B and Charm Mixing and CP Violation

- Introduction
- CKM Matrix and CPV in the Standard Model
- Mixing in B and D systems
- CP Violation in B and Charm decays
- Overall CKM fit status

Central questions in Flavor Physics

- Does the SM explain all flavor changing interactions?
- If does not: at what level we can see deviations? New Physics effects?

- The goal is to over constrain the SM description of flavor by many redundant measurements

- Requirements for success:

  Experimental and theoretical precision

Why B and Charm Physics?

In the B meson system large variety of interesting processes:

- Top quark loops neither GIM nor CKM suppressed:
  - Large mixing
  - Large CP violating effects possible
- Many of them have a clean theoretical interpretation
- In other cases hadronic physics effects can be understood in a model independent way ($m_b \gg \Lambda_{QCD}$)

In both cases NP new physics can negate SM predictions on many observables that are experimentally measurable

Charm: $m_c \ll m_b$: hadronic interactions effects important (and not always easy to calculate)

BUT:

- Charm is unique probe of up-type quark sector (down quarks in the loops)
- SM contributions in charm sector (CPV, mixing) small (large GIM suppressions, FCNC) -> sensitive to new physics/non SM sources of CPV
- Measurements of absolute rates (semi)-leptonic decays provide information to test QCD calculations needed in B

CKM Matrix

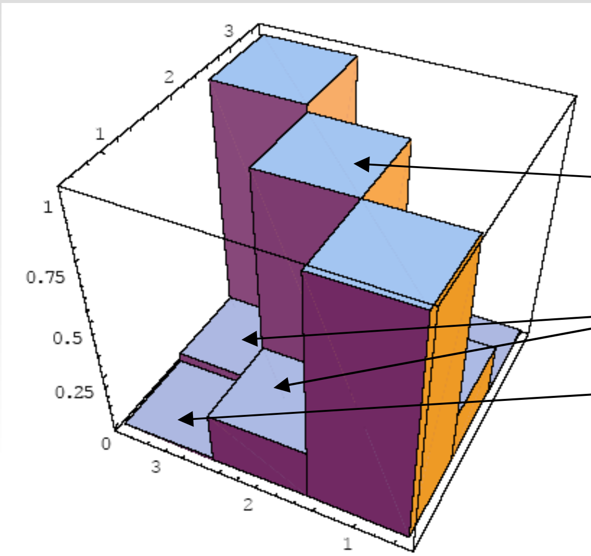
- In the SM SU(2)xU(1) quarks and leptons are assigned to be left-handed doublets and right-handed singlet
- Quark mass eigenstates are not the same as the weak egeienstates, the matrix relating these bases defined for 6 quarks and parameterized by Kobayashi and Maskawa by generalization of 4 quark case described by the Cabibbo angle
- By convention, the matrix is often expressed in terms of a 3x3 unitary matrix, V, operating on the charge -1/3 quark eigenstates (d,s,b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Elements depend on 4 real parameters (3 angles and 1 CPV phase)

V_{CKM} is the only source of CPV in the SM

V_{CKM}: Wolfenstein parametrization



The CKM Matrix is hierarchical

Vud, Vcs, Vtb	~ 1
Vus, Vcd	$\sim \lambda$
Vcb, Vts	$\sim \lambda^2$
Vub, Vtd	$\sim \lambda^3$

$\lambda = |V_{us}| = \sin(\theta_c) \sim 0.22$

It is convenient to exhibit the hierarchical structure by expansion in powers of λ

$A, \rho, \eta \sim O(1)$

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Present uncertainties:

$\lambda \sim 0.5\%$, $A \sim 4\%$, $\rho \sim 19\%$, $\eta \sim 6\%$

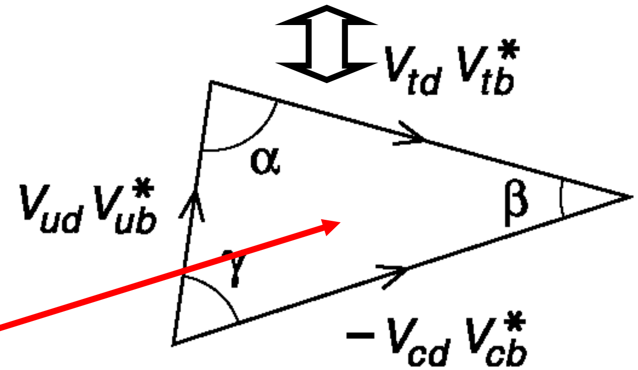
Unitarity Triangles (UT)

- A simple and vivid summary of the CKM mechanism
- V_{CKM} is unitary: $VV^{\dagger}=V^{\dagger}V=1$
- The orthogonality of columns (or rows) provides 6 triangle equations in the complex plane:

Example: first and third column:

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

$$V=\begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix} \Rightarrow$$



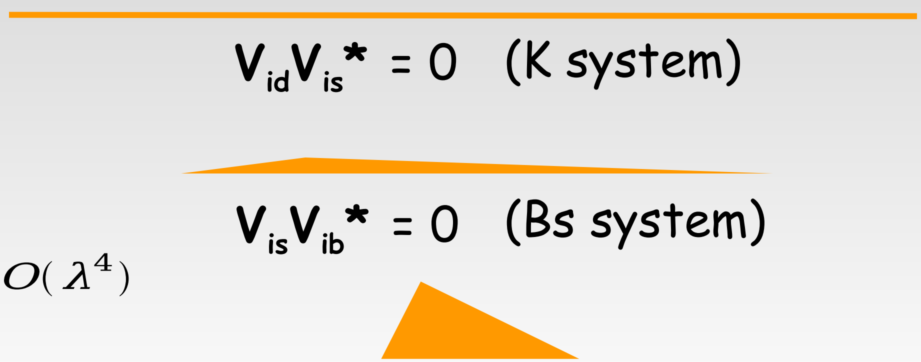
CPV in SM ∝ Triangle Area

Angles and sides are directly measurable

More on UT

There are 6 UT triangles
Columns and rows relations
give similar results

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



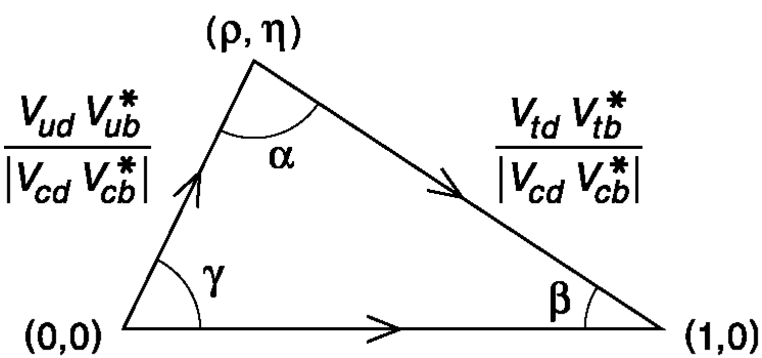
$V_{id}V_{is}^* = 0$ (K system)

$V_{is}V_{ib}^* = 0$ (Bs system)

$V_{id}V_{ib}^* = 0$ (Bd system)

- All triangles have the same area: $\propto A\lambda^6\eta$
- The "$V_{id}V_{ib}^*$" triangle is "special": all sides $O(\lambda^3)$ → large angles → large CPV in the B system

Measurements usually summarized by plotting their constraints in the ρ-η plane



$$\alpha=\arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)=\tan^{-1}\left(\frac{\bar\eta}{\bar\eta^2+\bar\rho(\bar\rho-1)}\right)$$

$$\beta=\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)=\tan^{-1}\left(\frac{\bar\eta}{1-\bar\rho}\right)$$

$$\gamma=\arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)=\tan^{-1}\left(\frac{\bar\eta}{\bar\rho}\right)$$

$$\beta_s=\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)=\lambda\eta^2+O(\lambda^4)$$

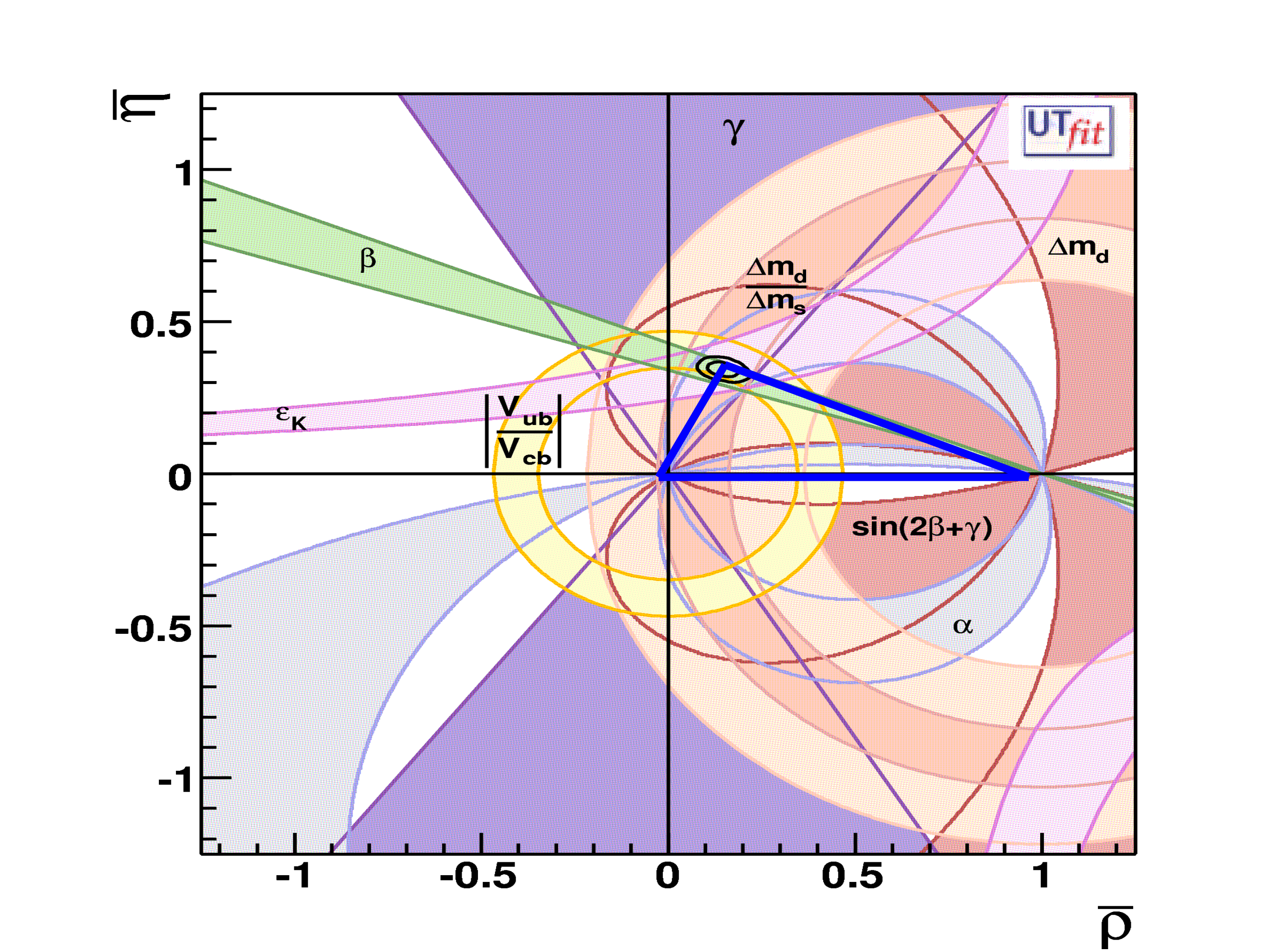
$$\bar\rho=\rho\left(1-\lambda^2/2\right)$$

$$\bar\eta=\eta\left(1-\lambda^2/2\right)$$

Constraints in the (ρ,η) plane

2 sides ; 3 angles ⇒ aim : to over-constrain this unitarity triangle

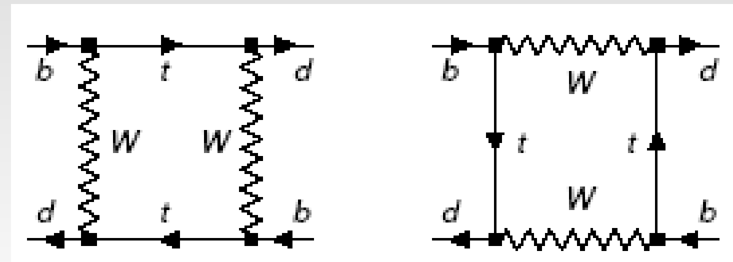
precision test of the Standard Model



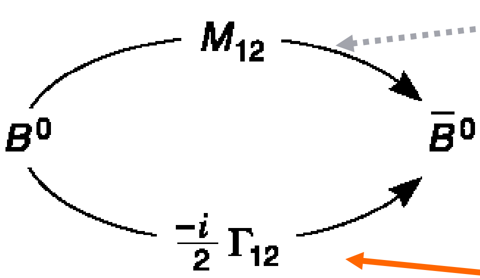
CP Violation in B Decays

Time evolution and mixing of two flavor eigenstates governed by Schrödinger equation:

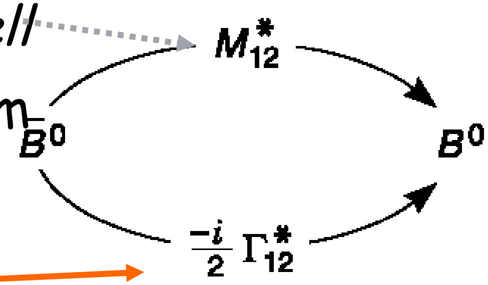
$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}$$



M,Γ are 2x2 time independent, Hermitian matrices; CPT invariance implies M_{11}=M_{22} and Γ_{11}=Γ_{22}, off-diagonals elements due to box diagrams dominated by top quarks are the source of mixing



M_{12} describes $B^0 \leftrightarrow B^0$ via *off-shell* states, e.g. the weak box diagram



Γ_{12} describes $B^0 \leftrightarrow f \leftrightarrow \bar{B}^0$ via *on-shell* states

Neutral meson Mixing

Mass eigenstates are eigenvectors of H:

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

$$|p|^2 + |q|^2 = 1$$

NOTE: In general $|B_H>$ and $|B_L>$ are not orthogonal to each other

The time evolution of the mass eigenstates is governed by:

$$|B_{H,L}(t)\rangle = e^{-\left(iM_{H,L}+\frac{\Gamma_{H,L}}{2}\right)\cdot t}|B_{H,L}(t=0)\rangle$$

In the $|\Gamma_{12}| \ll |M_{12}|$ limit, which holds for both B_d and B_s:

$$\Delta m = M_H - M_L = 2|M_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\varphi \qquad \varphi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$\frac{q}{p} = -\frac{2M_{12}^{*} - i\Gamma_{12}^{*}}{\Delta m + i\,\Delta\Gamma/2} = -e^{-i\varphi_M}\left[1 - \frac{1}{2}\operatorname{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$$M_{12} = |M_{12}|e^{i\varphi_M}$$

Neutral meson Mixing in the SM

$$\Delta m_q = \frac{G_F^2}{6\pi^2}|V_{tb}|^2|V_{tq}|^2 M_W^2 M_{B_q^0} \underbrace{f_{B_q^0}^2 B_{B_q^0}}_{\text{non perturbative QCD}} \eta_{B_q^0} S\left(\frac{M_t^2}{M_W^2}\right)$$

$\eta_{B_q^0}$: perturbative QCD

$$\frac{\Delta m_d}{\Delta m_s} = \frac{|V_{td}|^2}{|V_{ts}|^2}\frac{M_{B_d^0}}{M_{B_s^0}}\frac{\eta_{B_d^0}}{\eta_{B_s^0}}\frac{f_{B_d^0}^2 B_{B_d^0}}{f_{B_s^0}^2 B_{B_s^0}}$$

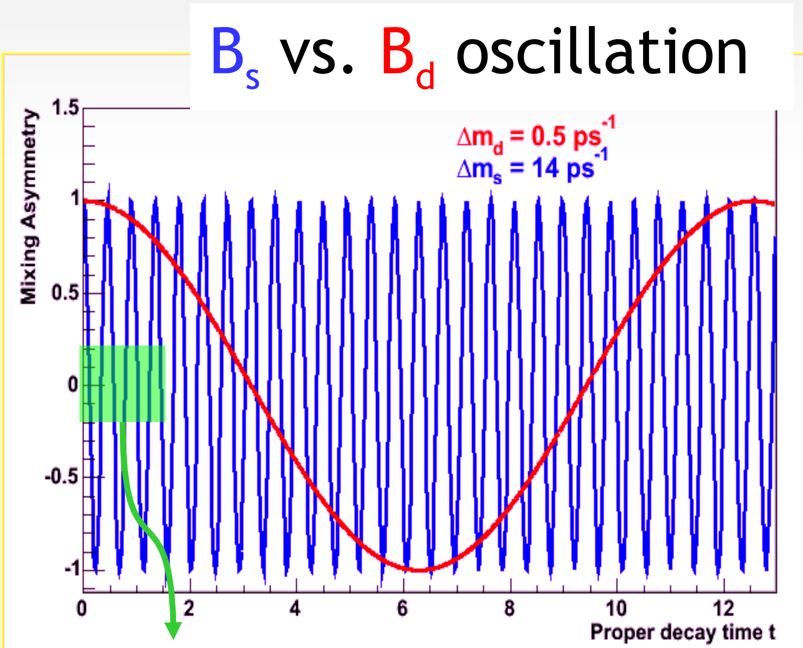
$\frac{\eta_{B_d^0}}{\eta_{B_s^0}} \cong 1$

SU(3) Flavor breaking
theoretical uncertainties <5%

B_s Mixing at CDF

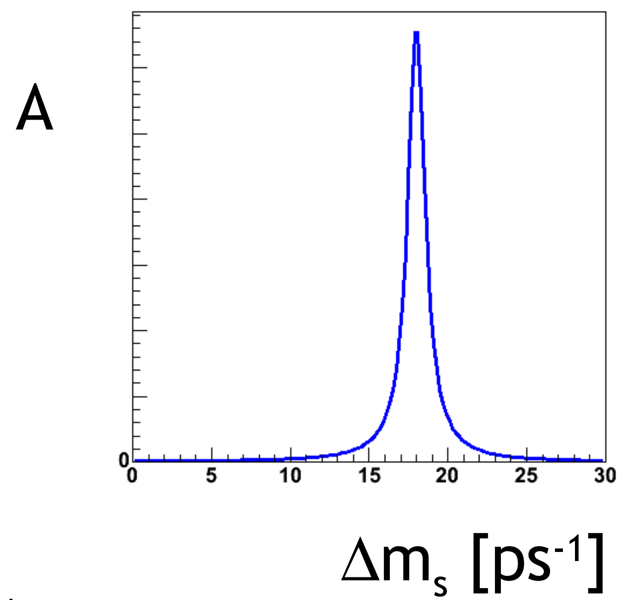
Measurement Principle in a Perfect World

$$P(t)_{B_q^0 \to \overset{(-)}{B}{}_q^0} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm \cos(\Delta m_q t)) \qquad A = \frac{N^{nomix} - N^{mix}}{N^{nomix} + N^{mix}} = \cos(\Delta m_s t)$$

