Mixing and CPV in D^0 and B_s^0

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- Introduction

  ... Formalism — differences between neutral mesons

- $D^0 - \overline{D}^0$ mixing

  ... Measurements and their interpretations

  ... Calculations of $\Delta\Gamma$ and Δm

- $B_s^0 - \overline{B}_s^0$ mixing

  ... Constraints on new physics

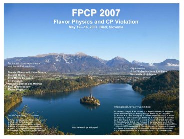
  ... Implications for LHC(b)

- Conclusions

Neutral meson mixings

1956, $K^0 - \overline{K}^0$: discovery of K_L (proposal of C non-conservation in '55)

1987, $B^0 - \overline{B}^0$: discovery of mixing ($\Rightarrow$ large m_t)



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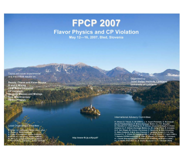

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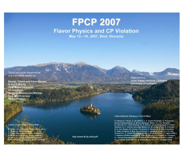
Q: If you asked someone last year when D^0 mixing would be observed...?

A: Probably not to be discovered for at least another decade...



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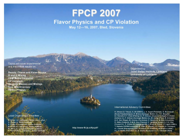
2007, $D^0 - \overline{D}^0$: growing evidence for $\Delta\Gamma = \mathcal{O}(0.01)$

What do the last two pieces of data tell us?



Mixing as a probe of NP

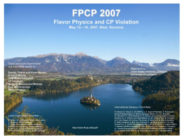
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CP violation scale

$$\epsilon_K\text{:}\ \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{TeV}, \qquad B_{d,s}\ \text{mixing:}\ \frac{(b\bar{q})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim \begin{cases} 10^3\,\text{TeV}\,, & B_d \\ 10^2\,\text{TeV}\,, & B_s \end{cases}$$

- Almost all extensions of the SM have new sources of CPV & flavor conversion
  - Originate at much higher scale than EWSB and are decoupled (MFV)?
  - Originate from EWSB-related NP, with non-trivial structure?

- Non-SM B_s^0 mixing: many models with new TeV-scale flavor physics; e.g., NMFV: Top may have special role in EWSB, strong coupling to NP, assume NP quasi-aligned with Yukawas (to suppress FCNC's) [Agashe, Papucci, Perez, Pirjol, hep-ph/0509117]

- Large D^0 mixing: quark-squark alignment ($m_{\tilde{g},\tilde{q}} \lesssim 1\text{TeV}$) predicts $\Delta m/\Gamma \sim \mathcal{O}(\lambda^2)$ (To not violate Δm_K bound, θ_C mostly from up sector, predicts sizable D mixing)



Neutral meson mixing

- Time evolution of two flavor eigenstates:

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|P^0(t)\rangle\\|\overline{P}^0(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|P^0(t)\rangle\\|\overline{P}^0(t)\rangle\end{pmatrix}$$

  M and Γ are 2×2 Hermitian matrices, CPT implies $M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$

- Mass eigenstates are eigenvectors of $\mathcal{H}$: $|P_{L,H}\rangle = p\,|P^0\rangle \pm q\,|\overline{P}^0\rangle$

  Time dependence involves mixing and decay: $|P_{L,H}(t)\rangle = e^{-(im_{L,H}+\Gamma_{L,H}/2)t}\,|P_{L,H}\rangle$

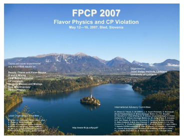
- Decay amplitudes: $A_f=\langle f|\mathcal{H}|P^0\rangle$, $\bar{A}_f=\langle f|\mathcal{H}|\overline{P}^0\rangle$

- Mass and width differences: $\Delta m = m_H - m_L\,(>0)$, $\quad\Delta\Gamma=\Gamma_H-\Gamma_L$

  Other phase convention independent observables:

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|,\qquad \left|\frac{q}{p}\right|,\qquad \lambda_f=\frac{q}{p}\,\frac{\bar{A}_f}{A_f}\,,\qquad \phi_{12}=\arg\left(\frac{M_{12}}{\Gamma_{12}}\right),\qquad \mathrm{Im}\frac{\Gamma_{12}}{M_{12}}=\frac{1-|q/p|^4}{1+|q/p|^4}$$

(CPV in decay, mixing, interference) (NP can easily modify) (a.k.a. A_{SL}; or $-2A_m$ if $|q/p|\approx 1$)



Not all neutral mesons are born equal

- General solution for eigenvalues:

$$(\Delta m)^2 - \frac{(\Delta\Gamma)^2}{4} = 4|M_{12}|^2 - |\Gamma_{12}|^2, \qquad \Delta m \Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*), \qquad \frac{q^2}{p^2} = \frac{2M_{12}^* - i\,\Gamma_{12}^*}{2M_{12} - i\,\Gamma_{12}}$$

- If $|\Delta\Gamma| \ll \Delta m$ ($|\Gamma_{12}/M_{12}| \ll 1$) — Holds for $B_{d,s}^0$ mixings (in the SM and beyond)

$$\Delta m = 2|M_{12}|\,(1+\ldots), \qquad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12}\,(1+\ldots)$$ [$\Rightarrow$ NP cannot enhance $\Delta\Gamma_{B_s}$]

$$\frac{q^2}{p^2} = \frac{(M_{12}^*)^2}{|M_{12}|^2}\,(1+\ldots) \qquad \Rightarrow \arg\frac{q}{p} \propto \phi_{12}$$ $\Rightarrow$ Good sensitivity to NP in M_{12}

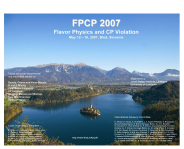
- If $|\Delta\Gamma| \gg \Delta m$ ($|M_{12}/\Gamma_{12}| \ll 1$) — Is this applicable for $D^0 - \overline{D}^0$ mixing?

$$\Delta\Gamma = 2|\Gamma_{12}|\,(1+\ldots), \qquad \Delta m = 2|M_{12}|\cos\phi_{12}\,(1+\ldots)$$ [Bergmann *et al.*, hep-ph/0005181]

$$\frac{q^2}{p^2} = \frac{(\Gamma_{12}^*)^2}{|\Gamma_{12}|^2}\,(1+\ldots)$$ $\Rightarrow$ sensitivity to M_{12} suppressed. If no CPV in D decay $\Rightarrow$

$$\arg\frac{q}{p}\,[\sim \arg(\lambda_{K^+K^-})] \propto 2\left|\frac{M_{12}}{\Gamma_{12}}\right|^2 \sin(2\phi_{12})$$ $\Rightarrow$ Weak sensitivity to NP in M_{12}

- If $|\Delta\Gamma| \gg \Delta m$ then sensitivity to NP in M_{12} is suppressed by $\Delta m/\Delta\Gamma$



New physics effects on mixing

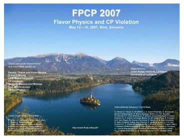
- New physics modifies M_{12}; CPV in mixing observable via $\phi = \arg(q/p)$ or $|q/p| \neq 1$

  Observing $\phi \neq$ SM prediction may be the best hope to find NP

- Mixing parameters: $B_{d,s}$: $\Delta\Gamma \ll \Delta m$, K: $\Delta\Gamma \approx -2\Delta m$, D: $\Delta\Gamma \gtrsim$ or $\gg \Delta m$
  - If $\Delta m \gg$ or $\ll \Delta\Gamma$ then $|q/p| \approx 1$ — If $\Delta\Gamma \sim \Delta m$ then $|q/p|$ may be far from 1
  - If $\Delta m \gg \Delta\Gamma$, the CPV phase can be **LARGE**: $\phi = \arg(M_{12}) + \mathcal{O}(\Gamma_{12}^2/M_{12}^2)$
  - If $\Delta m \ll \Delta\Gamma$, the CPV phase becomes **SMALL**: $\phi = \mathcal{O}(M_{12}^2/\Gamma_{12}^2) \times \sin(2\phi_{12})$

