)} < 0.10$$



Mode	ε	$n_{\rm sig}$	$\mathcal{B}$ ($\times 10^{-6}$)
$\rho^0\rho^0$	17.6	$9.7^{+11.9}_{-9.4} \pm 2.0$	< 2.1 (90% C.L.)

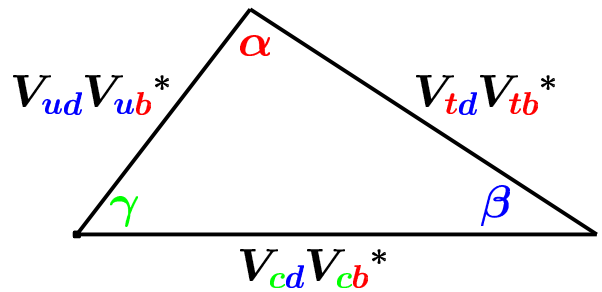


Phys.Rev.Lett 91, 171802 (2003), hep-ex/0308024

Advantage of $B \to \rho\rho$

- Small penguin "pollution" in $\rho\rho$:

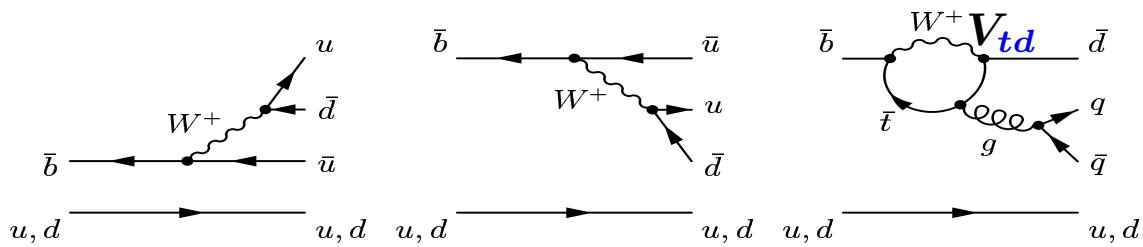
$$\frac{|A_0(B^0 \to \rho^0\rho^0)|^2}{|A_0(B^+ \to \rho^0\rho^+)|^2} < 0.10 \quad \Rightarrow \quad |\alpha_{\rm eff} - \alpha| < 19^\circ \quad (90\%\ \text{C.L.})$$



- Best mode to measure $\sin 2\alpha$

  compare $B \to \pi\pi$ $|\alpha_{\rm eff} - \alpha| < 51^\circ$

$$\alpha_T \cdot T \quad + \quad \alpha_C \cdot C \quad + \quad \alpha_P \cdot P$$

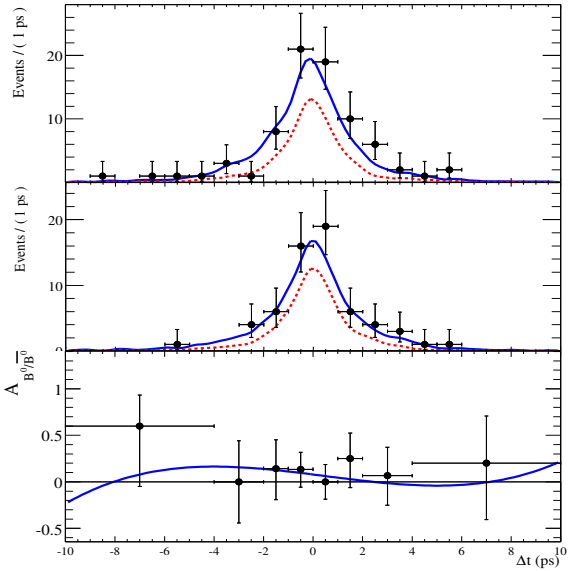


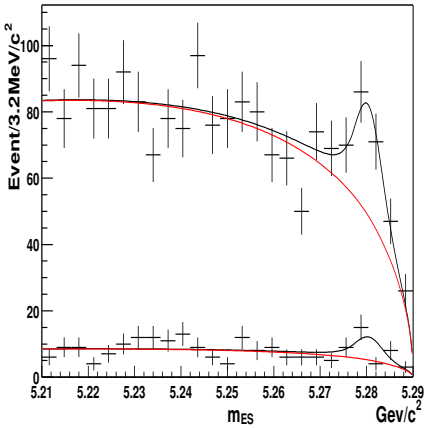
B decay mode		α_T	α_C	α_P	$\mathcal{B}(10^{-6})$ $\pi\pi$	$\mathcal{B}(10^{-6})$ $\rho\rho$
$\pi^-\pi^+$	$\rho^-\rho^+$	$\sqrt{2}$	0	$\sqrt{2}$	$4.7 \pm 0.6 \pm 0.2$	$25^{+7}_{-6}{}^{+5}_{-6}$
$\pi^0\pi^+$	$\rho^0\rho^+$	1	1	0	$5.5\ ^{+1.0}_{-0.9} \pm 0.6$	$22.5^{+5.7}_{-5.4} \pm 5.8$
$\pi^0\pi^0$	$\rho^0\rho^0$	0	1	-1	$2.1 \pm 0.6 \pm 0.3$	< 2.1

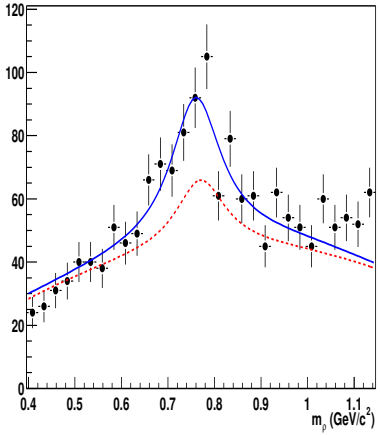
Time-evolution in $B \to \rho^+\rho^-$

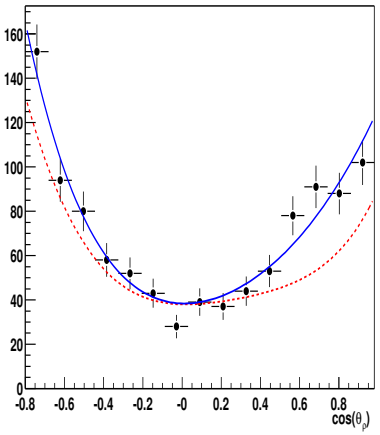
- New result (*BABAR*, Moriond-2004):
  - data through 2003
  - partially reconstructed events (∼40%)
  - SVT-only tracks with low momentum
  - B-tagging and Δt

$n_{\rm sig} = 314 \pm 34$
$S_L = -0.19 \pm 0.33 \pm 0.11$
$C_L = -0.23 \pm 0.24 \pm 0.14$