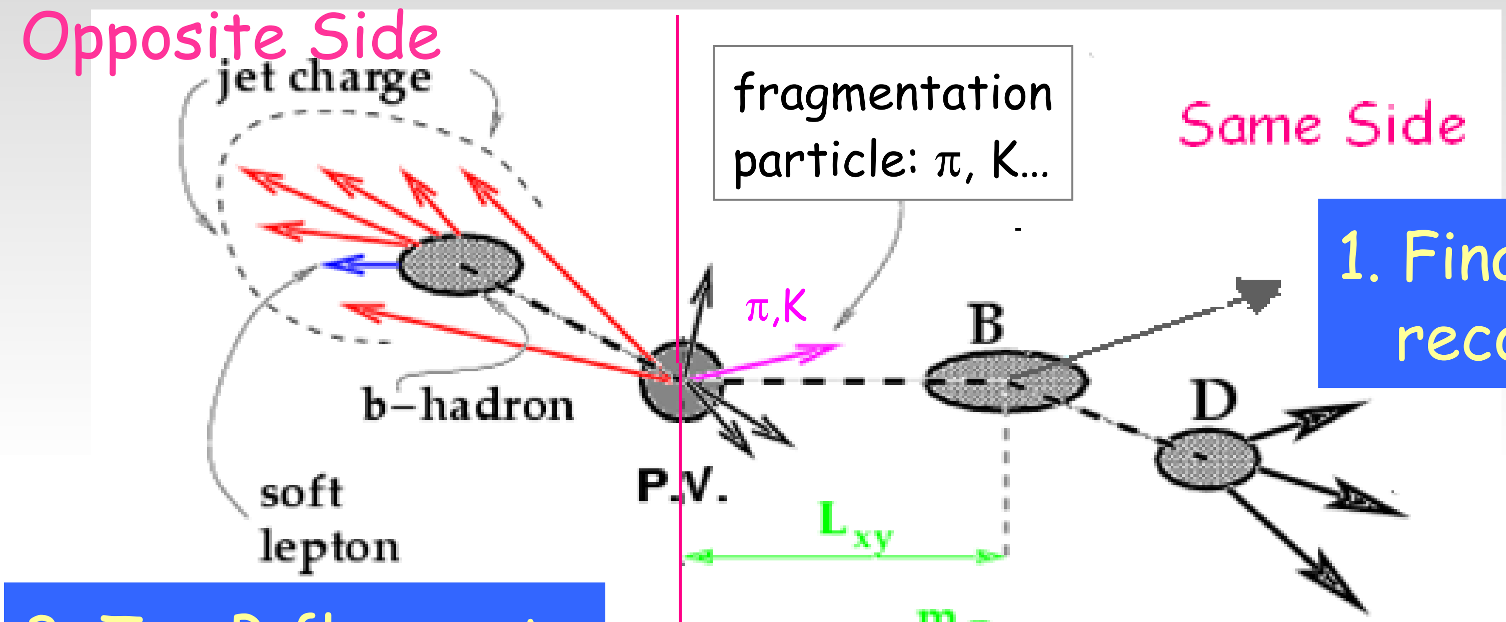


B lifetime

Rather than fit for frequency perform a 'Fourier transform'



Road Map to Δm_s Measurement



1. Final state reconstruction

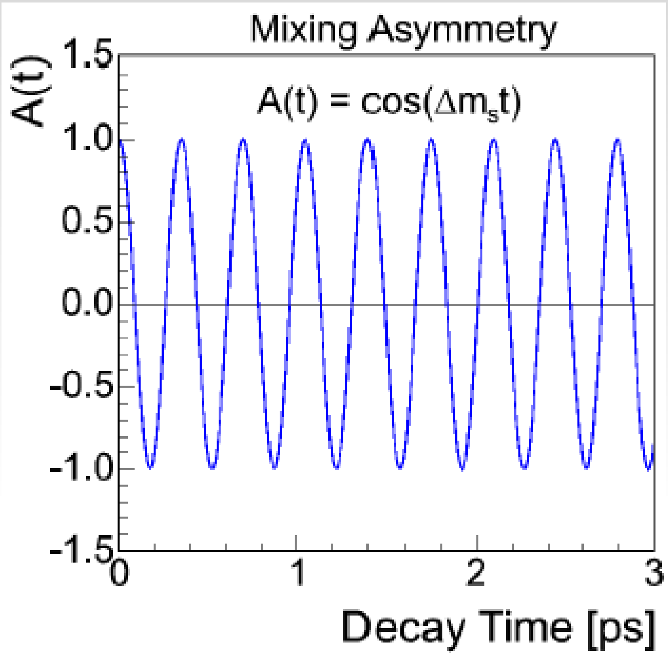
$$ct = L_{xy}\frac{m_B}{p_T}$$

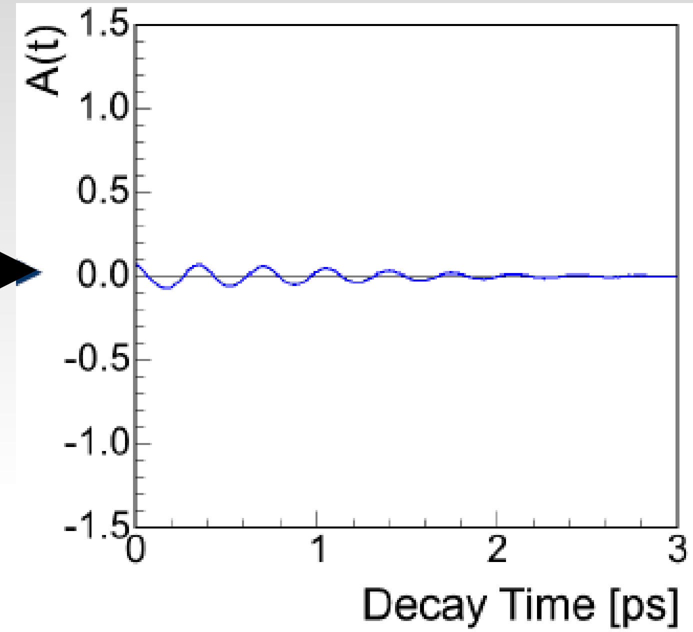
$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

3. Tag B flavor at production time

Adding all realistic effects





Flavor tagging power

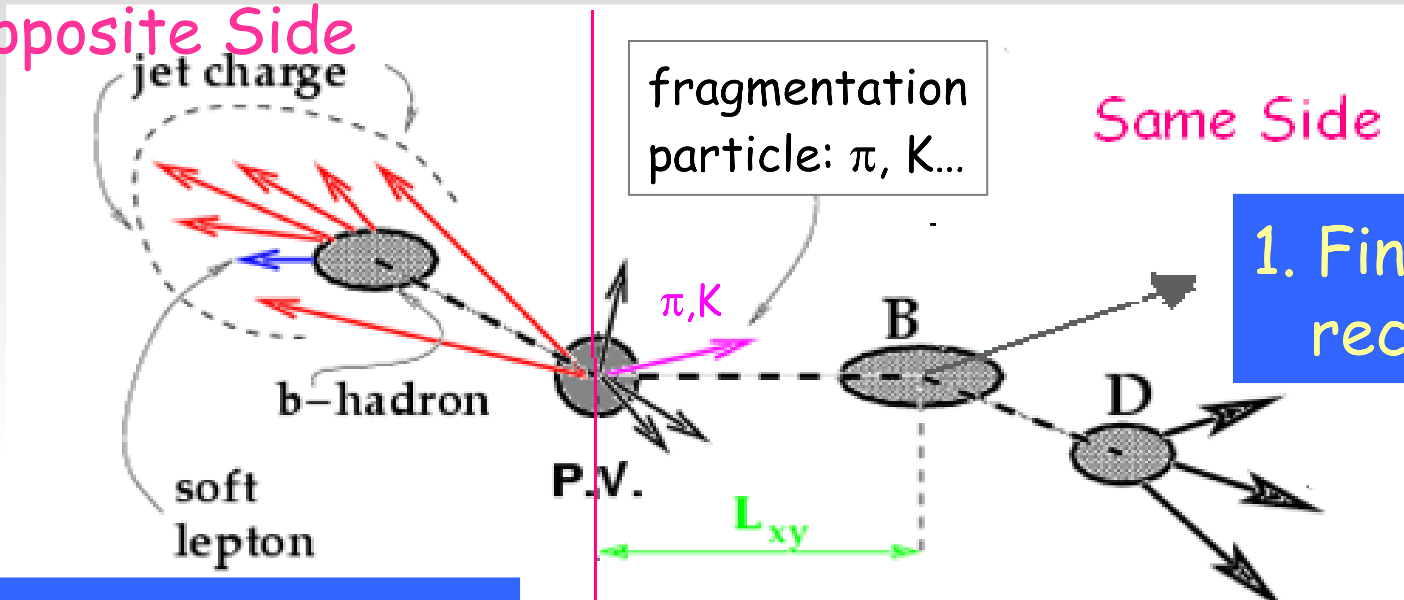
Proper time resolution

$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

Road Map to Δm_s Measurement

Opposite Side



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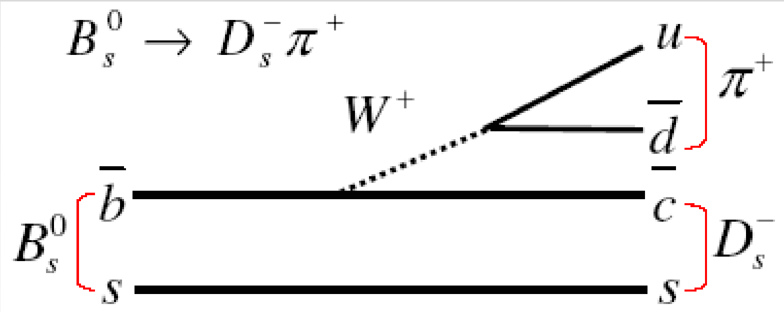
2. High resolution on proper decay length

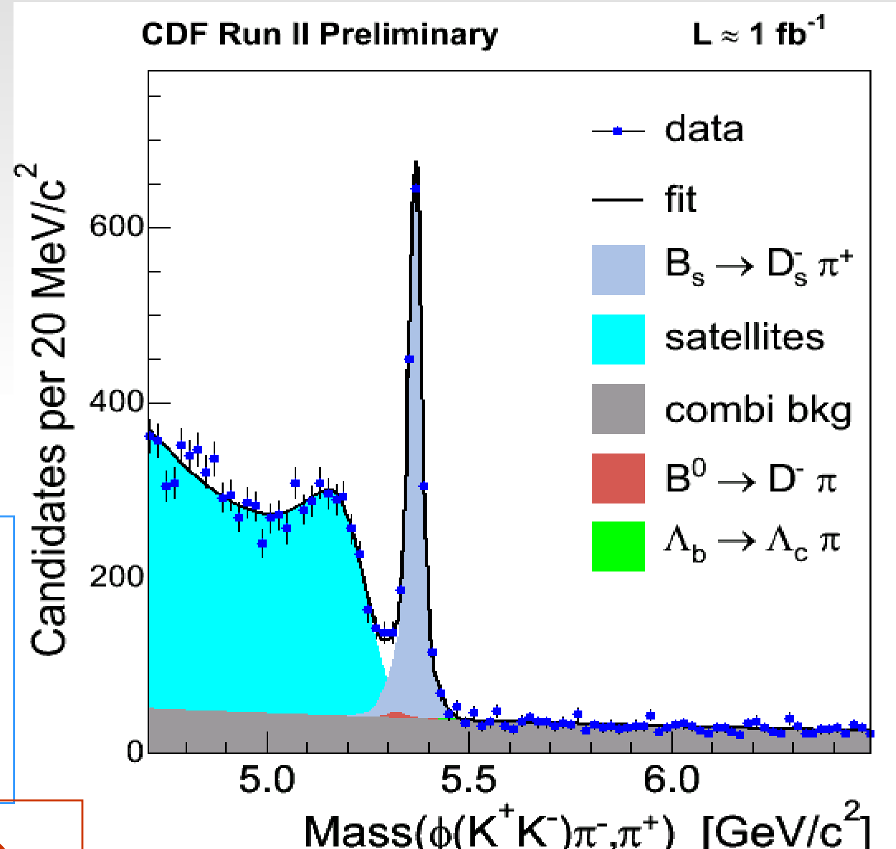
3. Tag B flavor at production time

measure efficiency ε and dilution D: εD^2 gives the "effective" number of events

B_s data Sample



Signal $B_s \rightarrow D_s\pi$ $D_s \rightarrow \phi\pi$



$B_s \rightarrow D_s\pi$

- $D_s \rightarrow \phi\pi$ $\phi \rightarrow KK$
- $D_s \rightarrow K^{*0}K$ $K^{*0} \rightarrow K\pi$
- $D_s \rightarrow 3\pi$

$B_s \rightarrow D_s 3\pi$

- $D_s \rightarrow \phi\pi$
- $D_s \rightarrow K^{*0}K$

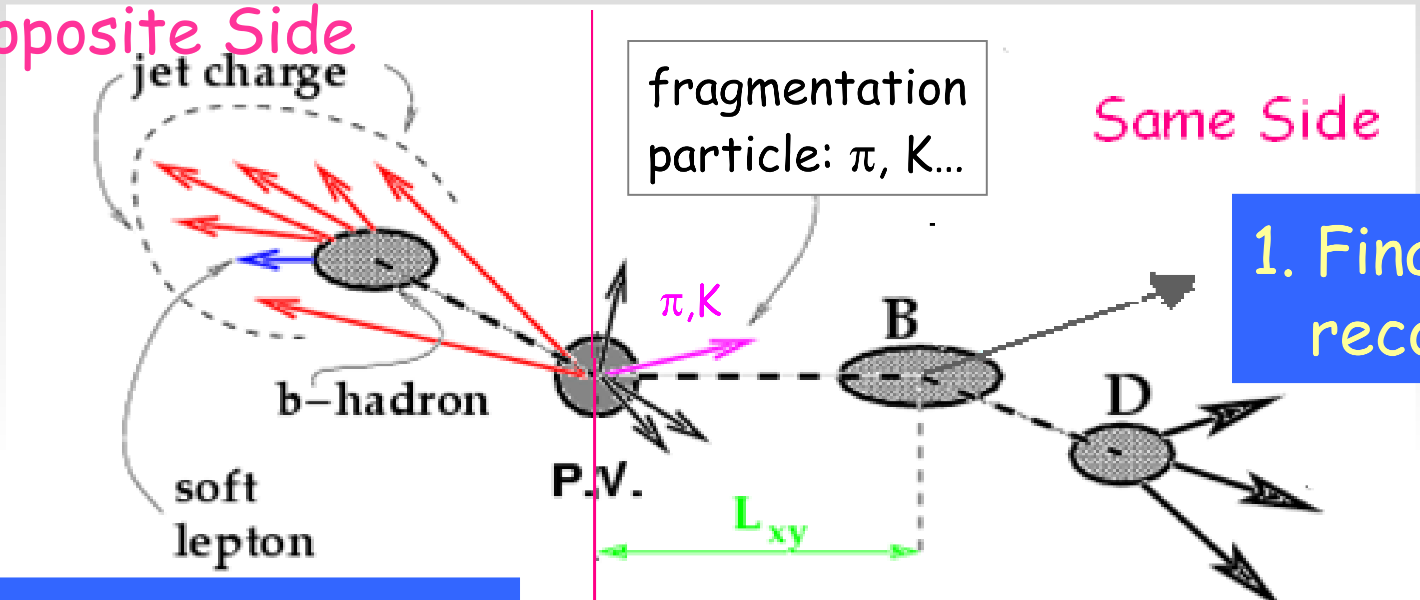
Partially reconstructed B mesons

$B^0 \rightarrow D^-\pi$

Combinatorial background

Road Map to Δm_s Measurement

Opposite Side



1. Final state reconstruction

3. Tag B flavor at production time

$$ct = L_{xy}\frac{m_B}{P_T}$$

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

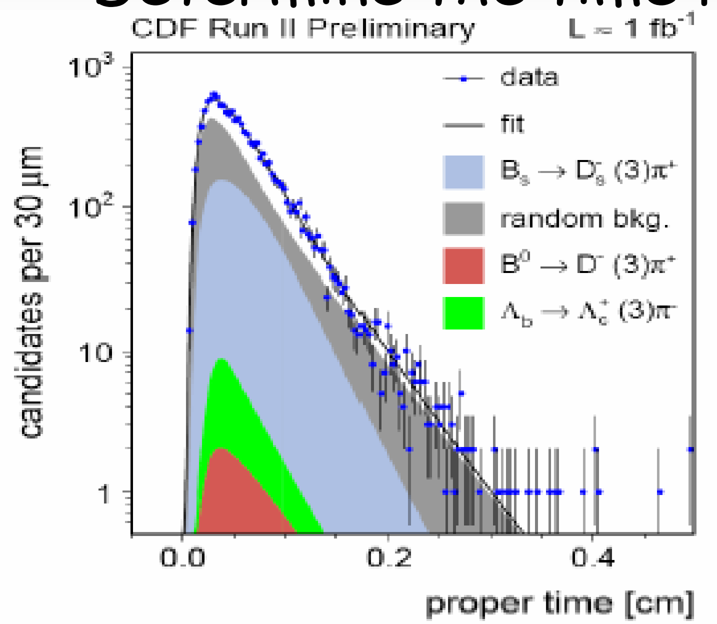
Proper decay time reconstruction

- Fully reconstructed events $ct = L_{xy}^{B} M^{B} / P_{t}^{B}$
- Semileptonic decay $ct = L_{xy}^{lD} M^{B} / P_{t}^{lD} \cdot K$

$K = \langle P_{t}^{lD} / P_{t}^{B} \cdot L_{xy}^{B} / L_{xy}^{lD} \rangle$

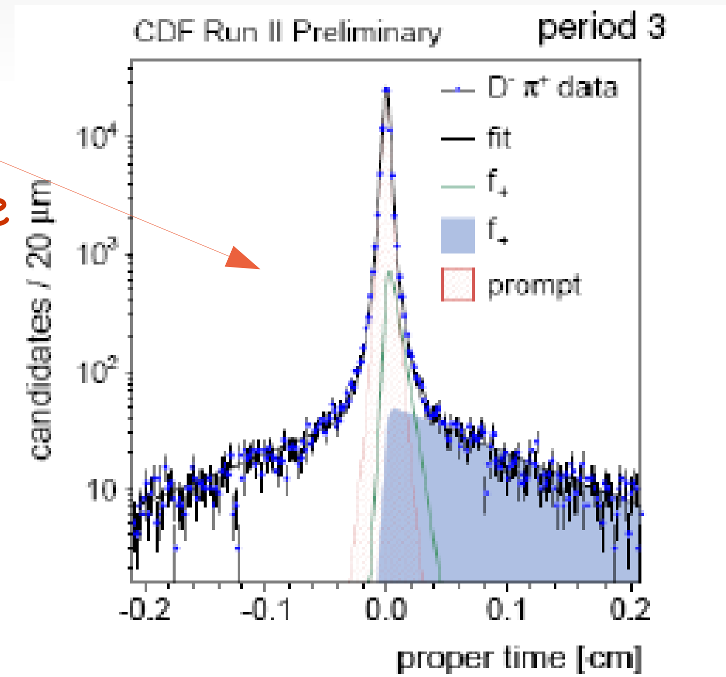
It is needed to:

- Measure the lifetime to establish the time scale
- Determine the time resolution



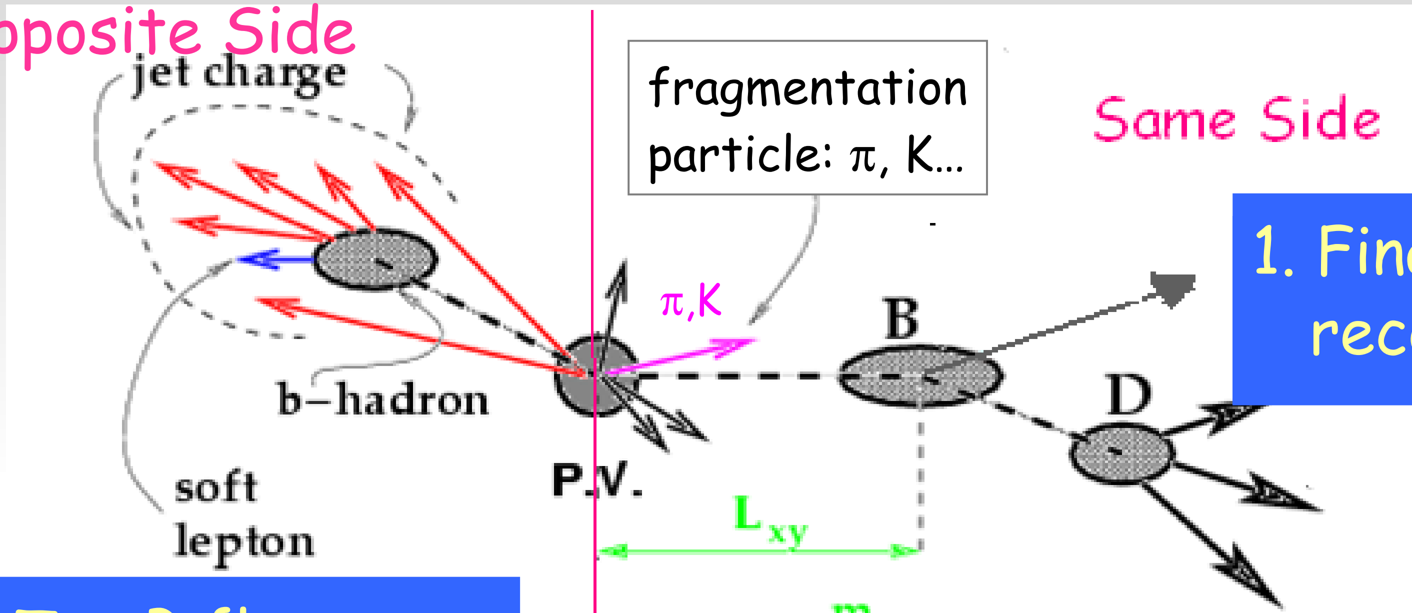
$c\tau(B_s) = 1.538 \pm 0.040(\text{stat})$ ps

Prompt Charm
+ track sample



Road Map to Δm_s Measurement

Opposite Side



1. Final state reconstruction

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$$ct = L_{xy}\frac{m_B}{P_T}$$

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

measure efficiency ε, dilution D

$$D = \frac{N_{right} - N_{wrong}}{N_{right} + N_{wrong}} = 2P_{right} - 1$$

εD^2 gives the "effective" number of events

Events Tagging

Opposite Side

- Use data to calibrate taggers and to evaluate D
- Fit semileptonic and hadronic B_d sample to measure: D, Δm_d

-lepton (electron or muon)

$$Q_J^\ell = \sum_i q^i p_T^i / \sum_i p_T^i$$

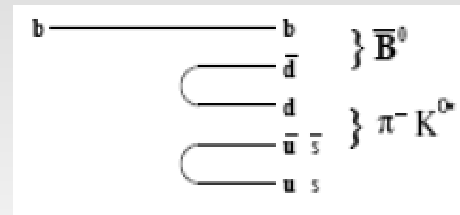
- Secondary Vertex

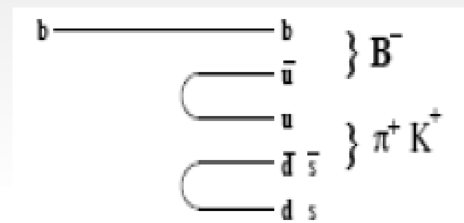
$$Q_{SV} = \sum_i (q^i p_L^i)^{0.6} / \sum_i (p_L^i)^{0.6}$$

- Event Charge

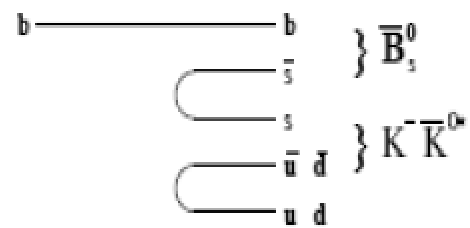
$$Q_{EV} = \sum_i q^i p_T^i / \sum_i p_T^i$$

Same Side





$B^0/B^{\pm}$ likely to have π nearby



B^0_s likely to have K

Tune Monte Carlo to reproduce B^0,B^- distributions then apply to B_s

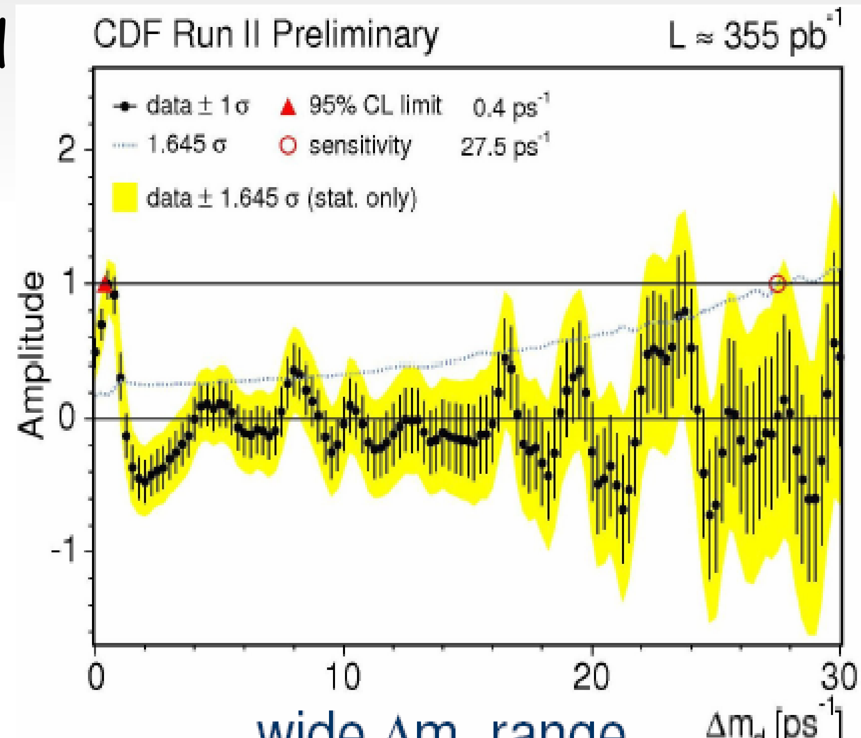
Amplitude scan notation

- A is introduced: $P(t)_{B_q^0 \to \overset{(-)}{B}_q^0} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm \mathrm{A}\cos(\Delta m_q t))$
  - A=1 when $\Delta m_s^{measured} = \Delta m_s^{true}$

In the figure:

- Points: A±σ(A) from Likelihood fit for different Δm
- Yellow band: A±1.645σ(A)
- Dashed line: 1.645σ(A) vs. Δm
- Δm excluded at 95% C.L. if A±1.645σ(A)<1
- Measured sensitivity: 1.645σ(A)=1

B^0 mixing in hadronic decay



wide Δm_s range

Choice of procedure

Before un-blinding: p-value probability that observed effect is due background fluctuation. No search window.

p-value<1%?

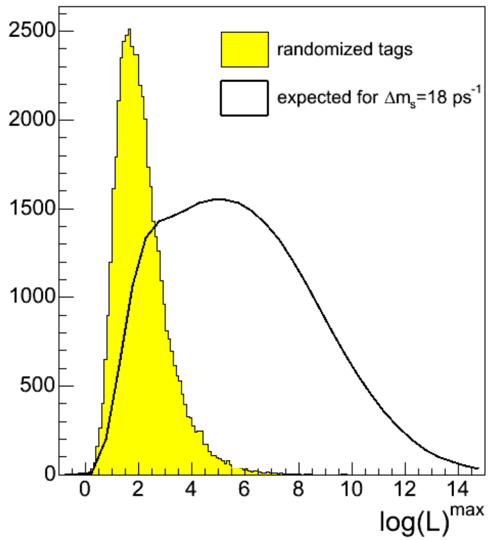
yes

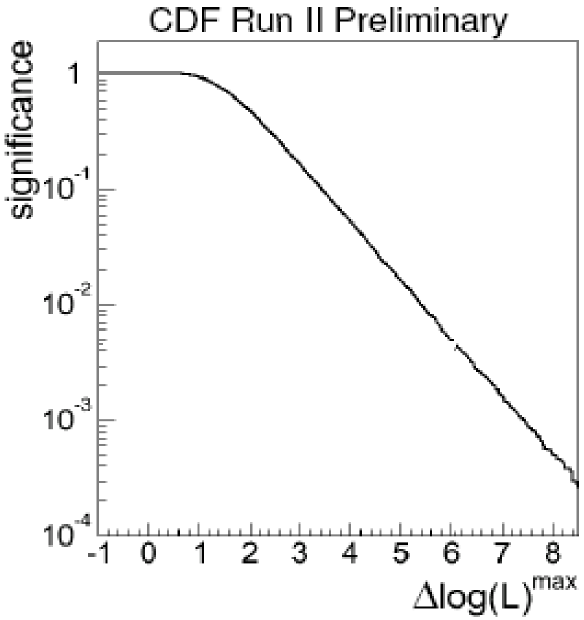
no

$\ln[L(A=1)/\ln L(A=0)]$

make double sided confidence interval from $\Delta(\ln(L))$, measure Δm_s

set 95% C.L. based on Amplitude Scan



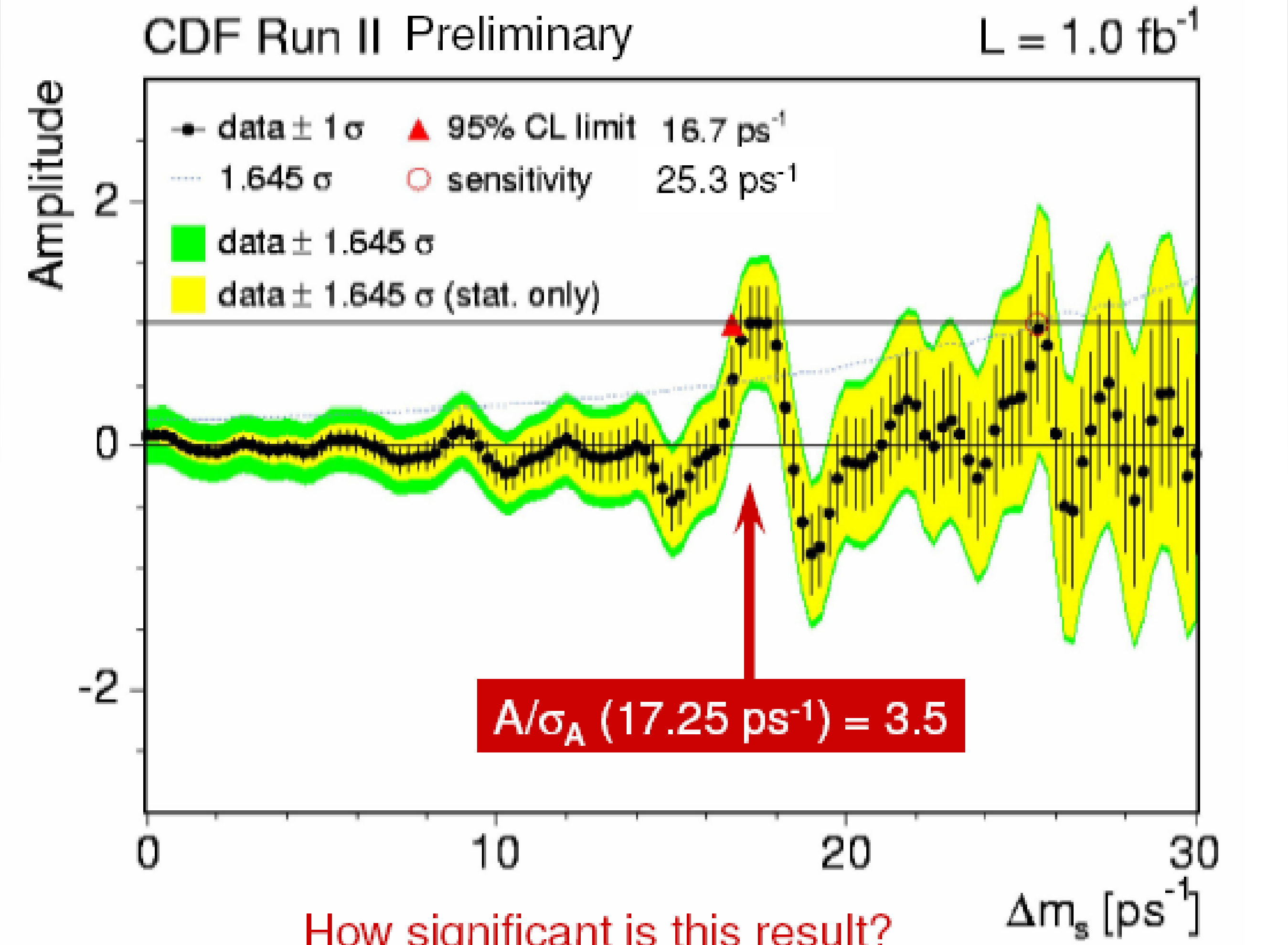


Probability of random tag fluctuation estimated on data (randomized tags) and checked with toy Monte Carlo

Amplitude Scan

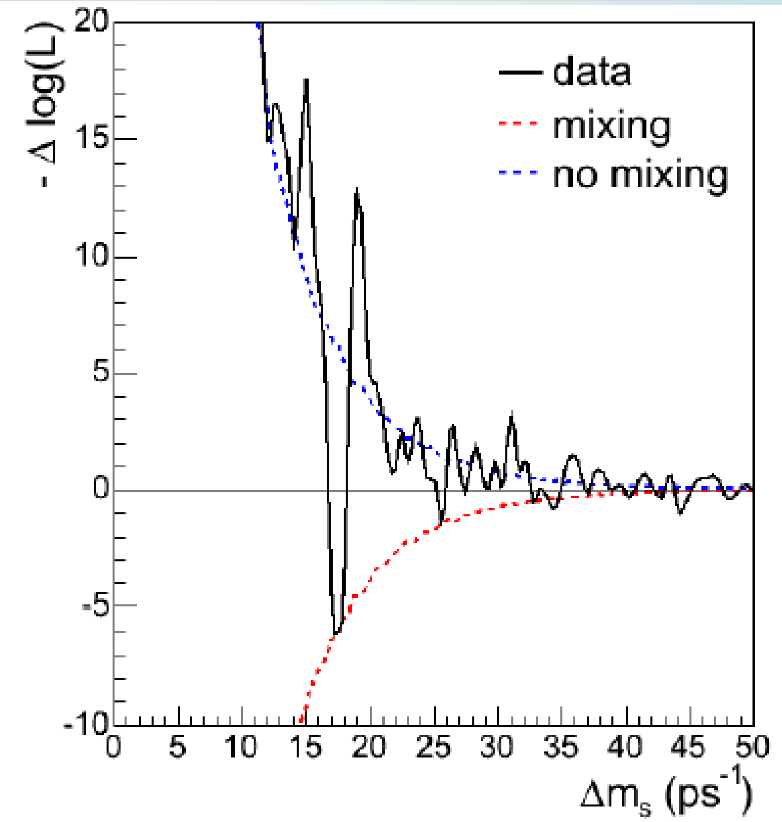
Sensitivity better than the W.A. 20.1 ps^{-1}

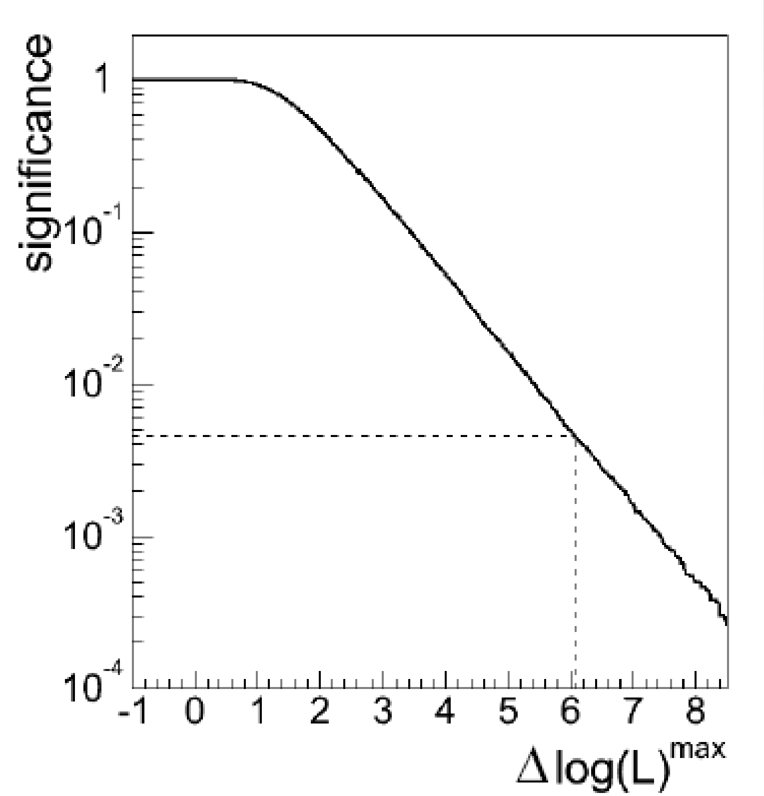
Rare case!!



How significant is this result?

