LHCb

B Physics & CP Violation

Part 2/4

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Outline

Part 1: Introduction to Flavour Physics

- What is flavour physics & why is it interesting?
- Brief history of discovery in flavour physics
- CKM mechanism and Unitarity Triangle (UT)
- B-physics Experiments

Part 2: CP violation & CKM measurements (Triumphs of the SM)

- Meson-antimeson oscillations
- Introduction to CP violation
- Measurement of UT angles
- Measurement of UT sides

Part 3: Search for New Physics

- Radiative Decays
- Tauonic Decays
- Purely Leptonic Decays

Part 4: The future

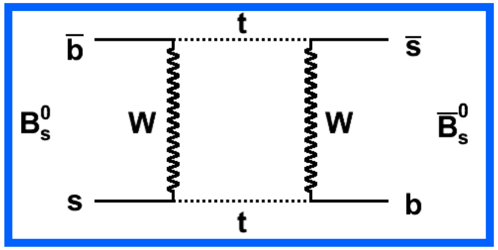
- Future B experiments

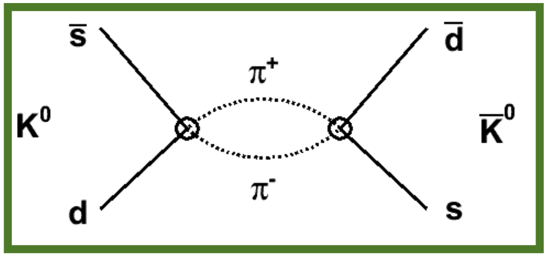
Neutral Meson Mixing

The eigenstates of flavour M^0 anti-M^0, degenerate in pure QCD, mix under weak interactions.

M^0 : K^0 (anti-s d), D^0(c anti-u), B^0(anti-b d), B_s^0(anti-b s)

Mixing can occur via short distance or long distance processes





Time dependent Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

H is Hamiltonian, **M** & **Γ** are 2x2 Hermitian matrices

CPT Theorem: particle and antiparticle have equal masses & lifetimes

$M_{11}=M_{22}$, $\Gamma_{11}=\Gamma_{22}$

Schrödinger equation

Physical states: eigenstates of the effective Hamiltonian

$$M_{S,L} = p\, M^0 \pm q\, \bar{M}^0$$

CP conserved if physical states = CP eigenstates (**|q/p|=1**)

Eigenvalues:

$$\lambda_{S,L} = m_{S,L} - ½i\Gamma_{S,L} = (M_{11} - ½i\Gamma_{11}) \pm (q/p)(M_{12} - ½i\Gamma_{12})$$

$$\Delta m = m_L - m_S \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

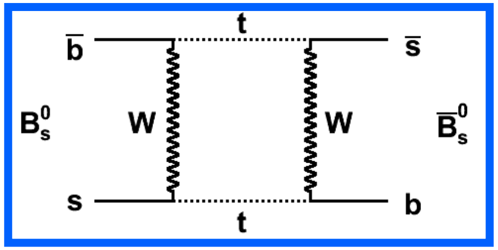
$$(\Delta m)^2 - ¼(\Delta\Gamma)^2 = 4(|M_{12}|^2 + ¼|\Gamma_{12}|^2)$$

$$\Delta m \Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

$$(q/p)^2 = (M_{12}^* - ½i\Gamma_{12}^*)/(M_{12} - ½i\Gamma_{12})$$

Neutral Meson Mixing: 2 Mechanisms

Δm: value depends on rate of mixing diagram

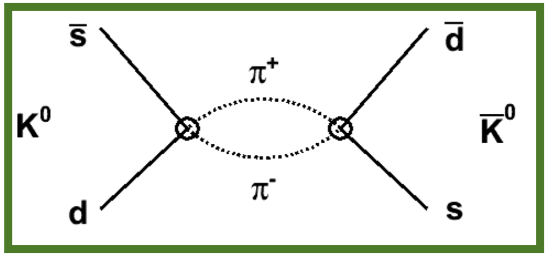


$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

$$x = \frac{\Delta m}{\Gamma} \sim \mathcal{O}(1)$$

ΔΓ: value depends on widths of decays into common final states (CP - eigenstates)

large for K, small for D and B

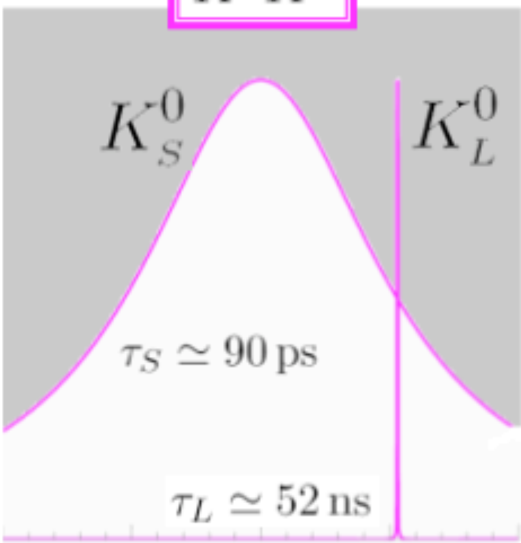


$$y = \frac{\Delta\Gamma}{\Gamma} \sim \mathcal{O}(1)$$

Note: CP violation in mixing when $|q/p| \neq 1$

The Neutral Meson-Antimeson Systems

$K^0\overline{K}^0$

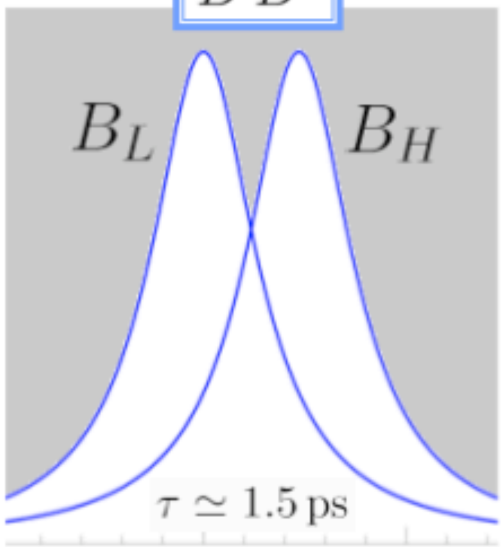


$\Delta m_K = 5\times10^{-3}\,\mathrm{ps}^{-1}$

x $\Delta m_K/\Gamma_K \simeq 0.945$

y $\Delta\Gamma_K/2\Gamma_K \approx -1$

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

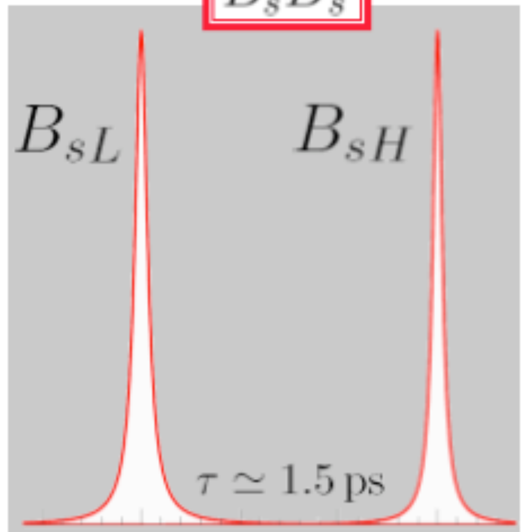


$\Delta m_d = 0.5\,\mathrm{ps}^{-1}$

x $\Delta m_d/\Gamma_d \simeq 0.75$

y $|\Delta\Gamma_d|/2\Gamma_d \ll 1$

$B_s\overline{B}_s$



$\Delta m_s = 18\,\mathrm{ps}^{-1}$

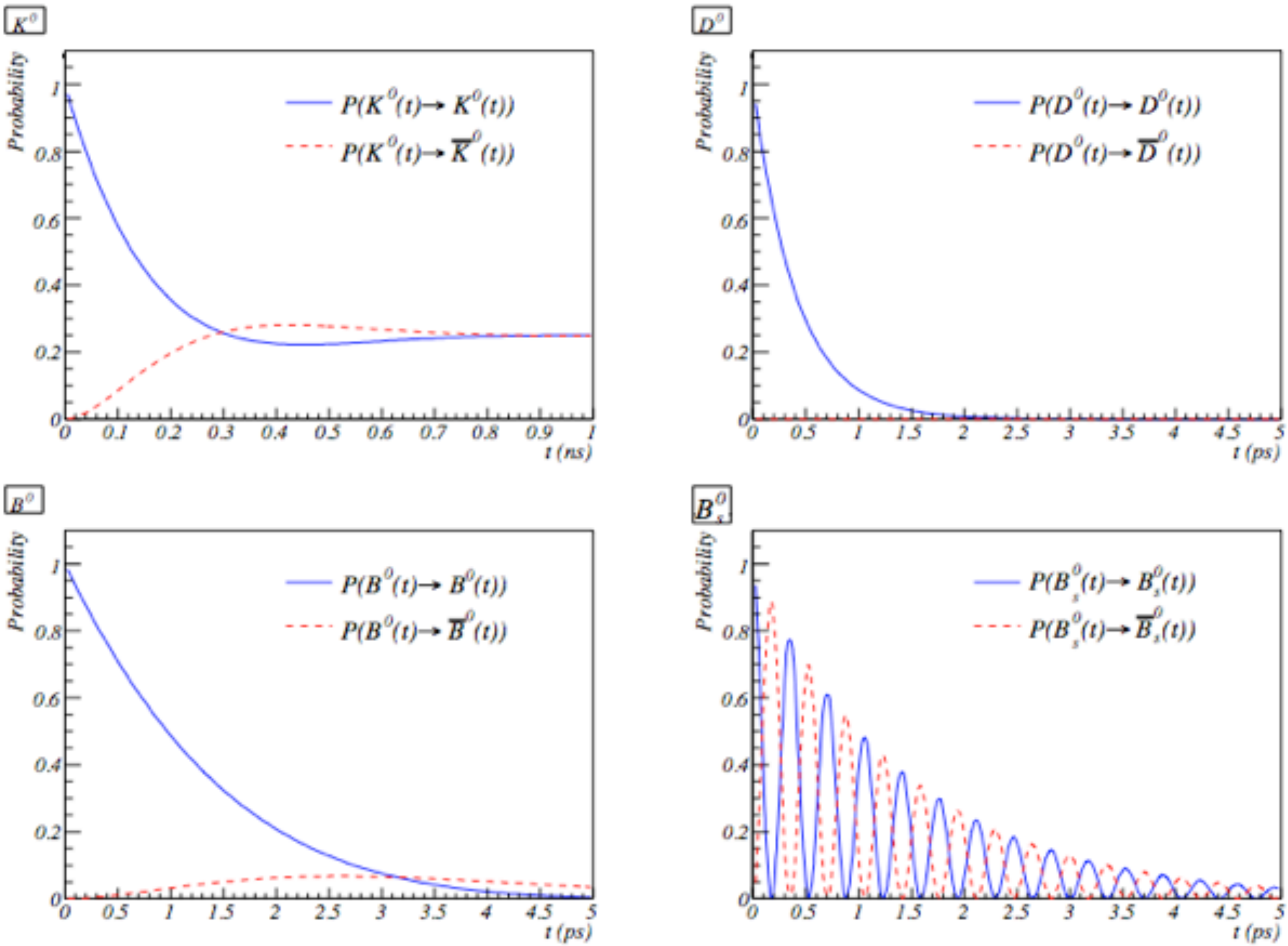
x $\Delta m_s/\Gamma_s = 26$

y $|\Delta\Gamma_s|/2\Gamma_s \approx 0.1$

$D^0/\overline{D^0}$
τ=0.4 ps^{-1}
mixes slowly
$\Delta m_D \sim 0.01$

Δm=2π ×frequency of flavour oscillation (1 ps^{-1} →160 GHz)

Mixing in the K, D, B, B_s Systems

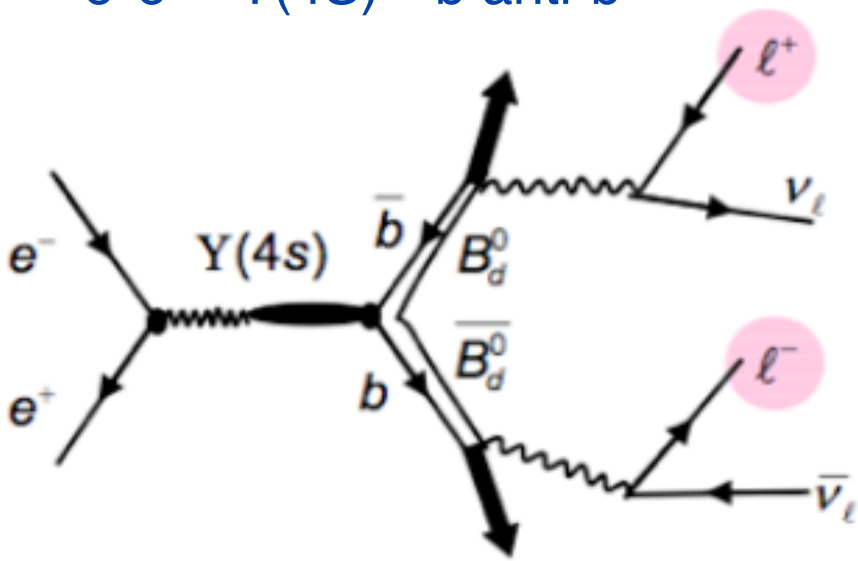


Discovery of Mixing in B-System

First e^+e^- B-factory at DESY:

at $\sqrt{s}$=10.58 GeV:

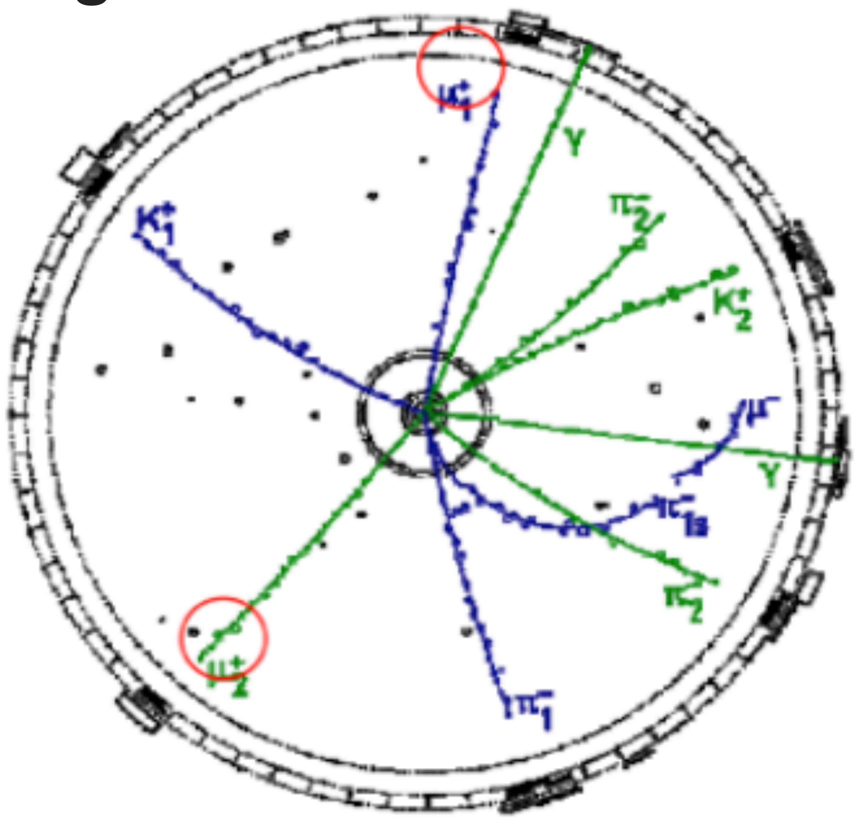
$e^+e^- \to \Upsilon(4S) \to$ b anti-b



unMixed $B^0\bar{B}^0 \to \ell^+\ell^-$

Mixed $B^0B^0 \to \ell^+\ell^+$, $\bar{B}^0\bar{B}^0 \to \ell^-\ell^-$ } **Same charge**

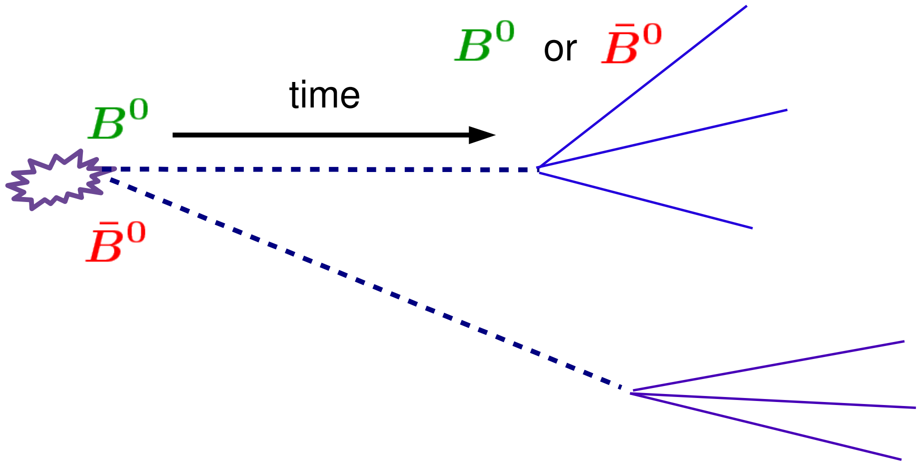
Argus 1987



$B^0 \to D^{*-}\mu^+\nu_\mu$, $D^{*-} \to \bar{D}^0\pi_s^-$, $\bar{D}^0 \to K^+\pi^-$

$B^0 \to D^{*-}\mu^+\nu_\mu$, $D^{*-} \to D^-\pi^0$, $\pi^0 \to \gamma\gamma$, $D^- \to K^+\pi^-\pi^-$

Measurement of mixing



"signal B" / "tagging B"

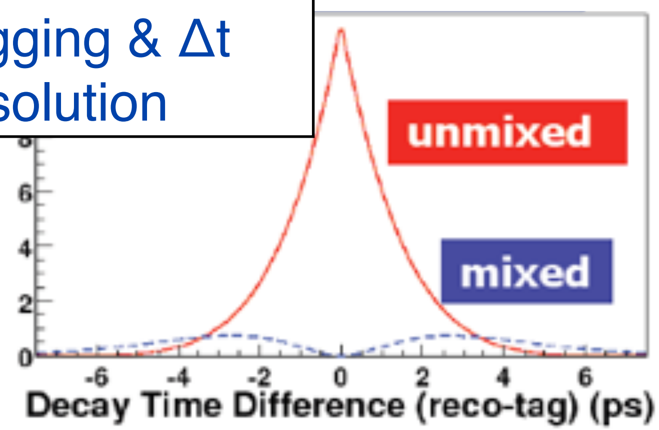
"tagging B" \ "signal B"	B^0	$\overline{B}^0$
B^0	mixed	unmixed
$\overline{B}^0$	unmixed	mixed

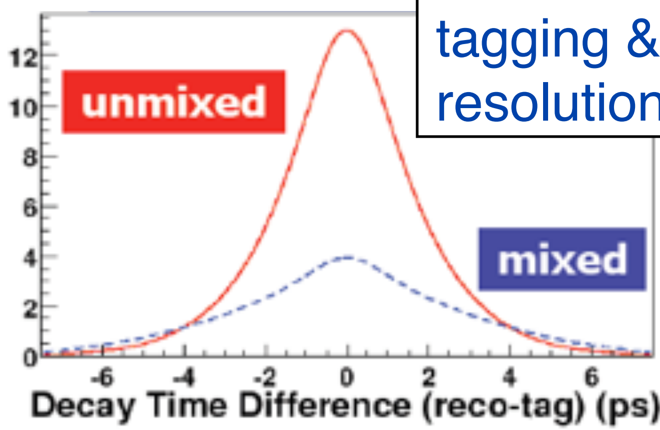
"tagging B"
can be charged or neutral

$$A_{\mathrm{mix}}(t) = \frac{N(B)_{\mathrm{un-mixed}}(t) - N(B)_{\mathrm{mixed}}(t)}{N(B)_{\mathrm{un-mixed}}(t) + N(B)_{\mathrm{mixed}}(t)} \sim \cos(\Delta m t)$$

perfect

tagging & Δt resolution



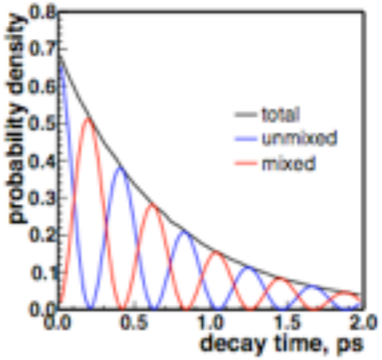


realistic

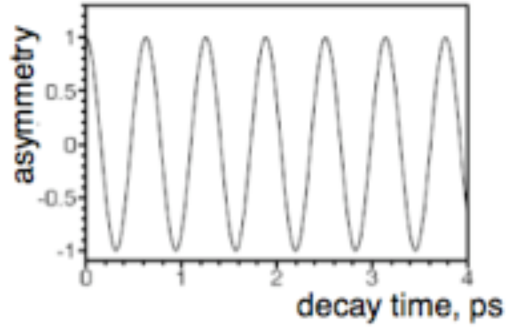
tagging & Δt resolution

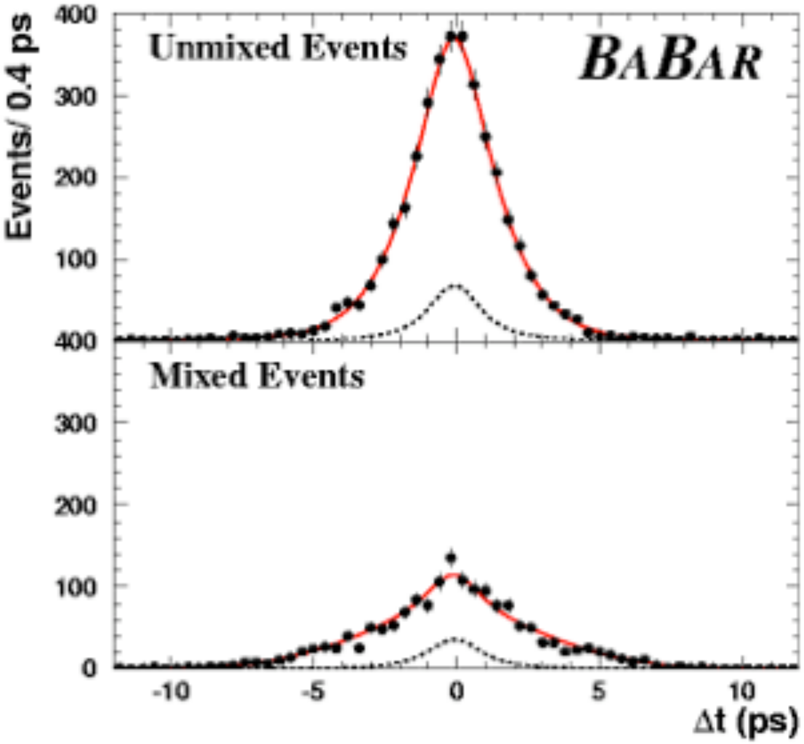
Negative Δt: Signal B decay before tagging B

