B_s DECAYS AND MIXING

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Presented by J. Rosner – Beauty 2011, Amsterdam – April 4, 2011

CP-violating mixing in $B_s(\bar{B}_s) \to J/\psi\phi$

Can one see explicit time-dependence showing CP violation?

Update of M. Gronau and J. L. Rosner, PL B **669**, 321 (2008)

D0 dimuon asymmetry – Is it due to b's? K's?

Can it be made to go away?

Vertex cut : M. Gronau and J. L. Rosner, PR D **82**, 077301 (2010)

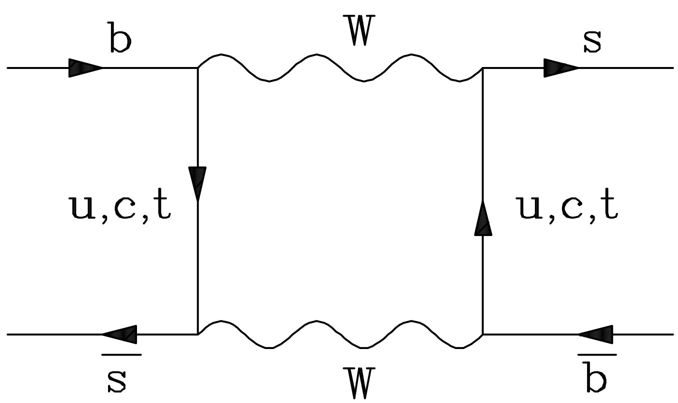
What do triple products in $B_{(s)} \to V_1V_2$ measure?

$Sometimes$ CP violation: A. Datta et al., arXiv:1103.2442v2

Cursory look at new physics scenarios

STRANGE B MIXING

Formalism: Lenz–Nierste–CKMfitter, PR D **83**, 036004 (2001)



B_s–$\overline{B}_s$ mixing dominated by t in loop

$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)$ ps^{-1} (CDF);
$\Delta m_s = (17.63 \pm 0.11 \pm 0.04)$ ps^{-1} (LHCb):
agrees with Standard Model

$$|B_{sL}\rangle = p|B_s\rangle + q|\bar{B}_s\rangle \; ; \quad |B_{sH}\rangle = p|B_s\rangle - q|\bar{B}_s\rangle$$

For $\Delta\Gamma \ll \Delta m$, $q/p \simeq \exp(2i\beta_s)$, $\beta_s^{\rm SM} = -{\rm Arg}\left(\frac{-V_{ts}^* V_{tb}}{V_{cs}^* V_{cb}}\right) \simeq 0.02$.

SM $B_s \to J/\psi\phi$ CP asymmetry governed by mixing $\phi_M = -2\beta_s$

2008: CDF and D0 favored mixing phase differing from $-2\beta_s$ by $\sim 2.2\sigma$ based on $B_s \to J/\psi\phi$