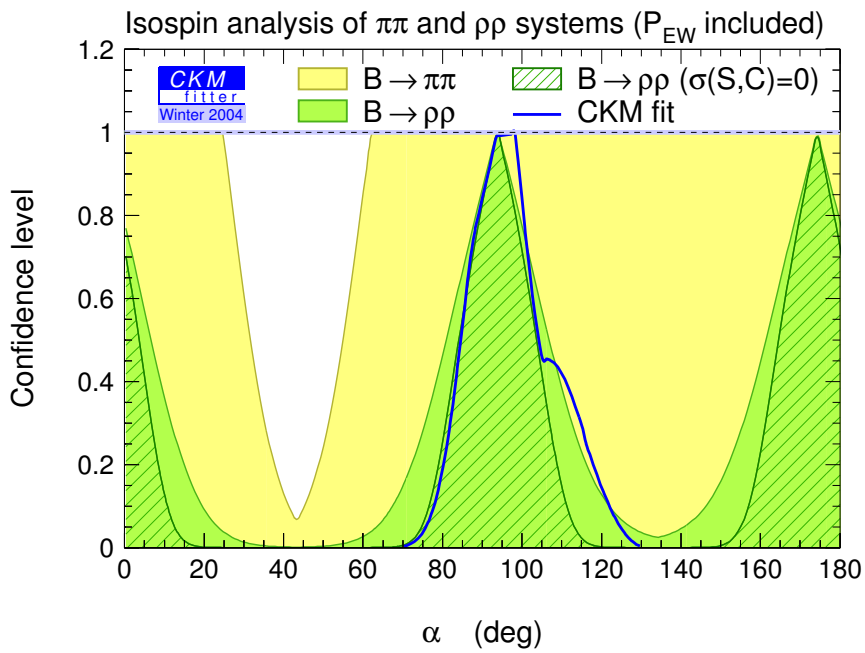


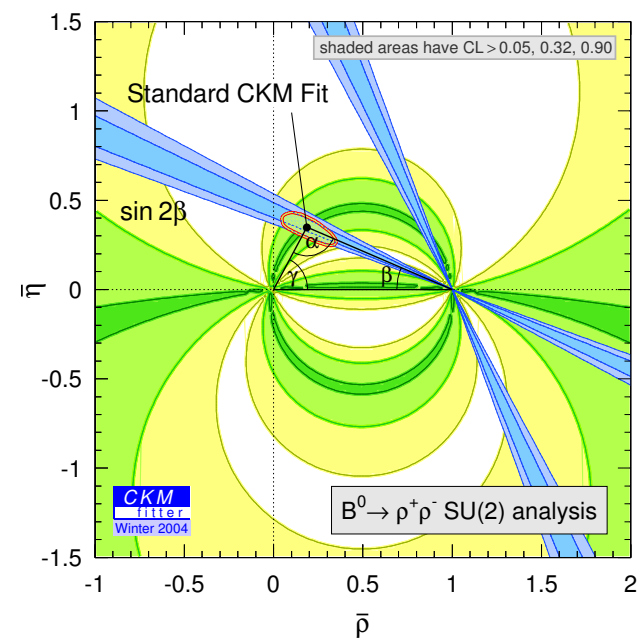
Constraints on α from $B \to \rho\rho$

- Extract α:
  - $S_L = \sqrt{1 - C_L{}^2}\sin(2\alpha_{\rm eff})$
  - $(\alpha_{\rm eff} - \alpha)$ from isospin $B \to \rho^0\rho^0/\rho^0\rho^+/\rho^+\rho^-$
  - neglect I=1, non-resonant ($< 10\%$)

$$\alpha = 96^\circ \pm 10^\circ \ (\text{stat}) \ \pm 4^\circ \ (\text{syst}) \ \pm 13^\circ \ (\text{penguin})$$

interpretation plots using CKMFitter http://www.slac.stanford.edu/xorg/ckmfitter/

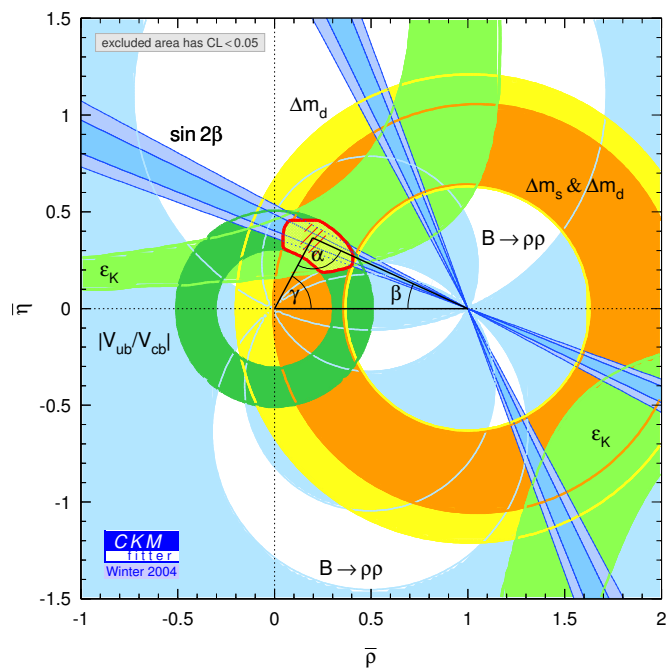




- Small "penguin pollution" in $\rho\rho$ makes a difference over $\pi\pi$
- Direct constraint on $\alpha \simeq$ indirect from other CKM

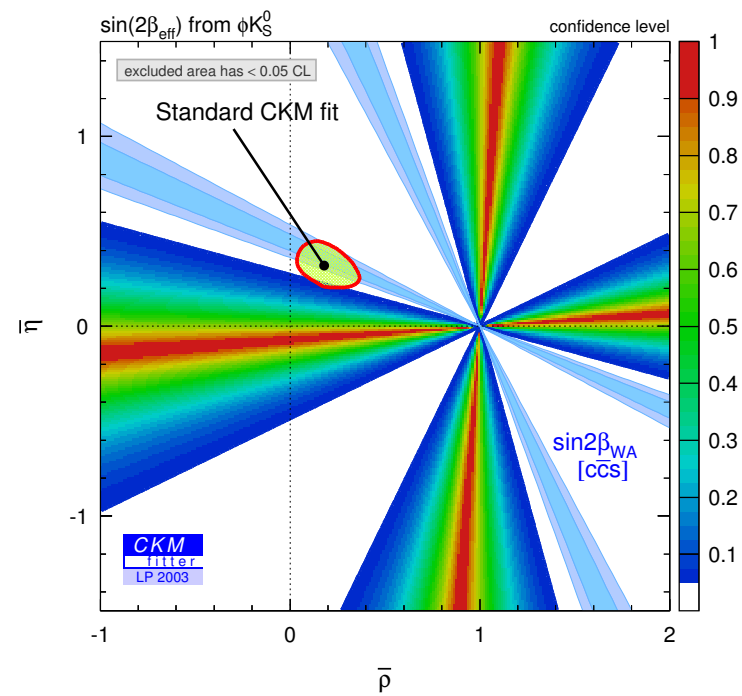
Is there any room for New Physics

Another constraint meets in CKM fit



Attention to "penguins"

