CP Violation

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Belle II Summer Workshop

Duke University

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What is CP Violation ?

- *Discrete symmetries (C,P,T) give insight into nature of interactions*
  - *CPT theorem:*

    "any Lorentz-invariant local quantum field theory with a Hermitian Hamiltonian must have CPT symmetry"
  - *Strong and EM interactions are invariant under C, P, and T*

$C:\ a \leftrightarrow \bar{a}$ ($\bar{a}$ is the antiparticle of a)

$P:\ \mathbf{x} \rightarrow -\mathbf{x}$ (parity inversion of spatial coordinates)

$T:\ t \rightarrow -t$ (motion or "time" reversal).

- *Parity violation was discovered by Wu in β decay in 1957*
  - *Predicted by Yang and Lee to solve the $\tau - \theta$ puzzle*
  - *Structure of weak interaction (V-A) implies PV*
  - *Combined symmetry of C and P (CP) still seemed to hold*

Phys. Rev. 105, 1413 (1957)

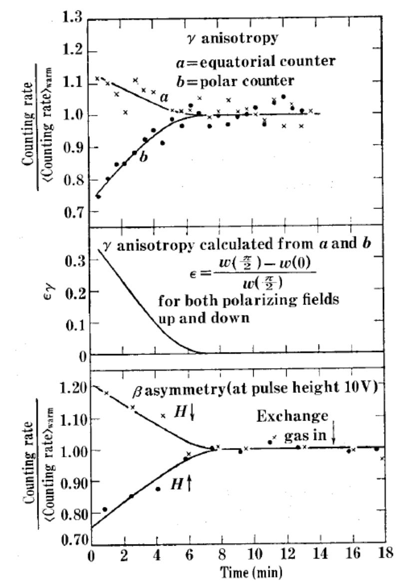
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)



- *CPV was discovered in K_L (CP-odd) decays to 2π (CP-even) by Cronin and Fitch in 1964*
  - *Small effect: $BR(K_L \rightarrow 2\pi) = 0.3\ \%$ (c.f. $BF(\pi l \nu + 3\pi) = 99.7\%$)*
  - *Not understood at the time*

PRL 13, 168 (1964)

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

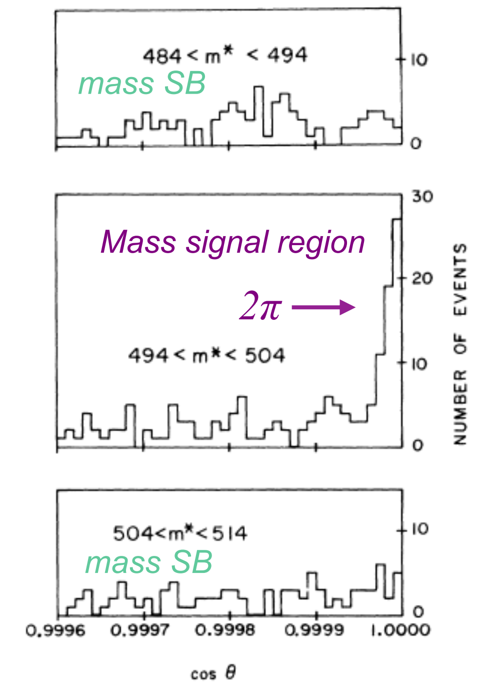
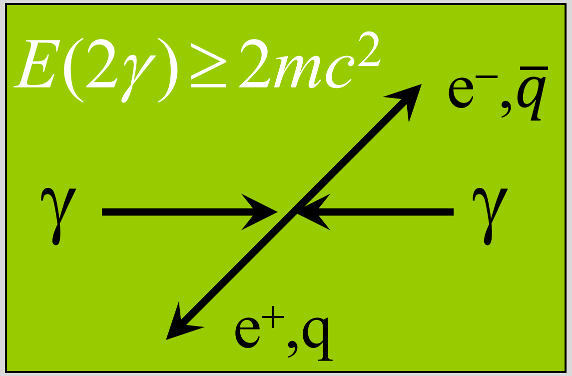


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

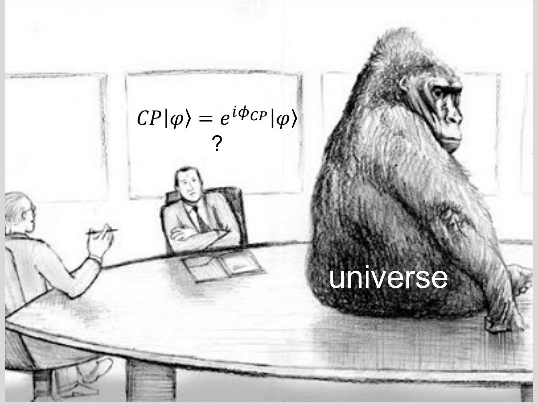
The Matter - Universe

- *13.8 × 10 ⁹ years ago big bang produced matter and antimatter in equal amounts*
  - *matter-antimatter symmetric EM and strong interactions*



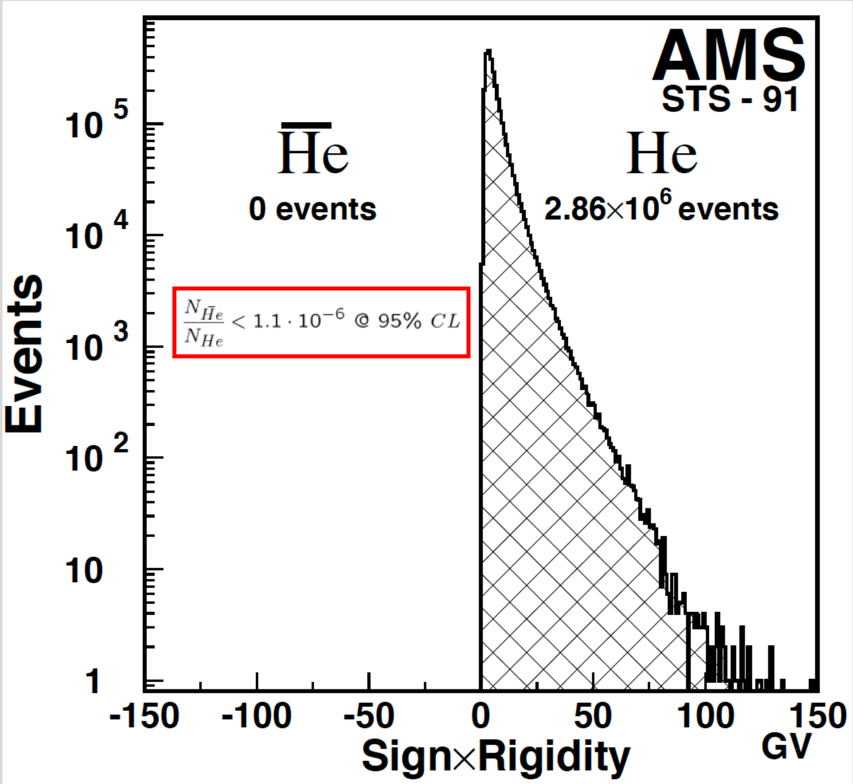
- *… but today we observe* ***absence*** *of*
  - *anti-nuclei amongst cosmic rays in our galaxy*
  - *intense γ–ray emission due to annihilation of distant galaxies in collision with antimatter*

Today, matter dominates !



"10^{53}lbs Gorilla in the room"

AMS, PLB 461, 387 (1999)



Where did all the anti-matter go?

- *Baryon to photon ratio determined from microwave anisotropy*

$$\boxed{\eta = \frac{N_{baryons}}{N_{photons}} = (6.5^{+0.4}_{-0.3}) \times 10^{-10}}$$

Almost all matter annihilated with anti-matter..., but not all !

WMAP

- *Sakharov showed that generation of a net baryon number requires:*

  1. *Baryon number violating processes (e.g. proton decay)*
  2. *Non-equilibrium state during the expansion of the universe*
  3. ***Difference in interaction rates for particles and antiparticles (C and CP violation)***

Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967)

Note, SM CPV is unlikely to be sufficient to explain universe matter content.
However, CPV from New Physics that played a role in the early universe might.

CPV in the Standard Model

- *Kobayashi and Maskawa proposed a three-generation **complex** quark mixing matrix between strong and weak quark eigenstates*

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

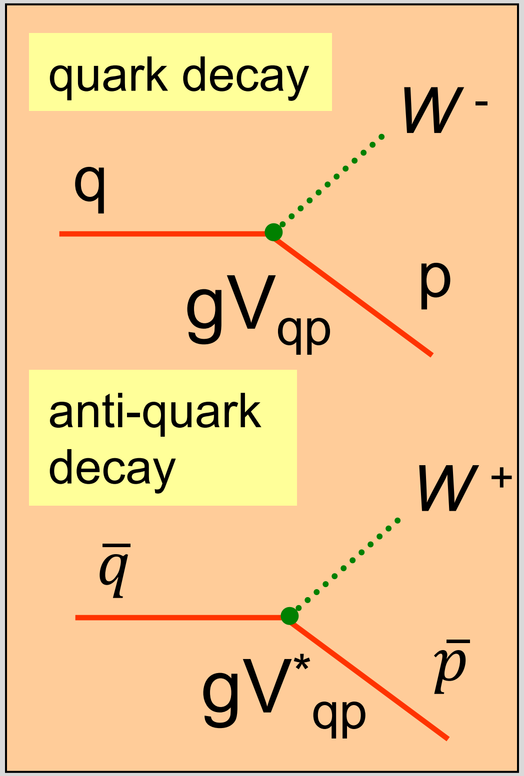
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

  - *CKM matrix elements modify weak charged current decay amplitude*
  - *Only 3 quark flavors (u, d, s) were discovered and quark model was not widely accepted, yet*
- *Today, all observed CPV can be described by the CKM matrix*
  - *No CPV in strong interactions*
  - *No CPV in the lepton sector (maybe soon)*

$$V_{CKM} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array} \begin{array}{c} \\ u \\ c \\ t \end{array}$$

Cabbibo-Kobayashi-Maskawa (CKM) matrix



g = weak Fermi coupling constant

Decay amplitude $\propto$ (complex) V_{qp}
Decay rate $\propto |V_{qp}|^2$

Complex matrix elements can lead to <u>different BFs for particles and antiparticles</u>

→ CP violation

A useful parameterization ("Wolfenstein")

Unitary 3×3 *matrix has only four independent parameters* (λ, A, ρ, η)

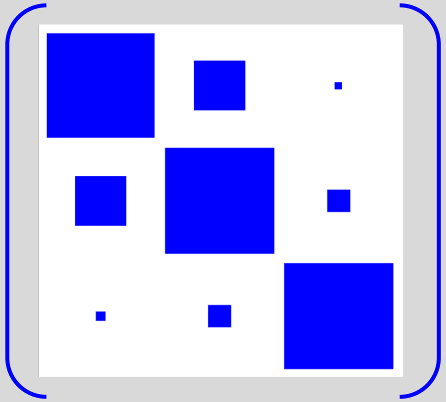
$$\mathbf{V}_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

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

Wolfenstein,
PRL 51, 1945 (1983)

Single complex phase η *generates* ***all*** *SM CPV*

relative magnitudes =



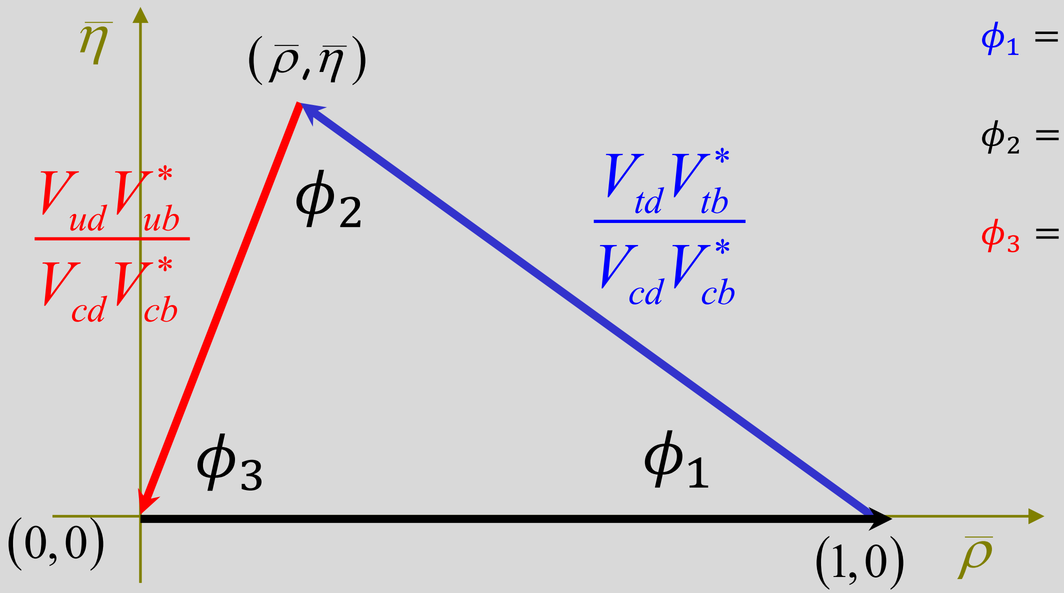
2 complex matrix elements:
V_{td} *and* V_{ub}

Careful ! This is an arbitrary phase convention.
But it allows to easily see where CPV occurs.

The B Unitarity Triangle

$$V^{\dagger}V = 1 \quad \rightarrow \quad V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

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



$$\phi_1 = \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right]$$

$$\phi_2 = \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right]$$

$$\phi_3 = \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

SM CP violation is very ***predictive****:*
complex CKM phase η is related to apex of UT

Can be determined from sides or angles ! Allows for consistency checks!

3 Types of CP Violation

1) CPV in decay

2) CPV in mixing

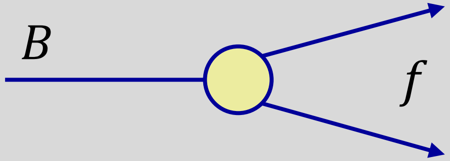
3) Mixing-induced CPV, or CPV in the interference between decay with and without mixing

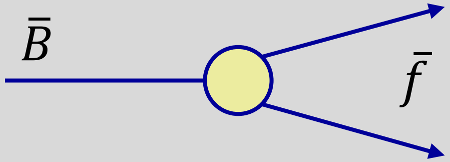
1) is also referred to as “direct CPV”
and 2) & 3) as “indirect CPV”

CPV in decay

- *Difference between magnitude of a decay amplitude and its CP-conjugate amplitude*

$$A = \langle f | O | B \rangle \qquad \bar{A} = \langle \bar{f} | O^{\dagger} | \bar{B} \rangle$$





Direct CPV: $|A| \neq |\bar{A}|$; $\qquad A_{CP} \equiv \frac{\Gamma(\bar{B}\to\bar{f}) - \Gamma(B\to f)}{\Gamma(\bar{B}\to\bar{f}) + \Gamma(B\to f)} \neq 0$

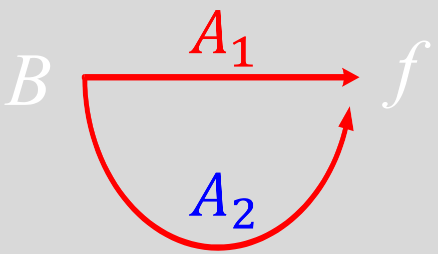
- *Only type of CPV possible for charged particle decays*
- *Relatively easy to measure: only BFs necessary*

Example: $\mathcal{B}(B^0 \to K^+\pi^-) \neq \mathcal{B}(\bar{B}^0 \to K^-\pi^+)$

  - *Direct CPV can also show up in differential BFs (e.g. across Dalitz plot) or in individual orbital angular momentum waves for VV final states*

CPV in decay: weak and strong phases

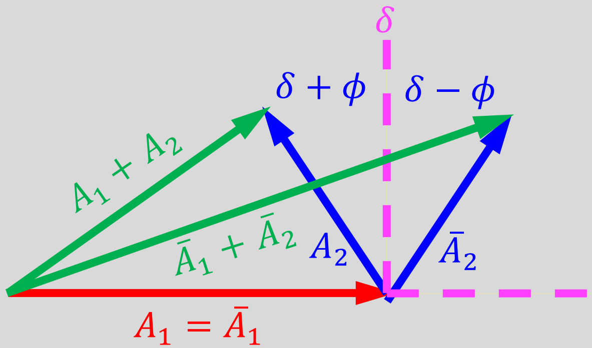
- *Easiest way to get CPV is with* ***2 interfering amplitudes*** *(e.g. tree and penguin) with different weak (CP-odd)* ***and*** *strong (CP-even) phases*



$$A(B \to f) = A = A_1 + A_2$$
$$A(\bar{B} \to \bar{f}) = \bar{A} = \bar{A}_1 + \bar{A}_2$$

CP transformation:
strong phase: $\delta \to \delta$
weak phase: $\phi \to -\phi$

$$A_1 = |A_1| \qquad \xrightarrow{\text{CP}} \qquad \bar{A}_1 = |A_1|$$
$$A_2 = |A_2| e^{i\delta} e^{i\phi} \qquad \qquad \bar{A}_2 = |A_2| e^{i\delta} e^{-i\phi}$$



$$|A| \neq |\bar{A}|$$

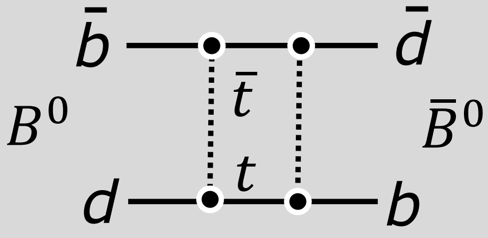
$r \equiv |A_2/A_1|$

$$\boxed{A_{CP} = \frac{2r \sin\delta \sin\phi}{1 + r^2 + 2r \cos\delta \cos\phi}}$$

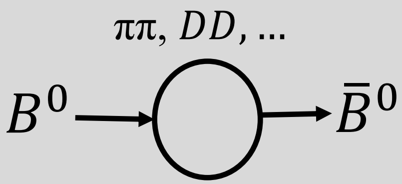
- *A_{CP} is large if the contributing amplitudes are of similar size ($r \approx 1, |A_1| \approx |A_2|$)*
- *Need external input on $|A_1|, |A_2|, \delta$ (usually not interesting) to measure ϕ (interesting)*
- *Observed in many b decays and recently in charm decays (LHCb, PRL 122, 211803 (2019))*

Neutral meson mixing ("2B or not 2B")

- *Weak transitions can transform P into $\bar{P}$ and vice versa*
  - *Physical neutral meson state ψ is a linear combination*
- *Time-evolution given by non-hermitian Hamiltonian*
  - *Diagonal terms give P mass M and width Γ (1/τ)*
  - *Off-diagonal terms describe mixing (incl. CPV)*
  - *Eigenstates of Hamiltonian have defined $M_{H,L}$ and $\tau_{S,L}$*
    (if no CPV in mixing they are CP eigenstates)
    - *virtual amplitude: $|\Delta M| = |2M_{12}|$*
    - *on-shell amplitude: $|\Delta\Gamma| = |2\Gamma_{12}|$*
- *Time-dependent $P - \bar{P}$ mixing:*



short-distance, virtual



long-distance, on-shell

$$\psi(t) = a(t)|P^0\rangle + b(t)|\bar{P}^0\rangle$$

$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

$$P(P \to \bar{P}) \propto e^{-\Gamma t}\left|\frac{q}{p}\right|^2 \left[\cosh\frac{\Delta\Gamma t}{2} - \cos\Delta M t\right]$$

$$P(\bar{P} \to P) \propto e^{-\Gamma t}\left|\frac{p}{q}\right|^2 \left[\cosh\frac{\Delta\Gamma t}{2} - \cos\Delta M t\right]$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- *CPV in mixing*

$$\boxed{P(P \to \bar{P}) \neq P(\bar{P} \to P) \qquad \left|\frac{p}{q}\right| \neq 1 \qquad |M_{12}||\Gamma_{12}|\sin(\theta_{M_{12}} - \theta_{\Gamma_{12}}) \neq 0}$$

  - *Results from interference between on-shell and virtual amplitudes*

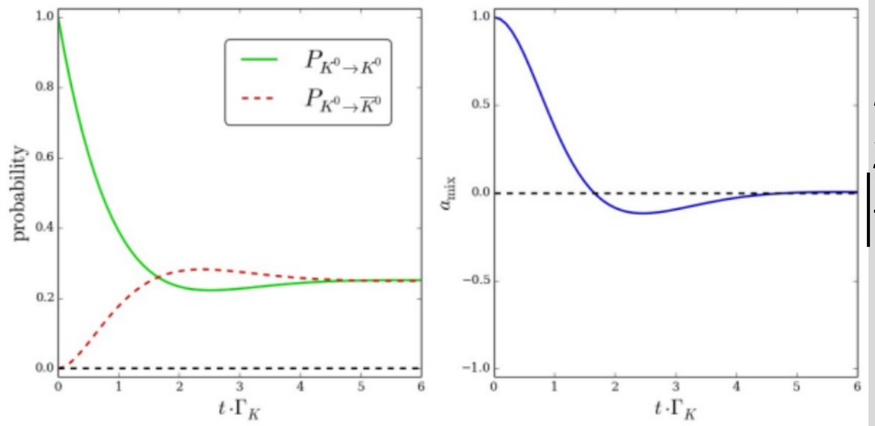
Neutral meson mixing comparison

Mixing asymmetry
(no CPV):

$$a_{mix}(t) = \frac{P(P^0 \to P^0) - P(P^0 \to \bar{P}^0)}{P(P^0 \to P^0) + P(P^0 \to \bar{P}^0)} = \frac{\cos(x\, t/\tau)}{\cosh(\, y\, t/\tau)}$$

