Measurement of sin2β

with charmonium decays and gluonic penguin decays

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Outline

- CP violation

  $N(B \rightarrow f)$? $N(\overline{B} \rightarrow \overline{f})$

- Introduction:
  Standard Model CP violation & the CKM mechanism

- Testing the Standard Model:
  measurement of $\sin(2\beta)$ from charmonium K_S decays

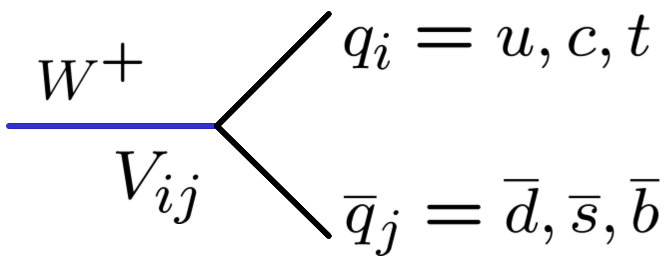
- Looking for signs of new physics:
  measurement of $\sin(2\beta)$ from $b \rightarrow s$ penguin decays

- Comparison and summary

The Cabibbo-Kobayashi-Maskawa matrix

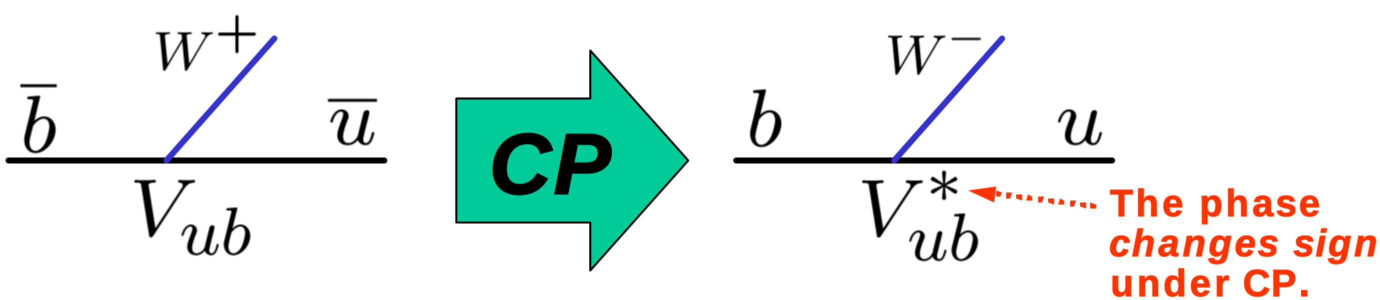
- In the Standard Model, the CKM matrix elements V_{ij} describe the electroweak coupling strength of the **W** to **quarks**
  - *CKM mechanism introduces quark* ***flavor mixing***

Mixes the *left-handed charge –1/3 quark* ***mass*** *eigenstates d,s,b* to give the ***weak*** *eigenstates d',s,b'.*



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

  - **Complex phases** in $\mathbf{V_{ij}}$ are the origin of SM **CP violation**

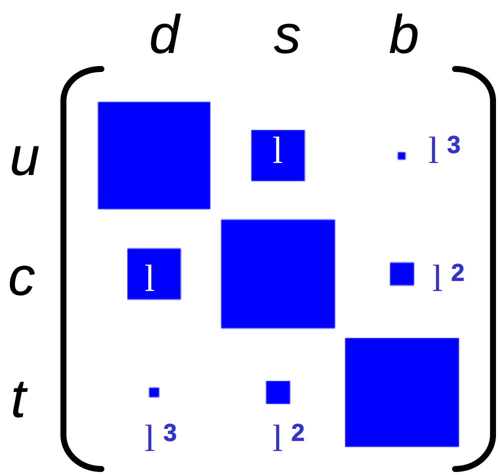


Transition amplitude violates CP if $\mathbf{V_{ub}}$ **?** $\mathbf{V_{ub}^*}$, i.e. if V_{ub} has a non-zero phase

Structure of the CKM matrix

- The CKM matrix $\boldsymbol{V_{ij}}$ is unitary with 4 independent fundamental parameters (including 1 irreducible complex phase)
  - Magnitude of elements strongly ranked (leading to ~diagonal form)
  - Choice of overall complex phase arbitrary – only $\boldsymbol{V_{td}}$ and $\boldsymbol{V_{ub}}$ have non-zero complex phases in Wolfenstein convention

CKM magnitudes



$\lambda = \cos(\theta_c) = 0.22$

CKM phases

(*in Wolfenstein convention*)

$$\begin{pmatrix} 1 & 1 & e^{-i?} \\ 1 & 1 & 1 \\ e^{-iß} & 1 & 1 \end{pmatrix}$$

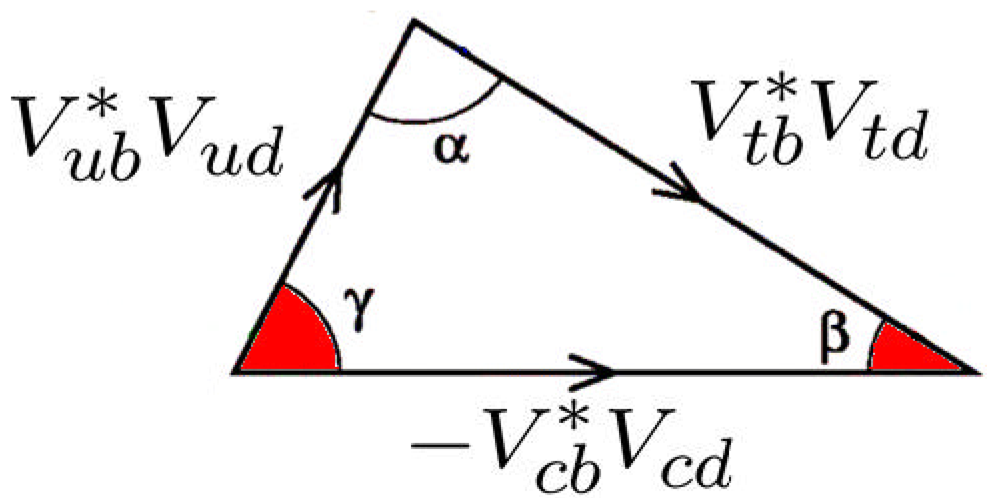
Some of the real elements in the Wolfenstein convention may have small O(l⁴) complex phases

- *Measuring SM CP violation → Measure complex phase of CKM elements*

Visualizing the phase – the unitarity triangle

- Phases of CKM elements V_{td} and V_{ub} are related to CPV in SM
  - Visualization: b and g are two angles of a triangle.
  - Surface of triangle is proportional to amount of CPV introduced by CKM mechanism

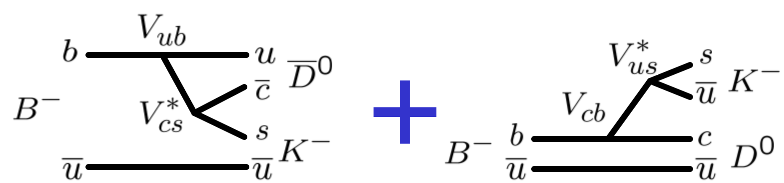
$$\begin{pmatrix} 1 & 1 & e^{-i?} \\ 1 & 1 & 1 \\ e^{-iß} & 1 & 1 \end{pmatrix}$$



Amplitude phases and observables CP violation

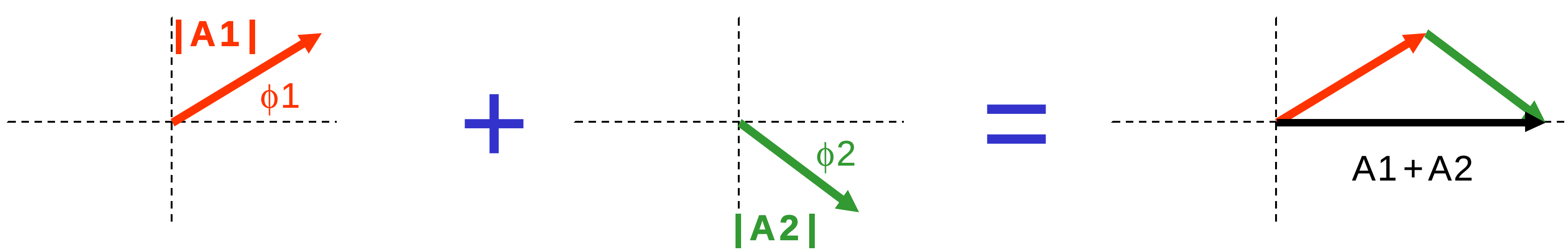
- How do complex phase affect decay rates
  - Only affects decays with >1 amplitude
  - Decay rate ∝ $|A|^2$ → phase of sole amplitude does not affect rate

- Consider case with 2 amplitudes with same initial and final state - Decay rate ∝ $|A_1 + A_2|^2$



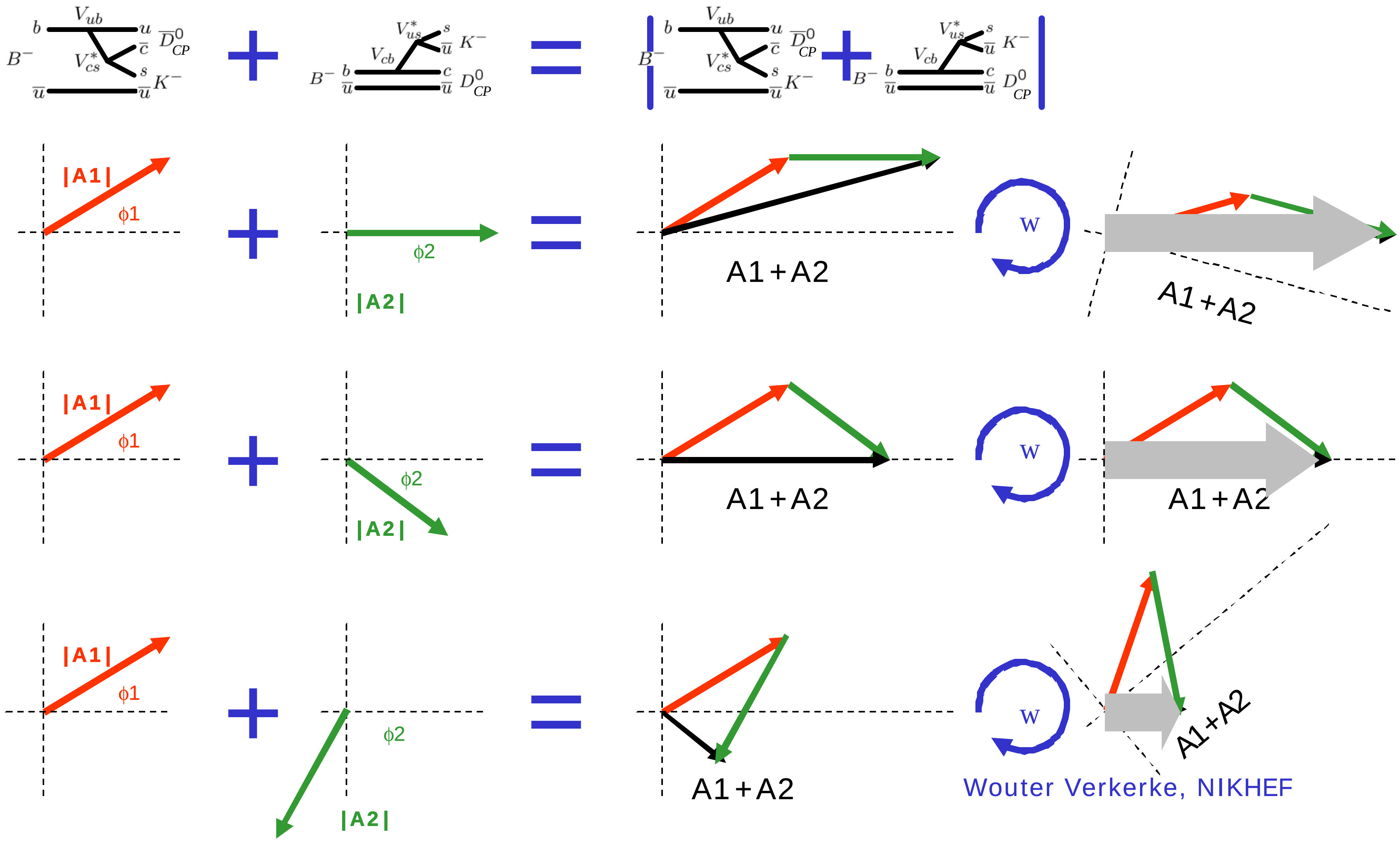
$$\left| \; \cdots \; \right|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos(\phi_1 - \phi_2)$$

$A_1 = |A_1| * exp(i\phi 1)$ $\qquad$ $A_2 = |A_2| * exp(i\phi_2)$



Amplitude phases and observables CP violation

- Observable summed amplitude clearly depends on phase difference



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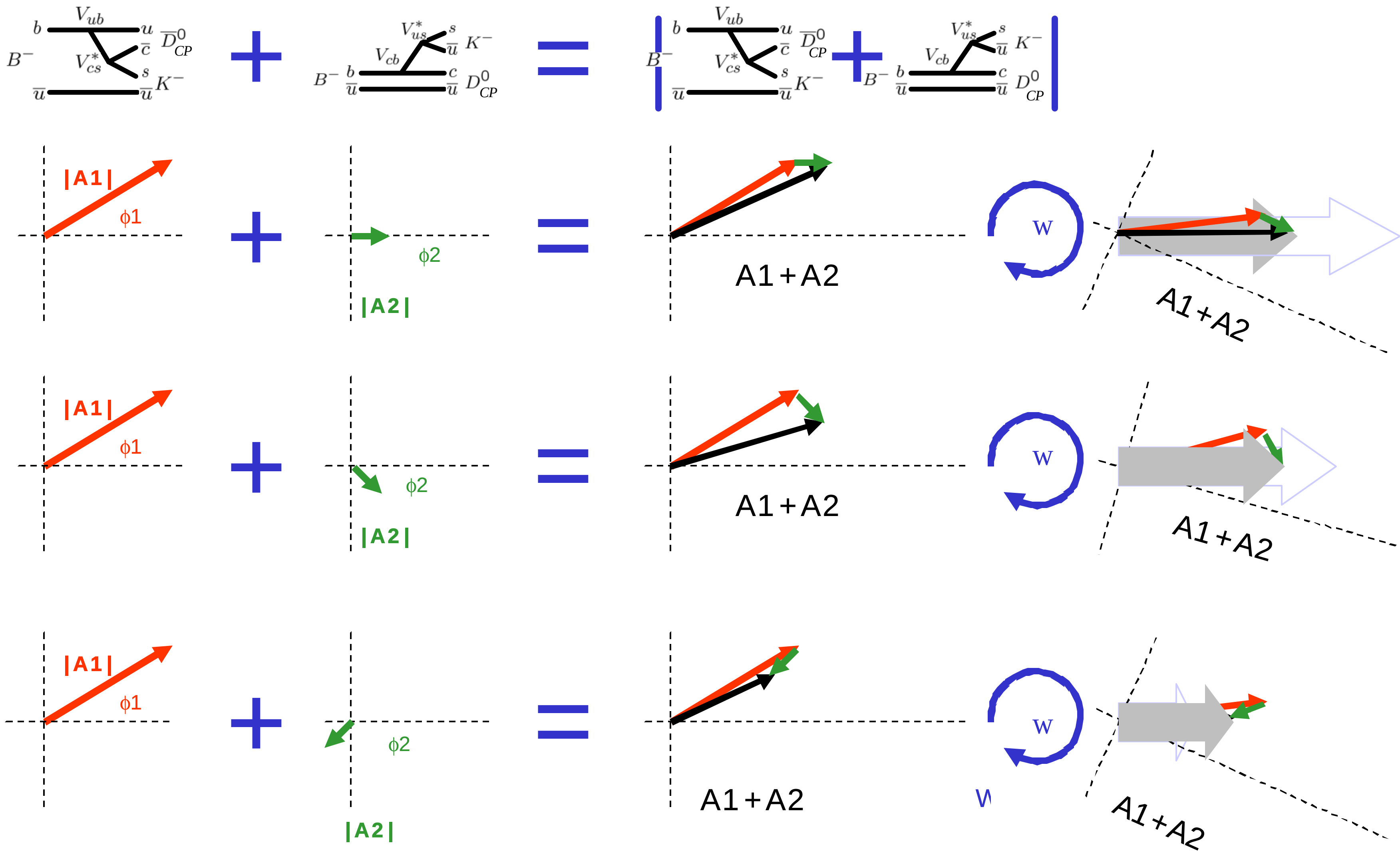
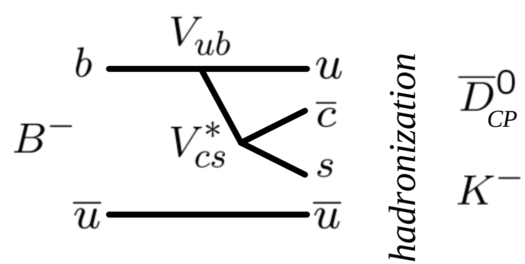
Amplitude phases and observables CP violation

- Dependence on Δφ scales with amplitude ratio
  - Observation in practice requires amplitudes of comparable magnitude

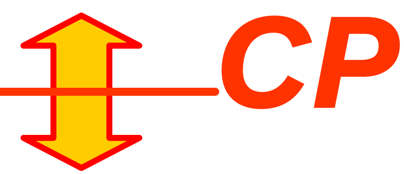


Measuring the CKM phases from CP violation

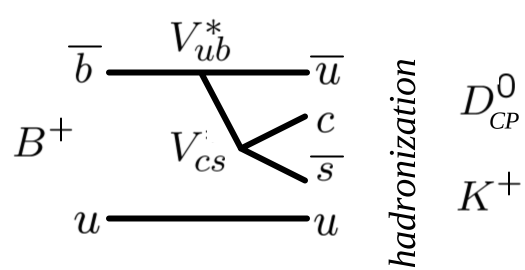
- Decay rate of interfering amplitudes sensitive to phase difference
  - *How disentangle weak phase* from overall phase difference between amplitudes?
- Exploit that *weak phase flips sign under CP transformation*
  - Look at decay rates for B → f and $\overline{B} \to \overline{f}$



$$A(B \to f) = |A_{B\to f}| \exp i(\varphi_{weak} + \delta_{other})$$



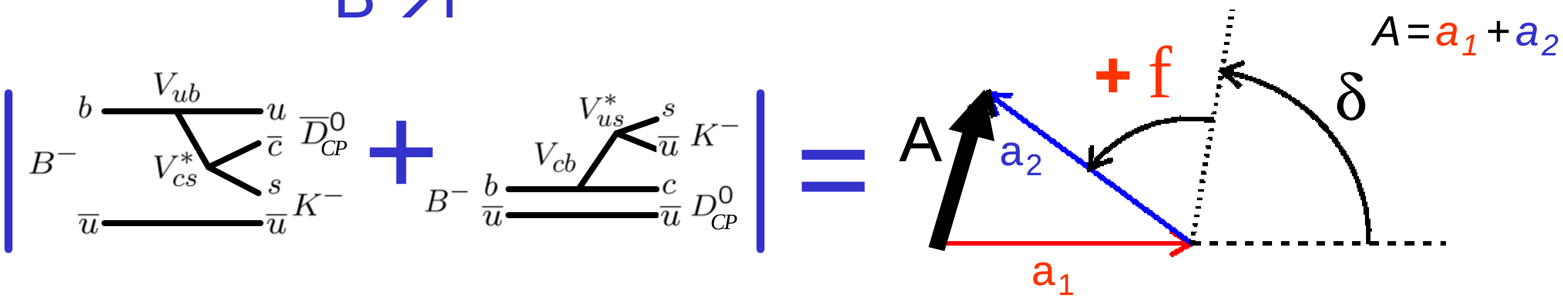
$$A(\overline{B} \to \overline{f}) = |A_{B\to f}| \exp i(-\varphi_{weak} + \delta_{other})$$



