B Meson Decays and CP (and T) Violation

Roland Waldi, Rostock University
XXXII Physics in Collision, Štrbské Pleso 2012

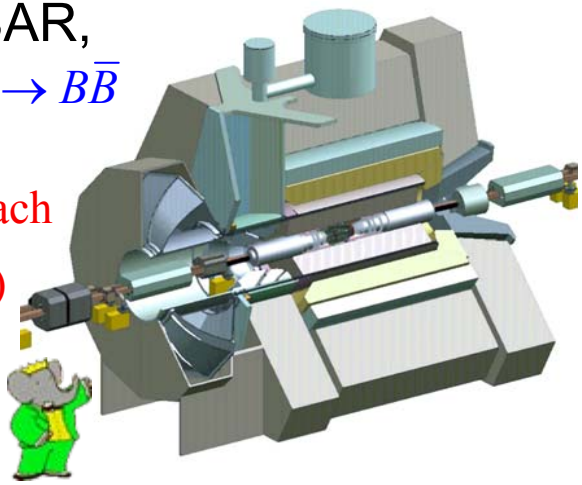
- CPV: $\beta = \phi_1$
- T-Violation
- *B* Decays: a Penguin & New Physics
- *B* Decays: a Tree & New Physics
- *B* Decays to Baryons
- Summary & Conclusions

The Players: Experiments

mostly BABAR,

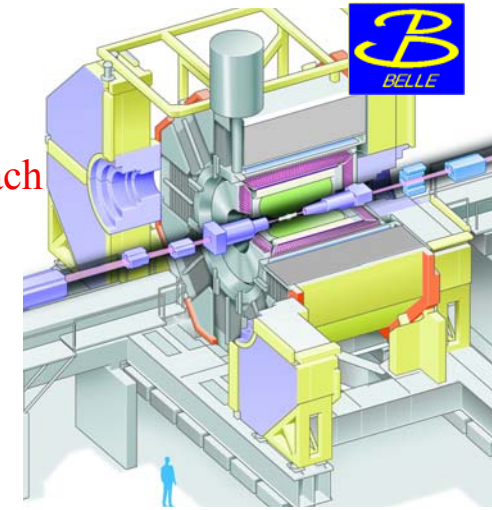
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$(\sim 235 \cdot 10^6$ of each $B^0, \bar{B}^0, B^+, B^-)$



Belle,

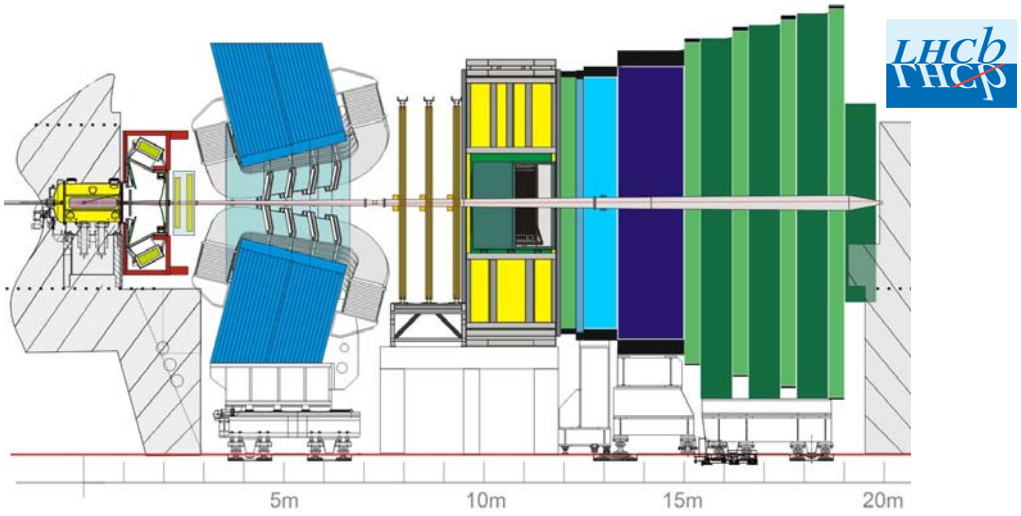
$(\sim 385 \cdot 10^6$ of each $B^0, \bar{B}^0, B^+, B^-)$



and recently LHCb

$pp \to b\bar{b}X$

$(> 20 \cdot 10^9$ of each $B^+, B^-, B^0, \bar{B}^0)$

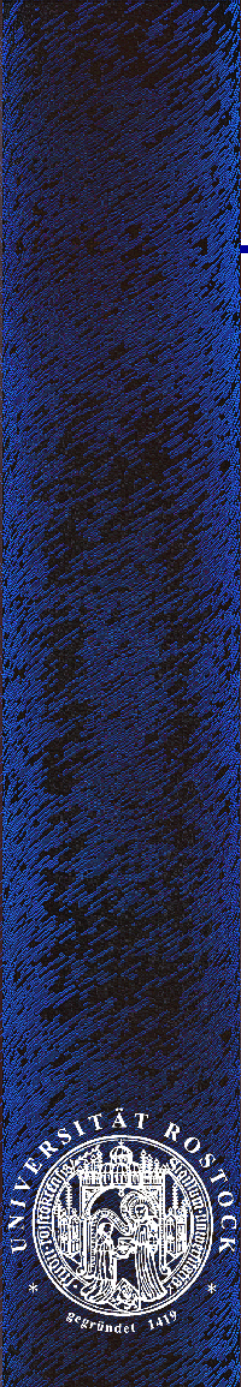


B Decays and CPV…

… help determine precise parameters of the Standard Model (SM)
(in particular CKM matrix elements)

… may show New Physics

… test low-q^2 QCD (form factors…)



The Unitary CKM Matrix

Cabibbo, Kobayashi, Maskawa

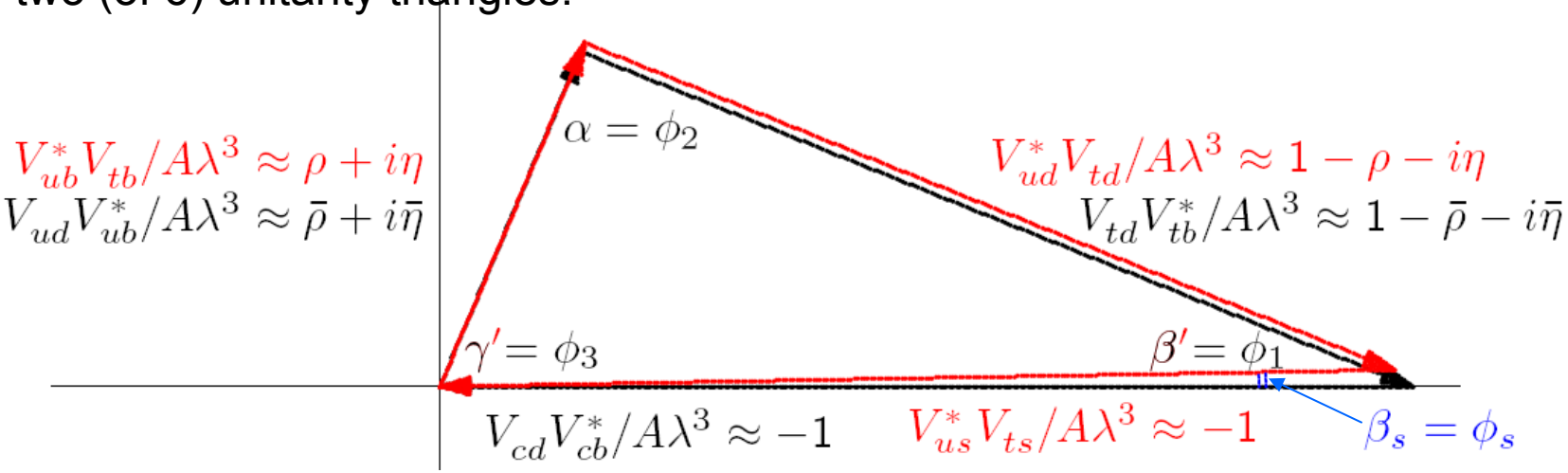
standard phase convention:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\tilde{\beta}_s} & |V_{tb}| \end{pmatrix}$$

alternative phase convention:

$$\begin{pmatrix} -|V_{ud}|e^{-i\alpha} & |V_{us}|e^{i\tilde{\gamma}} & |V_{ub}| \\ -|V_{cd}|e^{i(\phi_4+\tilde{\beta})} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}| & -|V_{ts}|e^{i\tilde{\beta}_s} & |V_{tb}| \end{pmatrix}$$

two (of 6) unitarity triangles:



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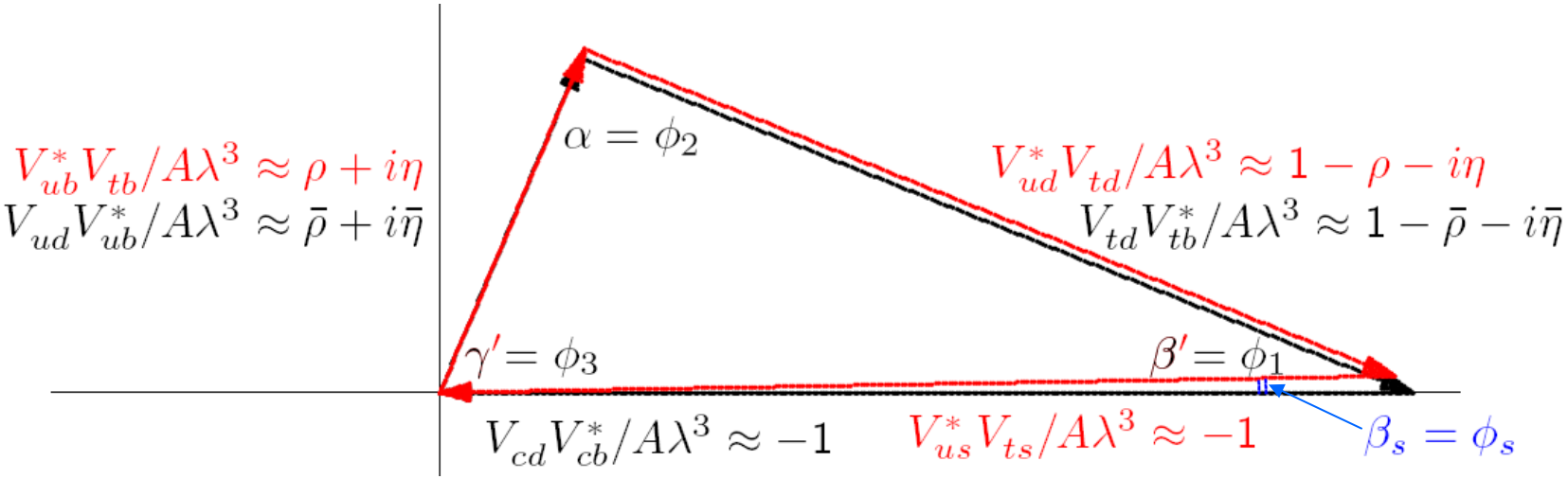
The Unitary CKM Matrix

Cabibbo, Kobayashi, Maskawa

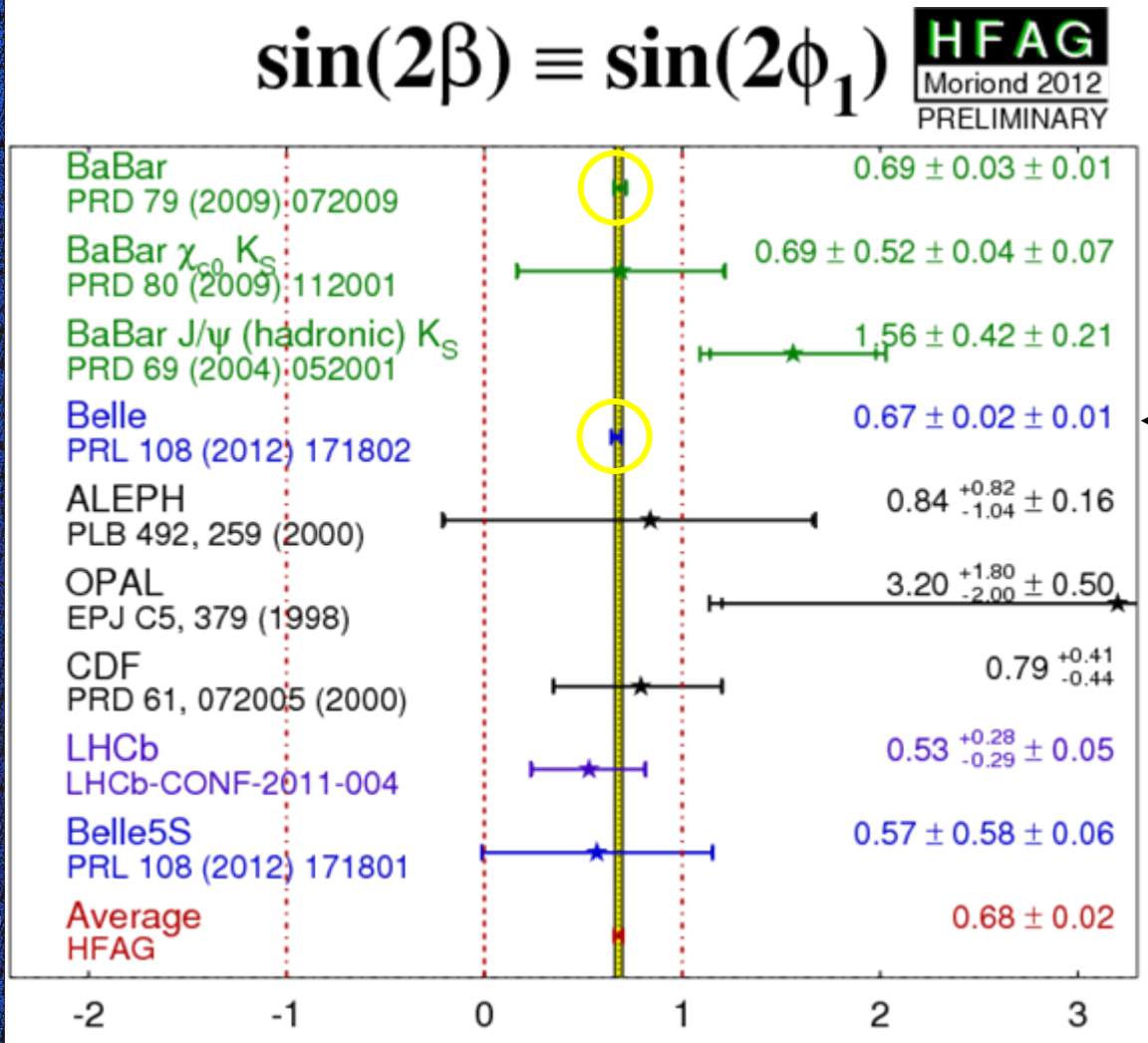
β: CPV in $B^0 \to J/\psi K^0_S$ ($K^0_S \to \pi\pi$ as CP+ state), D^+D^- etc.