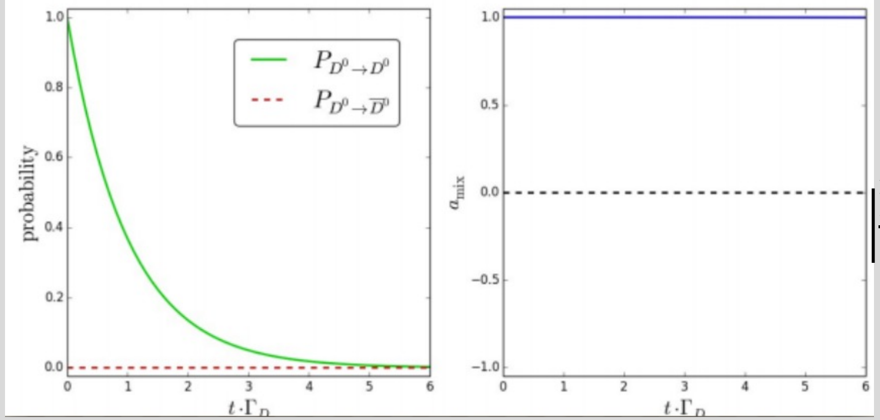
$x = \Delta M\, \tau$
$y = \Delta\Gamma\, \tau/2$

K⁰
$x_K \approx 0.95$
$y_K \approx -1$
$\left|\frac{p}{q}\right|_K \approx 0.9967$
Strong damping,
only K_L are left
after 1 oscillation



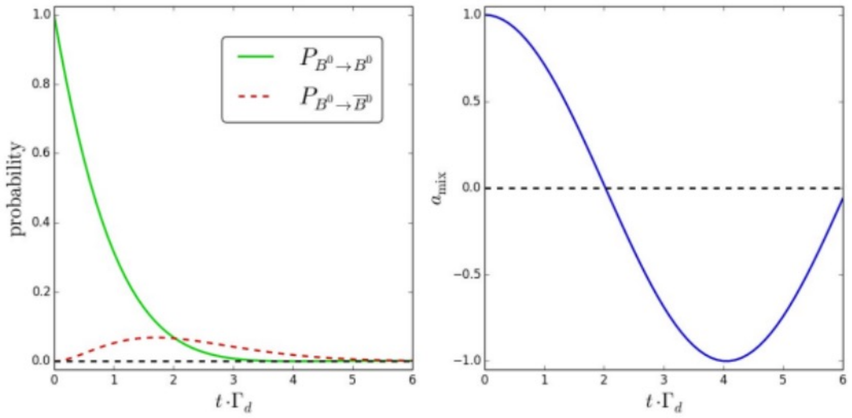
D⁰
$x_D \approx 5\times10^{-3}$
$y_D \approx (7.2 \pm 0.1)\times10^{-3}$
$\left|\frac{p}{q}\right|_K \sim 1$

Very small mixing



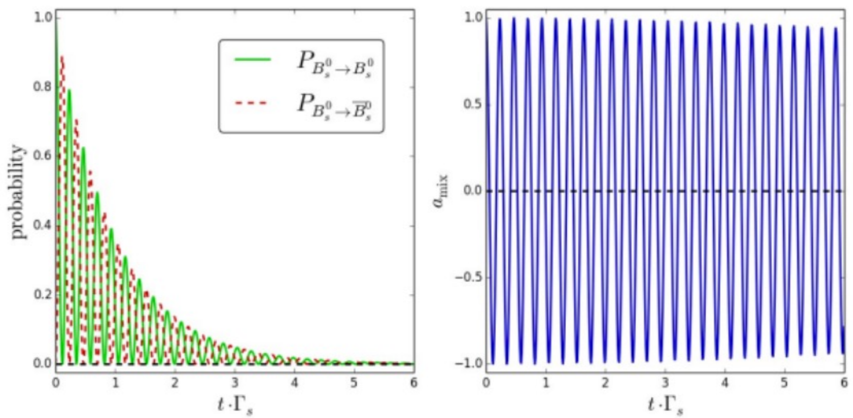
$\boldsymbol{B_d^0}$
$x_d = 0.775 \pm 0.006$
$y_d = 0.007 \pm 0.009$
$\left|\frac{p}{q}\right|_d = 1.0010 \pm 0.0008$

Significant mixing



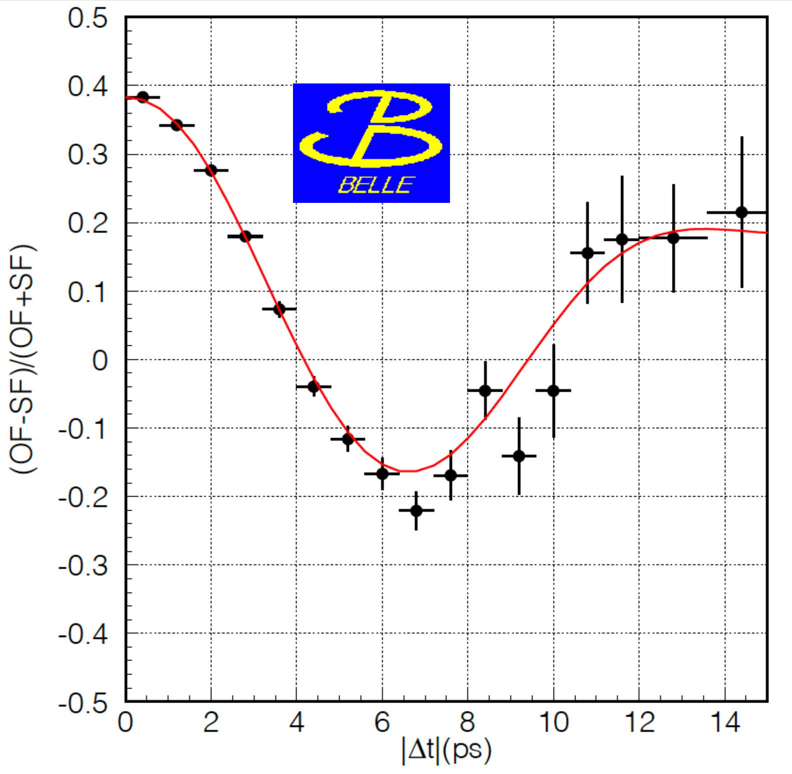
$\boldsymbol{B_s^0}$
$x_s = 26.8 \pm 0.23$
$y_s = 0.058 \pm 0.010$
$\left|\frac{p}{q}\right|_s = 1.0003 \pm 0.0014$

Fast oscillations,
complete mixing



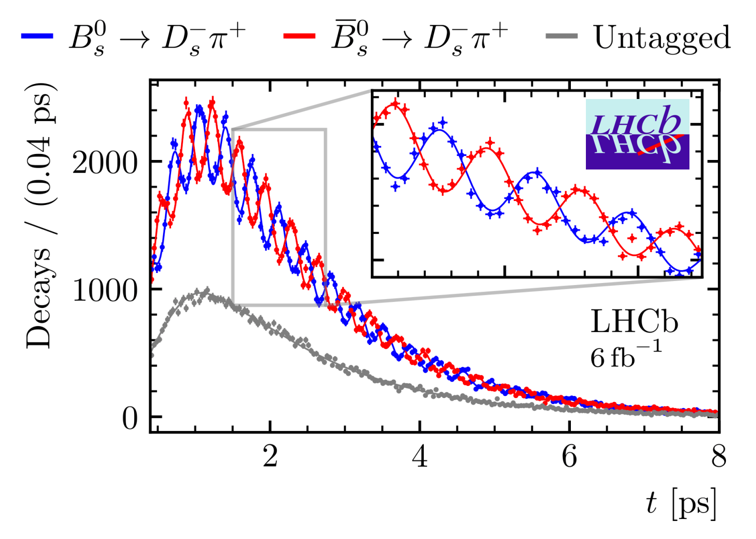
Neutral $B_{d,s}$ mixing and CPV

Belle, PRD 71, 072003 (2005)



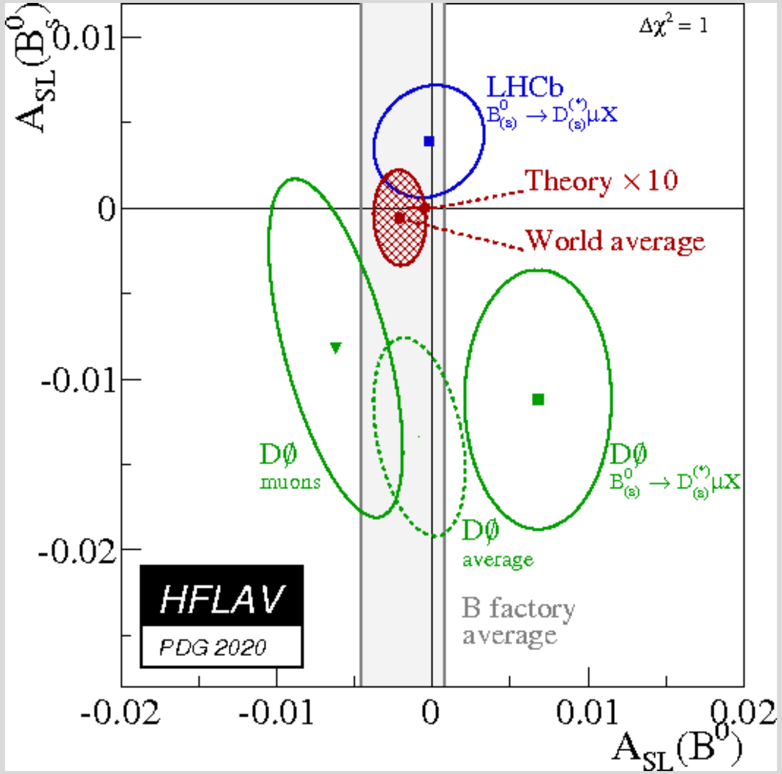
B_d *mixing*

LHCb, arXiv:2104.04421



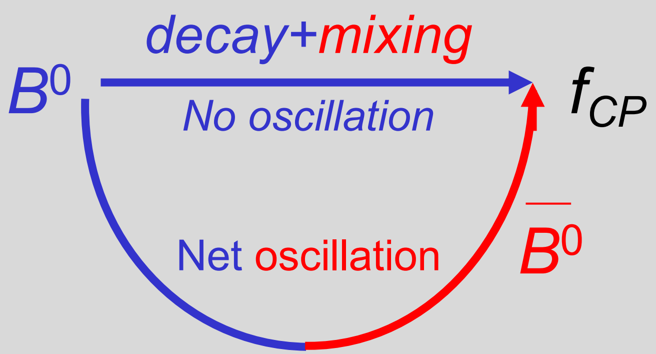
B_s *mixing*

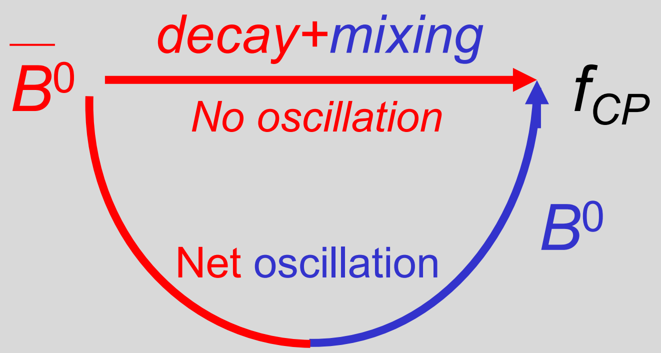
$$A_{SL} = \frac{1 - \left|\frac{q}{p}\right|^4}{1 + \left|\frac{q}{p}\right|^4}$$



No CPV in $B_{d/s}$ mixing !

Mixing-induced CP Violation





$$CPV:\ \Gamma\ \left(B^0\ \to f_{CP}\right) \neq \Gamma\ \left(\bar{B}^0\ \to f_{CP}\right)$$

$$\Gamma\,(\bar{B}^0/B^0 \to f_{CP}) \propto e^{-t/\tau}\left(1 \pm \underbrace{\frac{2\,\mathrm{Im}\,\lambda_{CP}}{1+|\lambda_{CP}|^2}}_{S_f} \sin\,(\Delta \mathrm{M}\ t) \mp \underbrace{\frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}}_{C_f} \cos\,(\Delta \mathrm{M}\ t)\right)$$

Time-dependent CP asymmetry

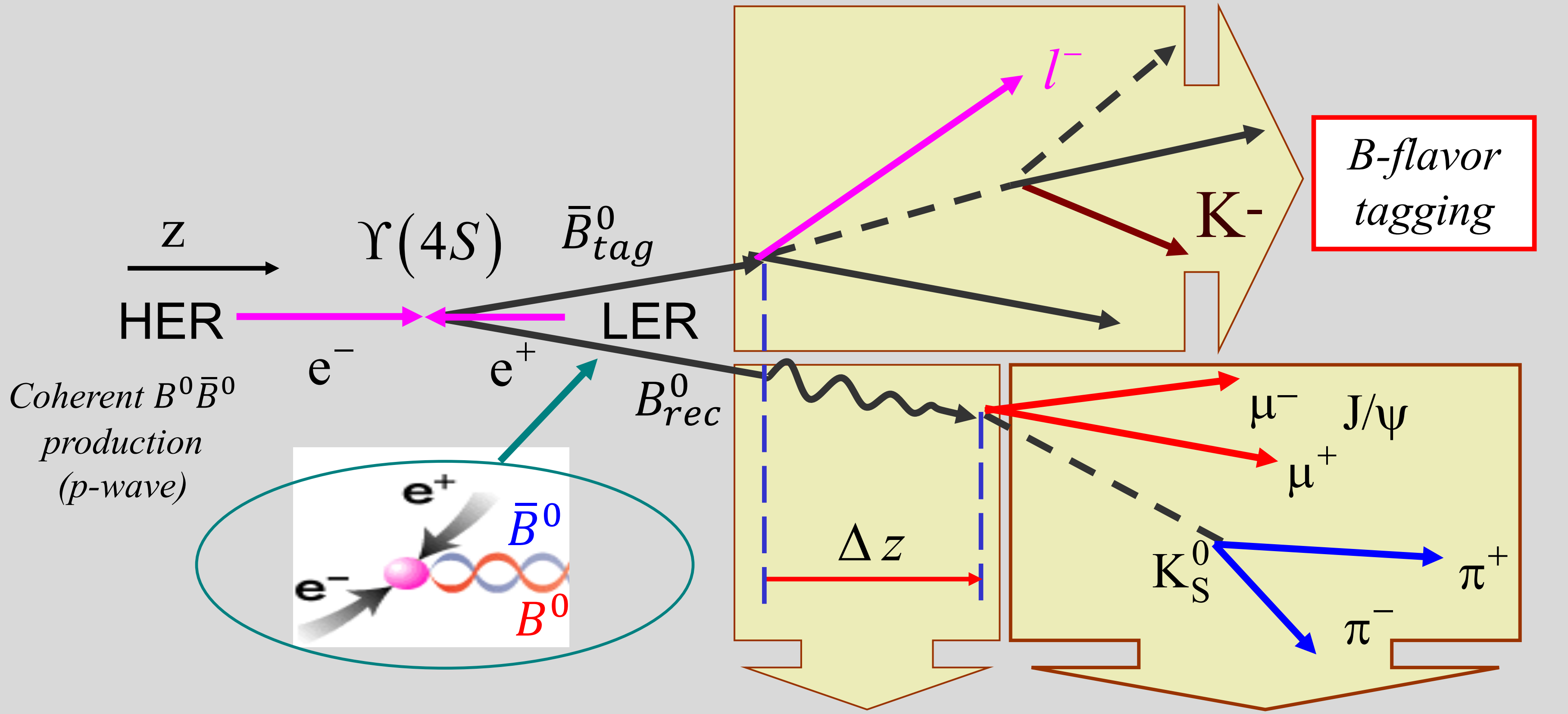
$$\boxed{\begin{aligned} A_{CP} &= \frac{\Gamma\ \ (\bar{B}^0 \to f_{CP}) - \Gamma\ \ (B^0 \to f_{CP})}{\Gamma\ \ (\bar{B}^0 \to f_{CP}) + \Gamma\ \ (B^0 \to f_{CP})} \\ &= -\ C_f \cos\,(\Delta \mathrm{M}\ t) + S_f \sin\,(\Delta \mathrm{M}\ t) \end{aligned}}$$

single weak amplitude: $|\lambda_{CP}| = 1$

$C_f\ = 0 \qquad S_f = -\mathrm{Im}\,\lambda_{CP}$

$\boxed{C_f\ \neq 0 \textit{ implies } \textbf{\textit{direct}} \textit{ CPV}}$

Measurement of time-dependent CP Violation at Belle II



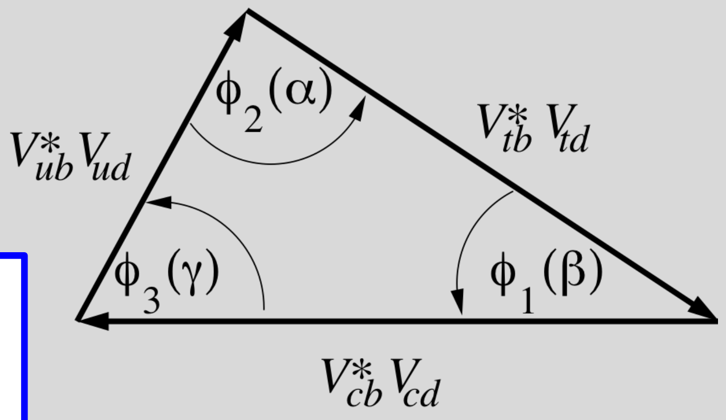
$$\Delta t = t_{rec} - t_{tag} \approx \Delta z / \langle \beta\gamma \rangle c$$

Reconstruction of B decays to exclusive final state

B decays sensitive to UT angles

Modes sensitive to ϕ_2

$B \to \pi^+\pi^-, \pi^\pm\pi^0, \pi^0\pi^0$
$B \to \rho^+\rho^-, \rho^\pm\rho^0, \rho^0\rho^0$
$B \to \pi^+\pi^- \pi^0$
$B \to a_1(\rho\pi)^\pm\pi^\mp$



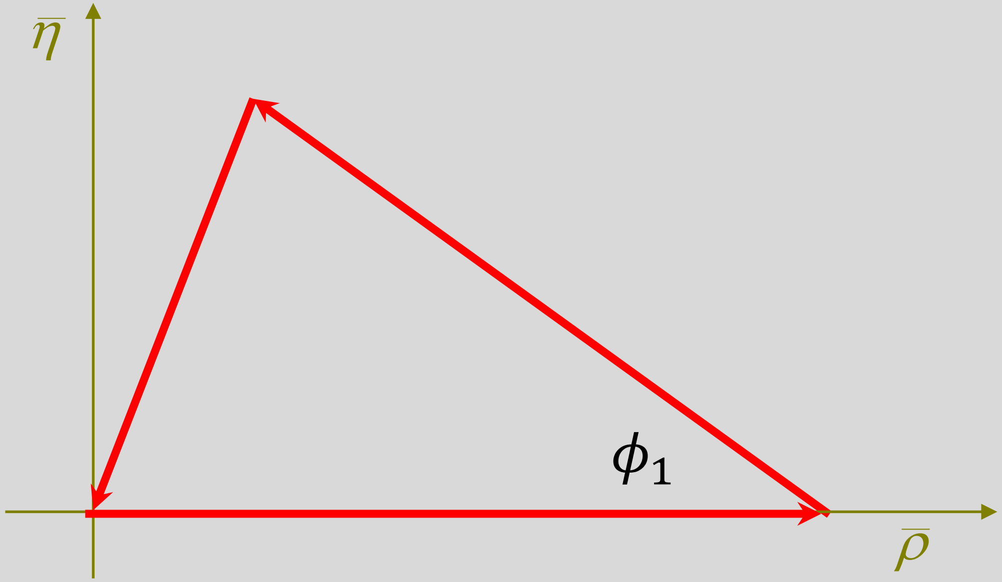
Modes sensitive to ϕ_1

$B \to J/\psi\, K_{S,L}^0$
$B \to J/\psi\, K^{*0}(K_S^0\pi^0)$
$B \to \psi(2S)K_S^0, \chi_{c0,1}K_S^0, \eta_c K_S^0$
$B \to D^*D^*K_S^0$
$B \to D^{(*)}h^0$
$B \to D^+D^-, D^{*+}D^{*-}, D^{*\pm}D^\mp$
$B \to J/\psi\, \pi^0$
$B \to \eta' K_S^0, \phi K_S^0, \pi^0 K_S^0, \rho^0 K_S^0, \omega K_S^0, f^0 K_S^0$
$B \to K^+K^-K_S^0, K_S^0K_S^0K_S^0$

