Determination of CKM angle γ and introduction to Dalitz analysis

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Flavor Physics Lectures
VII / XII

Karlsruhe Institute of Technology

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Reading material and references

Lecture material based on several textbooks and online lectures/notes.
Credits for material and figures include:

Literature

- Perkins, Donald H. (2000), *Introduction to High Energy Physics*.
- Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*.
- Stone, Sheldon (2nd edition), B *decays*.

Online Resources

- Belle/BaBar Collaborations, *The Phyiscs of the* B*-Factories*.
  http://arxiv.org/abs/1406.6311
- Bona, Marcella (University of London), CP *Violation Lecture Notes*,
  http://pprc.qmul.ac.uk/ bona/ulpg/cpv/
- Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and* CP *Violation*.
  http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf
- Thomson, Mark (Cambridge University), *Particle Physics Lecture Handouts*,
  http://www.hep.phy.cam.ac.uk/ thomson/partIIIparticles/welcome.html
- Grossman, Yuval (Cornell University), *Just a Taste. Lectures on Flavor Physics*,
  http://www.lepp.cornell.edu/ pt267/files/notes/FlavorNotes.pdf
- Kooijman, P. & Tuning, N., CP *Violation*,
  https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Recap & outline

So far, we:

- Learned how to measure CMK angles β and α through various channels:
  - We looked at theoretically clean "benchmark" decays (e.g., $B \to J/\psi K_S^0$) and also several decays dominated by $b \to s$ penguin diagrams where we can probe for new physics.
  - We saw how penguin pollution complicates the extraction of α. We learned how to exploit isospin relations to help resolve the ambiguity.

Today, we'll:

- Learn now to measure the final CKM angle γ.
- Along the way, we'll introduce the Dalitz analysis technique.

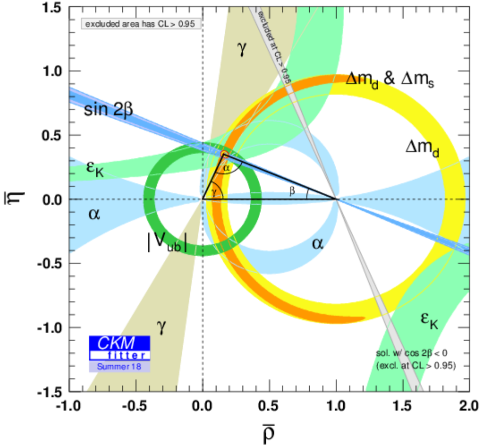
Credits for additional material and figures:
Tim Gershon, Tom Latham, and Brian Lindquist

Measurements of angle $\gamma = \phi_3$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right] \approx \arg V^*_{ub}$$

- The standard candle along with V_{ub}/V_{cb}.
- Less precise than ϕ_2.
  - Limited by the small branching fractions of the processes used in its measurement.

⇒ *The one place a large experimental gain in UT metrology can be made*

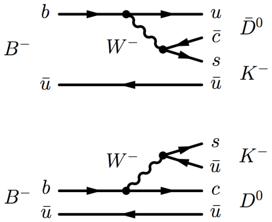


http://ckmfitter.in2p3.fr

Determine γ from CP asymmetries in $B \to DK$ decays

Tree-level Determination

- $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes in the charged-B meson decays to open-charm final states.
  - $\Rightarrow$ Interference between same final state for D and $\overline{D}$ $\Rightarrow$ possibility of $DCPV$.



* No penguin contribution (no theoretical uncertainty)
$\Rightarrow$ *All hadronic unknowns obtainable from experiment:*

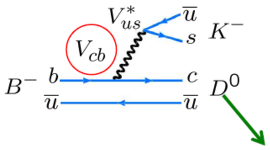
r_B = magnitude of the ratio of the amplitudes for $B^- \to \overline{D}^0 K^-$ and $B^- \to D^0 K^-$.

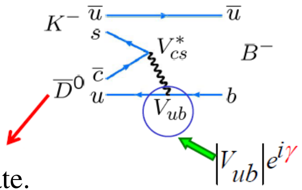
δ_B = the relative strong phase between these 2 amplitudes.

! Challenging: Small overall $\mathcal{B}$ from 5×10^{-6} to 10^{-9}.
$\Rightarrow$ *Precise measurement of ϕ_3 requires a very large data sample.*

Determine γ from CP asymmetries in $B \to DK$ decays

A_1 $\qquad\qquad$ $A_1 r_B e^{i(\delta_B - \gamma)}$





D^0 and $\overline{D}^0$ decays to a common final state.

Grouped into 3 categories:

(1) Flavor eigenstate: $K^+\pi^-$, $K^+\pi^-\pi^0$
(2) CP eigenstate: K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0$
(3) 3-body decay: $K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$

Relative strength of the two B decay amplitudes important for interference

$$r_B = \left| \frac{A(b \to u)}{A(b \to c)} \right| \sim 0.1 - 0.3$$

Large $r_B \Rightarrow$ large CP asymmetry

More on these 3 types of final states

Each category corresponds to a method, whose names reflect the authors who first described them:

The 3 methods according to final state are:

(1) Cabibbo-favored and double-CS final states ($K^+\pi^-$, $K^+\pi^-\pi^0$) ["ADS Method"]

Atwood, Dunietz & Soni Phys. Rev. D **63**, 036005 (2001)

(2) Cabibbo-suppressed (CS) D decays to CP-eigenstates (K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0$) ["GLW Method"]

Gronau & London Phys. Lett. B **253**, 483 (1991), Gronau & Wyler Phys. Lett. B **265**, 172 (1991)

(3) Dalitz plot distribution of the products of D decays to multi-body self-conjugate final states ($K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$) ["GGSZ Method"]

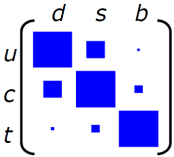
Giri, Grossman, Soffer and Zupan Phys. Rev. D **68**, 054018 (2003); Bondar (unpublished)