How the weak phase introduces observable CPV

- Effect of weak phase sign flip on interfering amplitudes

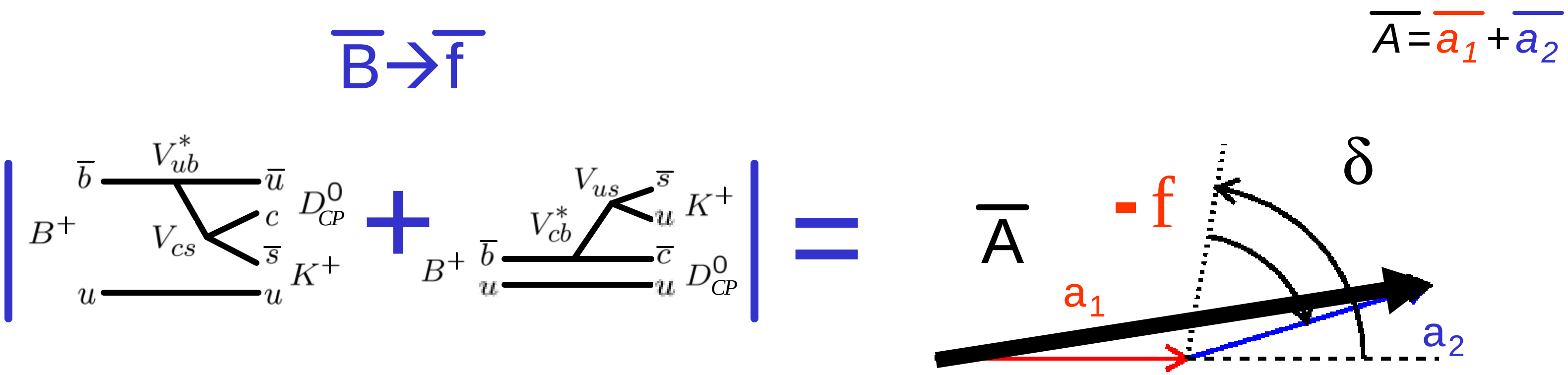
B→f



CP

$$A_{CP} = \frac{|\overline{A}|^2 - |A|^2}{|\overline{A}|^2 + |A|^2}$$ **related to φ$_{weak}$**

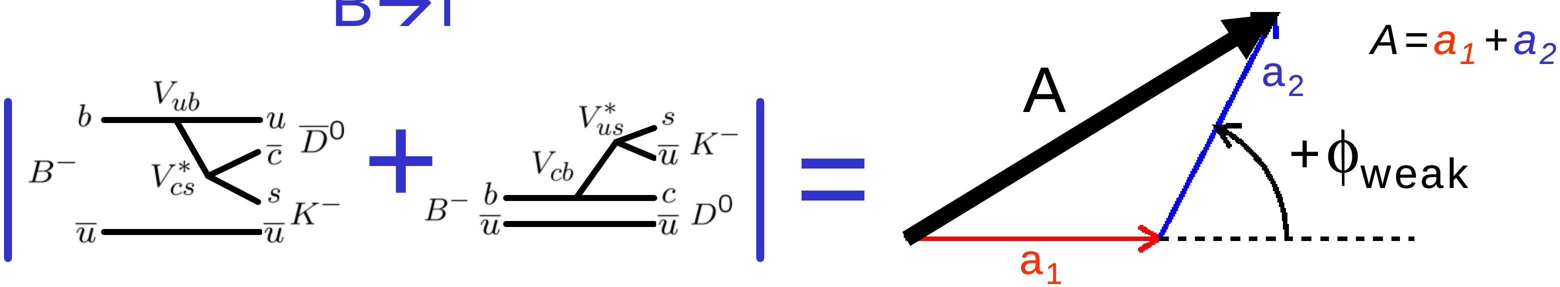
$\overline{\text{B}}$→$\overline{\text{f}}$



But not always...

- Effect of weak phase sign flip on interfering amplitudes

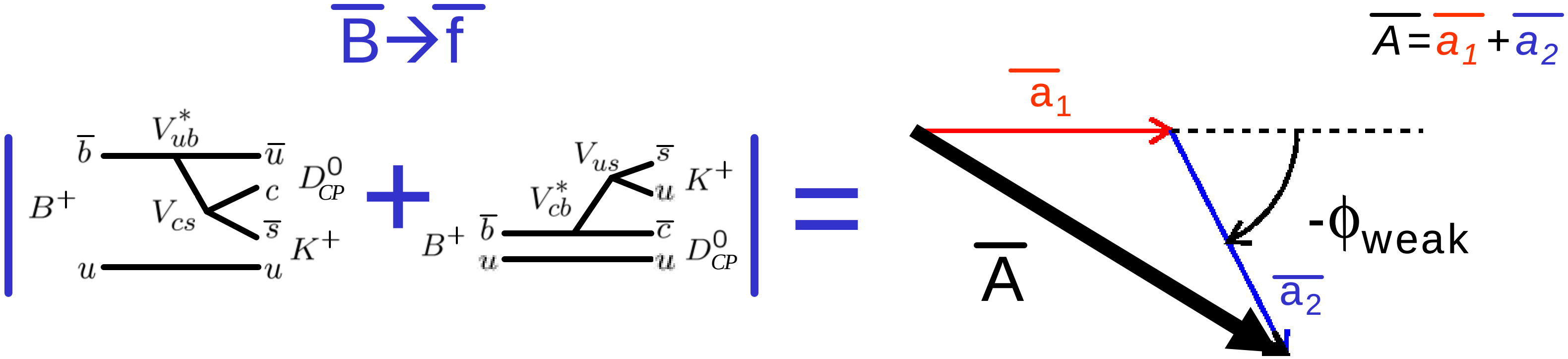
B→f



CP

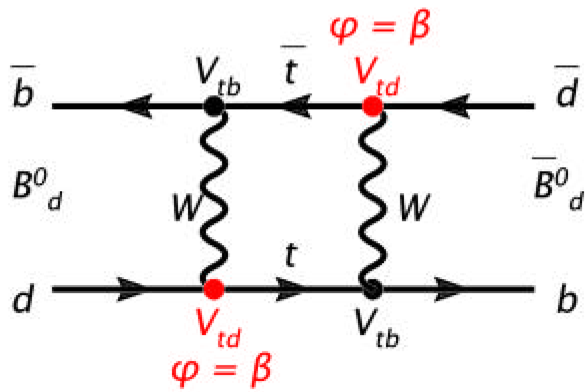
$$A_{CP} = \frac{|\overline{A}|^2 - |A|^2}{|\overline{A}|^2 + |A|^2}$$ = 0, need d? 0 too!

$\overline{B}$→$\overline{f}$



A clean way to measure the CP angle β

- Find 2 interfering amplitudes with relative weak phase β
  - Requires CKM element V_{td}
  - V_{td} appears twice B^0-B^0 mixing process



$$\begin{pmatrix} 1 & 1 & e^{-i?} \\ 1 & 1 & 1 \\ e^{-iß} & 1 & 1 \end{pmatrix}$$

  - Mixing process introduces a weak phase of 2β and a CP-invariant phase of π/2

- Find process with two interfering amplitudes: one *with* mixing and one *without*
  - **B → f** phase = ϕ_{decay}
  - **B → $\bar{B}$ → f** phase = $\phi_{decay} + \phi_{mixing}$

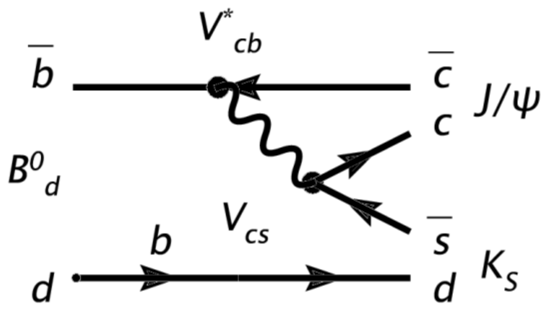
  } Df = f $_{\textbf{mixing}}$

  - Final state *f* must be CP eigenstate as both B and $\bar{B}$ must decay into it

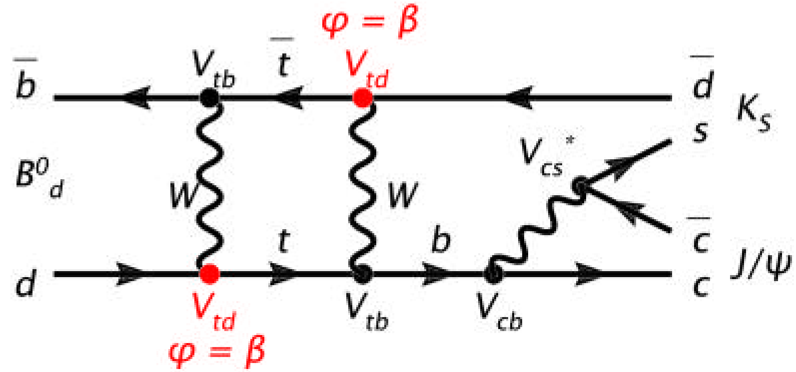
The golden mode B0 → J/ψ K_S

- An experimentally and theoretically clean CP eigenstate f_{CP} with no weak phase of its own is B^0 → J/ψ K_S

$B^0 \to f$

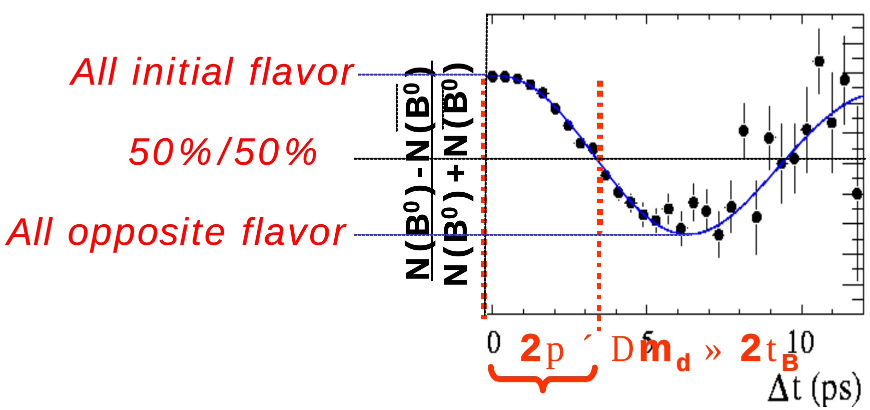


$B^0 \to \overline{B^0} \to f$



- But mixing amplitude is decay time dependent

$B^0 - B^0$ mixing oscillation vs decay time



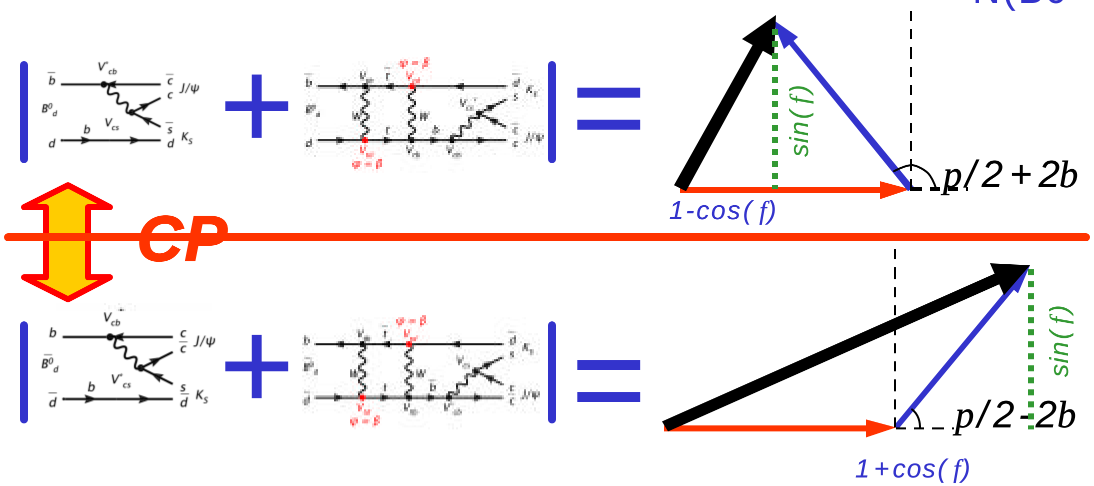
$B^0 \to \overline{B^0} \to f$ amplitude is decay time dependent

Interference and observable CPV is decay time dependent

Maximal CPV when amplitudes equal, around t = $2\pi \times \Delta m_d$ ~= $2\tau_B$

The golden mode B0 → J/ψ K_S

- When mixed and unmixed amplitude are of *equal magnitude*



N(B0 → f) ∝ $|A|^2$ ∝ $(1-\cos\phi)^2+\sin^2\phi$
= $1 - 2\cos\phi+\cos^2\phi+\sin^2\phi$
= $2-2\cos(\pi/2+2\beta)$
∝ $1-\sin(2\beta)$

$$A_{CP} = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2b)$$

N($\overline{\text{B0}}$ → f) ∝ $(1+\cos\phi)^2+\sin^2\phi$
= $2+2\cos(\pi/2-2\beta)$
∝ $1+\sin(2\beta)$

- Working out the more general case gives

$$A_{CP}(f;t) = \sin(2b)\sin(\Delta m_d t)$$

Generalized for any decay time

(sin(2b) if |l|=1) *(0 if |l|=1)*

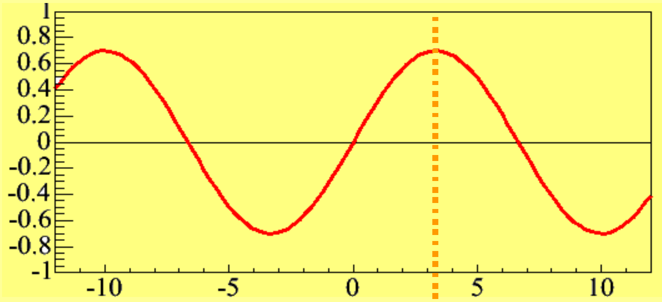
$$A_{CP}(f;t) = \frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}\sin\Delta m_d t - \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta m_d t$$

$$l_f = e^{-i2b}\frac{A(\overline{B}^0 \to f)}{A(B^0 \to f)}$$

Even more general form that also allows for CP violation in decay amplitude

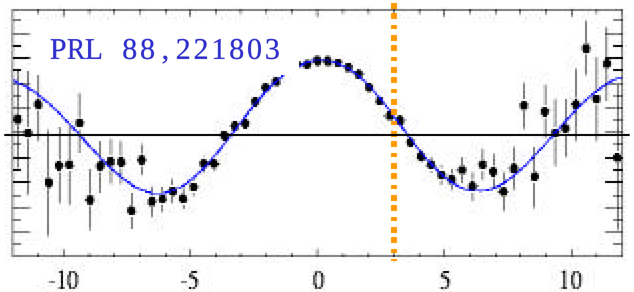
The golden mode B0 → J/ψ K_S

- What will it look like?



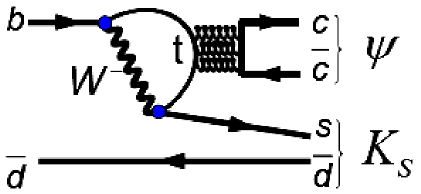
$$A_{CPV} = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{\overline{B^0}\to f} + N_{B^0\to f}} = \sin(2b)\sin(\Delta m \cdot t)$$

Maximal CPV if A(B→f)=A(B→B→f)



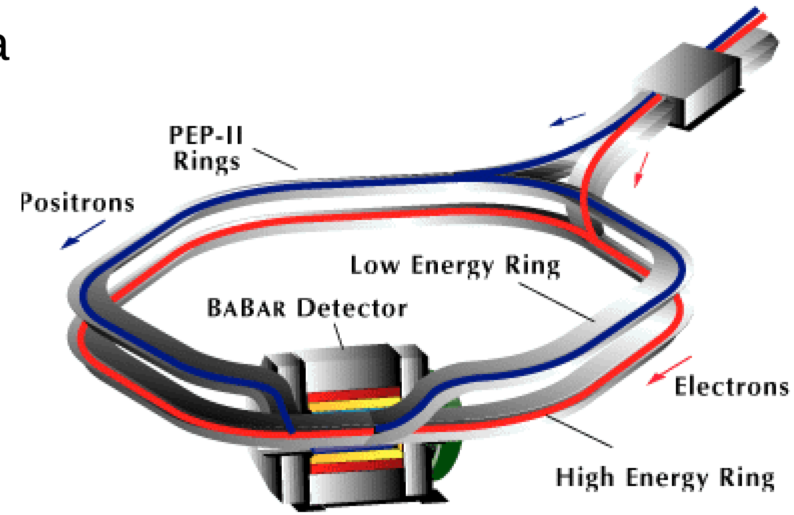
$$A_{MIX} = \frac{N_{\overline{B^0}} - N_{B^0}}{N_{\overline{B^0}} + N_{B^0}} = \cos(\Delta m \cdot t)$$

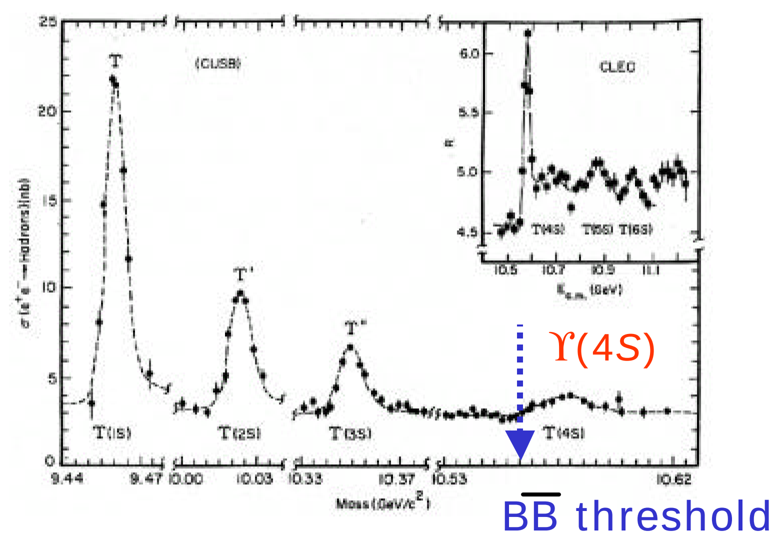
- Why is it 'golden'?
  - Virtually free of Standard Model pollution. Next largest decay amplitude for B^0 → J/ψ K_S has same weak phase as leading diagram.
  - Theoretical uncertainty on procedure of order 1%



The PEP-II B factory – specifications

- Produces $B^0\overline{B}^0$ and B^+B^- pairs via Y(4s) resonance (10.58 GeV)
- Asymmetric beam energies
  - Low energy beam 3.1 GeV
  - High energy beam 9.0 GeV
- Boost separates B and $\overline{B}$ and allows measurement of B^0 life times
- Clean environment
  - ~28% of all hadronic interactions is $B\overline{B}$





