ARGUS Fest

20 years of B meson oscillations

1987 - 2007

B Physics: Past and Present

Zoltan Ligeti

Symposium, DESY
09 November 2007

Remember 1987?

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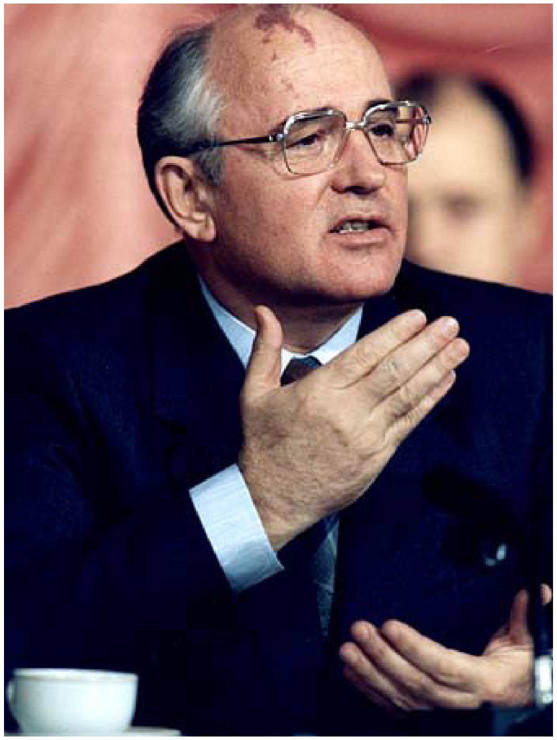

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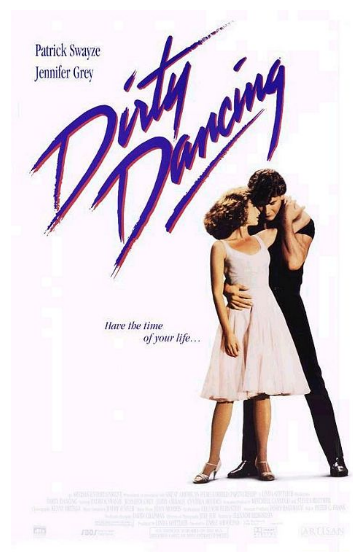
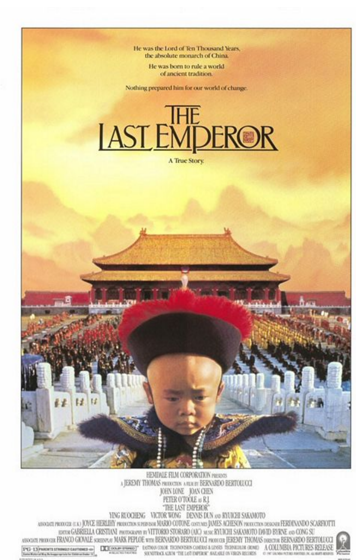
Movies: Dirty Dancing, The Last Emperor, etc.





Sports in 1987

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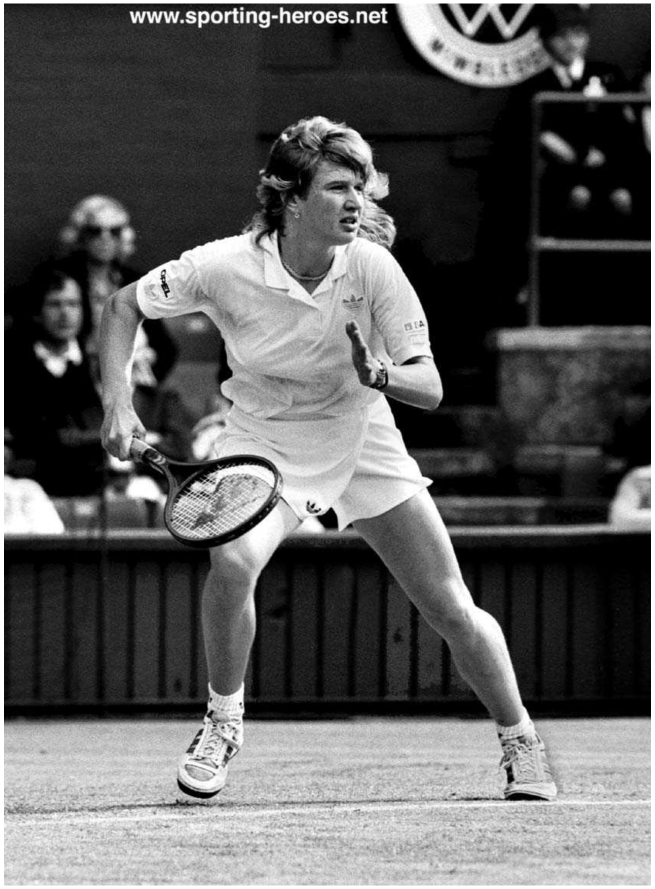
(men: Lendl, Cash, Edberg, Wilander...)