All methods are statistics-limited but have common B parameters

$\Rightarrow$ *Perform a simultaneous fit using the results of all methods.*

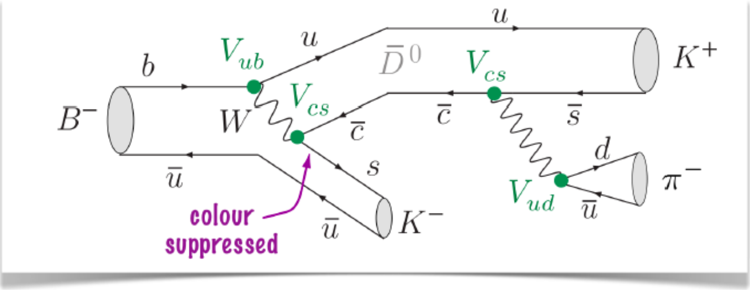
Aside: Cabbibo suppression

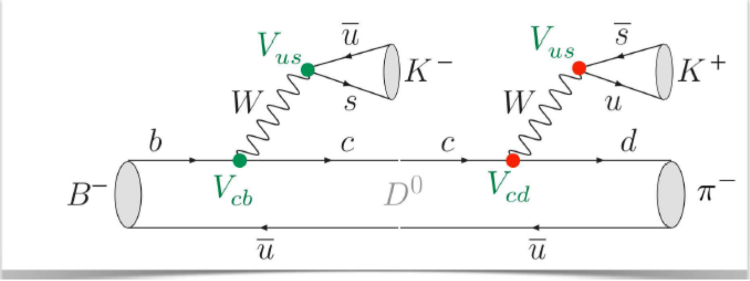
Recall the magnitude of the CKM matrix elements (represented by □)



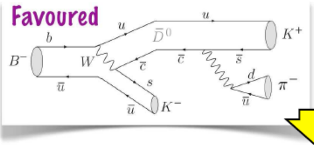
- Weak decays whose amplitudes contain only diagonal CKM elements are referred to as Cabbibo favored.
- Those with one factor of V_{us}, V_{cb}, V_{cd}, or V_{ts} are singly Cabbibo suppressed.
- Decays containing 2 of these factors, or one of V_{ub} or V_{td} are doubly Cabbibo suppressed.

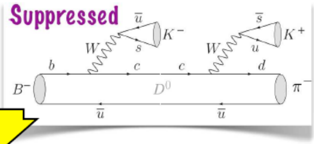
Cabibbo-favored and double-CS final states [ADS]

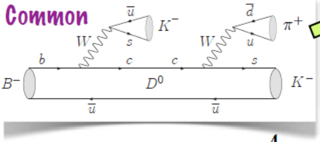




Cabibbo-favored and double-CS final states [ADS]







$$\mathcal{R}_{DK} = \frac{\Gamma([K^+\pi^-]K^-) + \Gamma([K^-\pi^+]K^+)}{\Gamma([K^-\pi^+]K^-) + \Gamma([K^+\pi^-]K^+)}$$

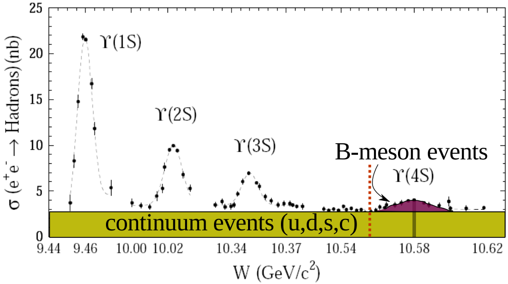
$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3$$

$$\mathcal{A}_{DK} = \frac{\Gamma([K^+\pi^-]K^-) - \Gamma([K^-\pi^+]K^+)}{\Gamma([K^-\pi^+]K^-) + \Gamma([K^+\pi^-]K^+)}$$

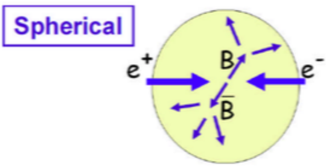
$$= 2\, r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3 \,/\, \mathcal{R}_{DK}$$

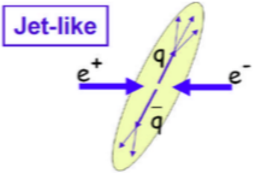
where $r_D = \left| \frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(\bar{D}^0 \to K^+\pi^-)} \right| = 0.0613 \pm 0.0010$

Recall $e^+e^- \to q\bar{q}$ continuum production



Different event topologies





B-mesons Continuum

Continuum suppression in ADS decay $B^- \to DK^-$ (I)

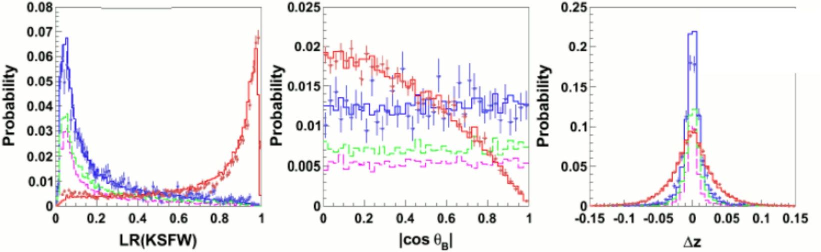
$B^- \to DK^-,\ D \to K^+\pi^-$ ADS

Main background is $e^+e^- \to q\bar{q}$ ($q=u, d, s, c$) continuum
combine 10 variables with neural network:

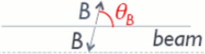
- Variables which have different distributions for signal and $q\bar{q}$ background are used.

$B^- \to D\pi^-$
$\to K^-\pi^+$
M_{bc}-sideband

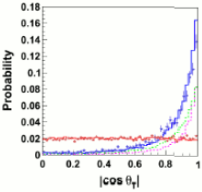
histogram: MC, dots: data
signal
qq = charm + uds



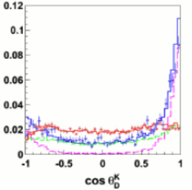
Likelihood ratio for KSFW.	*θ_B is angle between B-flight direction and beam axis.*	*Vertex separation between reconstructed B and the other B.*



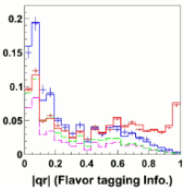
Continuum suppression in ADS decay $B^- \to DK^-$ (II)



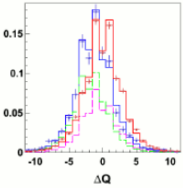
Angle between thrust axes of B decay and remainder.
No full correlation to LR(KSFW).



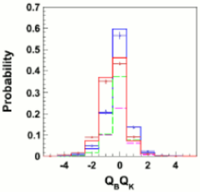
Decay angle of $D \to k\pi$.



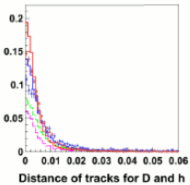
Flavor tagging Info. by MDLH. (NB possible.)



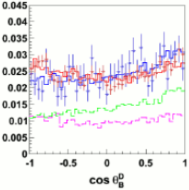
Difference of charges in D hemisphere and opposite hemisphere.



