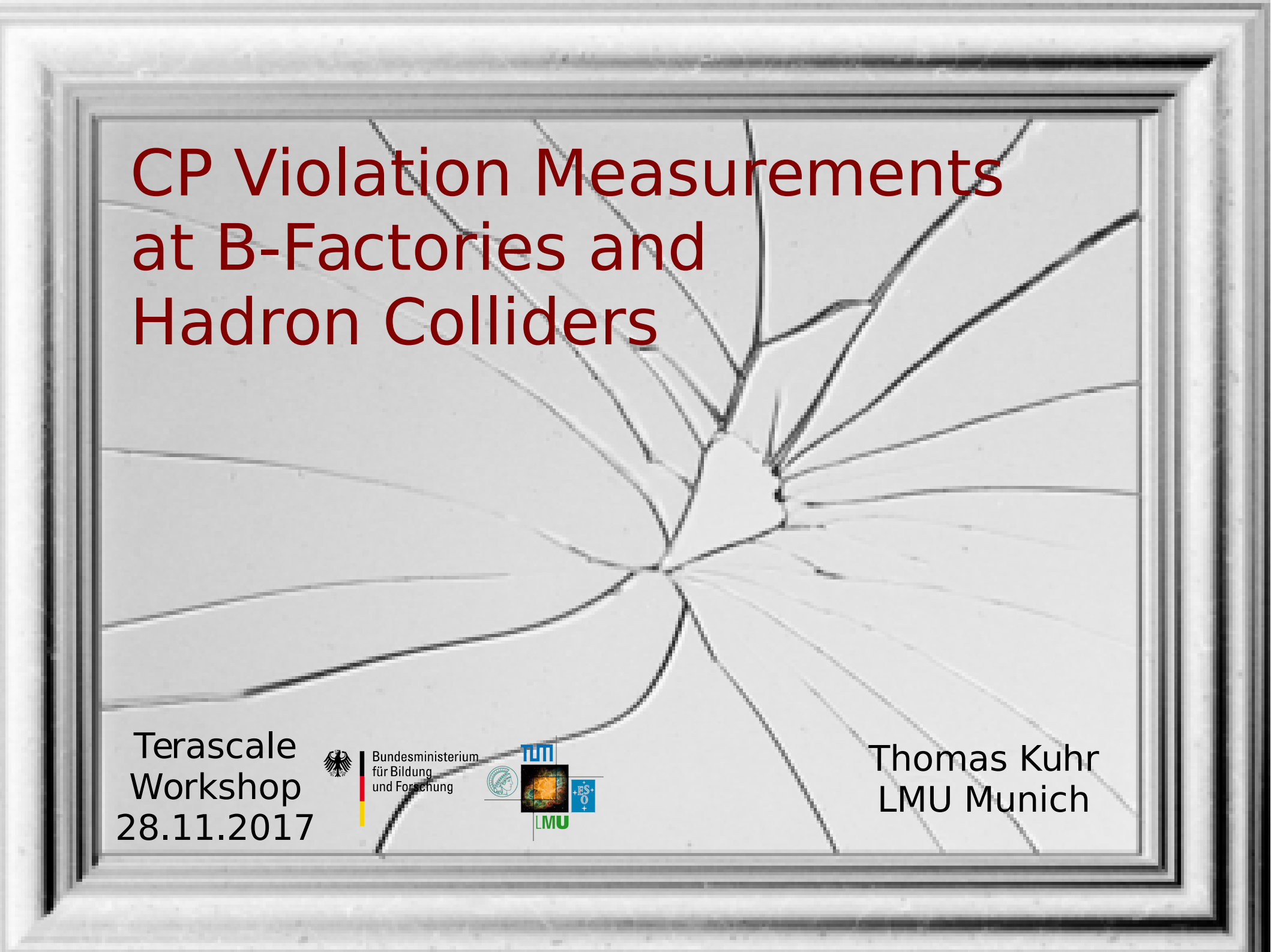
CP Violation Measurements at B-Factories and Hadron Colliders



Terascale Workshop
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Bundesministerium für Bildung und Forschung

Thomas Kuhr
LMU Munich

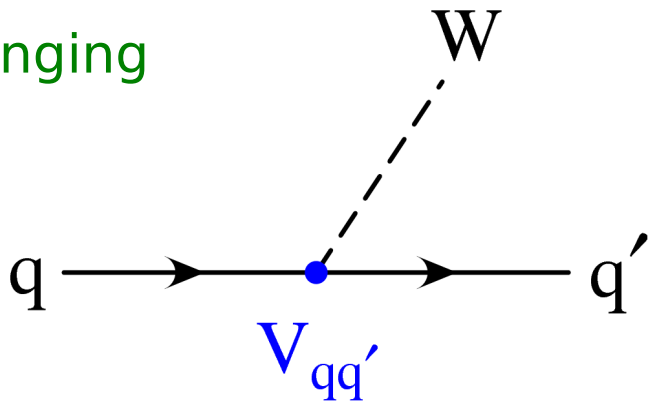
CP Violation

Condition for matter anti-matter asymmetry in the universe

- CP Violation:
  rate(process) ≠
  rate(process after parity and charge conjugation transformation)

→ So far only observed in quark flavor changing charged weak interaction processes

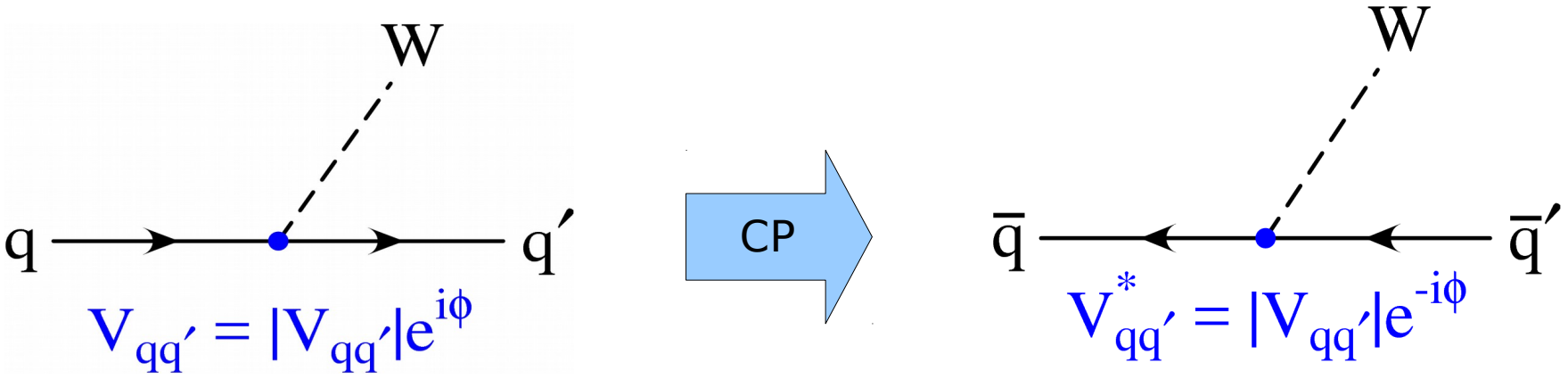
- W boson coupling strength to quark pairs given by CKM matrix:
  4 free parameters,
  e.g. three angles and one phase δ



$$V_{CKM} = \begin{pmatrix} \cos\theta_{12}\cos\theta_{13} & \sin\theta_{12}\cos\theta_{13} & \sin\theta_{13}e^{-i\delta} \\ -\sin\theta_{12}\cos\theta_{23} - \cos\theta_{12}\sin\theta_{23}\sin\theta_{13}e^{i\delta} & \cos\theta_{12}\cos\theta_{23} - \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}e^{i\delta} & \sin\theta_{23}\cos\theta_{13} \\ \sin\theta_{12}\sin\theta_{23} - \cos\theta_{12}\cos\theta_{23}\sin\theta_{13}e^{i\delta} & -\cos\theta_{12}\sin\theta_{23} - \sin\theta_{12}\cos\theta_{23}\sin\theta_{13}e^{i\delta} & \cos\theta_{23}\cos\theta_{13} \end{pmatrix}$$

→ CP inverts phase: $V_{qq'} \rightarrow V_{qq'}^{*}$

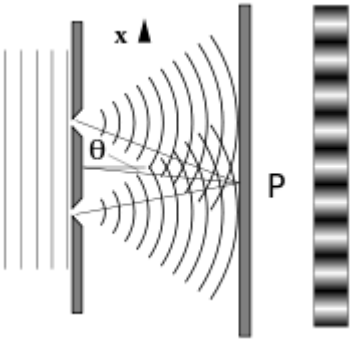
CP Violation → Interference



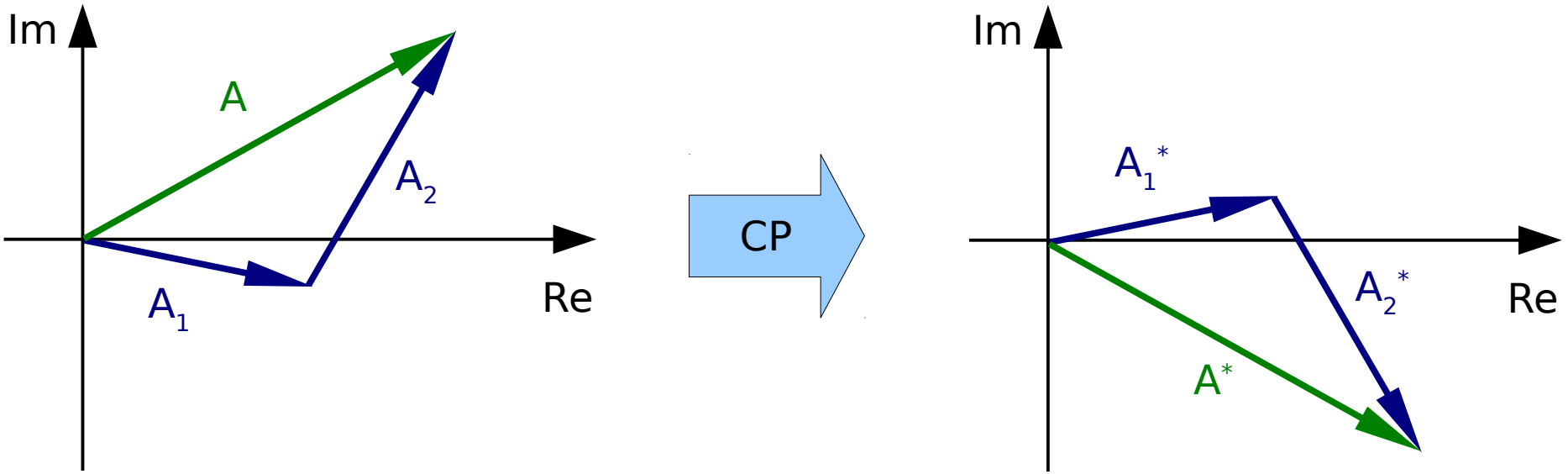
$|A|^2$ = $|A^*|^2$

- No CP violation

- Interference of two amplitudes required for CP violation
- Relative phase ↔ interference pattern
- Potentially sensitive to new physics:
  $|A_{SM} + A_{NP}|^2 = |A_{SM}|^2 + 2\mathrm{Re}(A_{SM}{}^* A_{NP}) + |A_{NP}|^2$

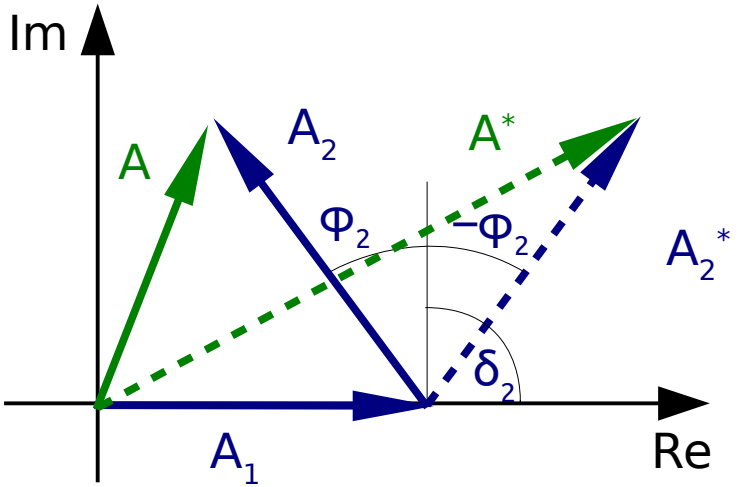


Interference of Two Amplitudes



- $|A|^2 = |A^*|^2 \rightarrow$ No CP violation

- CP violation requires interference of two amplitudes with different
  - CP violating (weak) phases Φ and
  - CP conserving (strong) phases δ

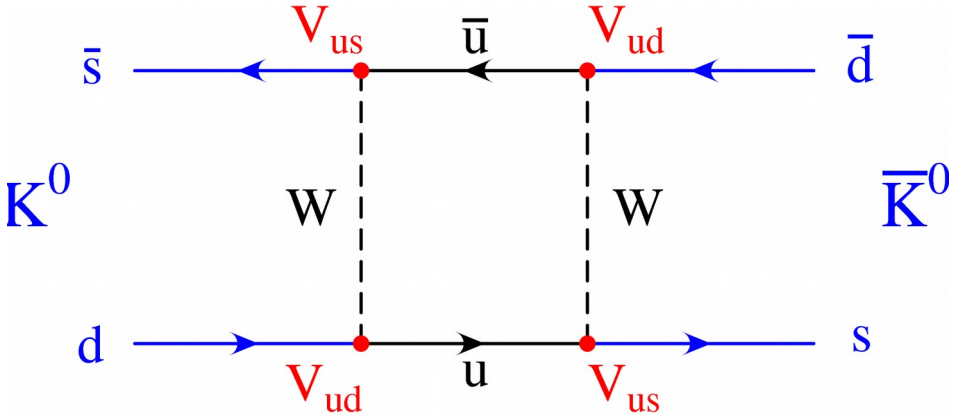


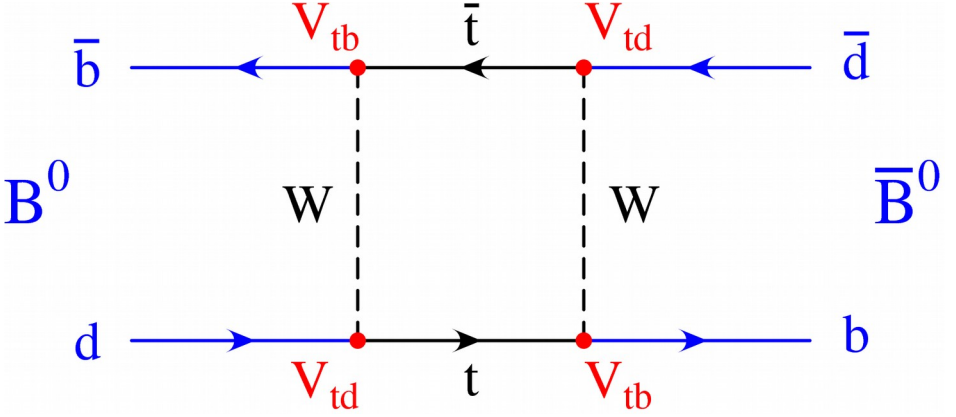
Types of CP Violation

- Direct CP violation: change of flavor quantum number by ±1
- CP violation in decay

$$A_{CP} = \frac{\Gamma(\bar{X} \to \bar{f}) - \Gamma(X \to f)}{\Gamma(\bar{X} \to \bar{f}) + \Gamma(X \to f)} = \frac{2|A_1||A_2| \sin\Delta\phi \sin\Delta\delta}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos\Delta\phi \cos\Delta\delta}$$

