# Why Super-$B$?

*Zoltan Ligeti*

SLAC, June 14

- Introduction
- Bounds on non-SM contributions
  Brief look at $B_d$ and $B_s$ mixing
- Some future clean measurements
  Few examples — fuller list in many reports
- Exciting theoretical developments
  Zero-bin factorization, annihilation
- Conclusions

[Höcker & ZL, hep-ph/0605217, to appear in ARNPS]

# We do not understand much about flavor

- SM flavor problem: hierarchy of masses and mixing angles
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

  $\epsilon_K$: $\dfrac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{TeV}$, $\qquad B_d$ mixing: $\dfrac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\text{TeV}$

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- Almost all extensions of the SM have new sources of CPV & flavor conversion
  (e.g., 43 new CPV phases in SUSY)
- A major constraint for model building
  (flavor structure: universality, heavy squarks, squark-quark alignment, ...)
- The observed baryon asymmetry of the Universe requires CPV beyond the SM
  (not necessarily in flavor changing processes, nor in the quark sector)

# Spectacular track record

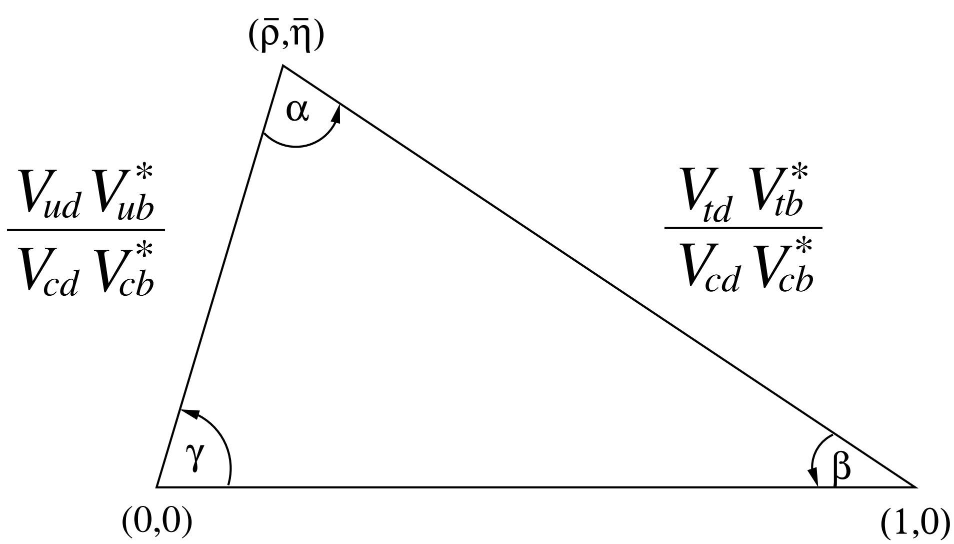
- Flavor and $CP$ violation are excellent probes of New Physics
  - $\beta$-decay predicted neutrino (Fermi)
  - Absence of $K_L \to \mu\mu$ predicted charm (GIM)
  - $\epsilon_K$ predicted 3rd generation (KM)
  - $\Delta m_K$ predicted charm mass (GL)
  - $\Delta m_B$ predicted heavy top
- If there is NP at the TEV scale, it must have a very special flavor / $CP$ structure
- Or will the LHC find just a SM-like Higgs?

# What is usually said to be done

- Exhibit hierarchical structure of CKM $(\lambda \simeq 0.23)$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Measurements often shown in the $(\bar\rho, \bar\eta)$ plane — a "language" to compare data

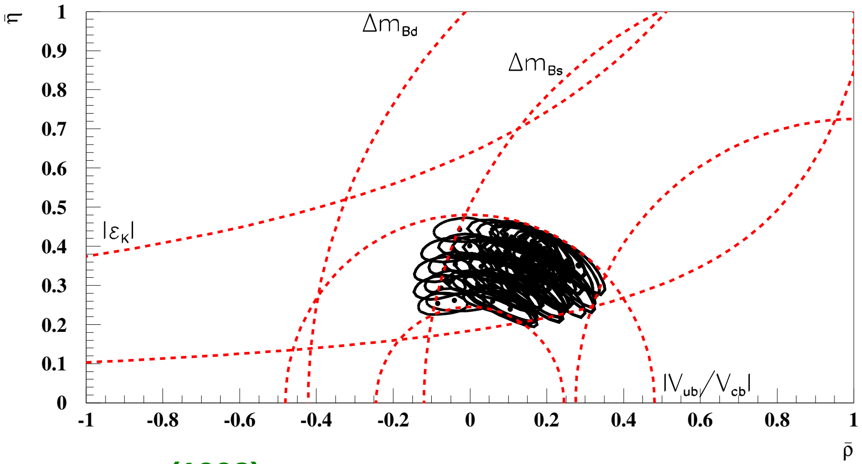



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Angles and sides are directly measurable in numerous different processes

Goal: overconstraining measurements sensitive to different short dist. phys.

# Remarkable progress at $B$ factories

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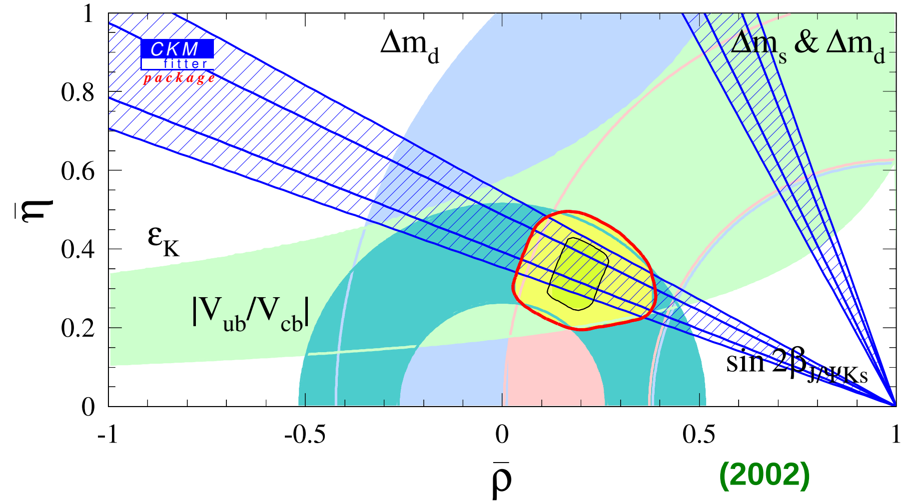