Product of charge of B and sum of charges for K not used in B reconstruction.



Distance of tracks for D and K.



Decay angle of $B \to DK$

10 variables combined to obtain a single NN output (NB)

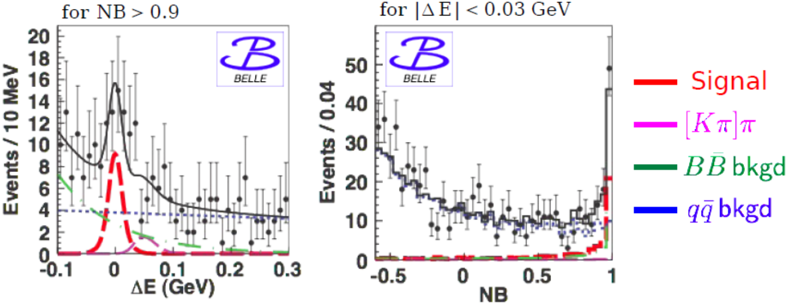
for example, at 99% bckg rej. signal eff. = 42% now becomes 60%

Belle result for ADS decay $B^- \to [K^+\pi^-]_D K^-$

Yields for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\bar{B}$ events

PRL 106, 231803 (2011)

Fit ΔE and NB distributions together to extract signal



$56.0^{+15.1}_{-14.2}$ events

$R_{DK} = (1.63^{+0.44}_{-0.41}{}^{+0.07}_{-0.13}) \times 10^{-2}$

$A_{DK} = -0.39^{+0.26}_{-0.28}{}^{+0.04}_{-0.03}$

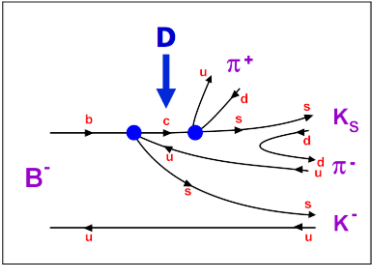
First evidence obtained with a significance of 4.1σ (including syst.)

Measurement of γ using Dalitz plot analysis [GGSZ]

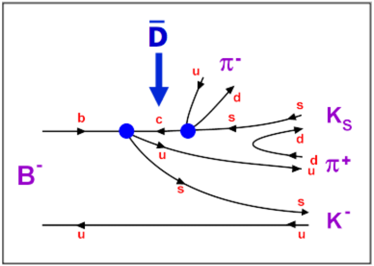
The basic idea of this method is to use final states accessible to both D^0 and $\overline{D}^0$ and to measure the phase of the interference between them in the decay of D mesons produced in $B^{\pm} \to DK^{\pm}$ transitions

The most convenient decay for this type of measurement is $D \to K^0_S \pi^+ \pi^-$

$B^- \to DK^- \to K^0_S \pi^+ \pi^- K^-$



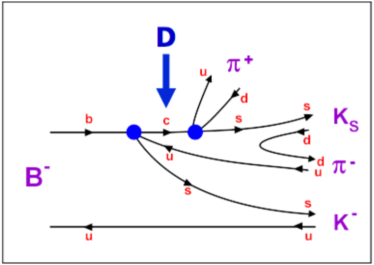
$B^- \to \overline{D}K^- \to K^0_S \pi^+ \pi^- K^-$



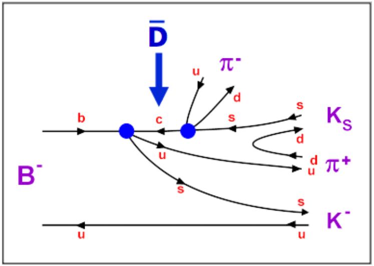
Unique combination of 3 advantages.

1) Large branching fraction.
2) Significant overlap of $D \to K_S^0 \pi^+ \pi^-$ and $\overline{D} \to K_S^0 \pi^+ \pi^-$ amplitudes which gives a large interference term sensitive to γ.
3) Rich resonant structure which provides large variations of the strong phase in D decays and results in sensitivity to to γ that is only weakly dependent on the values of γ and strong phase δ_B.

$B^- \to DK^- \to K_S^0 \pi^+ \pi^- K^-$



$B^- \to \overline{D}K^- \to K_S^0 \pi^+ \pi^- K^-$



Intermission - Dalitz plot formalism

What is a Dalitz plot?

- Visual representation of
  - the phase-space of a three-body decay
    - involving only spin-0 particles
    - (term often abused to refer to phase-space of any multibody decay)
  - Named after it's inventor, Richard Dalitz (1925–2006):
  - “On the analysis of tau-meson data and the nature of the tau-meson.”
    - R.H. Dalitz, Phil. Mag. 44 (1953) 1068
    - (historical reminder: tau meson = charged kaon)
  - For scientific obituary, see
    - I.J.R. Aitchison, F.E. Close, A. Gal, D.J. Millener,
    - Nucl.Phys.A771:8-25,2006

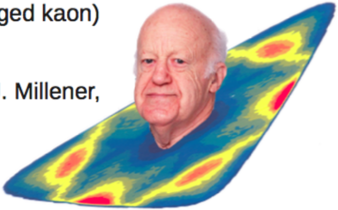


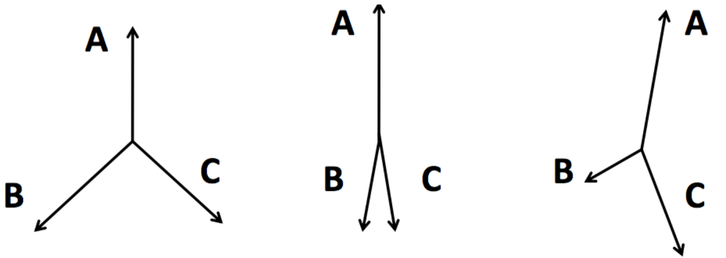
Image credit: Mike Pennington

Tim Gershon
Introduction to Dalitz Plot Analysis

3-body decays

For 2-body decays, $M \to ab$, p_a and p_b are completely determined by E, p conservation.

3-body decays have additional degrees of freedom; different values of p_a, p_b and p_c are possible, depending on the decay configuration.



Degrees of freedom (d.o.f)

For 3-body decays, $M \to abc$, where a, b and c are spin-0, the final state can be described by three 4-vectors: p_a^μ, p_b^μ and p_c^μ.