Likelihood Profile & significance



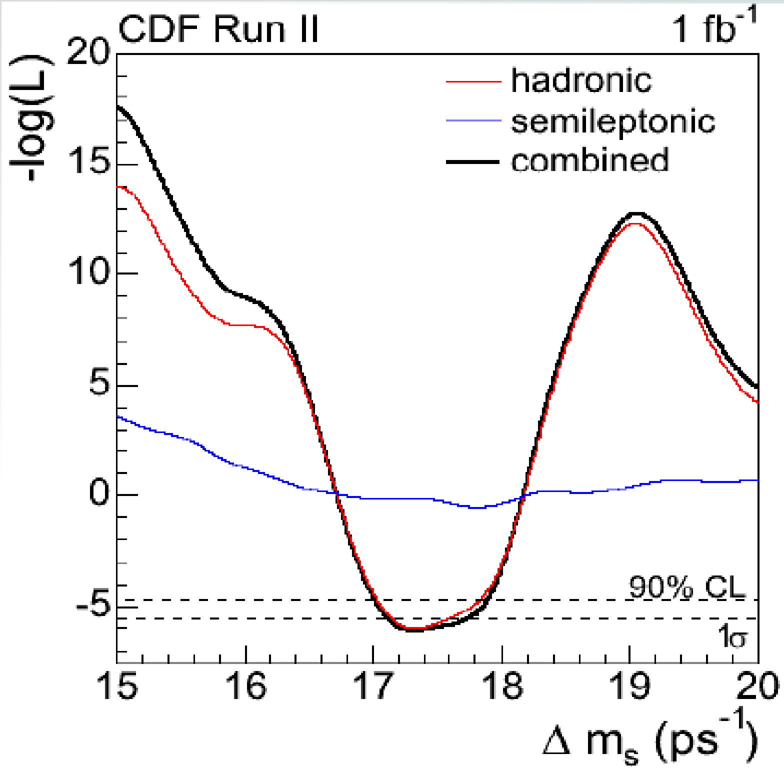


How often random tags produce a likelihood deep this dip?

Probability of fake: p-value=0.5%

Measure Δm_s !!!

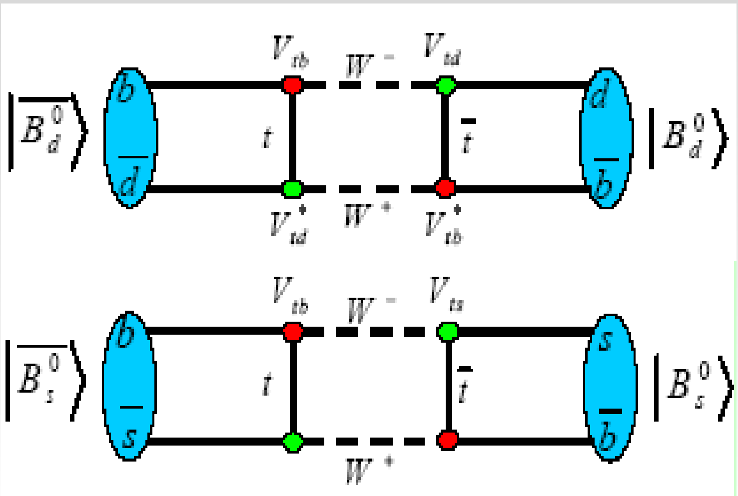
Measurement of Δm_s



$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07\ ps^{-1}$$

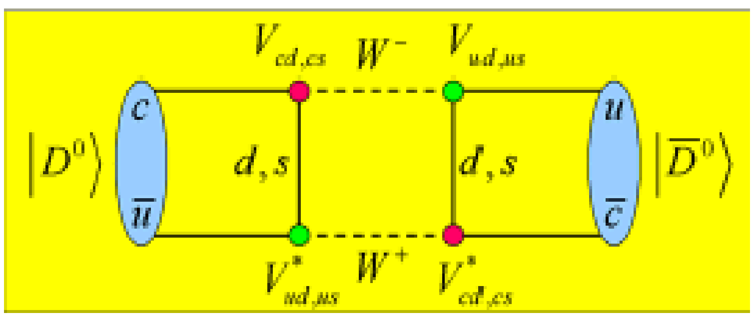
$17.00 < \Delta m_s < 17.91\ ps^{-1}$ at 90% C.L. $\quad 16.94 < \Delta m_s < 17.97\ ps^{-1}$ at 95% C.L.

Mixing in Charm decays



dominated by top -> large

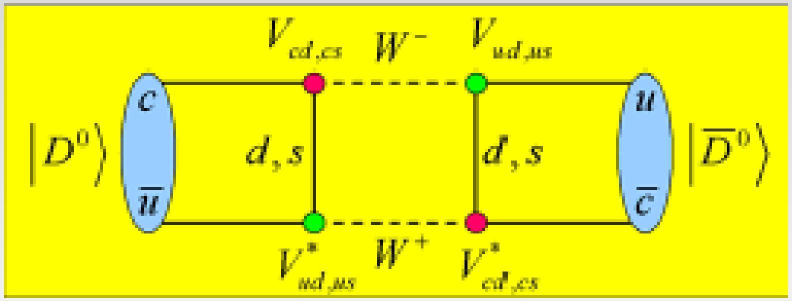
	$\Delta M/\Gamma$	$\Delta\Gamma/\Gamma$
K^0	0.474	0.997
B^0	0.77	<0.01
B_s	27	0.15
D^0	< few%	< few%



dominated by strange-> suppressed

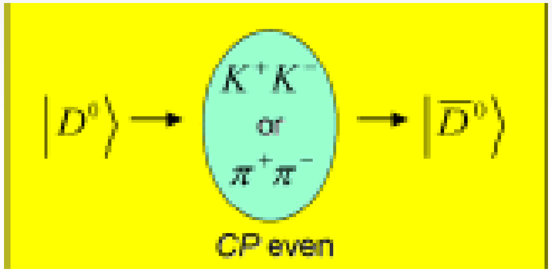
Goal of the search for D^0 mixing is not to constraint the CKM parameters but rather to probe NP

D Mixing



$$x = \frac{\Delta m}{\Gamma}$$

X mixing: channel for NP



$$y = \frac{\Delta\Gamma}{2\Gamma}$$

Y (long-range) mixing:
SM background

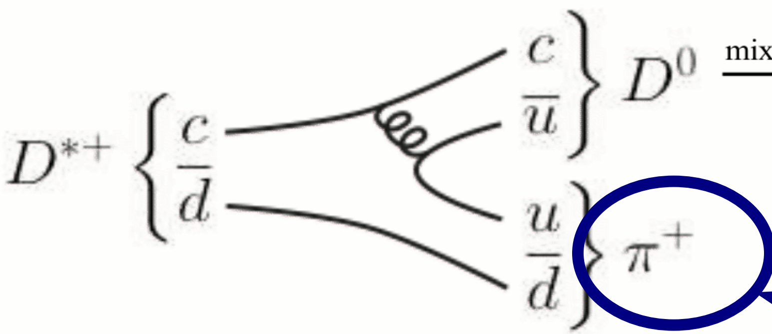
$$R_{mix} = \frac{1}{2}\left(x^2 + y^2\right)$$

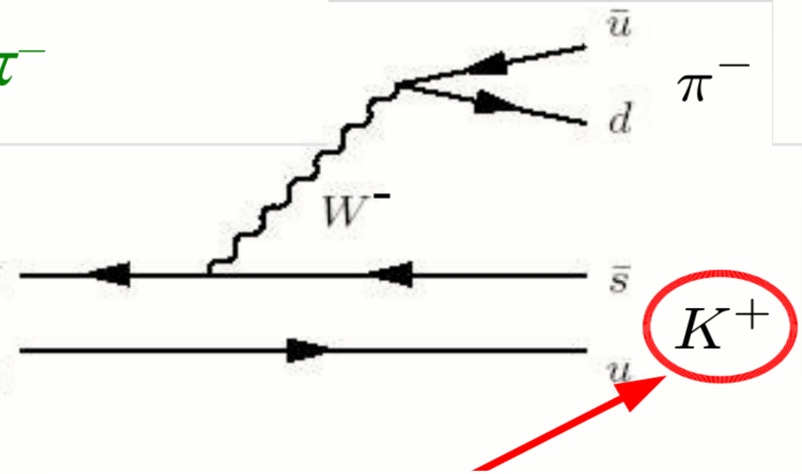
NP will enhance x but not y

NP in loops implies x >> y, but long range effects complicate predictions

D Mixing measurements at Babar

- Use decay mode $\overline{D}^0 \rightarrow K^+\pi^-$

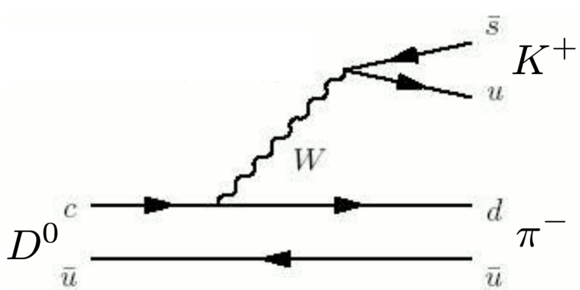




K charge tags the decay flavor

π_s charge tags production flavor

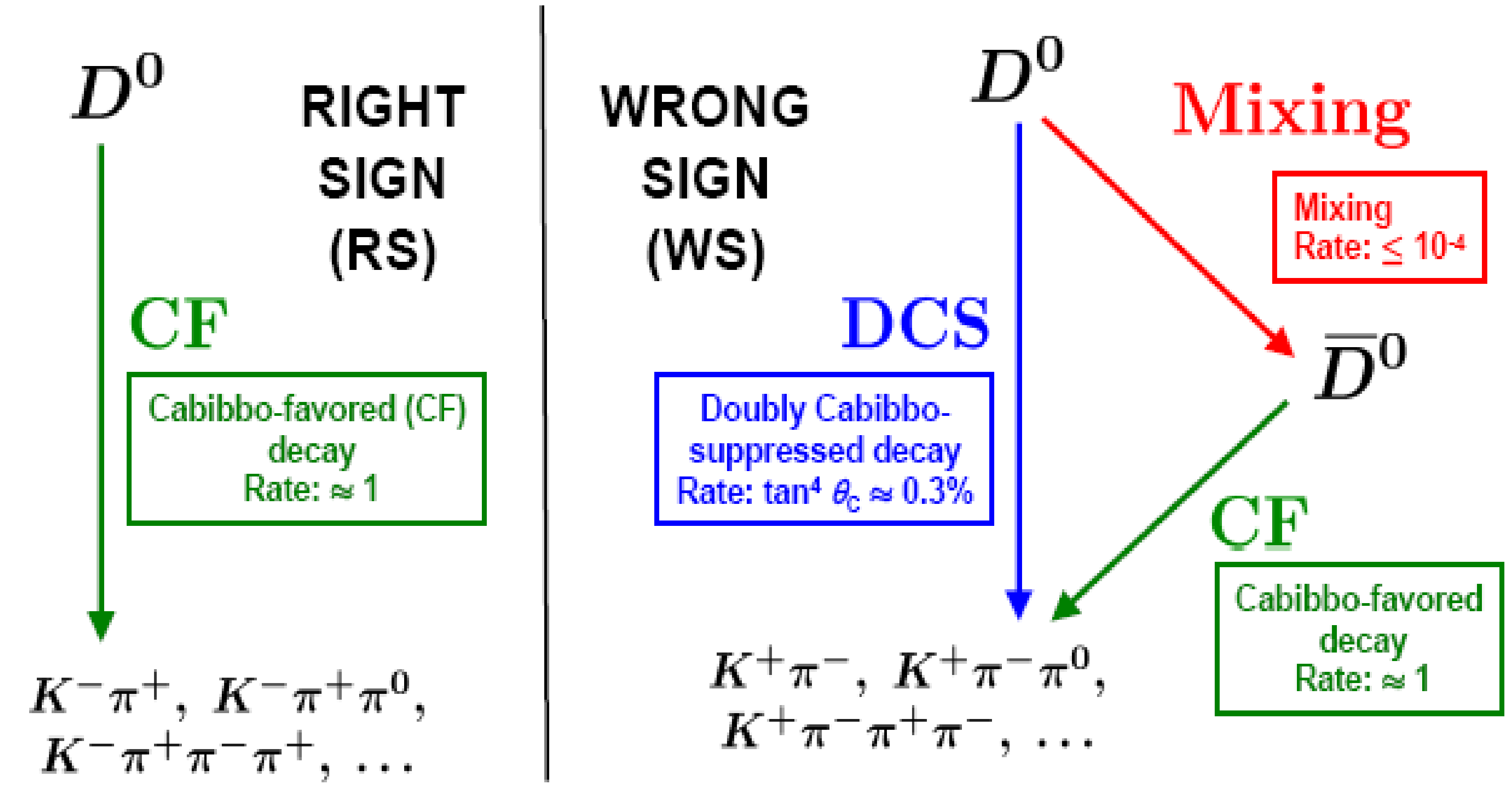
Final state accessible via DCS



MIXING and DCS interference

D Mixing: WS and RS

Determine the $\overline{D}^0$ flavor at production and at decay



D Mixing: Decay time distribution

For $x, y \ll 1$

$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(\underbrace{R_{\mathrm{D}}}_{\text{DCS decay}} + \underbrace{\sqrt{R_{\mathrm{D}}}\,y'\,\Gamma t}_{\text{Interference between DCS and mixing}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

Allows for a strong phase difference $\delta_{K\pi}$ between CF and DCS direct decay

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}, \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

This phase may differ between decay modes

Time-integrated mixing rate R_M defined by $R_M = \dfrac{x^2+y^2}{2}$

D Mixing:event reconstruction

Reconstruction

- Identify as $D^0/\bar{D}^0$ at production & decay
- Determine $m_{K\pi}$, Δm, proper-time t and error δ_t

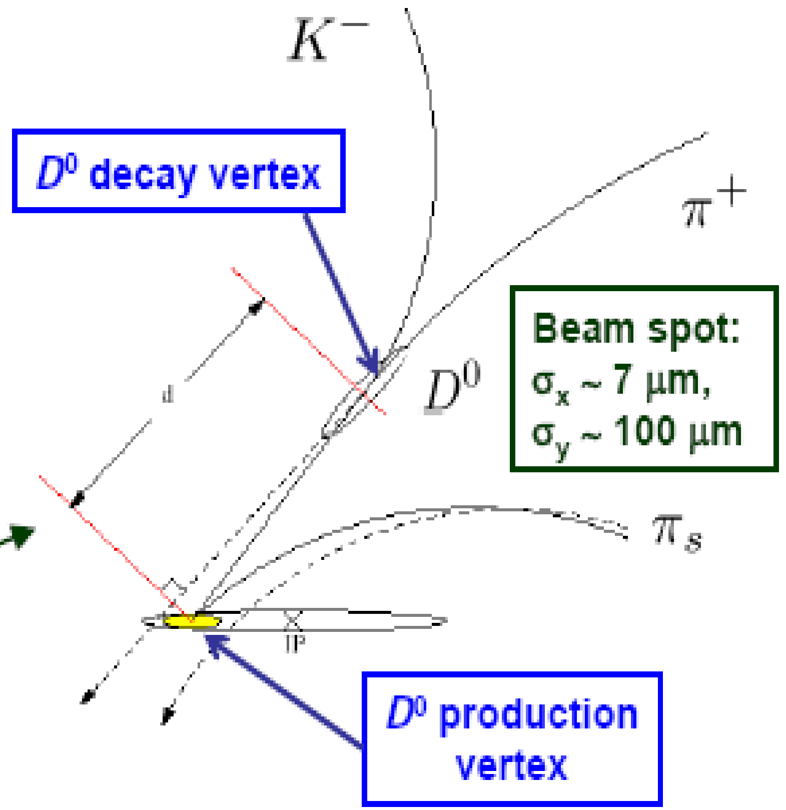
$$\Delta m = m(D^{*+}_{\rm rec}) - m(D^0_{\rm rec})$$

Vertex fit uses beamspot constraint

- Improves the decay-time error
- Improves the Δm resolution

Shown: right-sign decay

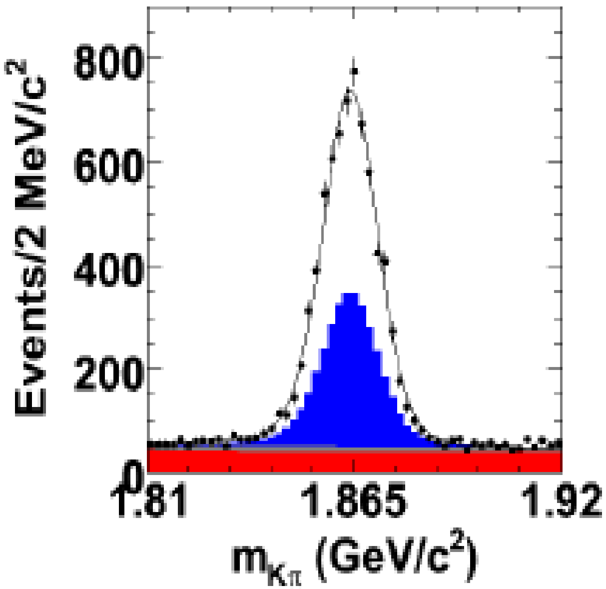
$$D^{*+} \rightarrow \pi_s^+ D^0,\ D^0 \rightarrow K^- \pi^+$$



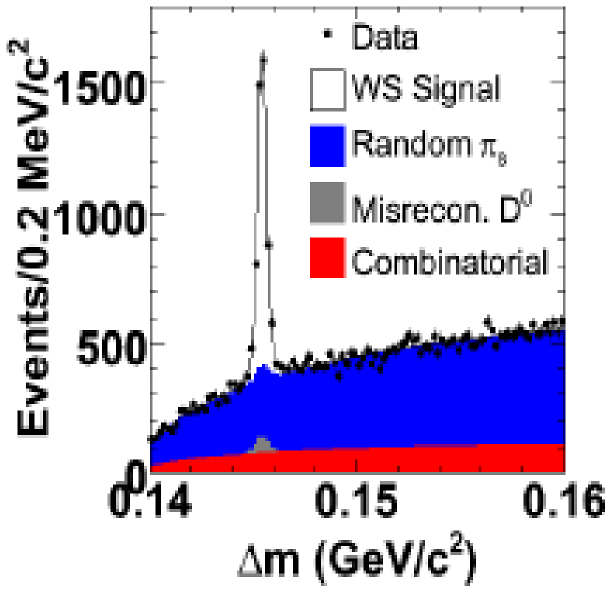
Typical D^0 flight length $d \sim 240\ \mu m$
Average resolution $\sigma_d \sim 95\ \mu m$

D Mixing: WS $m_{k\pi}$ and Δm fit

The $m_{K\pi}$, Δm fit determines the WS b.r. $R_{WS} = N_{WS}/N_{RS}$



4,030 ± 90
WS signal events



BABAR (384 fb^{-1}): R_{WS} = (0.353 ± 0.008 ± 0.004)% (PRL 98, 211802 (2007))
BELLE (400 fb^{-1}): R_{WS} = (0.377 ± 0.008 ± 0.005)% (PRL 96, 151801 (2006))

