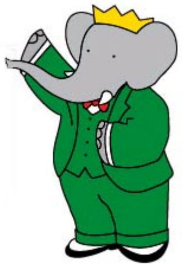
Recent Results on Charmless Hadronic Decays at BABAR



Gagan Mohanty, Tata Institute
(formerly at University of Warwick)

KEK Physics Seminar

28 April 2009

Where is BABAR these days?

Was in Stockholm few months back

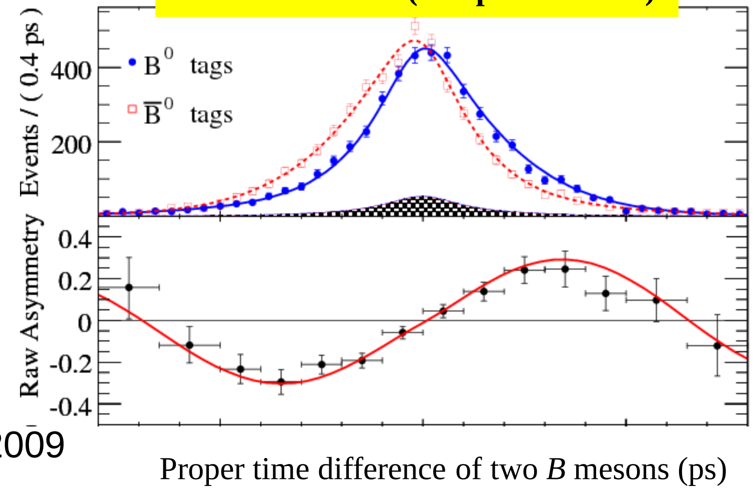
Half of the 2008 Nobel prize in Physics goes to...

Makoto Kobayashi, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
and
Toshihide Maskawa, Yukawa Institute for Theoretical Physics (YITP), Kyoto University, and Kyoto Sangyo University, Japan

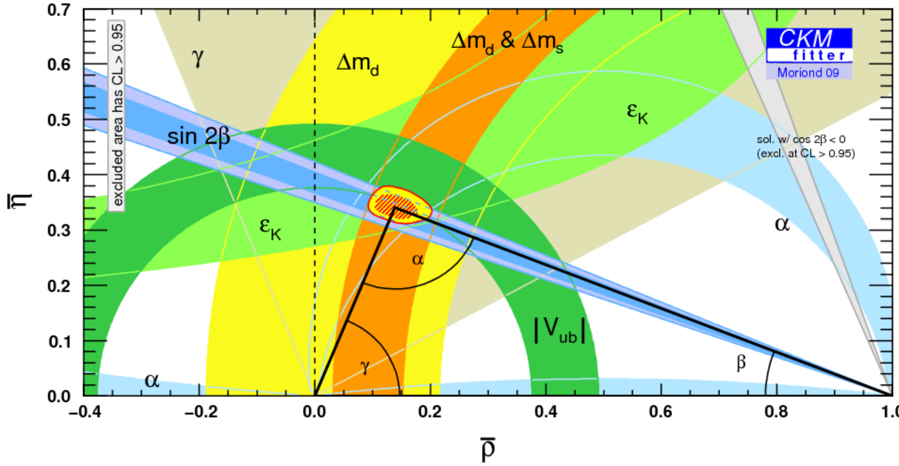
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

…As late as 2001, the two particle detectors **BABAR** at Stanford, USA and **Belle** at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as **Kobayashi** and **Maskawa** had predicted almost three decades earlier…

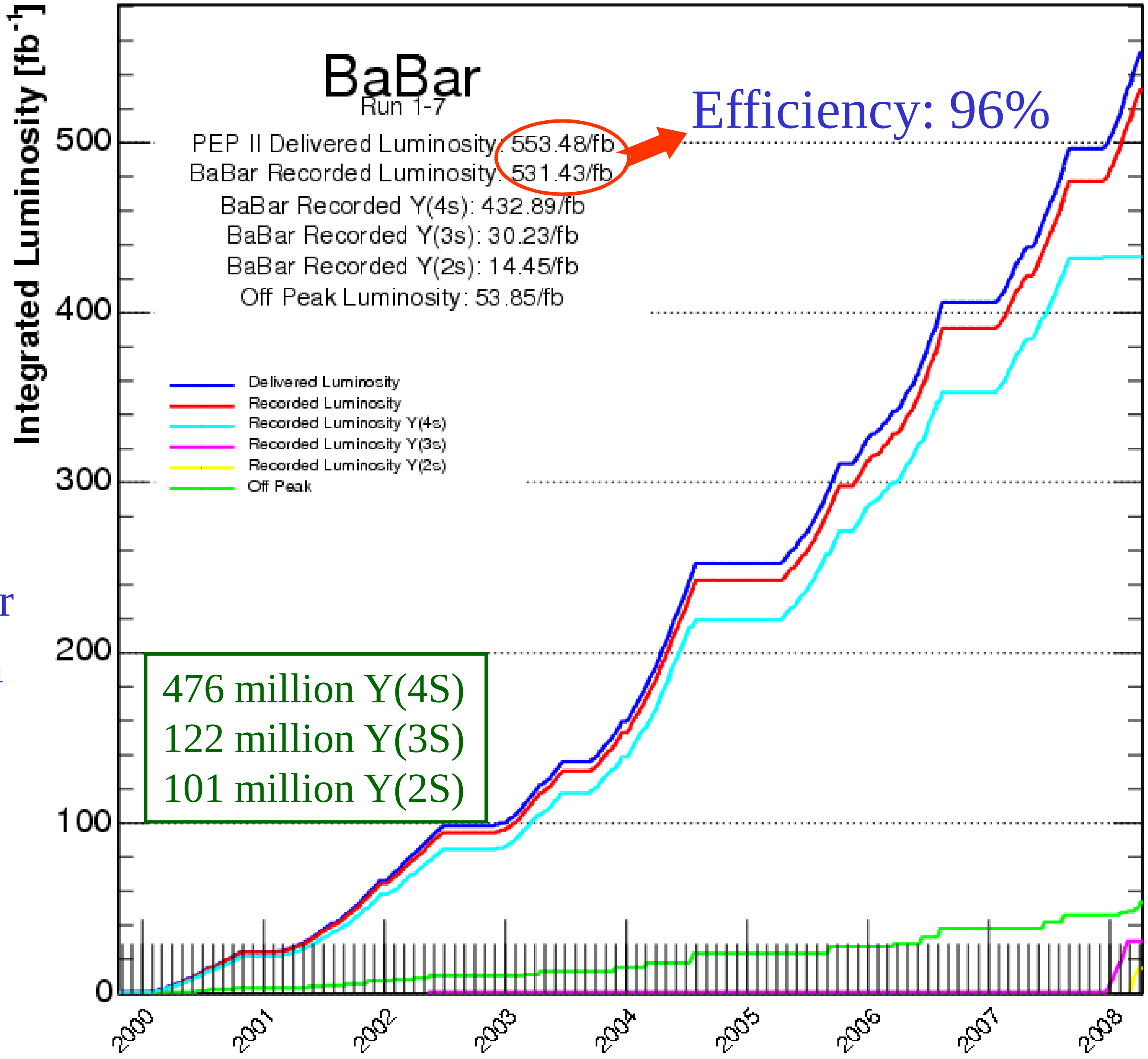
arXiv:0902.1708 (accepted to PRD)



The Unitarity Triangle (UT)



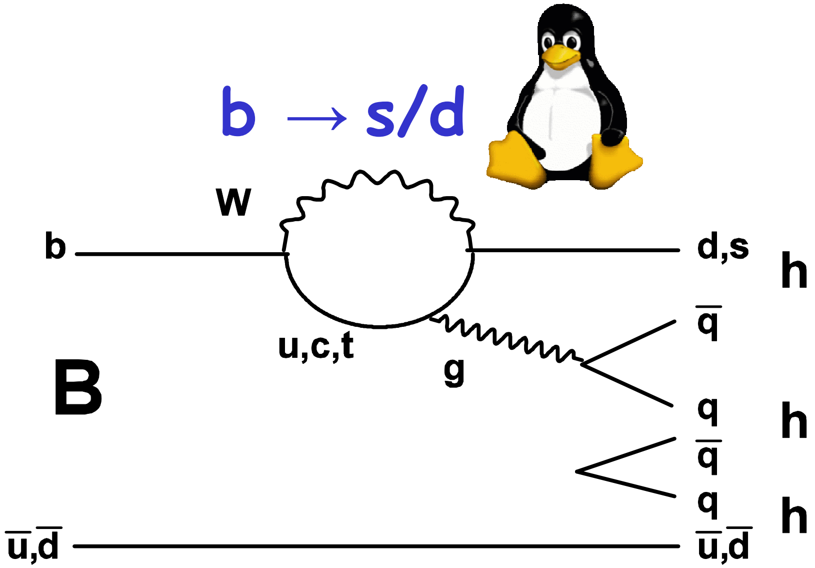
Final spreadsheet

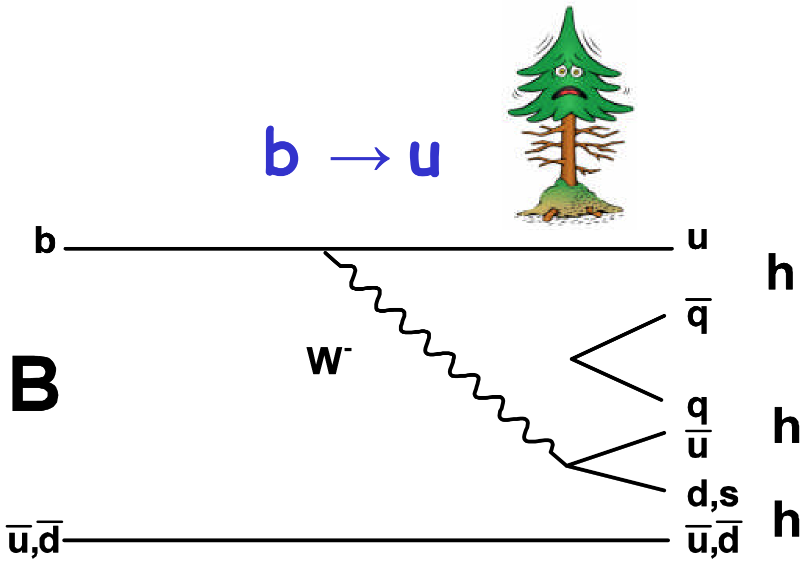


- One cycle is over
- Working hard on the next one:

Physics
Physics
Physics

Define Charmless Decays





- Typical diagrams for charmless three-body *B* decays (h denotes *K* or π)

b→s loop (penguin) transition contributes only to the final states with odd number of kaons due to presence s quark *e.g. Kππ, KKK*

Final states with even number of kaons, such as *KKπ* get contributions from b→u tree (suppressed with V_{ub} factor) and b→d penguin diagrams

