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 ($m_b >> \Lambda_{QCD}$)

Charm: $m_c << m_b$: 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

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 ($m_b >> \Lambda_{QCD}$)

In both cases New Physics (NP) can negate SM predictions on many observables that are experimentally measurable

Charm: $m_c << m_b$: 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

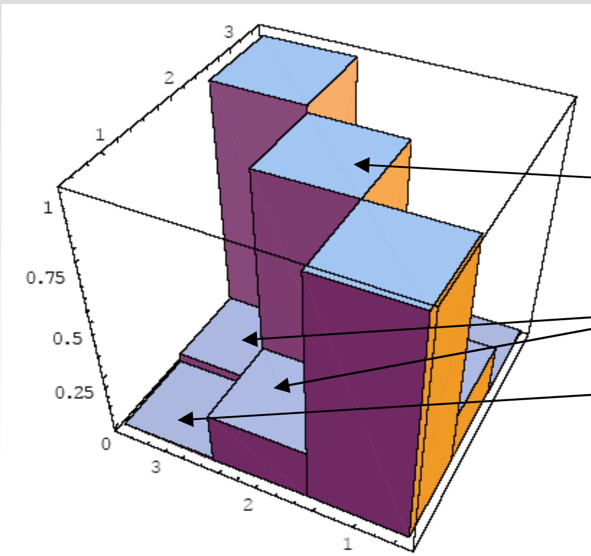
CKM Matrix

- 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	~ λ
Vcb, Vts	~ λ^2
Vub, Vtd	~ λ^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:

λ~0.5%, A~4%, ρ~14%, η~4%

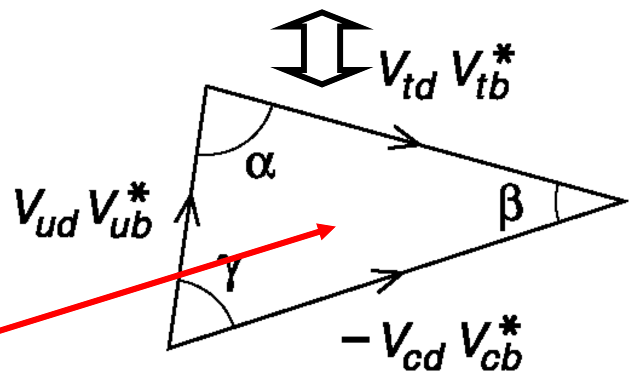
Unitarity Triangles (UT)

- 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:

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

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



CPV in SM ∝ Triangle Area

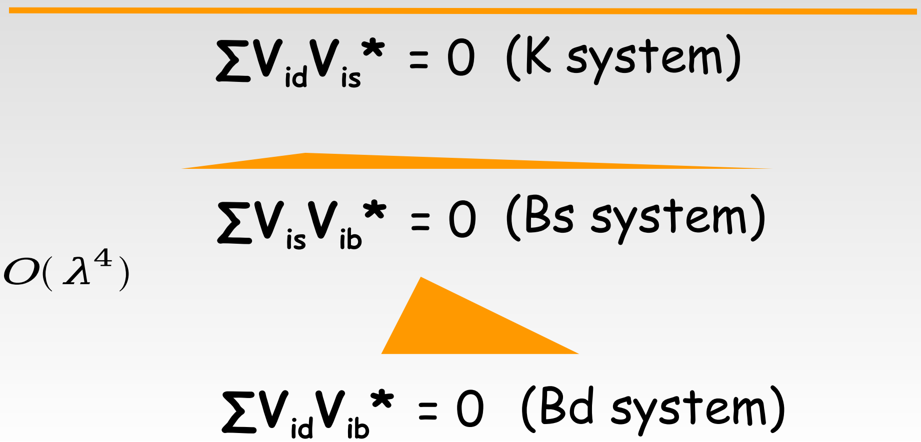
Angles and sides are directly measurable

More on UT

There are 6 UT triangles

Columns and rows relations

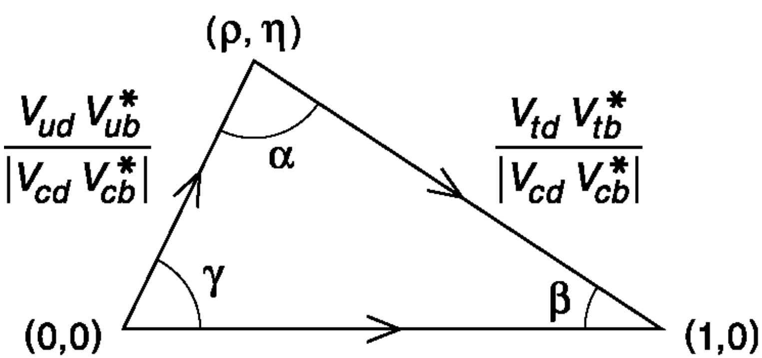
give similar results



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

- 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



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

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

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

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

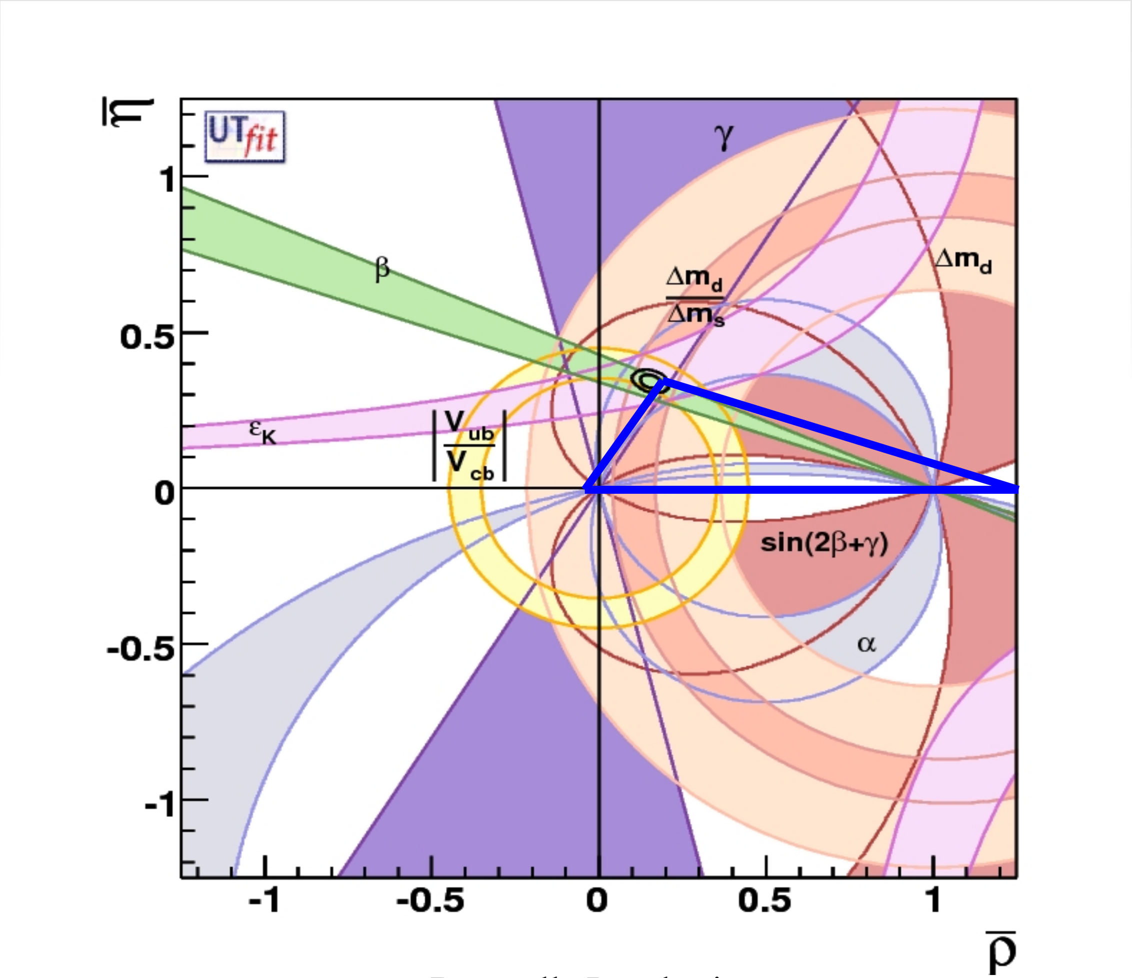
$$\bar\rho = \rho\left(1-\lambda^2/2\right)$$

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

Constraints in the (ρ,η) plane

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

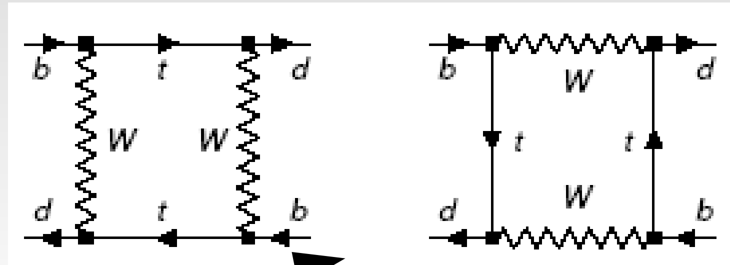
precision test of the Standard Model



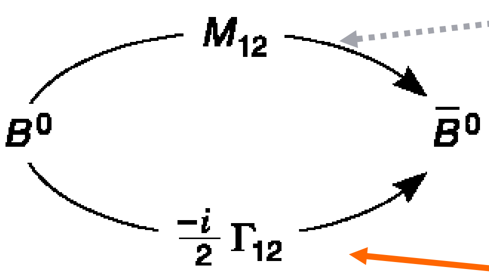
CP Violation in B Decays

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

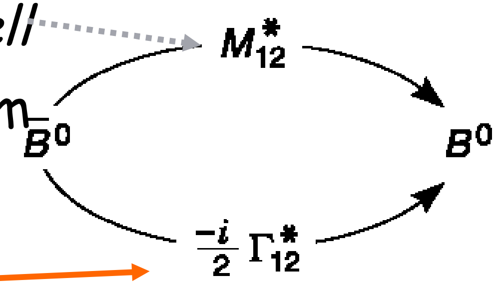
$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle\\ |\bar{B}(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B(t)\rangle\\ |\bar{B}(t)\rangle\end{pmatrix}$$



M,Γ are 2x2 time independent, Hermitian matrices; CPT invariance implies $M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$, 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:

$$\left|B_H\right\rangle = p\left|B^{\cdot}\right\rangle + q\left|\bar{B}^{\cdot}\right\rangle$$

$$\left|B_L\right\rangle = p\left|B^{\cdot}\right\rangle - q\left|\bar{B}^{\cdot}\right\rangle$$

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

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:

$$\Delta m = M_H - M_L = ٢\,|M_{١٢}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = ٢\,|\Gamma_{١٢}|\cos\varphi \qquad \varphi = \arg\left(-\frac{M_{١٢}}{\Gamma_{١٢}}\right)$$

$$\frac{q}{p} = -\frac{٢M^*_{١٢} - i\Gamma^*_{١٢}}{\Delta m + i\,\Delta\Gamma/٢} = -e^{-i\varphi_M}\left[١ - \frac{١}{٢}\mathrm{Im}\left(\frac{\Gamma_{١٢}}{M_{١٢}}\right)\right]$$

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

Neutral meson Mixing in the SM

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

non perturbative QCD ($f_{B_q^0}^2 B_{B_q^0}$)

perturbative QCD ($\eta_{B_q^0}$)

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

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

SU(3) Flavor breaking
theoretical uncertainties <5%

B_s Mixing at CDF

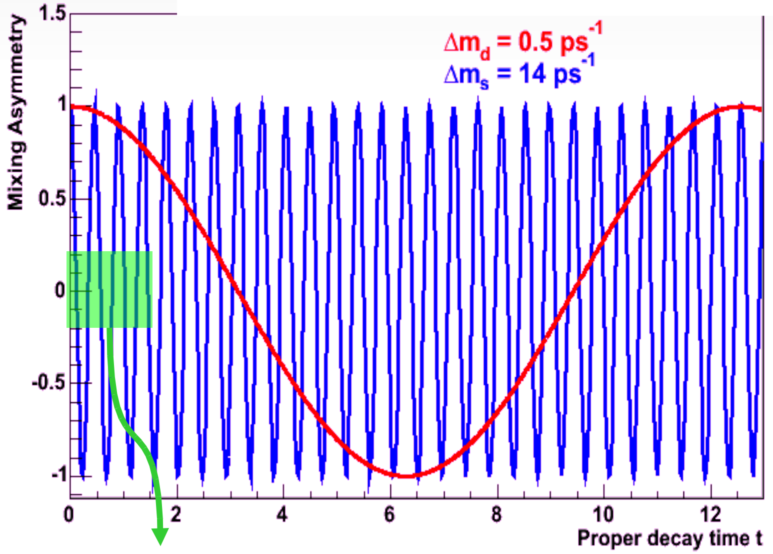
Measurement Principle in a Perfect World

$$P(t)_{B_q^0 \to \overset{(-)}{B}{}_q^0} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm \cos(\Delta m_q t))$$

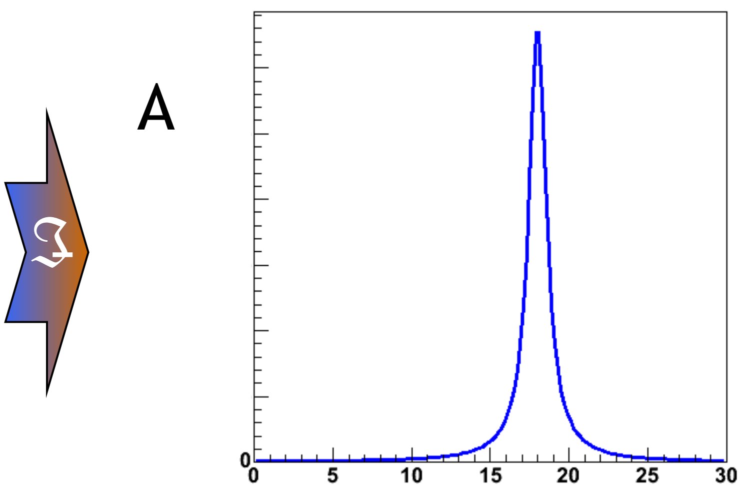
$$A = \frac{N^{nomix} - N^{mix}}{N^{nomix} + N^{mix}} = \cos(\Delta m_s t)$$

Rather than fit for frequency perform a 'Fourier transform'

B_s vs. B_d oscillation

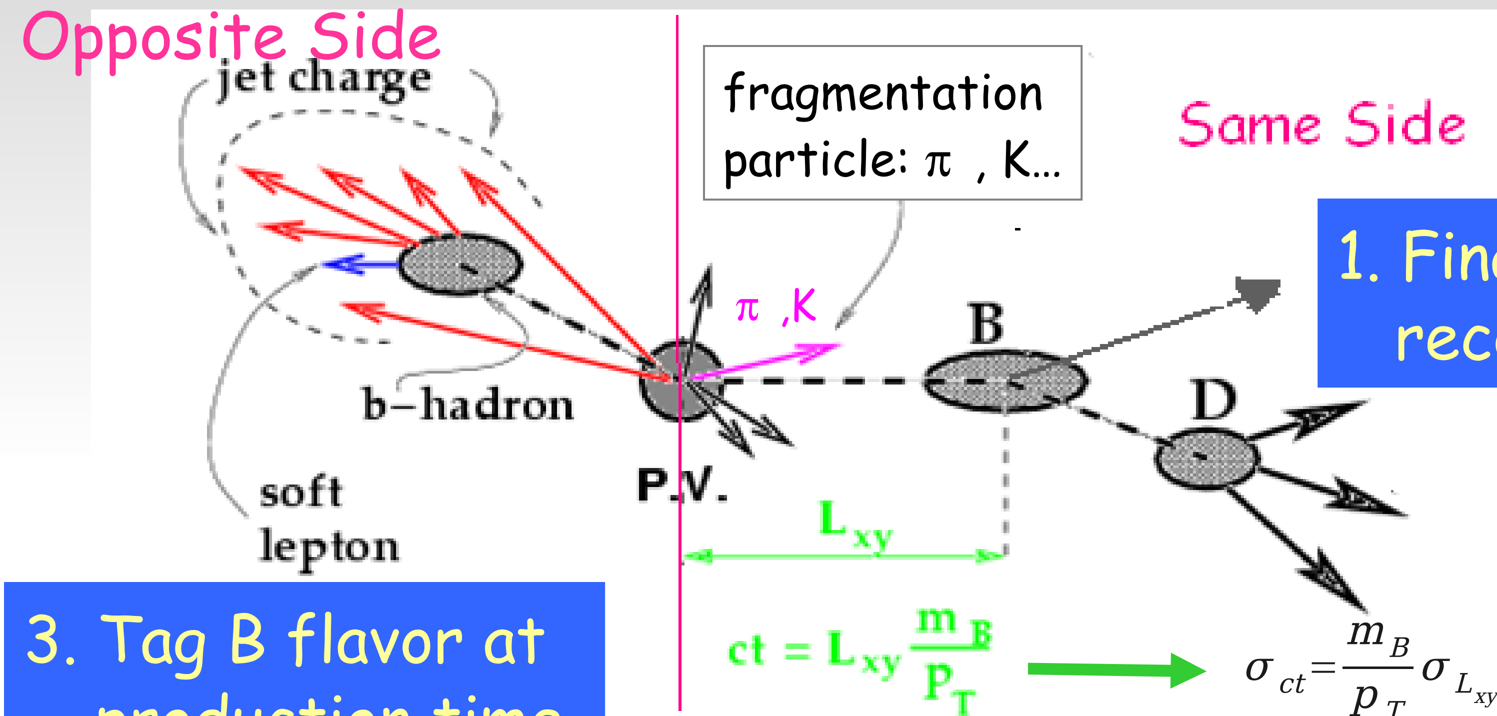


B lifetime



$\Delta\ m_s$ [ps^{-1}]