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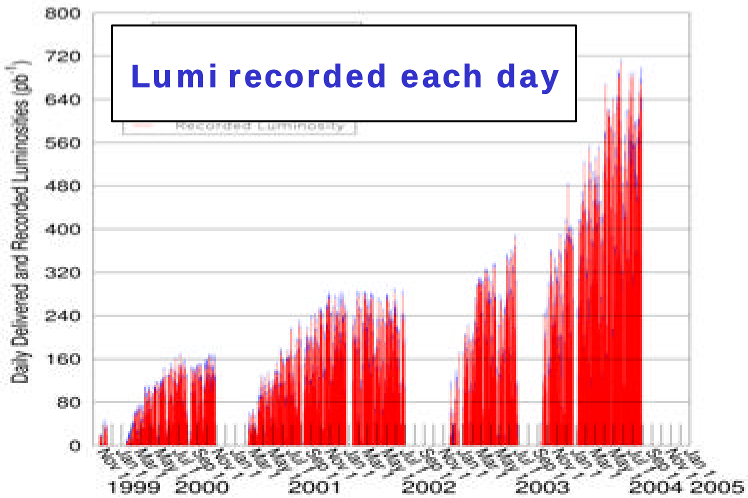
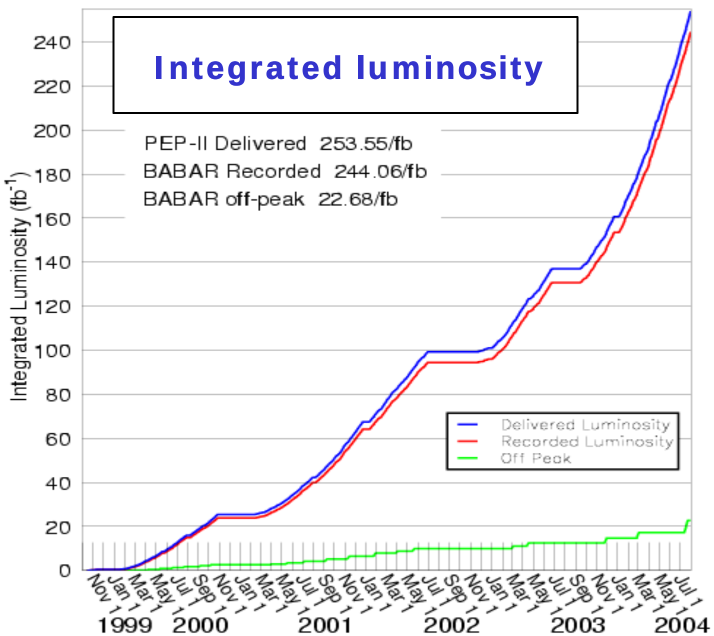
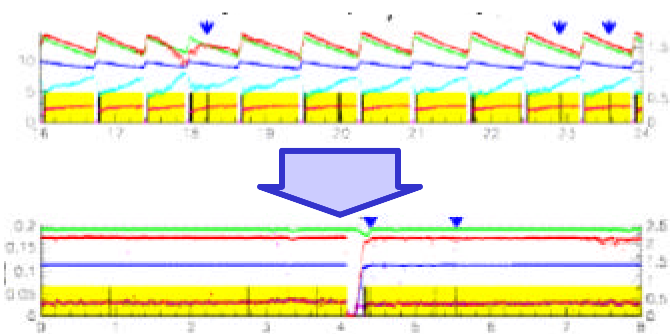
The PEP-II B factory – performance





- PEP-II top lumi: $9.2 \times 10^{33}\ cm^{-2}s^{-1}$
  - ~10 BB pairs per second
- Continuous 'trickle' injection
  - Reduces data taking interruption for 'top offs'



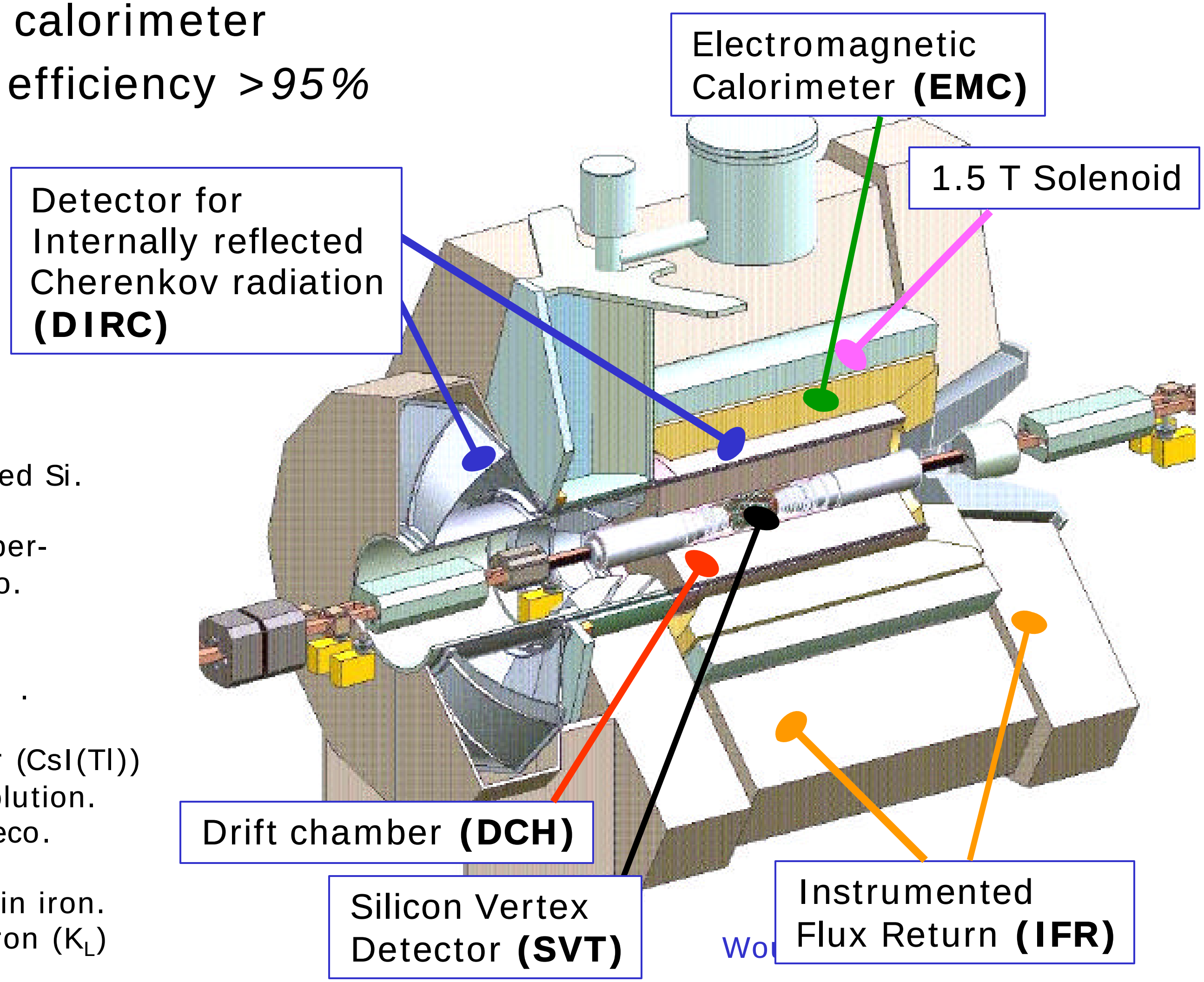
beam currents

beam currents

- Integrated luminosity
  - PEP-II delivered: 254 fb^{-1}
  - BaBar recorded: 244 fb^{-1}
  - Most analyses use 205fb^{-1} of on-peak data (227M *BB* pairs)

The BaBar experiment

- Outstanding $K^{\pm}$ ID
- Precision tracking (Δt measurement)
- High resolution calorimeter
- Data collection efficiency *>95%*



SVT: 5 layers double-sided Si.

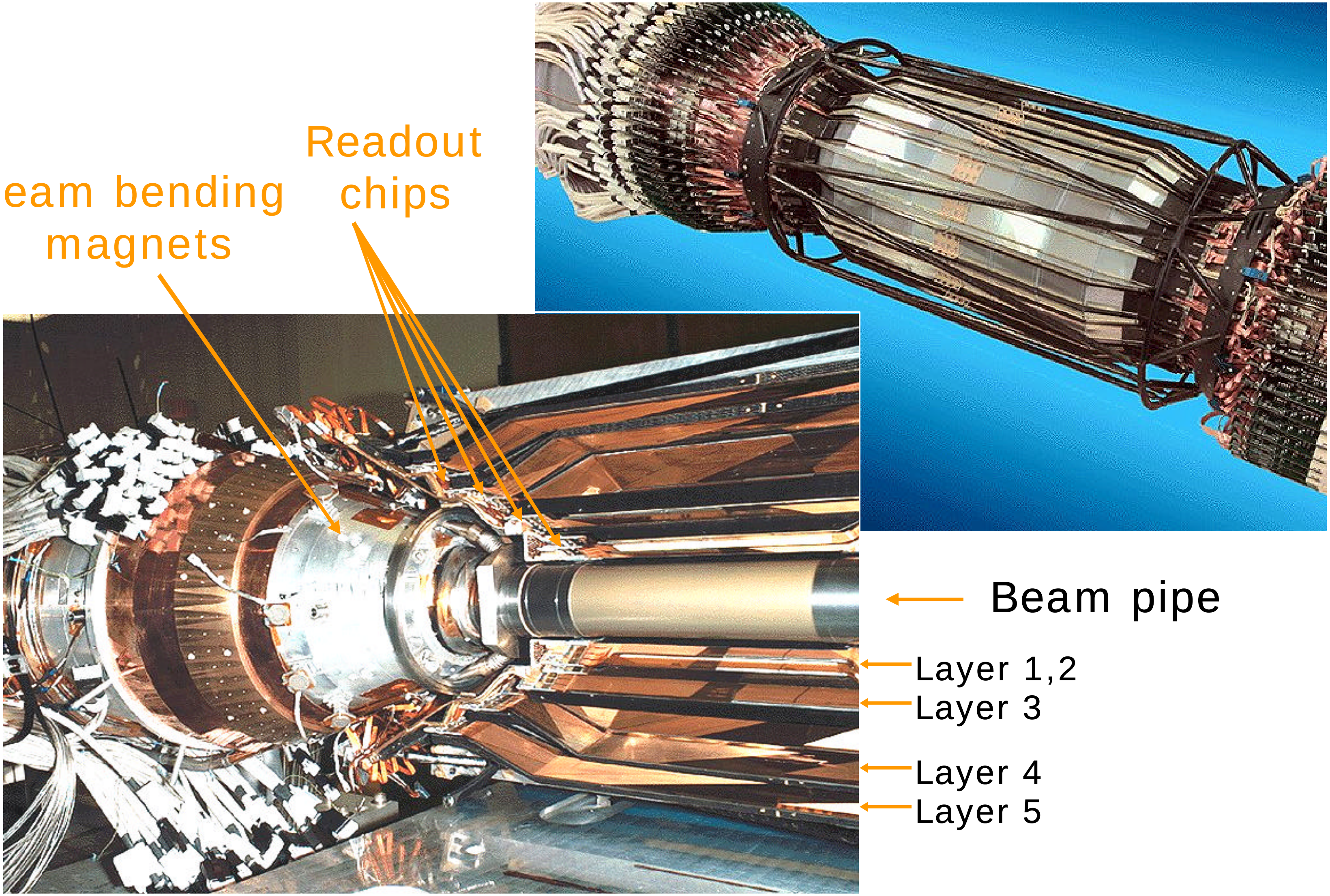
DCH: 40 layers in 10 super-layers, axial and stereo.

DIRC: Array of precisely machined quartz bars. .

EMC: Crystal calorimeter (CsI(Tl)) Very good energy resolution. Electron ID, π^0 and γ reco.

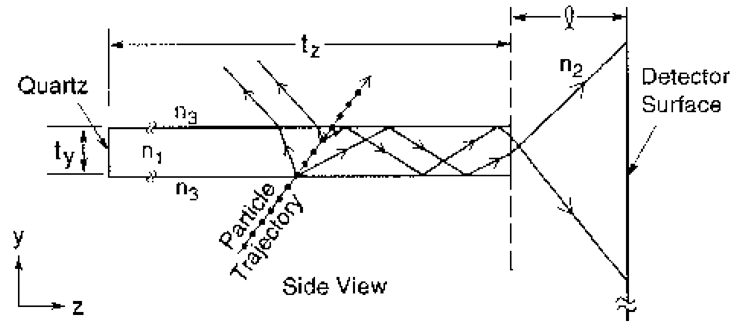
IFR: Layers of RPCs within iron. Muon and neutral hadron (K_L)

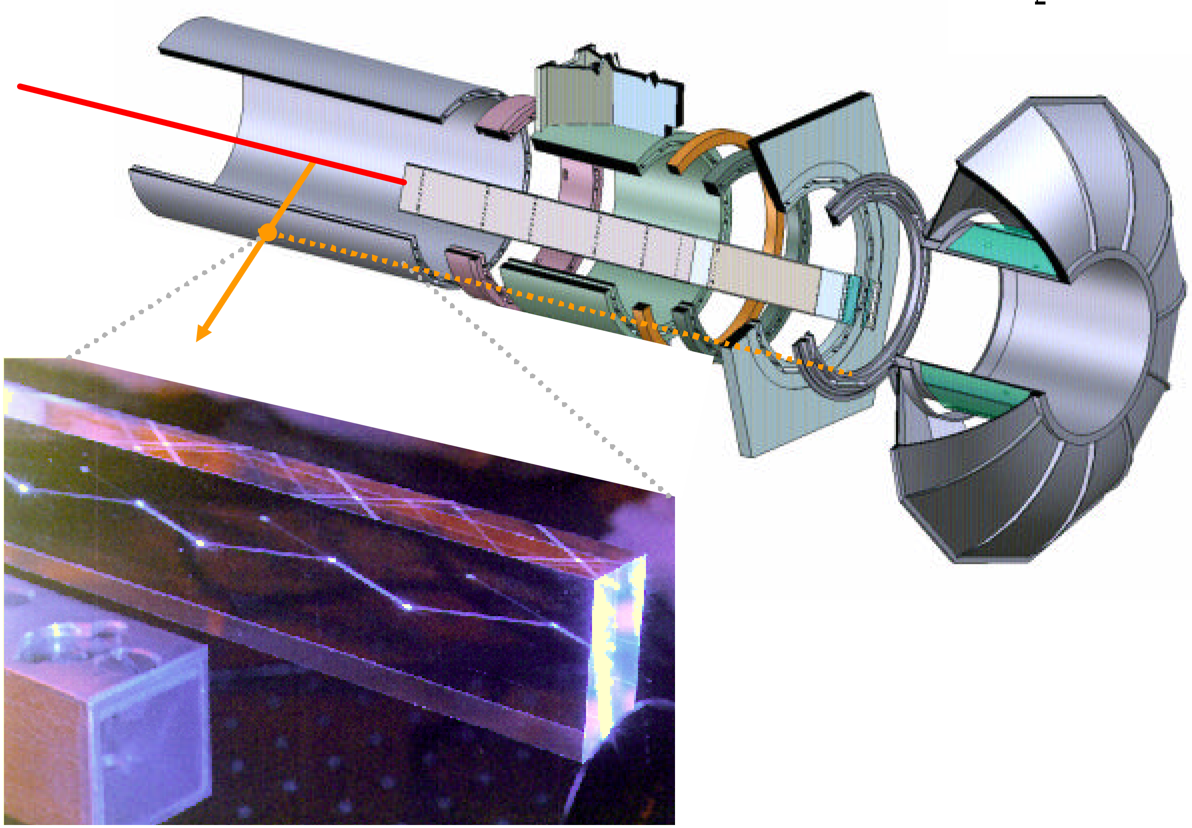
Silicon Vertex Detector

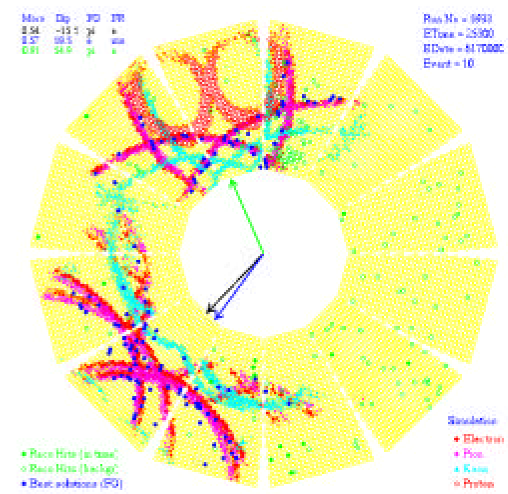


Cerenkov Particle Identification system

- Cerenkov light in quartz
  - Transmitted by internal reflection
  - Rings projected in standoff box
  - Thin (in X_0) in detection volume, yet precise…







Selecting B decays for CP analysis

- Principal event selection variables
  - Exploit kinematic constraints from beam energies
  - Beam energy substituted mass has better resolution than invariant mass

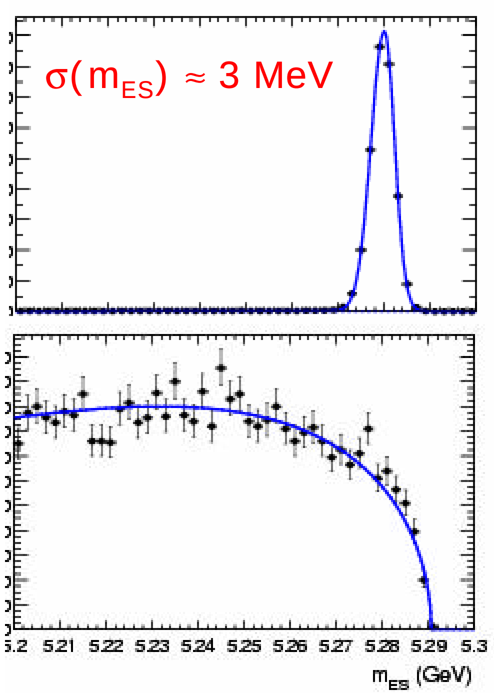
Energy-substituted mass | **Energy difference** | **Event shape**

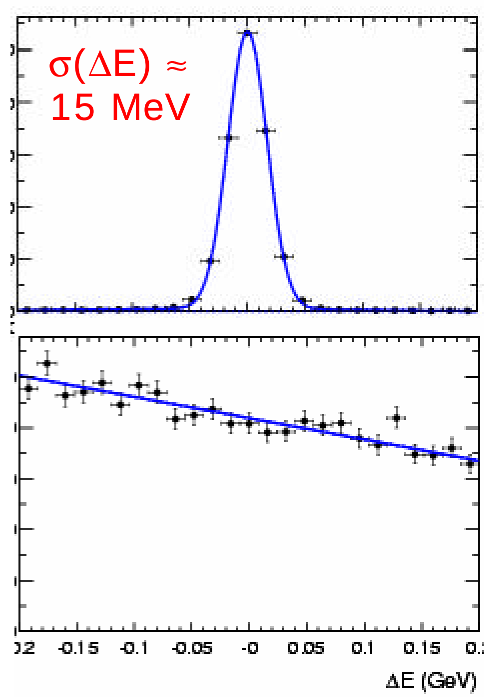
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

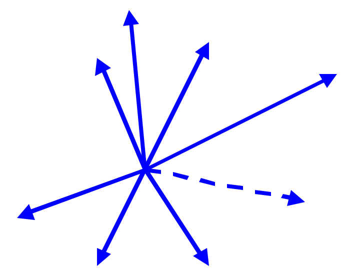
$$\Delta E = E_B^* - E_{beam}^*$$

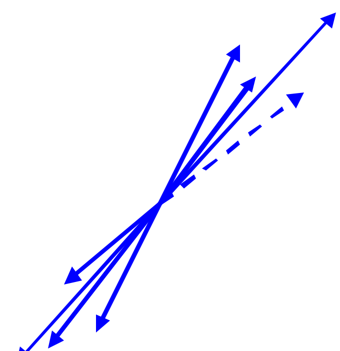
$B\overline{B}$ events

$q\overline{q}$ events ($q=u,d,s,c$)