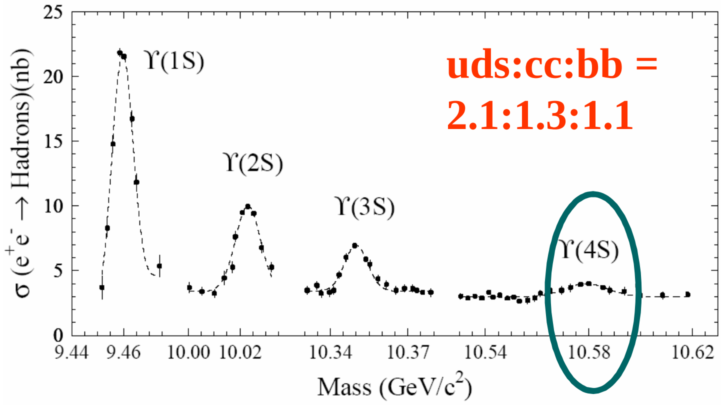
Its key role in testing SM

- Interfering tree and penguin amplitudes ➡ good place to look for direct *CP* violation
- Non-SM particles can appear in the loop diagrams (signature of new physics)
- Probes flavor sector by measuring
  - sin(2β) or just β in the $K_S h^+ h^-$ (K/π) Dalitz plot
  - α in the modes: ππ, ρπ and ρρ
  - γ using flavour symmetries (isospin, U-spin *etc*.)
- Low-lying meson spectroscopy
- Test varieties of dynamical models for hadronic *B* decays – pQCD, factorization, SU(3) flavor symmetry …

Analysis Strategy

Inclusive

- Background fighting:
  - ✓ Continuum (event topology)
  - ✓ Other types of *B* decays (PID, charm and charmonia veto)
- Signal extraction (kinematics)



Full (3body) or partial (*Q2B*)

- Dalitz plot technique (three-body decays having reasonable signal size)

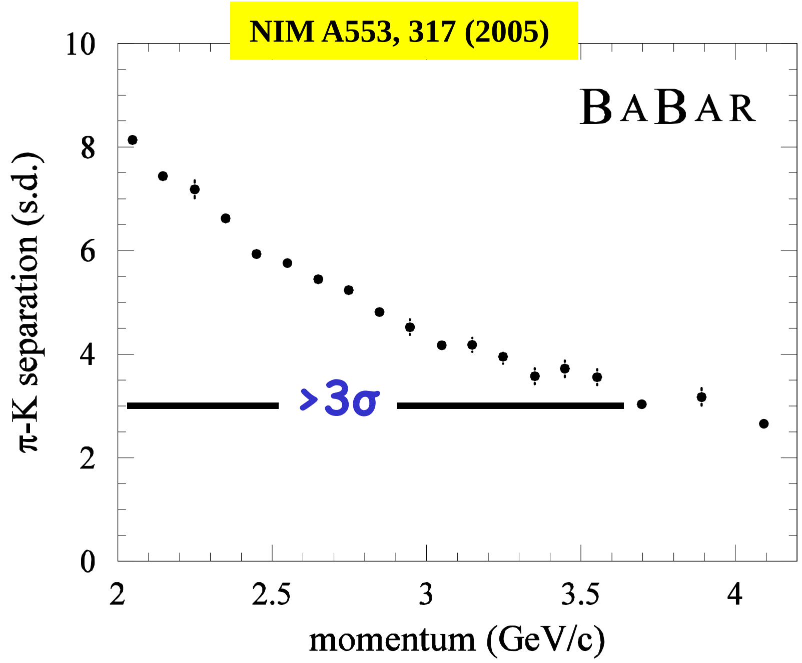
Time-dependent DP (3body)

- Time-dependent analysis in neutral *B* meson decays to determine *CP* violation parameters at each point of the phase space