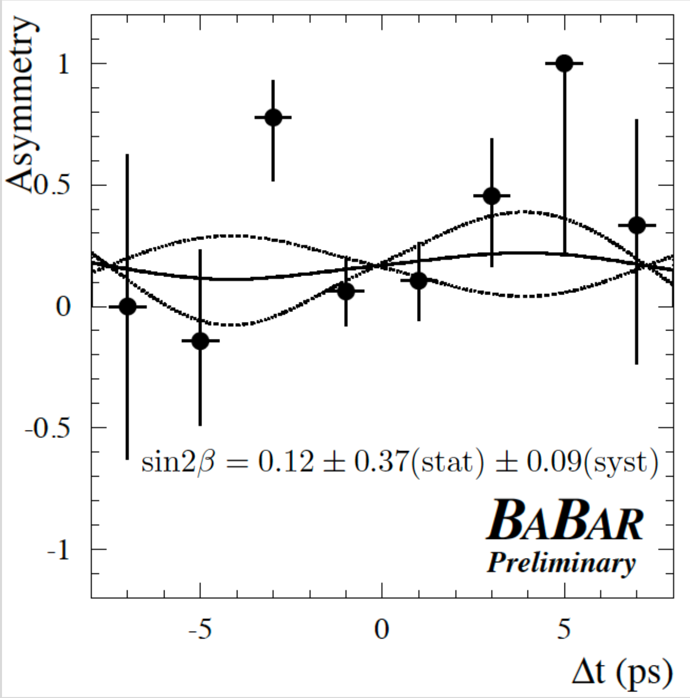
Modes sensitive to ϕ_3

$B^- \to D_{CP}^{(*)}K^{(*)-}$
$B^0 \to D_{CP}K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)K^{(*)-}$
$B^- \to D^{(*)}(K^+\pi^-)\pi^-$
$B^- \to D^{(*)}(K_S^0h^+h^-)K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)K^-$
$B^- \to D(K_S^0K^+\pi^-)K^-$

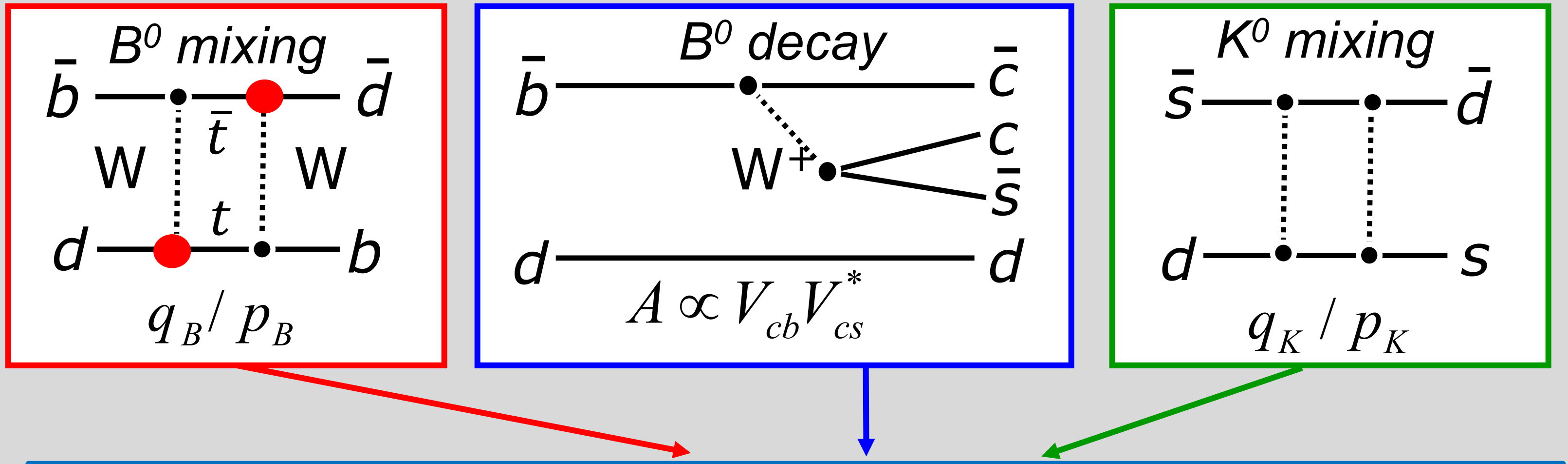
ϕ_1 , the B Factories' "CP or not CP"



Hitlin, ICHEP 2000



$\sin 2\phi_1$ *from* $B^0 \to J/\psi\, K_{S,L}$ *decays*



$$\lambda_{J/\psi\, K^0_{S,L}} = \frac{q_B}{p_B}\frac{\bar{A}_{J/\psi\, K^0_{S,L}}}{A_{J/\psi\, K^0_{S,L}}} = \mp \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = \mp \frac{V_{tb}^* \boldsymbol{V_{td}}}{V_{tb} \boldsymbol{V_{td}^*}}\frac{V_{cb}}{V_{cb}^*}\frac{V_{cd}^*}{V_{cd}}$$

$$\left|\lambda_{J/\psi\, K^0_{S,L}}\right| = 1 \Rightarrow C_{J/\psi\, K^0_{S,L}} = 0$$

$$S_{J/\psi\, K^0_{S,L}} = \mathrm{Im}\, \lambda_{J/\psi\, K^0_{S,L}} = \pm \sin 2\phi_1$$

$$\Gamma(B^0 \to f_{CP}) \propto e^{-t/\tau}[1 + \eta_{CP} \sin 2\phi_1 \sin \Delta M\, \Delta t]$$

$$\Gamma(\bar{B}^0 \to f_{CP}) \propto e^{-t/\tau}[1 - \eta_{CP} \sin 2\phi_1 \sin \Delta M\, \Delta t]$$

$$A_{CP}(t) = -\,\eta_{CP} \sin 2\phi_1 \sin \Delta M\, \Delta t$$

$\eta_{CP} = -1(+1)$ for $J/\psi\, K^0_{S(L)}$

The "gold-plated modes": $B \to J/\psi K_S^0$ and other $b \to c\bar{s}s$ transitions

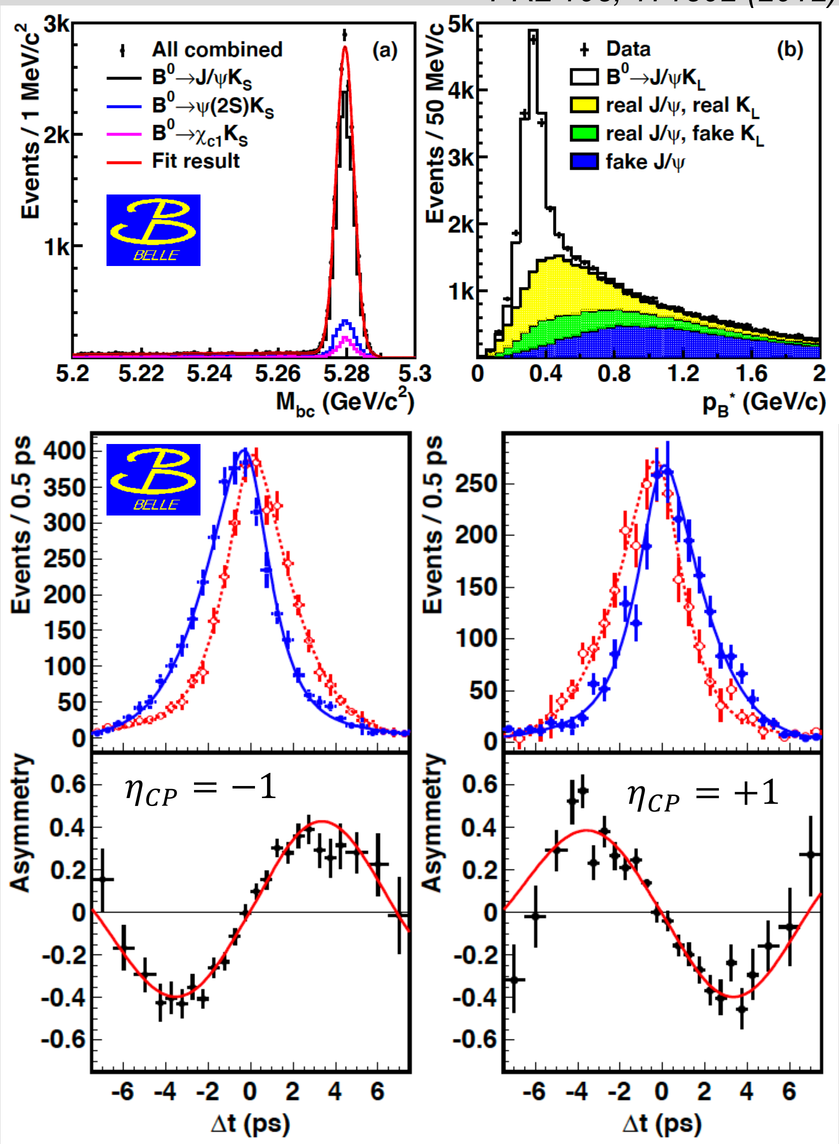
- *$B \to J/\psi(\to l^+l^-)K_S^0$ dominates $\sin 2\phi_1$ measurement*
  - *Relatively large BF*
  - *Low background*
  - *Small theoretical uncertainties*

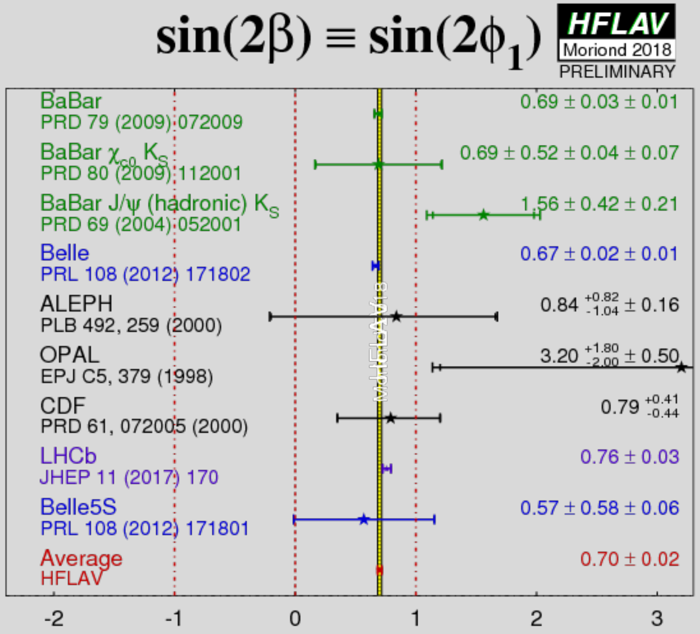
- *LHCb error on $\sin 2\phi_1$ is now 0.014*
  - *Dominated by statistical error*

- *Eventually, Belle II will be systematics limited*

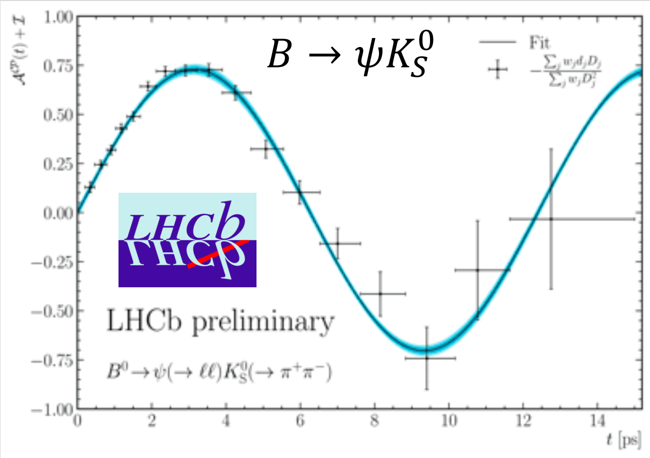
	No improvement	Vertex improvement	Leptonic categories
$S_{J/\psi K_S^0}$ (50 ab^{-1})			
stat.	0.0035	0.0035	0.0060
syst. reducible	0.0012	0.0012	0.0012
syst. irreducible	0.0082	0.0044	0.0040
$A_{J/\psi K_S^0}$ (50 ab^{-1})			
stat.	0.0025	0.0025	0.0043
syst. reducible	0.0007	0.0007	0.0007
syst. irreducible	$^{+0.043}_{-0.022}$	$^{+0.042}_{-0.011}$	0.011

PRL 108, 171802 (2012)



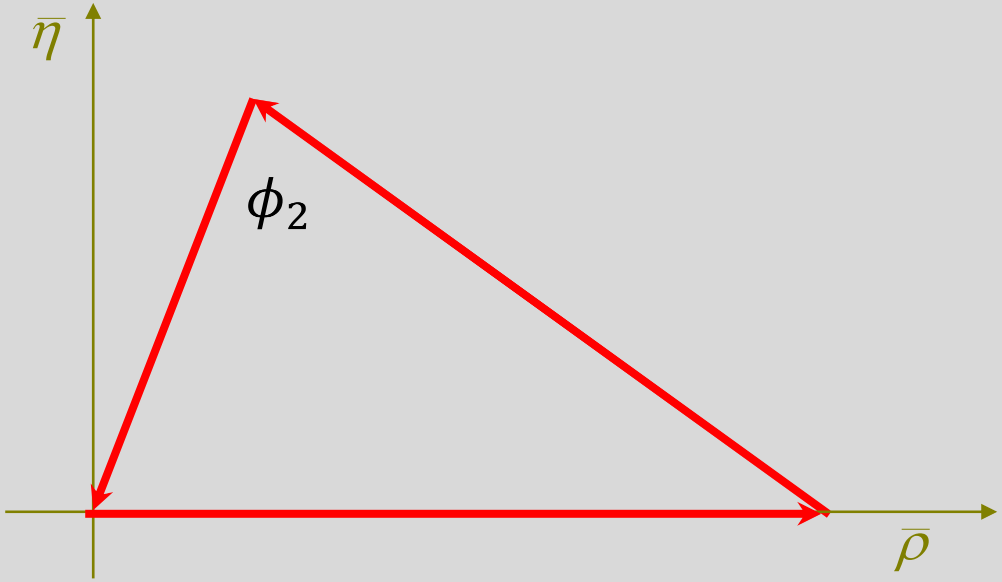


June 2023



$\sin 2\beta = 0.716 \pm 0.013 \pm 0.008$

ϕ_2 , *a story with some twists and turns*

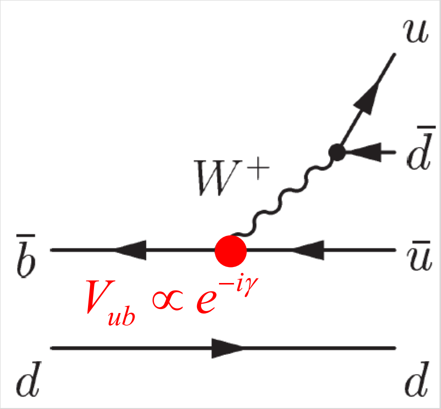


Original idea: time-dependent analysis of $B \to \pi^+\pi^-$

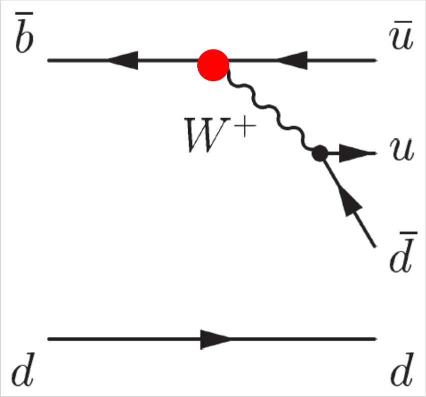
- *Only tree amplitudes were expected to contribute to $B \to \pi^+\pi^-$*
  - *penguin amplitude was expected to be negligible !*

- *Weak phase $2\phi_3$ between $B \to \pi^+\pi^-$ and $\bar{B} \to \pi^+\pi^-$ combines with mixing phase $2\phi_1$*

- *Time-dependent CP asymmetries would be*
  - $S = \sin 2\phi_2$ *and* $C = 0$



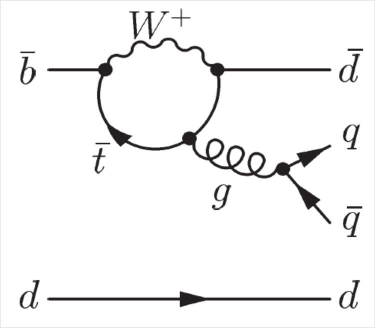
external tree (T)



internal or color-suppressed tree (C)

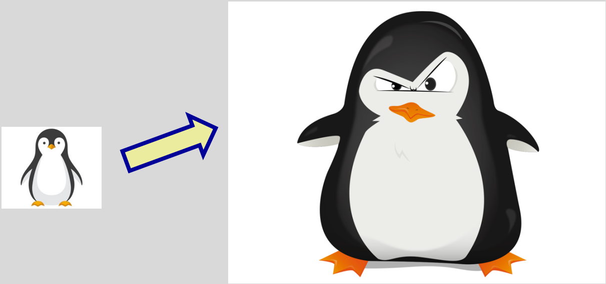
Weak phase:

$$\lambda = \underbrace{\left(\frac{q}{p}\right)}_{mixing} \underbrace{\frac{\bar{A}}{A}}_{decay}$$
$$= e^{-i2\phi_1}\, e^{-i2\phi_3}$$
$$= e^{i2\phi_2}$$

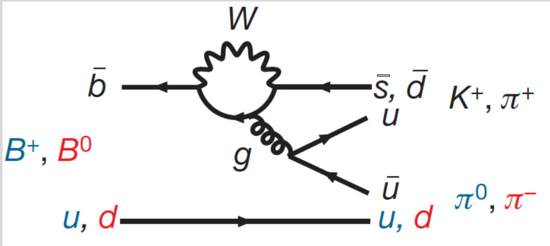


Penguin (P)

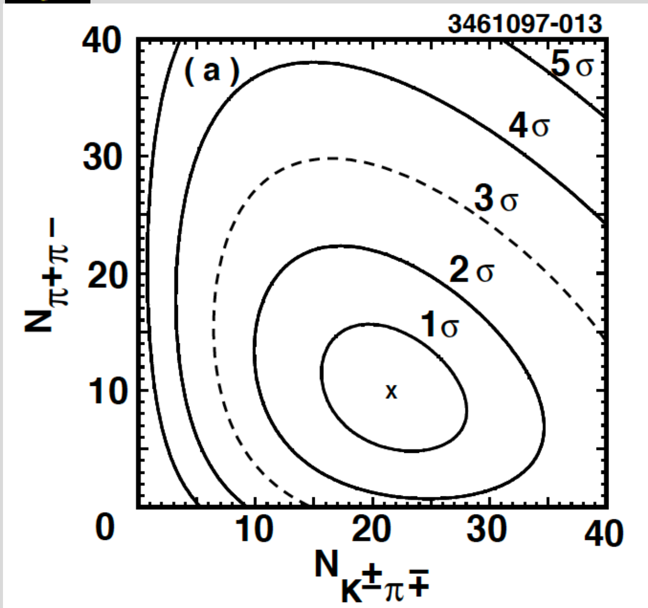
The rise of the penguins

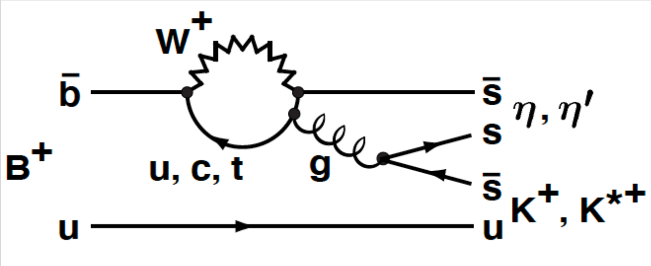


- *Just before the start of data taking of the B factories there was troublesome news*
  - $\bar{B} \to K^+\pi^-$ *and* $B^+ \to \eta' K^+$ *were discovered with unexpectedly large BFs*
  - *On the other hand* $B \to \pi^+\pi^-$ *hadn't been seen, yet*
  - *Shortly after* $B \to \pi^+\pi^-$ *was discovered, BF(*$B \to \pi^0\pi^0$*) was found larger than expected*
- *Penguins could not be neglected!*
- *But if penguins are large,* ϕ_2 *can't be extracted from* $C_{\pi^+\pi^-}$ *and* $S_{\pi^+\pi^-}$ *(alone)* 😕

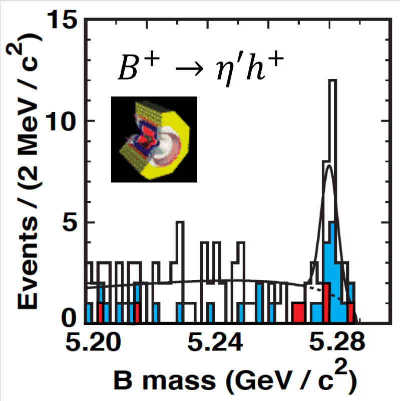


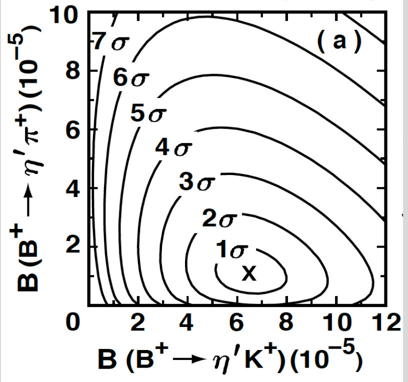
PRL 80, 3456 (1998)