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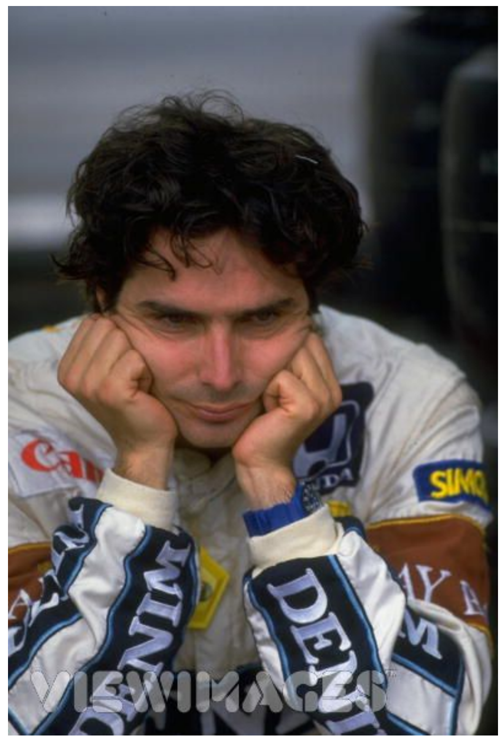

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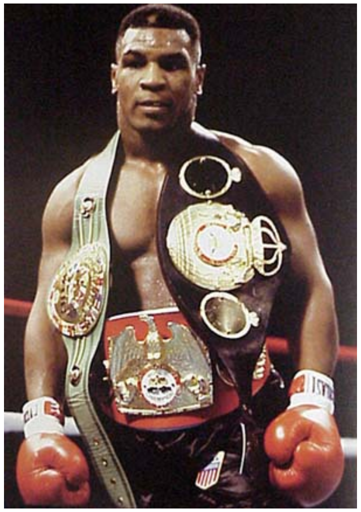

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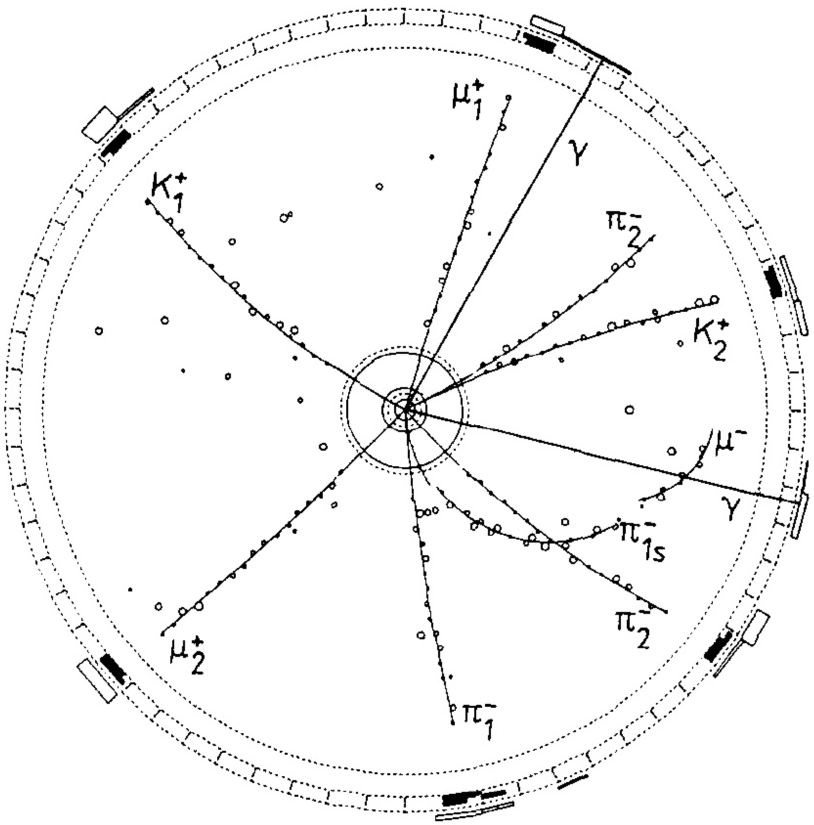
[not only vice presidents...]

Super Bowl XXI: New York Giants vs. Denver Broncos (39-20)

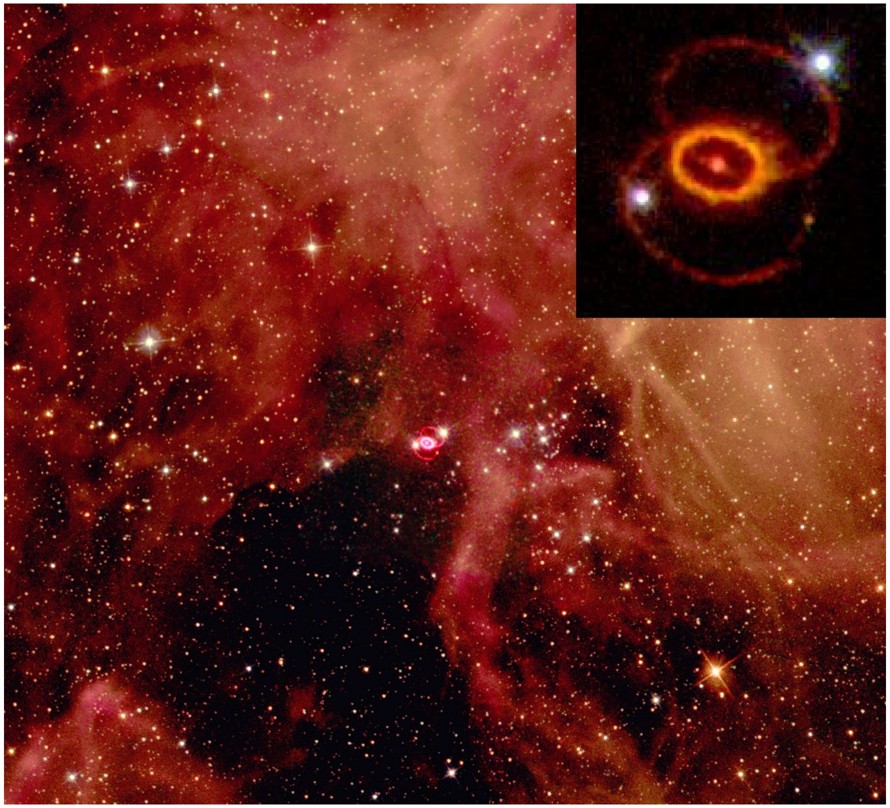
World series: Minnesota Twins vs. St. Louis Cardinals (4-3)