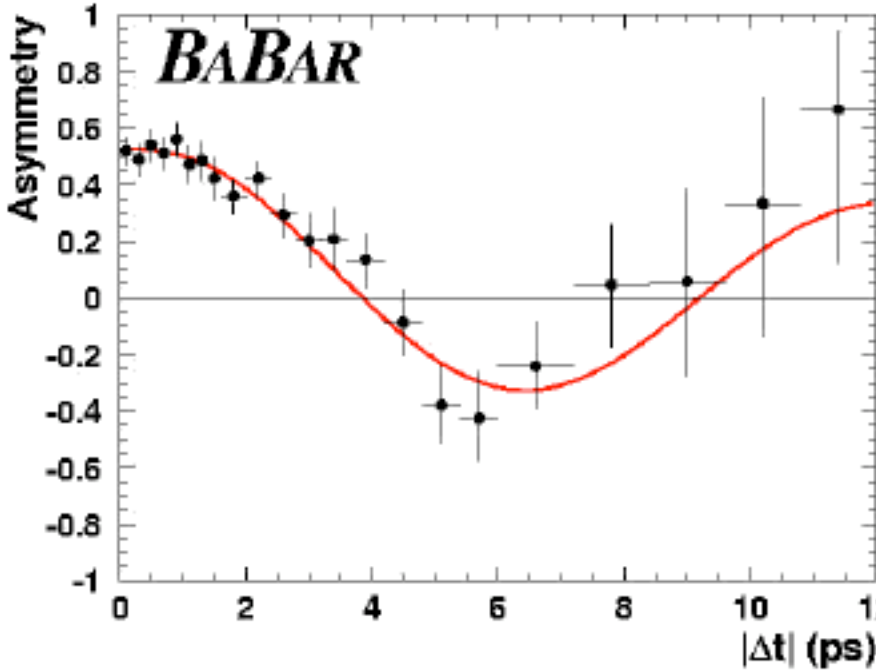
B Mixing Results (BaBar, 2001)



$$\mathcal{A} = \frac{\#unmixed - \#mixed}{\#unmixed + \#mixed}$$



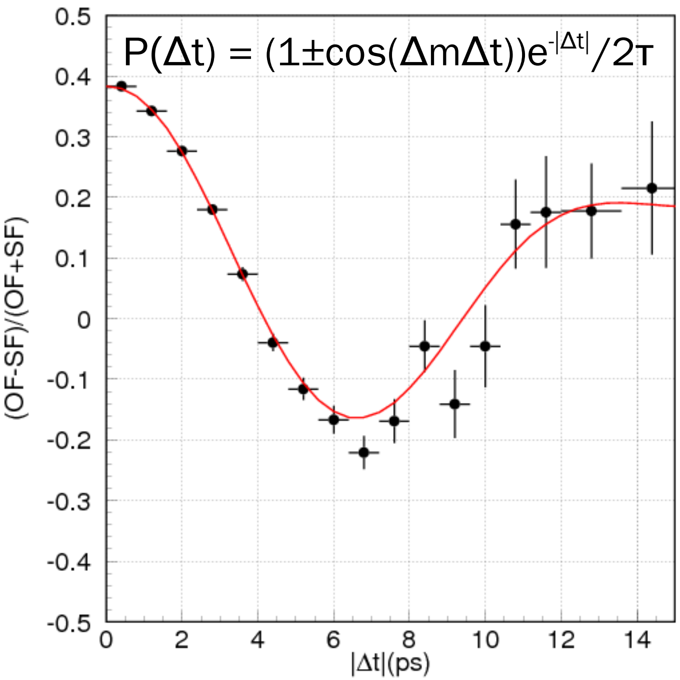




B and B_s Mixing at LHCb (2013)

$$A^{mix} = \frac{N^{unmixed}(t) - N^{mixed}(t)}{N^{unmixed}(t) + N^{mixed}(t)}$$

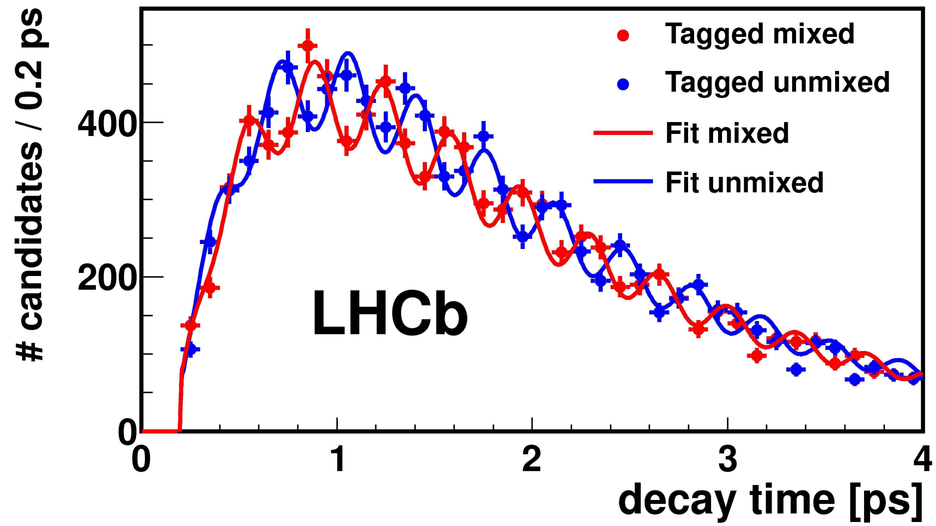
$B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$



$\Delta m_d = (0.511 \pm 0.005 \pm 0.006)\ ps^{-1}$

PRD 71, 072003 (2005)

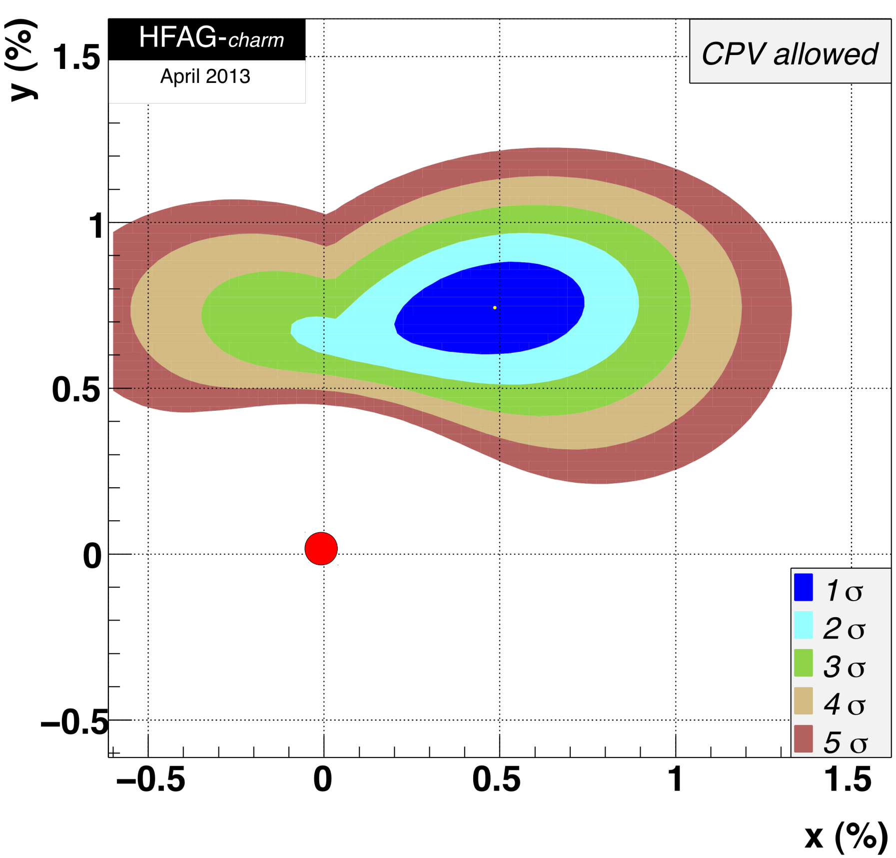
$B_s \to D_s(3)\pi$



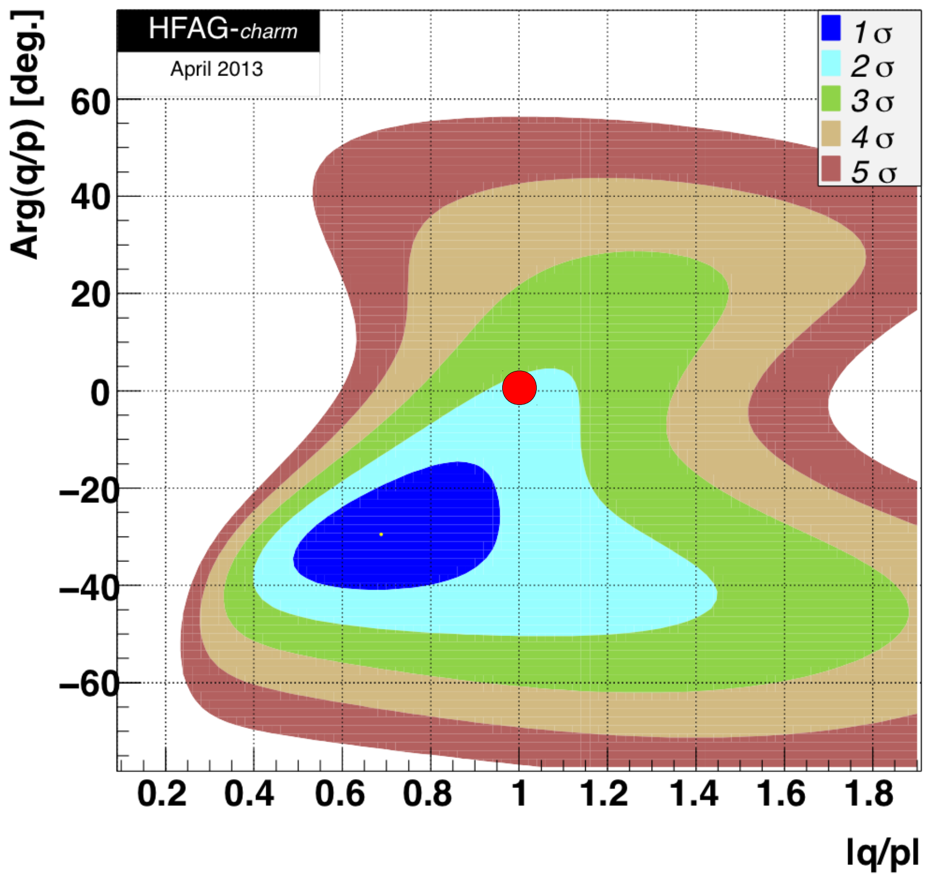
$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ ps^{-1}$

NJP 15 (2013) 053021

D Meson Mixing (&CP Violation)



Inconsistent with no mixing point (0,0)



Consistent with no CP violation point (1,0)

LHCb making huge progress on CPV measurements.
Keep an eye out.

CP Violation

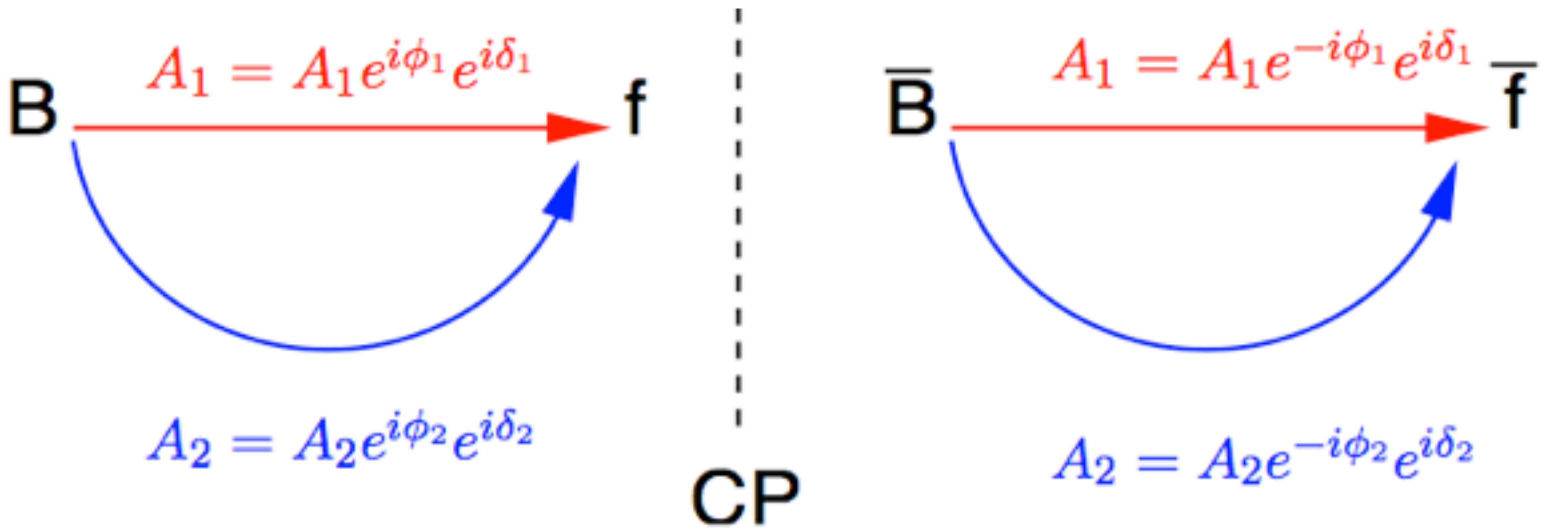
Formalism & measurements in B decays

CP Violation

CP violation caused by different interference effects in particle and anti-particle decays

One of the two amplitudes could be from mixing

Due to complex part of CKM matrix



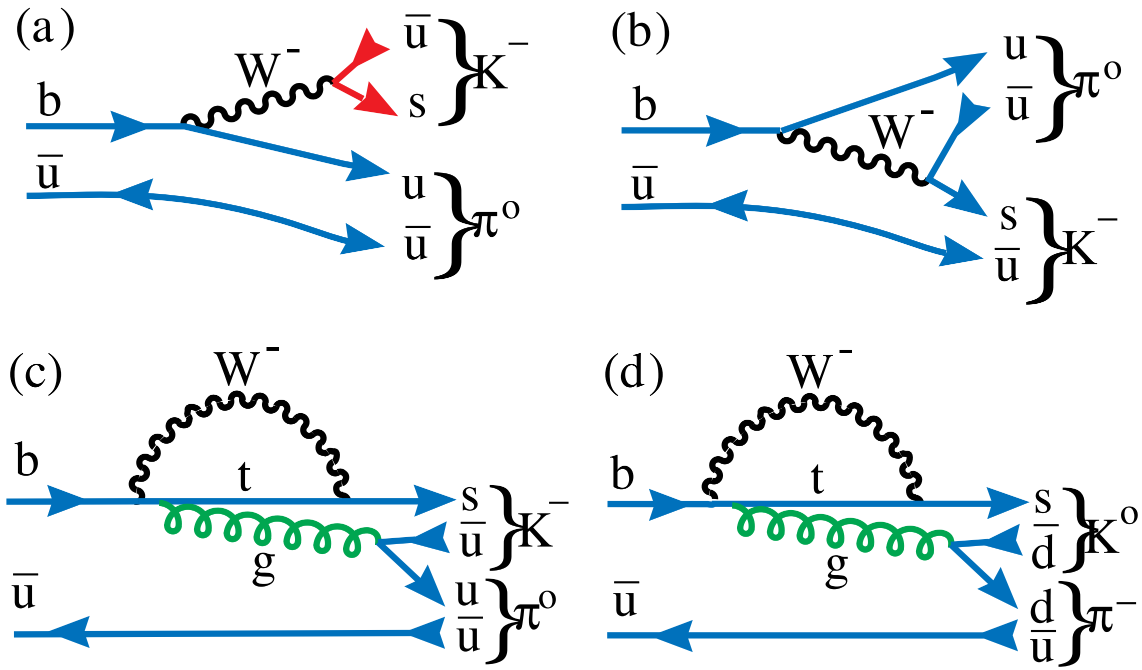
$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(-\Delta\phi + \Delta\delta)$$

For CPV A1 and A2 need to have **different weak phases Φ** and different **CP invariant (e.g. strong) phases δ**

CPV in Charged B decays

- Consider charged $B^+ \to K\pi$ decays.
- For $K^-\pi^0$, there are 3 diagrams, but only 1 for $K^0\pi^-$
- Therefore we expect CP violation in $K^-\pi^0$ but not in $K^0\pi^-$



- However, because we don't know the strong phases its difficult to get useful information on the weak phases.

Time Dependent CPV Formalism

Consider arbitrary final state f

Decay amplitudes of flavour states

$$\begin{cases} A_f \equiv A(P^0 \to f) = \langle f|H|P^0\rangle \\ \bar{A}_f \equiv A(\bar{P}^0 \to f) = \langle f|H|\bar{P}^0\rangle \end{cases}$$

Define

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

General time dependence of decay rate for initially pure flavour states

$$\Gamma(P^0 \to f)(t) = |A_f|^2(1+|\lambda_f|^2)\tfrac{1}{2}e^{-\Gamma t}\left[\cosh(\frac{1}{2}\Delta\Gamma t) + D_f\sinh(\frac{1}{2}\Delta\Gamma t) + C_f\cos(\Delta m t) - S_f\sin(\Delta m t)\right]$$

$$\Gamma(\bar{P}^0 \to f)(t) = |A_f|^2|\tfrac{p}{q}|^2(1+|\lambda_f|^2)\tfrac{1}{2}e^{-\Gamma t}\left[\cosh(\frac{1}{2}\Delta\Gamma t) + D_f\sinh(\frac{1}{2}\Delta\Gamma t) - C_f\cos(\Delta m t) + S_f\sin(\Delta m t)\right]$$

$$D_f = \frac{2\mathrm{Re}\{\lambda_f\}}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad S_f = \frac{2\mathrm{Im}\{\lambda_f\}}{1+|\lambda_f|^2}$$

- For a given final state **f**, the parameter $\boldsymbol{\lambda_f}$ fully describes the CPV in the decay (oscillation) of the meson

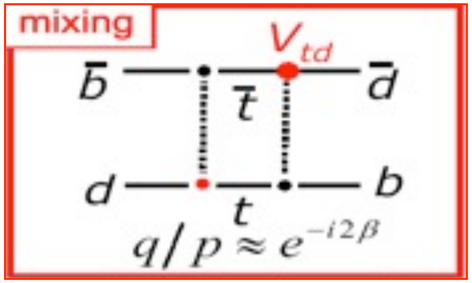
Classification of CP-violating Effects

- Condition for CP conservation

$$|\langle f_{\rm CP}|H|P^0(t)\rangle|^2 = |\langle f_{\rm CP}|H|\bar{P}^0(t)\rangle|^2$$

- CP Conservation implies

$$|q/p| = 1$$
$$|\lambda_{f_{CP}}| = 1$$
$$\mathrm{Im}\lambda_{f_{\rm CP}} = 0$$



1. CP violation in the decay
   (**direct CP violation**)

$$\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f}) \Leftrightarrow \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

2. CP violation in mixing
   (**indirect CP violation**)

$$\Gamma(P^0 \to \bar{P}^0) \neq \Gamma(\bar{P}^0 \to P^0) \Leftrightarrow \left|\frac{q}{p}\right| \neq 1$$

3. CP violation in mixing/
   decay **interference**

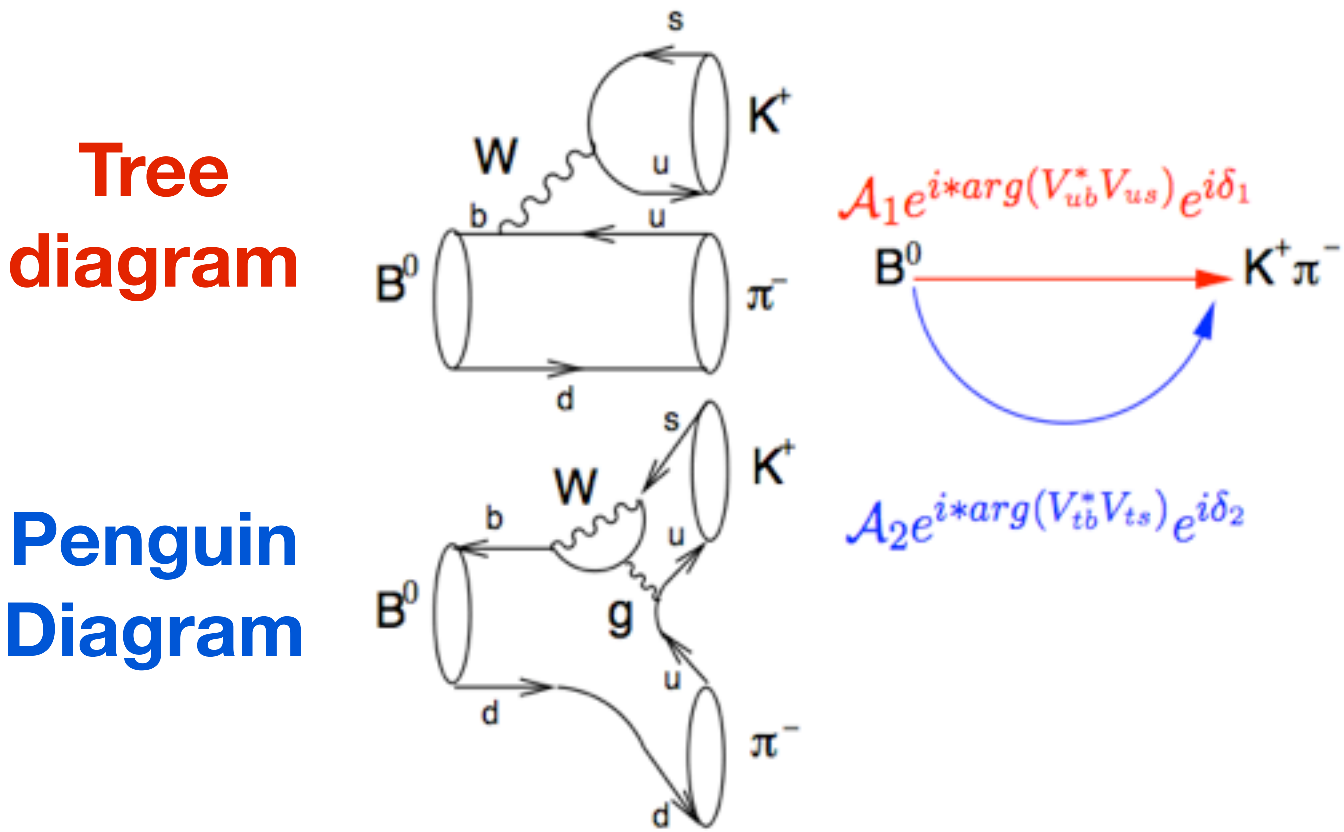
$$\Gamma(P^0(\rightsquigarrow \bar{P}^0) \to f)(t) \neq \Gamma(\bar{P}^0(\rightsquigarrow P^0) \to f)(t)$$

CP Violation

1. Direct

1. Direct CP Violation: $B^0 \rightarrow K^+\pi^-$

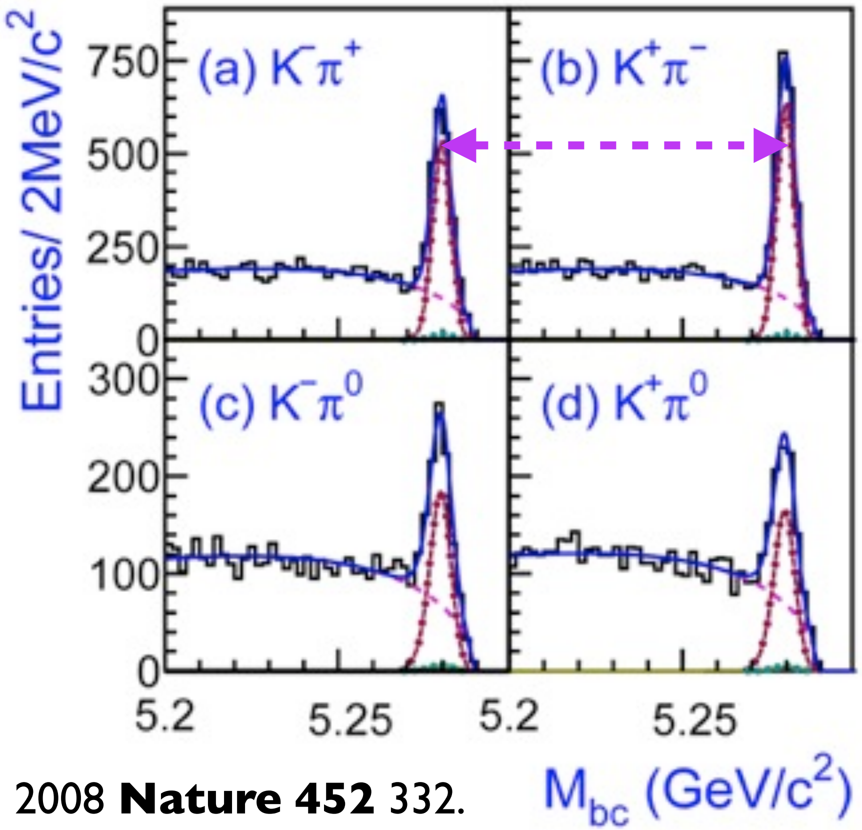
e.g.: B→Kπ



Measure asymmetry between $B^0 \rightarrow K^+\pi^-$ and $B^0 \rightarrow K^-\pi^+$

$$|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2 = 2|A_1||A_2|[\cos(arg(V_{tb}^* V_{ts}) + \Delta\delta) - \cos(arg(V_{tb}^* V_{ts}) - \Delta\delta)]$$

Direct CP Violation $B^o \to K^+\pi^-$



2008 **Nature 452** 332.