$B \to \phi K$

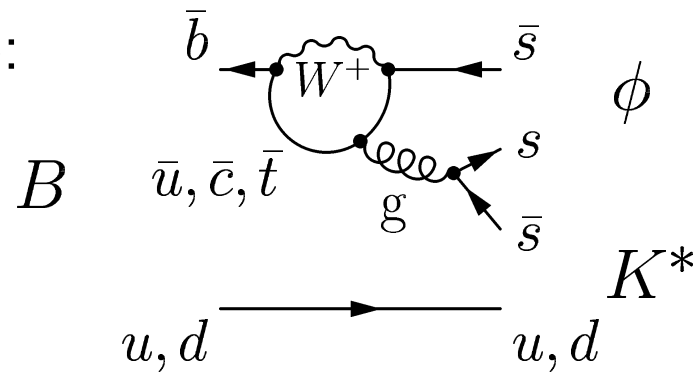


How to See New Physics in B Decays

- $B \to \phi K^{(*)}$ Pure penguin loop:

  best hints of New Physics

  Higgs$^+$, SUSY in loops?



- How to measure New Physics:

  (1) $B^+ \to \phi K^+$: 2 observables $|A|$ and $|\bar{A}|$

  $\mathcal{B}$ranching $= (10.0 \pm 0.9 \pm 0.5) \times 10^{-6}$

  $\mathcal{A}_{CP} = +0.04 \pm 0.09 \pm 0.01$ Phys. Rev. D 69, 011102 (2004)

  (2) $B^0 \to \phi K^0$: 3 observables $|A|$, $|\bar{A}|$, arg$(A/\bar{A})$

  e.g. $\mathcal{B}$ranching, C=-$\mathcal{A}_{CP}$, $S \propto \mathcal{I}\mathrm{m}(\frac{q}{p} \times A/\bar{A})$

  (3) $B \to \phi K^*$: 11 observables (!) $|A_i|$, arg$(A_i/\bar{A}_j)$, etc

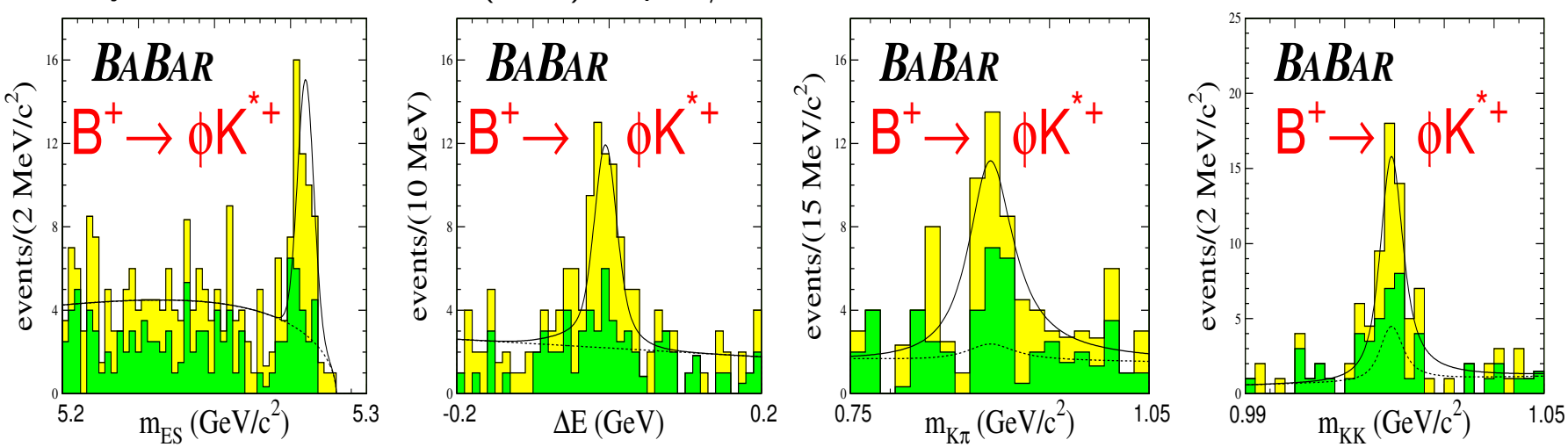
  Results for 10 of them today

Observation of $B^+ \to \phi K^{*+}$

- First observation (21fb^{-1}): *BABAR*, Phys.Rev.Lett 87,151801(2001)
  First *BABAR* paper after $\sin 2\beta$

• 2003 (82fb^{-1})	$\phi K^{*+}_{K^0\pi^+}$ (●)	$\phi K^{*+}_{K^+\pi^0}$ (●)	ϕK^{*+}
Signal yield ($n_{\rm sig}$)	$33.3^{+7.2}_{-6.4}$	$22.3^{+7.5}_{-6.5}$	–
Polarization (f_L)	$0.50\ ^{+0.14}_{-0.15} \pm 0.03$	$0.40\ ^{+0.20}_{-0.19} \pm 0.06$	$0.46 \pm 0.12 \pm 0.03$
Direct-CP ($\mathcal{A}_{CP}$)	$-0.02 \pm 0.20 \pm 0.03$	$+0.63\ ^{+0.25}_{-0.31} \pm 0.05$	$+0.16 \pm 0.17 \pm 0.03$
TripleP.-asymm. ($\mathcal{A}_{\rm tp}$)	$-0.28\ ^{+0.21}_{-0.20} \pm 0.03$	$+0.12\ ^{+0.34}_{-0.34} \pm 0.06$	$-0.02 \pm 0.18 \pm 0.03$
Branching fr. ($\mathcal{B}$, 10^{-6})	$13.9^{+3.0}_{-2.7} \pm 1.2$	$10.7^{+3.6}_{-3.1} \pm 1.8$	$12.7^{+2.2}_{-2.0} \pm 1.1$