Physics in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing"
[June 25: Phys. Lett. B **192** (1987) 245]



Febr. 23: Supernova 1987A observed
[first naked-eye supernova since 1604]



Nobel prize: Georg Bednorz and Alex Müller (high T_c superconductors)

B^0–$\overline{B}^0$ mixing in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing" (PLB, 25 June 1987, Submitted Apr 9)

The direct bound was $m_t > 23\,\mathrm{GeV}$

RE-EXAMINATION OF THE STANDARD MODEL IN THE LIGHT OF B MESON MIXING

John ELLIS, J.S. HAGELIN [1]
CERN, CH-1211 Geneva 23, Switzerland

and

S. RUDAZ
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

Received 26 March 1987

(DESY seminar: Feb. 24; Moriond: Mar 8–15)

B^0–$\overline{B}^0$ mixing in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing" (PLB, 25 June 1987, Submitted Apr 9)

The direct bound was $m_t > 23\,\mathrm{GeV}$

FROM A NEW SMELL TO A NEW FLAVOUR
– B_d–$\bar{B}_d$ MIXING, *CP* VIOLATION AND NEW PHYSICS ☆

I.I. BIGI [1]
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

and

A.I. SANDA
Rockefeller University, New York, NY 10021, USA

Received 4 May 1987

B^0–$\overline{B}^0$ mixing in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing" (PLB, 25 June 1987, Submitted Apr 9)

The direct bound was $m_t > 23\,\mathrm{GeV}$

B_d^0–$\bar{B}_d^0$ OSCILLATIONS AND THE TOP QUARK MASS

V. BARGER, T. HAN, D.V. NANOPOULOS

Physics Department, University of Wisconsin, Madison, WI 53706, USA

and

R.J.N. PHILLIPS

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, UK

Received 4 May 1987

B^0–$\overline{B}^0$ mixing in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing" (PLB, 25 June 1987, Submitted Apr 9)

The direct bound was $m_t > 23\,\mathrm{GeV}$

B^0–$\overline{B}^0$ mixing within and beyond the standard model

G. Altarelli and P.J. Franzini
CERN, CH-1211 Geneva 23, Switzerland

Received 9 June 1987

B^0–$\overline{B}^0$ mixing in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing" (PLB, 25 June 1987, Submitted Apr 9)

The direct bound was $m_t > 23\,\mathrm{GeV}$

B–B̄ MIXING AND RELATIONS AMONG QUARK MASSES, ANGLES AND PHASES

Haim HARARI and Yosef NIR [1]

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

Received 15 June 1987

- SM interpretation: $m_t > (50 - 100)\,\mathrm{GeV}$

  Preferred f_B was way too small; PDG '86: $|V_{cb}| = 0.045 \pm 0.008$, $|V_{ub}/V_{cb}| < 0.2$

- Possibly $m_t > m_W$? No top hadrons? SM predicts B_s mixing near maximal

B^0–$\overline{B}^0$ mixing in 1987

ARGUS: "Observation of B^0–$\overline{B}^0$ mixing" (PLB, 25 June 1987, Submitted Apr 9)

The direct bound was $m_t > 23\,\mathrm{GeV}$

A LIGHT TOP QUARK AFTER ALL?

Sheldon L. GLASHOW and Elizabeth E. JENKINS [1]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 2 July 1987

NO LIGHT TOP QUARK AFTER ALL ☆

Yosef NIR
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

Received 1 December 1989

- New physics interpretation: depends on models and on other measurements
- Papers on: SUSY, 4th generation, mass matrix textures, Z' bosons, etc.
- A very influential discovery to date

Outline

- Introduction
  ... Flavor physics in the SM and beyond
- B physics at ARGUS and CLEO
  ... Some key measurements then — and now
- CP violation at BaBar and Belle
  ... Implications of some of the cleanest measurements
- $B_s^0 - \overline{B}{}_s^0$ and $D^0 - \overline{D}{}^0$ mixing
  ... Constraints on new physics and looking into the future
- Conclusions

Why is flavor physics interesting?

- SM flavor problem: hierarchy of masses and mixing angles; why ν's are different

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

$$\epsilon_K\colon \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{TeV}, \quad \Delta m_B\colon \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\text{TeV}, \quad \Delta m_{B_s}\colon \frac{(b\bar{s})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\text{TeV}$$

  – Almost all extensions of the SM have new sources of CPV & flavor conversion

  – A major constraint for model building

  – The observed baryon asymmetry of the Universe requires CPV beyond the SM
  Not necessarily in flavor changing processes in the quark sector
  Flavor suppression destroys KM baryogenesis; flavor matters for leptogenesis

---

- If $\Lambda_{\text{NP}} \gg 1\,\text{TeV}$: no observable effects $\Rightarrow$ precise SM measurements
  If $\Lambda_{\text{NP}} \sim 1\,\text{TeV}$: sizable effects possible $\Rightarrow$ could get detailed information on NP

Neutral meson systems

- $K^0 - \overline{K}^0$: 1956 discovery of K_L (proposal of C non-conservation in 1955)

  ϵ_K predicted 3rd generation

  Δm_K predicted $m_c \sim 1.5\,\mathrm{GeV}$

- $B^0 - \overline{B}^0$: 1987 discovery of mixing (long lifetime 1983)

  Δm_B predicted large m_t

Crucial for development / confirmation of SM + Strong constraints on new physics

---

- 2006, $B_s^0 - \overline{B}_s^0$: measurement of Δm_{B_s} in agreement with SM

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

What do these measurements tell us?