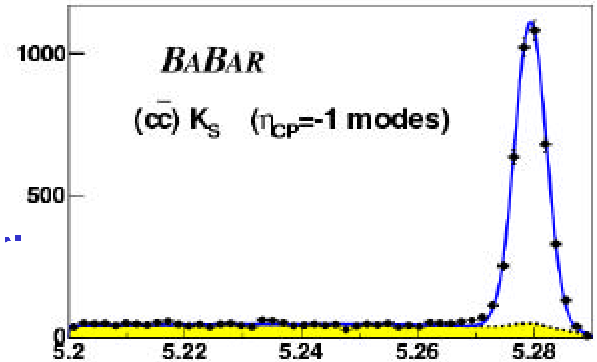


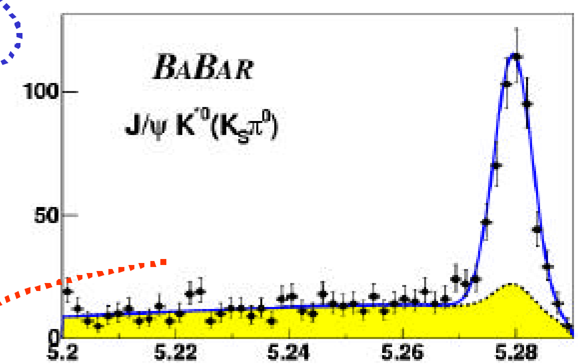


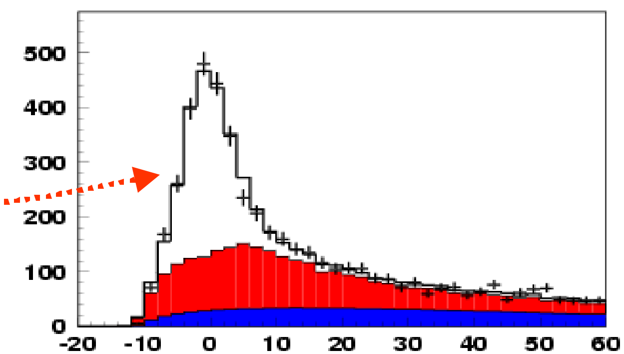
Collecting CP event samples

- Collect as many (cc)s decay modes as possible in increase statistics

CP sample	N_{TAG}	purity	$?_{CP}$
J/? K_S (K_S? p^+p^-)	2751	96%	-1
J/? K_S (K_S? p^0p^0)	653	88%	-1
? (2S) K_S (K_S? p^+p^-)	485	87%	-1
$?_{c1}$ K_S (K_S? p^+p^-)	194	85%	-1
$?_c$ K_S (K_S? p^+p^-)	287	74%	-1
Total for $?_{CP}$=-1	**4370**	**92%**	**-1**
J/? K^{*0}(K^{*0}? K_Sp^0)	572	77%	+0.51
J/? K_L	2788	56%	+1
Total	**7730**	**78%**	

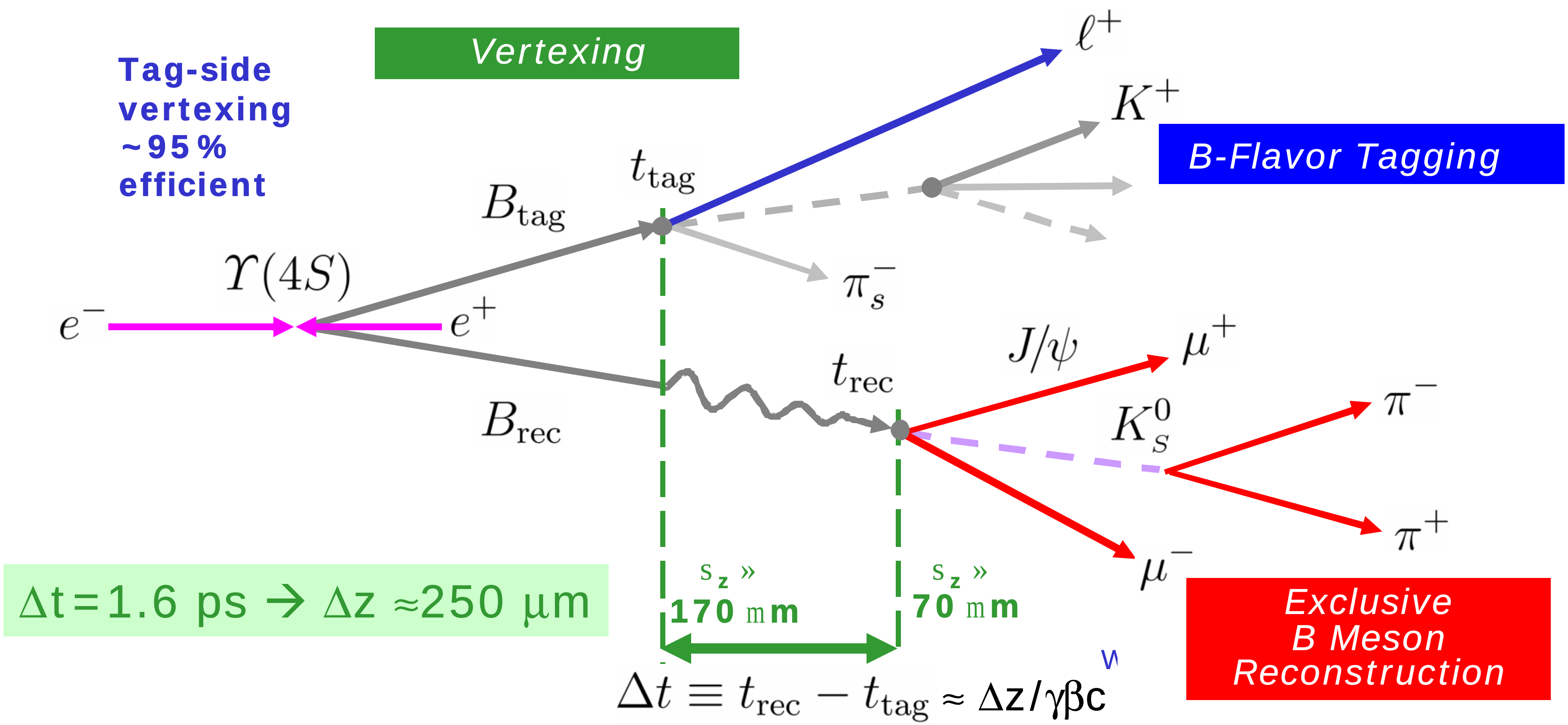




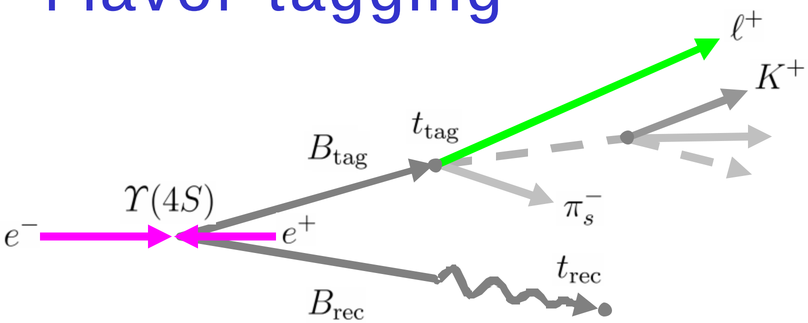


Measuring (time dependent) CP asymmetries

- Need to measure N($B^0 \rightarrow f$) and N($\overline{B^0} \rightarrow f$)
  - So need to know initial flavor of decay. Exploit fact that $B^0\overline{B^0}$ system evolves coherently → Flavor of 'other B' tags flavor of B0 → f at t=0
  - Measure N(Υ(4s) → $\overline{B^0}$(→ f_{flav}) $\underline{B^0}$(→ f_{CP})) ,
    N(Υ(4s) → B^0(→ f_{flav}) B^0(→ f_{CP})) and **decay time difference**

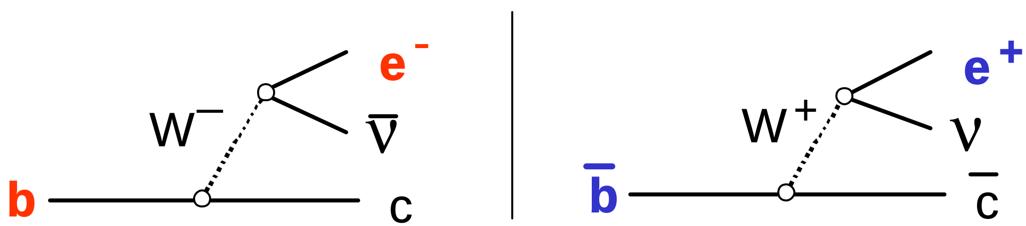


Flavor tagging

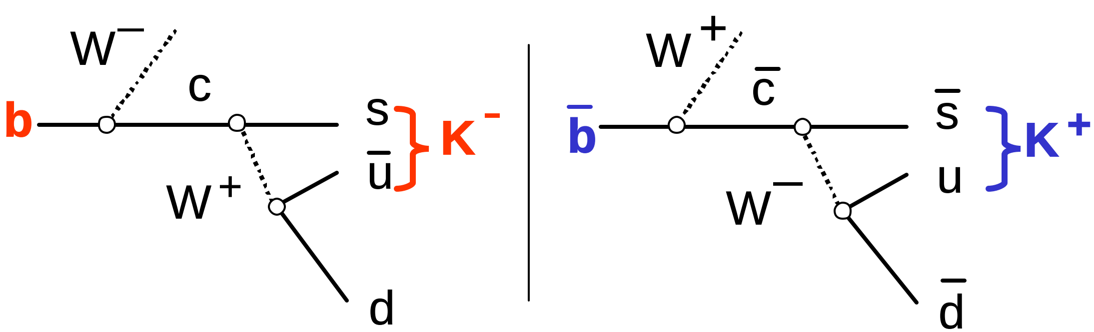


Determine flavor of $B_{tag} \equiv \overline{B_{CP}(\Delta t=0)}$ from partial decay products

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Full tagging algorithm combines all in neural network

Four categories based on particle content and NN output.

Tagging performance

efficiency *mistake rate*

$$\sum_i \epsilon_i (1 - 2\omega_i)^2$$

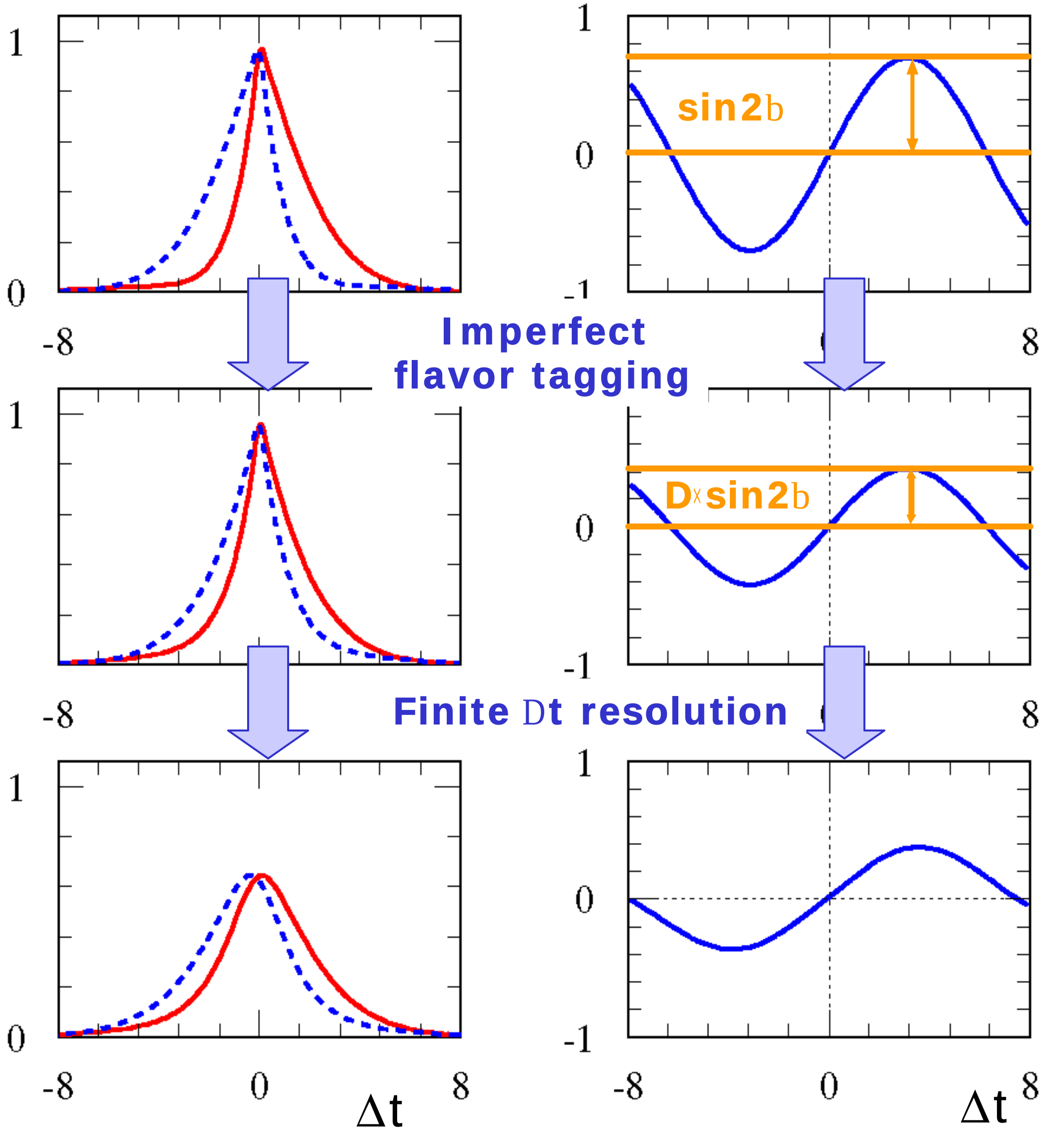
$$Q = 30.5\%$$

$$s_{tagging} \propto \sqrt{Q \cdot N}$$

Putting it all together: sin(2β) from $B^0 \rightarrow J/\psi\ K_S$

$B^0(\Delta t)$ $\overline{B}^0(\Delta t)$

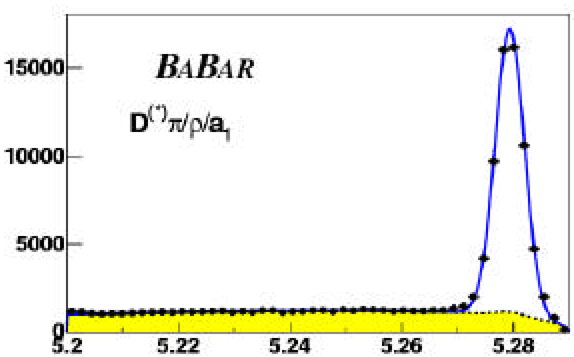
$$A_{CP}(\Delta t) = \boldsymbol{S}\cdot\sin(\Delta m_d \Delta t) + \boldsymbol{C}\cdot\cos(\Delta m_d \Delta t)$$



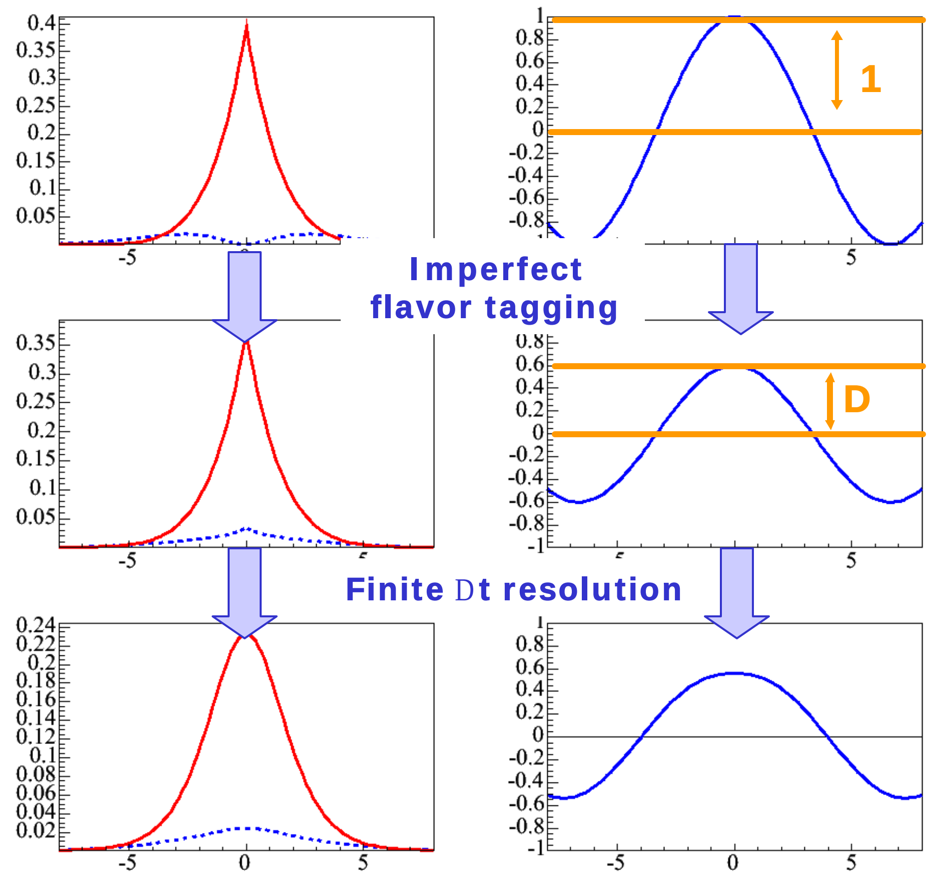
- Effect of detector imperfections
  - Dilution of A_{CP} amplitude due imperfect tagging
  - Blurring of A_{CP} sine wave due to finite Δt resolution

Measurement method: tagging efficiency & time resolution

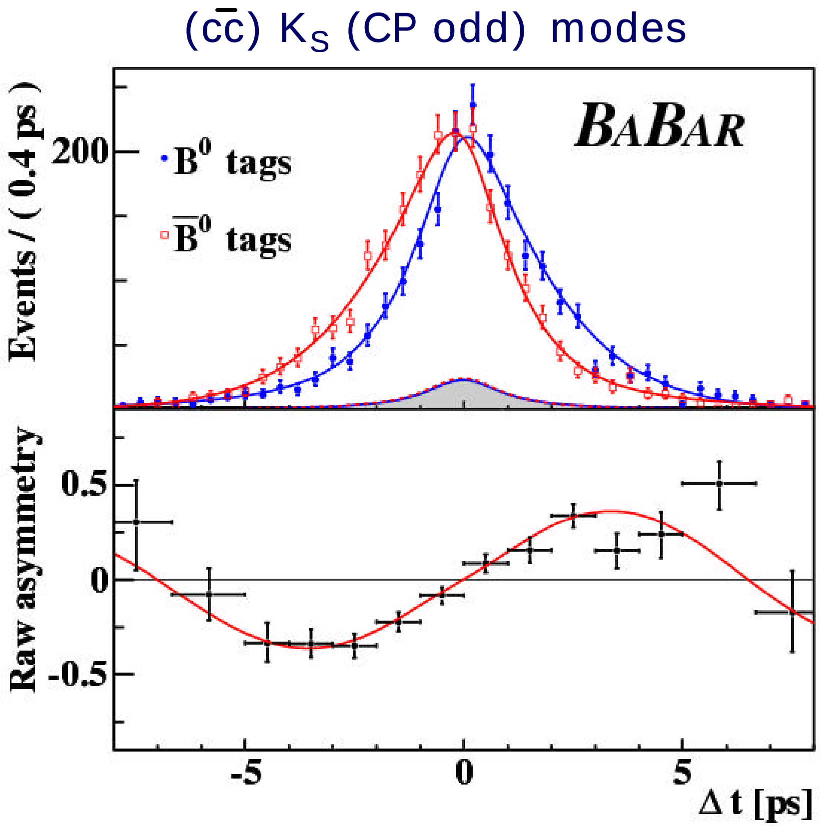
- Flavor tagging performance and decay time resolution are measured from sample of Υ(4s) → $B^0(f_{flav})$ $\overline{B}^0(f_{flav})$ events
  - Determine flavor of 1st B with usual flavor tagging algorithm
  - Determine flavor of 2nd B from explicit reconstruction in flavor eigenstate