Phys.Rev.Lett 91, 171802 (2003), hep-ex/0303020

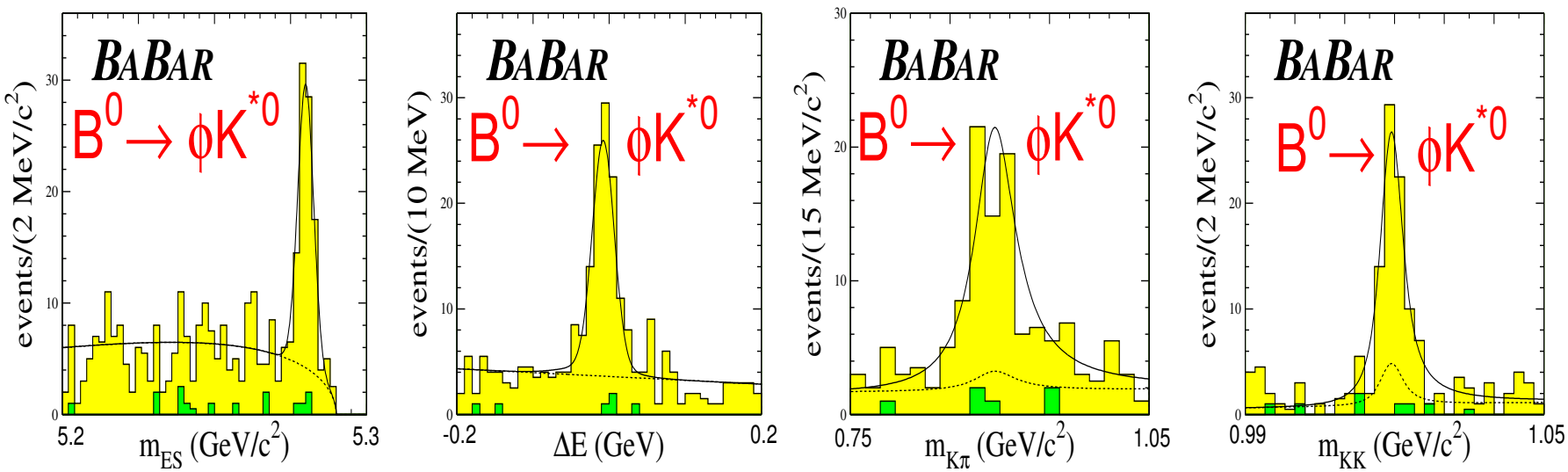


$B^0 \to \phi K^{*0}$

	$\phi K^{*0}_{K^+\pi^-}$ (●)	$\phi K^{*0}_{K^0\pi^0}$ (●)	ϕK^{*0}
Signal yield ($n_{\rm sig}$)	101^{+12}_{-11}	$2.0^{+3.4}_{-1.3}$	–
Polarization (f_L)	$0.64 \pm 0.07 \pm 0.02$	$1.00\,^{+0.00}_{-0.66} \pm 0.25$	$0.65 \pm 0.07 \pm 0.02$
Direct-CP ($\mathcal{A}_{CP}$)	$+0.04 \pm 0.12 \pm 0.02$	–	$+0.04 \pm 0.12 \pm 0.02$
TripleP.-asymm. ($\mathcal{A}_{\rm tp}$)	$+0.06 \pm 0.12 \pm 0.02$	–	$+0.06 \pm 0.12 \pm 0.02$
Branching fr. ($\mathcal{B}$, 10^{-6})	11.7 ± 1.4	$3.8^{+6.6}_{-2.5}$	$11.2 \pm 1.3 \pm 1.1$

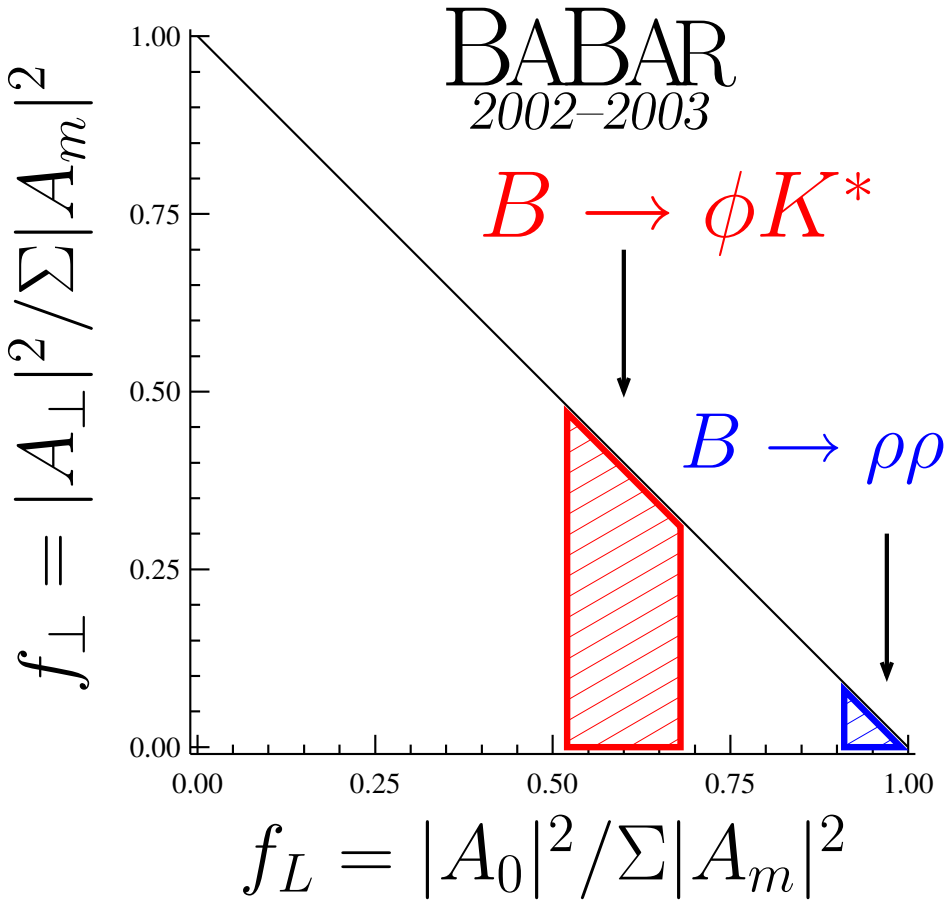
Phys.Rev.Lett 91, 171802 (2003), hep-ex/0303020

First results on polarization – puzzle of low f_L



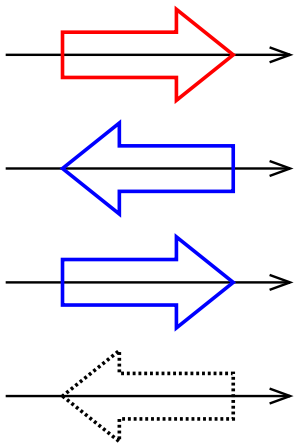
Polarization Puzzle

- Puzzle: in $B \to \rho\rho$ $|A_0|^2 \sim 0.98$ ("tree")
  in $B \to \phi K^*$ $|A_0|^2 \sim 0.60$ ("penguin")



expected

$$|A_0|^2 \sim 1 - \frac{m_V^2}{m_B^2} \sim 0.96$$



Hint of New Physics (?)