Road Map to Δm_s Measurement



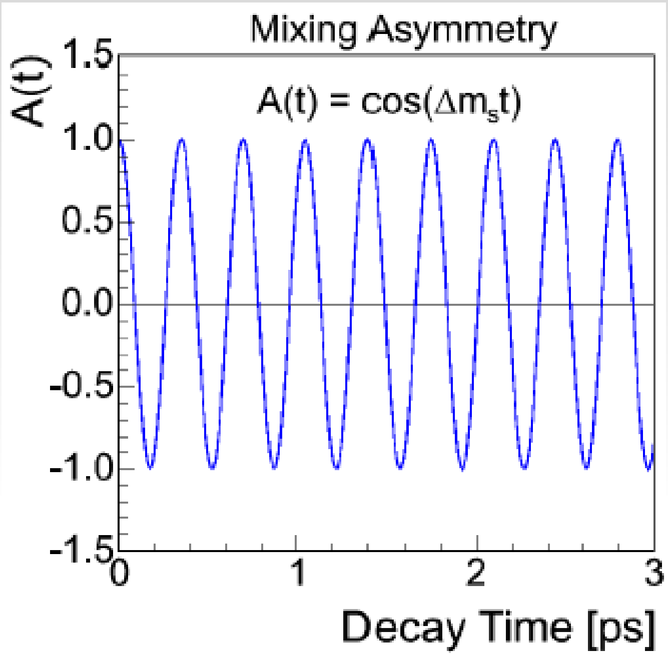
1. Final state reconstruction

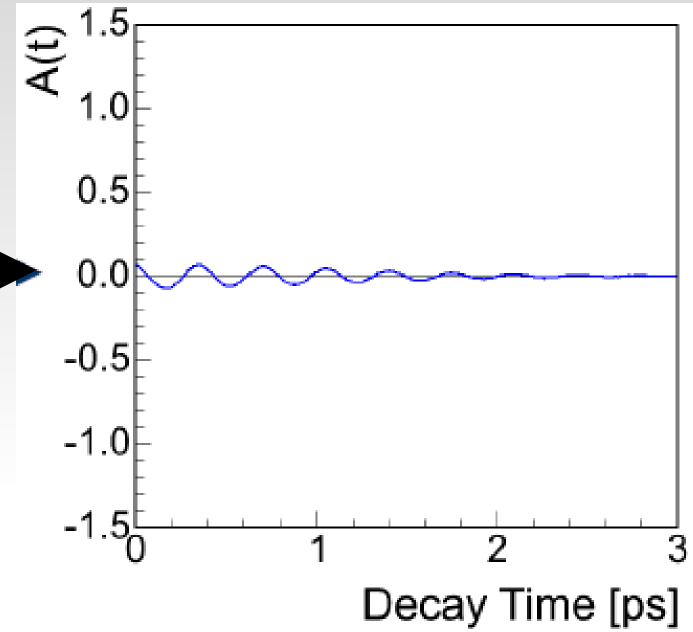
$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

3. Tag B flavor at production time

Adding all realistic effects





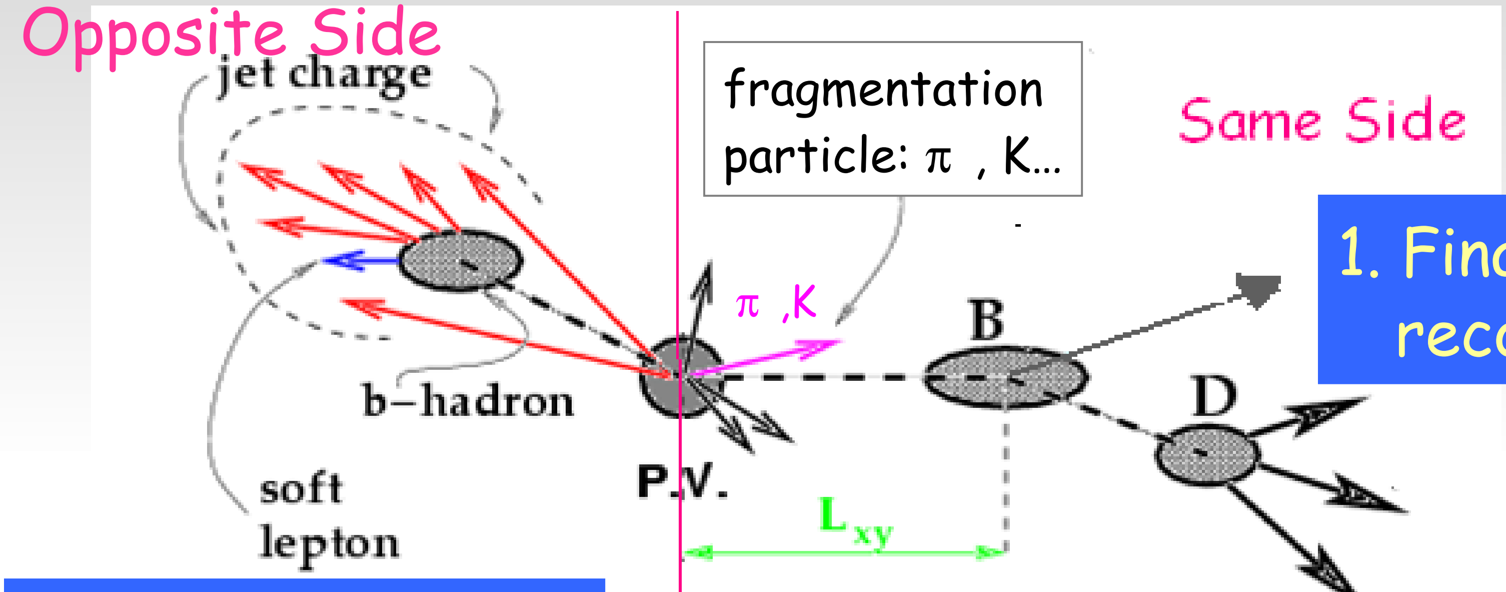
Flavor tagging power

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 $\Delta\ m_s$ Measurement



1. Final state reconstruction

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

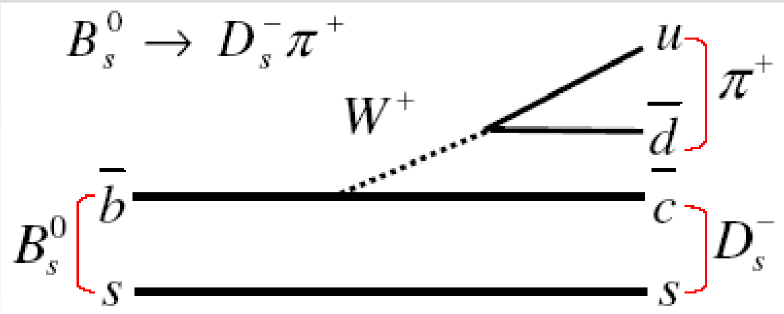
$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

3. Tag B flavor at production time

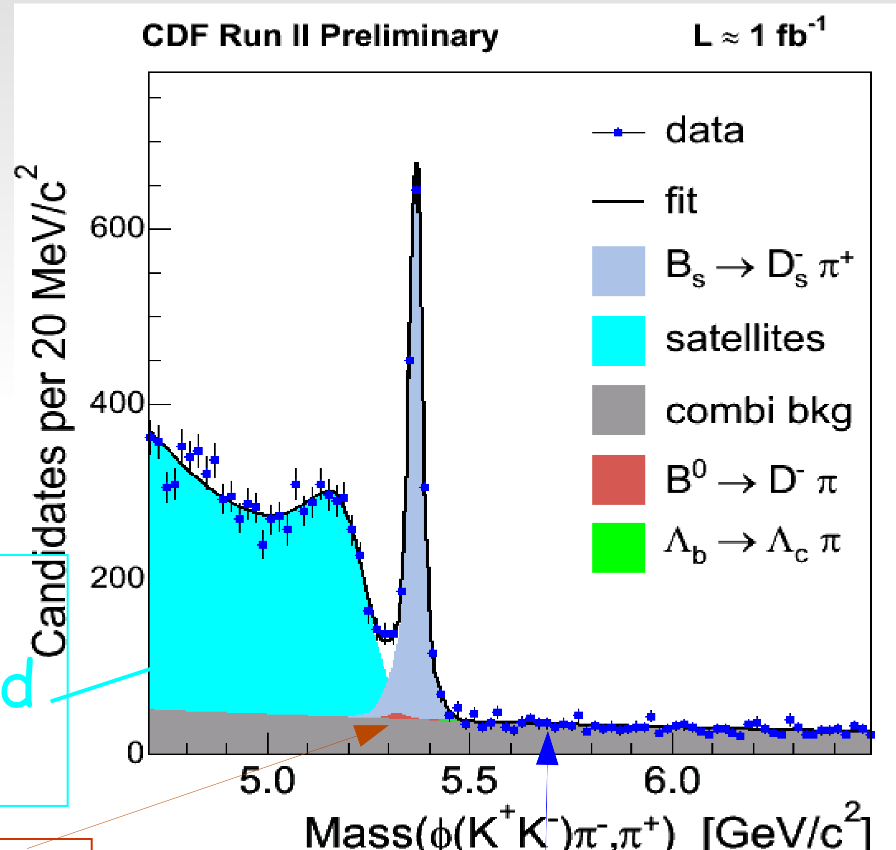
2. High resolution on proper decay length

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

B_s data Sample



Signal $B_s \to D_s\pi$ $D_s \to \phi\pi$



$B_s \to D_s\pi$

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

$B_s \to D_s 3\pi$

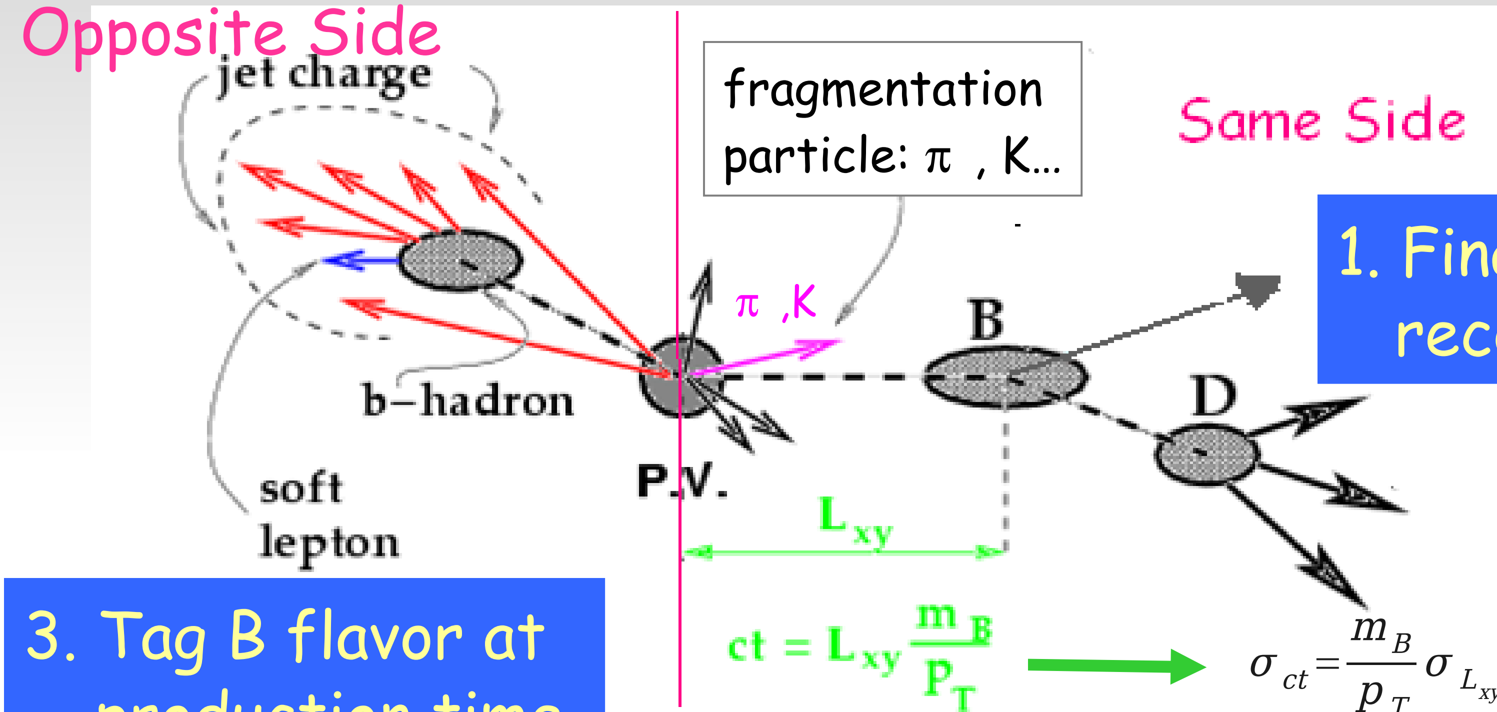
- $D_s \to \phi\pi$
- $D_s \to K^{*0}K$

Partially reconstructed B mesons

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

Combinatorial background

Road Map to $\Delta\ m_s$ Measurement



1. Final state reconstruction

2. High resolution on proper decay length

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

3. Tag B flavor at production time

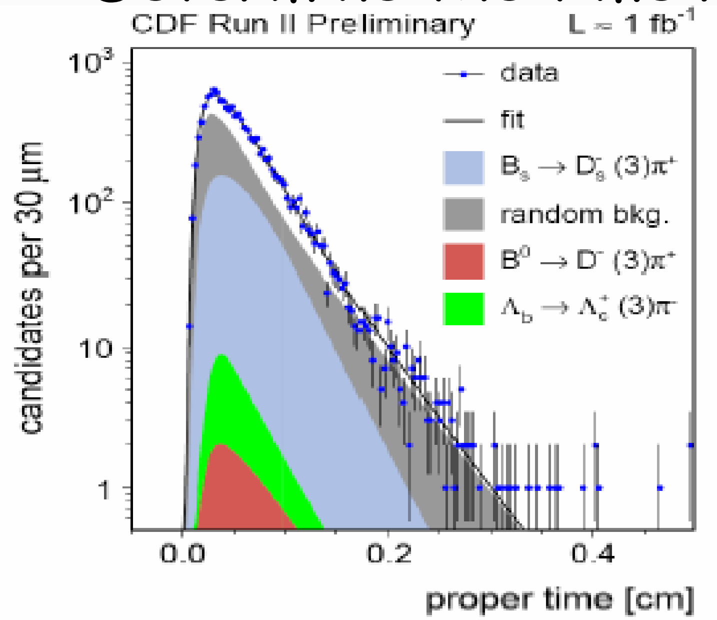
Proper decay time reconstruction

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

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

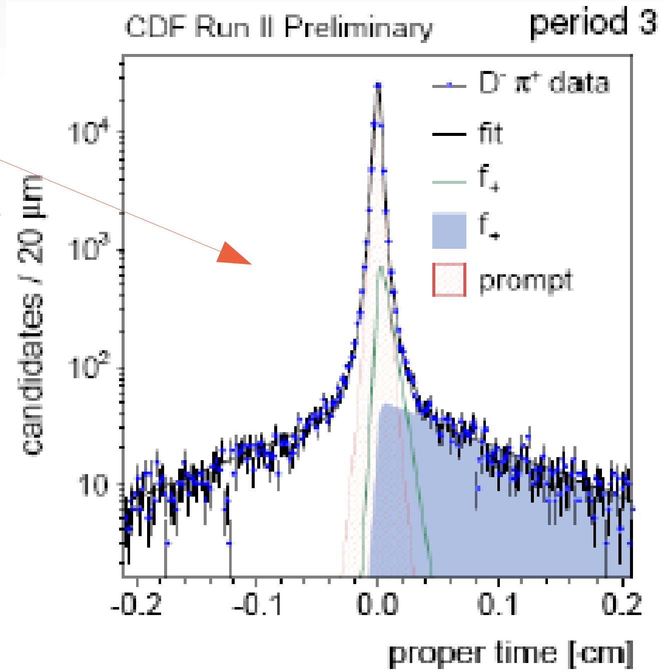
It is needed to:

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

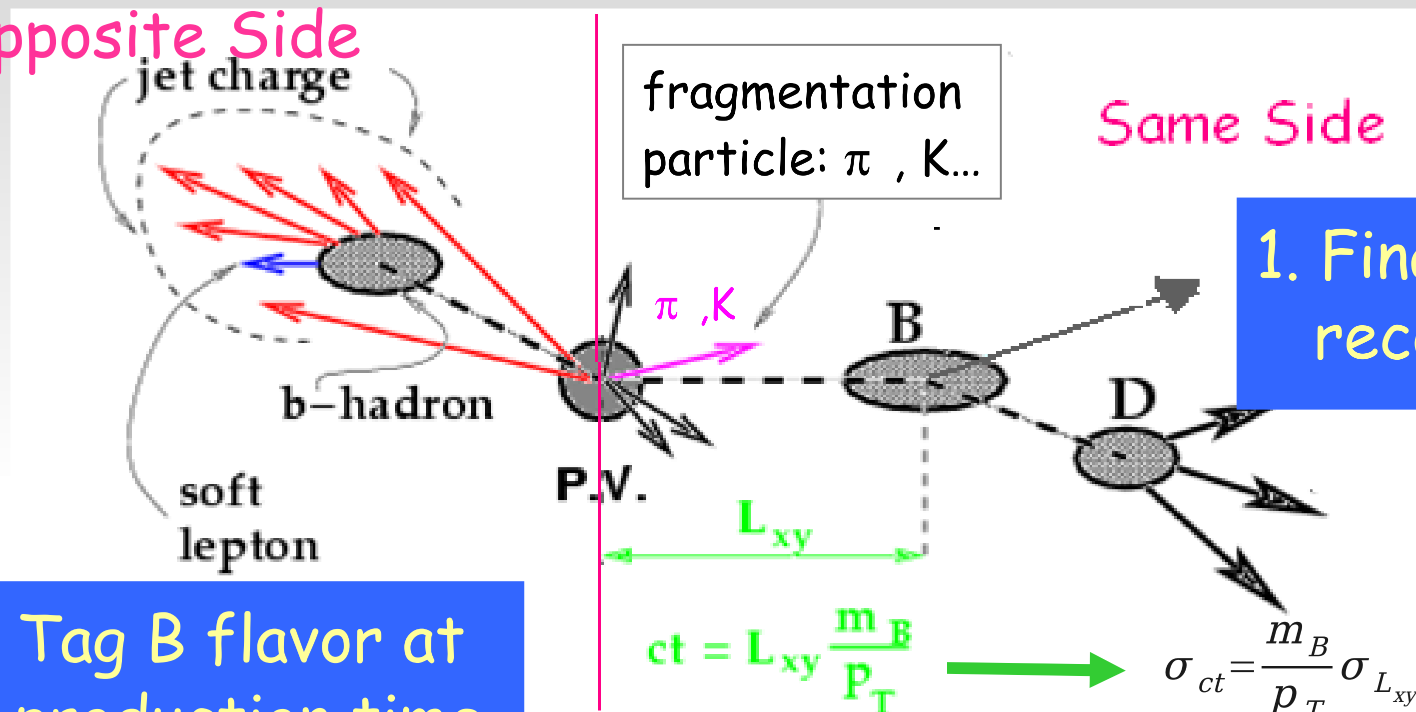


$c\tau\ (B_s) = 1.538 \pm 0.040 (stat)$ ps

Prompt Charm + track sample



Road Map to $\Delta\ m_s$ Measurement



1. Final state reconstruction

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

2. High resolution on proper decay length

3. Tag B flavor at production time

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, Δ m_d

-lepton (electron or muon)

$$Q^{\ell}_J = \sum_i q^i p^i_T / \sum_i p^i_T$$

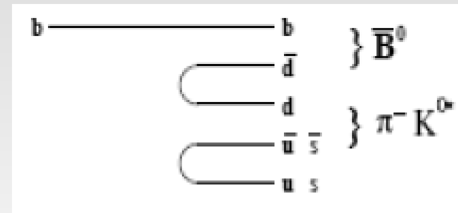
- Secondary Vertex

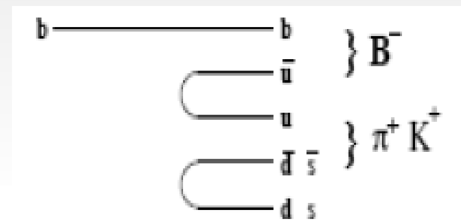
$$Q_{\rm SV} = \sum_i (q^i p^i_L)^{0.6} / \sum_i (p^i_L)^{0.6}$$

- Event Charge

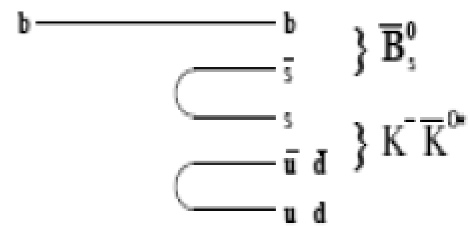
$$Q_{\rm EV} = \sum_i q^i p^i_T / \sum_i p^i_T$$

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

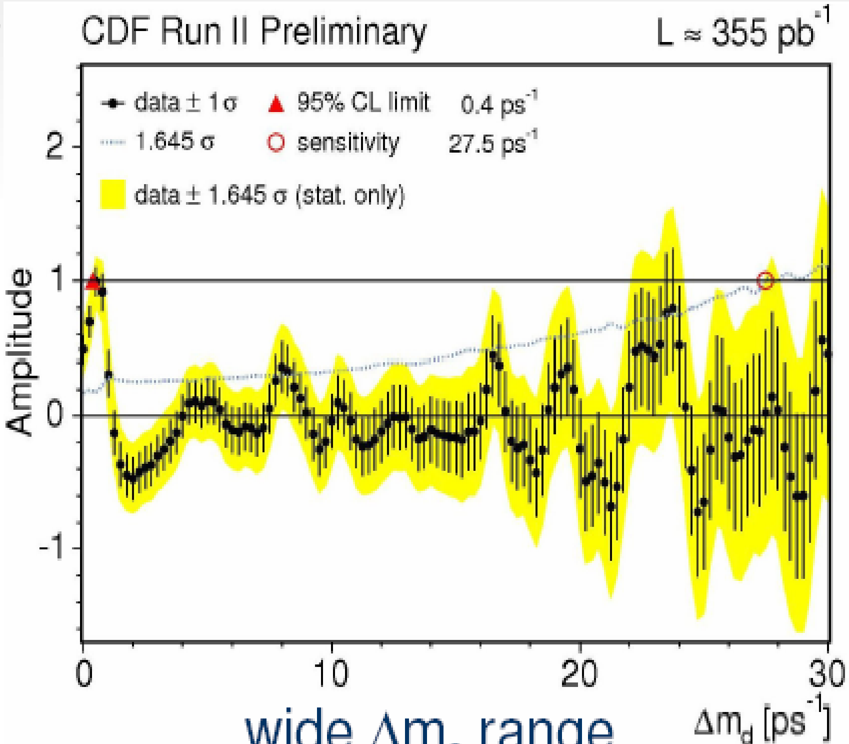
Amplitude scan notation

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

In the figure:

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

B⁰ 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%?

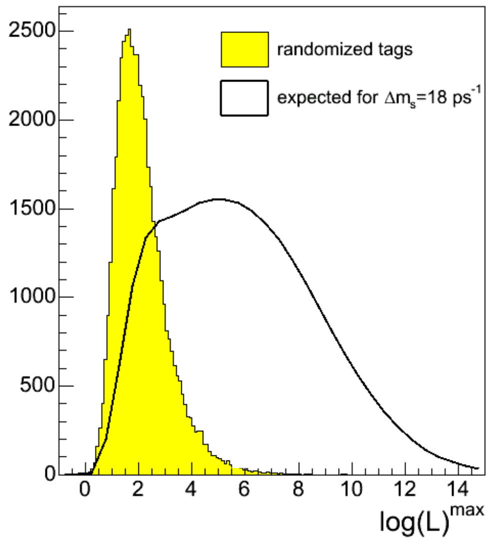
$\ln[\mathcal{L}(A=1)/\ln\mathcal{L}(A=0)]$

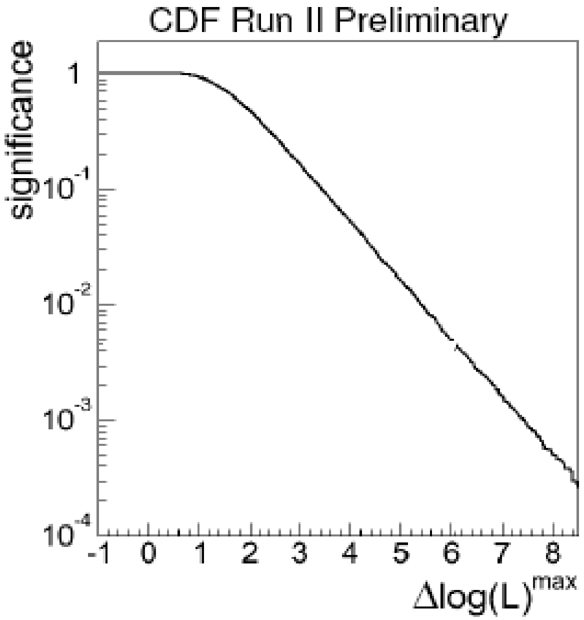
yes

no

make double sided confidence interval from Δ ($\ln(\mathcal{L})$), measure

set 95% C.L. based on Amplitude Scan



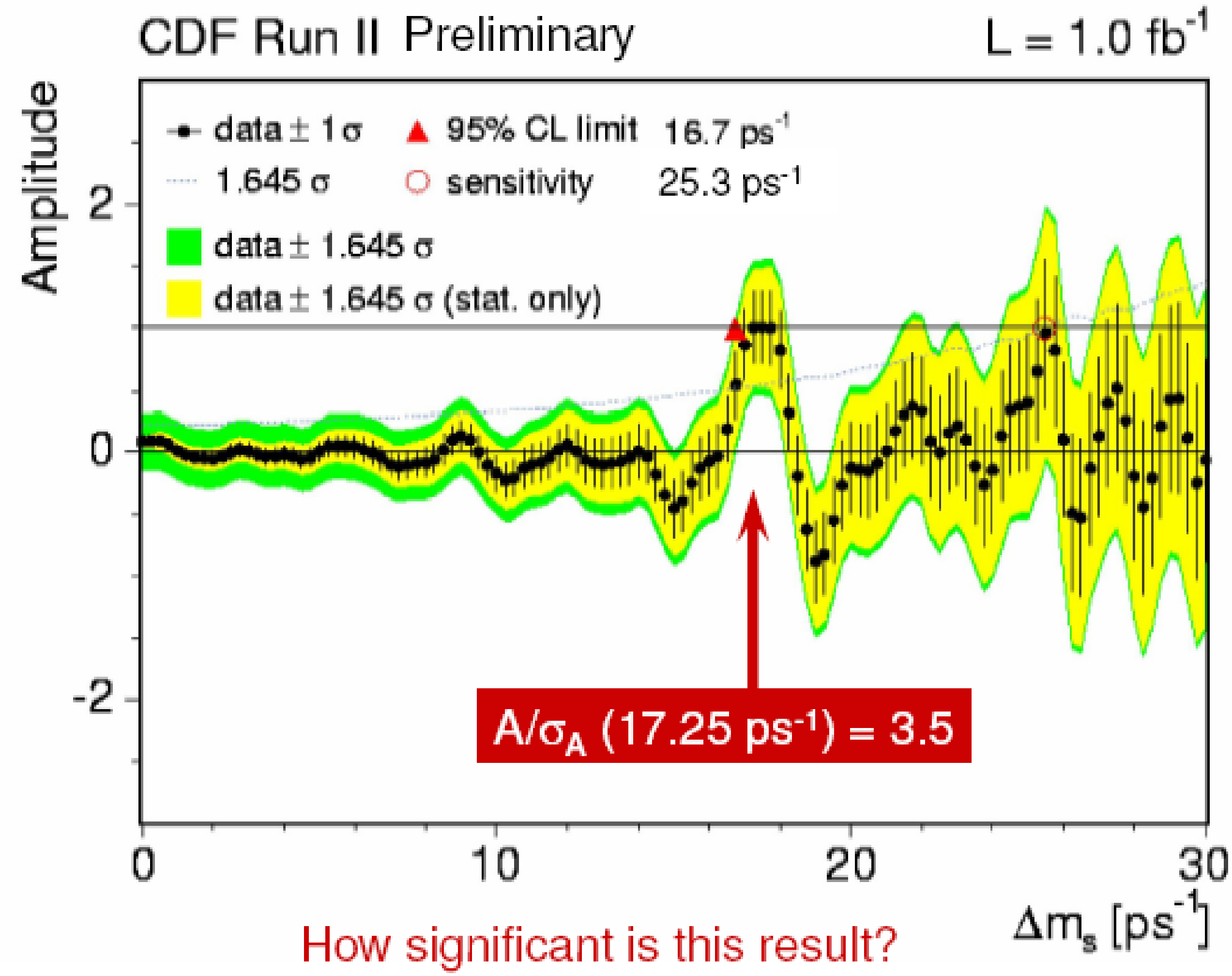


Probability of random tag fluctuation estimated on data (randomized tags) and checked with toy Monte Carlo

Amplitude Scan

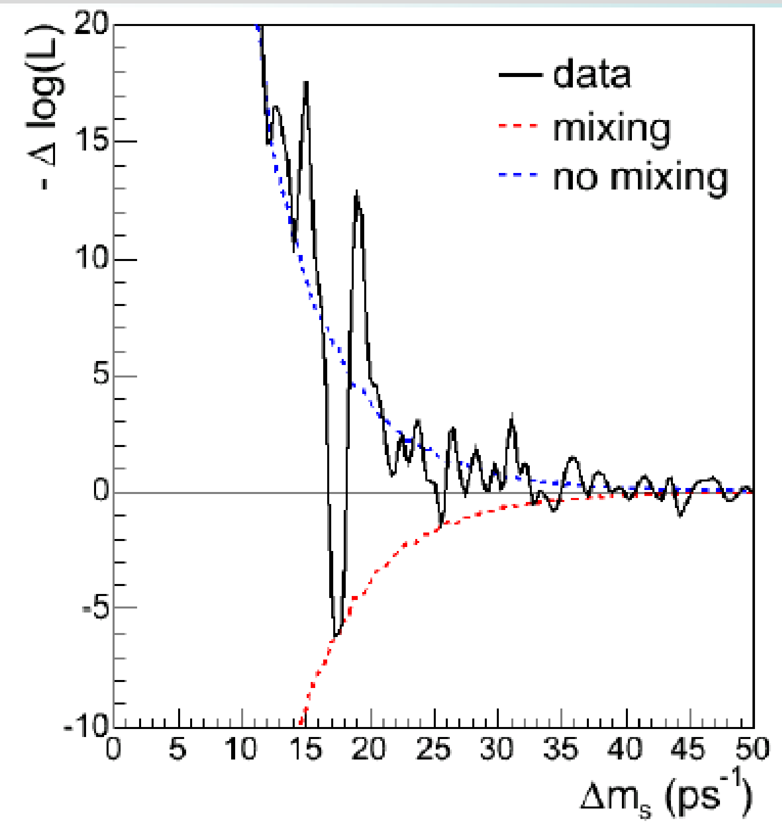
Sensitivity better than the W.A. 20.1 ps^{-1}

Rare case!!