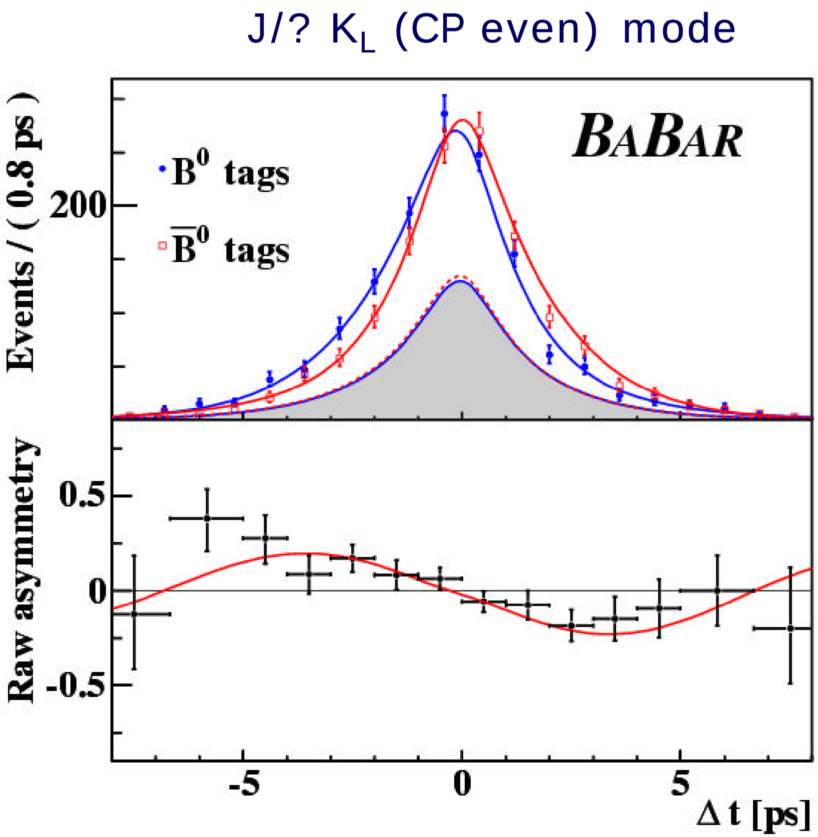


BFlav sample	N_{TAG}	purity
D^- p$^+$/?$^+$/a_1^+	32974	83.1%
D^{*-} p$^+$/?$^+$/a_1^+	35008	89.4%
J/? K^{*0}(K^{*0}? K^+p^-)	4896	95.8%
Total	**72878**	



Combined golden modes result for sin2b





sin2ß = 0.722 ± 0.040 (stat) ± 0.023 (sys)

No evidence for additional CPV in decay |?|=0.950±0.031(stat.)±0.013

(2002 measurement: sin(2ß) = 0.741±0.067±0.034)

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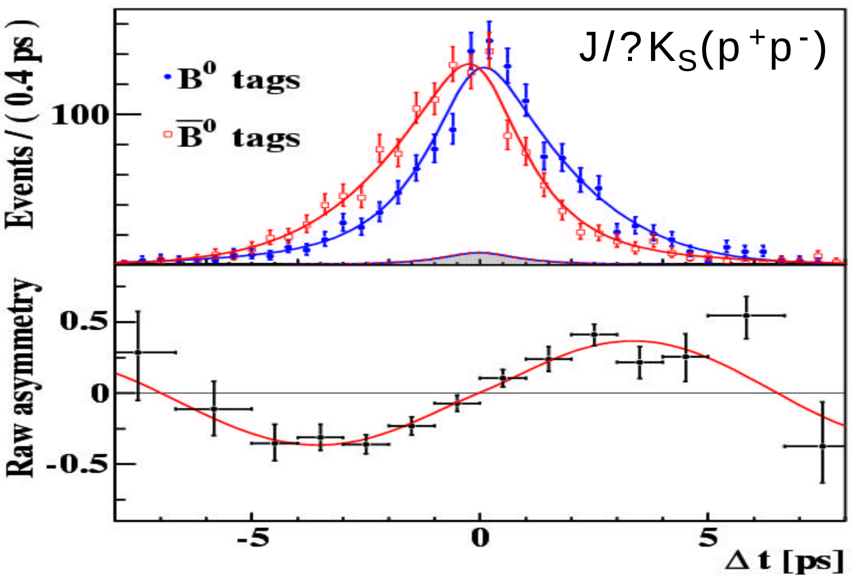
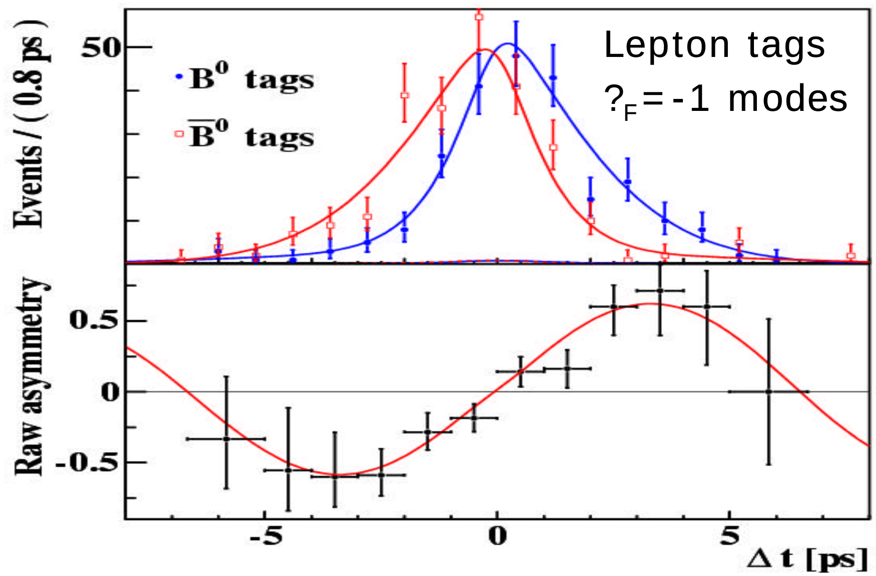
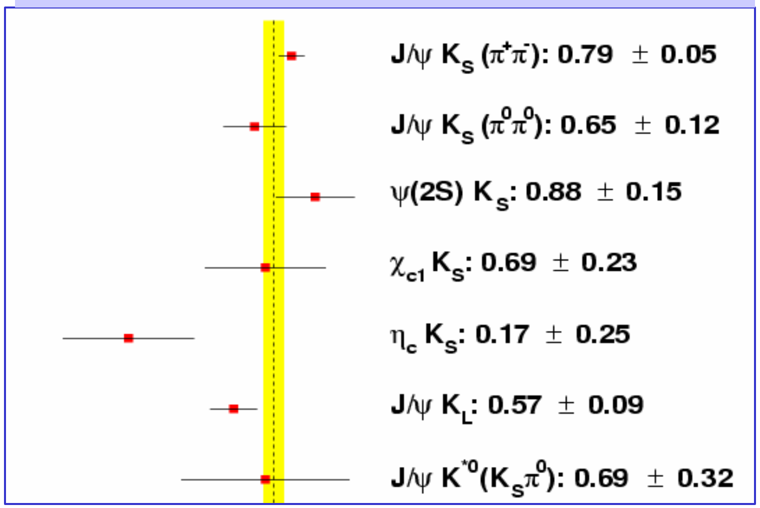
Consistency checks

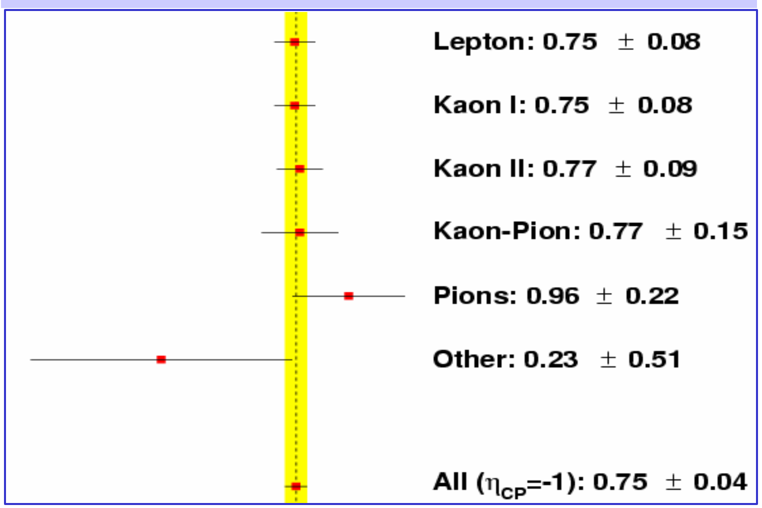




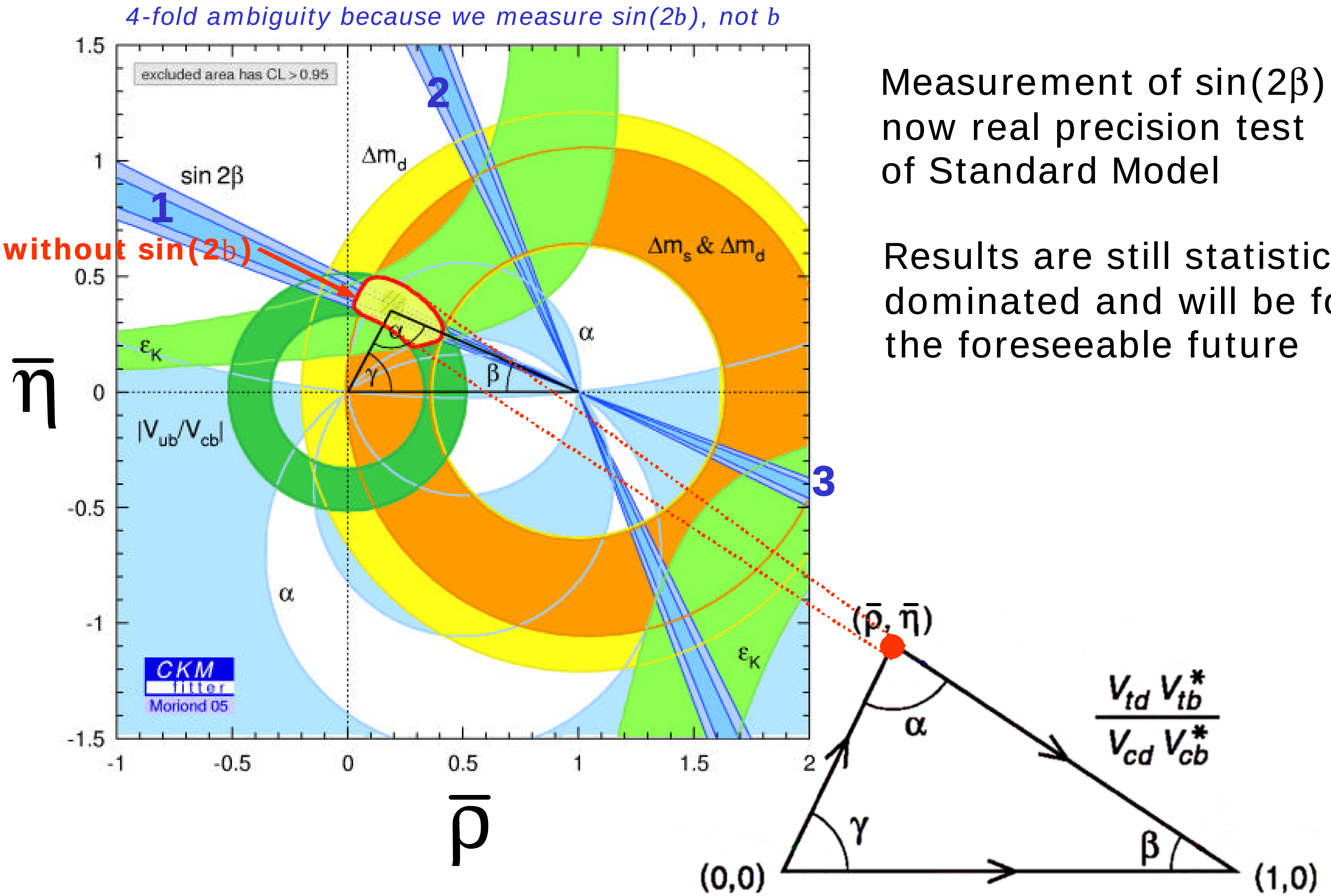
$?^2$=11.7/6 d.o.f. Prob ($?^2$)=7%

$?^2$=1.9/5 d.o.f. Prob ($?^2$)=86%





Standard Model interpretation



Measurement of sin(2β) now real precision test of Standard Model

Results are still statistics dominated and will be for the foreseeable future

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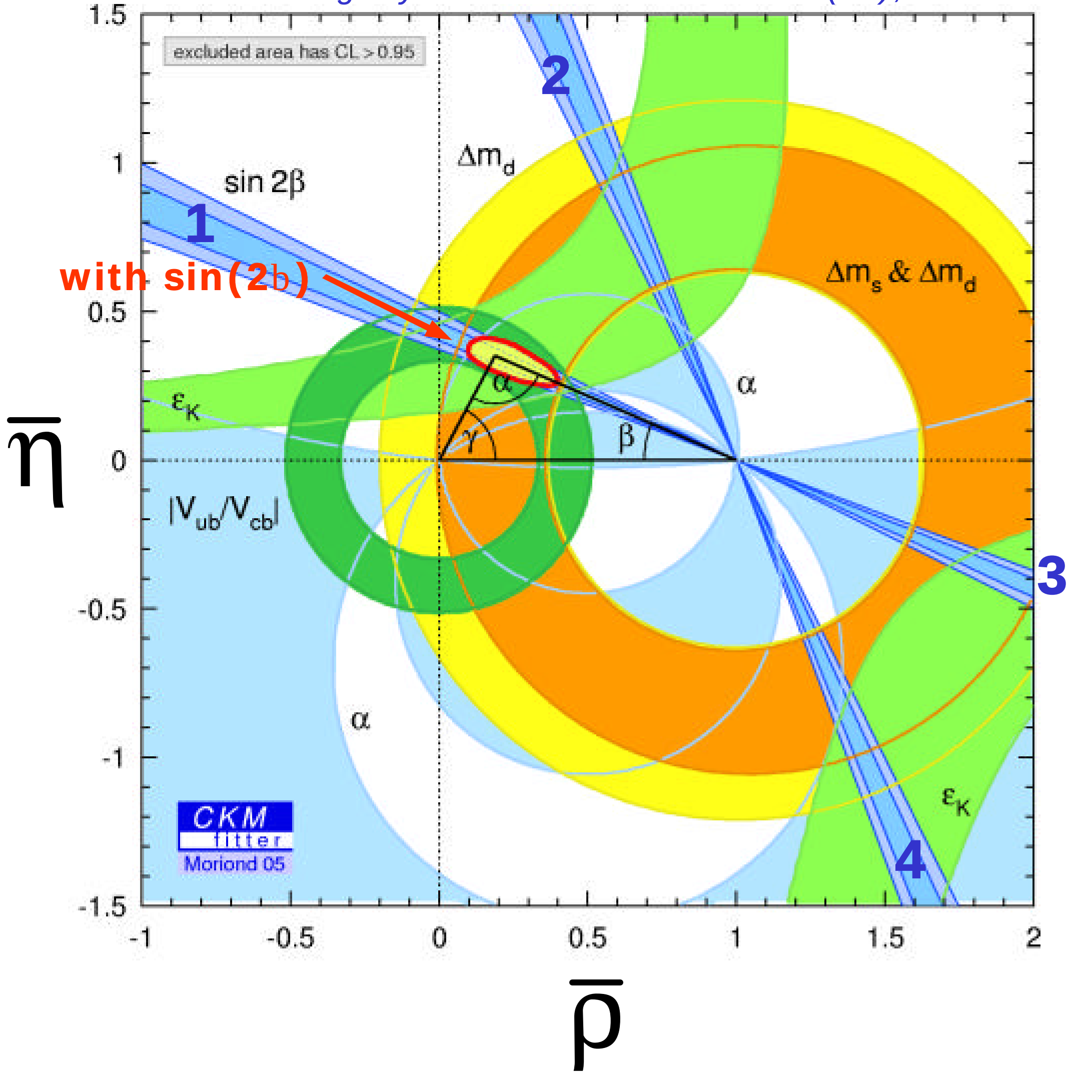
Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001

Standard Model interpretation

4-fold ambiguity because we measure sin(2b), not b



Measurement of sin(2β) now real precision test of Standard Model

Results are still statistics dominated and will be for the foreseeable future

Four-fold ambiguity because we measure sin(2β), not β

$\beta \rightarrow -\beta, \quad \beta \rightarrow \beta+\pi$

We can eliminate 1st ambiguity if we also know **cos**(2β)

More precisely, we only need to know the ***sign*** *of cos(2b)*

Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001

Measuring cos(2ß) with B^0? J/? $K^{*0}(K_S p^0)$

- Decay B^0 → J/? $K^{*0}(K_S\pi^0)$ is one of charmonium samples used to measure sin(2β)
  - But it is a scalar → vector vector decay, so there are 3 decay amplitudes with different polarizations

- Composition in terms of amplitudes (in transversity basis)
  - A_0 – Longitudinal polarization **(57%)**
  - $A_{//}$ – Transverse polarization **(20%)**
    J/y and K* polarization parallel
  - A_T – Transverse polarization, **(23%)**
    J/y and K* polarization perpendicular

A_0 and $A_{//}$: **CP-even (h=+1)**

A_T: **CP-odd (h=-1)**

- In sin2β measurement we account for this by using a *weighted average* of CP eigenvalues of +0.51

Measuring cos(2ß) with B^0? J/? $K^{*0}(K_S p^0)$

- But if you also include *angular information* from the decay products you can disentangle the 3 amplitudes
  - Many extra terms in time-dependent decay rate, including two that are proportional to **cos(2ß)** :

$$g(\vec{w}, \mathbf{A}(t), \sin 2b, \cos 2b) = \ldots.$$

$$\pm e^{-\Gamma|\Delta t|} f_4(\vec{w}) |A_T| |A_\parallel| \cos(d_T - d_\parallel) \cos(2b) \sin(\Delta m \Delta t)$$

$$\pm e^{-\Gamma|\Delta t|} f_6(\vec{w}) |A_T| |A_0| \cos(d_T - d_0) \cos(2b) \sin(\Delta m \Delta t)$$

angular amplitudes

decay angles:

$$\vec{w} = (\cos(q_{K^*}), \cos(q_{tr}), f_{tr})$$

$$A_T = |A_T| e^{id_T} \text{ (CP odd)}$$

$$A_0 = |A_0| e^{id_0} \text{ (CP even)}$$

$$A_\parallel = |A_\parallel| e^{id_\parallel} \text{ (CP even)}$$

Measuring cos(2ß) with B^0? J/? $K^{*0}(K_S p^0)$

- We know many of the amplitudes, phase differences
  - From measurement of $B^{\pm}$? $J/\psi K^{*\pm}$ and B^0? $J/\psi K^{*0}$ $(K^+\pi^-)$ using time-integrated angular analysis

Amplitude magnitudes

$$|A_0|^2 = 0.566 \pm 0.012 \pm 0.005$$

$$|A_{\parallel}|^2 = 0.204 \pm 0.015 \pm 0.005$$

$$|A_T|^2 = 0.230 \pm 0.015 \pm 0.004$$

Amplitude phase differences (with 2-fold ambiguity)

"solution 1"

$$d_{\parallel} - d_0 = 2.729 \pm 0.0101 \pm 0.052$$

$$d_T - d_0 = 0.184 \pm 0.070 \pm 0.046$$

"solution 2"

$$d_{\parallel} - d_0 = -2.729 \pm 0.0101 \pm 0.052$$

$$d_T - d_0 = 2.958 \pm 0.070 \pm 0.046$$

Plug into time dependent cross section

$$\pm e^{-\Gamma|\Delta t|} f_4(\vec{w})|A_T||A_{\parallel}|\cos(d_T - d_{\parallel})\cos(2b)\sin(\Delta m \Delta t)$$

$$\pm e^{-\Gamma|\Delta t|} f_6(\vec{w})|A_T||A_0|\cos(d_T - d_0)\cos(2b)\sin(\Delta m \Delta t)$$

Measuring cos(2ß) with B^0? J/? $K^{*0}(K_S p^0)$

- We know many of the amplitudes, phase differences
  - From measurement of $B^{\pm}$? $J/\psi K^{*\pm}$ and B^0? $J/\psi K^{*0}$ $(K^+\pi^-)$ using time-integrated angular analysis

PROBLEM!

