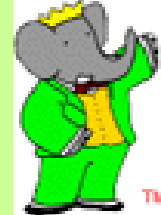


Strong interactions physics in heavy quark decays and spectroscopy @ BaBar

Michele Pioppi

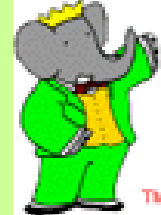
Universita' di Perugia – INFN

DIS2004, Štrbské Pleso 14/04/2004

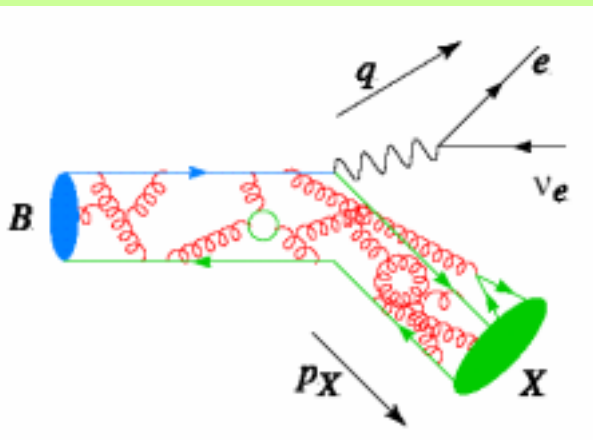


New important results on strong interactions

- Semileptonic B decays:
from hadronic-mass and lepton-energy moments to $|V_{cb}|$
- $B \rightarrow J/\psi K\pi$ events: how to determine the sign of $\cos(2\beta)$
- Recent results in charmonium sector



Heavy Quark Expansion in semileptonic B decays

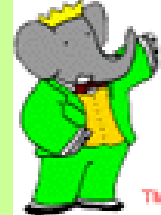


- $\Gamma(B \rightarrow X_c l \nu) \propto |V_{cb}|^2 m_b^2 (m_b - m_c)^3$
- Leptonic and hadronic currents factorise
- Hadronic matrix element has to be corrected for interactions with rest of B meson
- Expand in powers of $1/m_b$ in terms of local operators
- Expectation values of these operators are properties of the b quark within the B meson.

HQE parameters can be obtained from moments of kinematic quantities

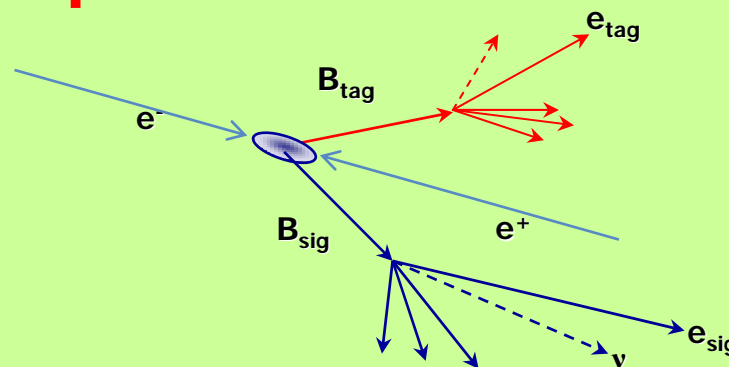
$$\langle X^n \rangle(E_{\text{cut}}) = \frac{\int_{E_{\text{cut}}}^{\infty} (X - X_0)^n \frac{d\Gamma}{dX} dX}{\int_{E_{\text{cut}}}^{\infty} \frac{d\Gamma}{dX} dX} = f_{\text{HQE}}$$

1. First 3 moments of lepton-energy $X = E_l$
2. First 4 moments of hadronic mass $X = M_x$



Lepton energy spectrum

- Tag events with high energetic electron ($p > 1.4$ GeV in $Y(4S)$ frame)
- Look for second electron in the event ($p > 0.5$ GeV in $Y(4S)$ frame)

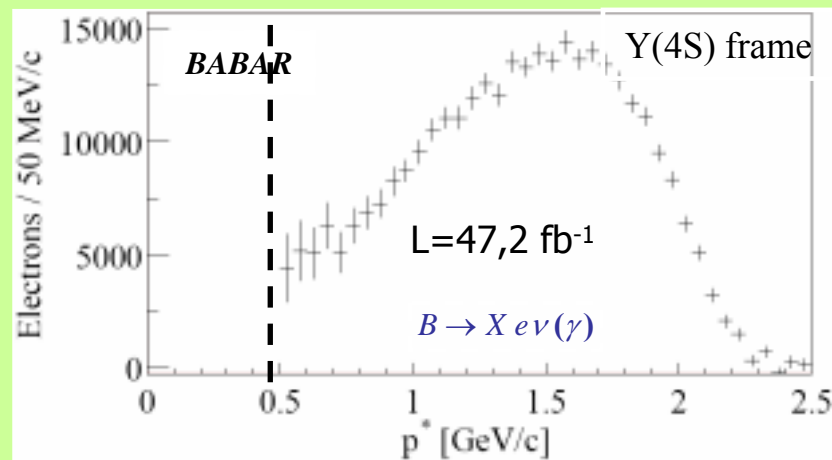


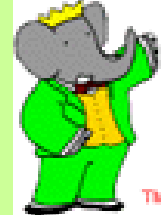
- Large statistics
- Suppress backgrounds from J/Ψ decays by cutting on invariant mass
- Backgrounds from secondary decays are reduced by cutting on opening angle
- Continuum background is subtracted by using the off-resonance data sample

Lepton momentum

spectrum($p_{\min}^* = 0.5$ GeV):

p^* =lepton momentum in $Y(4s)$ rest frame





Lepton energy moments

results :

*To be submitted to Phys
Rev. D hep/ex 0403030*

$$\text{Br}(B \rightarrow X_{\ell\nu}(\gamma), (E_e > 0.6 \text{ GeV})) = (10.36 \pm 0.06_{\text{stat}} \pm 0.23_{\text{syst}})\%$$