CKM tests with kaons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)

  In PDG '86, still $|\epsilon'/\epsilon| = 0$ within 1σ; Summer '87: $\epsilon'/\epsilon = (3.5 \pm 3.0 \pm 2.0) \times 10^{-3}$ (FNAL, ref. [3])

  $\epsilon'/\epsilon = (3.5 \pm 0.7 \pm 0.4 \pm 1.2) \times 10^{-3}$ (NA 31, ref. [4]) .

- $K \to \pi\nu\bar{\nu}$: Theoretically clean, but small rates $\sim 10^{-10}(K^\pm)$, $10^{-11}(K_L)$

  Observation (3 events): $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.5^{+1.3}_{-0.9}) \times 10^{-10}$ — need more data

---

- Does the SM (integrating out virtual W, Z, and quarks in tree and loop diagrams) explain all flavor changing interactions? (correlations? FCNCs? tree vs. loop?)
- B system: many doable and clean measurements to overconstrain CKM

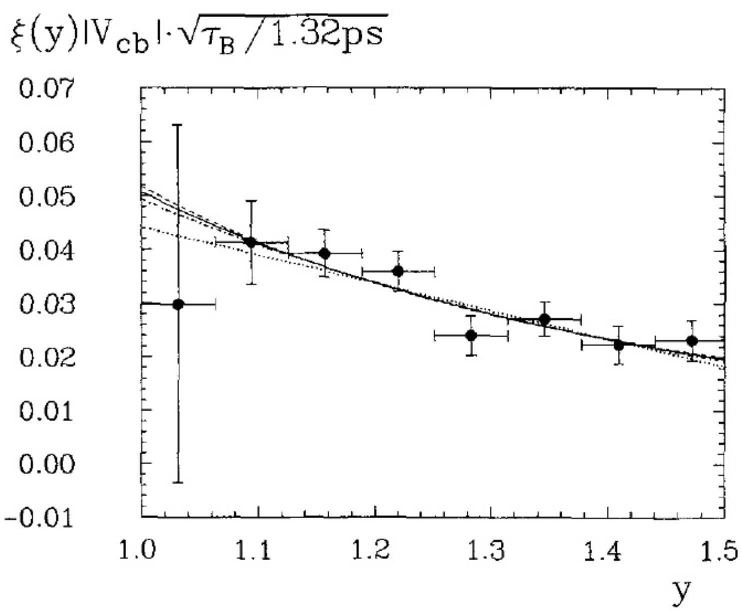
A few B physics topics

$B \to D^*\ell\bar{\nu}$: heavy quark symmetry

- Form factor relations at arbitrary "recoil", $y = v \cdot v'$, in $B \to D^{(*)}\ell\bar{\nu}$ [Isgur & Wise]

  Observed earlier, new look to extract $|V_{cb}|$ model independently

- Rate is model independent at zero recoil [Isgur & Wise; Luke; Voloshin & Shifman; Nussinov & Wetzel]



[ARGUS, Z. Phys. C **57** (1993) 533; Mea culpa for missing CLEO refs.]

	$\xi(y)$	$\lvert V_{cb}\rvert \times 10^3$	ρ	χ^2/df
A	$1 - \rho^2(y-1)$	$45 \pm 5 \pm 3$	$1.08 \pm 0.11 \pm 0.03$	$5.1/6$
B	$\frac{2}{y+1}\exp\left[-(2\rho^2-1)\frac{y-1}{y+1}\right]$	$53 \pm 8 \pm 3$	$1.52 \pm 0.21 \pm 0.10$	$4.3/6$
C	$\left(\frac{2}{y+1}\right)^{2\rho^2}$	$51 \pm 8 \pm 3$	$1.45 \pm 0.19 \pm 0.09$	$4.3/6$
D	$\exp\left[-\rho^2(y-1)\right]$	$50 \pm 8 \pm 2$	$1.37 \pm 0.19 \pm 0.08$	$4.4/6$

Table 5: Results on $|V_{cb}|$ and the "charge radius" ρ from various parametrizations of the Isgur-Wise-function $\xi(y)$ [22] for fitting the q^2-distribution

- Exclusive $|V_{cb}|$ measurements are similar to date

  New theory inputs: constraints on shape [Boyd, Grinstein, Lebed], $F(1)$ from LQCD [Fermilab]

