In pursuit of determining the B_s mixing phase β_s

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Continuous Advances in QCD 2011

Outline

- CP violation in B_s system
- An example of a minimal flavour violation model: how does β_s change?
- Modes to access β_s : $B_s \to X_{cc}$ L (L=light meson) and the special case of $B_s \to f_0(980)$
- New Physics effects in non leptonic B_s decays

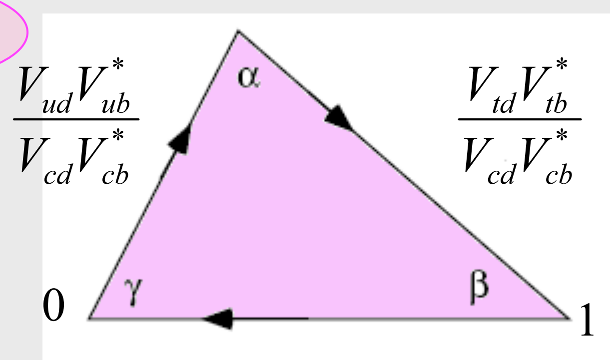
Based on works in collaboration with P. Colangelo and W. Wang

$\mathrm{B_s}$ system

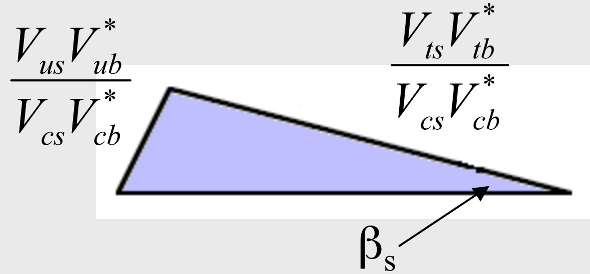
Analysis of the $\mathrm{B_s}$ unitarity triangle is an important test of the SM description of CP violation

$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

$B_d - \overline{B}_d$



$B_s - \overline{B}_s$



$$\beta_d = \arg\left(-\frac{V_{tb}V_{td}^{*}}{V_{cb}V_{cd}^{*}}\right) = 0.38 \pm 0.02 \quad rad$$

$$\beta_s = \arg\left(-\frac{V_{tb}V_{ts}^{*}}{V_{cb}V_{cs}^{*}}\right) \approx 0.02 \quad rad$$

$$\boxed{B_s \to J/\psi\phi}$$

The final state is an admixture of different CP eigenstates
⟶ can be disentangled considering the angular distribution of the decay products:

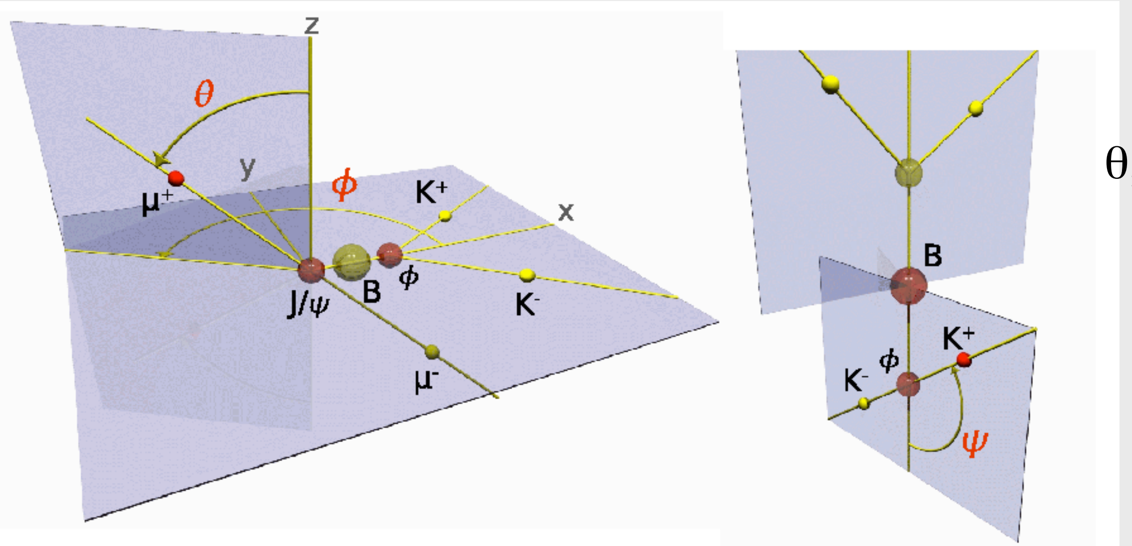
$$\boxed{J/\psi \to \ell^+\ell^- \qquad \phi \to K^+K^-}$$

Three independent polarization amplitudes:

$$\underbrace{A_0(t),\quad A_\parallel(t),}_{\text{CP even}}\quad \underbrace{A_\perp(t)}_{\text{CP odd}}$$

with

$$\boxed{|A|^2 = |A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$



J/ψ rest frame

ϕ rest frame

θ, ϕ, ψ, transversity angles

$B_s \to J/\psi\phi$

combined result (HFAG)

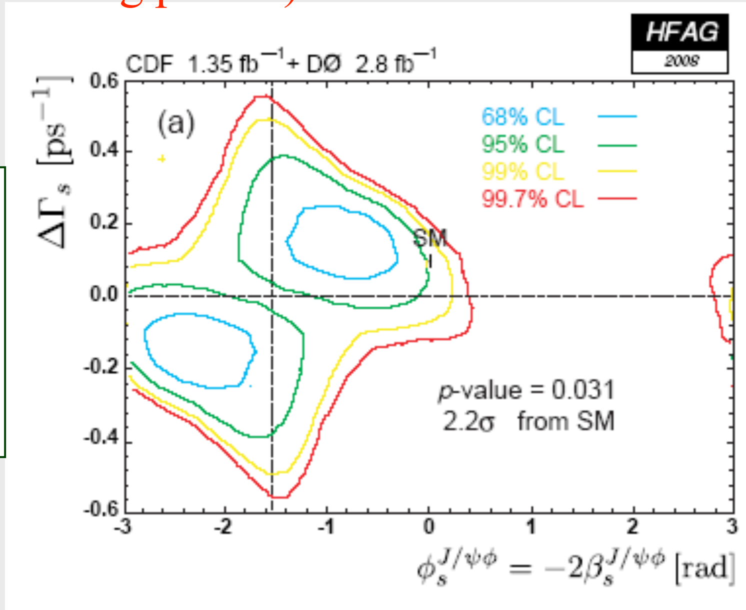
(no assumption on the strong phases)