We don't know the sign of the phase difference, so we can only measure cos(2β) ***except for its sign***

But to break the ambiguity in b we precisely ***need the sign!***

Amplitude phase differences (with 2-fold ambiguity)

ion 1"

$$d_{\parallel} - d_0 = 2.729 \pm 0.0101 \pm 0.052$$

$$d_T - d_0 = 0.184 \pm 0.070 \pm 0.046$$

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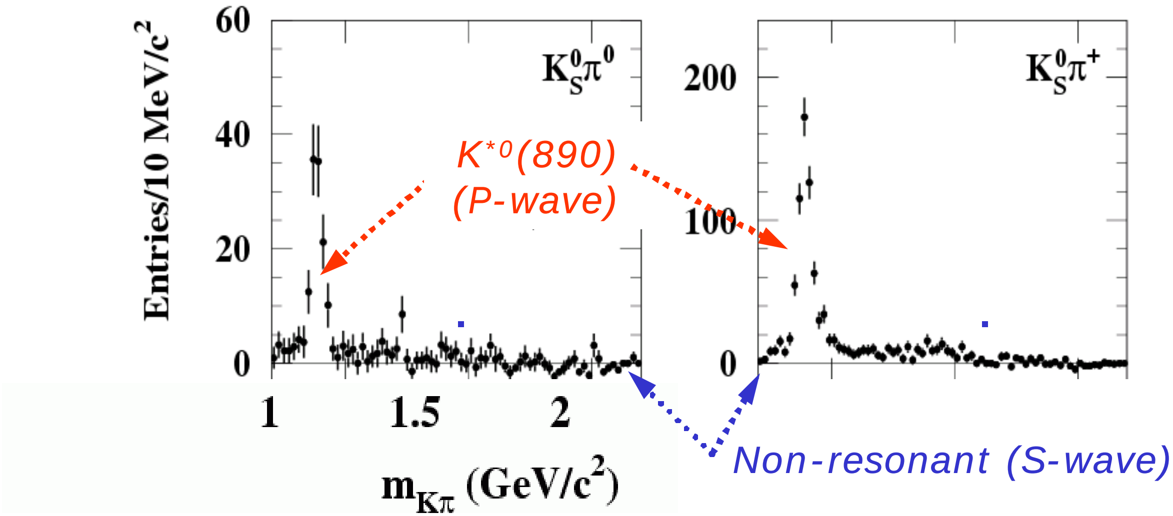
$$\pm e^{-\Gamma|\Delta t|} f_4(\vec{w}) |A_T||A_{\parallel}| \cos(d_T - d_{\parallel}) \cos(2b) \sin(\Delta m \Delta t)$$

$$\pm e^{-\Gamma|\Delta t|} f_6(\vec{w}) |A_T||A_0| \cos(d_T - d_0) \cos(2b) \sin(\Delta m \Delta t)$$

Measuring cos(2ß) with B^0? J/? $K^{*0}(K_S p^0)$

- Solution: find a new way to measure the sign of the phase differences $\delta_{//}-\delta_0$ and $\delta_T-\delta_0$
  - Central idea: include ($K\pi$) S-wave in angular analysis 'non-resonant events': $A_S = |A_S| e^{id_S}$



  - Extra terms due to interference of S-wave and P-wave contributions to $K\pi$ final state and help solve the ambiguity

$$\pm f_8(?)|A_{\parallel}||A_S|\cos(d_{\parallel} - d_S)\ldots \quad \pm f_{10}(?)|A_0||A_S|\cos(d_S - d_0)\ldots$$

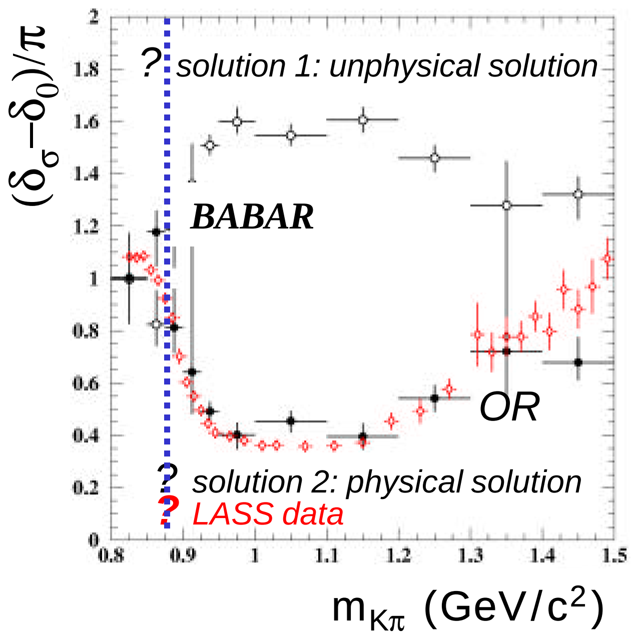
$$\pm f_9(?)|A_T||A_S|\cos(d_T - d_S)\ldots$$

Breaking the ambiguity

- Why it works: Phase difference δ_s-δ_0 has special property as consequence of Wigner causality:

$$\frac{d(d_S - d_0)}{dm_{Kp}} < 0 \Big|_{m_{Kp} = m(K^{*0})}$$

Physical solution must have *negative slope* around m(K^*)



"solution 1"

$$d_{\parallel} - d_0 = 2.729 \pm 0.0101 \pm 0.052$$

$$d_T - d_0 = 0.184 \pm 0.070 \pm 0.046$$

"solution 2"

$$d_{\parallel} - d_0 = -2.729 \pm 0.0101 \pm 0.052$$

$$d_T - d_0 = 2.958 \pm 0.070 \pm 0.046$$

cos(2ß) with B^0? J/? $K^{*0}(K_S p^0)$ – result

- cos(2ß) from 104 tagged B^0? $J/\psi(K_S\pi^0)^{*0}$ decays

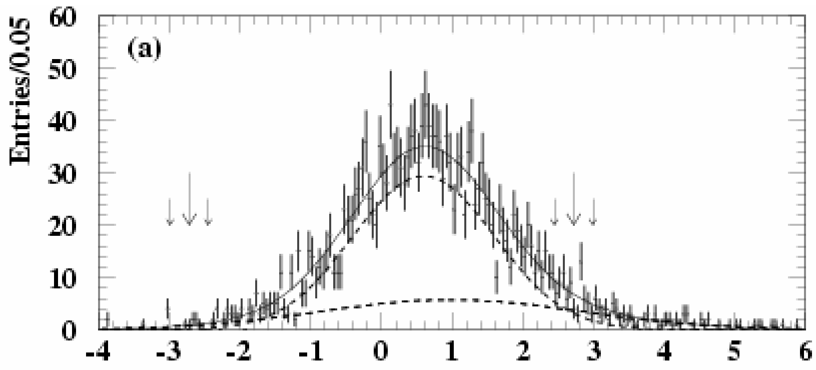
with floating sin(2ß)

$$\cos(2ß) = 3.32^{+0.76}_{-0.96}(stat.) \pm 0.27(syst.)$$
$$\sin(2ß) = -0.1 \pm 0.57$$

with sin(2ß) fixed to 0.731

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

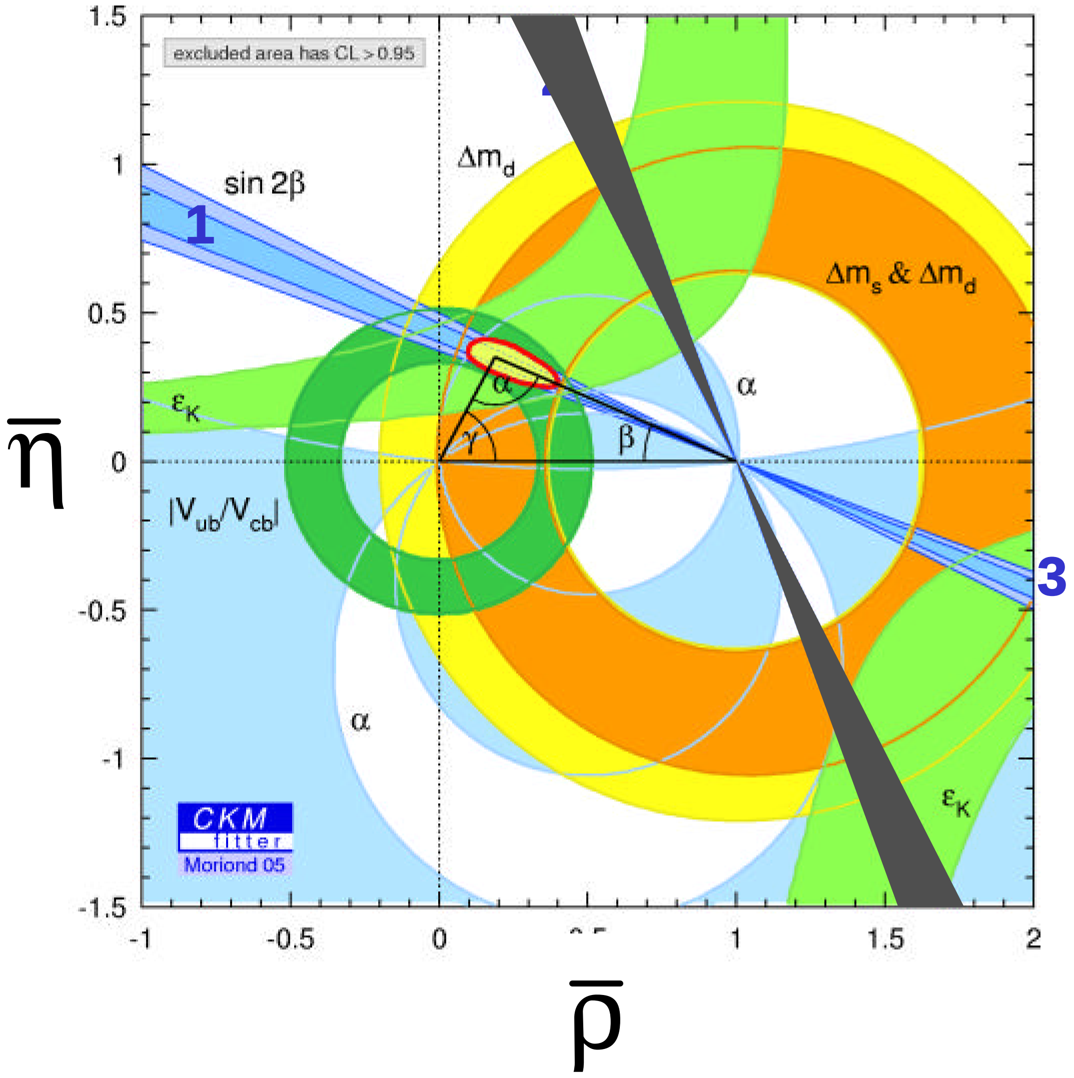
- Now quantify probability that sign of cos(2β) >0
  - Use MC approach to include non-Gaussian effects



distribution of cos(2ß) results from a set of 2000 data-sized Monte Carlo samples, generated with cos(2ß)=0.68

Negative value of cos(2b) excluded at 86.6% CL

Standard Model interpretation



Measurement of sin(2β) now real precision test of Standard Model

Results are still statistics dominated and will be for the foreseeable future

Solutions 2 & 4 excluded at 86.6% CL

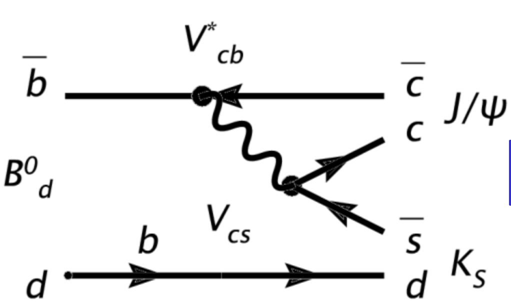
Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001

Switching from charmonium to penguin modes

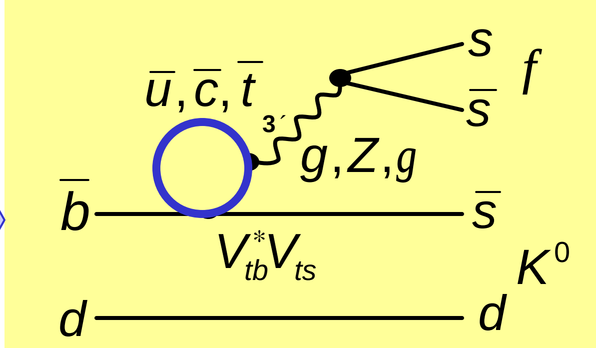
- Golden mode B0 → J/ψ K_S now precision measurement of CKM CPV
  - But CPV also a good place to look for signs of new physics
  - 'New Physics' couplings are expected to have non-zero phases, and may cause deviations in measured CPV

- Good place to look for new physics are loop diagrams
  - Loop diagrams are dominated by heavy particles in the loop → contribution of new physics may be non-negligible
  - Look at decay modes where loop diagram is leading order: b→s penguins

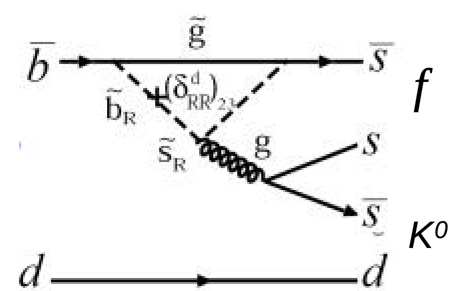
charmonium decay (ϕ_{weak}=0)



b→s penguin decay (ϕ_{weak}=0)



new physics?



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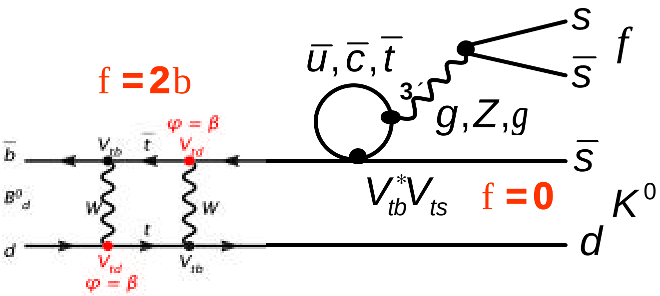
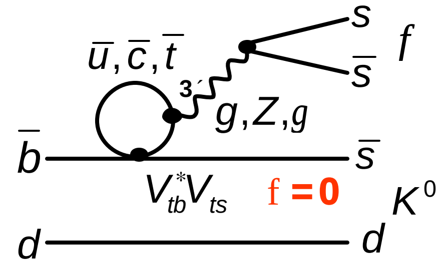
Switching from charmonium to penguin modes

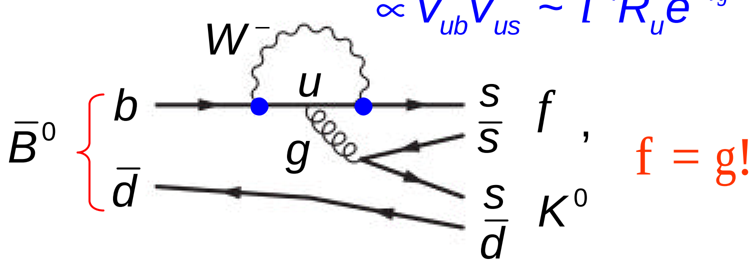
- Measurement works otherwise as usual
  - Interfere decay amplitude with mixing + decay amplitude
  - Also works with several other decay amplitudes (η'K⁰, f⁰K⁰,...)





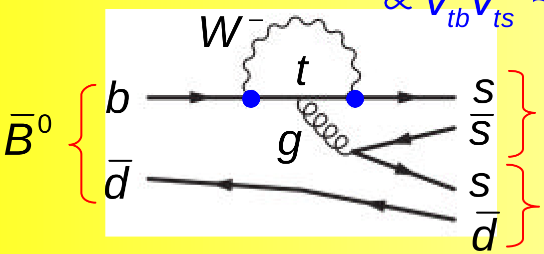
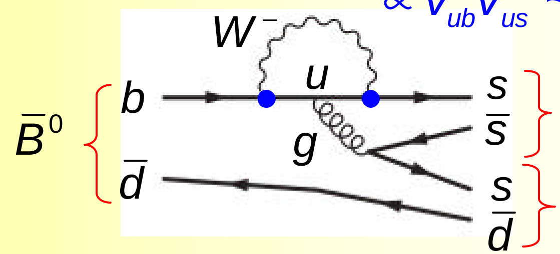
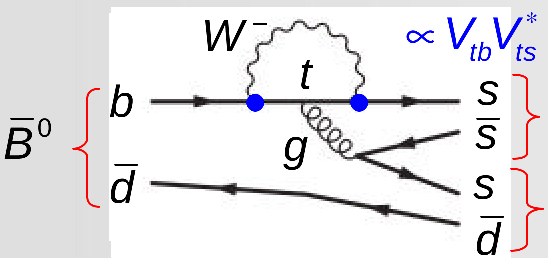
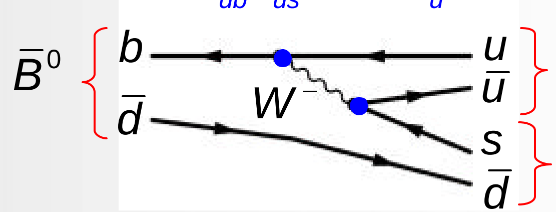
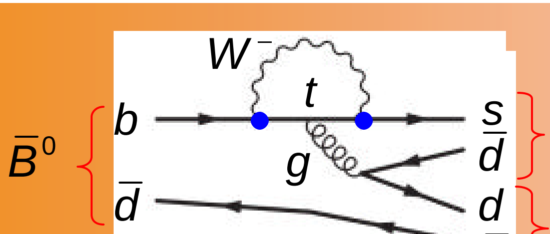
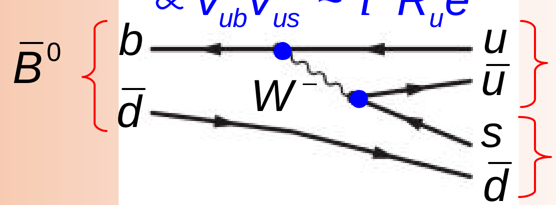
- Leading order SM for CPV is same as golden modes
  - But not all modes are as clean as $B^0 \rightarrow J/\psi\ K_S$ golden mode, so
  - *Watch for other SM decay amplitudes* that contribute, e.g.

$$\propto V_{ub}V_{us}^{*} \sim l^{4}R_{u}e^{-ig}$$



But highly suppressed as $|V_{ub}|$ tiny

Penguin olympia – ranking channels by SM pollution

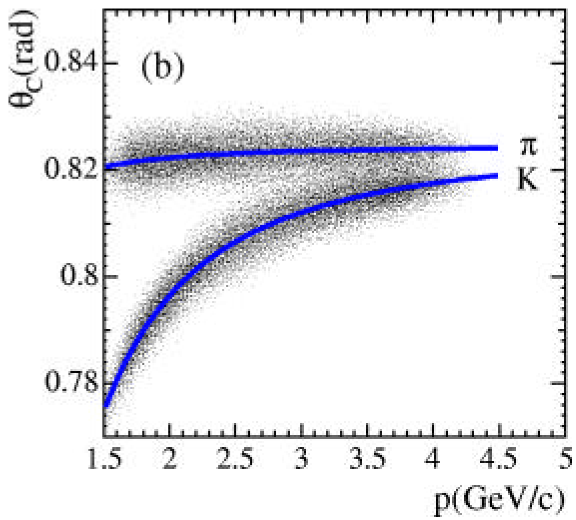
	Decay amplitude of interest		SM Pollution		Naive (dimensional) uncertainties on sin2β
Gold	$\propto V_{tb}V_{ts}^{*} \sim l^{2}$ 	f, K^0	$\propto V_{ub}V_{us}^{*} \sim l^{4}R_u e^{-ig}$ 	f, K^0	$O(l^{2})$ $\sim 5\%$
Silver	$\propto V_{tb}V_{ts}^{*} \sim l^{2}$ 	h', f_0, K^0	$\propto V_{ub}V_{us}^{*} \sim l^{4}R_u e^{-ig}$ 	h', f_0, K^0	$O(l^{2}(1+f_{q\bar{q}}/\bar{l}))$ $\sim 10\%$
Bronze	 $\propto V_{tb}V_{ts}^{*} \sim l^{2}$	K^0, p^0, r^0, w	$\propto V_{ub}V_{us}^{*} \sim l^{4}R_u e^{-ig}$ 	p^0, r^0, w, K^0	$O(l^{2}/\bar{l})$ $\sim 20\%$

Note that within QCD Factorization these uncertainties turn out to be much smaller !

