Searches for NP in $\sin 2\beta$, determination of α, and the polarization puzzle in $B \to VV$ decays

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Flavor Physics Lectures
VI / XII

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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*.
  https://courses.physics.ucsd.edu/2010/Winter/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:

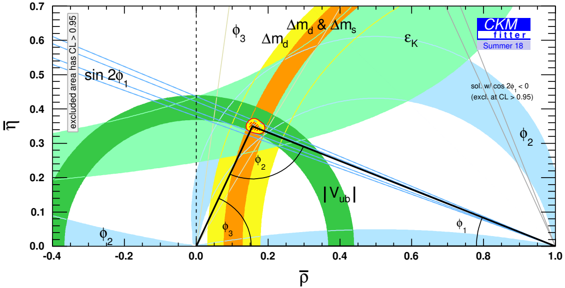
- Derived an expression for the asymmetry due to CP violation in the interference between mixing and decay.
- Focused on the golden mode for measuring the angle β: the $b \to c\bar{c}s$ decay $B \to J/\psi K^0_S$.

Today, we'll:

- See how we can search for New Physics in alternative measurements of β.
- Learn how to measure the angle $\alpha (= \phi_2)$ from $B \to \pi\pi$ and $B \to \rho\rho$ decays
- Study polarization in scalar $\to$ vector vector decays and introduce the "polarization puzzle."

CKM Fits

Some tensions exist, but overall there is very good agreement over large sets of measurements.



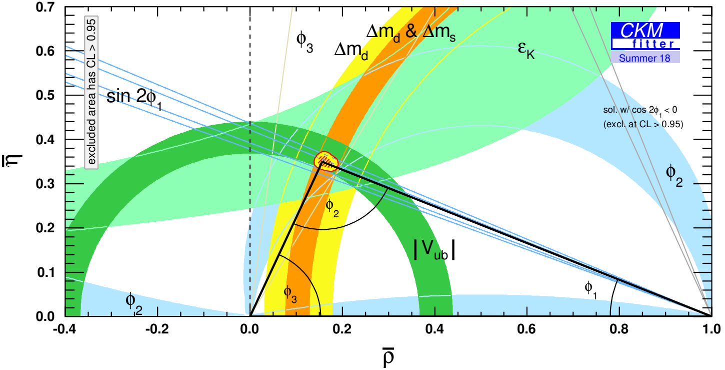
What we observe in nature is Standard model + possible New Physics contributions. To set constraints on NP

- Assume tree level diagrams are dominated by SM and loops could contain NP (needs precision CKM measurements)

We need to dig deeper...

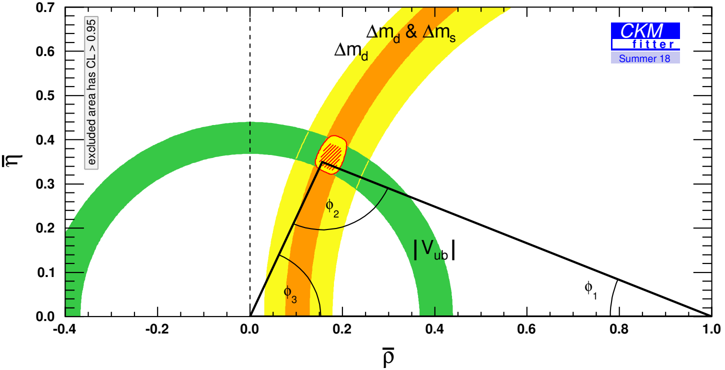
Remember lesson from Kaon CPV!

CKM Fits



- Global CKM fit: 68% CL.
- CP conserving: $|V_{ub}|/|V_{cb}|$, Δm_d, Δm_s, $B^+ \to \tau^+\nu_\tau$.
- CP violating: $\sin 2\phi_1$, ϕ_2, ϕ_3, ϵ_k.
- Tree: $\phi_3(DK)$, ϕ_2 from Isospin analysis.
- Loop.

CKM Fits



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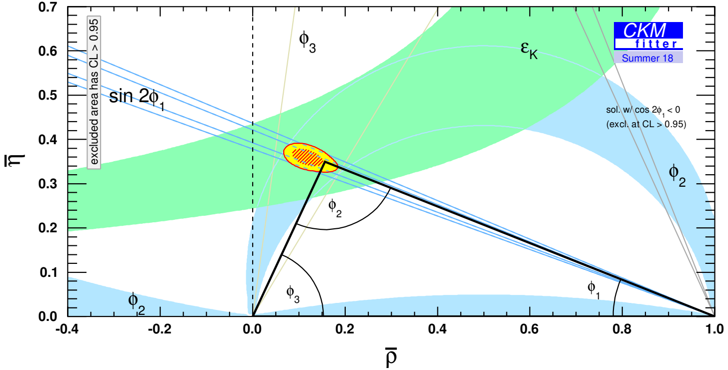

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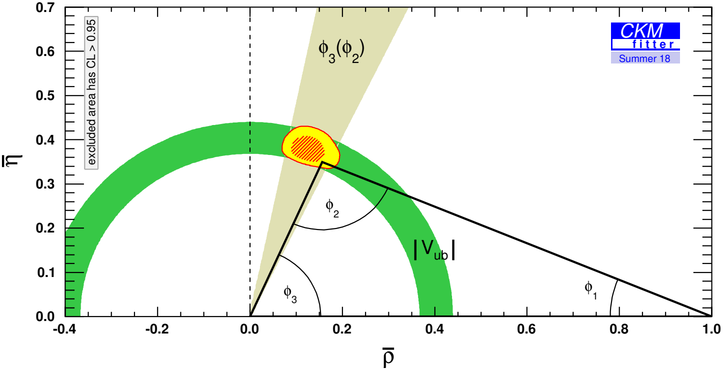

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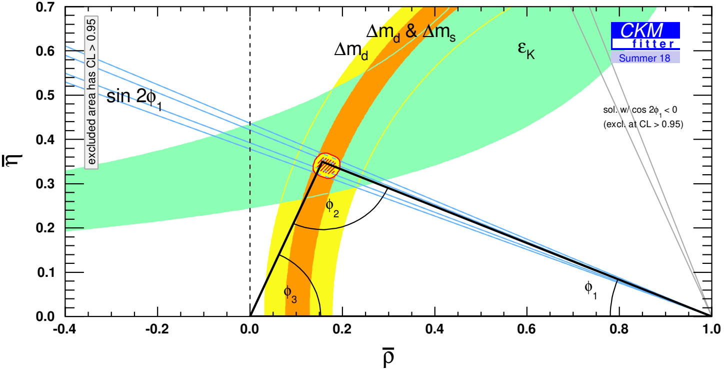