Complexity

Particle Identification

- PID is crucial for these analyses
  - distinguish K vs. π

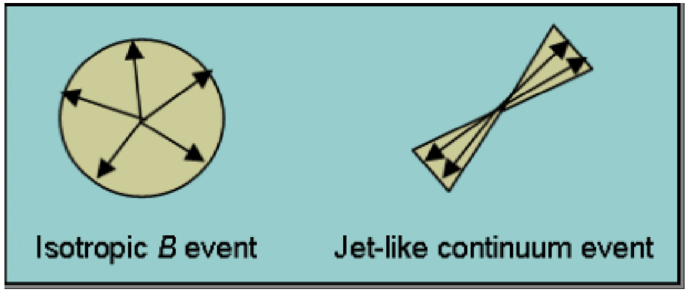


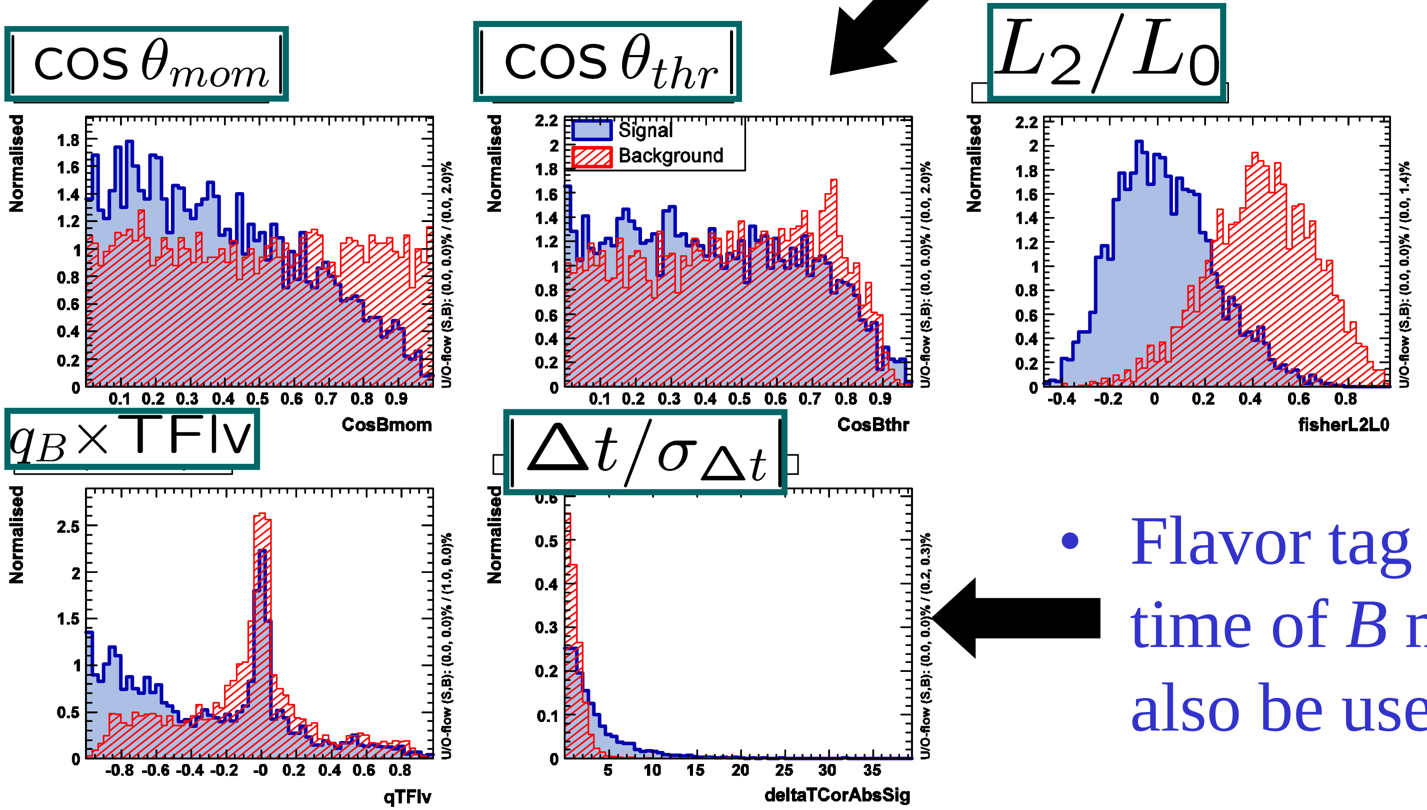
Ultimate PID

- Makes use of info from other sub-detectors, *e.g.* tracker, calorimeter

Continuum Suppression

- Exploit event topology
  - *B* meson produced at rest
  - Jet-like udsc events



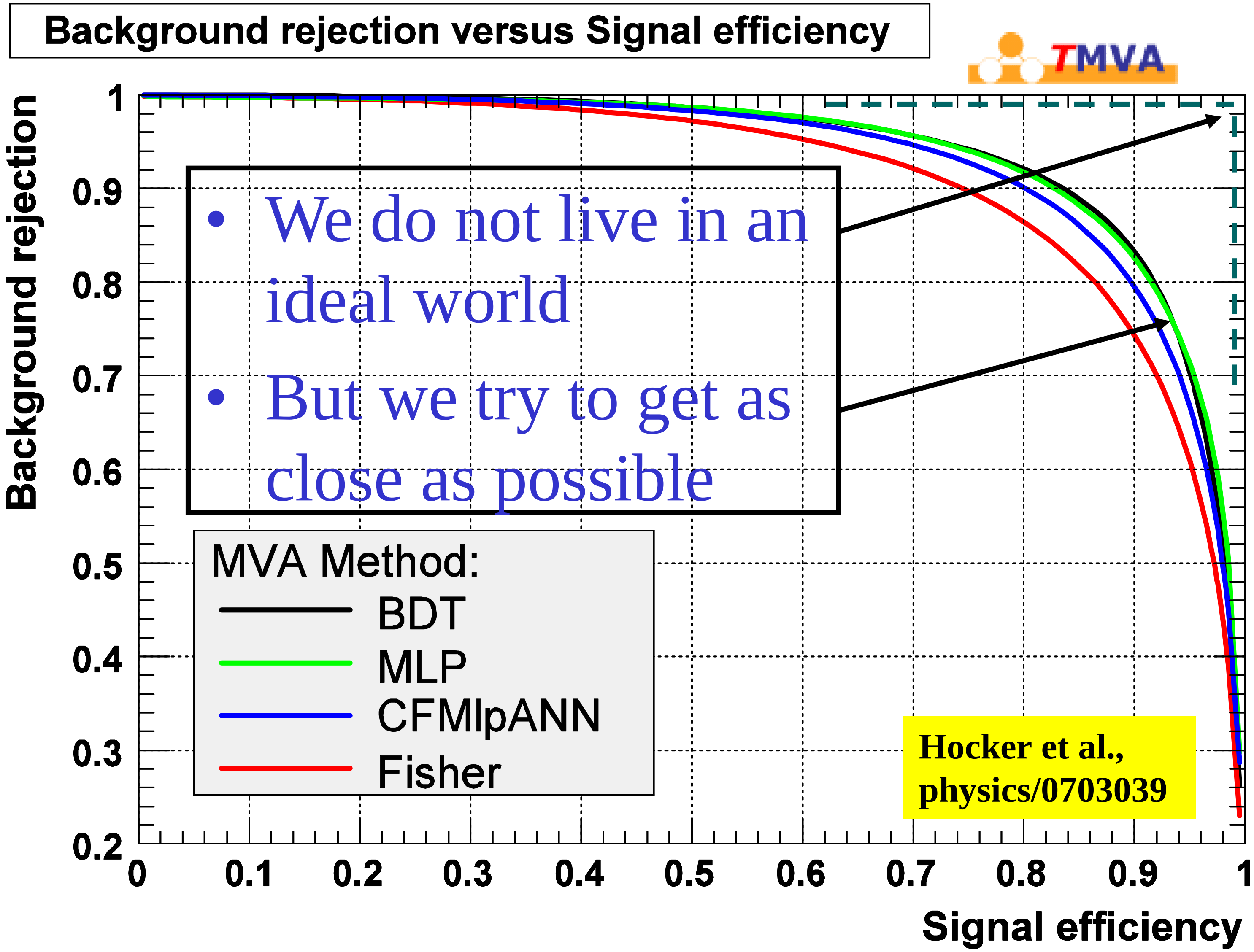


Signal

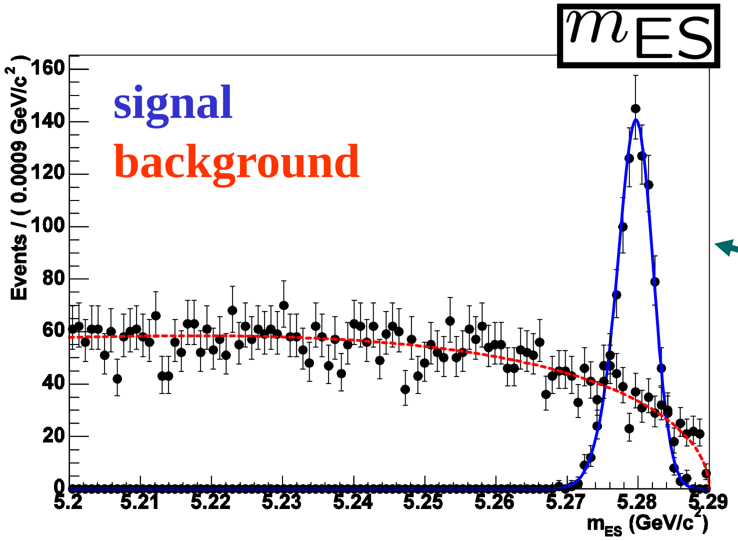
Background

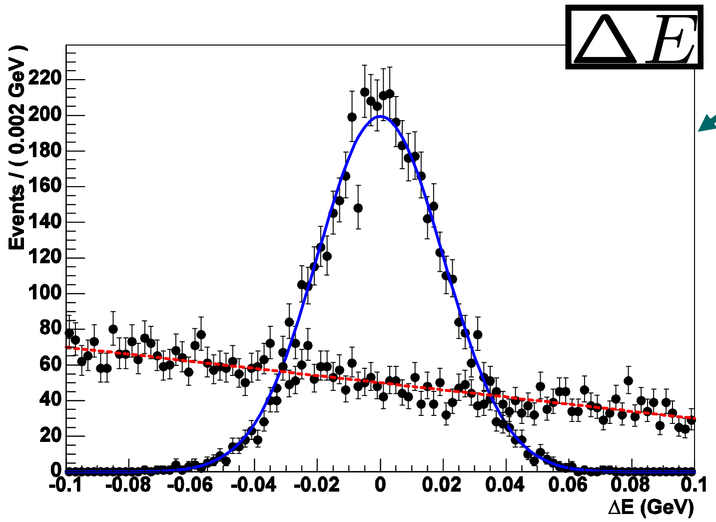
- Flavor tag and decay-time of *B* mesons can also be useful

Typical Performance



Kinematic Variables

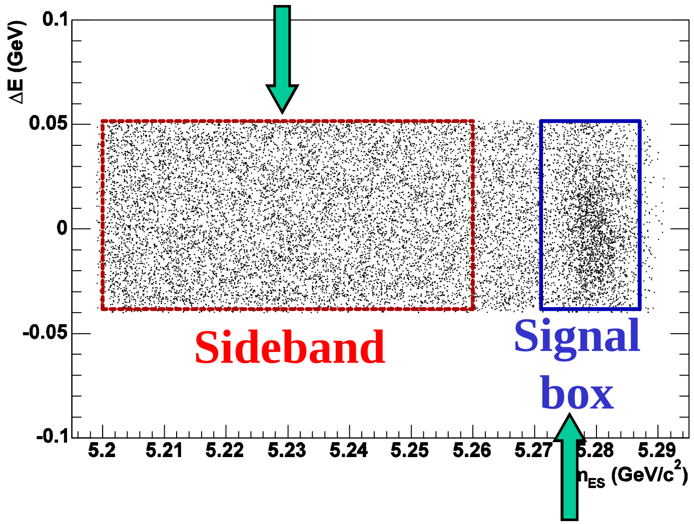




- Utilize the precise beam energy information and $(E,\mathbf{p})$ conservation

- $m_{ES} = \sqrt{E^{\star 2}_{beam} - \mathbf{p}^{\star 2}_{B}}$
- $\Delta E = (E^{\star}_{B} - E^{\star}_{beam})$

Background

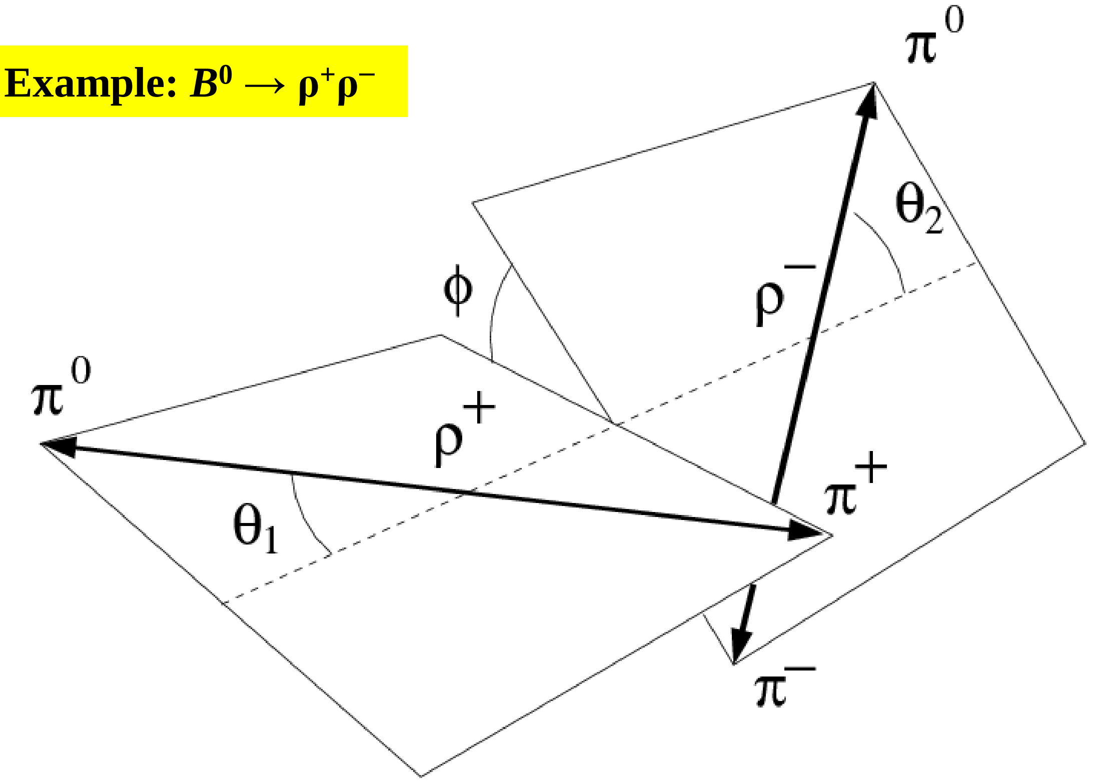


Analysis

$B \rightarrow VV$

Physics Observables

Example: $B^0 \to \rho^+\rho^-$



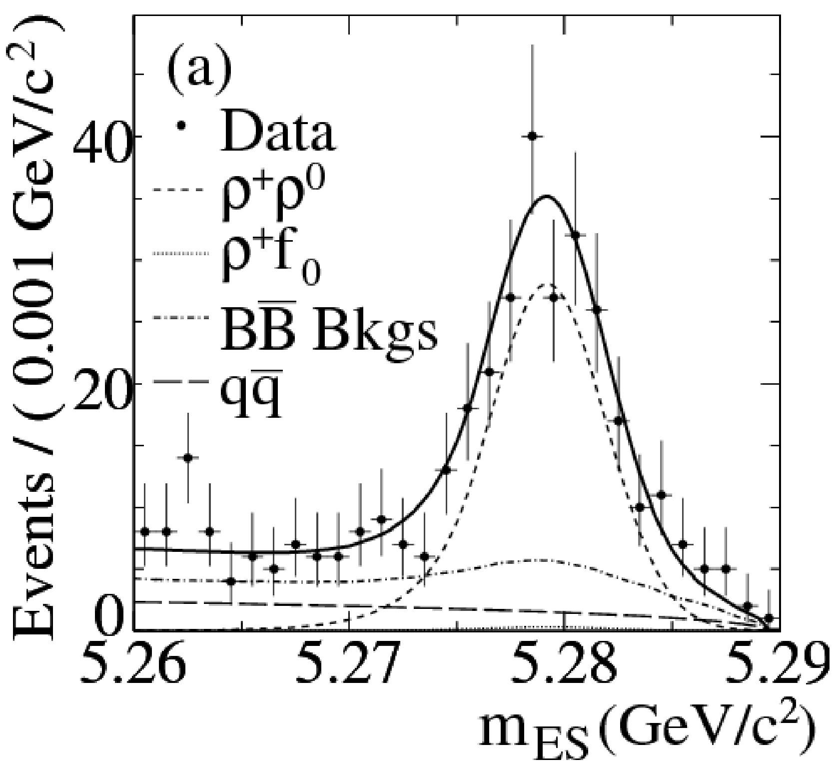
$$\frac{d^2N}{d\cos\theta_1\, d\cos\theta_2} = 4f_L\cos^2\theta_1\cos^2\theta_2 + (1-f_L)\sin^2\theta_1\sin^2\theta_2$$

