Branching Fractions and Direct CP Violation Measurements in B → PP(PV)

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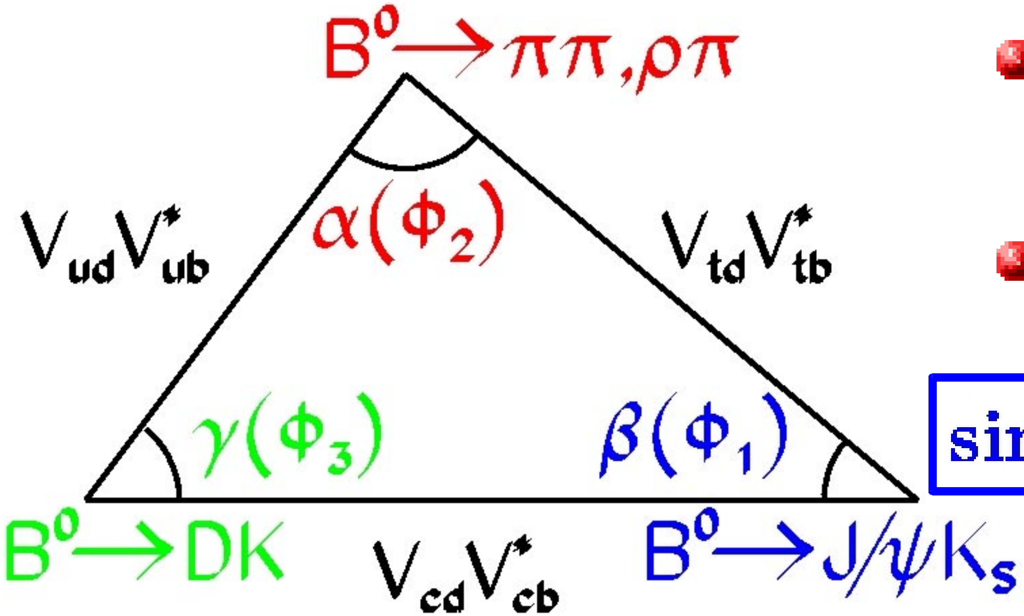
CP violation in the Standard Model (SM):

- CP symmetry can be violated in any field theory with at least one irremovable phase in the Lagrangian
- This condition is satisfied in the SM through the three-generation CKM quark-mixing matrix

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

Unitarity Triangle:

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



- The angles are related to CP-violating asymmetries in specific B decays
- already good precision on $\beta(\Phi_1)$: (B. Ford's talk)

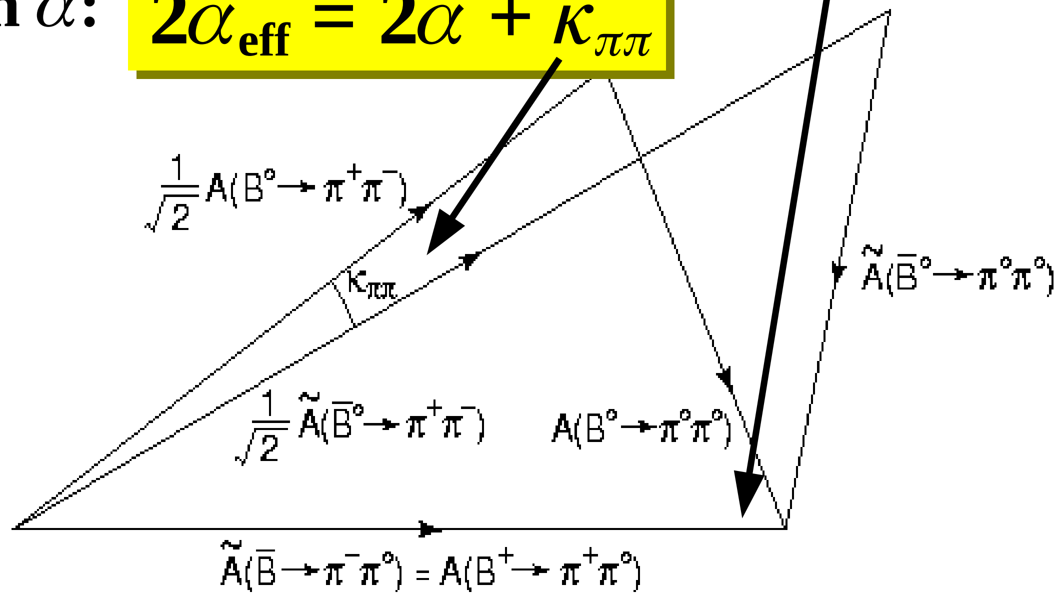
$$\sin 2\beta_{WA} = 0.734 \pm 0.055$$

What about $\alpha(\phi_2)$? (H. Sagawa's talk)
from α_{eff}: isospin triangle analysis

- The decays B → $\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ are related by isospin
- $\pi\pi$ states can have I = 2 or I = 0
  - gluonic penguins only contribute to I = 0 (ΔI=1/2)
  - $\pi^+\pi^0$ is a pure I = 2 (ΔI = 3/2) so it has only tree amplitude
- triangle relations allow determination of penguin-induced shift in α: $2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$

$|A^{+0}|=|A^{-0}|$

Both BR(B^0) and BR($\bar{B}^0$) have to be measured in the $\pi\pi$ modes



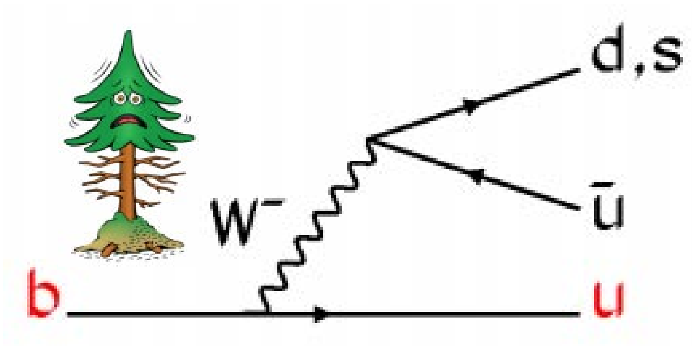
And finally $\gamma(\phi_3)$ (A. Golutvin's talk)

- γ is the weak phase difference between **b → u tree** and **b → s penguin** amplitudes
  - comparable tree and penguin contributions facilitate sensitivity to γ
- Challenges:
  - Strong phases
  - Electroweak penguins (EWP)
  - Rescattering
- All **two-body modes** are useful:
  - $K\pi$, $K^*\pi$, $K\rho$: sensitivity to γ
  - $\pi\pi$: $A(\pi^+\pi^0)$ ~ pure tree → $A_{CP} \sim 0$

    → cross-check for the EWP suppression
  - KK: constraints on rescattering

Charmless two-body (or quasi two-body) decays: $K\pi$ ($K\rho$, $K^*\pi$, ..)

- rare decays: 10^{-5}-10^{-6}:
  - tree: Cabibbo suppressed ($\propto |V_{ub}|^2$)
  - penguin: new physics in the loops?



- $K\pi$ modes: theoretically cleaner

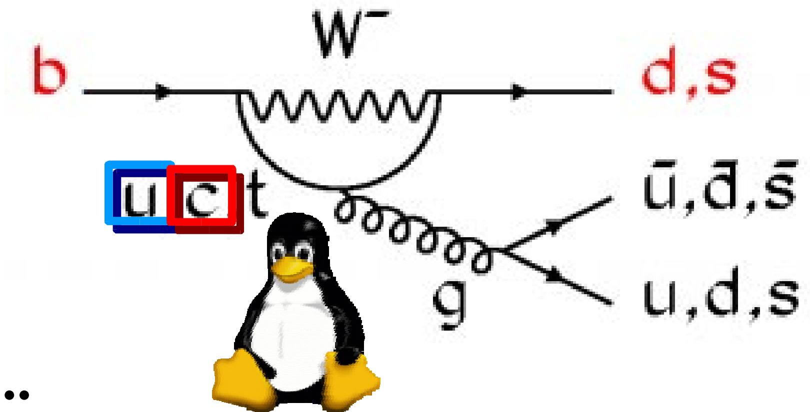
penguin amplitude favoured by CKM factor

- $K^+\pi^-$: $P_c(\lambda^2)$ + $T_{CA}(\lambda^4)$
- $K^0\pi^+$: $P_c(\lambda^2)$
- $K^+\pi^0$: $P_c(\lambda^2)$ + $T_{CA+CS}(\lambda^4)$
- $K^0\pi^0$: $P_c(\lambda^2)$ + $T_{CS}(\lambda^4)$

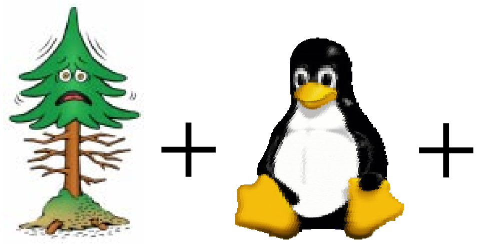
$V_{cs}V^*_{cb}$

$V_{us}V^*_{ub}$

$T_{CA}(\lambda^4)$, $T_{CS}(\lambda^4)$, $P_u(\lambda^4)$, etc...