HFAG, 0808.1297

Numerical results for the two solutions:

$$\begin{aligned} \Delta\Gamma_s &= 0.154^{+0.054}_{-0.070}\ \mathrm{ps}^{-1}\,, \\ &\in [+0.036, +0.264] \text{ at } 90\% \text{ CL} \\ \phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} &= -0.77^{+0.29}_{-0.37}\ \mathrm{rad}\,, \\ &\in [-1.47, -0.29] \text{ at } 90\% \text{ CL}\,, \end{aligned}$$

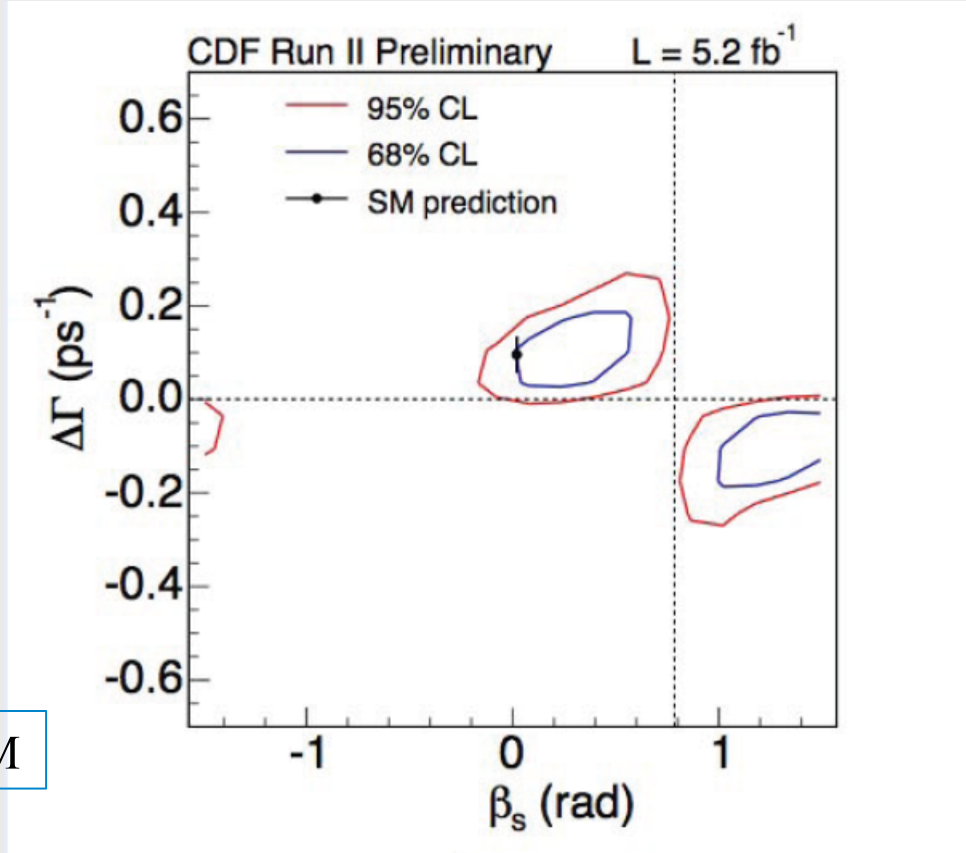
$$\begin{aligned} \Delta\Gamma_s &= -0.154^{+0.070}_{-0.054}\ \mathrm{ps}^{-1}\,, \\ &\in [-0.264, -0.036] \text{ at } 90\% \text{ CL} \\ \phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} &= -2.36^{+0.37}_{-0.29}\ \mathrm{rad}\,, \\ &\in [-2.85, -1.65] \text{ at } 90\% \text{ CL}\,. \end{aligned}$$



HFAG: consistency of SM predictions is at level of 2.2 σ new CDF measurement of β_s

$$\beta_s \in [0.0, 0.5] \cup [1.1, 1.5] \quad 68\%\ \mathrm{CL}$$

$$\beta_s \in [-0.1, 0.7] \cup \left[0.9, \frac{\pi}{2}\right] \quad 95\%\ \mathrm{CL}$$