Discovered in 2004 (BaBar & Belle)

$$A_{CP} = \frac{N(\bar{B}^0 \to K^+\pi^-) - N(B^0 \to K^-\pi^+)}{N(\bar{B}^0 \to K^+\pi^-) + N(B^0 \to K^-\pi^+)}$$

$A_{CP}(K^-\pi^+) = -0.082 \pm 0.006$

$A_{CP}(K^-\pi^0) = +0.040 \pm 0.021$

"Kπ puzzle"

$$P(B^0 \to K^+\pi^-) > P(\bar{B}^0 \to K^-\pi^+)$$

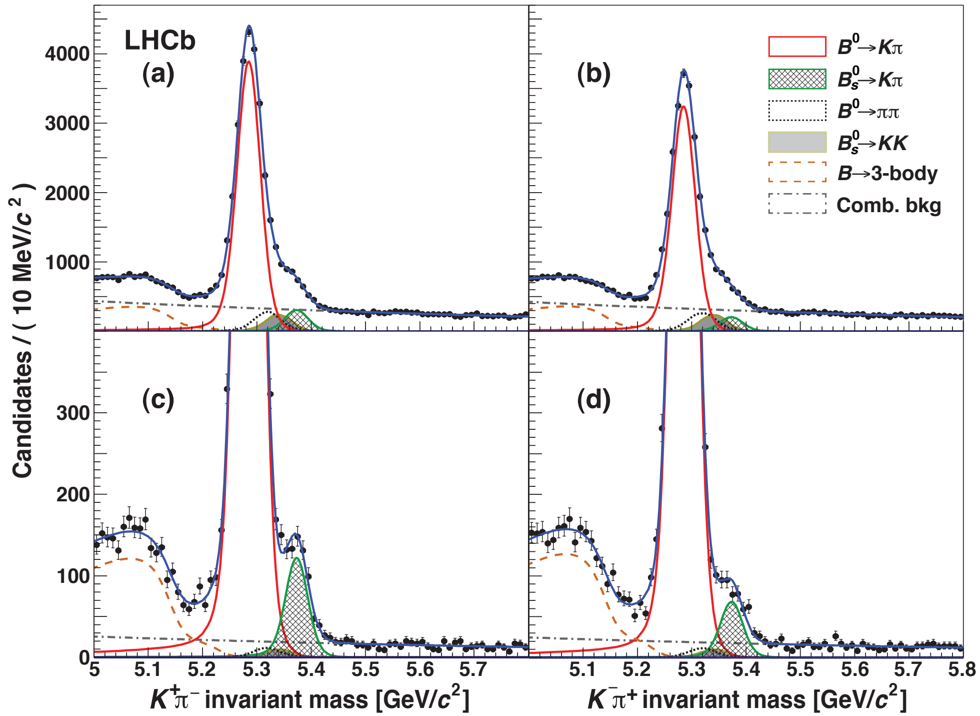
Could be a sign of new physics ...

... but first need to rule out possibility of larger than expected QCD corrections

How to rule out QCD effects?

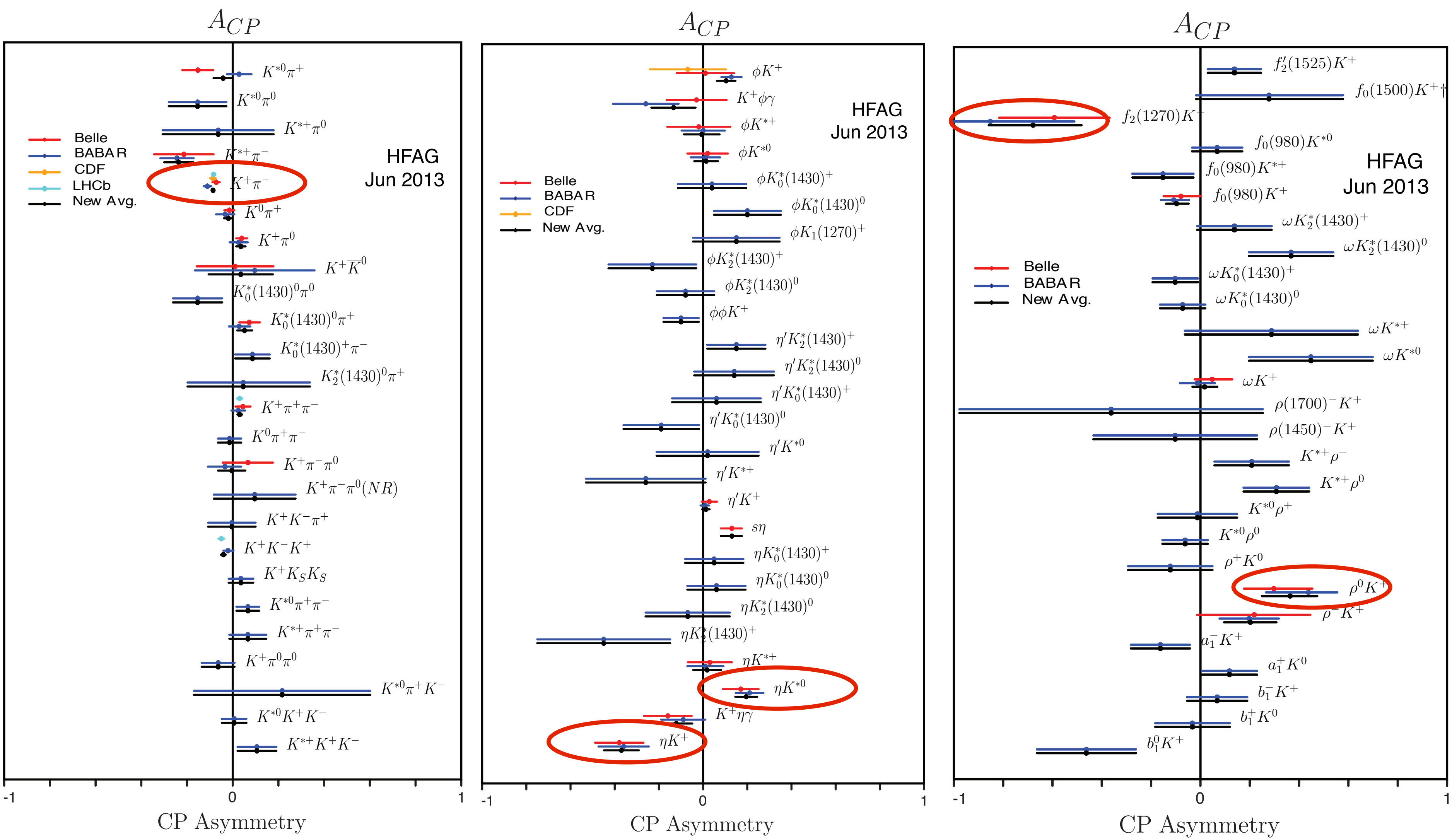
- How to rule out QCD effects?
  - Measure more $B_{u,d} \to K\pi$ decays & relate by isospin
  - Perform similar analyses on $B \to K^*\pi$ &/or $B \to K\rho$
  - Measure $B_s \to KK$ decays & relate by U-spin
- First evidence of CPV in B_s ==>

PRL 110 (2013) 221601



$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst}).$$

Status of Direct CP Violation Measurements



CP Violation

2. Mixing

CP violation in Mixing

- ***$B^0 \to X l^+ \nu$***
- Lepton charge identifies B^0 flavour in semileptonic decays:

$$\begin{aligned} B^0 &: \quad b \to \bar{c}\ell^+\nu \\ \bar{B}^0 &: \quad \bar{b} \to c\ell^-\bar{\nu} \end{aligned}$$

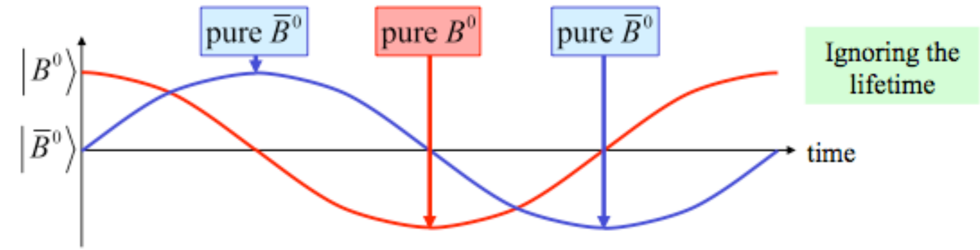
$$\text{If CPV} \Rightarrow P(B^0 \to \bar{B}^0) \neq P(\bar{B}^0 \to B^0)$$

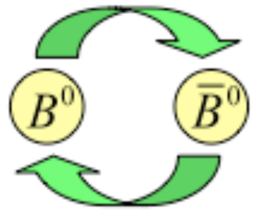
  - Probability to observe two **negatively** charged leptons
  - Probability to observe two **positively** charged leptons
  - **$N^{--} \neq N^{++}$**

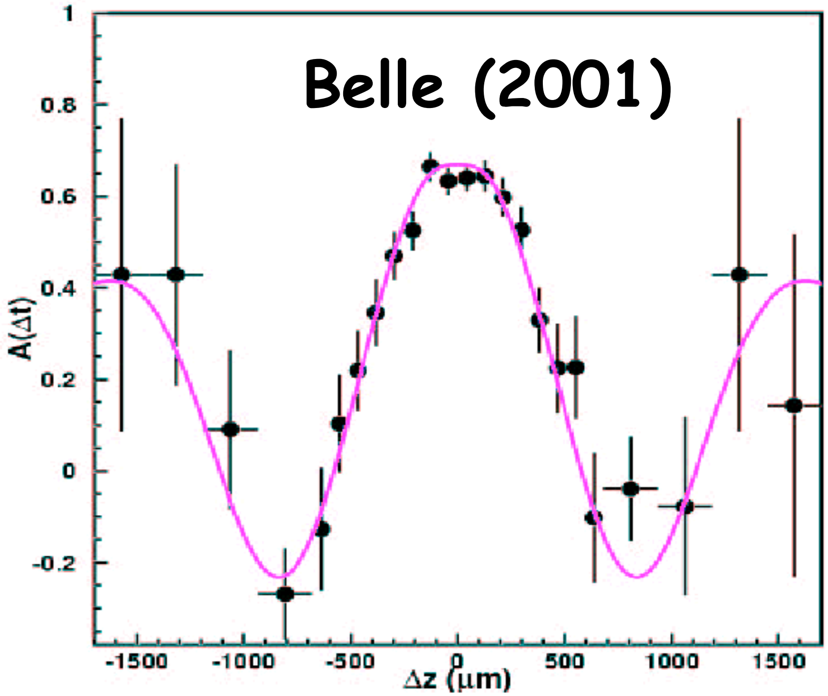
$$A_{CP} = \frac{P(\bar{B}^0 \to B^0) - P(B^0 \to \bar{B}^0)}{P(\bar{B}^0 \to B^0) + P(B^0 \to \bar{B}^0)} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{1 - |\frac{1}{p}|^4}{1 + |\frac{1}{p}|^4}$$

CP violation in Mixing

Starting from a pure $|B^0\rangle$ state, the wave function evolves as







$$A(\Delta t) = \frac{N^{+-} - N^{\pm\pm}}{N^{+-} + N^{\pm\pm}} \sim \cos \Delta m \Delta t$$

$N^{++}-N^{--} / N^{++}+N^{--} = 1-|q/p|^4 / 1+|q/p|^4$

⇒ $|q/p| = 1.0024 \pm 0.0023$

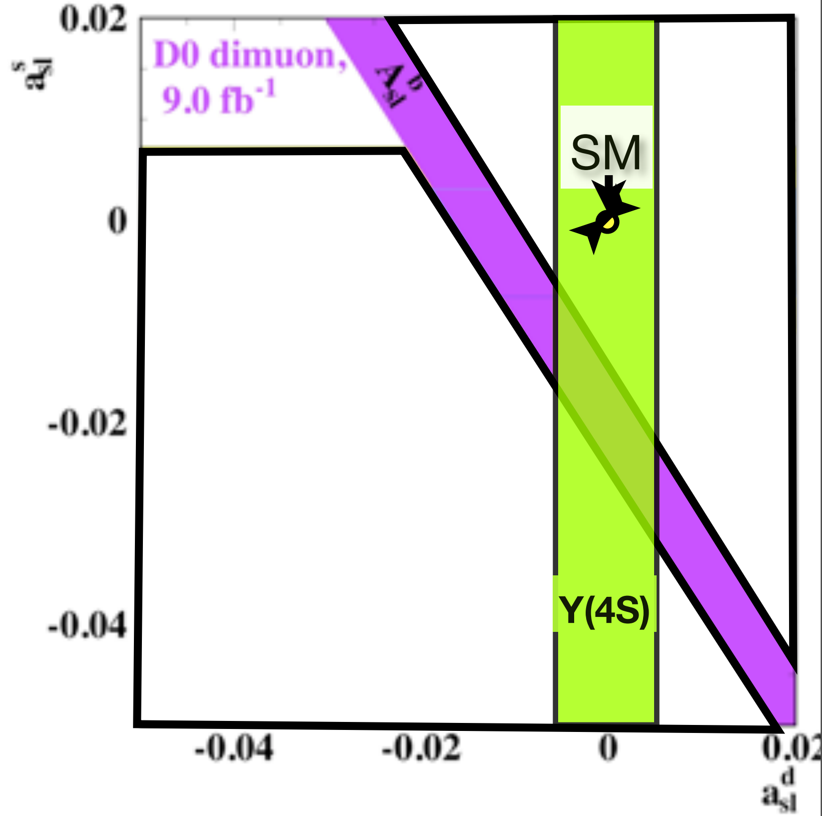
⇒ CPV in mixing negligible in B system

CPV in Mixing: Semileptonic B_s decays

- D0: μμ inclusive - similar to Y(4S) approach (subtract effect of B_d)
  - ➡3.9σ from SM!
- LHCb & D0: $D_s\mu$ (purified B_s sample)

$$a_{sl}^{s} \equiv \frac{\Gamma(\bar{B}_s^0 \to D_s^- \mu^+) - \Gamma(B_s^0 \to D_s^+ \mu^-)}{\Gamma(\bar{B}_s^0 \to D_s^- \mu^+) + \Gamma(B_s^0 \to D_s^+ \mu^-)}$$

- ➡agrees with SM



Thursday, 29 August 13

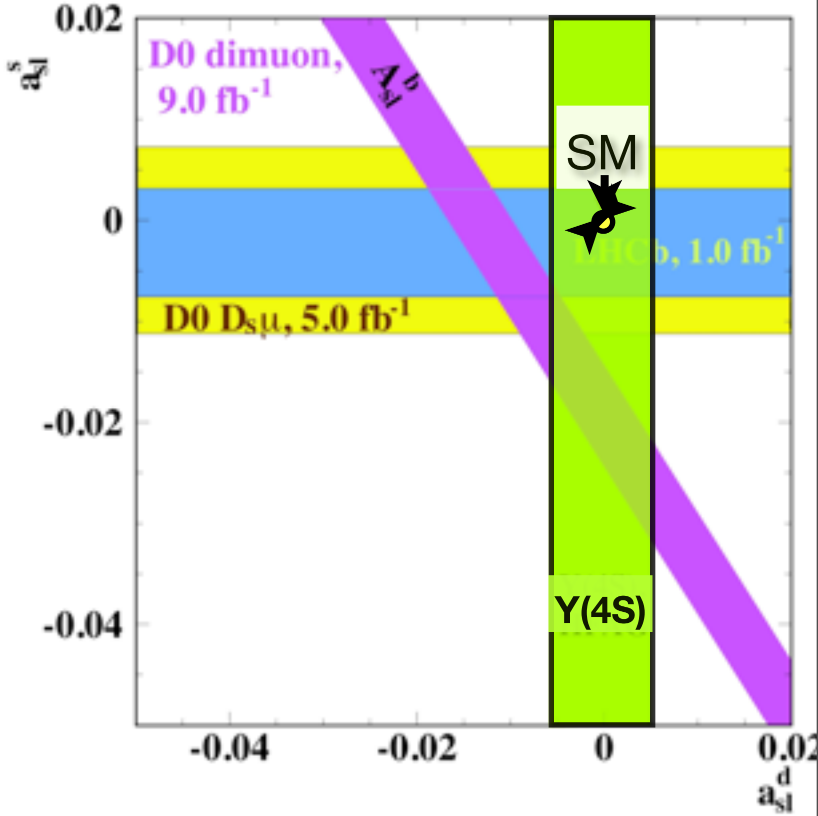
CPV in Mixing: Semileptonic B_s decays

- D0: μμ inclusive - similar to Y(4S) approach (subtract effect of B_d)
  - ➡3.9σ from SM!

- LHCb & D0: $D_s\mu$ (purified B_s sample)

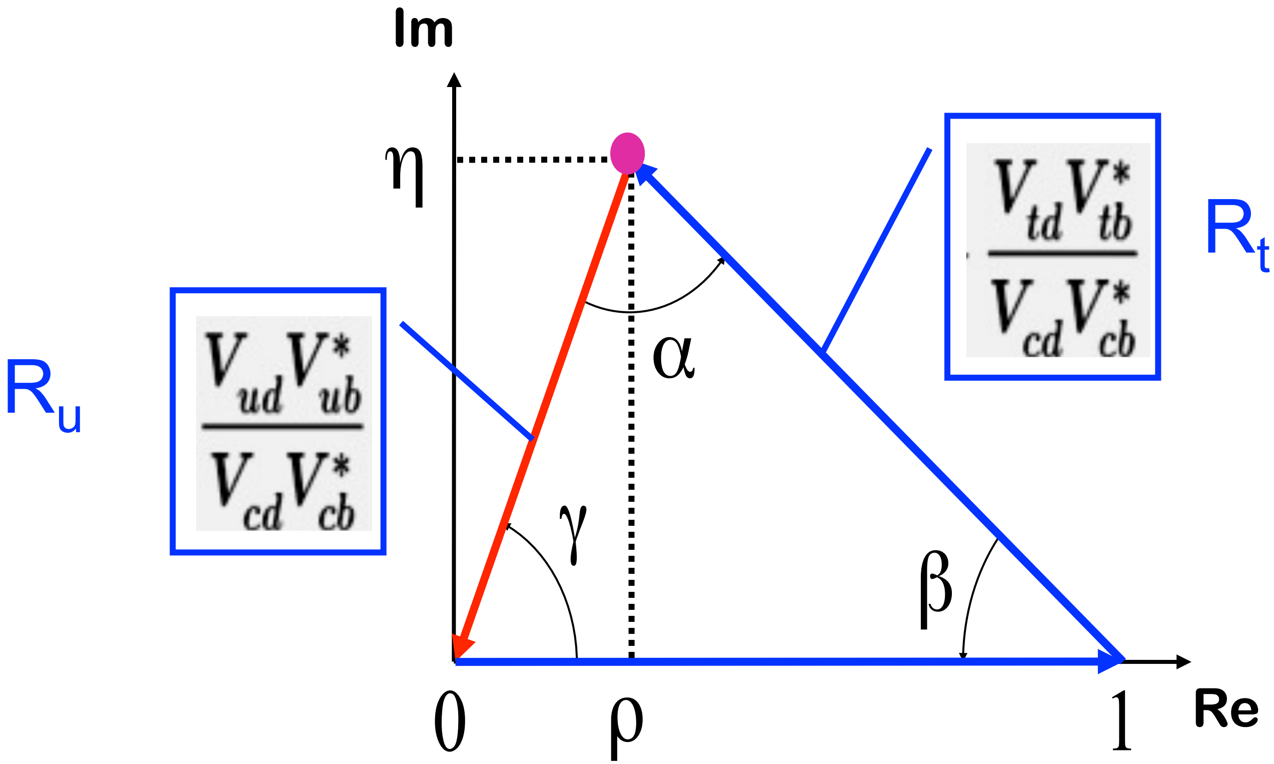
$$a_{sl}^{s} \equiv \frac{\Gamma(\bar{B}_s^0 \to D_s^-\mu^+) - \Gamma(B_s^0 \to D_s^+\mu^-)}{\Gamma(\bar{B}_s^0 \to D_s^-\mu^+) + \Gamma(B_s^0 \to D_s^+\mu^-)}$$

  - ➡agrees with SM



CP Violation

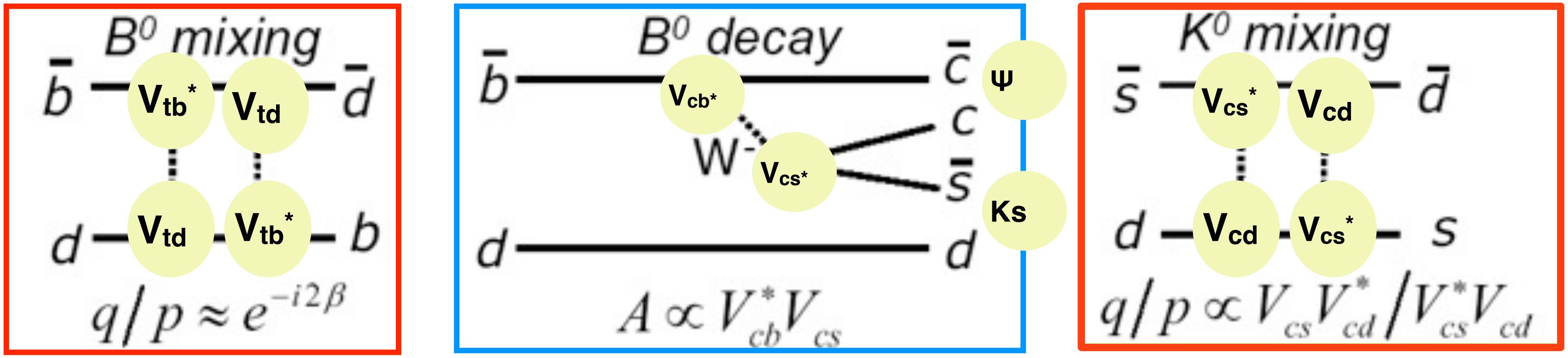
3. Interference



3.1 Measurement of angle β using CP eigenstates

More precisely: CP violation in interference between **decay** w/ and w/o **mixing**

The "Golden Decay": $B^0 \rightarrow J/\Psi\, K^0$ (theoretically clean: tree diagram dominates)



Select K_S through decays

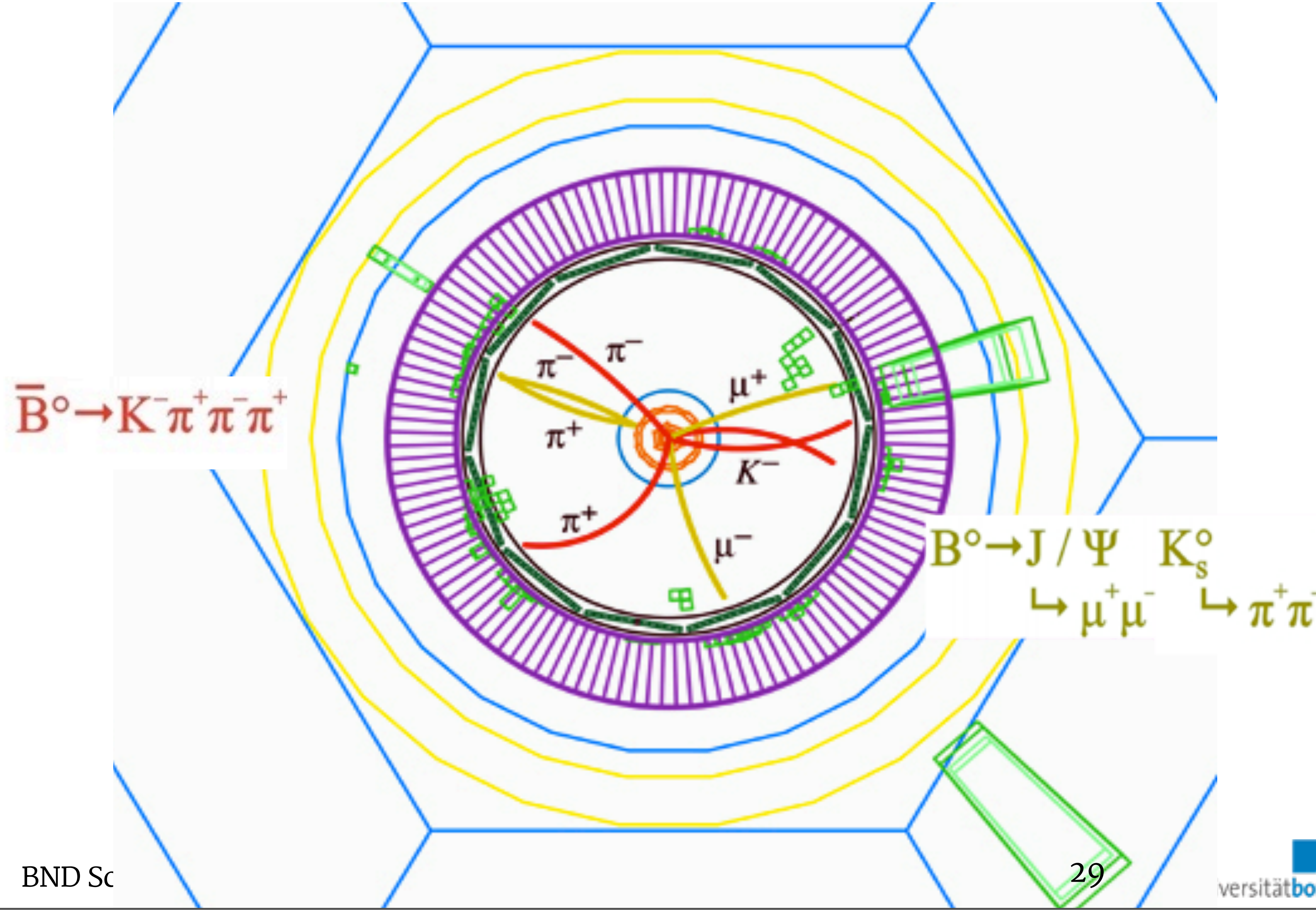
$$|K_s^0\rangle \approx p|K^0\rangle + q|\bar{K}^0\rangle$$
$$|K^0\rangle = \frac{1}{2p}(|K_S\rangle + |K_L\rangle)$$

$$K_s^0 \rightarrow \pi^+\pi^-$$
$$K_L^0 \rightarrow \pi^+\pi^-\pi^0, \quad \pi^-\ell^+\nu$$

decay **decay + mixing**

$$\arg(V_{cs}V_{cb}^*) - \arg(V_{td}^2 V_{tb}^2 V_{cb} V_{cs}^* V_{cs}^2 V_{cd}^{*2}) = -2\beta$$