Charmless two-body (or quasi two-body) decays: $\pi\pi$, ($\pi\rho$, ..) and KK

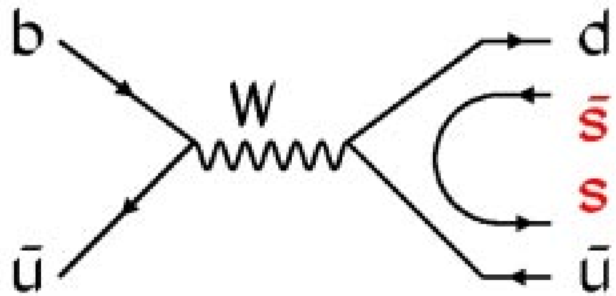


- **$\pi\pi$ modes: all contributions of the same λ^3 order**
  - $\pi^+\pi^-$: $T_{CA}(\lambda^3) + P_u(\lambda^3) + \ldots + P_c(\lambda^3)$
  - $\pi^+\pi^0$: $T_{CA+CS}(\lambda^3) + \ldots$
  - $\pi^0\pi^0$: $T_{CS}(\lambda^3) + P_u(\lambda^3) + \ldots + P_c(\lambda^3)$

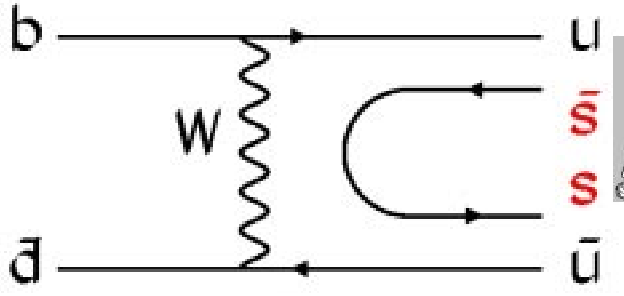
pure tree: $T[\pi^+\pi^-]+T[\pi^0\pi^0]$

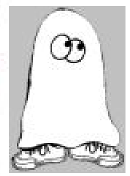
$V_{ud}V^*_{ub}$

$V_{cd}V^*_{cb}$



- **KK modes: similar to $\pi\pi$, but no tree contributions**
  - K^+K^-: W-exchange(λ^3)
  - K^0K^+: $P_u(\lambda^3)$+annihilation(λ^3) + $P_c(\lambda^3)$
  - $K^0\overline{K^0}$: pure penguin: $P_u(\lambda^3)$ + $P_c(\lambda^3)$





Direct CP violation:

interesting modes
for new physics search:
- $K^0\pi^+$: pure penguin
- $K^0\pi^0$: color suppressed tree
- ~ 0 asymmetry expected in the SM

- both charged and neutral Bs
- tagging is not always necessary
  - charged and self-tagging modes
  - higher efficiency
- interference between (at least) two amplitudes leading to the same final state

$$A_f = a_1 \exp\left[i(\delta_1 + \phi_1)\right] + a_2 \exp\left[i(\delta_2 + \phi_2)\right]$$
$$\bar{A}_{\bar{f}} = a_1 \exp\left[i(\delta_1 - \phi_1)\right] + a_2 \exp\left[i(\delta_2 - \phi_2)\right]$$

δ_i: strong phase
CP-even

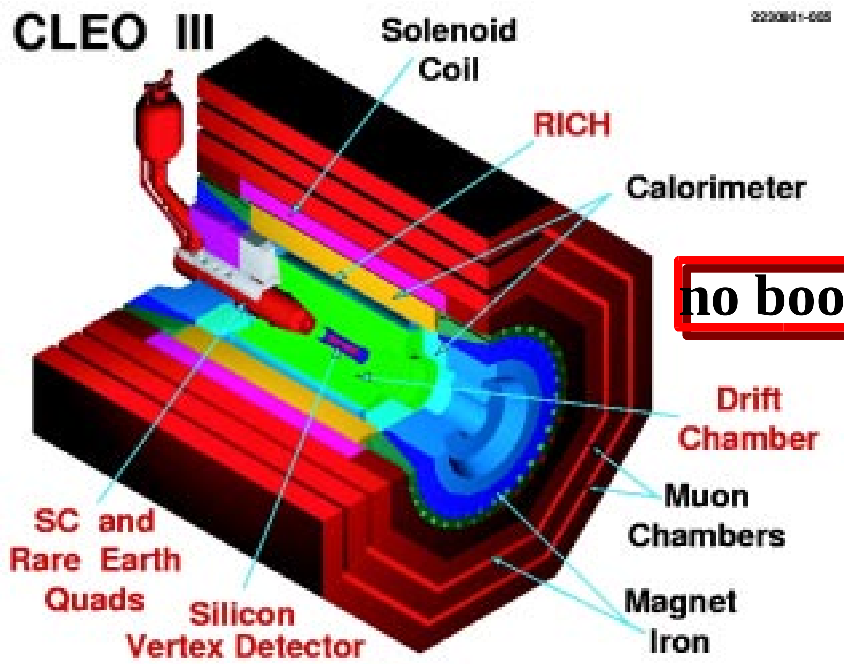
ϕ_i: weak phase
CP-odd

- the measured asymmetry is:

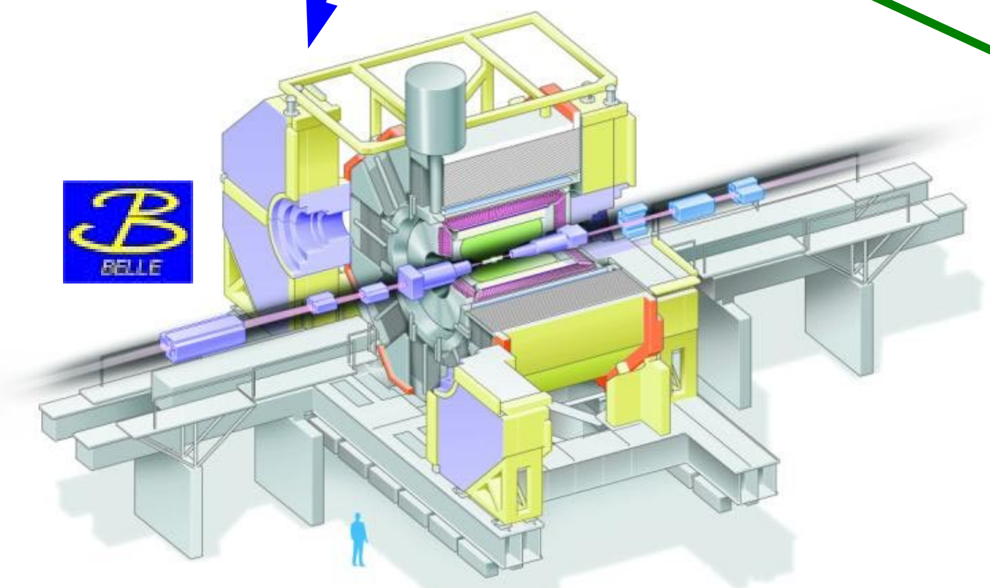
$$A_{CP} \equiv \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \sim \sum_{i,j} a_i\, a_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j)$$

B-Factory detectors:

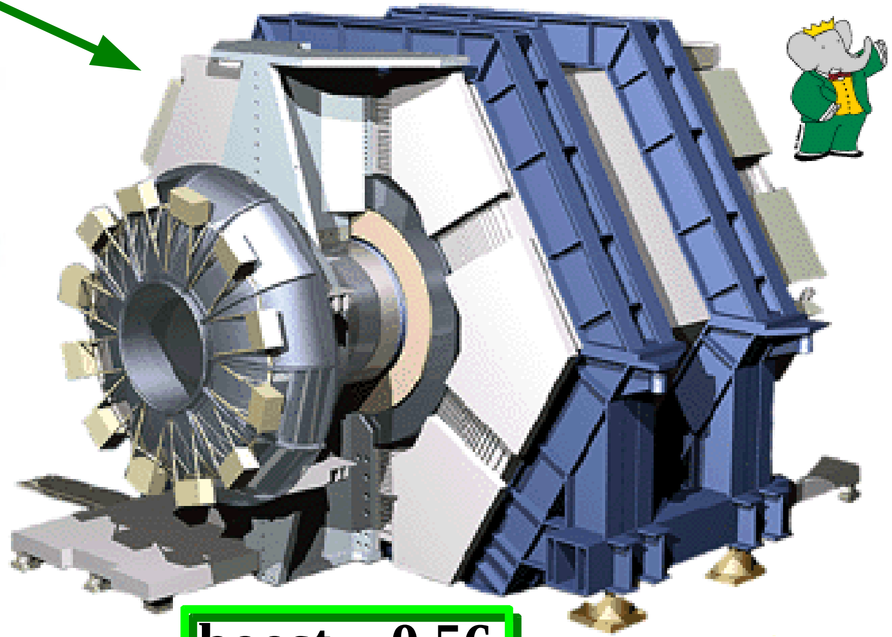
- CLEO
- BaBar
- Belle



no boost



boost ~ 0.43



boost ~ 0.56

Analysis overview:

- **Features of the analyses:**
  - event selection: exclusive B reconstruction (m_{ES} and ΔE)
  - high background from continuum
    - continuum suppression based on topological information
    - cross-feed from other B decays for $\pi^0(\rho)$ modes
  - crucial K/π separation: excellent particle identification needed to distinguish among various final states
    - Cleo and Belle: cut on a likelihood (dE/dx + Cherenkov angle)
    - BaBar: include the Cherenkov angle measurement in the maximum likelihood (ML) fit
  - finally to separate signal from light-quark background:
    - maximum likelihood fit (Cleo and BaBar)
    - ΔE fit (Belle)

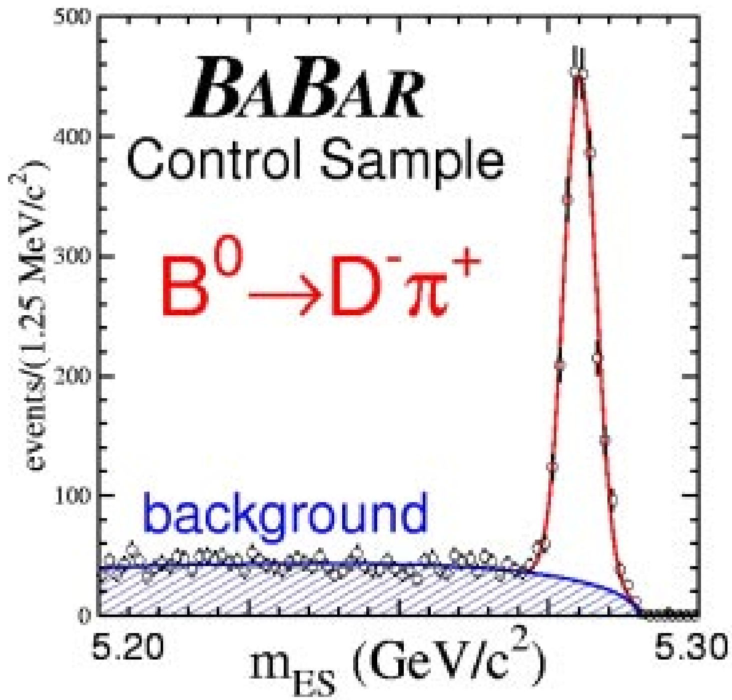
Event selection:

- **Kinematically select B candidates with m_{ES} and ΔE**

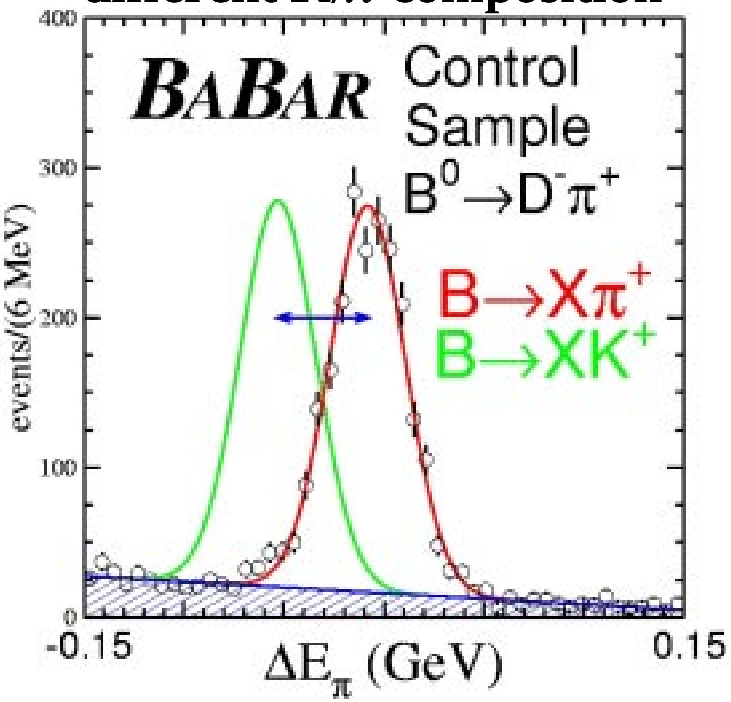
$$m_{ES} = \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$$

$$\Delta E = E_B^* - \sqrt{s}/2$$

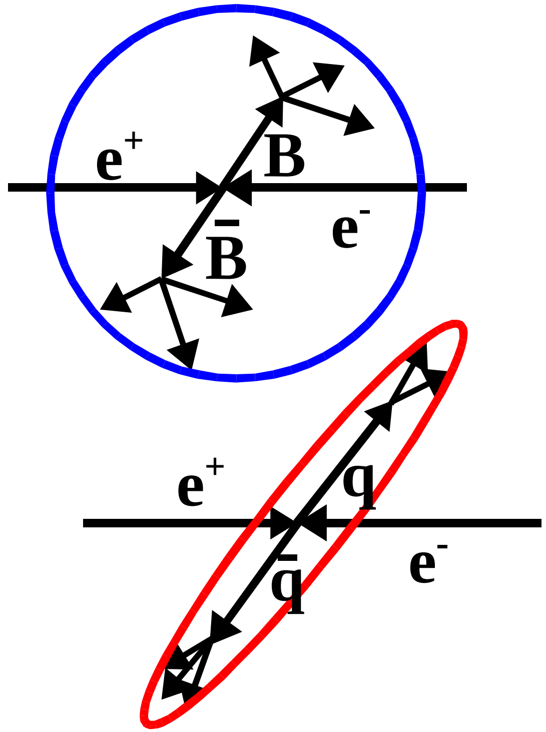
- **m_{ES}: powerful variable to separate signal from light-quark continuum**



- **ΔE: some separation power for final states with different K/π composition**



Continuum suppression (I):

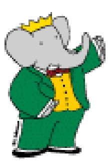


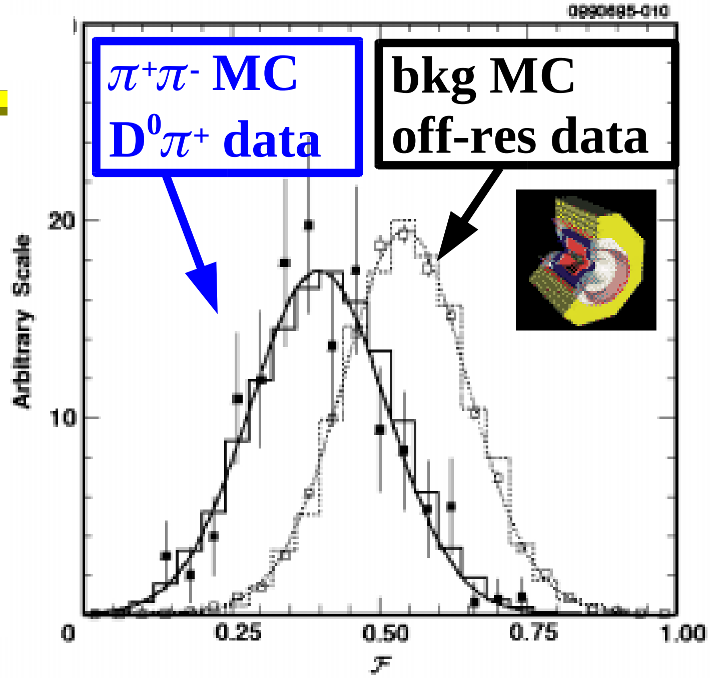
- spherical B events vs jet-like continuum
  - several techniques exploiting event topology or angular distribution
    - selection cuts on:
      - Fox-Wolfram moments
      - sphericity, cos θ_S
      - B direction (cos θ_B)
    - build Fisher discriminants:
      - to be included in a likelihood variable to cut on (Belle)
      - to be included in the maximum likelihood fit (Cleo and BaBar)