- Indirect CP violation: change of flavor quantum number by ±2
- Neutral weakly decaying mesons (K^0, D^0, B^0, B_s^0)





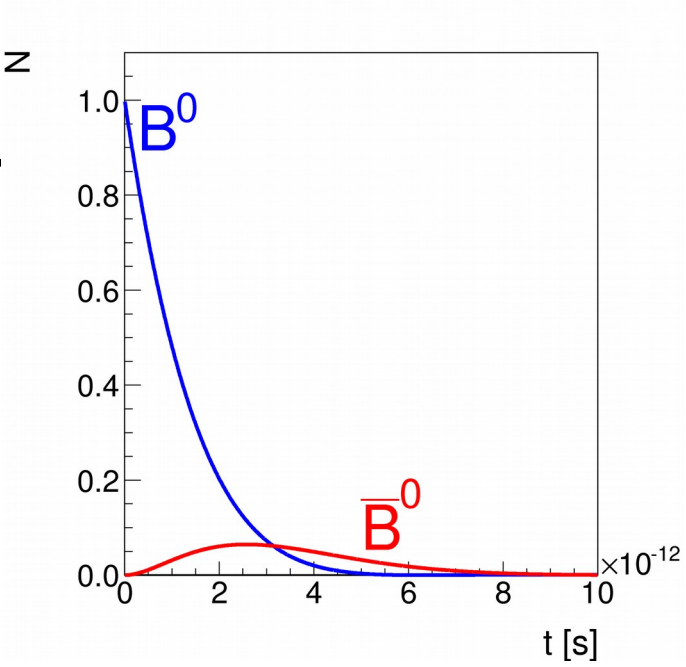
CP Violation in Mixing

- Oscillation of flavor eigenstates
  → mass/lifetime eigenstates

$$\left|B_L^0\right\rangle = p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle, \quad |p|^2 + |q|^2 = 1$$
$$\left|B_H^0\right\rangle = p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle$$

- Oscillation frequency: $\Delta m = m_H - m_L$

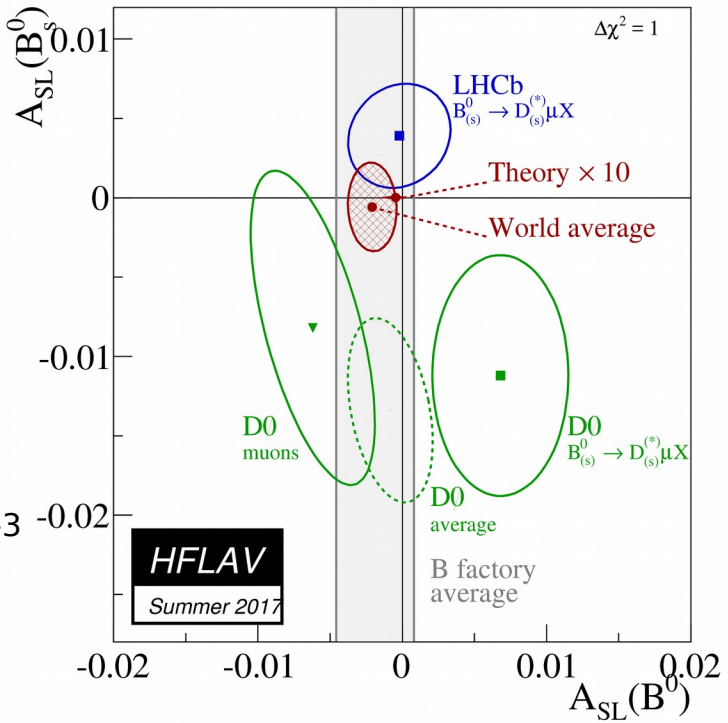
$$A_{mix}(t) = \frac{\Gamma(B^0 \to B^0) - \Gamma(B^0 \to \bar{B}^0)}{\Gamma(B^0 \to B^0) + \Gamma(B^0 \to \bar{B}^0)} = \cos(\Delta m t)$$



- CP violation in mixing
- Condition: $|q/p| \neq 1$

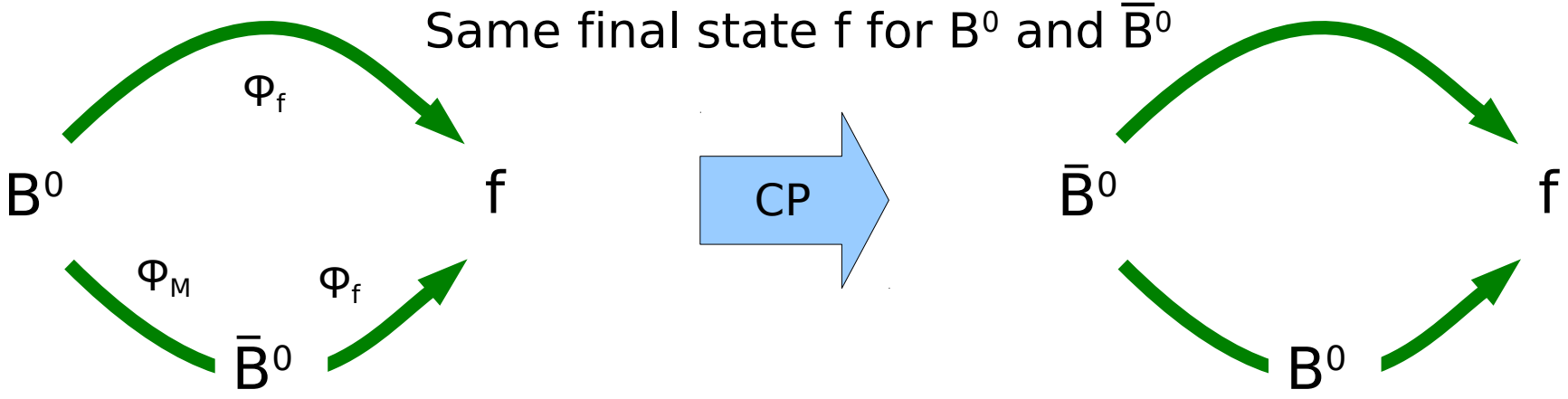
$$a_{SL} = \frac{\Gamma(\bar{B}^0 \to B^0) - \Gamma(B^0 \to \bar{B}^0)}{\Gamma(\bar{B}^0 \to B^0) + \Gamma(B^0 \to \bar{B}^0)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

- Observed for kaons: $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$



Mixing Induced CP Violation

- CP violation in interference of mixing and decay



- Condition: Im(λ_f) ≠ 1 $\quad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$

$$A_f(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} = C\cos(\Delta m t) + S\sin(\Delta m t)$$

$$C = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S = \frac{2\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2}$$

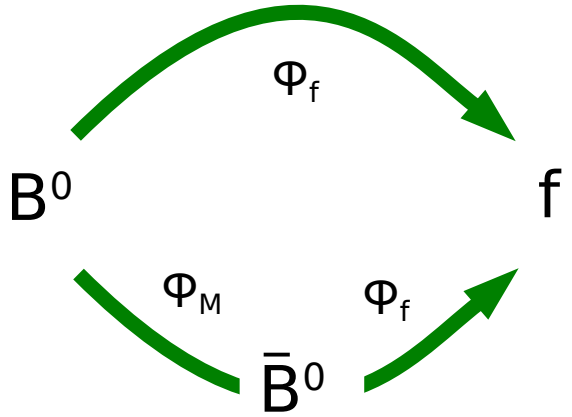
- For CP(f) = η_f f and no CP violation in mixing and decay:

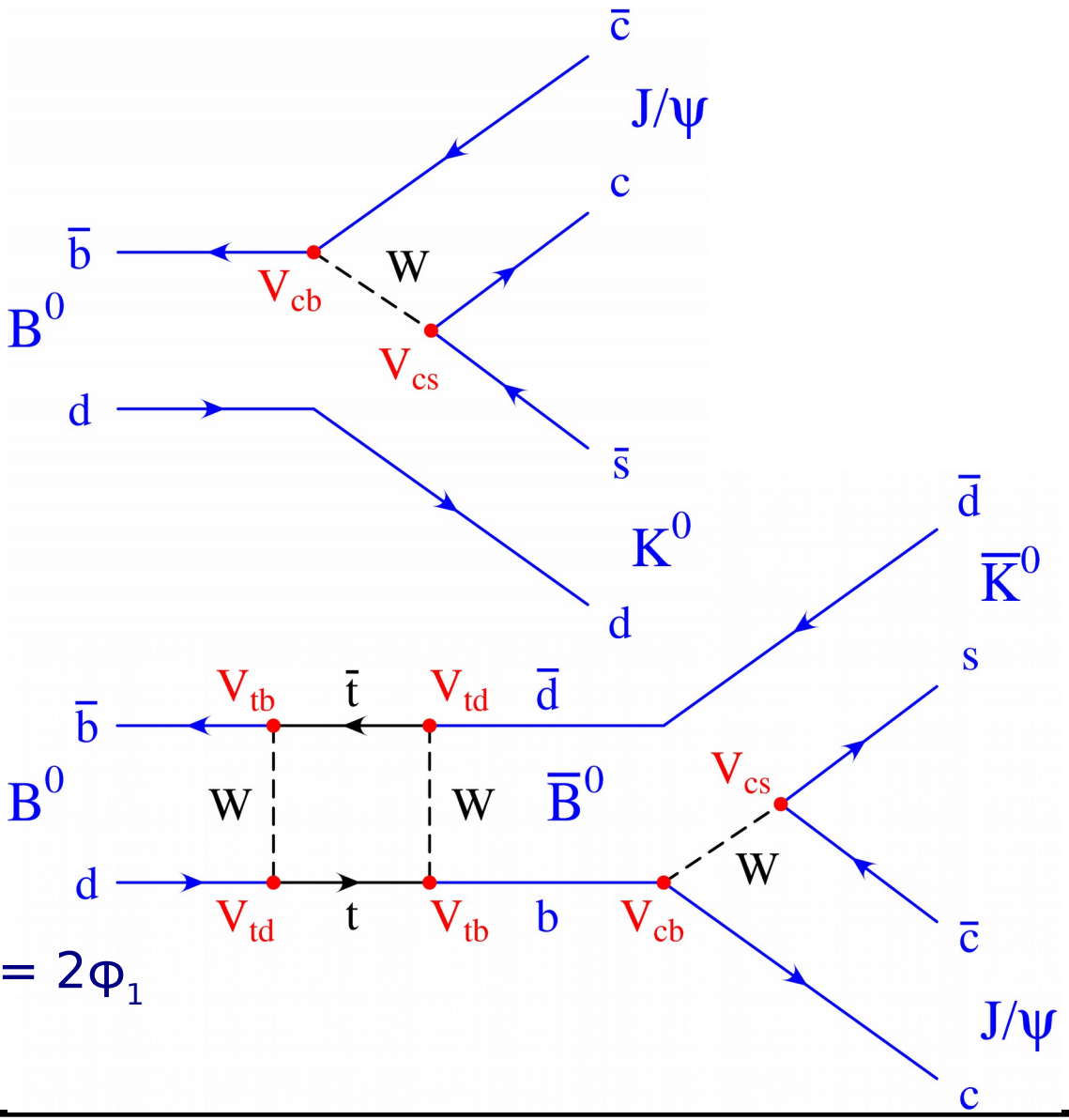
$$S_{\mathrm{CP}} = -\eta_{\mathrm{CP}}\sin(\phi_M - 2\phi_f)$$

Golden Mode ($b \to c\bar{c}s$)

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

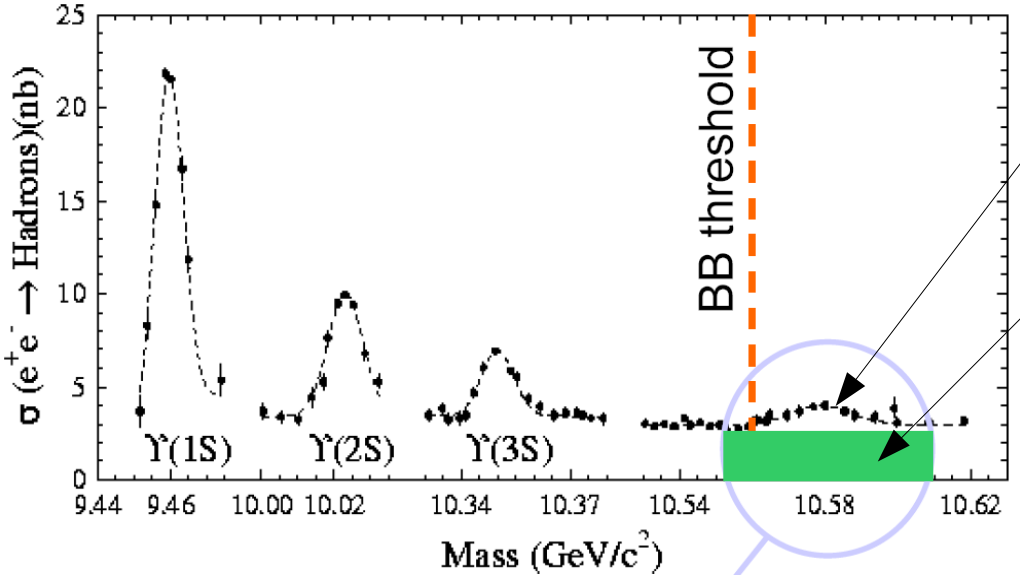
- $B^0 \to J/\psi\, K^0_S$
  $J/\psi \to \ell^+\ell^-$
  $K^0_S \to \pi^+\pi^-$