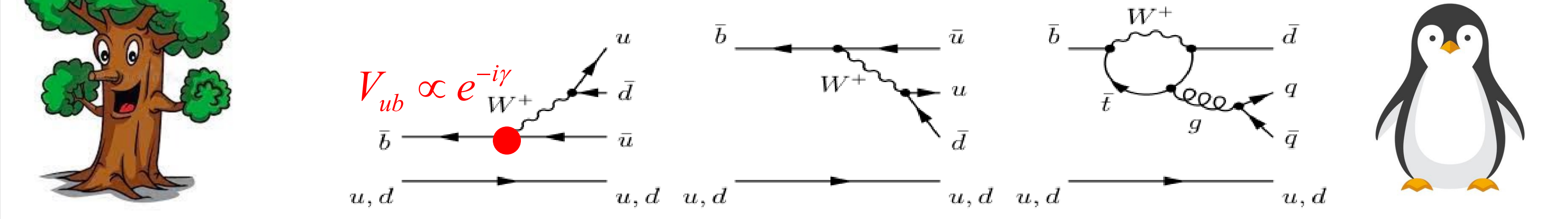
PRL 80, 3710 (1998)





ϕ_2 *from* $B \to \pi\pi$

$$A = \alpha_T \cdot T + \alpha_C \cdot C + \alpha_P \cdot P$$

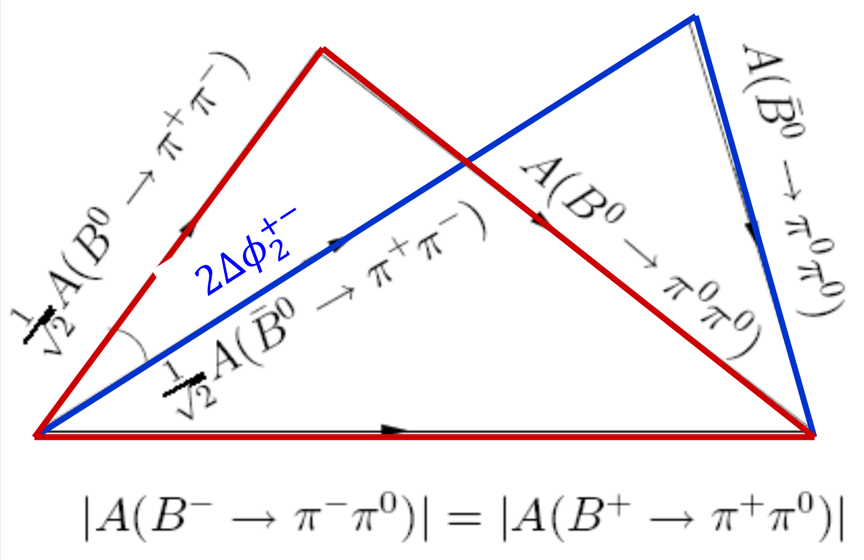


ϕ_2 can be extracted with an isospin decomposition of $B \to \pi^+\pi^-$

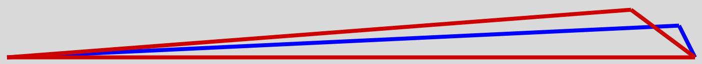
	isospin factors α_T	α_C	α_P
$B \to \pi^+\pi^-$	$\sqrt{2}$	0	$\sqrt{2}$
$B \to \pi^+\pi^0$	1	1	0
$B \to \pi^0\pi^0$	0	1	-1

$$\boxed{S = \sqrt{1 - C^2} \times \sin\left(2\phi_2 - 2\Delta\phi_2^{+-}\right)}$$

Gronau and London, PRL 65, 3381 (1990)

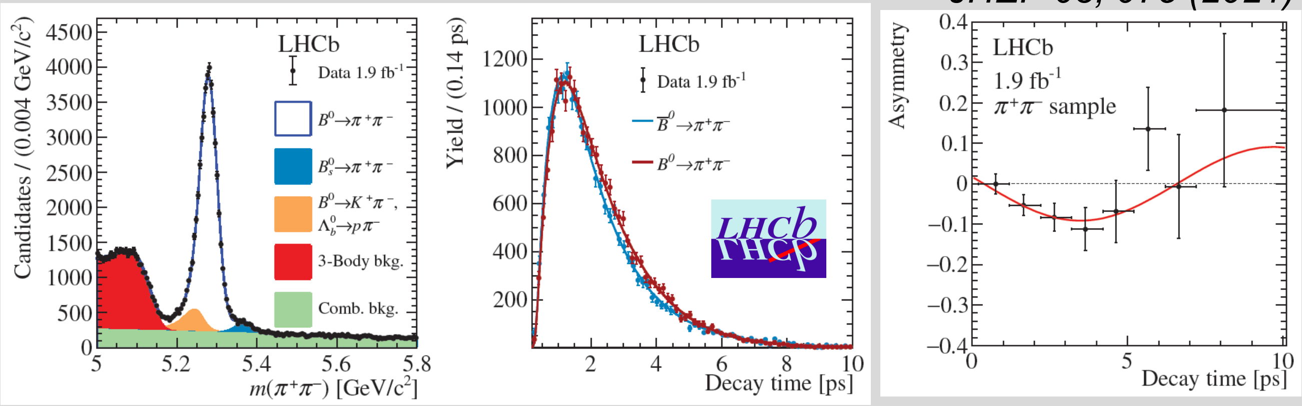


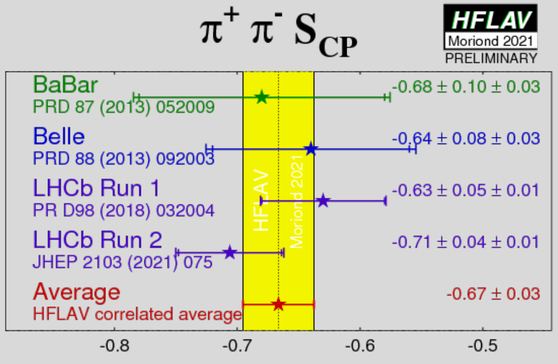
<u>Optimal case:</u> $\Gamma(\pi^0\pi^0) \ll \Gamma(\pi^\pm\pi^0), \Gamma(\pi^+\pi^-)$

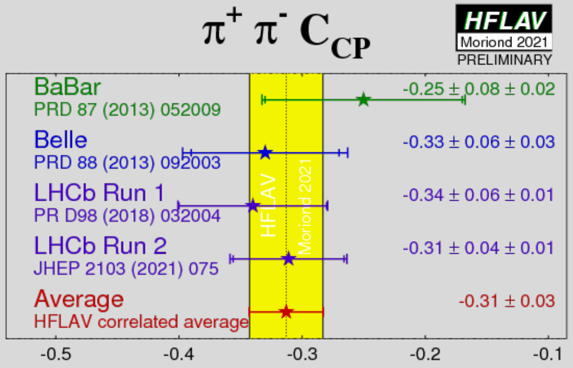


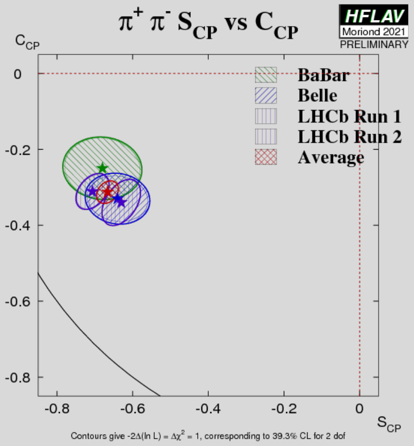
$B^0 \to \pi^+\pi^-$ CPV and BF

JHEP 03, 075 (2021)

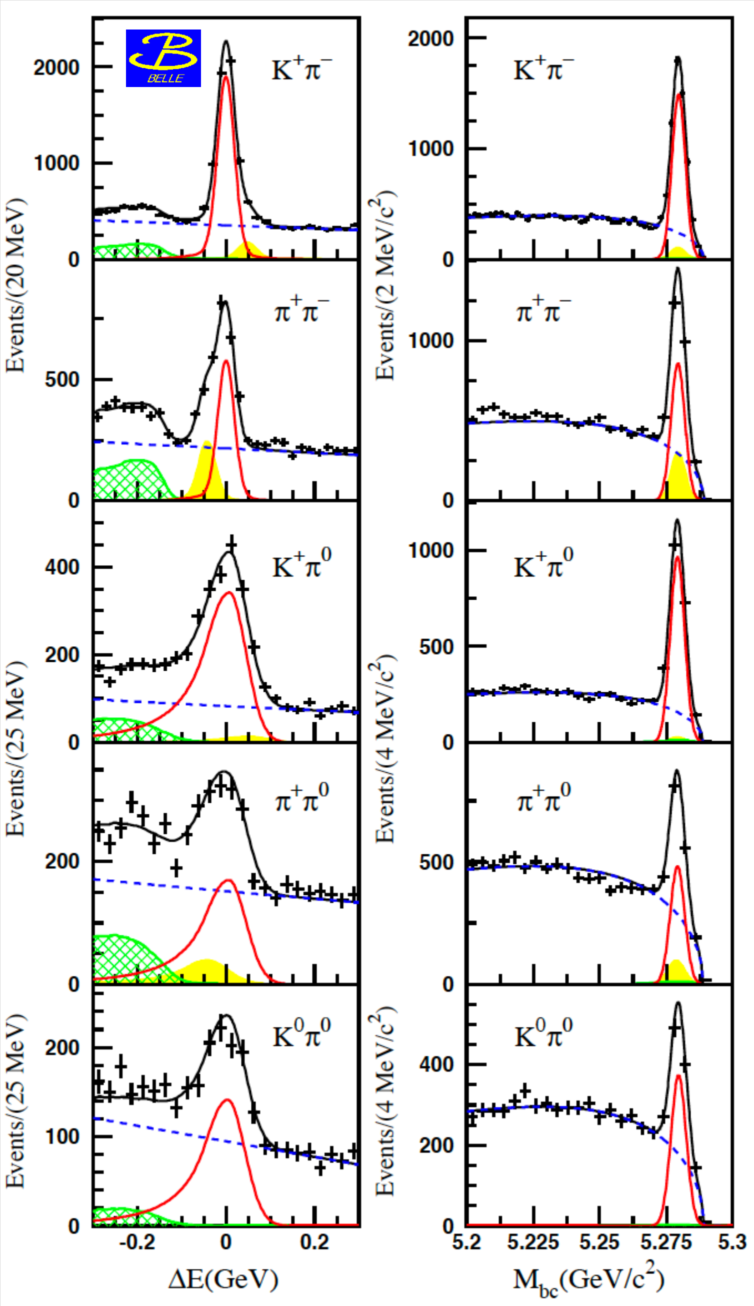








PRD 87, 031103 (2013)



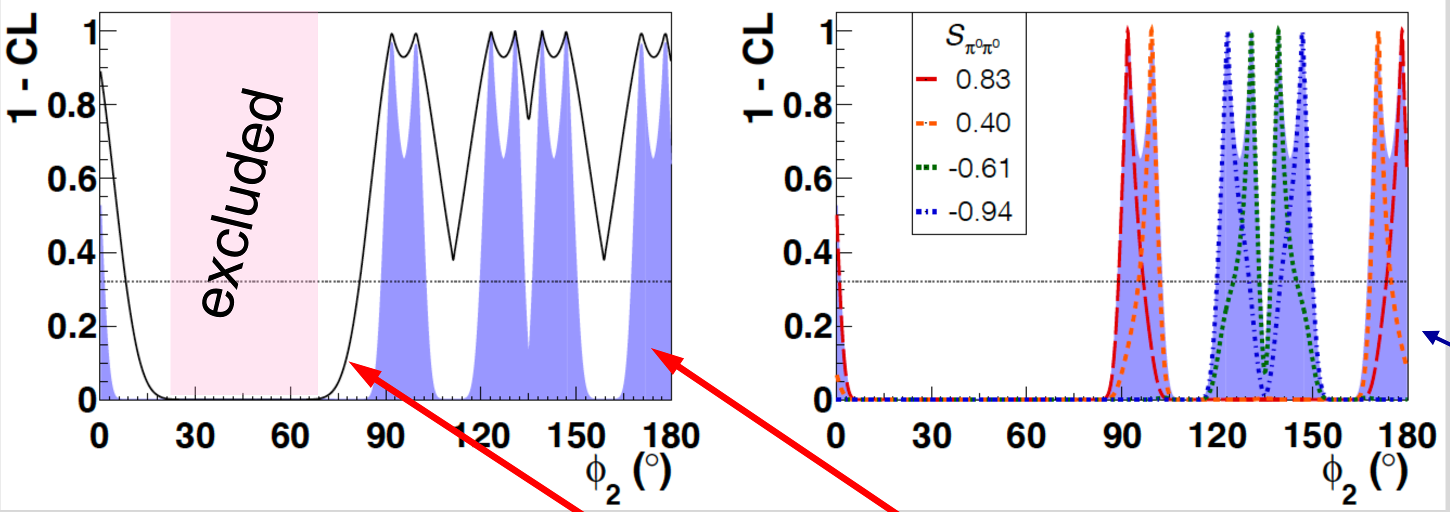
CPV in $B \to \pi^+ \pi^-$ is significant !

$$BF(B \to \pi^+\pi^-) = (5.10 \pm 0.19)\times 10^{-6}$$
$$BF(B \to \pi^+\pi^0) = (5.5 \pm 0.4) \times 10^{-6}$$
$$BF(B \to \pi^0\pi^0) = (1.59 \pm 0.26)\times 10^{-6}$$
$$A_{CP}(B \to \pi^+\pi^0) = +0.03 \pm 0.04$$
$$C(B \to \pi^0\pi^0) = -0.33 \pm 0.22$$

Unfortunately

$$\Gamma_{\pi^0\pi^0} \sim \Gamma_{\pi^+\pi^-}, \Gamma_{\pi^\pm\pi^0}$$

Constraints on ϕ_2 from $B \to \pi\pi$ *(now and with Belle II)*



	Value	0.8 ab^{-1}	50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm0.21 \pm 0.18$ [727]	$\pm0.03 \pm 0.08$
$\mathcal{B}_{\pi^0\pi^0}$ [10^{-6}]	1.31	$\pm0.19 \pm 0.19$ [712]	$\pm0.03 \pm 0.03$
$\mathcal{B}_{\pi^+\pi^0}$ [10^{-6}]	5.86	$\pm0.26 \pm 0.38$ [727]	$\pm0.03 \pm 0.09$
$A_{\pi^+\pi^-}$	0.33	$\pm0.06 \pm 0.03$ [728]	$\pm0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm0.08 \pm 0.03$ [728]	$\pm0.01 \pm 0.01$
$A_{\pi^0\pi^0}$	0.14	$\pm0.36 \pm 0.10$ [712]	$\pm0.03 \pm 0.01$

- *Discrete ambiguities complicate constraints on ϕ_2*
  - *Belle II can substantially reduce uncertainties*
- *$S(B \to \pi^0\pi^0)$ could resolve discrete ambiguities*
  - *Very hard measurement*
  - *Expected Belle II error ~0.3*
- *$B \to \pi\pi$ was assumed to be B factories' best shot at ϕ_2*
  - *Other $b \to u\bar{u}d$ modes, like $B \to \pi\rho$ and $B \to \rho\rho$ would have additional problems (low π^0 efficiency, time-dep. Dalitz analysis, VV polarization amplitudes)*

3 pleasant surprises in $B \to \rho\rho$

$Br(B^0 \to \rho^+\rho^-) = (27.7 \pm 1.9)\times10^{-6}$
$Br(B^\pm \to \rho^\pm\rho^0) = (24.0 \pm 1.9)\times10^{-6}$
$Br(B^0 \to \rho^0\rho^0) = (0.96 \pm 0.15)\times10^{-6}$

$f_L^{+-} = 0.990^{+0.021}_{-0.019}$
$f_L^{+0} = 0.950 \pm 0.016$
$f_L^{00} = 0.71^{+0.08}_{-0.09}$

$A_{CP}^{+0} = -0.05 \pm 0.05$

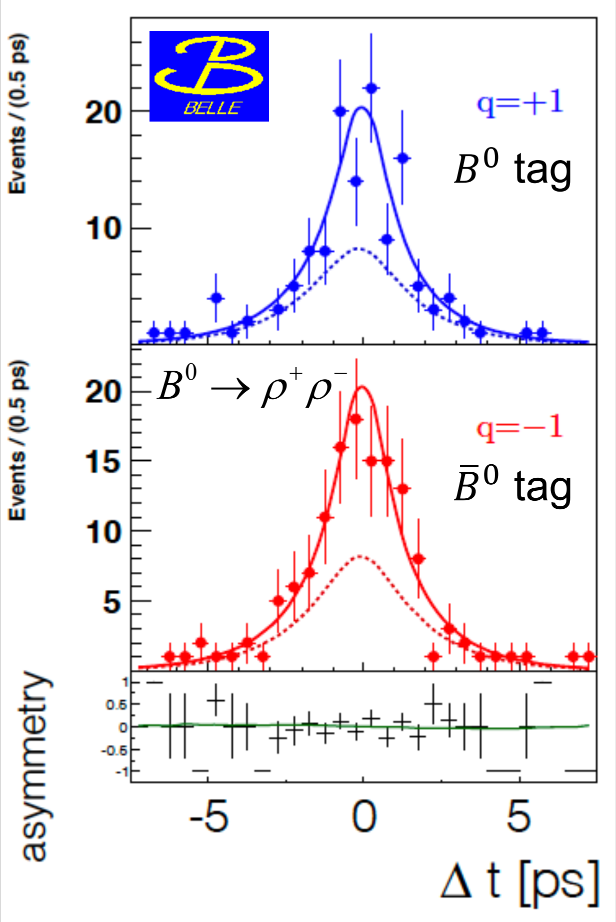
$S^{+-} = -0.14 \pm 0.13$
$C^{+-} = +0.00 \pm 0.09$

Large branching fraction !
(large sample despite π^0 in final state)

Small penguins !
(effective ϕ_2 constraint)

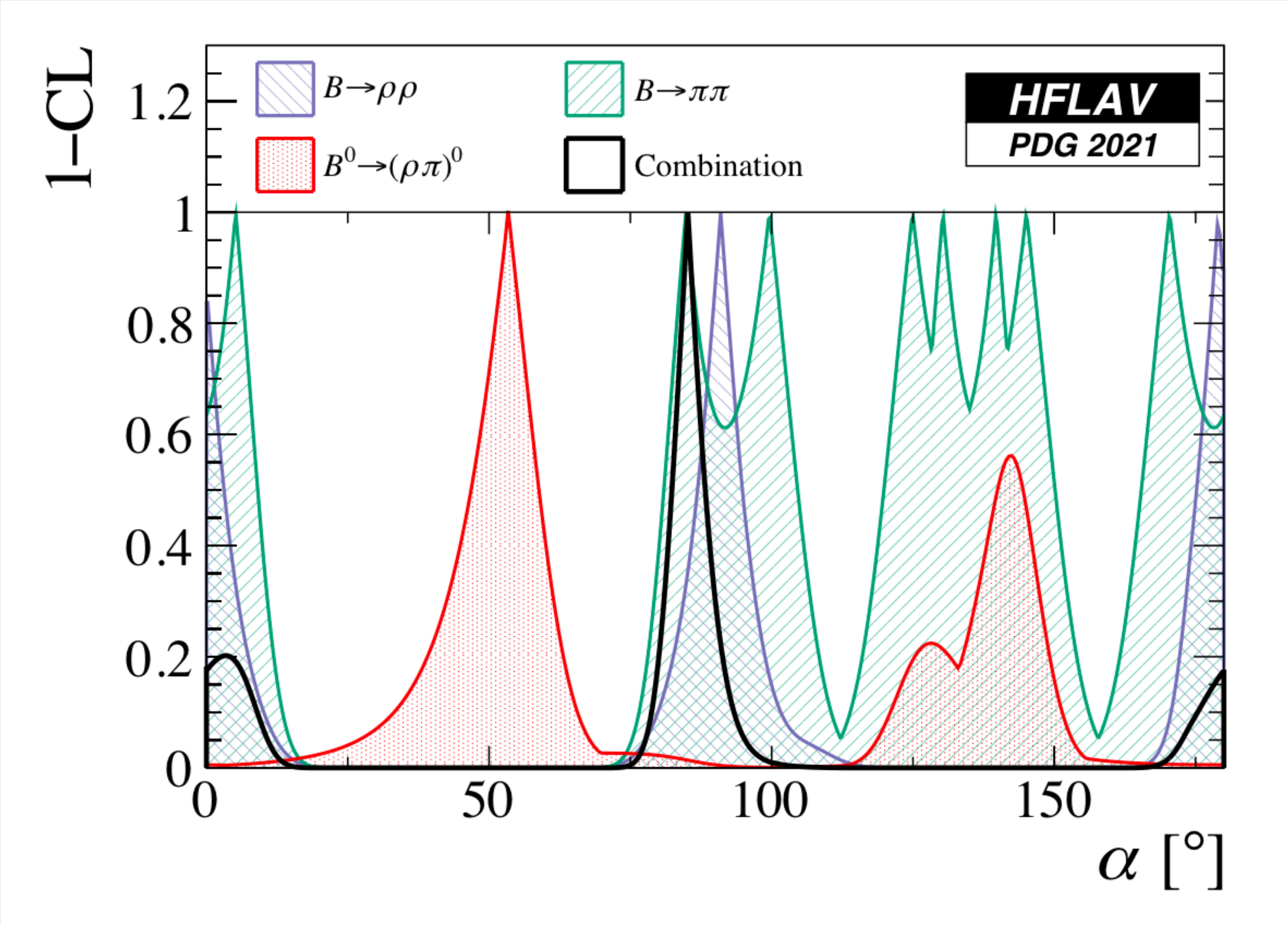
Dominantly longitud. polarized !
(no need for full angular analysis)