  $\Rightarrow$ It is of prime importance to determine relative magnitudes of Δm_D and $\Delta\Gamma_D$

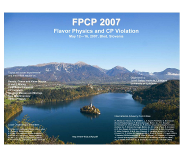
- Since Δm_D not yet measured, use $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle$ instead of $|D_{L,H}\rangle$



$D^0 - \overline{D}^0$ mixing

Special features of the $D^0 – \overline{D}^0$ system

- Of the neutral meson systems $D^0 – \overline{D}^0$ mixing is unique in that:
  - The only meson where mixing is generated by the down type quarks
  - It involves only the first two generations: CPV $> 10^{-3}$ would signal new physics
  - Expected to be small in the SM: $\Delta m,\, \Delta\Gamma \lesssim 10^{-2}\,\Gamma$, since they are DCS and vanish in the flavor $SU(3)$ symmetry limit
  - Sensitive to new physics: NP can easily enhance Δm but unlikely to affect $\Delta\Gamma$
    If $\Delta\Gamma \gtrsim \Delta m$: probably large $SU(3)$ breaking — If $\Delta m > \Delta\Gamma$: probably NP
  - Mixing has finally been observed!



Time dependence of decay rates

- Interplay of mixing and decay — Allow CPV in mixing (not in decay)

Denote: $x = \Delta m/\Gamma$, $y = \Delta\Gamma/(2\Gamma)$ $\quad R = \left|\frac{\lambda_{K^-\pi^+}}{\lambda_{K^+\pi^-}}\right| = \mathcal{O}(\tan\theta_C^4)$ $\quad x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$ ← strong phase

DCS:

$$\Gamma[D^0(t)\to K^+\pi^-] \propto e^{-\Gamma t}\left[R + \sqrt{R}\left|\frac{q}{p}\right|(y'\cos\phi - x'\sin\phi)\Gamma t + \left|\frac{q}{p}\right|^2 \frac{y^2+x^2}{4}(\Gamma t)^2\right]$$

$$\Gamma[\overline{D}^0(t)\to K^-\pi^+] \propto e^{-\Gamma t}\left[R + \sqrt{R}\left|\frac{q}{p}\right|^{-1}(y'\cos\phi + x'\sin\phi)\Gamma t + \left|\frac{q}{p}\right|^{-2} \frac{y^2+x^2}{4}(\Gamma t)^2\right]$$

SCS:

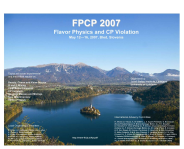
$$\Gamma[D^0(t)\to K^+K^-] \propto e^{-\Gamma t}\left[1 - \left|\frac{q}{p}\right|(y\cos\phi - x\sin\phi)\Gamma t\right]$$

$$\Gamma[\overline{D}^0(t)\to K^+K^-] \propto e^{-\Gamma t}\left[1 - \left|\frac{q}{p}\right|^{-1}(y\cos\phi + x\sin\phi)\Gamma t\right]$$

CF:

$$\Gamma[D^0(t)\to K^-\pi^+] = \Gamma[\overline{D}^0(t)\to K^+\pi^-] \propto e^{-\Gamma t}$$

- Setting $\phi = 0$: no CPV in mixing and choosing $|D_1\rangle = CP$-odd ($|D_2\rangle = CP$-even)



Mixing parameters from lifetimes

- Measure lifetimes, fitting exponential time dependences in decays to flavor and CP eigenstates (e.g., K^+K^- and π^+K^-)

$$y_{CP} = \frac{\hat{\tau}(D^0 \to K^-\pi^+)}{\hat{\tau}(D^0 \to K^+K^-)} - 1 = \frac{y\cos\phi}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - \frac{x\sin\phi}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)$$

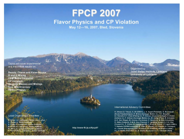
$$A_\Gamma = \frac{\hat{\tau}(\overline{D}^0 \to K^+K^-) - \hat{\tau}(D^0 \to K^+K^-)}{\hat{\tau}(\overline{D}^0 \to K^+K^-) + \hat{\tau}(D^0 \to K^+K^-)} = \frac{y\cos\phi}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - \frac{x\sin\phi}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)$$

If CP is conserved: $A_\Gamma = 0$ and $y_{CP} = \pm y$

- Results: $y_{CP} = 0.011 \pm 0.003 \;\; (3.5\sigma)$ [HFAG — Belle, BaBar, E791, FOCUS, CLEO]
  $A_\Gamma = 0.0001 \pm 0.0034$ [Belle, hep-ex/0703036]

- If $y\cos\phi$ dominates y_{CP}: $\frac{A_\Gamma}{y_{CP}} \approx \frac{|q/p|^2 - 1}{|q/p|^2 + 1} - \frac{x}{y}\tan\phi$ (smaller error?) [Nir, hep-ph/0703235]

- Observed value of y_{CP} could be explained by $y \approx 0.01$ or large x, $|q/p| - 1$, and ϕ



Mixing parameters from $D \to K^{\pm}\pi^{\mp}$

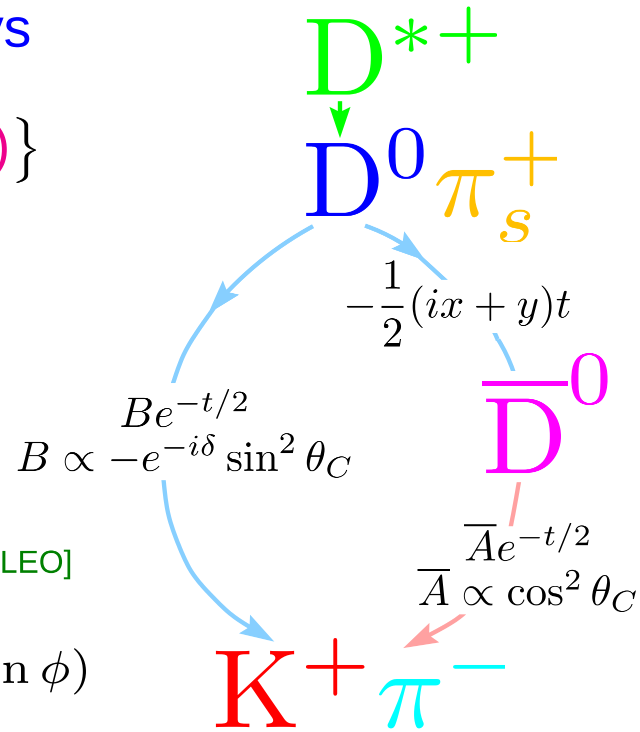
- Measure time dependence of “wrong sign” DCS decays

  Fit to: $e^{-\Gamma t}\{$(dir-DCS) $+ (\Gamma t)$(int-SCS) $+ (\Gamma t)^2$(mix-CF)$\}$

  Neglecting CPV, 3 fit parameters: $R(\equiv R_D)$, x', y'

  $$\left.\begin{aligned} y' &= 0.0097 \pm 0.0054 \\ x'^2 &= (-2.2 \pm 3.7) \times 10^{-4} \end{aligned}\right\}$$ 3.9σ evidence for mixing

  [BaBar, hep-ex/0703020]



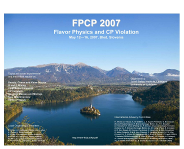
- Fits allowing CPV: $R^{\pm}$, $x'^{\pm}$, $y'^{\pm}$ [BaBar + Belle + FOCUS + CLEO]

  $$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}(x'\cos\phi \pm y'\sin\phi), \quad y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}(y'\cos\phi \mp x'\sin\phi)$$

- If y' dominates $y'^{\pm}$: $\dfrac{y'^{+} - y'^{-}}{y'^{+} + y'^{-}} \approx \dfrac{|q/p|^2 - 1}{|q/p|^2 + 1} - \dfrac{x'}{y'}\tan\phi$ (smaller error?) [Nir, hep-ph/0703235]

- Unless there is CPV in decay, $R^{+} = R^{-}$! — Please do 5 param fit with $A_D \to 0$

  (Early days of $B \to \psi K_S$: quote $S_{\psi K}$ with $|\lambda_{\psi K}| = 0$; maybe bigger impact here?)