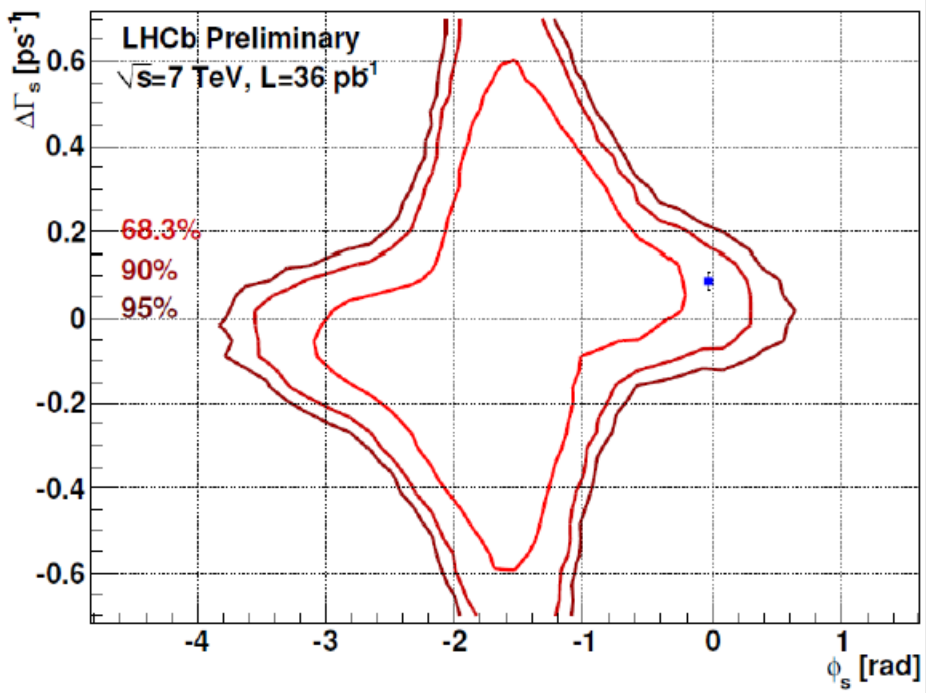
reconciles measurement with SM

…but

from L. Oakes, CDF Collab., 1102.0436
talk at FPCP, Torino May 2010

LHCb measurement of β_s

from U. Uwer, talk at Beauty 2011

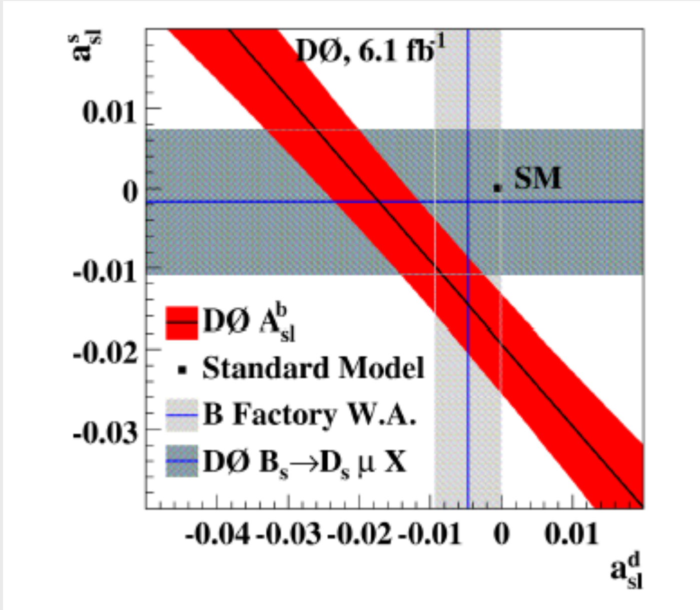


← SM *P*-value: 22% ("1.2σ")

$\phi_s \in [-2.7, -0.5]$ rad at 68% CL
$\phi_s \in [-3.5, 0.2]$ rad at 95% CL

News in B_s phenomenology from D0 Collaboraration

PRD82 (2010) 032001
PRL 105 (2010) 081801



Measurement of the asymmetry: $A^b_{sl} = \dfrac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$

$N_b^{++} \longrightarrow$ number of events with two b-hadrons decaying semileptonically producing two positively charged muons

$$A^b_{sl}(SM) = (-2.3 \pm^{0.5}_{0.6}) \times 10^{-4}$$

while $A^b_{sl} = -0.00957 \pm 0.00251(\text{stat}) \ \pm 0.00146(\text{syst})$

The asymmetry is interpreted as due to the mixing of the neutral mesons decaying semileptonically
The discrepancy signals an anomalous CP-violation in the oscillation process

Example of a MFV model

Appelquist-Cheng-Dobrescu (ACD) Model
with a single Universal Extra Dimension (UED)

- Compactification on a orbifold: the 5th dim ***y*** varies on a circle of radius **R** with periodic boundary conditions; fields are required to have a definite parity under $y \rightarrow -y$

- The existence of an extra dim reflects in the appearance of a tower of KK modes for each particle of the model

Modification of the Wilson coefficients in effective hamiltonians

$$C\left(x_t, \frac{1}{R}\right) = \underbrace{C_{(0)}(x_t)}_{\text{SM result}} + \sum_{n=1}^{\infty} C_n(x_t, x_n) \qquad x_n = \frac{m_n^2}{M_W^2}$$

$$m_n = \frac{n}{R}$$

Unitarity triangles in the ACD model

ACD is a minimal flavour violation model:

- CKM has the same structure as in the SM
- CKM is unitary and described by 4 parameters, one of which is a complex phase
- the CKM phase is the only source of CP violation

What about the unitarity triangles?

- CKM elements extracted from tree level processes where KK modes do not contribute should be the same, i.e. $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$

- Quantities obtained from loop-induced processes where the KK contribute could be different, i.e. $|V_{td}|$, $|V_{ts}|$

bs triangle in the ACD model

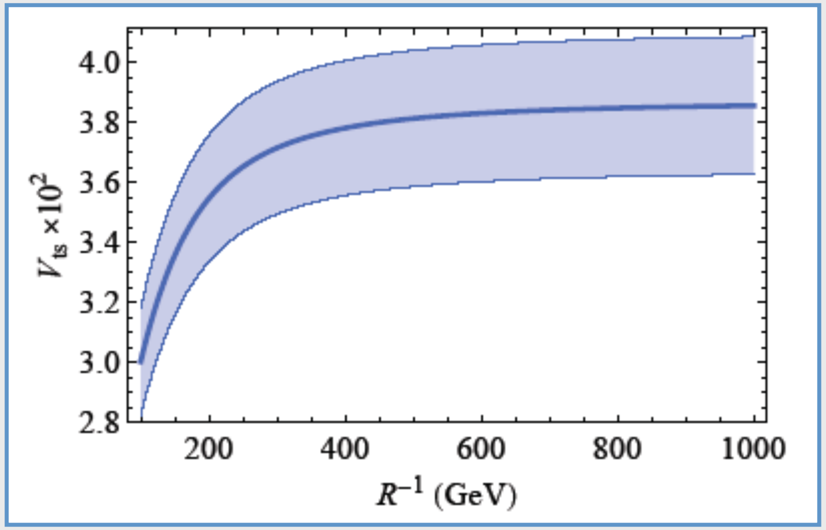
$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

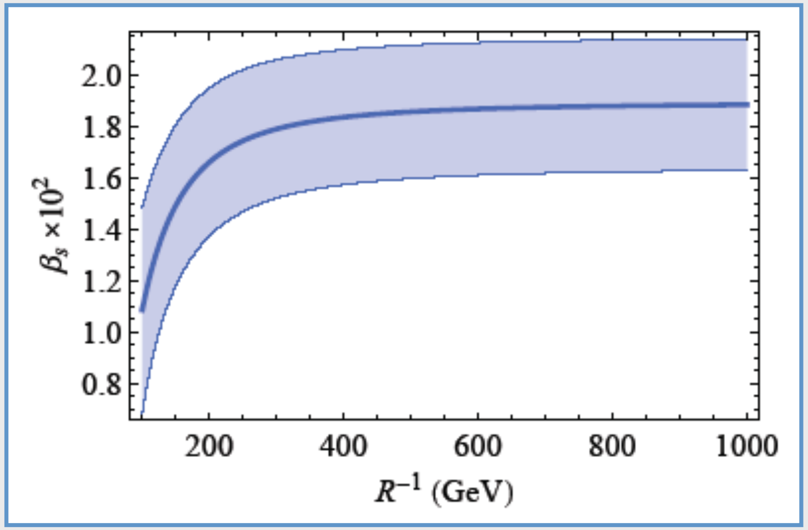
from $B_s - \overline{B}_s$ mixing:

$$|V_{ts}|_{ACD} = |V_{ts}|_{SM}\sqrt{\frac{S_0(x_t)}{S(x_t,1/R)}}$$

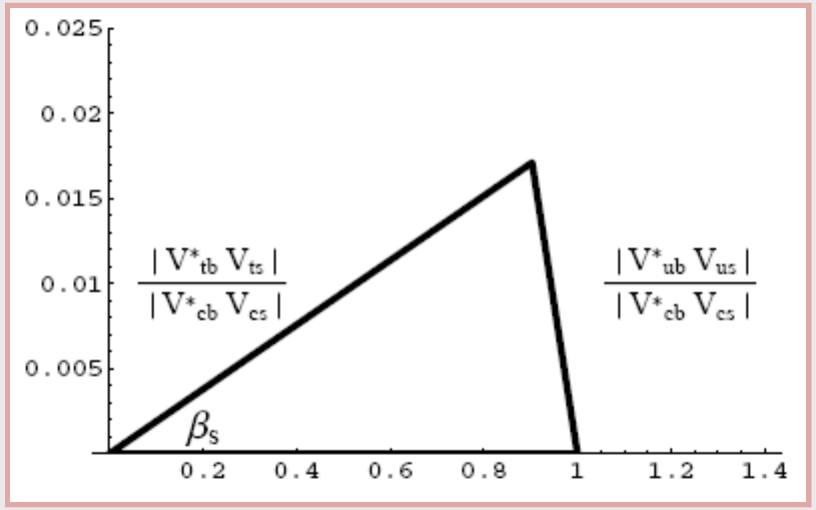
$$\beta_s = Arg\left[-\frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}}\right]$$

also becomes 1/R dependent





bs triangle



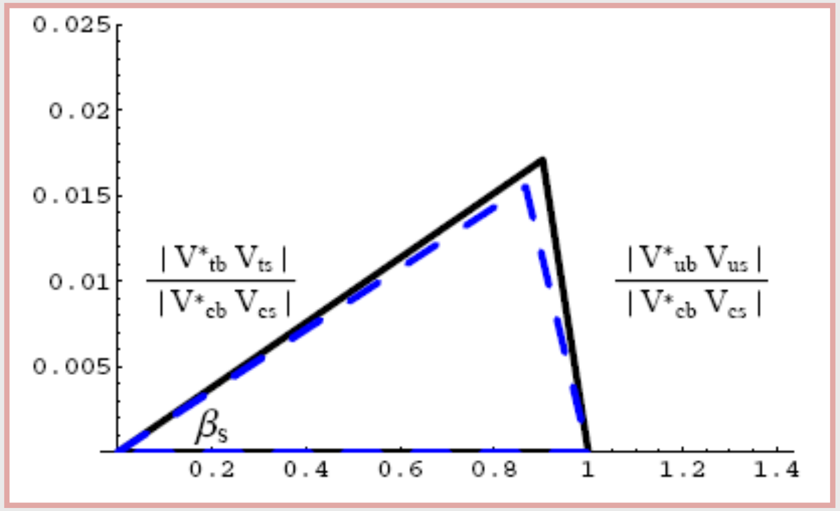
→ Notice the different scale on the two axes!

SM triangle

$$\beta_s\big|_{SM} \cong 0.017 \quad \text{rad}$$

bs triangle in the ACD model

M.V. Carlucci, P. Colangelo, FDF
Phys.Rev.D80:055023,2009.



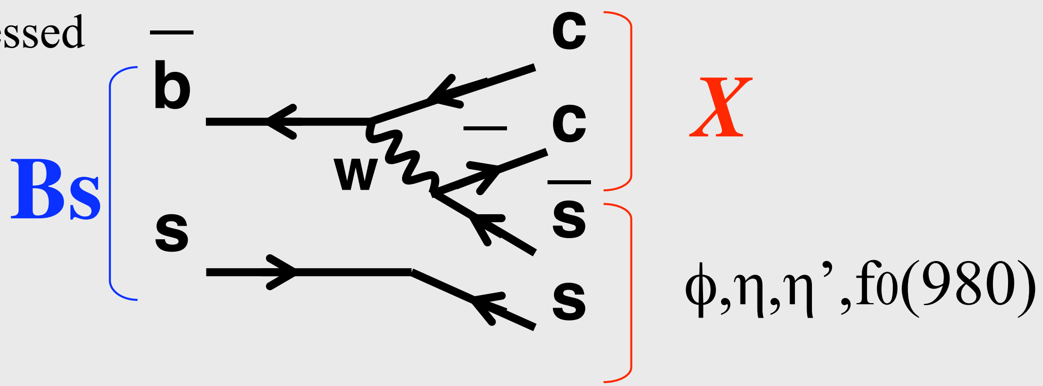
→ Notice the different scale on the two axes!

ACD triangle for $\frac{1}{R} = 300 \quad \text{GeV}$

Most MFV models cannot justify large values of β_s if experimentally found

$\boxed{B_s \longrightarrow X_{c\bar{c}} L}$

Tree level, colour suppressed



$$X_{c\bar{c}} = J/\psi, \eta_c, \Psi(2S), \eta_c(2S), \chi_{c0,c1,c2}, h_c$$

$$L = \phi, \eta, \eta', f_0(980)$$

$B_s \to f_0(980)$ form factors

Definition:

$$\langle f_0(p_{f_0})|\bar{s}\gamma_\mu\gamma_5 b|\overline{B}_s(p_{B_s})\rangle = -i\Big\{F_1(q^2)\Big[P_\mu - \frac{m_{B_s}^2 - m_{f_0}^2}{q^2}q_\mu\Big] + F_0(q^2)\frac{m_{B_s}^2 - m_{f_0}^2}{q^2}q_\mu\Big\}$$

$$\langle f_0(p_{f_0})|\bar{s}\sigma_{\mu\nu}\gamma_5 q^\nu b|\overline{B}_s(p_{B_s})\rangle = -\frac{F_T(q^2)}{m_{B_s}+m_{f_0}}\Big[q^2 P_\mu - (m_{B_s}^2 - m_{f_0}^2)q_\mu\Big]$$

Quantities computed using QCD Sum Rules

$B_s \to f_0(980)$ form factors in light-cone sum rules

Starting point: a correlation function

external state

$$\Pi(p_{f_0}, q) = i \int d^4x e^{iq\cdot x}\langle f_0(p_{f_0})|\mathrm{T}\{j_{\Gamma_1}(x), j_{\Gamma_2}(0)\}|0\rangle$$