Really Full Angular Analysis

- First precedence of 10 measurements ("+" for $\bar{B}$, "−" for B):

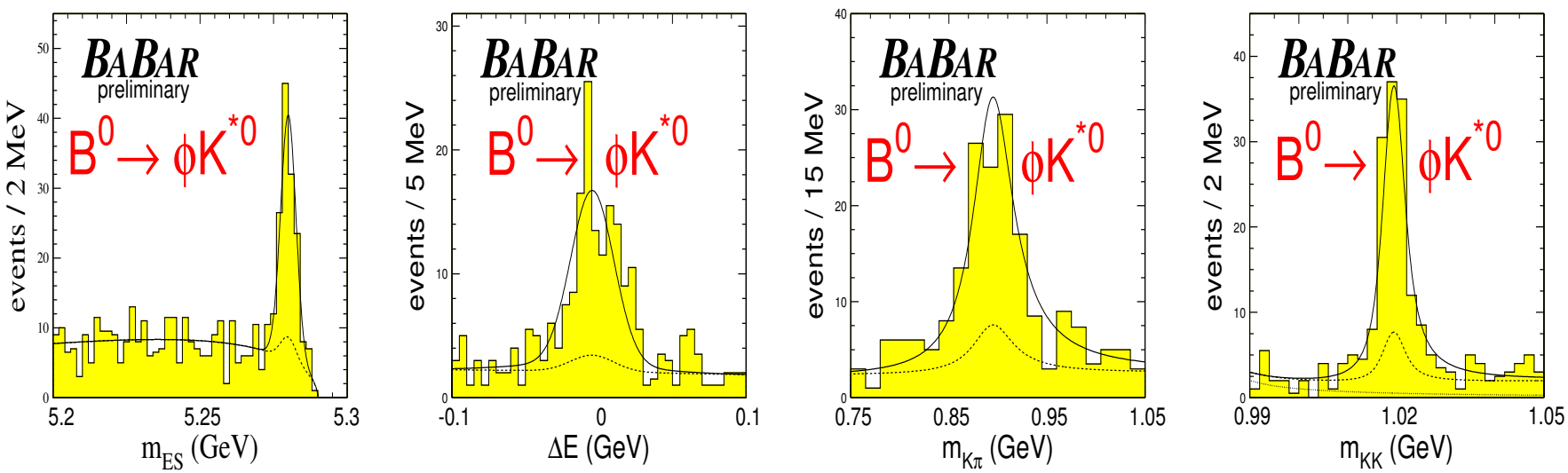
$$n_{\rm sig}^{\pm} = n_{\rm sig} \cdot (1 \pm \mathcal{A}_{CP})/2$$
$$f_L^{\pm} = f_L \cdot (1 \pm \mathcal{A}_{CP}^0)$$
$$f_\perp^{\pm} = f_\perp \cdot (1 \pm \mathcal{A}_{CP}^\perp)$$
$$\phi_\parallel^{\pm} = \phi_\parallel \pm \Delta\phi_\parallel$$
$$\phi_\perp^{\pm} = \phi_\perp \pm \Delta\phi_\perp + \frac{\pi}{2} \pm \frac{\pi}{2}$$

- With 124 million $B\bar{B}$:

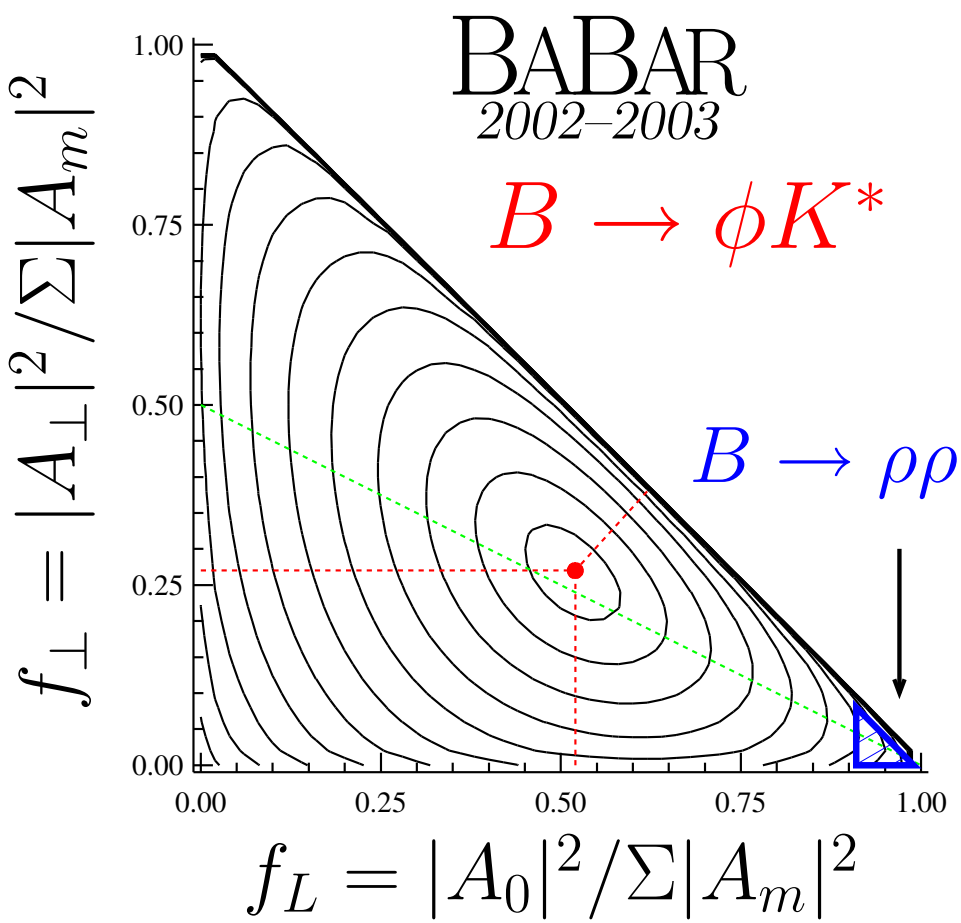
$$n_{\rm sig} = 129 \pm 14 \pm 9$$

- Derived TP:

$$\mathcal{A}_T^{\parallel,0} = \frac{1}{2}\left(\frac{\mathrm{Im}(A_\perp^+ A_{\parallel,0}^{+*})}{\Sigma|A_m^+|^2} + \frac{\mathrm{Im}(A_\perp^- A_{\parallel,0}^{-*})}{\Sigma|A_m^-|^2}\right)$$



Polarization Results



$f_L = 0.52 \pm 0.07 \pm 0.02$

$f_\perp = 0.27 \pm 0.07 \pm 0.02$

correlation -52%

$f_L + f_\perp + f_\parallel = 1$

$|A_0|$, $|A_\perp|$, $|A_\parallel|$ $>5\sigma$ each

$|A_+| \gg |A_-| \Rightarrow f_\perp \simeq f_\parallel$

Puzzle of low f_L remains

$f_L \sim 1 - \frac{m_V^2}{m_B^2} \sim 0.96$

(?) hint of New Physics

(?) long-distance FSI

(look at strong phases)

Results on FSI

$\phi_{\parallel} = 2.63^{+0.24}_{-0.23} \pm 0.04$ (rad)