There are 12 parameters in total, but not all are independent:

- Set $p_{i,z} = 0$ since a, b and c all decay in the same plane; removes 3 d.o.f.
- Remove 3 d.o.f. by $E_i = \sqrt{m_i^2 + p_i^2}, \ \ (i = a, b, c)$
- Remove 3 d.o.f. by $\vec{p}_M = \vec{p}_a + \vec{p}_b + \vec{p}_c$ and $E_M = E_a + E_b + E_c$.
- Can rotate entire entire system in $x - y$ plane without effect; removes 1 d.o.f.

$\Rightarrow$ Only 2 d.o.f. left.

What should we use?!

To answer this, lets look at the differential decay probability of $M \to abc$.

Kinematic constraints

For a particle of mass M decaying into 3 particles denoted as a, b and c, the differential decay probability is:

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|A|^2 dm_{ab}^2 dm_{bc}^2$$

where m_{ab} and m_{bc} are the invariant masses of the pairs of particles ab and bc, respectively (i.e., $m_{ab}^2 = (p_a^\mu + p_b^\mu)^2$).

Use m_{ab} and m_{bc} (or m_{ab} & m_{ac}) as our 2 d.o.f.

The invariant masses of pairs of final-state particles are related by the linear dependence:

$$m_{ab}^2 + m_{bc}^2 + m_{ac}^2 = M^2 + m_a^2 + m_b^2 + m_c^2$$

Kinematic constraints

The range of invariant masses m^2_{bc} can be written in terms of either one of the other squared invariant masses (e.g., for m^2_{ab}):

$$(m^2_{bc})_{\max} = (E^*_b + E^*_c)^2 - (p^*_b - p^*_c)^2$$
$$(m^2_{bc})_{\min} = (E^*_b + E^*_c)^2 - (p^*_b + p^*_c)^2$$

where the energies of the particles b and c in the ab rest frame are

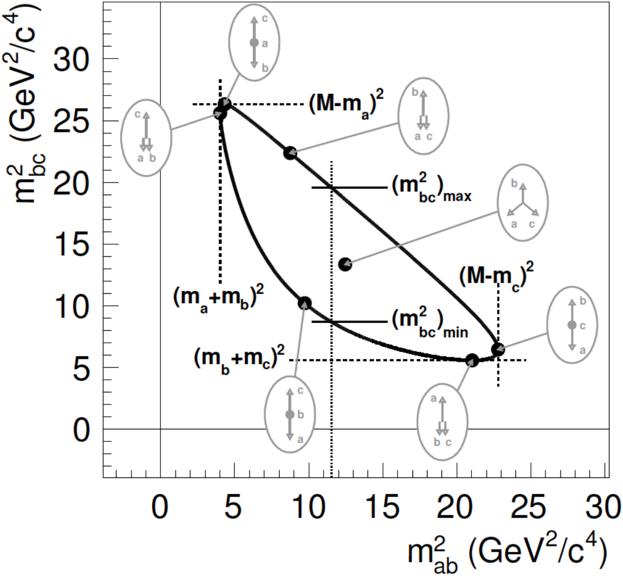
$$E^*_b = \frac{m^2_{ab} - m^2_a + m^2_b}{2m_{ab}}, E^*_c = \frac{M^2 - m^2_{ab} + m^2_c}{2m_{ab}}$$

and their corresponding momenta are:

$$p^*_b = \sqrt{E^*_b - m^2_b}, p^*_c = \sqrt{E^*_c - m^2_c}$$

Click here for a PDF containing a complete derivation of the kinematic limits (i.e., boundary curve on next slide) of the Dalitz plot [eqn 39]

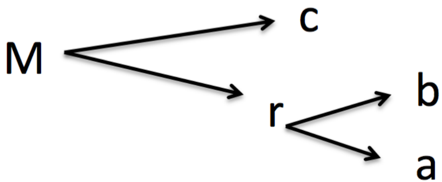
Kinematic boundaries of the 3-body decay phase space



Decay of M via resonances

Sometimes M will decay directly to a, b, c; this is called non-resonant (NR) or "phase space" decay.

The majority of times M will decay through intermediate particles (or "resonances") r

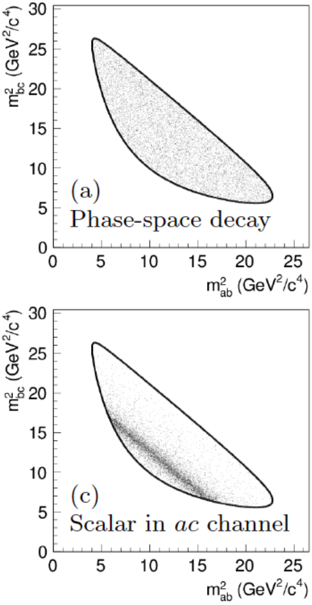


r is typically very short lived $\Rightarrow$ *can't observe directly.*

But can study r with a Dalitz plot.

E and p conservation imply that if $r \rightarrow ab$, then $m_{ab}^2 = m_r^2$
These resonances show up as bands on the Dalitz plot

Dalitz plot for NR decay and for spin-0 resonances



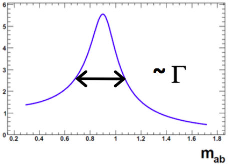
Resonance lifetimes I

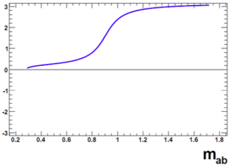
- Recall $\Delta E \Delta t \sim \hbar$
- Short-lived resonances have broad peaks.
- Commonly described using a relativistic Breit-Wigner (RBW) parameterization with mass-dependent width.

$$A_{\mathrm{RBW}} = \frac{1}{m_r^2 - m_{ab}^2 - i m_r \Gamma_{ab}}$$

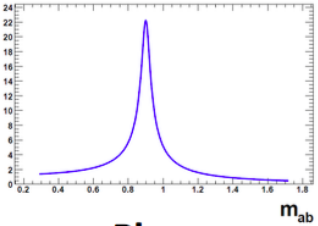
where the width is inversely proportional to the lifetime $\Gamma = \frac{\hbar}{\tau}$