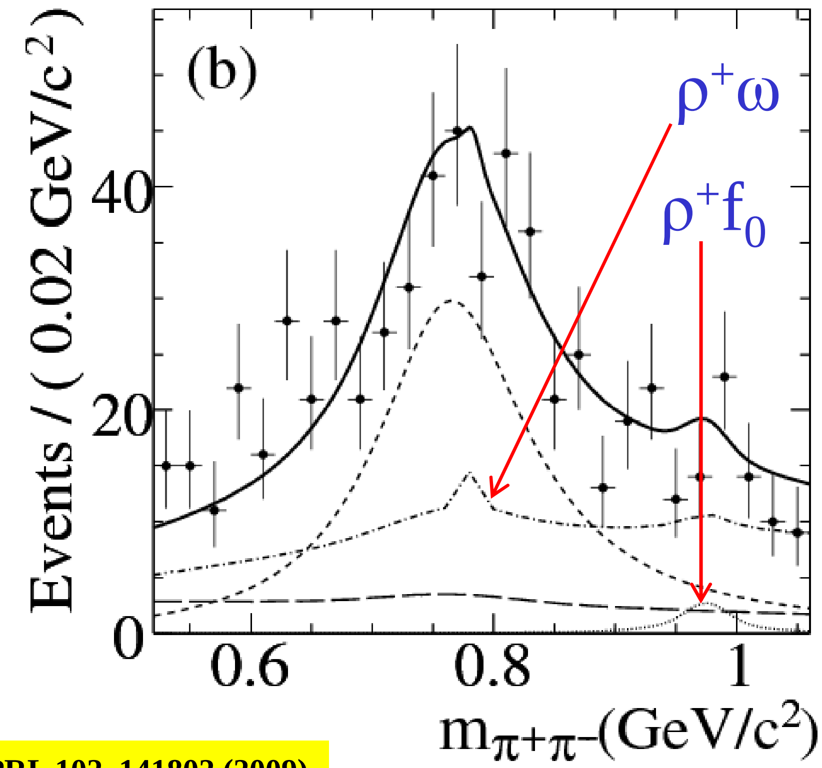
⟵ Longitudinal ⟶ ⟵ Transverse ⟶

- Measure the branching fraction and fraction of longitudinal polarization (f_L) simultaneously

Results on $B^+ \to \rho^+\rho^0$

- Fit m_{ES}, ΔE, NN, mass and helicity of two ρ candidates, constructed as $\pi^+\pi^0\pi^+\pi^-$





PRL 102, 141802 (2009)

$N(B^+ \to \rho^+\rho^0) = 1122 \pm 63$

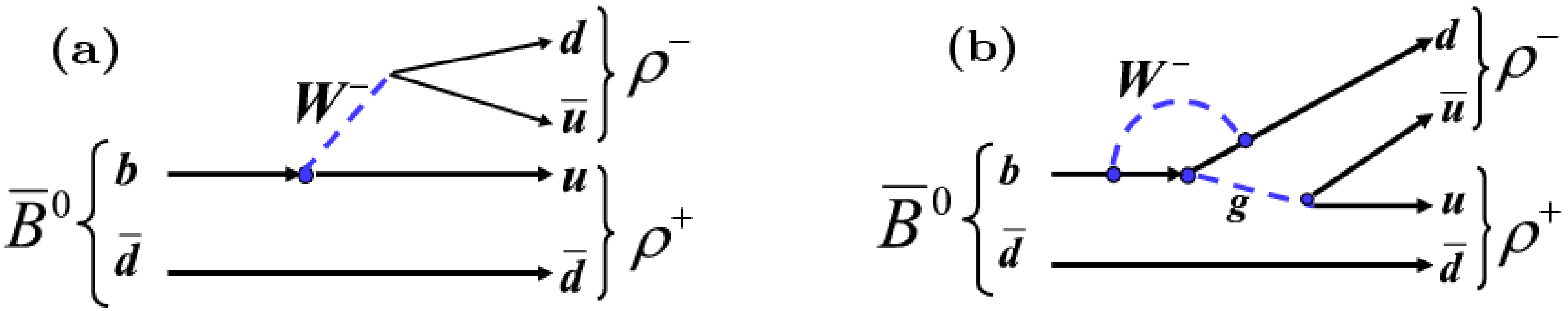
$BF(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4)\times10^{-6}$

$A_{CP} = -0.054 \pm 0.055 \pm 0.010$

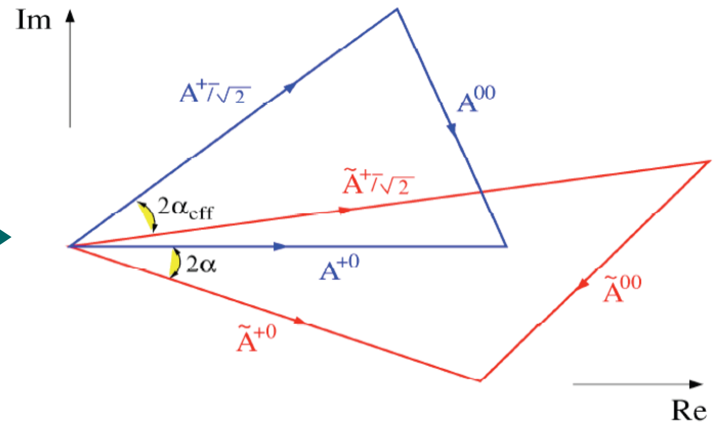
$f_L = 0.950 \pm 0.015 \pm 0.006$

Isospin Analysis of $B \to \rho\rho$ system

- The $b \to u$ tree amplitude (a) and $B^0\overline{B}^0$ mixing allow us to measure the UT angle α $(\pi-\beta-\gamma)$ in $B^0 \to \rho^+\rho^-$
- Modifies to α_{eff} due to the possible $b \to d$ penguin contribution (b)

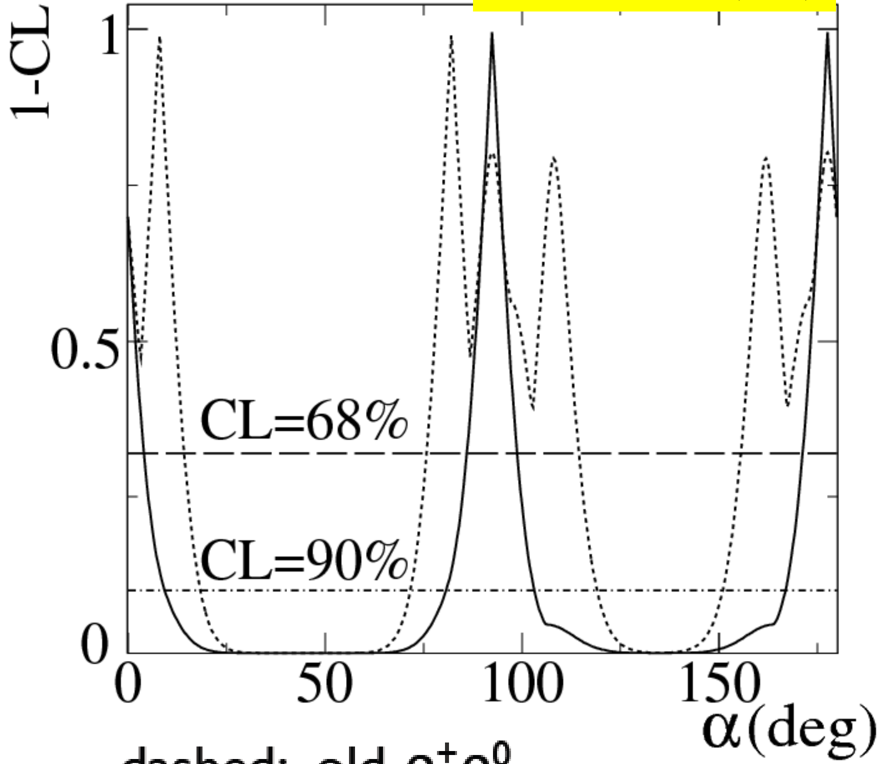


- Use SU(2) isospin symmetry to
  - ✓ relate all $B \to \rho\rho$ amplitudes
  - ✓ get a handle on $\Delta\alpha$ $(\alpha-\alpha_{eff})$



Measurement of angle $\alpha(\varphi_2)$

PRL 102, 141802 (2009)