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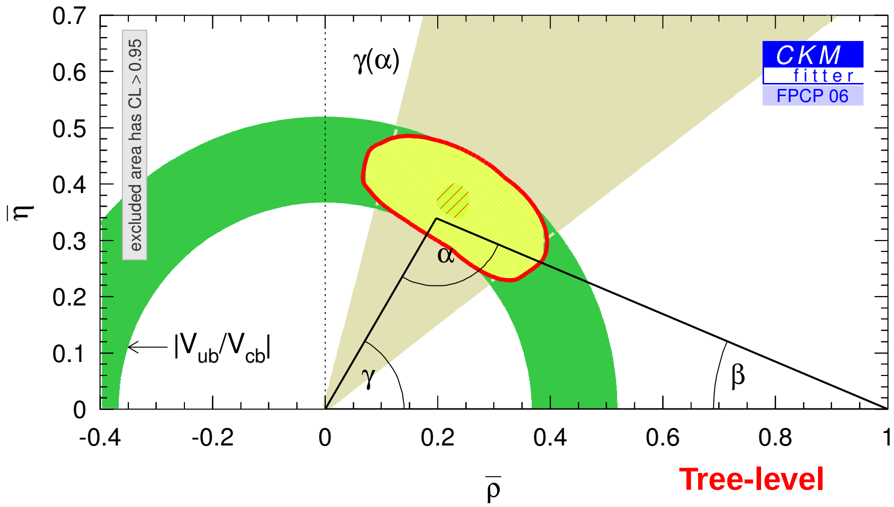
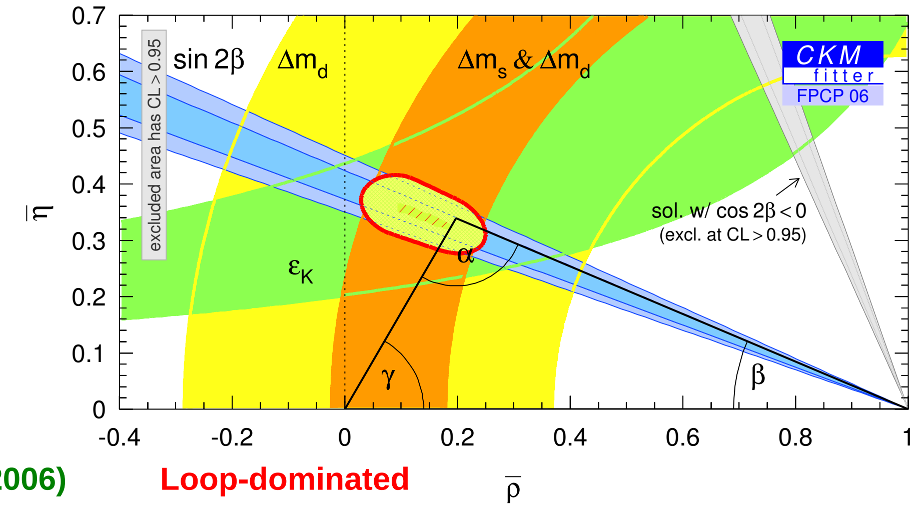



Tree-level

(2006)




Loop-dominated

- The CKM picture is verified ⇒ looking for corrections rather than alternatives

# Missing messages

- $\mathcal{O}(20-30\%)$ non-SM contribution to most loop-mediated transitions still allowed

  Stopping at $\mathcal{O}(1\,\mathrm{ab}^{-1})$ datasets and giving up approaching percent level constraints would be a little bit like not having LEP after SPS, or ILC after LHC

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- We continue to fail to convey excitement of this program to non-experts:
  - The interesting messages are not simple to explain

    Not just one, single, critical measurement; theory is often quite complicated
  - The simple messages are not interesting

    Lincoln Wolfenstein does not care what $\rho$ and $\eta$ are, so why should you / I / ...?

# Bounds on non-SM

# Important features of the SM

- The SM flavor structure is very special:
  - Single source of $CP$ violation in CC interactions
  - Suppressions due to hierarchy of mixing angles
  - Suppression of FCNC processes (loops)
  - Suppression of FCNC chirality flips by quark masses (e.g., $S_{K^*\gamma}$)

  Many suppressions that NP might not respect $\Rightarrow$ sensitivity to very high scales

- It is interesting / worthwhile / possible to test all of these

# Parameterization of NP in mixing

- Assume: (i) $3 \times 3$ 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:

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

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

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

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

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

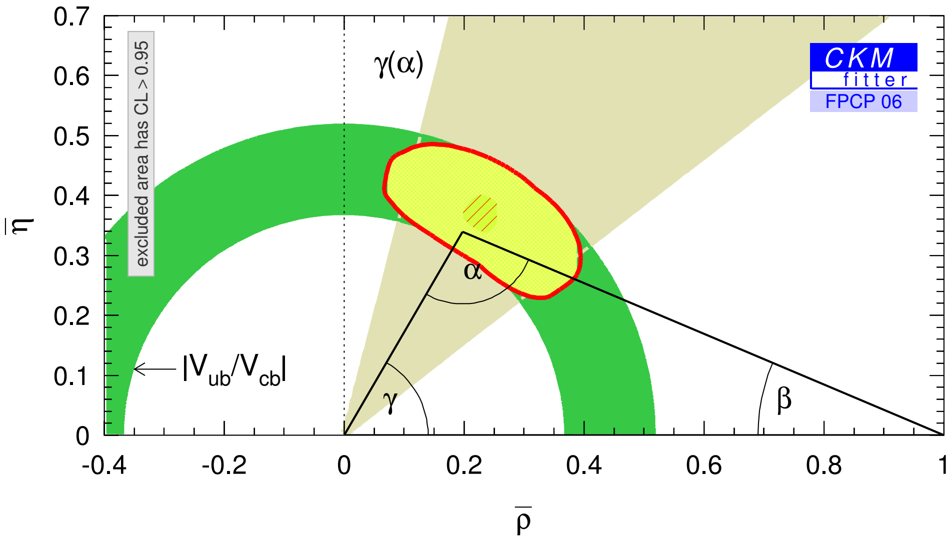
$$S_{\psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