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Mixing parameters from $D \to K_S \pi^+ \pi^-$

- Study interference in $m_{K\pi^+} - m_{K\pi^-}$ Dalitz plot — sensitive directly to x and y

  Models well-tuned for measurement of CKM angle γ from $B^\pm \to D_{(K_S\pi\pi)} K^\pm$

  Some strong phases are known & vary on smaller scales than others ($\Gamma_{K^*} \ll m_D$)

- Assuming CP cons.: $x = (0.80 \pm 0.29^{+0.09+0.15}_{-0.12-0.14})\%$, $y = (0.33 \pm 0.28^{+0.07+0.08}_{-0.12-0.09})\%$

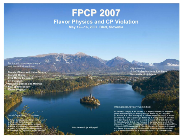
  [Belle, arXiv:0704.1000]

  (I'm a bit concerned about uncertainties related to the fact that we need the amplitude across the Dalitz plot, but have mostly tested its modelling with rates... [maybe it's only me...] CP tagged D decays will help.)

- Measurements of wrong sign semileptonic rate ($D^0 \to K^+ \ell \bar{\nu}$) sensitive to $x^2 + y^2$

  Weaker bounds at present: $x^2 + y^2 = 0.0010 \pm 0.0009$ [Belle, BaBar, CLEO, E791]

- In the limit of larger data sets: measurements with linear sensitivity to x, y



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Some tensions in data?

- Summary of measurements:

Lifetimes: $y_{CP} = 0.011 \pm 0.003$

$A_\Gamma = 0.0001 \pm 0.0034$

BaBar $K\pi$: $y' = 0.0097 \pm 0.0054$

$x'^2 = -0.00022 \pm 0.00037 \qquad x' < 0.023\ (2\sigma)$

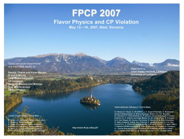
Belle $K\pi\pi$: $x = 0.0080 \pm 0.0034$

$y = 0.0033 \pm 0.0028$

- It seems to me that 1σ ranges of x, y, y_{CP}, A_Γ have no solution for $|q/p|$, $\cos\phi$ (y' also depends on δ, and x'^2 alone not very restrictive)

  Not very significant, but there is room for better consistency

- There is lot to be learned from more precise measurements



Calculations of $\Delta\Gamma$ and Δm

OPE analysis ($m_c \gg \Lambda$)

- $D^0 - \overline{D}^0$ mixing only arises at order $m_s^2/\Lambda_{\chi\text{SB}}^2$ (if $SU(3)$ violation is perturbative)

  [Falk *et al.*, hep-ph/0110317]

  $SU(3)$ suppression & DCS $\Rightarrow$ hard to estimate x, y in the SM: $x, y \sim \sin^2\theta_C\, \epsilon_{SU(3)}^2$

- Short distance box diagram: $x \propto \dfrac{m_s^2}{m_W^2} \times \dfrac{m_s^2}{m_c^2} \to 10^{-5}$

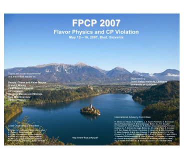
  y has additional m_s^2/m_c^2 helicity suppression

- Higher order terms in the OPE are suppressed by fewer powers of m_s [Georgi '92]

	4-quark	6-quark	8-quark
$\dfrac{\Delta m}{\Delta m_{\text{box}}}$	1	$\dfrac{\Lambda^2}{m_s m_c}$	$\dfrac{\Lambda^4}{m_s^2 m_c^2}\ \dfrac{\alpha_s}{4\pi}$
$\dfrac{\Delta\Gamma}{\Delta m}$	$\dfrac{m_s^2}{m_c^2}$	$\dfrac{\alpha_s}{4\pi}$	$\dfrac{\alpha_s}{4\pi}\,\beta_0$

[Bigi & Uraltsev ('00) claimed that $x, y \propto m_s$ is possible]

- Obtain $x, y \lesssim 10^{-3}$, with some assumptions about the matrix elements ($\Lambda \sim 4\pi f_\pi$)



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Long distance analysis (few final states)

- May be large, but extremely hard to estimate: $y \sim \frac{1}{2\Gamma} \sum_n \rho_n \langle \overline{D}^0 | H_w | n \rangle \langle n | H_w | D^0 \rangle$

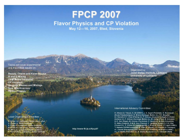
  $SU(3)$ breaking has been argued to be $\mathcal{O}(1)$ based on $\dfrac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)} \approx 2.8$

  Contribution to y: large cancellations possible, sensitive to strong phase:

  $$y_{PP} = \mathcal{B}(D \to \pi^+\pi^-) + \mathcal{B}(D \to K^+K^-) - 2\cos\delta \sqrt{\mathcal{B}(D \to K^-\pi^+)\,\mathcal{B}(D \to K^+\pi^-)}$$
  $$\approx (5.76 - 5.29\cos\delta) \times 10^{-3}$$ (from measured rates)

- Assuming $\cos\delta \sim 1$ [$SU(3)$ limit] and that these states are representative (many other DCS rates poorly known), it was often stated that $x \lesssim y <$ few $\times 10^{-3}$

- The most important long distance effect may be due to phase space:
  - Contrary to $SU(3)$ breaking in matrix elements, this $SU(3)$ violation is calculable model independently with mild assumptions
  - Negligible for lightest PP final states; important for states with mass near m_D



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$\Delta\Gamma$ from $SU(3)$ breaking in phase space

- Phase space difference between final states containing fewer or more strange quarks is a calculable source of $SU(3)$ breaking — these are "threshold effects"

  [Falk *et al.*, hep-ph/0110317]

- For any final state F in any $SU(3)$ representation R (e.g., PP can be in 8 or 27), we can calculate the "would-be" value of y, if D only decayed to the states in F_R

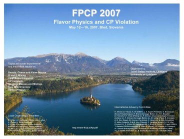
$$y_{F,R} = \frac{\sum_{n \in F_R} \langle \overline{D}^0 | H_w | n \rangle \rho_n \langle n | H_w | D^0 \rangle}{\sum_{n \in F_R} \Gamma(D^0 \to n)}$$

- E.g.: $D \to PP$ with U-spin: $s_1^2 \left[\Phi(\pi^+, \pi^-) + \Phi(K^+, K^-) - 2\Phi(K^+, \pi^-) \right] / \Phi(K^+, \pi^-)$

  Result is explicitly proportional to $s_1^2 \equiv \sin^2\theta_C$ and vanishes in $SU(3)$ limit as m_s^2

- If decay rates to all representations were known, we could reconstruct y from $y_{F,R}$

$$y = \frac{1}{\Gamma} \sum_{F,R} y_{F,R} \left[\sum_{n \in F_R} \Gamma(D^0 \to n) \right]$$



Our estimate of $\Delta\Gamma$

- The 2-, 3-, and 4-body final states account for sizable fraction of the D width

  Small contribution from two- and three-body final states (the PP contribution is “anomalously” small)