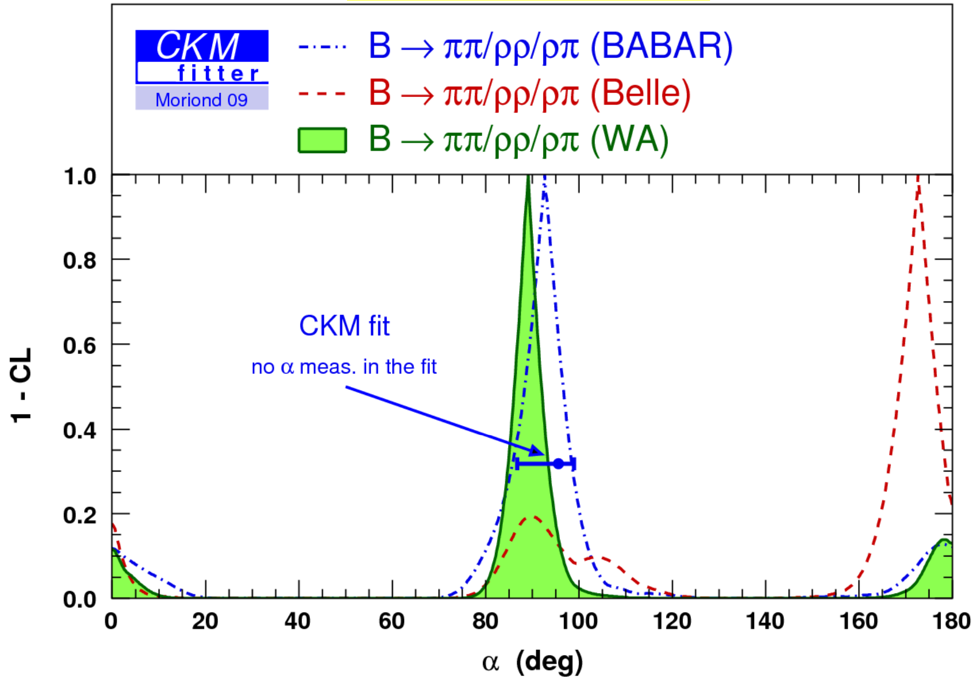


dashed: old $\rho^+\rho^0$

solid: new $\rho^+\rho^0$

$$\alpha = (92.4^{+6.0}_{-6.5})^o$$

Current world-average



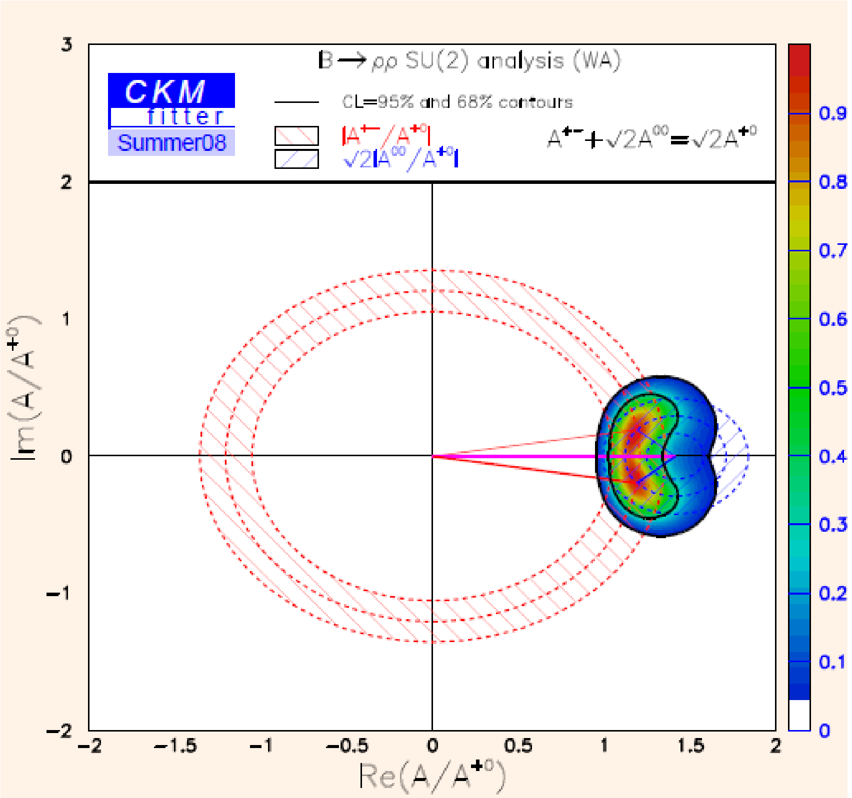
direct measurement

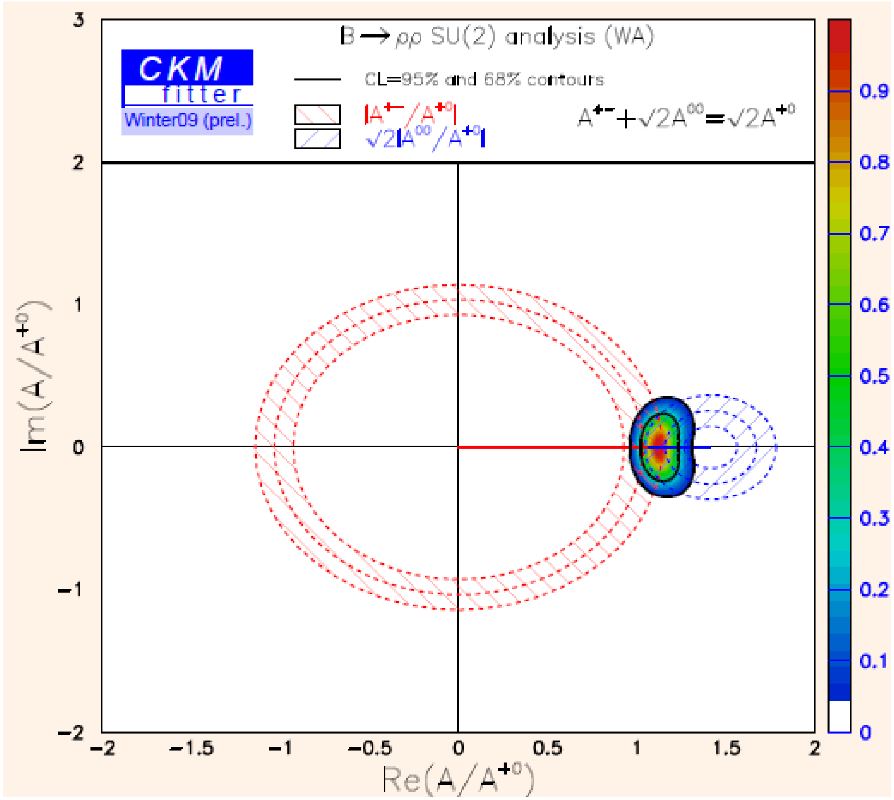
$$\alpha = (89.0^{+4.4}_{-4.2})^\circ$$

indirect CKM fit

$$\alpha = (95.6^{+3.3}_{-8.8})^\circ$$

How did it improve so much?

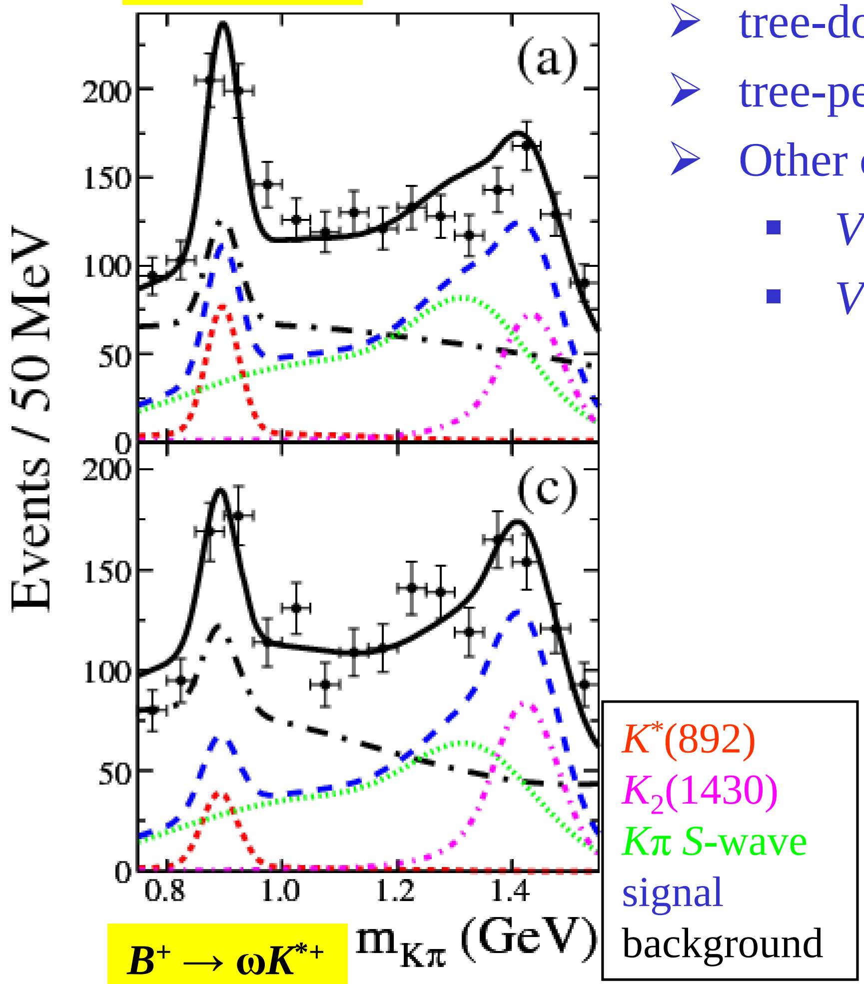




- Isospin angle flattens out, thanks to the large base formed by BF($B^+ \to \rho^+\rho^0$)
- Two distinct solutions (left) → single solution (right)
- Belle's final results on $B \to \rho\rho$, especially $\rho^+\rho^0$, are eagerly awaited for

Results on $B \to \omega\rho$, ωf_0 and ωK^*

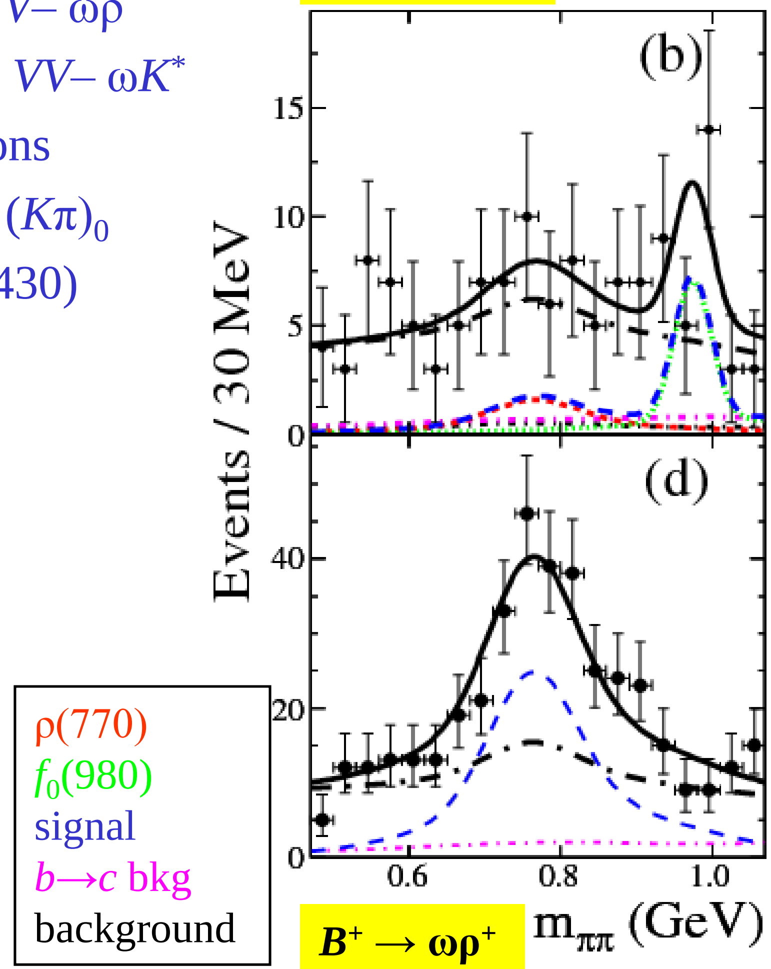
$B^0 \to \omega K^{*0}$



$B^+ \to \omega K^{*+}$

- Total 9 decay modes
  - tree-dominated *VV* – $\omega\rho$
  - tree-penguin mix *VV* – ωK^*
  - Other combinations
    - *VS* – ωf_0 or $(K\pi)_0$
    - *VT* – $\omega K_2(1430)$

$B^0 \to \omega\rho^0/f_0$



$B^+ \to \omega\rho^+$

Results on $B \to \omega\rho$, ωf_0 and ωK^*

1st observation

Mode	BF(×10⁻⁶)	Signif.	A_{CP}	f_L
$\omega\rho^0$	0.8±0.5±0.2	1.9	–	–
ωf_0	1.0±0.3±0.1	4.5	–	–
$\omega\rho^+$	15.9±1.6±1.4	9.8	−0.20±0.09±0.02	0.90±0.05±0.03
ωK^{*0}	2.2±0.6±0.2	4.1	0.45±0.25±0.02	0.72±0.25±0.02
ωK^{*+}	2.4±1.4±0.2	2.5	0.29±0.35±0.02	0.41±0.18±0.05
$\omega(K\pi)_0^{*0}$	18.4±1.8±1.7	9.8	−0.07±0.25±0.02	–
$\omega(K\pi)_0^{*+}$	27.5±3.0±2.6	9.2	−0.10±0.09±0.02	–
ωK_2^{*0}	10.1±2.0±1.1	5.0	−0.37±0.17±0.02	0.45±0.12±0.02
ωK_2^{*+}	21.5±3.6±2.4	6.1	0.14±0.15±0.02	0.56±0.10±0.04

- A_{CP} is measured by looking at the charge of B (K) in the charged (neutral) B meson decay
- $(K\pi)_0$ is parameterized with LASS line shape – the $K_0^*(1430)$ plus an effective-range nonresonant component