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

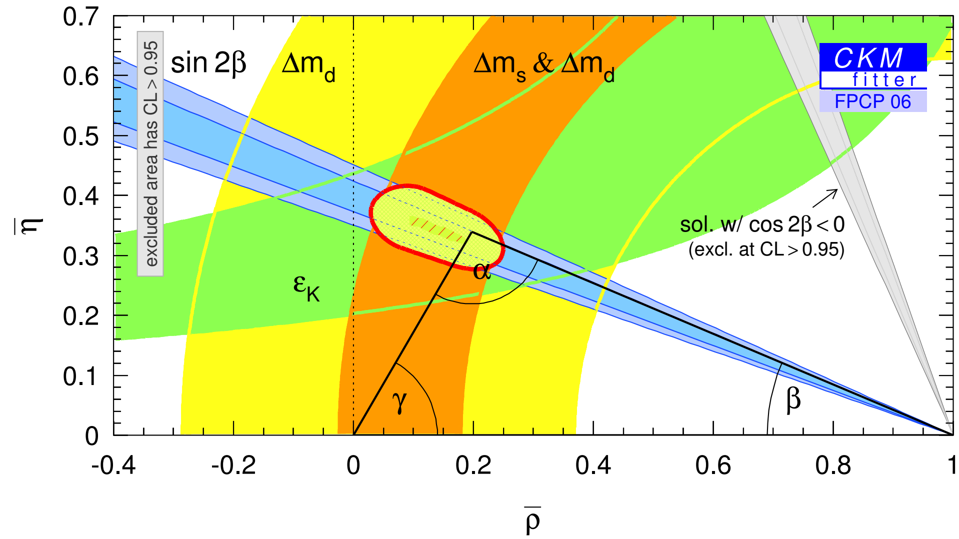
# Constraining new physics in loops

- $B$ factories: $\bar{\rho}, \bar{\eta}$ determined from (effectively) tree-level & loop-induced processes

Tree-level




Loop-induced

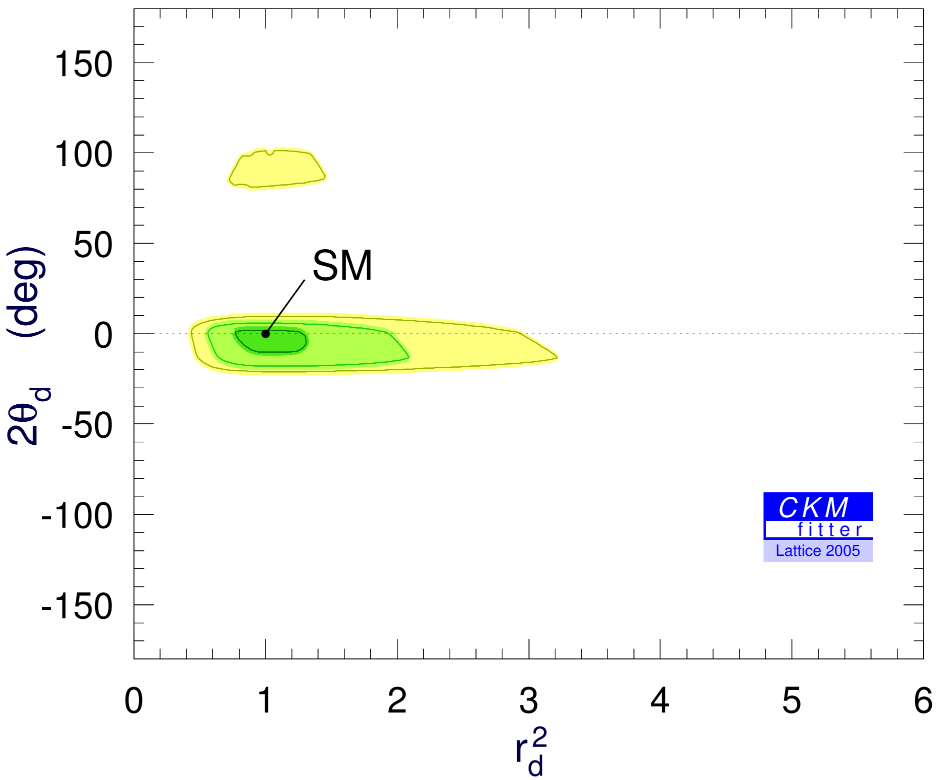


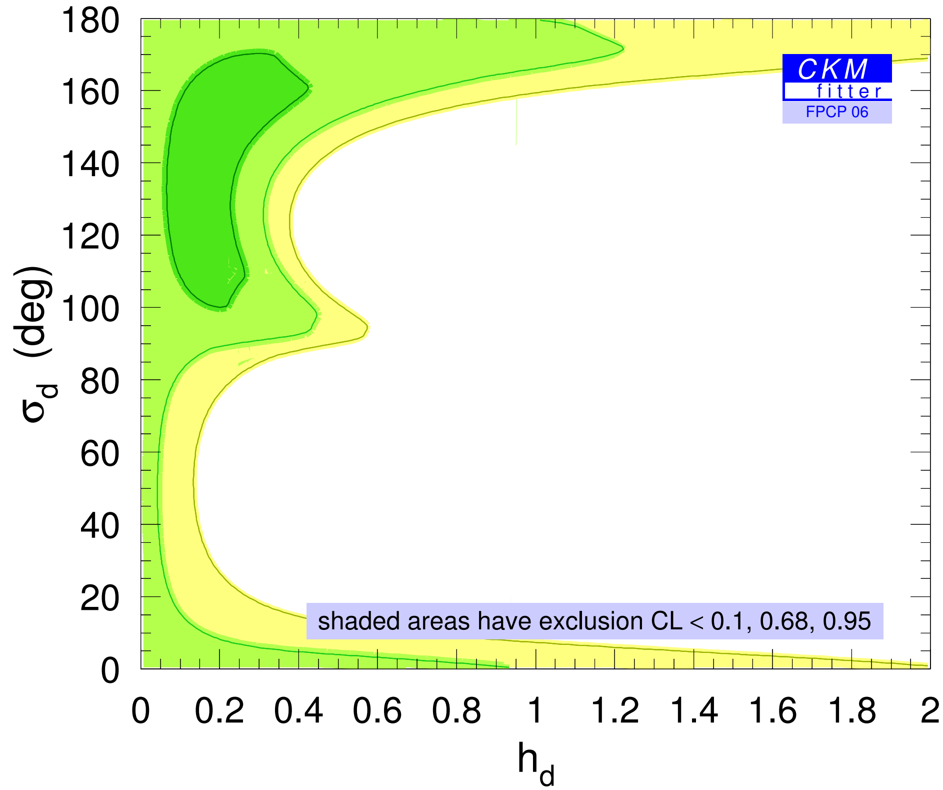

- $\bar{\rho}, \bar{\eta}$ constrained to SM region even in the presence of NP in loops

- $\epsilon_K$, $\Delta m_d$, $\Delta m_s$, $|V_{ub}|$, etc., can be used to overconstrain the SM and test for NP