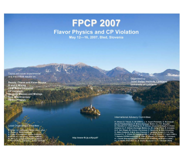
- Large $SU(3)$ breaking when some states are not allowed at all $(4m_K > m_D)$ in heavier multiplets: $y_{4P} = \mathcal{O}(s_1^2)$

  (Only studied smallest symmetric representations for $4P$)

rounded to nearest 5%	
final state	fraction
PP	5%
PV	10%
$(VV)_{s\text{-wave}}$	5%
$(VV)_{d\text{-wave}}$	5%
$3P$	5%
$4P$	10%

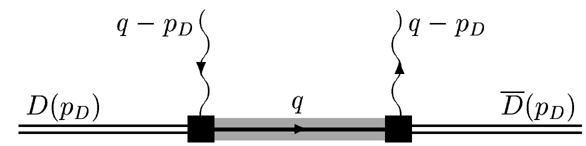
- There are other large rates near threshold, e.g.: $\mathcal{B}(D^0 \to K^- a_1^+) = (7.5 \pm 1.1)\%$
  Sizable contributions likely, but are untractable

- Morals: There are final states that can contribute to y near the 1% level
  It would require cancellations to suppress y_{CP} much below 1%



Connecting $\Delta\Gamma$ with Δm

- A dispersion relation in HQET relates Δm to an integral of $\Delta\Gamma$ over the mass M of a heavy "would-be D meson"



[Falk *et al.*, hep-ph/0402204]

$$\Delta m = -\frac{1}{2\pi}\,\mathrm{P}\int_{2m_\pi}^{\infty} \mathrm{d}M\, \frac{\Delta\Gamma(M)}{M - m_D} + \dots$$

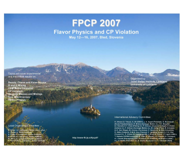
(Dispersion relations used before; I don't know how to justify them in full QCD)

- Assuming that phase space is only source of $SU(3)$ breaking, hadronic matrix elements cancel in y but not in x (need to know M-dependence of decay rates)

  2-body: Many interesting subtleties (chiral, intermediate, heavy mass regions) Most guidance for PP from theory on modelling M-dependence $\Rightarrow$ obtain small x

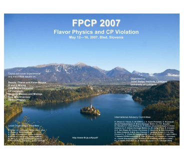
  4-body: can get sizable contributions to x, but typically $x \lesssim y$

- Conclusion was: if $y \sim 1\%$ then we expect $10^{-3} < |x| < 10^{-2}$
  Uncertainties much larger than for the estimate of y



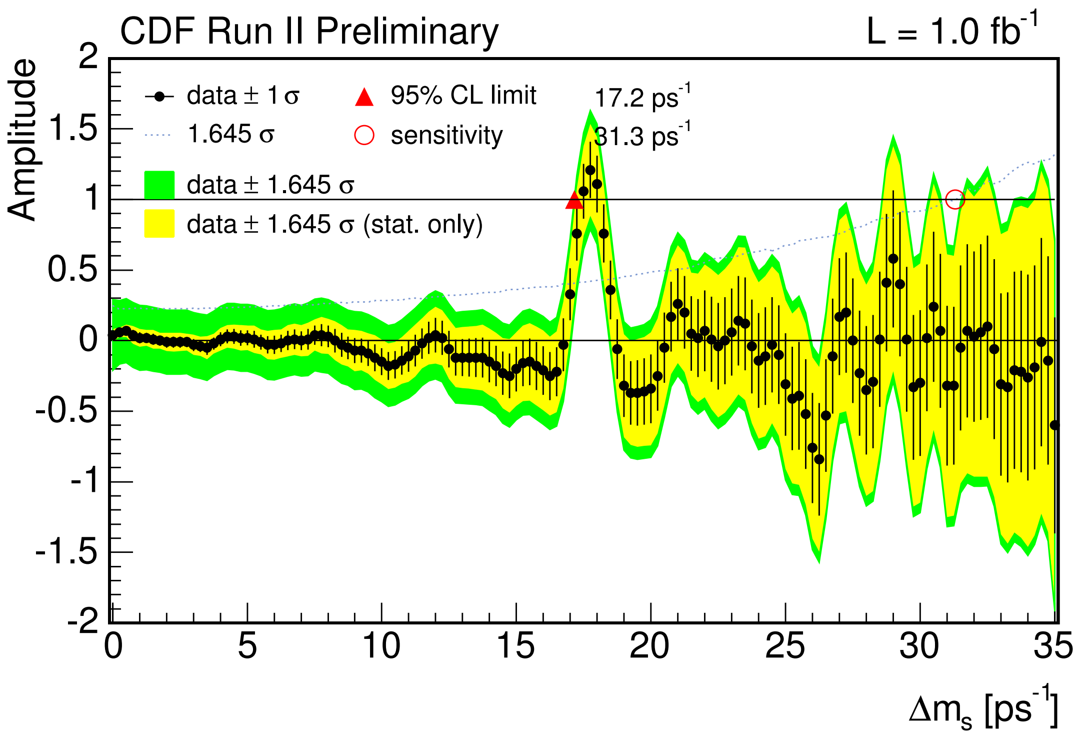
Summary for $D^0 - \overline{D}^0$ mixing

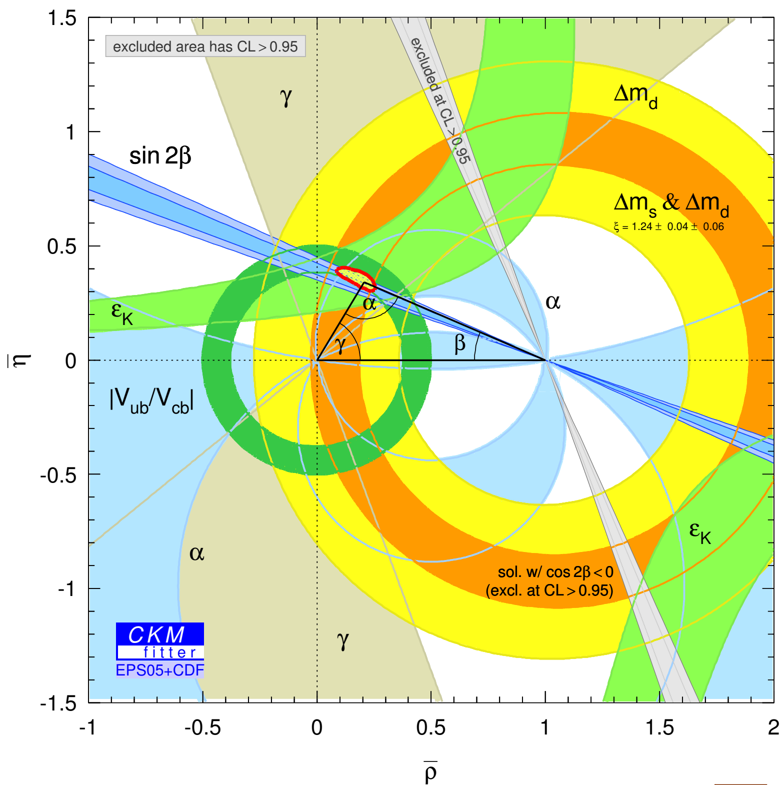
- It is possible that $\Delta\Gamma/\Gamma \sim 1\%$ in the SM (calculation w/o ad hoc assumptions)
- It is likely that $x < y$ in the SM (with some assumptions, predict $x \lesssim y$)
- If this is the case then sensitivity to NP is reduced, even if NP dominates M_{12}
- The central values of recent experimental results may be due to SM physics
- SM predictions of Δm and $\Delta\Gamma$ remain uncertain $\Rightarrow$ measurements of Δm and $\Delta\Gamma$ alone (especially since $\Delta m \lesssim \Delta\Gamma$) cannot be interpreted as new physics
- Important to improve constraints on both $\Delta\Gamma$ and Δm, and continue to look for CP violation, which remains a potentially robust signal of new physics



$B_s^0 - \overline{B}_s^0$ mixing

The news of 2006: Δm_{B_s} measured





- $\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\,\mathrm{ps}^{-1}$

  A 5.4σ measurement [CDF, hep-ex/0609040]

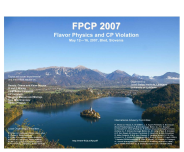
  Uncertainty $\sigma(\Delta m_s) = 0.7\%$ is already smaller than $\sigma(\Delta m_d) = 0.8\%$!