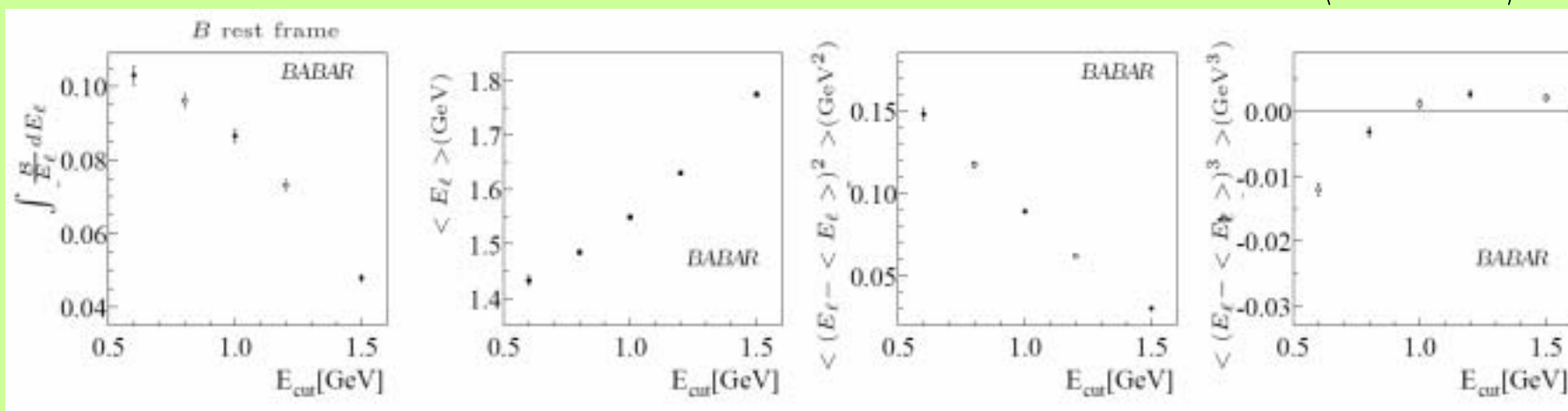
First three lepton energy moments

$\text{Br}(B \rightarrow X_{\ell\nu})$

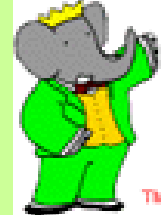
$\langle E_e \rangle$

$\langle (E_e - \langle E_e \rangle)^2 \rangle$

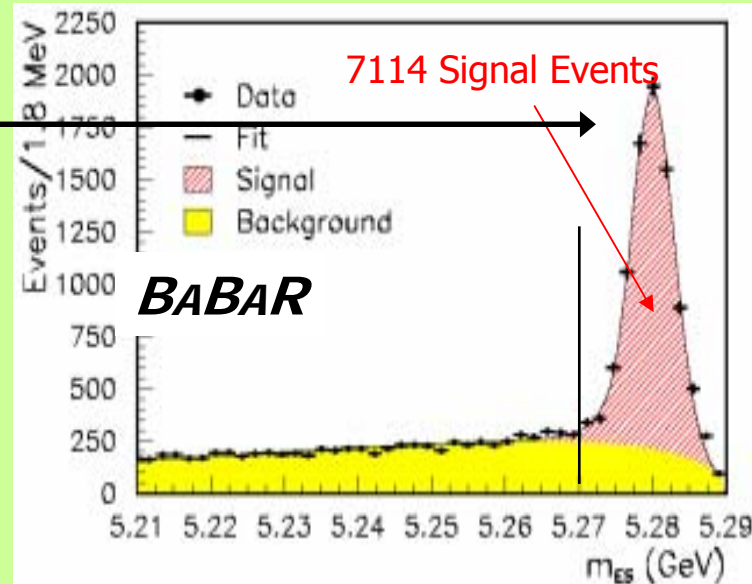
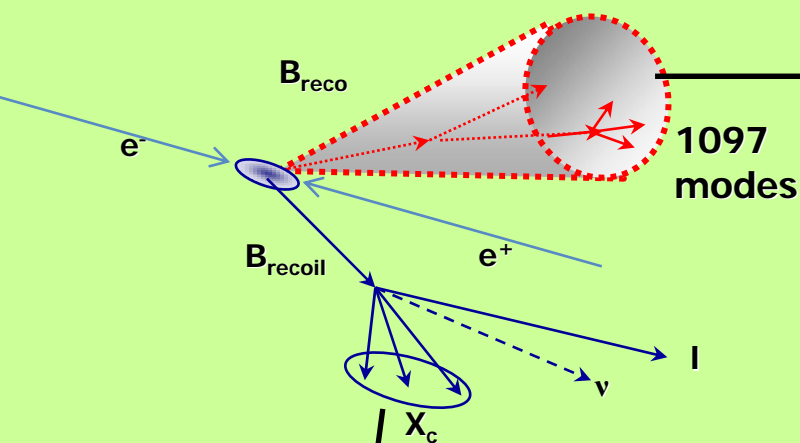
$\langle (E_e - \langle E_e \rangle)^3 \rangle$



Individual measurements are highly correlated

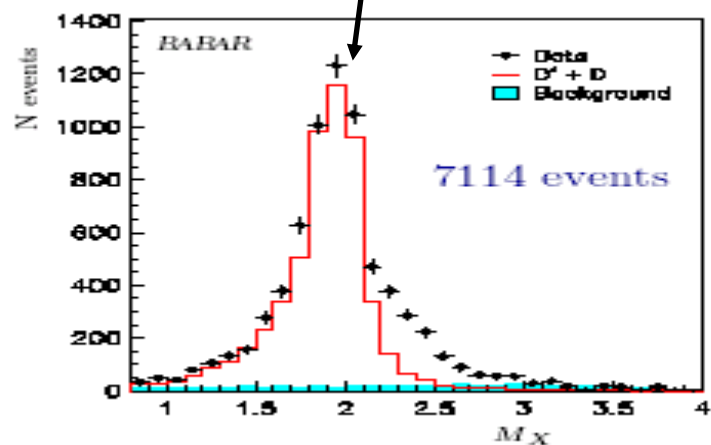


Hadronic mass spectrum



$L=82\text{fb}^{-1} \sim 88$ milion BB pairs

Hadronic Mass (M_X) spectrum



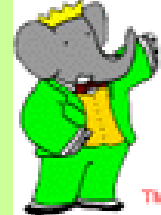
Analysis performed on recoil of fully reconstructed B decays:

- B-flavor and 4-momentum known
- $M_{ES} = (s/4 - (p_B^*)^2)^{1/2}$ for bkg subtraction

14/04/2004

Michele Pioppi

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Hadronic mass moments

Moments $\langle M_X^n \rangle$ ($n=1, \dots, 4$) of the hadronic mass spectrum in $B \rightarrow X_c l \nu$ decays for $0.9 \text{ GeV} < p_{\text{min}}^* < 1.6 \text{ GeV}$

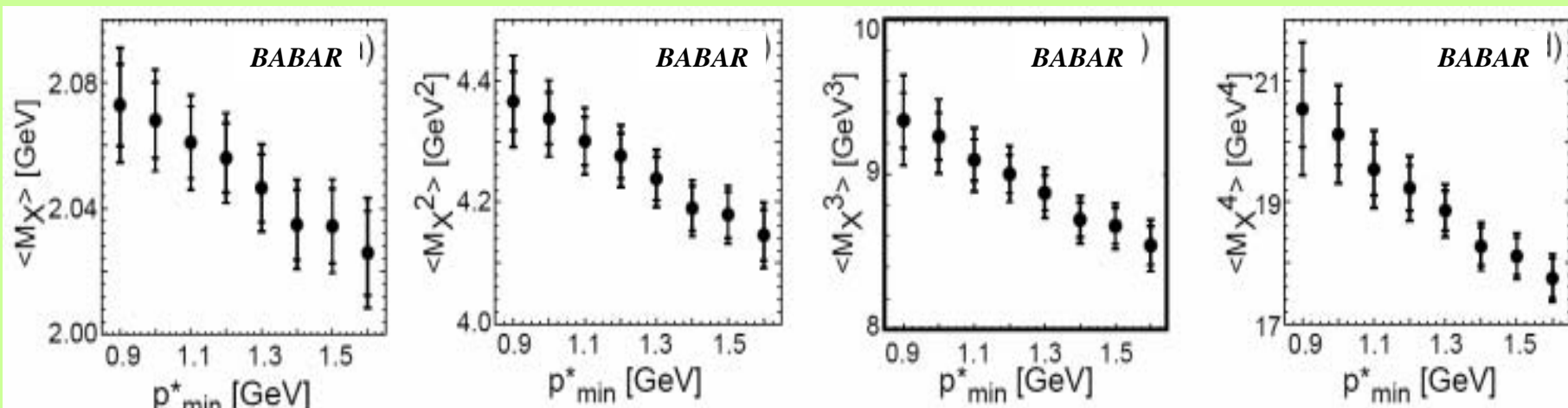
*To be submitted to Phys Rev.D
hep/ex 0403031*

$\langle M_X \rangle$

$\langle M_X^2 \rangle$

$\langle M_X^3 \rangle$

$\langle M_X^4 \rangle$



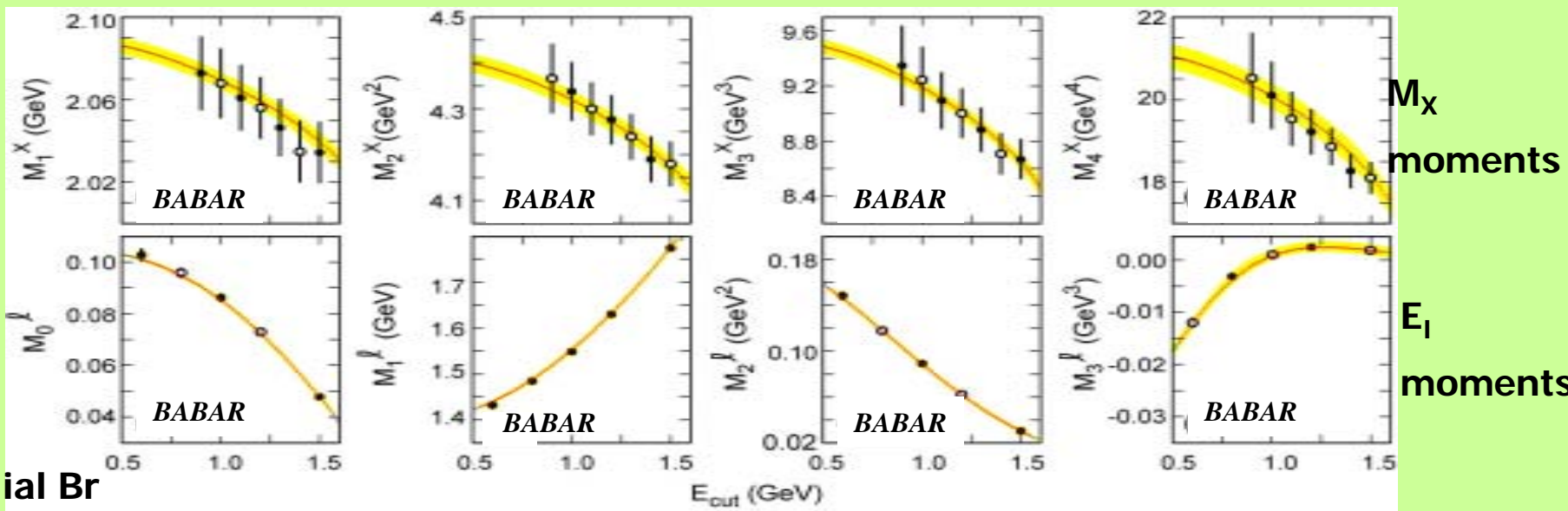
- Clear p_{min}^* dependence
- Individual measurements are highly correlated