  NP: more parameters $\Rightarrow$ independent measurements critical

# The parameter space $r_d^2, \theta_d$ and $h_d, \sigma_d$



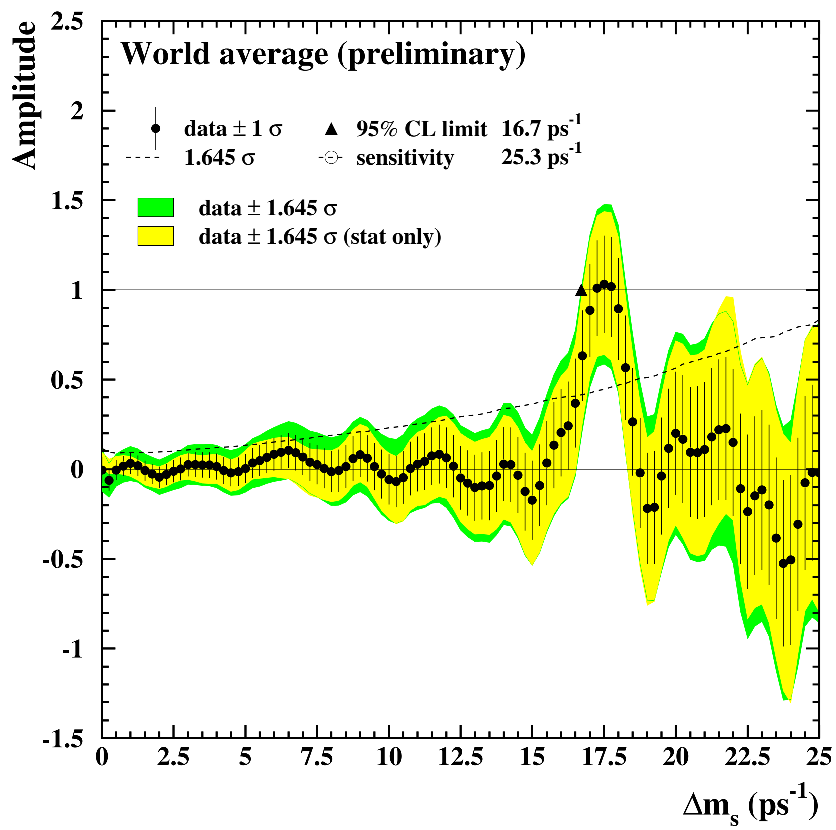

$r_d^2, \theta_d$: $|M_{12}/M_{12}^{\rm SM}|$ can only differ significantly from $1$ if $\arg(M_{12}/M_{12}^{\rm SM}) \sim 0$

$h_d, \sigma_d$: NP may still be comparable to SM: $h_d = 0.23\,^{+0.57}_{-0.23}$, i.e., $h_d < 1.7$ ($95\%$ CL)

- Recent data restricts NP in mixing for the first time — still plenty of room left

# News of the year: $\Delta m_s$

- $\Delta m_s = (17.31\,^{+0.33}_{-0.18} \pm 0.07)\ \text{ps}^{-1}$ [CDF, hep-ex/0606027] (prob. of bkgd fluctuation: $0.2\%$)




CDF: $\sim 3\sigma$; world average: $\sim 4\sigma$

**Weights in world average at 17.5 ps$^{-1}$**

| | | | |
|---|---|---|---|
| ALEPH | 10.2% | LEP | 14.6% |
| DELPHI | 4.1% | | |
| OPAL | 0.4% | | |
| SLD | 8.2% | SLC | 8.2% |
| CDF1 | 0.9% | Tevatron | 77.2% |
| CDF2 | 67.9% | | |
| D0 | 8.4% | | |

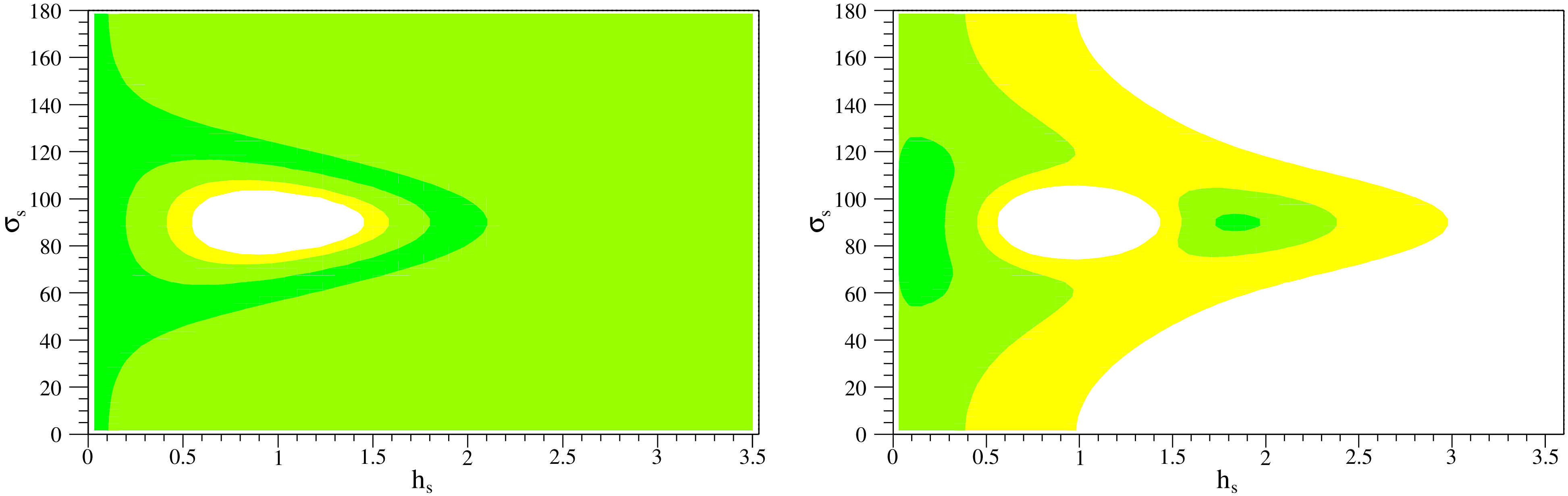
[from O. Schneider]

First time that sensitivity is significantly greater than where (hint of) signal is seen

A $> 5\sigma$ measurement before the LHC turns on now appears certain

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

- Before and after the measurement of $\Delta m_s$ (and $\Delta\Gamma_s$ ): [ZL, Papucci, Perez, hep-ph/0604112]