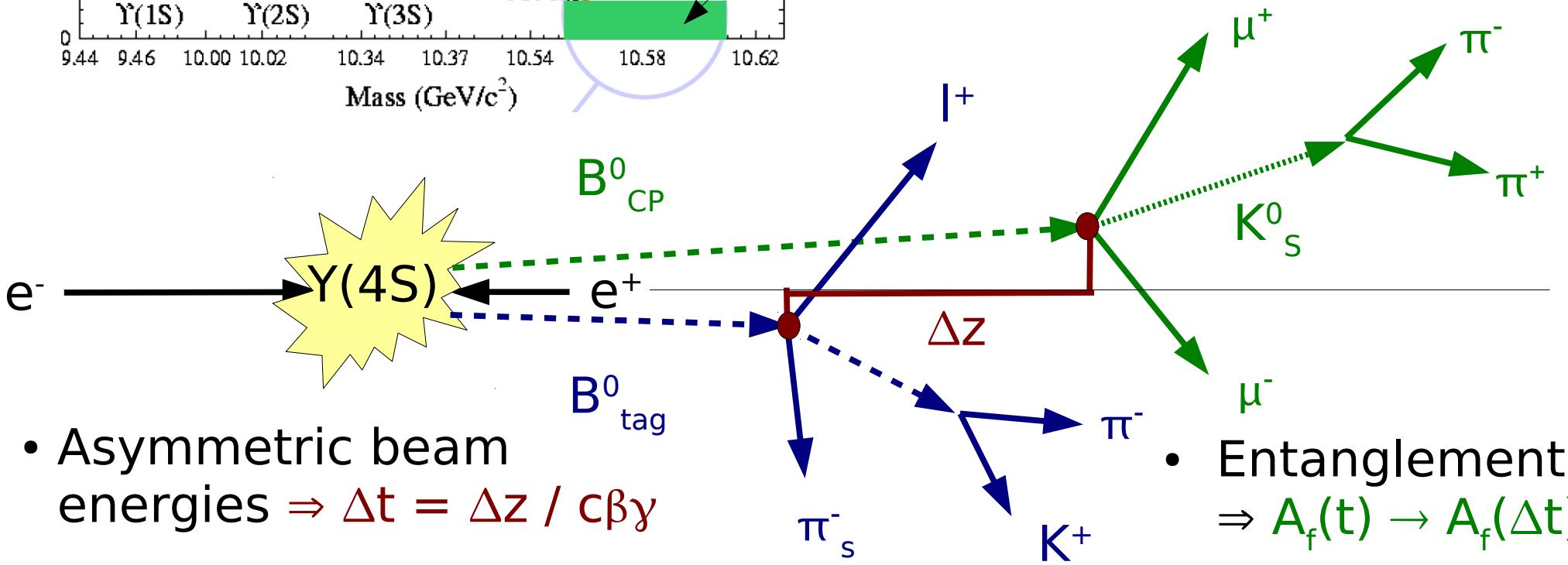


- $\Phi_f \approx 0$
  $\Phi_M \approx 2\arg(V_{td}^* V_{tb}) \approx 2\beta = 2\Phi_1$
- → $S = \sin(2\beta) = \sin(2\Phi_1)$

CP Measurement at B Factories



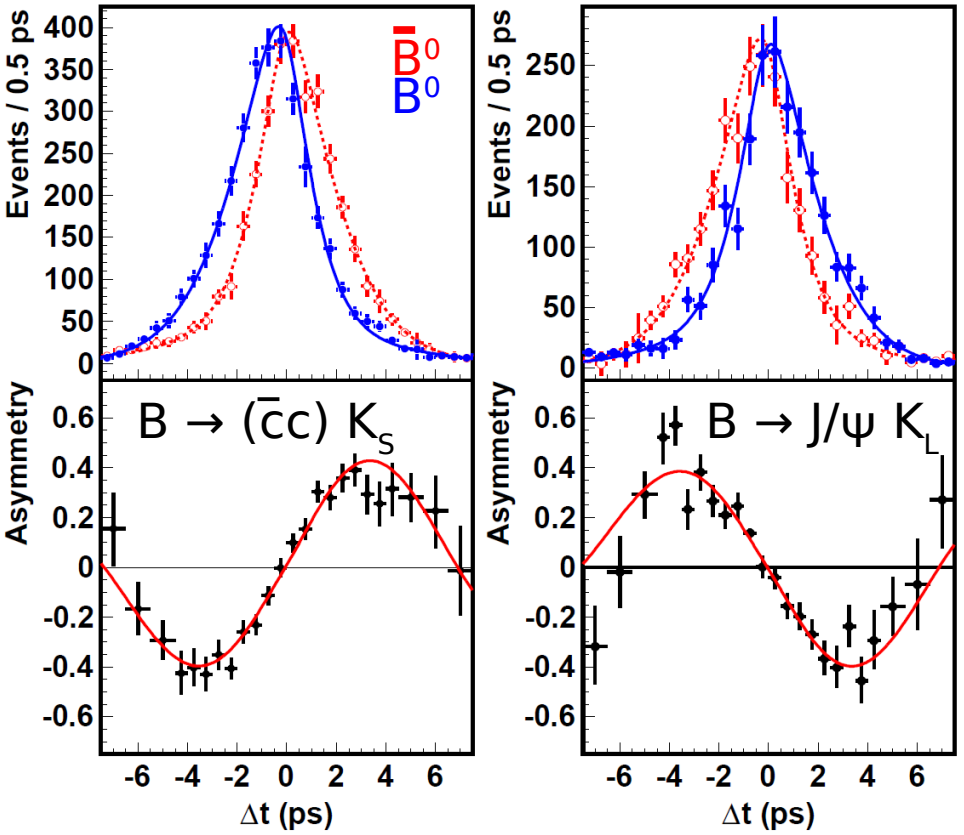
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$ (50%)
  $\rightarrow B^+B^-$ (50%)
- Continuum background

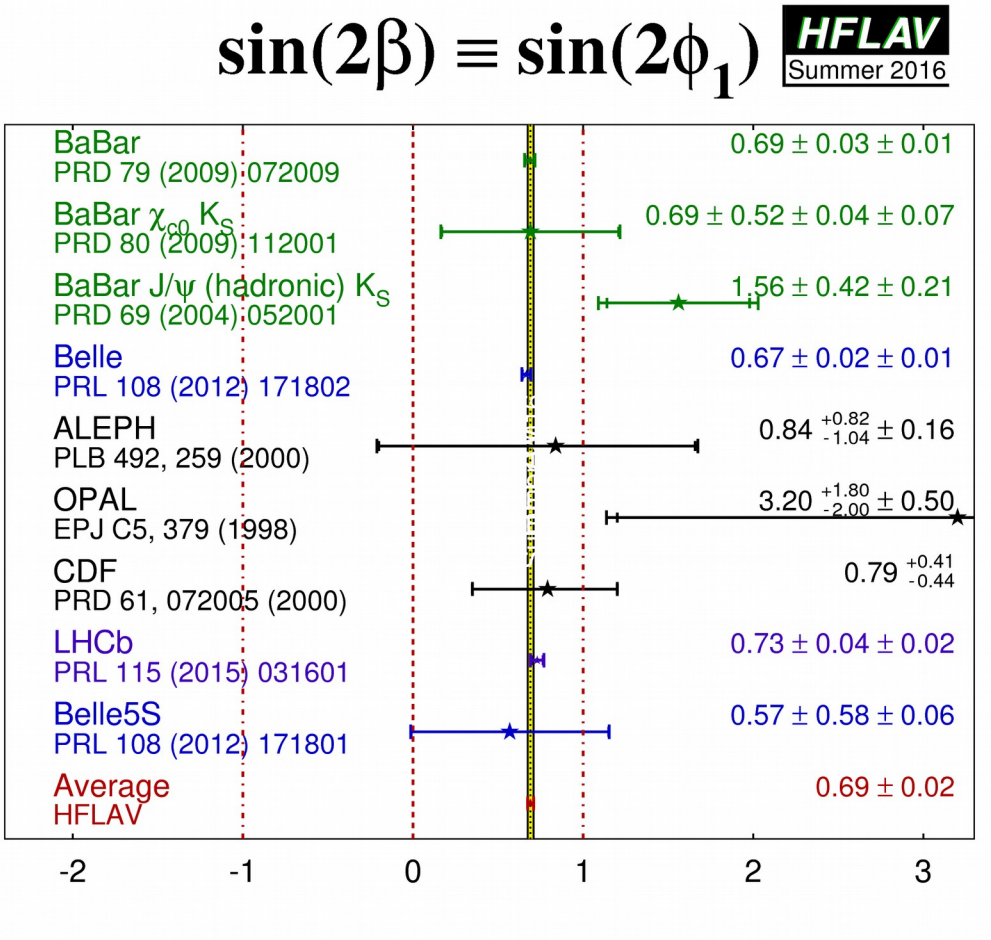


- Asymmetric beam energies $\Rightarrow \Delta t = \Delta z / c\beta\gamma$
- Entanglement $\Rightarrow A_f(t) \rightarrow A_f(\Delta t)$