Inclusive semileptonic $b \longrightarrow c$ decays then

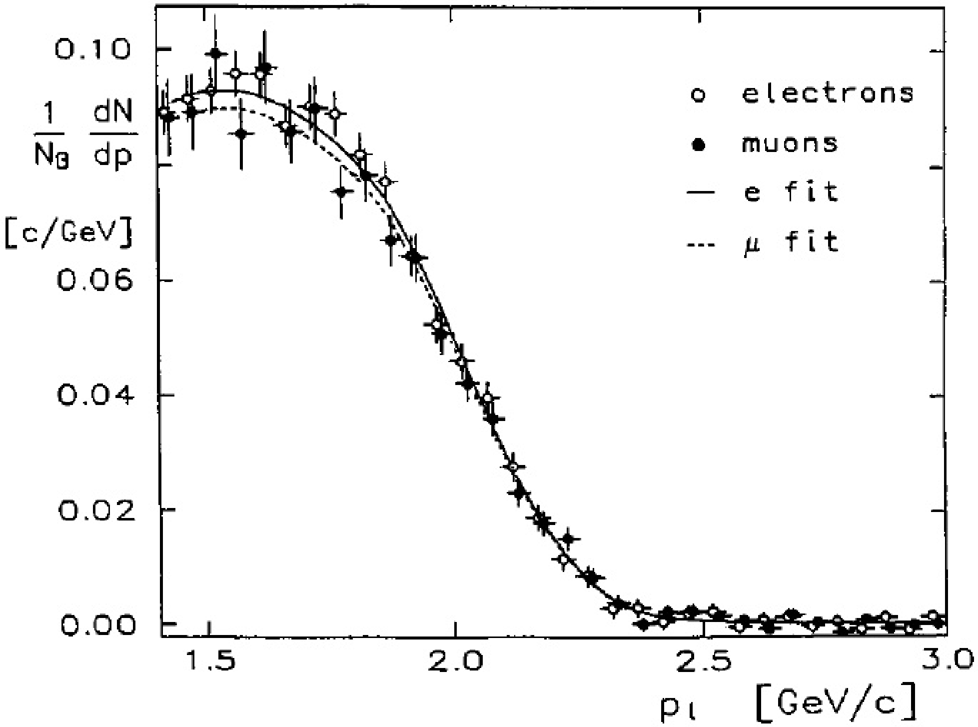


Fig. 3. Corrected momentum distribution of electrons and muons from $\Upsilon(4S)$ decays. The solid and dashed lines are the fits of the GISW model to the electron and muon data respectively.

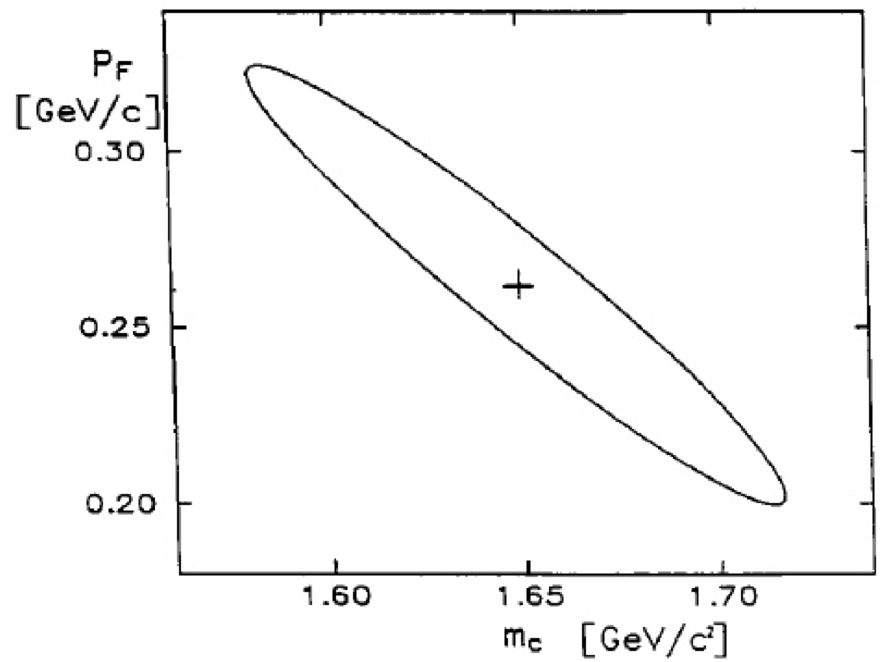


Fig. 4. Best fit and 1σ contour for p_F and m_c in the ACM model.

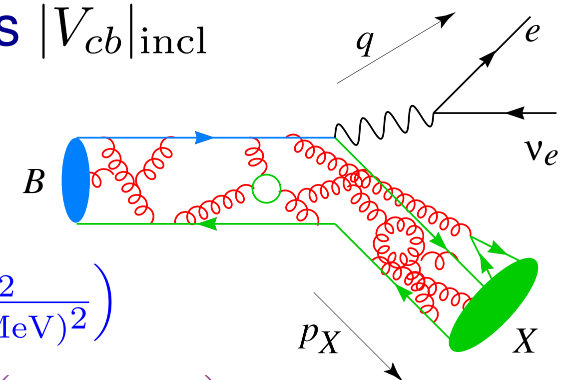
[ARGUS, PLB **249** (1990) 359]

- Preceeded theoretical foundations of how to derive from QCD something similar

  Rates: OPE in Λ_{QCD}/m_b [Chay, Georgi, Grinstein; Bigi, Shifman, Uraltsev, Vainshetein; Manohar & Wise; Mannel]