PRD 93, 032010 (2016)



Time-dependent CP asymmetry in $B^0 \to \rho^+\rho^-$

ϕ_2 World Average



$\boxed{\phi_2(PDG) = (85.2^{+4.8}_{-4.3})^\circ}$

ϕ_2 world average is dominated by $B \to \rho\rho$

From CKM fit

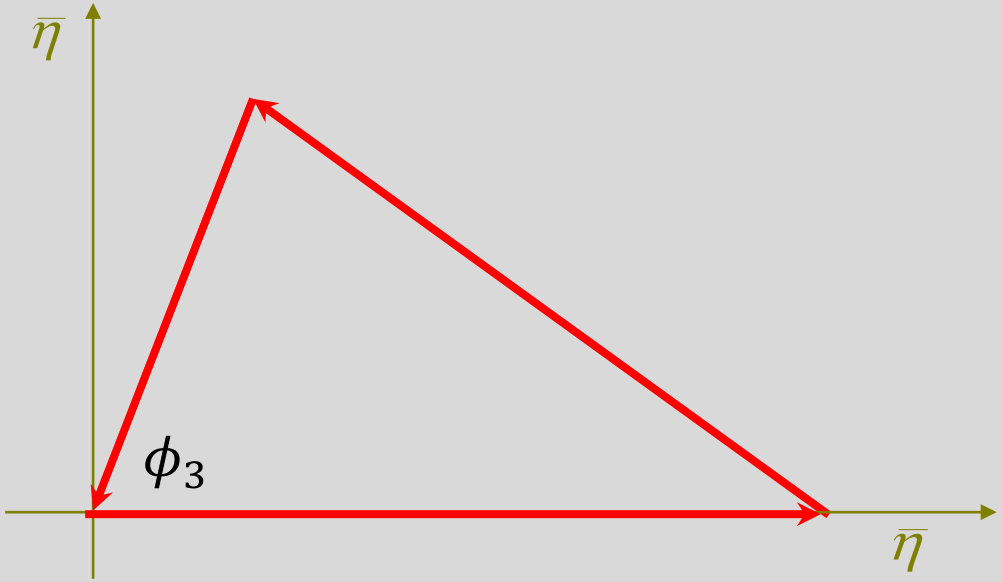
(UT$_{\text{fit}}$, 2018):

$$\phi_2 = (90.1 \pm 2.2)^\circ$$

Modes with $\pi^0(\rho^\pm \to \pi^\pm\pi^0)$ are much easier at Belle II than at LHCb

Expected ϕ_2 error: $\Delta_{\phi_2} \sim 0.6^\circ$

The UT angle ϕ_3



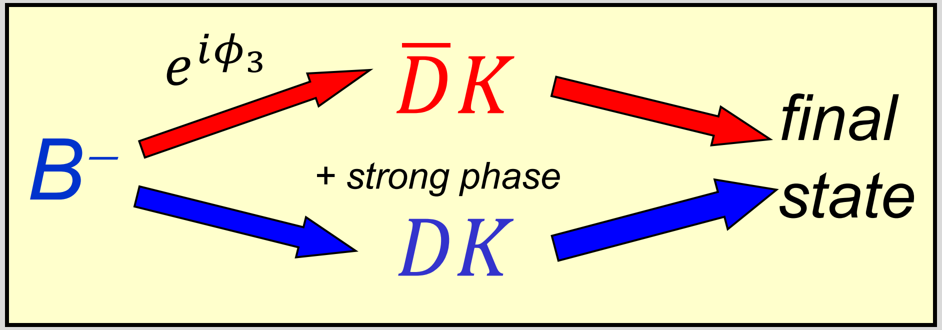
"hard to reach"

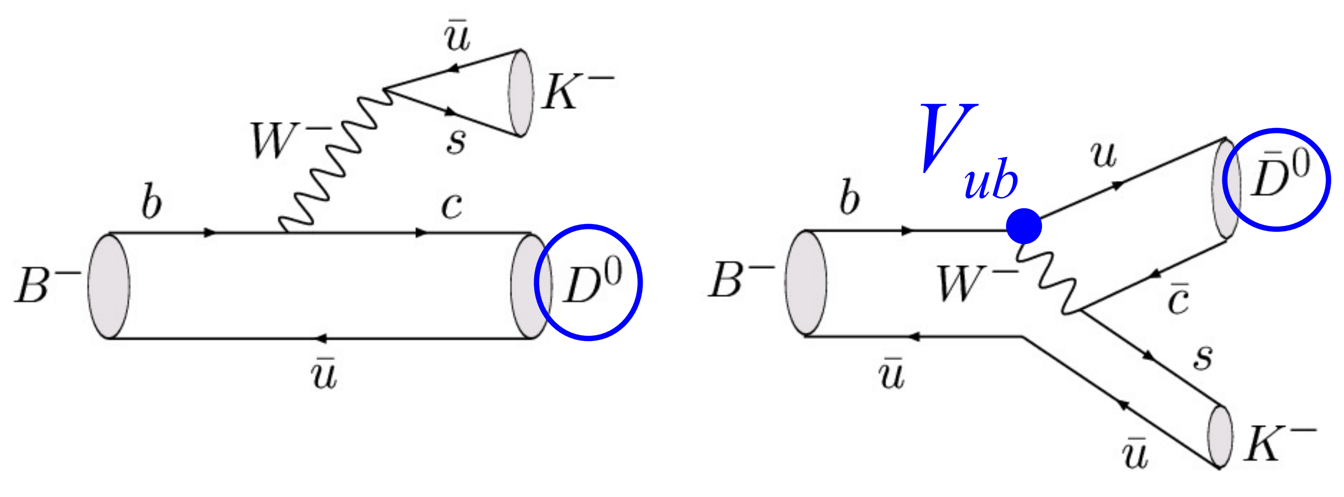
Determination of ϕ_3 with $B^- \to D^{(*)}K^{(*)-}$

Measure ϕ_3 with charged B decays

(interference between $\overline{D}K$ and DK intermediate states where $\overline{D}$ and D decay to same final state)

One amplitude involves V_{ub}





Many D^0 final states investigated:

CP eigenstates ($\pi\pi$, KK; $K_S(\pi^0,\omega,\eta,\varphi)$)

Flavor eigenstates ($K\pi$)

Three-body decays ($K_S\pi\pi$, K_SKK, $\pi\pi\pi^0$)

Gronau & London, PLB 253, 483 (1991)
Gronau & Wyler, PLB 265, 172 (1991)
Atwood, Dunietz, & Soni, PRL 78, 3257 (1997),
Atwood, Dunietz, & Soni, PRD 63, 036005 (2001)
Giri, Grossman, Soffer, & Zupan, PRD 68, 054018 (2003)
Belle, Poluektov et al., PRD 70, 072003 (2004)
Bondar & Poluektov, EPJC 47,347 (2006)

BPGGSZ analysis of $B \to D^{(*)} K^{(*)}$ with $D \to K_S^0\pi^+\pi^-$

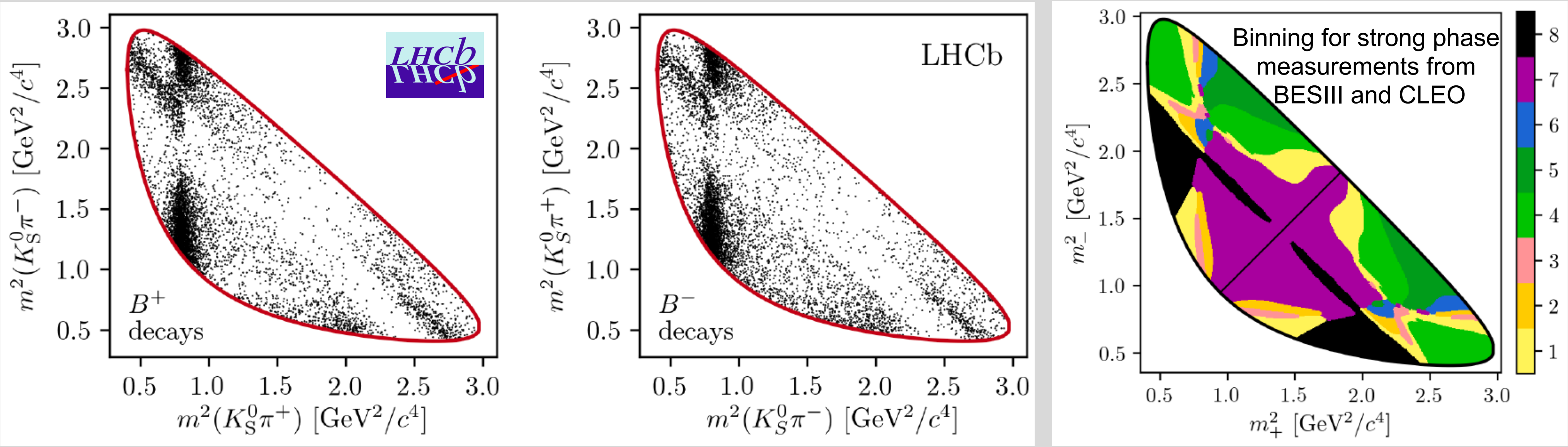
- *D Dalitz plot has complicated structure of several interfering amplitudes*
  - *Interference between D decays to Cabibbo-allowed, Cabibbo-suppressed and CP final states*

$$\mathrm{d}\Gamma_{B^-}(m_+^2, m_-^2) \propto |A_+|^2 + r_B^2|A_-|^2 + 2r_B|A_+||A_-|\left(\cos\delta_D\cos(\delta_B+\phi_3) - \sin\delta_D\sin(\delta_B+\phi_3)\right)\mathrm{d}p$$

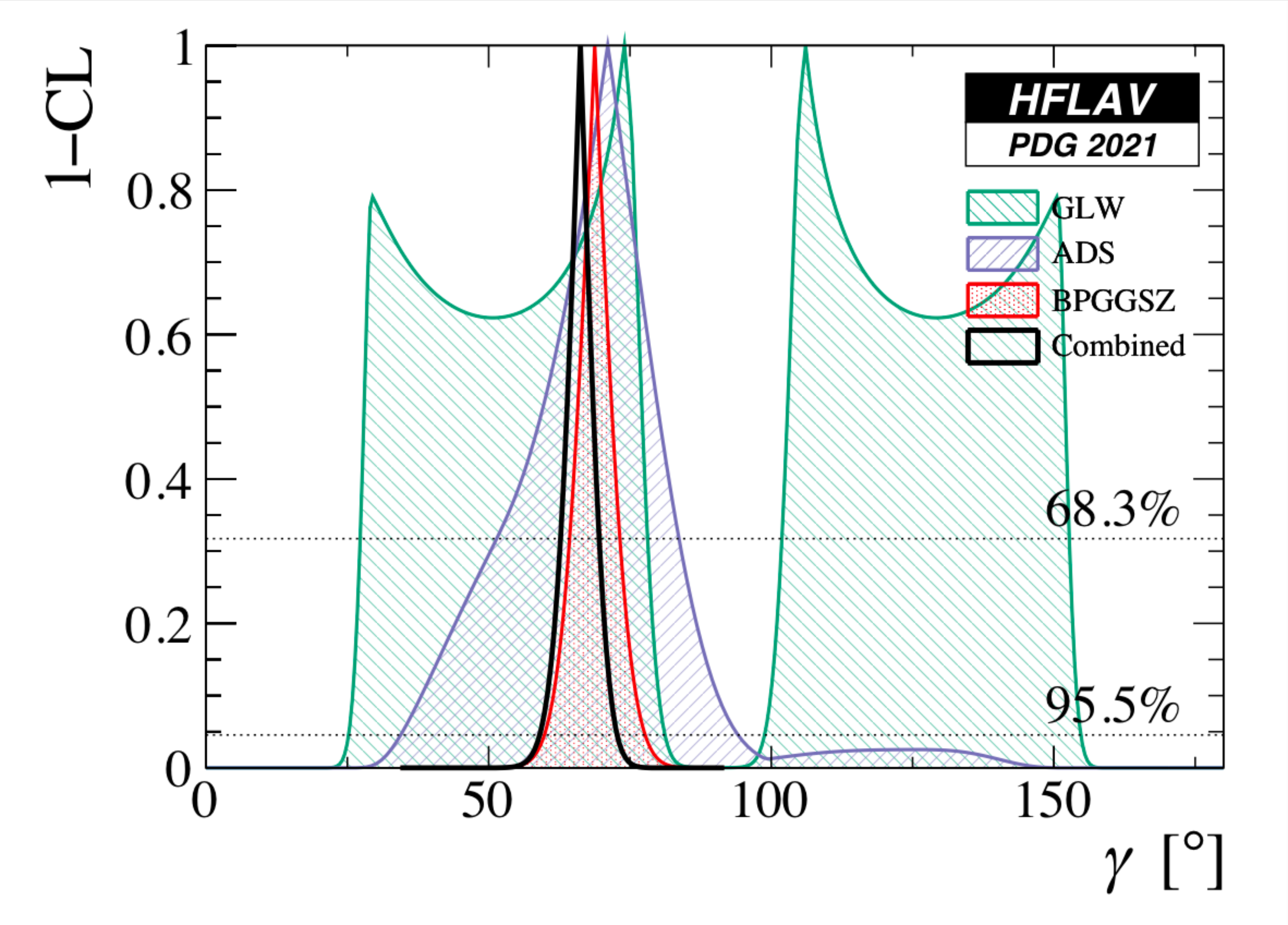
$$A_\pm = A_D\left(m_\pm^2, m_\mp^2\right)$$

- *Model-independent method*
  - *Binned fit to Dalitz plot → get δ_D for each bin from coherent $D\bar{D}$ production at CLEO-c or BESII*

JHEP 2021, 169 (2021)



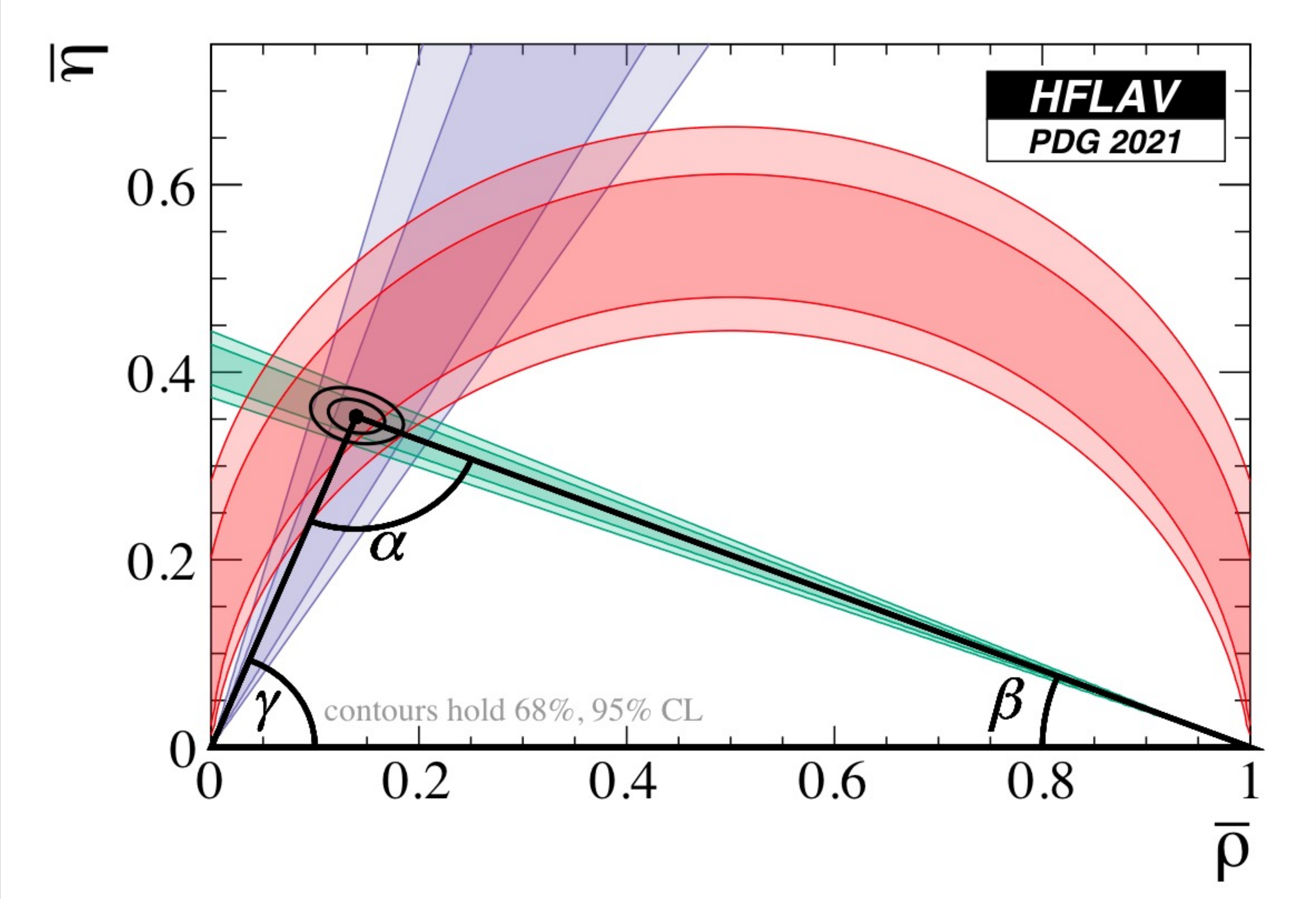
ϕ_3 World Average



$\phi_3(HFLAV) = (66.2^{+3.4}_{-3.6})^\circ$

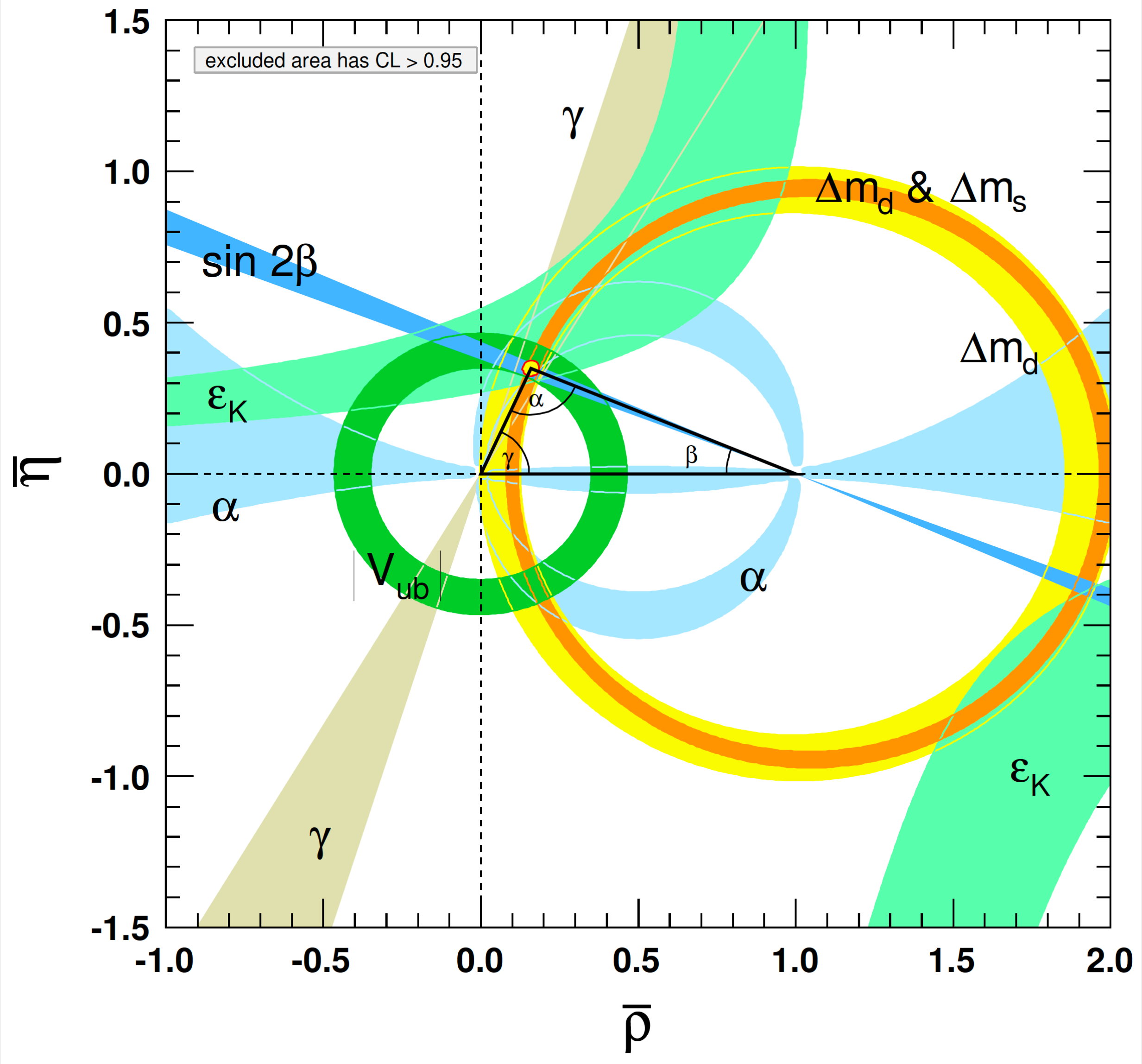
From CKM fit
(UT_{fit}, 2018):
$\phi_3 = (65.8 \pm 2.2)^\circ$

Angles of the UT show consistent picture



... also with the UT sides !