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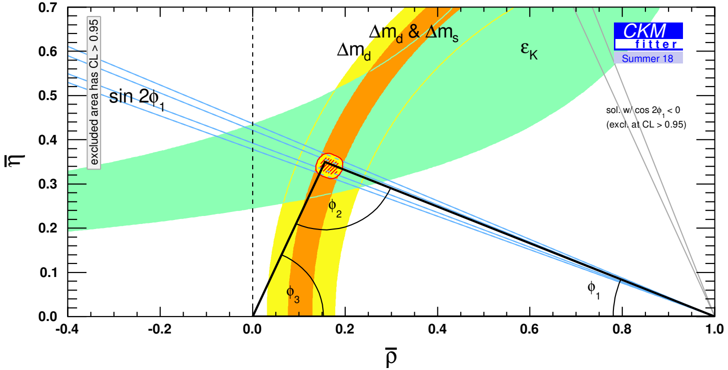

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- CP violating: $\sin 2\phi_1$, ϕ_2, ϕ_3, ϵ_k.
- Tree: $\phi_3(DK)$, ϕ_2 from Isospin analysis.
- Loop. $\Rightarrow$ *Still room for corrections from NP at $\mathcal{O}(0.1)$.*

Measurements of angle $\beta = \phi_1$

Recap: Time-dependent CP asymmetry and β

Recall the asymmetry for CP violation in interference between mixing and decay

$$\mathcal{A}_{\mathcal{CP}}(t) = \frac{\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 - \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2}{\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 + \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2}$$

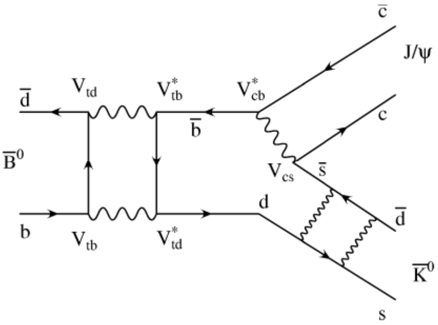
$$= \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m t) - \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}\sin(\Delta m t)$$

$$= A_f \cos(\Delta m t) - S_f \sin(\Delta m t)$$

$$A_f \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad S_f \equiv \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}$$

sometimes called A_{CP} and S_{CP}, or just A and S

The golden mode for β: $B^0 \to J/\psi K_S^0$ $(b \to c\bar{c}s)$

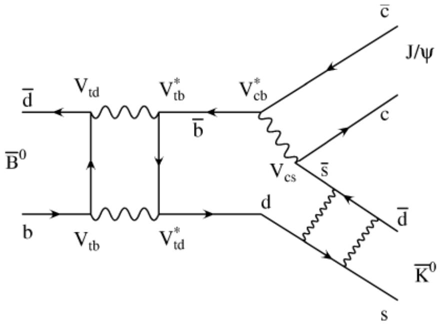


Two important criteria:

- The $J\psi K_S^0$ is a CP eigenstate accessible to **both** B^0 and $\overline{B}^0$.
- This is the only major diagram contributing to this decay, so there is only one weak phase ϕ.

Here CPV manifests from interference between the decays $B^0 \to J/\psi K_S^0$ and $B^0 \to \overline{B}^0 \to J/\psi K_S^0$ in this single tree diagram.

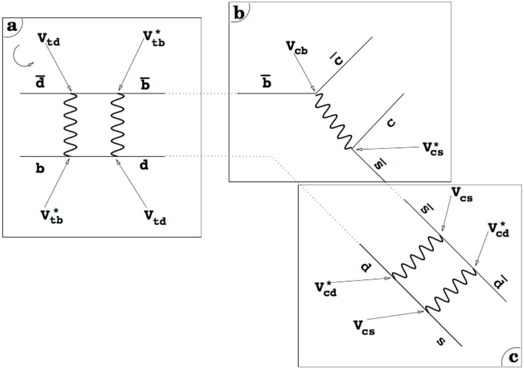
The golden mode for β: $B^0 \to J/\psi K_S^0$ $(b \to c\bar{c}s)$



$$\lambda_{J\psi K_S^0} = \left(\frac{q}{p}\right)_{B^0} \left(\eta_{J/\psi K_S^0} \frac{\overline{A}_{J/\psi K_S^0}}{A_{J/\psi K_S^0}}\right) = -\left(\frac{q}{p}\right)_{B^0} \left(\frac{\overline{A}_{J/\psi \overline{K}^0}}{A_{J/\psi K^0}}\right) \left(\frac{p}{q}\right)_K$$

Recall why we need K^0-$\overline{K}^0$ mixing:
$B^0 \to J\psi K^0$ but $\overline{B}^0 \to J\psi \overline{K}^0$, so the K^0's must mix in order to reach the same final state f for the B^0 and $\overline{B}^0$ decay (recall $|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$) .

The golden mode for β: $B^0 \to J/\psi K^0_S$ $(b \to c\bar{c}s)$



In terms of the CKM matrix elements

(a) B^0-$\overline{B}^0$ mixing:
$$\left(\frac{q}{p}\right)_{B^0} = \frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}$$

(b) $b \to c$ decay
$$\left(\frac{\overline{A}}{A}\right) = \frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}$$

(c) K^0-$\overline{K}^0$ mixing:
$$\left(\frac{p}{q}\right)_{K} = \frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}}$$

The golden mode for β: $B^0 \to J/\psi K_S^0$ $(b \to c\bar{c}s)$

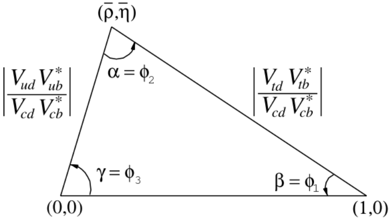
Putting the pieces together

$$\lambda_{J/\psi K_S^0} = (-1)\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \cdot \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}$$

$$= (-1)\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}$$

$$= -e^{-2i\beta}$$

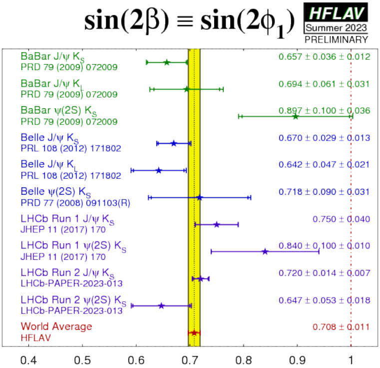
$$\Rightarrow \mathrm{Im}\lambda_{J/\psi K_S^0} = \sin 2\beta$$



$$\beta = \arg\left[-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right]$$

$$\boxed{\mathcal{A}_{\mathcal{CP}}(\Delta t) = -\sin(2\beta)\sin(\Delta m \Delta t)}$$

Combination of $b \to c\bar{c}s$ results for β from all experiments



- Large CPV in $B^0 \to J/\psi K_S^0$ observed in 2001 by Belle and Babar.