β′: CPV in $B^0 \to \phi K^0_S$ etc. (penguins)

β_s: see next talk (B_s)



sin 2β ($b\bar{d} \to c\bar{c}s\bar{d} \to c\bar{c}d\bar{d}$)



CPV established by BFactories in 2001

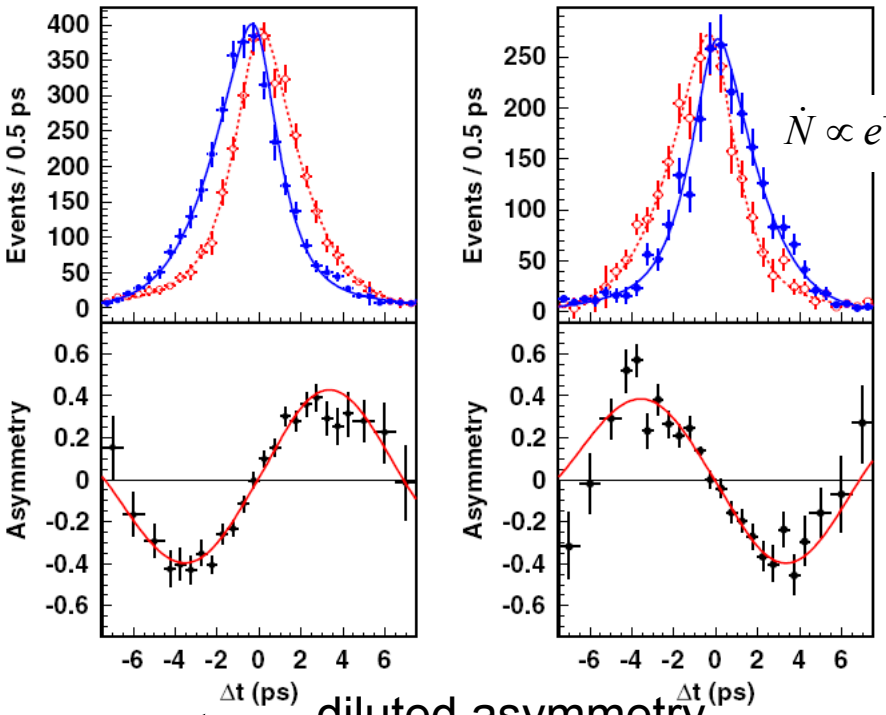
← new Belle 2012

mostly J/ψ K^0_S

sin 2β ($b\bar{d} \to c\bar{c}s\bar{d} \to c\bar{c}d\bar{d}$)

$e^+e^- \to \Upsilon(4S) \to (B\bar{B} - \bar{B}B)$

CP=−1 ($J/\psi\, K_S \ldots$) CP=+1 ($J/\psi\, K_L$) $B_{tag}=B^0$ / $B_{tag}=\bar{B}^0$



$$\dot{N} \propto e^{-\Gamma|\Delta t|}\left(1 + S_{tag,signal}\sin\Delta m\Delta t + C_{tag,signal}\cos\Delta m\Delta t\right)$$

± (convention!)

diluted asymmetry

lifetime difference
$t(B_{signal}) - t(B_{tag})$

dilution-corrected asymmetry:

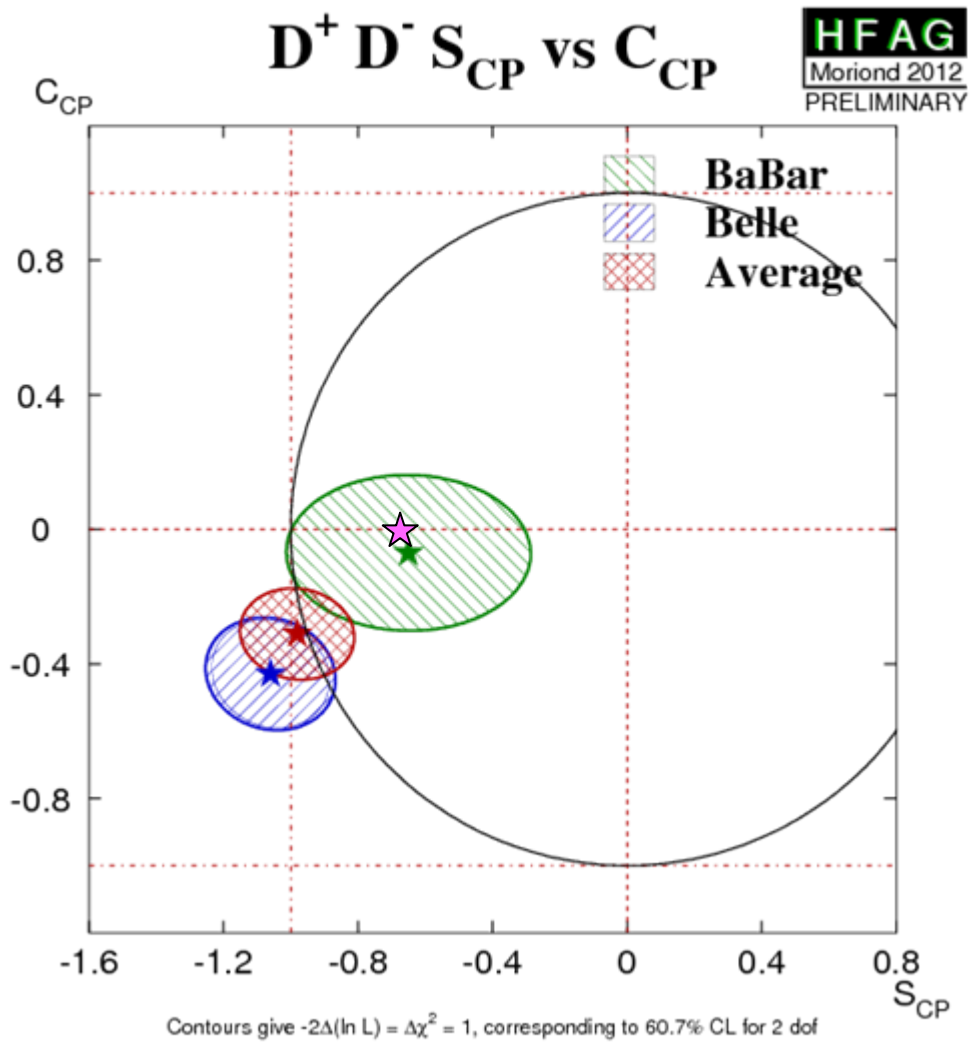
$$a(\Delta t) = \frac{N(B+f) - N(\bar{B}+f)}{N(B+f) + N(\bar{B}+f)} = S_{B,signal}\sin\Delta m\Delta t + C_{B,signal}\cos\Delta m\Delta t$$

$S_{B,KS} = -S_{B,KL} = \sin 2\beta \quad = 0.667 \pm 0.023 \pm 0.012$

$C_{B,KS} = C_{B,KL} \approx 0 \quad = 0.006 \pm 0.016 \pm 0.012$

Belle, PRL 108, 171802 (2012)

sin 2β ($b\bar{d} \to c\bar{c}d\bar{d}$)

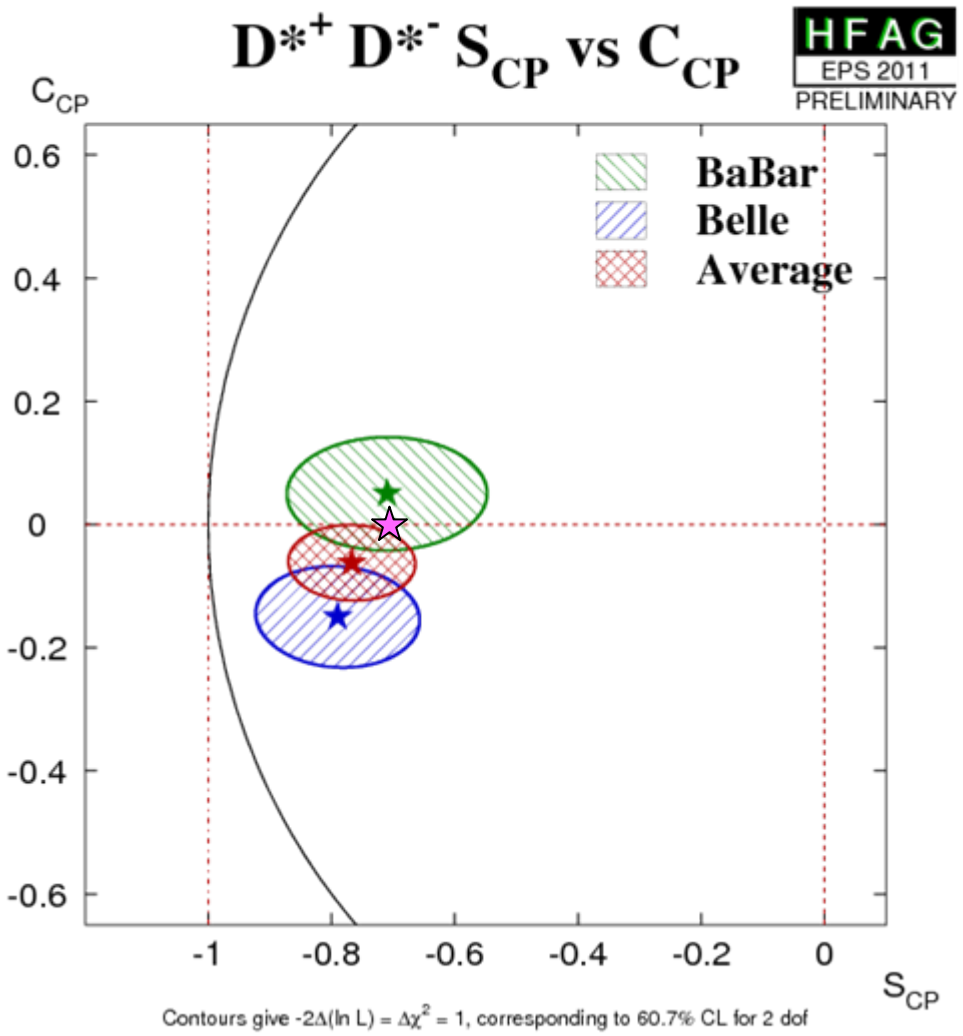


SM:
$S = -\sin 2\beta$, $C = 0$
for tree ★

but:
beware of penguins!
they modify S and C

sin 2β ($b\bar{d} \to c\bar{c}d\bar{d}$)

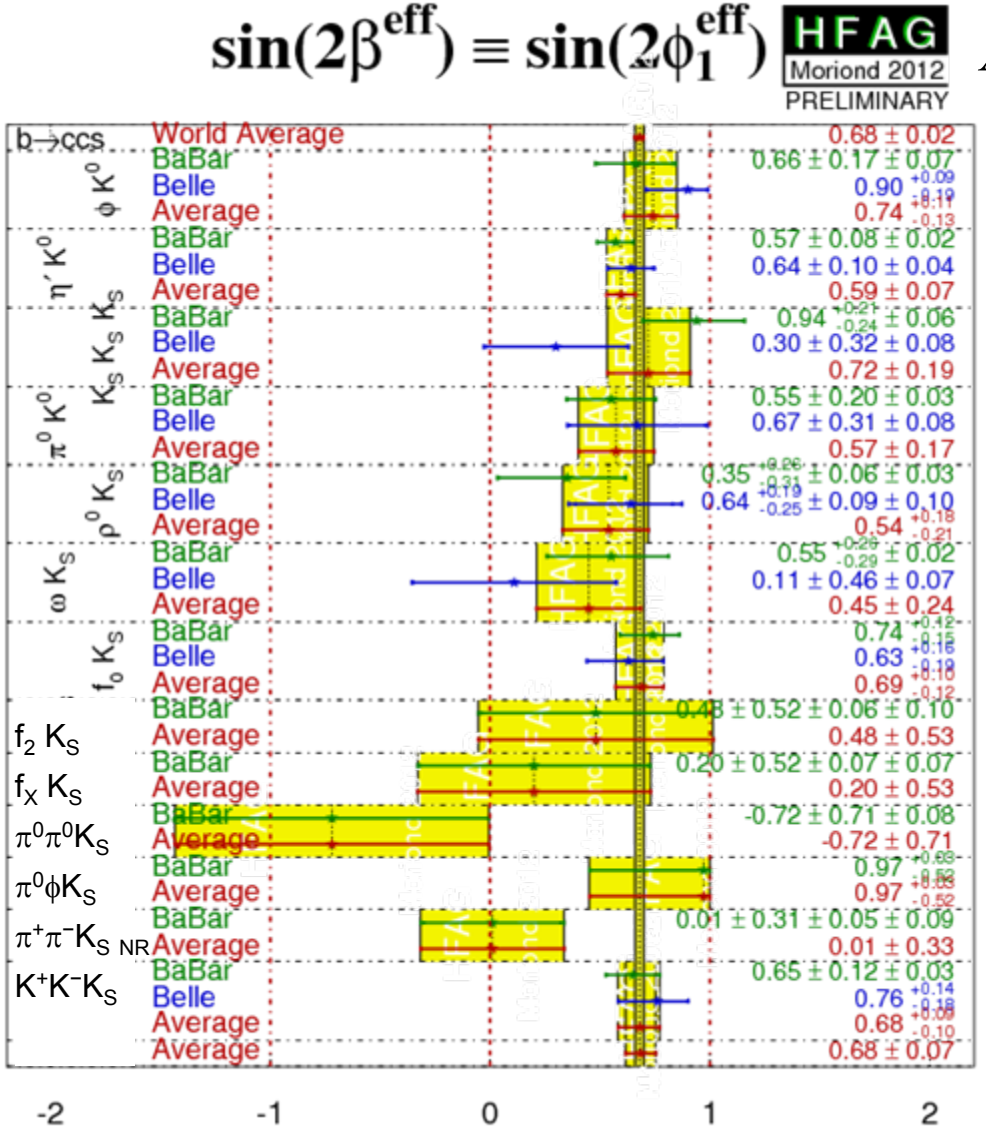
disentangle CP=+1 / −1 (L=even / odd)



SM:
$S = -\sin 2\beta$, $C = 0$
for tree ☆

compatible!

sin 2β′ (b → s penguins w/K^0_S)



$$A \propto S_f \sin \Delta m \Delta t - C_f \cos \Delta m \Delta t$$

$\beta' = \beta + \beta_s \approx \beta$

other diagrams contribute (different phases)

theoretical corrections tend to increase $\sin 2\beta^{\rm eff}$

no (more) discrepancy with SM

if other diagrams contribute → direct CPV but no significant $C \neq 0$ seen.