Largest uncertainty: $\xi = \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$

Lattice QCD: $\xi = 1.24 \pm 0.04 \pm 0.06$

Chiral logs: $\xi \sim 1.2$

SM CKM fit: $\xi = 1.158^{+0.096}_{-0.064}$

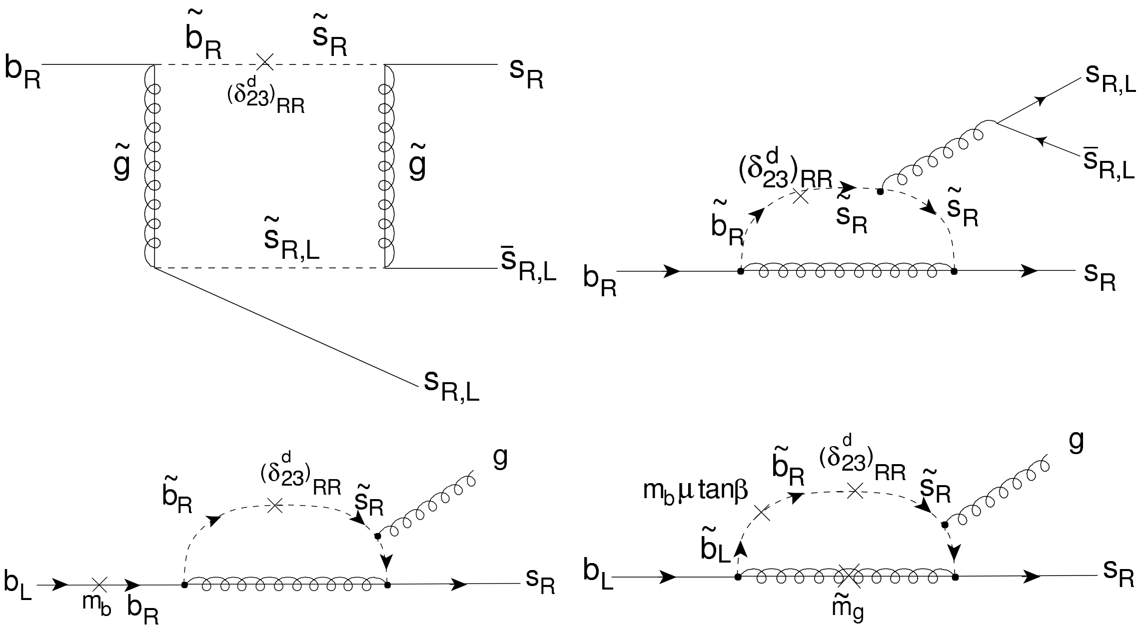


Some models to enhance Δm_s

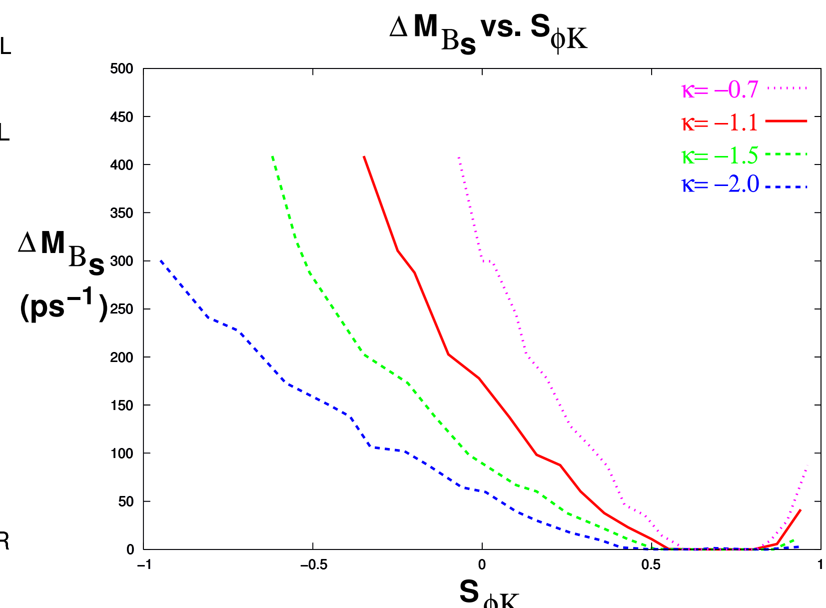
- SUSY GUTs: near-maximal $\nu_\mu - \nu_\tau$ mixing may imply large mixing between s_R and b_R, and between $\tilde{s}_R$ and $\tilde{b}_R$

  Mixing among right-handed quarks drop out from CKM matrix, but among right-handed squarks it is physical

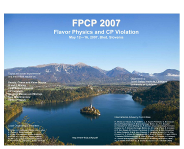
$$\begin{pmatrix} \tilde{s}_R \\ \tilde{s}_R \\ \tilde{s}_R \\ \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix} \longleftrightarrow \begin{pmatrix} \tilde{b}_R \\ \tilde{b}_R \\ \tilde{b}_R \\ \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}$$



$\mathcal{O}(1)$ effects in $b \to s$ possible



[Harnik, Larson, Murayama, Pierce, hep-ph/0212180]



Some models to suppress Δm_s

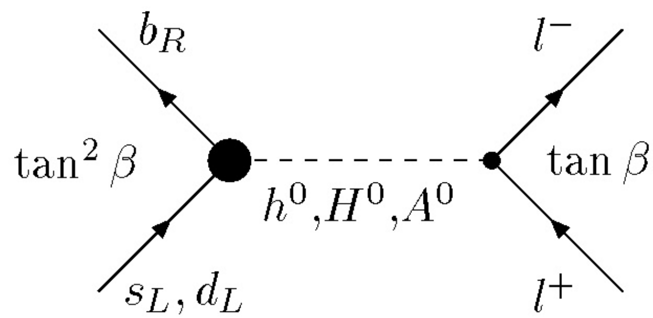
- Neutral Higgs mediated FCNC in the large $\tan\beta$ region:

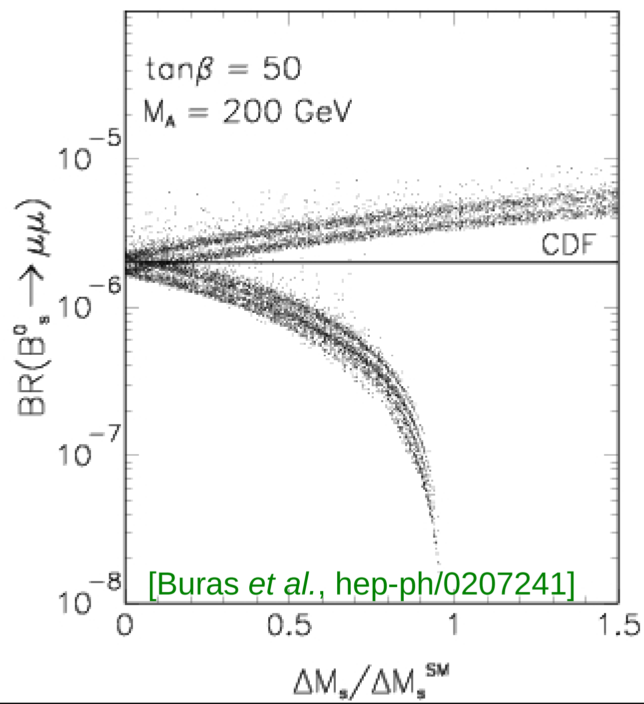
  Enhancement of $\mathcal{B}(B_{d,s} \to \mu^+\mu^-) \propto \tan^6\beta$ up to two orders of magnitude above the SM