$\phi_{\perp} = 2.71^{+0.22}_{-0.24} \pm 0.03$ (rad)

correlation +59%

– about 2.3σ evidence

$\neq \{\pi, \pi\} \Rightarrow$ FSI

$|A_+| \gg |A_-| \Rightarrow \phi_{\perp} \simeq \phi_{\parallel}$

– Ambiguities:

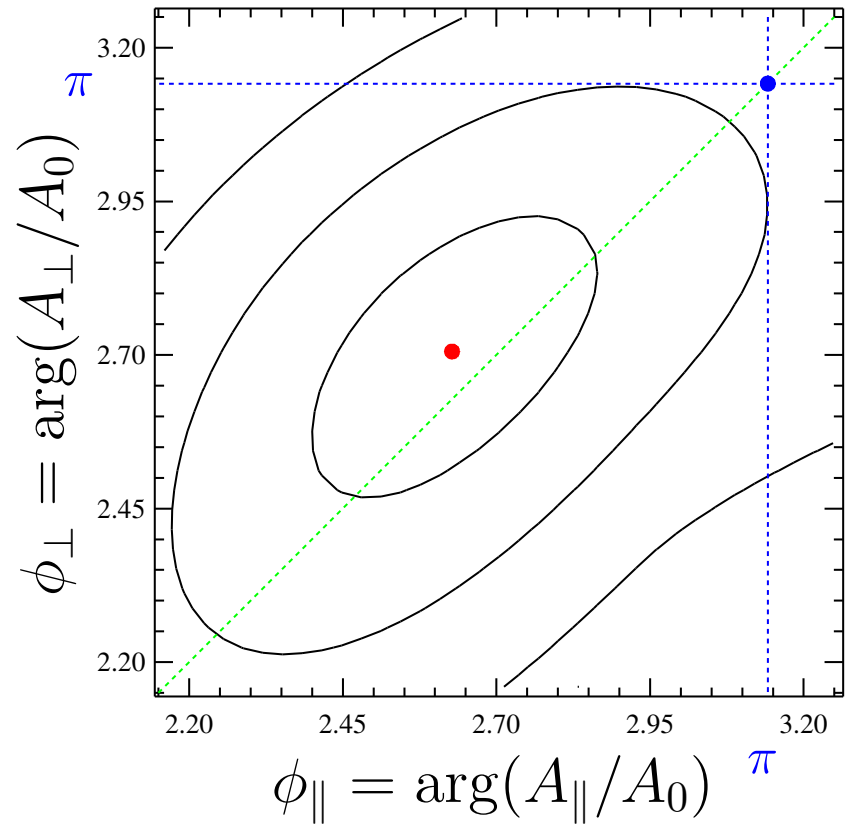
$\{-\phi_{\parallel}, \pi - \phi_{\perp}\}$ valid too

$\sin(\phi_{\perp} - \phi_{\parallel})$, $\cos(\phi_{\parallel})$, $\sin(\phi_{\perp})$

$\{\pi, \pi\} \Leftrightarrow |A_+| \gg |A_-|$

$\{\pi, 0\} \Leftrightarrow |A_-| \gg |A_+|$

BABAR *preliminary* $B^0 \to \phi K^{*0}$



- $|A_+| \gg |A_-|$ solved in $B \to J/\psi K^*$ with $K\pi$ S-wave interference

Angular Projections

- $\cos\theta_1$ and $\cos\theta_2$ (averaged over Φ)

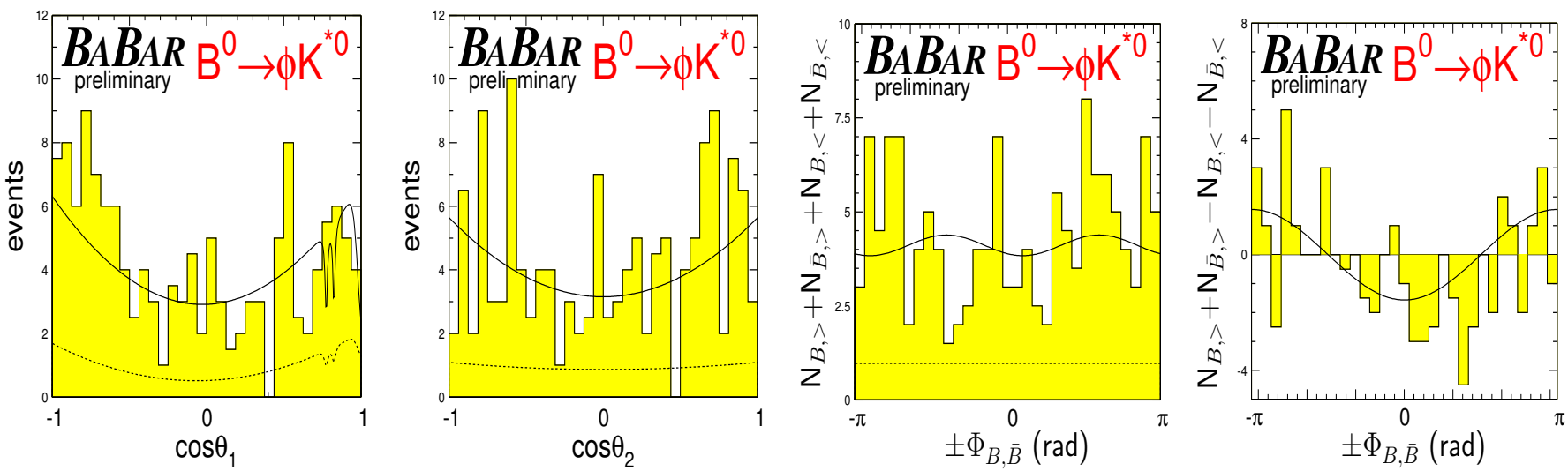
  $|A_0|^2 \Rightarrow \cos^2\theta_i$ (large) $\qquad (|A_\perp|^2 + |A_\parallel|^2) \Rightarrow (1-\cos^2\theta_i)$ (large)

- Φ (averaged over $\cos\theta_i$)

  $(|A_\perp|^2 - |A_\parallel|^2) \Rightarrow \cos 2\Phi$ (small) $\qquad \mathrm{Im}(A_\perp A_\parallel{}^*) \Rightarrow \sin 2\Phi$ (small)

- $\Phi\ (\cos\theta_1\cos\theta_2 > 0) - \Phi\ (\cos\theta_1\cos\theta_2 < 0)$

  $\mathrm{Re}(A_\parallel A_0{}^*) \Rightarrow \cos\Phi$ (large) $\qquad \mathrm{Im}(A_\perp A_0{}^*) \Rightarrow \sin\Phi$ (small)