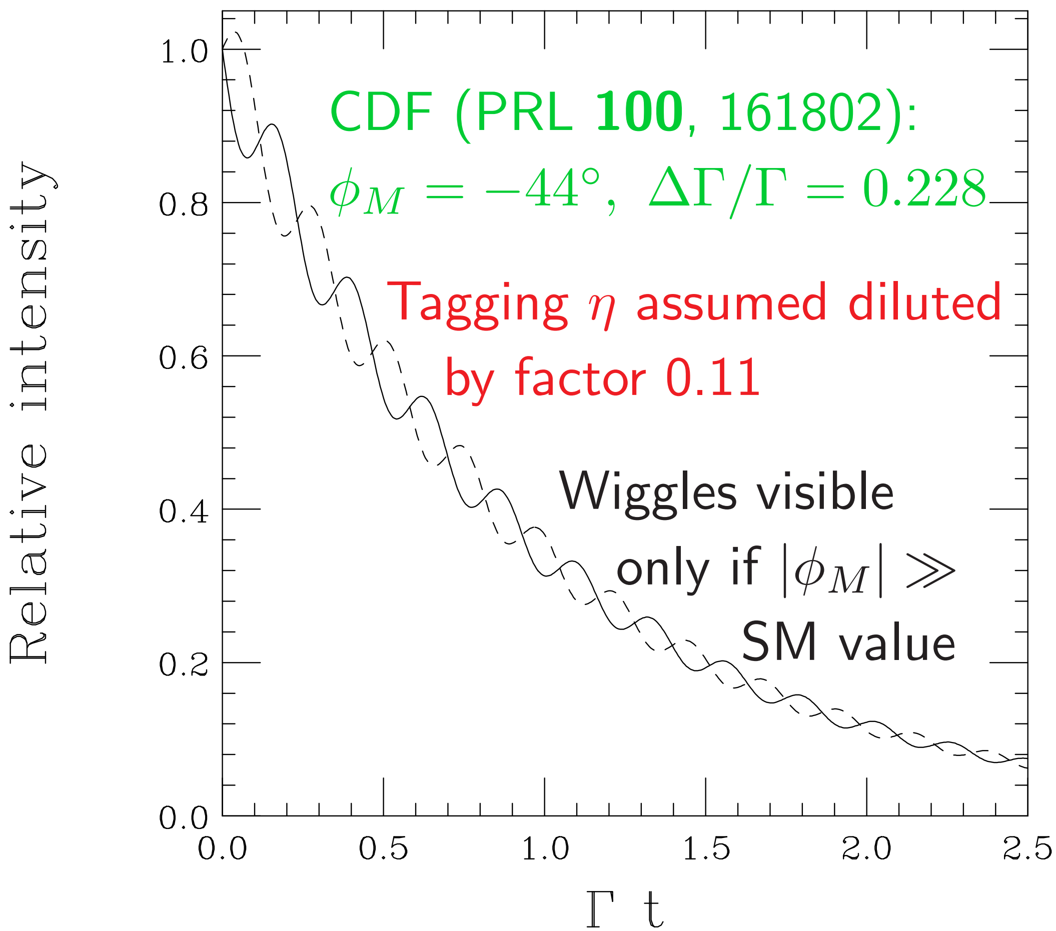
Gronau and JLR pointed out that large mixing phase (illustrative value was then $\phi_M = -44^\circ$) would imply detectable time-dependence of angular distribution coefficients, differing for tagged B_s and $\overline{B}_s$

B_s DECAYS: TIME-DEPENDENCE

CP test: tag at $t = 0$: $\eta = \pm 1$ for tagged $(B_s, \bar{B}_s)$

$\mathcal{T}_+$, $\mathcal{T}_-$ $\Leftrightarrow$ $|A_\parallel|^2$, $|A_\perp|^2$ (different angular dependences)

$$\mathcal{T}_\pm \equiv e^{-\Gamma t}[\cosh(\Delta\Gamma t)/2 \mp \cos(\phi_M)\sinh(\Delta\Gamma t)/2) \pm \eta \sin(\phi_M) \sin(\Delta m_s t)]$$



Time-dependence of $\mathcal{T}_\pm$ based on CDF (2008) for $B_s \to J/\psi\phi$

Solid: $\mathcal{T}_+$, B_s tag;

Dashed: $\mathcal{T}_+$, $\bar{B}_s$ tag;

Similar curves for $\mathcal{T}_-$

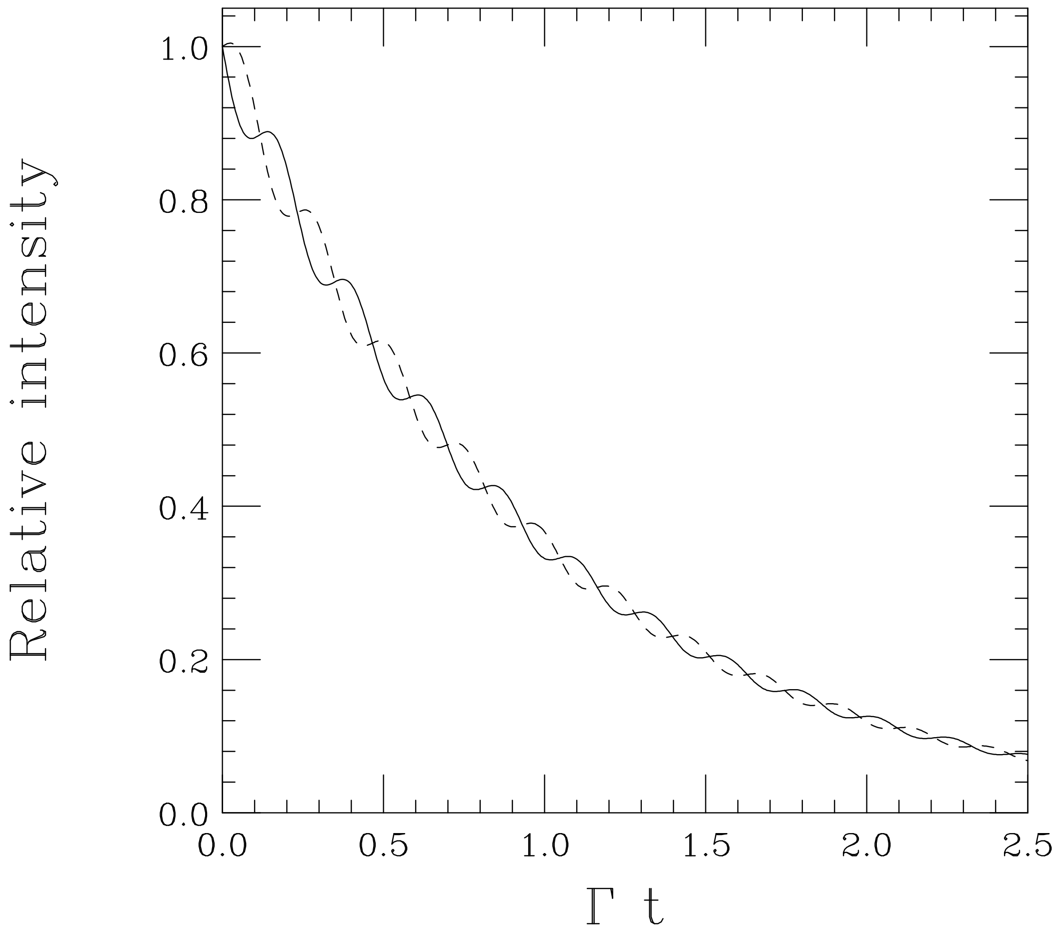
Advocated such a plot as evidence for CP violation in $B_s \to J/\psi\phi$ at level beyond the Standard Model