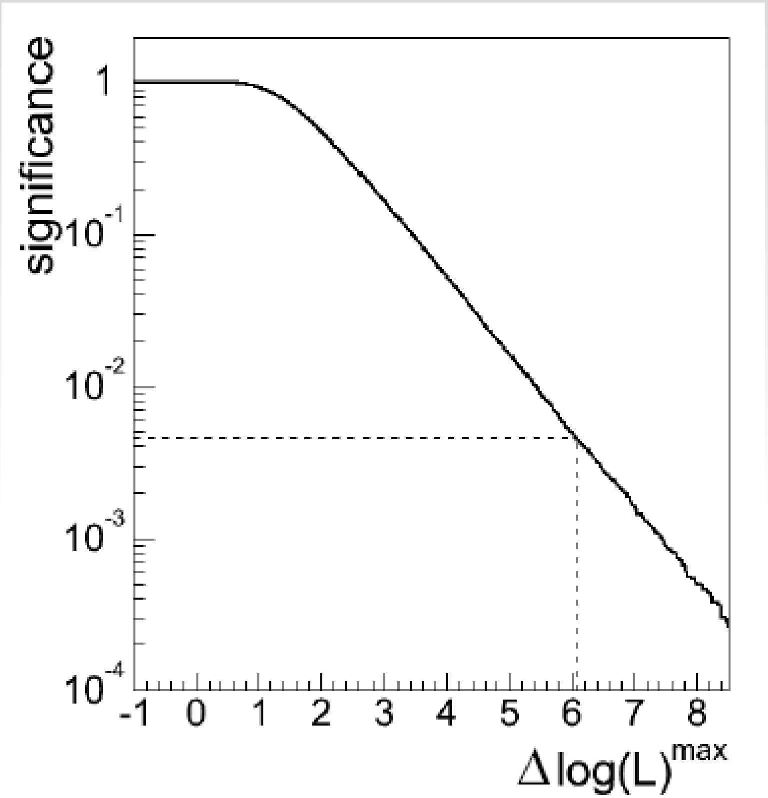


How significant is this result?

Likelihood Profile & significance



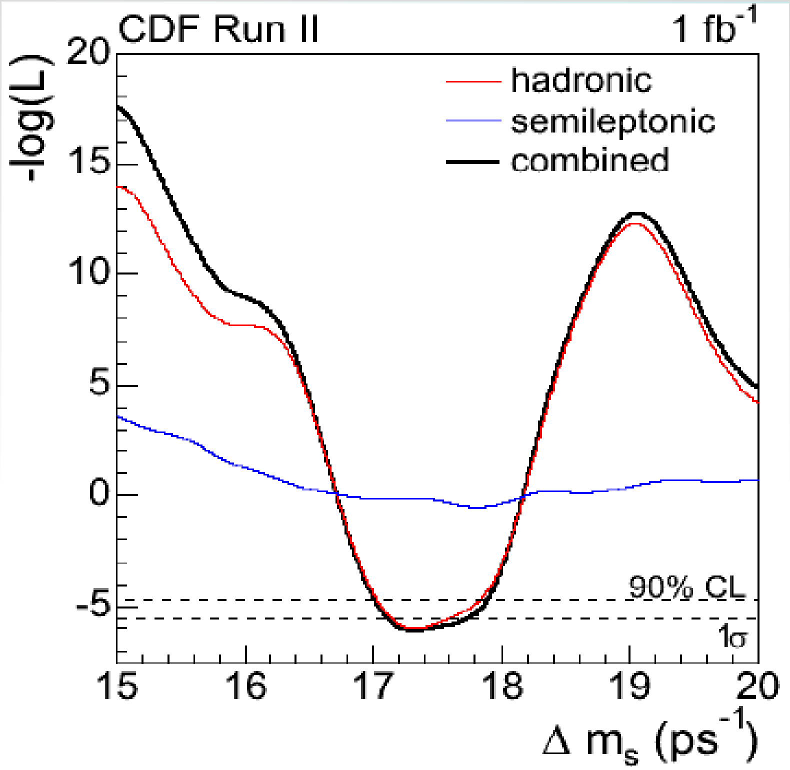
How often random tags produce a likelihood deep this dip?



Probability of fake: p-value=0.5%

Measure $\Delta\ m_s$!!!

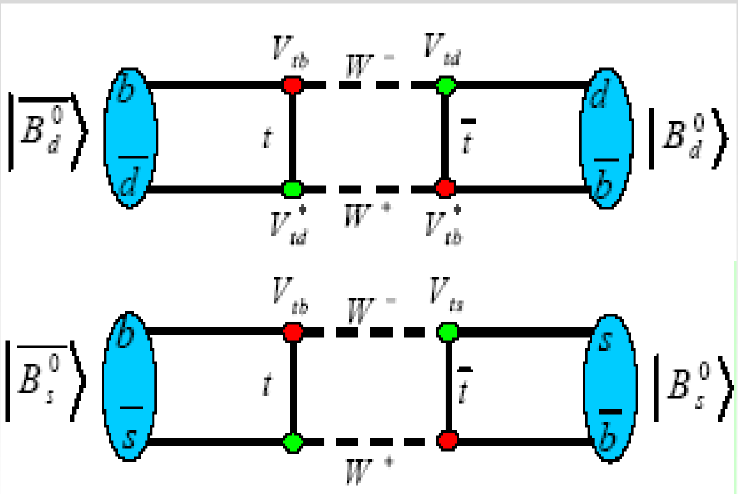
Measurement of Δm_s



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

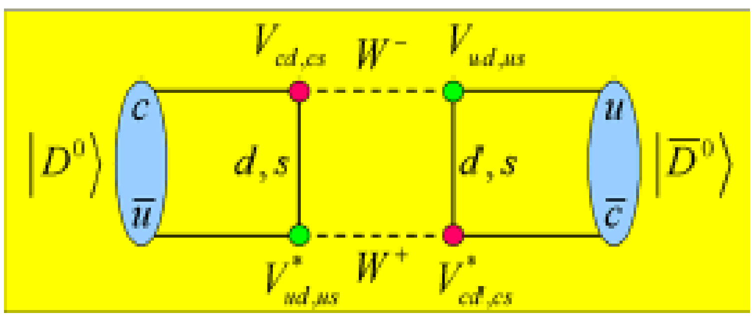
$17.00 < \Delta m_s < 17.91$ ps^{-1} at 90% C.L. $16.94 < \Delta m_s < 17.97$ ps^{-1} at 95% C.L.

Mixing in Charm decays



dominated by top -> large

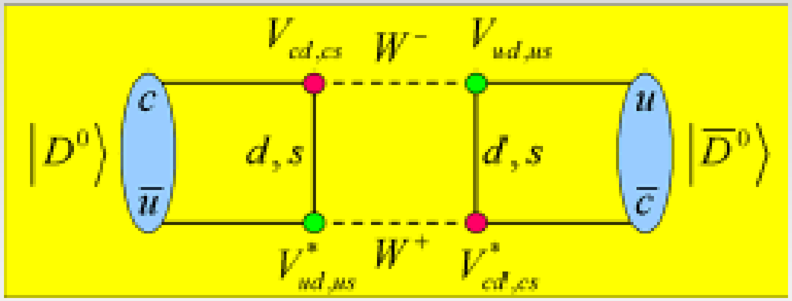
	$\Delta M/\Gamma$	$\Delta\Gamma/\Gamma$
K^0	0.474	0.997
B^0	0.77	<0.01
B_s	27	0.15
D^0	< few%	< few%



dominated by strange-> suppressed

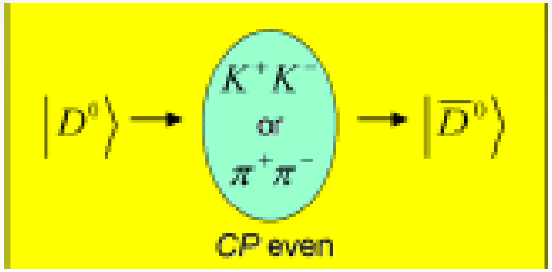
Goal of the search for D^0 mixing is not to constraint the CKM parameters but rather to probe NP

D Mixing



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

X mixing: channel for NP



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

Y (long-range) mixing:
SM background

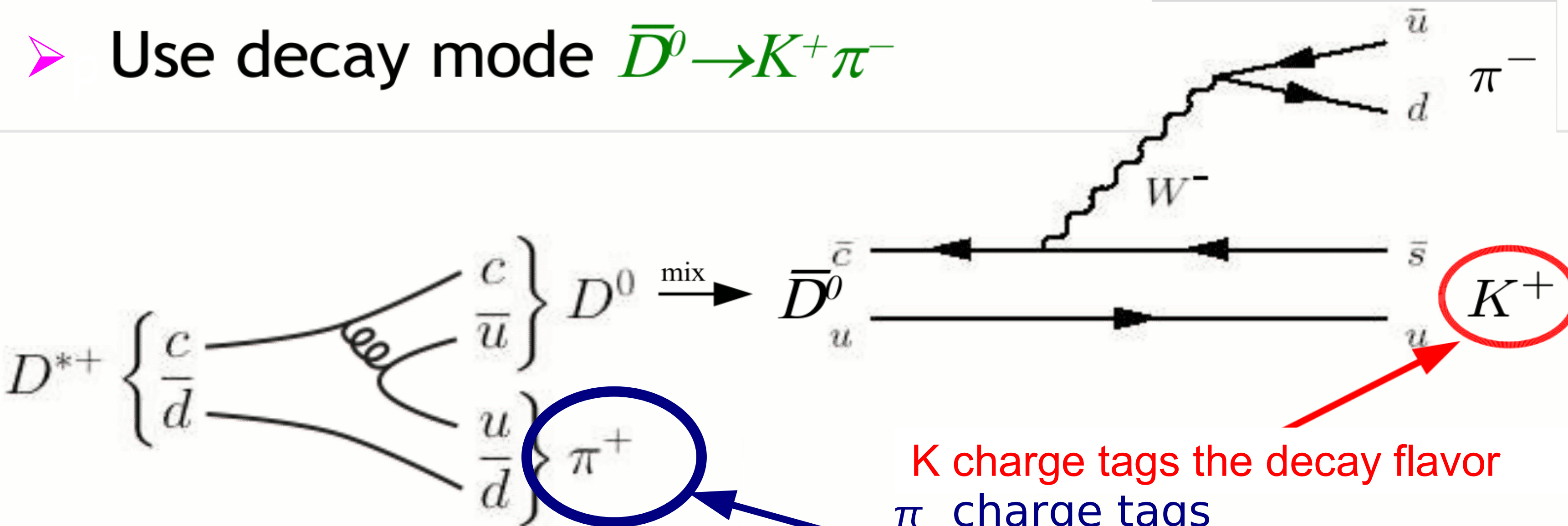
$$R_{mix} = \frac{1}{2}\left(x^2 + y^2\right)$$

NP will enhance x but not y

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

D Mixing measurements at Babar

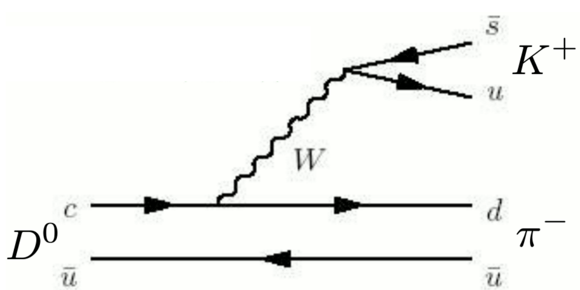
- Use decay mode $\bar{D}^0 \rightarrow K^+\pi^-$



K charge tags the decay flavor

π_s charge tags production flavor

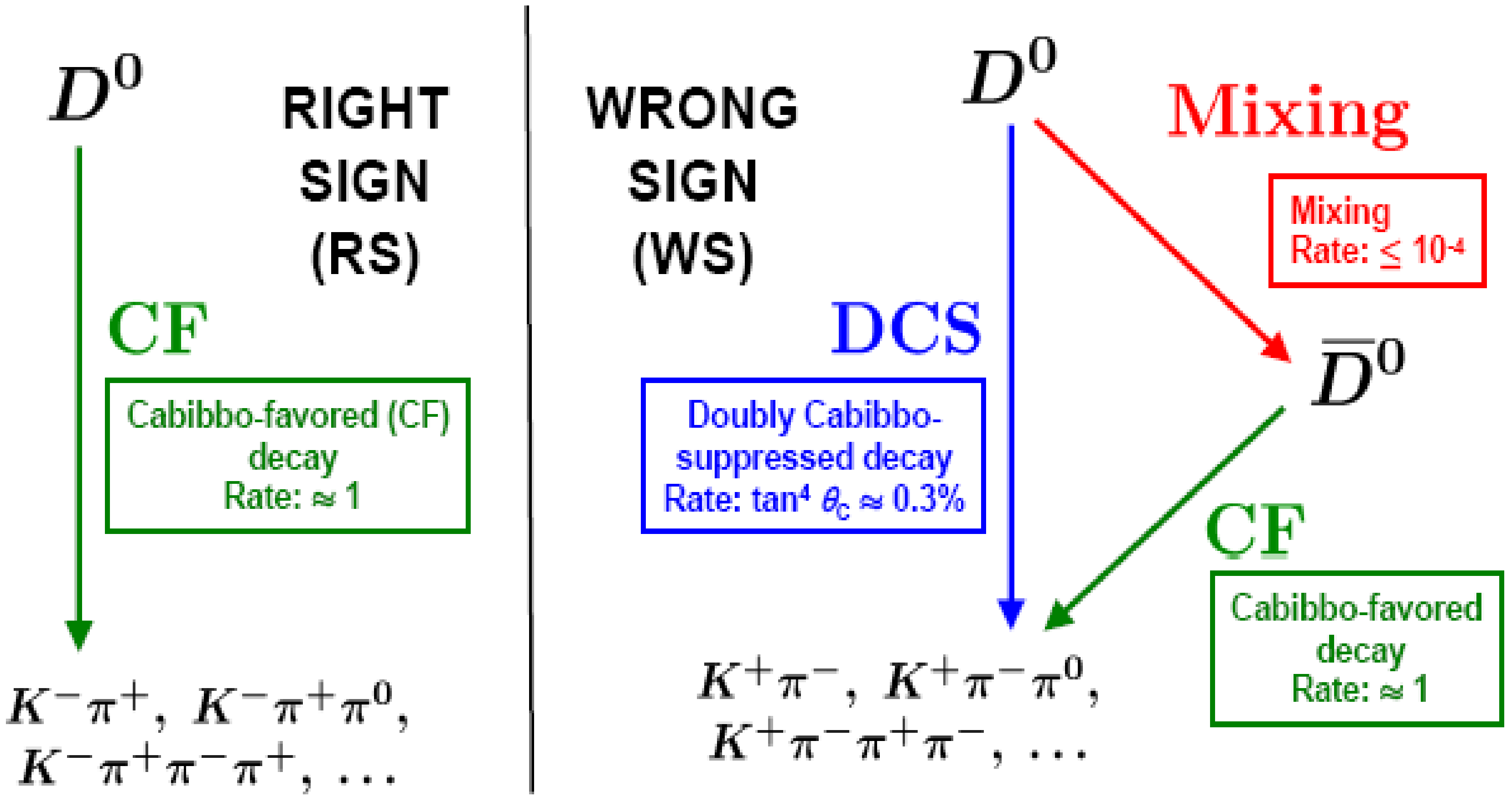
Final state accessible via DCS



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 $x, y \ll 1$

$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(R_D + \sqrt{R_D}\,y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$