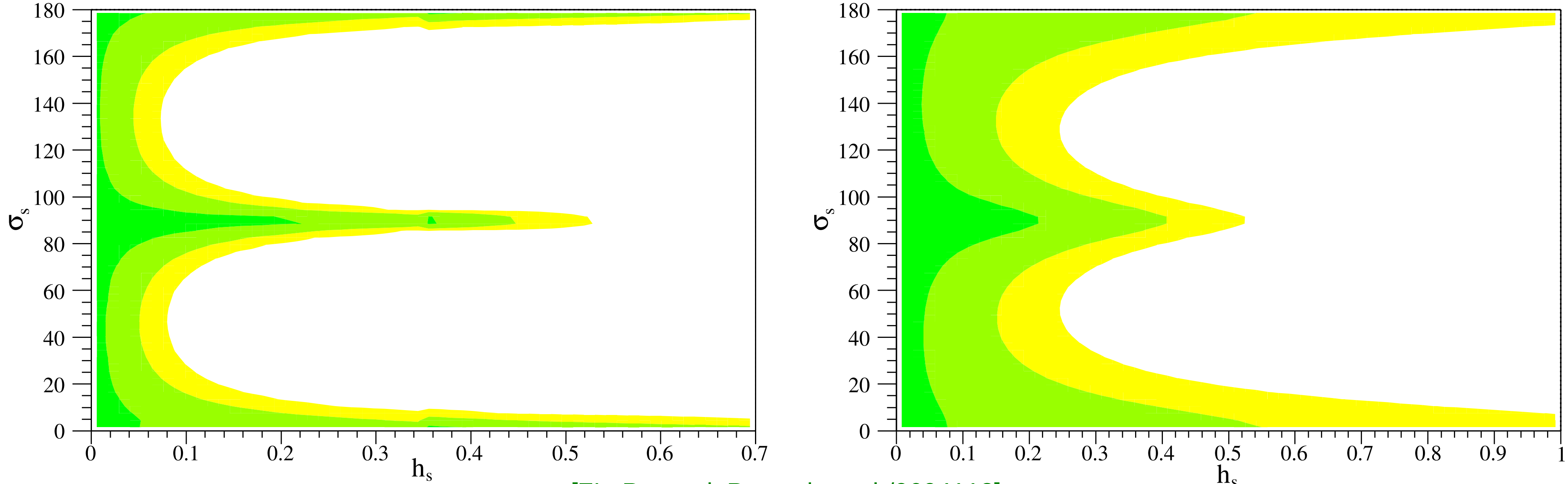

- To learn more about the $B_s^0$ system, need $CP$ asymmetry in $B_s \to \psi\phi$, etc.

# Constraints with measurement of $S_{B_s \to \psi\phi}$

- $S_{\psi\phi}$ is analog of $S_{\psi K}$ $(\sin 2\beta)$, and similarly clean

  In SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = \mathcal{O}(\lambda^2)$; prediction: $\sin 2\beta_s = 0.0365 \pm 0.0020$

- Assume $S_{\psi\phi}$ measured to be SM $\pm 0.03\,/\pm 0.10$ ($1/0.1$ yr nominal LHCb data)



[ZL, Papucci, Perez, hep-ph/0604112]

- Unless there is an easy-to-find narrow resonance at ATLAS & CMS, this could be (one of) the most interesting early measurements(s)

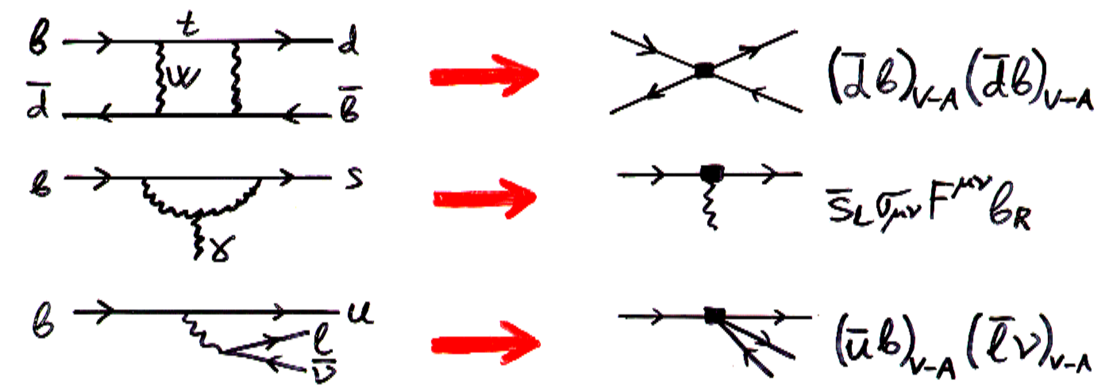
# Some important processes

# What are we really after?

- At scale $m_b$, flavor changing processes are mediated by $\mathcal{O}(100)$ higher dimension operators

  Depend only on a few parameters in SM $\Rightarrow$ intricate correlations between $s, c, b, t$ decays

weak / NP scale $\sim 5$ GeV



E.g.: in SM $\dfrac{\Delta m_d}{\Delta m_s}, \dfrac{b \to d\gamma}{b \to s\gamma}, \dfrac{b \to d\ell^+\ell^-}{b \to s\ell^+\ell^-} \propto \left|\dfrac{V_{td}}{V_{ts}}\right|$, but test different short dist. physics

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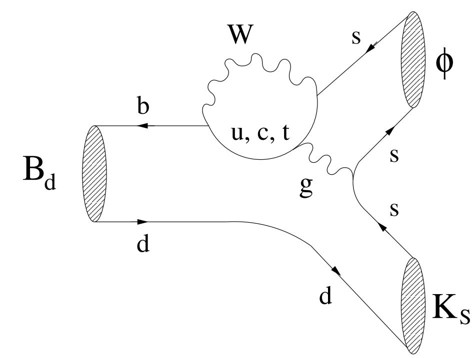
- Question: does the SM (i.e., integrating out virtual $W$, $Z$, and quarks in tree and loop diagrams) explain all flavor changing interactions? Right coeff's? Right op's?

- New physics most likely to modify SM loops, so study:
  mixing & rare decays, compare tree and loop processes, $CP$ asymmetries

# CPV in $b \to s, d$ penguins

- Measuring same angle in decays sensitive to different short distance physics may give best sensitivity to NP ($f_s = \phi K_S$, $\eta' K_S$, etc.)

