Branching Fractions and CP Violation in $B_d \to K\bar{K}$ at BaBar

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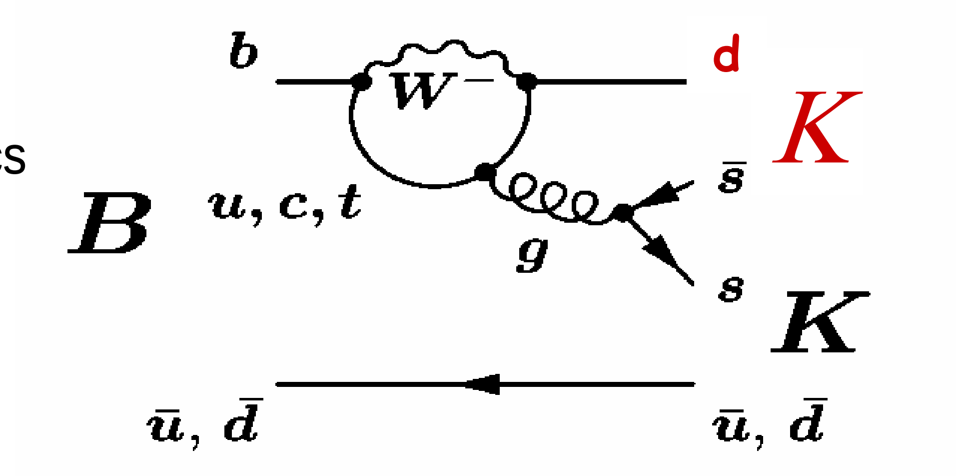
$B_d \to K^0\overline{K^0}$: Pure b → d Penguin Amplitude

- Modes dominated by loop (penguin) diagrams are sensitive to New Physics contributions
- Many New Physics models contribute additional CP-violating phases.
- $B \to K^0\overline{K^0}$ is dominated by the $b \to d$ transition
- Analogous to $b \to s$ penguins in ϕK_S
  - But new physics might affect $b \to d$ differently than $b \to s$
- Same penguin as in $B \to \pi^+\pi^-$ and $B \to \overline{K^0}K^+$
  - Useful for extracting α in the former and the annihilation contribution in the latter



Penguin modes are suppressed in the standard model

$b \to d$ further suppressed by $|V_{td} / V_{ts}|^2 = 0.043$ with respect to $b \to s$

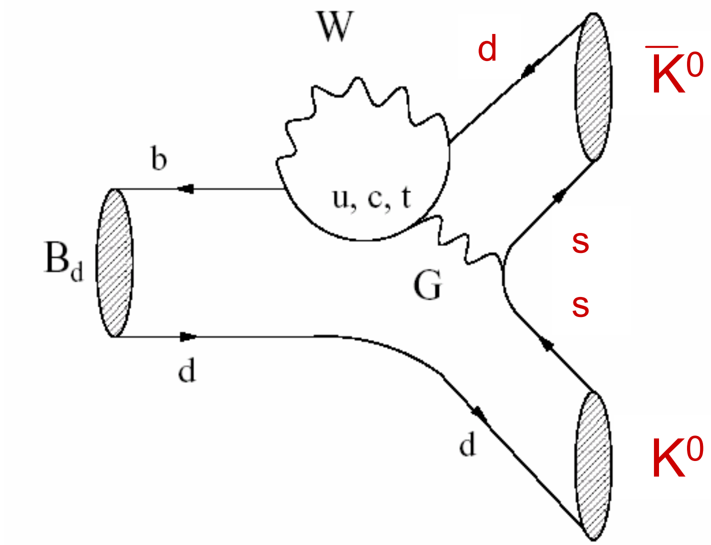
⇒ Small branching fractions

$B_d \to K^0\overline{K}^0$: Expectations from the Standard Model

- Assuming top-quark dominance:
  - BF ~ 10^{-6}
  - Decay weak phase exactly cancels mixing phase

$$\lambda \equiv \frac{q}{p}\frac{\overline{A}}{A} = \left(\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}\right)\left(\frac{V_{tb}V_{td}^{*}}{V_{tb}^{*}V_{td}}\right) = 1$$

  - Expect zero indirect CP violation
    - $S(K^0\overline{K}^0) = 0$
    - → any non-zero value would indicate New Physics
- Expect a small contribution from u- and c-penguins
  - $S(K^0\overline{K}^0) < 0.10$, sensitive to combination of all three UT angles



R. Fleischer and S. Recksiegel, Eur.Phys.J.C38:251-259,2004

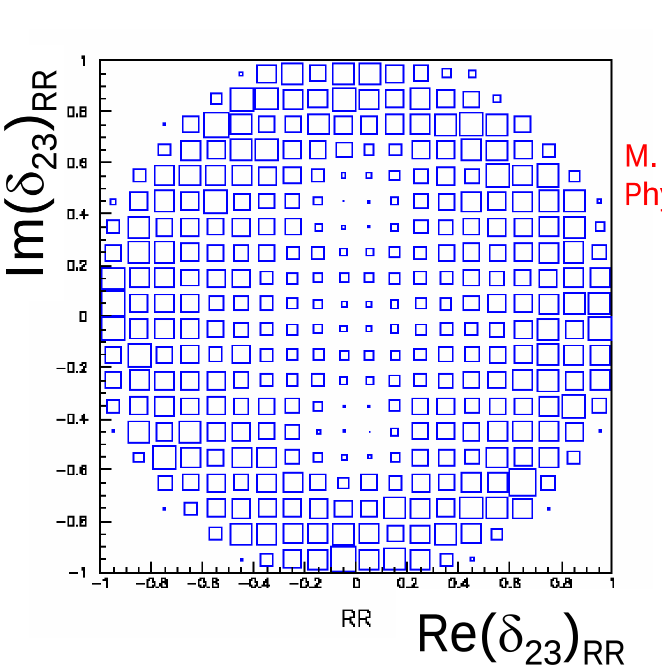
$$S_{KK}(\mathrm{SM}) = \frac{\sin 2\alpha + 2r\cos\delta\sin(2\beta+\gamma) - r^2\sin 2\beta}{1 + r^2 - 2r\cos\delta\cos\gamma}$$

$$C_{KK}(\mathrm{SM}) = \frac{-2r\sin\delta\sin\gamma}{1 + r^2 - 2r\cos\delta\cos\gamma} \qquad r = \frac{1}{\sqrt{\overline{\rho}^2 + \overline{\eta}^2}}\left|\frac{P_{ct}}{P_{ut}}\right|$$

Predictions (using QCD FA):

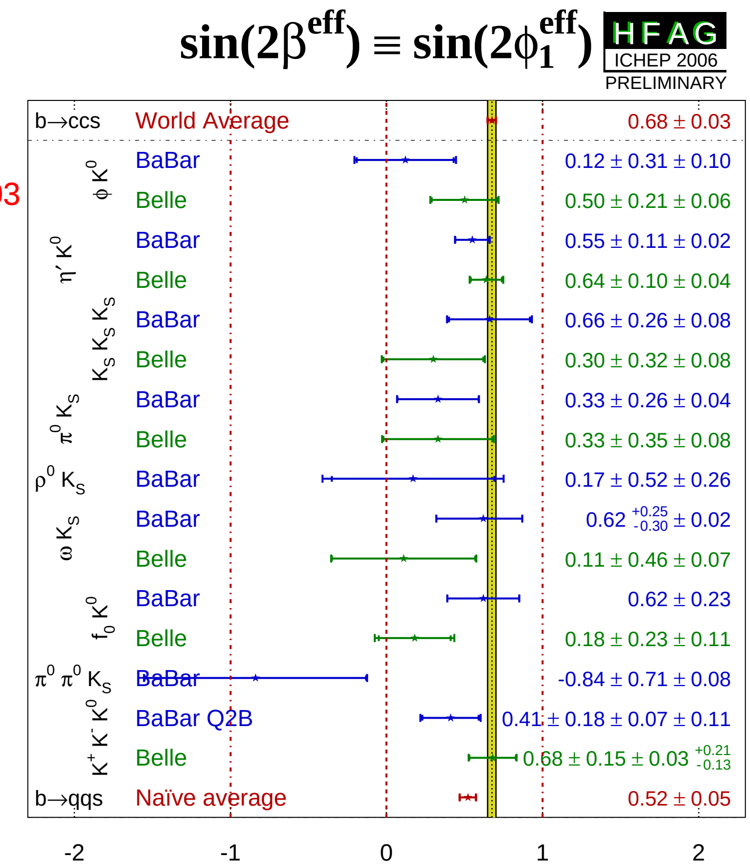
$$0.02 < S_{KK}(\mathrm{SM}) < 0.13$$
$$-0.17 < C_{KK}(\mathrm{SM}) < -0.15$$