Fit method

We use calculations in kinetic mass scheme by Gambino and Uraltsev
hep/ph 0401063

- Eight Fit Parameters: $B(B \rightarrow X_c e \nu)$, $|V_{cb}|$, m_b and m_c
- μ_π^2 - expectation value of kinetic energy of b quark inside B meson
- μ_G^2 - expectation value of chromomagnetic operator
- ρ_D^3 - expectation value of Darwin operator
- ρ_{LS}^3 - expectation value of Spin-Orbit operator



Partial Br

Fit results

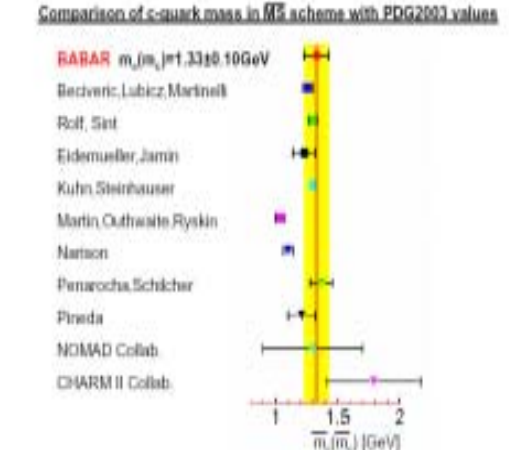
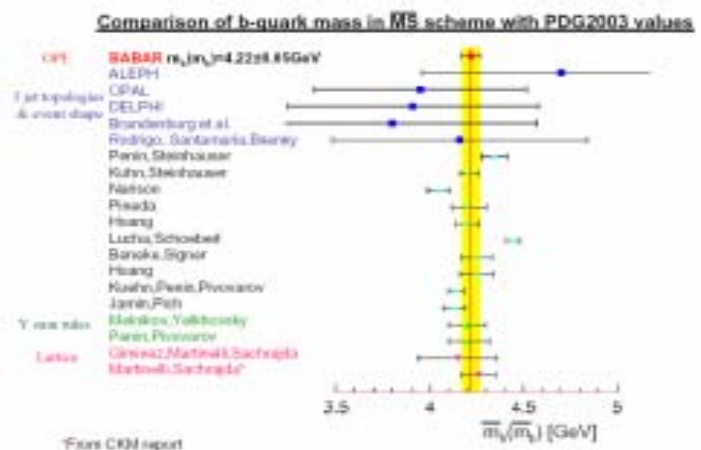
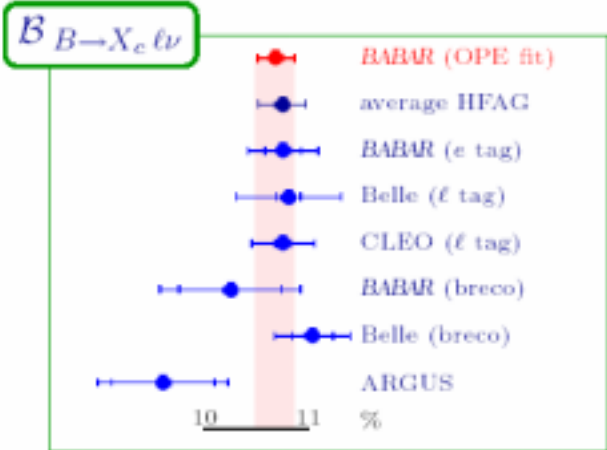
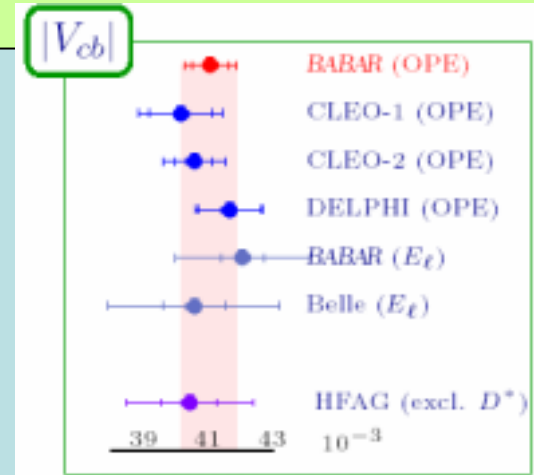


$$|V_{cb}| = (41.4 \pm 0.4_{\text{exp}} \pm 0.4_{\text{HQE}} \pm 0.6_{\text{th}}) \times 10^{-3}$$

$$\text{Br}(B \rightarrow X_c \ell \nu) = (10.62 \pm 0.16_{\text{exp}} \pm 0.06_{\text{HQE}})\%$$

$$m_b(1 \text{ GeV}) = (4.61 \pm 0.05_{\text{exp}} \pm 0.04_{\text{HQE}} \pm 0.02_{\text{th}})\text{GeV}$$

$$m_c(1 \text{ GeV}) = (1.18 \pm 0.07_{\text{exp}} \pm 0.06_{\text{HQE}} \pm 0.02_{\text{th}})\text{GeV}$$





cos(2β) from $B^0 \rightarrow J/\psi K^*(892) \rightarrow K\pi$

- CP content of $J/\psi K^*(892)$ is both odd (A_{\perp}) and even (A_0, A_{\parallel}) depending on polarization of $S \rightarrow VV$ decay (p-wave)
- Ambiguity on strong phase differences of A_i amplitudes.
- $\cos(2\beta)$ appears in the interference term between CP-odd and CP-even amplitudes of time-dependent decay rate, in the observables:

$$\cos(\delta_{\parallel} - \delta_{\perp}) \cdot \cos 2\beta$$

$$\cos(\delta_{\perp} - \delta_0) \cdot \cos 2\beta$$

Only the relative sign between cos of strong phases diff. and $\cos(2\beta)$ is unambiguous

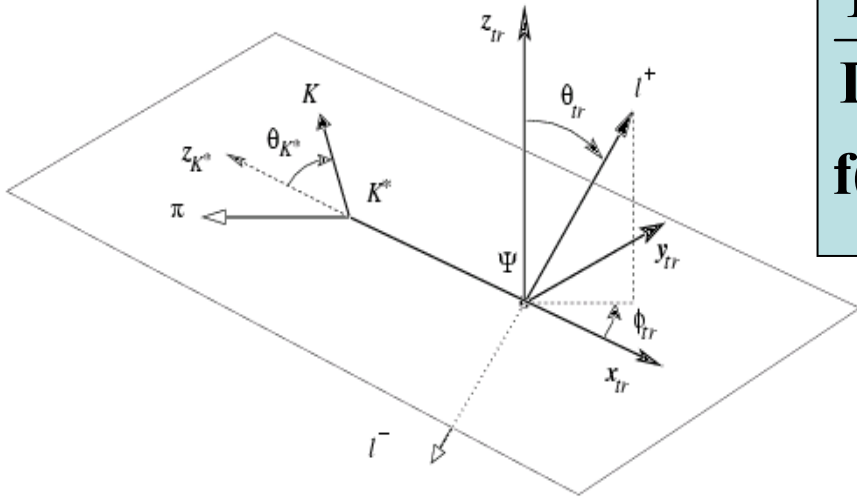
Very precise measure
 $\sin(2\beta) = 0.731 \pm 0.056$

$$\begin{aligned} \beta &\approx 0.42 \\ \beta &\approx 0.42 + \pi \\ \beta &\approx 1.15 \\ \beta &\approx 1.15 + \pi \end{aligned}$$

Sign of $\cos(2\beta)$ reduces the ambiguity on β from 4 to 2 possible solutions



Amplitudes and strong phases(1)



$$\frac{1}{\Gamma} \frac{d^3 \Gamma}{d\cos\theta_K * d\cos\theta_{tr} d\phi_{tr}} = f(|A_{\perp}|, |A_{\parallel}|, |A_0|, \cos(\delta_{\perp} - \delta_{\parallel}), \cos(\delta_{\parallel} - \delta_0))$$