Results on $B^+ \to \overline{K}^{*0} K^{*+}$

- Occurs through both electroweak and gluonic b→d loop
- Expected branching fraction is in the range $(0.5\text{-}0.6)\times10^{-6}$

NPB 774, 64 (2007)

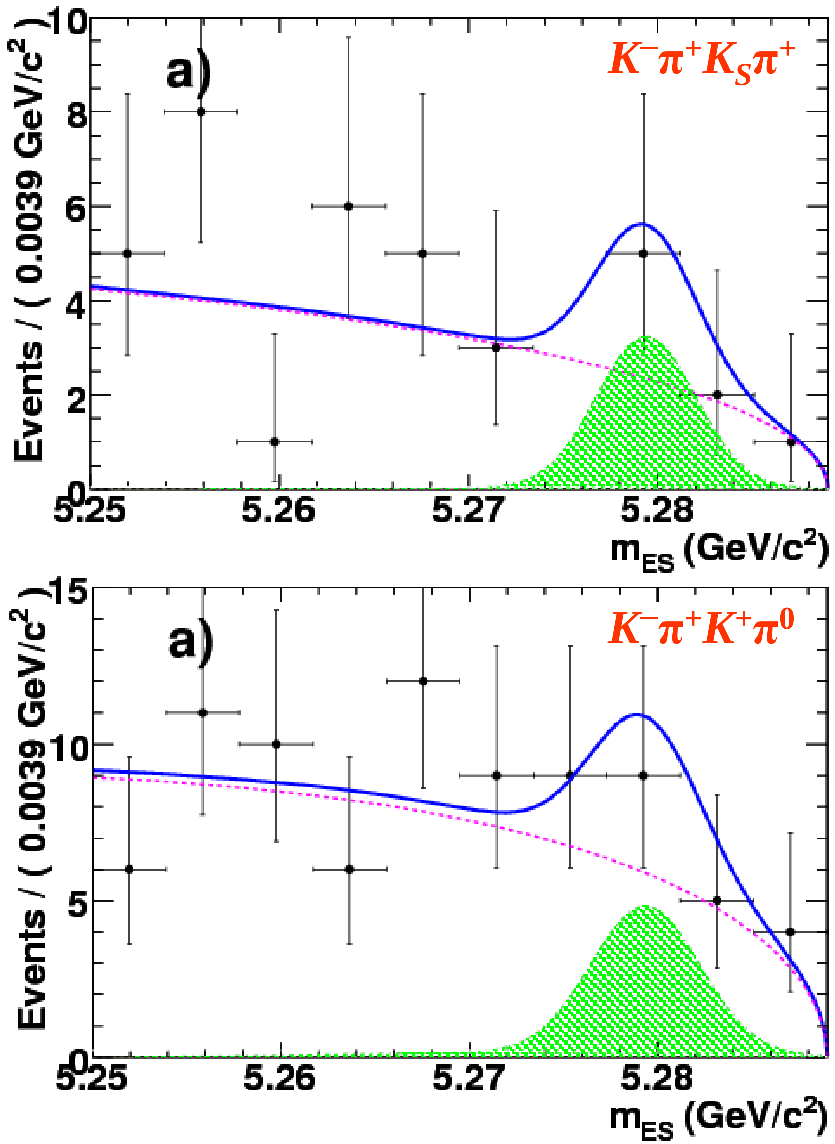
PRD 78, 094001 (2008)

- Fit to m_{ES}, ΔE, NN, mass and helicity of the two K^* candidates

arXiv:0901.1223 [hep-ex]

$$\mathcal{B} = (1.2 \pm 0.5 \pm 0.1) \times 10^{-6}$$
$$f_L = 0.75^{+0.16}_{-0.26} \pm 0.03$$

- 3.7σ significance including systematic and set 90% CL upper limit at 2×10^{-6}



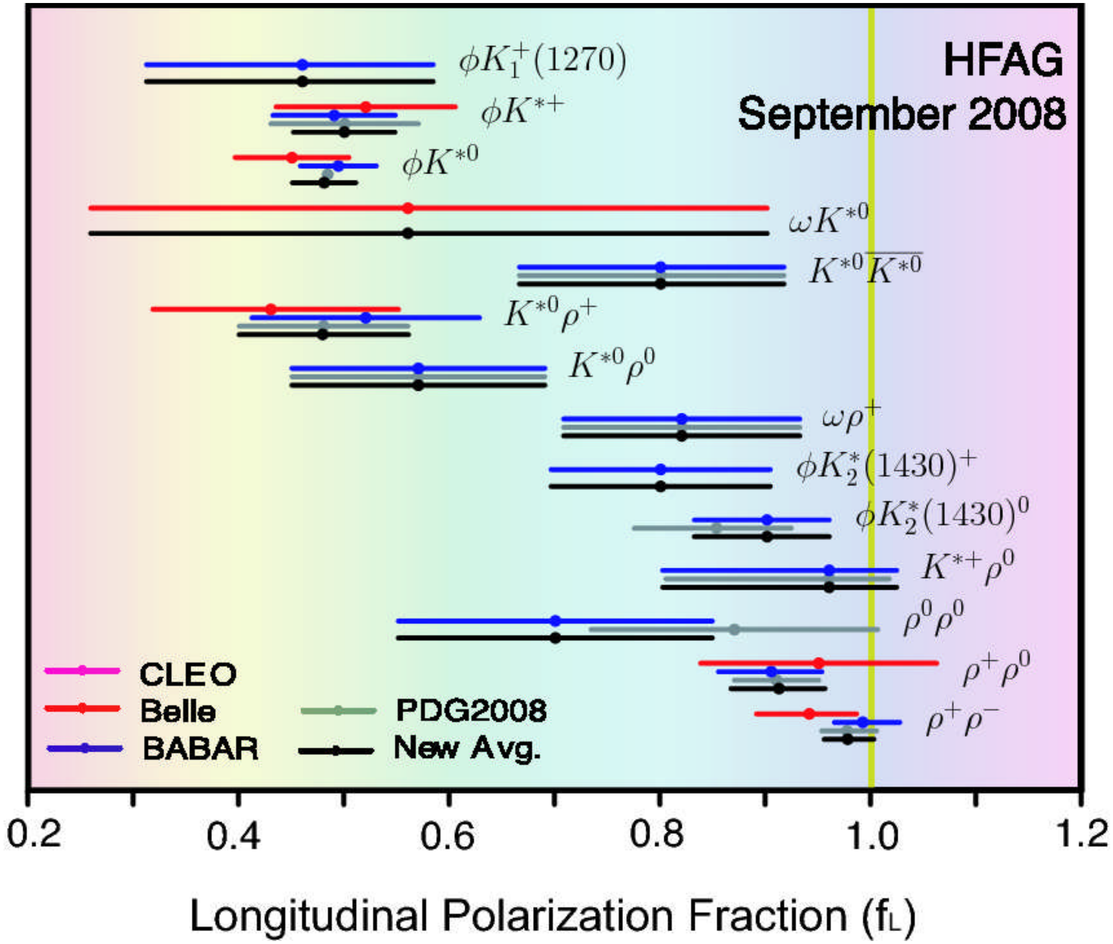
Polarization Puzzle

- $B \to \rho\rho$ decays fit to the expected pattern:

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

- One could say, within errors f_L for $K^*\overline{K}^{*0}$, $\omega\rho^+$, φK_2^* and ρK^{*+} follow the trend

- But what is going on for some of loop-dominated modes, e.g., φK^* or $\rho^+ K^{*0}$?



Nice review talks by Adrian and Nagashima-san at HINTS09

http://belle.kek.jp/hints09/program.html

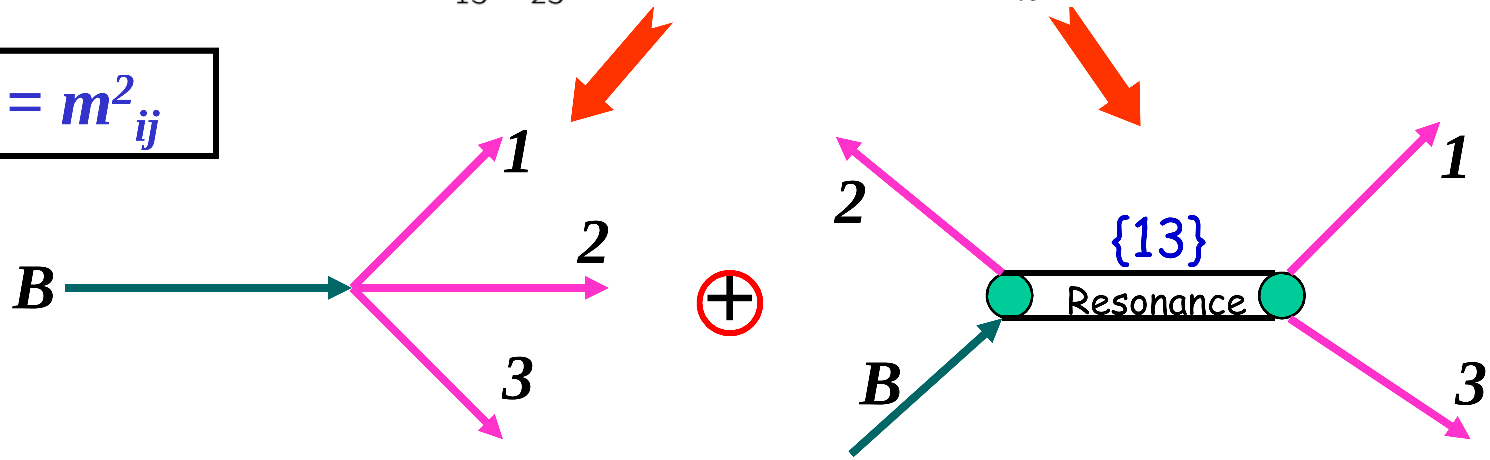
$B \rightarrow PPP$

Dalitz plot Analysis

- Powerful technique relying on Lorentz invariant phase-space variables in a three-body decay

Decay rate, $|\mathcal{A}|^2 = \frac{d\Gamma}{ds_{13}ds_{23}} \propto |c_{NR}e^{i\theta_{NR}} + \sum_k c_k e^{i\theta_k}\mathcal{D}_k(s_{13}, s_{23})|^2$

$s_{ij} = m^2_{ij}$



- Extract $\theta_{k,NR}$ and $c_{\theta,NR}$ in a maximum likelihood fit

$$\mathcal{L}(s_{13}, s_{23}) = f_{sig} \cdot \mathcal{L}_{sig}(\text{Model}, \epsilon_{sig}) + f_{bkg} \cdot \mathcal{L}_{bkg}$$

Dalitz plot Analysis [2]