Direct CP Violation Results

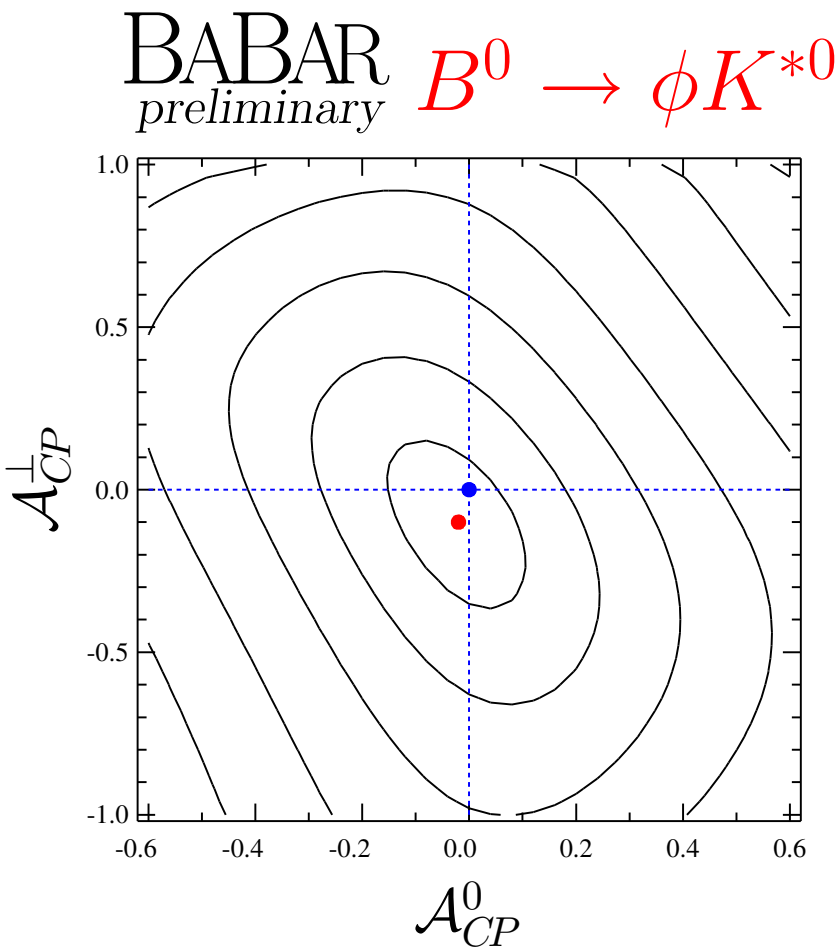
$\mathcal{A}_{CP} = -0.12 \pm 0.10 \pm 0.03$

$\mathcal{A}^0_{CP} = -0.02 \pm 0.12 \pm 0.01$

$\mathcal{A}^\perp_{CP} = -0.10^{+0.25}_{-0.27} \pm 0.04$

$\mathcal{A}^0_{CP}$-$\mathcal{A}^\perp_{CP}$ correlation -52%

(like f_L-$f_\perp$)



No significant direct-CP

(strong phase could be small)

$\propto \sin \Delta\delta_{\text{strong}} \sin \Delta\phi_{\text{weak}}$

More interesting TP $\propto \cos \Delta\delta_{\text{strong}} \sin \Delta\phi_{\text{weak}}$

Triple-Product Asymmetry Results

$\Delta\phi_{\parallel} = 0.38^{+0.23}_{-0.24} \pm 0.04$ (rad)

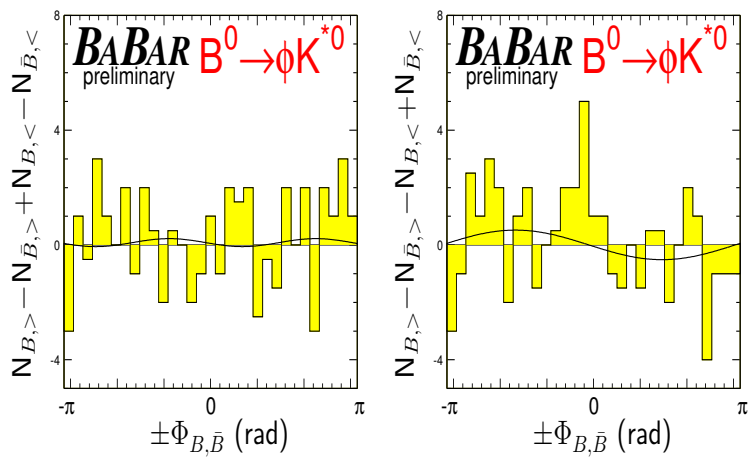
$\Delta\phi_{\perp} = 0.30^{+0.24}_{-0.22} \pm 0.03$ (rad)

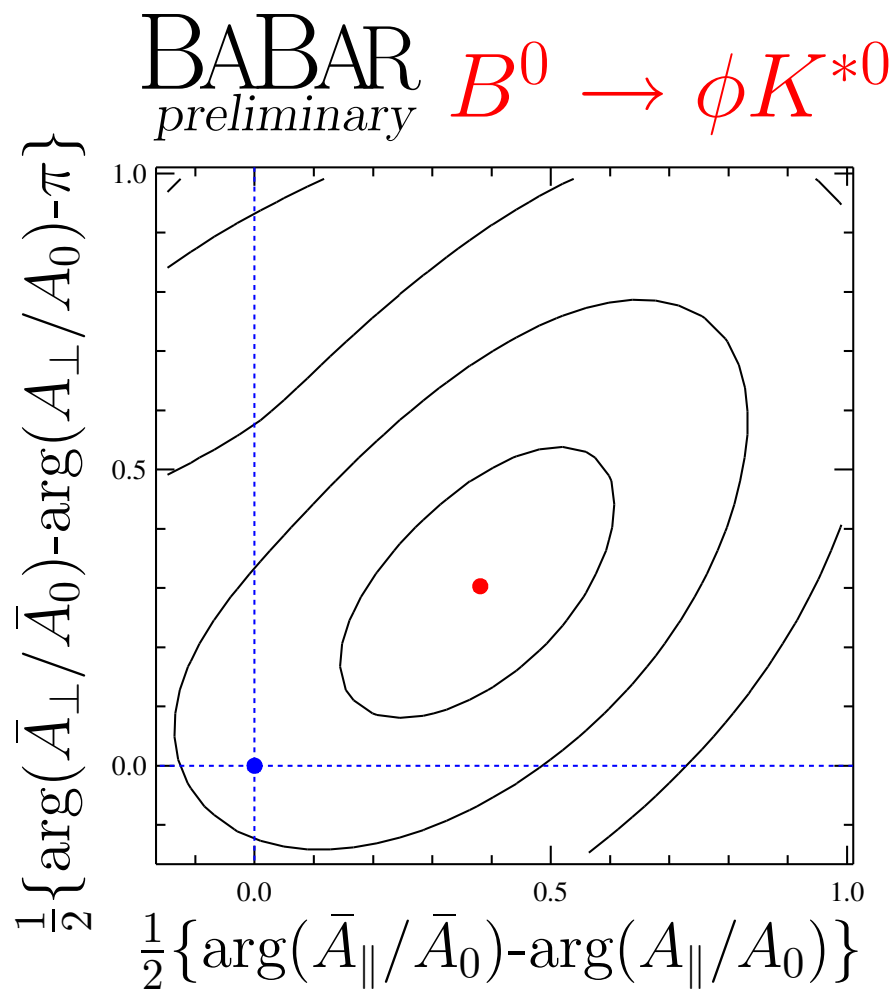
– New Physics $\neq \{0, 0\}$ $\sim 1.7\sigma$