Determining $|V_{cb}|$ now

- Rely on heavy quark expansions; theoretically cleanest is $|V_{cb}|_{\rm incl}$



$$\Gamma(B \to X_c \ell \bar\nu) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} \left(\frac{m_\Upsilon}{2}\right)^5 (0.534) \times \Bigg[1$$
$$- 0.22\left(\frac{\Lambda_{1S}}{500\,\mathrm{MeV}}\right) - 0.011\left(\frac{\Lambda_{1S}}{500\,\mathrm{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{(500\,\mathrm{MeV})^2}\right) - 0.071\left(\frac{\lambda_2}{(500\,\mathrm{MeV})^2}\right)$$
$$- 0.006\left(\frac{\lambda_1\Lambda_{1S}}{(500\,\mathrm{MeV})^3}\right) + 0.011\left(\frac{\lambda_2\Lambda_{1S}}{(500\,\mathrm{MeV})^3}\right) - 0.006\left(\frac{\rho_1}{(500\,\mathrm{MeV})^3}\right) + 0.008\left(\frac{\rho_2}{(500\,\mathrm{MeV})^3}\right)$$
$$+ 0.011\left(\frac{T_1}{(500\,\mathrm{MeV})^3}\right) + 0.002\left(\frac{T_2}{(500\,\mathrm{MeV})^3}\right) - 0.017\left(\frac{T_3}{(500\,\mathrm{MeV})^3}\right) - 0.008\left(\frac{T_4}{(500\,\mathrm{MeV})^3}\right)$$
$$+ 0.096\epsilon - 0.030\epsilon^2_{\rm BLM} + 0.015\epsilon\left(\frac{\Lambda_{1S}}{500\,\mathrm{MeV}}\right) + \ldots\Bigg]$$

Corrections: $\mathcal{O}(\Lambda/m)$: $\sim 20\%$, $\mathcal{O}(\Lambda^2/m^2)$: $\sim 5\%$, $\mathcal{O}(\Lambda^3/m^3)$: $\sim 1-2\%$,
$\mathcal{O}(\alpha_s)$: $\sim 10\%$, Unknown terms: $< 2\%$

- Fit $\mathcal{O}(100)$ observables: test theory + determine $|V_{cb}|$ & hadronic matrix elements
- Error of $|V_{cb}| \sim 2\%$! Also important for ϵ_K (error $\propto |V_{cb}|^4$) and for $K \to \pi\nu\bar\nu$

Semileptonic $b \to u$ decays then

ARGUS, PLB **234** (1990) 409, Received 28 Nov 1989 $(201+69\,\mathrm{pb}^{-1})$

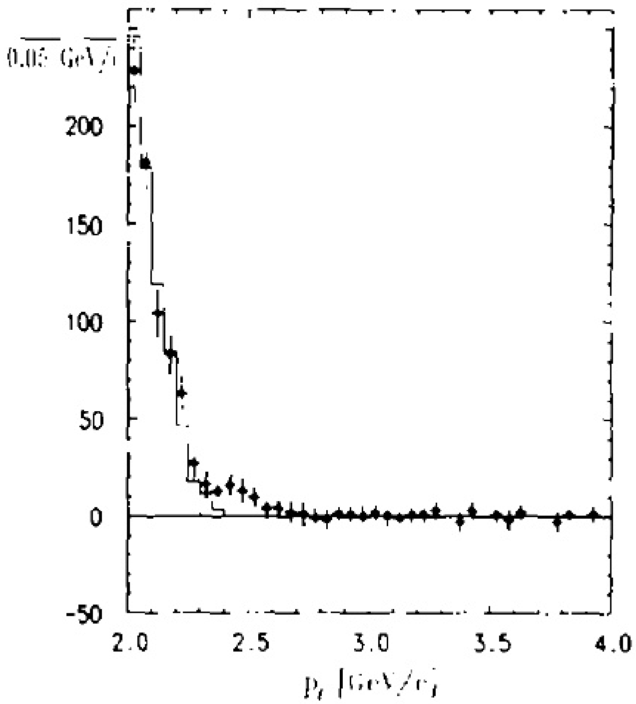


Fig. 5. Combined lepton momentum spectrum for direct $\Upsilon(4S)$ decays: the histogram is a $b \to c$ contribution normalized in the region 2.0–2.3 GeV/c.

"If interpreted as a signal of $b \to u$ coupling ... $|V_{ub}/V_{cb}|$ of about 10%."

CLEO, PRL **64** (1990) 16, Received 8 Nov 1989 $(212+101\,\mathrm{pb}^{-1})$

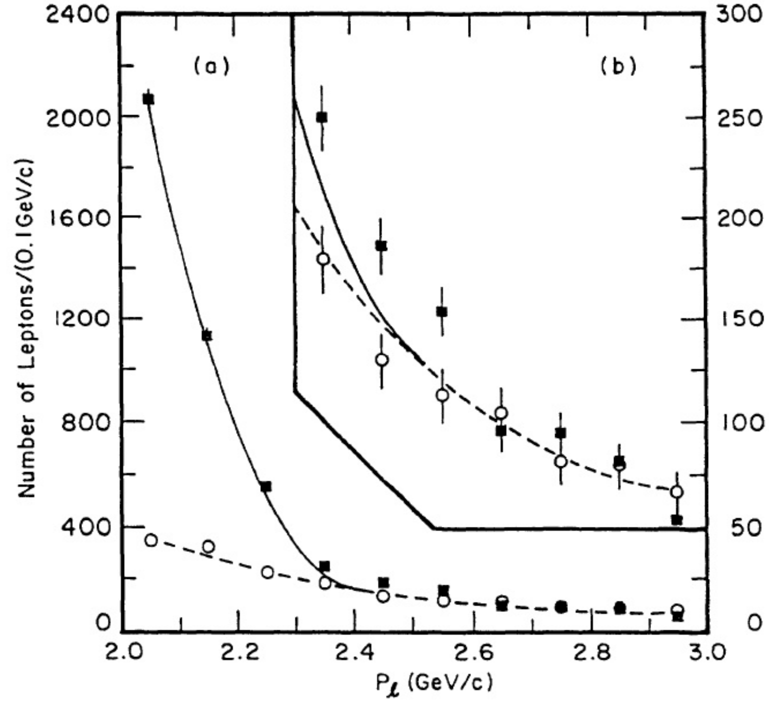


FIG. 1. Sum of the e and μ momentum spectra for ON data (filled squares), scaled OFF data (open circles), the fit to the OFF data (dashed line), and the fit to the OFF data plus the $b \to c l \nu$ yield (solid line). Note the different vertical scales in (a) and (b).