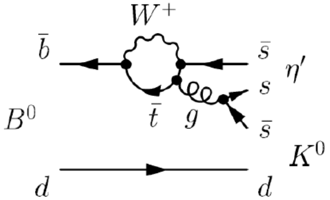
  $\Rightarrow$ *First instance outside the Kaon system.*

- Confirms the mechanism of CPV by Kobayashi and Maskawa introduced in 1972.
- Establishes technique for extracting A_{CP} and S_{CP} that can be used for other final states.
- Measured $\sin(2\beta)$ provides a reference point to search for NP.

Is there somewhere we can look for hints of NP in measurements of β?

What about in charmless decays?

Within the SM:



$\beta = \phi_1$ and $\gamma = \phi_3$

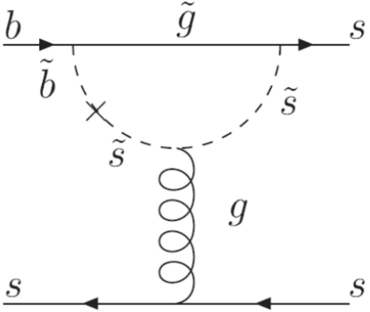
$V_{tb}V^*_{ts}A^{(t)}_f$	λ^2	$\sin(2\beta) \times 1.033$
$V_{cb}V^*_{cs}A^{(c)}_f$	λ^2	$\sin(2\beta)$
$V_{ub}V^*_{us}A^{(u)}_f$	λ^4	$\sin(2\beta + 2\gamma)$

Several SM amplitudes $\Rightarrow$ measure $\sin 2\beta^{eff.}$

$\sin 2\beta$ from $b \to s\bar{s}s$ decays (Charmless penguins)

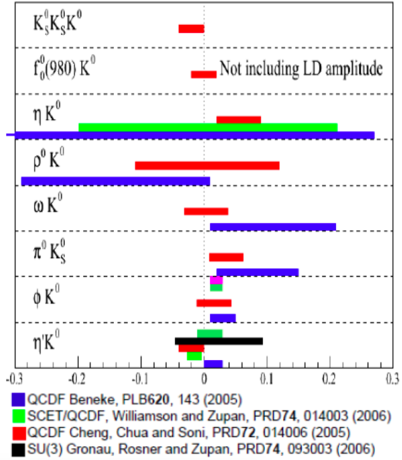
$$\Delta S = S_{s\bar{s}s} - S_{c\bar{c}s}$$

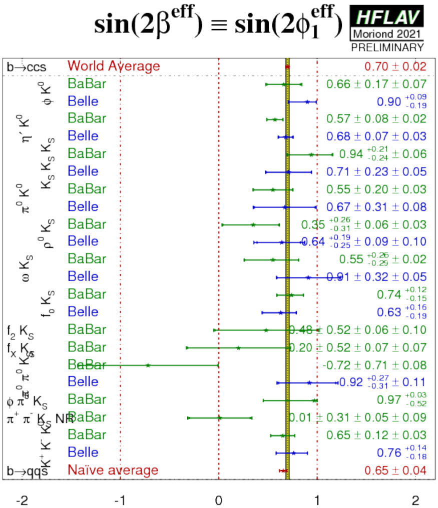
NP in the loop may introduce new source(s) of CPV



$\Delta S \neq \Delta S_{SM}$

ΔS_{SM} (mode dependent)



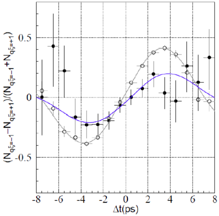


Majority of results on the "wrong" side of the $b \to c\bar{c}s$ value.

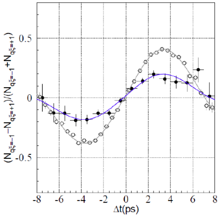
Tension, but not significant $\Rightarrow$ *Need larger sample!*

$B^0 \to \phi K^0_S$ (closed circles)

@ 5 ab^{-1}

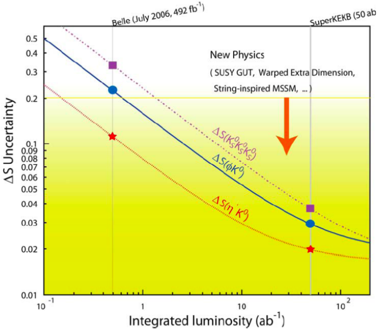


@ 50 ab^{-1}



Input: $S_{\phi K_S} = +0.39$ and $A_{\phi K_S} = 0$

Physics at Super B Factory [arXiv:1002.5012]

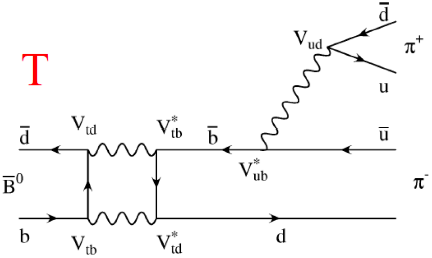


Belle II can provide precision measurements of ΔS, up to the limit of hadronic uncertainties, which will be at a few percent level.

Measurements of angle $\alpha = \phi_2$

$\alpha = \phi_2$ from $b \to u\bar{u}d$ (e.g $B^0 \to \pi^+\pi^-$)

Tree diagram similar to measurement of β.



$$\lambda_{\pi^+\pi^-} = \underbrace{\left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)}_{\text{mixing}}\underbrace{\left(\frac{V^*_{ud}V_{ub}}{V_{ud}V^*_{ub}}\right)}_{\text{decay}}$$

Recall the Wolfenstein phase convention

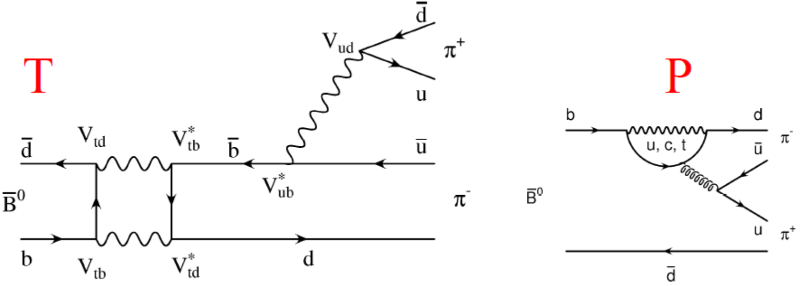
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

$$\Rightarrow \mathrm{Im}(\lambda_{\pi^+\pi^-}) = \sin(2\pi - 2\beta - 2\gamma) = \sin 2\alpha$$

Unfortunately not so easy... *First results showed that penguin pollutions, which have a different weak phase, are too large to be ignored*

$\alpha = \phi_2$ from $b \to u\bar{u}d$ (e.g $B^0 \to \pi^+\pi^-$)

Including penguin diagram



- Weak phase in penguin term is $\arg(V_{td}^* V_{tb}) \quad \Rightarrow$ *different from tree*
  - It modifies $\mathrm{Im}(\lambda_{\pi^+\pi^-})$ and $|\lambda_{\pi^+\pi^-}|$ depending on the relative strength with respect to the tree.