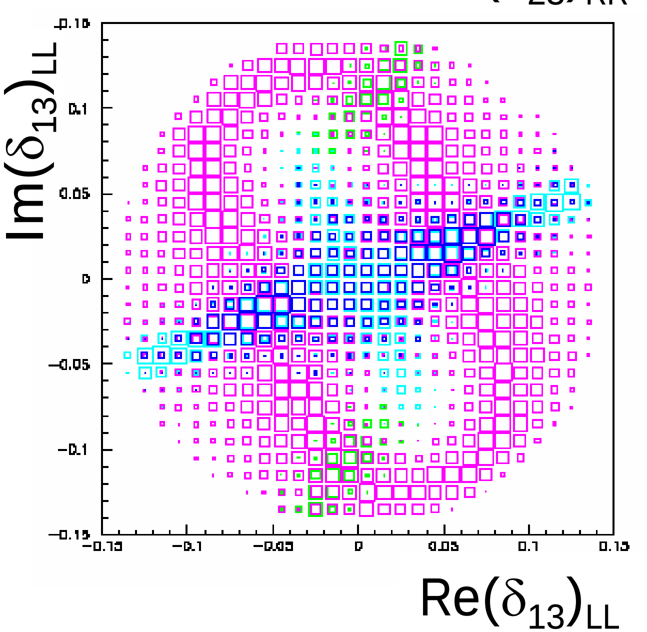
Flavor-Changing New Physics in Theory and Experiment



M. Ciuchini and L. Silvestrini, Phys. Rev. Lett. 97 (2006) 021803

b→s





M. Ciuchini *et al.*, hep-ph/0512141

b→d

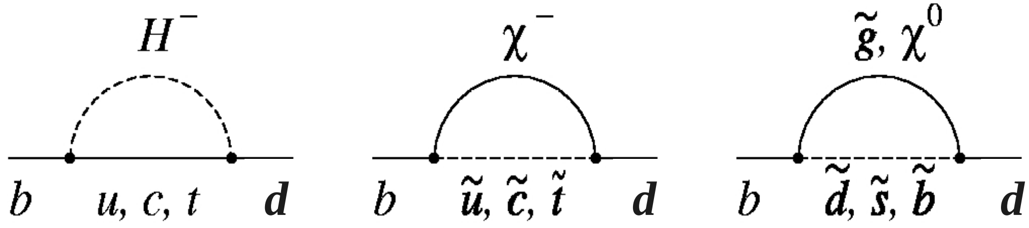
The experimental program is just beginning:

$B \to \rho\gamma$

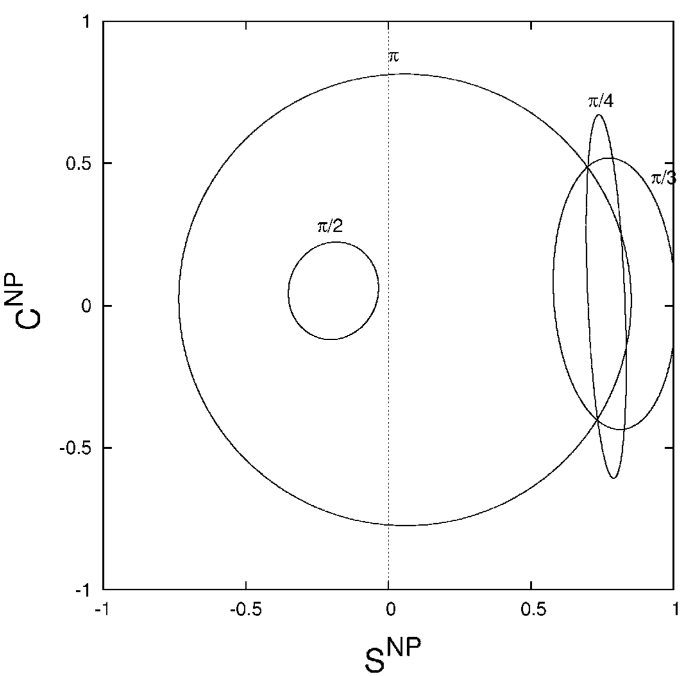
$B \to K\bar{K}$ ...

Need to explore the *b→d* sector and add another constraint

$B \to K^0 \bar{K}^0$: Example of a Potential New Physics Scenario



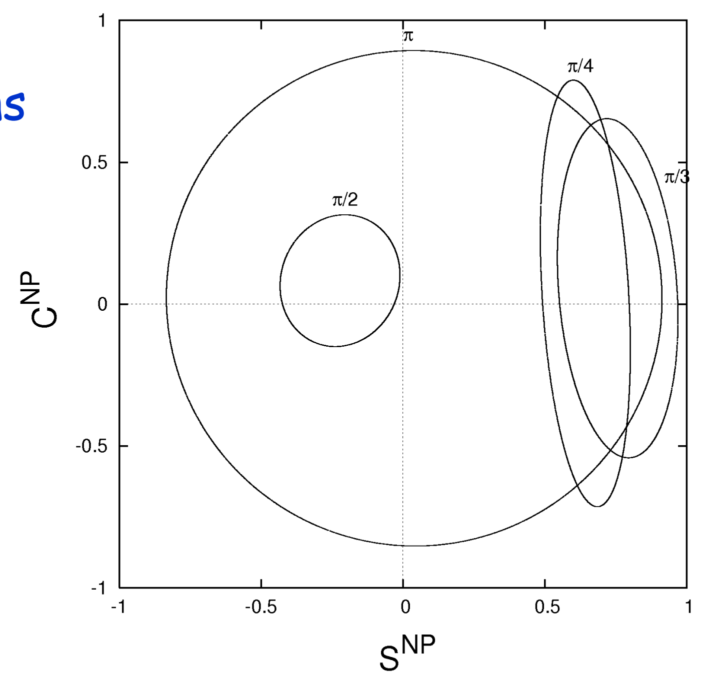
A. Giri and R. Mohanta, JHEP 11, 084 (2004)



Predictions for various assumptions on the weak phase θ_{NP} and strong phase δ_{NP} between NP amplitudes:

$$\theta_{\rm NP} = \frac{\pi}{4}, \frac{\pi}{3}, \frac{\pi}{2}, \pi$$

$$0 < \delta_{\rm NP} < 2\pi$$



Note: this scenario does not include all experimental constraints

Evidence for $B_d \to K^0\overline{K^0}$ (ICHEP 2004)

$$N(K_s^0 K_s^0) = 23.0^{+7.7}_{-6.7}\ {}^{+1.9}_{-2.0}\quad(4.5\sigma)$$

$$\mathrm{B}(B^0 \to K^0\overline{K}^0) = (1.19^{+0.40}_{-0.35} \pm 0.13)\times 10^{-6}$$

PRL 95: 221801, 2005 (227 million BB pairs)

$$N(K_s^0 K_s^0) = 15.6 \pm 5.8^{+1.1}_{-0.6}\quad(3.5\sigma)$$

$$\mathrm{B}(B^0 \to K^0\overline{K}^0) = (0.8 \pm 0.3 \pm 0.1)\times 10^{-6}$$

PRL 95: 231802, 2005 (275 million BB pairs)

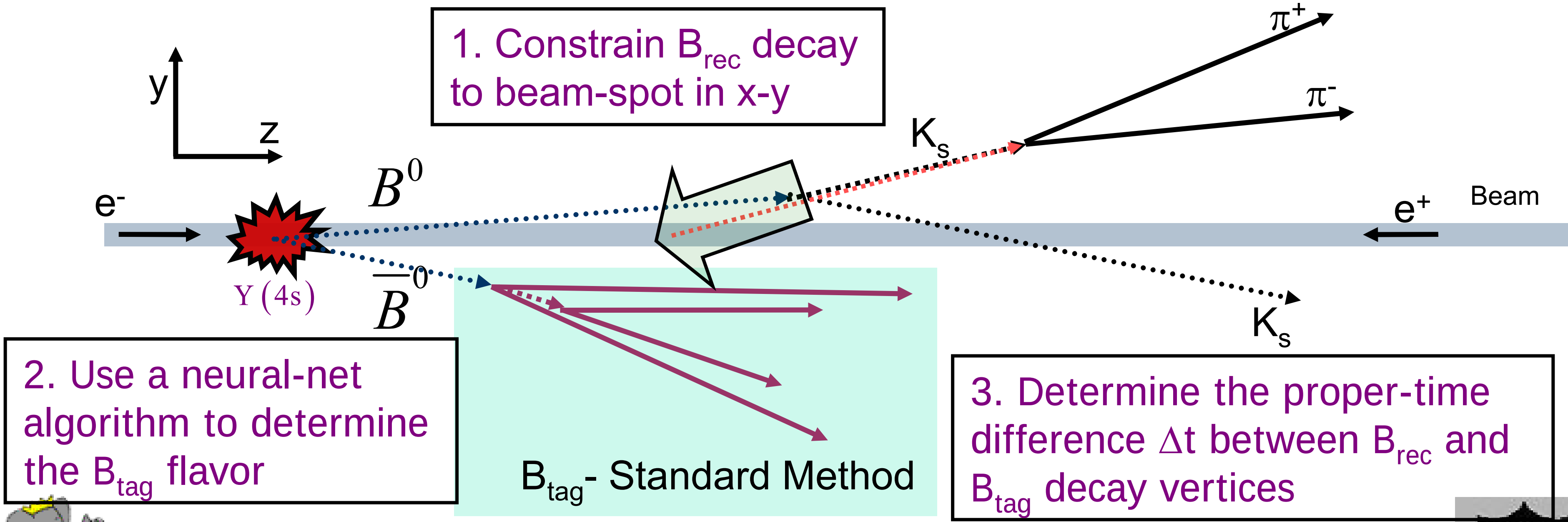
Next Step for BaBar: Observe the mode and measure CP asymmetries with ~350 million $B\overline{B}$ pairs

Measuring S_{KK} at BaBar

Challenge: Need to vertex a decay with no primary tracks from the e^+e^- interaction point

Solution: Exploit precise knowledge of the interaction point and fit the entire Υ(4S) decay chain using beam-spot constraints.