$\sin(2\beta) = \sin(2\phi_1)$

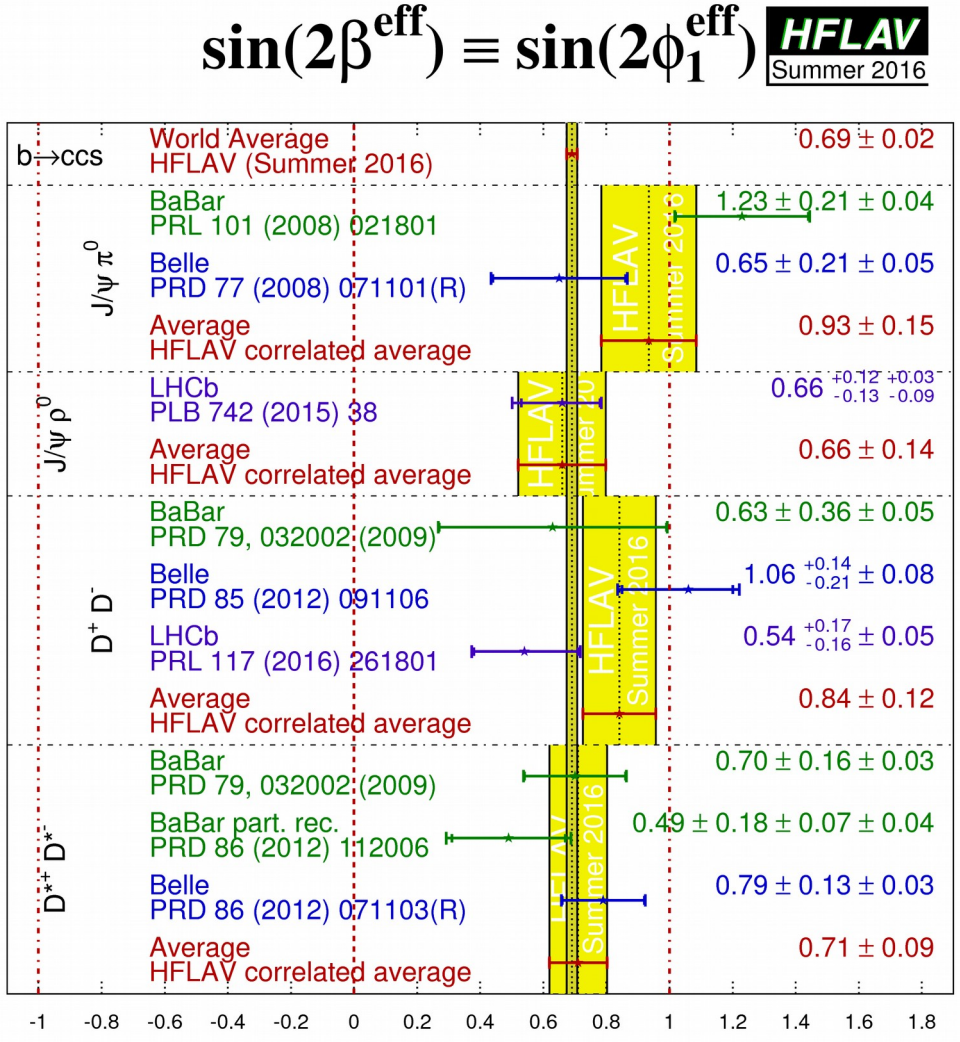
PRL 108,171802 (2012) 772 x 10^6 BB

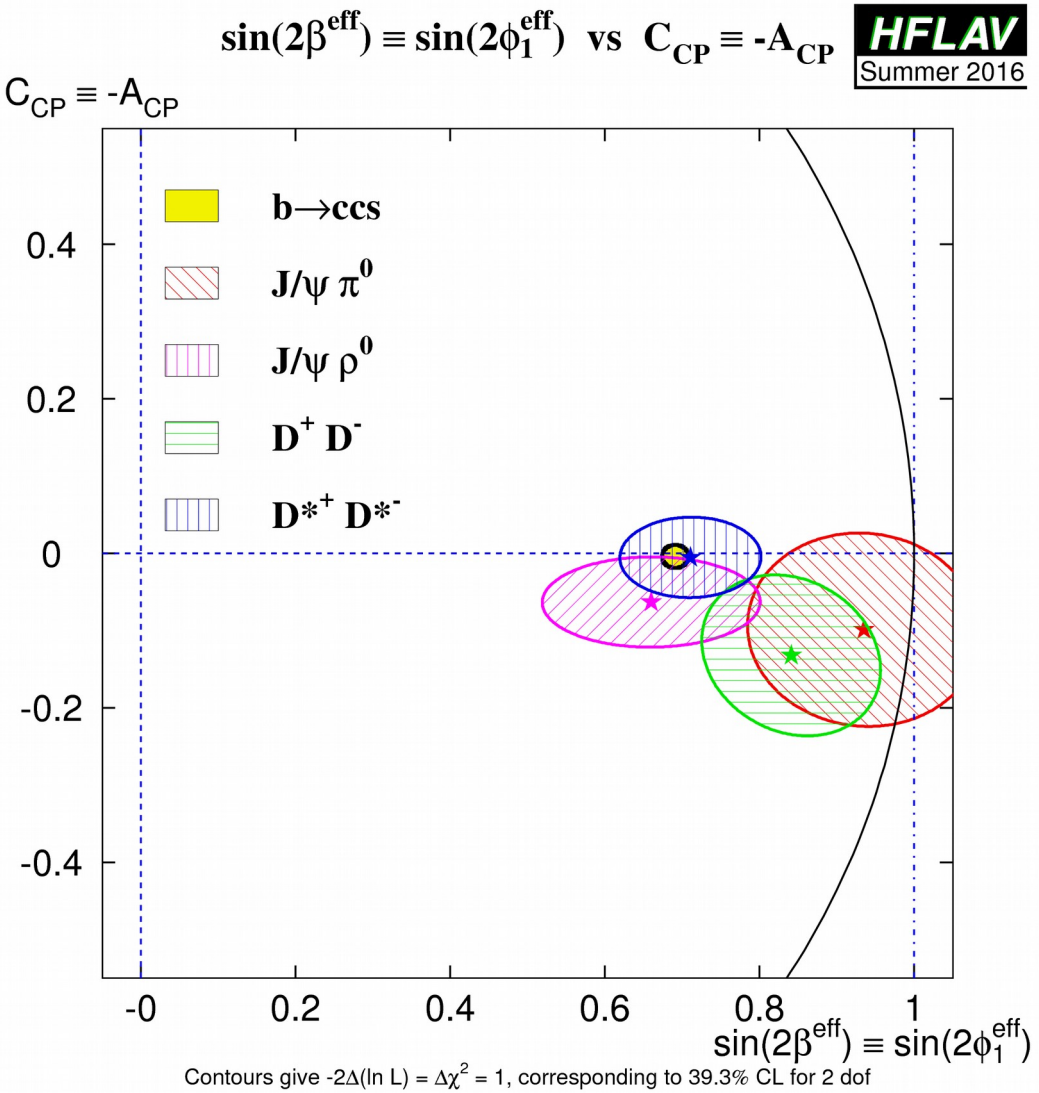




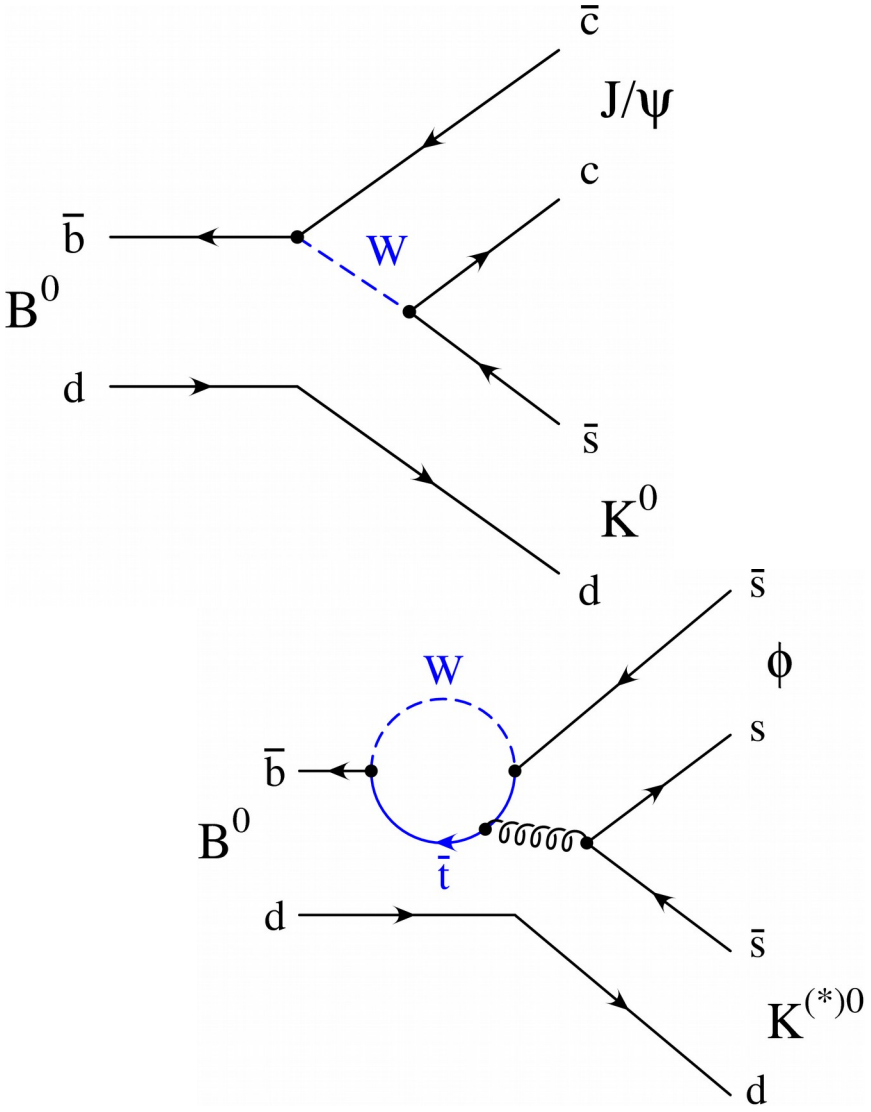
- LHCb (arXiv:1709.03944): S = (0.760 ± 0.034)

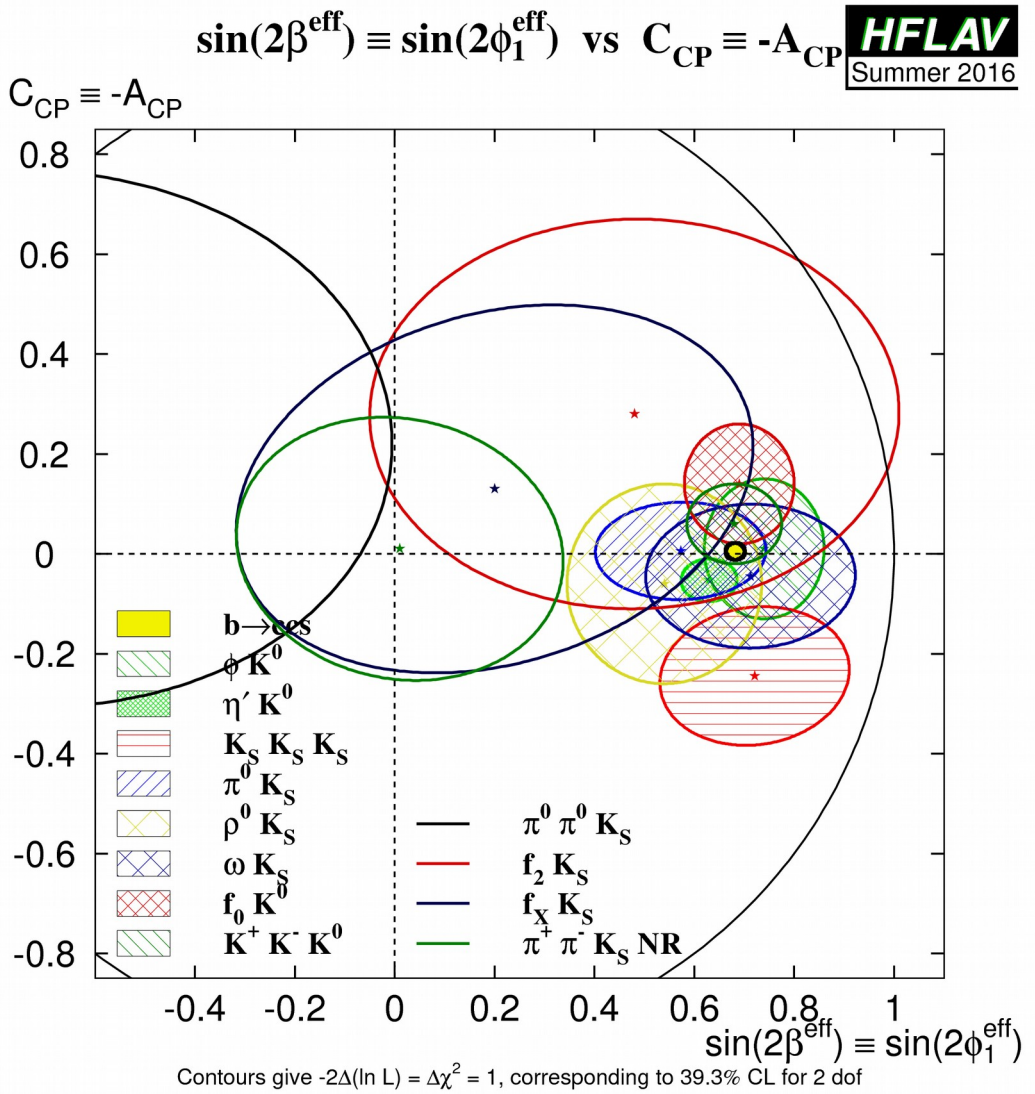
$b \to c\bar{c}d$


$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$
HFLAV Summer 2016
b→ccs
World Average
HFLAV (Summer 2016)
0.69 ± 0.02
J/ψ π0
BaBar
PRL 101 (2008) 021801
1.23 ± 0.21 ± 0.04
Belle
PRD 77 (2008) 071101(R)
0.65 ± 0.21 ± 0.05
Average
HFLAV correlated average
0.93 ± 0.15
J/ψ ρ0
LHCb
PLB 742 (2015) 38
0.66 +0.12 +0.03 -0.13 -0.09
Average
HFLAV correlated average
0.66 ± 0.14
D+ D-
BaBar
PRD 79, 032002 (2009)
0.63 ± 0.36 ± 0.05
Belle
PRD 85 (2012) 091106
1.06 +0.14 -0.21 ± 0.08
LHCb
PRL 117 (2016) 261801
0.54 +0.17 -0.16 ± 0.05
Average
HFLAV correlated average
0.84 ± 0.12
D*+ D*-
BaBar
PRD 79, 032002 (2009)
0.70 ± 0.16 ± 0.03
BaBar part. rec.
PRD 86 (2012) 112006
0.49 ± 0.18 ± 0.07 ± 0.04
Belle
PRD 86 (2012) 071103(R)
0.79 ± 0.13 ± 0.03
Average
HFLAV correlated average
0.71 ± 0.09
HFLAV Summer 2016
-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8


$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$ vs $C_{CP} \equiv -A_{CP}$
HFLAV Summer 2016
$C_{CP} \equiv -A_{CP}$
b→ccs
J/ψ π0
J/ψ ρ0
D+ D-
D*+ D*-
0.4
0.2
0
-0.2
-0.4
-0
0.2
0.4
0.6
0.8
1
$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$
Contours give -2Δ(ln L) = $\Delta\chi^2$ = 1, corresponding to 39.3% CL for 2 dof

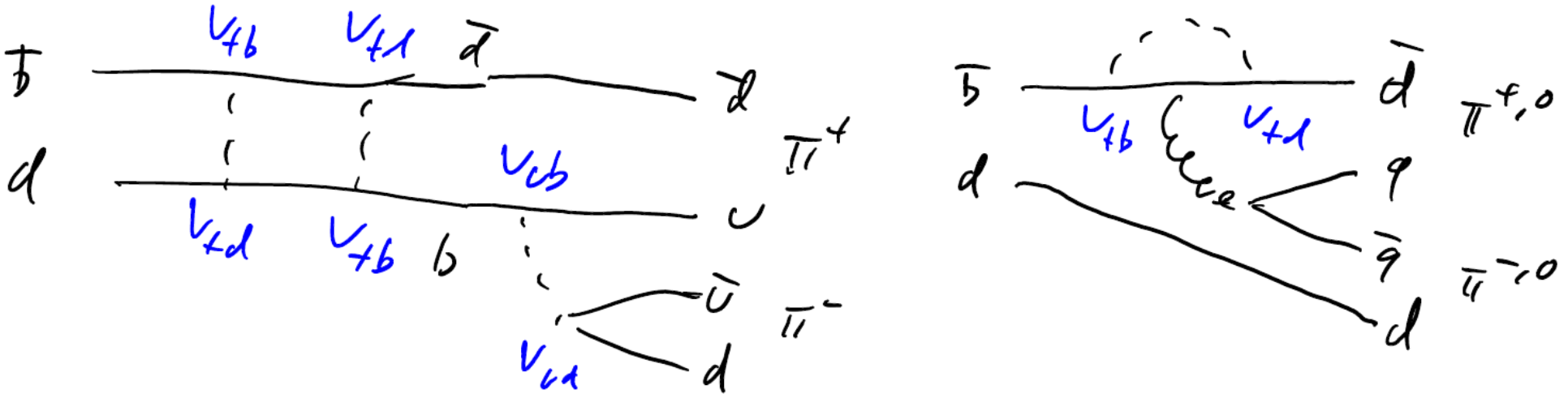
$b \to q\bar{q}s$


c̄
J/ψ
c
b̄
W
B0
d
s̄
K0
d
s̄
W
ϕ
b̄
s
B0
t̄
d
s̄
K(*)0
d


sin(2β^eff) ≡ sin(2φ1^eff) vs CCP ≡ -ACP
HFLAV
Summer 2016
CCP ≡ -ACP
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
sin(2β^eff) ≡ sin(2φ1^eff)
b→ccs
φ K0
η′ K0
KS KS KS
π0 KS
ρ0 KS
ω KS
f0 K0
K+ K- K0
π0 π0 KS
f2 KS
fX KS
π+ π- KS NR
Contours give -2Δ(ln L) = Δχ2 = 1, corresponding to 39.3% CL for 2 dof

$\alpha = \Phi_2$

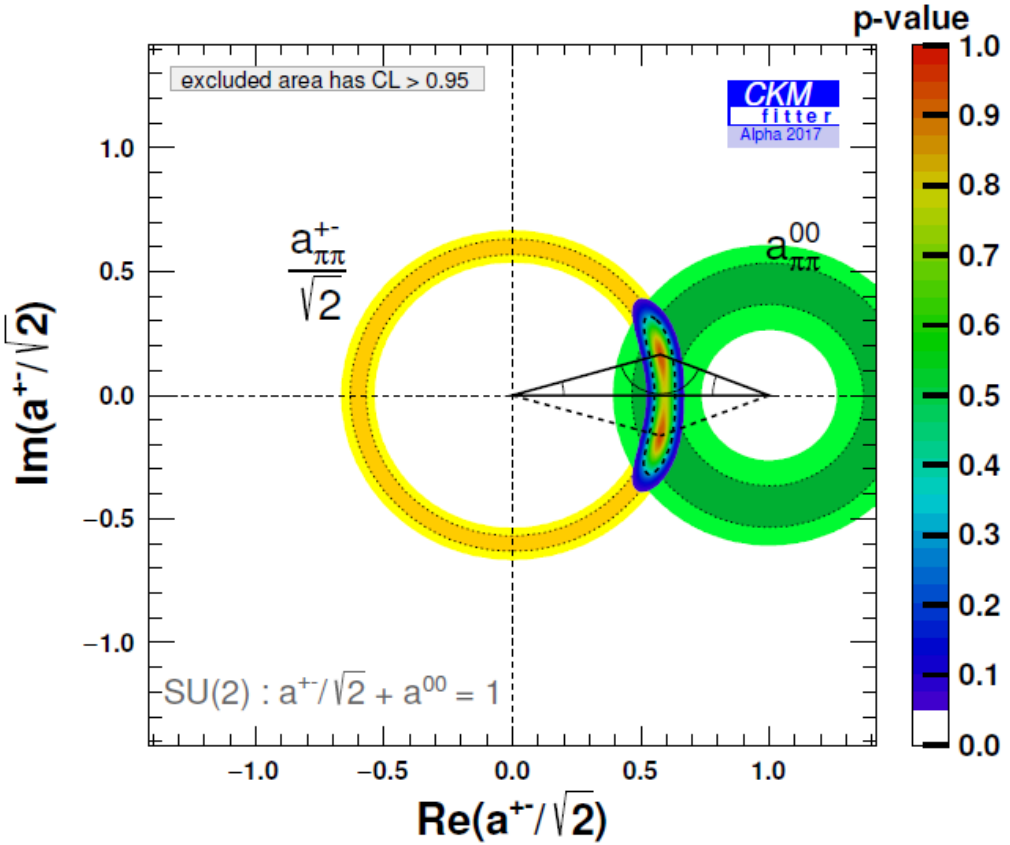
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