UPDATED t-DEPENDENCE

$\phi_M = -39^\circ$ (my est.), $\Delta\Gamma/\Gamma = 0.143$, dilution $= 11\%$

CDF Public Note CDF/ANAL/BOTTOM/PUBLIC/10206 Version 1.1

Oscillations a bit smaller; still should be visible



O. Leroy, LHCb, La Thuile: est. CDF $\phi_M = (-31 \pm 29)^\circ$

D0 6098-CONF: $(-44^{+22}_{-21} \pm 1)^\circ$

My average: $(-39 \pm 17)^\circ$

$\Delta\Gamma_s$ in ps^{-1}:

CDF: $0.075 \pm 0.035 \pm 0.010$

D0: $0.15 \pm 0.06 \pm 0.01$

LHCb: $\phi_M \in [-2.7, -0.5]$ (68% c.l.), 1.2σ from SM

Waiting for ATLAS, CMS

$\mu^\pm\mu^\pm$ BACKGROUND CHECK

Standard Model predicts small asymmetry in yield of same-sign muon pairs due to $b\bar{b}$ production followed by meson $\Leftrightarrow$ antimeson oscillation:

$A^b_{sl} \equiv \frac{N^{++}-N^{--}}{N^{++}+N^{--}} = (-2.0 \pm 0.3) \times 10^{-4}$ (Lenz-Nierste 1102.4274)

D0 reports $A^b_{sl} = (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$, nearly $50\times$ SM: PR D **82**, 032001 (2010); PRL **105**, 081801 (2010). CDF: $\bar{\chi}$

Interpreted as 3.2σ evidence for CP violation in neutral B mixing

D0: 16 systematic checks $\Rightarrow$ results consistent with nominal

Correct kaon decay BG crucial; Gronau and JLR suggested to see if a smaller asymmetry was obtained in a sample depleted in $b\bar{b}$ pairs

Reduce maximum allowed impact parameter of muon tracks and see if signal vanishes more rapidly than background