Method developed by BaBar, described in PRL 93: 131805, 2004 and PRD 71: 111102, 2005



Use K_S's that decay in the Silicon Vertex Tracker

Classes of K_S decays:

35% Class I – both pions have hits in inner layers

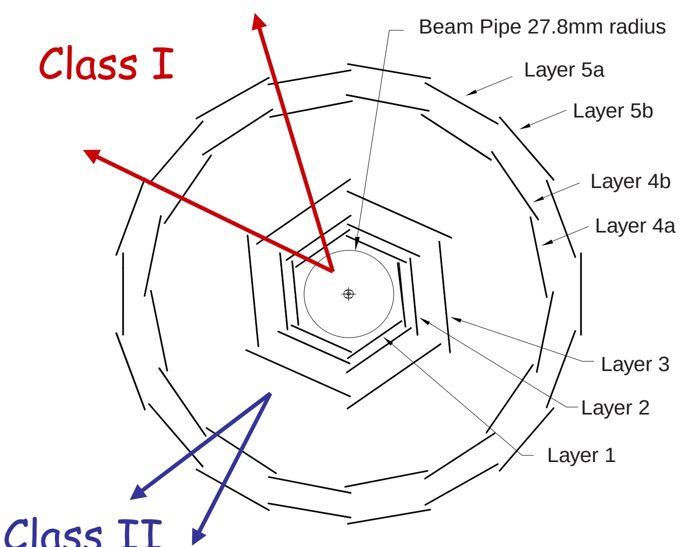
25% Class II – not Class I, both pions have hits in SVT

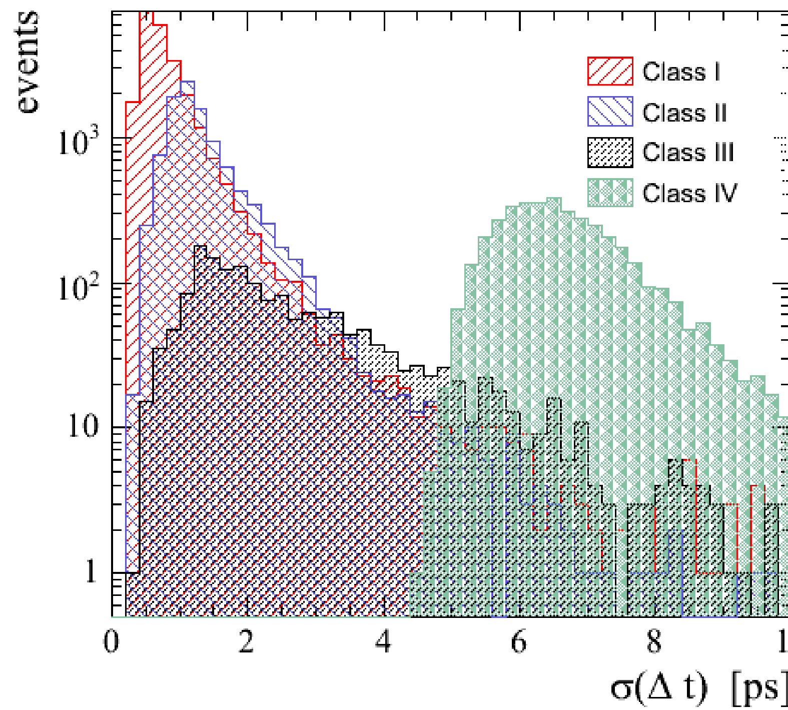
40% Class III and IV: not used for time-dependent measurement

Have two K_S's but need only one to vertex the signal B

Class I B^0's: 58%

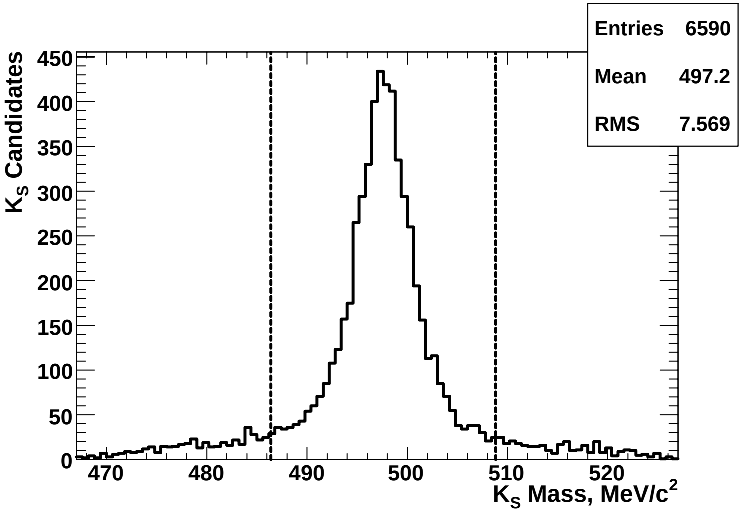
Class II B^0's: 26%





Analysis Overview

- The data sample consists of 347 million $\Upsilon(4S) \to B\bar{B}$ pairs (316 fb^{-1}) collected with the BaBar detector
- $B \to K^0\bar{K}^0$ reconstructed in $K^0\bar{K}^0 \to K_S K_S$ and $K_S \to \pi^+\pi^-$
- Efficiency: $8.5 \pm 0.3\%$ (including secondary branching fractions)
- Unbinned Maximum-likelihood fit
  - Four variables: m_{ES} , ΔE, Fisher, Δt
  - Extract signal yield, background yield, and the time-dependent CP-violating asymmetry parameters S and C



$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

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

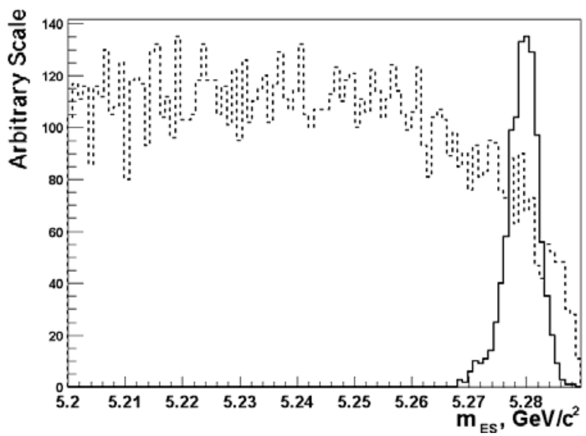
Unbinned Maximum Likelihood Fit and Discriminating Variables

$$\mathcal{L} = \exp\left(-\sum_i n_i\right)\prod_{j=1}^{N}\left[\sum_i n_i \mathcal{P}_i\right]$$

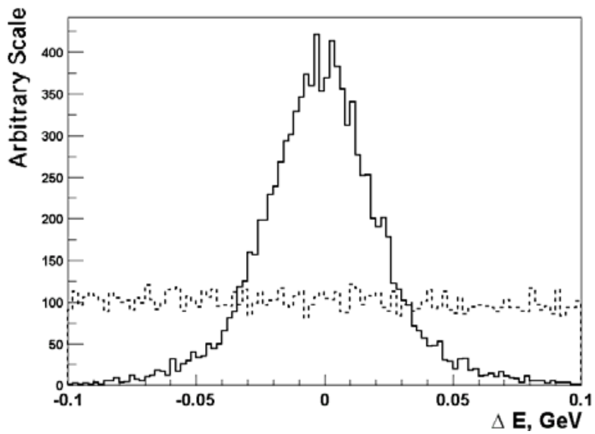
n_i = candidate category, signal or background
P_i = probability density for category i
N = number of events