$B^{\pm}$ (b → s penguins)

if other diagrams contribute → direct CPV

New: LHCb direct CPV
in charged *B* decay:

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.034 \pm 0.009(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(J/\psi K^{\pm})$$
$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.046 \pm 0.009(\text{stat}) \pm 0.005(\text{syst}) \pm 0.007(J/\psi K^{\pm})$$

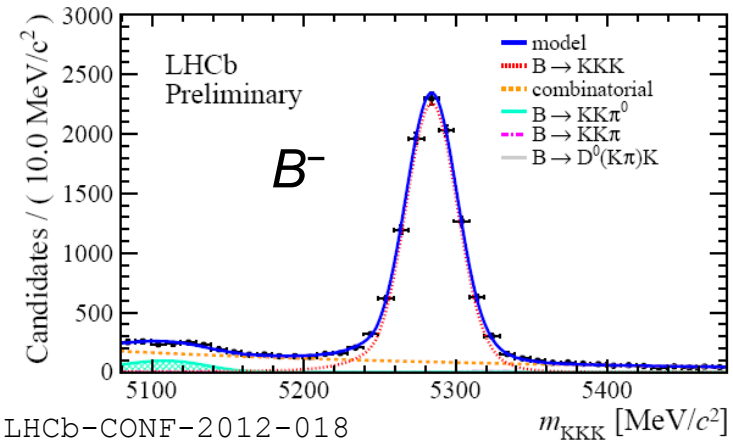
(2.8 and 3.7σ)

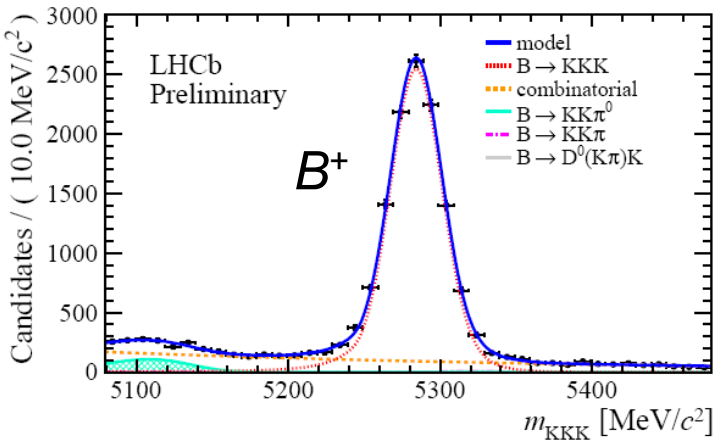
calibration channel

$$A_{CP}^{\text{RAW}} = \frac{N_{B^-} - N_{B+}}{N_{B^-} + N_{B+}}$$

$$A_{CP}(K^{\pm}h^{+}h^{-}) = A_{CP}^{\text{RAW}}(K^{\pm}h^{+}h^{-}) - A_{CP}^{\text{RAW}}(J/\psi K^{\pm}) + A_{CP}(J/\psi K^{\pm})$$

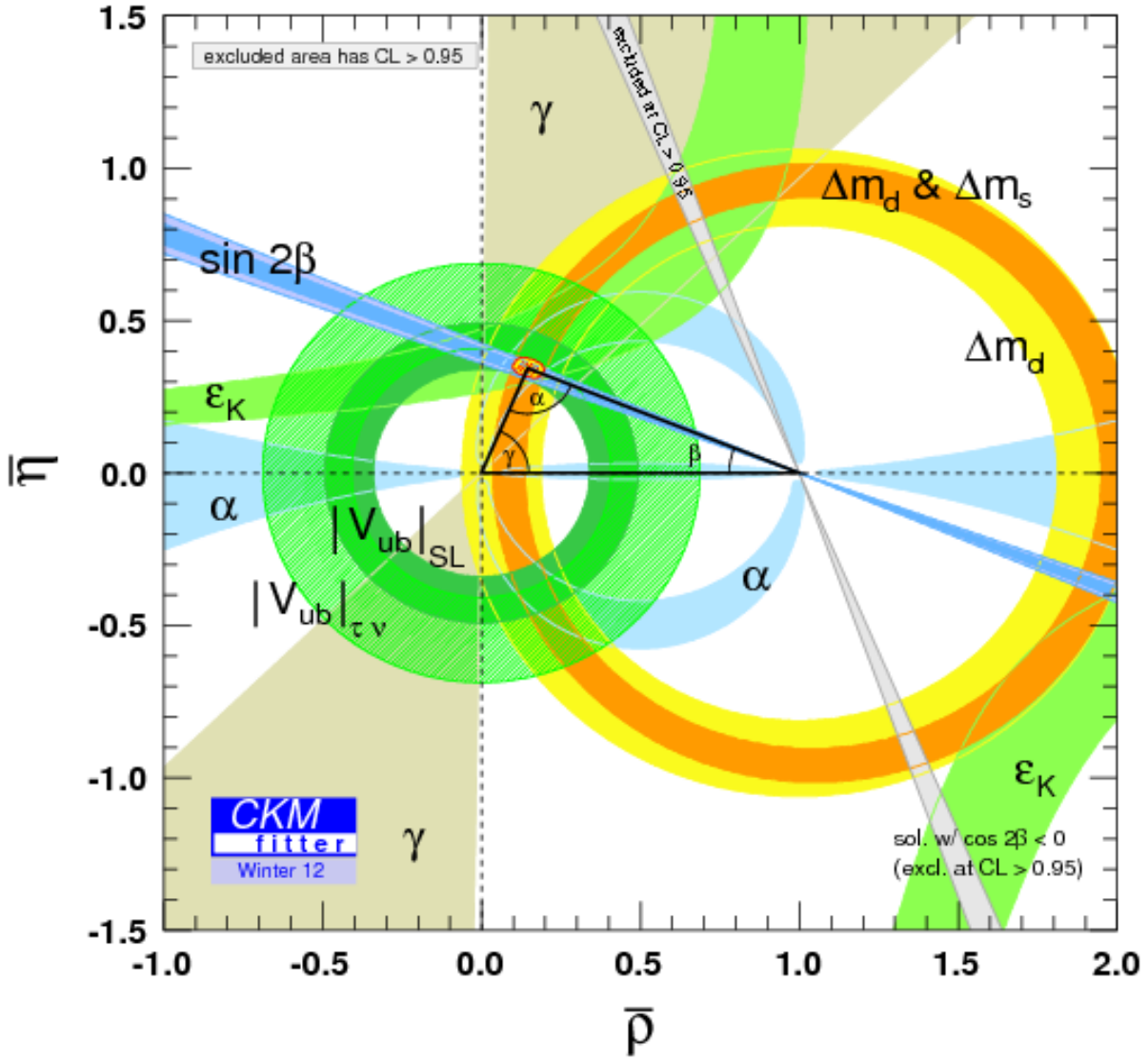
$A_{CP}^{RAW}(B^{\pm} \to J/\psi K^{\pm}) = -0.0087 \pm 0.0038$





LHCb-CONF-2012-018

More measurements…



…on

α (CPV),

γ (CPV),

$|V_{ub}|$ (semilept.),
$f_B|V_{ub}|$ ($B\to\tau\nu$)

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T Violation (Time Reversal)

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow [B^0\bar{B}^0 - \bar{B}^0B^0] = [B_+B_- - B_-B_+]$$

$L=1$: odd $1 \leftrightarrow 2$ wave function

entangled state

tag $1=B^0 \quad \Rightarrow \quad 2=\bar{B}^0$

tag $1=B_+ \quad \Rightarrow \quad 2=B_-$

what are $B_\pm$? two orthogonal states decaying to $J/\psi\, K_L(K_S)$
i.e. to CP=+1 and −1 final states
→ use sin 2β analysis

example
time t_1: observe $1=B^0 \rightarrow X_c l^+$ → particle $2=\bar{B}^0$
time $t_2>t_1$: observe $2=B_- \rightarrow J/\psi\, K_S$
→ transition $\bar{B}^0 \rightarrow B_-$