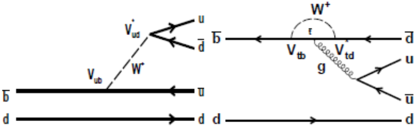
$$\lambda_{\pi^+\pi^-} = e^{i2\alpha} \frac{T + Pe^{+i\gamma} e^{i\delta}}{T + Pe^{-i\gamma} e^{i\delta}}$$

- Measure an effective α:

$$S_{\pi^+\pi^-} \propto \sin(2\alpha_{\text{eff}}) = \sin(2(\alpha + \Delta\alpha))$$

$B^0 \to \pi^+\pi^-$ measurement from Belle

- simultanious fit of branching ratios and CP asymmetries
- $b \to u\bar{u}d$, sensitive to ϕ_2, but penguins



$\rightarrow$measured observable:

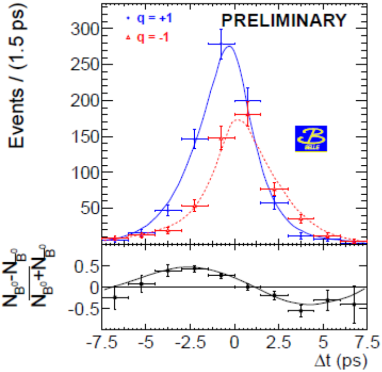
$$\phi_2^{eff} = \phi_2 + \Delta\phi_2$$

- previous Belle result:

$$\mathcal{S}^{\pi^+\pi^-}_{CP,prev.} = -0.61 \pm 0.10 \pm 0.04$$

$$\mathcal{A}^{\pi^+\pi^-}_{CP,prev.} = +0.55 \pm 0.08 \pm 0.05$$

New results



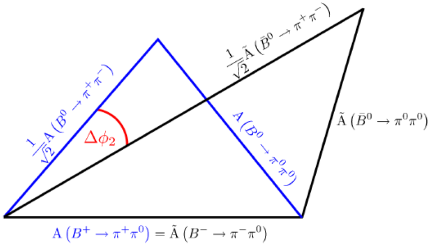
$$\mathcal{S}^{\pi^+\pi^-}_{CP} = -0.636 \pm 0.082 \pm 0.027$$

$$\mathcal{A}^{\pi^+\pi^-}_{CP} = +0.328 \pm 0.061 \pm 0.027$$

Measure penguin pollution $\Delta\alpha$

Penguin pollution can be estimated using $SU(2)$ Isospin analysis
Gronau, London PRL65, 3381 (1990)

- $B \to \pi\pi$ can have $I = 0$ and $I = 2$
- Expansion of amplitudes for $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ and c.c. in terms of $I = 0$ and $I = 2$ leads to a relations of 2 complex triangles sharing same base ($B^+ \to \pi^+\pi^0$ tree only amplitude).

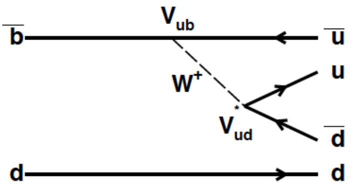


Need to measure 6 physical observables:
$\mathcal{B}(B^0 \to \pi^+\pi^-)$, $\mathcal{B}(B^0 \to \pi^0\pi^0)$, $\mathcal{B}(B^+ \to \pi^+\pi^0)$, $A_{\pi^+\pi^-}$, $S_{\pi^+\pi^-}$, $A_{\pi^0\pi^0}$

Long and complicated history of $B^0 \to \pi^0\pi^0$ decays

Important input for isospin analysis in $B \to \pi\pi$ (significant penguin pollution)

- color-suppressed $b \to u$ transition
- $\pi^0 \to \gamma\gamma \Rightarrow 4\gamma$ final state, photon conversion ($\gamma \to e^+e^-$) considered
- ECL trigger time cut removes 99% pile-up, retains 99% signal



Previous measurements

Experiment	$\mathcal{BR}(\times 10^{-6})$	$\mathcal{A}_{CP}$	$N(B\bar{B})$
Belle (PRL **94** 181803 (2005))	$2.4 \pm 0.4 \pm 0.5$	$0.44^{+0.53}_{-0.52} \pm 0.17$	275M
Belle (ICHEP 2006 *unpublished*)	$1.1 \pm 0.3 \pm 0.1$	$0.41^{+0.73+0.62}_{-0.04-0.06}$	532M
BaBar (PRD **87**, 052009 (2013))	$1.83 \pm 0.21 \pm 0.13$	$0.43 \pm 0.26 \pm 0.05$	467M

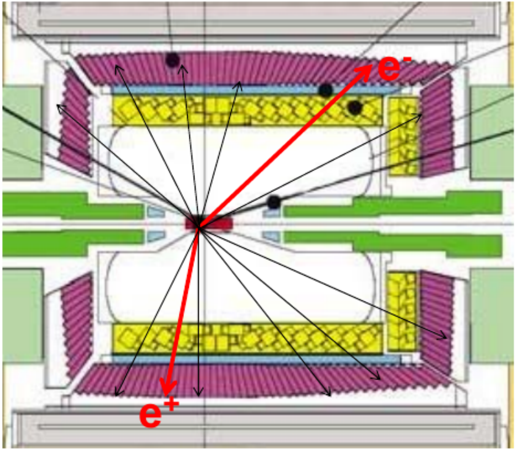
Theory (QCDF): $\mathcal{BR} \times 10^{+6} \leq 1$ (Nucl.Phys. **B**675 333 (2003))

The Belle 2005 measurement does not include this ECL trigger time cut. Caused a lot of confusion since QCDF predicts $\mathcal{B} \leq 1 \times 10^{-6}$.

Out of time ECL background

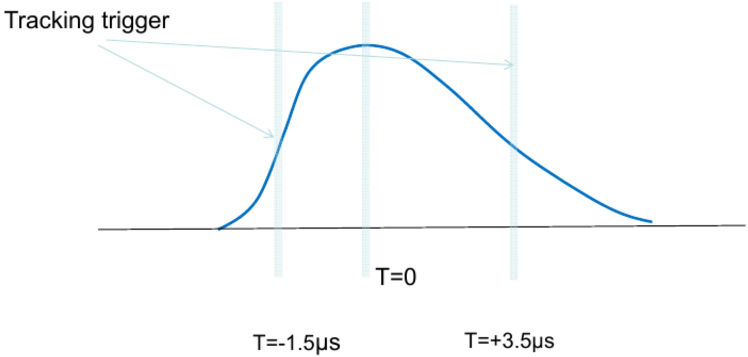
- "Pile-up" from $e^+e^-(\gamma)$ scatter within a few microseconds of $e^+e^- \rightarrow B\overline{B}$ event.