- Plot of magnitude and phase of $A_{\mathrm{RBW}} = |A| e^{i\phi}$

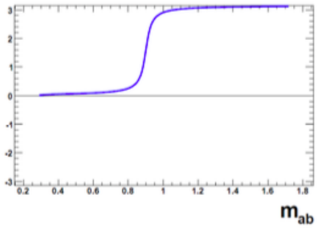


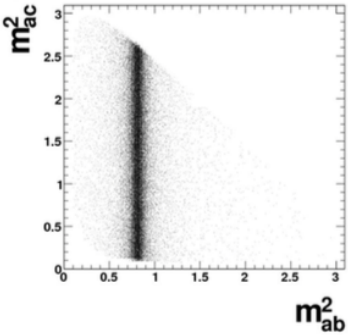


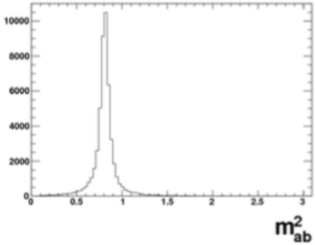
Magnitude



Phase

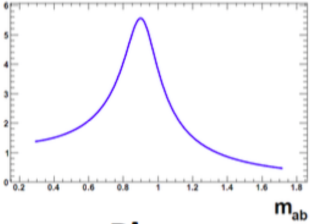




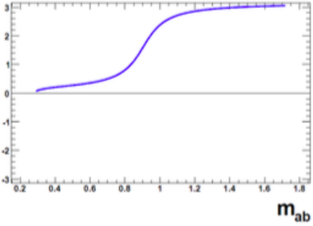


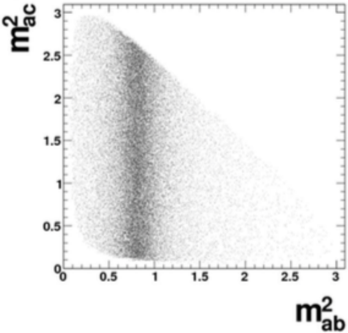
Resonance lifetimes III

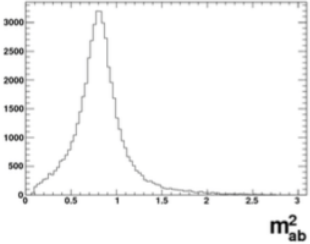
Magnitude



Phase





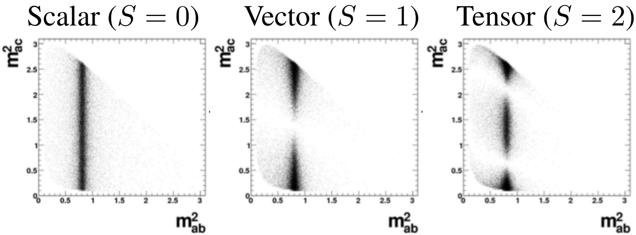


Resonance spins

- If the resonance has spin S, and M, a, b, and c are $S = 0$, the decay amplitude is proportional to Legendre polynomials:

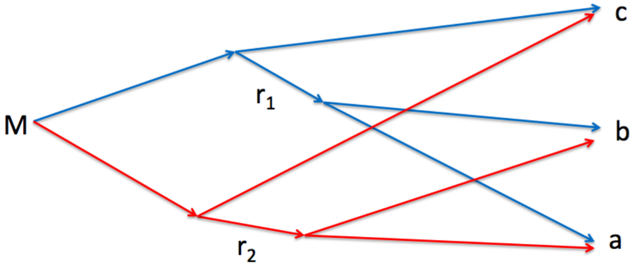
$$A \propto A_{\mathrm{RBW}}(m_{ab}) P_S(\cos\theta)$$

$$P_0(\cos\theta) = 1$$
$$P_1(\cos\theta) = \cos\theta$$
$$P_2(\cos\theta) = \frac{1}{2}\left(3\cos^2\theta - 1\right)$$



Multiple resonances

- Typically M can decay to the same final state through multiple resonances.
- Results in interference as in Young's double slit experiment.



Isobar model

- The usual strategy is to model the total decay amplitude as a sum of individual resonances plus a non-resonant term:

$$A = \Sigma_r a_r e^{i\phi_r} A_r + a_{\mathrm{NR}} e^{i\phi_{\mathrm{NR}}} A_{\mathrm{NR}}$$

  where $A_r(m_{ab}^2, m_{ac}^2)$ are the Dalitz plot dependent amplitudes which are of the form

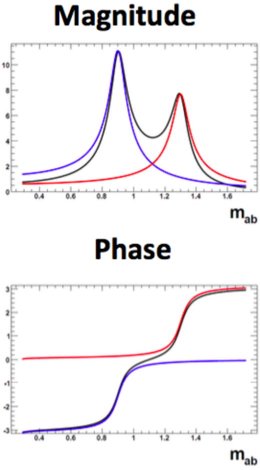
$$A_r = F_P \times \mathcal{F}_r \times A_{\mathrm{RBW}} \times W_r$$

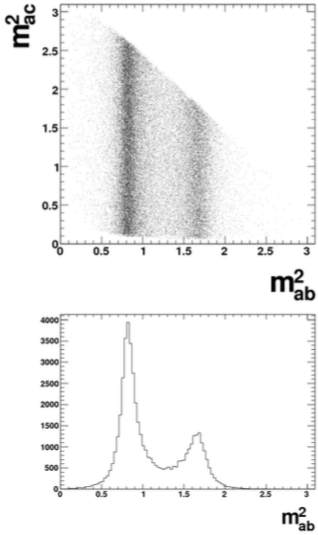
  and a_r and ϕ_r can be measured in a maximum-likelihood fit.
- Here, $A_{\mathrm{RBW}} \times W_r$ is the resonance propagator, where W_r describes the angular distribution of the decay (and recall we used a relativistic BW as the dynamical function of the resonance: A_{RBW})[1] .
- F_P and F_r are the transition form factors of the parent particle and resonance, respectively.

⇒ *now lets look at an example of 2 interfering amplitudes*

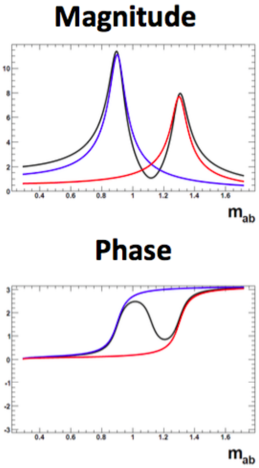
[1] Strictly speaking the RBW works well only in the case of narrow states. The use of the mass-dependent width results in the amplitude becoming a non-analytic function. An alternative parametrization proposed by Gounaris and Sakurai (GS) recovers the analyticity of the amplitude and provides a better description for broad vector resonances.