“Golden-Decay” Event in the BaBar Detector



Time dependent asymmetry

- Define the time-dependent CP asymmetry

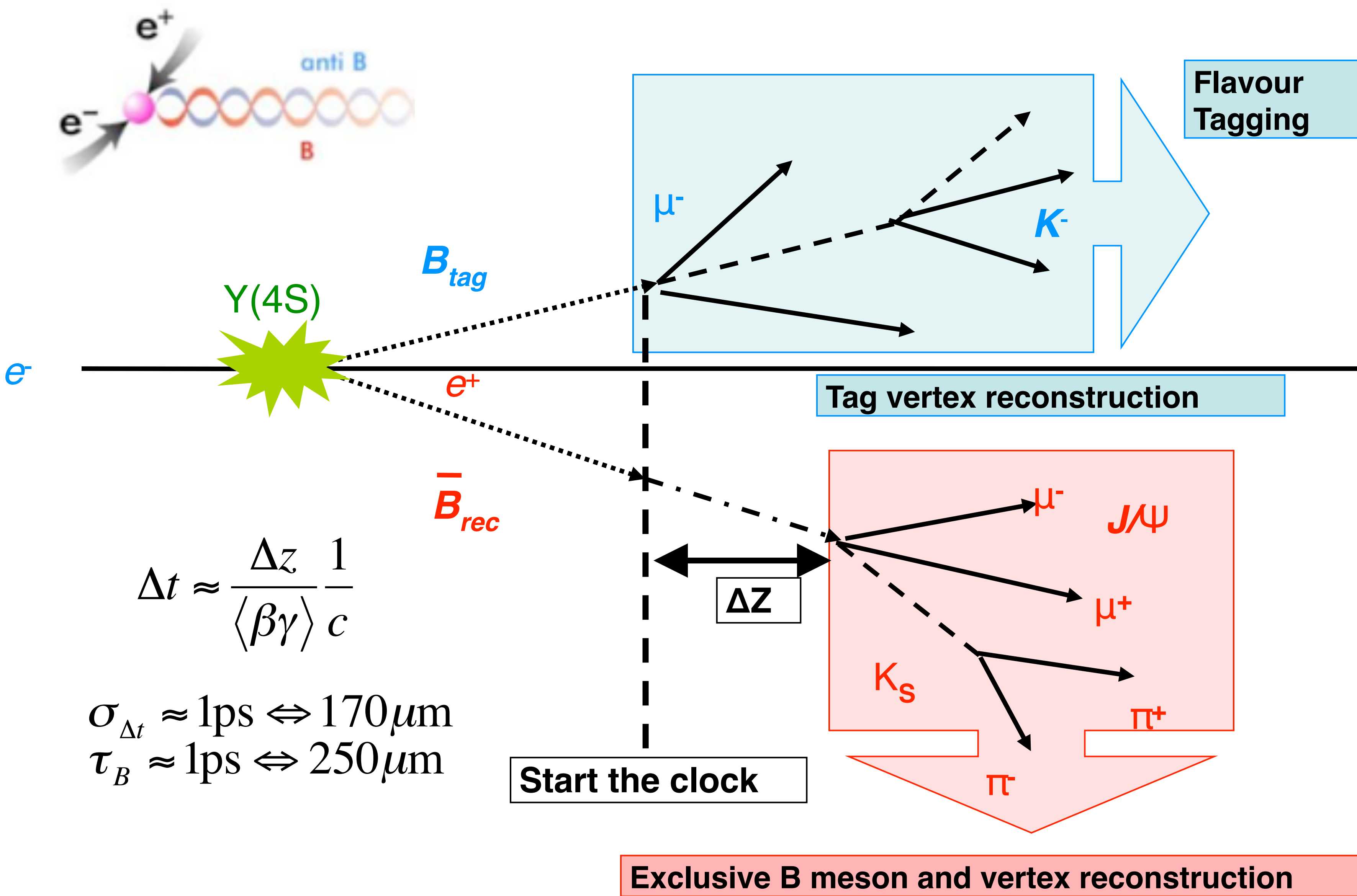
$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \to J/\psi K_S^0) - N(B^0(t) \to J/\psi K_S^0)}{N(\bar{B}^0(t) \to J/\psi K_S^0) + N(B^0(t) \to J/\psi K_S^0)} = \sin(2\beta)\sin(\Delta m t)$$

- We can measure the angle of the UT

What do we have to do to measure $A_{CP}(t)$?

- Step 1: Produce and detect $B^0 \to f_{CP}$ events
- Step 2: Separate B^0 from $\bar{B}^0$
- Step 3: Measure the decay time t

Measuring time dependent CP asymmetries

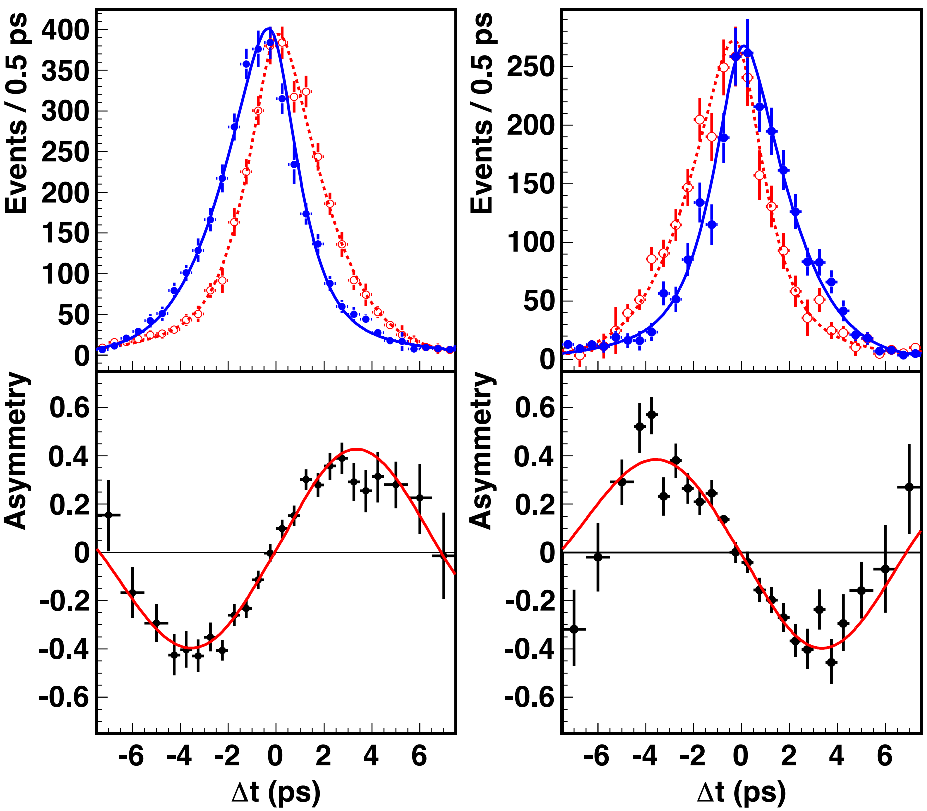


$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle}\frac{1}{c}$$

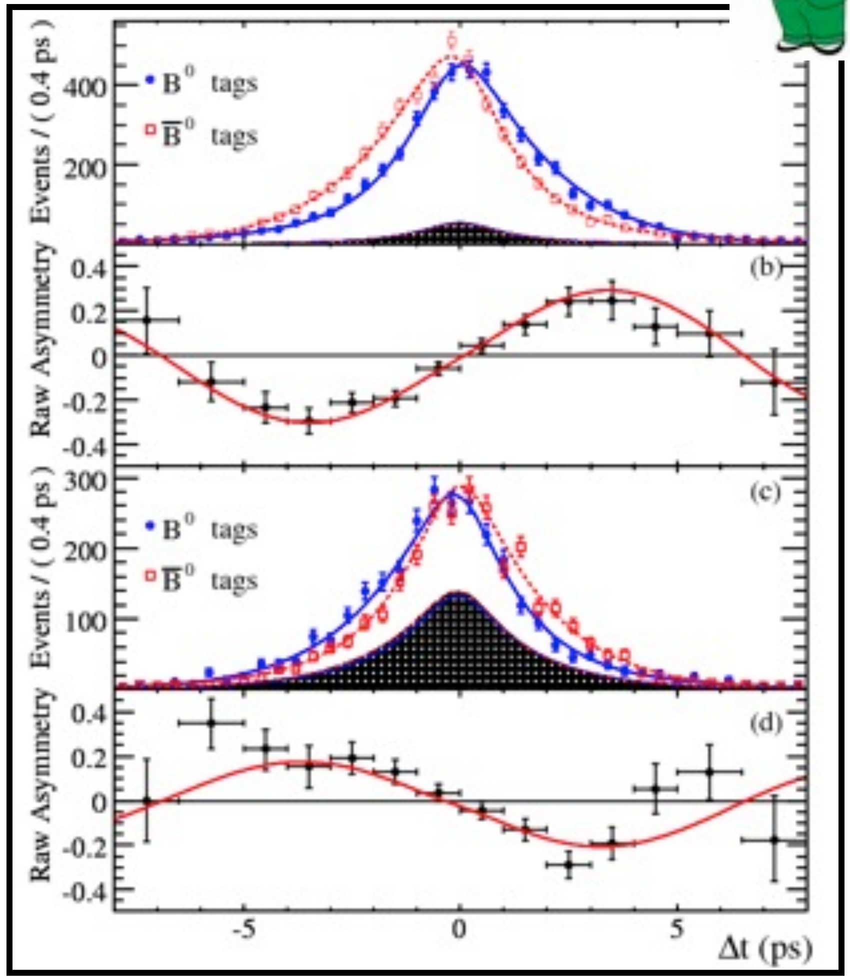
$$\sigma_{\Delta t} \approx 1\text{ps} \Leftrightarrow 170\mu\text{m}$$
$$\tau_B \approx 1\text{ps} \Leftrightarrow 250\mu\text{m}$$

sin2β Results

772M BB; PRL 108, 171802 (2012)



465M BB; PRD79 (2009) 072009



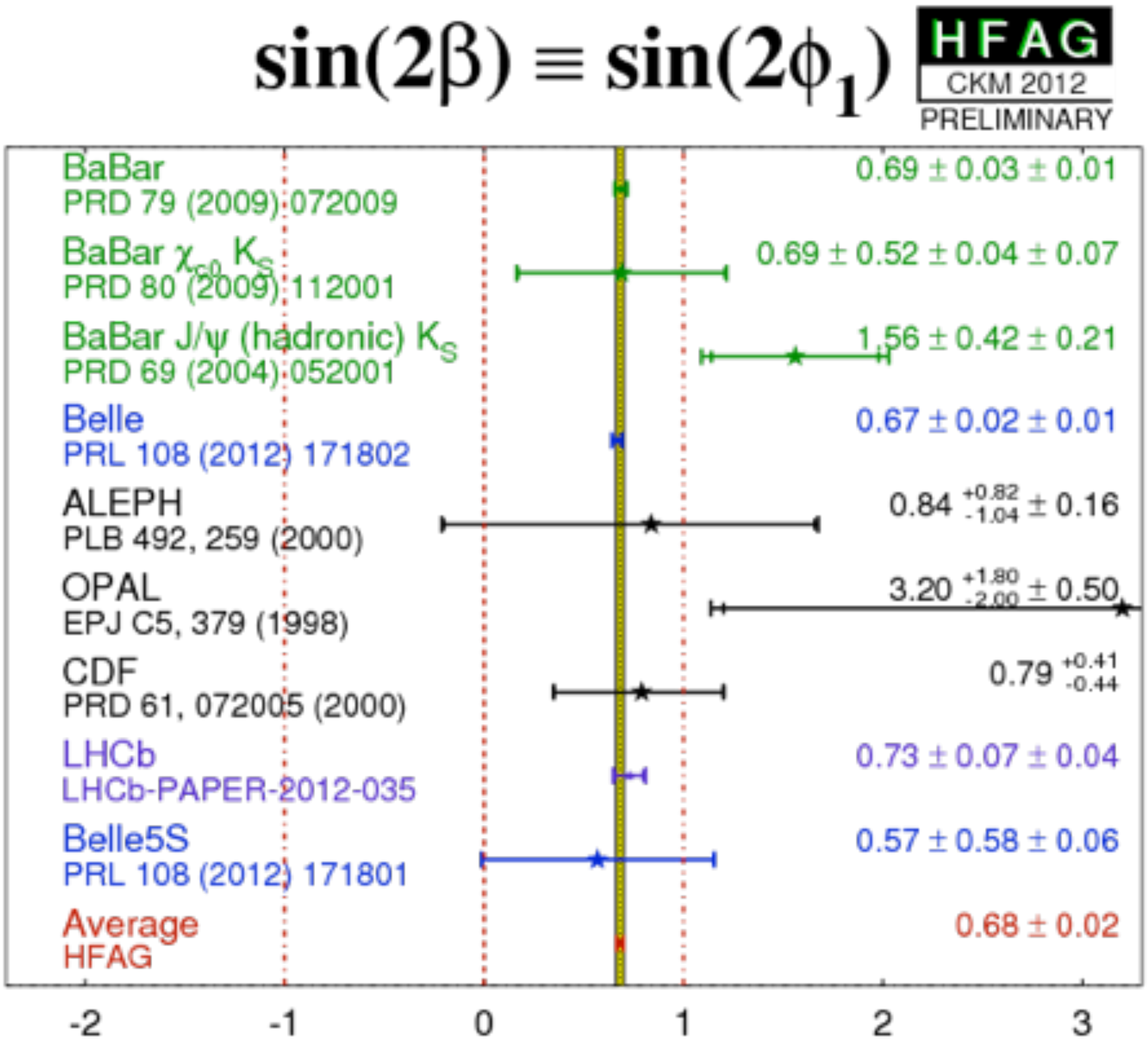
$$\sin 2\beta = 0.667 \pm 0.023 \pm 0.012$$

$$\sin 2\beta = 0.666 \pm 0.031 \pm 0.013$$

sin2β and the Nobel Prize

"... As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier."

World Average for sin2β Measurements



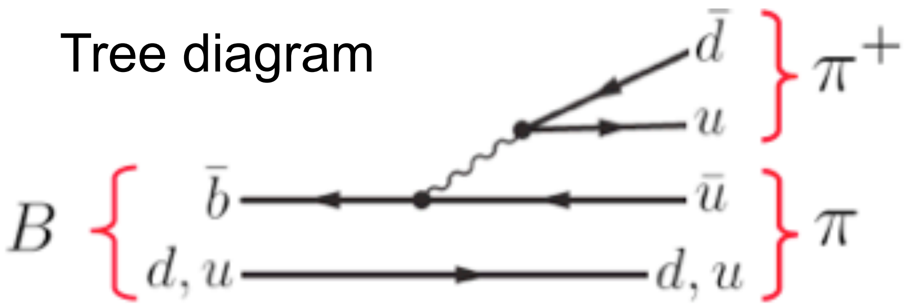
Notation:

Belle	ϕ_1	ϕ_2	ϕ_3
Babar, LHCb	β	α	γ
Belle II	?	?	?

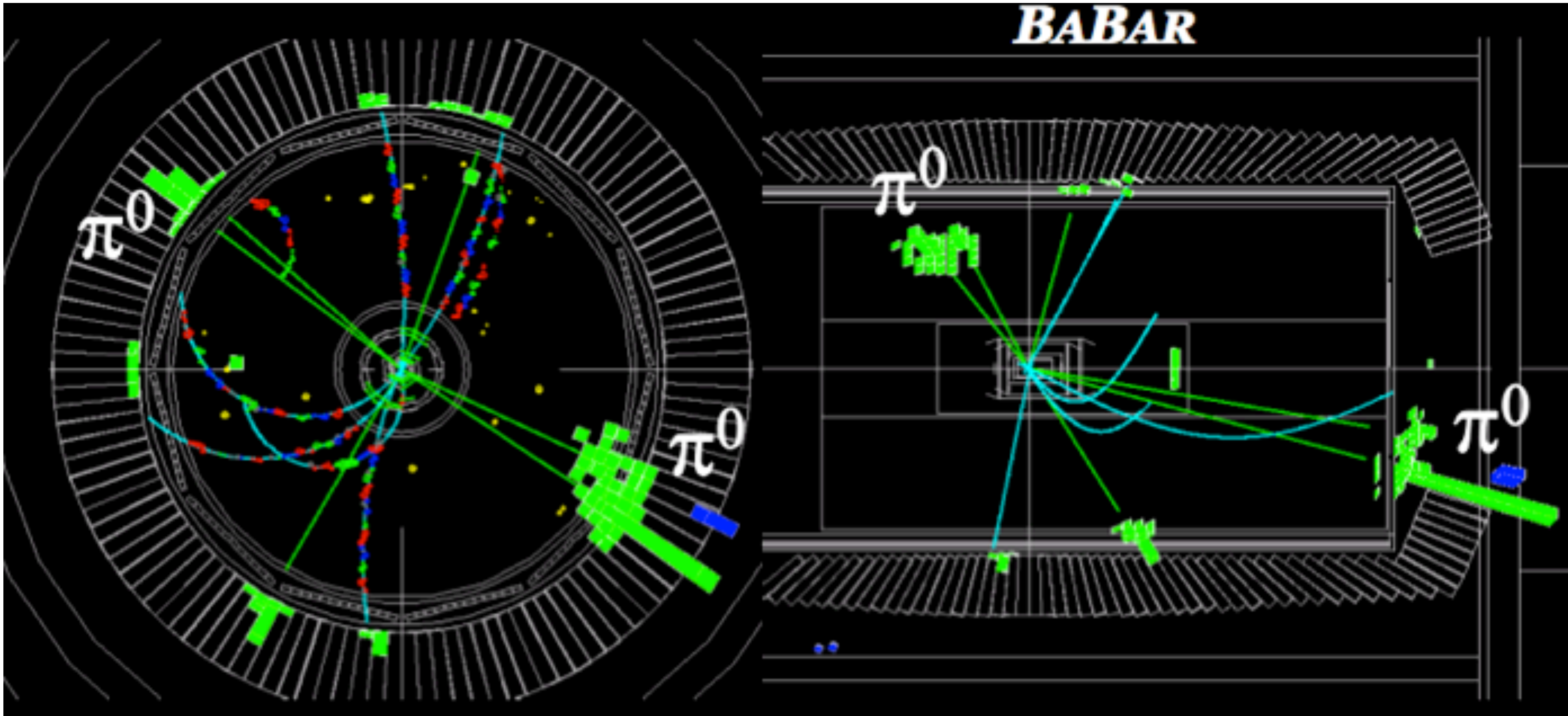
$\sin(2\beta)$

3.2 Angle α from B → ππ

Tree diagram



- Small BF ~ 10^{-6}
- $\pi^+\pi^-$ CP eigenstate with CP = -1

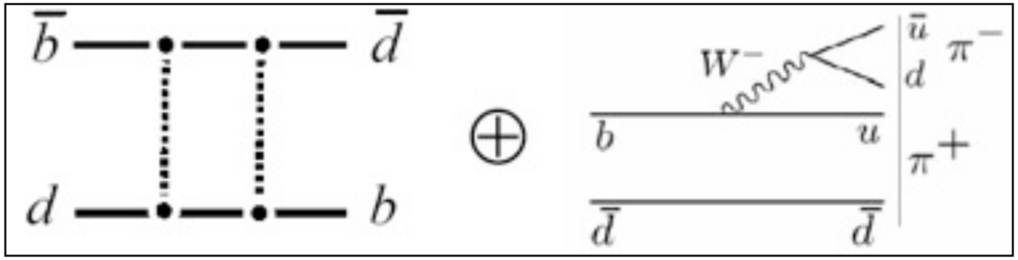


Sin2α/φ_2 from B→ππ, ρπ, ρρ

Interference of **suppressed *b→u* "tree"** decay with mixing

But "**penguin**" is sizeable!

B^0 mixing *B^0 decay: tree* *B^0 decay: penguin*



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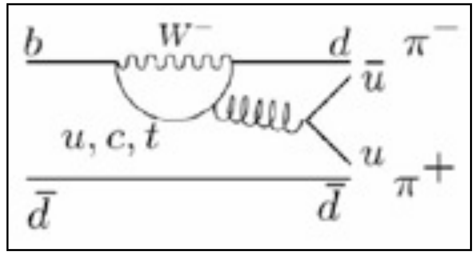


$q/p \propto 1$ $A \propto \lambda^3$ $A \propto \lambda^3$

$$\lambda_{\pi\pi} = \frac{q}{p}\frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}} = e^{-i2\phi_1}e^{-i2\phi_3} = e^{-i2\phi_2}$$

$$\lambda_{\pi\pi} = e^{i2\phi_2}\frac{T + Pe^{i\phi_3}e^{i\delta}}{T + Pe^{-i\phi_3}e^{i\delta}}$$

Coefficients of time dependent CP asymmetry

neglecting penguins just like sin2beta!!