Current defining the transition matrix element

Interpolating current for the B_s meson

The sum rule consists in evaluating the correlator in two ways: at ***hadronic level*** and in *QCD*

Equating the two representations provides with a ***Sum Rule*** allowing to calculate the form factors

$B_s \to f_0(980)$ form factors in light-cone sum rules

Hadronic representation:

$$\Pi^{HAD}(p_{f_0}, q) = \frac{\langle f_0(p_{f_0})|j_{\Gamma_1}|\bar{B}_s(p_{f_0}+q)\rangle\langle \bar{B}_s(p_{f_0}+q)|j_{\Gamma_2}|0\rangle}{m_{B_s}^2-(p_{f_0}+q)^2} + \int_{s_0}^{\infty} ds \frac{\rho^h(s,q^2)}{s-(p_{f_0}+q)^2}$$

contribution of B_s depends on the FF to compute

spectral function describing the contribution of higher resonances and continuum of states

QCD representation:

$$\Pi^{QCD}(p_{f_0}, q) = \frac{1}{\pi}\int_{(m_b+m_s)^2}^{\infty} ds \frac{\mathrm{Im}\Pi^{QCD}(s,q^2)}{s-(p_{f_0}+q)^2}$$

effective threshold

obtained expanding the T-product near the light-cone

written in terms of the f_0 light cone distribution amplitudes

$$\begin{aligned}
\langle f_0(p_{f0})|\bar{s}(x)\gamma_\mu s(0)|0\rangle &= \bar{f}_{f0}p_{f0\mu}\int_0^1 du e^{iup_{f0}\cdot x}\Phi_{f0}(u) \\
\langle f_0(p_{f0})|\bar{s}(x)s(0)|0\rangle &= m_{f0}\bar{f}_{f0}\int_0^1 du e^{iup_{f0}\cdot x}\Phi^s_{f0}(u) \\
\langle f_0(p_{f0})|\bar{s}(x)\sigma_{\mu\nu}s(0)|0\rangle &= -\frac{m_{f0}}{6}\bar{f}_{f0}(p_{f0\mu}x_\nu - p_{f0\nu}x_\mu)\int_0^1 du e^{iup_{f0}\cdot x}\Phi^\sigma_{f0}(u)
\end{aligned}$$

twist 2

twist 3

$B_s \to f_0(980)$ form factors in light-cone sum rules

Final steps in the sum rule:

- global duality assumption

$$\int_{s_0}^{\infty} ds \frac{\rho^h(s, q^2)}{s - (p_{f_0} + q)^2} = \frac{1}{\pi} \int_{s_0}^{\infty} ds \frac{\mathrm{Im}\Pi^{QCD}(s, q^2)}{s - (p_{f_0} + q)^2}.$$

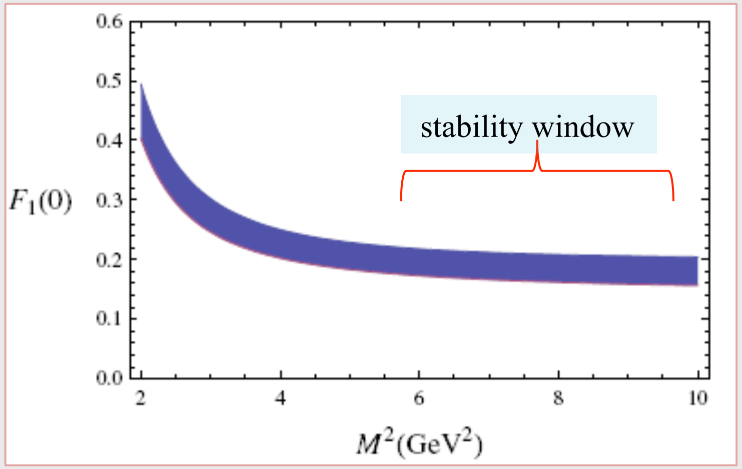
- Borel transform
  - improves the convergence of the OPE
  - suppresses higher states contribution

$$\mathcal{B}\left[\frac{1}{(s + Q^2)^n}\right] = \frac{\exp(-s/M^2)}{(M^2)^n (n-1)!}$$

final sum rule

$$\frac{\langle f_0(p_{f_0})|j_{\Gamma_1}|\overline{B_s}(p_{f_0}+q)\rangle\langle\overline{B_s}(p_{f_0}+q)|j_{\Gamma_2}|0\rangle}{m_{B_s}^2 - (p_{f_0}+q)^2} = \frac{1}{\pi}\int_{(m_b+m_s)^2}^{s_0} ds \frac{\mathrm{Im}\Pi^{QCD}(s, q^2)}{s - (p_{f_0}+q)^2}$$