  CDF & DØ: $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ (95% CL)

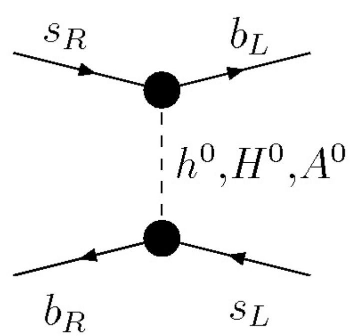
  [Bernhard, yesterday]

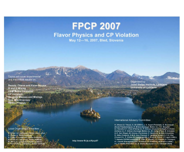
  SM: 3.4×10^{-9} — measurable at LHC





- Suppression of $\Delta m_s \propto \tan^4\beta$ in a correlated way





New physics in B mixing

- $B_{d,s}$ mixings are short distance dominated, so: theory errors $\ll$ measured values
  (For Δm_D and ϵ'/ϵ we only know NP $<$ measurement; $\Delta\Gamma_s$ ($\Delta\Gamma_s^{CP}$) in between)

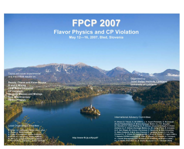
  Assume: (i) 3×3 CKM matrix is unitary
  (ii) Tree-level decays dominated by SM

- Concentrate on NP in $\Delta F = 2$: two parameters for each meson mixing amplitude

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r^2\, e^{2i\theta}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h\, e^{2i\sigma})}_{\text{easy to relate to models}}$$

- $B\overline{B}$ mixing dependent observables sensitive to h, σ: $\Delta m_{d,s}$, S_{f_i}, $A_{\rm SL}^{d,s}$, $\Delta\Gamma_s^{CP}$
  (Hadronic uncertainty sizable in $A_{\rm SL}^{d,s}$ and $\Delta\Gamma_s^{CP}$, but in SM $A_{\rm SL}^{d,s} \ll$ current bound)

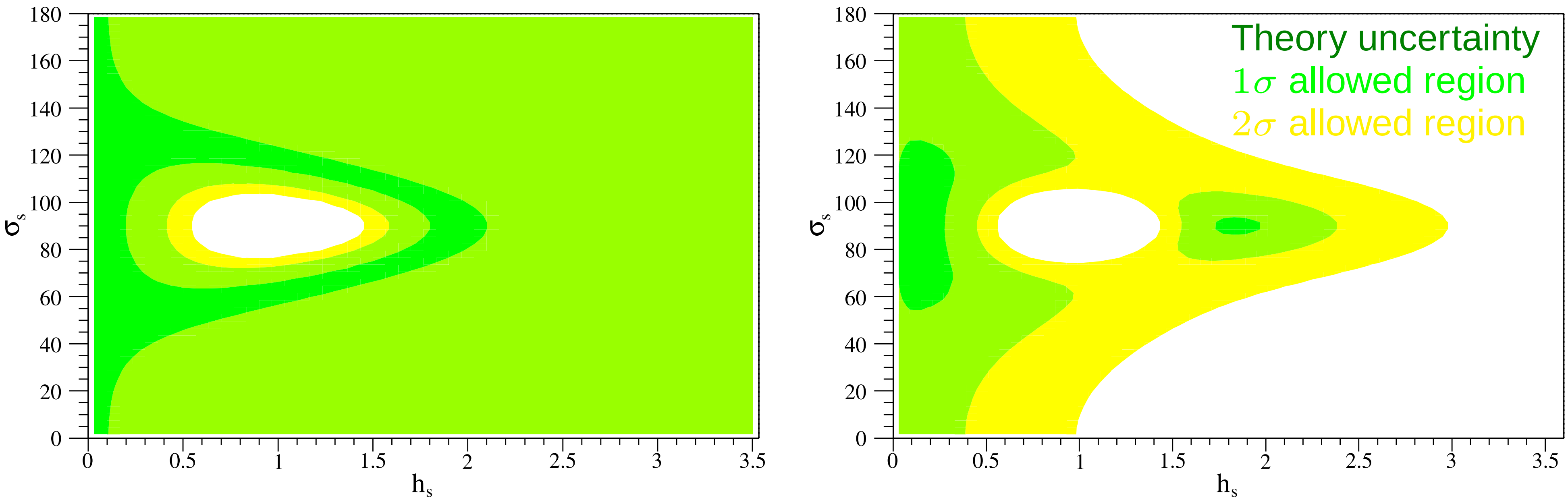
- Tree-level CKM constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)
  (neglect NP in $\Delta F = 1$, and possible correlations between $b \to d$ and $b \to s$)



New physics in $B_s^0 - \overline{B}_s^0$ mixing

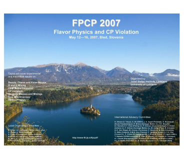
- Constraints before (left) and after (right) measurement of Δm_s and $\Delta\Gamma_s^{CP}$

  Recall parameterization: $M_{12} = M_{12}^{\rm SM}\,(1 + h_s\, e^{2i\sigma_s})$ [ZL, Papucci, Perez, hep-ph/0604112]



- To learn more about the B_s system, need data on CP asymmetry in $B_s \to J/\psi\,\phi$

- h measures "tuning": $h \sim (4\pi v/\Lambda)^2$, so $\begin{cases} h \sim 1 & \Rightarrow \Lambda_{\rm flavor} \sim 2\,{\rm TeV} \sim \Lambda_{\rm EWSB} \\ h < 0.1 & \Rightarrow \Lambda_{\rm flavor} > 7\,{\rm TeV} \gg \Lambda_{\rm EWSB} \end{cases}$



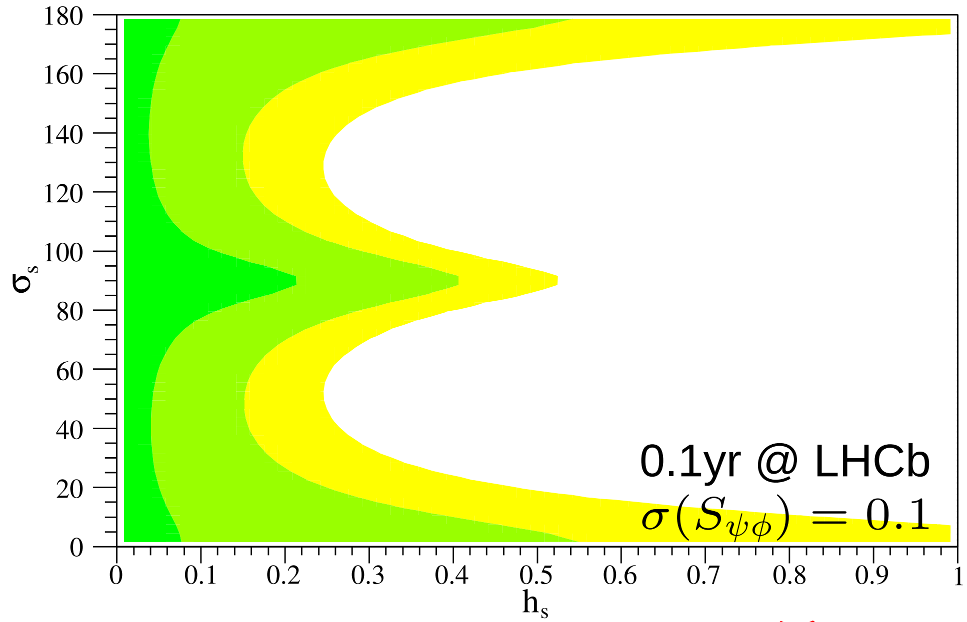
Next milestone in B_s: $S_{B_s\to\psi\phi,\,\psi\eta^{(\prime)}}$