Effect of suggested cut $b < 100$ μm not yet known to us

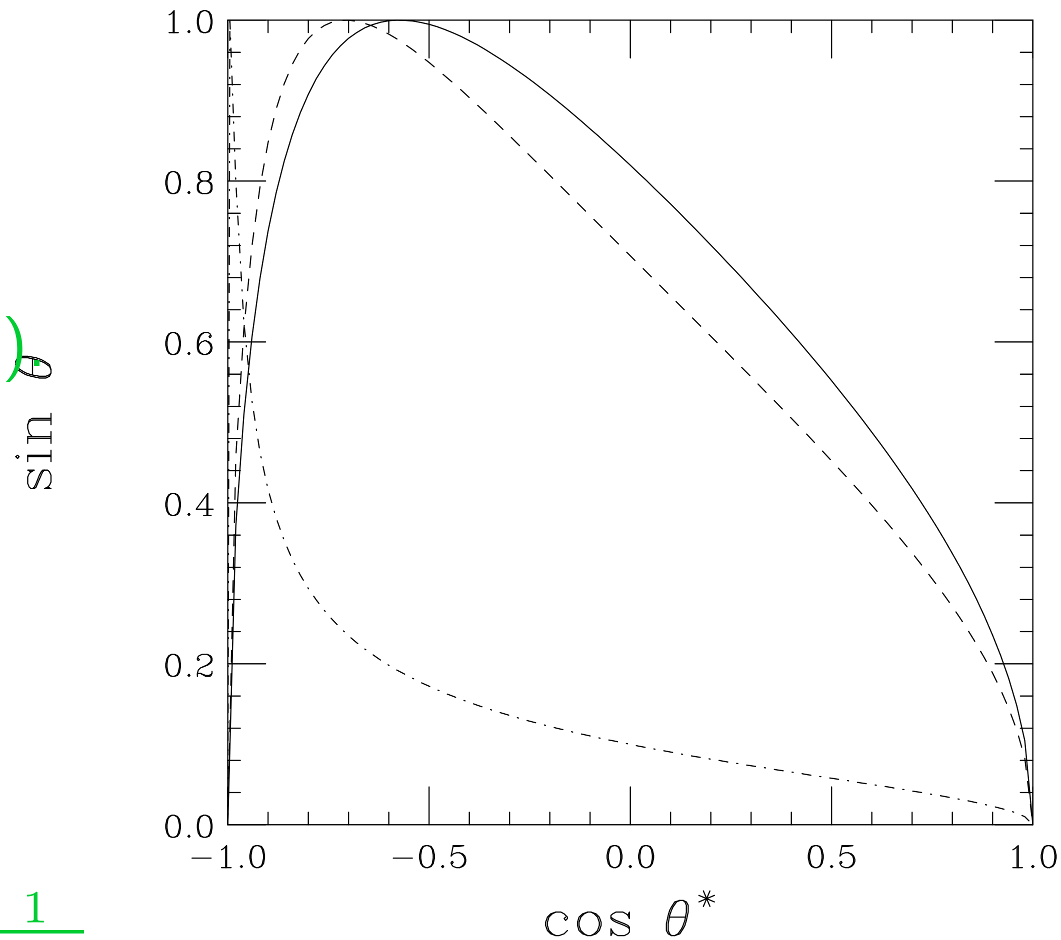
DECAY KINEMATICS

B rest frame: *; laboratory frame: no *; $E_B/m_B = \gamma = 1/\sqrt{1-\beta^2}$

Muon angles with respect to B boost: θ^* in B rest frame; θ in lab

$\sin\theta = \sin\theta^*/[\gamma(1+\beta\cos\theta^*)]$

$\beta\gamma = 0.7$ $[\beta = 0.573]$ (solid),
$\beta\gamma = 1$ $[\beta = 0.707]$ (dashed),
$\beta\gamma = 10$ $[\beta = 0.995]$ (dot-dash).



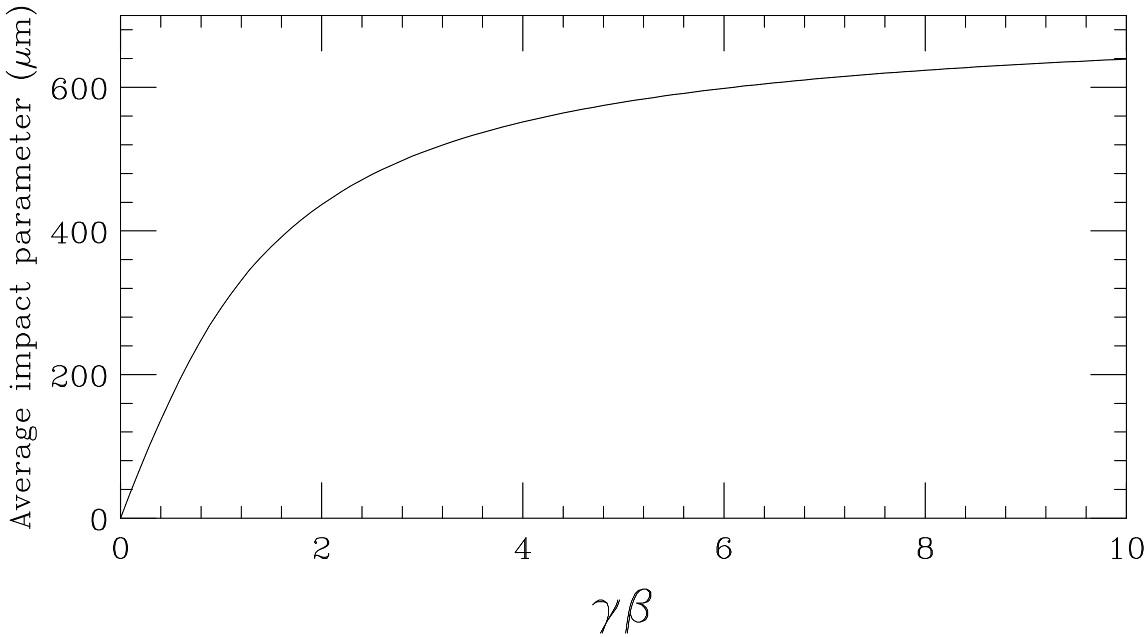
Isotropy of muon emission in $\cos\theta^* \Rightarrow \langle\sin\theta\rangle$, $\langle b\rangle$ vs $\beta\gamma$:

$$\langle b\rangle = \gamma\beta\langle\sin\theta\rangle c\tau$$

where $c\tau \sim 450$ μm and

$$\langle\sin\theta\rangle = \frac{1}{2}\int_0^\pi \frac{\sin^2\theta^* d\theta^*}{\gamma(1+\beta\cos\theta^*)} = \frac{\pi}{2}\frac{1}{1+\gamma}$$

$\langle b \rangle$ AS FUNCTION OF $\gamma\beta$



Eyeball fit to CDF b distribution [PR D **77**, 072004] $\Rightarrow \langle b \rangle = 350$ μm

Discard $b > b_0$ events; fraction remaining for given $\langle b \rangle$:

b_0 (μm) / $\langle b \rangle$ (μm)	100	200	300	400	500
150	0.237	0.542	0.748	0.866	0.930
300	0.080	0.237	0.400	0.542	0.658
450	0.040	0.129	0.237	0.347	0.450

D0 CRITERIA

Transverse impact parameter relative to closest primary vertex: $b_\perp$

Longitudinal distance from point of closest approach to this vertex: $b_\parallel$

D0 chooses $b_\perp < 3000\ \mu$m, $b_\parallel < 5000\ \mu$m ; how related to b?

Transverse and longitudinal components of muon momentum in lab:

$$p^\mu_\perp = p^\mu \sin\psi,\ p^\mu_\parallel = p^\mu \cos\psi$$

Distance d of a point along μ trajectory from vertex ($s =$ distance along μ trajectory from transverse point of closest approach):

$$d^2 = b^2_\perp + (s\sin\psi)^2 + (s\cos\psi - b_\parallel)^2$$

Minimum of d is $b = d_{\min} = [b^2_\perp + (b_\parallel \sin\psi)^2]^{1/2}$

D0 see little signal reduction with $b_\perp < 500\ \mu$m, $b_\parallel < 500\ \mu$m

Key question with regard to D0 muons: are they really from b decays?

TRIPLE PRODUCTS

Spinless particle ("B" decaying to four spinless particles: Three independent momenta in B rest frame; can form a T-odd expectation value out of (e.g.) $p_1 \times p_2 \cdot p_3$

Early suggestion G. Valencia (1989): PR D **39**, 3339 (1989); recently A. Datta *et al.*, arXiv:1103.2442, and references therein

Famous example: KTeV asymmetry in $K_L \to \pi^+\pi^-e^+e^-$ [PRL **96**, 101801 (2006)]: $(13.6 \pm 1.4 \pm 1.5)\%$

What if two or more of the final-state particles are identical?

Consider double-Dalitz decay of CP-mixture (like K_L) to $e^+e^-e^+e^-$

See, e.g., G. D. Barr *et al.*, Z. Phys. C **65**, 361 (1995)

Low $M(e^+e^-)$: like $K_L \to \gamma\gamma$: $(\|, \perp)$ polarizations for CP $=$ (+,-).

Interference between CP-even and -odd decays gives $\langle \sin\phi \cos\phi \rangle \neq 0$ ($\phi =$ angle between normals to e^+e^- planes)

CASE OF $B \to V_1 V_2$

Each V decaying to two pseudoscalars P

A. Datta and D. London, IJMPA **19**, No. 15, 2505 (2004)

Triple products (TP's) from angular analysis; tiny in Standard Model

$$A_T \equiv \frac{\Gamma(\mathrm{TP}>0)-\Gamma(\mathrm{TP}<0)}{\Gamma(\mathrm{TP}>0)+\Gamma(\mathrm{TP}<0)} \;;\quad \mathrm{TP} \equiv p_1 \cdot (p_2 \times p_3)$$