"$|V_{ub}/V_{cb}|$ ... is approximately 0.1; it is sensitive to the theoretical model."

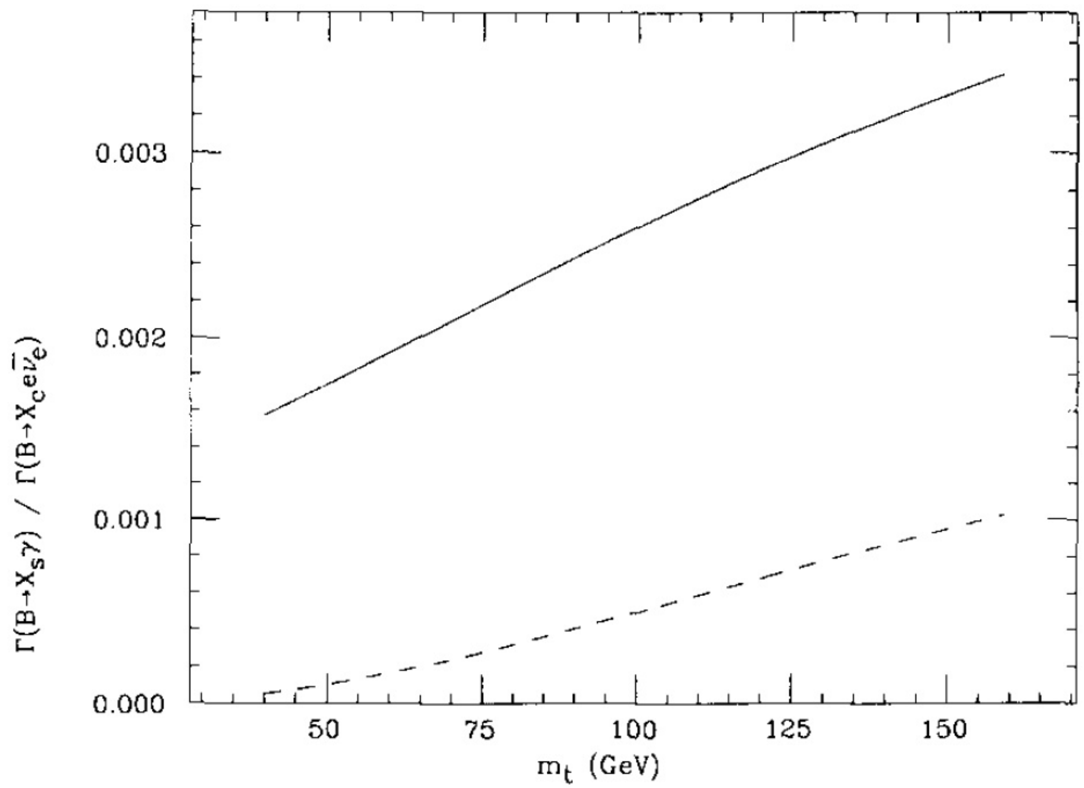
Interlude: $B \to X_s\gamma$ in 1987

- Series of elaborate calculations of inclusive rare B decays also started about ’87

EFFECTIVE HAMILTONIAN FOR WEAK RADIATIVE B-MESON DECAY ☆

Benjamin GRINSTEIN [1], Roxanne SPRINGER and Mark B. WISE [2]
California Institute of Technology, Pasadena, CA 91125, USA

Received 18 November 1987



Interlude: $B \to X_s\gamma$ in 2007

- One (if not "the") most elaborate SM calculations

  Constrains many models: 2HDM, SUSY, LRSM, etc.

- NNLO practically completed [Misiak et al., hep-ph/0609232]

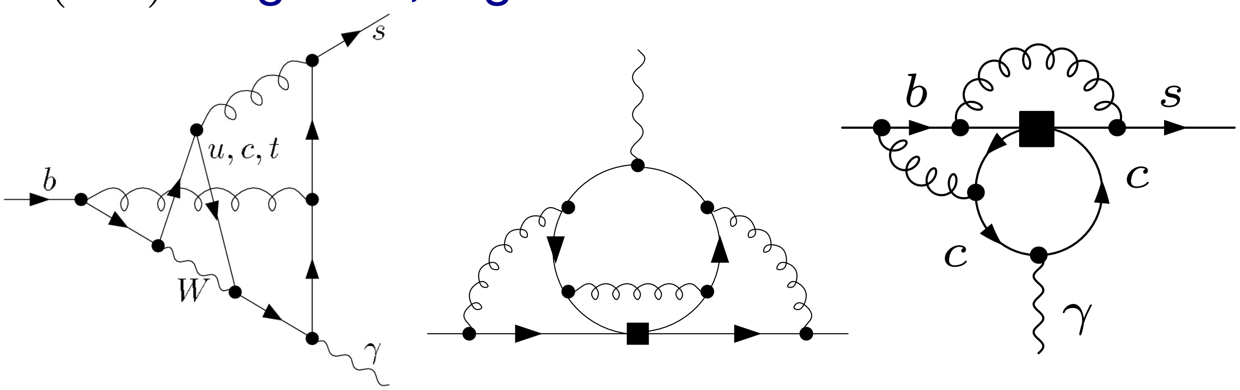
  4-loop running, 3-loop matching and matrix elements