$B_s \to f_0(980)$ form factors : results

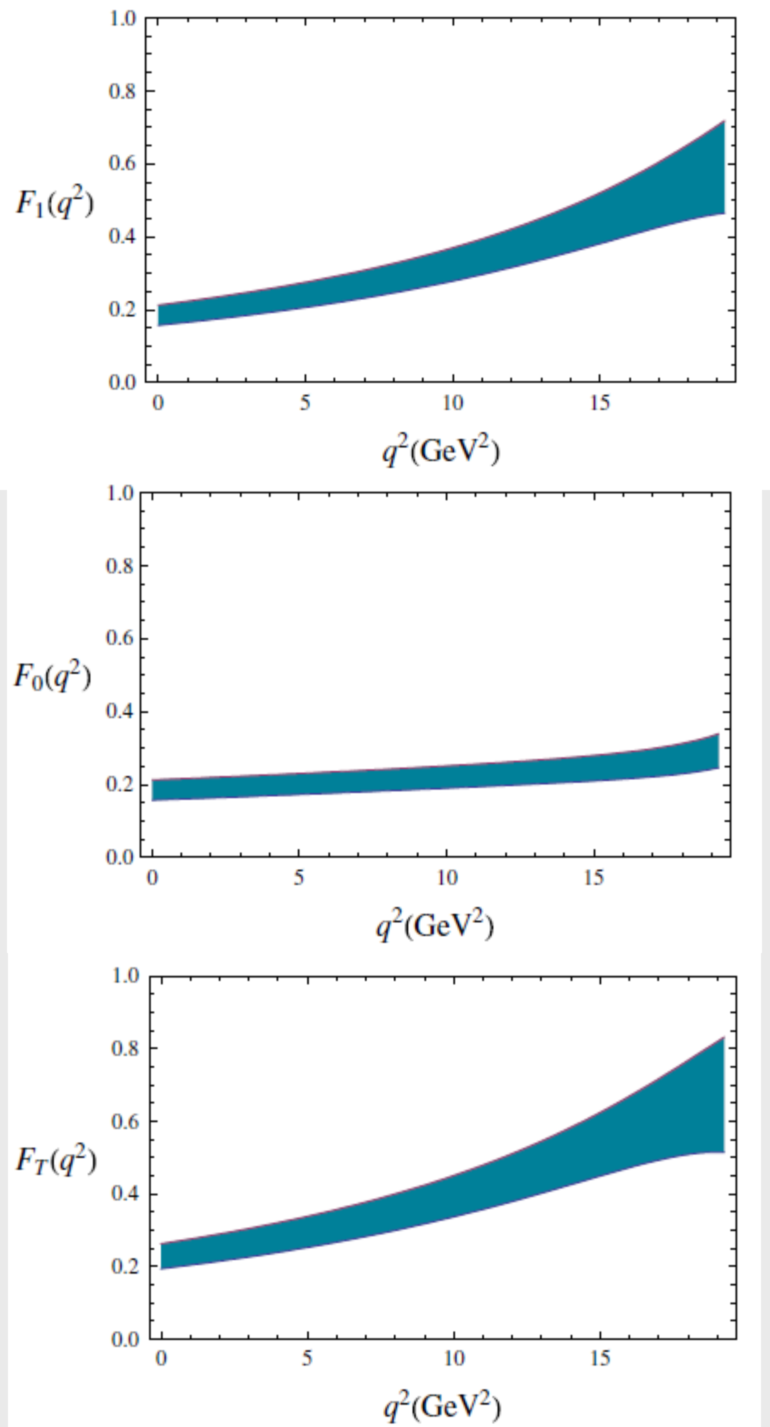


Parameters of the $B_s \to f_0$ form factors by LCSR at the leading order.

	$F_i(q^2=0)$	a_i	b_i	$F_i(q^2_{\max})$
F_1	0.185 ± 0.029	$1.44^{+0.13}_{-0.09}$	$0.59^{+0.07}_{-0.05}$	$0.614^{+0.158}_{-0.102}$
F_0	0.185 ± 0.029	$0.47^{+0.12}_{-0.09}$	$0.01^{+0.08}_{-0.09}$	$0.268^{+0.055}_{-0.038}$
F_T	0.228 ± 0.036	$1.42^{+0.13}_{-0.10}$	$0.60^{+0.06}_{-0.05}$	$0.714^{+0.197}_{-0.126}$

$$F_i(q^2) = \frac{F_i(0)}{1 - a_i q^2/m_{B_s}^2 + b_i (q^2/m_{B_s}^2)^2},$$

P.Colangelo, W.Wang, FDF PRD81:074001,2010



$B_s \rightarrow J/\Psi\ f_0(980)$

Factorization assumption

$$\mathcal{A}(\bar{B}_s \to J/\psi f_0) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2 m_\psi f_{J/\psi} F_1^{B_s \to f_0}(m_{J/\psi}^2) 2(\epsilon^* \cdot p_{B_s})$$

can be extracted from B→ J/Ψ K
assuming it is the same

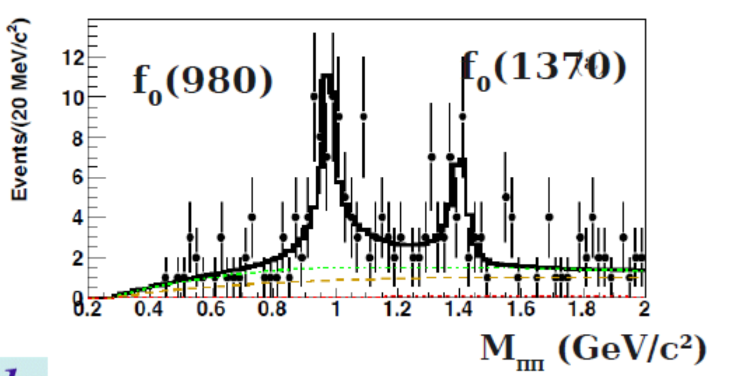
$$\mathcal{BR}(\bar{B}_s \to J/\psi f_0) = (3.1 \pm 2.4) \times 10^{-4}$$

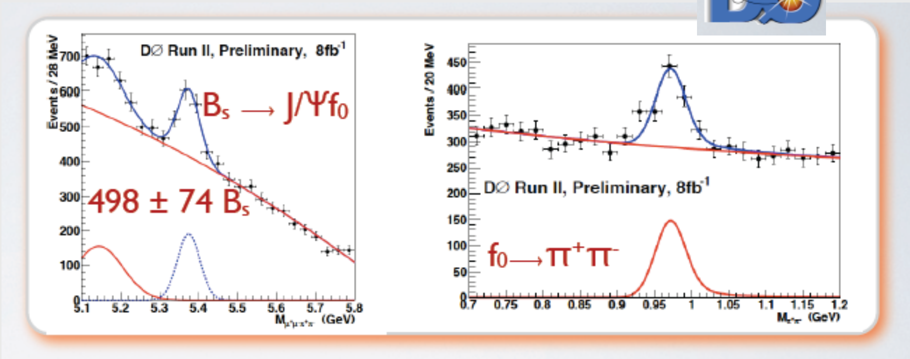
comparing to the *golden mode*

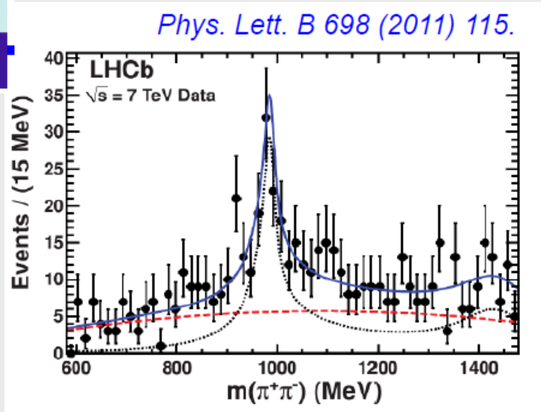
$$\frac{\mathcal{BR}(B_s \to J/\psi f_0)}{\mathcal{BR}(B_s \to J/\psi_L \phi_L)} \simeq \frac{[F_1^{B_s \to f_0}(m_\psi^2)]^2 \lambda(m_{B_s}^2, m_\psi^2, m_{f_0}^2)}{[A_1^{B_s \to \phi}(m_\psi^2)(m_{B_s} + m_\phi)\frac{(m_{B_s}^2 - m_\psi^2 - m_\phi^2)}{2m_\phi} - A_2^{B_s \to \phi}(m_\psi^2)\frac{\lambda(m_{B_s}^2, m_\psi^2, m_\phi^2)}{2m_\phi(m_{B_s} + m_\phi)}]^2} = 0.13 \pm 0.06$$