Angular analysis of 4 final states:

$$B^0 \rightarrow J/\psi K_s^0 \pi^0 + \text{c.c.}$$

$$B^0 \rightarrow J/\psi K^{\pm} \pi^{\mp} + \text{c.c.}$$

$$B^+ \rightarrow J/\psi K^+ \pi^0 + \text{c.c.}$$

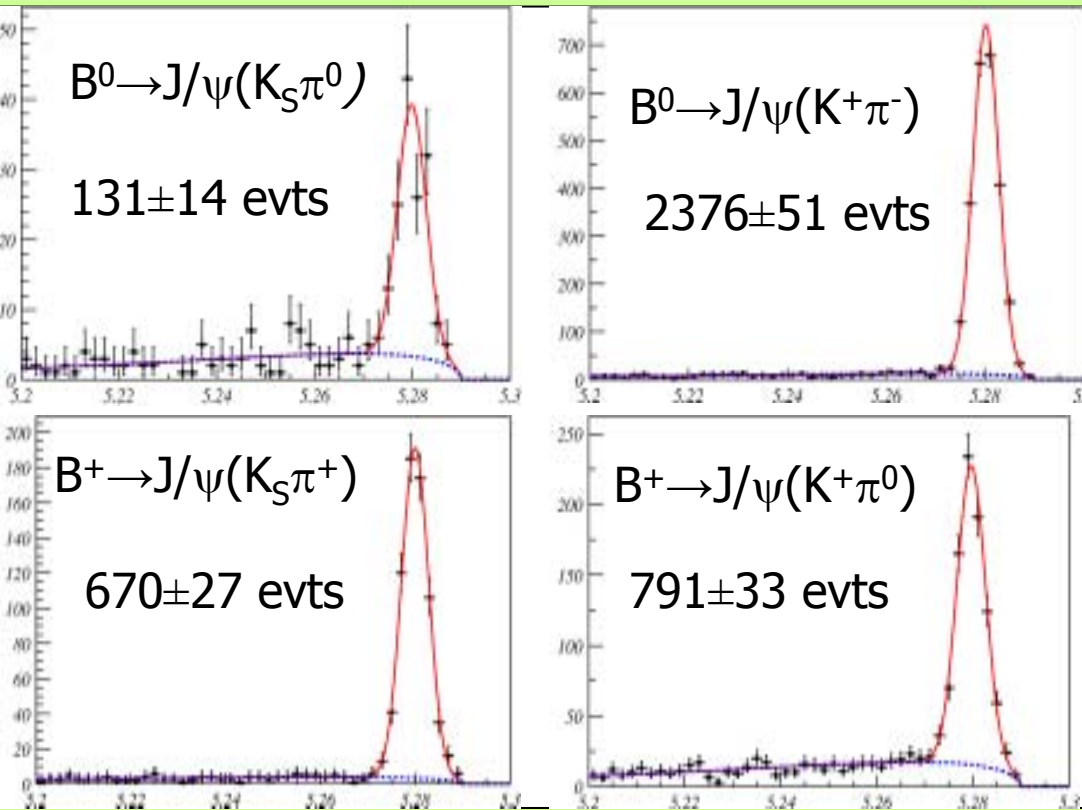
$$B^+ \rightarrow J/\psi K_s^0 \pi^+ + \text{c.c.}$$

Isospin symmetry guarantees same amplitudes for these channels



Amplitudes and strong phases(2)

Signal yields from $Mes = (s/4 - (\vec{p}_B^*)^2)^{1/2}$ distributions



$L = 82 \text{ fb}^{-1} \sim 88$ million BB pairs

Results:

	value	stat.	syst.
$ A_0 ^2$	0.566	± 0.012	± 0.005
$ A_{ } ^2$	0.204	± 0.015	± 0.005
$ A_{\perp} ^2$	0.230	± 0.015	± 0.004
$\delta_{ } - \delta_0$	2.729	± 0.101	± 0.052
$\delta_{\perp} - \delta_0$	0.184	± 0.070	± 0.046

Results in agreement with
CLEO, CDF and BELLE

7.6 σ significance non-trivial
strong phase

$$\delta_{||} - \delta_{\perp} = 0.597 \pm 0.077 \pm 0.017$$

2nd solution:

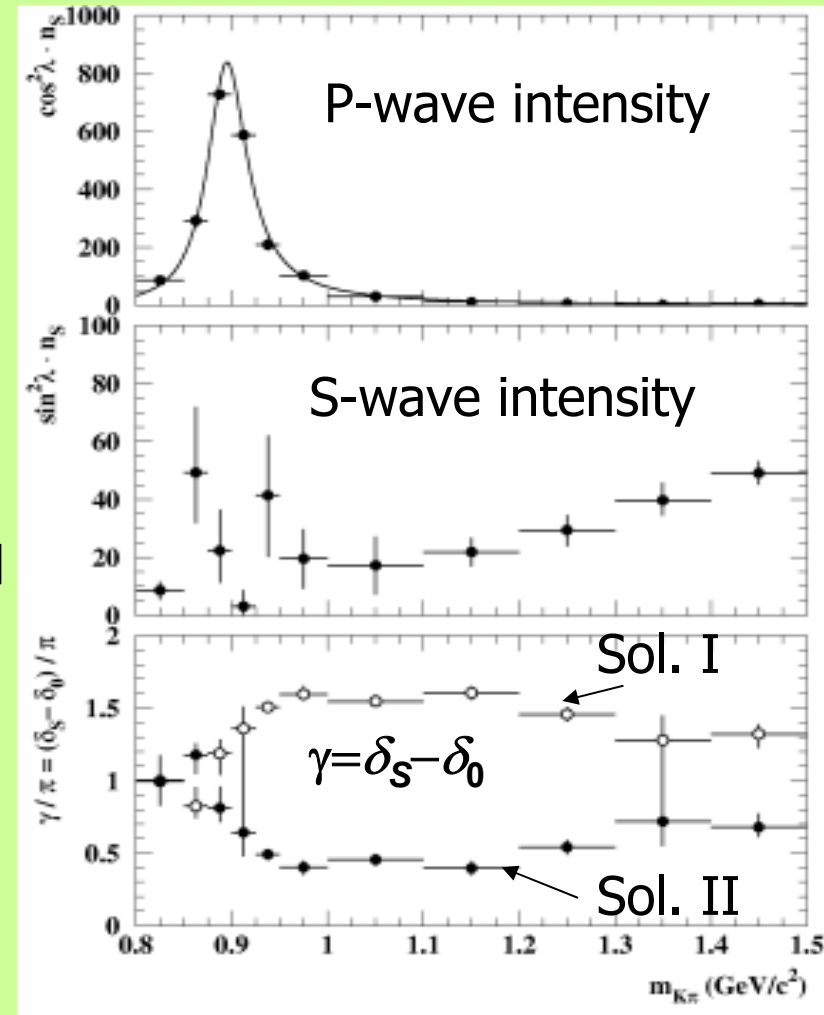
$$\delta_{||} - \delta_0 = 3.554$$

$$\delta_{\perp} - \delta_0 = 2.958$$

$K\pi$ s-wave: how to break strong phases ambiguity



- $K\pi$ mass spectrum shows a broad s-wave structure that lies in $K^*(892)$ region too
- Introduction of a new amplitude and a new relative phase $\gamma = \delta_s - \delta_0$
- Phase of a resonance rotates clockwise with mass because of Wigner causality principle
- In $K^*(892)$ region p-wave rotates fast and s-wave slow $\implies \gamma$ **must rotate counterclockwise**
- Fit for p and s-waves intensity and γ by $M(K\pi)$ bin fixing $\delta_{\parallel} - \delta_0$ and $\delta_{\perp} - \delta_0$ to:
Sol. I = (2.729, 0.184)
Sol. II = (3.554, 2.958)