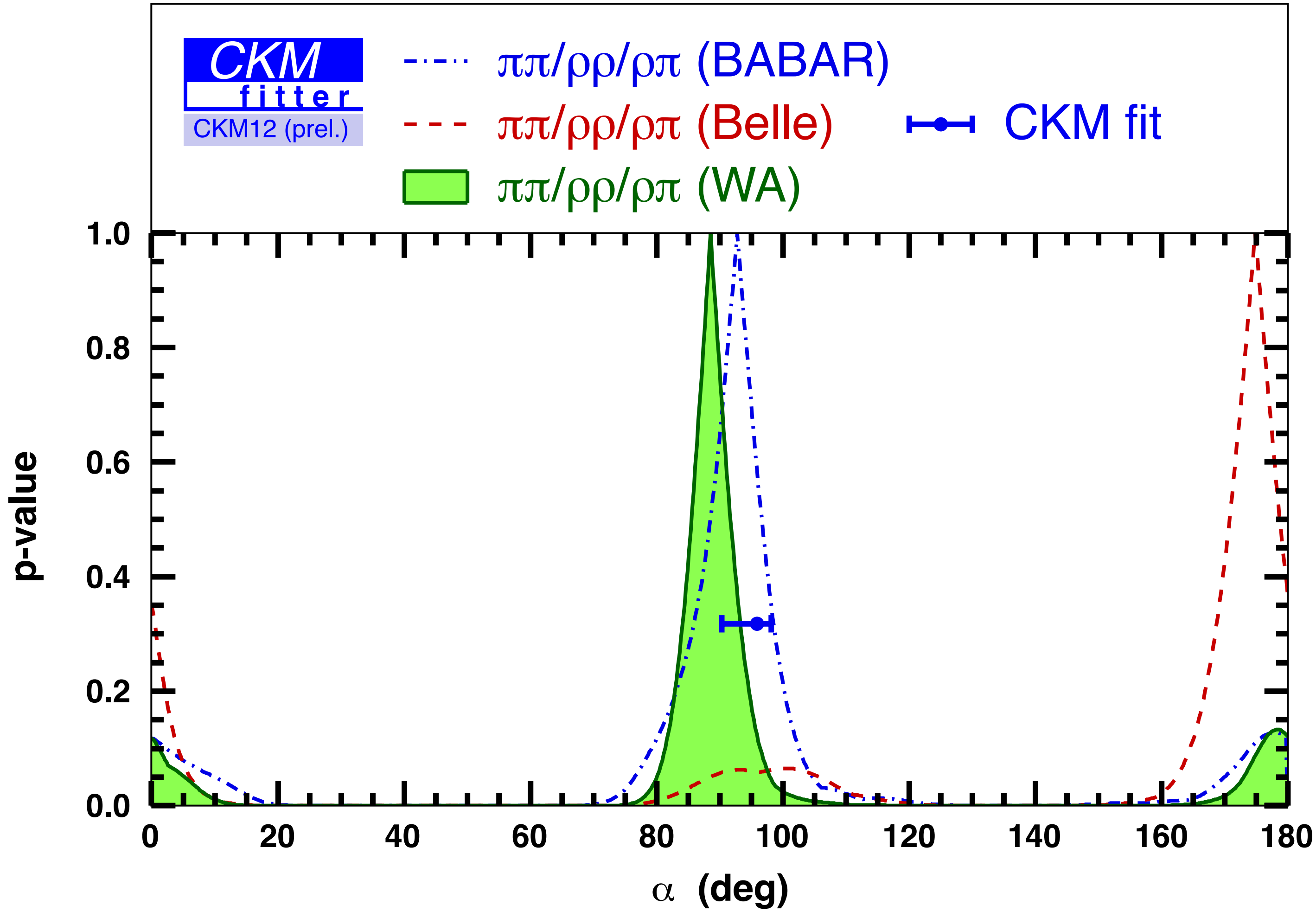
$$S_{\pi\pi} = \sin 2\phi_2$$
$$C_{\pi\pi} = 0$$

But: large strong penguins expected

IP/TI~0.3

$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2}\,\sin 2\phi_{2eff}$$
$$C_{\pi\pi} \propto \sin\delta$$

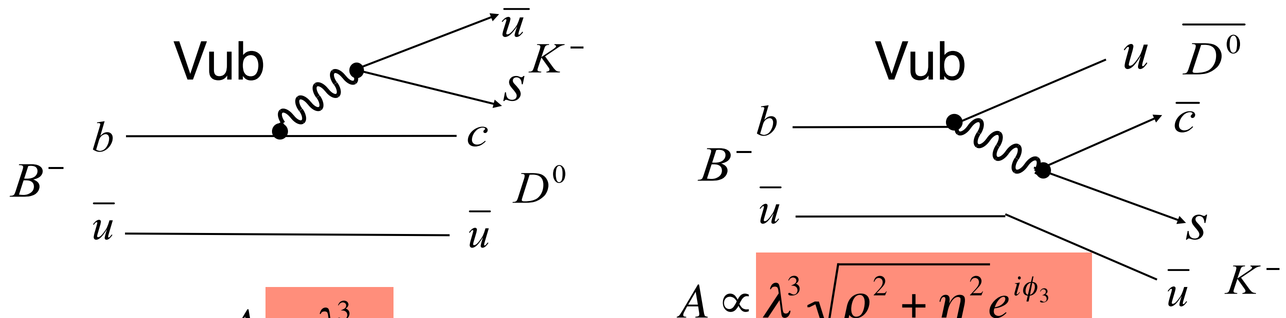
Summary for α



$$\alpha[WA,all]=(88.5^{+4.7}_{-4.4})^{\circ}$$

3.3 Angle γ from B→DK

Theoretically clean measurement of γ in the interference between the decays $B \to D^0 K$ and $B \to \overline{D^0} K$



$A \propto \lambda^3$ $\qquad A \propto \lambda^3 \sqrt{\rho^2 + \eta^2} e^{i\phi_3}$

the only CP violating parameter that can be measured through tree decays

Common parameters:

- CKM angle γ
- Amplitude ratio r_B
- Strong phase difference δ_B

$$\frac{\langle B \to \overline{D^0} K \rangle}{\langle B \to D^0 K \rangle} = r_B e^{i(\delta_B - \gamma)}$$

$$r_B \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times |\mathrm{col.supp}| = 0.1 - 0.2$$

Precision on γ very sensitive to value of r_B

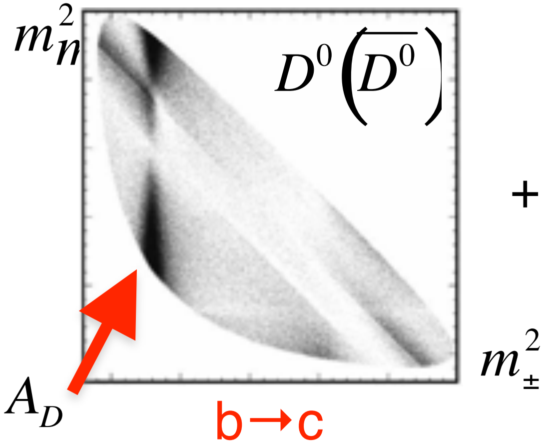
Dalitz Plot Method

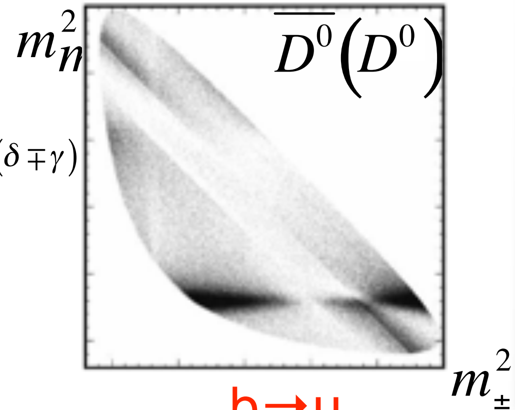
Reconstruct D in final states accessible to both D^0 and $\overline{D^0}$

Study interference pattern in D^0(anti-D^0) Dalitz plot for

$$B^{\mp} \to D\left(K_s h^+ h^-\right)K^{\mp}$$

$$|A_m|^2 = \left| A_D \; + r_B \, e^{i(\delta \mp \gamma)} \; \right|^2$$





schematic

$$m_\pm^2 = m^2\left(K_s h^\pm\right)$$

Sensitivity varies over Dalitz plane

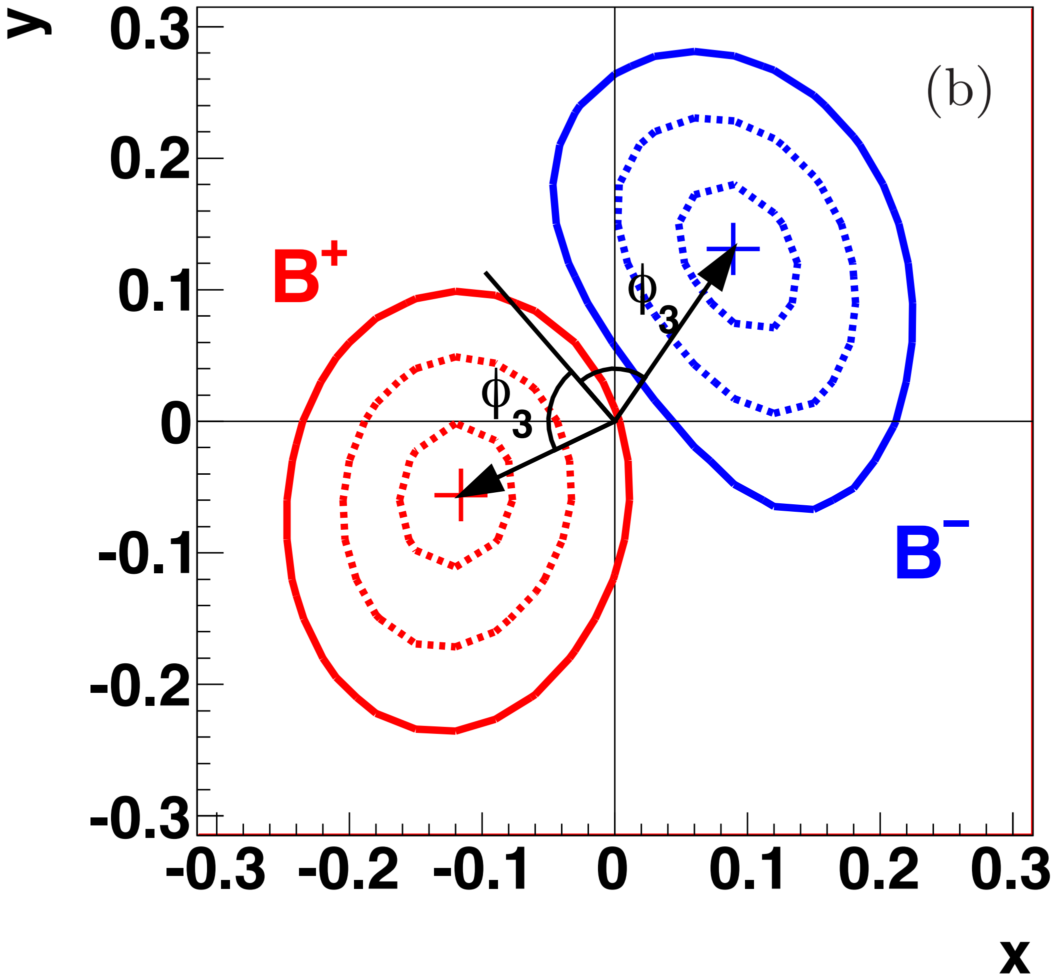
Input: D decay amplitude → model uncertainty

Simultaneous fit to Dalitz plot density for B^+ and B^- decays in data

Angle γ from B→DK

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$

$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$



PRD 85, 112014 (2012).

$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^{\circ}$

$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$

$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^{\circ}$

model error

$\gamma = (76 \pm 22 \pm 5 \pm 5)^{\circ}$

$B \to DK, D^{*}K, DK^{*}$

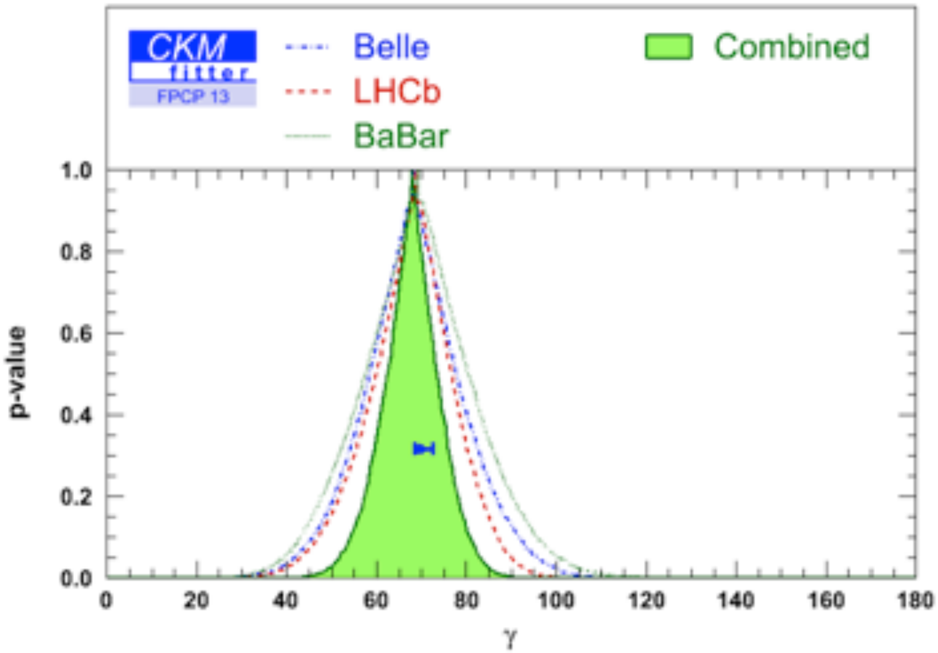
$D \to K_s\pi^{+}\pi^{-}, K_sK^{+}K^{-}$

Difference in Belle & BaBar stat. errors due to values of r_B

γ from combination of $B^+ \to DK^+$ modes

- All direct CPV effects caused by γ in SM
  - Negligible theory uncertainty
  - Several B and D decays used
  - Combination: from GLW/ADS ($D \to hh$) & GGSZ ($D \to K_S hh$)

BaBar PRD 87 (2013) 052015
Belle CKM2012 preliminary
LHCb-PAPER-2013-020
& LHCb-CONF-2013-006



$\gamma[\text{BaBar}] = (69 \pm 17)^\circ$
$\gamma[\text{Belle}] = (68 \pm 14)^\circ$
$\gamma[\text{LHCb}] = (69^{+11}_{-13})^\circ$
$\gamma[\text{combined}] = (68.0^{+8.0}_{-8.5})^\circ$

3.4 The B_s CKM angle β_s

- Analogous to $B \to J/\psi\, K$, time dependent CPV in B_s

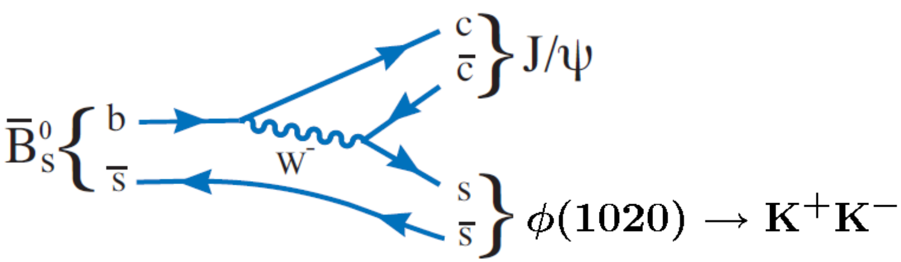
$$S_{\Psi\phi} \equiv \text{"}\sin\phi_s\text{"} = \sin(-2\beta_s^{SM} + \phi_s^{NP})$$

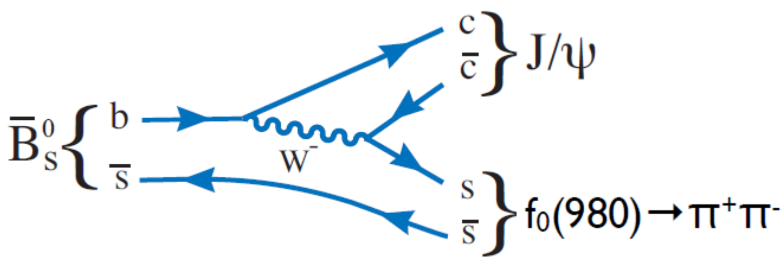
- In contrast to β, CKM angle β_s is very small

$$-2\beta_s^{SM} = (-2.08 \pm 0.10)^\circ$$

(PRD83, 036004 (2011))

- Two interesting modes



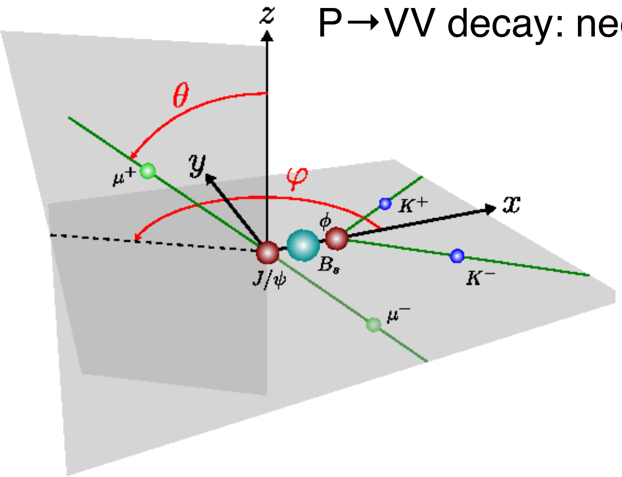


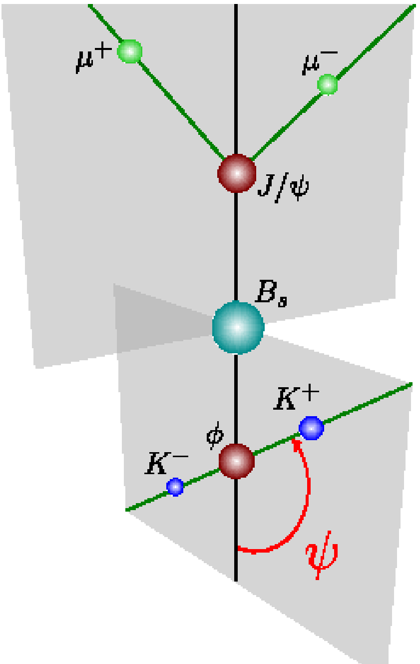
pseudoscalar to vector vector decay
Fit with 10 physics parameters:
7 angular amplitudes and phases +
Γ_s, $\Delta\Gamma_s$, ϕ_s

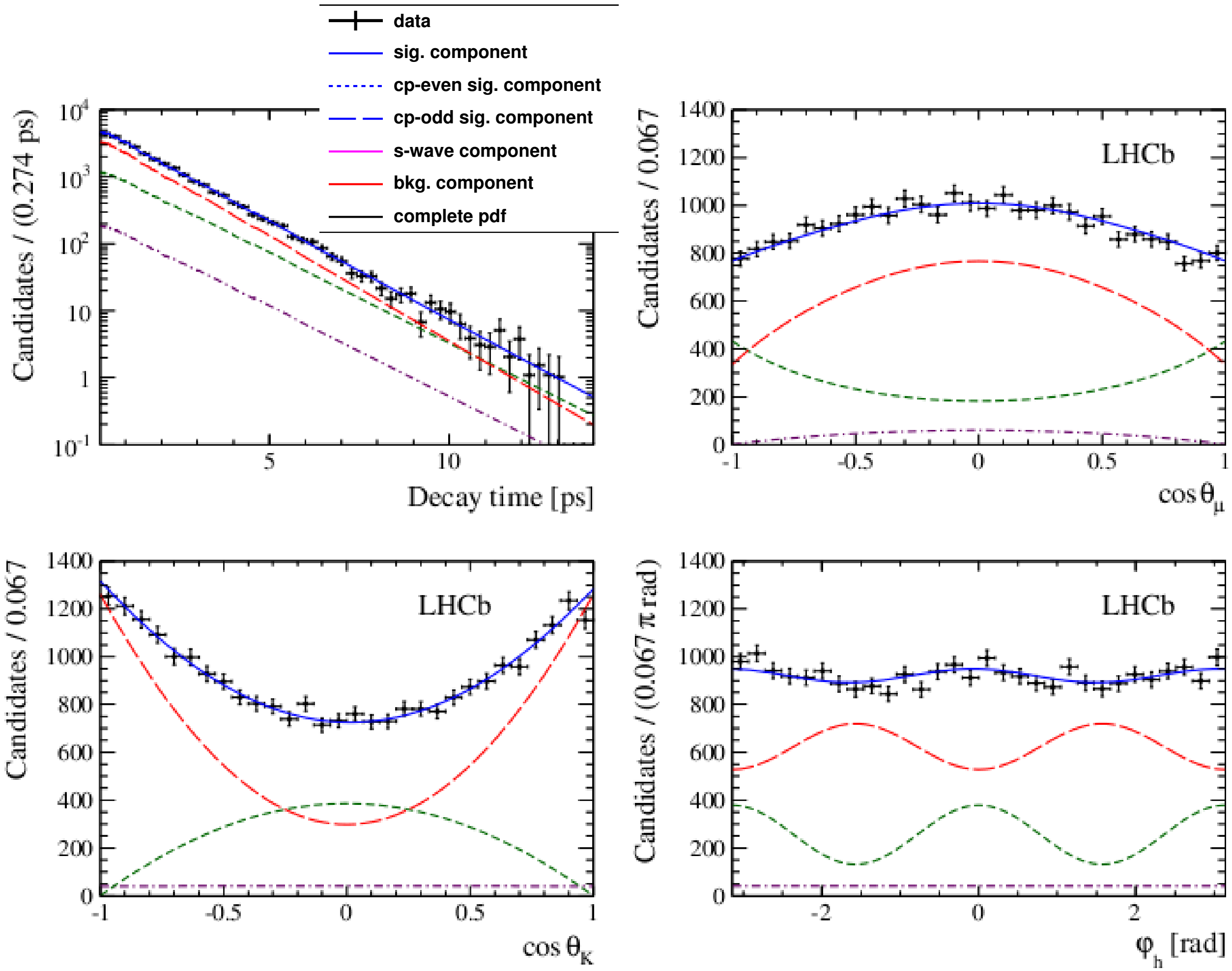
vector-pseudoscaler final state ("S-wave")
single CP odd eigenstate
no angular analysis needed

$B_s^0 \rightarrow J/\psi\ \phi$ analysis

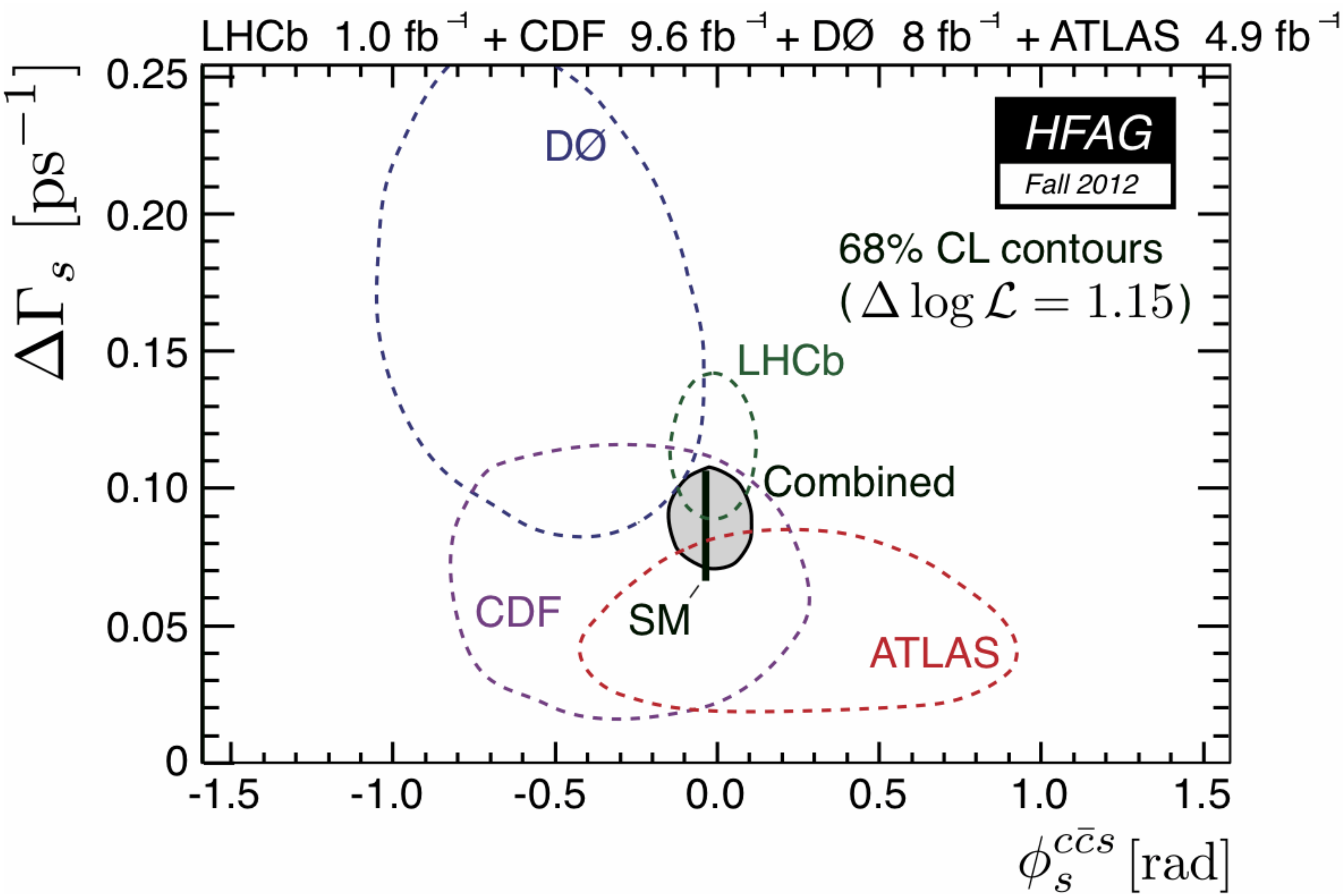
P→VV decay: needs an angular analysis to resolve CP-even and CP-odd components