True T-violation: $\mathcal{A}_T^{\mathrm{true}} \equiv \frac{\Gamma(\mathrm{TP}>0)+\bar{\Gamma}(\mathrm{TP}>0)-\Gamma(\mathrm{TP}<0)-\bar{\Gamma}(\mathrm{TP}<0)}{\Gamma(\mathrm{TP}>0)+\bar{\Gamma}(\mathrm{TP}>0)+\Gamma(\mathrm{TP}<0)+\bar{\Gamma}(\mathrm{TP}<0)}$

The following discussion is from Datta et al., arXiv:1103.2442v2

Matrix element for $B(p) \to V_1(k_1, \epsilon_1) + V_2(k_2, \epsilon_2)$:

$$M = a\epsilon_1^* \cdot \epsilon_2^* + \frac{b}{m_B^2}(p \cdot \epsilon_1)(p \cdot \epsilon_2) + i\frac{c}{m_B^2}\epsilon_{\mu\nu\rho\sigma}p^\mu q^\nu \epsilon^{*\rho}\epsilon^{*\sigma} \;;\quad q \equiv k_1 - k_2$$

Helicity amplitudes $A_\|(a)$; $A_0(a, b)$; $A_\perp(c)$

Under CP conjugation, $a \to \bar{a}$, $b \to \bar{b}$, $ic \to -i\bar{c}$

ANGULAR DISTRIBUTIONS

Define polar angles θ_1, θ_2, each in rest frame of decaying V_1 or V_2

$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \sim |A_0|^2 \cos^2\theta_1 \cos^2\theta_2 + (1/2)|A_\perp|^2 \sin^2\theta_1 \sin^2\theta_2 \sin^2\phi$$

$$+(1/2)|A_\parallel|^2 \sin^2\theta_1 \sin^2\theta_2 \cos^2\phi + (1/2\sqrt{2})\mathrm{Re}(A_0 A_\parallel^*) \sin 2\theta_1 \sin 2\theta_2 \cos\phi$$

$$-(1/2\sqrt{2})\mathrm{Im}(A_\perp A_0^*) \sin 2\theta_1 \sin 2\theta_2 \sin\phi - (1/2)\mathrm{Im}(A_\perp A_\parallel^*) \sin^2\theta_1 \sin^2\theta_2 \sin 2\phi$$

Last two terms are T-odd; two distinct types

Weak phase difference ϕ_w; strong phase difference δ

"Fake" TP: $\mathcal{A}_T^{\mathrm{fake}} = \frac{\Gamma(\mathrm{TP}>0)-\bar{\Gamma}(\mathrm{TP}>0)-\Gamma(\mathrm{TP}<0)+\bar{\Gamma}(\mathrm{TP}<0)}{\Gamma(\mathrm{TP}>0)+\bar{\Gamma}(\mathrm{TP}>0)+\Gamma(\mathrm{TP}<0)+\bar{\Gamma}(\mathrm{TP}<0)}$

$\mathrm{TP}_{\mathrm{true}} \propto \sin\phi_w \cos\delta$, $\mathrm{TP}_{\mathrm{fake}} \propto \cos\phi_w \sin\delta$

$$A_T^{(1)} \equiv \frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2} , \quad A_T^{(2)} \equiv \frac{\mathrm{Im}(A_\perp A_\parallel^*)}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$

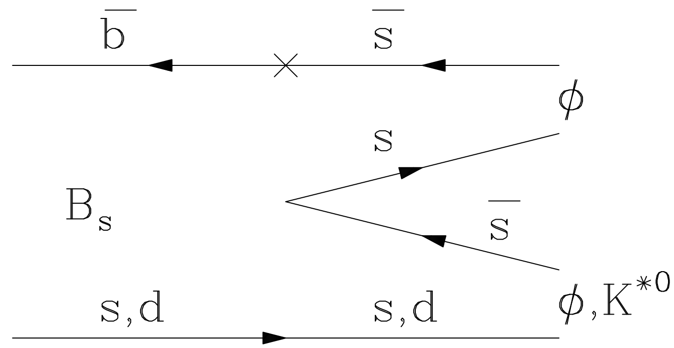
CP conjugates: similar definitions (barred amplitudes); minus sign

M. Dorigo (Thu.) "u" $\leftrightarrow A_T^{(2)}$; "$v$" $\leftrightarrow A_T^{(1)}$ for $B_s \to \phi\phi$!

$B \to \phi K^*$ AND $B_s \to \phi\phi$

Dominated by $b \to s$ penguin:

Factorization prediction for helicity structure: dominant longitudinal pol. doesn't hold for penguin-dominated decays