Amplitudes with one weak phase expected to dominate:

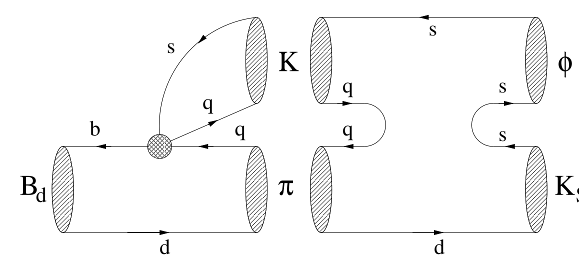



$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{\langle \text{“}P\text{”} \rangle}_{1} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{\langle \text{“}P + T_u\text{”} \rangle}_{\mathcal{O}(1)}$$

SM: expect: $S_{f_s} - S_{\psi K}$ and $C_{f_s} \lesssim 0.05$

NP: $S_{f_s} \neq S_{\psi K}$ possible; expect mode-dependent $S_f$

Depend on size & phase of SM and NP amplitude




NP could enter $S_{\psi K}$ mainly in mixing, while $S_{f_s}$ through both mixing and decay

- Interesting to pursue independent of present results — there is room left for NP

# Is there NP in $b \to s$ transitions?

| $f_{CP}$ | SM predictions for $(-\eta_{f_{CP}} S_{f_{CP}} - \sin 2\beta)$ my estimates* | BHNR | Beneke | $-\eta_{f_{CP}} S_{f_{CP}}$ |
|---|---|---|---|---|
| $\psi K$ | $0.01$ | | | $+0.687 \pm 0.032$ |
| $\eta' K$ | $0.05$ | $+0.01^{+0.01}_{-0.02}$ | $+0.01^{+0.01}_{-0.01}$ | $+0.48 \pm 0.09$ |
| $\phi K$ | $0.05$ | $+0.02$ | $+0.02^{+0.01}_{-0.01}$ | $+0.47 \pm 0.19$ |
| $\pi^0 K_S$ | $0.15$ | $+0.06^{+0.04}_{-0.03}$ | $+0.07^{+0.05}_{-0.04}$ | $+0.31 \pm 0.26$ |
| $K^+ K^- K_S$ | $0.15$ | | | $+0.51 \pm 0.17$ |
| $K_S K_S K_S$ | $0.15$ | | | $+0.61 \pm 0.23$ |
| $f^0 K_S$ | $0.25$ | | | $+0.75 \pm 0.24$ |
| $\omega K_S$ | $0.25$ | $+0.19^{+0.06}_{-0.14}$ | $+0.13^{+0.08}_{-0.08}$ | $+0.63 \pm 0.30$ |

* What I consider reasonable limits (strict bounds worse, model calculations better)

Buchalla, Hiller, Nir, Raz and Beneke use QCDF; $SU(3)$ bounds weaker [Grossman, ZL, Nir, Quinn]

- Estimates model dependent: theory has to develop further to firm up predictions

  There are also SM predictions with $S_{\eta' K^0} - \sin 2\beta < 0$ [Williamson & Zupan, hep-ph/0601214]

- Will significance of hints of deviations from SM increase or decrease...?

# $\alpha$ from $B \to \rho\rho,\ \rho\pi,\ \pi\pi$

- $S_{\rho^+\rho^-} = \sin[(B\text{-mix} = -2\beta) + (\overline{A}/A = -2\gamma + \ldots) + \ldots] = \sin(2\alpha) + \text{small}$

  (1) Longitudinal polarization dominates (could be mixed $CP$-even/odd)

  (2) Small rate: $\mathcal{B}(B \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ (90% CL) $\Rightarrow$ small $\Delta\alpha$

  $\frac{\mathcal{B}(B\to\pi^0\pi^0)}{\mathcal{B}(B\to\pi^+\pi^0)} = 0.26 \pm 0.06$ vs. $\frac{\mathcal{B}(B\to\rho^0\rho^0)}{\mathcal{B}(B\to\rho^+\rho^0)} < 0.06$ (90% CL)

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This year the penguins started to bite

$\Rightarrow$ Need more data

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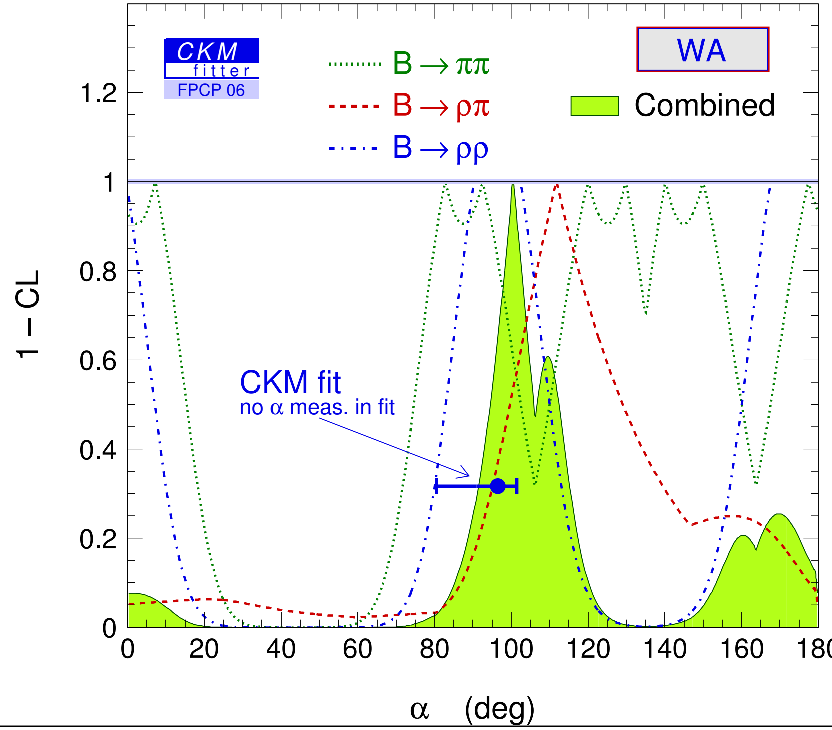
- Isospin bound: $|\Delta\alpha| < 17°$

  $S_{\rho^+\rho^-}$ yields: $\alpha = (100^{+13}_{-20})°$

  More complicated than $\pi\pi$, $I = 1$ possible due to $\Gamma_\rho \neq 0$; its $\mathcal{O}(\Gamma_\rho^2/m_\rho^2)$ effects can be constrained with more data [Falk, ZL, Nir, Quinn]




- All measurements combined: $\alpha = (102^{+15}_{-9})°$

# $\gamma$ from $B^\pm \to DK^\pm$

- Tree level: interfere $b \to c\ (B^- \to D^0 K^-)$ and $b \to u\ (B^- \to \overline{D}{}^0 K^-)$

  Need $D^0, \overline{D}{}^0 \to$ same final state; determine $B$ and $D$ decay amplitudes from data

  Sensitivity driven by: $r_B = |A(B^- \to \overline{D}{}^0 K^-)/A(B^- \to D^0 K^-)| \sim 0.1 - 0.2$

  Many variants according to $D$ decay: $D_{CP}$ [GLW], DCS/CA [ADS], CS/CS [GLS]

- Best measurement was: $D^0, \overline{D}{}^0 \to K_S\, \pi^+\pi^-$

  [Giri, Grossman, Soffer, Zupan; Bondar]

  – Both amplitudes Cabibbo allowed

  – Can integrate over regions in $m_{K\pi^+} - m_{K\pi^-}$ Dalitz plot

Also got a lot harder this year!