- Fit fraction is the ratio of the integral of a single decay amplitude squared to the coherent sum of all

$$\sum_k F_k \neq 1$$

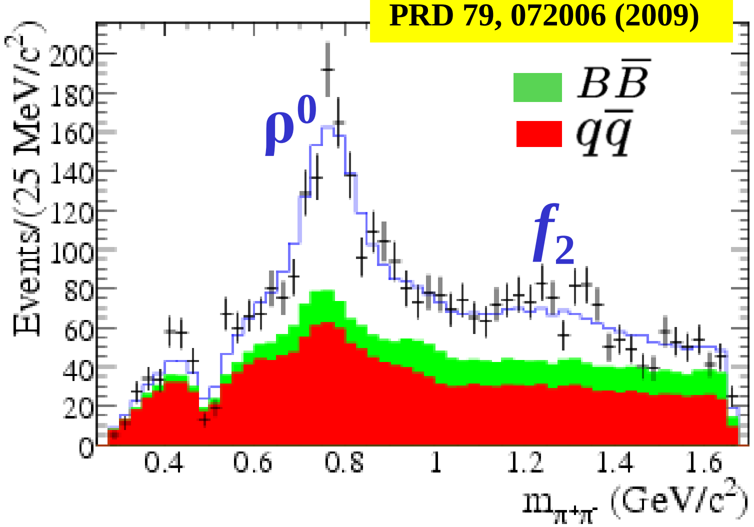
$$\mathcal{B}_k \Leftarrow \left(\frac{N_{sig}}{\bar{\epsilon} N_{B\bar{B}}}\right) \times$$

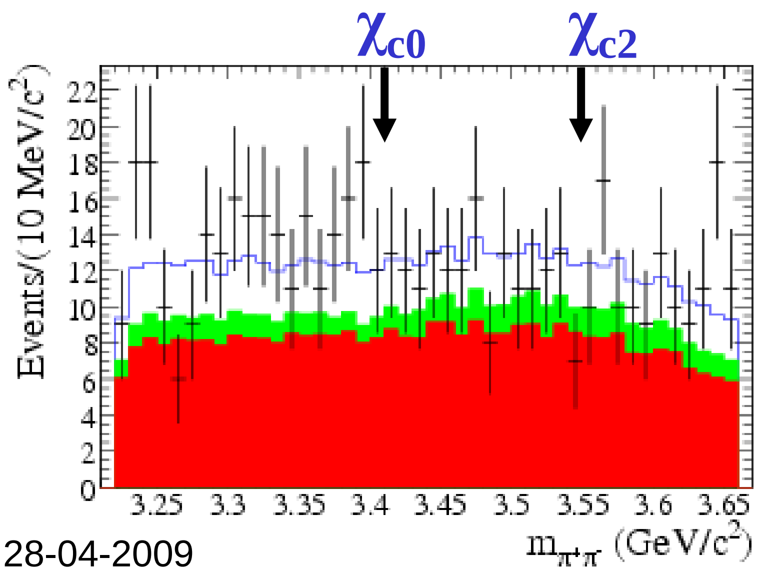
$$F_k = \frac{\int |c_k e^{i\theta_k} \mathcal{D}_k(s_{13}, s_{23})|^2 ds_{13} ds_{23}}{\int |\sum_j c_j e^{i\theta_j} \mathcal{D}_j(s_{13}, s_{23}) ds_{13} ds_{23}|^2}$$

- Measure *CP* violation asymmetries by comparing *B* and $\bar{B}$ decay amplitudes
  - Difference in the rate as well as in the phase

$B^+ \to \pi^+\pi^+\pi^-$ DP Analysis

PRD 79, 072006 (2009)

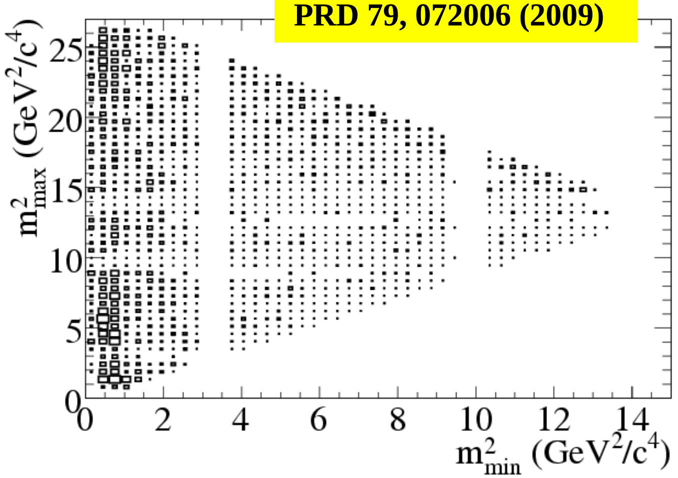


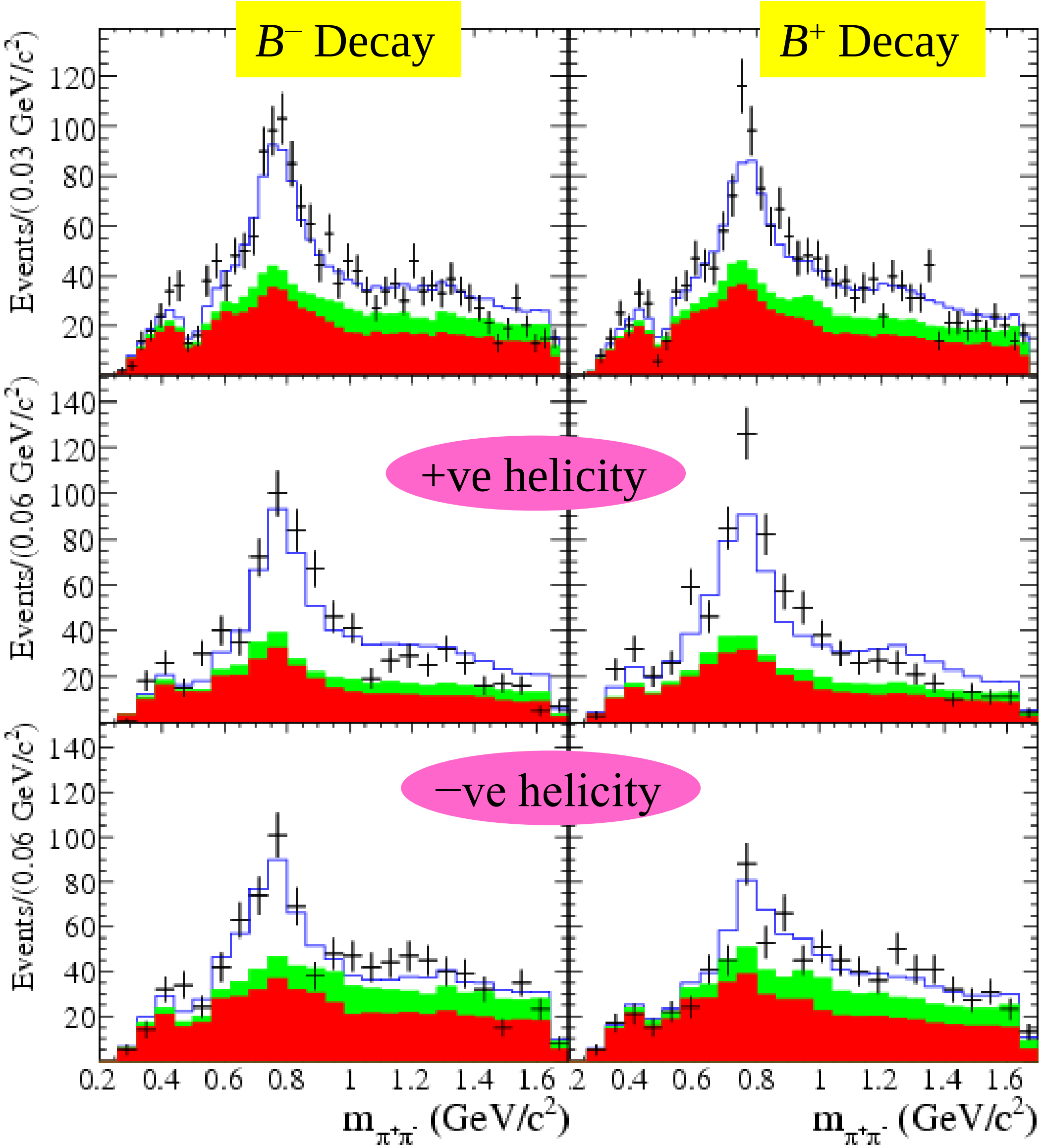


- ✓ Only available measurement of the charged $B \to \pi\pi\pi$ Dalitz plot
- ✓ First observation of tensor-pseudo scalar decay $B^\pm \to f_2(1270)\pi^\pm$
- ✓ Useful inputs toward a precision measurement of the UT angle α
  - ❑ Time-dependent analysis of $B^0 \to (\rho\pi)^0$ Dalitz plot PRD 48, 2139 (1993)
- ✓ No signatures of χ_{c0} and χ_{c2}
- ✓ Precludes the measurement of the UT angle γ PRL 81, 9067 (1998)

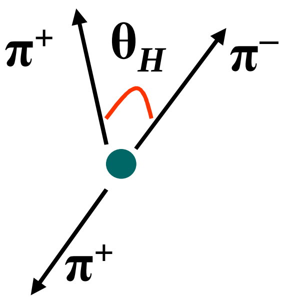
$B^+ \to \pi^+\pi^+\pi^-$ DP analysis

PRD 79, 072006 (2009)





- (Top) Background-subtracted Dalitz plot of candidate events
- No evidence for *CP* violation



Wealth of Measurements

PRD 79, 072006 (2009)

Mode	Fit Fraction (%)	$\mathcal{B}(B^\pm \to \text{Mode})(10^{-6})$	$\mathcal{A}_{CP}$ (%)
$\pi^\pm\pi^\pm\pi^\mp$ Total		$15.2 \pm 0.6 \pm 1.2\,^{+0.4}_{-0.3}$	$+3.2 \pm 4.4 \pm 3.1\,^{+2.5}_{-2.0}$
$\rho^0(770)\pi^\pm$; $\rho^0(770) \to \pi^+\pi^-$	$53.2 \pm 3.7 \pm 2.5\,^{+1.5}_{-7.4}$	$8.1 \pm 0.7 \pm 1.2\,^{+0.4}_{-1.1}$	$+18 \pm 7 \pm 5\,^{+2}_{-14}$
$\rho^0(1450)\pi^\pm$; $\rho^0(1450) \to \pi^+\pi^-$	$9.1 \pm 2.3 \pm 2.4\,^{+1.9}_{-4.5}$	$1.4 \pm 0.4 \pm 0.4\,^{+0.3}_{-0.7}$	$-6 \pm 28 \pm 20\,^{+12}_{-35}$
$f_2(1270)\pi^\pm$; $f_2(1270) \to \pi^+\pi^-$	$5.9 \pm 1.6 \pm 0.4\,^{+2.0}_{-0.7}$	$0.9 \pm 0.2 \pm 0.1\,^{+0.3}_{-0.1}$	$+41 \pm 25 \pm 13\,^{+12}_{-8}$
$f_0(1370)\pi^\pm$; $f_0(1370) \to \pi^+\pi^-$	$18.9 \pm 3.3 \pm 2.6\,^{+4.3}_{-3.5}$	$2.9 \pm 0.5 \pm 0.5\,^{+0.7}_{-0.5}$ (< 4.0)	$+72 \pm 15 \pm 14\,^{+7}_{-8}$
$\pi^\pm\pi^\pm\pi^\mp$ nonresonant	$34.9 \pm 4.2 \pm 2.9\,^{+7.5}_{-3.4}$	$5.3 \pm 0.7 \pm 0.6\,^{+1.1}_{-0.5}$	$-14 \pm 14 \pm 7\,^{+17}_{-3}$
$f_0(980)\pi^\pm$; $f_0(980) \to \pi^+\pi^-$	—	< 1.5 (90% CL)	—
$\chi_{c0}\pi^\pm$; $\chi_{c0} \to \pi^+\pi^-$	—	< 0.1 (90% CL)	—
$\chi_{c2}\pi^\pm$; $\chi_{c2} \to \pi^+\pi^-$	—	< 0.1 (90% CL)	—