	$B_s \to \phi\phi$ CDF Note 10120	$B^+ \to \phi K^{*+}$ BaBar, PRL **99**	$B^+ \to \rho^0 K^{*+}$ BaBar, PRL **97**, 201801 (2006)	$B^0 \to \rho^0 K^{*0}$
f_L	0.348±0.041±0.021	0.49±0.05±0.03	0.52±0.10±0.04	0.57±0.09±0.08
f_T	0.652±0.041±0.021	0.51±0.05±0.03	0.48±0.10±0.04	0.43±0.09±0.08

Contrast with $B^0 \to \rho^+\rho^-$ where $f_L = 0.992 \pm 0.024^{+0.026}_{-0.013}$ [BaBar, PR D **76**, 052007 (2007)] (nearly 1, as predicted)

No reason to trust factorization for penguin amplitude, which may be due to rescattering from charm-anticharm intermediate states

From $B^0 \to \phi K^{*0}$ amplitudes quoted by Datta *et al.* we estimate

$A_T^{(1)}$=–0.260±0.048 ; $\bar{A}_T^{(1)}$=0.203±0.050 ; $A_T^{(2)}$=0.005±0.070 ; $\bar{A}_T^{(2)}$=0.010±0.064

Large fake $A_T^{(1)}$; no true $A_T^{(1)}$; no fake *or* true $A_T^{(2)}$

$B_s \to J/\psi\phi$ VS $B_s \to J/\psi f_0$

Helicity or transversity analysis for $B_s \to J/\psi\phi$ (S-, P-, D-wave) avoided for $B_s \to J/\psi f_0$ (pure P-wave)

CP(J/ψ) = CP(f_0) = +; overall final state is CP odd

S. Stone and L. Zhang, PR D **79**, 074024 (2009) estimated BR:

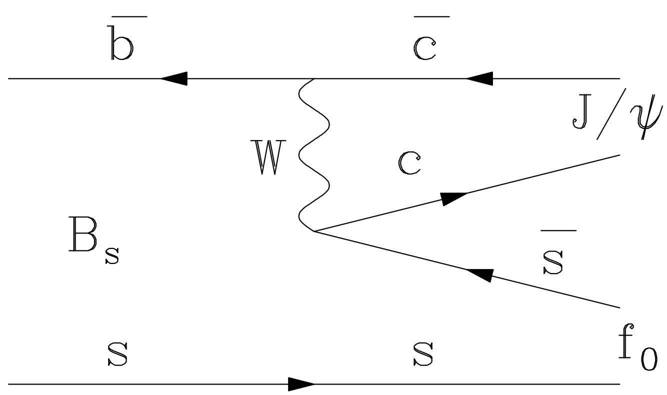
$$R_{f_0/\psi} \equiv \frac{\Gamma(B_s \to J/\psi f_0,\ f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\phi,\ \phi \to K^+K^-)} \simeq 20\%,$$ vs experimental values:

LHCb [PL B **698**, 115 (2011)]: $R_{f_0/\psi} = 0.252^{+0.046+0.027}_{-0.032-0.033}$

Belle (arXiv:1102.2759): $R_{f_0/\psi} \simeq 0.18$ ($\sim 30\%$ stat. error)

CDF (this Conference): $R_{f_0/\psi} = 0.292 \pm 0.020 \pm 0.017$

CKM structure same as for $B_s \to J/\psi\phi$:



Although f_0 decays mainly to $\pi\pi$, it seems to be "fed" mainly from $s\bar{s}$, as observed long ago by comparing $J/\psi \to \phi\pi\pi$ and $J/\psi \to \omega\pi\pi$

A $\pi\pi$ peak at $M(f_0) \simeq 980$ MeV in $\phi\pi\pi$, not $\omega\pi\pi$

NEW PHYSICS CONSTRAINTS

Two (of ~ 100) theoretical analyses: (1) Z. Ligeti *et al.*, PRL **105**, 131601 (2010); (2) Y. Bai and A. Nelson, PR D **82**, 114027; correlation between a^q_{sl}, Δm_q, $\Delta\Gamma_q$, and mixing angle ϕ_q, where

$$A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$$

Two questions: (1) Nonstandard β_s; (2) Nonstandard a^q_{sl}

$$a^q_{sl} = (|\Delta\Gamma_q|/\Delta m_s)\tan\phi_q$$

If dimuon asymmetry mainly from a^s_{sl}, Bai and Nelson find $a^s_{sl} = (-12.5 \pm 4.8) \times 10^{-3}$ by combining with D0 measurement $(-1.7 \pm 9.1) \times 10^{-3}$ [PR D **82**, 012003 (2010)]

(CDF,LHCb) average $\Delta m_s = (17.70 \pm 0.08)$ ps^{-1}, (CDF,D0) average $\Delta\Gamma_s = 0.094 \pm 0.031$ ps^{-1}, $\Rightarrow \phi_s = (-67^{+18}_{-7})^\circ$; $\phi^s_M = (-39 \pm 17)^\circ$ favors slightly larger $\Delta\Gamma_s$ or nonstandard a^d_{sl}

Lenz *et al.* [PR D **83**, 036004]: Respect SM prediction of Δm_q. New physics must affect mainly *phases* of mixing amplitudes.