DCS decay

Interference between DCS and mixing

Mixing

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 $R_M = \frac{x^2 + y^2}{2}$

D Mixing:event reconstruction

Shown: right-sign decay

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

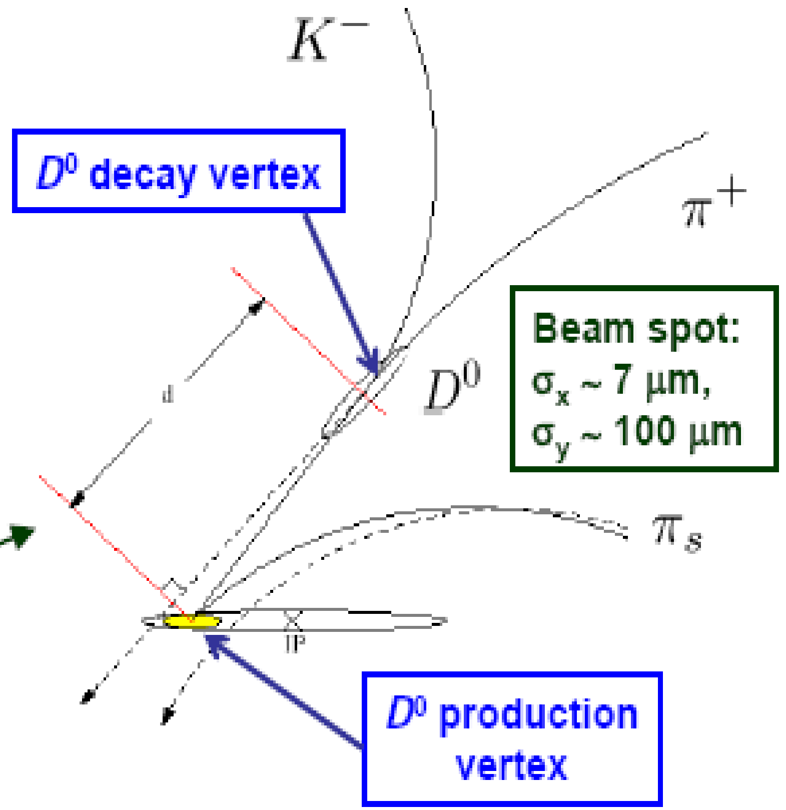
Reconstruction

- 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

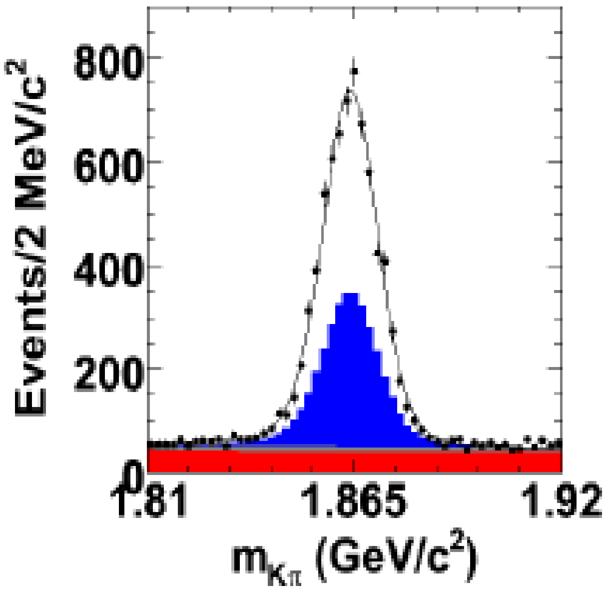
- Improves the decay-time error
- Improves the Δm resolution



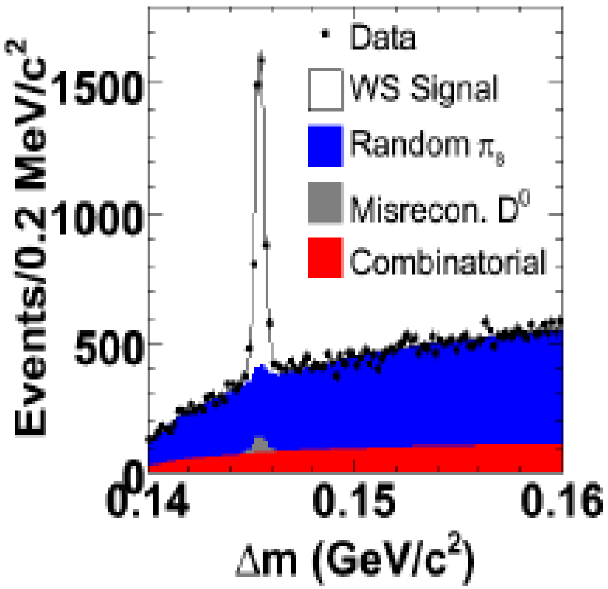
Typical D^0 flight length $d \sim 240\ \mu m$
Average resolution $\sigma_d \sim 95\ \mu m$

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

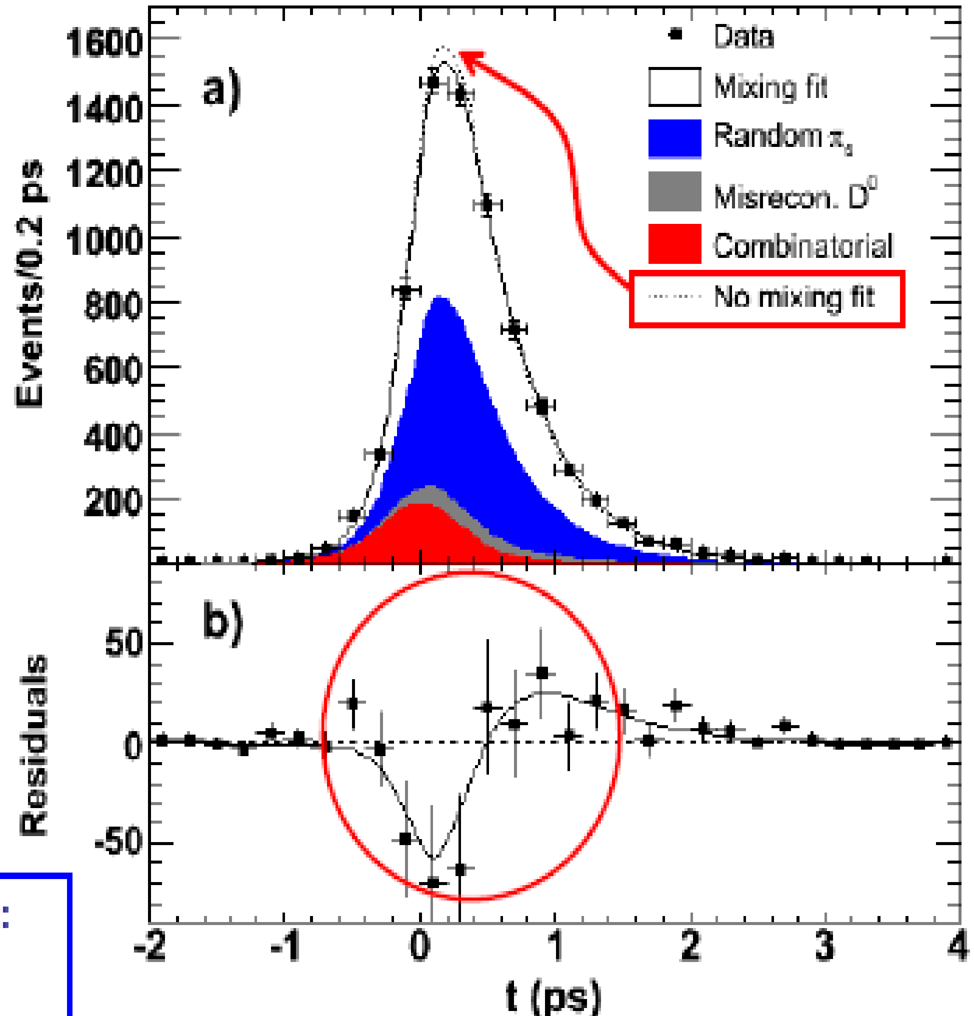
Fit WS proper time

- 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:

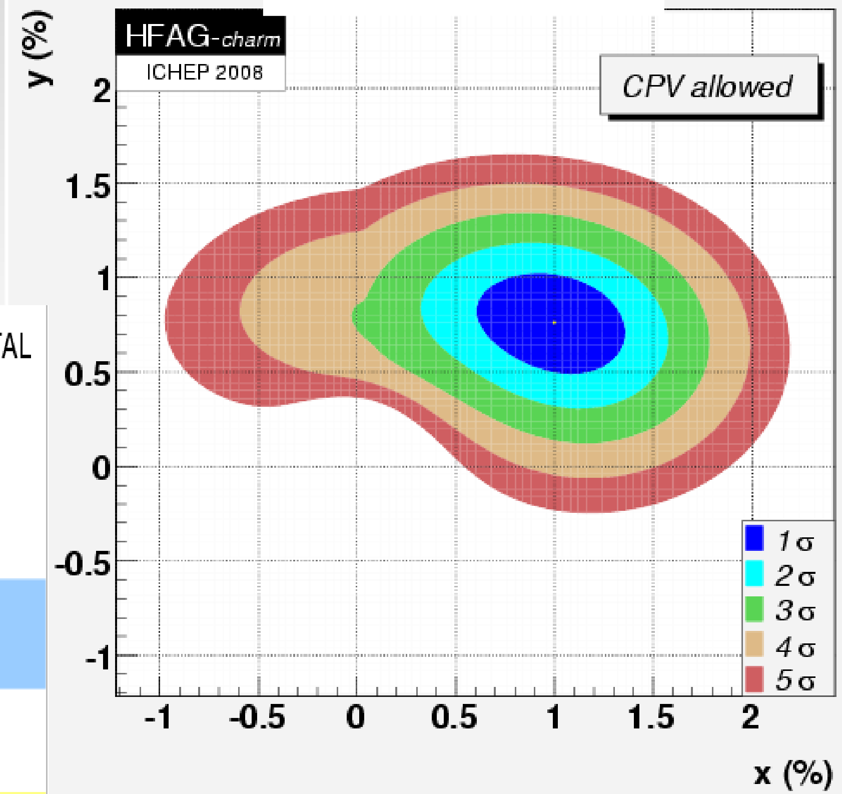
- other decay modes
- Belle
- CDF

FCN= 25.26738 FROM MINOS STATUS=SUCCESSFUL 1613 CALLS 4085 TOTAL

EDM= 0.33E-09 STRATEGY=1 ERROR MATRIX UNCERTAINTY= 2.0%

EXT PARAMETER			PARABOLIC	MINOS ERRORS	
NO.	NAME	VALUE	ERROR	NEGATIVE	POSITIVE
1	x	0.99965	0.24661	-0.25641	0.24007
2	y	0.76262	0.17669	-0.17991	0.17350
3	delta	0.39294	0.18362	-0.19126	0.18117
4	rd	0.33636	0.0085859	-0.0085469	0.0085815
5	ad	-2.1324	2.4412	-2.4119	2.4365
6	qovp	0.85727	0.16198	-0.14867	0.17447
7	phi	-0.15392	0.12928	-0.12608	0.13222
8	delta2	0.19508	0.37460	-0.39263	0.36089

Combination



http://www.slac.stanford.edu/xorg/hfag/

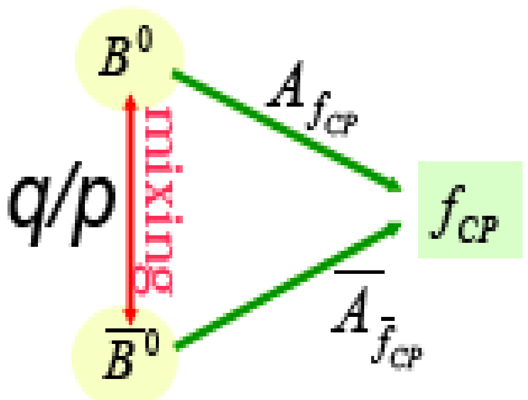
CP Violation

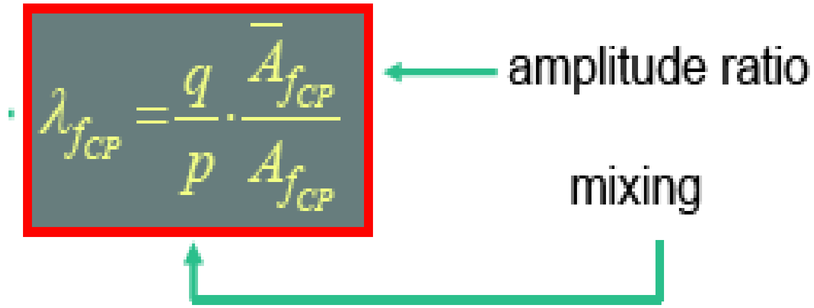
Inside the SM there are three types of CP violation:

- ✔ CPV in the mixing

  $|p/q| \neq 1 \approx 10^{-3}$ in SM
- ✔ CPV in the direct decay

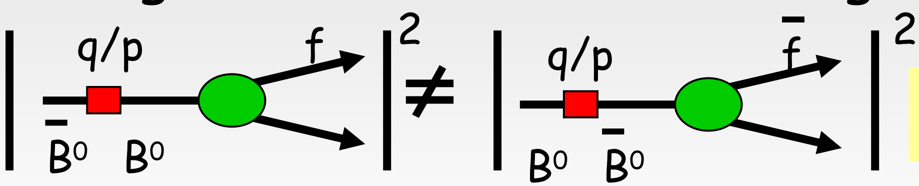
  $|A/\bar{A}| \neq 1$
- ✔ CPV in interference between mixing and decay





CP Violation in mixing

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



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

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

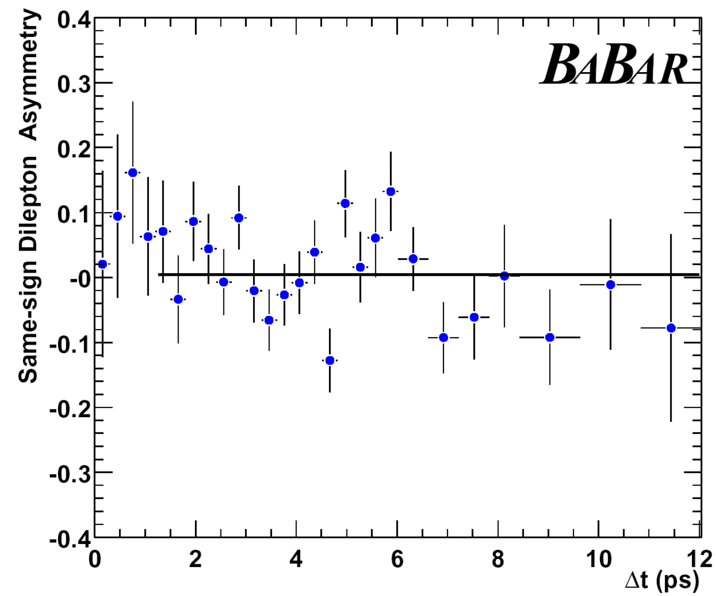
- Do not expect much interference: need 2 amplitudes of comparable size
- Little chance of seeing CP violation in $B^0\bar{B}^0$ mixing…
- Calculation of Γ_{12} has large hadronic uncertainties: Asymmetry $\propto \mathrm{Im}(\Gamma_{12}/M_{12}) \sim O(10^{-2\div 3})$ for B mesons
- But an interesting place to look for NP effects

CPV in B^0-$\bar{B}^0$ Mixing: inclusive dilepton events

$B^0\bar{B}^0 \to$

- $B^0\bar{B}^0$ $\quad l^+l^-X$
- B^0B^0 $\quad \pi \quad l^+l^+X \quad □ \; P\left(\bar{B}^0 \to B^0\right)$
- $\bar{B}^0\bar{B}^0$ $\quad □ \quad l^-l^-X \quad □ \; P\left(B^0 \to \bar{B}^0\right)$
- $\bar{B}^0B^0$ $\quad □ \quad l^-l^+X$