$e^+e^-(\gamma)$ scatter is Back-to-back In CM



Out of time ECL background

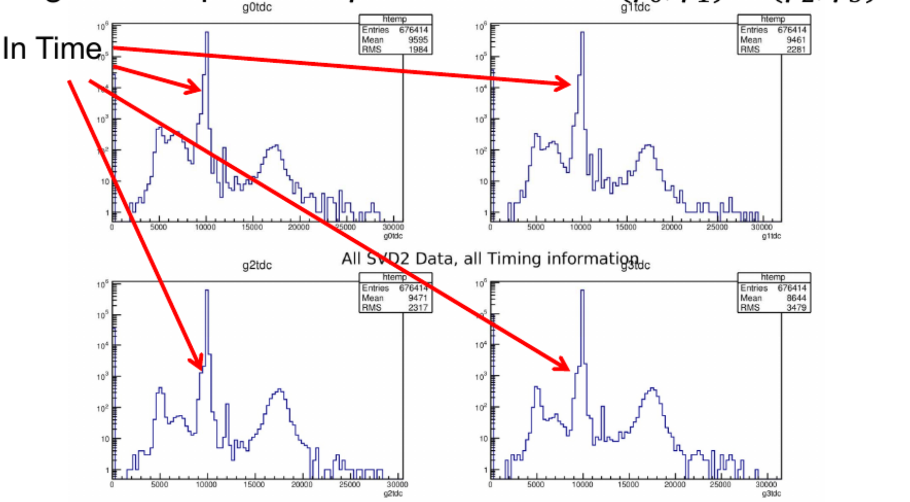
Output of CsI crystals is processed with 1μsec shaping time



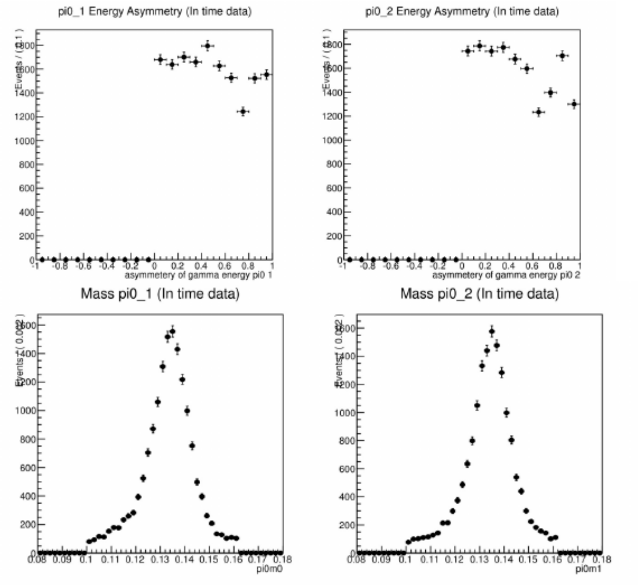
Trigger from B B_bar event within a few microseconds samples non-peak part of ECL.
Shows up as high energy photons located back-to-back in ECL.
Photons pick up low energy photon from rest of BB-bar event to form fake pi0's
Momentum dominated by high energy deposits. Vector sum ~ 0 So Mbc ~ B_mass

Out of time ECL background

Logarithmic plots of 4γ's from $B^0 \to \pi^0(\gamma_0,\gamma_1)\pi^0(\gamma_2,\gamma_3)$



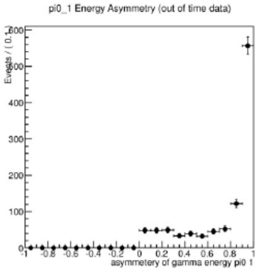
Data with timing cuts

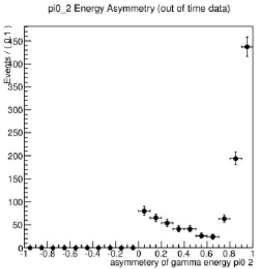


$$\frac{E_{\gamma 1} - E_{\gamma 2}}{E_{\gamma 1} + E_{\gamma 2}}$$

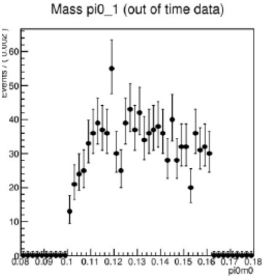
π^0 Invariant mass

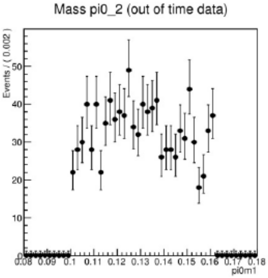
Out of time data





$$\frac{E_{\gamma 1} - E_{\gamma 2}}{E_{\gamma 1} + E_{\gamma 2}}$$

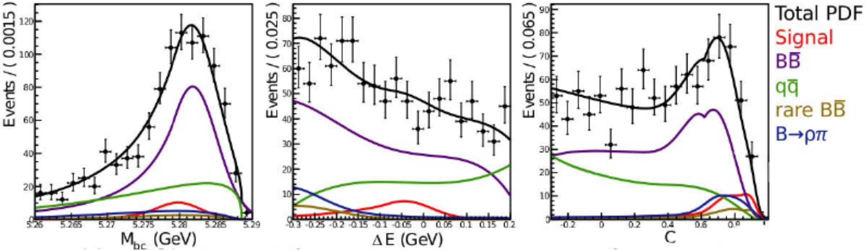




π^0 Invariant mass

$B^0 \to \pi^0\pi^0$ out of time background

- substantial background from out of time showers in the electromagnetic calorimeter (τ_{ECL} = 1.5μ s) (Pileup)
- out of time ECL hit + BB event → peaking background

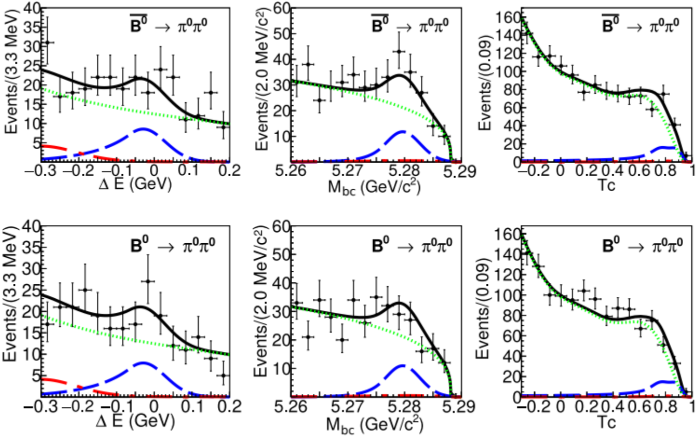


Timing cut on ECL Trigger crystals removes 99% of the background and keeps 99% of the signal