Selecting penguin decays – Experimental issues

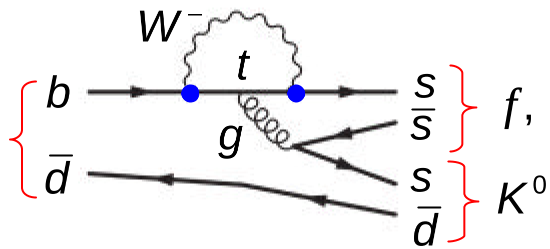
- From an experimental point of view, penguin decays are more difficult to select
  - Signal branching fraction *O*(20) times smaller
  - Particle identification more challenging (high-*p* $K^{\pm}$ PID vs $l^{\pm}$ PID)

- Basic fit strategy same as for J/ψ K_S except
  - Strong DIRC Particle ID to separate pions from kaons → Cherenkov PID performance
  - Event shape monomials (*L*0,*L*2), and *B* kinematics optimally combined in Multivariate Analyzer [MVA]
    - Neural Network (NN) or Fisher Discriminant
  - 6-dimensional ML fit using
    (1) beam-energy substituted *B* mass (m_{ES}),
    (2) *B*-energy difference (ΔE),
    (3) the resonance mass,
    (4) the resonance decay angle,
    (5) the Multivariate Analyzer, and *(6)* Δt

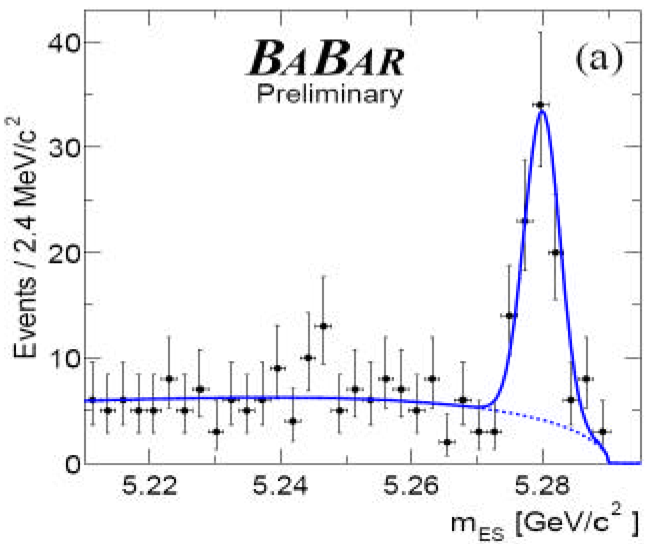


Selection of 'golden penguin mode' $B^0 \to f\ K^0$

- Modes with K_S and K_L are both reconstructed

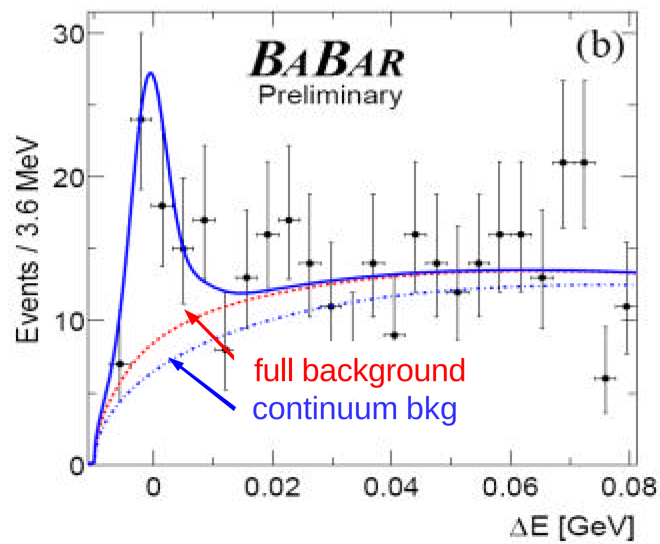


$B^0 \to f K_S^0 \to K^+ K^- p^+ p^-$



114 ± 12 signal events

$B^0 \to f K_L^0$ *(Opposite CP)*

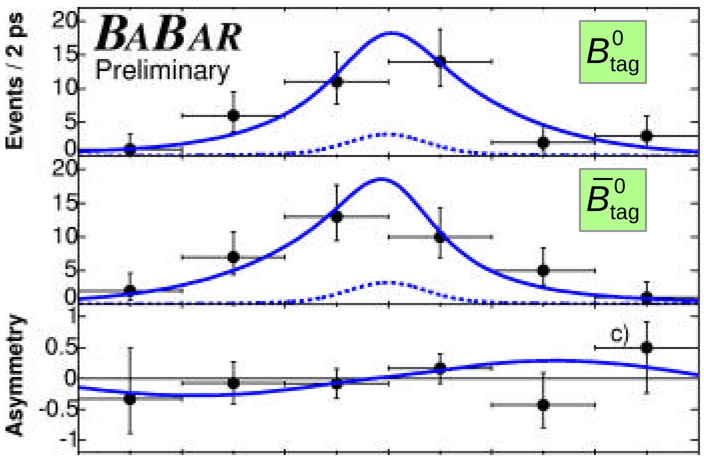


98 ± 18 signal events

Plots shown are 'signal enhanced' through a cut on the likelihood on the dimensions that are not shown, and have a lower signal event count

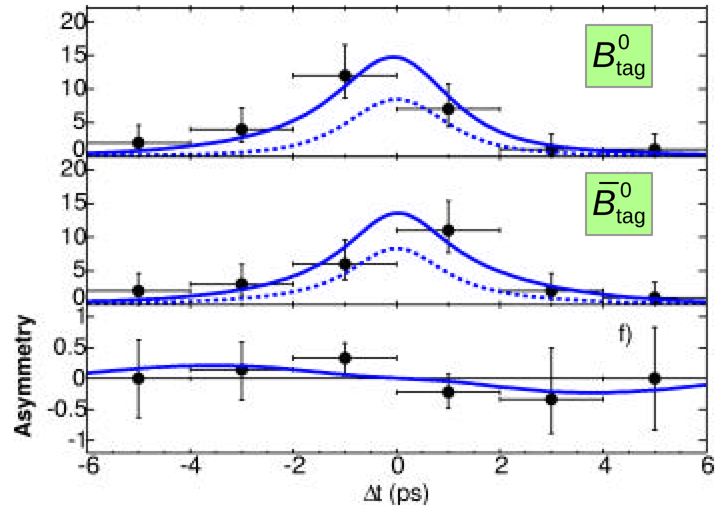
CP analysis of 'golden penguin mode' $B^0 \rightarrow f\, K^0$

$B^0 \rightarrow f K^0_S \rightarrow K^+K^- p^+ p^-$



S(fK$_S$) = +0.29 ± 0.31(stat)

$B^0 \rightarrow f K^0_L$ *(Opposite CP)*



S(fK$_L$) = -1.05 ± 0.51(stat)

Combined fit result

(assuming fK$_L$ and fK$_S$ have opposite CP)

$$\eta_{\phi K0} \times S_{fK^0} = +0.50 \pm 0.25\ ^{+\,0.07}_{-\,0.04}$$

$$C_{fK^0} = +0.00 \pm 0.23 \pm 0.05$$

0.9σ

Standard Model Prediction

S(φK^0) = sin2β = 0.72 ± 0.05

C(φK^0) = 1-|λ| = 0

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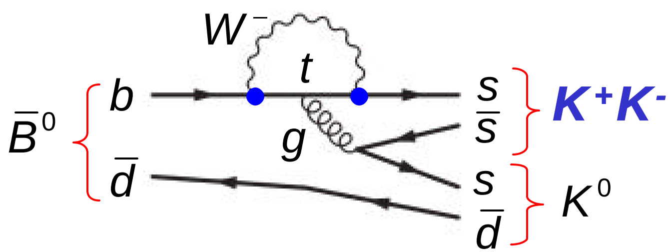
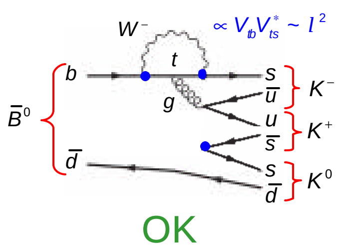
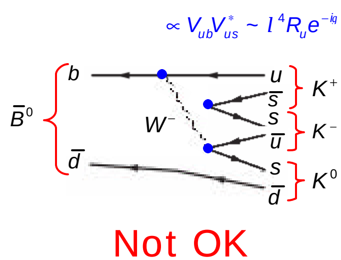
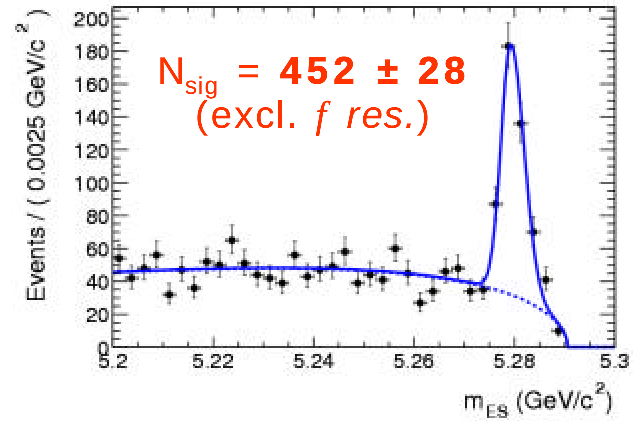
Reaching for more statistics – $B^0 \rightarrow f\ K^0$ revisited

- Analysis does not require that *ss* decays through ϕ resonance, it works with non-resonant K^+K^- as well
  - 85% of KK is non-resonant – can select clean and high statistics sample
  - But not ‘golden’ due to possible additional SM contribution with ss popping







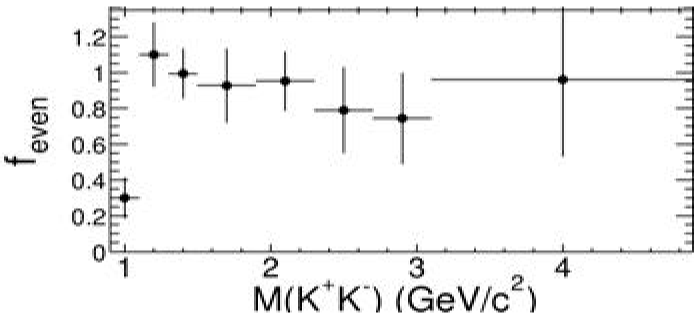


- But need to understand CP eigenvalue of $K^+K^-K_S$:
  - ϕ has well defined CP eigenvalue of +1,
  - CP of non-resonant KK depends angular momentum L of KK pair
- Perform partial wave analysis
  - Estimate fraction of S wave (CP even) and P wave (CP odd) and calculate average CP eigenvalue from fitted composition

CP analysis of $B \to K^+K^- K_S$

- Result of angular analysis

$$f_{CP\text{-even}} = \frac{A_s^2}{A_s^2 + A_p^2} = 0.89 \pm 0.08 \pm 0.06$$



  - Result consistent with cross check using iso-spin analysis (Belle)

$$f_{CP\text{-even}} = \frac{2\Gamma(B^+ \to K^+ K_S^0 K_S^0)}{\Gamma(B^0 \to K^+ K^- K^0)} = 0.75 \pm 0.11$$

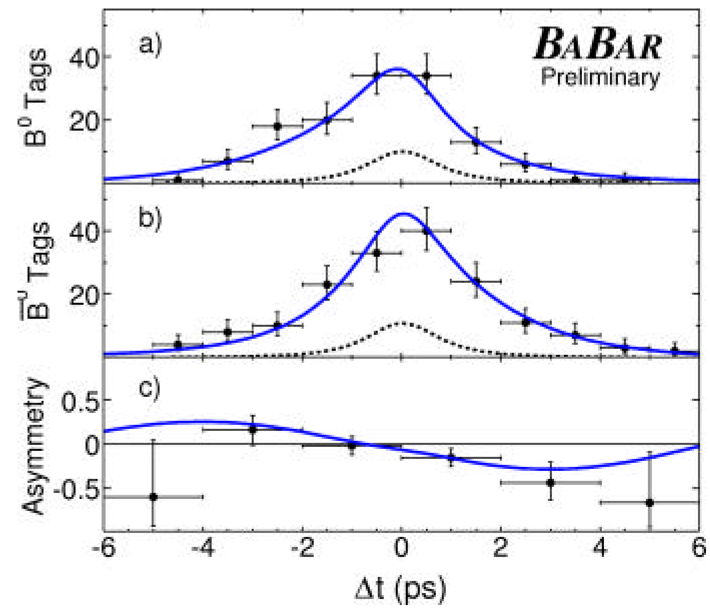
- Result of time dependent CP fit

$$S_{K^+K^-K_S^0} = -0.42 \pm 0.17 \pm 0.04$$

$$C_{K^+K^-K_S^0} = +0.10 \pm 0.14 \pm 0.06$$

$\eta_f \times S_{K+K-KS} / (2\mathbf{f}_{\mathbf{CP\text{-}even}} - 1)]$ =

+0.55 ±0.22 ± 0.04 ±0.11
(stat) (syst) ($f_{CP\text{-even}}$)



hep-ex/0502017 hep-ex/0406040

The Silver penguin modes: $B^0 \to \eta' K_S$ & $B^0 \to f_0 K_S$

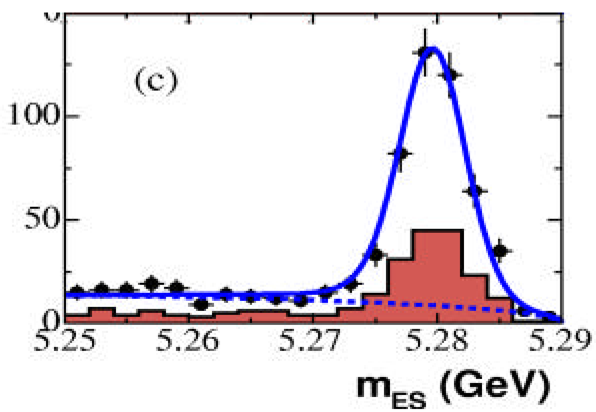
$B^0 \to \eta' K_S$

- Large statistics mode

$$BR(B^0 \to \eta' K^0) \sim 65.2 \times 10^{-6}$$

$$BR(B^0 \to \eta'_{rec} K^0_S) \sim 14.9 \times 10^{-6}$$

- Reconstruct many modes
  - $\eta' \to \eta\pi^+\pi^-, \rho^0\gamma$
  - $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$
  - $K_S \to \pi^+\pi^-, \pi^0\pi^0$



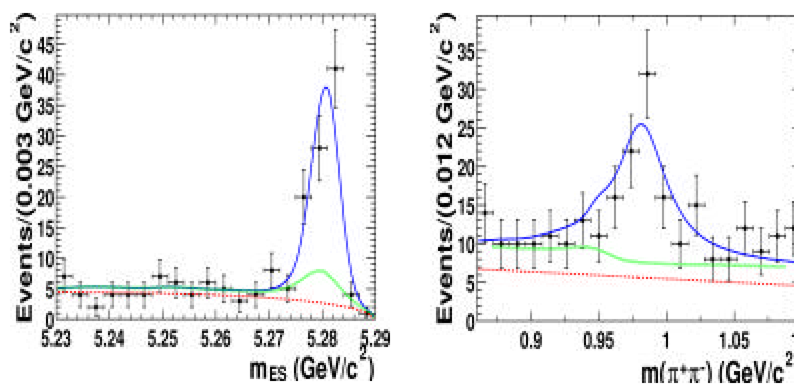
Fit finds 819 ± 38 events

$B^0 \to f_0(980) K_S$

- Modest statistics mode

$$BR(B^0 \to f_0(980) K^0_S) \sim 6.0 \times 10^{-6}$$

- CP analysis more difficult
  - Requires thorough estimate of *CP* dilution due to interference in $B0 \to \pi^+\pi^- K_S$ Dalitz plot



Fit finds 152 ± 19 events

The Silver penguin modes: $B^0 \rightarrow \eta' K_S$ & $B^0 \rightarrow f_0 K_S$

$B^0 \rightarrow \eta' K_S$

$$\eta_{\phi K0} \times S_{h'K^0_S} = +0.27 \pm 0.14 \pm 0.03$$

$$C_{h'K^0_S} = -0.21 \pm 0.10 \pm 0.03$$

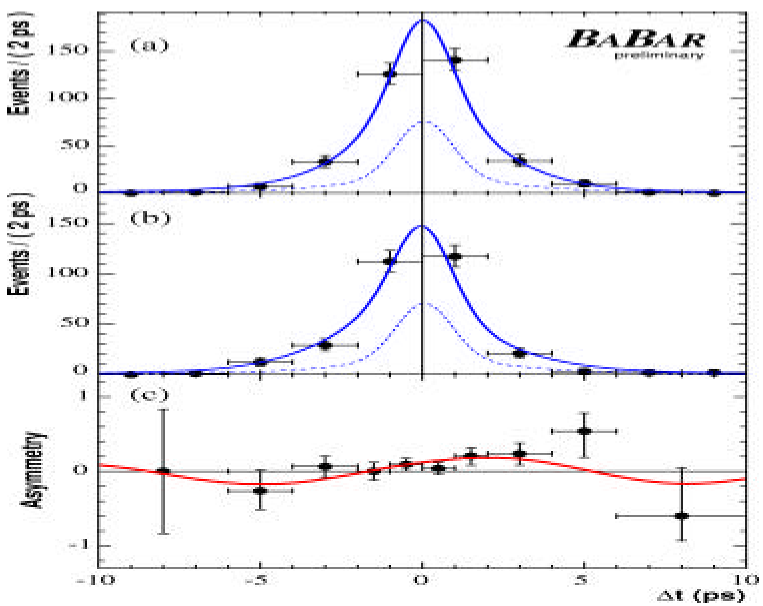
sin2*b* [cc] @ 3.0σ

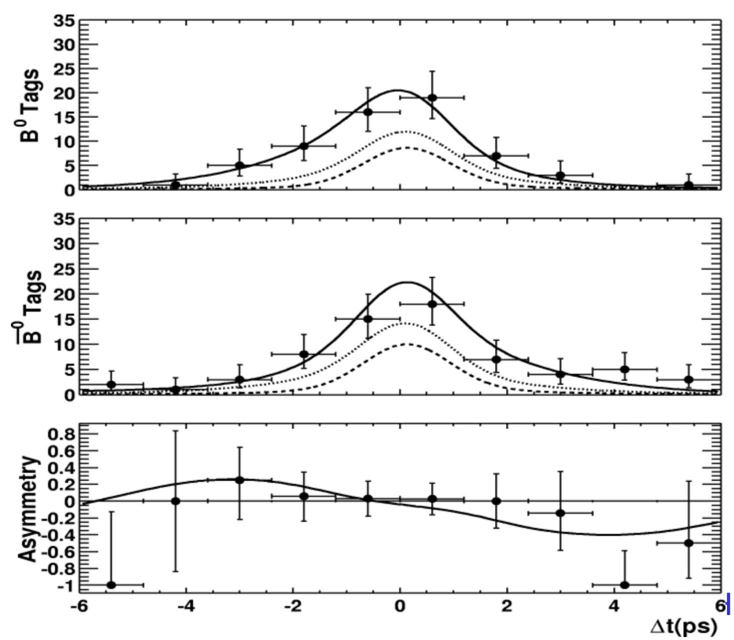
$B^0 \rightarrow f_0(980) K_S$

$$\eta_{\phi K0} \times S_{f_0 K^0_S} = +0.95\ ^{+0.32}_{-0.23} \pm 0.10$$

$$C_{f_0 K^0_S} = -0.24 \pm 0.31 \pm 0.15$$

sin2*b* [cc] @ 0.6σ

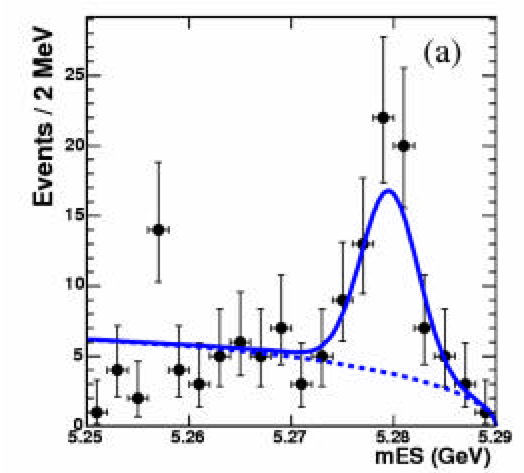




IEF

The bronze penguin modes: $B^0 \to \omega K_S$ (New!)