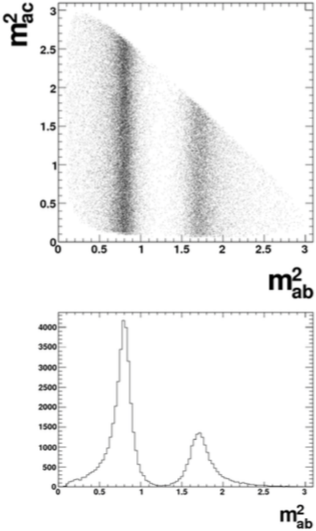
Constructive interference



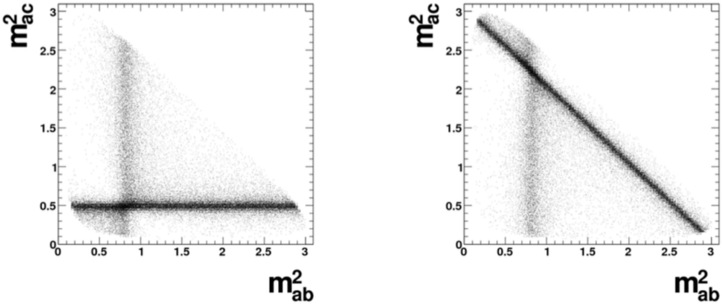


Destructive interference



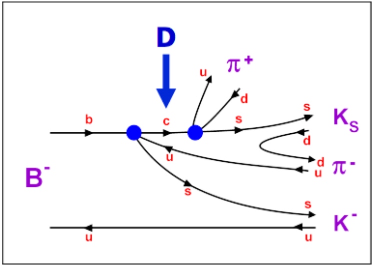


Cross-channel interference

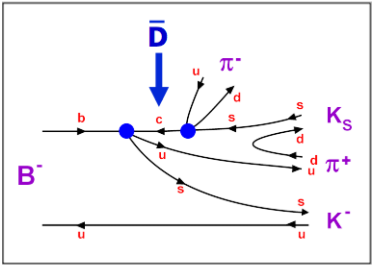


Back to measuring γ with $B \to DK$ decays

$B^- \to DK^- \to K_S^0\pi^+\pi^-K^-$



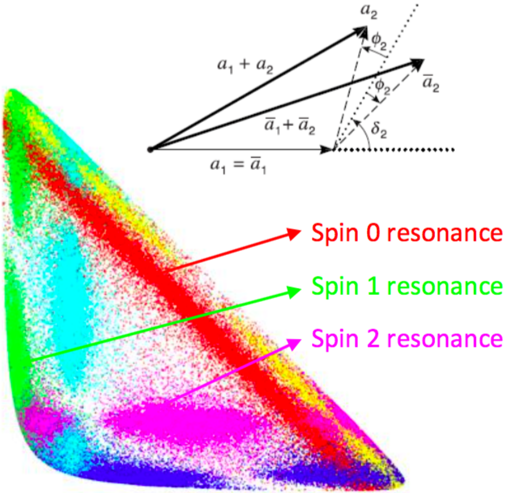
$B^- \to \overline{D}K^- \to K_S^0\pi^+\pi^-K^-$



Resonance structure in $D \to K_S^0 \pi^+ \pi^-$ Dalitz plane

- Green & blue: $K^{*0}(892)$ [vector]
- Cyan & magenta: $K_2^*(1430)$ [tensor]
- yellow: $\rho(770)$ [vector]
- red: $f_0(980)$ [scalar]
- ... even more which are not simulated here (fit result table)

Main advantage of Dalitz plots is the ability to exploit the interference between different resonances.



Belle measurement

- Define the 2 dalitz plot variables as
  $m_+^2 \equiv m_{K_S^0\pi^+}^2$
  $m_-^2 \equiv m_{K_S^0\pi^-}^2$
- The amplitude for the $B^\pm \to DK^\pm$ decays are

$$A_{B^+}(m_+^2, m_-^2) = \overline{A}_D + r_B e^{i(\delta_B+\gamma)} A_D$$
$$A_{B^-}(m_+^2, m_-^2) = A_D + r_B e^{i(\delta_B-\gamma)} \overline{A}_D$$

where

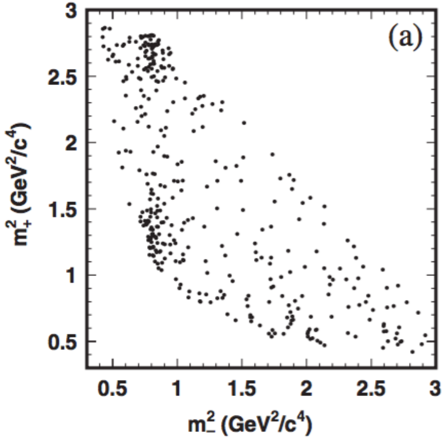
$A_D = A_D(m_+^2, m_-^2)$ is the complex amplitude of $D^0 \to K_S^0\pi^+\pi^-$
$\overline{A}_D = \overline{A}_D(m_+^2, m_-^2)$ is the complex amplitude of $\overline{D}^0 \to K_S^0\pi^+\pi^-$

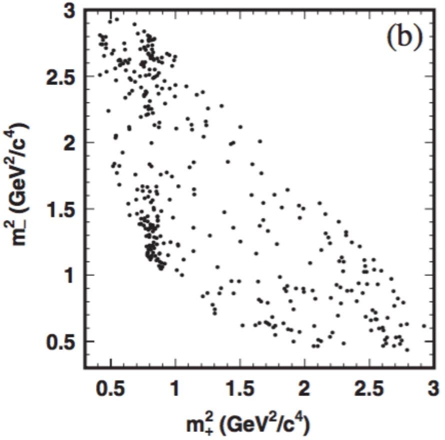
Recall:

r_B = magnitude of the ratio of the amplitudes for $B^- \to \overline{D}^0 K^-$ and $B^- \to D^0 K^-$.

δ_B = the relative strong phase between these 2 amplitudes.