Kinematic

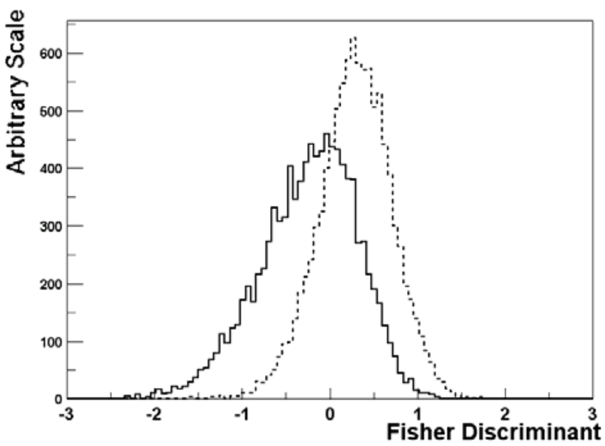
m_{ES}



ΔE



Event-shape



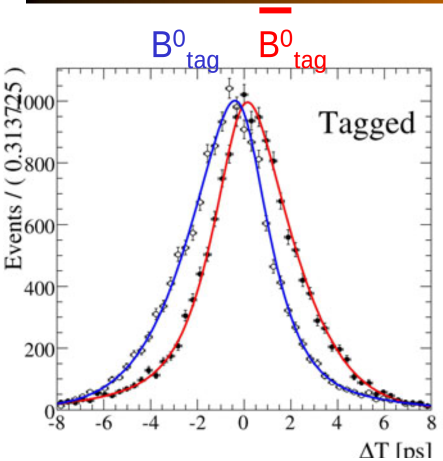
Fisher discriminant

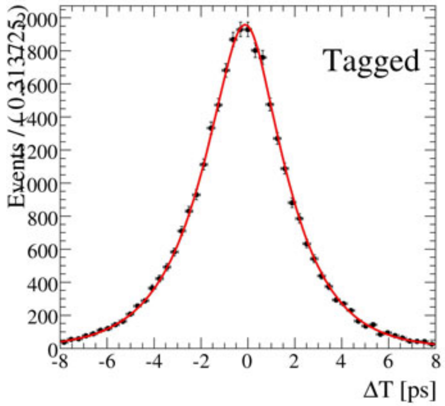
➡ optimized compound variable

Distributions from the final fit model

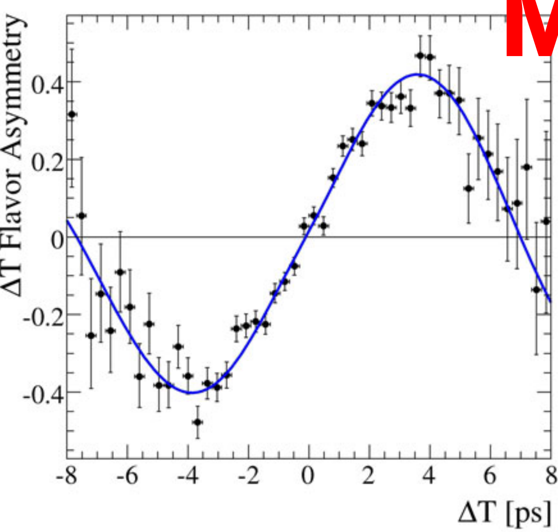
Solid histogram = Signal
Dashed histogram = Background

Δt PDFs

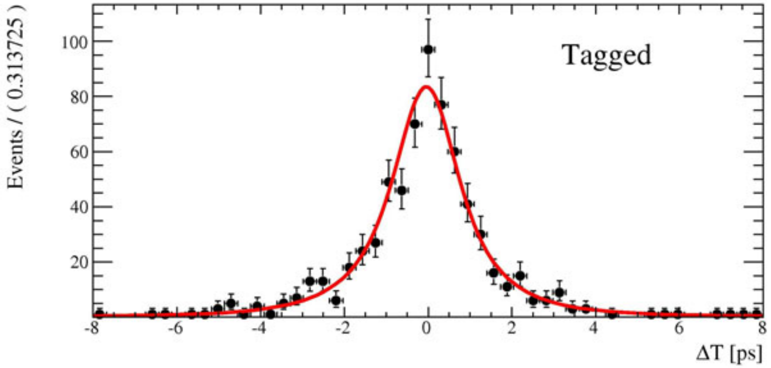


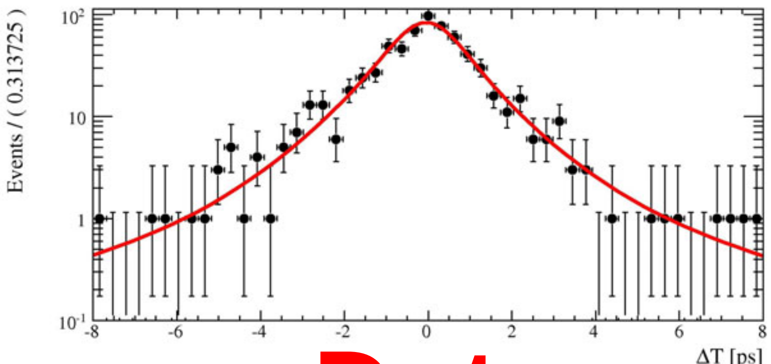


MC



Fit result closely tracks the generated CP-violating structure

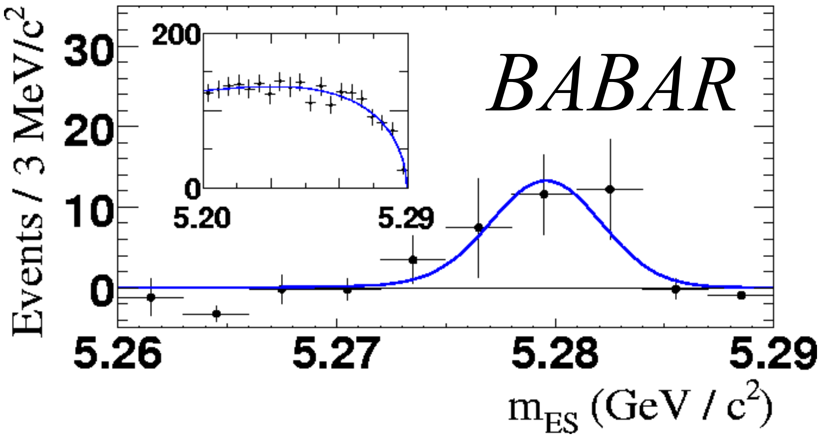




Data

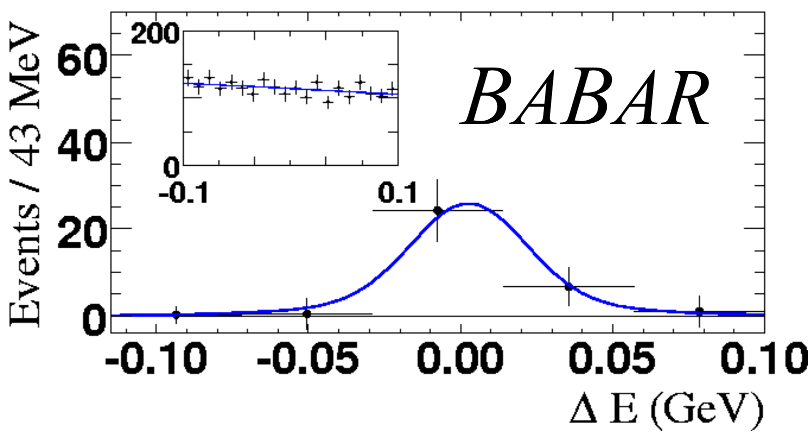
Resolution function characterizes the data well

Results: Branching Fraction



$$N(K_s^0 K_s^0) = 32 \pm 8 \pm 3 \;(7.3\sigma)$$

$$B(B^0 \to K^0 \overline{K}^0) = (1.08 \pm 0.28 \pm 0.11) \times 10^{-6}$$

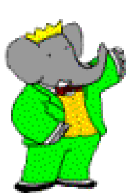


PRL 97: 171805, 2006

Dominant systematic uncertainties:
→ Fitter bias
→ Uncertainty in PDF shapes in the fit

sPlots

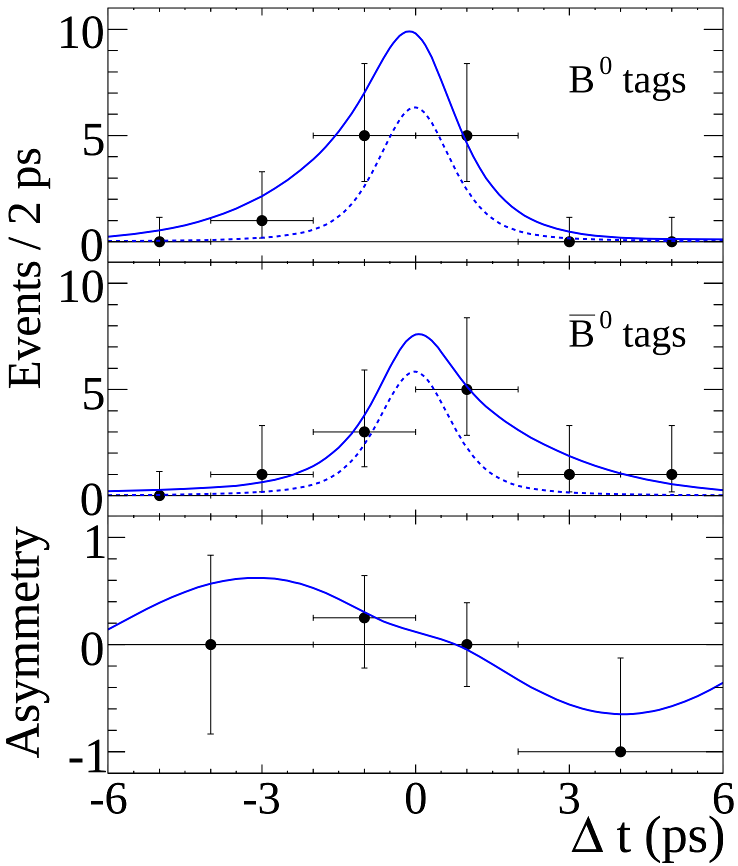
M.Pivk and F.R.Le Diberder,
“sPlot: A Statistical Tool to Unfold Data Distributions,”
Nucl. Instrum. Meth. A **555**, 356 (2005)