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



BaBar using 23 millions $B\bar{B}$ pairs

As expected, no asymmetry has been observed…

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

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

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

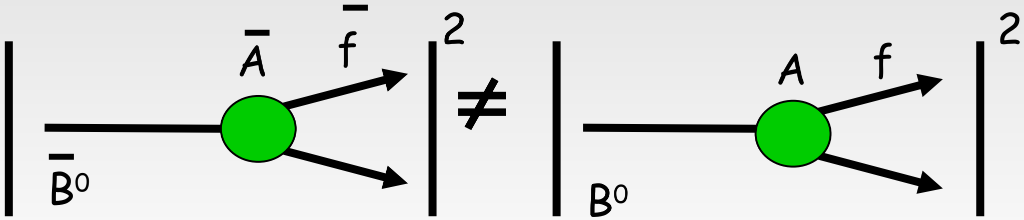
Decay amplitudes can, in general, receive many contributions:

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

- 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

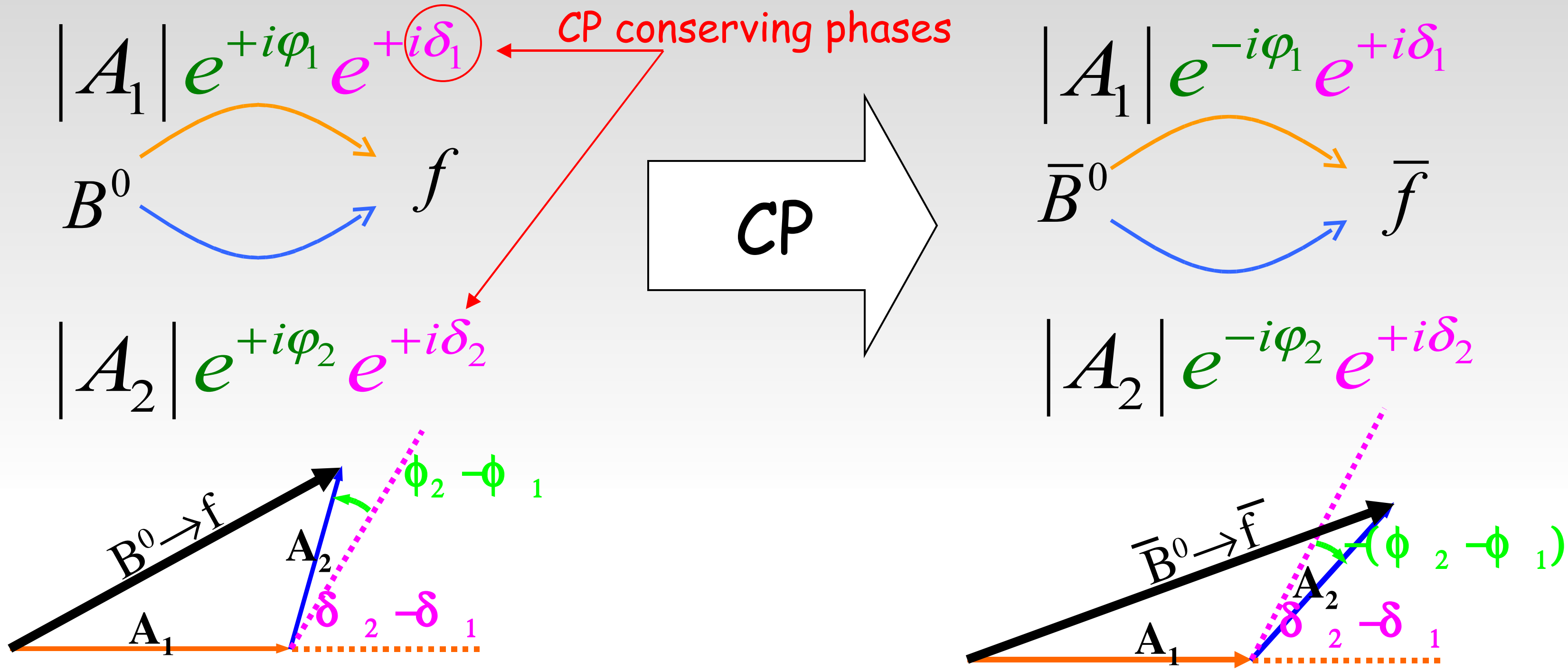
- Requires at least two different decays amplitudes with different strong and weak phases



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

- 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



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

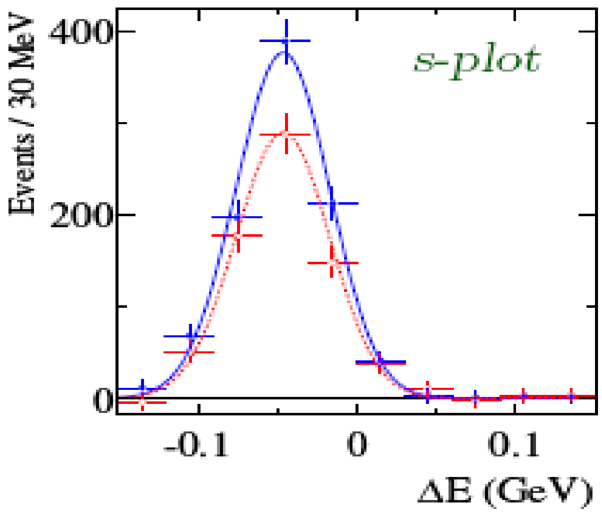
To get unitarity triangle angle(s) ($\phi_1 - \phi_2$) we need to know the non-CKM phase shift ($\delta_1 - \delta_2$). Due to long-distance QCD effects in generally not calculable, but it may be possible to measure it

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 $\bar{B}^0 \to K^-\pi^+$

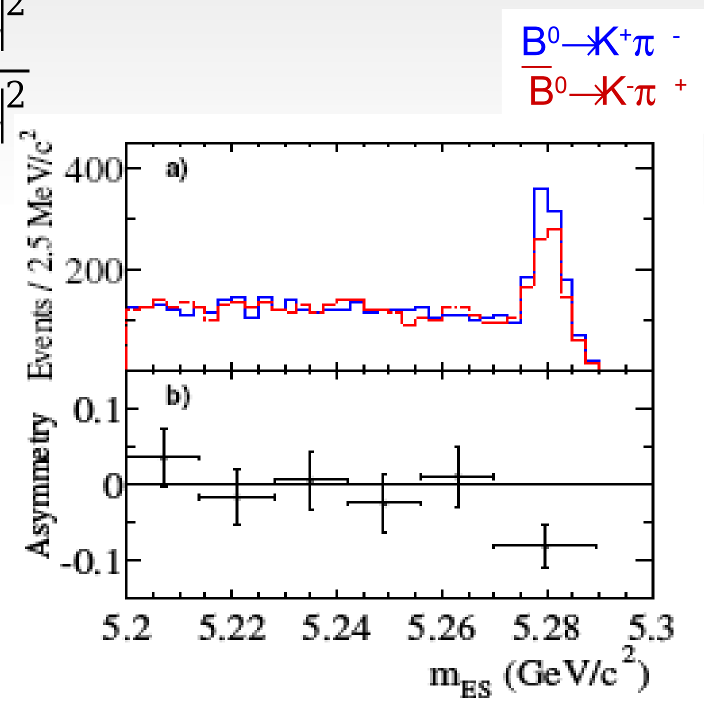
$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} = \frac{1 - |\bar{A}_{\bar{f}}/A_f|^2}{1 + |\bar{A}_{\bar{f}}/A_f|^2}$$



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

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

both zero for signal

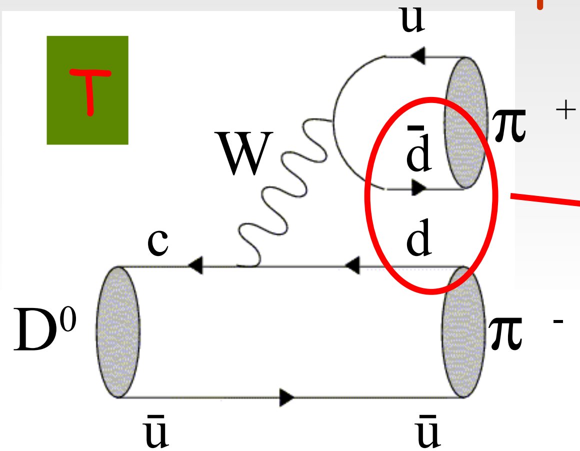


$$A_{K\pi} = -0.133 \pm 0.030(\text{stat}) \pm 0.009(\text{syst})$$

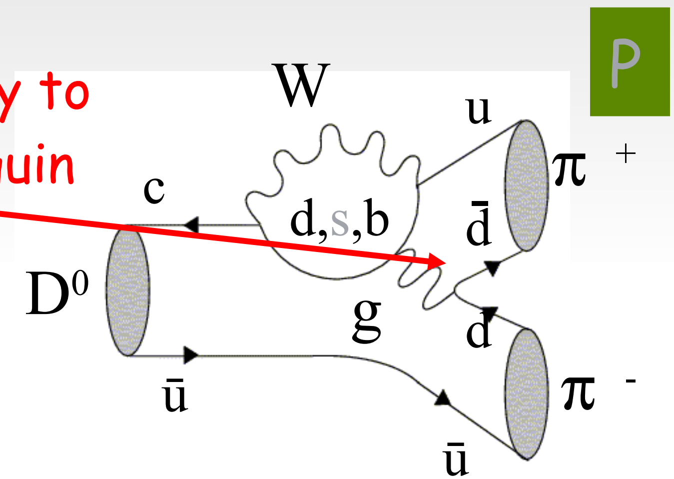
Direct A_{CP} in Charm Decays

Direct (Δ C=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:

- Vcd*Vud VS Vcs*Vus → different weak phases
- Δ I = 1/2,3/2 VS Δ I = 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 N P

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:

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

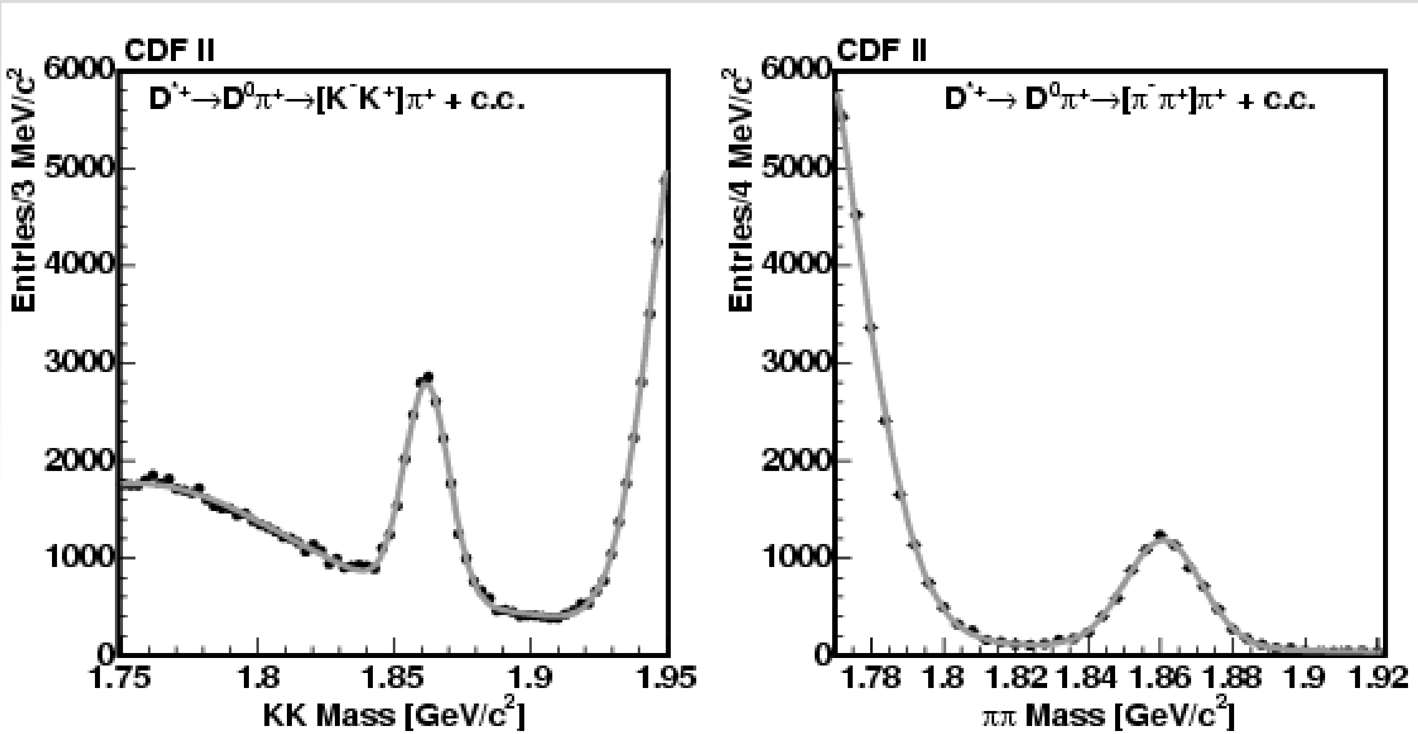
- Main systematic effect:

  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

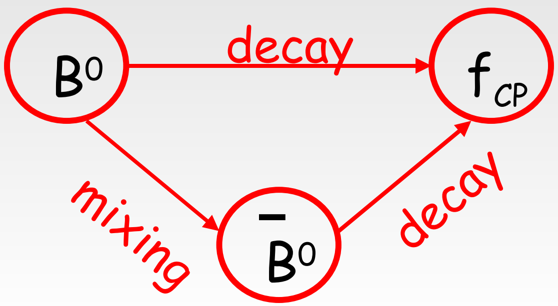
7334 ± 97 $D^0\pi\pi$ signal events

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

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

CPV in interference between decay-mixing

If both B^0 and $\bar{B}^0$ 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:

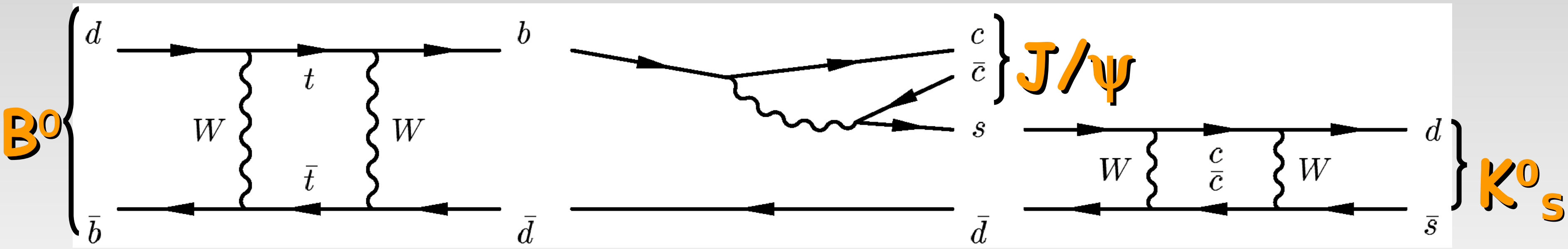
$$A_{f_{CP}} = \frac{\Gamma\left(\bar{B}^0(t)\to f_{CP}\right) - \Gamma\left(B^0(t)\to f_{CP}\right)}{\Gamma\left(\bar{B}^0(t)\to f_{CP}\right) + \Gamma\left(B^0(t)\to f_{CP}\right)} = -C_{f_{CP}}\cos(\Delta m\cdot t) + S_{f_{CP}}\sin(\Delta m\cdot t)$$

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

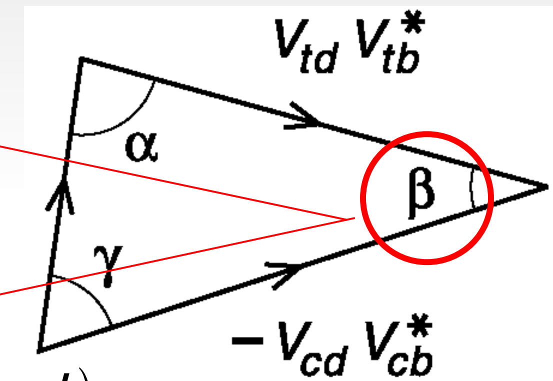
CP is violated either if $|\lambda\ | \neq 1$ due to CPV in mixing and/or decay, or if $|\lambda\ |=1$, but $\mathrm{Im}\lambda \neq 0$ due to CPV in interference