Belle data for $D \to K_S^0 \pi^+ \pi^-$

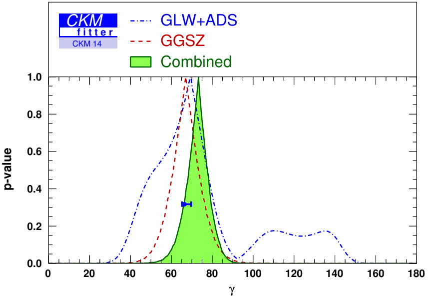




Fit result to Belle data for $D \to K_S^0 \pi^+ \pi^-$

Intermediate state	Amplitude	Phase (°)	Fit fraction (%)
$K_S^0 \sigma_1$	1.56 ± 0.06	214 ± 3	11.0 ± 0.7
$K_S^0 f_0(980)$	0.385 ± 0.006	207.3 ± 2.3	4.72 ± 0.05
$K_S^0 \sigma_2$	0.20 ± 0.02	212 ± 12	0.54 ± 0.10
$K_S^0 f_0(1370)$	1.56 ± 0.12	110 ± 4	1.9 ± 0.3
$K_S^0 \rho(770)^0$	1.0 (fixed)	0 (fixed)	21.2 ± 0.5
$K_S^0 \omega(782)$	0.0343 ± 0.0008	112.0 ± 1.3	0.526 ± 0.014
$K_S^0 f_2(1270)$	1.44 ± 0.04	342.9 ± 1.7	1.82 ± 0.05
$K_S^0 \rho^0(1450)$	0.49 ± 0.08	64 ± 11	0.11 ± 0.04
$K_0^*(1430)^- \pi^+$	2.21 ± 0.04	358.9 ± 1.1	7.93 ± 0.09
$K_0^*(1430)^+ \pi^-$	0.36 ± 0.03	87 ± 4	0.22 ± 0.04
$K^*(892)^- \pi^+$	1.638 ± 0.010	133.2 ± 0.4	62.9 ± 0.8
$K^*(892)^+ \pi^-$	0.149 ± 0.004	325.4 ± 1.3	0.526 ± 0.016
$K^*(1410)^- \pi^+$	0.65 ± 0.05	120 ± 4	0.49 ± 0.07
$K^*(1410)^+ \pi^-$	0.42 ± 0.04	253 ± 5	0.21 ± 0.03
$K_2^*(1430)^- \pi^+$	0.89 ± 0.03	314.8 ± 1.1	1.40 ± 0.06
$K_2^*(1430)^+ \pi^-$	0.23 ± 0.02	275 ± 6	0.093 ± 0.014
$K^*(1680)^- \pi^+$	0.88 ± 0.27	82 ± 17	0.06 ± 0.04
$K^*(1680)^+ \pi^-$	2.1 ± 0.2	130 ± 6	0.30 ± 0.07
non-resonant	2.7 ± 0.3	160 ± 5	5.0 ± 1.0

Combination of results from 3 methods



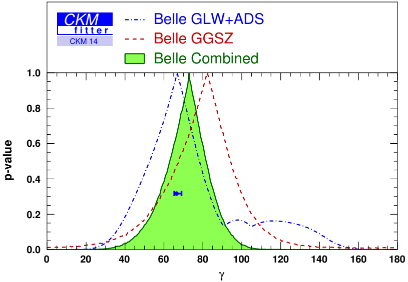
Constraints on γ from world average $B^{\pm} \to D^{(*)}K^{(*)\pm}$ decays (GLW+ADS) and Dalitz analyses (GGSZ)

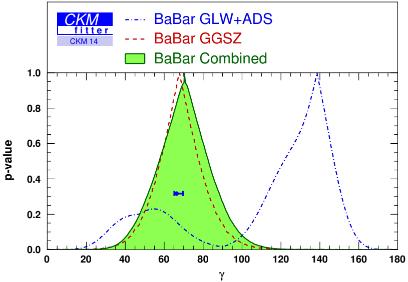
$$\gamma(\text{combined}) = (73.2^{+6.3}_{-7.0})^{\circ}$$

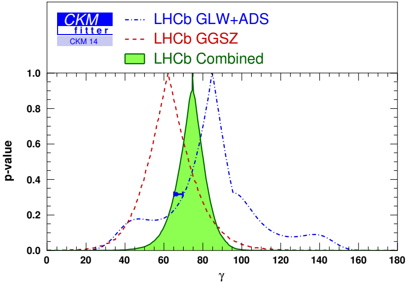
Compared to the prediction from the global CKM fit (not including these measurements):

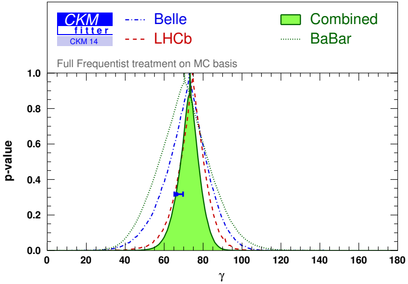
$$\gamma(\text{fit}) = (66.9^{+1.0}_{-3.7})^{\circ}$$

Separated by experiment

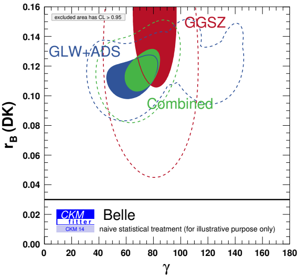


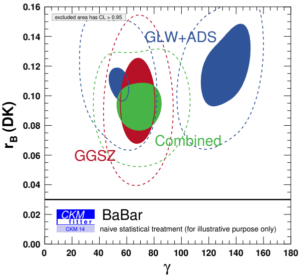


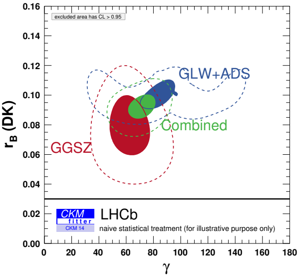


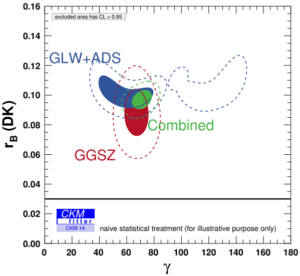


Results for r_B vs. γ









$$\gamma = (73.2^{+6.3}_{-7.0})^\circ$$
$$r_B = (0.097 \pm 0.006)$$
$$\delta_B = (125.4^{+7.0}_{-7.8})$$

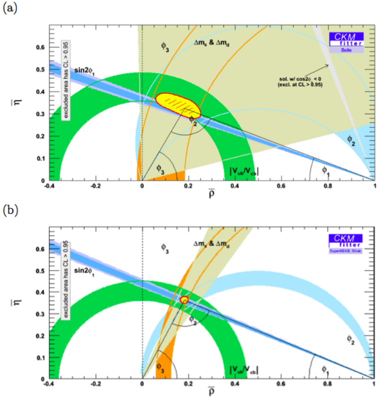
Prospects @ Belle II

All methods reproducible at Belle II

- Improvements in PID and $q\bar{q}$ suppression using neural networks Nucl. Instrum. Meth. A654: 432 (2011)
- Systematic errors from peaking charmless background, and PDFs from $D\pi$ and sidebands will decrease with statistics.
- Elimination of D model uncertainty using samples of neutral D mesons decaying into CP eigenstates from charm factories CLEO-c and BESIII (via $\psi(3770) \to DD$).