Results: CP Violation

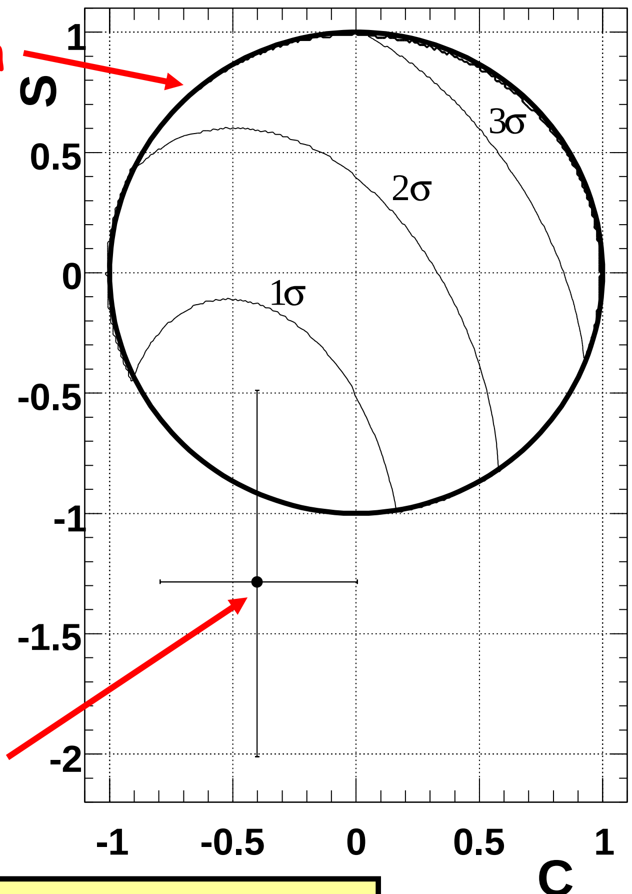
Projection Plots

PRL 97: 171805, 2006



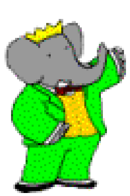
BABAR

nσ Contours



$$S(K_S^0 K_S^0) = -1.28\ ^{+0.80}_{-0.73}\ ^{+0.11}_{-0.16}$$

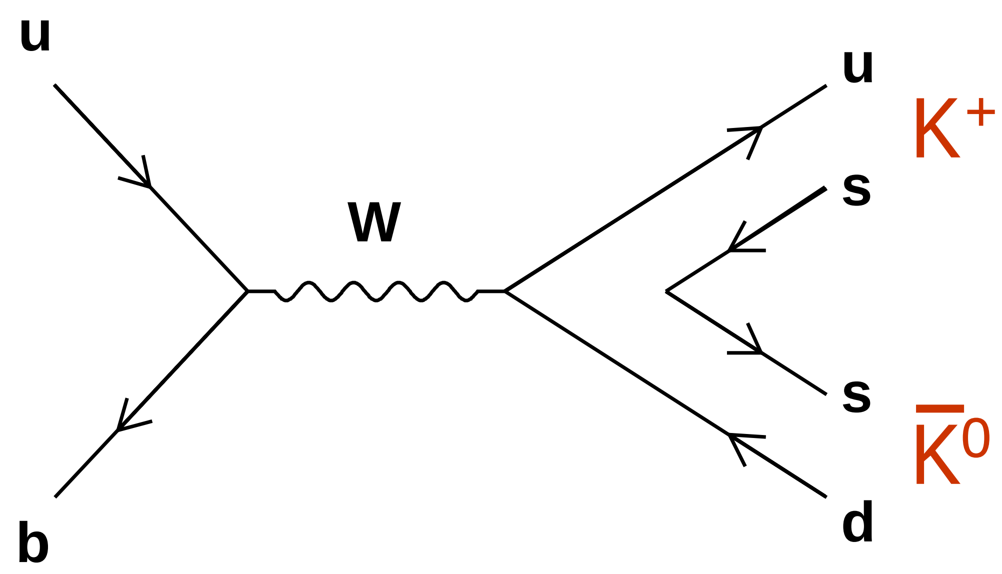
$$C(K_S^0 K_S^0) = -0.40 \pm 0.41 \pm 0.06$$



$$B^+ \longrightarrow \overline{K}^0 K^+$$

Penguin + Annihilation Amplitudes

- Same penguin amplitude as in $B^0 \to K^0 \overline{K}^0$
- Annihilation contribution may affect branching fraction
- Need comparison with $B^0 \to K^0 \overline{K}^0$ to estimate the size of this effect



Analysis Overview

- The data sample consists of 347 million $\Upsilon(4S) \rightarrow B\bar{B}$ pairs (316 fb^{-1})
- $B^+ \rightarrow K^0 h^+$ reconstructed in $K_S \rightarrow \pi^+\pi^-$, no vertexing
- Use the Detector of Internally Reflected Cherenkov light to separate pion and kaon bachelor tracks
  - DIRC model is the same as in the $B \rightarrow K^+\pi^- / \pi^+\pi^-$ analysis (see previous talk by Xuanzhong Li)
  - Pion mass is assumed for the track
  - ➡ Additional PID from ΔE, where the $K_S K^+$ peak is displaced -45 MeV relative to the $K_S \pi^+$ peak
- Efficiency: 12.9 ± 0.4 % $K_S\pi^+$, 12.6 ± 0.4 % $K_S K^+$
- Fit simultaneously for $K_S\pi^+$ and $K_S K^+$ using m_{ES}, ΔE, Fisher, DIRC
- Extract two signal and two background yields and the corresponding charge asymmetries

Results

$$N_{K_S^0\pi^+} = 1072 \pm 46\ {}^{+32}_{-37}$$

$$N_{K_S^0K^+} = 71 \pm 19 \pm 4\ \ (5.3\sigma)$$

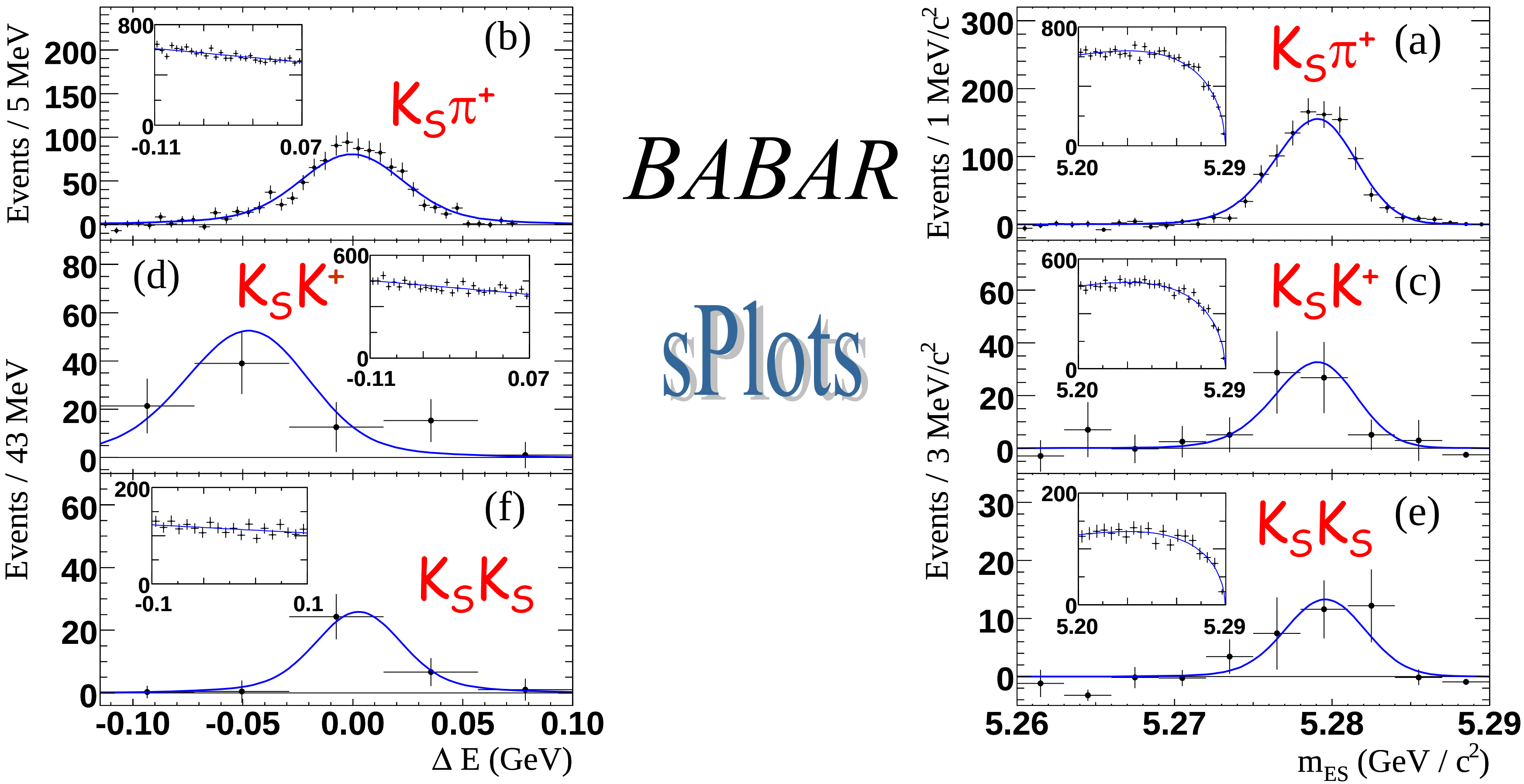
$$\mathrm{B}(B^+ \to K^0\pi^+) = (23.9 \pm 1.1 \pm 1.0) \times 10^{-6}$$