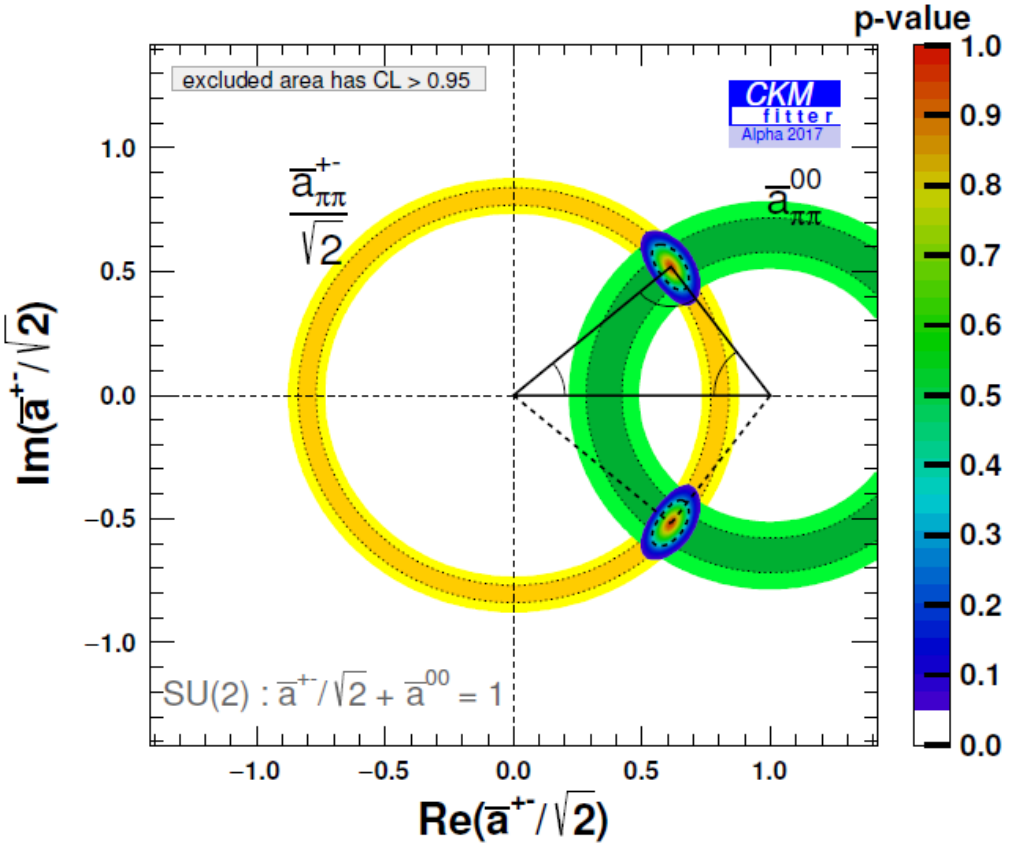


- Penguin pollution can be determined with isospin analysis
- $A^{+-} = A(B^0 \to \pi^+\pi^-)$, $A^{00} = A(B^0 \to \pi^0\pi^0)$, $A^{+0} = A(B^+ \to \pi^+\pi^0)$
- $A^{+-}/\sqrt{2} + A^{00} = A^{+0}$ → Triangle in complex plane
- Only tree contribution to A^{+0} → $|A^{+0}| = |\bar{A}^{-0}|$
- Different triangles for B and $\bar{B}$ → Penguin pollution

B → ππ

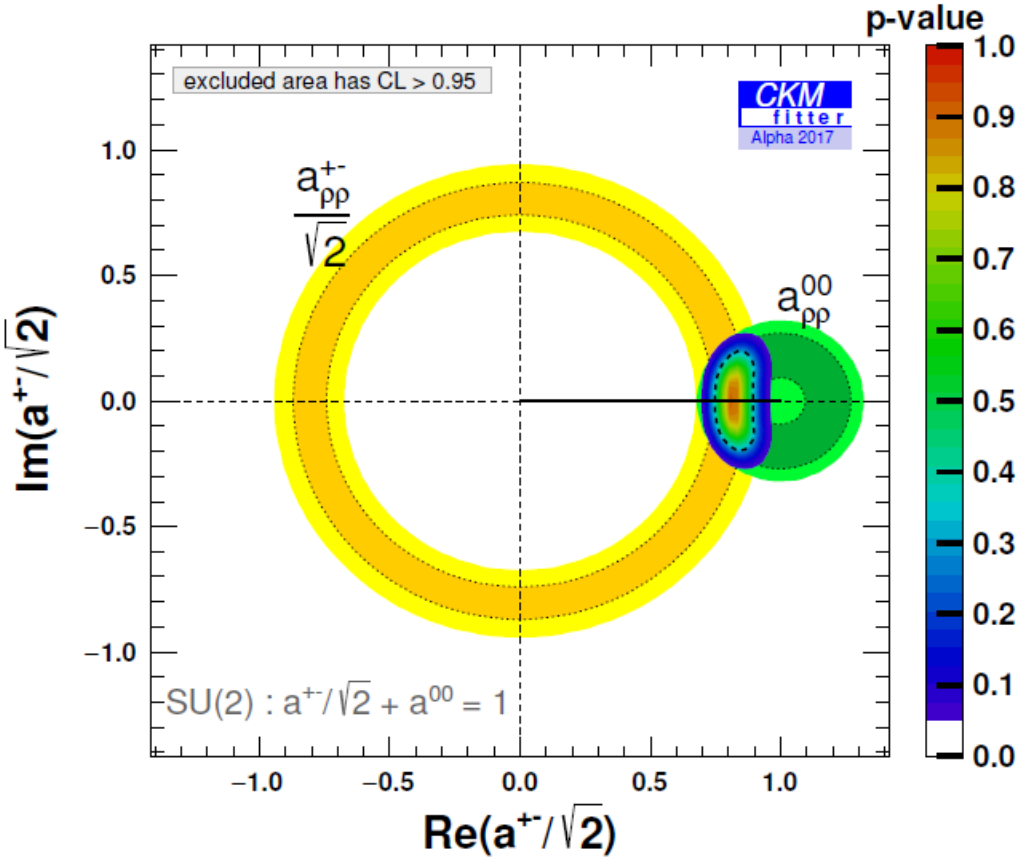
- $a^{ij} = A^{ij} / A^{+0} \quad \rightarrow \quad a^{+-}/\sqrt{2} + a^{00} = 1$

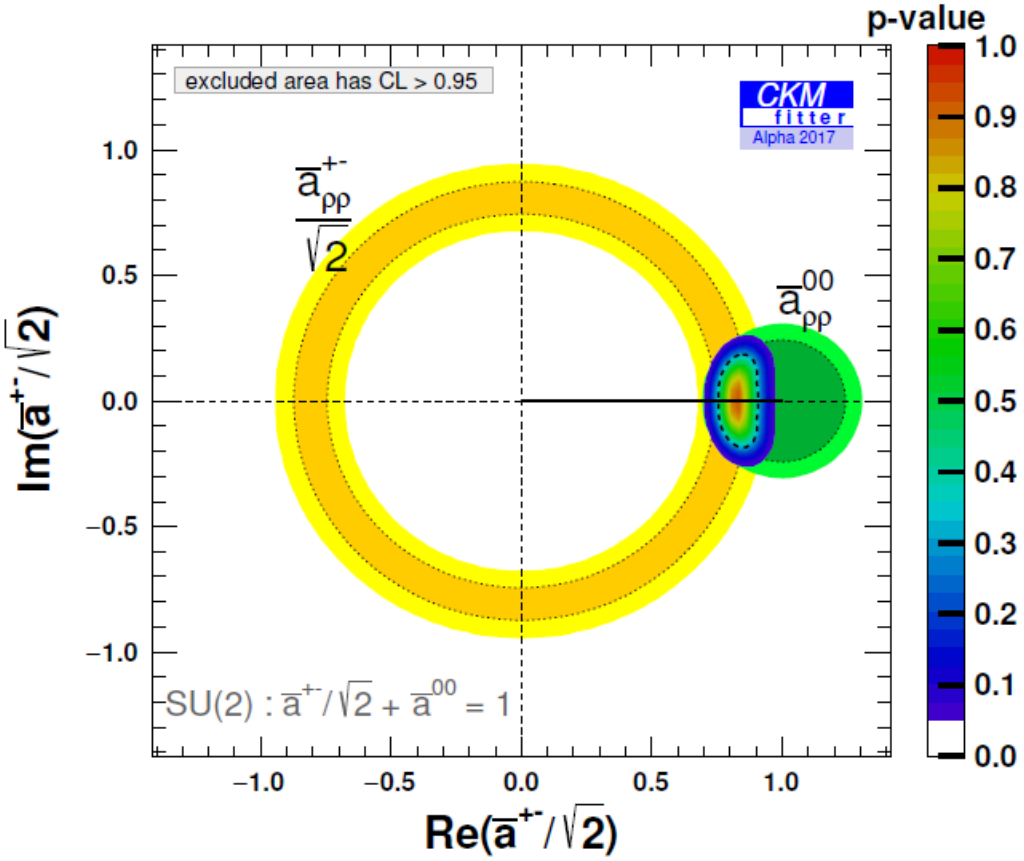




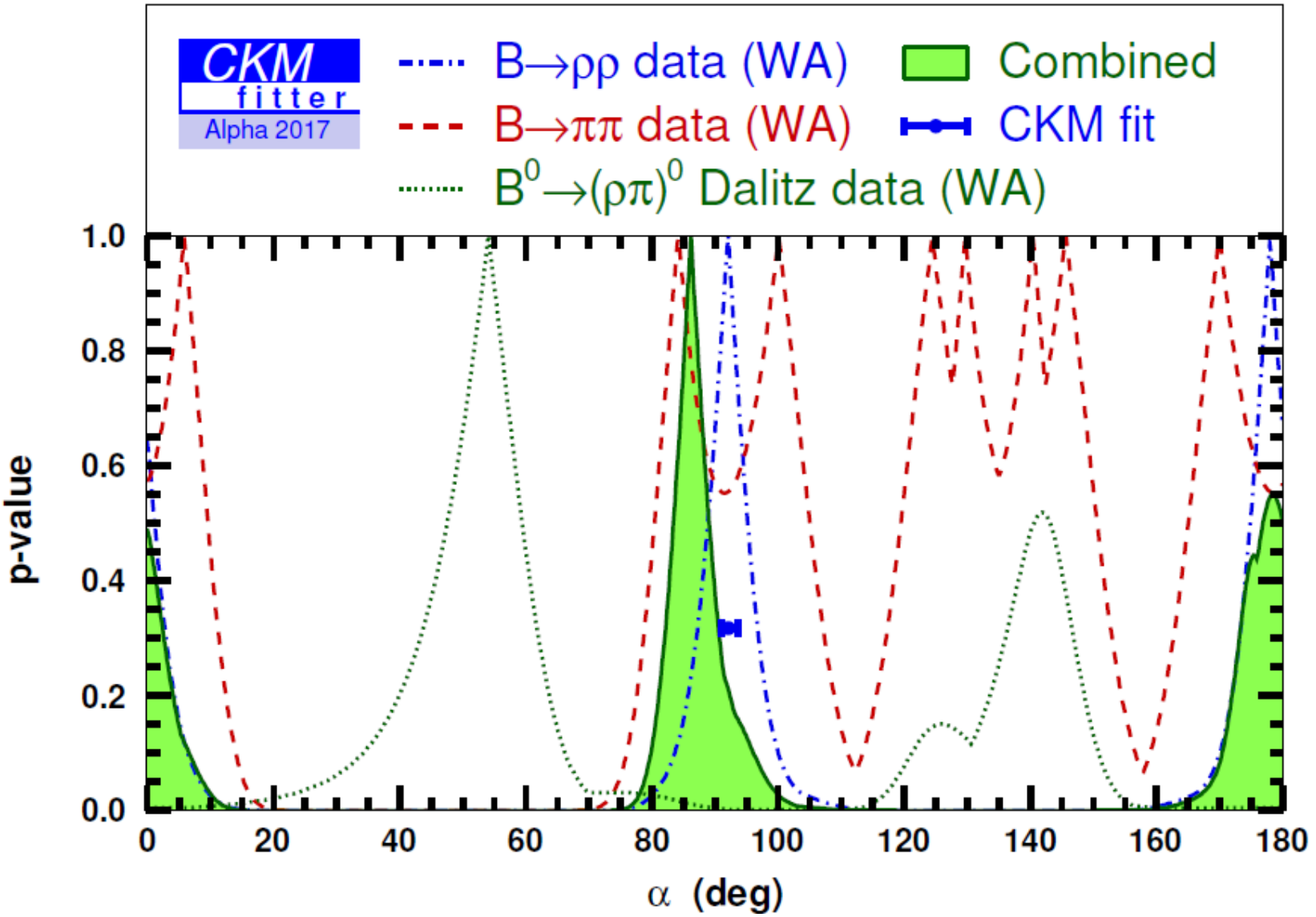
B → ρρ

- J(ρ) = 1 → ρρ final state is mixture of CP even and odd
- Angular analysis: $f_L(B^0 \to \rho^+\rho^-) = 0.99 \pm 0.02$