– Triple-products instead:

$$\mathcal{A}_T^{\parallel} = +0.02 \pm 0.05 \pm 0.01$$

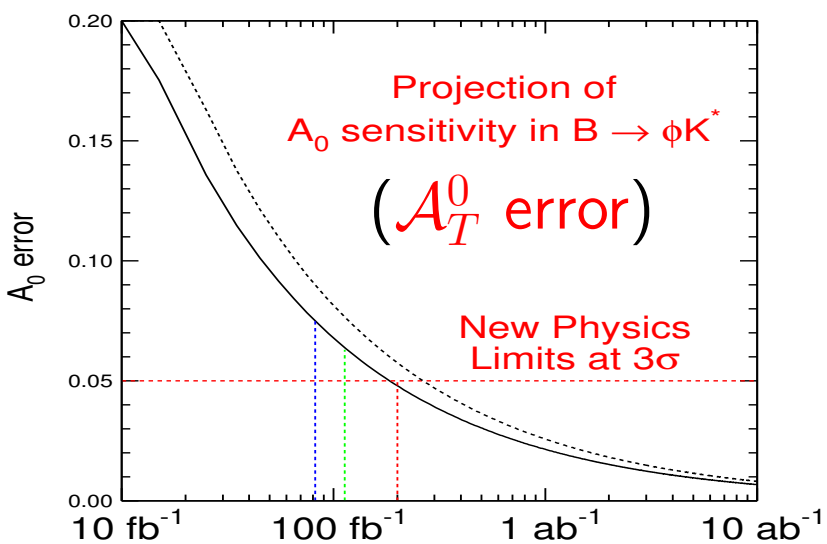
$$\mathcal{A}_T^{0} = +0.11 \pm 0.07 \pm 0.01$$

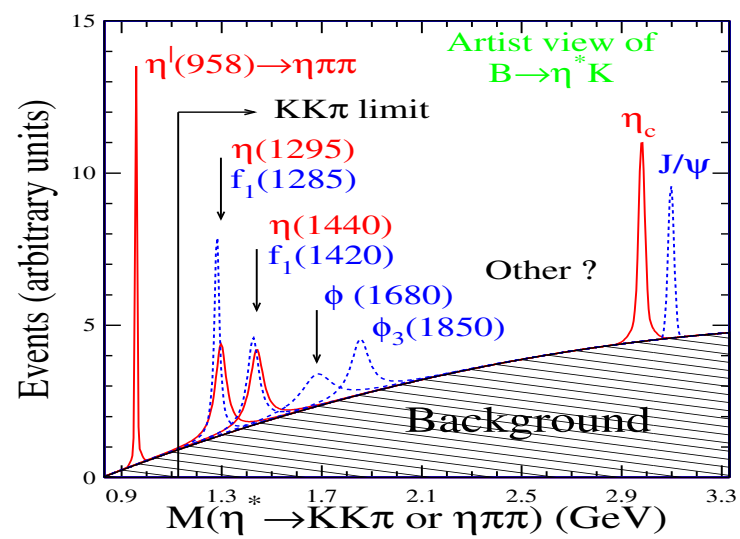




What we have learned from $B \to \phi K^*$

- Small A_0 gives a window of opportunity:
  - $|A_0| \simeq |A_\pm|$ not understood (puzzle)
  - $|A_\pm| \gg |A_\mp|$ consistent
  - arg$(A_\pm/A_0)$ small FSI
  - First 5 angular CP-asymmetries ($\mathcal{A}_T^0$ projection left plot)
- Looking for other $b \to s g^*$ decays with "exotics" (glueballs) (some candidates: right plot)





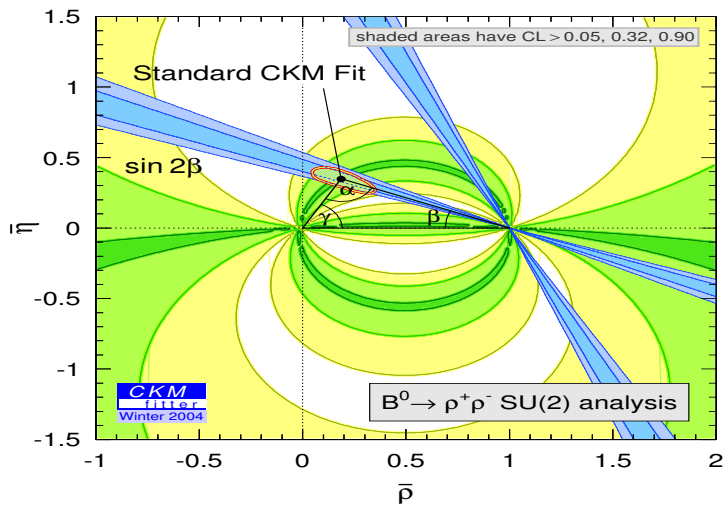
Summary

- Is Standard Model complete? Likely not... What is Beyond?
- Two ways to proceed:

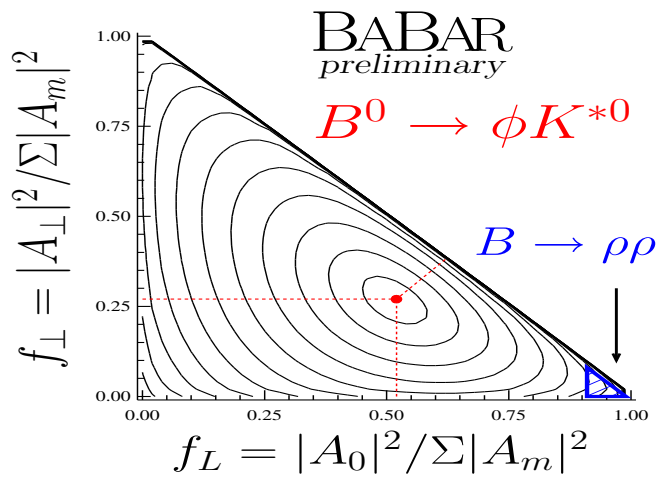
  (1) try highest energy accelerator to reach Beyond (e.g. LHC in 2007)
  (2) try Standard Model predictions with heavy quark decays (e.g. b)

- Examples of two novel approaches:

$\sin(2\alpha)$ with $B \to \rho\rho$



Spin and CP with $B \to \phi K^*$



- Gluonic penguins play a key role (observed in 1996/97):

  pollution for $\sin(2\alpha)$ best hints of "Beyond"