$B^0 \to \pi^0\pi^0$ decays

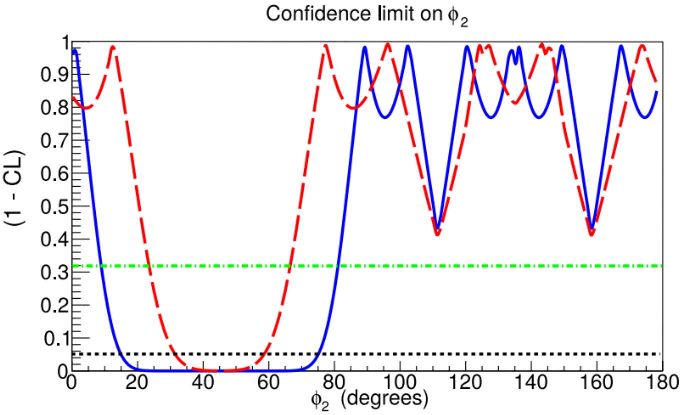
- Final result from Belle after removing the out of time background:

$$\mathcal{B} = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6} \qquad A_{CP} = 0.14 \pm 0.36 \pm 0.10$$



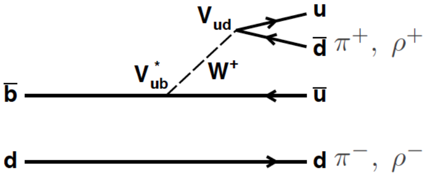
Constraint on ϕ_2 by Belle

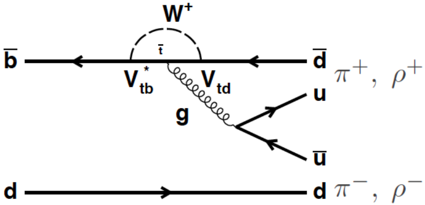
- The dashed red curve shows the previous constraint from Belle data [7]. The solid blue curve includes the new results.
- The updated result for $B^0 \to \pi^0\pi^0$ exclude $9.5^\circ < \phi_2 < 81.6^\circ$ at the 68% CL and $15.5^\circ < \phi_2 < 75.0^\circ$ at the 95% CL



$\alpha = \phi_2$ from $B^0 \to \rho^+\rho^-$ decays

Also accessible via $B^0 \to \rho^+\rho^-$ decays ($b \to u\bar{u}d$)

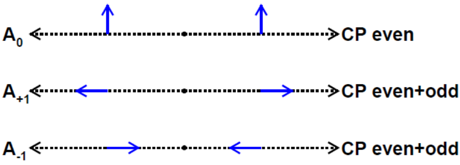


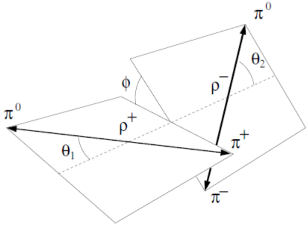


$B^0 \to \rho^+\rho^-$ decays

Scalar $\to$ Vector Vector decay ($S \to VV$)

- Need to perform an angular analysis to determine the CP-even (-odd) fractions.





$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2} \propto 4 f_L \cos\theta_1^2 \cos\theta_2^2 + (1 - f_L) \sin\theta_1^2 \sin\theta_2^2$$

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_{-1}|^2 + |A_{+1}|^2}$$

$B^0 \to \rho^+\rho^-$ measurement by Belle

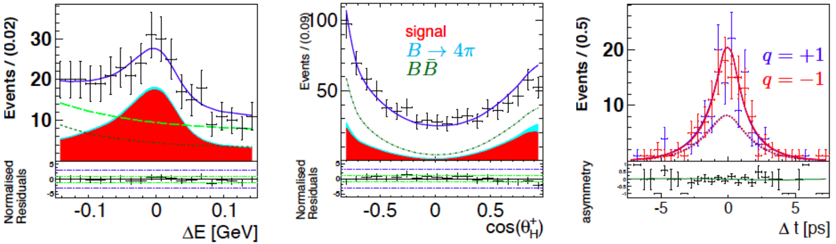
9D MLH fit to $\Delta E, M_{bc}, \mathcal{F}_{S/B}, m_1(\pi^+\pi^0), m_2(\pi^-\pi^0), \cos\theta_H^+, \cos\theta_H^-, \Delta t, q$

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (28.3 \pm 1.5\ (\text{stat}) \pm 1.4\ (\text{syst})) \times 10^{-6},$$
$$f_L = 0.988 \pm\ 0.012\ (\text{stat}) \pm\ 0.023(\text{syst}),$$
$$\mathcal{S}_{CP} = -0.13 \pm 0.15(\text{stat}) \pm 0.05\ (\text{syst}),$$
$$\mathcal{A}_{CP} = 0.00 \pm 0.10(\text{stat}) \pm 0.06\ (\text{syst})$$

PRELIMINARY

NEW

772M $B\bar{B}$ pairs



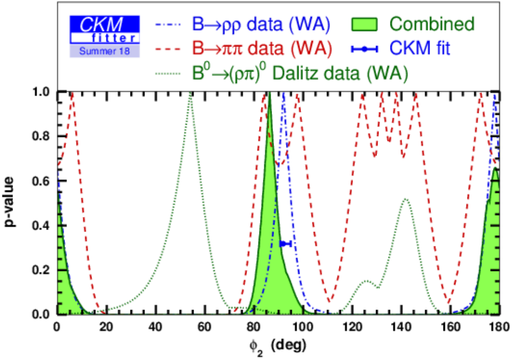
$\Delta E \equiv E_{B_{\text{rec}}^{\text{CMS}}} - E_{\text{beam}}^{\text{CMS}}$ (signal enhanced projections) $M_{bc} \equiv \sqrt{E_{\text{beam}}^{\text{CMS}\,2} - \vec{p}^{\,2}_{B_{rec}^{\text{CMS}}}}$

Almost pure CP-even eigenstate

$\alpha = \phi_2$ from $B \to \rho\rho,\ \pi\pi$, and $\rho\pi$

- $B \to \rho\rho$ decays turned out to provide best way to measure α
  - $B^0 \to \rho^+\rho^-$ has $6\times$ larger branching ratio compared to $B^0 \to \pi^+\pi^-$
  - branching ratio of $B^0 \to \rho^0\rho^0$ much smaller then $B^{+,0} \to \rho^{+,0}\rho^0$

    $\Rightarrow$ *much better constraint on* $\Delta\alpha$
  - 100% longitudinally polarized $\Rightarrow$ pure CP eigenstate