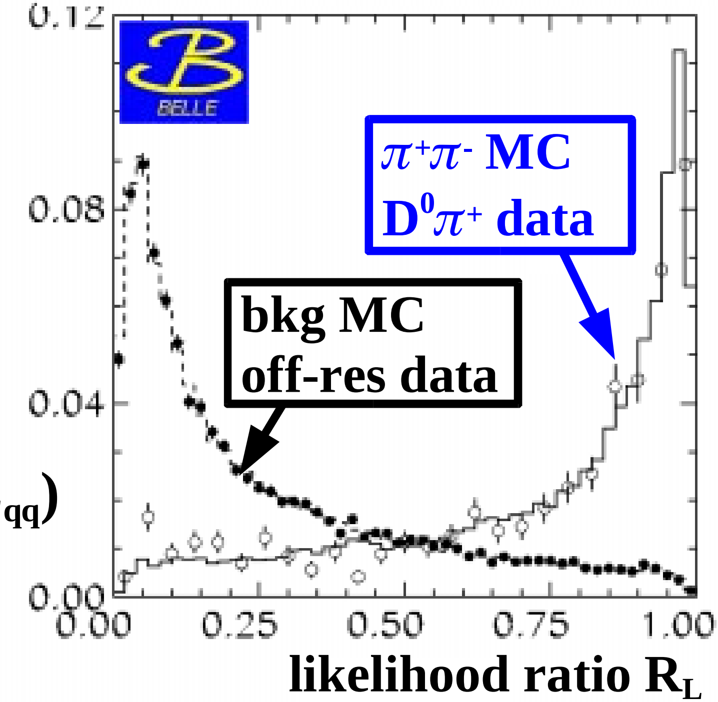
angle between the sphericity axis of the B and the sphericity axis of the rest of the event

Continuum suppression (II):

- **Fisher discriminants:**
  - **Cleo: 14 variables**
    - **9 energy cones, cos θ_{THR}, 4 momenta of the fastest e, μ, K, p**
    - **Fisher variable included in the ML fit**
  - **BaBar: 2 variables**
    - **2 Legendre Polinomials: $P^0(p^*_i)$ and $P^2(p^*_i, \cos\theta^*_i)$**
    - **Fisher variable included in the ML fit**
  - **Belle: 6 variables**
    - **Fox-Wolfram moment ratios**
    - **adding cos θ_B to build a likelihood:**
    - **cut on the likelihood ratio $R_L = L_B/(L_B+L_{qq})$**

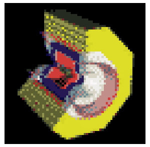




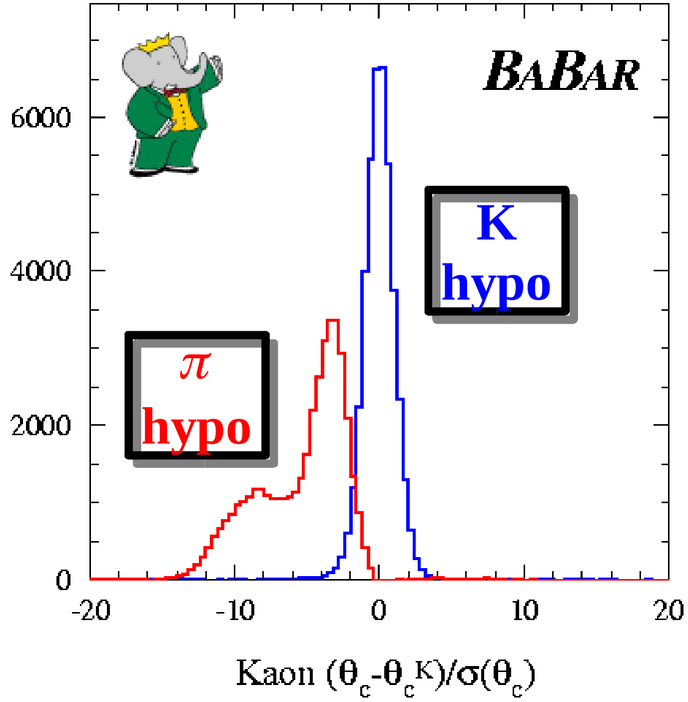


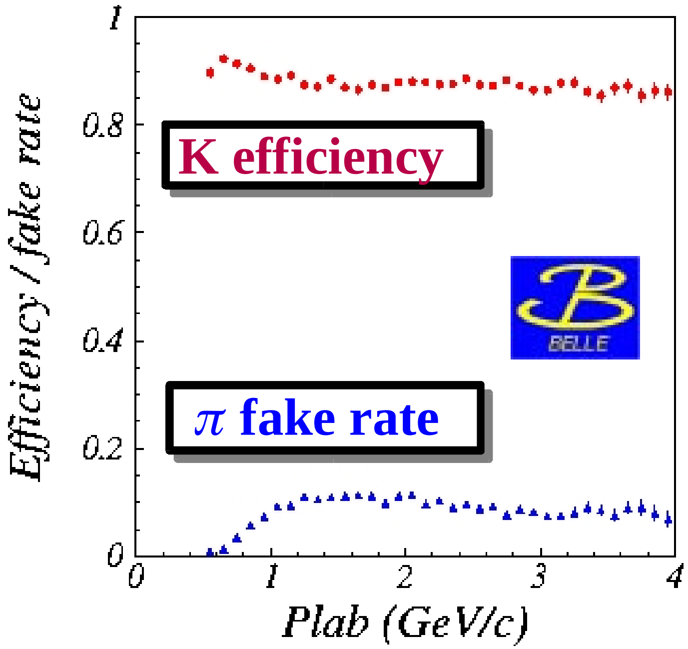
K/π separation:

- **Cleo:**
  - **Cherenkov angle from RICH + dE/dx from the drift chamber together in a χ^2 to cut on**
  - **misidentification: 11% kaons as pions (8% pions as kaons) @ 2.6 GeV/c**



- **BaBar:**
  - **Cherenkov angle from the DIRC**
  - **θ_C included in the ML fit**
  - **separation: 4σ @ 3 GeV/c**
- **Belle:**
  - **Cherenkov angle from the ACC + dE/dx from the drift chamber**
  - **cut on the likelihood ratio $L_K/(L_\pi+L_K)$**