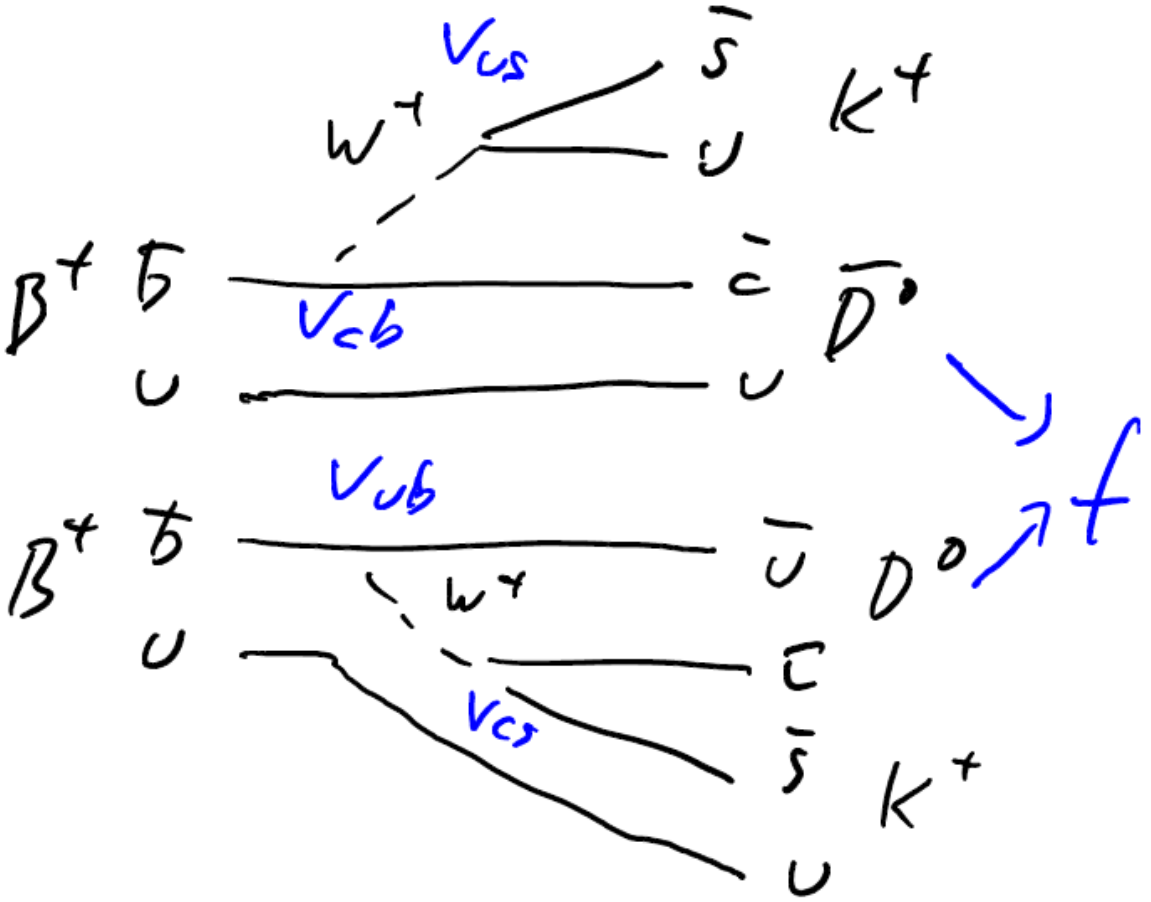


$\alpha = \varphi_2$



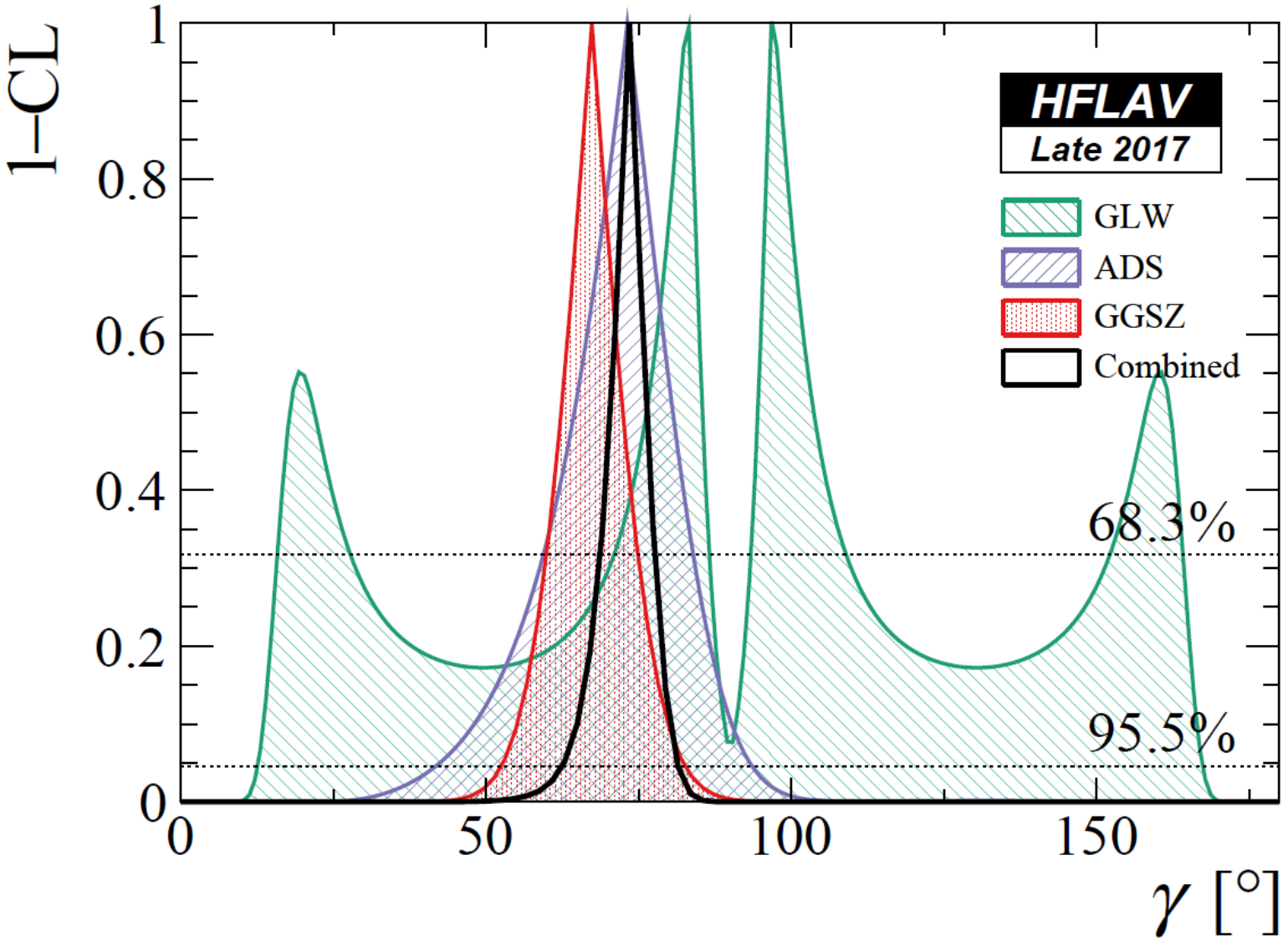
$\gamma = \Phi_3$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

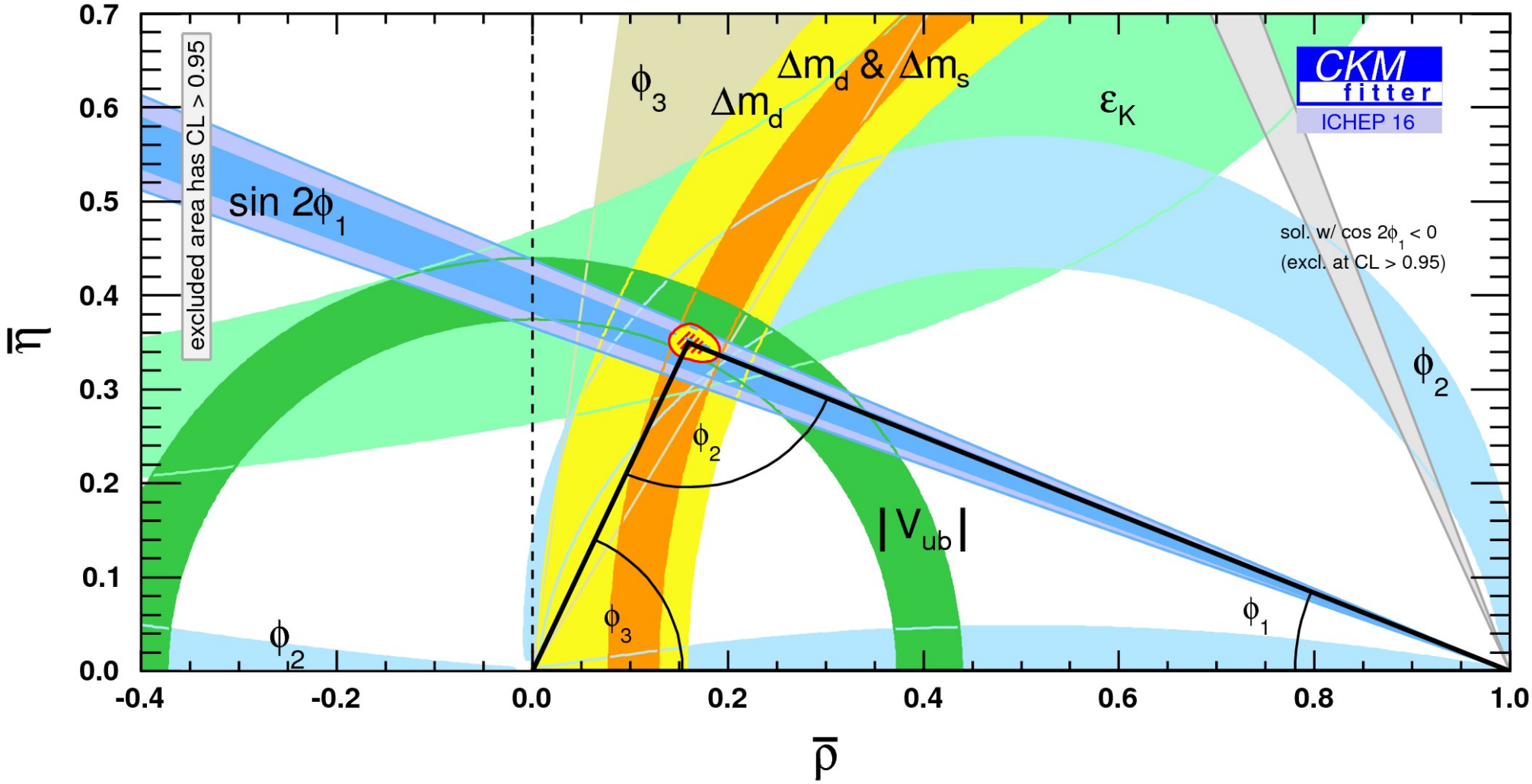


- GLW (Gronau, London, Wyler)
  → CP eigenstates:
  K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0$
- ADS (Atwood, Dunietz, Soni)
  → CF/DCS flavor eigenstates:
  $K^-\pi^+(\pi^0)$
- GGSZ (Gigi, Grossman, Soffer, Zupan)
  → 3 body decays:
  $K^0_S\pi^+\pi^-$, $K^0_SK^+K^-$

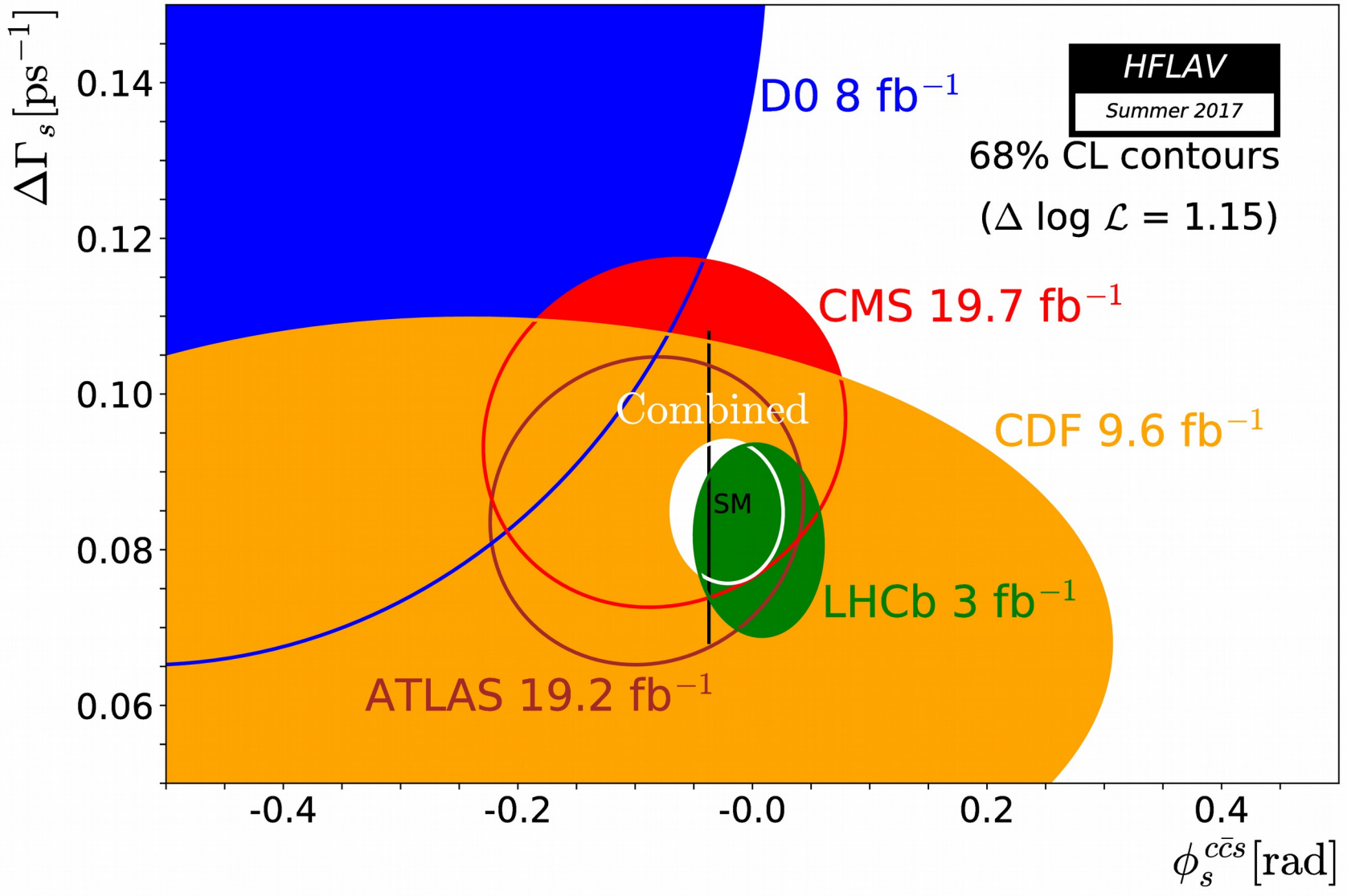
$\gamma = \Phi_3$


1–CL
1
0.8
0.6
0.4
0.2
0
0
50
100
150
γ [°]
HFLAV
Late 2017
GLW
ADS
GGSZ
Combined
68.3%
95.5%