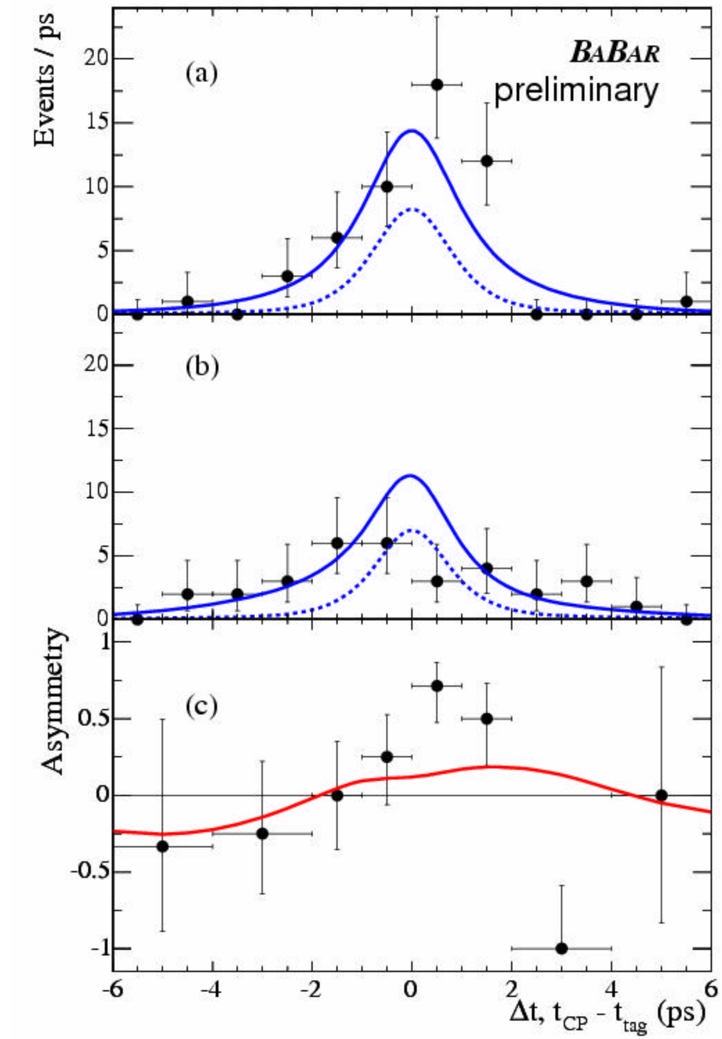
- Modest statistics mode (BF ≈ 5 x 10^{-6})



N_{sig} = 96 ± 14

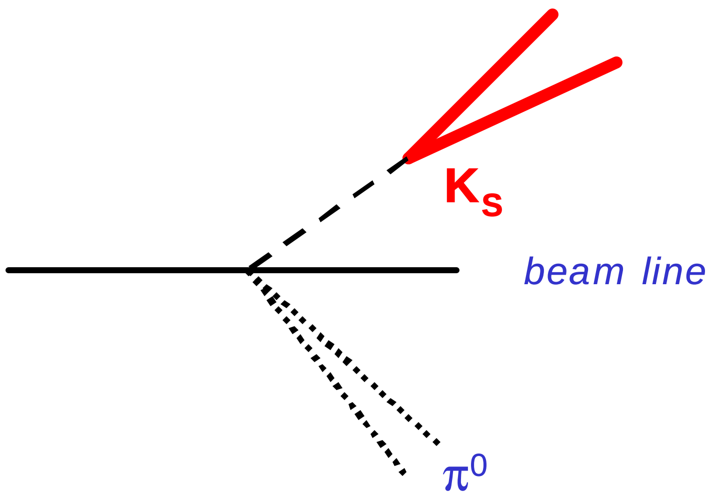
$$h_f \times S = +0.50 \pm^{0.34}_{0.38} \pm 0.02$$
$$C = -0.56 \pm^{0.29}_{0.27} \pm 0.03$$

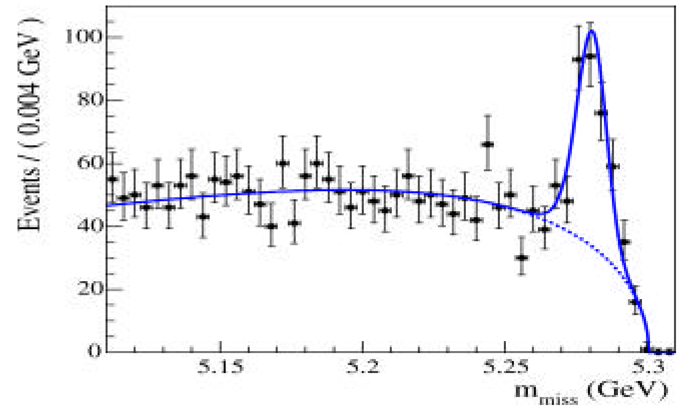
sin2*b* [cc] @ 0.7σ

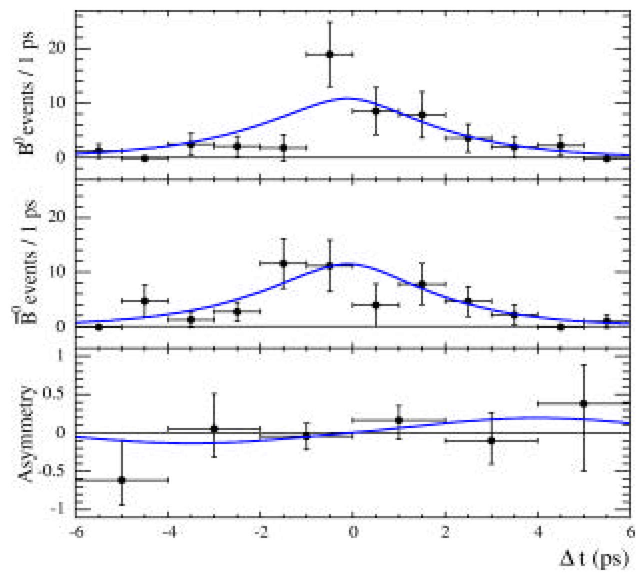


The bronze penguin modes: $B^0 \rightarrow \pi_0 K_S$

- Experimentally challenging! – Construct decay vertex, decay time without tracks from primary vertex
  - Use beam line as constraint
  - Use only K_S decays with at least 4 hits in the silicon tracker to obtain required precision, ~60% meets requirements







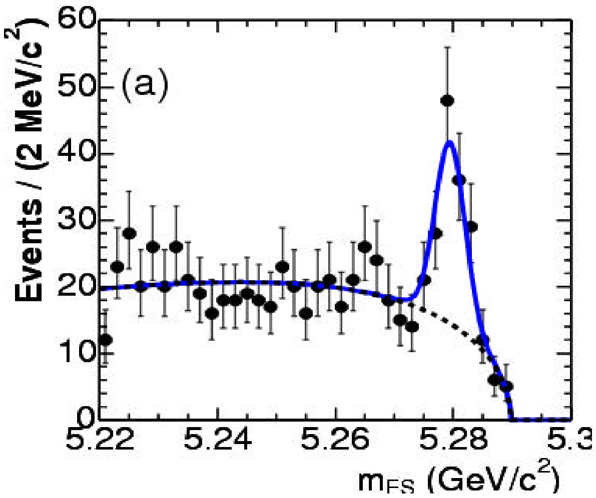
$$\eta_{\phi K0} \times S_{p^0 K_S^0} = +0.35\ ^{+0.30}_{-0.33} \pm 0.04$$

$$C_{p^0 K_S^0} = +0.06 \pm 0.18 \pm 0.06$$

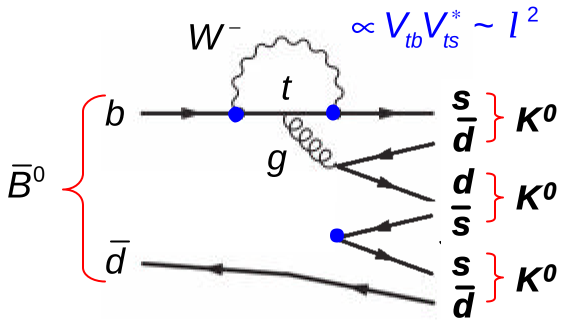
sin2*b* [cc] @ 1.3σ

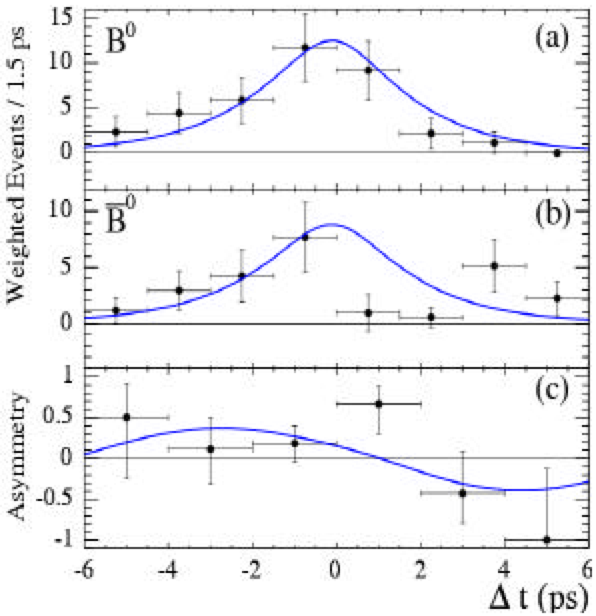
More vertexing exercises – $B^0 \to K_S K_S K_S$

- But wait! If you can vertex $B^0 \to \pi^0 K_S$ with sufficient precision for a time dependent CP fit, then you can also analyze $B^0 \to K_S K_S K_S$
  - *Average Ks momentum lower than in $p^0 K_S$, larger fraction of events will have SVT hits*



- Decay $B^0 \to K_S K_S K_S$ is 'golden' penguin – little SM pollution expected





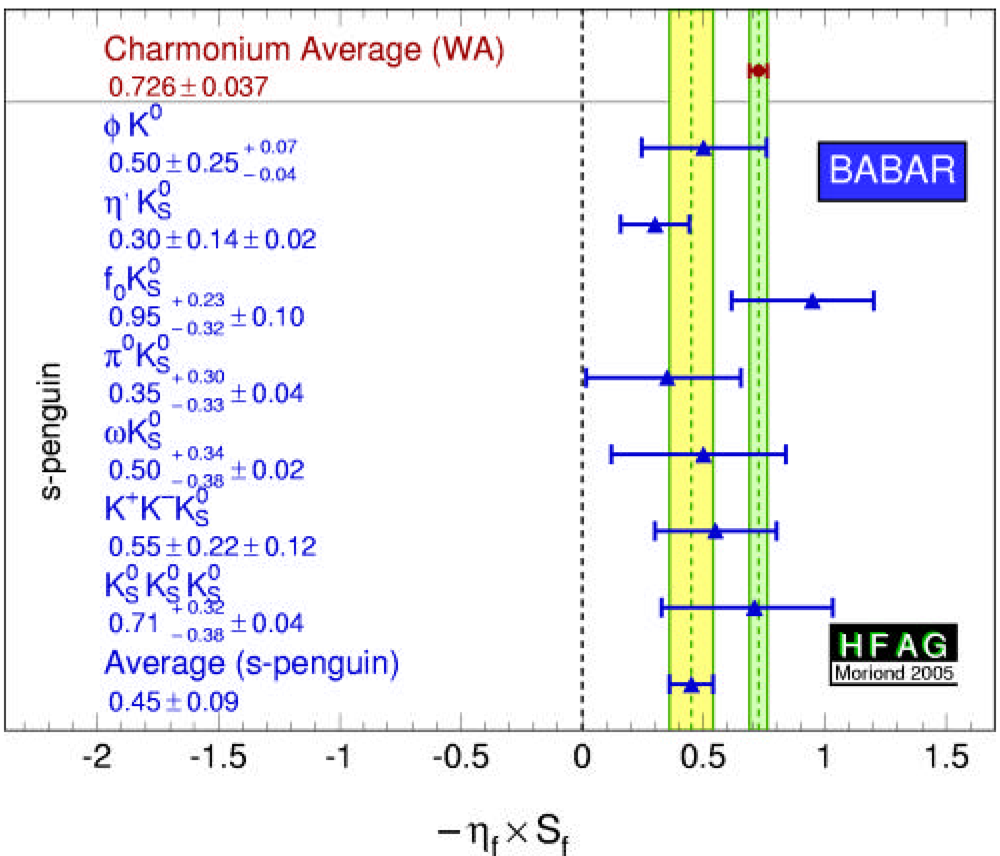
- Result consistent with SM

$$\eta_{\phi K0} \times S = +0.71 \pm^{0.38}_{0.32} \pm 0.04$$

$$C = -0.34 \pm^{0.28}_{0.25} \pm 0.05$$

Sin2b from b→s penguins – summary of BaBar results

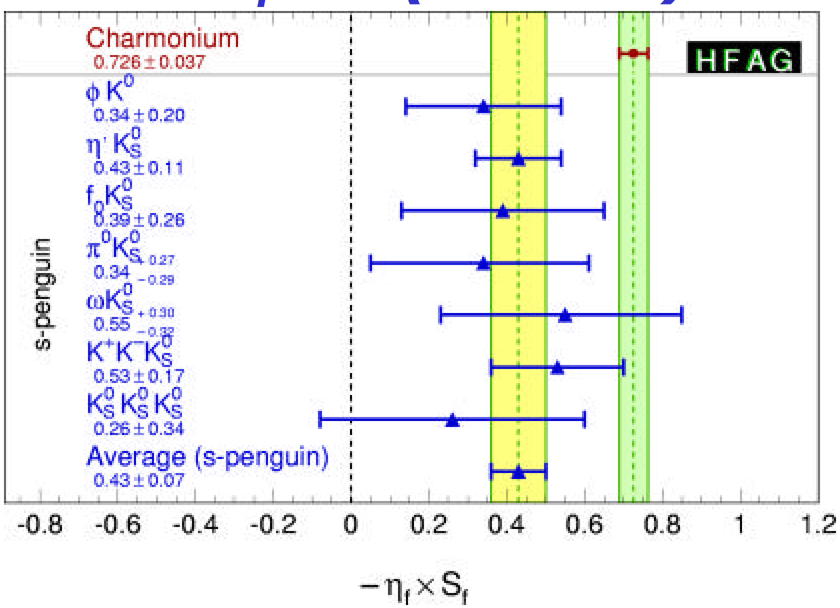
- None if the *individual* results (except perhaps $\eta' K_S$) has a sizeable discrepancy with SM
  - But penguin *average* 2.8σ away from (cc)s value…
  - Note that new physics will generally have different effect on modes – averaging not necessarily sensible…



sin2b from b→s penguins – World averages

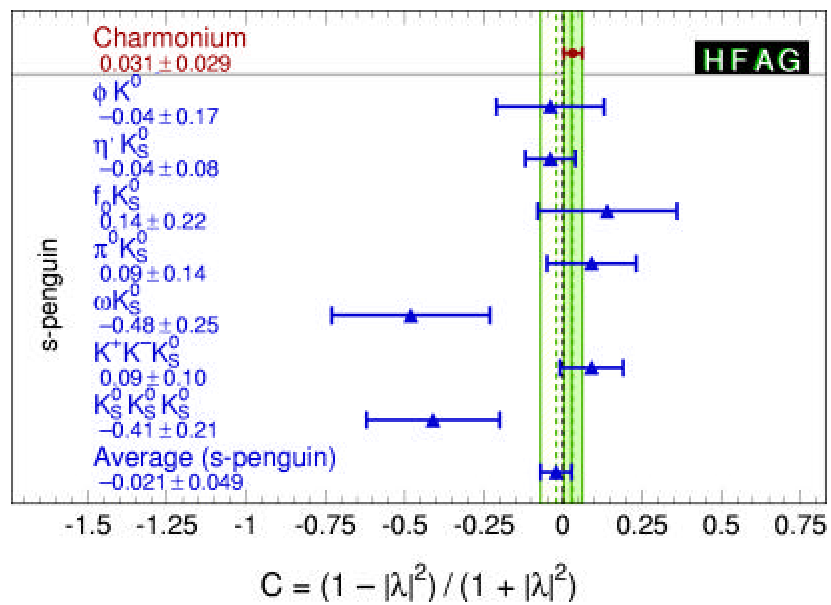
- And the discrepancy becomes more significant in a BaBar/Belle average: 3.7σ
  - But note that uncertainty due to sub-leading SM contributions are ignored in this discrepancy statement
  - What is SM prediction for sin(2β) various penguin modes?

$-h_f \times S$ ('sin2b')



Average(s-penguin) S = 0.43 ± 0.07

C ('direct CPV')



Average(s-penguin) C = -0.021 ± 0.05

Various approaches to predict SM value of $\sin(2\beta)_{peng}$

- **Naïve approach**
  - Calculate relative importance of 'polluting terms' using powers of λ, ignore strong phase differences
  - Easy, but may not be good enough (for all modes)

  [Kirkby,Nir, Phys. Lett. B592 (PDG review)]
  [Hoecker, hep-ex/0410069]

- **Model calculations**
  - Best limits, but results dependent on models and model assumptions (e.g. QCD factorization)
  - Some models have problems predicting known BFs...

  [Beneke, Buchalla, Neubert, Sachrajda, NPB591]
  [Buras,Fleischer,Recksiegel,Schwab, NPB697]
  [Ciuchini at al.,hep-ph/0407073]

- **Flavor symmetry**
  - Relate hadronic processes in ***b→dqq*** (tree dominated) and ***b→sqq*** (penguin dominated)
  - Assumes SU(3) flavor symmetry, but no other model assumptions
  - Limits not yet very good. Need to measure many suppressed BF, but will improve over time

  [Grossman, Isidori, Worah, Phys Rev D58]
  [Grossman, Liget, Nir, Quinn, Phys Rev D68]
  [Gronau, Rosner, Phys.Lett. B564]
  [Gronau, Grossman, Rosner, Phys.Lett.B579]
  [Gronau, Rosner, Zupan, Phys.Lett.B596]
  [Chiang,Gronau,Rosner,Suprun, Phys.Rev.D70]

	'Gold'	'Bronze'
	$\Delta S(\phi K_S)$	$\Delta S(\pi^0 K_S)$
Naïve approach	**~0.06**	**~0.3**
Model calculations	**0.025** ± 0.012 ± 0.01	**0.13** ± 0.07
Flavor symmetry	**~0.3**	**~0.2**

Summary

- Precise measurement of sin(2β) from charmonium K_S events

$$\sin 2\beta_{ccs} = 0.722 \pm 0.040\ (\text{stat}) \pm 0.023\ (\text{sys})$$

- Measurement of sin(2β) from b→s penguin decays

$$\langle \sin 2\beta \rangle_{peng} = 0.45 \pm 0.09$$

- Belle/BaBar combined results show an apparent discrepancy of 3.7σ between these results
  - Present challenge to theorists and experimentalists: Is the apparent discrepancy real?