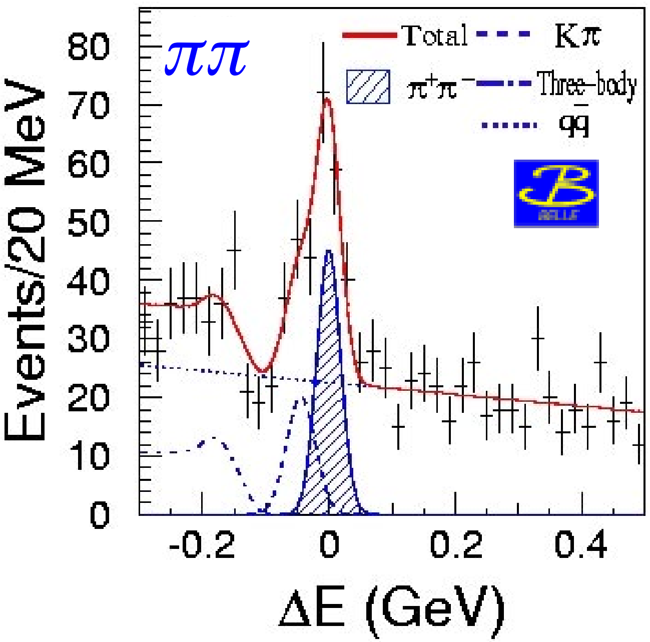


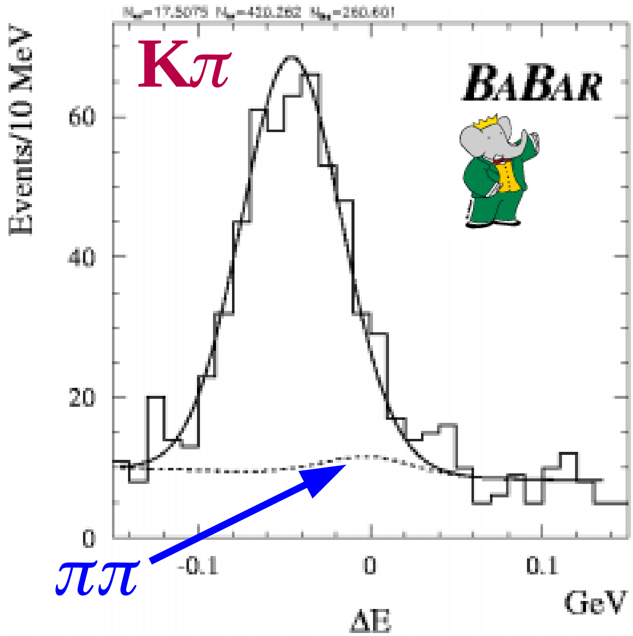


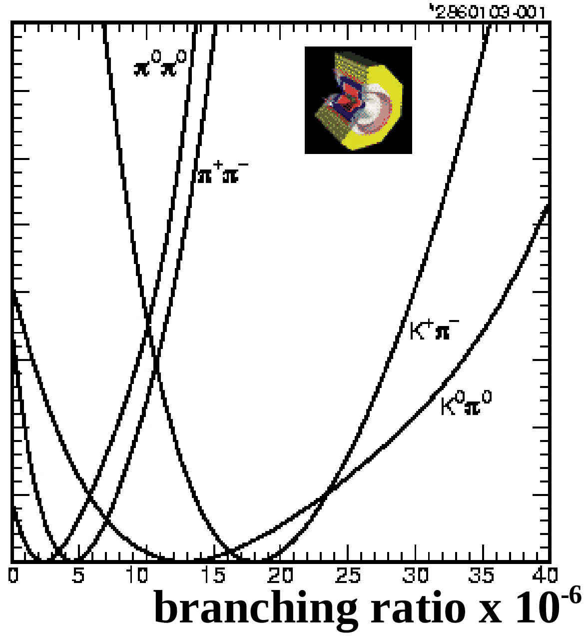
Branching Ratio (BR) results: h^+h^- with $h=\pi$, K

Cleo 15 fb^{-1} BaBar 81 fb^{-1} Belle 78 fb^{-1}

mode	BR (10^{-6}) [UL @ 90% CL]			
	Cleo	BaBar	Belle	WA
$B^0 \to \pi^+\pi^-$	$4.5^{+1.4+0.5}_{-1.2-0.4}$	$4.7 \pm 0.6 \pm 0.2$	$4.4 \pm 0.6 \pm 0.3$	4.6 ± 0.4
$B^0 \to K^+\pi^-$	$18.0^{+2.3+1.2}_{-2.1-0.9}$	$17.9 \pm 0.9 \pm 0.7$	$18.5 \pm 1.0 \pm 0.7$	18.2 ± 0.8
$B^0 \to K^+K^-$	< 0.8	< 0.6	< 0.7	< 0.6







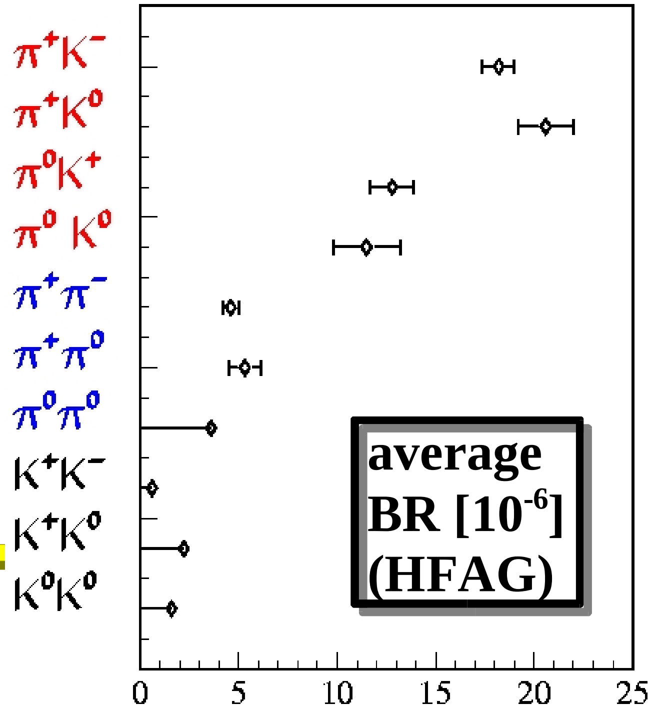
BR results: $K\pi$ ...

15 fb^{-1} 81 fb^{-1} 78 fb^{-1}

mode	BR (10^{-6})			
	Cleo	BaBar	Belle	WA
$B^+ \to K^0\pi^+$	$18.8^{+3.7+2.1}_{-3.3-1.8}$	$20.0 \pm 1.6 \pm 1.0$	$22.0 \pm 1.9 \pm 1.1$	20.6 ± 1.4
$B^+ \to K^+\pi^0$	$12.9^{+2.4+1.2}_{-2.2-1.1}$	$12.8^{+1.2}_{-1.0} \pm 1.0$	$12.8 \pm 1.4^{+1.4}_{-1.0}$	12.8 ± 1.1
$B^0 \to K^0\pi^0$	$12.8^{+4.0+1.7}_{-3.3-1.4}$	$10.4 \pm 1.5 \pm 1.8$	$12.6 \pm 2.4 \pm 1.4$	11.5 ± 1.7

... and KK

mode	UL on BR (10^{-6}) @ 90% CL		
	Cleo	BaBar	Belle
$B^+ \to K^0K^+$	< 3.3	< 2.2	< 3.4
$B^0 \to K^0\bar{K}^0$	< 3.3	< 1.6	< 3.2



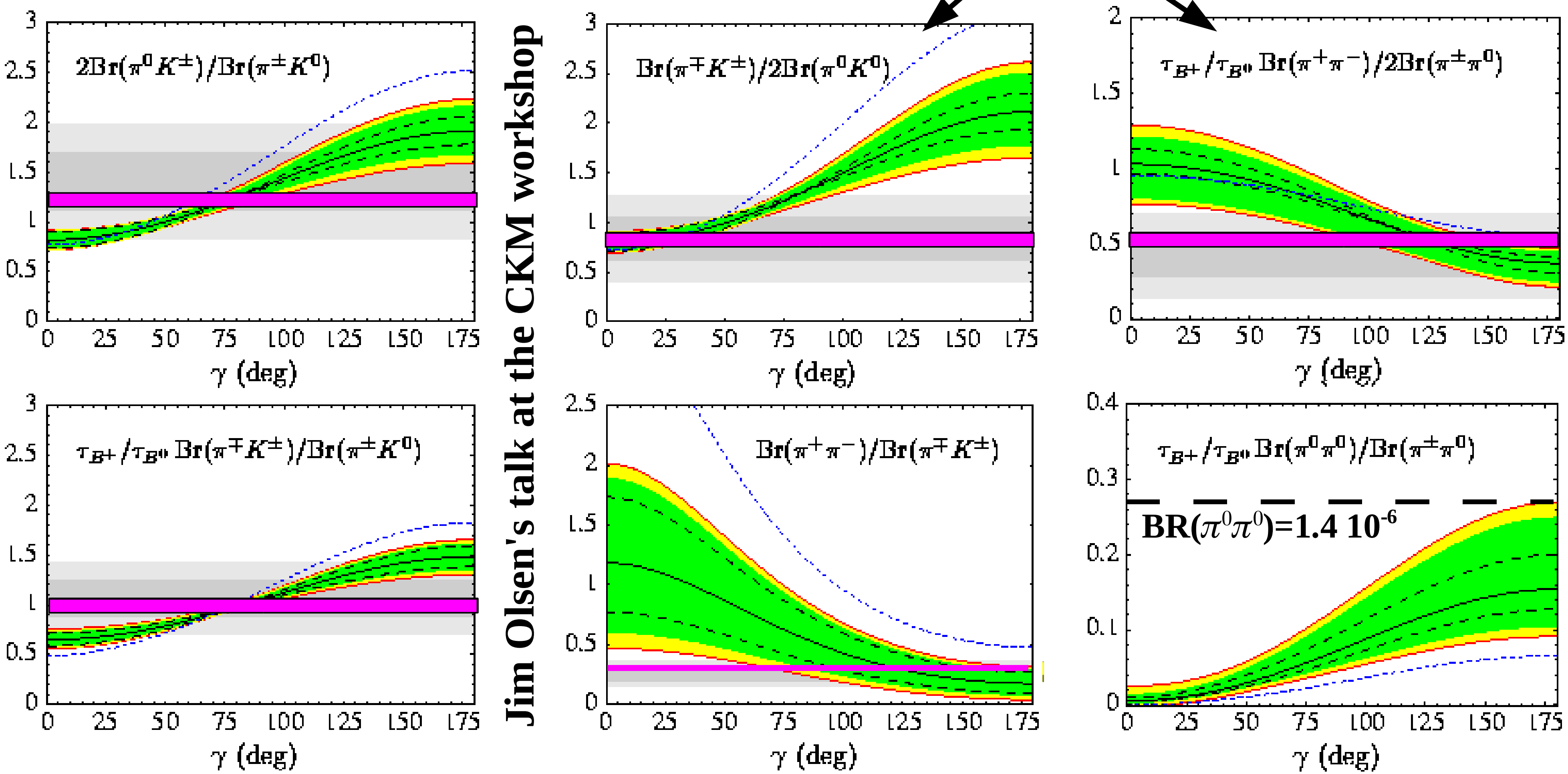
QCD factorization and present results:

BBNS [Nuclear Physics, B606, 245, 2001]

Data 2001

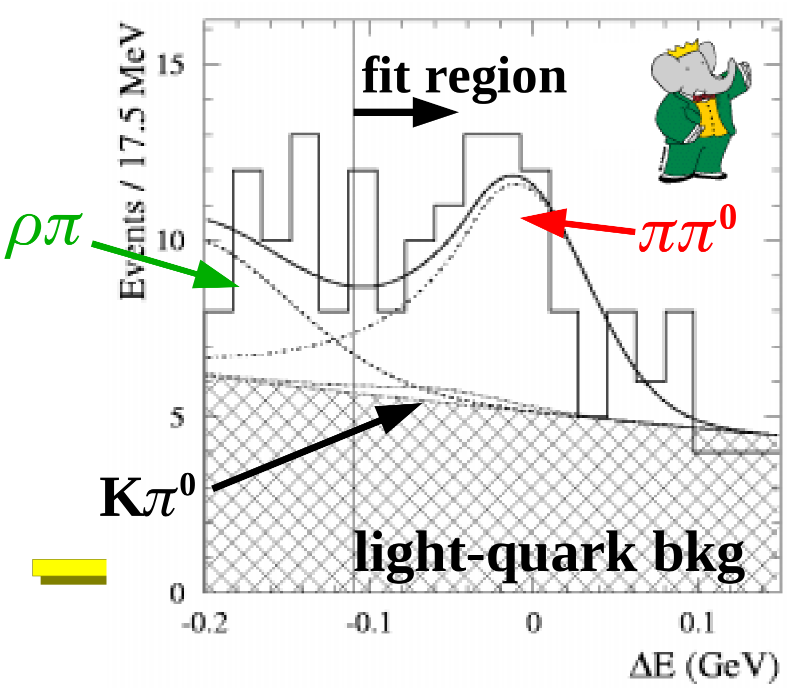
Data 2003

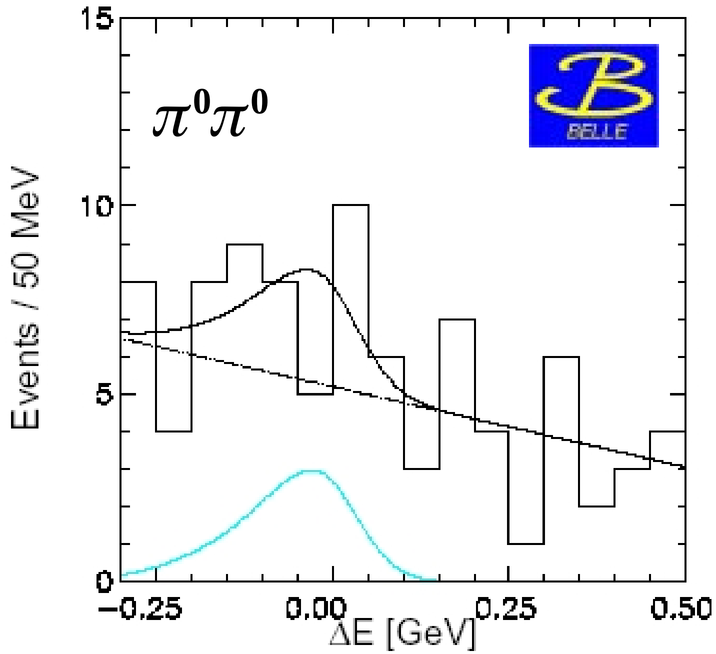
Inconsistent?



The other sides of the isospin triangles: BR results for $\pi^\pm\pi^0$ and $\pi^0\pi^0$

mode	BR (10^{-6}) [UL @ 90% CL]			
	Cleo	BaBar	Belle	WA
$B^+ \to \pi^+\pi^0$	$4.6^{+1.8+0.6}_{-1.6-0.7}$	$5.5^{+1.0}_{-0.9} \pm 0.6$	$5.3 \pm 1.3 \pm 0.5$	5.3 ± 0.8
$B^0 \to \pi^0\pi^0$	< 4.4	< 3.6	< 4.4	< 3.6





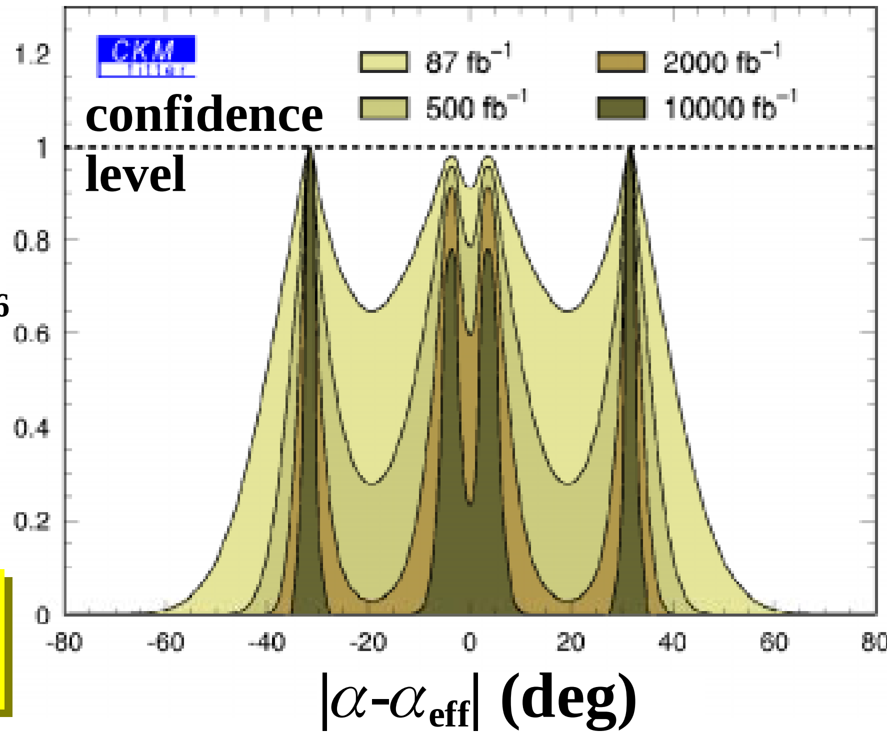
With an upper limit on the BR($\pi^0\pi^0$):

- **it is possible to get information on α with only an upper limit on $\pi^0\pi^0$**
  - **for example: Grossman-Quinn bound (assume only isospin)**

$$\cos 2(\alpha_{eff} - \alpha) > 1 - 2\frac{B^{00}}{B^{+0}}$$

  - **$|\alpha_{eff} - \alpha| < 51^o$ @ 90% CL from the best UL**

- **trying the isospin triangle analysis for $\pi\pi$:**
  - **using the BaBar $C_{\pi\pi}$ and $S_{\pi\pi}$, WA BRs and BR($\pi^0\pi^0$) = $2.0 \cdot 10^{-6}$ with $|A^{00}|=|A^{00}|$**
  - **but scaling the errors to higher statistics: 500 fb^{-1}**