Each of these methods satisfies the NIMSBHO principle:
Not Inherently More Sensitive But Helps Overall
(despite possible claims to the contrary…)

[Soffer @ 2004 Hawaii Super-$B$ workshop]

$\Rightarrow$ Need a lot more data

- Average of all measurements: $\gamma = \left(62^{+35}_{-25}\right)^\circ$

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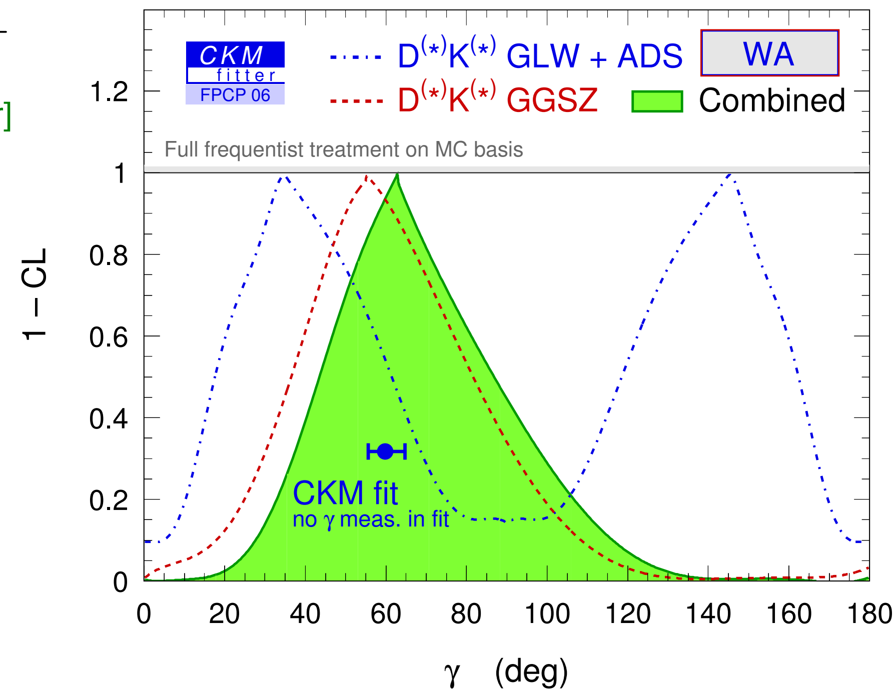


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# Rare $B$ decays

- Important probes of new physics
  - $B \to K^*\gamma$ or $X_s\gamma$: Best $m_{H^\pm}$ limits in 2HDM — in SUSY many param's
  - $B \to K^{(*)}\ell^+\ell^-$ or $X_s\ell^+\ell^-$: $bsZ$ penguins, SUSY, right handed couplings

A crude guide ($\ell = e$ or $\mu$)

| Decay | $\sim$ SM rate | physics examples |
|---|---|---|
| $B \to s\gamma$ | $3 \times 10^{-4}$ | $\lvert V_{ts}\rvert$, $H^\pm$, SUSY |
| $B \to \tau\nu$ | $1 \times 10^{-4}$ | $f_B \lvert V_{ub}\rvert$, $H^\pm$ |
| $B \to s\nu\nu$ | $4 \times 10^{-5}$ | new physics |
| $B \to s\ell^+\ell^-$ | $6 \times 10^{-6}$ | new physics |
| $B_s \to \tau^+\tau^-$ | $1 \times 10^{-6}$ | |
| $B \to s\tau^+\tau^-$ | $5 \times 10^{-7}$ | ⋮ |
| $B \to \mu\nu$ | $5 \times 10^{-7}$ | |
| $B_s \to \mu^+\mu^-$ | $4 \times 10^{-9}$ | |
| $B \to \mu^+\mu^-$ | $2 \times 10^{-10}$ | |

Replacing $b \to s$ by $b \to d$ costs a factor $\sim 20$ (in SM); interesting to test in both: rates, $CP$ asymmetries, etc.

In $B \to q\, l_1\, l_2$ decays expect $10$–$20\%$ $K^*/\rho$, and $5$–$10\%$ $K/\pi$ (model dept)

Many of these (cleanest inclusive ones) impossible at hadron colliders

# Some theory excitements

$B$ physics has been and continues to be fertile ground for theoretical developments

HQET, ChPT, SCET, Lattice QCD, ...

# Charmless $B \to M_1 M_2$ decays

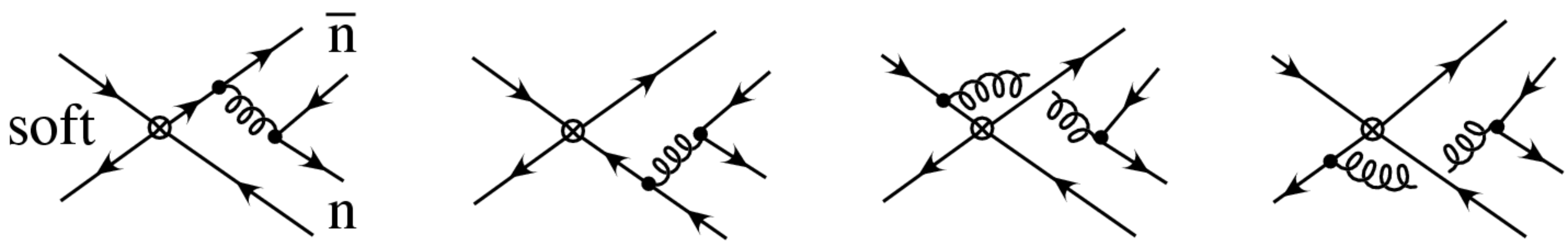
- BBNS (QCDF) factorization proposal:

$$\langle \pi\pi | O_i | B \rangle \sim F_{B\to\pi}\, T(x) \otimes \phi_\pi(x) + T(\xi, x, y) \otimes \phi_B(\xi) \otimes \phi_\pi(x) \otimes \phi_\pi(y)$$