$B_s \rightarrow J/\Psi\ f_0(980)$ could be accessed:
- the BR is smaller than for the golden mode
- no angular analysis is required
- f_0 can be reconstructed in two charged pions

$B_s \to J/\Psi\ f_0(980)$: recent experimental data







from talks at Beauty 2011, Amsterdam

$$B(B_s \to J/\psi\ f_0(980)) = (3.2 \pm 1.3) \times 10^{-4}$$

$$(2.32 \pm 0.96) \times 10^{-4}$$

$$(3.7 \pm 1.3) \times 10^{-4}$$

LHCb Collab. PLB 648 (11) 115

Belle Collab. 1102.2759

CDF Collab. Note cdf10404.pdf

all compatible with our prediction

Other modes induced by $b \to c\,\bar{c}\,s$ transition

P. Colangelo, W. Wang, FDF
PRD 2011

Amplitude in generalized factorization:

$$\mathcal{A}(\bar{B}_a \to M_{c\bar{c}} L) = \frac{G_F}{\sqrt{2}} V_{cb} V^*_{cs} a_2^{eff}(\mu) \langle M_{c\bar{c}} | \bar{c}\gamma^\mu(1-\gamma_5)c\,|0\rangle \langle L|\,\bar{s}\gamma_\mu(1-\gamma_5)b\,|\bar{B}_a\rangle$$

can be fitted from B decays assuming $SU(3)_F$
and used to predict corresponding B_s decays

Using 2 sets of form factors

mode	$\mathcal{B}$ (CDSS)$\times 10^4$	$\mathcal{B}$ (BZ)$\times 10^4$	Exp.	mode	$\mathcal{B}$ (CDSS)$\times 10^4$	$\mathcal{B}$ (BZ) $\times 10^4$
$J/\psi\,\eta$	4.3 ± 0.2	4.2 ± 0.2	3.32 ± 1.02	$\eta_c\,\eta$	4.0 ± 0.7	3.9 ± 0.6
$J/\psi\,\eta'$	4.4 ± 0.2	4.3 ± 0.2	3.1 ± 1.39	$\eta_c\,\eta'$	4.6 ± 0.8	4.5 ± 0.7
$\psi(2S)\,\eta$	2.9 ± 0.2	3.0 ± 0.2		$\eta_c(2S)\,\eta$	1.5 ± 0.8	1.4 ± 0.7
$\psi(2S)\,\eta'$	2.4 ± 0.2	2.5 ± 0.2		$\eta_c(2S)\,\eta'$	1.6 ± 0.9	1.5 ± 0.8
$J/\psi\,\phi$	—	16.7 ± 5.7	13 ± 4	$\eta_c\,\phi$	—	15.0 ± 7.8
$\psi(2S)\,\phi$	—	8.3 ± 2.7	6.8 ± 3.0			
$\chi_{c1}\,\eta$	2.0 ± 0.2	2.0 ± 0.2		$\chi_{c1}\,f_0$	1.88 ± 0.77	0.73 ± 0.30
$\chi_{c1}\,\eta'$	1.9 ± 0.2	1.8 ± 0.2		$\chi_{c1}\,\phi$	—	3.3 ± 1.3
$J/\psi\,f_0$	4.7 ± 1.9	2.0 ± 0.8	< 3.26	$\eta_c\,f_0$	4.1 ± 1.7	2.0 ± 0.9
$\psi(2S)\,f_0$	2.3 ± 0.9	0.89 ± 0.36		$\eta_c(2S)\,f_0$	0.58 ± 0.38	1.3 ± 0.8

Other modes induced by $b \to c\,\bar{c}\,s$ transition

Modes with χ_{c0}, χ_{c2} or h_c in the final states have vanishing amplitude in the factorization approach
We can fit from corresponding B decays the whole amplitude without assuming a factorized form for it

mode	$\mathcal{B}$ $\times 10^4$	mode	$\mathcal{B}$	mode	$\mathcal{B}$ $\times 10^4$
$\chi_{c0}\,\eta$	0.85 ± 0.13	$\chi_{c2}\,\eta$	< 0.17	$h_c\,\eta$	< 0.23
$\chi_{c0}\,\eta'$	0.87 ± 0.13	$\chi_{c2}\,\eta'$	< 0.17	$h_c\,\eta'$	< 0.23
$\chi_{c0}\,f_0$	1.15 ± 0.17	$\chi_{c2}\,f_0$	< 0.29	$h_c\,f_0$	< 0.30
$\chi_{c0}\,\phi$	1.59 ± 0.38	$\chi_{c2}\,\phi$	$< 0.10 (0.62 \pm 0.17)$	$h_c\,\phi$	(< 1.9)

Subsequent decays of χ_{c0} have BRs of $O(10^{-2})$:

$$\chi_{c0} \to \rho^+\pi^-\pi^0,\ \rho^-\pi^+\pi^0,\ \pi^+\pi^-\pi^+\pi^-$$

In the case of $B_s \to \chi_{c0}\phi$ the final state consists of 6 charged hadrons
$\to$ suitable candidate to be accessed at LHCb

New Physics in non leptonic B_s decays

NP in $B_s - \overline{B}_s$ mixing

and/or

NP in B_s decay amplitudes

⇓

Modifies the mixing phase β_s
This effect is the same for all decay modes

⇓

Can affect various channels in different ways

Modes induced by the $b \rightarrow c\ \bar{c}\ s$ transition receive contribution from tree level + loop diagrams

There are scenarios in which new particles can contribute significantly as intermediate states in the loop the result being competitive with the SM tree level one

Example: supersymmetric scenarios with one loop gluino exchange contributing to $b \rightarrow s$ transition

New Physics in non leptonic B_s decays

General NP scenario (not specified) modifying the amplitudes

$A_f = A(B_s \to f)$ and $\bar{A}_f = A(\bar{B}_s \to f)$ (f= CP eigenstate) and

$$\lambda_f = e^{-2i\beta_s^{eff}} \left(\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \right)$$