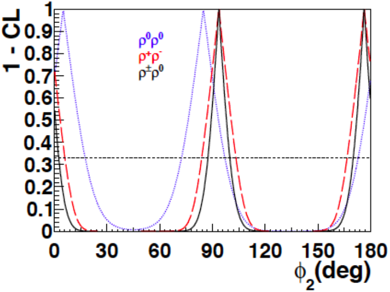


$$\alpha = (91.6^{+1.7}_{-1.1})^\circ$$

The future: $\alpha = \phi_2$ with Belle II

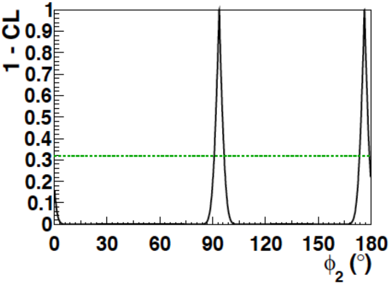
Toy studies: extrapolate Belle result's to

$1ab^{-1}$ (Update $B^+ \to \rho^+\rho^0$)



$\delta\phi_2 \sim 6°$

$50ab^{-1}$ (Belle2)



$\delta\phi_2 \sim 3°$

Belle2: Combing with other ϕ_2 constraints ($B \to \pi\pi, \rho\pi$)$\to$ $\delta\phi_2 \sim 1°$

Polarization Puzzle in $B \to VV$ Decays

Interlude: $B \to VV$

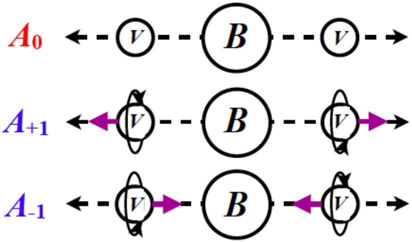
- We saw that the pseudoscalar-pseudoscalar ($\pi\pi$) and vector-vector ($\rho\rho$) final states have the same quark composition.
- How does the spin-1 nature of the vector resonances complicate things?

Spin configurations in $B \to VV$ decays

- Three configurations:

Longitudinal

Transverse



- Complex amplitude:

$$\langle VV | H | B \rangle = A_0 + A_{+1} + A_{-1}$$

- Naive factorization for B^0 decays:

PLB **601**, 151 (2004)

$$A_0 : A_{+1} : A_{-1} = 1 : \frac{m_V}{m_B} : \frac{m_V^2}{m_B^2}$$

✓ *experimentally confirmed in tree level $B \to \rho\rho$ decays*

strongly violated in penguin dominated $B \to \Phi K^*$ and $B \to \rho K^{*0}$ decays

➡ *there are non-factorizable contributions to the decay amplitude which play a significant role*

Why the "expected" hierarchy?

Follows from the $V - A$ structure of the weak interactions in the SM.

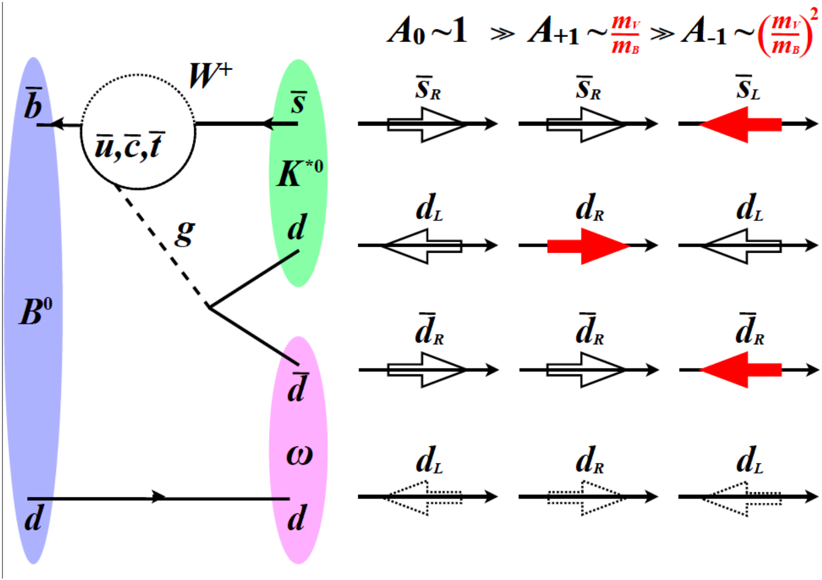
- Dictates that the W boson only couples to left-handed quarks (q_L) and right-handed anti-quarks ($\overline{q}_R$).

Lets look at the $b \to s$ penguin decay $B^0 \to \omega K^{*0}$ as an example.

- The leading operator in the $B^0 \to \omega K^{*0}$ channel generates decays of the form $\overline{b} \to \overline{s}_R d_L \overline{d}_R$.
- This configuration is clearly manifest in the A_0 state: the $\overline{s}$ and d ($\overline{d}$ and d) quark constituents of the K^{*0} (ω) meson are right- and left-handed, respectively. [see next slide]
- To achieve the A_{+1} configuration, the collinear d quark (produced from the gluon) must undergo a 'helicity-flip' to make the K^{*0} positively polarized. The spectator d quark does not undergo a weak interaction, and thus it can be left- or right-handed
- In the A_{-1} state, both the $\overline{s}$ quark from the K^{*0} and the $\overline{d}$ from the ω must undergo helicity flips for the mesons to be negatively polarized.

$\Rightarrow$ *Each helicity flip reduces the amplitude by a factor of* $1/m_B$

Spin flips


$A_0 \sim 1 \gg A_{+1} \sim \frac{m_V}{m_B} \gg A_{-1} \sim \left(\frac{m_V}{m_B}\right)^2$
W^+
$\bar{b}$
$\bar{u},\bar{c},\bar{t}$
$\bar{s}$
K^{*0}
g
d
B^0
$\bar{d}$
ω
d
d
$\bar{s}_R$
$\bar{s}_R$
$\bar{s}_L$
d_L
d_R
d_L
$\bar{d}_R$
$\bar{d}_R$
$\bar{d}_R$
d_L
d_R
d_L

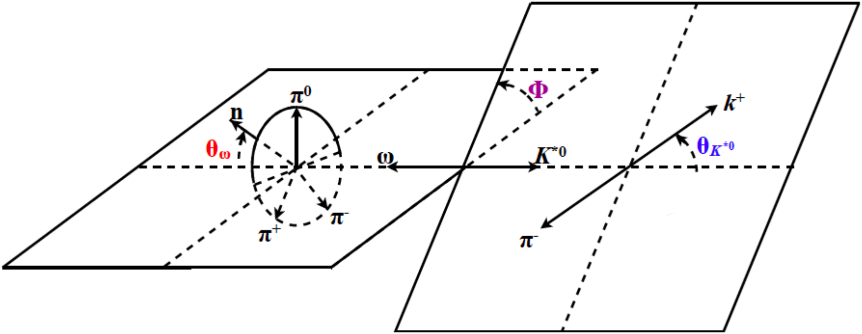
Angular dependence

- In general, the angular dependence for $B \to V_1 V_2$ decays, where the vector mesons decay to spinless particles, can be expressed in terms of the spherical harmonics as