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

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



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

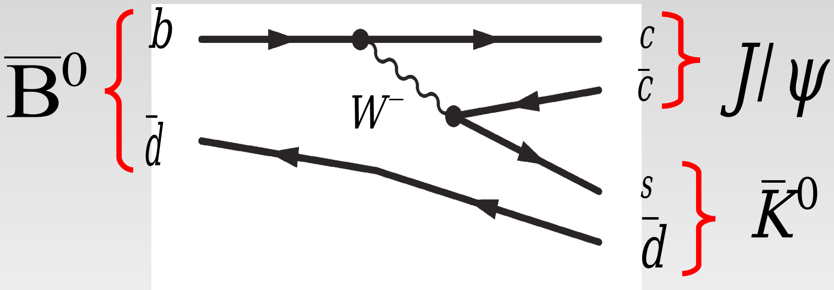


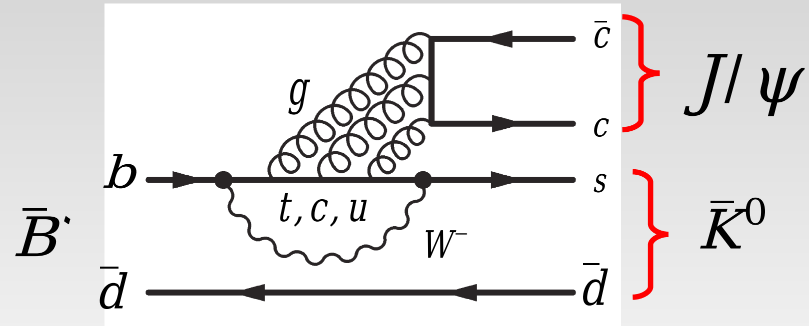
$\mathrm{Im}\lambda = \sin 2\beta$

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

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

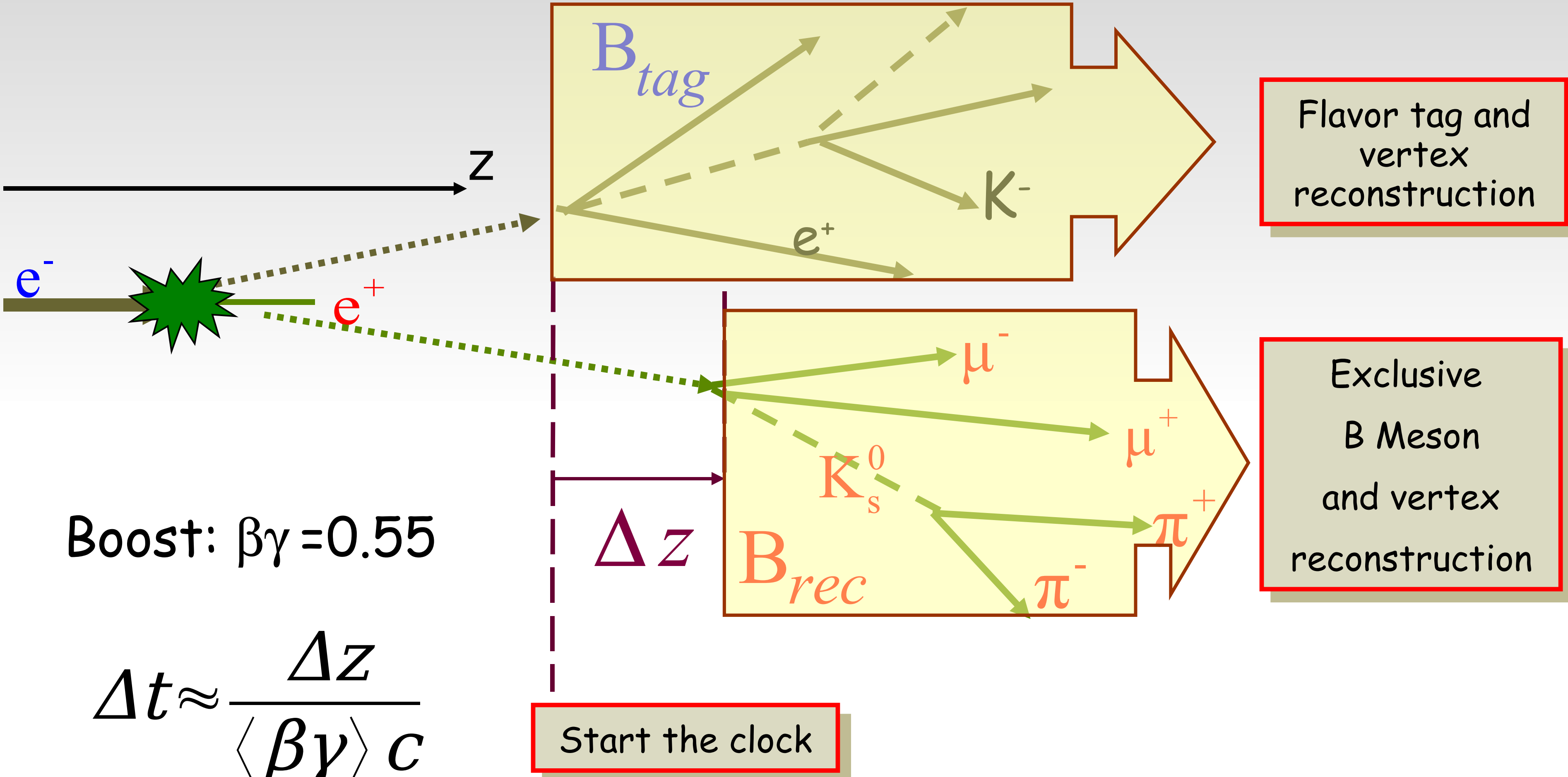
Rewriting P using unitarity: $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$

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

Leading penguin contribution has *same* weak phase as tree

Extraction of sin(2β) from J/ψK_S is "theoretically clean"

Steps to measure sin2β

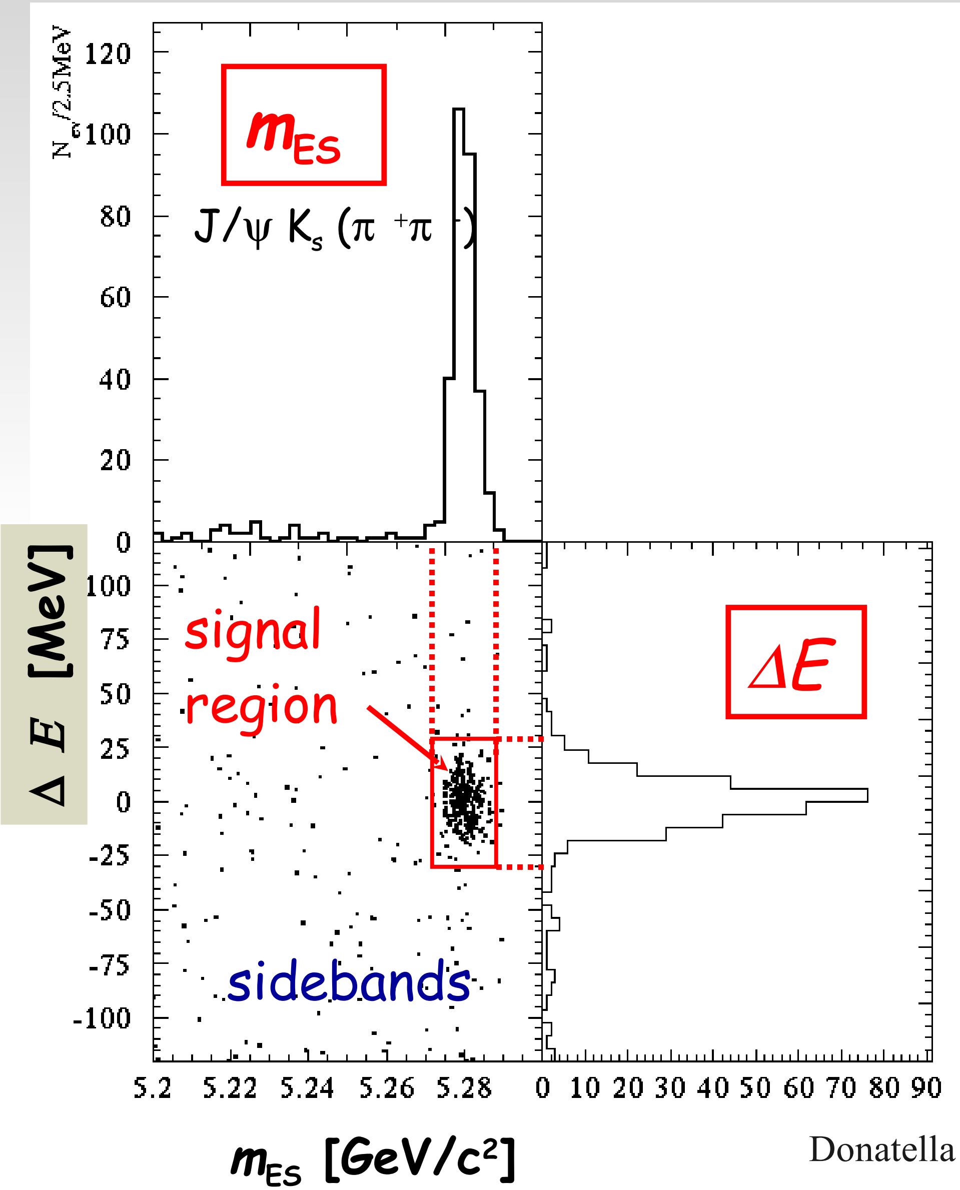


Boost: βγ =0.55

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

$$e^+ e^- \to \Upsilon(4S) \to B\bar{B}$$

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

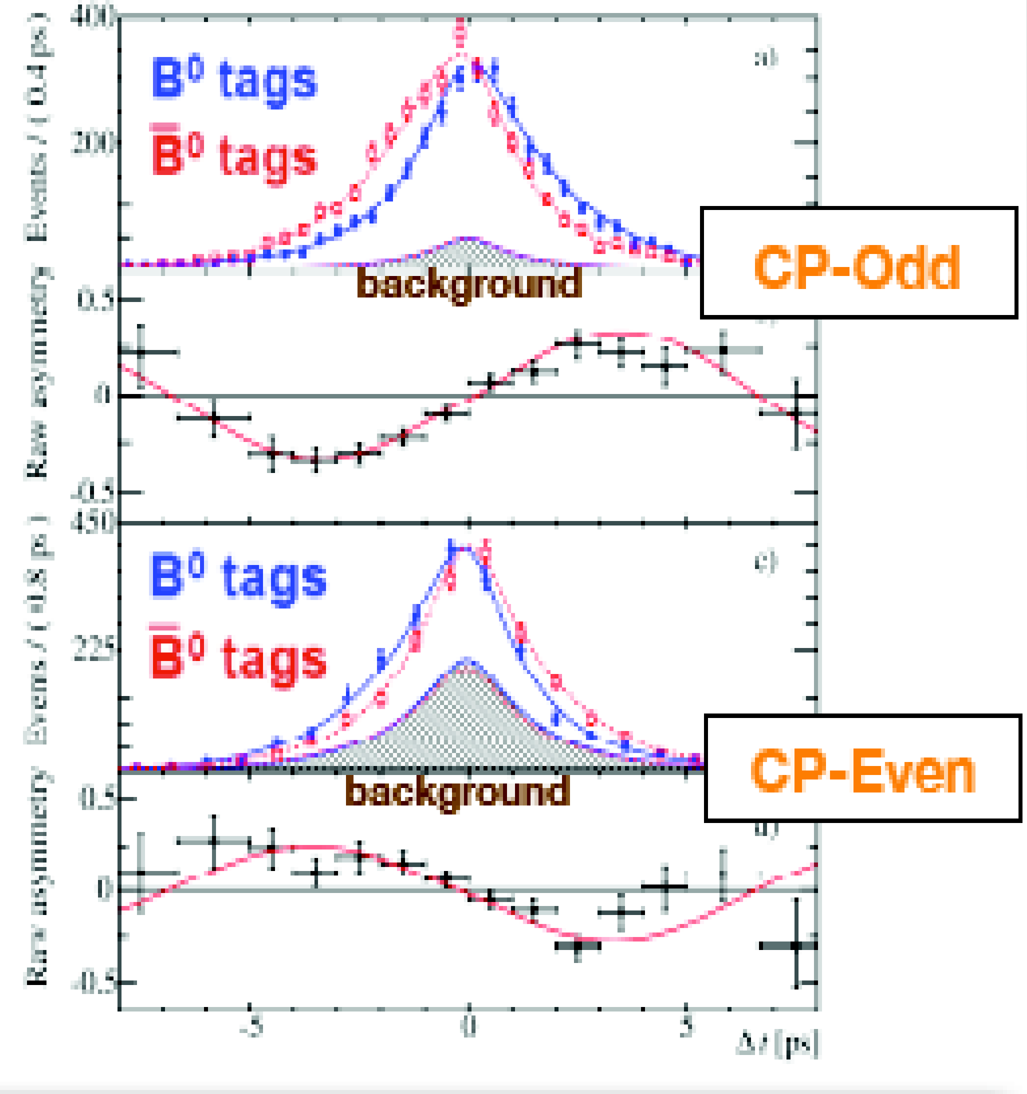
$\sigma(M_{ES}) \sim$ 2.6 MeV

BaBar measured asymmetries

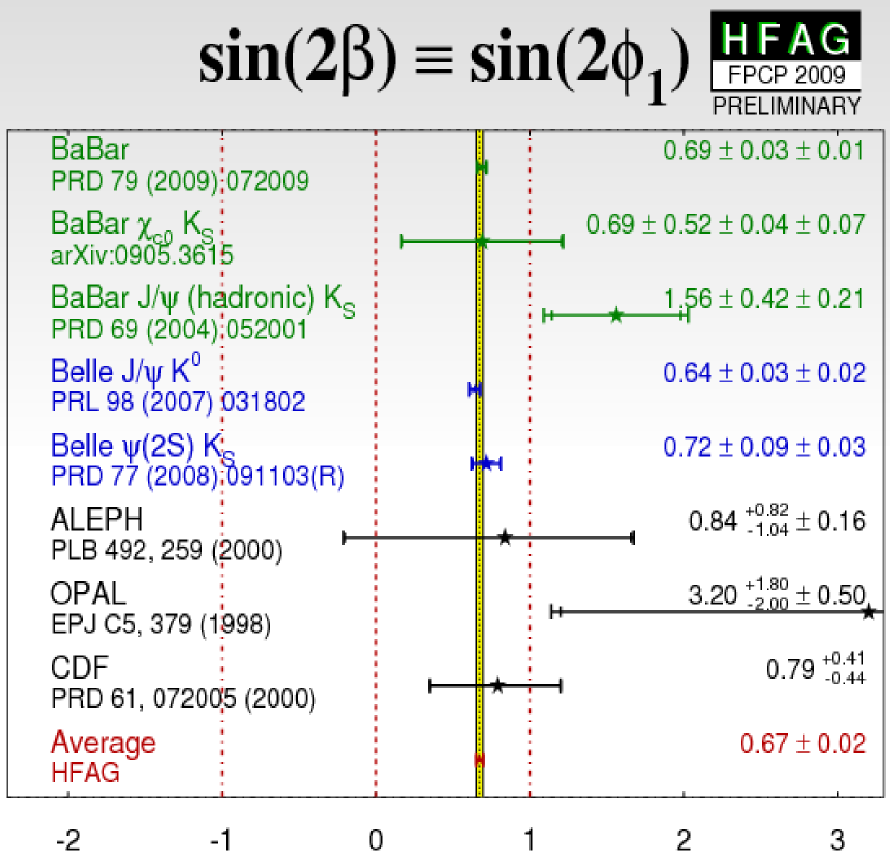
$$B^0 \rightarrow J/\psi K_S^0, J/\psi K^{*0}, \psi(2S)K_S^0, J/\psi K_L^0, \eta_c K_S^0, \chi_{c1} K_S^0$$