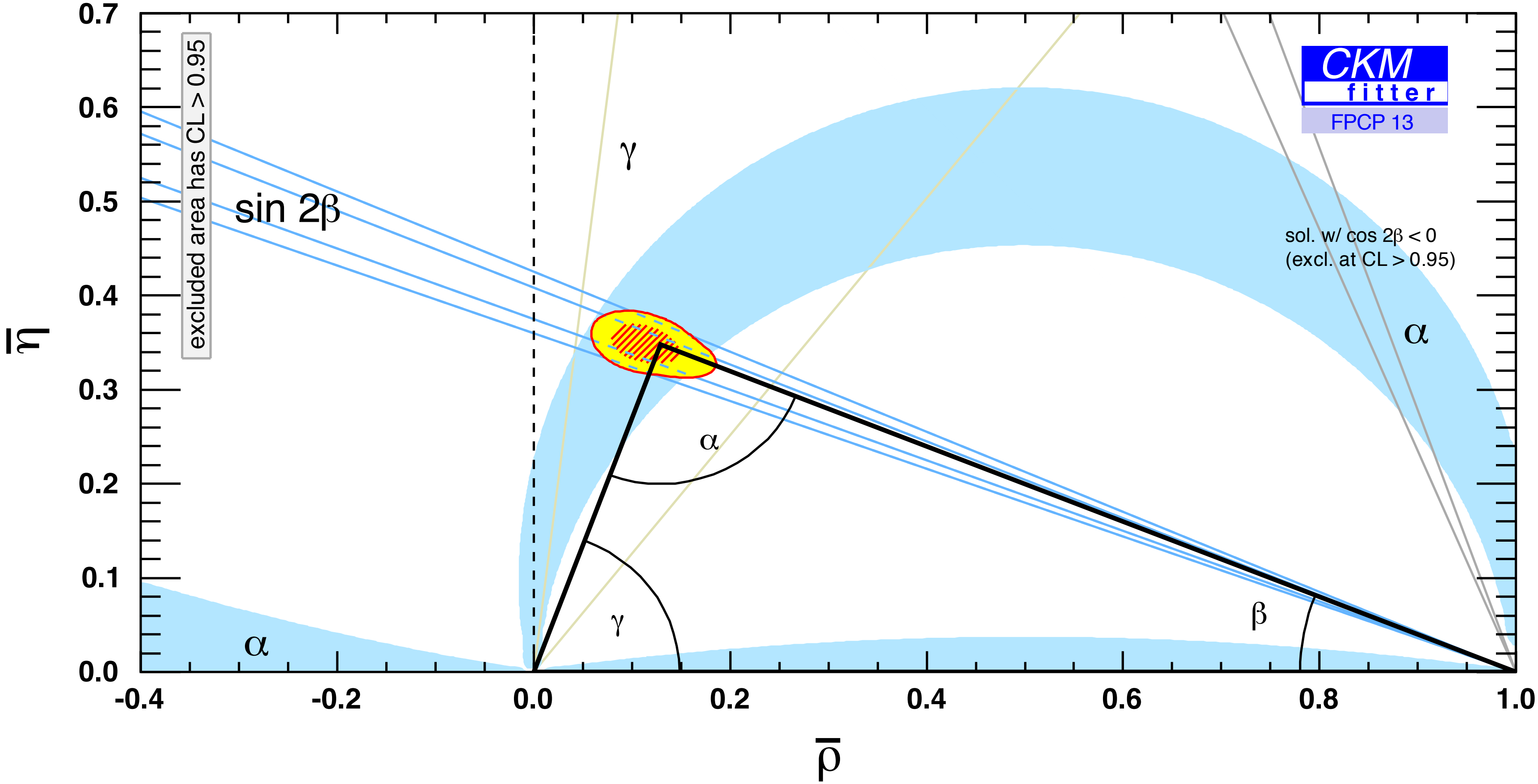


CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$



universitätbonn

Summary: Measurements of Angles



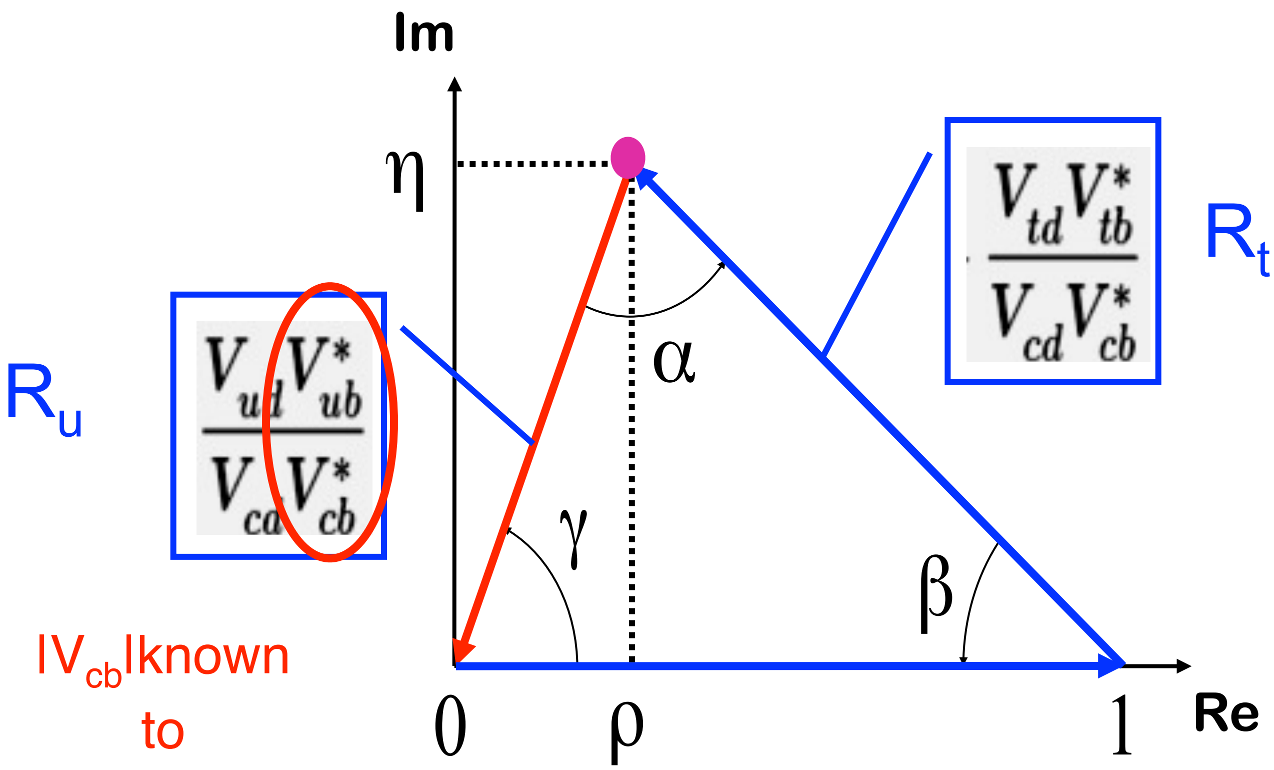
Note: $\bar{\rho} = \rho(1-\lambda^2/2)$

$\bar{\eta} = \eta(1-\lambda^2/2)$

UT sides

R_u

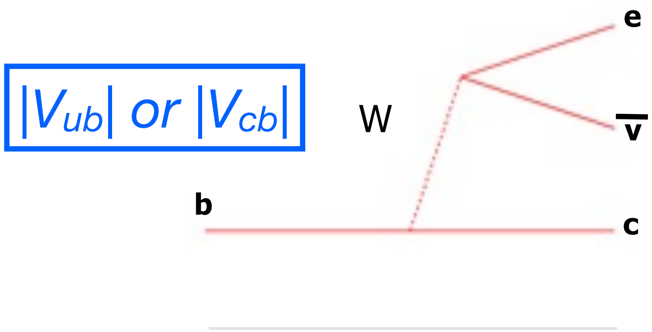
Measurements of Sides: The Left Side R_u



$|V_{cb}|$known to < 2%

Semileptonic Decays

$b \rightarrow c\, e\, \nu$

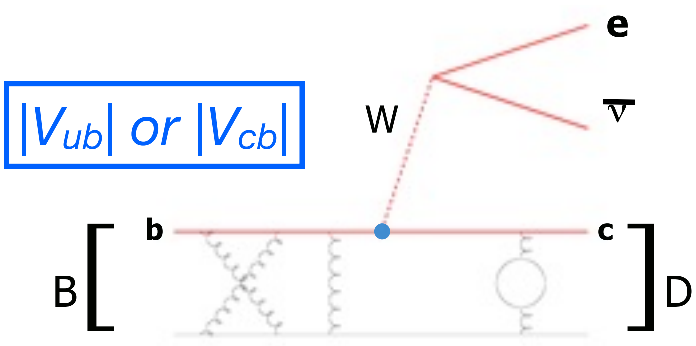


Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b: perturbative (α_s^n).

- $|V_{ub}| \approx 0.004$ the smallest element – not easy!

Semileptonic Decays

B → D e ν



Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b:
perturbative (α_s^n).

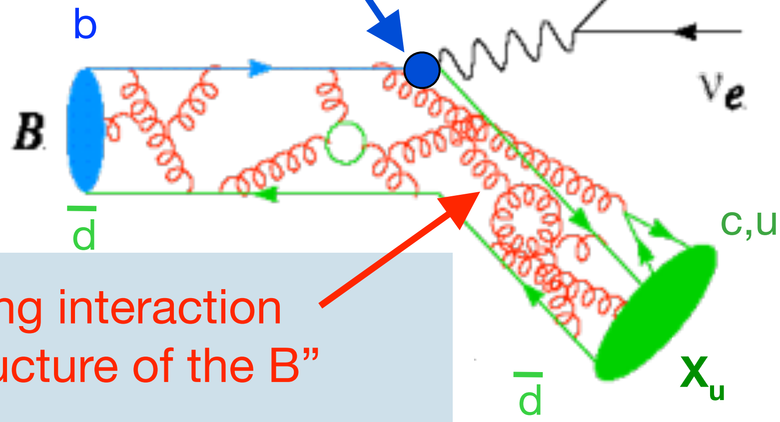
Quarks are bound in hadrons.
Interactions of *b*-quark & light-quark in the *B are very important.*

- $|V_{ub}| \approx 0.004$ the smallest element – not easy!

Measurements of $|V_{cb}|$ & $|V_{ub}|$

$$\Gamma(B \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2$$

Weak interaction
$|V_{cb}|$, $|V_{ub}|$



$\times$

$$\left(1 + \text{補正項}\right)$$

Strong interaction
"Structure of the B"

2 Approaches in B decays

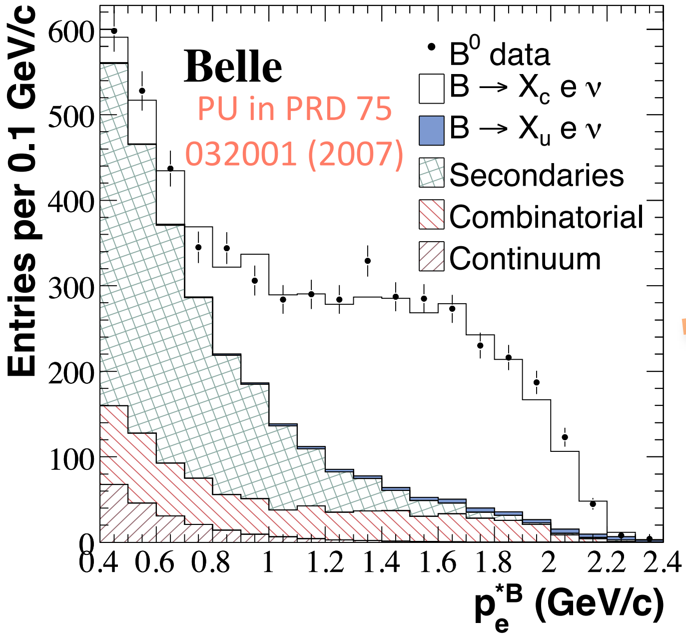
Inclusive $X_{u,c}$ = sum of all final states.
Framework: Operator Production Expansion.

Exclusive X_c=D, X_u=π: Specific final state.
Theory: Lattice QCD.

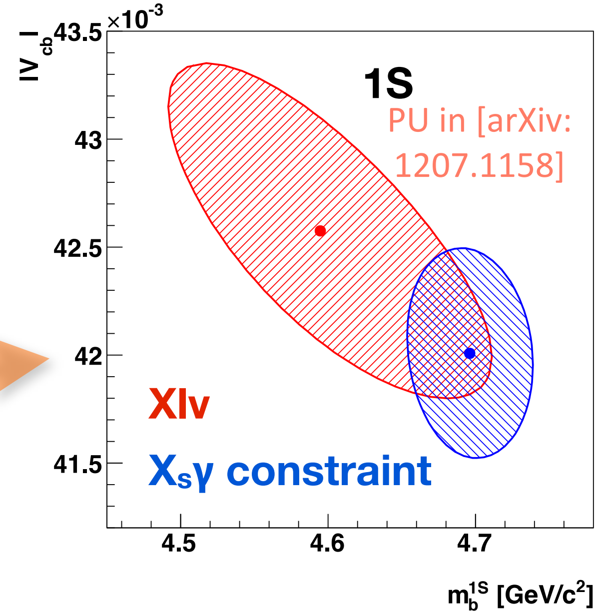
Different theory frameworks. Cross check each other.

$|V_{cb}|$ Determination

$|V_{cb}|$, m_b & *b* fermi motion extracted from Semileptonic (and Radiative) spectra.

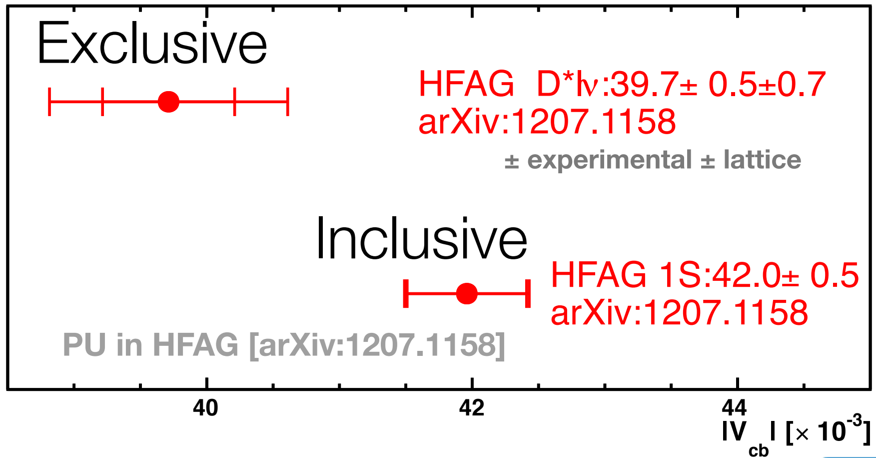


Global fit from 6 experiments



Inconsistent

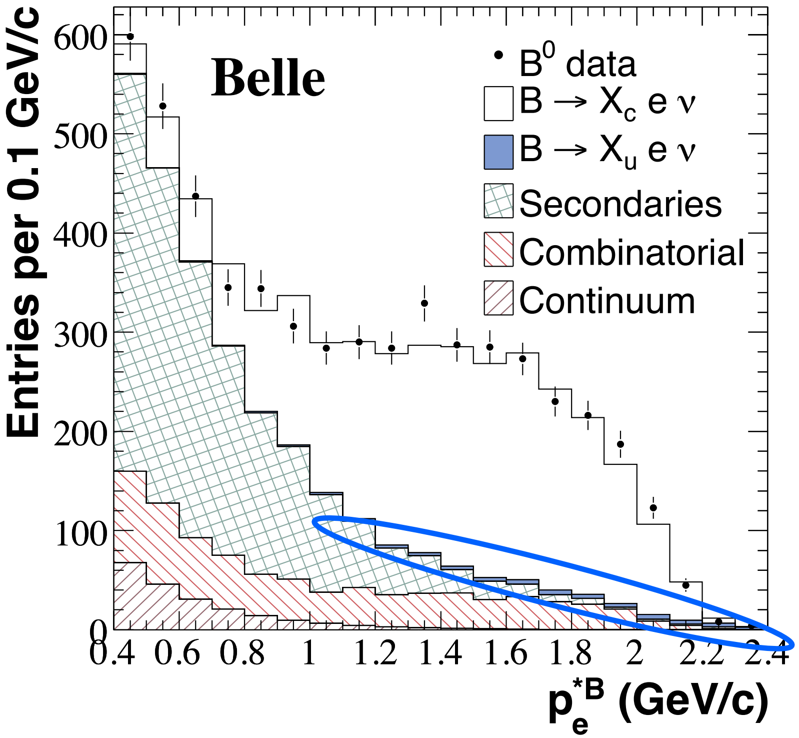
- New Physics unlikely
- b-quark dynamics?
- Problem with measurements?

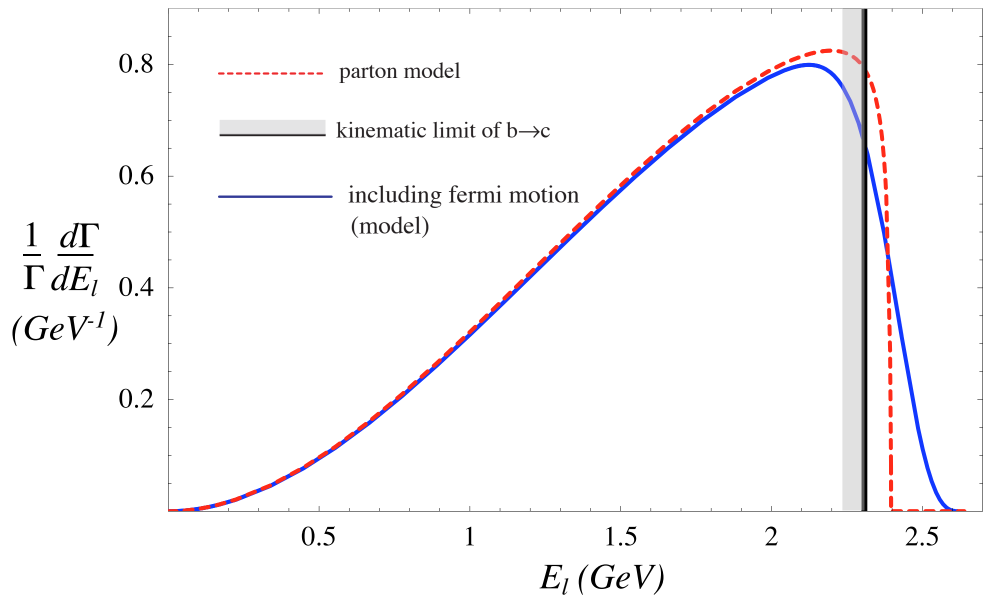


$|V_{ub}|$

- Problem: b→clν rate 50x larger
- Overcoming this background increases *Fermi motion* dependence.

$$\frac{\Gamma(b \to u\ell\bar{\nu})}{\Gamma(b \to c\ell\bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$





$|V_{ub}|$ from Inclusive $B\to X_u l\nu$

- To remove ***b→clv***: lose part of **b→ulv**.

Measure $\Gamma(B \to X_u \ell \nu) \times f_C \propto |V_{ub}|^2 (1 + \text{補正項})$

Fraction of signal measured
→ large theoretical uncertainties

If f_c<80%, theory error dominates precision

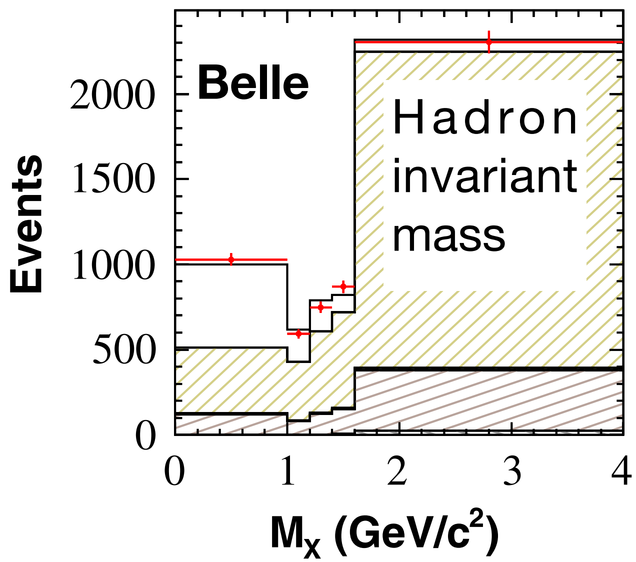
- New paradigm: B-“tagging” & Data mining techniques (Neural networks & Decision Trees)

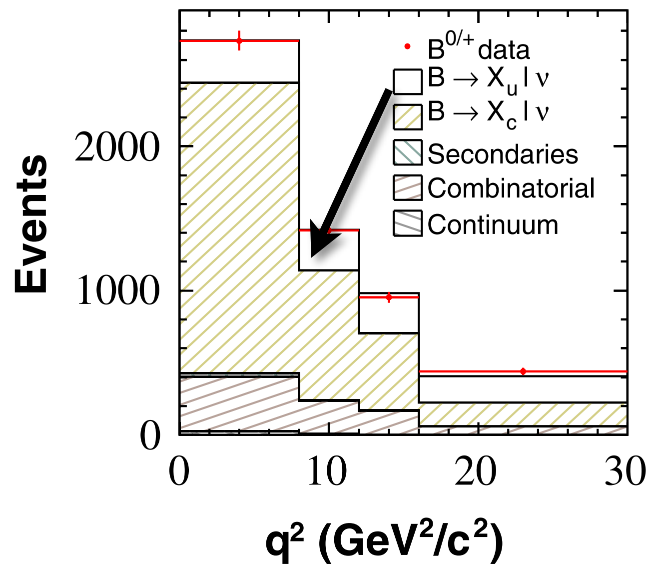
Access ~90% phase space (p_{lep}^*>1 GeV)

“Breakthrough”

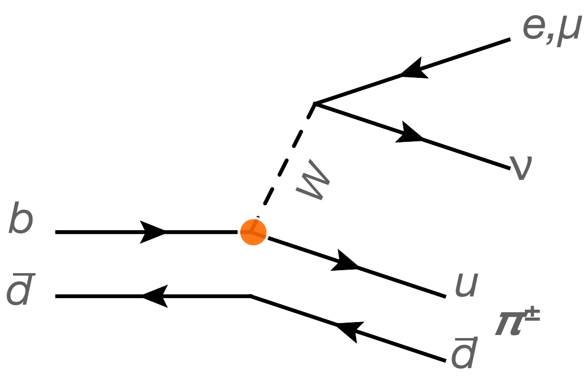
PU in

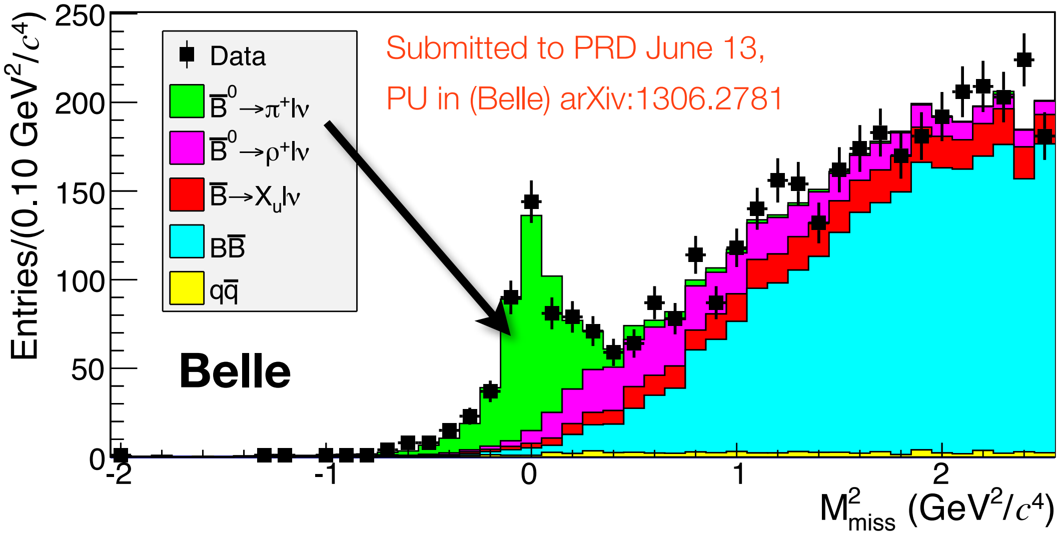
PRL 104 021801 (2010)