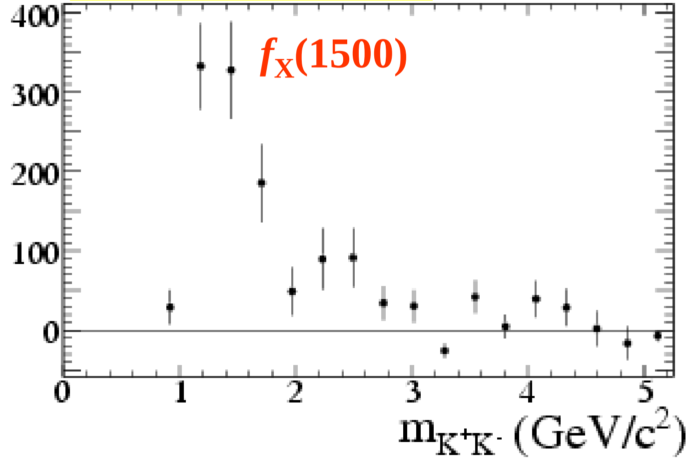
- Second solution: worse by 10 units of 2×NLL and $f_0(1370)\pi^\pm$ fit fraction is consistent with zero (3.0±1.9%)

- The *CP* asymmetry of $\rho^0(770)\pi^\pm$ has strong dependence on the presence or absence of the $f_0(1370)$ component

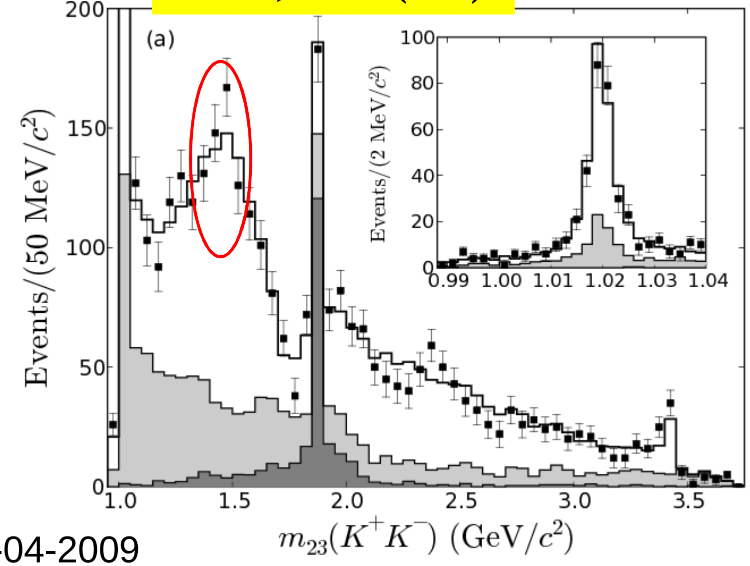
Search for the decay $B^+ \to K_S K_S \pi^+$

- Motivation from our earlier observation of an unexpected peak near 1.5 GeV/c^2 in the K^+K^- invariant-mass spectrum of the decay $B^+ \to K^+K^-\pi^+$
- Similar structures seen in DP analyzes of $B^+ \to K^+K^-K^+$ and $B^0 \to K_S K^+ K^-$

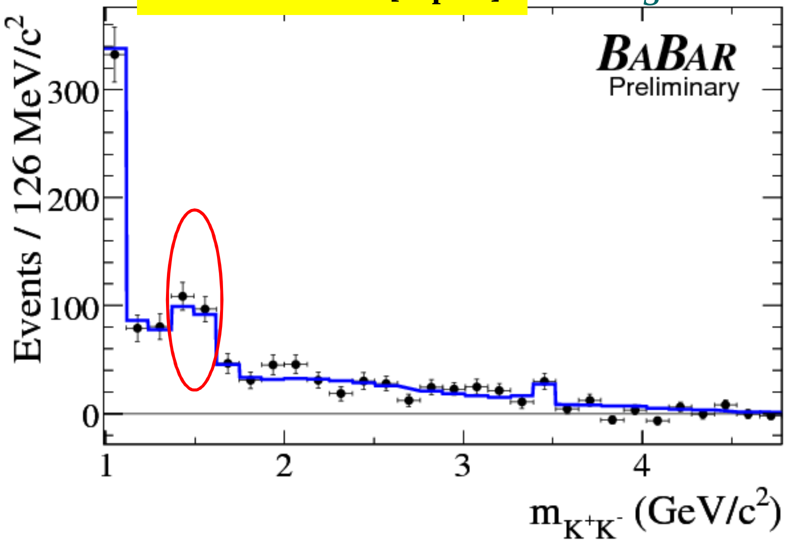
PRL 99, 221801 (2007) — $K^+K^-\pi^+$



PRD 74, 032003 (2006) — $K^+K^-K^+$



arXiv:0808.0700 [hep-ex] — $K_S K^+ K^-$



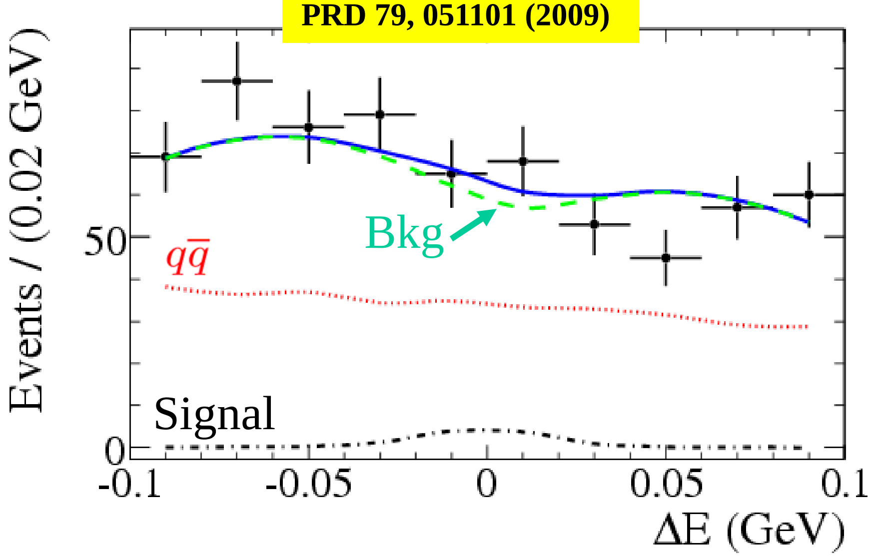
Search for the decay $B^+ \to K_S K_S \pi^+$

- Now the question is:
  - Is the $f_X(1500)$ a scalar or vector?
  - Does its decay obey isospin?
- Probe the decay of $B^+ \to K_S K_S \pi^+$ that is related by isospin
- No signal events are found
- Improved current BF upper limit by almost an order of magnitude

$32 \to 5\times10^{-7}$ @ 90%CL

- Result disfavours models in which the $f_X(1500)$ has even spin and decays with isospin symmetry

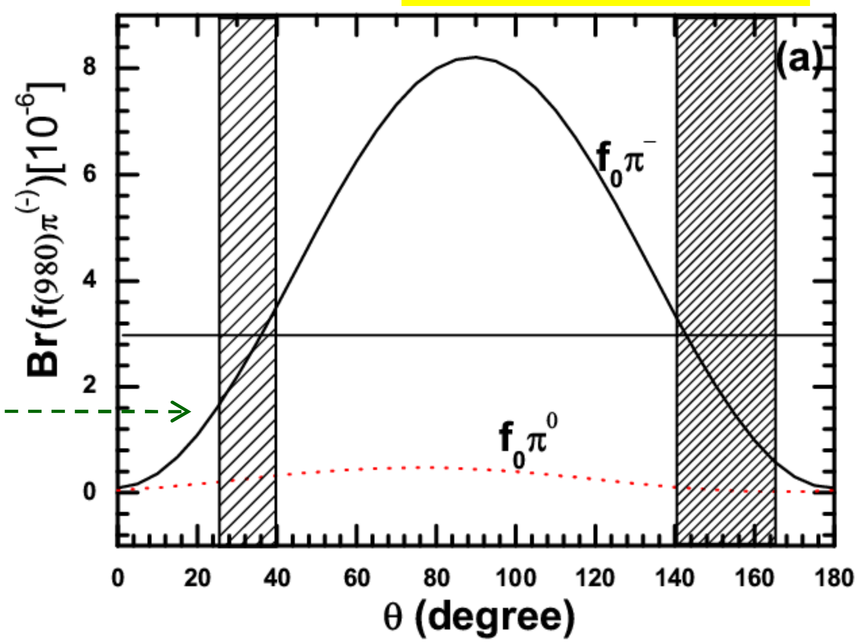
PRD 79, 051101 (2009)



SMS in Charmless *B* Decays

- Scalar Meson Spectroscopy
  - What are the $f_0(980)$, $f_0(1370)$, $f_X(1500)$...?
- Our results provide useful input to pin down properties of scalar mesons
  - The $f_0(980)$ seems to have a dominant $s\bar{s}$ component
  - If the $f_X(1500)$ is found to be a scalar, results on $B^+ \to K^+K^-\pi^+$ and $K_SK_S\pi^+$ indicate that it may have an exotic quark structure

arXiv: 0812.2314 [hep-ph]



- Would be nice to look for related decays of *B* mesons
  - $K_SK^+\pi^-$, $K^+K^-\pi^0$, $K_SK^+\pi^0$, and so on...

Closing Remarks

- A number of recent measurements in the charmless B decays performed with the full BABAR dataset at the Υ(4S) peak
  - $B^+ \to \rho^+\rho^0$
  - $B \to \omega K^*, \omega\rho, \omega f_0$
  - Evidence for $B^+ \to \overline{K}^{*0} K^{*+}$
  - Analysis of $B^+ \to \pi^+\pi^+\pi^-$ Dalitz plot
  - Search for $B^+ \to K_S K_S \pi^+$

- Ideal probe for the Standard Model
  - Weak interaction (CKM physics) by measuring the UT angle
    - ♠ Precision measurement of $\alpha(\varphi_2)$
  - Strong interaction (low energy spectroscopy) in the decays involving the $f_X(1500)$ *etc.*

- Mantle to be passed on to the next generation of flavor experiments ➡ LHCb and superKEKB