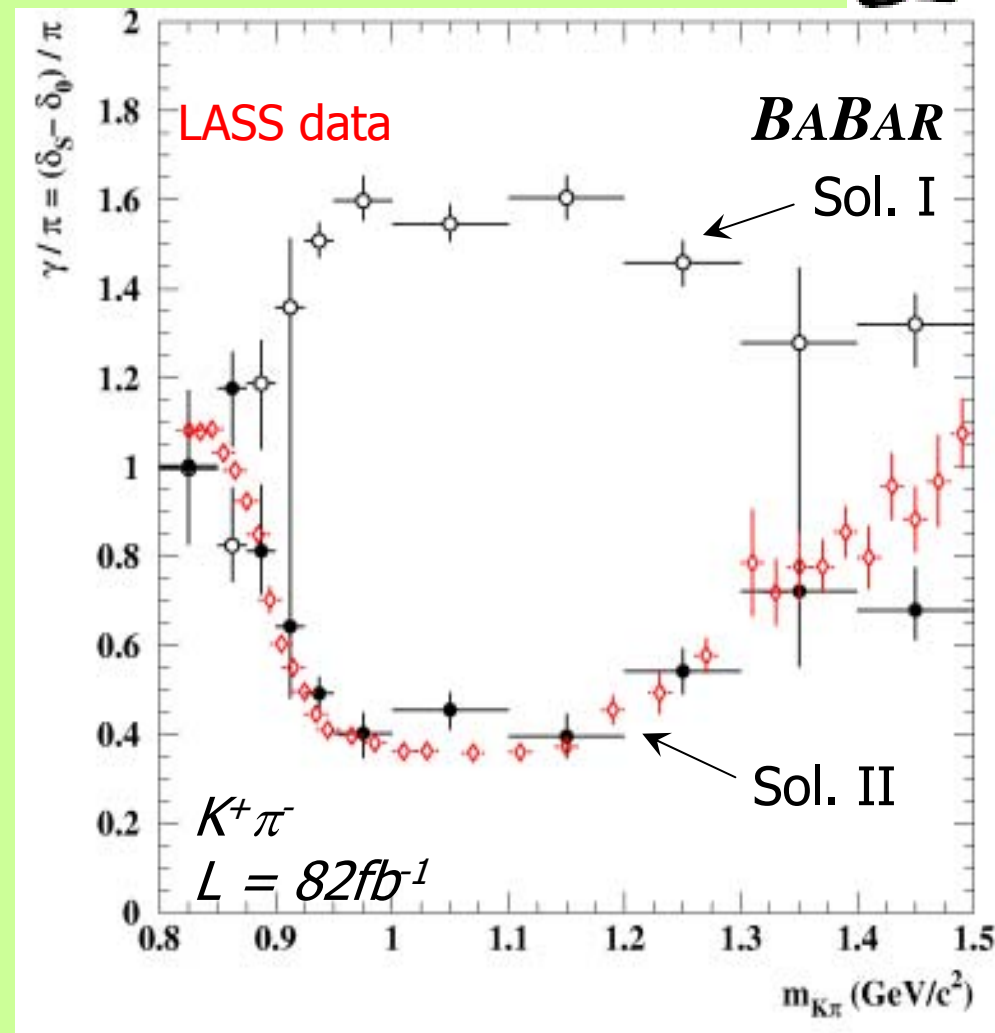


Comparison with LASS data



- Compare with LASS data#;
 - $Kp \rightarrow K\pi(n)$
 - $\delta_{s(I=1/2)} - \delta_p$
 - Global phase π added to LASS data points;
- Remarkable agreement

Solution II is the physical solution



Nucl.Phys. B296,
493(1988)



cos(2β): value and sign

cos(2β) from time and angular analysis of
B0 → J/ψ(K_s⁰π⁰)*0

Sample of 104 tagged events: low
statistics!

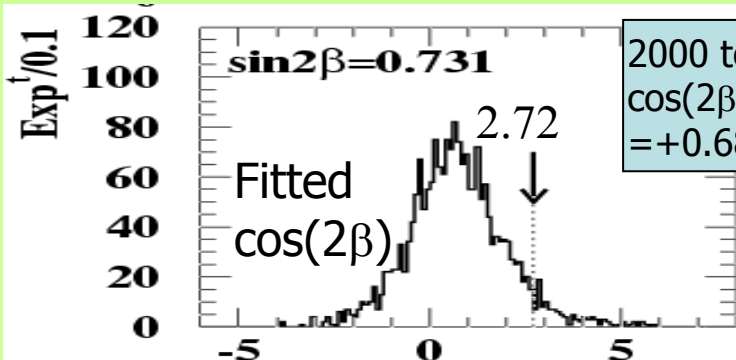
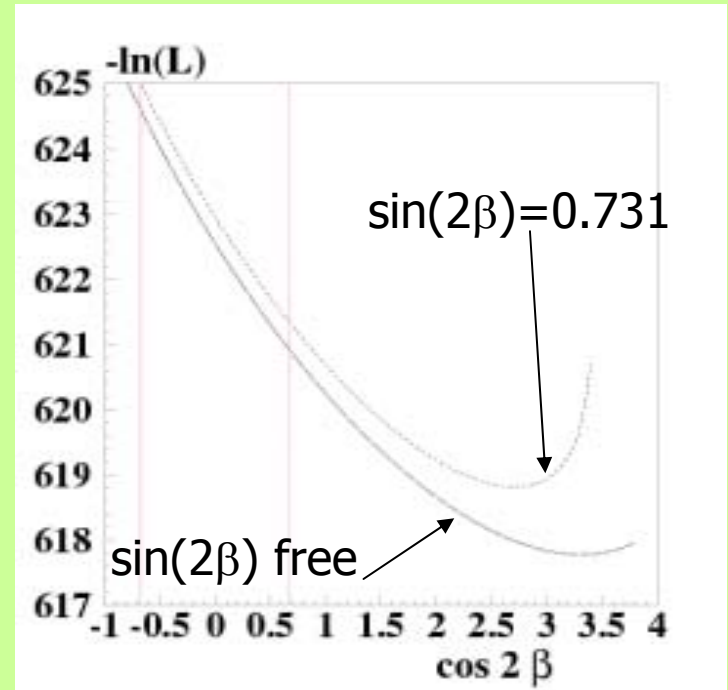
Fit with sin(2β) free:

$$\cos 2\beta = +3.32^{+0.76}_{-0.96} \text{ (stat)} \pm 0.27 \text{ (syst)}$$

$$\sin 2\beta = -0.10 \pm 0.57$$

Fit with sin(2β)=0.731

$$\cos 2\beta = +2.72^{+0.50}_{-0.79} \text{ (stat)} \pm 0.27 \text{ (syst)}$$



2000 toy mc exp. with
 $\cos(2\beta)_{\text{gen}} = (1 - 0.731^2)^{1/2}$
 $= +0.68$

We exclude $\cos(2\beta) =$
 $-(1 - \sin^2(2\beta))^{1/2} = -0.68$
@ 89% CL



Charmonium sector

$$B^- \rightarrow J/\psi K^- \pi^+ \pi^-$$

Analysis performed on 117.2 million of BBpairs

*X(3872) observed by Belle and CDF.
Possible $1^3D_2^\#$ charmonium state or
 $D^{(*)}$ mesons molecule $^\#$*

Signal Yield from M_{ES}
distribution:

$N_{sig} = (2540 \pm 72) \text{ events}$

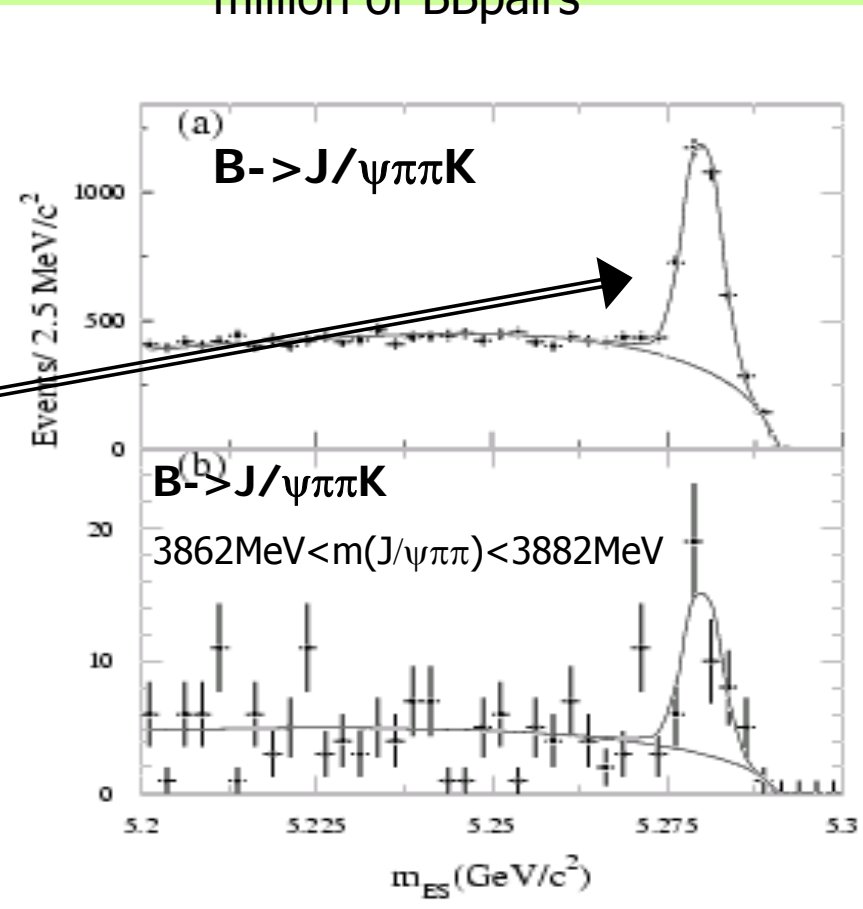
$Br(B^- \rightarrow J/\psi \pi^- \pi^+ K^-) =$

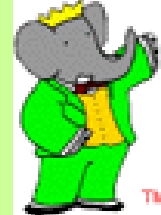
$(11.6 \pm 0.7_{stat} \pm 0.9_{syst}) \times 10^{-4}$

Phys.Rev.Lett. **89**,162002 (2002)