test CP:	$B^0 \rightarrow B_-$
test T:	$B_- \rightarrow \bar{B}^0$

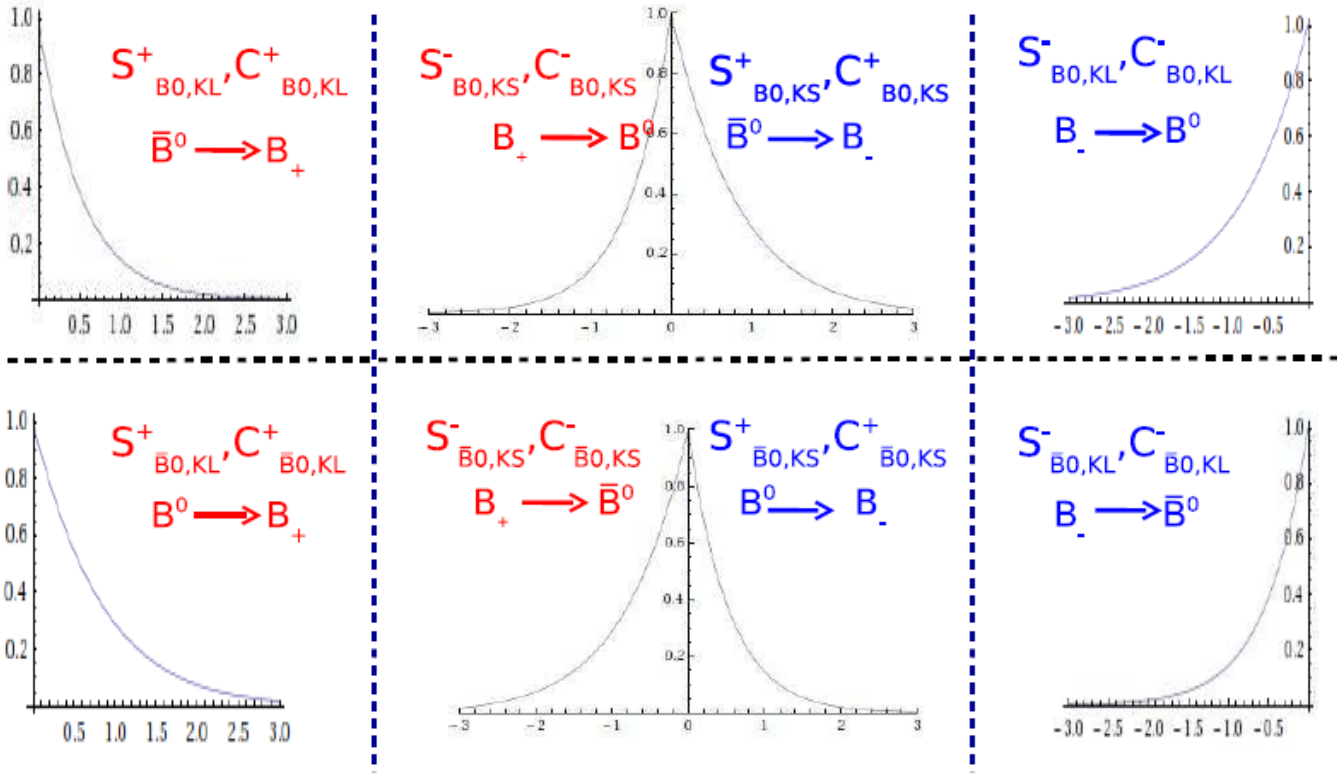
T Violation

use sin 2β analysis

$$A \propto S^{\pm} \sin \Delta m \Delta t + C^{\pm} \cos \Delta m \Delta t$$

$$S^{+} = S^{-} = \pm \sin 2\beta$$

$$C^{+} = C^{-} \approx 0$$



$J/\psi\ K_L$ $J/\psi\ K_S$ $J/\psi\ K_L$

T Violation

$$A \propto S^{\pm} \sin \Delta m \Delta t + C^{\pm} \cos \Delta m \Delta t$$

$$S^{+} = S^{-} = \pm \sin 2\beta$$

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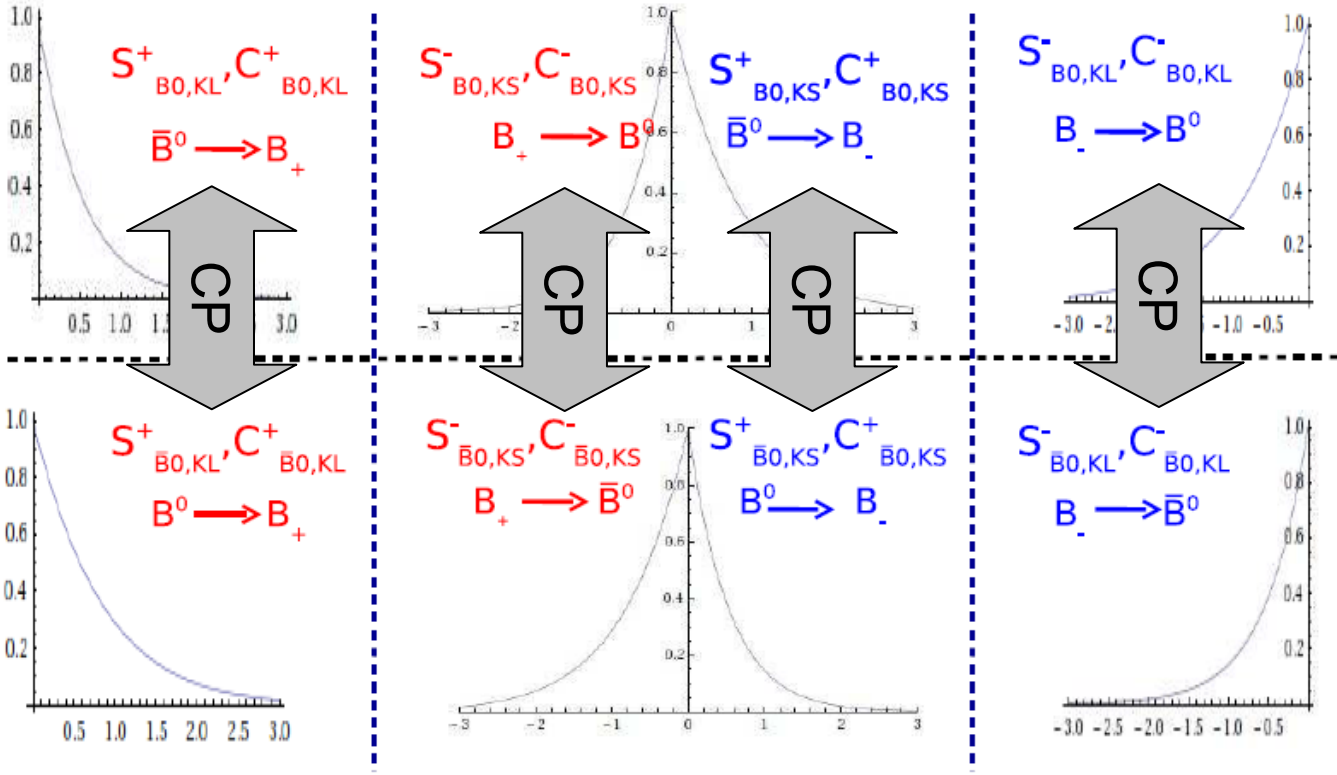

$J/\psi\ K_L$ $J/\psi\ K_S$ $J/\psi\ K_L$

T Violation

$$A \propto S^{\pm} \sin \Delta m \Delta t + C^{\pm} \cos \Delta m \Delta t$$

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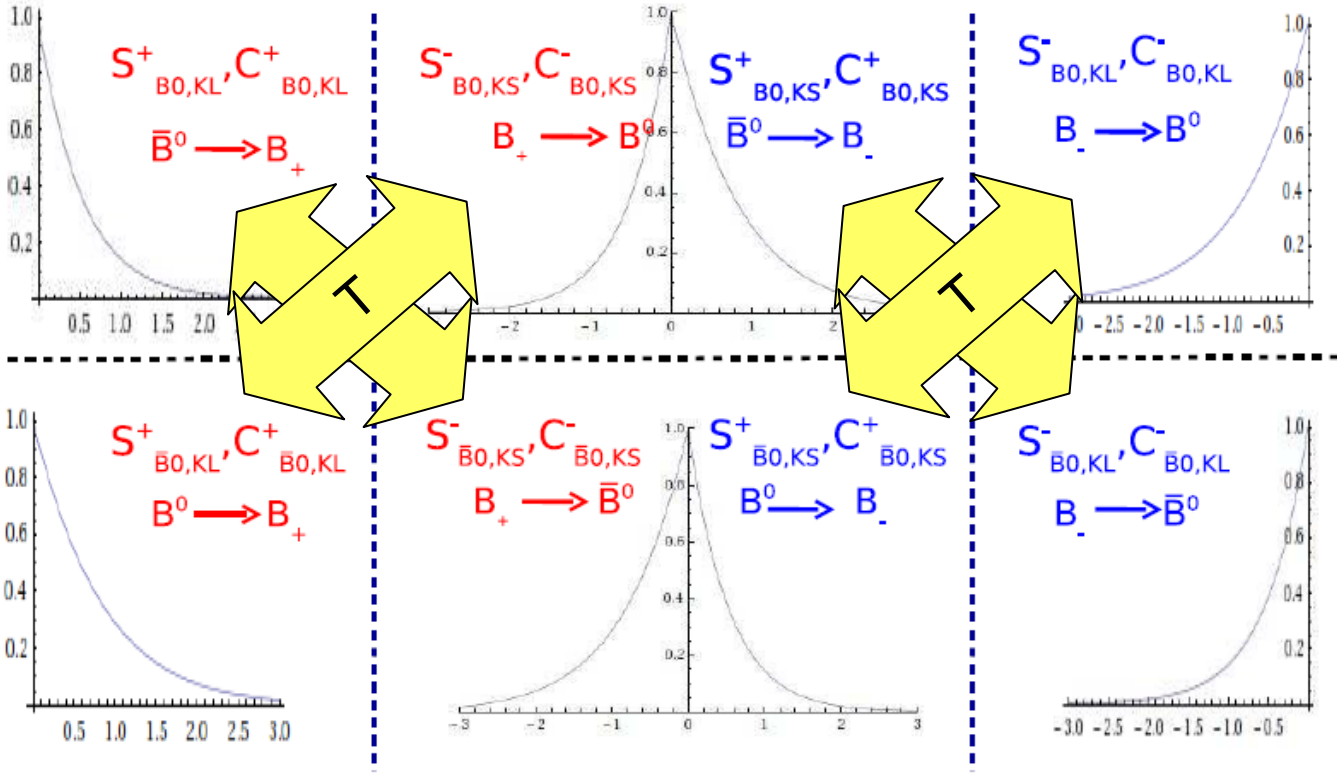


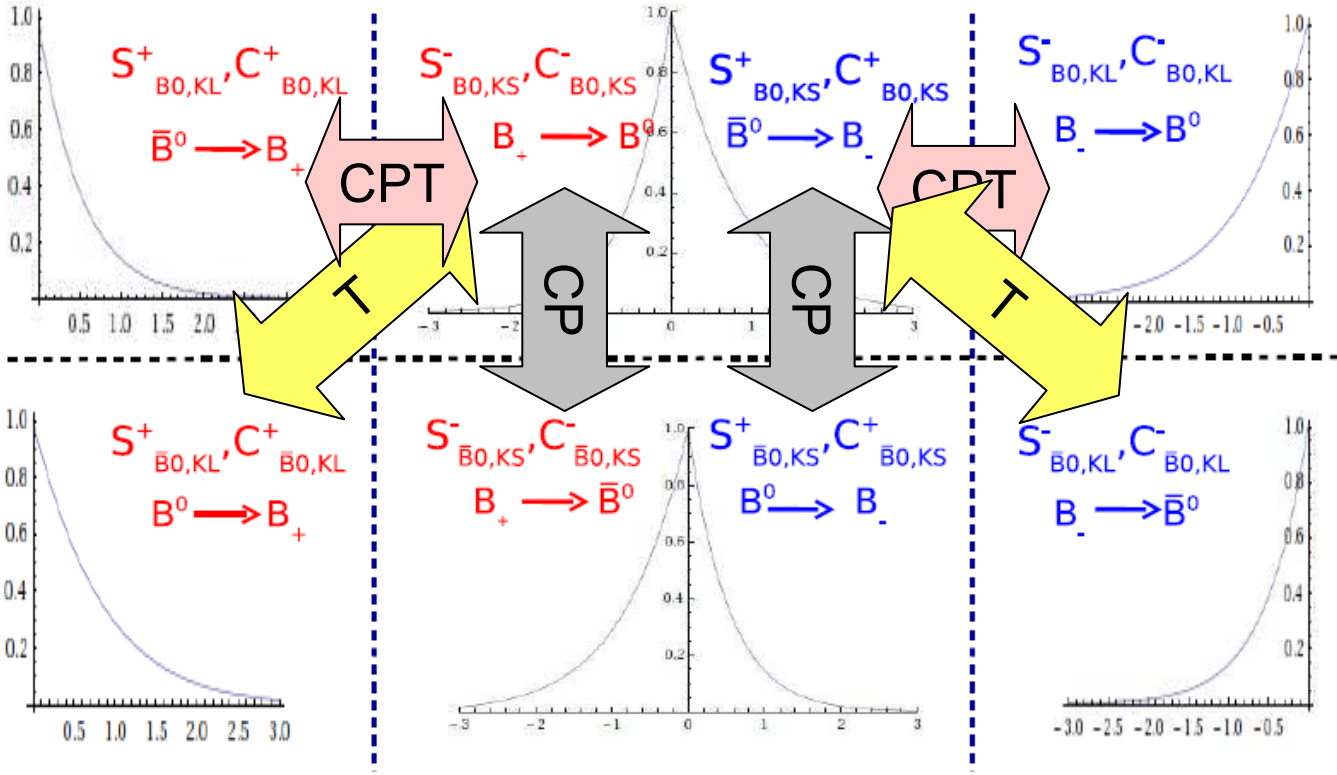
$J/\psi\ K_L$ $J/\psi\ K_S$ $J/\psi\ K_L$

T Violation

$$A \propto S^{\pm} \sin \Delta m \Delta t + C^{\pm} \cos \Delta m \Delta t$$

$$S^{+} = S^{-} = \pm \sin 2\beta$$

$$C^{+} = C^{-} \approx 0$$



T Violation Results

Parameter		Result	
$\Delta S_{\mathcal{T}}^{+} = S_{\ell^-,K_L^0}^{-} - S_{\ell^+,K_S^0}^{+}$	= −2 sin 2β	$-1.37 \pm 0.14 \pm 0.06$	T-Viol.
$\Delta S_{\mathcal{T}}^{-} = S_{\ell^-,K_L^0}^{+} - S_{\ell^+,K_S^0}^{-}$	= 2 sin 2β	$1.17 \pm 0.18 \pm 0.11$	
$\Delta C_{\mathcal{T}}^{+} = C_{\ell^-,K_L^0}^{-} - C_{\ell^+,K_S^0}^{+}$		$0.10 \pm 0.14 \pm 0.08$	=
$\Delta C_{\mathcal{T}}^{-} = C_{\ell^-,K_L^0}^{+} - C_{\ell^+,K_S^0}^{-}$		$0.04 \pm 0.14 \pm 0.08$	
$\Delta S_{\mathcal{CP}}^{+} = S_{\ell^-,K_S^0}^{+} - S_{\ell^+,K_S^0}^{+}$	= −2 sin 2β	$-1.30 \pm 0.11 \pm 0.07$	CP-Viol.
$\Delta S_{\mathcal{CP}}^{-} = S_{\ell^-,K_S^0}^{-} - S_{\ell^+,K_S^0}^{-}$	= 2 sin 2β	$1.33 \pm 0.12 \pm 0.06$	
$\Delta C_{\mathcal{CP}}^{+} = C_{\ell^-,K_S^0}^{+} - C_{\ell^+,K_S^0}^{+}$		$0.07 \pm 0.09 \pm 0.03$	
$\Delta C_{\mathcal{CP}}^{-} = C_{\ell^-,K_S^0}^{-} - C_{\ell^+,K_S^0}^{-}$		$0.08 \pm 0.10 \pm 0.04$	
$\Delta S_{\mathcal{CPT}}^{+} = S_{\ell^+,K_L^0}^{-} - S_{\ell^+,K_S^0}^{+}$		$0.16 \pm 0.21 \pm 0.09$	no CPT Viol.
$\Delta S_{\mathcal{CPT}}^{-} = S_{\ell^+,K_L^0}^{+} - S_{\ell^+,K_S^0}^{-}$		$-0.03 \pm 0.13 \pm 0.06$	
$\Delta C_{\mathcal{CPT}}^{+} = C_{\ell^+,K_L^0}^{-} - C_{\ell^+,K_S^0}^{+}$		$0.14 \pm 0.15 \pm 0.07$	
$\Delta C_{\mathcal{CPT}}^{-} = C_{\ell^+,K_L^0}^{+} - C_{\ell^+,K_S^0}^{-}$		$0.03 \pm 0.12 \pm 0.08$	

BABAR, arXiv:1207.5832

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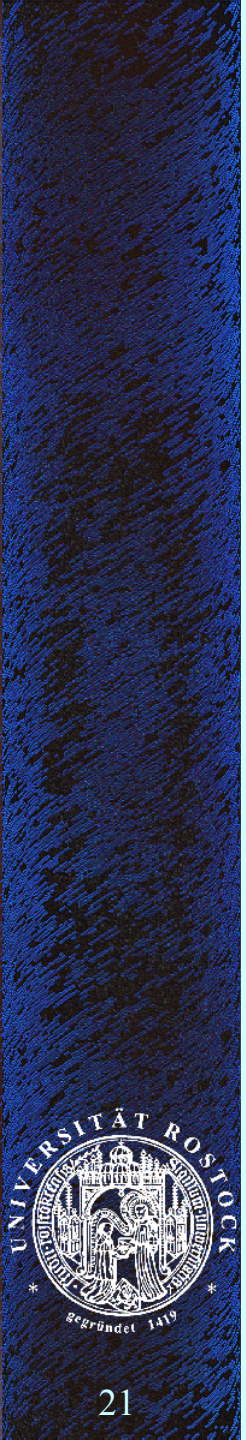
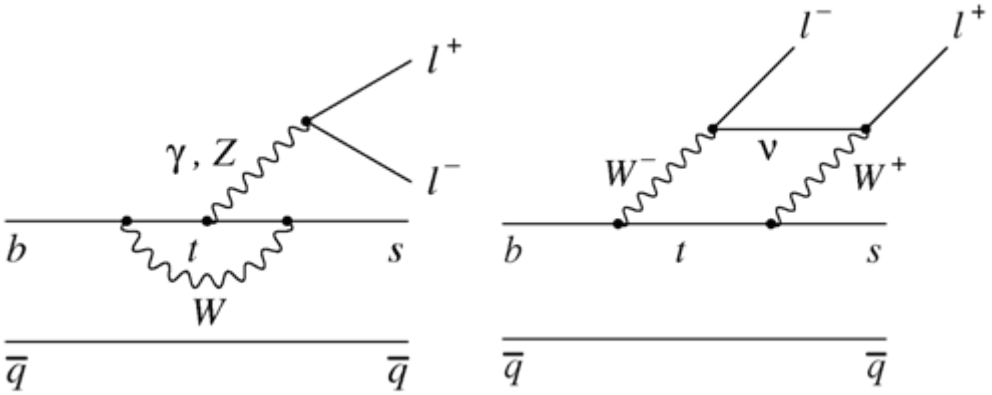
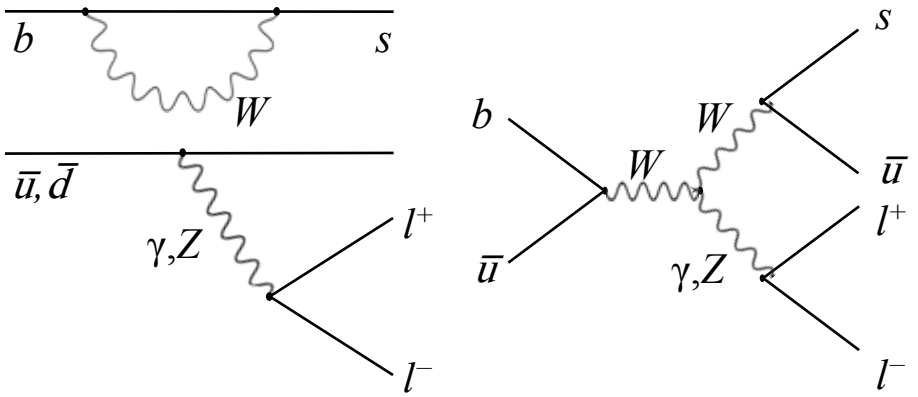