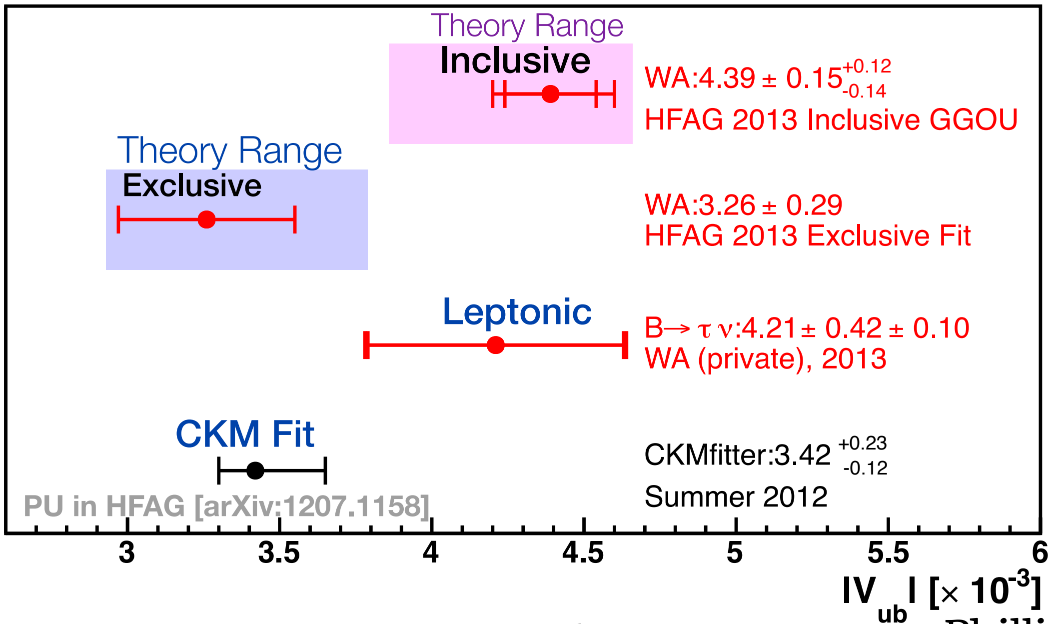




B→πlν Exclusive





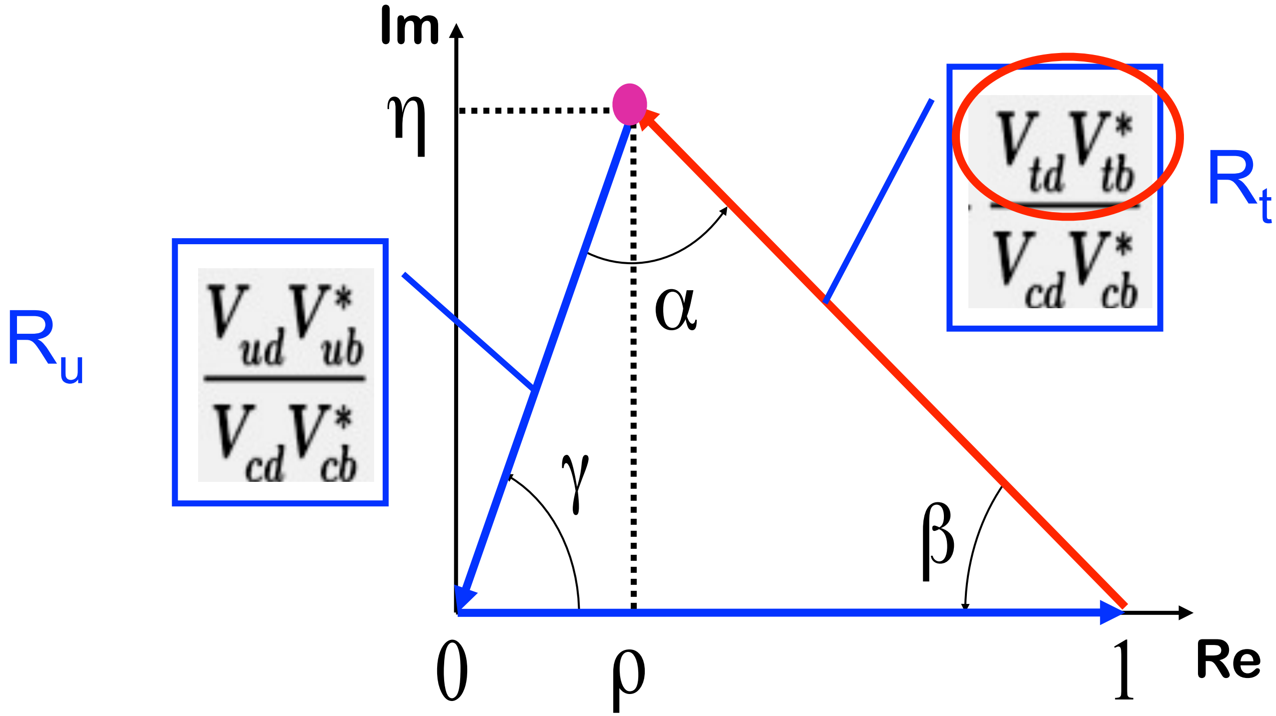


European Strategy Group for Particle Physics (Jan 2013) identified $|V_{ub}|$ top priority in flavour.

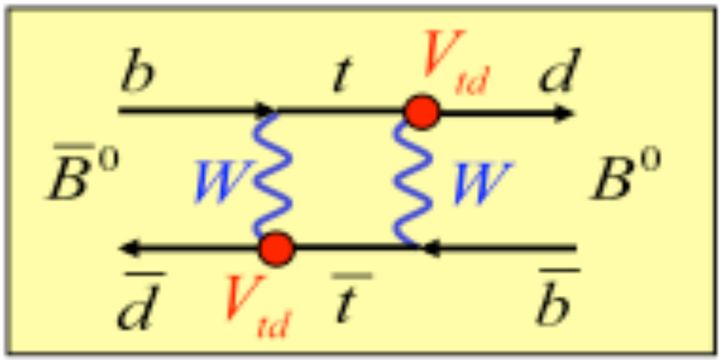
UT sides

R_t

The Right Side R_t



Must use loop processes
where b→t→d



V_{td} from B Mixing

- Relation between B mixing & CKM elements:

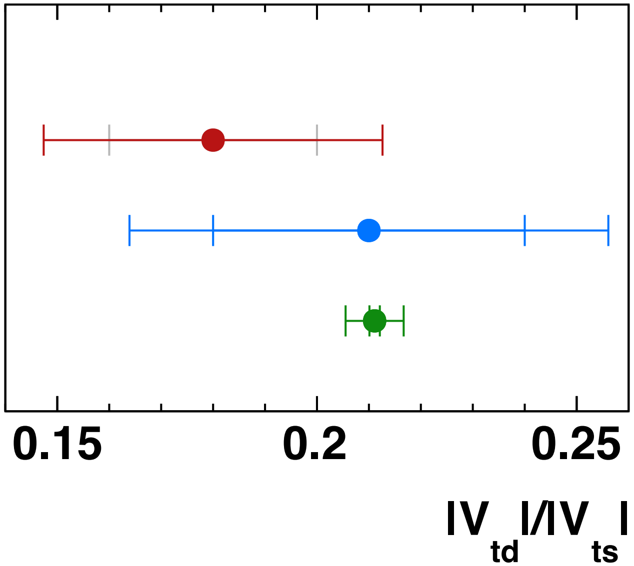
$$x \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} B_B f_B^2 m_B \tau_B \left| V_{tb}^* V_{td} \right|^2 m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD}$$

- F is a known function, η_{QCD}~0.8
- **B_B** and **f_B** are currently determined only **theoretically**.
  - **f_B** very difficult to measure experimentally (**$B\to l\nu$**).
  - Best hope **lattice QCD, slightly more precise for Bs mixing**
- **Ratio needed in UT (cancels parameters)**
  $|V_{td}|^2/|V_{ts}|^2=[(1-\rho)^2+\eta^2]$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

ps^{-1}	Belle/Babar	WA(inc LHCb)	Δ%
Δm_d	0.508±0.005	0.507±0.004	0.8
Δm_s		17.72±0.04	0.2

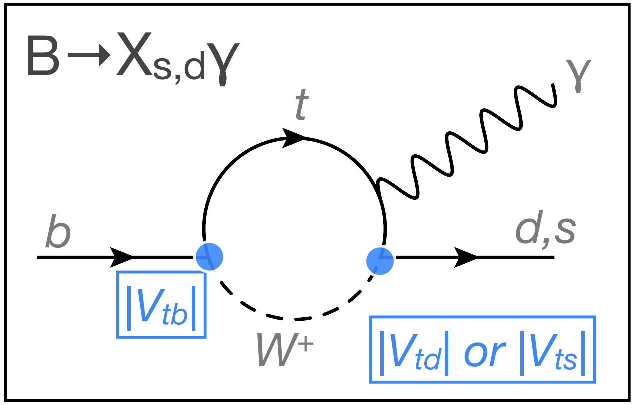
$|V_{tq}|$ Summary



Inclusive Radiative ($\Delta\zeta$*~1%)

Exclusive Radiative ($\Delta\zeta$~17%)
(Assumes isospin symmetry)

Mixing ($\Delta\zeta$~2.6%) (PDG 2013)



- $|V_{ts}|=|V_{cb}|$ with UT constraint,
  - Can also precisely extract $|V_{ts}|$ from $B(B \to X_s\gamma)$

Most precise $|V_{tq}|$ (PDG)	
$|V_{td}|$ (mix)	$(8.4\pm0.6)10^{-3}$
$|V_{ts}|$ (rad)	$(42.9\pm2.6)10^{-3}$
$|V_{td}|/|V_{ts}|$	0.211 ± 0.006
$|V_{ts}|/|V_{cb}|$	$1.04\pm0.04\pm0.03$
$|V_{tb}|$**	~1.03 ± 0.04

Assuming $|V_{tb}|=1$

c.f. $|V_{cb}|$	$(40.9\pm1.1)10^{-3}$

CKM Picture

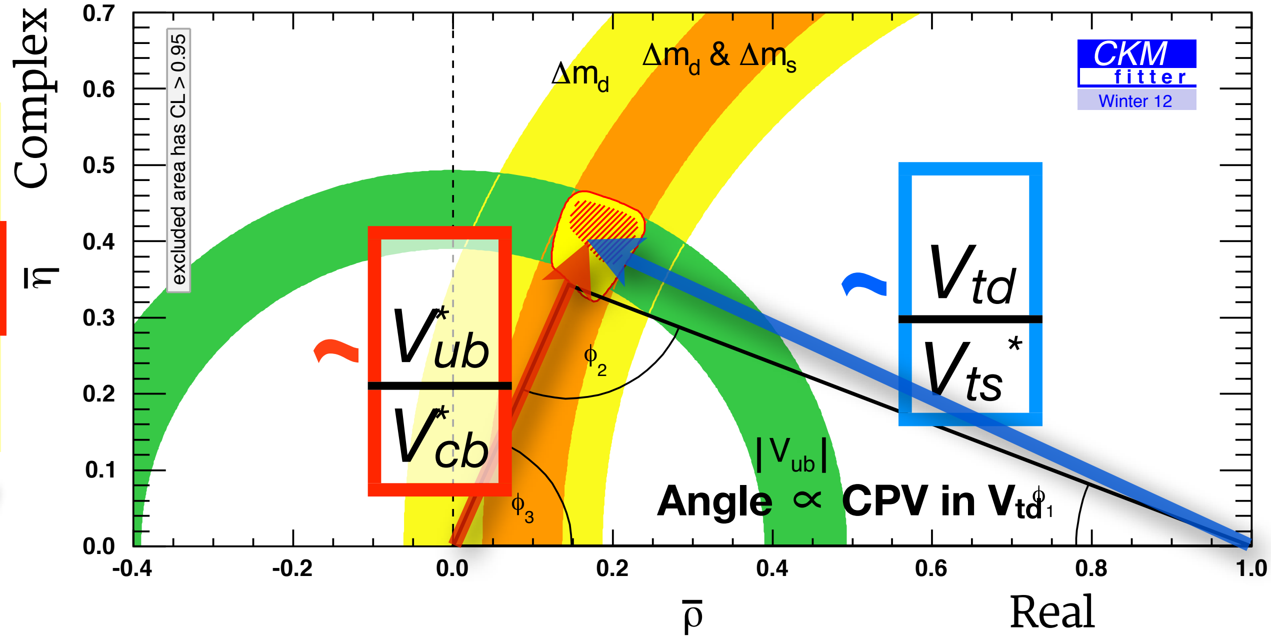
- $V^{\dagger}V = 1$ gives us

$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$$

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

$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

A triangle on the complex plane



UT CKM Parameter	Measurement	δV/V	Ref.
V_{ub}**	$(4.4\pm0.5)10^{-3}$	10%	PDG
V_{cb}	$(4.1\pm0.1)10^{-2}$	3%	
V_{td}/V_{ts}		3%	
V_{cd}	0.228±0.006	3%	1209.0085
V_{tb}	~1.03±0.04	4%	1302.1773

CKM Picture

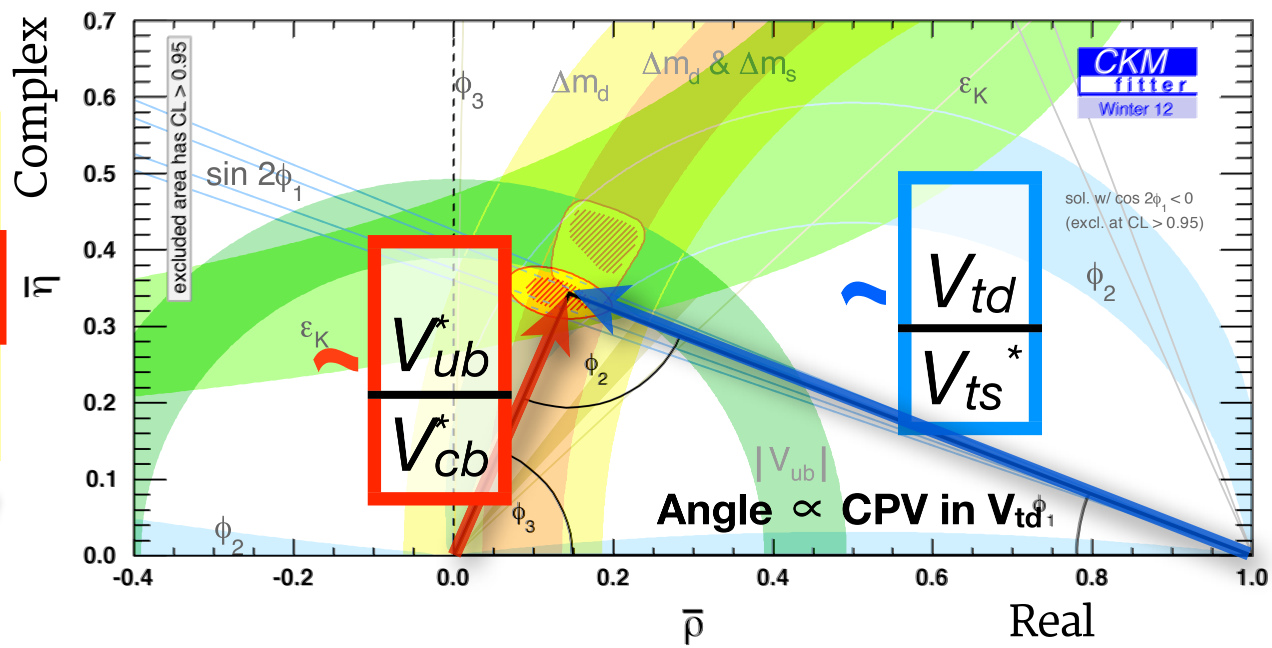
- $V^{\dagger}V = 1$ gives us

$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$$

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

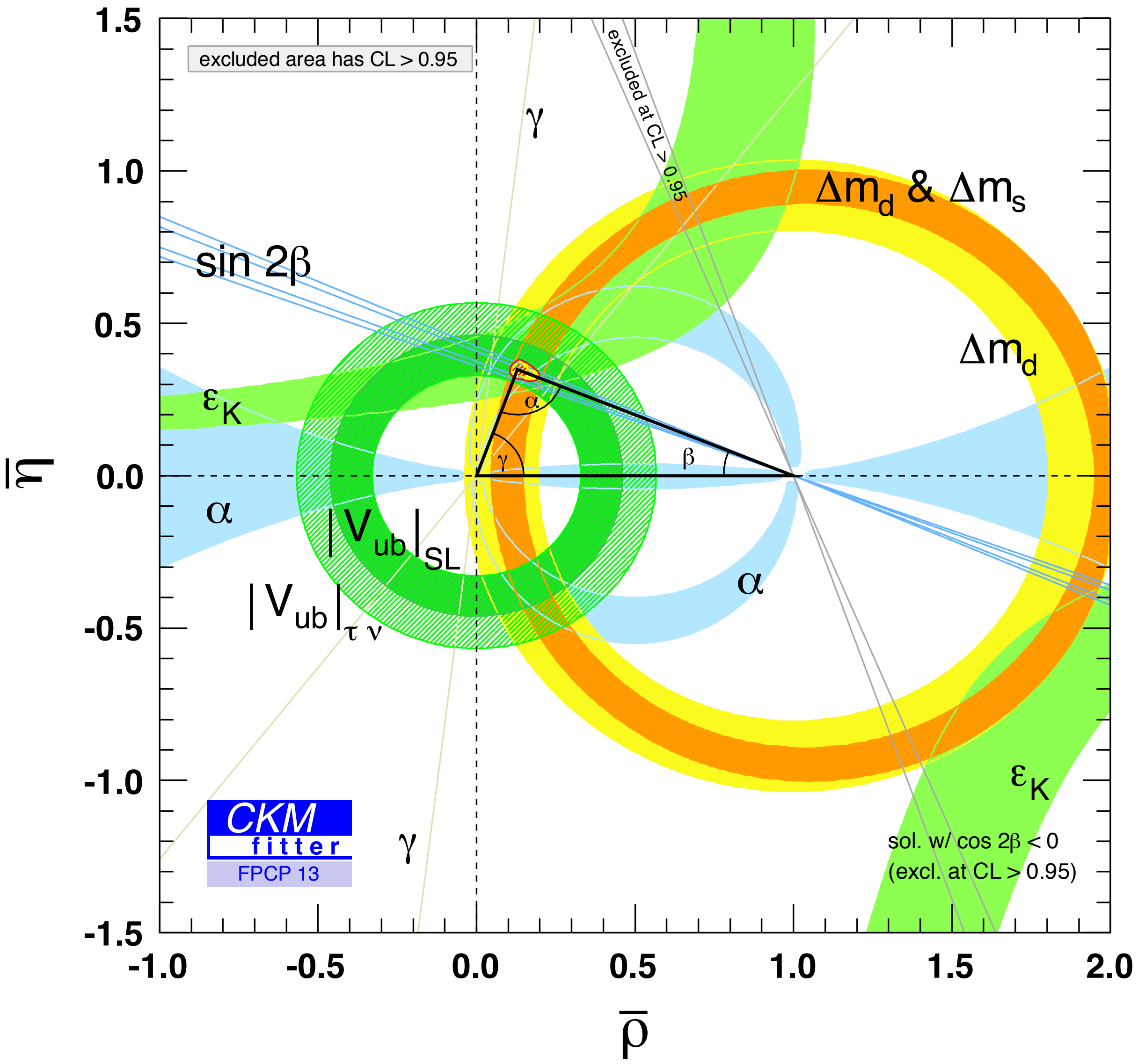
$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

A triangle on the complex plane



UT CKM Parameter	Measurement	δV/V	Ref.
V_{ub}**	$(4.4\pm0.5)10^{-3}$	10%	PDG
V_{cb}	$(4.1\pm0.1)10^{-2}$	3%	
V_{td}/V_{ts}		3%	
V_{cd}	0.228 ± 0.006	3%	1209.0085
V_{tb}	$\sim1.03\pm0.04$	4%	1302.1773

Putting it all together



Putting it all together

Kandinsky

End of Part 2

Homework: CP Eigenstates

- Which of these is a CP eigenstate?
  - $B^o \rightarrow \pi^+\pi^-$
  - $K^o \rightarrow \pi^+\pi^-$
  - $B^o \rightarrow J/\psi\ K_s$
  - $B^o \rightarrow \pi^+\pi^-\pi^o$
  - $K^o \rightarrow \pi^+\pi^-\pi^o$
  - $B_s \rightarrow J/\psi\ \phi$
  - $B_s \rightarrow J/\psi\ \eta'$
  - $B^o \rightarrow \rho^o\pi^o$
  - $B^o \rightarrow \rho^o\rho^o$

Aside: The origin of “penguins”

Symmetry Magazine Jan/Feb 2007

The origin of penguins

Told by John Ellis:

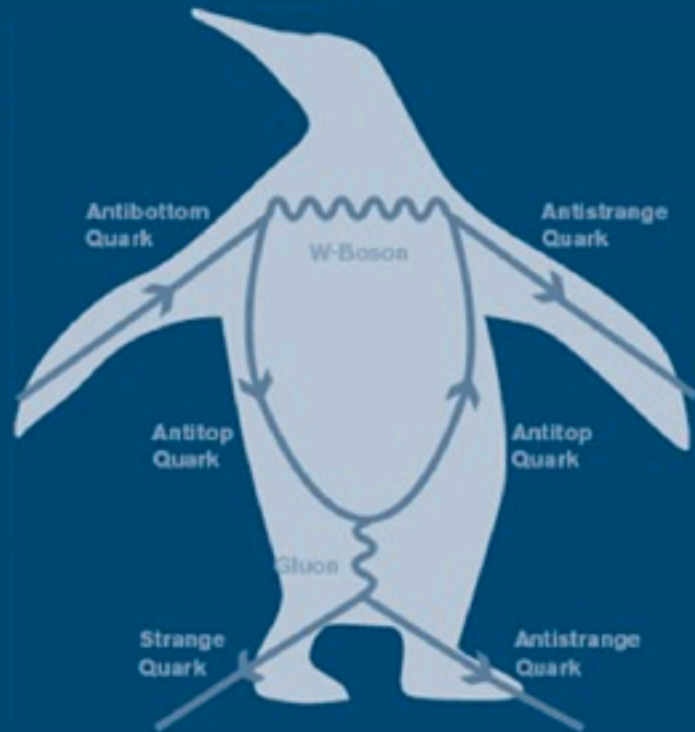
"Mary K. [Gaillard], Dimitri [Nanopoulos], and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976… The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K. and I wrote a paper on GUTs [Grand Unified Theories] predicting the *b* quark mass before it was found. When it was found a few weeks later, Mary K., Dimitri, Serge Rudaz and I immediately started working on its phenomenology.

That summer, there was a student at CERN, Melissa Franklin, who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

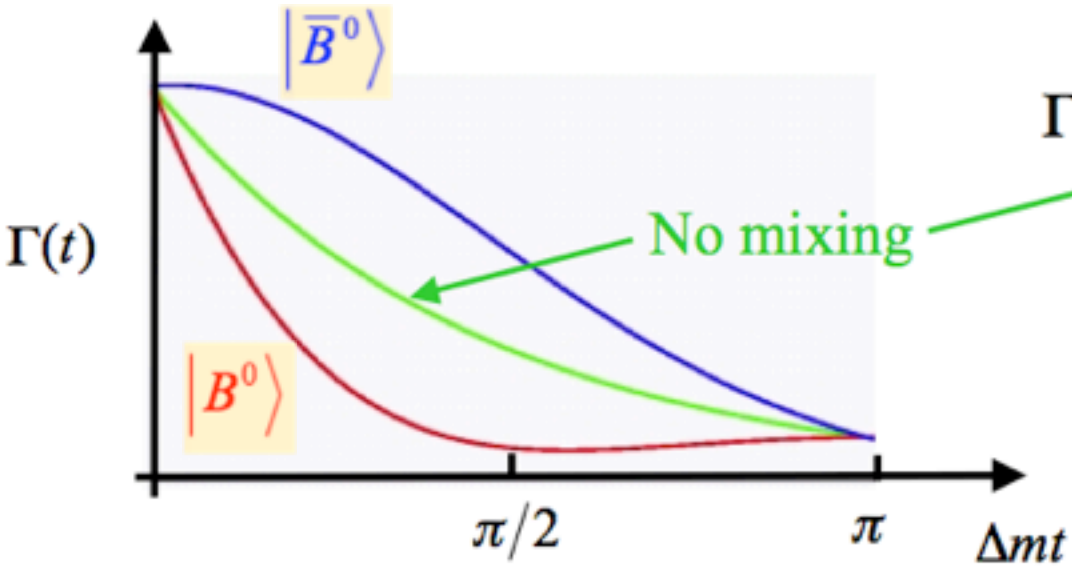
For some time, it was not clear to me how to get the word into this *b* quark paper that we were writing at the time…. Later…I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."