PDG 2022



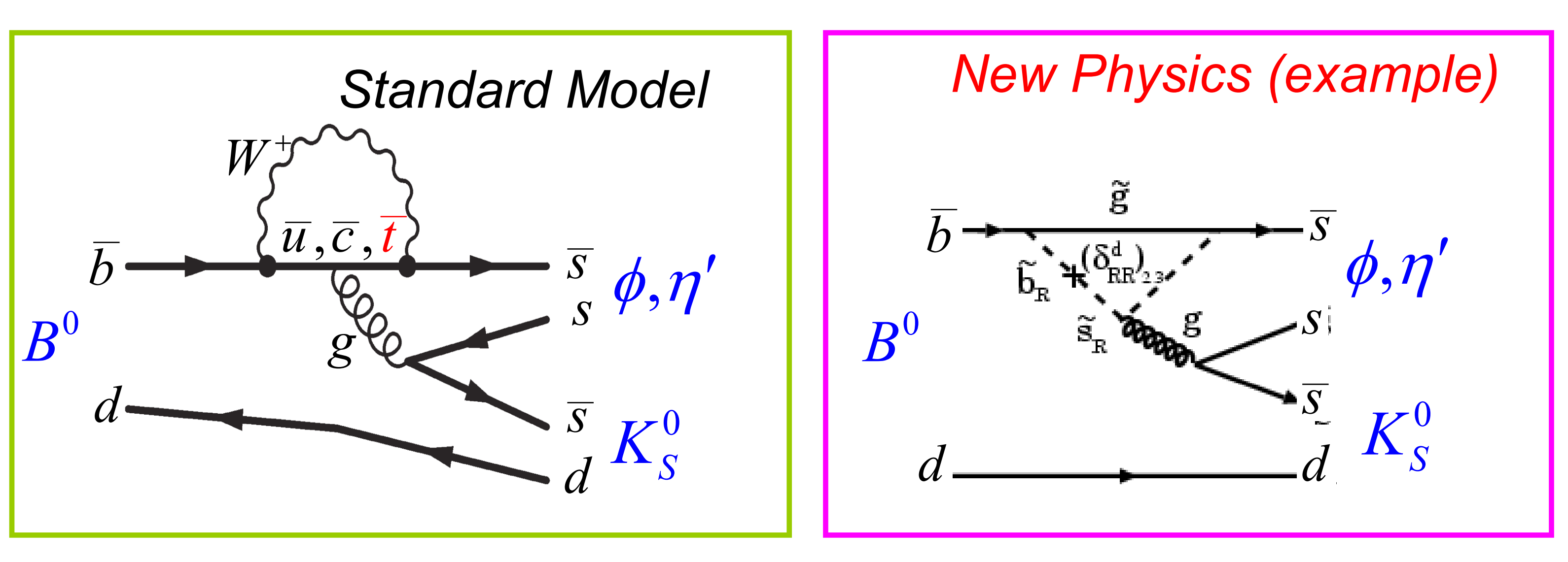
UT parameters consistent at the few percent level !

$$\lambda = 0.22500 \pm 0.00067\,, \qquad A = 0.826^{+0.018}_{-0.015}\,,$$
$$\bar{\rho} = 0.159 \pm 0.010\,, \qquad \bar{\eta} = 0.348 \pm 0.010$$

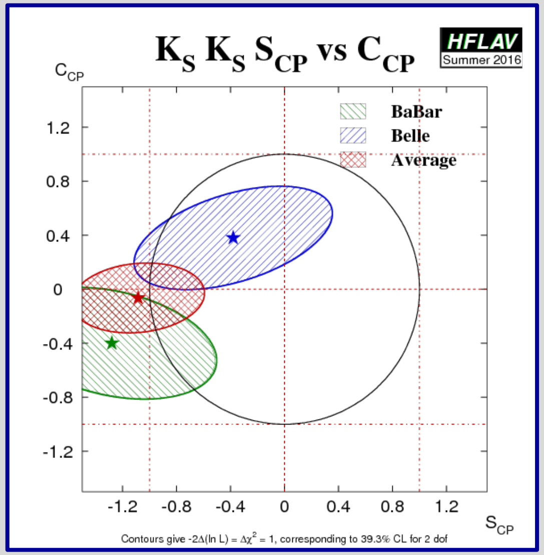
Beyond SM CPV searches (“Hic sunt dracones”)

Penguin-dominated $b \to sq\bar{q}$ decays

- *Penguin loops can receive contributions from New Physics*



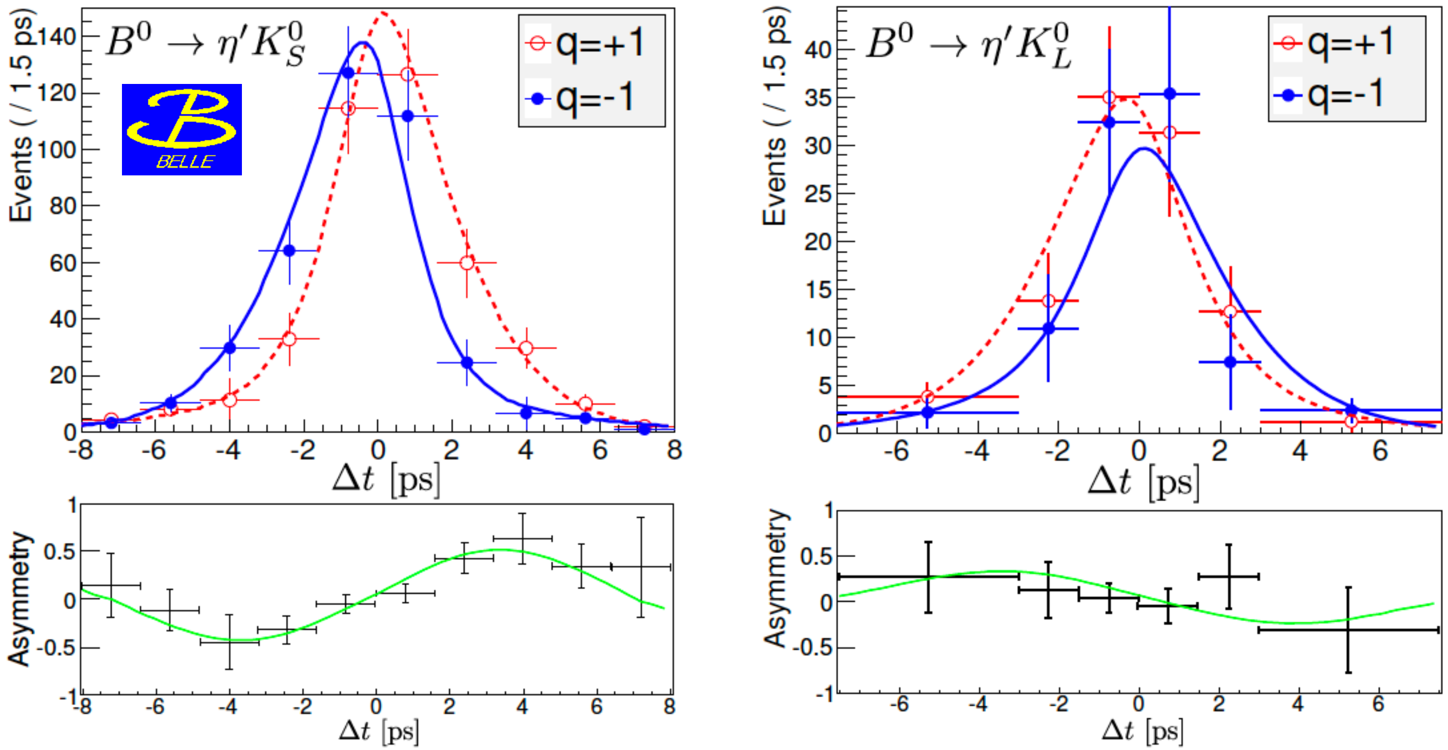
- *Weak phase of $b \to s\bar{q}q$ penguin is same as for $b \to c\bar{c}s$ in SM*
  - *Top quark contribution dominates loop amplitude*
  - *CP asymmetries are also $C = 0$ and $S = -\eta_{CP} \sin 2\phi_1$*
  - *Contributions of sub-leading diagrams could change S and C*



No CPV expected in $b \to d\bar{q}q$ penguins (e.g. $B \to K_S^0 K_S^0$): Loop phase cancels mixing phase for dominant diagram

Penguin-dominated $b \to sq\bar{q}$ decay: $B \to \eta' K^0$

JHEP 1410 (2014) 165

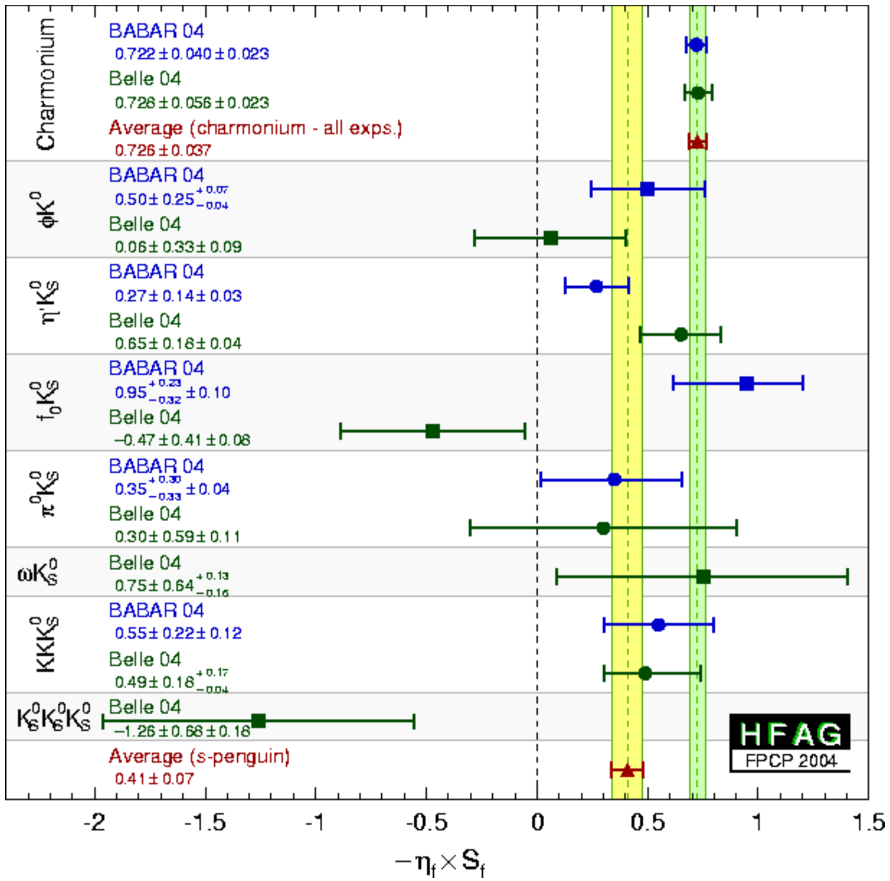


Decay mode	$\sin 2\phi_1^{\rm eff}$	$\mathcal{A}_f$
$\eta' K^0_S$	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
$\eta' K^0_L$	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
$\eta' K^0$	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

Most precise "$\sin 2\phi_1$ from a charmless mode"

CP Asymmetries in Penguin Decays

- *Theoretical predictions for $\delta S = S_{sq\bar{q}} - \sin 2\phi_1$ are small and typically positive*
  - *Large δS could be evidence for new physics*
- *Most significant difference in "naïve" $S_{sq\bar{q}}$ average reached in 2004*
  - *Caused a lot of excitement*
  - *Neglects theo. uncertainties and correlation of experimental uncertainties*
  - *HFLAV: "We do not advocate its use, and provide it only for academic interest.* ***Use with extreme caution, if at all****."*
- *More precise measurements have since decreased significance below 1σ*
  - *Still a good place to look for New Physics*
  - *Note, some measurements come from complicated 3-body time-dependent Dalitz analyses*



2004: $\delta S = -0.32 \pm 0.07\ (3.9\sigma)$

CP Asymmetries in Penguin Decays

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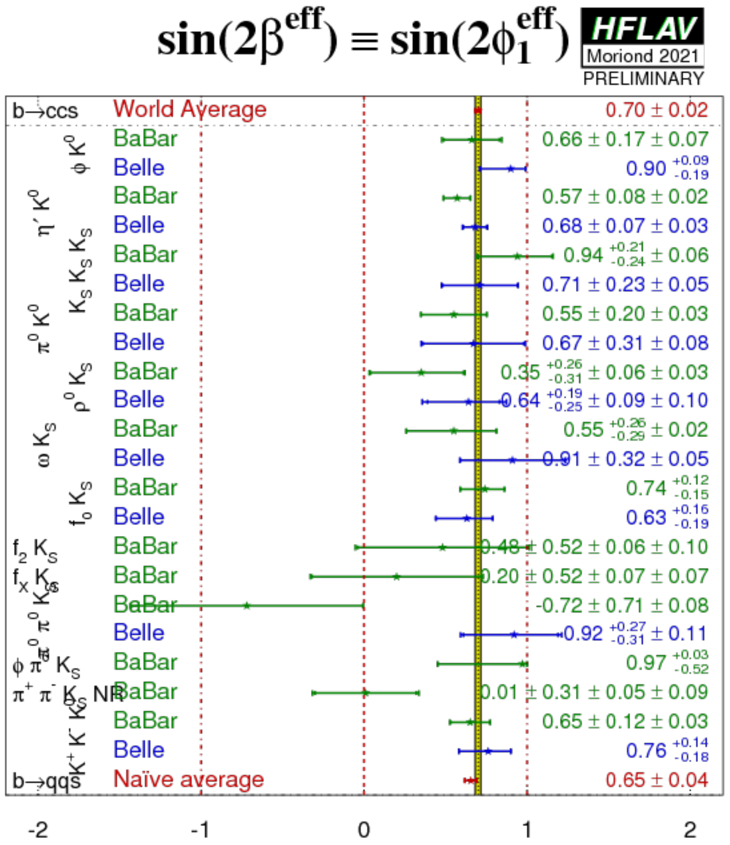
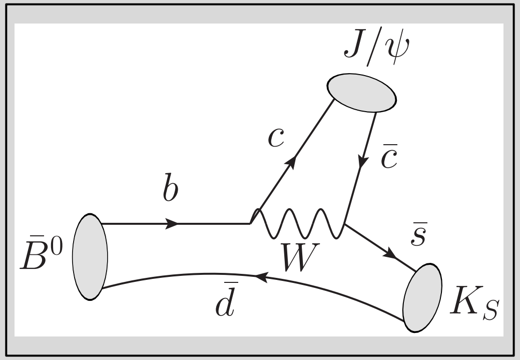


2021: $\delta S = -0.05 \pm 0.04$

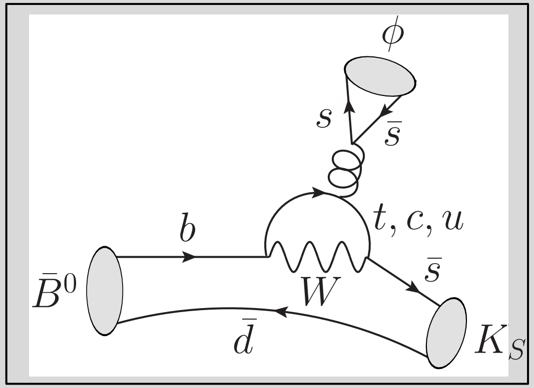
Belle II potential for CPV in penguin decays

$B^0 \to J/\psi K_S$ *(the "Golden" mode):*
→ *constrains the UT*



expected 50 ab^{-1} uncertainty: $\delta\phi_1$ = 0.4°
(less than the current theory error of 1-2°)

$B^0 \to \phi K_S, \eta' K_S, \omega K_S, \pi^0 K_S$ *("penguin" modes):*



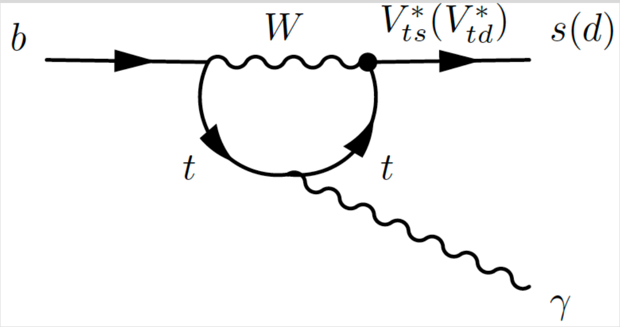
$$A_{CP} = A\cos(\Delta M \Delta t) + S\sin(\Delta M \Delta t)$$

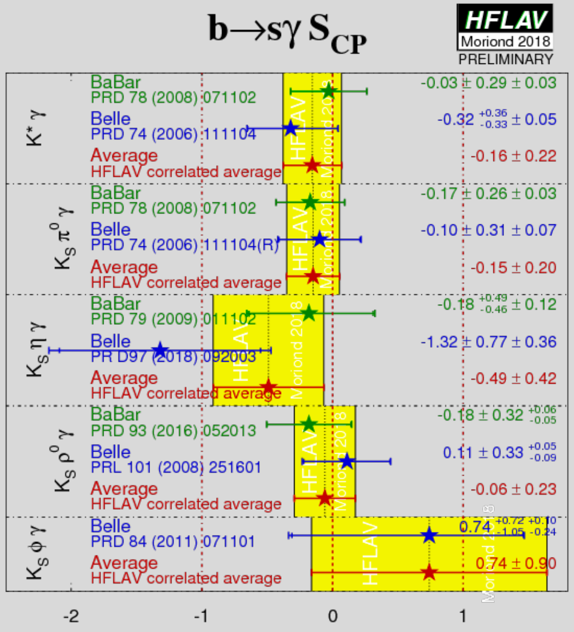
	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK^0_S	0.21	0.14	0.08	0.06	0.024	0.020
$K^0_S \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K^0_S \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

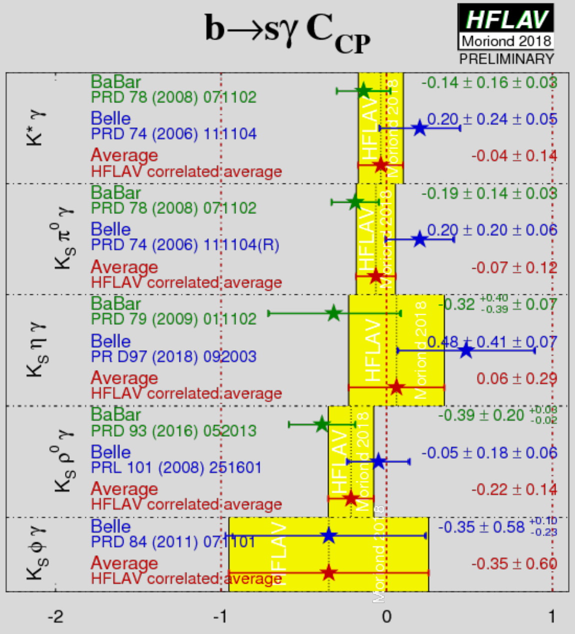
Belle II expected to improve precision in S from 10-20% to 2-3%

Radiative B decays:

TDCPV of $b \to s\gamma$ and $b \to d\gamma$



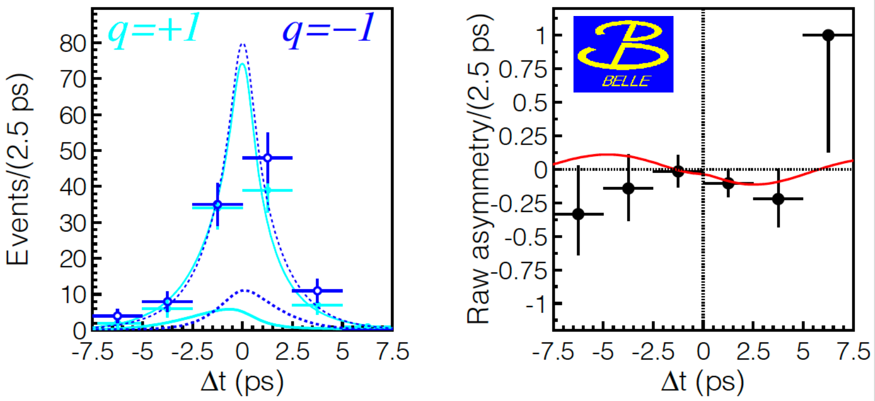




- *Expect CPV to be small ($S \sim -2(m_s/m_b)\sin(2\phi_1)$)*
  - *γ helicity dominantly LH for $b \to s(d)\gamma$, and RH for $\bar{b}$*
  - *$B^0 \to K^{*0}(K_S^0\pi^0)\gamma$ behaves like effective flavor eigenstate (assuming dipole operator is dominant)*
- *Similar situation for $B^0 \to \rho^0\gamma$*
  - *However, since weak phase from $b \to d\gamma$ decay amplitude cancels that from $B^0\bar{B}^0$ mixing, CPV is suppressed further*
- *Observed CPV would be sign of NP amplitude emitting RH photons and with NP weak phase*
- *Belle II potential: $\sigma(S_{\rho\gamma}) \sim 0.07$*

All measurements consistent with no CPV, as expected in the SM

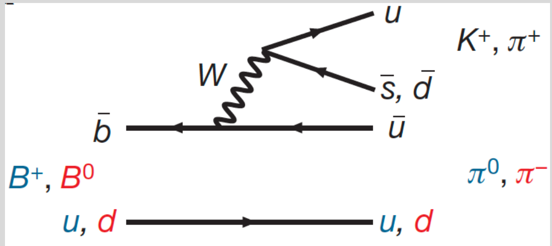
PRL 100, 021602 (2008)

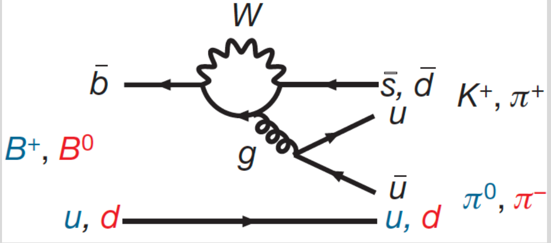


$$\mathcal{S}_{\rho^0\gamma} = -0.83 \pm 0.65(\text{stat}) \pm 0.18(\text{syst}), \text{ and}$$
$$\mathcal{A}_{\rho^0\gamma} = -0.44 \pm 0.49(\text{stat}) \pm 0.14(\text{syst}),$$

Direct CP relations: The Kπ Puzzle

- *First discovery of direct CPV in B decays with $B \to K^{\pm}\pi^{\mp}$*
  (BaBar, PRL 93 (2004) 131801; Belle, PRL 93 (2004) 131802)
  - *dCPV caused by interference between loop and tree amplitudes*





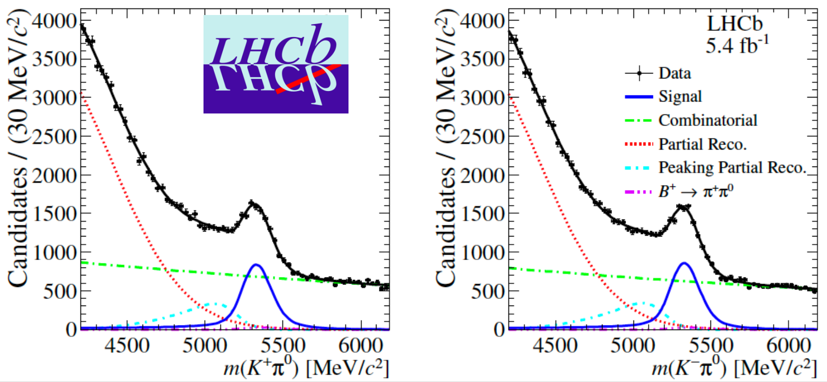
- *Naive assumption that modes related by isospin of spectator quark have similar A_{CP} … turned out to be wrong*

$$A_{CP}(B^0 \to K^+\pi^-) = -0.084 \pm 0.004$$
$$A_{CP}(B^+ \to K^+\pi^0) = 0.040 \pm 0.021$$
5.5 standard deviations (σ)

- *More accurate sum rule predicts $A_{CP}^{K^0\pi^0} = -0.138 \pm 0.025$ (with recent LHCb $K^{\pm}\pi^0$ measurement)*

$$A_{CP}(K^+\pi^-)+A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+}+A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

PRL126, 091802 (2021)



- *Expect error $\sigma\left(A_{CP}^{K^0\pi^0}\right)$~0.04 with Belle II*

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{A}_{CP}(B \to K^0\pi^0)[\%]$	$-0.05 \pm 0.14 \pm 0.05$	0.07	0.04

LHCb doing π^0 final state 😮

References

- [Heavy-quark physics and CP violation](), *J. Richman, Les Houches Lectures (1998)*
  - *A little older, but still an excellent pedagogical introduction to SM CP violation*
- [The Physics of the B Factories](), *A. Bevan et al., Eur. Phys. J. C (2014) 74, 3026*
  - *Comprehensive description of CPV measurements at Belle and BaBar*
- [HFLAV website](), *Heavy Flavor Averaging Group,*
  - *Up-to-date averages of CPV measurements*
- [The Belle II Physics Book](), *E. Kou et al., Prog. Theor. Exp. Phys. (2019) 123C01*
  - *Best predictions for Belle II potential for CPV measurements*

Conclusions

- *CPV observed in many processes, no inconsistency with SM prediction of single complex phase of CKM matrix*
  - *UT angles and sides are consistent*
  - *Still plenty of room for New Physics to hide (at few % level)*

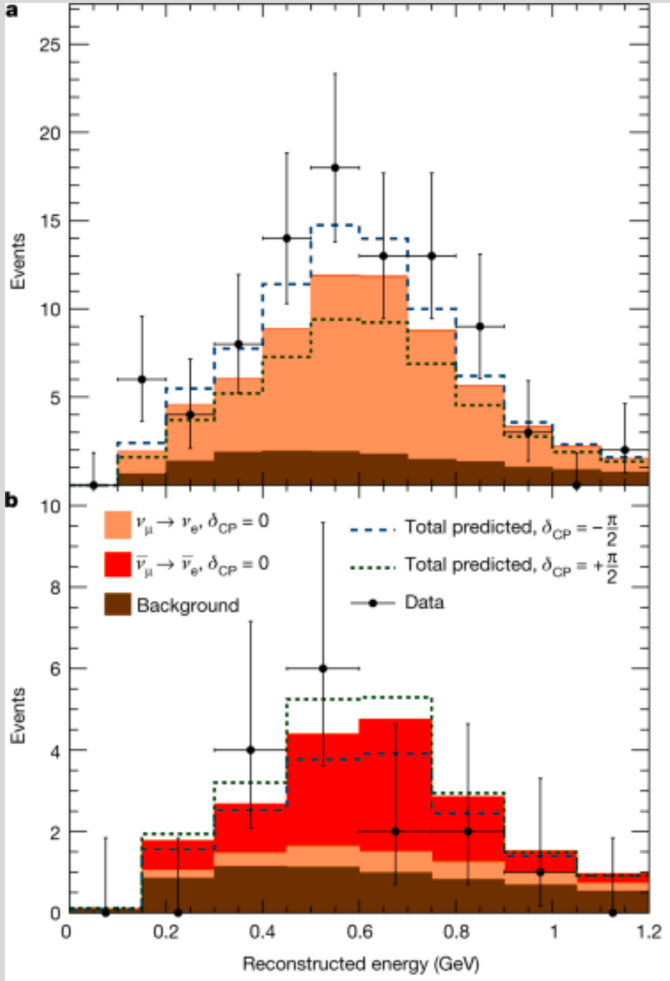
- *Belle II (and LHCb & others) will tackle many open issues in CPV over next decade*
  - *Most sensitive techniques often not even considered at start of experiment*

> *"[CP violation] is telling us that there is a fundamental asymmetry between matter and antimatter, […] We must continue to seek the origin of the CP symmetry violation by all means at our disposal. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in the coming decades. We are hopeful then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered."*
>
> *James Cronin, Nobel lecture, 8 December, 1980*

Back-Up Slides

CPV in Neutrinos

T2K, Nature 580, 339 (2020)



c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

Neutrino mixing matrix (PMNS matrix)

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

CPV phase for normal (inverted) hierarchy

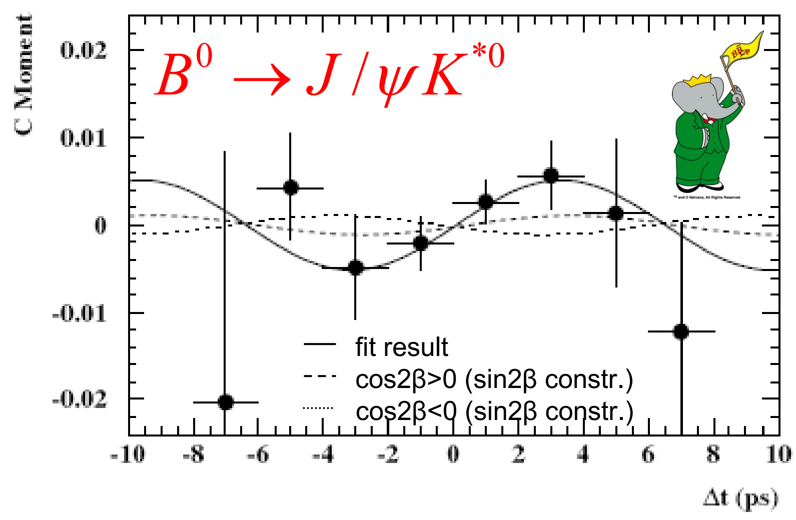
$$\delta_{CP} = -1.89^{+0.70}_{-0.58} \; (-1.38^{+0.48}_{-0.54})$$

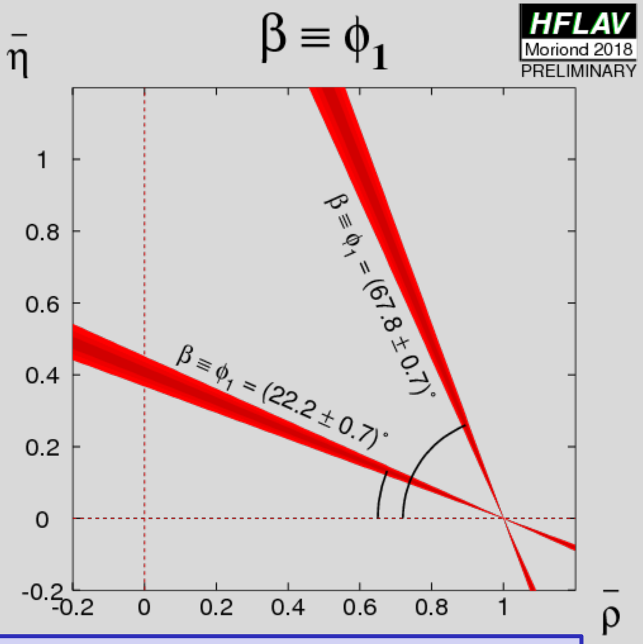
Zero CP violation ruled out at 2σ

Removing the 90° – ϕ_1 ambiguity

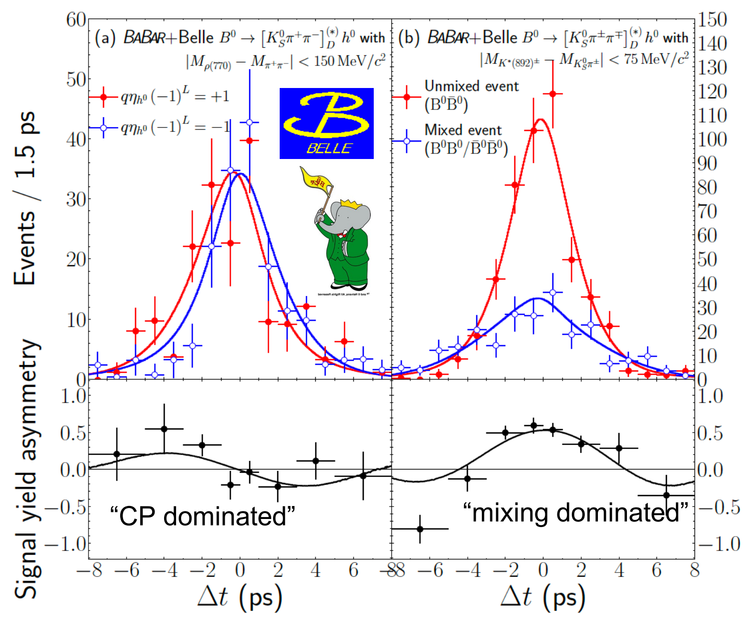
- *Sign of* $\cos 2\phi_1$ *resolves 90° – ϕ_1 ambiguity from* $\sin 2\phi_1$
- *Need second interfering (strong) decay amplitude to measure* $\cos 2\phi_1$
  - *e.g. between CP-odd and CP-even amplitudes in 3-body or VV B decays*
  - *Requires time-dependent angular or Dalitz plot analysis to extract* $\cos 2\phi_1$

PRD 71, 032005 (2005)





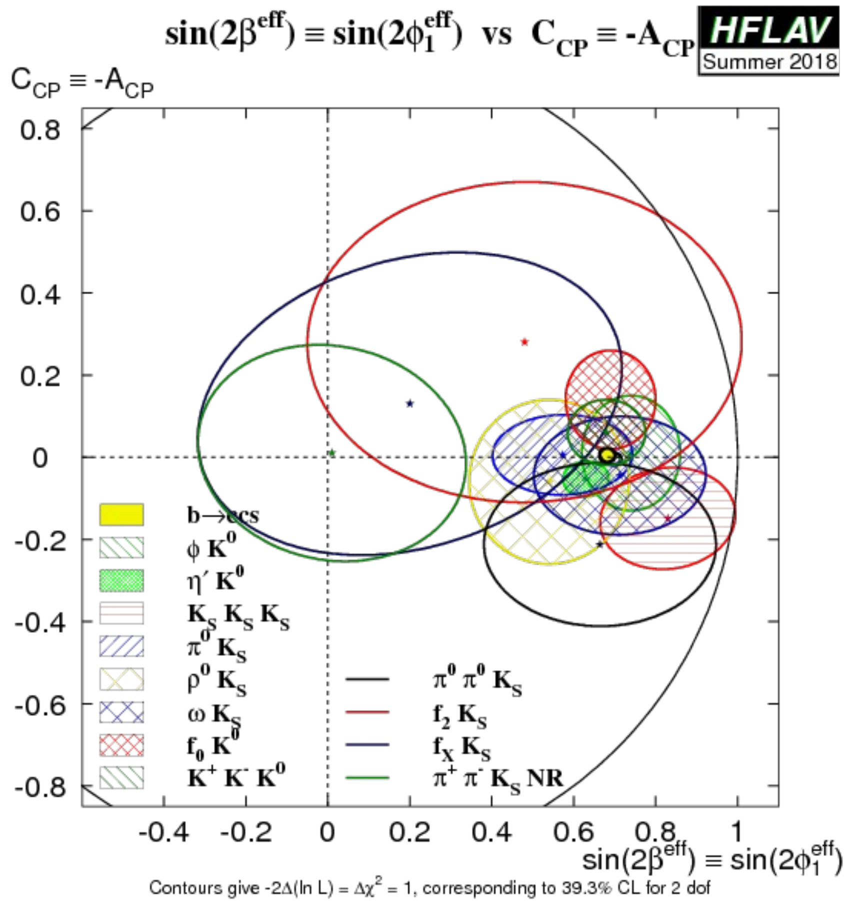
PRL 121, 261801 (2018)



cos2 ϕ_1 < 0 excluded:
ϕ_1 = (22.2 ± 0.7)°

$B^0 \to J/\psi K^{*0}$ [BABAR, PRD 71, 032005 (2005)]: $\cos 2\phi_1 > 0$ @ 89% C.L.
$B^0 \to D^{(*)0}(\to K_S^0\,\pi^+\pi^-)h^0$ [BABAR+Belle, PRL 121, 261801 (2018)]: $\cos 2\phi_1 > 0$ @ 3.7σ
$B^0 \to D^{*+}D^{*-}K_S^0$ [BABAR, PRD 74, 091101 (2006)]: $\cos 2\phi_1 > 0$ @ 94% C.L.
$B^0 \to K^+K^-K_S^0$ [BABAR, PRD 85, 112010 (2012)]: $\cos 2\phi_1 > 0$ @ 4.8σ

CP Asymmetries in Penguin Decays



$$\delta S = -0.05 \pm 0.04$$

GLW measurements for ϕ_3

- *Most sensitive B final states*
  - $D_{CP}K^-$
  - $D^*_{CP}\,K^-$
  - $D_{CP}K^{*-}$
  - $D_{CP}K\pi\pi$

$$R_{CP\pm} \equiv 2\frac{\Gamma\left(B^- \to D^{(*)}_{CP\pm}K^{(*)-}\right)+\Gamma\left(B^+ \to D^{(*)}_{CP\pm}K^{(*)+}\right)}{\Gamma\left(B^- \to D^{(*)}_{flav}K^{(*)-}\right)+\Gamma\left(B^+ \to D^{(*)}_{flav}K^{(*)+}\right)}$$

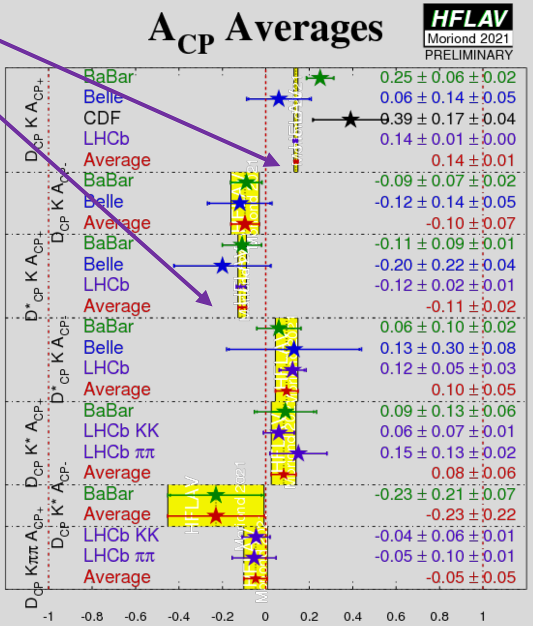
$$= 1 + r_B^2 \pm 2r_B\cos\delta_B \cos\phi_3$$

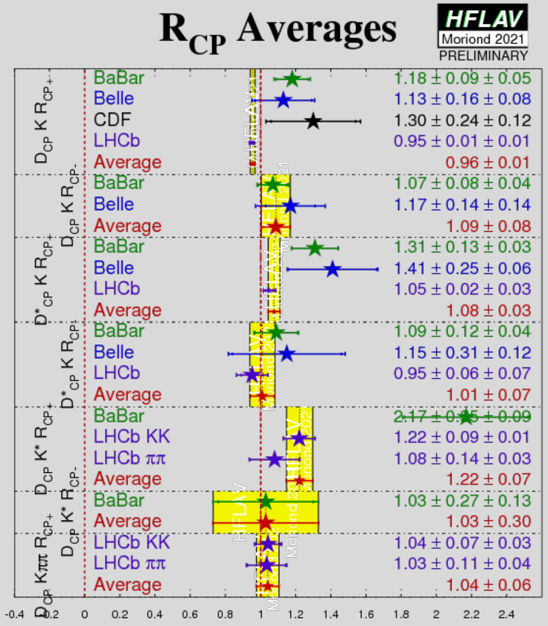
$$A_{CP\pm} \equiv \frac{\Gamma\left(B^- \to D^{(*)}_{CP\pm}K^{(*)-}\right)-\Gamma\left(B^+ \to D^{(*)}_{CP\pm}K^{(*)+}\right)}{\Gamma\left(B^- \to D^{(*)}_{CP\pm}K^{(*)-}\right)+\Gamma\left(B^+ \to D^{(*)}_{CP\pm}K^{(*)+}\right)}$$

$$= \pm 2r_B\sin\delta_B \sin\phi_3 \;/\; R_{CP\pm}$$

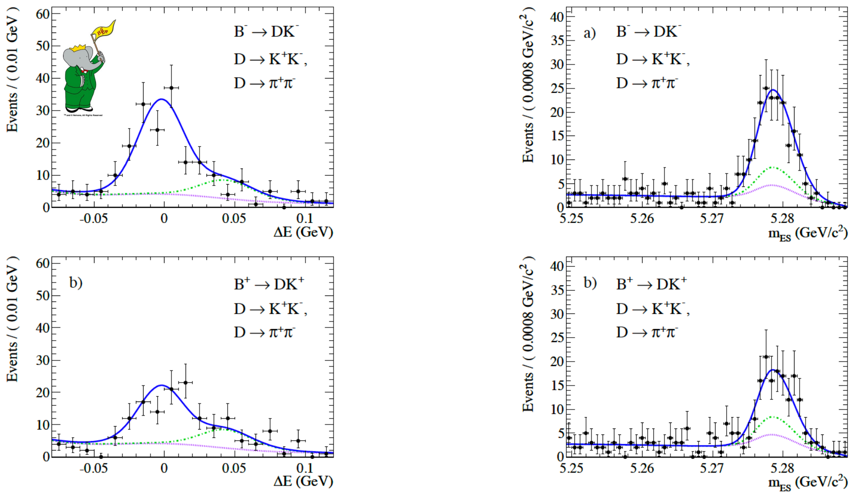
r_B and δ_B depend on B decay mode

CPV in $B \to D^{(*)}_{CP}K$ is significant !