D Mixing: decay time fit

Fit WS proper time

Dotted line is the no-mixing fit

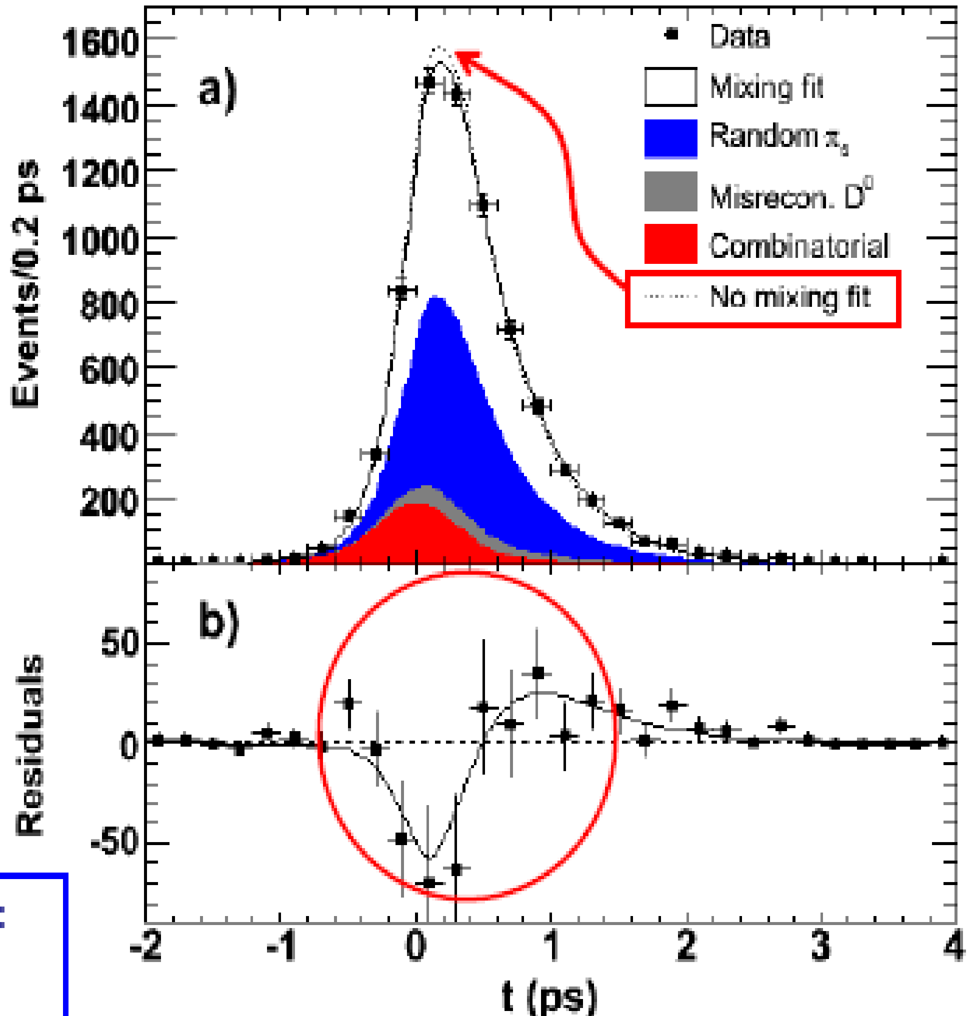
Solid line is the mixing fit

Result:

$x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

$y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

Projection of events in signal region:
$1.843\ \mathrm{GeV}/c^2 < m < 1.883\ \mathrm{GeV}/c^2$
$0.1445\ \mathrm{GeV}/c^2 < \Delta m < 0.1465\ \mathrm{GeV}/c^2$

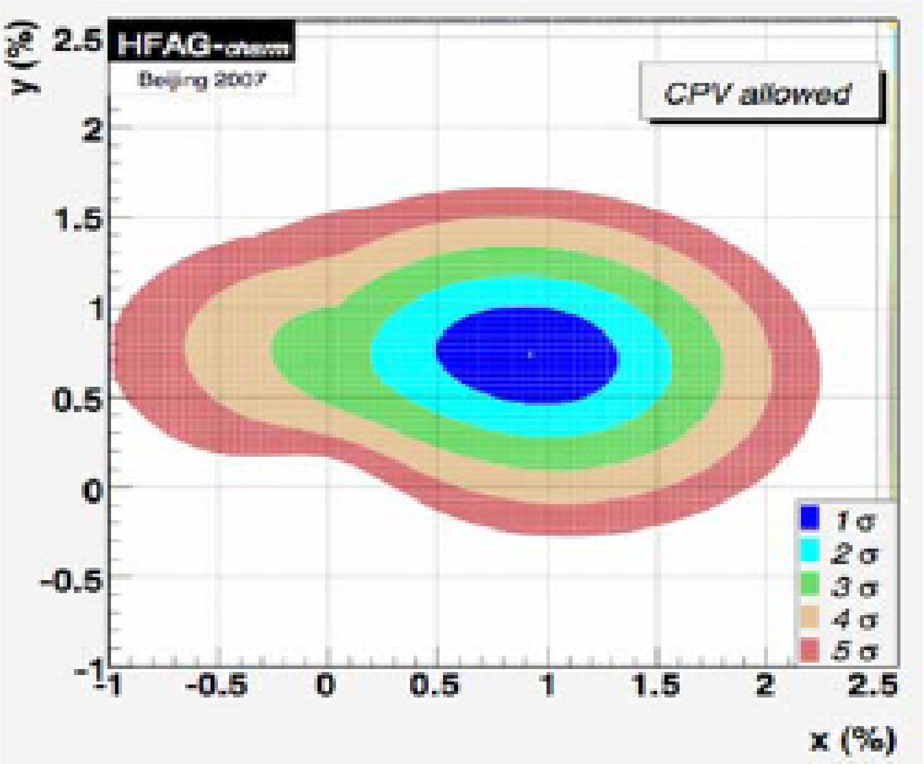


D Mixing measurements summary

Other measurements:
- other decay modes
- Belle
- CDF

Combination

$$x_{avg} = \left(0.97\,^{+0.27}_{-0.29}\right) \times 10^{-2}$$
$$y_{avg} = \left(0.78\,^{+0.18}_{-0.19}\right) \times 10^{-2}$$



CP Violation

Inside the SM there are three types of CP violation:

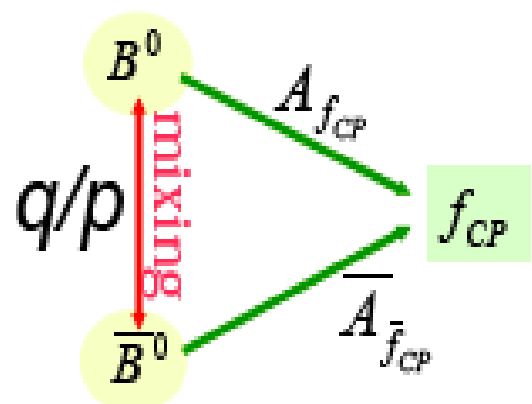
- ✔ CPV in the mixing

  $|p/q| \neq 1 \approx 10^{-3}$ in SM

- ✔ CPV in the direct decay

  $|A/A| \neq 1$

- ✔ CPV in interference between mixing and decay



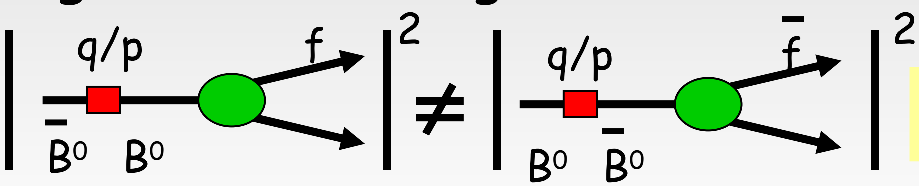
$$\boxed{\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}}$$

amplitude ratio

mixing

CP Violation in mixing

CP violation can occur in the interference between the on-shell and off-shell amplitudes, it is the results from the mass egienstates being different from the CP egienstates



$Prob(\bar{B}^0 \to B^0) \neq Prob(B^0 \to \bar{B}^0) \Leftrightarrow |q/p| \neq 1$

For B^0 mesons Γ_{12} is very small mixing dominated by $\Delta m = 2M_{12}$

- Do not expect much interference: need 2 amplitudes of comparable size
- Little chance of seeing CP violation in $B^0\bar{B}^0$ mixing…
- Calculation of Γ_{12} has large hadronic uncertainties: Asymmetry $\propto Im(\Gamma_{12}/M_{12}) \sim O(10^{-2\div3})$ for B mesons
- But an interesting place to look for NP effects

CPV in B⁰-B̄⁰ Mixing: inclusive dilepton events

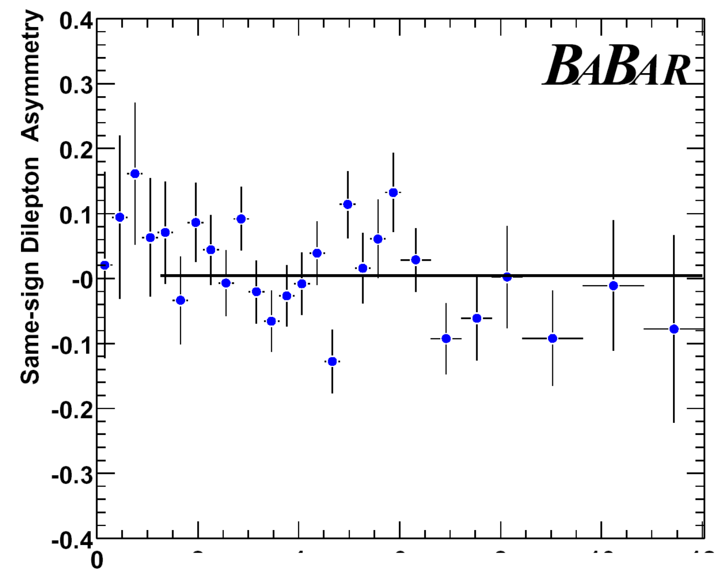
$$B^0\bar{B}^0 \rightarrow \begin{cases} B^0\bar{B}^0 & \ell^+\ell^- X \\ B^0 B^0 & \ell^+\ell^+ X \quad P\left(\bar{B}^0 \rightarrow B^0\right) \\ \bar{B}^0\bar{B}^0 & \ell^-\ell^- X \quad P\left(B^0 \rightarrow \bar{B}^0\right) \\ \bar{B}^0 B^0 & \ell^-\ell^+ X \end{cases}$$

$$A_{T/CP}\left(\Delta t\right) = \frac{N_{++}\left(\Delta t\right) - N_{--}\left(\Delta t\right)}{N_{++}\left(\Delta t\right) + N_{--}\left(\Delta t\right)} = \frac{1-\left|q/p\right|^4}{1+\left|q/p\right|^4}$$

As expected, no asymmetry has been observed...

$$A_{T/CP} = (0.5 \pm 1.2(stat) \pm 1.4(syst))$$

$$\left|\frac{q}{p}\right| = 0.998 \pm 0.006(stat) \pm 0.007(syst)$$



BaBar using 23 millions BB pairs

FIG. 3: Correct... ...unc-tion of Δt. The line shows the result of the fit for the dileptons with $\Delta z > 200\ \mu$m.

CP Violation in the decay

Occurs when $|A/\bar{A}|\neq 1$, where $\bar{A}$ is the amplitude for $\bar{B}$ decays into a state $\bar{f}$ and A is the amplitude of B decays into the CP conjugate state f

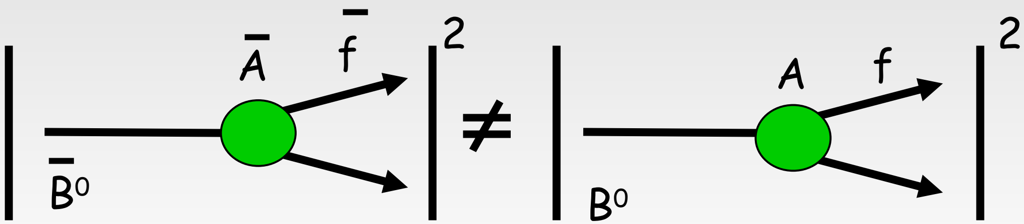
Decay amplitudes can, in general, receive many contributions:

$$A_f = \langle f|H|B\rangle = \sum_k A_k e^{i\delta_k} e^{i\varphi_k} \qquad \bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{B}\rangle = \sum_k A_k e^{i\delta_k} e^{-i\varphi_k}$$

- ϕ_k: "weak phases" complex parameters in Lagrangian (in V_{CKM} in the SM)
- δ_k: "strong phases" on-shell intermediate states rescattering, absorbitive parts

CP Violation in the decay cont'd

- Requires at least two different decays amplitudes with different strong and weak phases



$$\mathrm{Prob}(\bar{B}^0 \to \bar{f}) \neq \mathrm{Prob}(B^0 \to f) \Rightarrow |\bar{A}/A| \neq 1$$

- Typical examples are direct CPV in charged mesons and baryon decays
- Can also occur in neutral B decays in conjunction with CPV in mixing not beneficial because source of hadronic uncertainties in the calculations of A_k and δ_k

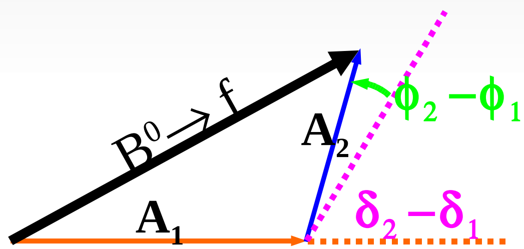
CPV in the decay cont'd

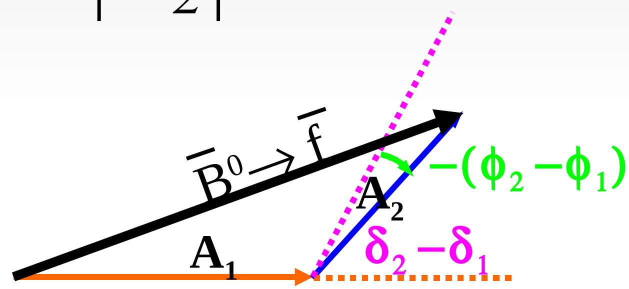
CP conserving phases

$$|A_1|e^{+i\varphi_1}e^{+i\delta_1} \qquad\qquad |A_1|e^{-i\varphi_1}e^{+i\delta_1}$$

$$B^0 \to f \qquad \xrightarrow{CP} \qquad \bar{B}^0 \to \bar{f}$$

$$|A_2|e^{+i\varphi_2}e^{+i\delta_2} \qquad\qquad |A_2|e^{-i\varphi_2}e^{+i\delta_2}$$





$$\left|B^0 \to f\right|^2 - \left|\bar{B}^0 \to \bar{f}\right|^2 = |A_1||A_2|\sin(\varphi_1 - \varphi_2)\sin(\delta_1 - \delta_2)$$

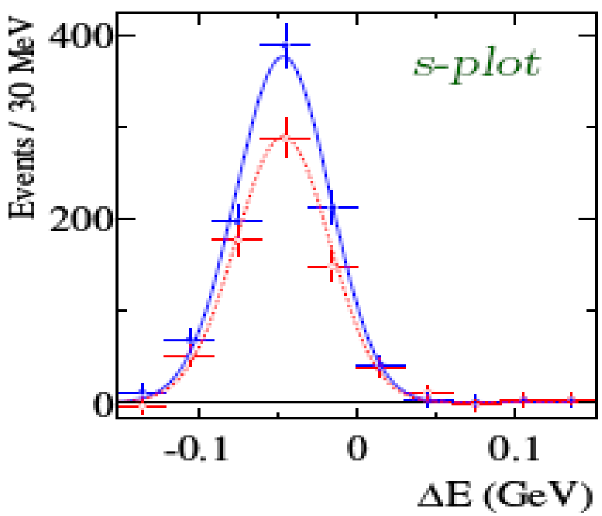
To get unitarity triangle angle(s) (ϕ_1 - ϕ_2) we need to know the non-CKM phase shift (δ_1 - δ_2). Due to long-distance QCD effects in generally not calculable, but it may be possible to measure it

Direct CP Asymmetries in $B^0 \to K^+\pi^-$

Direct CPV in B decays observed for the first time at the B-factories in 2004 using $B^0 \to K^+\pi^-$

Self tagged decay $B^0 \to K^+\pi^-$ and $\bar{B}^0 \to K^-\pi^+$

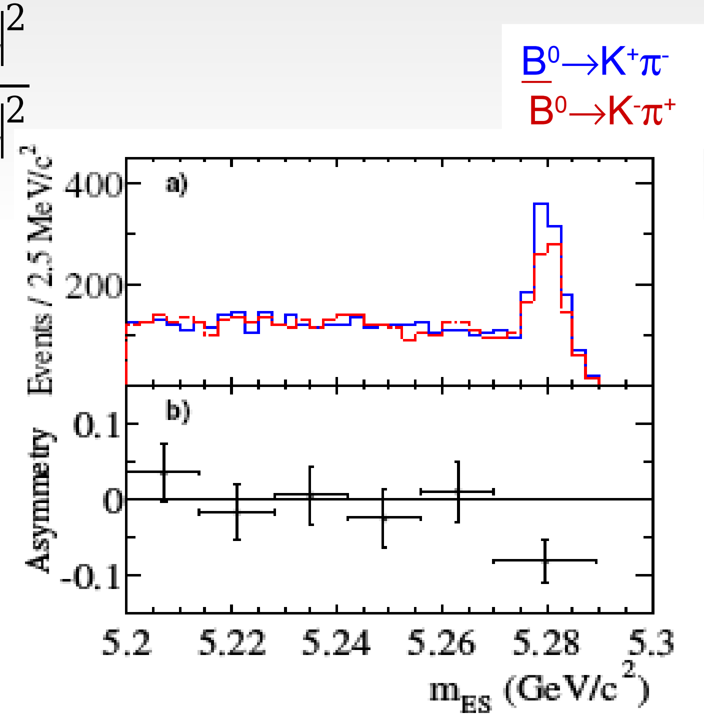
$$A_{CP} = \frac{\Gamma\left(\bar{B}^0 \to K^- \pi^+\right) - \Gamma\left(B^0 \to K^+ \pi^-\right)}{\Gamma\left(\bar{B}^0 \to K^- \pi^+\right) + \Gamma\left(B^0 \to K^+ \pi^-\right)} = \frac{1 - |\bar{A}_{\bar{f}} / A_f|^2}{1 + |\bar{A}_{\bar{f}} / A_f|^2}$$



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

$$m_{ES} = \sqrt{E_{beam}^{*2} - |\vec{p}_B^{\,*}|^2}$$

both zero for signal

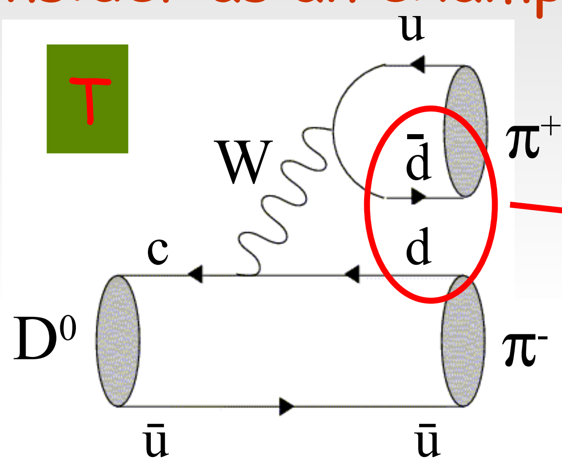


$$A_{K\pi} = -0.133 \pm 0.030(\text{stat}) \pm 0.009(\text{syst})$$

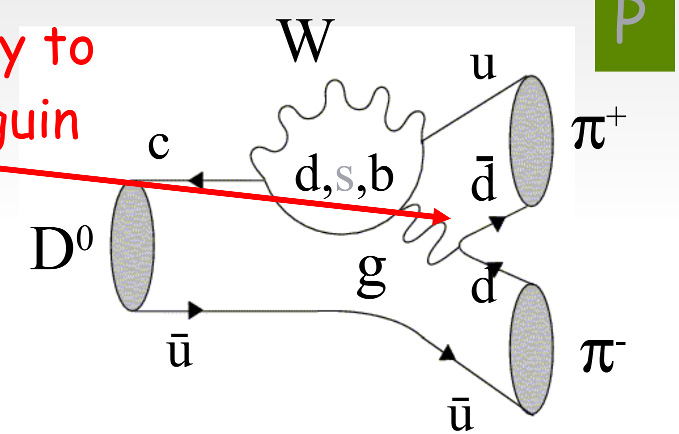
Direct A_{CP} in Charm Decays

Direct (ΔC=1) CPV is a powerful probe to search for non-CKM sources of CP Violation

Consider as an example CS D^0 decays ($D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$,...)