$$\mathrm{B}(B^+ \to \overline{K^0}K^+) = (1.61 \pm 0.44 \pm 0.09) \times 10^{-6}$$

$$A_{K_S^0\pi^+} = -0.029 \pm 0.039 \pm 0.010$$

$$A_{K_S^0K^+} = 0.10 \pm 0.26 \pm 0.03$$

Results



PRL 97: 171805, 2006

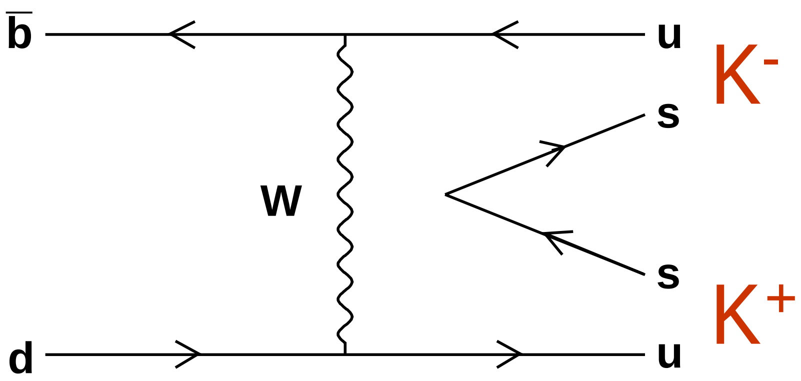
$B^0 \to K^+K^-$

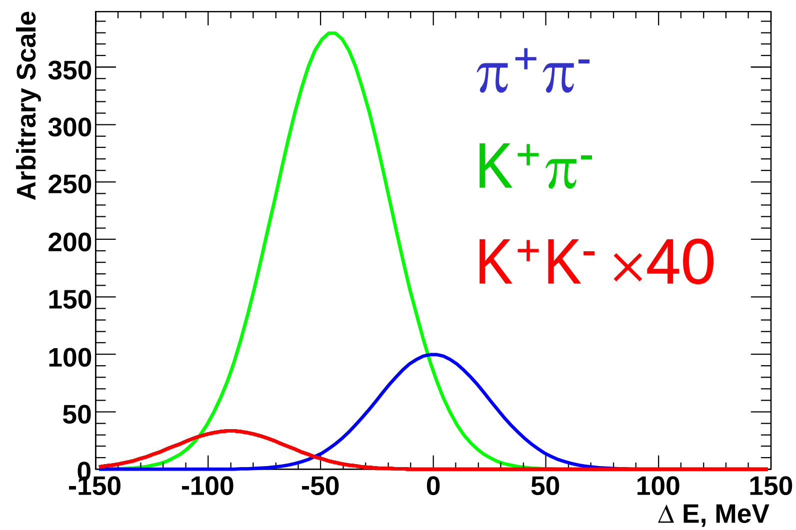
W Exchange Amplitude

- $B(B^0 \to K^+K^-) \sim (0.7\text{–}8) \times 10^{-8}$ in the standard model

  Beneke and Neubert, Nucl. Phys. B 675, 333 (2003)
- Rescattering or new physics could enhance the branching fraction
- Yield extracted from the $B^0 \to K^+\pi^-$ / $\pi^+\pi^-$ fit (see previous talk by Xuanzhong Li)
  - Use DIRC and ΔE to separate from the other two components
  - K^+K^- peak in ΔE lies on the low tail of the large $K^+\pi^-$ peak

➡ Difficult to measure



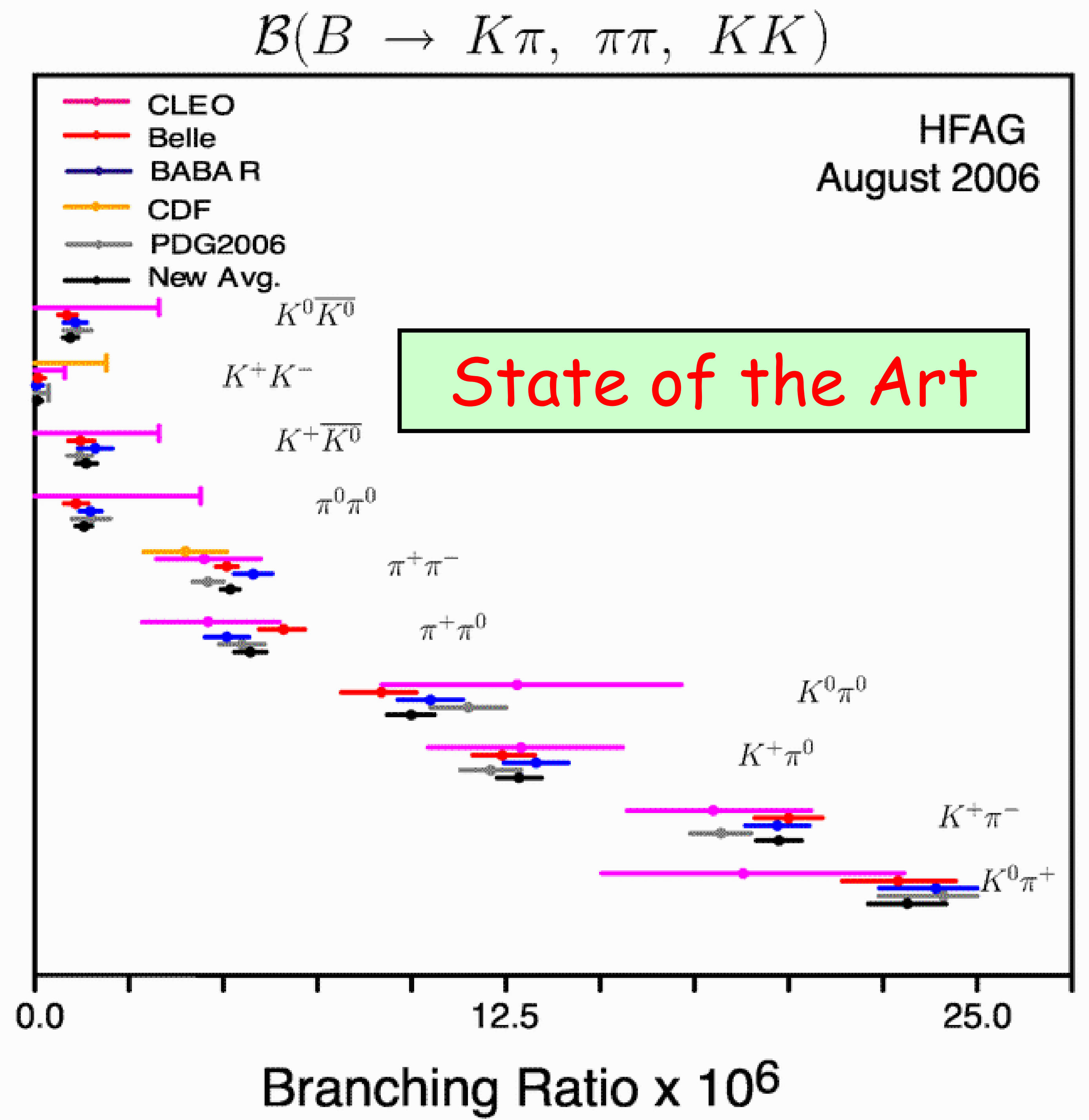


Results

- 227 million $B\bar{B}$ pairs
- $3 \pm 13 \pm 7$ events
- $\mathcal{B}(B^0 \rightarrow K^+K^-) < 0.40 \times 10^{-6}$ (90% confidence level)
- Submitted to PRD