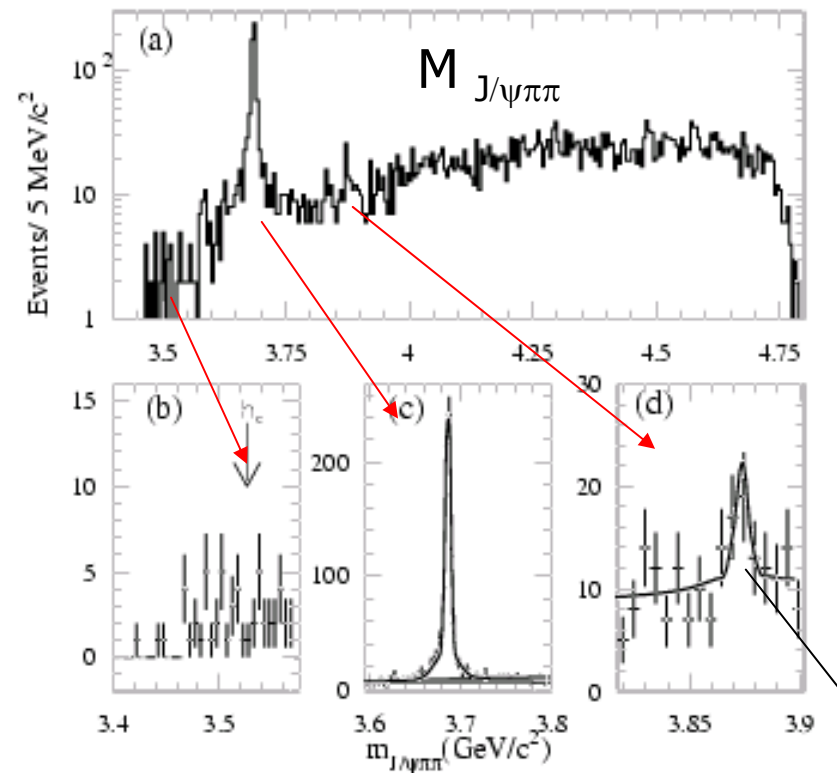
Phys.Lett.B **579**, 67(2004)

14/04/2004





Narrow states in $J/\psi\pi\pi$ mass spectrum



h_c

$\psi(2s)$

Used for
normalization

$X(3872)$

Signal significance
 3.5σ

Results:

$$M_{X(3872)} = (3873.4 \pm 1.4) \text{ MeV}$$

Agreement with Belle and CDF

$$\text{Br}(B^- \rightarrow X(3872)K^-) \times \text{Br}(X(3872) \rightarrow J/\psi \pi\pi) = (1.28 \pm 0.41) \times 10^{-5}$$

$$\text{Br}(B^- \rightarrow h_c K^-) \times \text{Br}(h_c \rightarrow J/\psi \pi\pi) < 3.4 \times 10^{-6} \text{ @ } 90\% \text{ CL}$$

$$\text{Br}(B^- \rightarrow J/\psi D^0 \pi^-) < 5.2 \times 10^{-5} \text{ @ } 90\% \text{ CL}$$

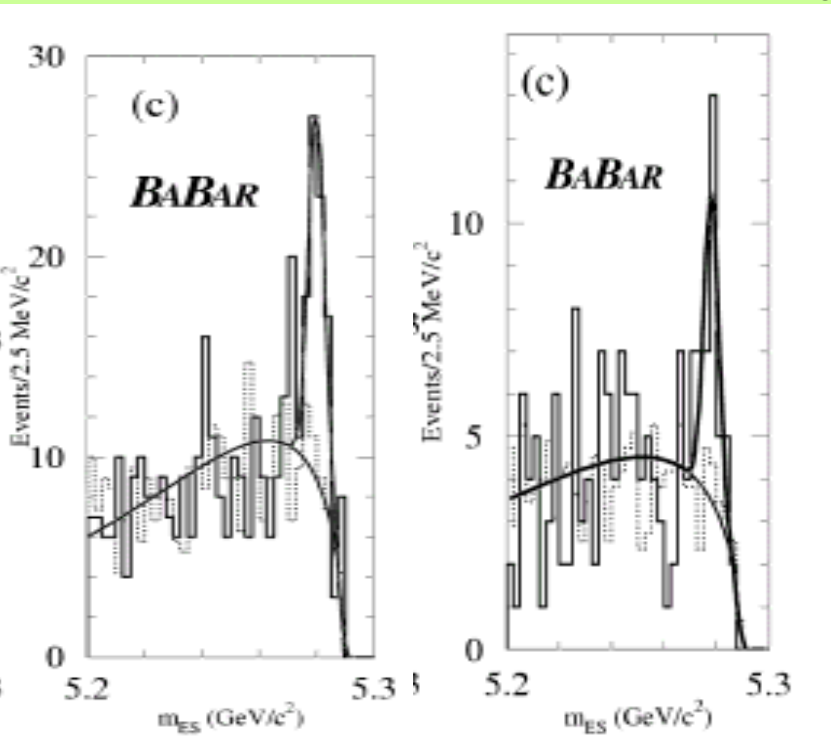


$B \rightarrow J/\psi \eta K$

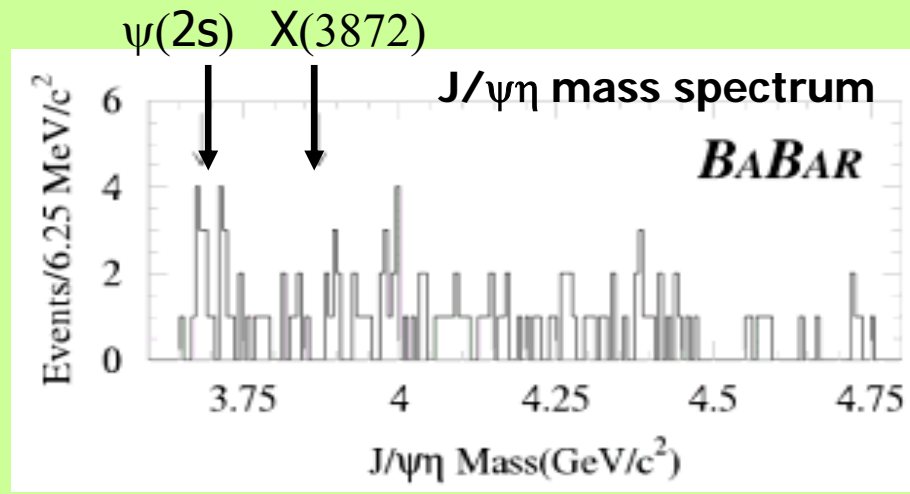
$B^\pm \rightarrow J/\psi \eta K^\pm$

$B^0 \rightarrow J/\psi \eta K_s^0$

Submitted to Phys Rev. Lett.
hep/ex 0402025

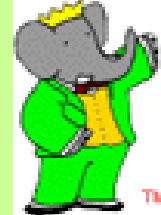


Search for $X(3872) \rightarrow J/\psi \eta$:



$Br(B^\pm \rightarrow J/\psi \eta K^\pm) = (10.8 \pm 2.3_{\text{stat}} \pm 2.3_{\text{syst}}) \times 10^{-5}$
 $Br(B^0 \rightarrow J/\psi \eta K_s^0) = (8.4 \pm 2.6_{\text{stat}} \pm 2.7_{\text{syst}}) \times 10^{-5}$
 $Br(B^\pm \rightarrow X(3872) K^\pm \rightarrow J/\psi \eta K^\pm) < 7.7 \times 10^{-5} @90\% \text{ CL}$

Analysis based on
90 million BB pairs



$B^\pm \rightarrow \chi_{c0} K^\pm$

89×10^{-6} BB pairs

Submitted to Phys Rev.D

hep/ex 0310015

$$\text{Br}(B^\pm \rightarrow \chi_{c0} K^\pm) \text{Br}(\chi_{c0} \rightarrow \pi^+ \pi^-) = (1.32 \pm 0.28 \pm 0.26) \times 10^{-6}$$

$$\text{Br}(B^\pm \rightarrow \chi_{c0} K^\pm) \text{Br}(\chi_{c0} \rightarrow K^+ K^-) = (1.49 \pm 0.36 \pm 0.22) \times 10^{-6}$$

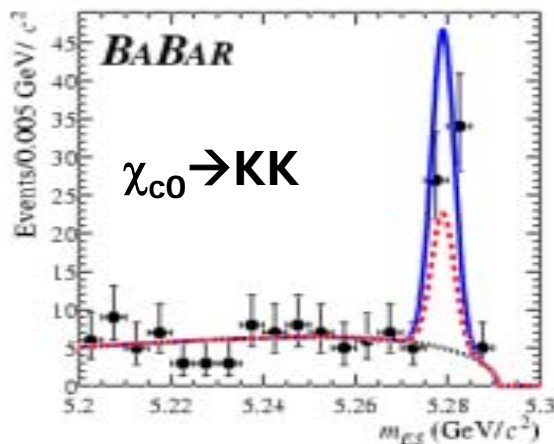
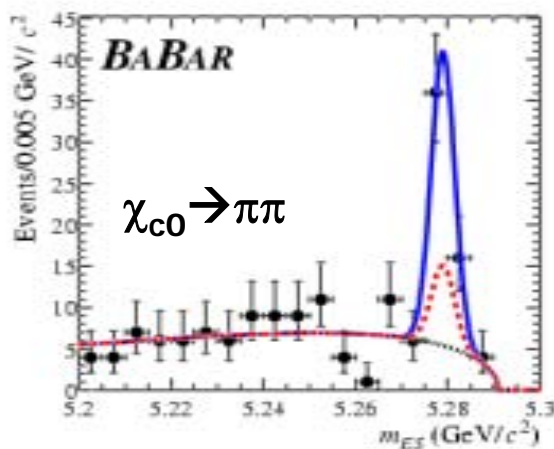
Using the Br of χ_{c0} decays by BES# we obtain:

$$\text{Br}(B^\pm \rightarrow \chi_{c0} K^\pm) = (2.7 \pm 0.7) \times 10^{-4}$$

The result is lower than BELLE result:

$$\text{Br}(B^\pm \rightarrow \chi_{c0} K^\pm) = (6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4}$$