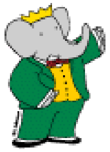


Roos's talk at the CKM workshop

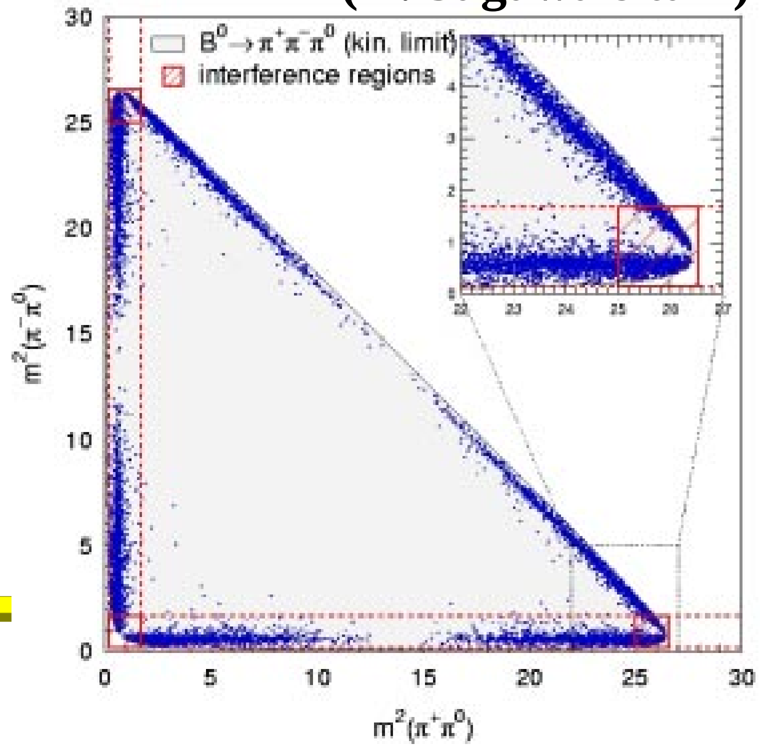
hope: not to measure such a high BR($\pi^0\pi^0$)

CP-violating asymmetries in B → $\rho^+\pi^-$

- in principle: direct measurement of α with the full three-body Dalitz plot analysis [A. Snyder, H. Quinn]
- but: much more difficult than in the $\pi\pi$ case
  - three-body topology with a neutral pion:
    - huge combinatorics, lower efficiency
  - high background from other B decays
- for the time being a quasi two-body analysis has been performed:
  - selection of the ρ-dominated Dalitz plane region
  - use of multivariate techniques to suppress light quark bkg
  - fit for $\rho^+\pi^-$, ρ^+K^- at the same time

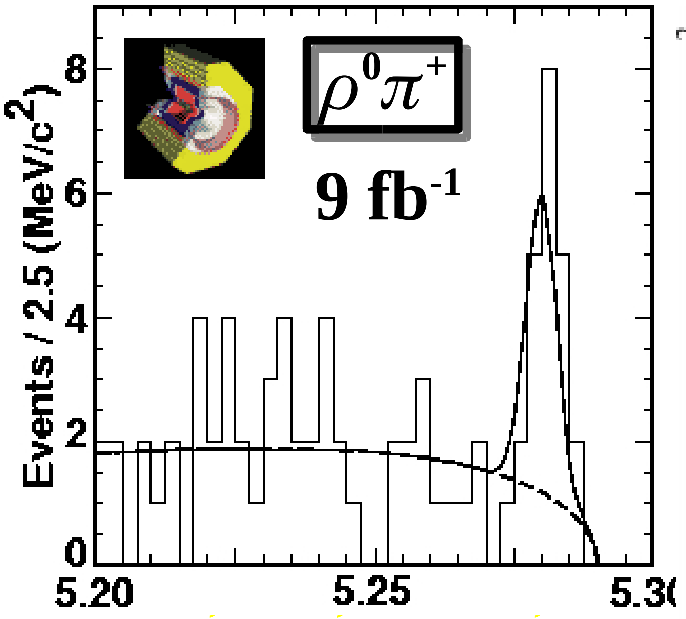


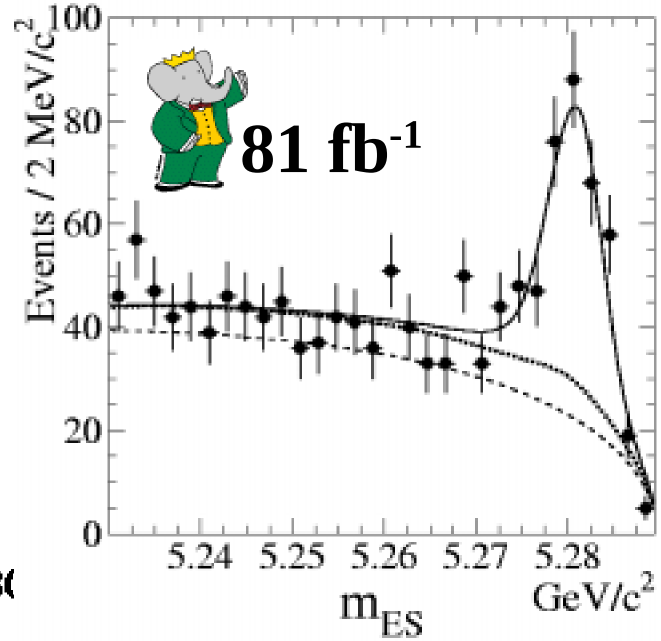
(H. Sagawa's talk)

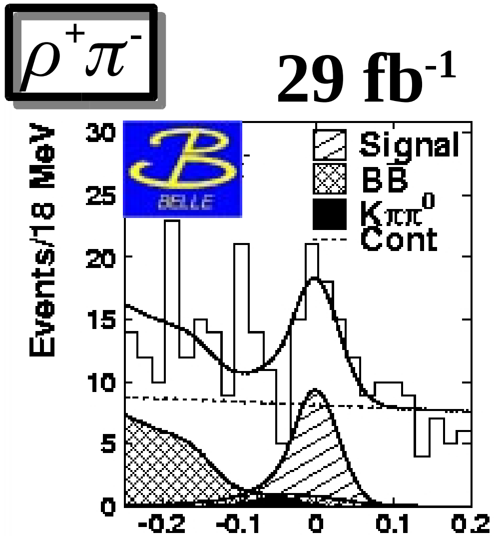


Branching fraction results $B \to \rho^+\pi^-$:

mode	BR (10^{-6}) [UL @ 90% CL]		
	Cleo	BaBar	Belle
$B^0 \to \rho^+\pi^-$	$27.6^{+8.4}_{-7.4} \pm 4.2$	$22.6 \pm 1.8 \pm 2.2$	$20.8^{+6.0+2.8}_{-6.3-3.1}$
$B^+ \to \rho^0\pi^+$	$10.4^{+3.3}_{-3.4} \pm 2.1$	$24 \pm 8 \pm 3$	$8.0^{+2.3}_{-2.0} \pm 0.7$
$B^+ \to \rho^+\pi^0$	< 43	–	–
$B^0 \to \rho^0\pi^0$	< 5.5	< 10.6	< 5.3