Simple way to get a penguin



Features:

- $V_{cd}^*V_{ud}$ VS $V_{cs}^*V_{us}$ → different weak phases
- ΔI = 1/2,3/2 VS ΔI = 1/2 → different strong phases are likely
- $m_s < m_c$ → long distance effects dominate
- Heavy exotic particles can run in the loop → sensitive to NP

Direct A_{CP} in Charm Decays @CDF

$$A_{CP} = \frac{N_{D^0 \to \pi\pi(KK)}/\varepsilon - N_{\bar{D}^0 \to \pi\pi(KK)}/\bar{\varepsilon}}{N_{D^0 \to \pi\pi(KK)}/\varepsilon + N_{\bar{D}^0 \to \pi\pi(KK)}/\bar{\varepsilon}}$$

- D^0 Flavor identified using π_s charge in $D^* \to D^0 \pi_s$ decays:

  $Q(\pi_s) > 0 \to D^0$

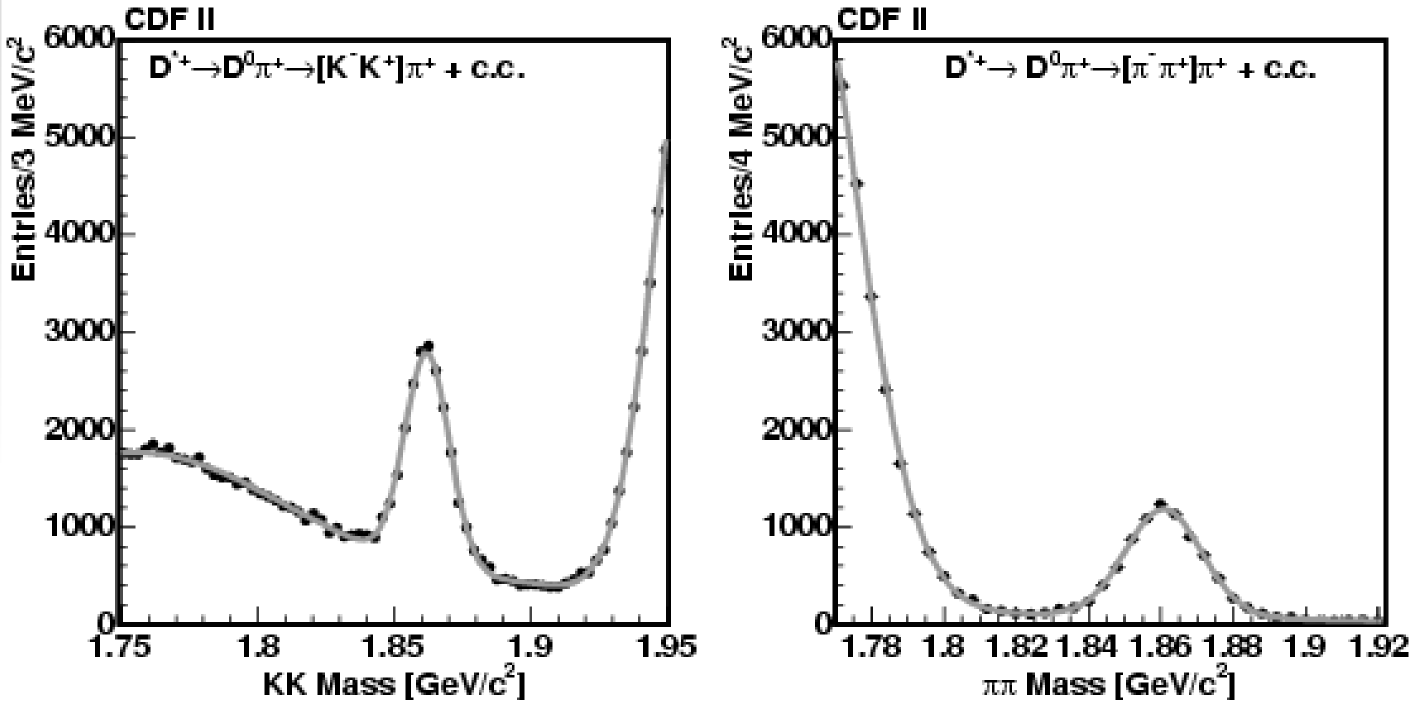
- Main systematic effect:

  detector asymmetry for low-Pt tracks: $\varepsilon \neq \bar{\varepsilon}$

  ✔ Measure detector asymmetry vs Pt and correct the observed A_{CP} (CDF)

  - Only based on data
  - Residual systematic measured on independent decays

Direct A_{CP} in Charm Decays @CDF



16220 ± 200 D^0KK signal events

7334 ± 97 $D^0\pi\pi$ signal events

$A_{CP}(D^0 \to KK) = 2.0 \pm 1.2\ (stat) \pm 0.6\ (syst)\ \%$

$A_{CP}(D^0 \to \pi\pi) = 1.0 \pm 1.3\ (stat) \pm 0.6\ (syst)\ \%$

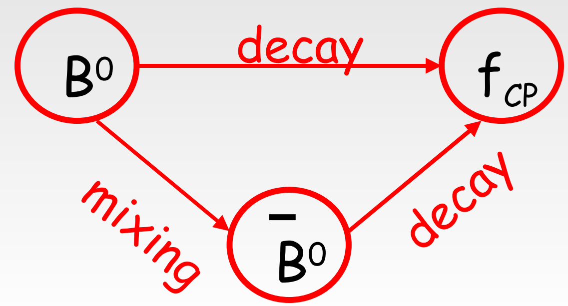
CPV in interference between decay-mixing

If both B^0 and $\overline{B}^0$ can decay to same final state |f> which is a CP eigenstate, there's another interesting possibility

Introducing:

$\eta_f = \pm 1$: eigenvalue of f_{CP}

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}}\frac{q}{p}\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$



We have:

$$A_{f_{CP}} = \frac{\Gamma\left(\bar{B}^0(t)\to f_{CP}\right) - \Gamma\left(B^0(t)\to f_{CP}\right)}{\Gamma\left(\bar{B}^0(t)\to f_{CP}\right) + \Gamma\left(B^0(t)\to f_{CP}\right)} = -C_{f_{CP}}\cos(\Delta m\cdot t) + S_{f_{CP}}\sin(\Delta m\cdot t)$$

$$C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2} \qquad S_{f_{CP}} = \frac{2\,\mathrm{Im}\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}$$

CP is violated either if $|\lambda| \neq 1$ due to CPV in mixing and/or decay, or if $|\lambda| = 1$, but $\mathrm{Im}\lambda \neq 0$ due to CPV in interference

In the case $|\lambda| = 1$ CP asymmetry measures phase differences in a theoretically clean way, if $|\bar{A}/A| = 1 \rightarrow$ $A_{f_{CP}} = \mathrm{Im}\,\lambda_{f_{CP}}\sin(\Delta m\cdot t)$

CPV & mixing in charm at Babar

D^0-$\bar{D}^0$ mixing & CPV in Lifetime Ratio of $D^0 \to K^+K^-, \pi^+\pi^-$ vs $D^0 \to K^-\pi^+$

D^0 mixing and CPV alter decay time distribution of CP eigenstates. Effective lifetimes τ_{hh}

Define: $\tau_{hh}^{+} = \tau(D^0 \to h^+ h^-)$ $\qquad$ $\tau_{hh}^{-} = \tau(\bar{D}^0 \to h^+ h^-)$

We measure: $y_{CP} = 2\dfrac{\tau_{K\pi}}{\tau_{hh}^{+} + \tau_{hh}^{-}} - 1$ $\qquad$ $\Delta Y = 2\dfrac{\tau_{K\pi}}{(\tau_{hh}^{+} + \tau_{hh}^{-})^2}(\tau_{hh}^{+} - \tau_{hh}^{-})$

$$y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$$

If CP conserved in mixing and decay, and violated in interference between them, y_{CP} and ΔY are related to mixing parameters

$y_{CP} = y$ if CP is conserved
$\Delta Y = 0$ if no mixing and no CPV

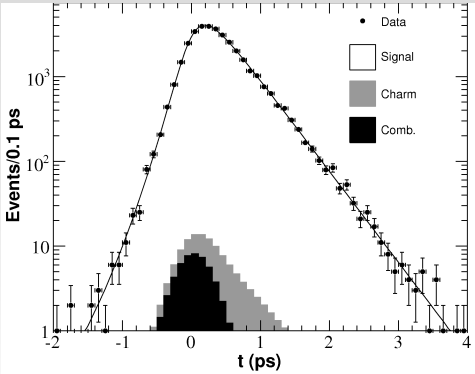
Direct CPV & mixing in charm at Babar (2)

D^0 Flavor identified using

π_S charge in $D^* \rightarrow D^0\pi_s$ decays:

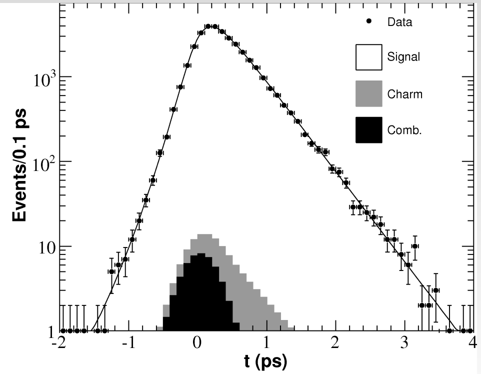
$Q(\pi_S) > 0 \rightarrow D^0$

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



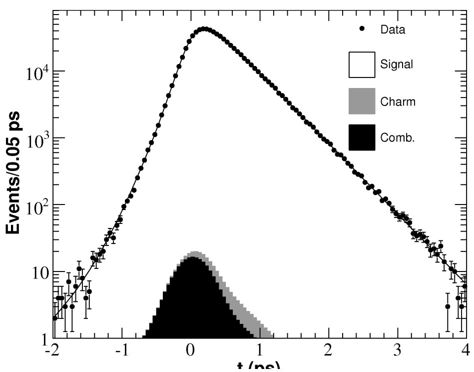
τ=401.3±2.5 fs

$\bar{D}^0 \to K^+ K^-$



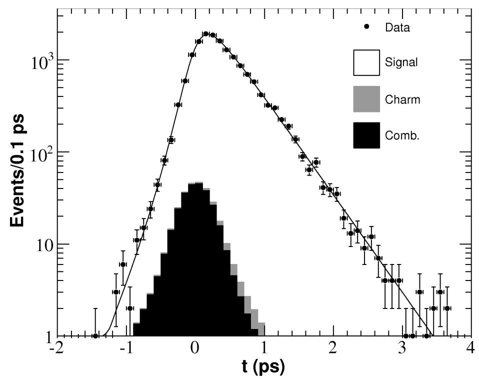
τ=404.5±2.5 fs

$D^0 \to K^- \pi^+$



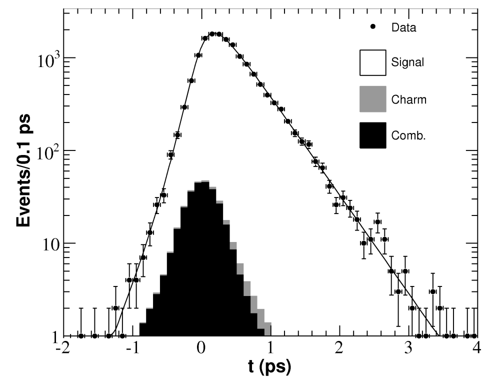
τ=409.3±0.7 fs

$D^0 \to \pi^+ \pi^-$



τ=407.6±3.7 fs

$\bar{D}^0 \to \pi^+ \pi^-$



τ=407.3±3.8 fs

Direct CPV & mixing in charm at Babar(3)

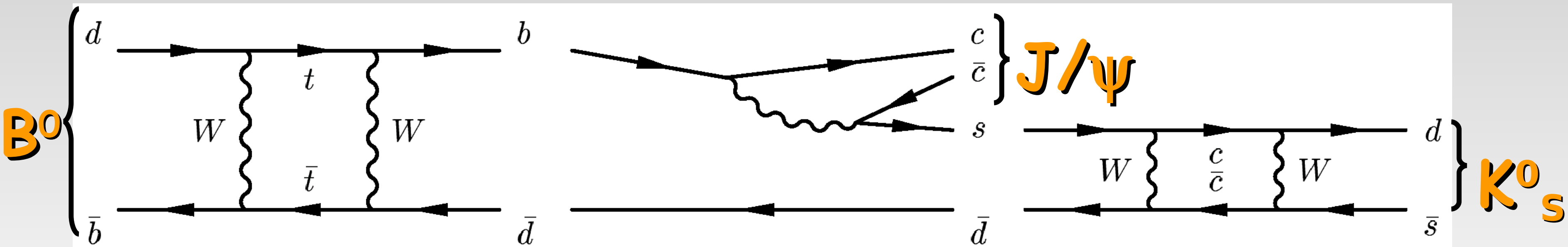
Tagged result with 384 fb^{-1} data sample

	y_{CP}	ΔY
K^+K^-	$(1.60 \pm 0.46(\mathrm{stat}) \pm 0.17(\mathrm{syst}))\%$	$(-0.40 \pm 0.44(\mathrm{stat}) \pm 0.12(\mathrm{syst}))\%$
$\pi^+\pi^-$	$(0.46 \pm 0.65(\mathrm{stat}) \pm 0.25(\mathrm{syst}))\%$	$(0.05 \pm 0.64(\mathrm{stat}) \pm 0.32(\mathrm{syst}))\%$
Combined	$\boxed{(1.24 \pm 0.39(\mathrm{stat}) \pm 0.13(\mathrm{syst}))\%}$	$(-0.26 \pm 0.36(\mathrm{stat}) \pm 0.08(\mathrm{syst}))\%$

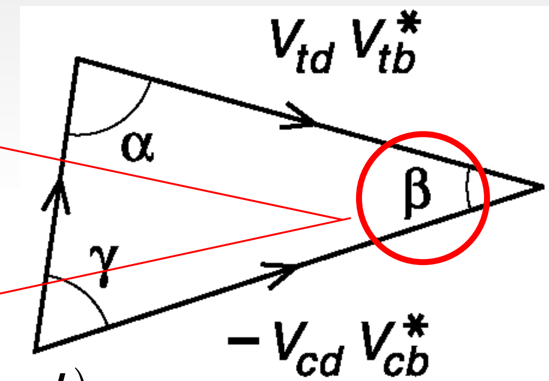
Evidence for mixing at 3σ level

No evidence of CP violation

Golden Mode $B^0 \to J/\psi K_s$



$$\lambda = -\eta_{CP}\left(\frac{V_{tb}^{*} V_{td}}{V_{tb} V_{td}^{*}}\right)\left(\frac{\cancel{V_{cs}^{*}} V_{cb}}{\cancel{V_{cs}} V_{cb}^{*}}\right)\left(\frac{V_{cd}^{*} \cancel{V_{cs}}}{V_{cd} \cancel{V_{cs}^{*}}}\right) = -e^{-2i\beta}$$

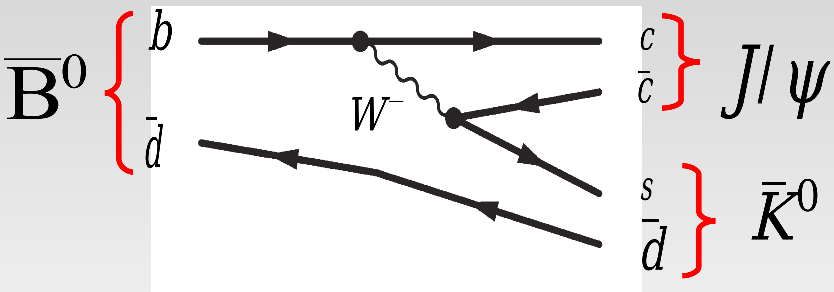


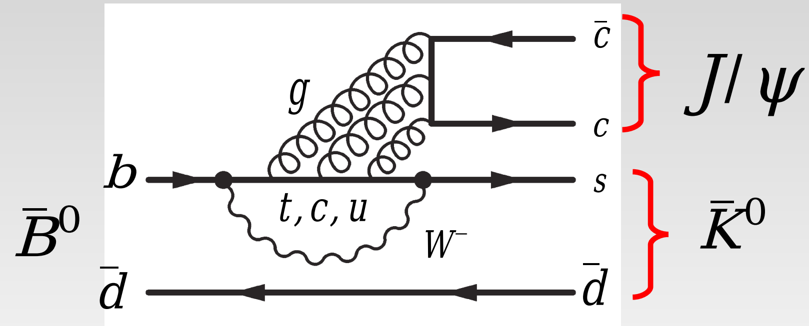
$\mathrm{Im}\lambda = \sin 2\beta$

$$A_{CP}(t) = C \cdot \cos(\Delta m t) - \eta_{CP} \sin(2\beta)\sin(\Delta m t)$$

- Theoretically clean way to measure β
- Clean experimental signature
- Branching fraction: $O(10^{-4})$ "Large" compared to other CP modes

Penguins and sin2β measurements





Tree: b→ccs: $A_T \sim V_{cb}V_{cs}^* \sim \lambda^2$

Penguin: $A_P \sim V_{tb}V_{ts}^* f(m_t) + V_{cb}V_{cs}^* f(m_c) + V_{ub}V_{us}^* f(m_u) \sim \lambda^2 + \lambda^2 + \lambda^4$