The KLS (pQCD) formulae involve only $\phi_B$, $\phi_{M_1}$, $\phi_{M_2}$, with $k_\perp$ dependence

- SCET: $\langle \pi\pi | O_i | B \rangle \sim \sum_{ij} T(x, y) \otimes \left[ J_{ij}(x, z_k, k_\ell^+) \otimes \phi_\pi^i(z_k)\, \phi_B^j(k_\ell^+) \right] \otimes \phi_\pi(y)$

- Weak annihilation (WA) gives power suppressed ($\Lambda/E$) corrections




Yields convolution integrals of the form: $\displaystyle\int_0^1 \frac{\mathrm{d}x}{x^2}\, \phi_\pi(x)\,, \qquad \phi_\pi(x) \sim 6x(1-x)$

- BBNS: interpret as IR sensitivity $\Rightarrow$ modelled by complex parameters

KLS: rendered finite by $k_\perp$, but sizable and complex contributions

# Subtractions for divergent convolutions

- Choose interpolating field for pion to be made of collinear quarks $(p_i^- \neq 0)$

$$\langle \pi_n^+(p_\pi)|\bar{u}_{n,p_1^-}\, \bar{n}\!\!\!/\gamma_5\, d_{n,-p_2^-}|0\rangle = -i f_\pi\, \delta(\bar{n}\cdot p_\pi - p_1^- - p_2^-)\, \phi_\pi(x_1,x_2,\mu)$$

Zero-bin: $p_i^- \neq 0$ (collinear quark with $p_i^- = 0$ is not a collinear quark)

Divergence in $\int_0^1 \phi_\pi(x)/x^2$ related to one of the quarks becoming soft near $x=0$

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- Zero-bin ensures there is no contribution from $x_i = p_i^-/(\bar{n}\cdot p_\pi) \sim 0$

Subtractions implied by zero-bin depend on the singularity of integrals, e.g.:

$$\int_0^1 \mathrm{d}x\, \frac{1}{x^2}\, \phi_\pi(x,\mu) \quad \Rightarrow \quad \int_0^1 \mathrm{d}x\, \frac{\phi_\pi(x,\mu) - x\, \phi_\pi'(0,\mu)}{x^2} + \phi_\pi'(0,\mu) \ln\left(\frac{\bar{n}\cdot p_\pi}{\mu_-}\right)$$

$=$ finite

[Manohar & Stewart, hep-ph/0605001]

# Weak annihilation

- Match onto six-quark operators of the form (only hard contributions, no jet scale):

$$O_{1d}^{(ann)} = \sum_q \underbrace{\big[\bar{d}_s \Gamma_s \, b_v\big]}_{\text{gives } f_B} \underbrace{\big[\bar{u}_{\bar{n},\omega_2} \Gamma_{\bar{n}} \, q_{\bar{n},\omega_3}\big]}_{\pi \text{ in } \bar{n} \text{ direction}} \underbrace{\big[\bar{q}_{n,\omega_1} \Gamma_n \, u_{n,\omega_4}\big]}_{\pi \text{ in } n \text{ direction}}$$

[Arnesen, ZL, Rothstein, Stewart]

Similar to leading order contributions to the amplitude

- At leading nonvanishing order in $\Lambda/m_b$ and $\alpha_s$:
  - Real, because there is no way for these matrix elements to be complex
  - Calculable, and do not introduce nonperturbative inputs beyond those that occur in leading order factorization formula

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- Constrain parameters in QCDF and pQCD to be real, which have been taken to be complex $\Rightarrow$ fewer unknowns

- Can try to disentangle charm penguin amplitudes from weak annihilation, etc.

# Final comments

# Outlook

- If there are new particles at TeV scale, new flavor physics could show up any time
- Goal for further flavor physics experiments:

  If NP is seen in flavor physics: study it in as many different operators as possible

  If NP is not seen in flavor physics: achieve what is theoretically possible
  could teach us a lot about the NP seen at LHC

  The program as a whole is a lot more interesting than any single measurement
- Try to distinguish: One / many sources of CPV? Only in CC interactions?

  NP couples mostly to up / down sector? 3rd / all generations? $\Delta(F) = 2$ or $1$?

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- Political and technical realities aside, I think the case is compelling

  Many interesting measurements, complementarity with high energy frontier

# Theoretical limitations (continuum methods)

- Many interesting decay modes will not be theory limited for a long time

| Measurement (in SM) | Theoretical limit | Present error |
|---|---|---|
| $B \to \psi K\ (\beta)$ | $\sim 0.2^\circ$ | $1.3^\circ$ |
| $B \to \eta' K,\ \phi K\ (\beta)$ | $\sim 2^\circ$ | $5,\ 10^\circ$ |
| $B \to \rho\rho,\ \rho\pi,\ \pi\pi\ (\alpha)$ | $\sim 1^\circ$ | $\sim 13^\circ$ |
| $B \to DK\ (\gamma)$ | $\ll 1^\circ$ | $\sim 20^\circ$ |
| $B_s \to \psi\phi\ (\beta_s)$ | $\sim 0.2^\circ$ | — |
| $B_s \to D_s K\ (\gamma - 2\beta_s)$ | $\ll 1^\circ$ | — |
| $\lvert V_{cb}\rvert$ | $\sim 1\%$ | $\sim 2\%$ |
| $\lvert V_{ub}\rvert$ | $\sim 5\%$ | $\sim 10\%$ |
| $B \to X_s\gamma$ | $\sim 5\%$ | $\sim 10\%$ |
| $B \to X_s\ell^+\ell^-$ | $\sim 5\%$ | $\sim 20\%$ |
| $B \to K^{(*)}\nu\bar{\nu}$ | $\sim 5\%$ | — |

For some entries, the shown theoretical limits require more complicated analyses

It would require major breakthroughs to go significantly below these theory limits

# Conclusions

- Despite tremendous progress, new physics in neutral meson mixings may still be comparable to the SM contributions (sensitive to scales $\gg$ LHC)

- Measurement of $S_{\psi\phi}$, etc., at LHC(b) will constrain $B_s$ sector much better
  Precise measurements in $B_{u,d}$ sector is crucial for this as well

- Exciting theory progress: zero-bin factorization $\Rightarrow$ no divergent convolutions
  Annihilation & "chirally enhanced" hard scattering contributions better understood

- If new physics shows up in the flavor sector, pursuing this program is a no-brainer

  If no unambiguous sign of NP is found in the flavor sector, constraints may still provide important clues to model building in the LHC era


# Backup slides