CKM Fit

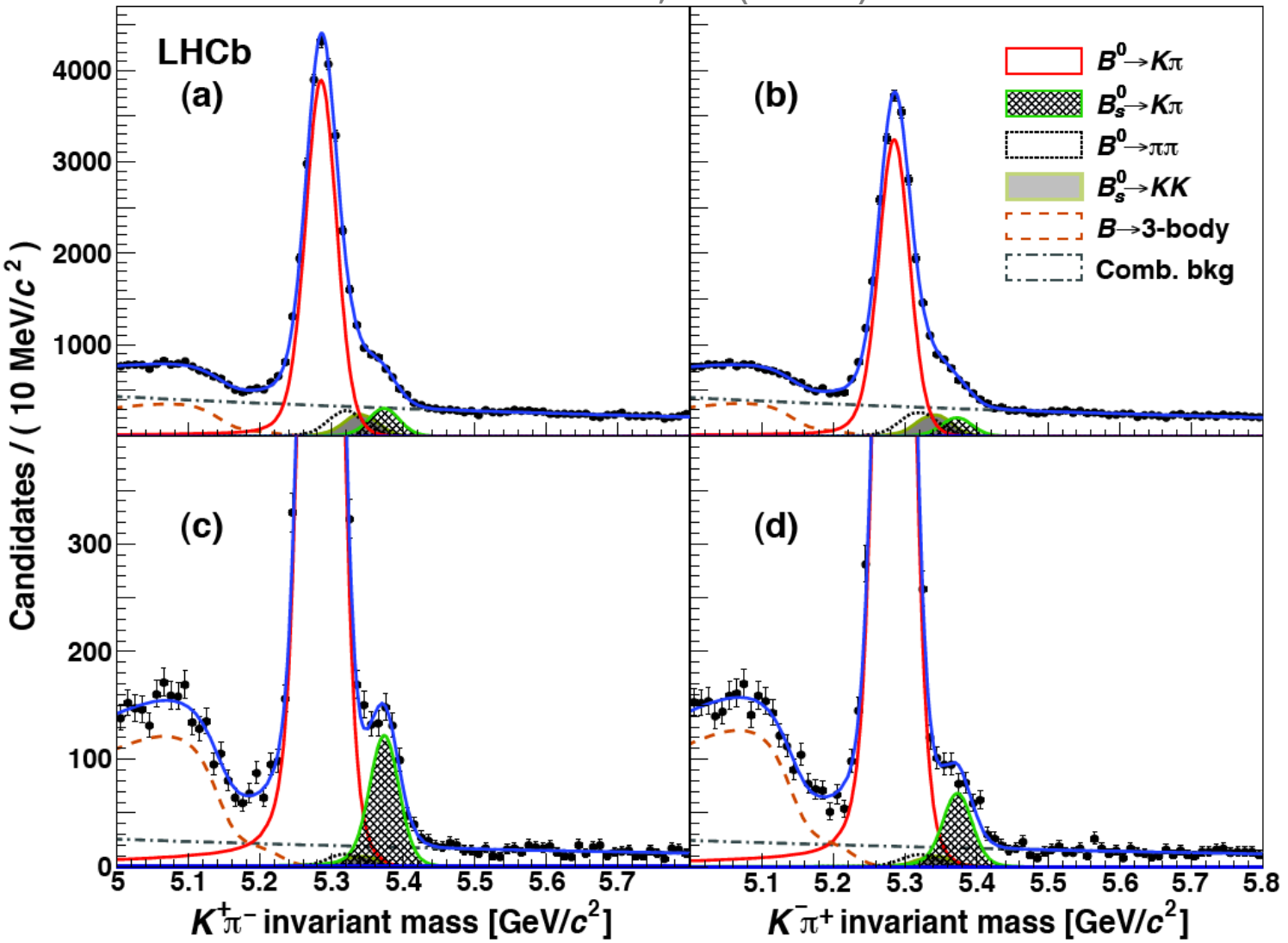

excluded area has CL > 0.95
sin 2ϕ1
ϕ3
Δmd
Δmd & Δms
εK
CKM fitter
ICHEP 16
sol. w/ cos 2ϕ1 < 0
(excl. at CL > 0.95)
ϕ2
ϕ2
|Vub|
ϕ3
ϕ2
ϕ1
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

CP Violation in B_s System

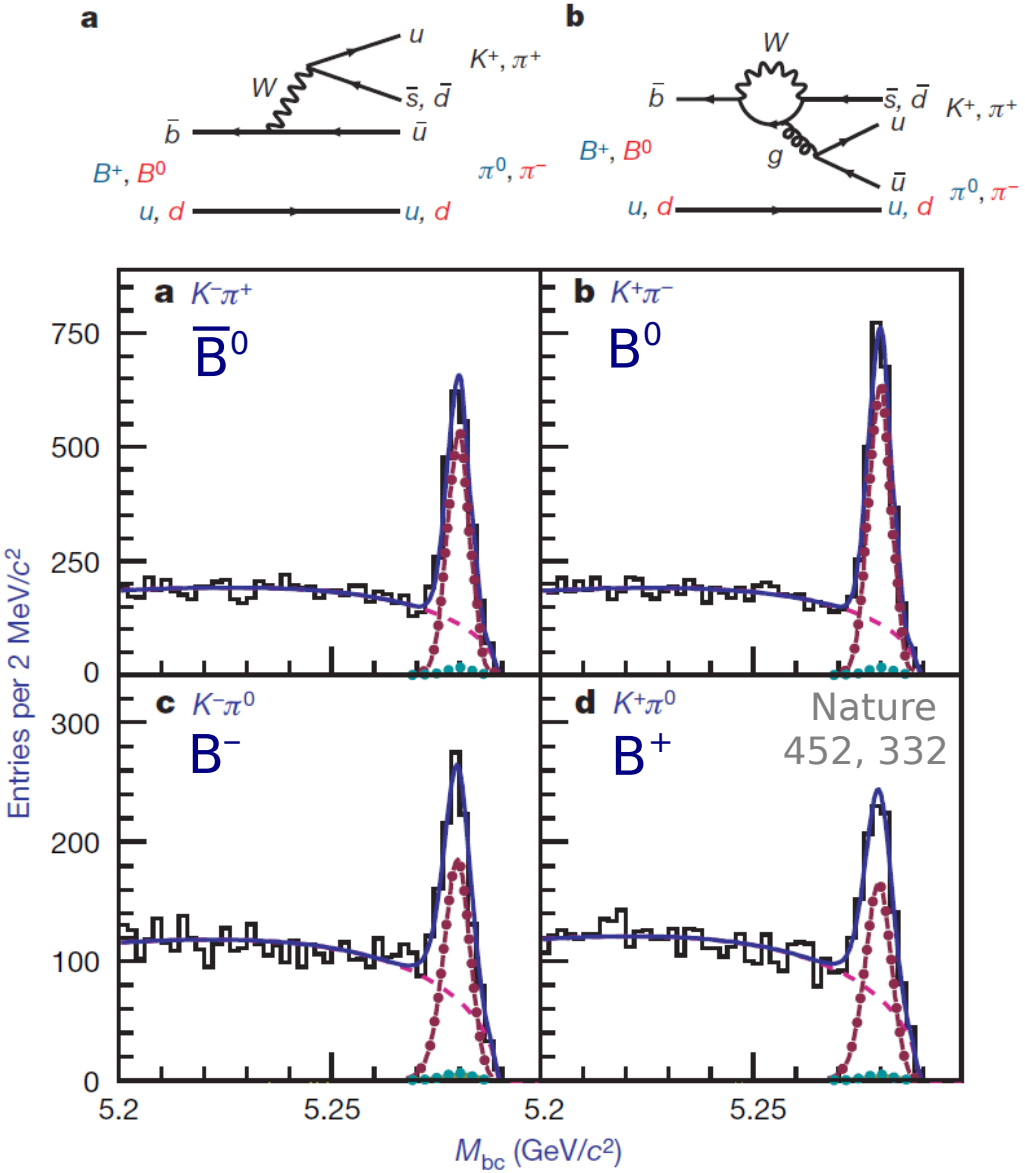


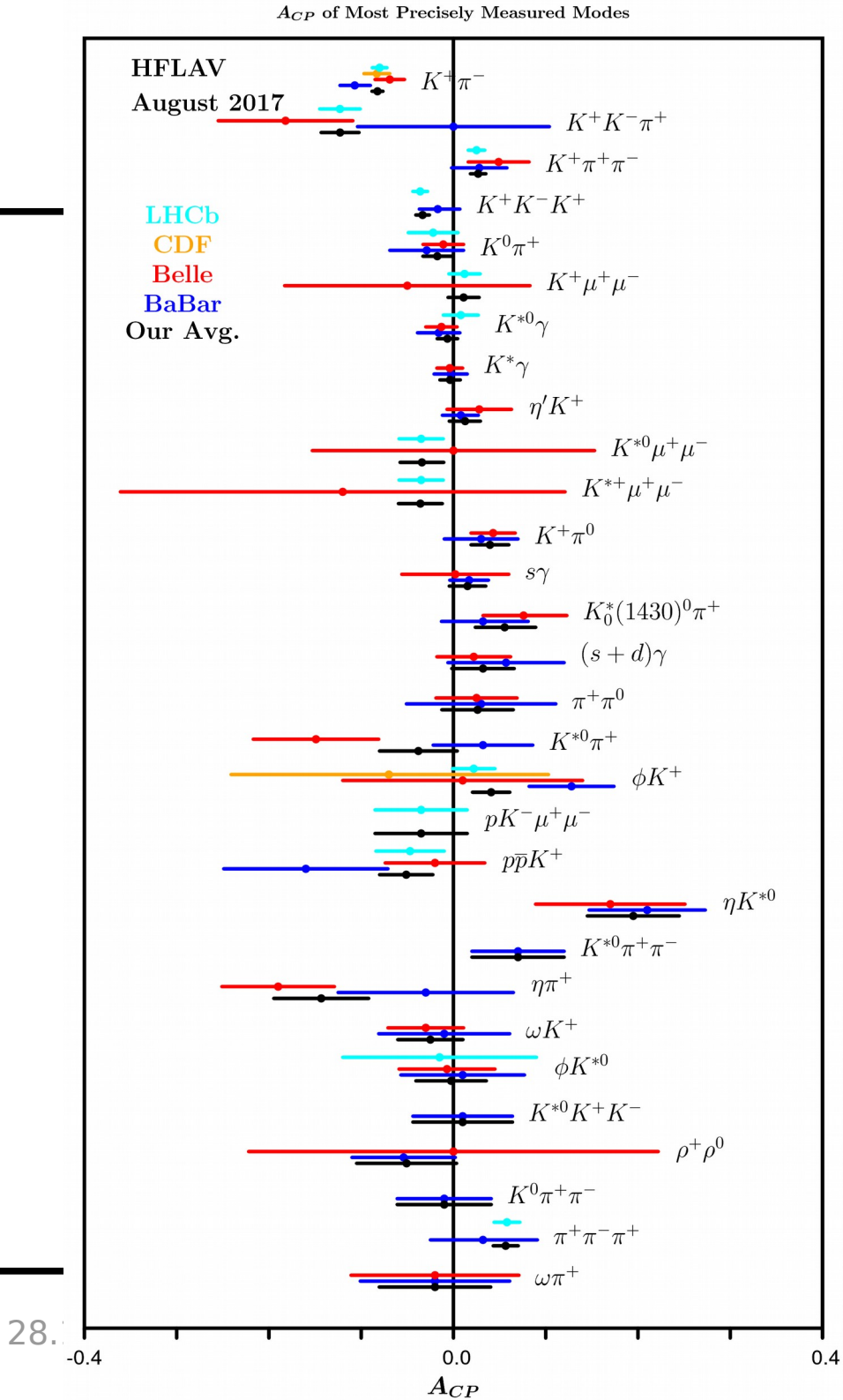
B_s: Direct CP Violation

PRL 110,22 (2013)