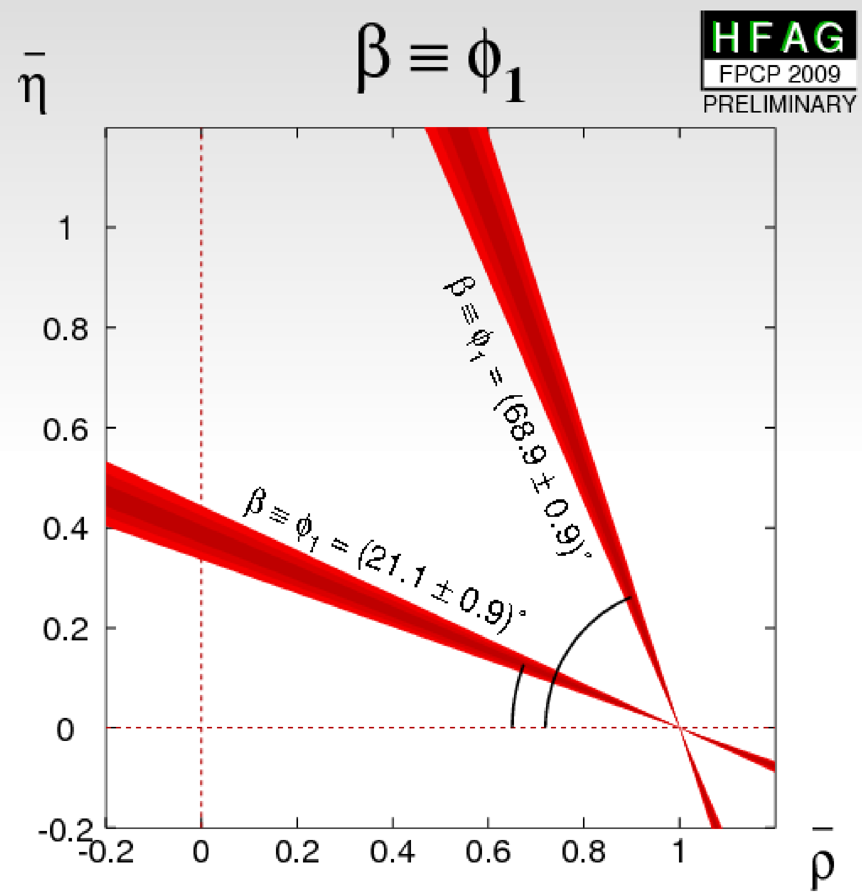
$$\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$$

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



Overall Status of sin2β

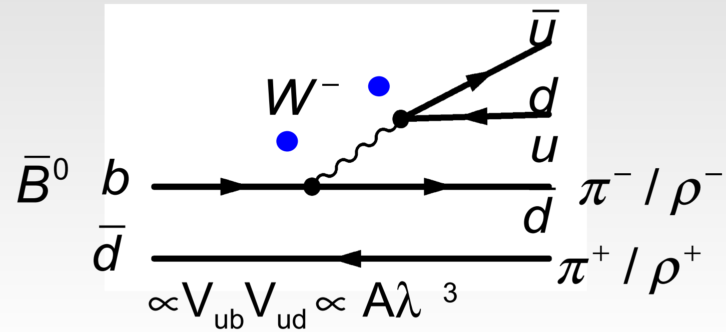




$B^0 \rightarrow \pi^+\pi^-/\rho^+\rho^-$: measurement of angle α

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:



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

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

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

→

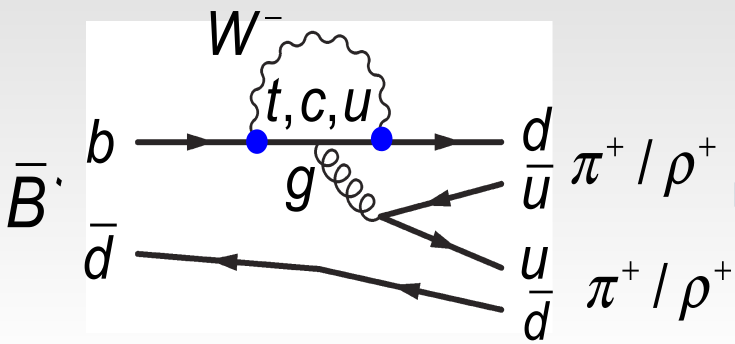
C=0

S=sin(2α)

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

$B^0 \to \pi^+\pi^-/\rho^+\rho^-$: 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

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

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

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 $\bar{B}^0$)

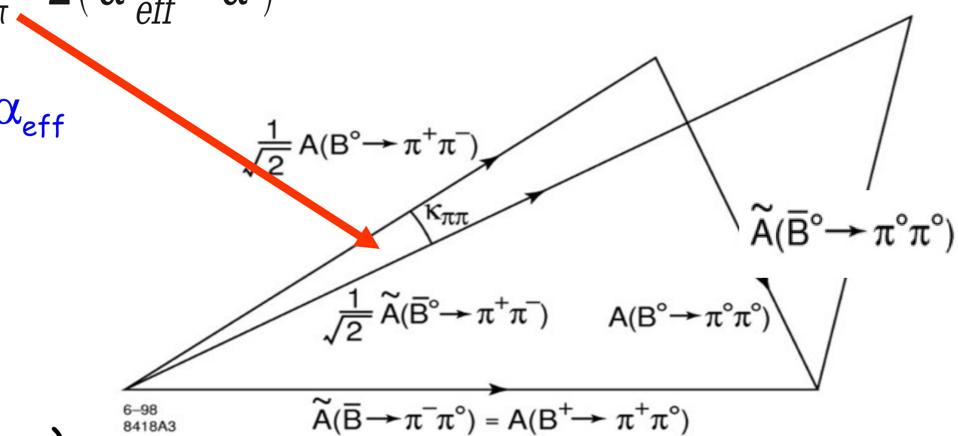
  Neglecting EW penguins (violate isospin), $B^+ \rightarrow \pi^+\pi^0$ is pure tree diagram $$A(B^+ \rightarrow \pi^+\pi^0) = \tilde{A}(B^- \rightarrow \pi^-\pi^0)$$
- Need to measure separate BF for B^0/B^0 and B^+/B^-
- Triangle relations allow determination penguin-induced shift in α

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

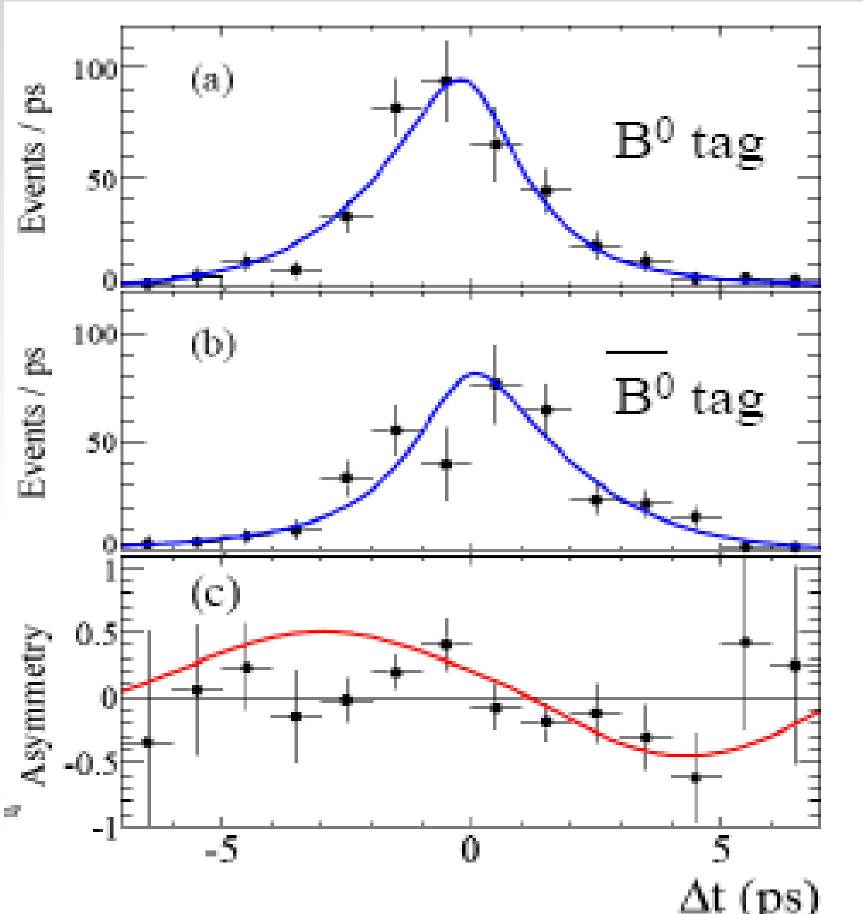
Problem: $\pi^0\pi^0$ is too small for a isospin analysis and too large to set a useful $\alpha - \alpha_{eff}$ limit…

Solution: use ρρ:

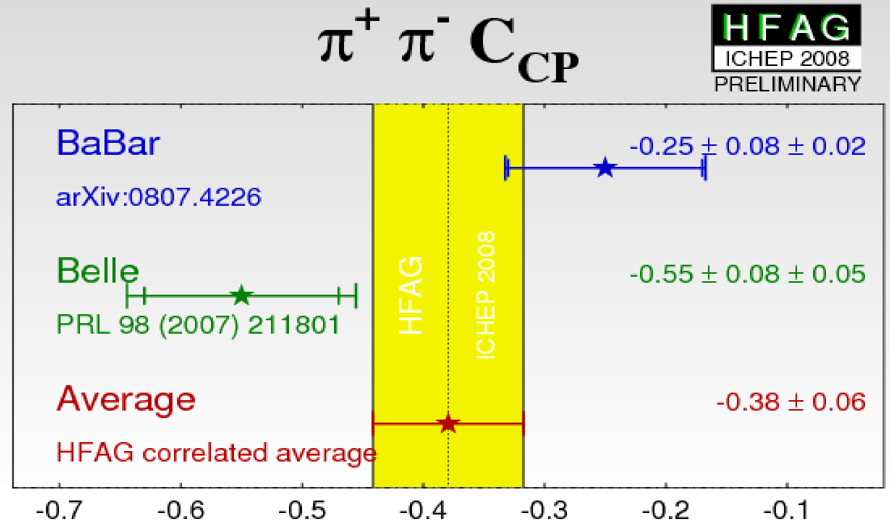
- larger BF, low penguin contamination
- VV final state, but dominated by longitudinal polarization (~pure CP-even)

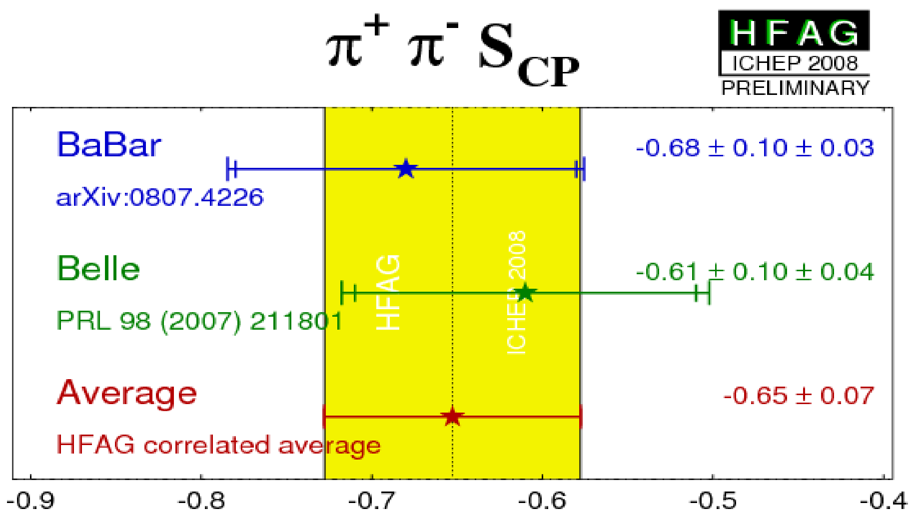


CP Asymmetries in B->π+π-



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





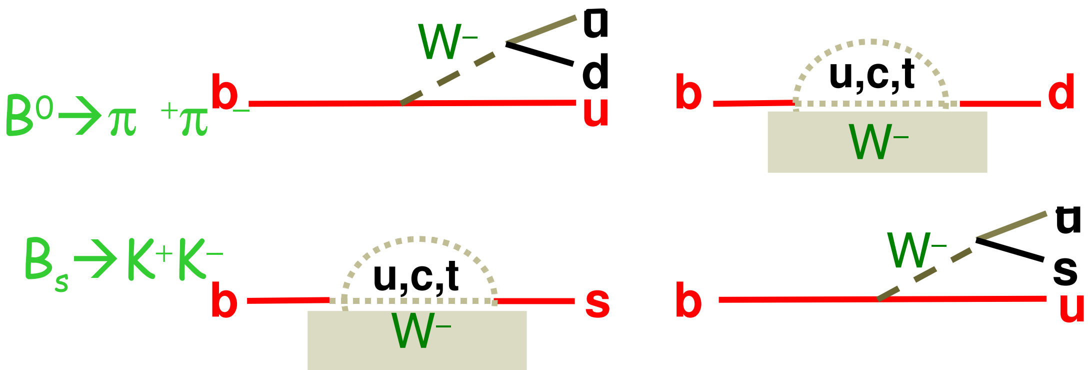
Using penguins to measure γ

- 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 $B_s \rightarrow K^+K^-$

Dominant Sub-dominant



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

Using penguins to measure γ cont'd

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

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

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

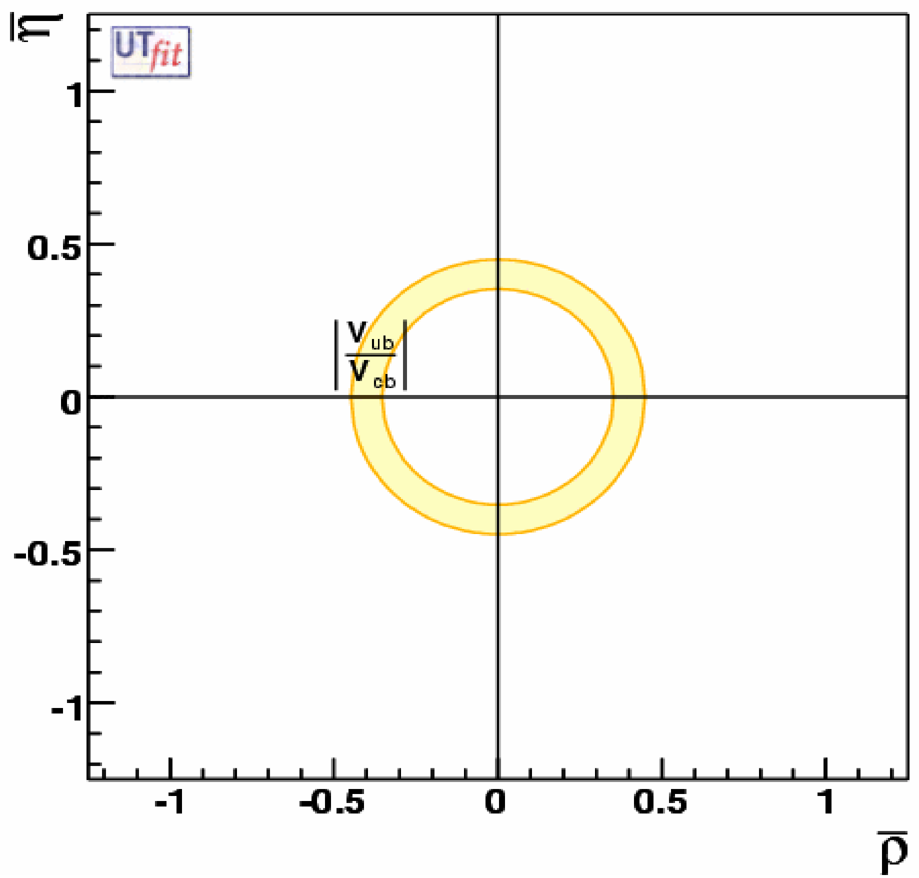
$$A_{CP}^{mix}(KK) = \frac{2\lambda^2}{d(1-\lambda^2)} \cos\theta \, \sin\gamma + O((\lambda^2/d)^2)$$

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

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



$\rho = 0.155 \pm 0.022$

$\eta = 0.342 \pm 0.014$

http://www.utfit.org/