NEW PHYSICS PROPOSALS

Supersymmetry has generic flavor-changing (but controllable) effects: arXiv:1001.3835, 1004.1993

Randall-Sundrum scenarios in which different quarks lie at different points along a fifth dimension offer a language for understanding quark mixings; no predictive scheme yet

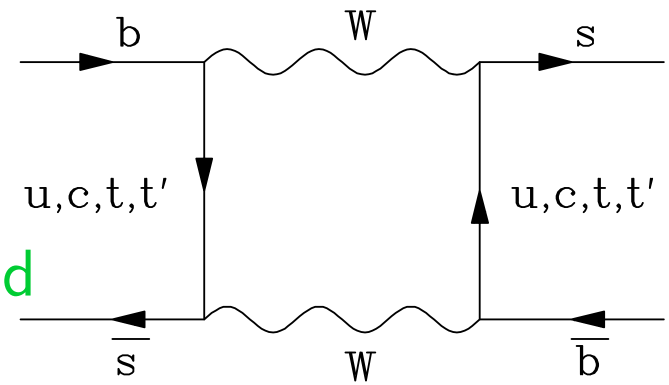
Theories with an extra (flavor-changing) Z can induce mixing as desired

Bai and Nelson introduce a contribution to $\Delta\Gamma$ through a new light pseudoscalar (on-shell state in $B_s \leftrightarrow \bar{B}_s$)

I recommend you search the nearly 100 citations of the D0 dimuon result and pick your favorite model. Some of them predict other observable consequences but there are too many to enumerate exhaustively.

TWO FAVORITES

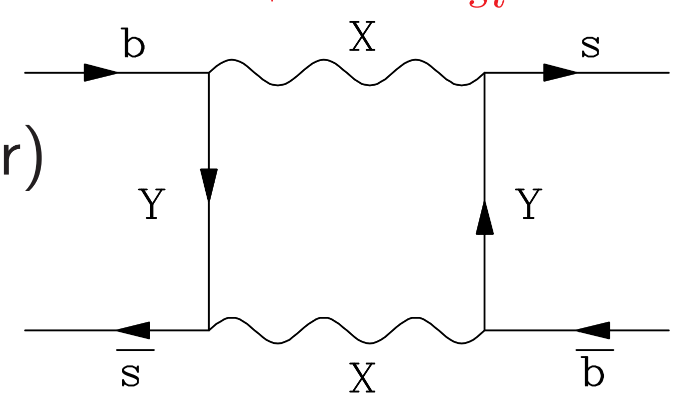
Fourth generation



Lunghi – Soni, PL B **697**, 323 (2011):
Tension between $\sin 2\beta = \sin 2\phi_3 = 0.668 \pm 0.023$ (measured in B decays) and that (0.867 ± 0.048) in (their) CKM fit

They note effects of new physics on both $\Delta\text{Flavor} = 1$ (penguin) and $\Delta\text{Flavor} = 2$ (box) amplitudes but no specifics on β_s or a^s_{sl}

Hidden sector



Extended gauge sector G (for dark matter)

Y with charges in SM and G

X with charges only in G

Type of matter	Std. Model	G	Example(s)
Ordinary	Charged	Uncharged	Quarks, leptons
Mixed (Y)	Charged	Charged	Superpartners
Shadow (X)	Uncharged	Charged	E_8' of $E_8 \otimes E_8'$

Many opportunities for new penguins and boxes

CONCLUSIONS

B_s decays and mixing: potential mirrors of new physics

- β_s has moved toward Standard Model value
- Even present β_s should show up in time-dependent quantities

Dimuon charge asymmetry

- D0 the only one claiming it so far; CDF remeasured $\bar{\chi}$
- Signal requires subtraction of big kaon background
- Is what's left really due to b quark decays?
- We have proposed an impact parameter cut of $b < 100\ \mu$m

Triple products in four-body decays

- T-odd observables provide strong phase, weak phase information
- Interest in what new physics one can learn from $B_s \to \phi\phi$

New physics?

- Have your favorite model ready; there are enough to go round