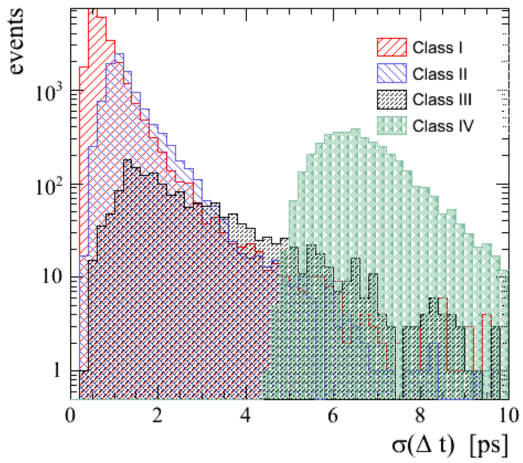
Summary

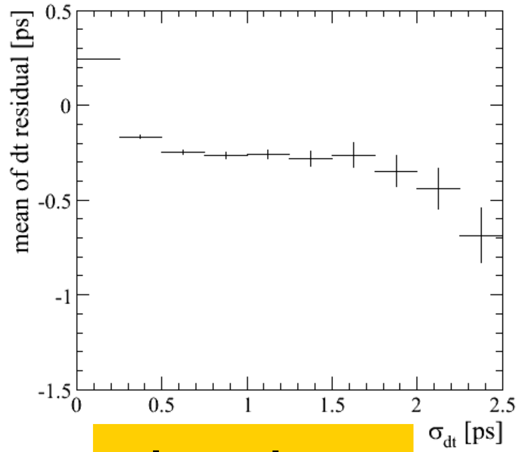
- Observation of $B^0 \to K^0\bar{K}^0$ and $B^+ \to \bar{K}^0K^+$, dominated by the $b \to dg$ penguin amplitude
  - With Belle, first observations of $B_d \to K\bar{K}$
  - Confirms standard model expectation of branching fractions
  - Branching fraction of $B^+ \to \bar{K}^0K^+$ larger than $B^0 \to K^0\bar{K}^0$ when combined with Belle's result
- First time-dependent CP measurement in a $b \to d$ penguin
  - Method is feasible at BaBar
  - Large positive values of S are disfavored
  - More data is needed to make stronger constraints
- Both modes published in PRL 97: 171805, 2006 for BaBar
- Non-observation of $B^0 \to K^+K^-$ is so far consistent with the standard model
  - Submitted to PRD
  - The only twobody charmless mode left to be observed

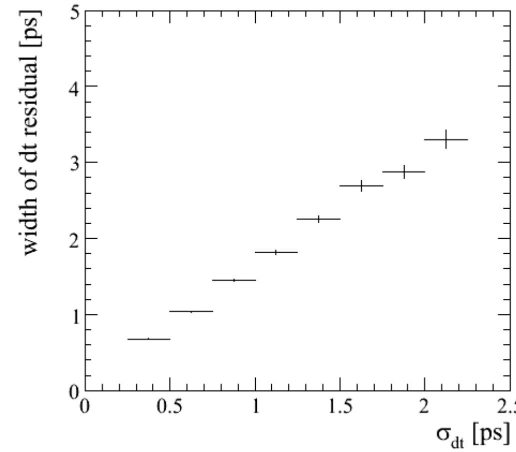

$\mathcal{B}(B \to K\pi,\ \pi\pi,\ KK)$
CLEO
Belle
BABA R
CDF
PDG2006
New Avg.
HFAG
August 2006
State of the Art
$K^0\overline{K^0}$
K^+K^-
$K^+\overline{K^0}$
$\pi^0\pi^0$
$\pi^+\pi^-$
$\pi^+\pi^0$
$K^0\pi^0$
$K^+\pi^0$
$K^+\pi^-$
$K^0\pi^+$
0.0
12.5
25.0
Branching Ratio x 10^6

Backup Slides

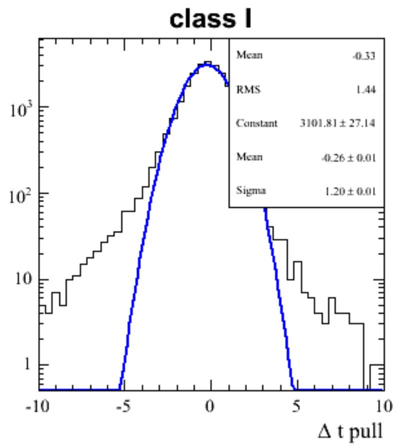
Vertexing Results

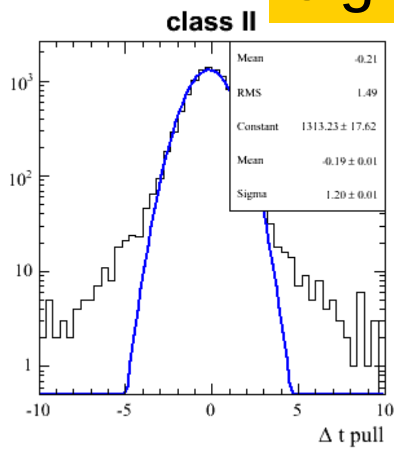


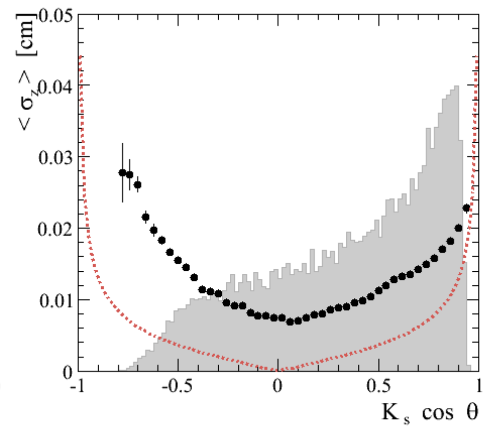


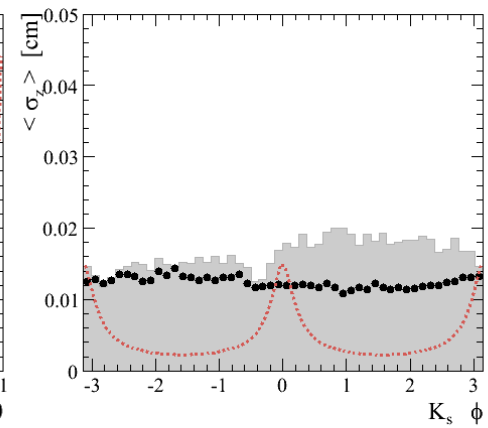


Signal MC



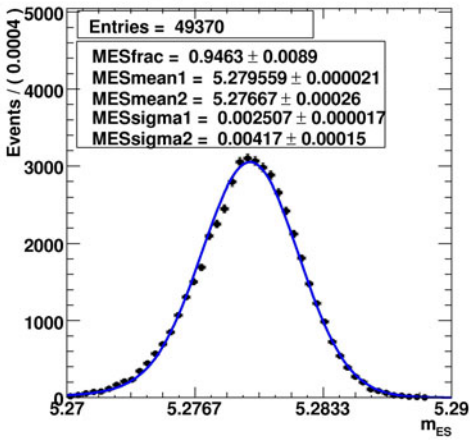




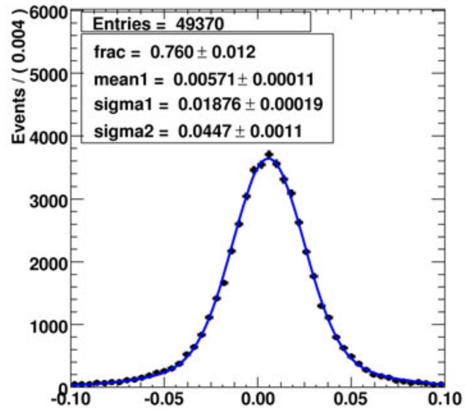


$K_S K_S$ PDFs

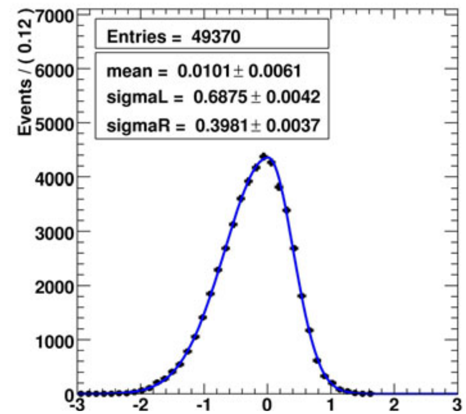
A RooPlot of "m_{ES}" double Gaussian



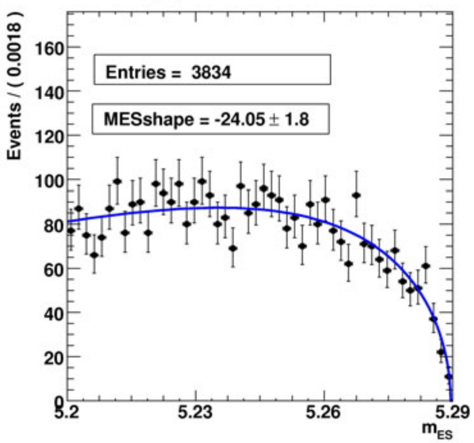
A RooPlot of "ΔE" double Gaussian



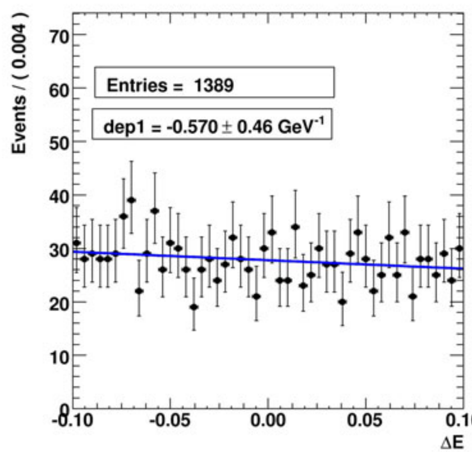
A RooPlot of "Fisher" bifurcated Gaussian