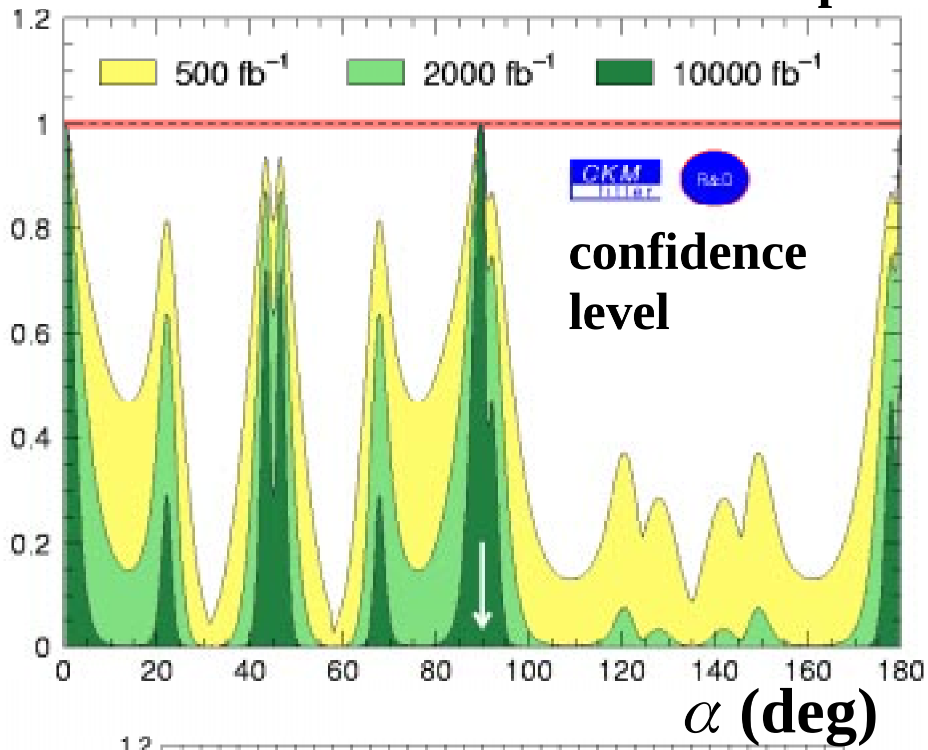




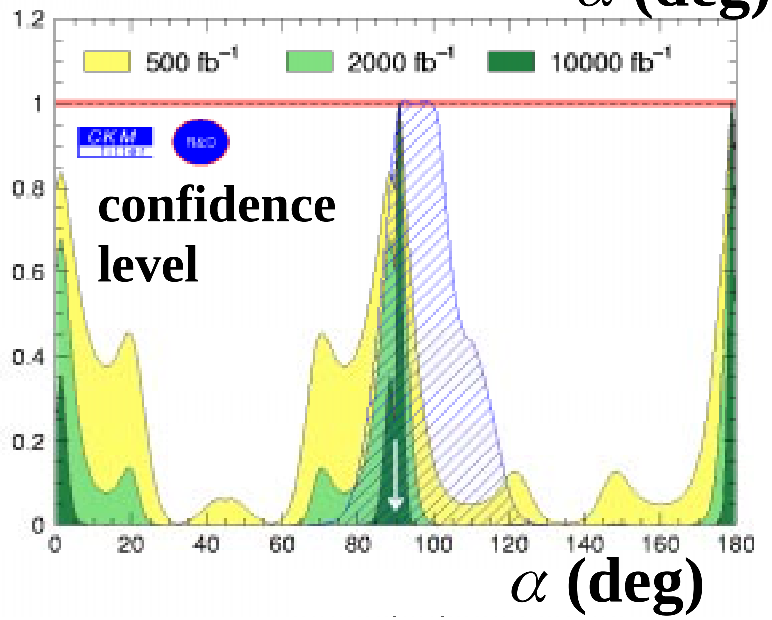
Trying the isospin triangle analysis for $\rho\pi$:

- on 500 fb^{-1} with the current WA BRs, C and S values and BR($B^0 \to \rho^0\pi^0$) = 0.9 · 10^{-6}
- not much sensitivity to α

Stark's talk at the CKM workshop

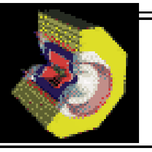


- assume BR($B^0 \to \rho^0\pi^0$) to be below experimental sensitivity:
  - improved constraints,
  - SU(2) analysis gives meaningful constraints on α above 2 ab^{-1}



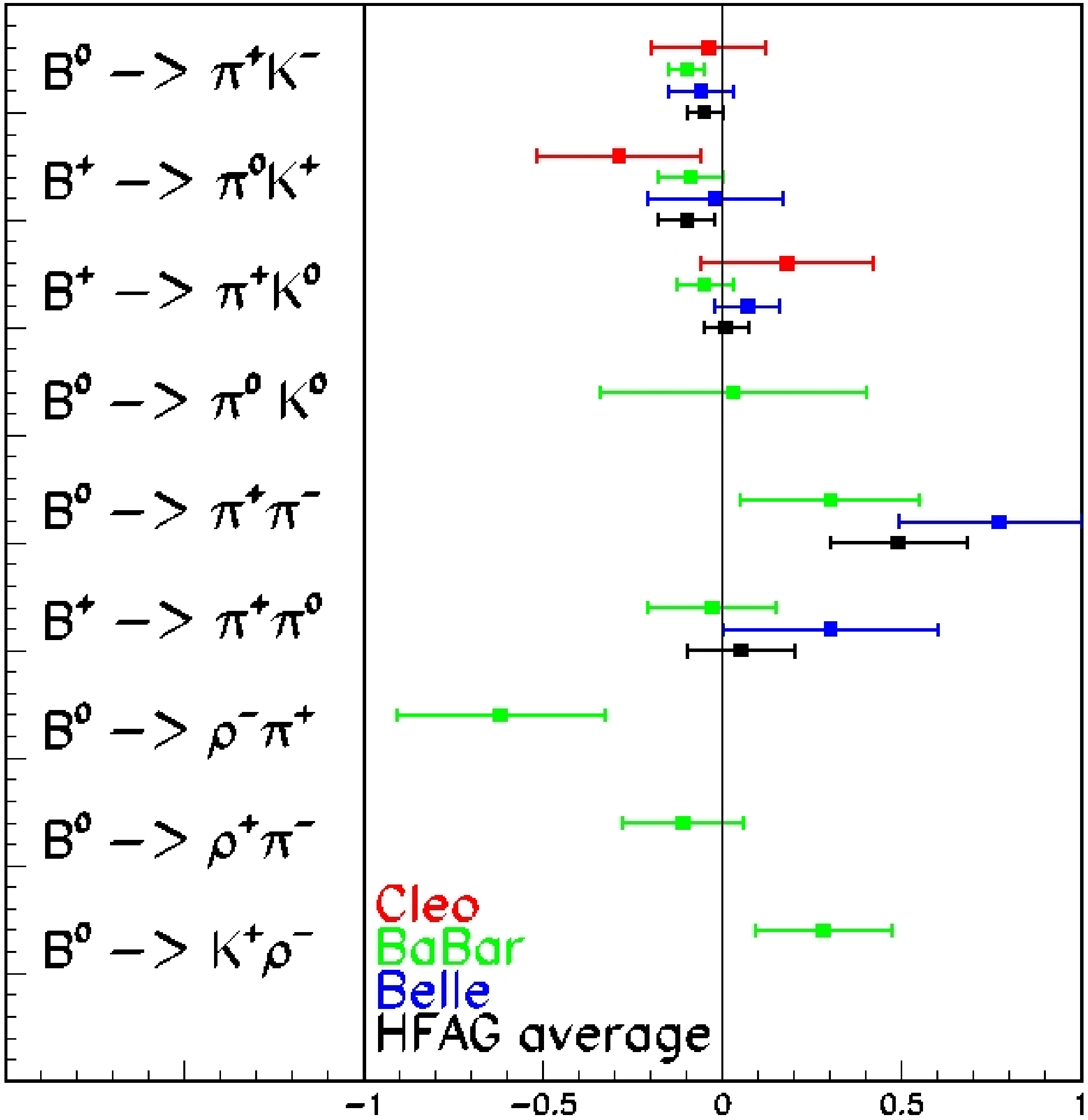
What's left? K$^*\pi$ and ρK...

- **K$^*\pi$ and ρK:**
  - same physics as Kπ
  - sensitivity to γ ?



mode	BR (10^{-6}) [UL @ 90% CL] Cleo	BaBar	Belle
$B^0 \to \rho^+ K^-$	$16^{+8}_{-6} \pm 3$	$7.3^{+1.3}_{-1.2} \pm 1.2$	$16 \pm 5^{+2}_{-3}$
$B^+ \to \rho^0 K^+$	< 17	< 29	< 12
$B^+ \to \rho^+ K^0$	< 48	$-$	$-$
$B^0 \to \rho^0 K^0$	< 39	$-$	< 12
$B^0 \to K^{*+} \pi^-$	$16^{+6}_{-5} \pm 2$	$-$	< 30
$B^+ \to K^{*0} \pi^+$	$7.6^{+3.5}_{-3.0} \pm 1.6$	$15.5 \pm 3.4 \pm 1.8$	$19.4^{+4.2+2.1+3.5}_{-3.9-2.1-6.8}$
$B^+ \to K^{*+} \pi^0$	< 31	$-$	$-$
$B^0 \to K^{*0} \pi^0$	< 3.6	$-$	$-$

Asymmetry measurements:



tagging needed for $K^0\pi^0$, $\pi^+\pi^-$ $\pi^+\rho^-$, $\pi^-\rho^+$

These measurements are still statistical dominated

$$A^{+-} = \frac{BR(\bar{B}^0 \to \rho^+\pi^-) - BR(B^0 \to \rho^-\pi^+)}{BR(\bar{B}^0 \to \rho^+\pi^-) + BR(B^0 \to \rho^-\pi^+)}$$

$$A^{-+} = \frac{BR(\bar{B}^0 \to \rho^-\pi^+) - BR(B^0 \to \rho^+\pi^-)}{BR(\bar{B}^0 \to \rho^-\pi^+) + BR(B^0 \to \rho^+\pi^-)}$$

Summary and conclusions:

- Charmless two-body PP decays: the picture is getting clearer
  - penguins don't seem to be negligible: Kπ vs $\pi\pi$
  - the inputs for the isospin triangle analysis (IA) are starting to be usable:
    - $\pi^+\pi^0$ has been measured
    - still an upper limit on $\pi^0\pi^0$ ⇒ if high BR, IA not feasible?
    - too early for a significant constraint
- Charmless PV decays:
  - $\rho^+\pi^0$ and $\rho^0\pi^0$ still missing for the IA
  - full Dalitz plot analysis on its way
  - more missing pieces in the K^* land
- next years will be really interesting
  - most measurements are statistically limited
  - exciting times for angles and direct asymmetries