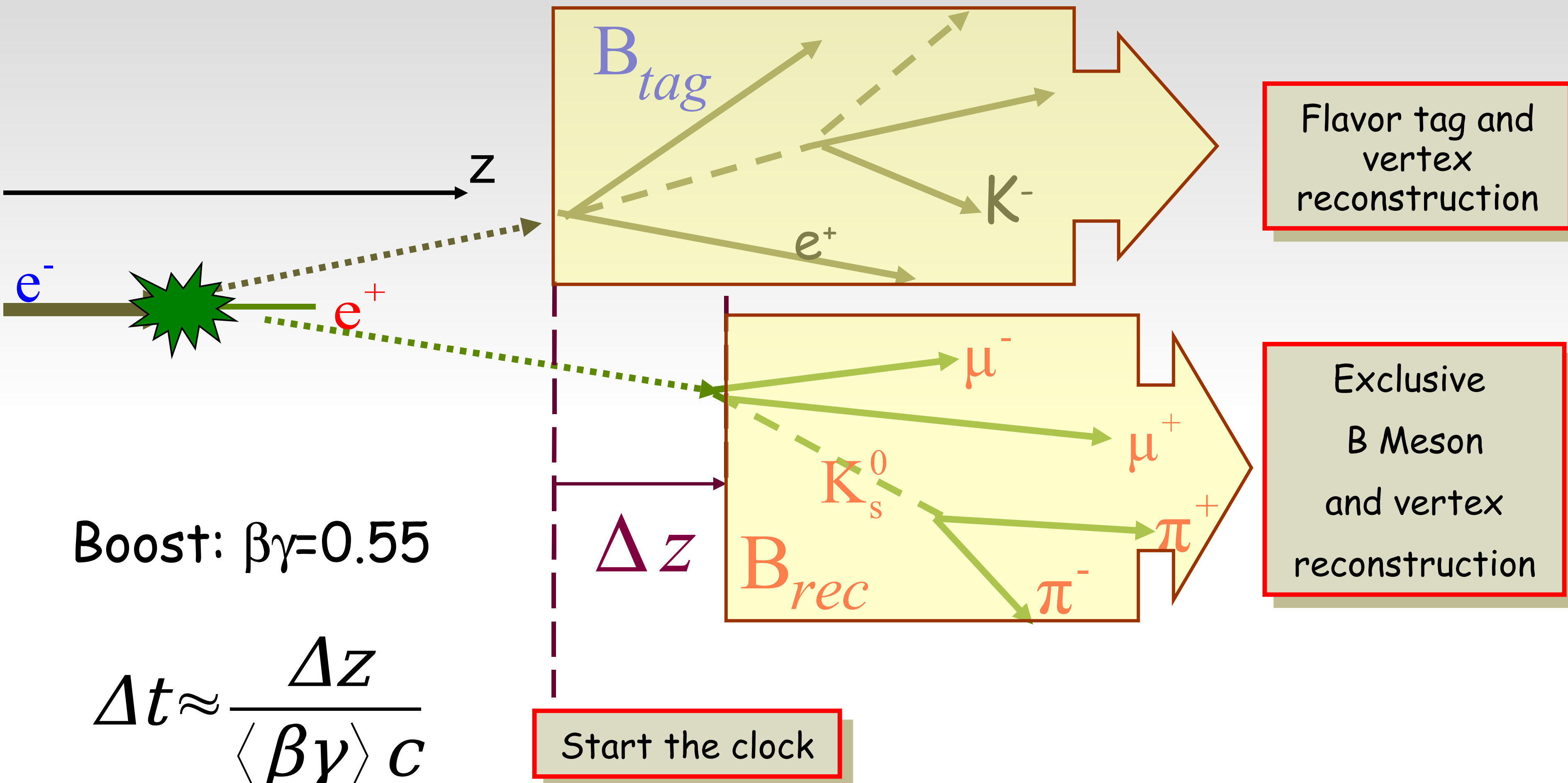
Rewriting P using unitarity: $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$

$$A(B\to J/\psi K) = \underbrace{V_{cb}V_{cs}^*\left(T+P^c-P^t\right)}_{\sim\lambda^2\text{: same for tree and penguins}} + \underbrace{V_{ub}V_{us}^*\left(P^u-P^t\right)}_{\text{suppressed by }\lambda^2}$$

Leading penguin contribution has *same* weak phase as tree

Extraction of sin(2β) from $J/\psi K_S$ is "theoretically clean"

Steps to measure sin2β

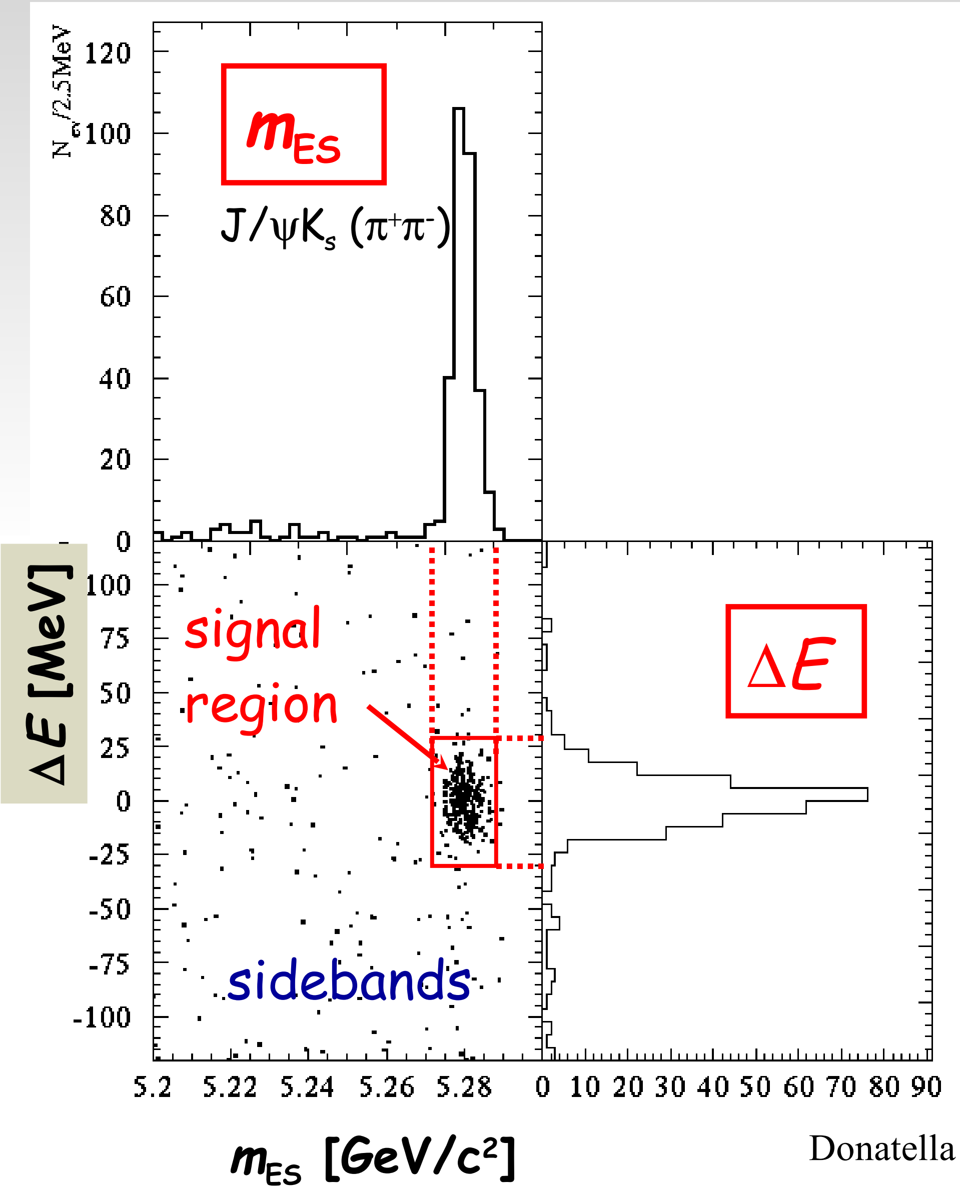


Boost: βγ=0.55

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

$$e^+ e^- \rightarrow Y(4S) \rightarrow B\bar{B}$$

Signal Reconstruction



Two main kinematic variables for exclusively reconstructed B candidates:

i) $\Delta E = E_B^{cms} - \sqrt{s}/2$

- There are exactly 2 B mesons produced, nothing else
- *A* signal B candidate must carry half the CMS energy

ii) $M_{ES} = \sqrt{s/4 - p_B^2}$

- Invariant mass, substituting the *measured* B energy with the better-known $\sqrt{s}/2$.

$\sigma(\Delta E) \sim$ 10-40 MeV

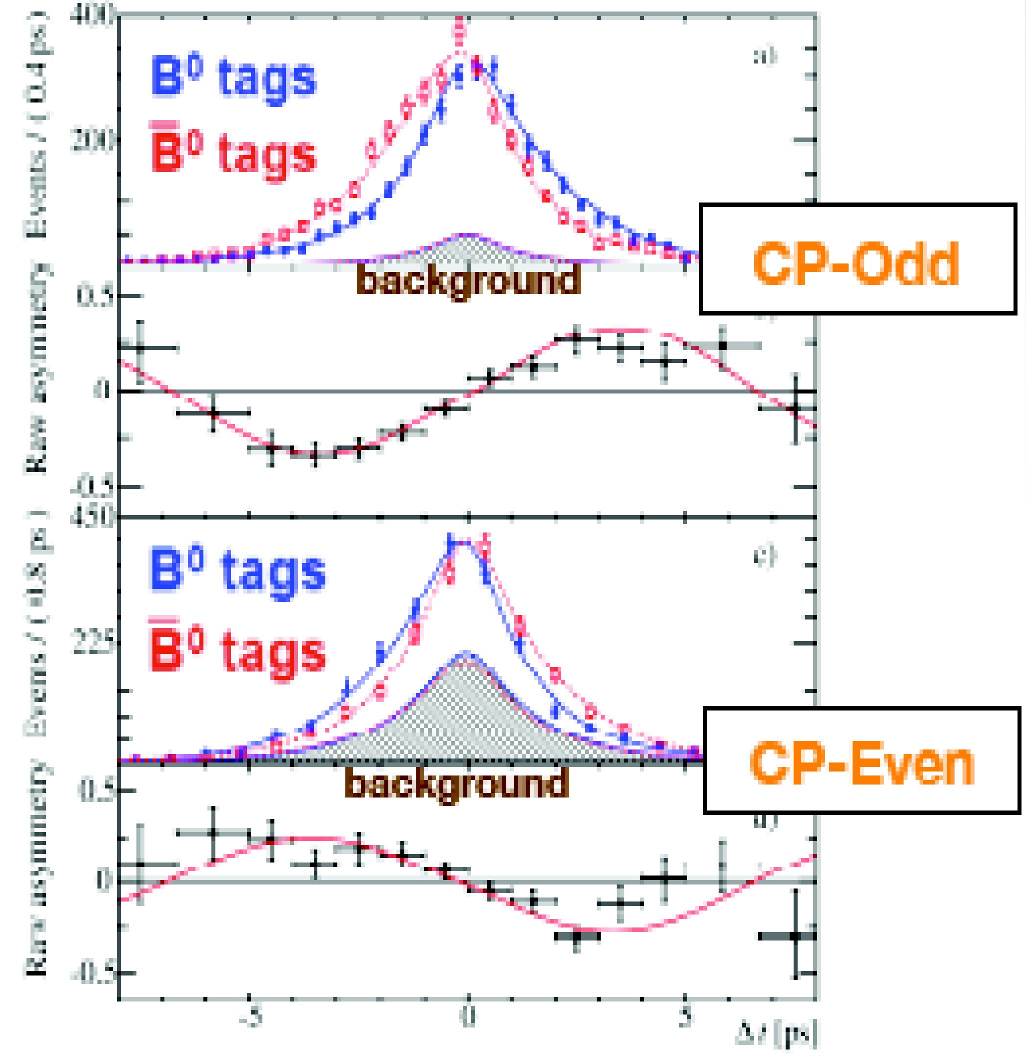
$\sigma(M_{ES}) \sim$ 2.6 MeV

BaBar measured asymmetries

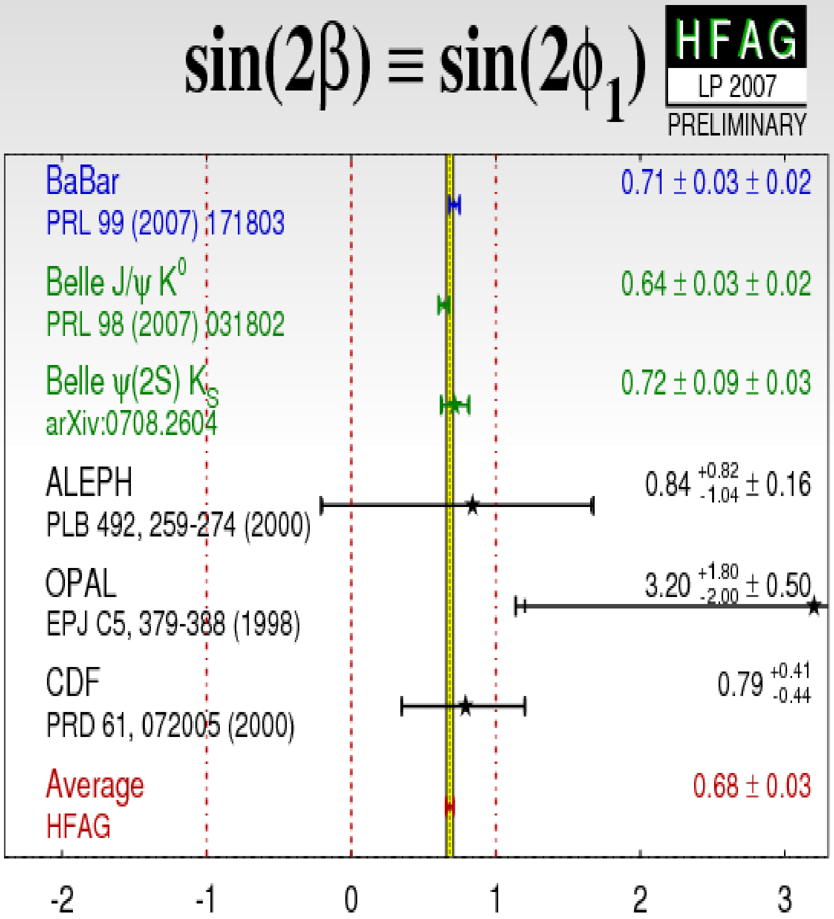
$$B^0 \rightarrow J/\psi K^0_S, J/\psi K^{*0}, \psi(2S)K^0_S, J/\psi K^0_L, \eta_c K^0_S, \chi_{c1} K^0_S$$

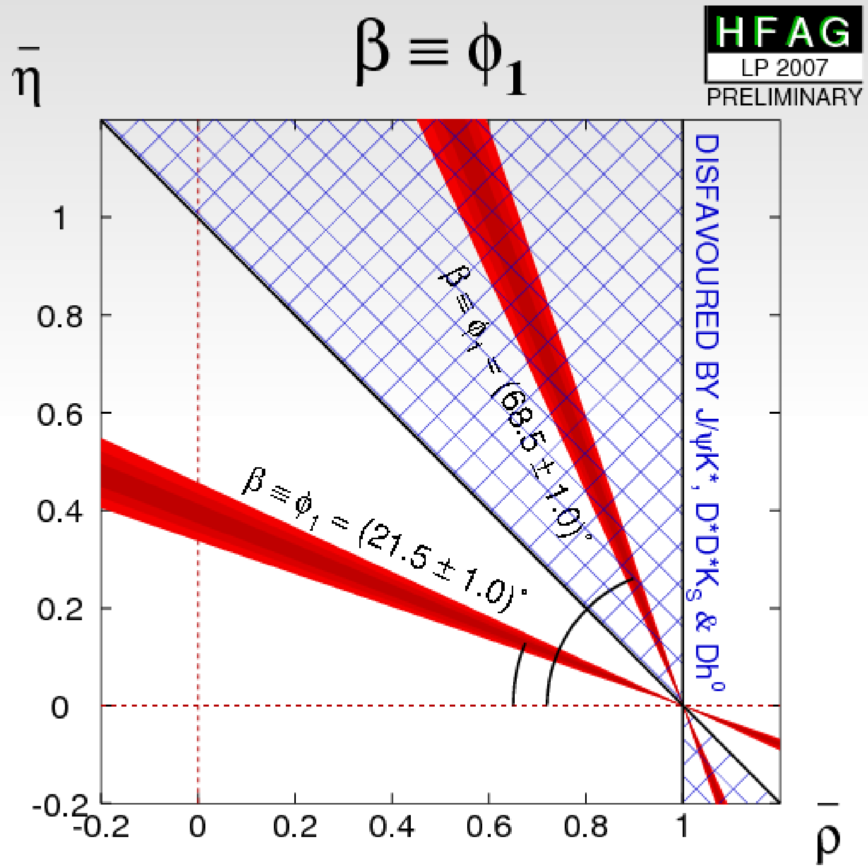
$$\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$$

$$C = 0.049 \pm 0.022 \pm 0.017$$



Overall Status of sin2β

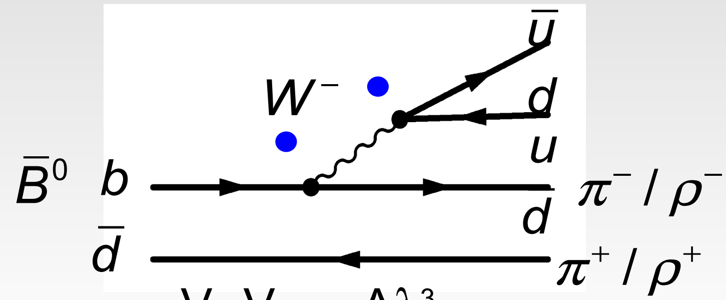




$B^0 \rightarrow \pi^+\pi^-/\rho^+\rho^-$: measurement of angle α

Access to α can be obtained from the interference of a $b\rightarrow u$ decay (γ) with and without $B^0\overline{B^0}$ mixing (β).