$B \to K^{(*)}\, l^+\, l^-$



B^0, B^+ isospin symmetry



isospin breaking in SM small

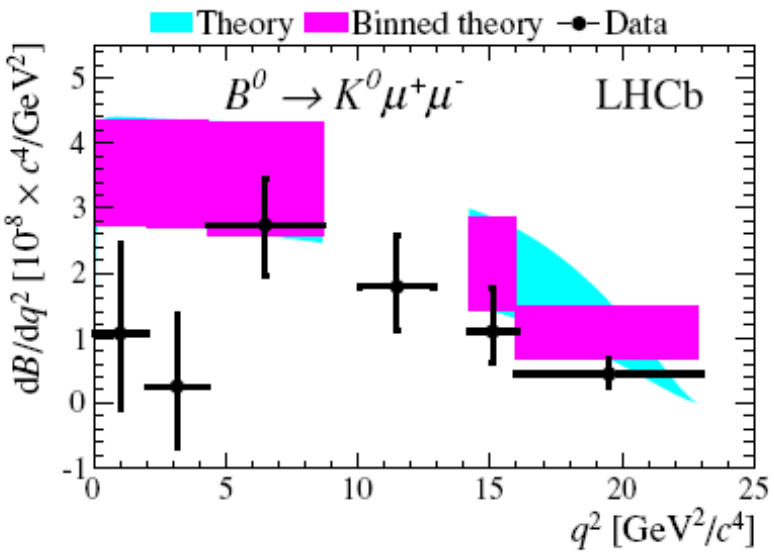
+ New Physics?

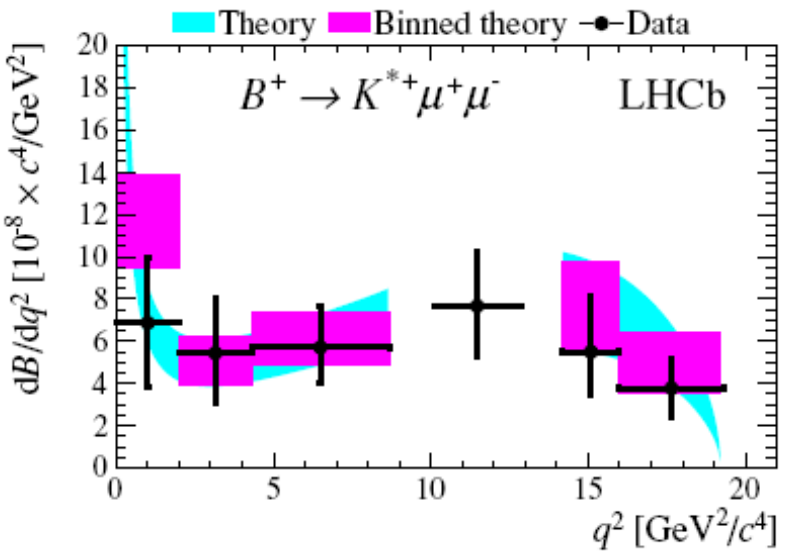
$B \to K^{(*)}\, l^+\, l^-$

BFs in q^2 bins:

$$\frac{d\mathcal{B}^i}{dq^2} = \frac{N^i(B \to K^{(*)}\mu^+\mu^-)}{N(B \to J/\psi K^{(*)})} \times \frac{\mathcal{B}(B \to J/\psi K^{(*)})\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\epsilon^i_{\rm rel}\Delta^i}$$

normalisation

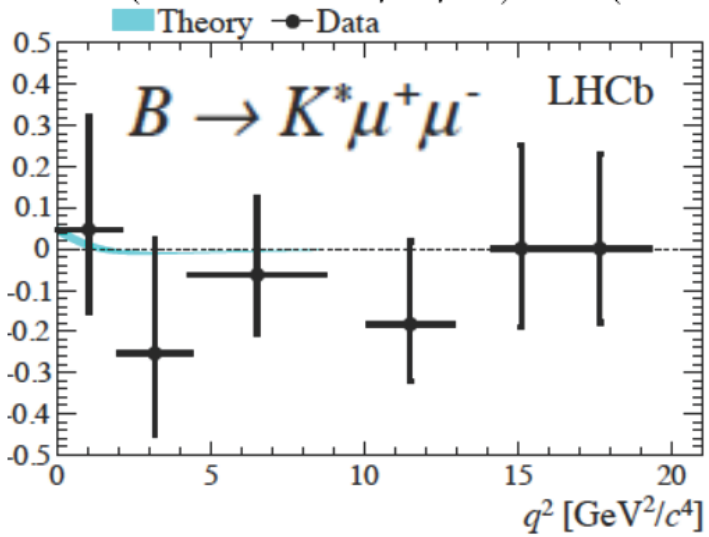


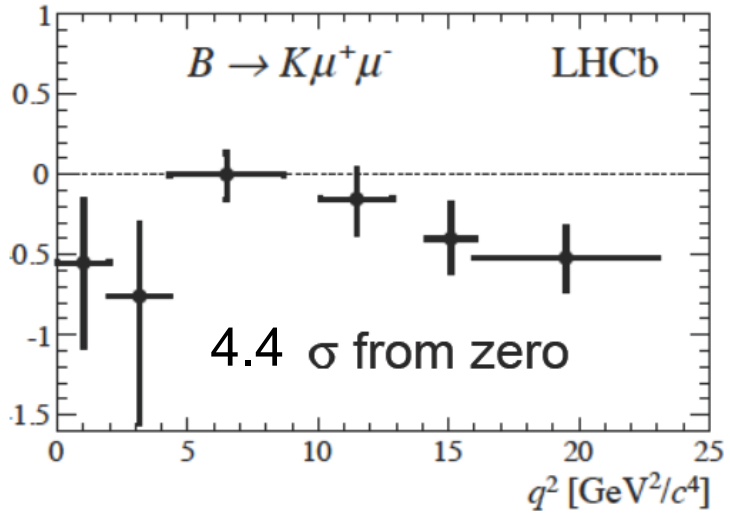


LHCb, arXiv:1205.3422

Isospin asymmetry

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$





K^*ll : $A_I \sim 0$

Kll :
$A_I < 0$ (more B^+ than B^0 decays!)

previous measurements
by BABAR, Belle, CDF
compatible but less sensitive

New Physics?

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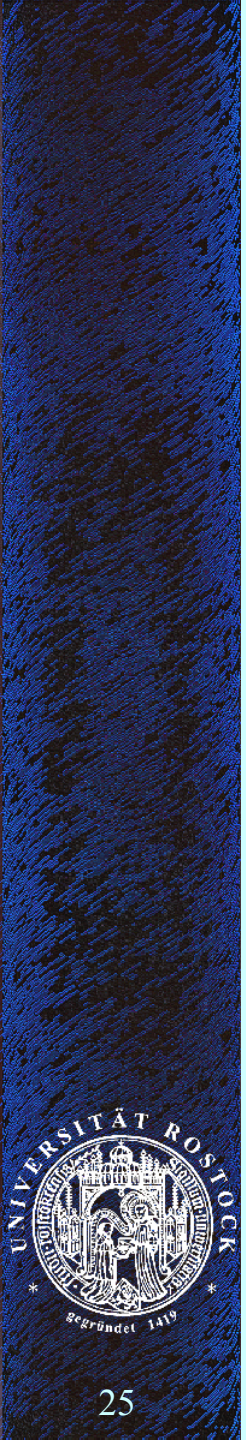
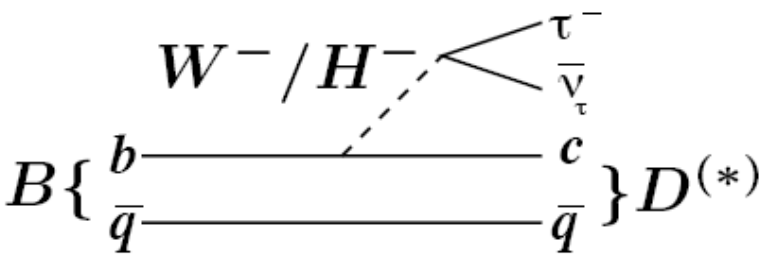


$B \to D^{(*)}\tau\nu$ vs. $D^{(*)}\ell\nu$ Decays

semileptonic decay (tree!)



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}_D| q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_t|^2\right]$$

τ sensitive to additional helicity amplitude H_t

1 fully reco'ed B_{tag} + $D^{(*)}\ell$, missing = 1 or 3 neutrinos

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

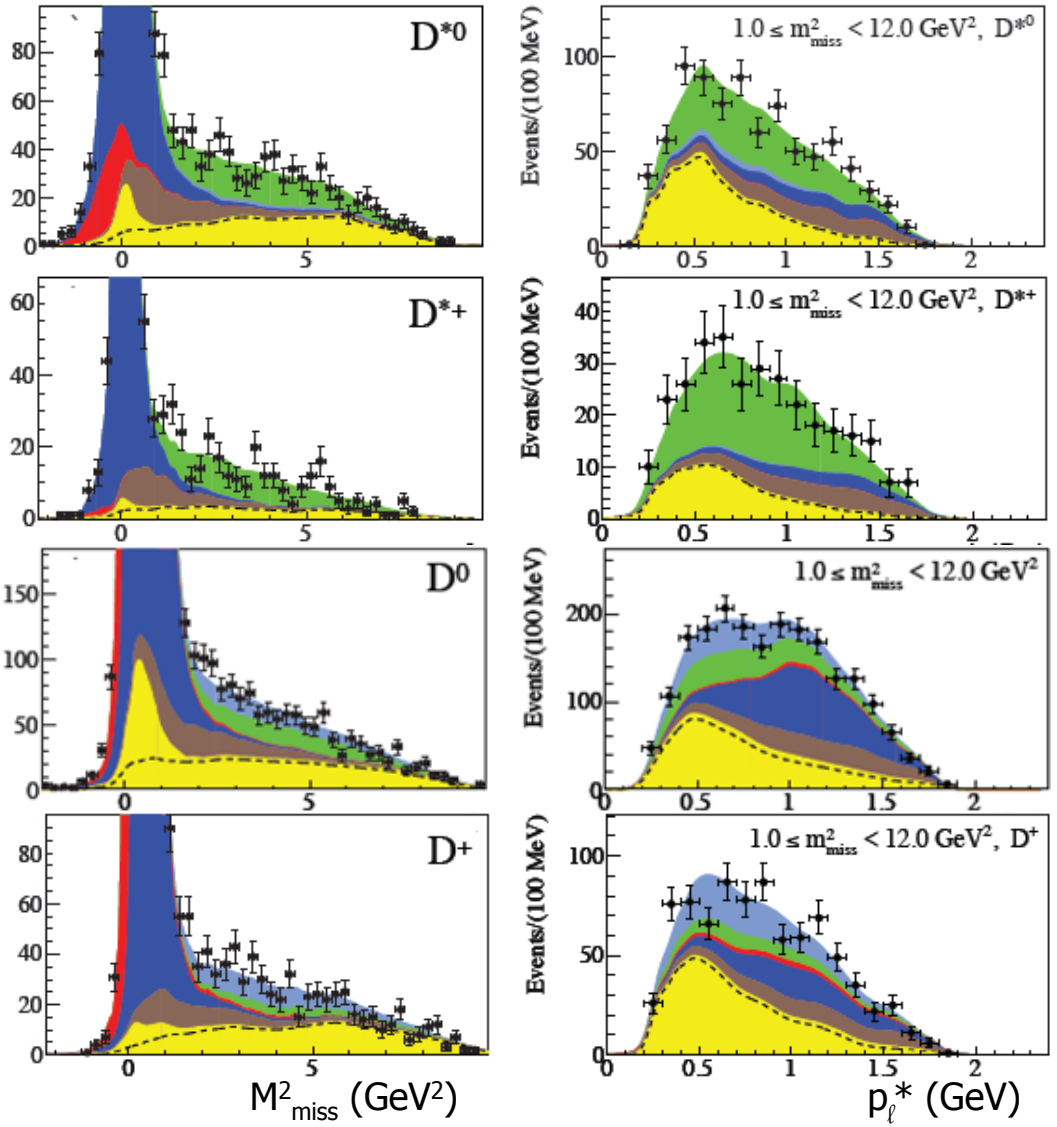
differ only in #ν

$\ell = e$ or μ

$\tau \to \ell\nu\overline{\nu}$

BABAR, PRL 109, 101802 (2012)