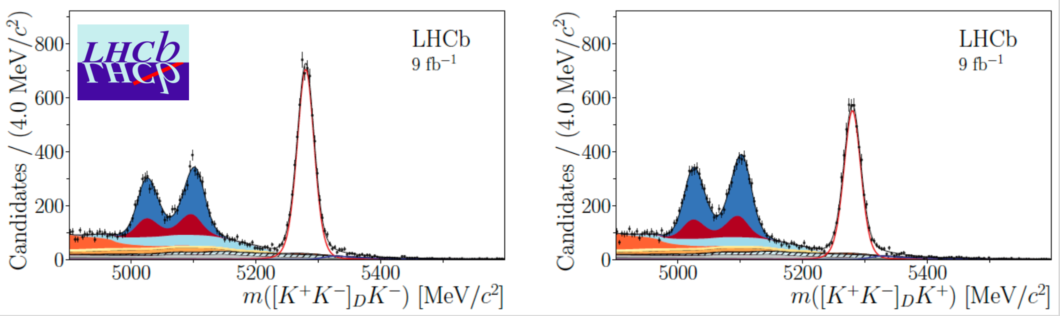




PRD 82 (2010) 072004



JHEP 2104 (2021) 081



ADS measurements for ϕ_3

- *Most sensitive B final states*
  - $(K\pi)_D K$
  - $(K\pi\pi^0)_D K$
  - $(K3\pi)_D K$
  - $(K\pi)_{D^*} K$
  - $(K\pi)_{D^*} K^*$

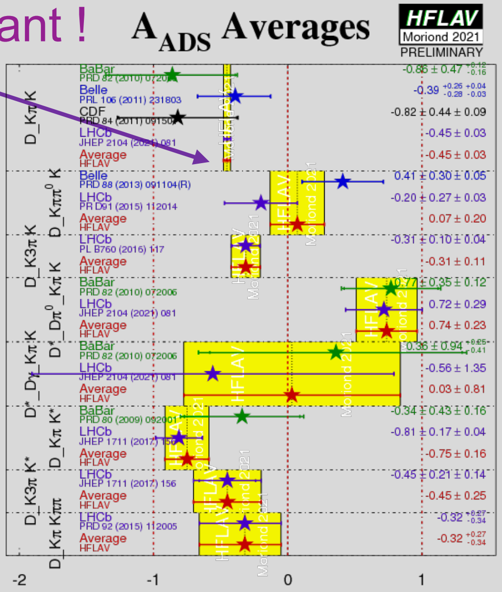
$$R_{ADS} \equiv \frac{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^-\pi^+]K^-) + \Gamma(B^+ \to [K^+\pi^-]K^+)}$$
$$= r_B^2 + r_D^2 \pm 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3$$

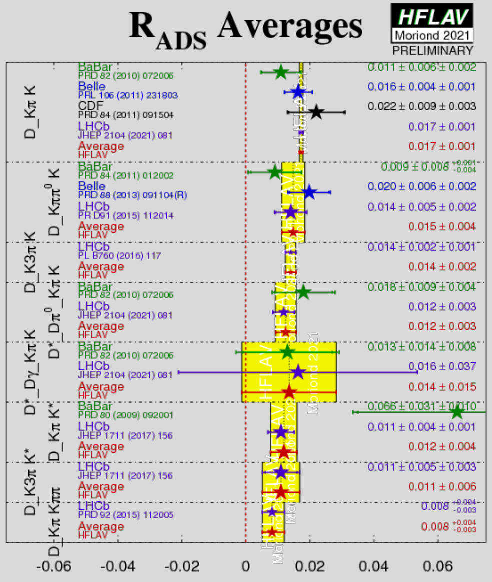
$$A_{ADS} \equiv \frac{\Gamma(B^- \to [K^+\pi^-]K^-) - \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)}$$
$$= 2 r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3 \,/\, R_{ADS}$$

Two more variables from D decay:

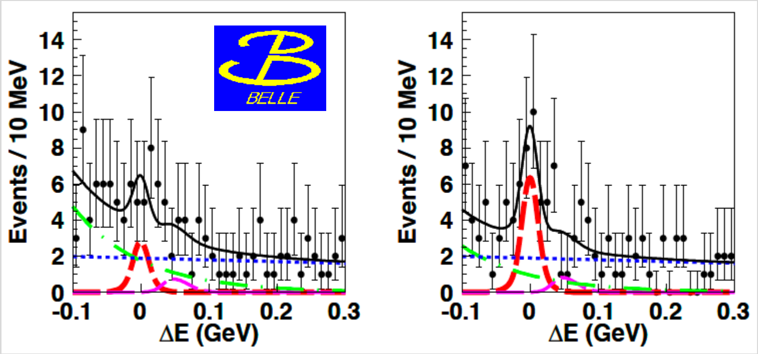
r_D and δ_D depend on D mode, can be measured at CLEO-c or BESIII

CPV in $B \to D^{(*)}_{flav} K$ is significant !

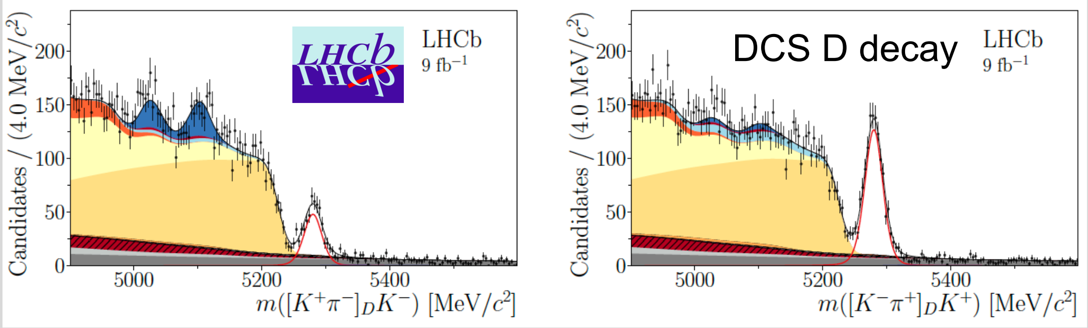




PRL 106 (2011) 231803



JHEP 2104 (2021) 081

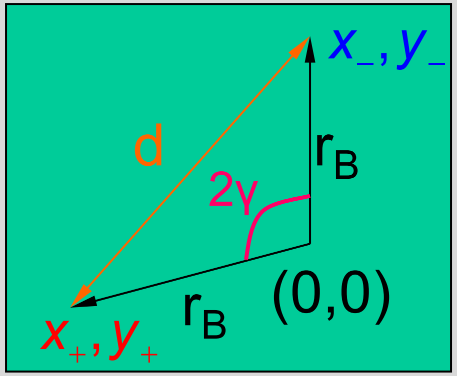


Sensitivity to ϕ_3

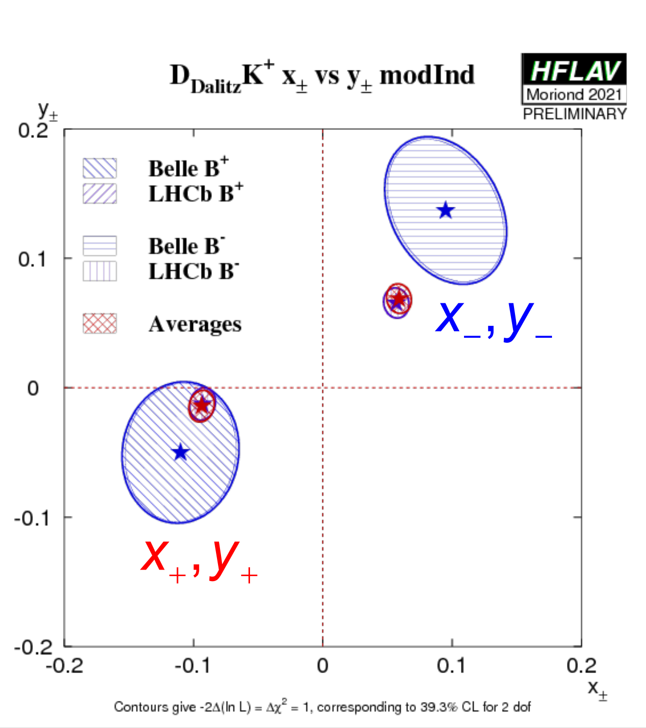
Extract ϕ_3 from fit to $D \to K_S^0\pi^+\pi^-$ and $D \to K_S^0 K^+ K^-$ Dalitz-plot distributions with variables *x* and *y*

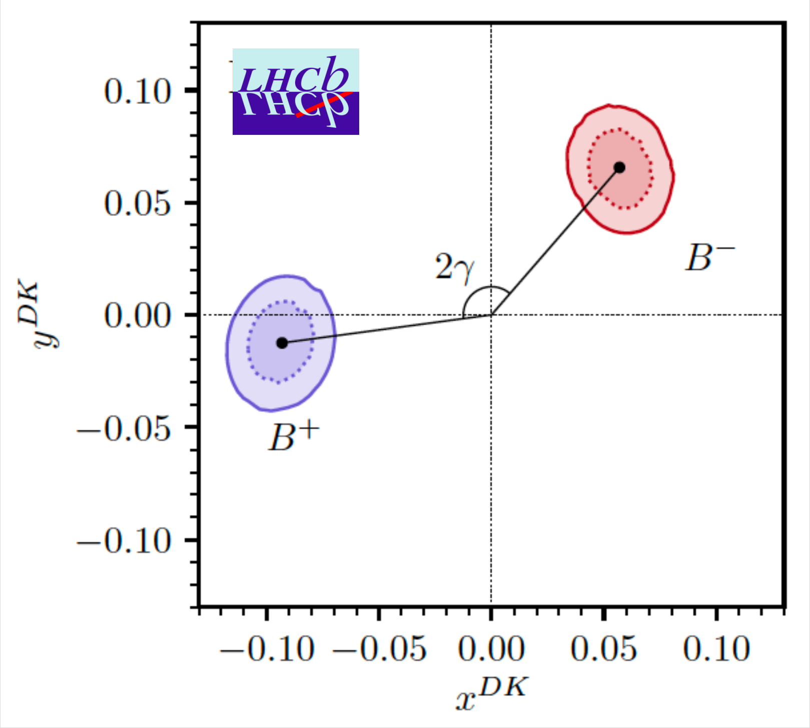
$$x_\pm \equiv r_B \cos(\delta_{st} \pm \gamma), \quad y_\pm \equiv r_B \sin(\delta_{st} \pm \gamma)$$

JHEP 2021, 169 (2021)



Direct CP violation, if $d = 2r_B\,|\sin\gamma| \neq 0$





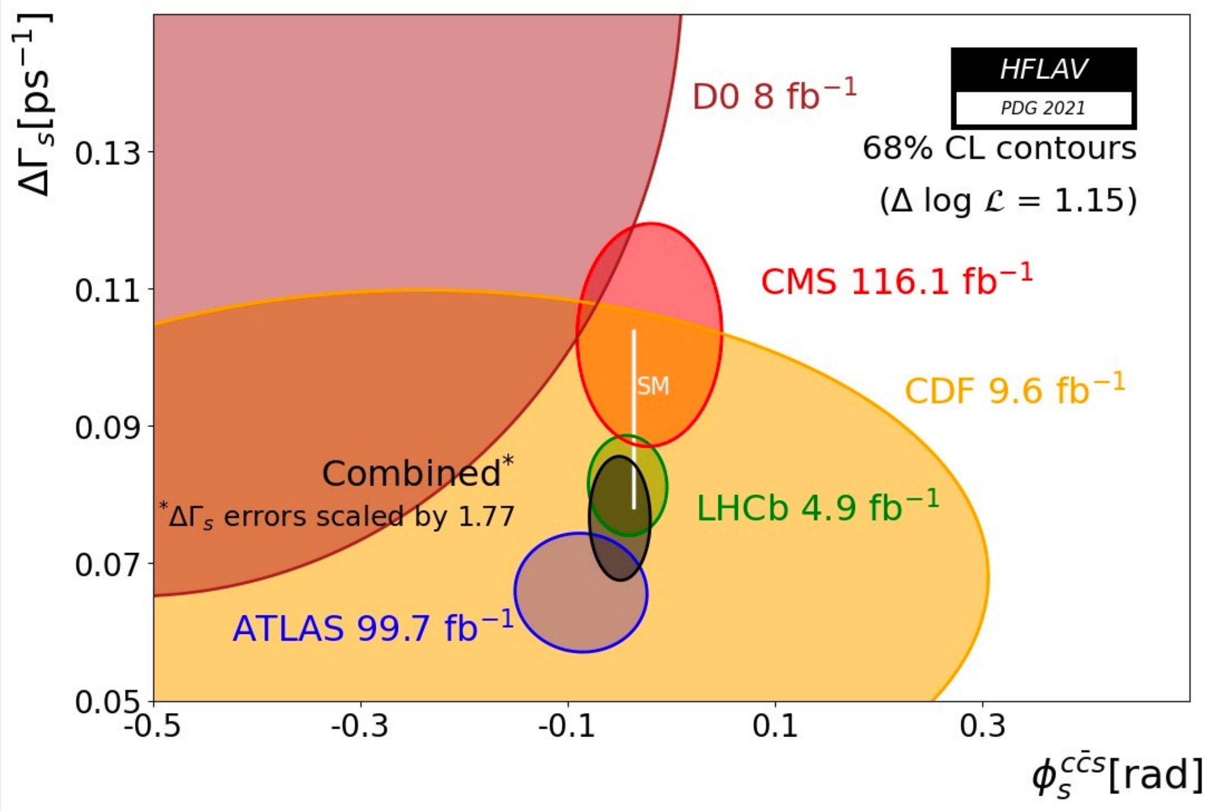
CPV in B_s Decays

CKM matrix up to O(λ^4)

$$V_{CKM,\mathrm{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

β_s is equivalent of ϕ_1 in time-dependent B_s CPV

$$\phi_s^{c\bar{c}s} \approx -2\beta_s$$



World average:
$\phi_s^{c\bar{c}s} = -0.050 \pm 0.019$

SM prediction:
$\phi_s^{c\bar{c}s} = -0.0370^{+0.0007}_{-0.0008}$

$B^{\pm} \to \pi^{\pm}\pi^{0}$ and $B \to \pi^{0}\pi^{0}$ CPV and BFs

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$

VALUE (units 10^{-6})	*CL%*	
1.59±0.26 OUR AVERAGE		(error scaled by 1.4)
1.31±0.19±0.19		Belle, PRD 96, 032007 (2017)
1.83±0.21±0.13		BaBar, PRD 87, 052009 (2013)

$C_{\pi^0\pi^0}(B^0 \to \pi^0\pi^0)$

VALUE	
−0.33±0.22 OUR AVERAGE	
−0.14±0.36±0.10	Belle, PRD 96, 032007 (2017)
−0.43±0.26±0.05	BaBar, PRD 87, 052009 (2013)

$\Gamma(\pi^+\pi^0)/\Gamma_{total}$

VALUE (units 10^{-6})	*CL%*	
5.5 ±0.4 OUR AVERAGE		(error scaled by 1.2)
5.86±0.26±0.38		Belle, PRD 87, 031103 (2013)
5.02±0.46±0.29		BaBar, PRD 76, 091102 (2007)
$4.6\ ^{+1.8}_{-1.6}\ ^{+0.6}_{-0.7}$		CLEO, PRD 68, 052002 (2003)

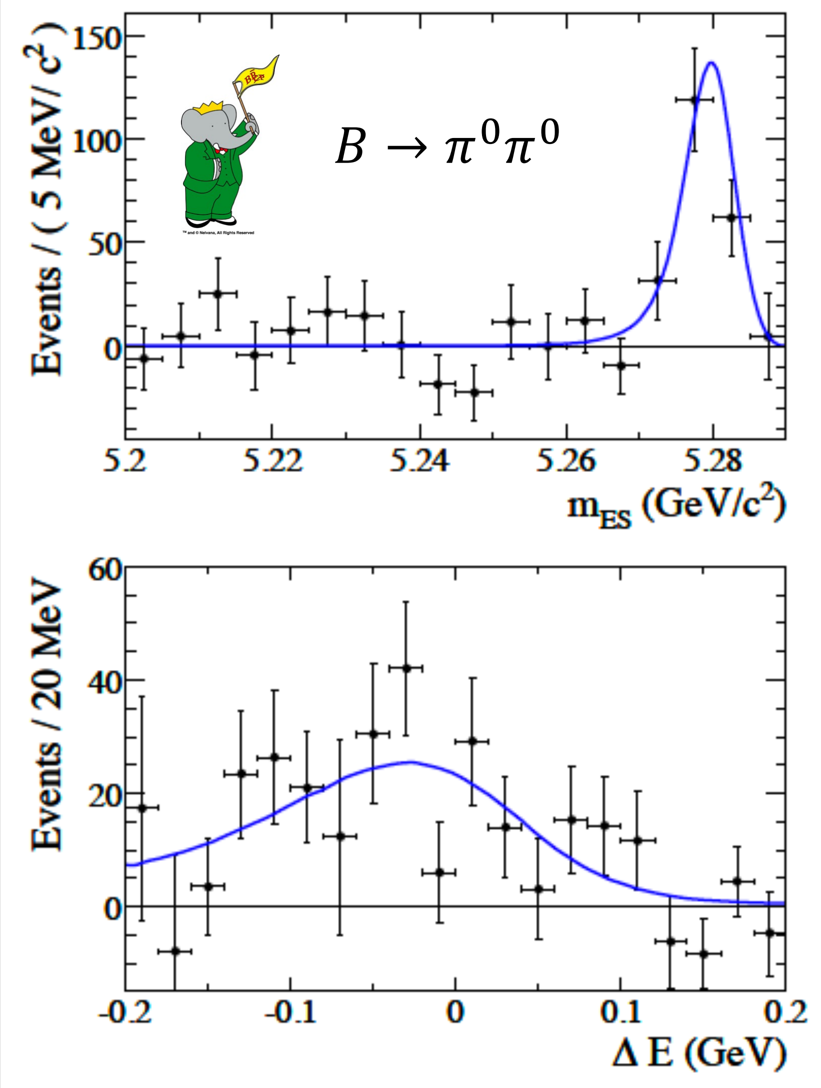
$5.48^{+0.35}_{-0.34}$ HFLAV average (no scale factor)

$A_{CP}(B^+ \to \pi^+\pi^0)$

VALUE	
0.03 ±0.04 OUR AVERAGE	
0.025±0.043±0.007	Belle, PRD 87, 031103 (2013)
0.03 ±0.08 ±0.01	BaBar, PRD 76, 091102 (2007)

0.026 ± 0.039 HFLAV average

PRD 87, 052009 (2013)



ϕ_2 from $B \longrightarrow \rho\rho$ with Belle II

- *Most measurements will still be statistically limited with 50/ab*
  - *Expected error*

    $\Delta\phi_2 \sim 1^\circ$ *without* $S_{\rho^0\rho^0}$ *constraint, and*

    $\Delta\phi_2 \sim 0.6^\circ$ *with* $S_{\rho^0\rho^0}$ *constraint*

- *The* $B^0 \rightarrow (\pi\rho)^0$ *Dalitz analysis*
  - *Done by both Belle and BaBar, but limited by spurious ambiguities due to small data samples*
  - *Analysis should be repeated with a few* ab^{-1} *, which will allow to estimate sensitivity with 50* ab^{-1}

	Value	0.8 ab^{-1}	50 ab^{-1}
$f_{L,\rho^+\rho^-}$	0.988	$\pm 0.012 \pm 0.023$ [725]	$\pm 0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm 0.20 \pm 0.15$ [729]	$\pm 0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm 1.5 \pm 1.5$ [725]	$\pm 0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ [10^{-6}]	1.02	$\pm 0.30 \pm 0.15$ [729]	$\pm 0.04 \pm 0.02$
$A_{\rho^+\rho^-}$	0.00	$\pm 0.10 \pm 0.06$ [725]	$\pm 0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm 0.15 \pm 0.05$ [725]	$\pm 0.02 \pm 0.01$
	Value	0.08 ab^{-1}	50 ab^{-1}
$f_{L,\rho^+\rho^0}$	0.95	$\pm 0.11 \pm 0.02$ [716]	$\pm 0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm 7.1 \pm 5.3$ [716]	$\pm 0.3 \pm 0.5$
	Value	0.5 ab^{-1}	50 ab^{-1}
$A_{\rho^0\rho^0}$	-0.2	$\pm 0.8 \pm 0.3$ [715]	$\pm 0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm 0.7 \pm 0.2$ [715]	$\pm 0.07 \pm 0.01$