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \propto \left| \sum_{\lambda=-1}^{1} A_\lambda \times Y_1^{\lambda}(\theta_1, \phi) \times Y_1^{-\lambda}(\pi - \theta_2, 0) \right|^2$$

- Making the substitutions $\theta_1 \to \theta_\omega$ and $\theta_2 \to \theta_{K^{*0}}$, and expanding the right hand side, we obtain the full angular distribution of $B^0 \to \omega K^{*0}$ decays in the helicity basis

Full angular distribution



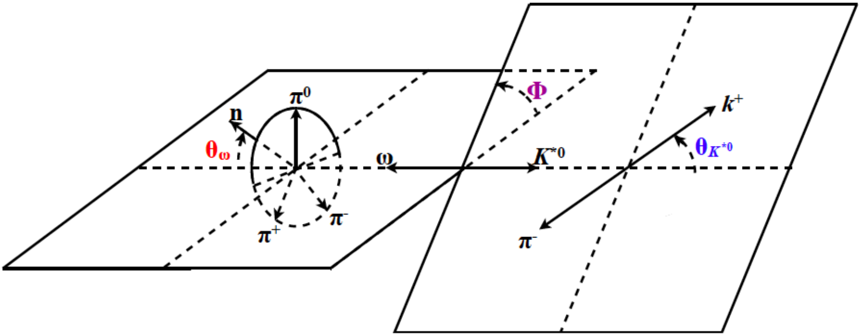
$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_\omega\, d\cos\theta_K\, d\Phi} = \frac{9}{16\pi}\frac{1}{|A_0|^2+|A_+|^2+|A_-|^2}$$

$$\Big\{\frac{1}{2}\sin^2\theta_\omega \sin^2\theta_K (|A_+|^2+|A_-|^2) + 2\cos^2\theta_\omega \cos^2\theta_K |A_0|^2$$

$$+\sin^2\theta_\omega \sin^2\theta_K [\cos 2\Phi\, \Re e(A_+A_-^*) - \sin 2\Phi\, \Im m(A_+A_-^*)]$$

$$-\frac{1}{2}\sin 2\theta_\omega \sin 2\theta_K [\cos\Phi\, \Re e(A_+A_0^* + A_-A_0^*) - \sin\Phi\, \Im m(A_+A_0^* - A_-A_0^*)]\Big\}$$

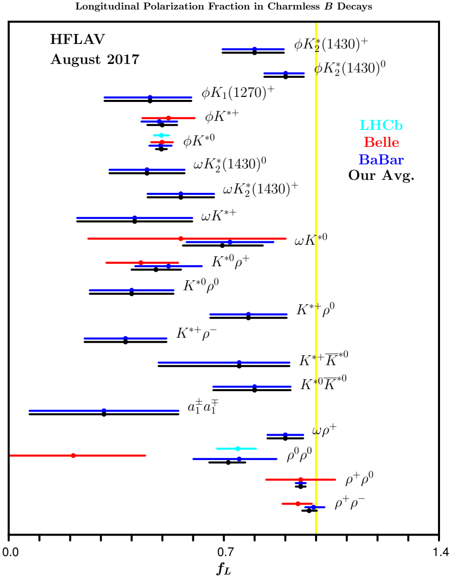
Integrate over Φ (angle between the decay planes)



$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_\omega\, d\cos\theta_K} = \frac{9}{4}\left\{\frac{1}{4}\underbrace{(1-f_L)\sin^2\theta_\omega \sin^2\theta_K}_{\text{transverse}} + \underbrace{f_L \cos^2\theta_\omega \cos^2\theta_K}_{\text{longitudinal}}\right\}$$

Longitudinal polarization fraction $f_L \equiv \frac{\Gamma_L}{\Gamma} = \frac{|A_0|^2}{|A_0|^2 + |A_+|^2 + |A_-|^2}$

$f_L \ll 1$ for $b \to s$ penguin decays (first observed in ϕK^*)

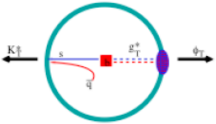


Possible explanations within the SM

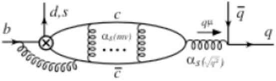
Some models in SM:

- QCD penguin annihilation PLB **601**, 151 (2004); hep-ph/0407076
  - large power corrections from annihiliation.
  - varying free parameters (not conclusive).

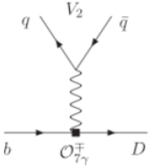
- Transverse gluon from $b \rightarrow sg$ (the magnetic penguin) hep-ph/0408007
  - QCD analog of the $b \rightarrow s\gamma$ transition.
  - not conclusive.



- Charming penguins PRD **70**, 054015 (2004)
  - long-distance effects from $c\bar{c}$ penguins.
  - many free parameters (not conclusive).



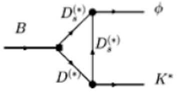
- EM penguin for neutral V mesons PRL **96**, 141801 (2006)
  - large transverse amplitude is described by a SD transition $b \rightarrow (d,s)\gamma$ followed by the transition of γ to the V meson.
  - similar to the polarization in $B \rightarrow K^*\gamma$.



+ some NP scenarios

SM (*continued*):

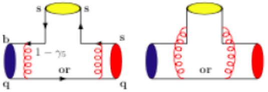
- Long-distance rescattering PLB **597**, 291 (2004); PRD **70**, 114025 (2004)
  - rescattering mediated by charm resonances.
  - model-dependent.



- New sets of form factors PLB **622**, 63 (2005)
  - smaller $B \to K^*$ form factor and inclusion of penguin annihilation and nonfactorizable contributions in pQCD approach.

New physics scenarios:

- NP operators of the form $\bar{b}\gamma_R s \bar{d}\gamma_R d$ or $\bar{b}\gamma_L s \bar{d}\gamma_L d$. PRD **72**, 094008 (2005)
- New right-handed currents. PRD **70**, 115014 (2004); hep-ph/0310229
- New type of scalar interation $\bar{b}(1\text{-}\gamma_5)s\bar{s}s$ with a simple Higgs model associated with tree-level FCNC. PRD **71**, 115004 (2005)



Extra reading

- Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*

  Flavour Symmetries (Section 4.5, page 116)

- Isospin Analysis of CP Asymmetries in B Decays

  Gronau, London PRL65, 3381 (1990)