Assuming that there is a single NP amplitude

$$\mathcal{A}_f = \mathcal{A}_f^{SM} (1 + R\, e^{i\theta_{NP}}\, e^{i\delta_{NP}})$$

new strong phase

new weak phase

$$R = \frac{|\mathcal{A}_f^{NP}|}{|\mathcal{A}_f^{SM}|}$$

Three observables: 1) branching ratio ***B***

2) Mixing induced CP asymmetry

3) direct CP asymmetry

$$S_f = \frac{2\Im(\lambda_f)}{1 + |\lambda_f|^2}$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

New Physics in non leptonic B_s decays

NP effects produce:

$$\boxed{\mathcal{B}^{exp} = \mathcal{B}^{SM}\left[1 + 2R\cos(\theta_{NP})\cos(\delta_{NP}) + R^2\right]}$$

$$\boxed{S_f = -\eta_f \frac{\sin(2\beta_s^{eff}) + 2R\cos\theta_{NP}\sin(2\beta_s^{eff} + \delta_{NP}) + R^2\sin(2\beta_s^{eff} + 2\delta_{NP})}{1 + 2R\cos\theta_{NP}\cos\delta_{NP} + R^2}}$$

$$\boxed{C_f = -\frac{2R\sin\theta_{NP}\sin\delta_{NP}}{1 + 2R\cos\theta_{NP}\cos\delta_{NP} + R^2}}$$

Quantities parametrizing deviations from SM:

$$\boxed{\Sigma = \frac{\mathcal{B}^{exp}}{\mathcal{B}^{SM}} - 1} \qquad \boxed{\tilde{S}_f = \frac{-\eta_f S_f - \sin(2\beta_s^{eff})}{\cos(2\beta_s^{eff})}}$$

$\Downarrow$

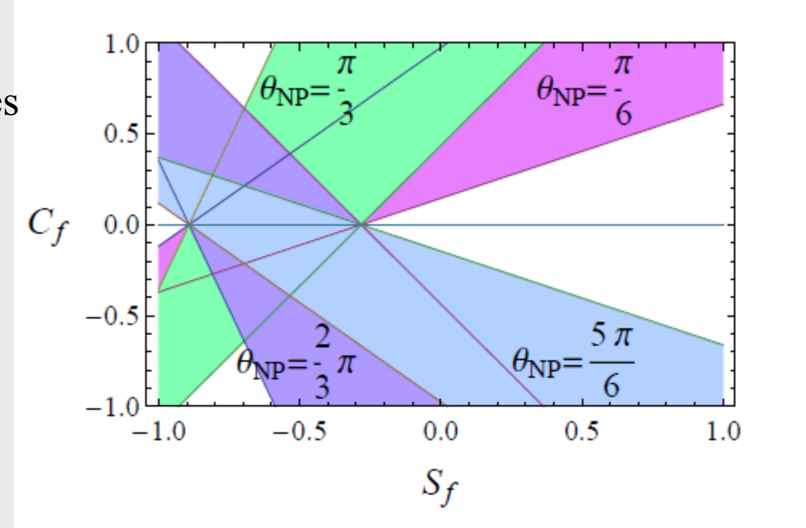
$$\boxed{\theta_{NP} = ArcTan\left(\frac{-C_f}{\tilde{S}_f}\right)} \qquad \boxed{\delta_{NP} = ArcTan\left[\frac{(1+\Sigma)}{\Sigma}\tilde{S}_f\right]} \qquad \boxed{R = \frac{\Sigma}{2\cos(\theta_{NP})\cos(\delta_{NP})}}$$

New Physics in non leptonic B_s decays

P. Colangelo, W. Wang, FDF
PRD 2011

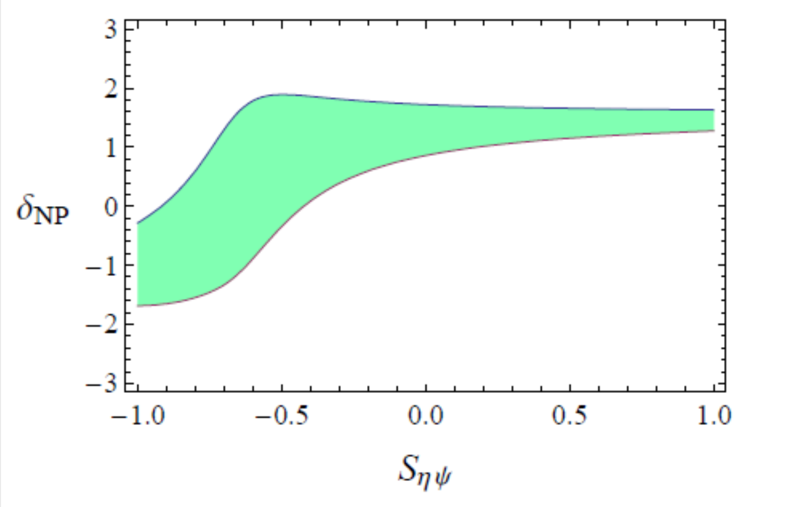
$$\theta_{NP} = ArcTan\left(\frac{-C_f}{\tilde{S}_f}\right)$$

Data on mixing-induced and direct CP asymmetries would constrain θ_{NP}



$$\delta_{NP} = ArcTan\left[\frac{(1+\Sigma)}{\Sigma}\tilde{S}_f\right]$$

δ_{NP} can be constrained knowing S_f and *B*



Example in the case of $B_s \to J/\psi\eta$ for which the branching ratio is measured

All the three observables are required to constrain R.

If *B*,C_f,S_f were known for at least two modes also β_s could be constrained

Conclusions

- Many interesting news in B_s decays
- others will probably (hopefully) come soon
- modes induced by $b \to c\bar{c}s$ transition are useful to determine β_s
- the sum rule calculation of $B_s \to f_0$ form factors allows to state that this mode is a promising alternative to the golden mode

Non factorizable effects

Uncertainties are due to - $SU(3)_F$ accuracy

- non factorizable effects

usually relevant when the factorizable term either is absent or is strongly suppressed (loop-induced decays, CKM suppression)

Polarization fractions are useful probes of such contributions

f_L $(\times 10^2)$ for B_s decays

Channel	Theory	Experiment
$J/\psi\,\phi$	51.3 ± 5.8	54.1 ± 1.7
$\psi(2S)\,\phi$	41.0 ± 3.7	
$\chi_{c1}\,\phi$	43.9 ± 4.4	

The only available measurement seems to indicate that non factorizable effects negligibly affect these modes