Assuming pure tree diagram:



$\propto V_{ub}V_{ud} \propto A\lambda^3$

$$P(\overset{(-)}{B}{}^0(t)) = e^{-t/\tau_B}\,|A|^2\,\frac{1+|\lambda|^2}{2}\left[1 \overset{(-)}{+} C\cos(\Delta m_d t) \overset{(+)}{-} S\sin(\Delta m_d t)\right]$$

$$S = \frac{2\;\,m(\lambda)}{1+|\lambda|^2}$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

$\Rightarrow$

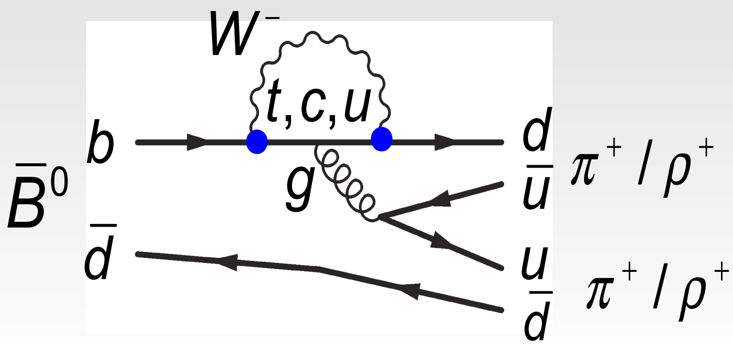
$C=0$

$S=\sin(2\alpha)$

$$\lambda = \frac{q}{p}\,\frac{\bar{A}}{A} = e^{-2i\beta}\,e^{-2i\gamma} = e^{2i\alpha}$$

$B^0 \to \pi^+\pi^- / \rho^+\rho^-$: measurement of angle α

But penguins may be of the same order of magnitude as trees:



$\propto V_{tb}V_{td} \propto A\lambda^3$

$$\lambda = e^{i2\alpha}\,\frac{T + P e^{+i\gamma} e^{i\delta}}{T + P e^{-i\gamma} e^{i\delta}}$$

δ relative strong phase between *T* and *P*

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} \quad 0$$

$$S = \sqrt{1-C^2}\,\sin(2\alpha_{eff})$$

To extract α from α_{eff} : use SU(2)-isospin

Isospin analysis to constraint α-α_{eff}

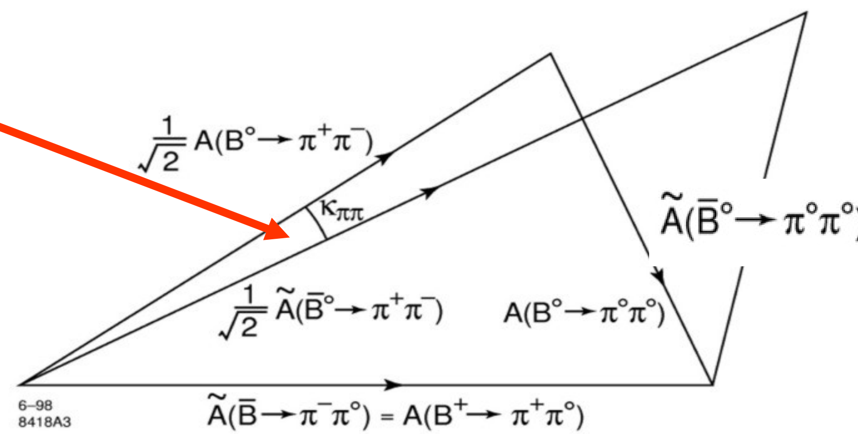
The decays $B \rightarrow \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$ are related by isospin symmetry

- The isospin decomposition can be represented with two triangles (one for B^0, one for $\overline{B}^0$)
- Neglecting EW penguins (violate isospin), $B^+ \rightarrow \pi^+\pi^0$ is pure tree diagram

$$A(B^+ \rightarrow \pi^+ \pi^0) = \tilde{A}(B^- \rightarrow \pi^- \pi^0)$$

- Need to measure separate BF for B^0/B^0 and B^+/B^-
- Triangle relations allow determination penguin-induced shift in α

$$k_{\pi\pi} = 2(\alpha_{eff} - \alpha)$$

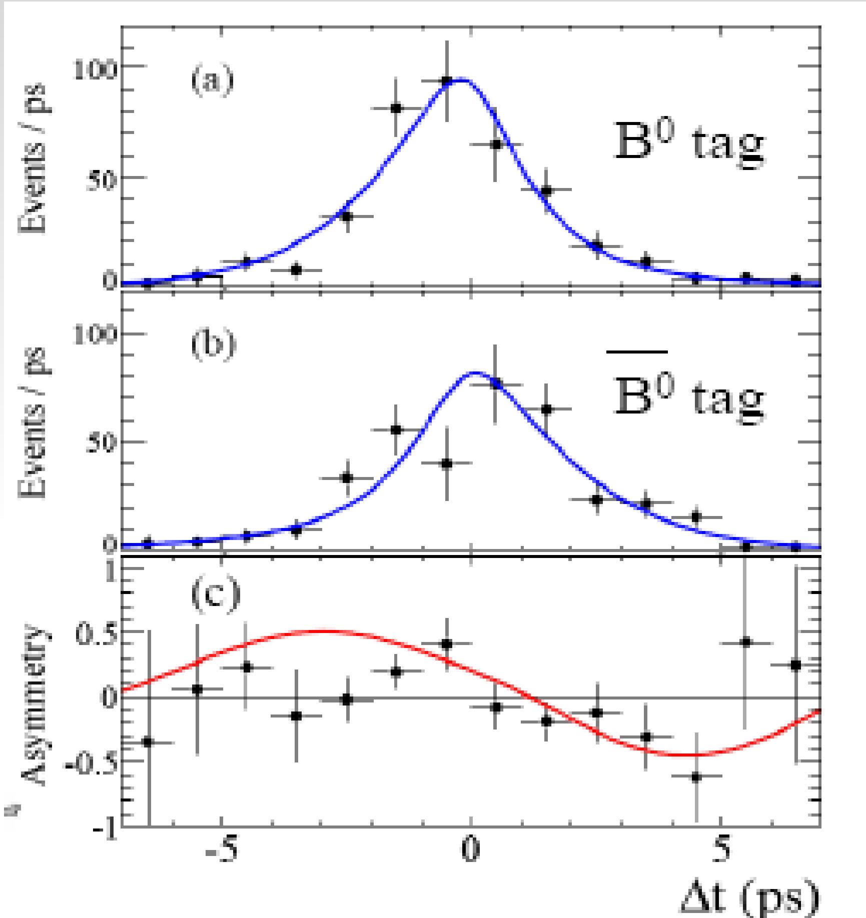


Problem: $\pi^0\pi^0$ is too small for a isospin analysis and too large to set a useful $|\alpha - \alpha_{eff}|$ limit…

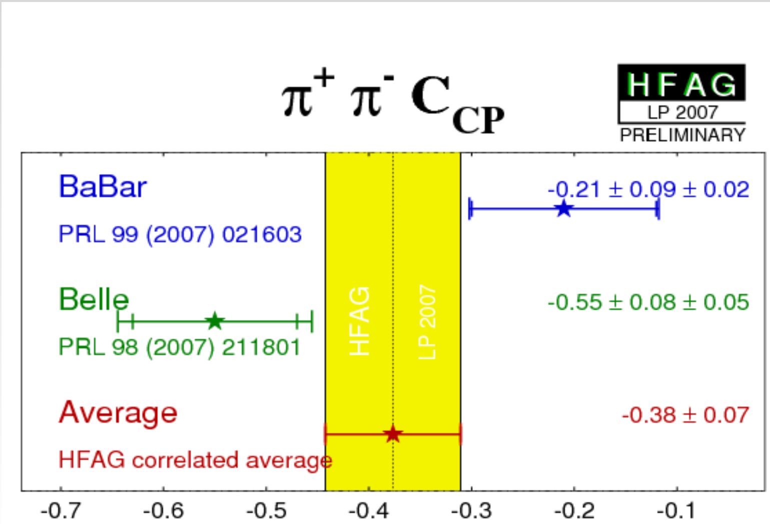
Solution: use $\rho\rho$:

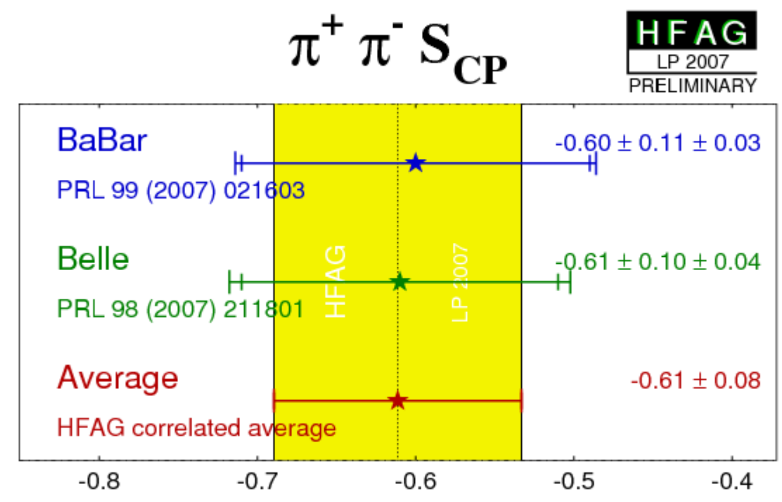
- larger BF, low penguin contamination
- VV final state, but dominated by longitudinal polarization (~pure CP-even)

CP Asymmetries in B->π+π-



$$S_{+-} = -0.60 \pm 0.11 \pm 0.03 \quad (5.1\sigma)$$
$$C_{+-} = -0.21 \pm 0.09 \pm 0.02 \quad (2.2\sigma)$$

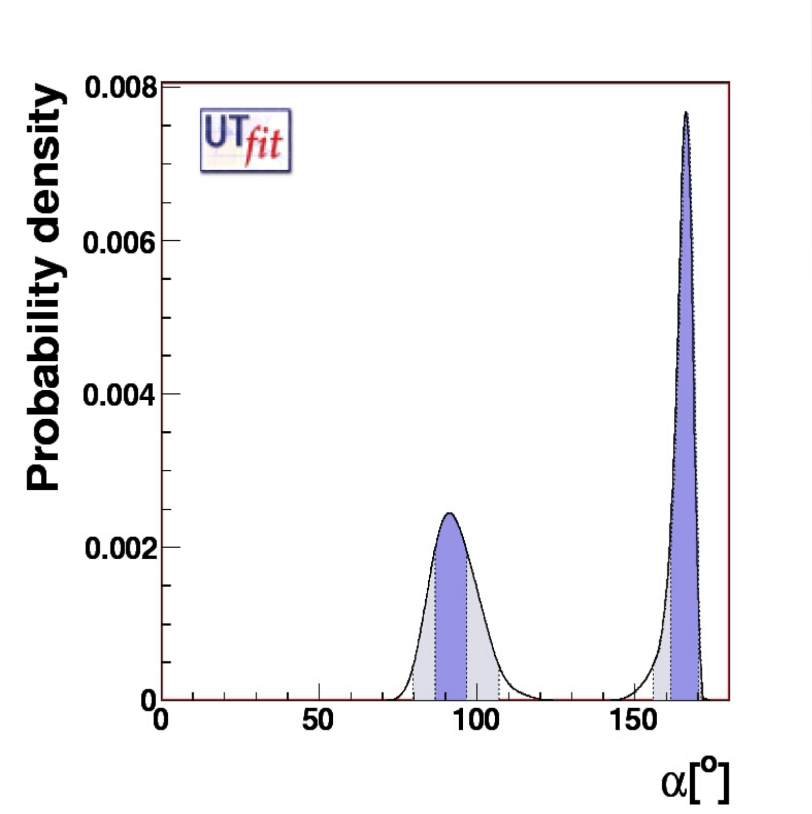




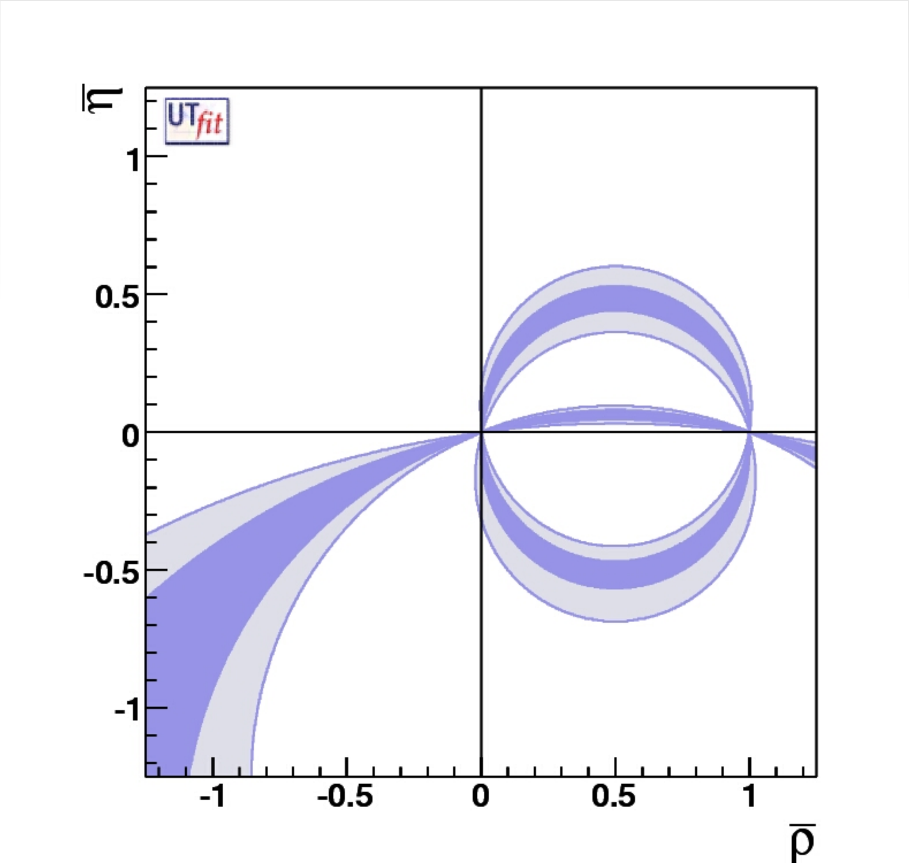
CP Asymmetries in B->π+π-

Combination of:

$B \to \pi^+\pi^-$ $B \to \rho^+\rho^-$ $B \to \rho\pi$



These masurements in the ρ-η plane:

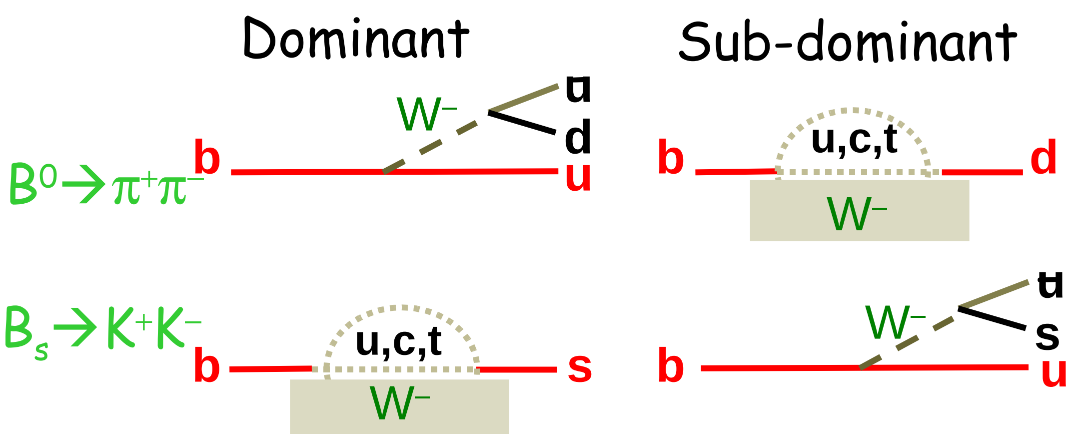


Using penguins to measure γ

- Promising way to measure γ at Tevatron

  (R.Fleischer hep-ph/9903456):

  - Time dependent asymmetry in $B^0 \rightarrow \pi^+\pi^-$ measures $\sin 2(\beta+\gamma)$ up to ~30% penguin pollution
  - Measure P/T ratio by simultaneous fit to the time dependent asymmetries in $B_s \rightarrow K^+K^-$



Diagrams can be obtained
and related via exchange
$d \leftrightarrow s$ (SU(3) U-spin)

Using penguins to measure γ cont'd

$$A_{CP}(t) = A_{CP}^{dir} \times \cos \Delta Mt + A_{CP}^{mix} \times \sin \Delta Mt$$

$$A_{CP}^{dir}(\pi\pi) = -2d \sin\theta \sin\gamma + O(d^2)$$

$$A_{CP}^{dir}(KK) = \frac{2\lambda^2}{d(1-\lambda^2)} \sin\theta \sin\gamma + O((\lambda^2/d)^2)$$

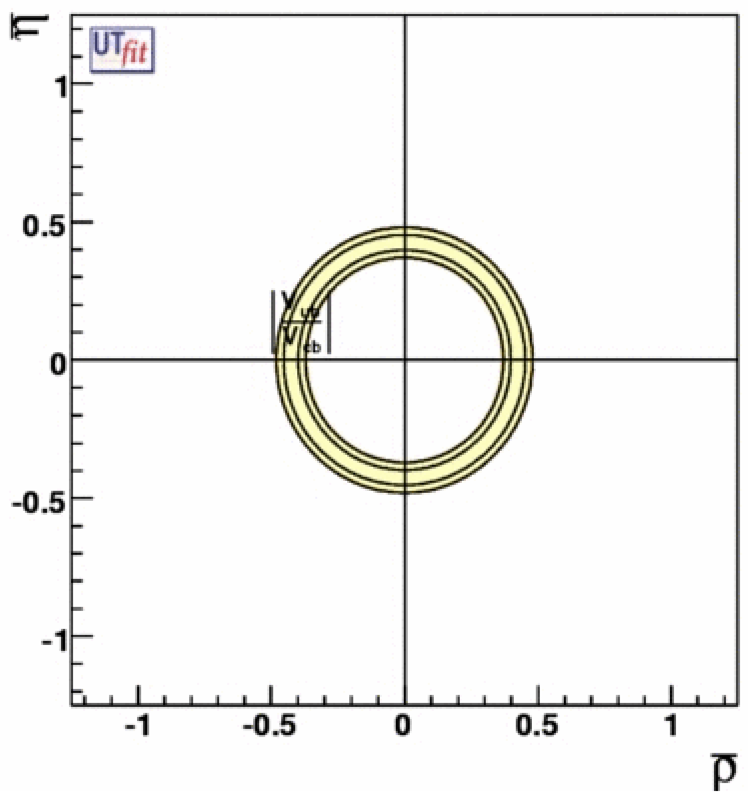
$$A_{CP}^{mix}(KK) = \frac{2\lambda^2}{d(1-\lambda^2)} \cos\theta \sin\gamma + O((\lambda^2/d)^2)$$

$$A_{CP}^{mix}(\pi\pi) = \sin 2(\beta+\gamma) + 2d \cos\theta \times [\cos\gamma \sin 2(\beta+\gamma) - \sin(2\beta+\gamma)] + O(d^2)$$

Procedure:

- Measure time dependent ACP(dir, mix) in $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$: 4 parameters
- Take sin(2β) from $J/\psi K_s$
- Only 3 parameters to fit: d=P/T ~ 0.3, θ=strong phase of P/T ratio, γ

Putting all together: Overall Status



$\rho = 0.147 \pm 0.029$

$\eta = 0.342 \pm 0.016$

http://www.utfit.org/