$B \to D^{(*)}\tau\nu$ vs. $D^{(*)}\ell\nu$



yields from
ML fit to 2D distr:

p_ℓ

$M^2_{\text{miss}} = (P_{\Upsilon(4S)} - P_{B_{\text{tag}}} - P_{D^{(*)}} - P_\ell)^2$

projections
← shown

- D*τν
- Dτν
- D*lν
- Dlν
- D**lν

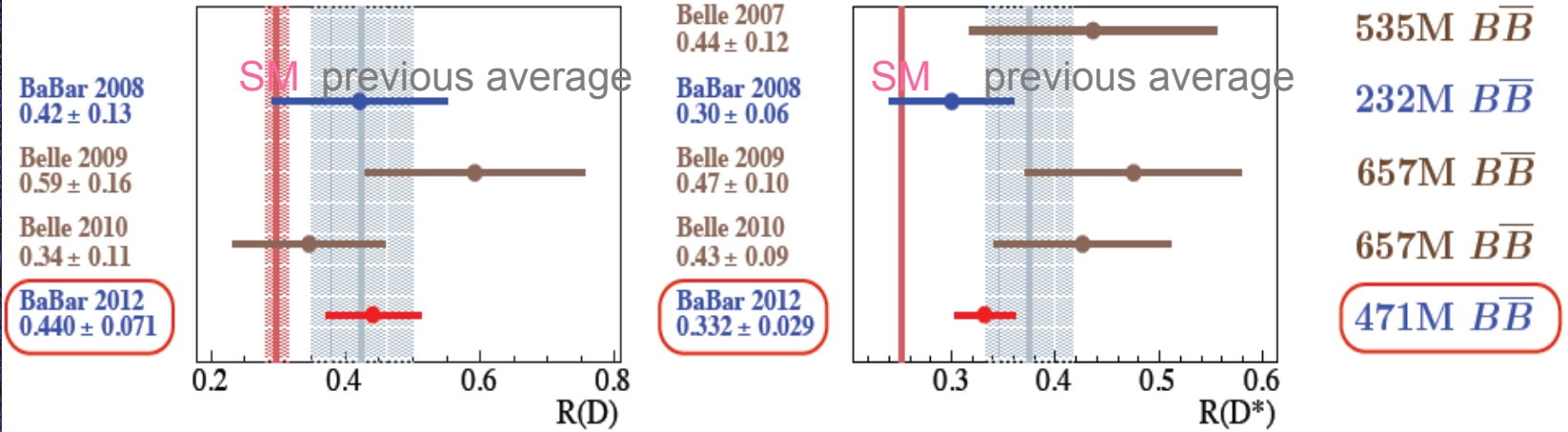
Free yields

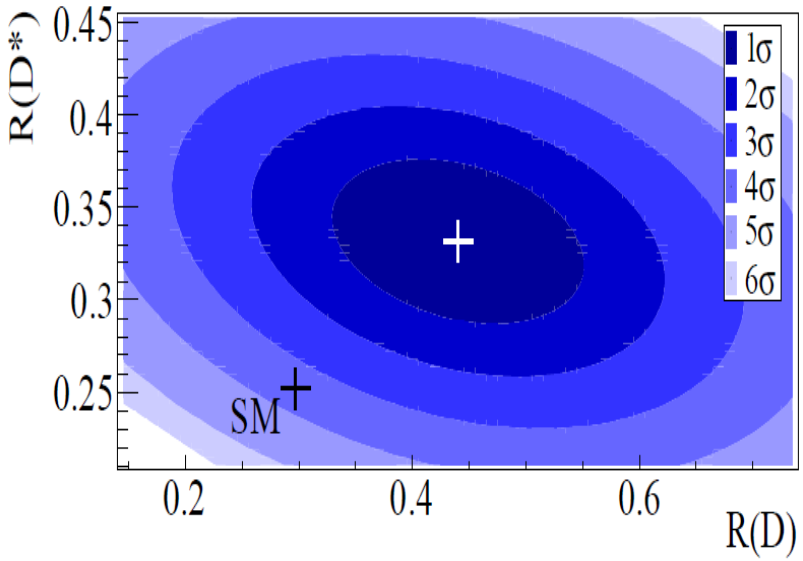
- Bkg.

Fixed yield

$B \to D^{(*)}\tau\nu$ vs. $D^{(*)}\ell\nu$

$$R(D^{(*)}) = \frac{\Gamma(\overline{B} \to D^{(*)}\tau\nu)}{\Gamma(\overline{B} \to D^{(*)}\ell\nu)}$$





	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.293 ± 0.017	0.252 ± 0.003
Diff:	2.0σ	2.7σ

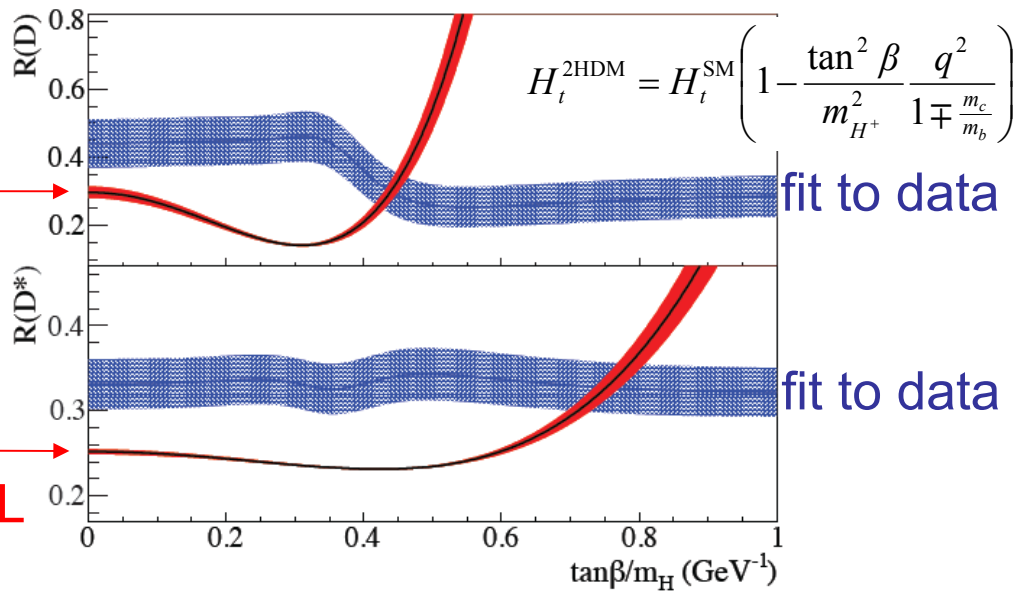
3.4σ from SM

$B \to D^{(*)}\tau\nu$ vs. $D^{(*)}\ell\nu$

3.4σ from SM

New Physics:

2 Higgs Doublets, type II



inconsistent @ >99.8% CL

2 Higgs Doublets, type III with u/c/t flavour-violation is possible [Crivellin, Greub, Kokulu arXiv:1206:2634]

B Meson Decays and CP (and T) Violation

Roland Waldi, Rostock University
XXXII Physics in Collision, Štrbské Pleso 2012

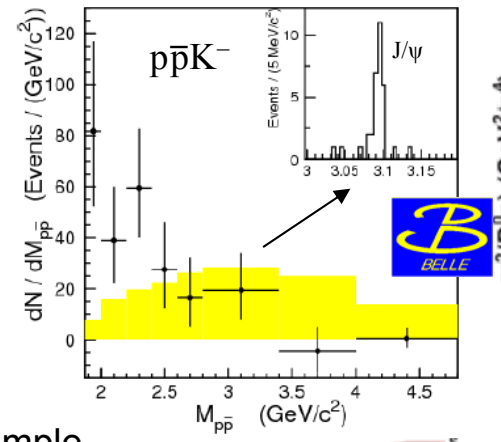
- CPV: $\beta = \phi_1$
- T-Violation
- *B* Decays: a Penguin & New Physics
- *B* Decays: a Tree & New Physics
- *B* Decays to Baryons
- Summary & Conclusions

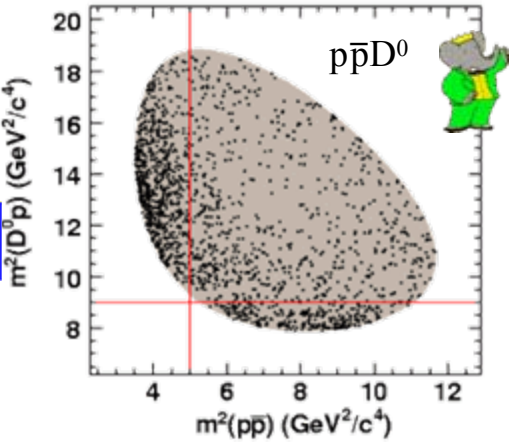
B Decays to Baryons

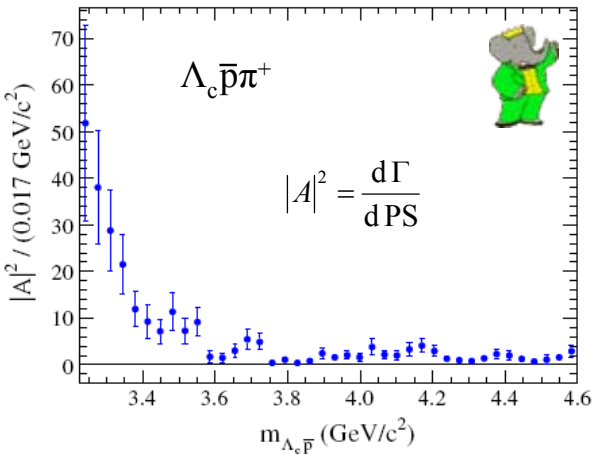
inclusive: (6.8±0.6)% (avg. B^0,B^+) [ARGUS, ZP C56, 1 (1992)]
exclusive: many channels, but
sum only (0.53±0.06)% B^0, (0.85±0.15)% B^+

features:
- 2-body BFs ≪ 3-body < 4-body
- baryon-antibaryon-mass threshold enhancement

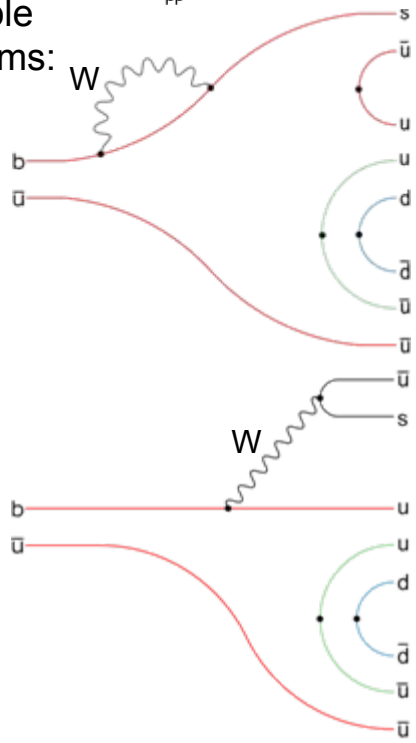
Threshold Enhancement

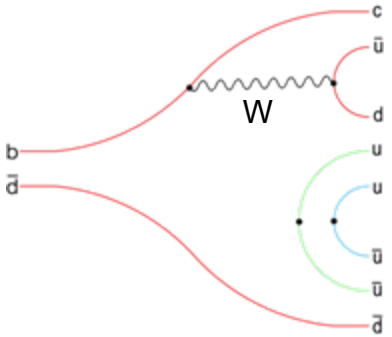


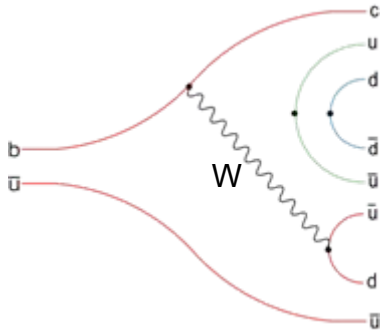




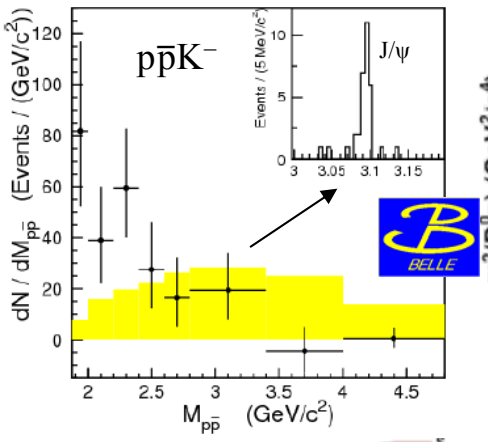
example diagrams:

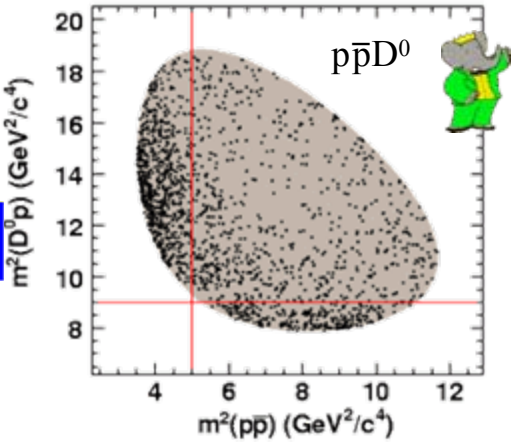


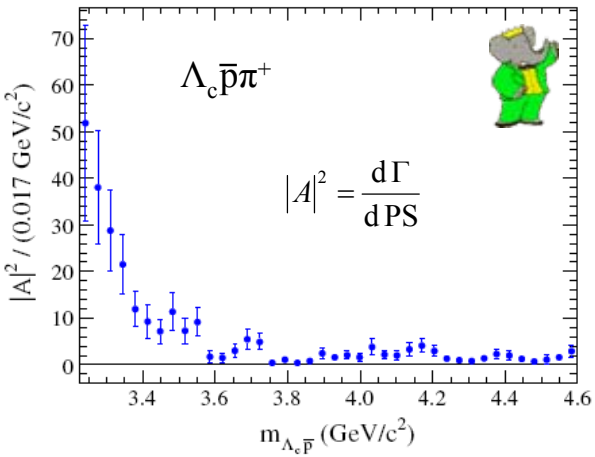


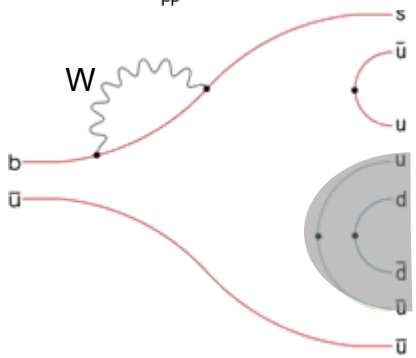


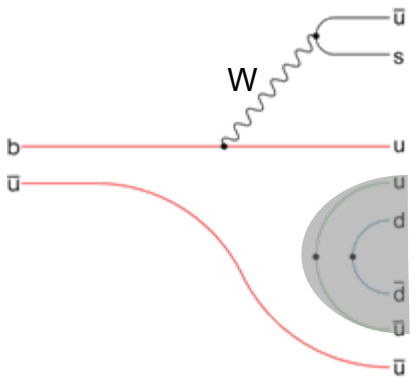
Threshold Enhancement

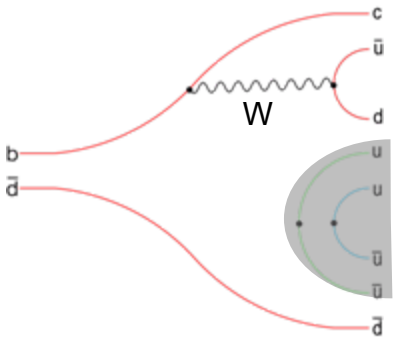


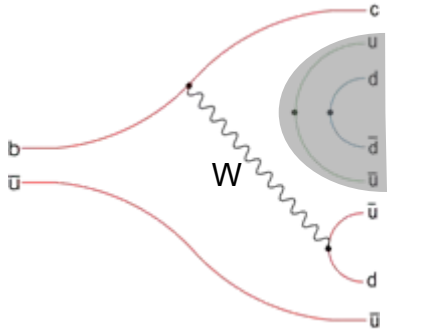








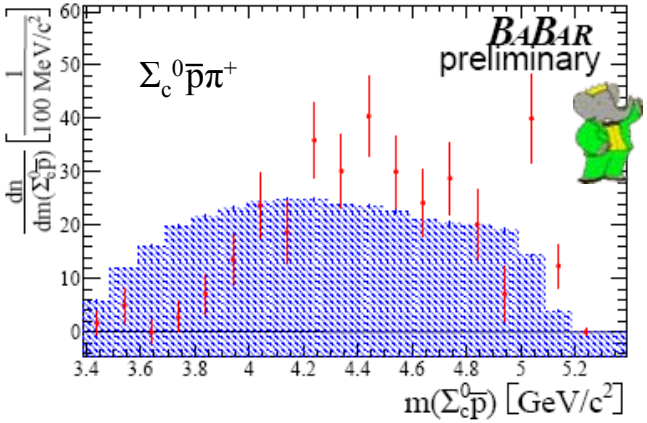




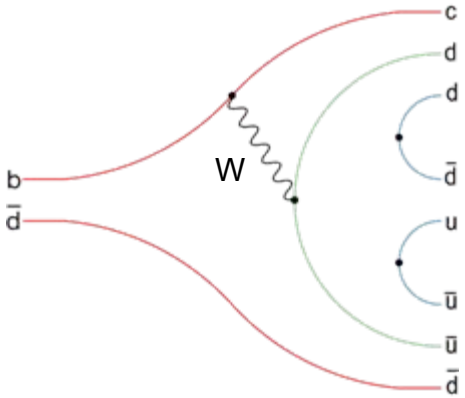
$$B \to (q\bar{q})(q\bar{q}) \to MM^* \to M(B\bar{B})$$

pole model: meson pole
QCD: soft gluons, $\alpha_S(q^2)$

No Threshold Enhancement



example diagram:



$$B \to (qq)(\bar{q}\bar{q}) \to B\bar{B}^* \to B(M\bar{B})$$

$$B \to (qq)(\bar{q}\bar{q}) \to B^*\bar{B} \to (BM)\bar{B}$$

pole model: baryon pole
QCD: hard gluons (2-body)
or extra mesons

Summary & Conclusions

sorry for the subjective selection – there are just too many analyses

- CKM parameters: precision increasing, SM ok
- T violation observed in $B^0, \bar{B}^0$ quantum state transitions

New Physics: no smoking gun, but some "tensions":

- isospin asymmetry in ll-penguins (pointing to no specific direction)
- semileptonic decays to τ (exotic charged Higgs?)
- Baryonic B decays: many data, threshold enhancement qualitatively understood, no quantitative theory

Thank you!

Additional Info

Another Isospin Asymmetry

Branching fractions (old data, <2008):

$B \to p\bar{p}K^+$ $(5.9\pm0.5)\cdot10^{-6}$

$B \to p\bar{p}K^{*+}$ $(3.69\pm0.8)\cdot10^{-6}$

$B \to p\bar{p}K^0$ $(2.7\pm0.3)\cdot10^{-6}$

$B \to p\bar{p}K^{*0}$ $(1.2\pm0.3)\cdot10^{-6}$

$$\frac{\Gamma(B^+)}{\Gamma(B^0)} = \frac{\mathcal{B}(B^+)\cdot\tau(B^0)\cdot\mathcal{B}(\Upsilon 4S \to B^0\bar{B}^0)}{\mathcal{B}(B^0)\cdot\tau(B^+)\cdot\mathcal{B}(\Upsilon 4S \to B^+B^-)}$$

→ ratios 1.91 ± 0.27, 2.7 ± 0.3

The Unitary CKM Matrix

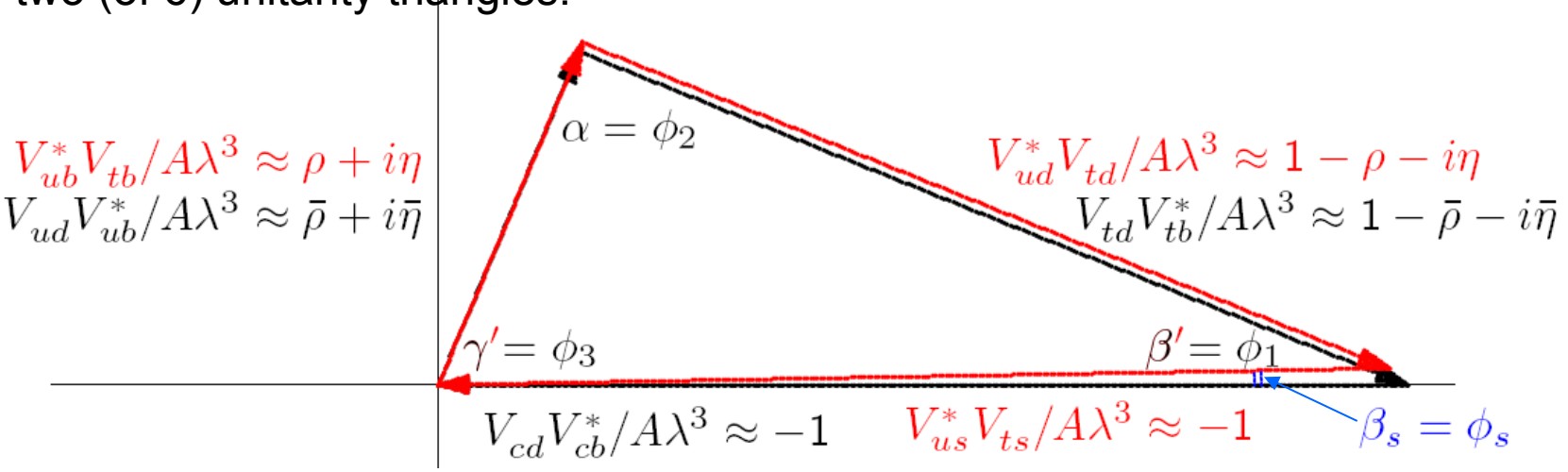
standard phase convention:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\tilde{\beta}_s} & |V_{tb}| \end{pmatrix}$$

Wolfenstein-like:

$$\begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda-A^2\lambda^5(\rho+i\eta-\frac{1}{2}) & 1-\frac{\lambda^2}{2}-(\frac{1}{8}+\frac{A}{2})\lambda^4 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)(1-\frac{\lambda^2}{2})] & -A\lambda^2-A\lambda^4(\rho+i\eta-\frac{1}{2}) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

two (of 6) unitarity triangles:



CPV Phenomenology

asymmetry

$$a(T) = \left.\frac{\dot{N}(\overline{B} \to f) - \dot{N}(B \to f)}{\dot{N}(\overline{B} \to f) + \dot{N}(B \to f)}\right|_T = C \cos xT + S \sin xT$$

where

$$xT = \Delta m \Delta t$$

$$C = \frac{|r|^2 - 1}{|r|^2 + 1}$$

$$S = \frac{2\,\mathcal{I}m\, r}{1 + |r|^2}$$

$$r_f := \frac{\langle f|\mathcal{H}|\overline{B}^0\rangle}{\langle f|\mathcal{H}|B^0\rangle}\frac{\langle \overline{B}^0|B_L\rangle}{\langle B^0|B_L\rangle}$$

$$J/\psi\, K_S^0: \quad r = e^{2i\beta}, S = \sin 2\beta, C = 0$$

$$J/\psi\, K_L^0: \quad r = e^{-2i\beta}, S = -\sin 2\beta, C = 0$$

CP-Asymmetry Example: B_s

$$a(T) = \left.\frac{\dot{N}(\overline{B}_s \to X) - \dot{N}(B_s \to X)}{\dot{N}(\overline{B}_s \to X) + \dot{N}(B_s \to X)}\right|_T = \frac{C\cos xT + S\sin xT}{\cosh yT + \Omega \sinh yT}$$

where

$$xT = \Delta m t \quad \text{or} \quad xT = \Delta m \Delta t$$
$$yT = \frac{\Delta\Gamma}{2} t \quad \text{or} \quad yT = \frac{\Delta\Gamma}{2}\Delta t$$

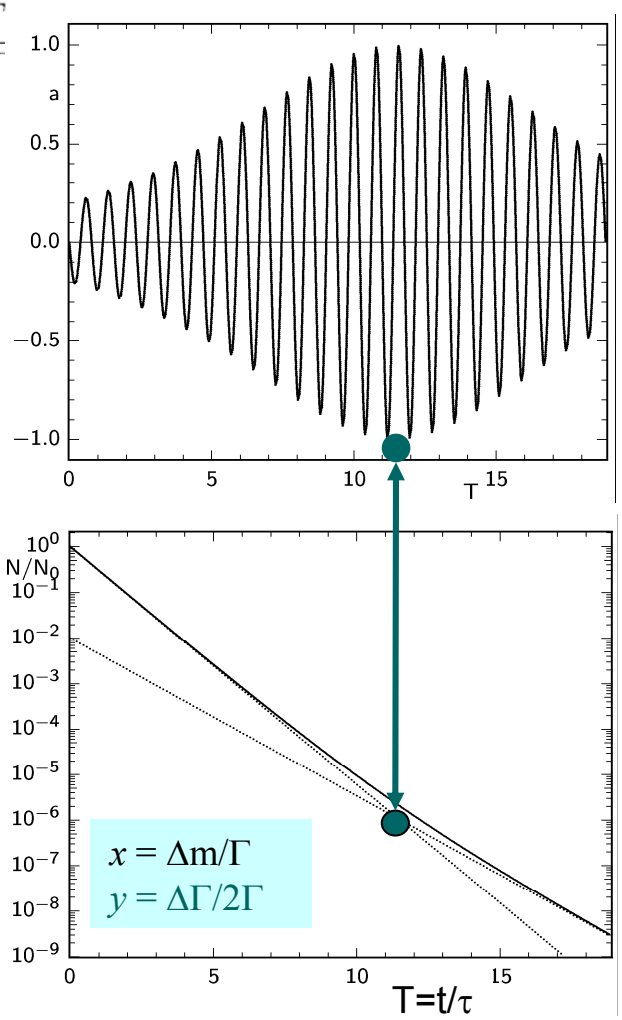
$$C = -\frac{2\,\mathcal{R}e\,\eta_f}{1+|\eta_f|^2} = \frac{|r|^2-1}{|r|^2+1} = \pm\sqrt{1-{D_P}^2}$$

$$S = -\frac{2\,\mathcal{I}m\,\eta_f}{1+|\eta_f|^2} = \frac{2\,\mathcal{I}m\,r}{1+|r|^2} = D_P \sin \arg r$$