Phys.Rev.Lett.
81,3091(1998)

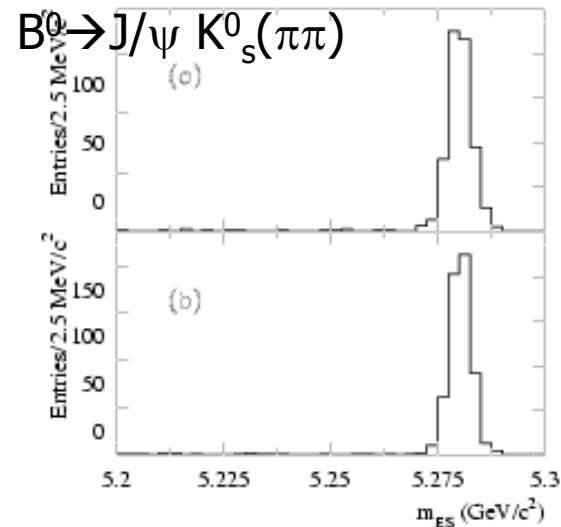




B^\pm/B^0 with charmonium

$$R^{+/0} = \frac{\Gamma(Y(4S) \rightarrow B^+ B^-)}{\Gamma(Y(4S) \rightarrow B^0 \bar{B}^0)} = \frac{N^+ \varepsilon^0 f \tau_0}{2N^0 \varepsilon^+ \tau_+}$$

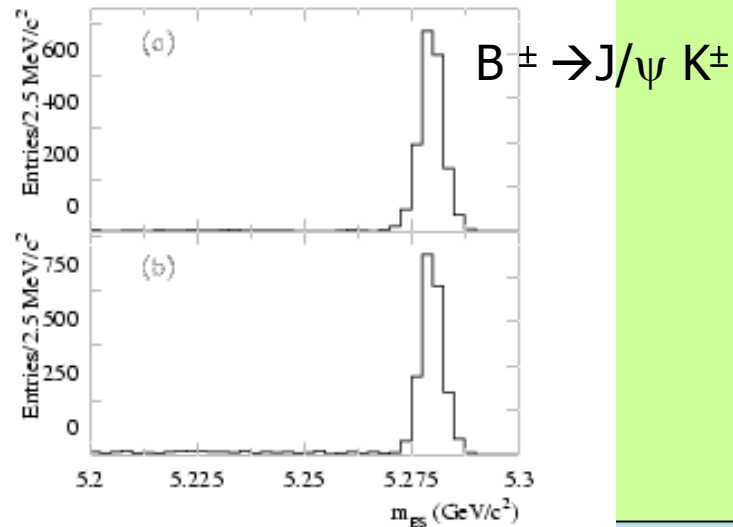
Submitted to Phys Rev.D
hep/ex 0401028



$J/\psi \rightarrow e^+e^-$

M_{ES}

$J/\psi \rightarrow \mu^+\mu^-$



$L=81.9\text{fb}^{-1}$

ε from MC, $f=\text{Br}(K_s^0 \rightarrow \pi\pi)$

$R^{+/0} (e^+e^-) = 1.019 \pm 0.054_{\text{stat}} \pm 0.031_{\text{syst}}$

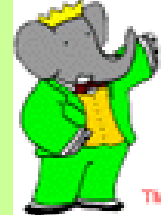
$R^{+/0} (\mu^+\mu^-) = 0.994 \pm 0.049_{\text{stat}} \pm 0.033_{\text{syst}}$

$R^{+/0} (\text{avg}) = 1.006 \pm 0.036_{\text{stat}} \pm 0.031_{\text{syst}}$

14/04/2004

Michele Pioppi

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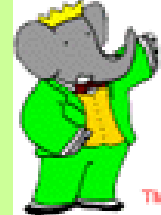


Summary

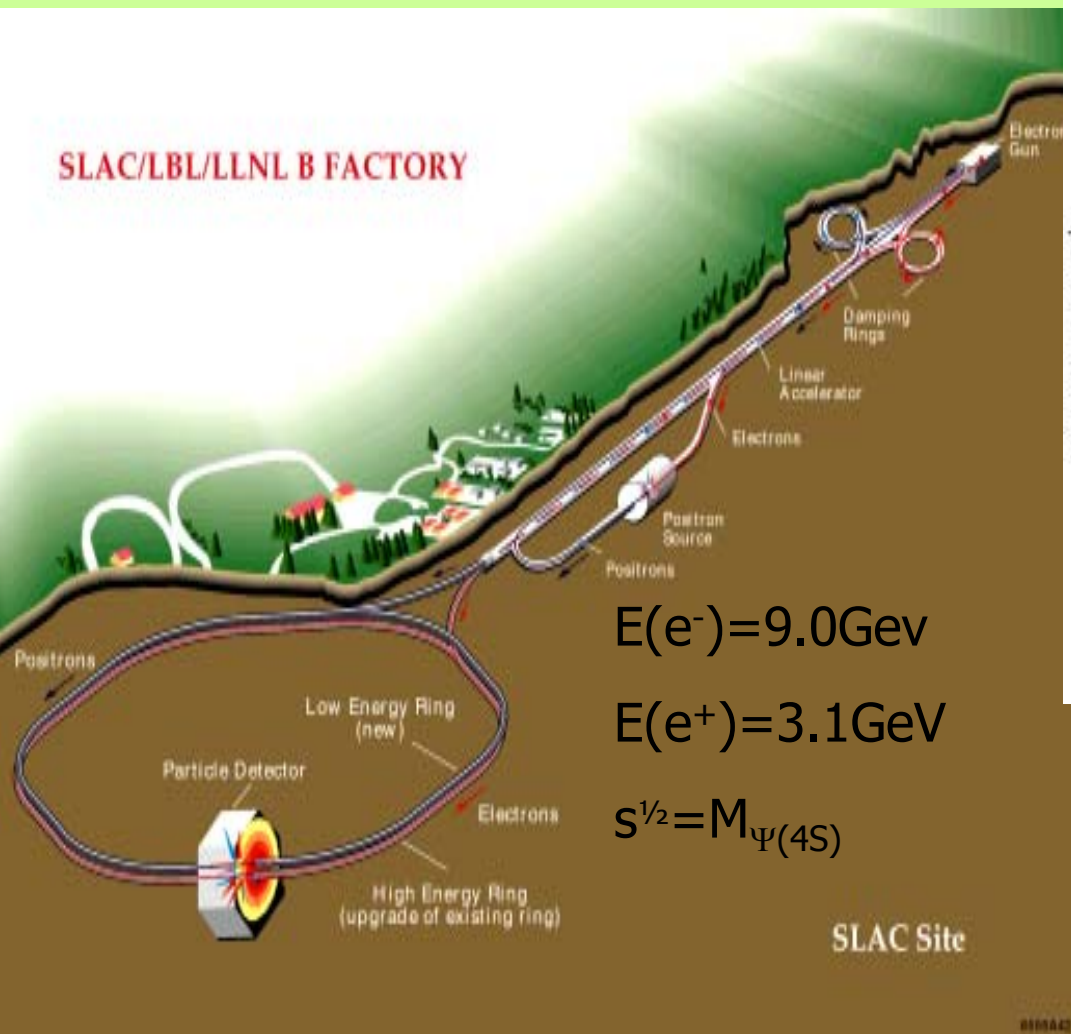
- **Semileptonic B decays**
 - Hadronic mass and lepton-energy moments
 - $|V_{cb}| = (41.4 \pm 0.4_{\text{exp}} \pm 0.4_{\text{HQE}} \pm 0.6_{\text{th}}) \times 10^{-3}$
 - $m_b(1 \text{ GeV}) = (4.61 \pm 0.05_{\text{exp}} \pm 0.04_{\text{HQE}} \pm 0.02_{\text{th}}) \text{ GeV}$
 - $m_c(1 \text{ GeV}) = (1.18 \pm 0.07_{\text{exp}} \pm 0.06_{\text{HQE}} \pm 0.02_{\text{th}}) \text{ GeV}$
- **J/ψ Kπ events**
 - New method to break strong phase ambiguity
 - Exclusion of negative values for $\cos(2\beta)$ @ 89% C.L.
- **Charmonium sector**
 - $M_{\chi(3872)} = (3873.4 \pm 1.4) \text{ MeV}$
 - $\text{Br}(B^- \rightarrow \chi(3872)K^-) \times \text{Br}(\chi(3872) \rightarrow J/\psi \pi\pi) = (1.28 \pm 0.41) \times 10^{-5}$
 - $\text{Br}(B^\pm \rightarrow J/\psi \eta K^\pm) = (10.8 \pm 2.3_{\text{stat}} \pm 2.3_{\text{syst}}) \times 10^{-5}$
 - $\text{Br}(B^0 \rightarrow J/\psi \eta K_s) = (8.4 \pm 2.6_{\text{stat}} \pm 2.7_{\text{syst}}) \times 10^{-5}$
 - $\text{Br}(B^\pm \rightarrow \chi_{c0} K^\pm) = (2.7 \pm 0.7) \times 10^{-4}$
 - $R^{+/0} = 1.006 \pm 0.036_{\text{stat}} \pm 0.031_{\text{syst}}$