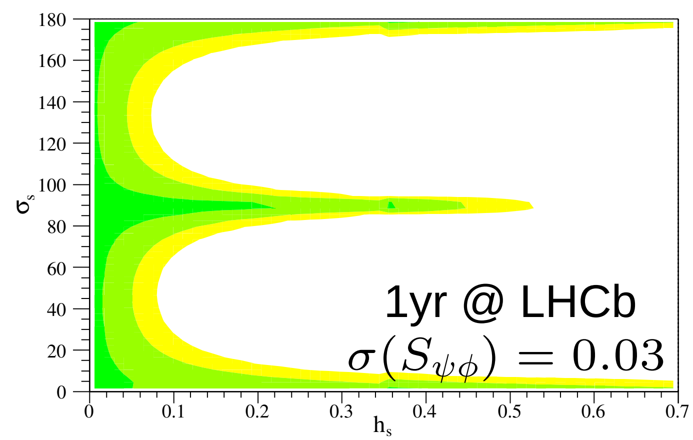
- $S_{\psi\phi}$ ($\sin 2\beta_s$ for CP-even) analog of $S_{\psi K}$
  CKM fit predicts: $\sin 2\beta_s = 0.0346^{+0.0026}_{-0.0020}$

- 2000: Is $\sin 2\beta$ consistent with ϵ_K, $|V_{ub}|$
  Δm_B and other constraints?
  2009: Is $\sin 2\beta_s$ consistent with ...?

- Plot $S_{\psi\phi}$ = SM value ± 0.10 / ± 0.03
  $0.1/1$ yr of nominal LHCb data ⇒

- With relatively little data, huge impact on our understanding; maybe one of the most interesting early measurements





Notice scales!

Another observable: $A_{\rm SL}^s$

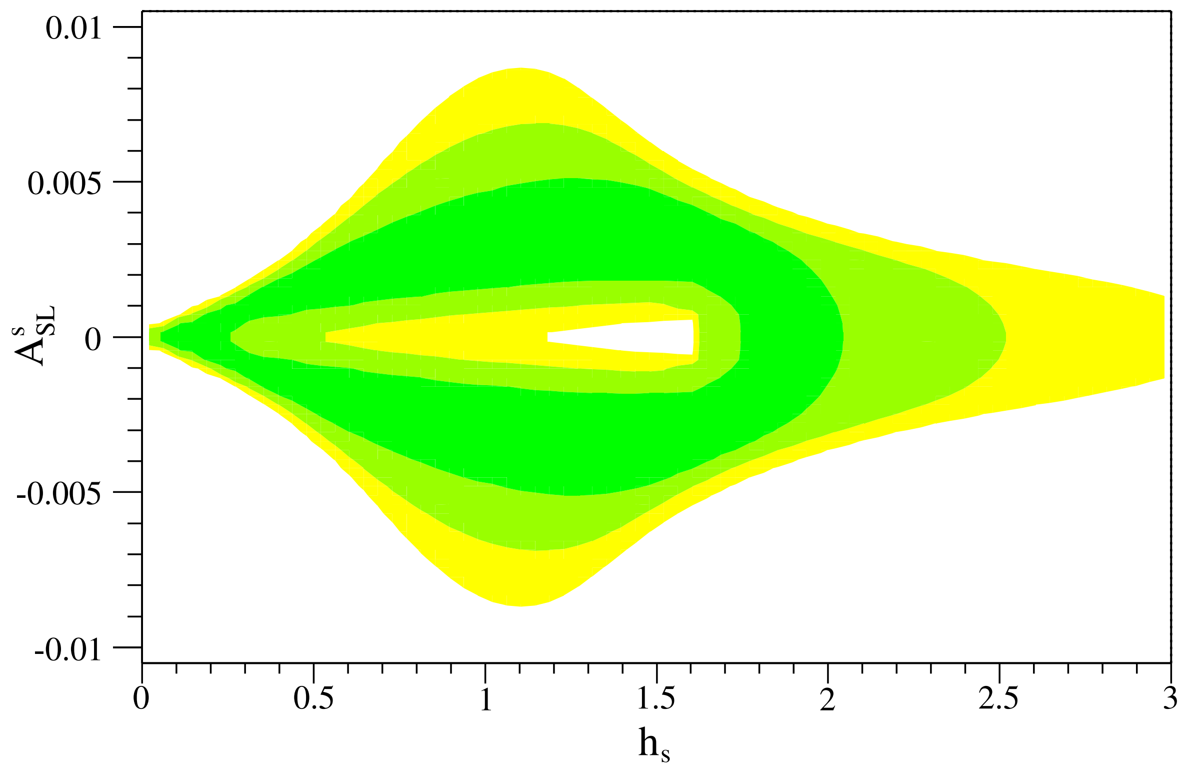
- Difference of $B \to \overline{B}$ vs. $\overline{B} \to B$ probability

$$A_{\rm SL} = \frac{\Gamma[\overline{B}{}^0_{\rm phys}(t) \to \ell^+ X] - \Gamma[B^0_{\rm phys}(t) \to \ell^- X]}{\Gamma[\overline{B}{}^0_{\rm phys}(t) \to \ell^+ X] + \Gamma[B^0_{\rm phys}(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx -2\left(\left|\frac{q}{p}\right| - 1\right)$$

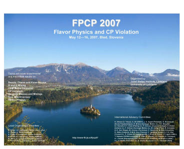
– Can be $\mathcal{O}(10^3)$ times SM

– $|A_{\rm SL}^s| > |A_{\rm SL}^d|$ possible (contrary to SM)

– In SM: $A_{\rm SL}^s \sim 3 \times 10^{-5}$ is unobservably small



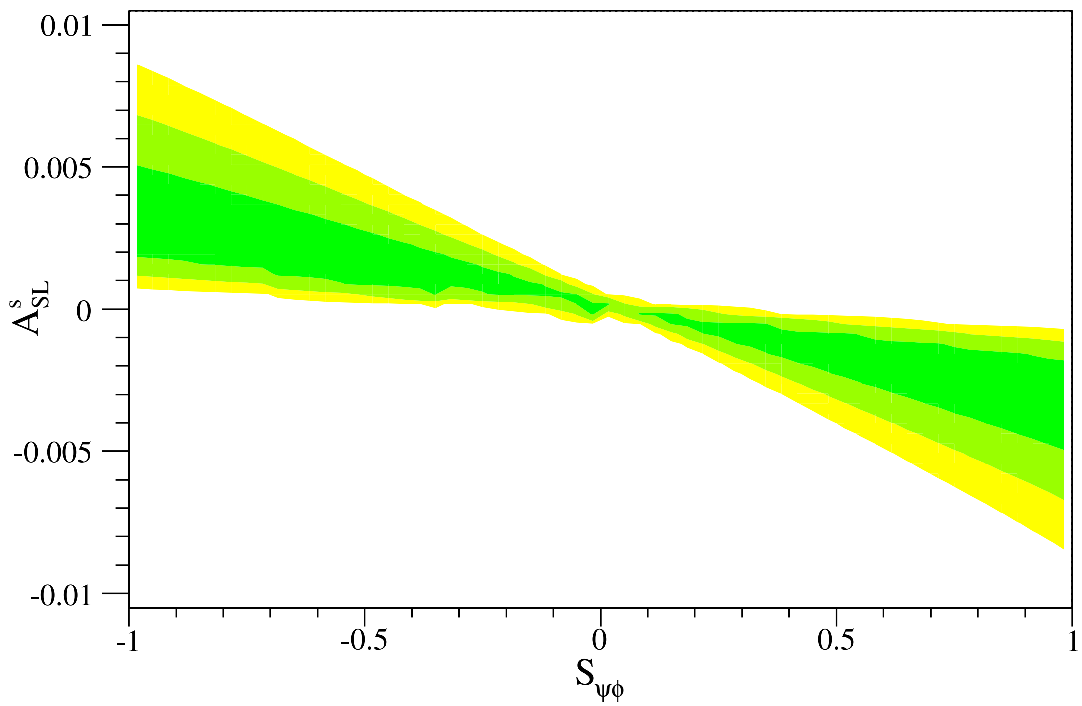
[see also: Buras *et al.*, hep-ph/0604057;
Grossman, Nir, Raz, hep-ph/0605028]