John Ellis in Mikhail Shifman's "ITEP Lectures in Particle Physics and Field Theory", *hep-ph/9510397*



John Ellis is the former director of Theoretical Particle Physics at CERN

sin2β Measurement Principle

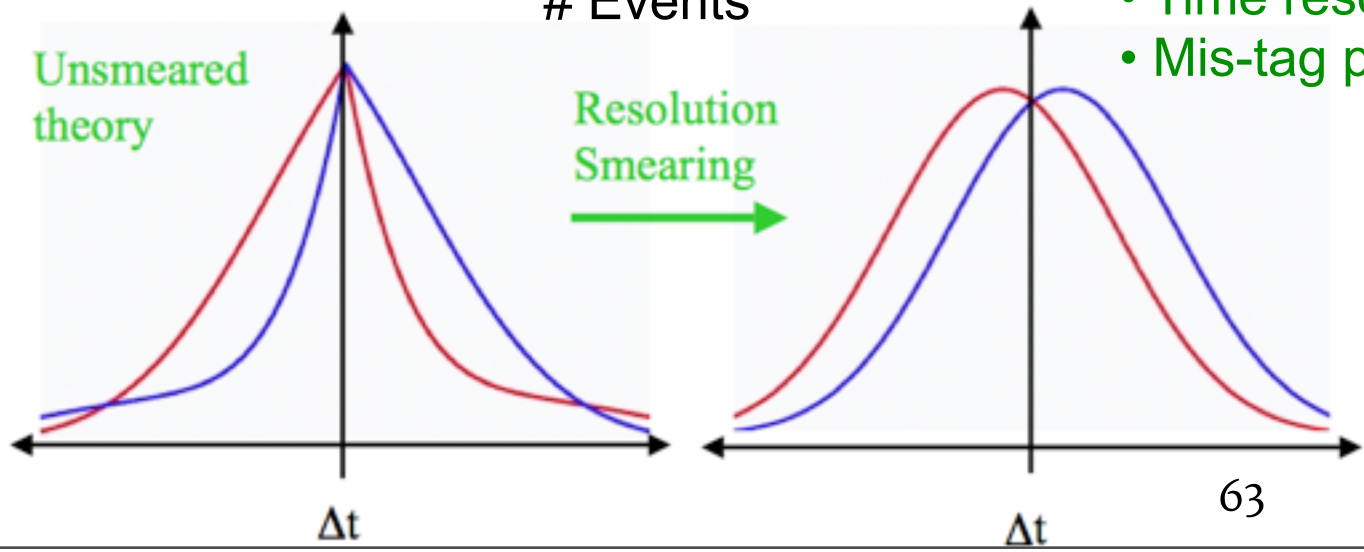


$$\Gamma(t) = \frac{e^{-t/\tau_B}}{\tau_B}$$

$\times$ [1 ± sin(2β) sin(Δmt)]

Events

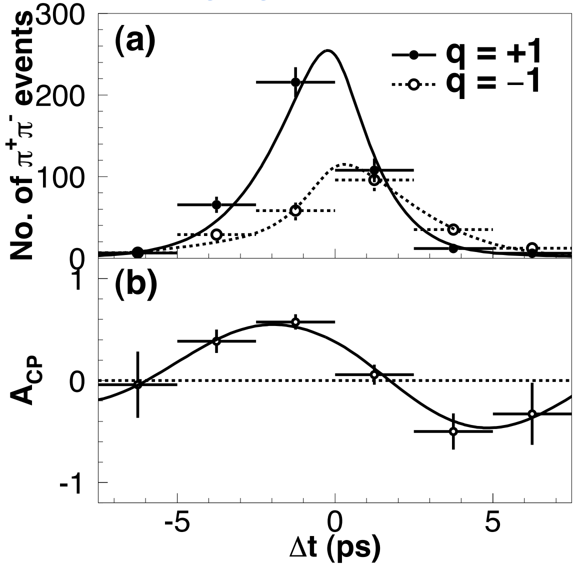
- Time resolution
- Mis-tag probability

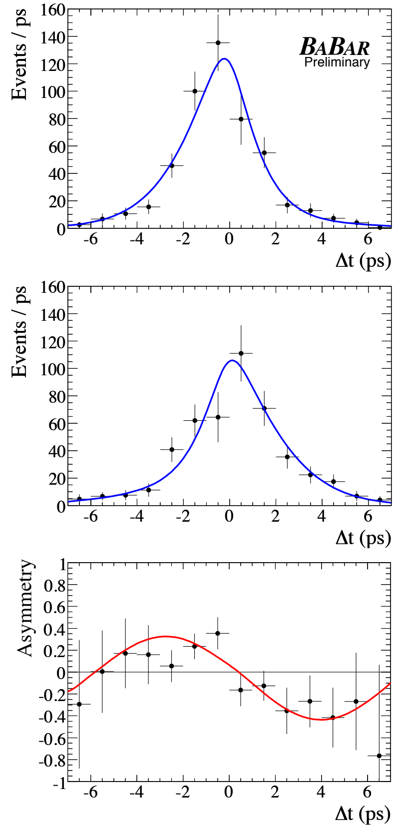


B → ππ Results

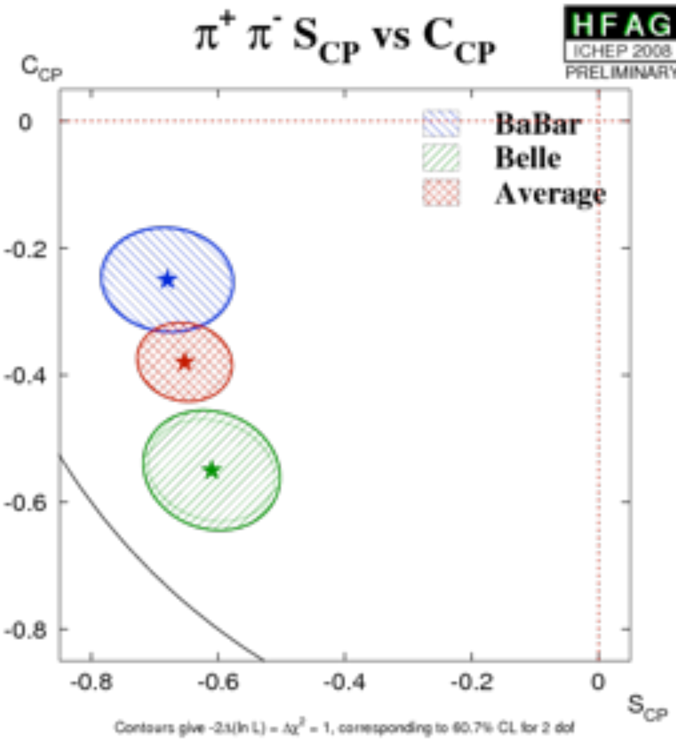
BaBar : 467M BB
arXiv:0807.4226
Belle : 535M BB
PRL98 (2007) 211801

Belle





Babar



$$C_{\pi^+\pi^-} \neq 0, \text{ and } S_{\pi^+\pi^-} = \sqrt{1 - C^2_{\pi^+\pi^-}} \sin 2\alpha_{\rm eff}$$

→ Observed two types of CP violation:

- Direct : C ≠ 0
- Mixing-induced: S ≠ 0

$\sigma(\alpha_{eff}) \sim 4^\circ$

From α_{eff} to α: Isospin Analysis

To correct for **penguin** contribution: Gronau-London method (**isopsin triangles**).

From flavour tagged decay rates of **$\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$**

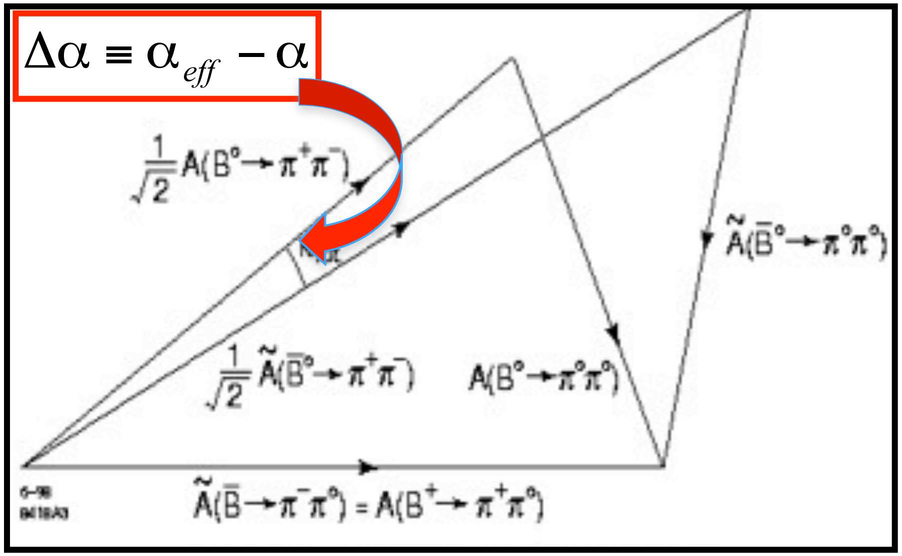
$$|\pi^+\pi^-\rangle = \sqrt{\frac{2}{3}}\,|\pi\pi, I=0\rangle + \sqrt{\frac{1}{3}}\,|\pi\pi, I=2\rangle$$

$$|\pi^0\pi^0\rangle = \sqrt{\frac{1}{3}}\,|\pi\pi, I=0\rangle - \sqrt{\frac{2}{3}}\,|\pi\pi, I=2\rangle$$

$$|\pi^+\pi^0\rangle = |\pi\pi, I=2\rangle$$

$$\Rightarrow \quad \frac{1}{\sqrt{2}}\overline{A}^{+-} + \overline{A}^{00} = \overline{A}^{0-}$$

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{0+}$$

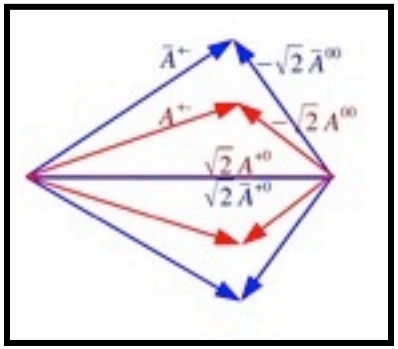


$$\arg(A^{+-}/\tilde{A}^{+-}) = 2\Delta\alpha = 2(\alpha - \alpha_{eff})$$

Ambiguities: 4 triangle orientations

$\Rightarrow$ 4-fold ambiguity for $\Delta\alpha$

$\alpha \leftrightarrow \pi-\alpha \quad \Rightarrow$ 8-fold ambiguity for α



α from Isospin Analysis

Input : $BF(B^0 \to \pi^+\pi^-), BF(B^+ \to \pi^+\pi^0), BF(B^0 \to \pi^0\pi^0), C_{+-}, S_{+-}, C_{00}$

Find minimum χ^2 in fit of isospin triangle to measurements. compute C.L.

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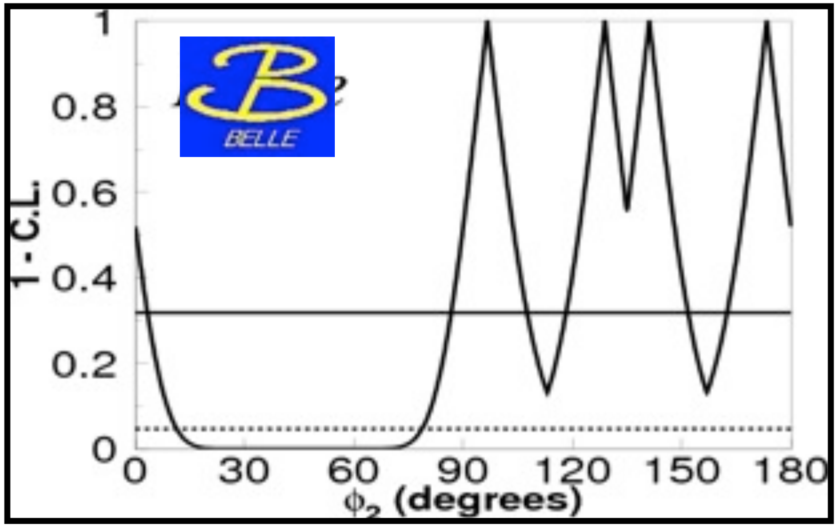
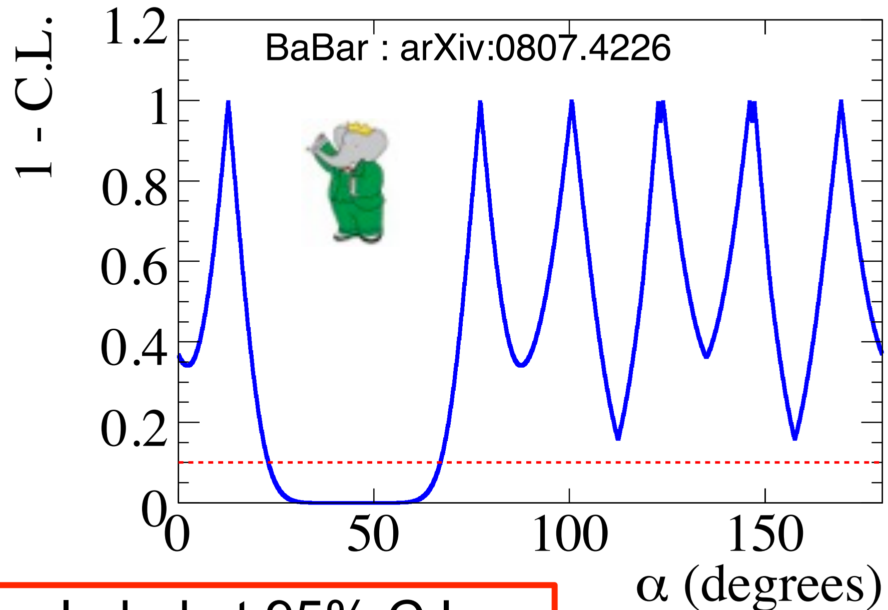




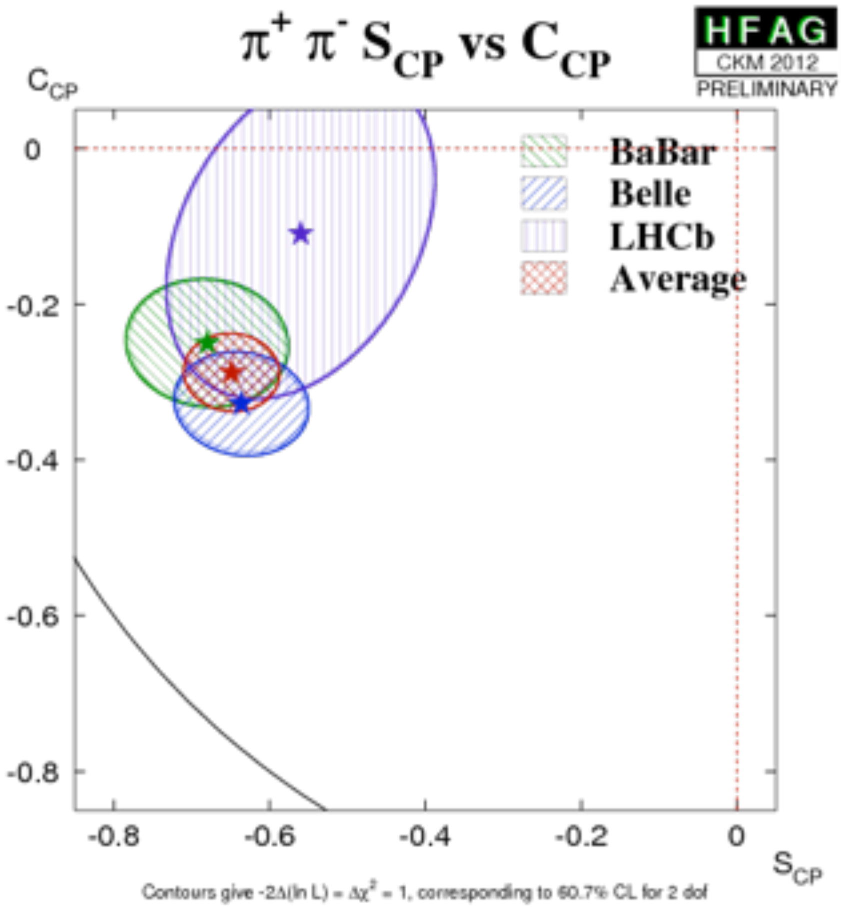
Belle:	$11 < \alpha < 79^o$	excluded at 95% C.L.
BaBar :	$23 < \alpha < 67^o$	excluded at 90% C.L.

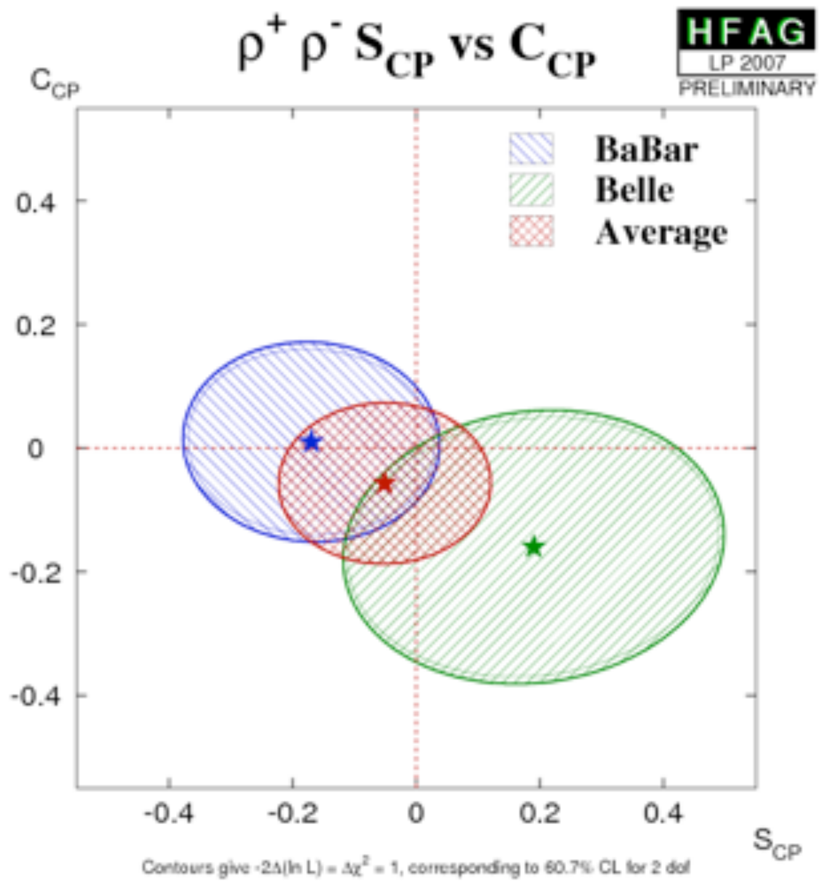
More promising: $B \to \rho\rho$

- 5× larger BF
- Much smaller penguin pollution: |P/T| ~ 4%
- Final state is mix of CP-odd and CP-even, but CP-even (longitudinal polarization) dominates

Experimental Situation

1. (Ideally) Use modes with small penguin contributions
2. Correct for penguin effects (isospin analysis)

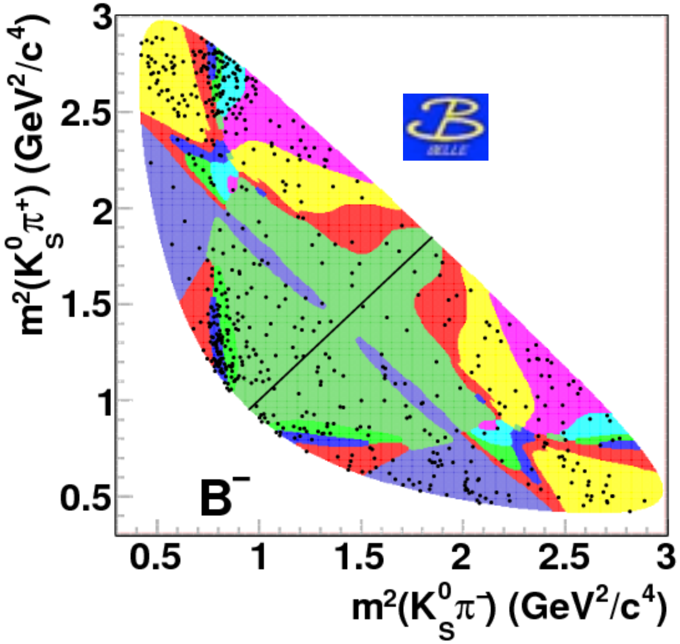




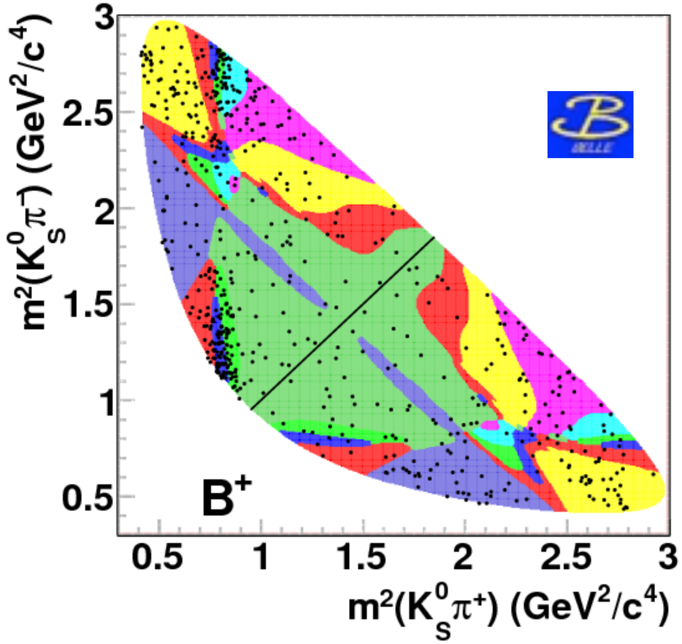
Dalitz Plot Measurement

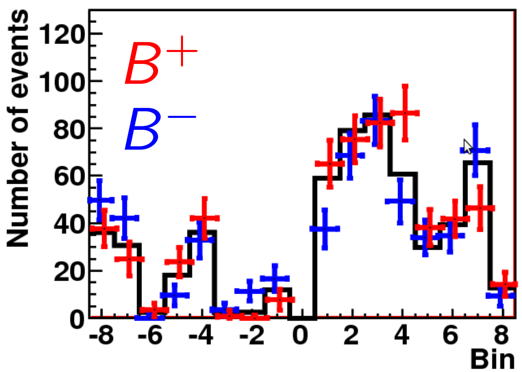
Compare regions of Dalitz space and quantify difference. PRD 85, 112014 (2012).

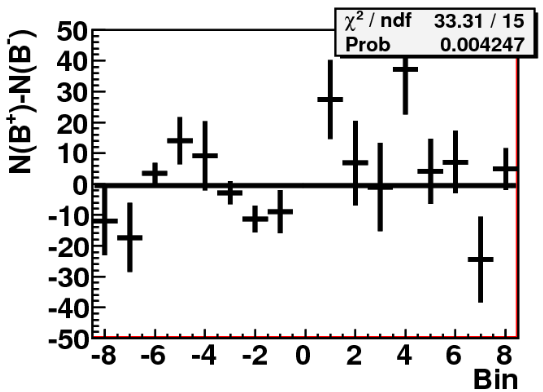
$B^- \to D^0 K^-$:



$B^+ \to D^0 K^+$:







$B^\pm \to DK^\pm$ sample