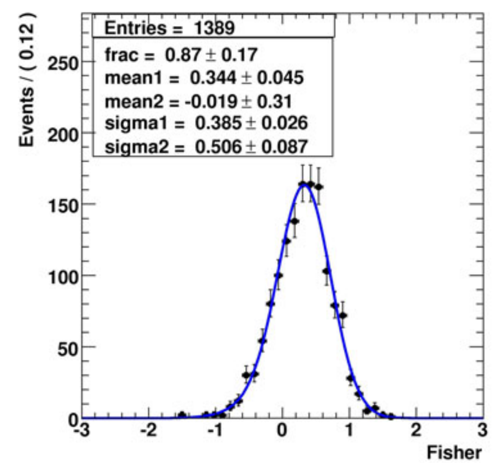
A RooPlot of "m_{ES}" Argus



A RooPlot of "ΔE" 1-degree polynomial



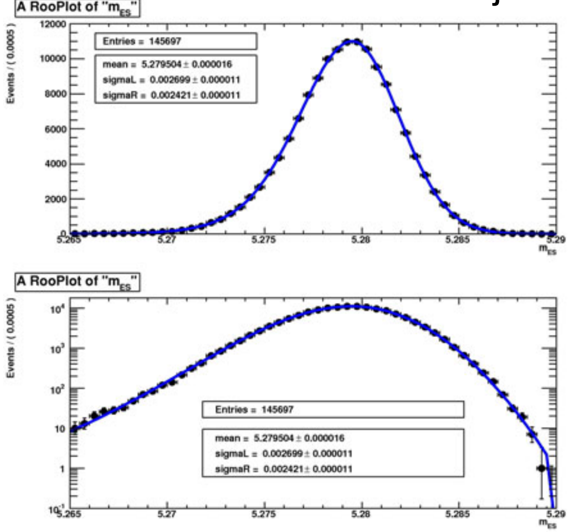
A RooPlot of "Fisher" double Gaussian



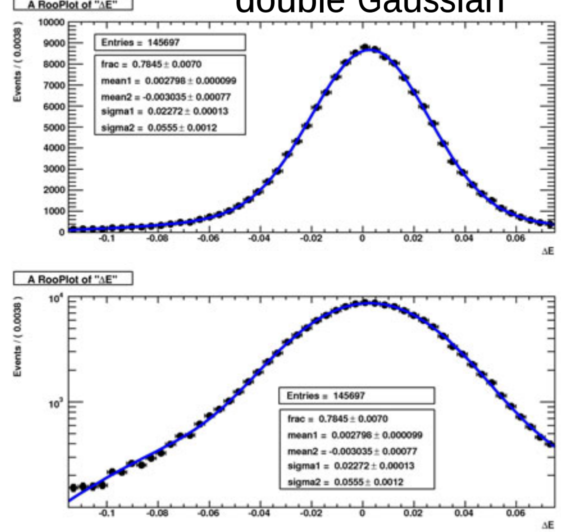
Background Parameters Floated

$K_S h^+$ PDFs

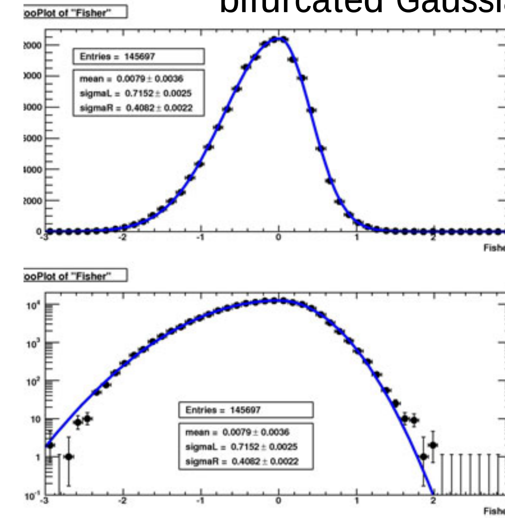
Cruijff



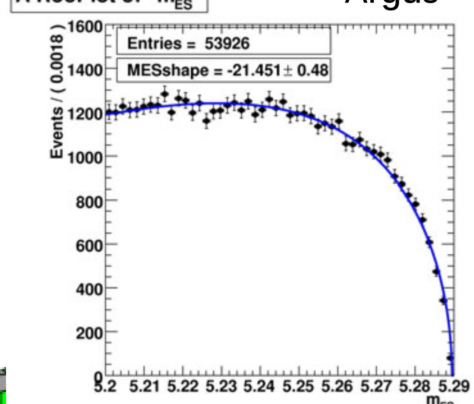
double Gaussian



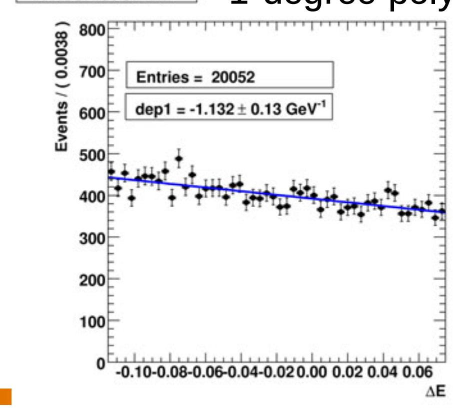
bifurcated Gaussian



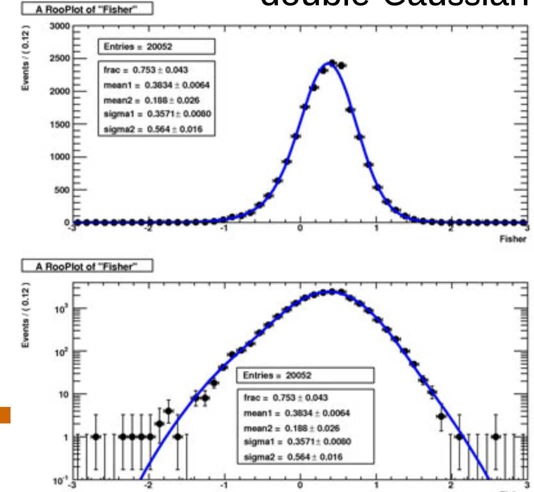
Argus



1-degree polynomial



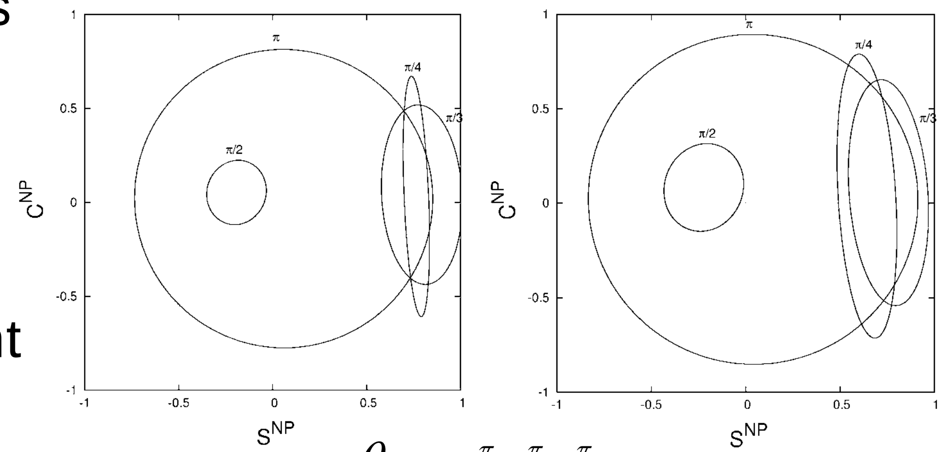
double Gaussian



New-Physics Predictions for TDCP

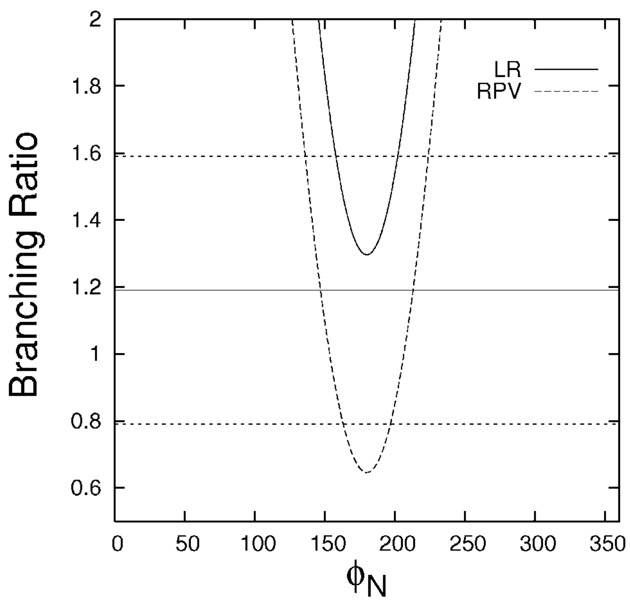
- Predictions for various assumptions on the weak phase θ_{NP} and strong phase δ_{NP} between NP amplitudes
  - Depending on the NP phase, S_{KK} (NP) could be large
- Current BF measurement consistent with NP scenario

A. Giri and R. Mohanta, JHEP 11, 084 (2004)



$$\theta_{NP} = \frac{\pi}{4}, \frac{\pi}{3}, \frac{\pi}{2}, \pi$$

$$0 < \delta_{NP} < 2\pi$$



- New physics in b → d penguins is highly constrained assuming three-generation unitarity
- But there's still room for NP
  - Measure TDCP in b →d penguins for the first time and add another constraint