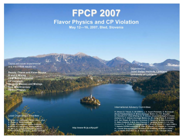
Correlation between $S_{\psi\phi}$ and $A_{\rm SL}^s$

- $A_{\rm SL}^s$ and $S_{\psi\phi}$ are strongly correlated in $h_s, \sigma_s \gg \beta_s$ region [ZL, Papucci, Perez, hep-ph/0604112]

$$A_{\rm SL}^s = -\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|^{\rm SM} S_{\psi\phi} + \mathcal{O}\left(h_s^2,\, \frac{m_c^2}{m_b^2}\right)$$

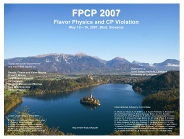


- Correlation only if NP does not alter tree level processes — test assumptions



Summary for $B_s^0 - \overline{B}_s^0$ mixing

- Measurements @ Tevatron started to constrain NP in $(b \to s)_{\Delta F=2}$ transitions
- Significant NP contributions are possible nevertheless
- Need measurements of more observables: $S_{\psi\phi}$ & $A_{\rm SL}^s$
  (Don't need sensitivity to SM prediction to have important implications!)
- LHCb can distinguish between MFV and non-MFV scenarios in the early LHC era
- If deviations found, correlations between $S_{\psi\phi}$ and $A_{\rm SL}^s$ can help understand the nature of NP



Conclusions

Some things we do know

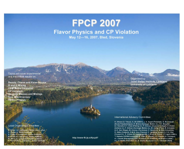
- We learned a lot about meson mixings in the past 1.5 years

	$x = \Delta m/\Gamma$ SM theory	data	$y = \Delta\Gamma/(2\Gamma)$ SM theory	data	$A = 1 - \lvert q/p\rvert^2$ SM theory	data
B_d	$\mathcal{O}(1)$	0.78	$y_s\,\lvert V_{td}/V_{ts}\rvert^2$	-0.005 ± 0.019	$-(5.5 \pm 1.5)10^{-4}$	$(-4.7 \pm 4.6)10^{-3}$
B_s	$x_d\,\lvert V_{ts}/V_{td}\rvert^2$	25.8	$\mathcal{O}(-0.1)$	-0.05 ± 0.04	$-A_d\,\lvert V_{td}/V_{ts}\rvert^2$	$(0.3 \pm 9.3)10^{-3}$
K	$\mathcal{O}(1)$	0.948	-1	-0.998	$4\,\mathrm{Re}\,\epsilon$	$(6.6 \pm 1.6)10^{-3}$
D	$\lesssim 0.01$	< 0.016	$\mathcal{O}(0.01)$	$y_{CP} = 0.011 \pm 0.003$	$< 10^{-4}$	$\mathcal{O}(1)$ bound only

- Identities, neglecting CPV in mixing (not the most interesting info, but amusing):

	CP even	CP odd	lifetime short	lifetime long	comments
B_s	even	odd	even	odd	In SM even = light, odd = heavy
B_d	heavy quark limit: same as for B_s				Not directly known yet
K	light	heavy	light	heavy	Known before the SM ;–)
D	even	odd	even	odd	Unknown which is heavy / light

Before 2006, we only knew experimentally the Kaon line of this table!



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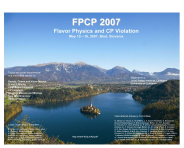
Some things I'd like to know

- $D^0 - \overline{D}^0$ mixing:
  - Values of Δm and $\Delta\Gamma$
  - Result of $K\pi$ fit with 5 parameters (allowing CPV in mixing, but not in decay)
  - Will CPV be observed? Is $|q/p|$ near 1?
- $B_s^0 - \overline{B}_s^0$ mixing:
  - Better constraint on / measurement of $S_{B_s \to \psi\phi}$
  - Improved bounds on $A_{\rm SL}$
  - Better lattice QCD results for Δm and $\Delta\Gamma$
- We can learn a lot more from improved measurements



Backup slides

$SU(3)$ analysis of D mixing

- Want to study: $\langle \overline{D}^0 | T\{H_w, H_w\} | D^0 \rangle = \langle 0 | D\, T\{H_w, H_w\} D | 0 \rangle$

  the field operator $D \in 3$ creates a D^0 or annihilates a $\overline{D}^0$

  $$H(\Delta C = -1) = (\bar{q}_i\, c)(\bar{q}_j\, q_k) \in 3 \times \overline{3} \times \overline{3} = \underbrace{\overline{15} + 6}_{\text{If 3rd gen. neglected}} + \overline{3} + \overline{3}$$

  $SU(3)$ breaking is introduced by $\mathcal{M}^i_j =$ diag$(m_u, m_d, m_s) \sim$ diag$(0, 0, m_s)$

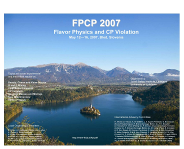
- A pair of D operators or a pair of H's is symmetric, so $D_i D_j \in 6$ and

  $$H^{ij}_k H^{lm}_n \in \left[(\overline{15} + 6) \times (\overline{15} + 6)\right]_S \to \overline{60} + 42 + 15'$$

  0. Since there is no $\overline{6}$ in $H_w H_w$ $\Rightarrow$ mixing vanishes in $SU(3)$ limit
  1. $DD\mathcal{M} \in 6 \times 8 = 24 + \overline{15} + 6 + \overline{3}$ $\Rightarrow$ no invariants with $H_w H_w$ at order m_s
  2. $DD\mathcal{M}\mathcal{M} \in 6 \times (8 \times 8)_S = 6 \times (27 + 8 + 1) = 60 + \overline{24} + \overline{15'} + \ldots$

- $D^0 - \overline{D}^0$ mixing only arises at order $m_s^2/\Lambda^2_{\chi\mathrm{SB}}$ (if $SU(3)$ violation is perturbative)

[Falk *et al.*, hep-ph/0110317]



Parameterization of NP in mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) Tree-level decays dominated by SM

  Concentrate on NP in mixing amplitude; two new param's for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})}_{\text{easy to relate to models}}$$

- Observables sensitive to $\Delta F = 2$ new physics:

$$\Delta m_{B_q} = r_q^2\, \Delta m_{B_q}^{\rm SM} = |1 + h_q e^{2i\sigma_q}|\Delta m_q^{\rm SM}$$

$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})]$$

$$S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

$$S_{B_s \to \psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q(1 + h_q e^{2i\sigma_q})}\right]$$

$$\Delta\Gamma_s^{CP} = \Delta\Gamma_s^{\rm SM} \cos^2(2\theta_s) = \Delta\Gamma_s^{\rm SM} \cos^2[\arg(1 + h_s e^{2i\sigma_s})]$$

- Tree-level constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)