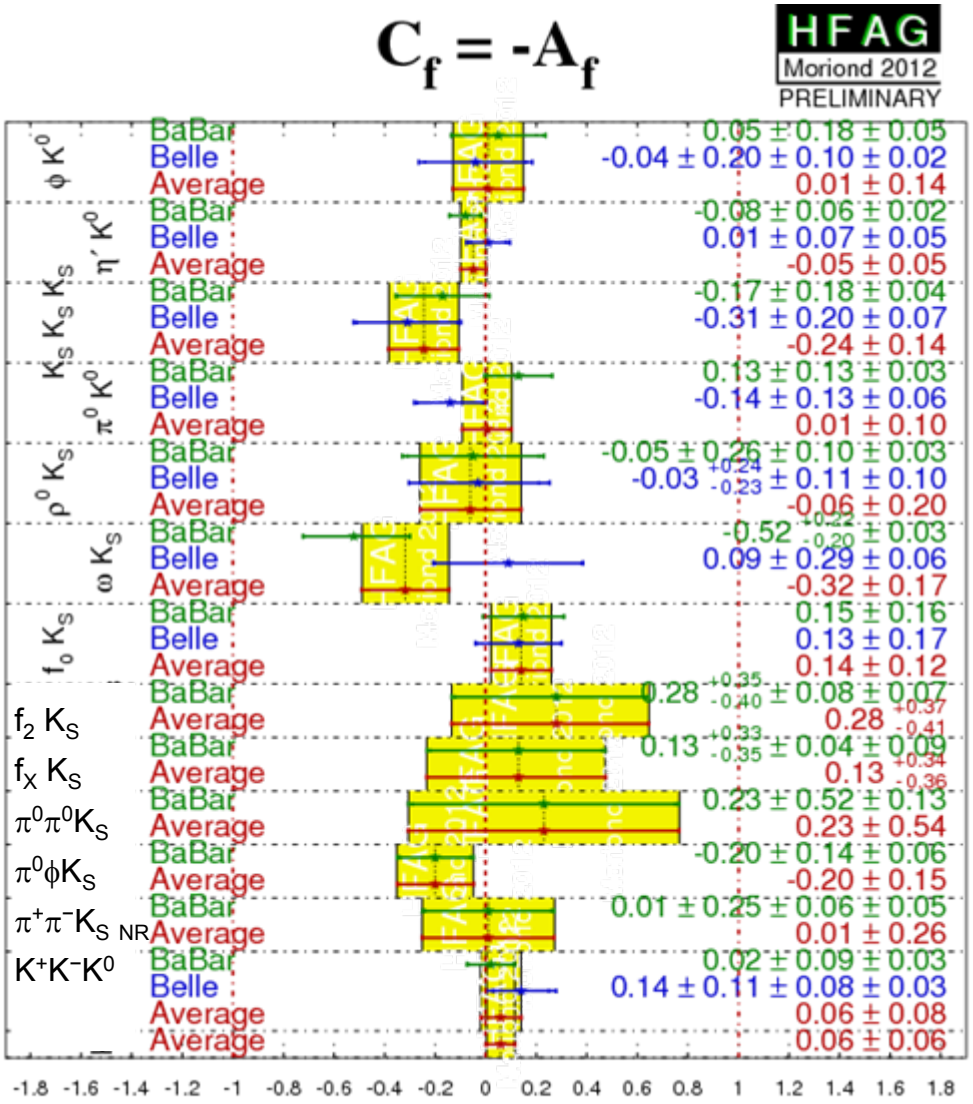
$$\Omega = \frac{1-|\eta_f|^2}{1+|\eta_f|^2} = \frac{2\,\mathcal{R}e\,r}{1+|r|^2} = D_P \cos \arg r$$

physics dilution $D_P = \dfrac{2|r|}{1+|r|^2}$

$$C^2 + S^2 + \Omega^2 = 1$$



sin 2β′ (b → s penguins)



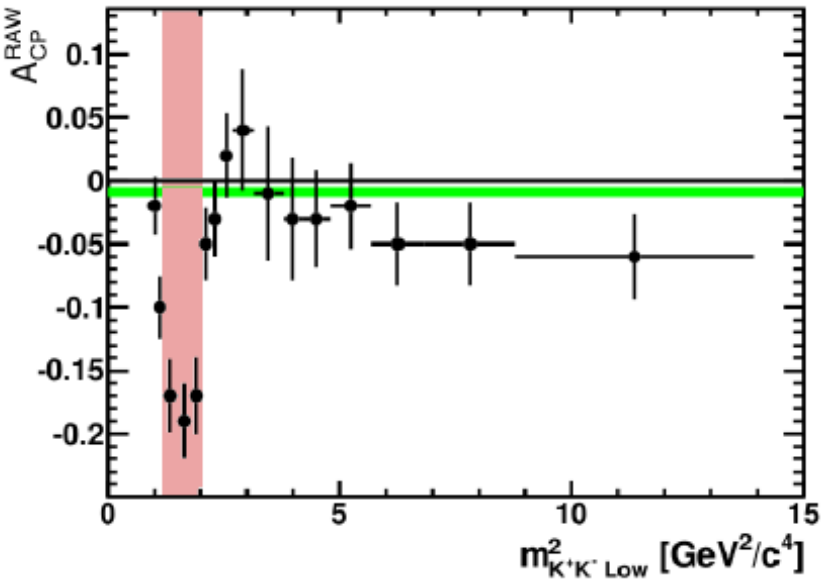
$$A \propto S_f \sin \Delta m \Delta t - C_f \cos \Delta m \Delta t$$

if other diagrams contribute → direct CPV

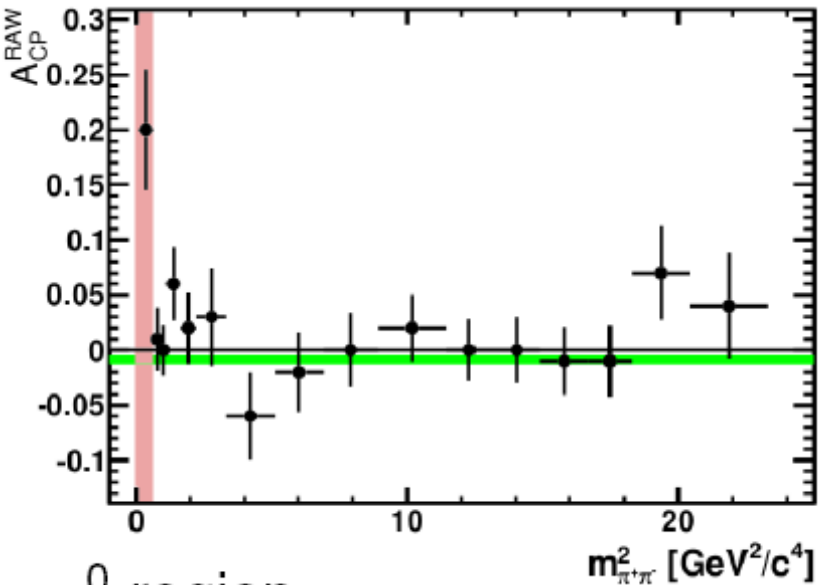
no significant $C \neq 0$ seen.

Raw CP Asymmetry

$B^{\pm} \to K^{\pm}K^{+}K^{-}$

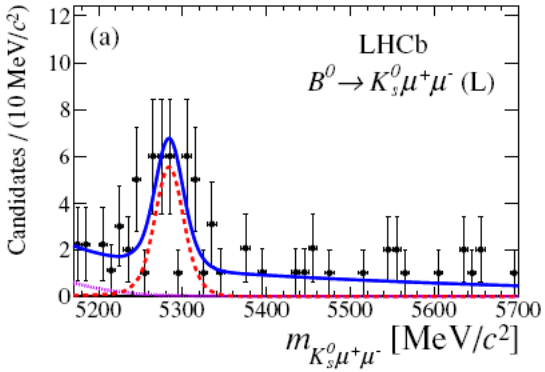


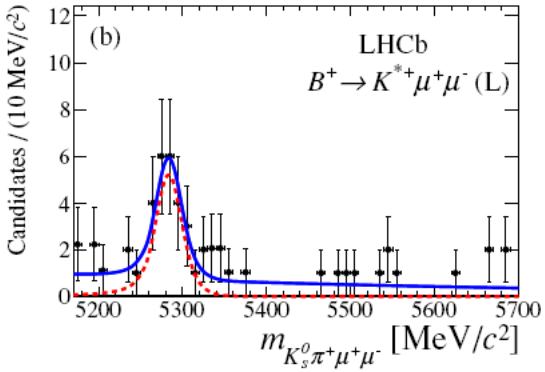
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

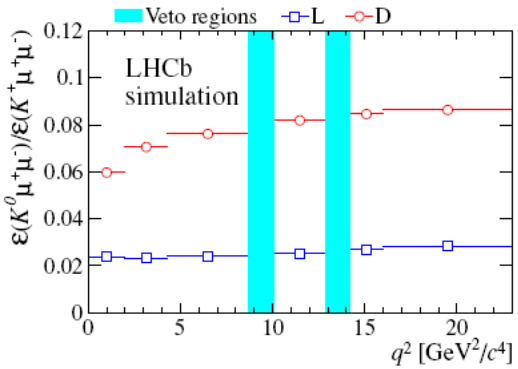


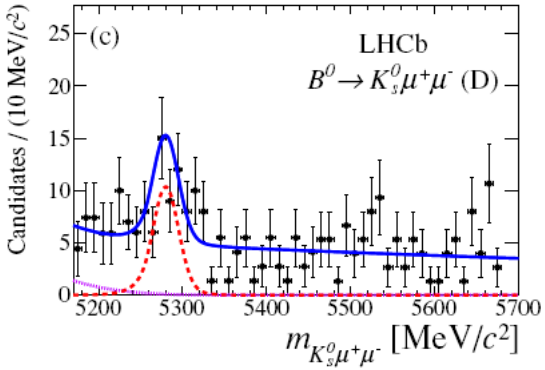
ρ^0 region

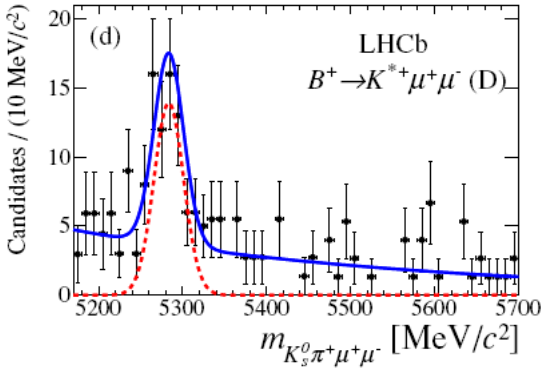
$B \to K^{(*)}\, l^+\, l^-$

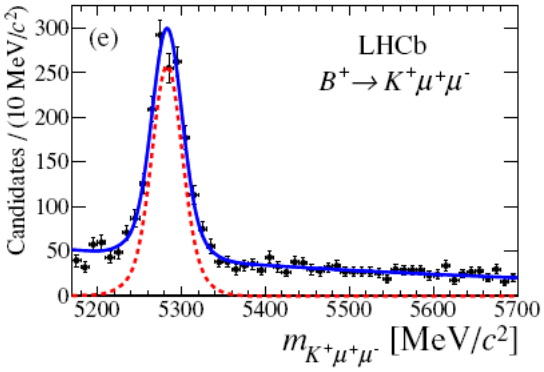

(a)
LHCb
$B^0 \to K^0_s \mu^+\mu^-$ (L)
Candidates / (10 MeV/c^2)
$m_{K^0_s\mu^+\mu^-}$ [MeV/c^2]

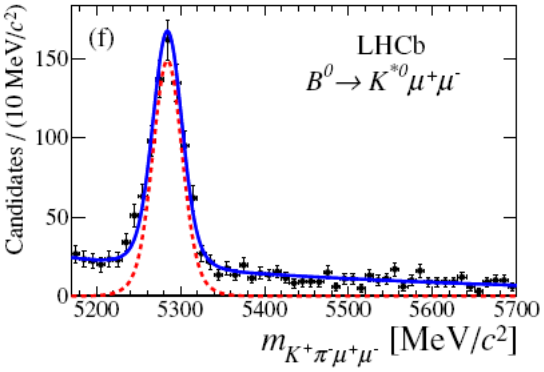

(b)
LHCb
$B^+ \to K^{*+}\mu^+\mu^-$ (L)
Candidates / (10 MeV/c^2)
$m_{K^0_s\pi^+\mu^+\mu^-}$ [MeV/c^2]


Veto regions
L
D
LHCb
simulation
$\varepsilon(K^{*0}\mu^+\mu^-)/\varepsilon(K^+\mu^+\mu^-)$
q^2 [GeV^2/c^4]


(c)
LHCb
$B^0 \to K^0_s \mu^+\mu^-$ (D)
Candidates / (10 MeV/c^2)
$m_{K^0_s\mu^+\mu^-}$ [MeV/c^2]


(d)
LHCb
$B^+ \to K^{*+}\mu^+\mu^-$ (D)
Candidates / (10 MeV/c^2)
$m_{K^0_s\pi^+\mu^+\mu^-}$ [MeV/c^2]


(e)
LHCb
$B^+ \to K^+\mu^+\mu^-$
Candidates / (10 MeV/c^2)
$m_{K^+\mu^+\mu^-}$ [MeV/c^2]


(f)
LHCb
$B^0 \to K^{*0}\mu^+\mu^-$
Candidates / (10 MeV/c^2)
$m_{K^+\pi^-\mu^+\mu^-}$ [MeV/c^2]

R(D) and R(D*) Measurement

significance

Mode	$N_{\rm sig}$	$N_{\rm norm}$	$R(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)\,(\%)$	$\Sigma_{\rm stat}(\sigma)$	$\Sigma_{\rm tot}(\sigma)$
$D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	$0.429 \pm 0.082 \pm 0.052$	$0.96 \pm 0.18 \pm 0.13$	5.5	4.7
$D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	$0.322 \pm 0.032 \pm 0.021$	$1.83 \pm 0.18 \pm 0.13$	11.3	9.6
$D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	$0.469 \pm 0.084 \pm 0.052$	$1.02 \pm 0.18 \pm 0.13$	6.1	5.3
$D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	$0.355 \pm 0.039 \pm 0.020$	$1.78 \pm 0.19 \pm 0.11$	11.6	10.5
$D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	$0.440 \pm 0.058 \pm 0.042$	$0.98 \pm 0.13 \pm 0.11$	8.4	6.8
$D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	$0.332 \pm 0.024 \pm 0.017$	$1.88 \pm 0.13 \pm 0.12$	16.4	13.4

Last two rows: Isospin constrained fit

$B \to D^{(*)}\tau\nu$ vs. $D^{(*)}\ell\nu$

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

$\ell = e$ or μ

	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
$N_{\rm sig}$	314 ± 60	177 ± 31	489 ± 63
Significance (σ)	5.5	6.1	8.4
$R(D)$	0.429 ± 0.082	0.469 ± 0.084	0.440 ± 0.058
$\mathcal{B}(\overline{B} \to D\tau^-\overline{\nu}_\tau)$ (%)	0.96 ± 0.18	1.02 ± 0.18	0.98 ± 0.13

	$D^{*0}\tau\nu$	$D^{*+}\tau\nu$	$D^*\tau\nu$
$N_{\rm sig}$	639 ± 62	245 ± 27	888 ± 63
Significance (σ)	11.3	11.6	16.4
$R(D^*)$	0.322 ± 0.032	0.355 ± 0.039	0.332 ± 0.024
$\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)$ (%)	1.83 ± 0.18	1.78 ± 0.19	1.88 ± 0.13

B Decays to Baryons

example: 3-body spectator decays

O_1, “external” O_2, “internal”