BACK UP SLIDES



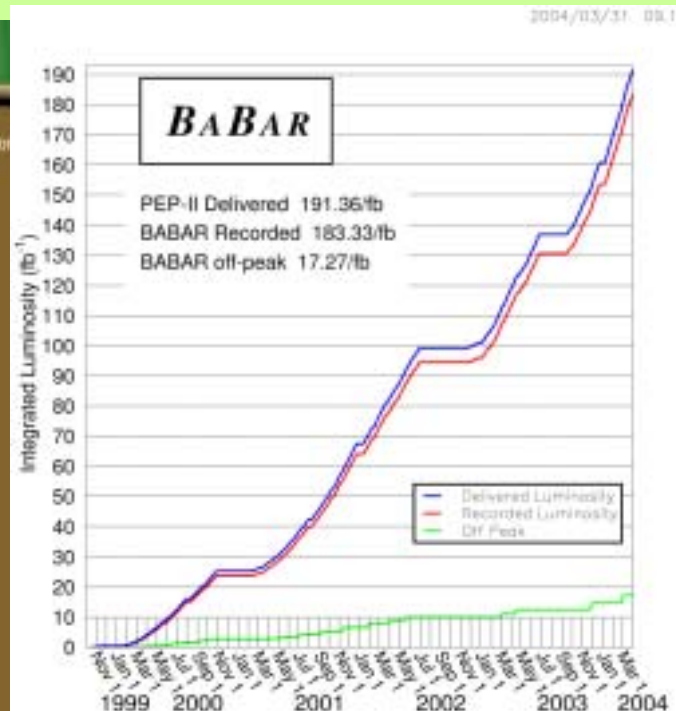
PEP II



$$E(e^-) = 9.0 \text{ GeV}$$

$$E(e^+) = 3.1 \text{ GeV}$$

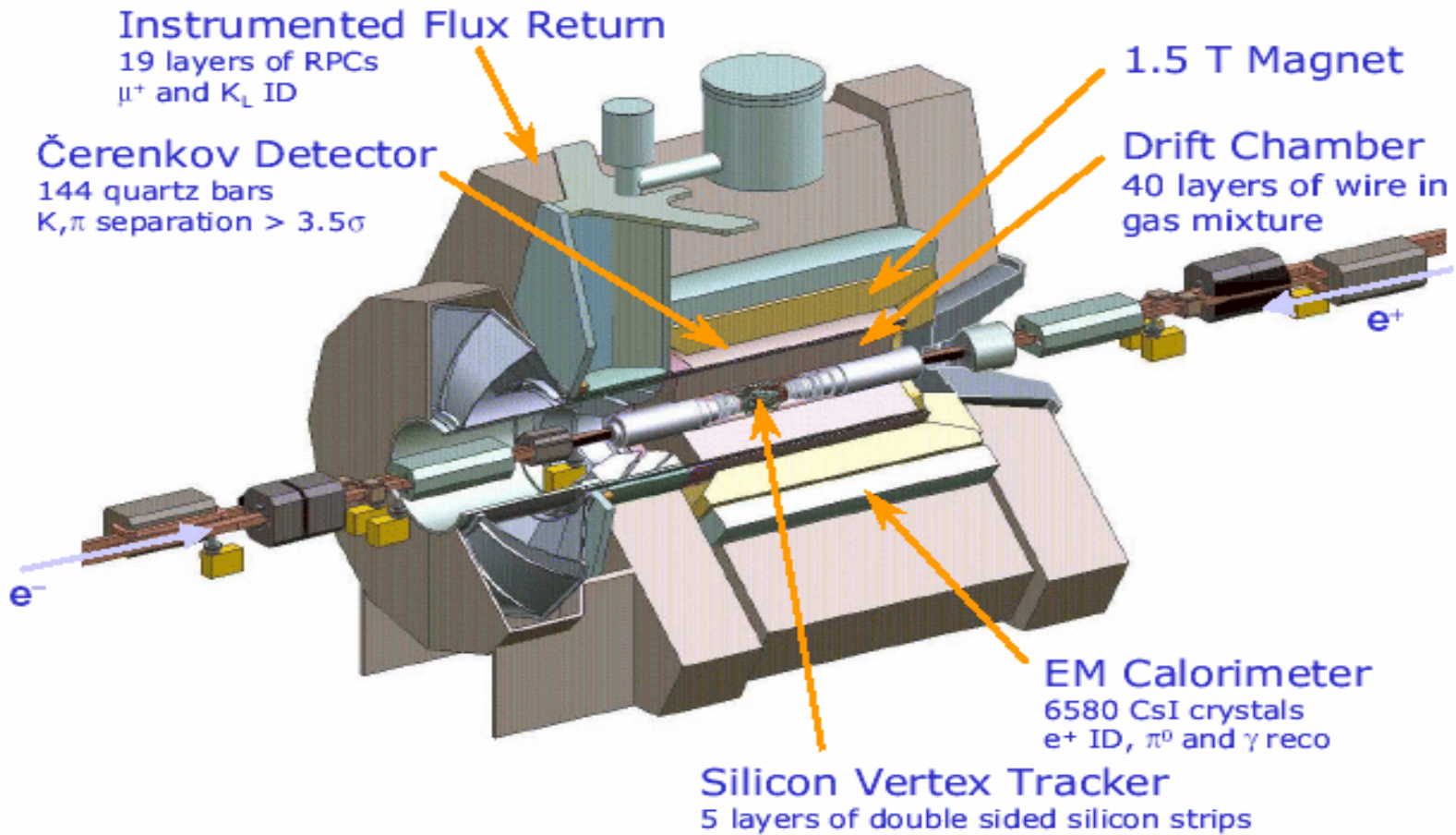
$$s^{1/2} = M_{\Psi(4S)}$$



$e^+e^- \rightarrow$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40



BaBar detector

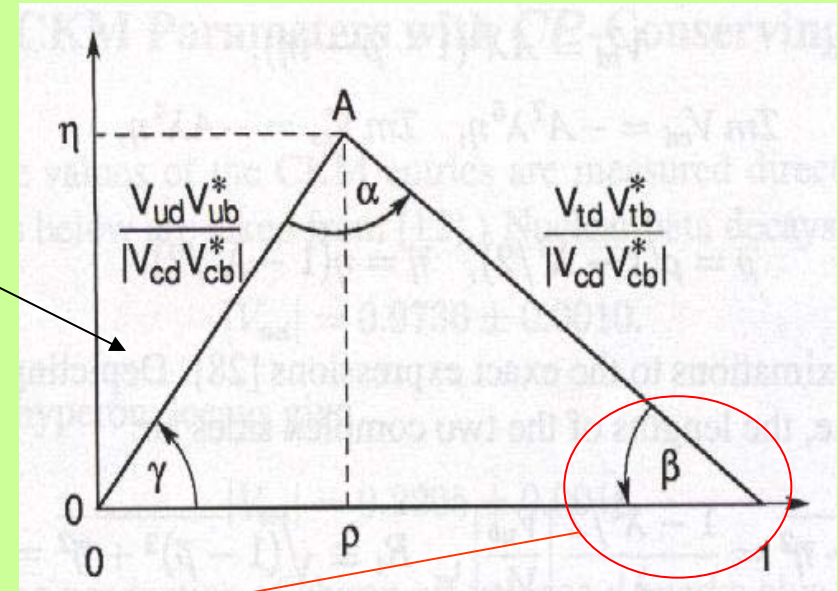




Unitarity triangle

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

Unitarity property of CKM matrix
can be seen as a triangle in
complex plane



$$\beta \equiv \arg \left[- \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right]$$

Golden channel to determine $\sin(2\beta)$

$B \rightarrow J/\psi K_s$