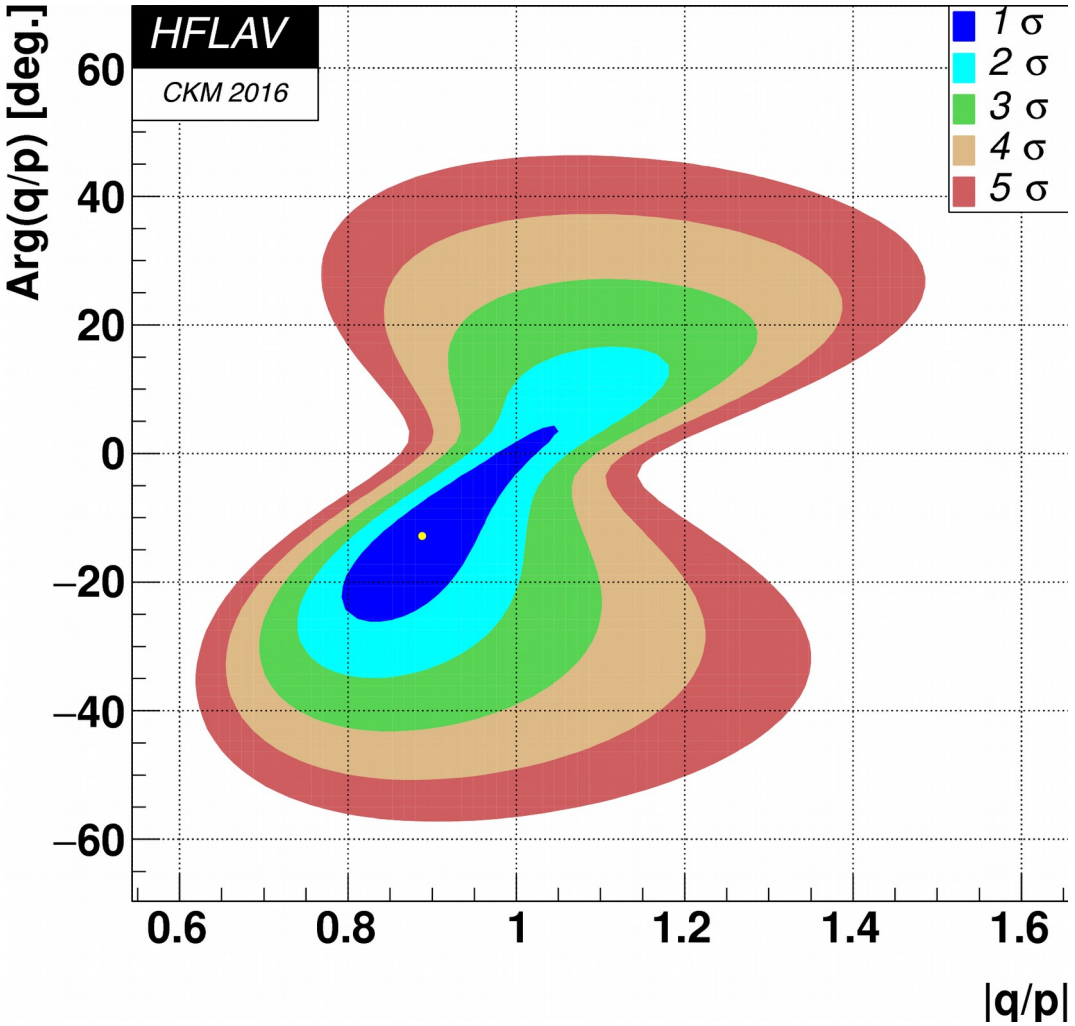


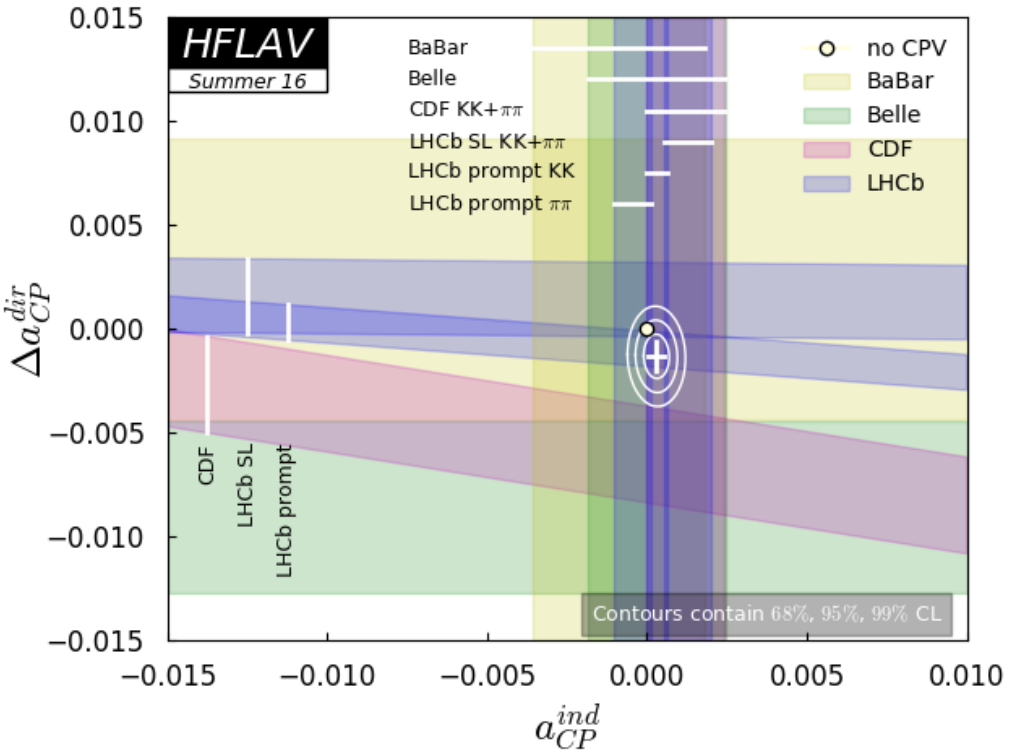
B: Direct CP Violation





Charm Mesons





Baryons, B_c

Heavy FLavor AVeraging group (HFLAV) - August 2017

Compilation of CP Asymmetries for Λ_b^0 baryons

In PDG2014 New since PDG2014 (preliminary) New since PDG2014 (published)

RPP#	Mode	PDG2014 Avg.	CDF	LHCb	Our Avg.
21	$p\pi^-$	0.03 ± 0.18	$0.06 \pm 0.07 \pm 0.03$		0.06 ± 0.08
22	pK^-	0.37 ± 0.17	$-0.10 \pm 0.08 \pm 0.04$		-0.10 ± 0.09
	$\overline{K^0}p\pi^-$			$0.22 \pm 0.13 \pm 0.03$	0.22 ± 0.13
	$\Lambda K^+\pi^-$			$-0.53 \pm 0.23 \pm 0.11$	-0.53 ± 0.26
	ΛK^+K^-			$-0.28 \pm 0.10 \pm 0.07$	-0.28 ± 0.12
	$pK^-\mu^+\mu^-$			$-0.035 \pm 0.05 \pm 0.002$	-0.035 ± 0.050

- No CP violation in baryon decays observed yet
- No CP asymmetry measurements of B_c decays yet

Summary and Outlook

- ✔ CP violation observed in quark flavor changing processes
- ➔ One parameter in CKM matrix → Powerful test of SM

Observable	**Current uncert.**	**Expected uncert.**	**Facility (2025)**
$\Phi_1 = \beta$ [°]	0.7	0.4	Belle II
$\Phi_2 = \alpha$ [°]	4.2	1.0	Belle II
$\Phi_3 = \gamma$ [°]	4.7	1.0	Belle II / LHCb
$S(B_s \to J/\psi\, \Phi)$	0.03	0.01	LHCb
$S(B \to \Phi\, K^0)$	0.14	0.02	Belle II
$\beta_s^{eff}(B_s \to \Phi\, \Phi)$ [rad]	0.15	0.10	LHCb
$A(B \to K^0\, \pi^0)$ $[10^{-2}]$	13	4	Belle II
$A(B \to K^+\, \pi^-)$ $[10^{-2}]$	0.6	0.2	LHCb / Belle II

Backup

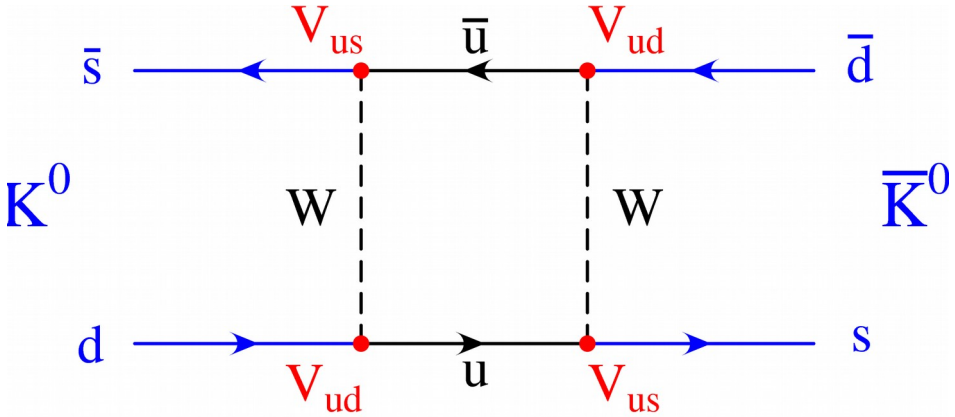
Wolfenstein Parametrization

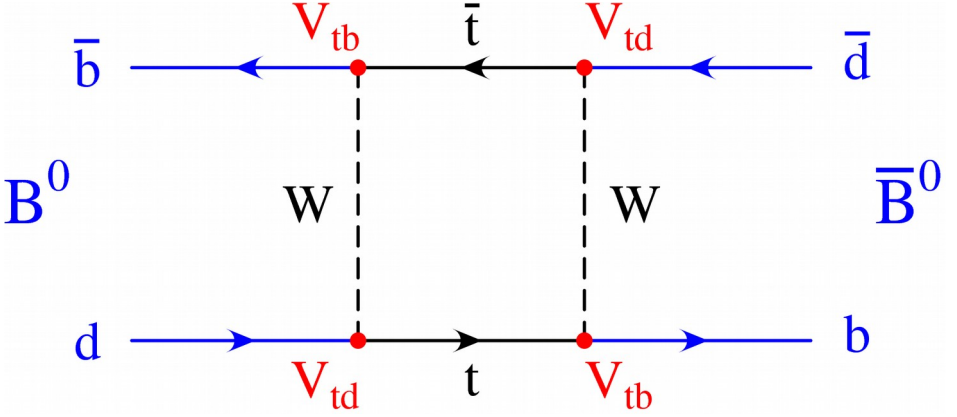
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

$\lambda \approx 0.22$, $A \approx 0.82$

$\rho \approx 0.22$, $\eta \approx 0.34$

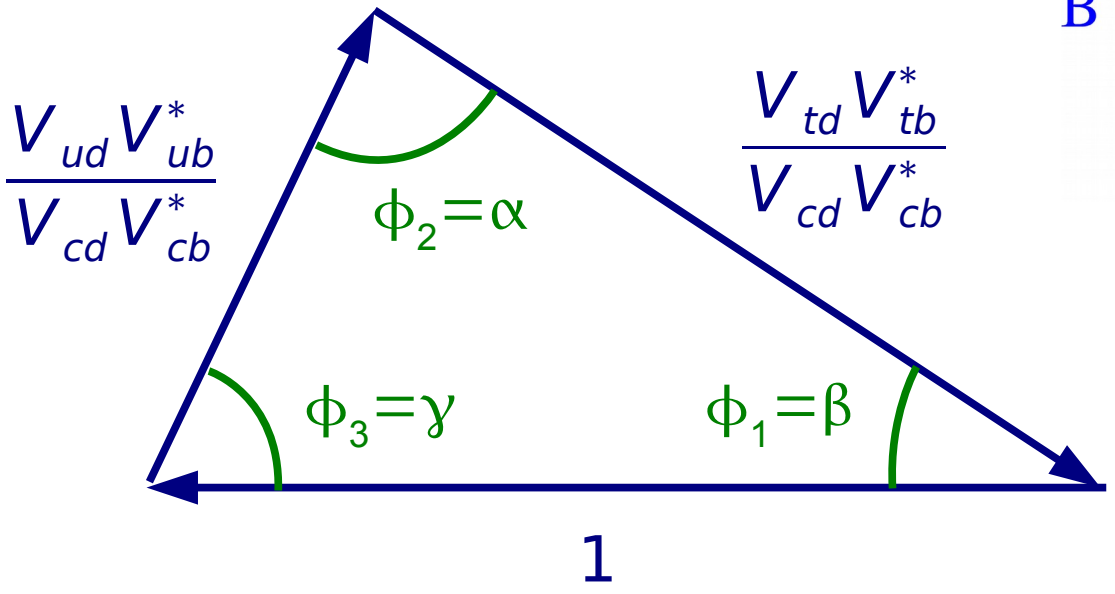


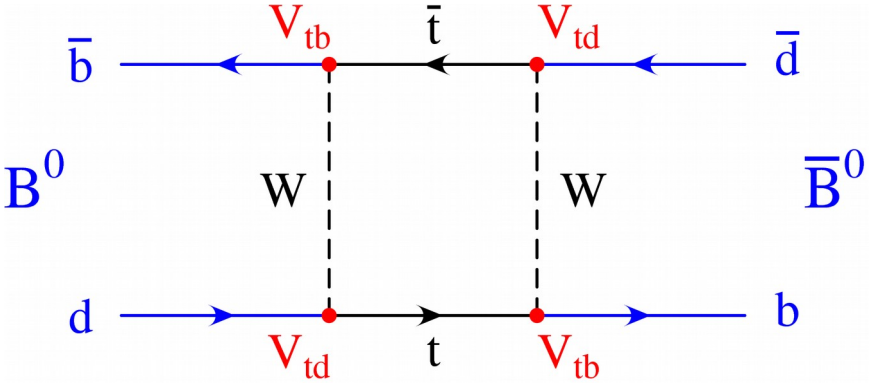


Unitarity Triangle

Graphical representation of unitarity condition: $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$

- e.g. for j=1, k=3: $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$





SM ⇒
closed triangle

Time Dependent Asymmetry

$$a_f(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)}$$

Decay to CP eigenstate f

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

$$= A\cos(\Delta m t) + S\sin(\Delta m t)$$

Decay

Interference

Mixing

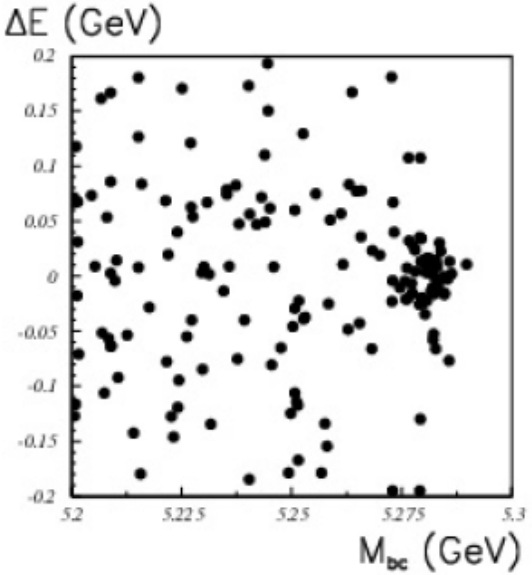
$$|B_L^0\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$
$$|B_H^0\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

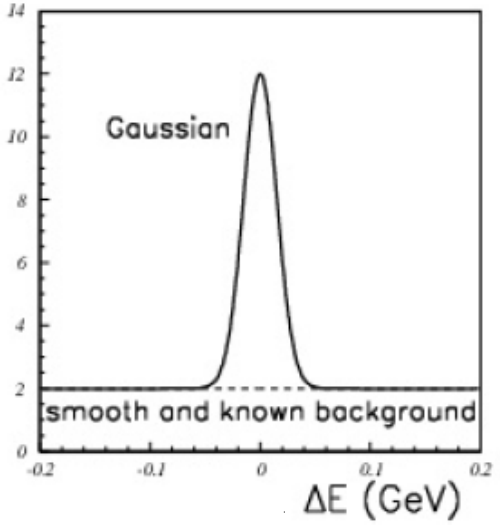
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \xi_f \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f}$$

Decay amplitude A_f

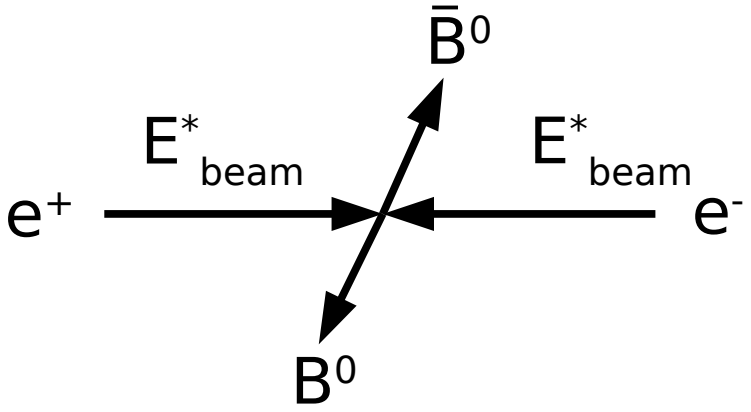
SM: $S = -\xi_f \sin(2\phi_1)$

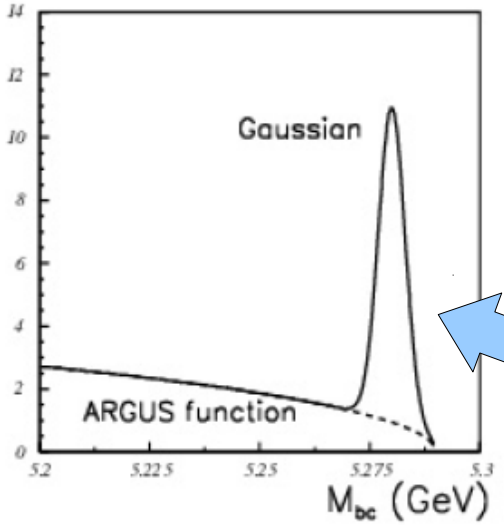
B^0 Reconstruction





In Y(4S) CMS:





$$\Delta E = \left(\sum_{\text{daughters}} E_i^\star \right) - E_{beam}^\star$$

$$M_{bc} = \sqrt{{E_{beam}^\star}^2 - \left(\sum_{\text{daughters}} \vec{p}_i^\star \right)^2}$$

Energy and momentum of B mesons determined by beam energy