  $\Rightarrow$ *Naive scaling of combination with ADS and GLW yeilds an error of* $1.5°$.

  Physics at Super B Factory, arXiv:1002.5012 (2010)



(a) Belle at 0.5ab^{-1} and (b) Belle II at 50ab^{-1}

Much more!

- Statistical error will be dominant and can be improved by including D decays to, e.g., $K_S^0 K^+ K^-$, $\pi^+\pi^-\pi^0$, $K_S^0\pi^+\pi^-\pi^0$ (2* $\mathcal{B}(K_S^0\pi^+\pi^-)$!).
- Use $D\pi$ in addition to DK

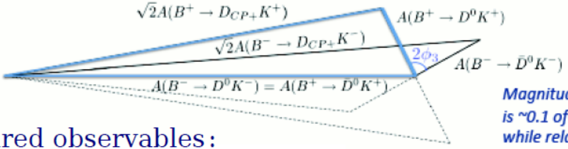
Extra material - GLW Method

Cabibbo-suppressed D decays to CP-eigenstates (GLW)

GLW with $D^{(*)}_{CP}K$

D decays to CP eigenstates

➤ **Amplitude triangle:**



Magnitude of one side is ~0.1 of the others while relative magnitude of the others help ϕ_3 constraint.

measured observables:

$$R_{CP\pm} \equiv \frac{Br(B^- \to D_{CP\pm}K^-) + Br(B^+ \to D_{CP\pm}K^+)}{Br(B^- \to D^0 K^-) + Br(B^+ \to \bar{D}^0 K^+)}$$

$$A_{CP\pm} \equiv \frac{Br(B^- \to D_{CP\pm}K^-) - Br(B^+ \to D_{CP\pm}K^+)}{Br(B^- \to D_{CP\pm}K^-) + Br(B^+ \to D_{CP\pm}K^+)}$$

Relation between $(A_{CP+}, A_{CP-}, R_{CP+}, R_{CP-})$ and (γ, r_B, δ_B)

$$A_{CP+} = \frac{+2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma} \qquad A_{CP-} = \frac{-2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 - 2 r_B \cos\delta_B \cos\gamma}$$

$$R_{CP+} = 1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma \qquad R_{CP-} = 1 + r_B^2 - 2 r_B \cos\delta_B \cos\gamma$$

$\Rightarrow$ look for $R_{CP\pm} \neq 1$ and $A_{CP\pm} \neq 0$

$\Rightarrow$ $\neq$ CP, $\neq$ sign of asymmetry

Cabibbo-suppressed D decays to CP-eigenstates (GLW)

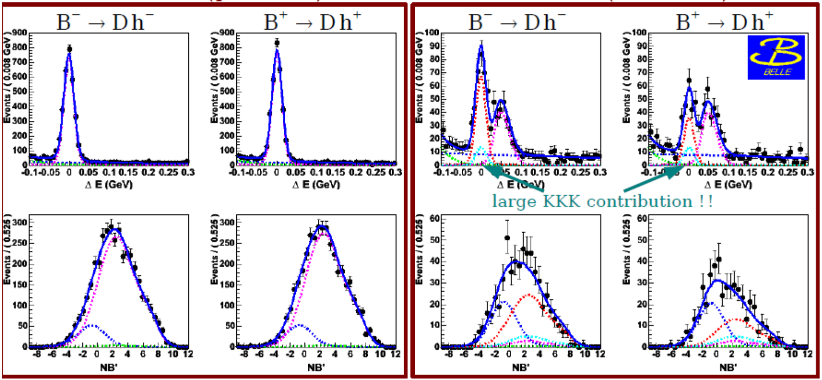
$B \to Dh,\ D \to K^+K^-,\ \pi^+\pi^- \ \to\ R_+$

Preliminary
LP 2011
($772\ \mathrm{M}B\bar{B}$)
$B \to D\pi$
$B \to DK$
$B\bar{B}$
continuum

Yields	$B\to D\pi$	$B\to DK$
$D\to K\pi$	50432 ± 243	3692 ± 83
$D\to KK,\pi\pi$	7696 ± 106	582 ± 40

$\Rightarrow\ R_{D_{fav}} = (7.32\pm0.16)\%$
$A(DK) = (1.4\pm2.0)\%$

KID< 0.6 (pion-like) **KID> 0.6 (kaon-like)**



$\Rightarrow\ R_{D_{CP+}} = (7.56\pm0.51)\%,\quad A_{D_{CP+}} = (28.7\pm6.0)\%$

large asymmetry !!

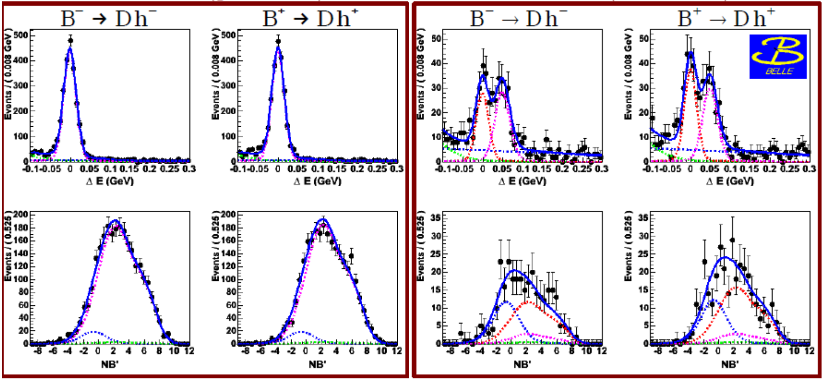
Cabibbo-suppressed D decays to CP-eigenstates (GLW)

$B \to Dh$, $D \to K_S\pi^0$, $K_S\eta$ $\to$ R_-

Preliminary
LP 2011
(772 $MB\bar{B}$)
$B \to D\pi$
$B \to DK$
$B\bar{B}$
continuum

Yields	$B \to D\pi$	$B \to DK$
$D \to K_S\pi^0$, $K_S\eta$	5745 ± 91	476 ± 37

KID< 0.6 (pion-like) KID> 0.6 (kaon-like)



$\Rightarrow R_{D_{CP-}} = (8.29 \pm 0.63)\%$, $A_{D_{CP-}} = (-12.4 \pm 6.4)\%$

opposite asymmetry !!

Summary of GLW results

GLW Results

Preliminary (LP 2011)

$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$
$$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$$

$$A_{CP+} = +0.29 \pm 0.06 \pm 0.02$$
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

CP-odd observables only available at B-factories

(systematics dominated by peaking background, double ratio approximation)