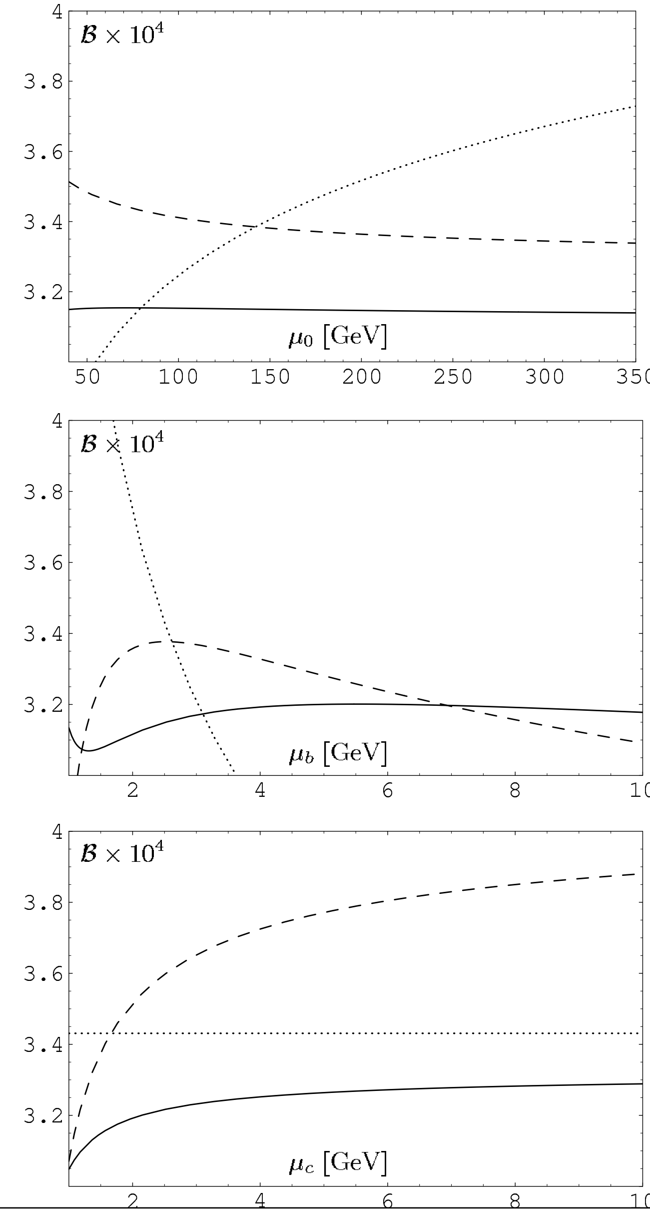
  Scale dependencies significantly reduced $\Rightarrow$

- $\mathcal{B}(B \to X_s\gamma)\big|_{E_\gamma>1.6\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$

  measurement: $(3.55 \pm 0.26) \times 10^{-4}$

$\mathcal{O}(10^4)$ diagrams, e.g.:





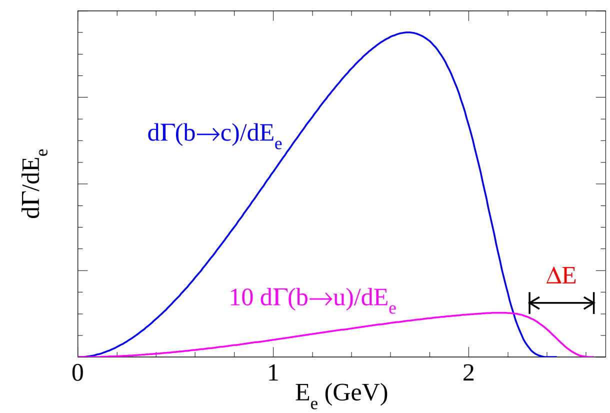
Measuring $|V_{ub}|$ since

- Side opposite to β; precision crucial to be sensitive to NP in $\sin 2\beta$ via mixing

- Inclusive: rate known to $\sim 5\%$; cuts to remove $B \to X_c \ell \bar{\nu}$ introduce small parameters that complicate expansions

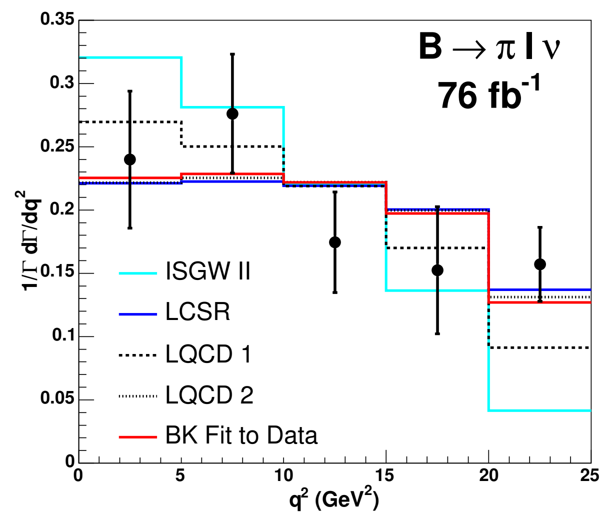
  Nonperturbative b distribution function ("shape function") enters due to phase space cuts: related to $\mathrm{d}\Gamma(B \to X_s \gamma)/\mathrm{d}E_\gamma$ at leading order, issues at order $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$

  [Neubert; Bigi, Shifman, Uraltsev, Vainshtein]



- Exclusive: $$\frac{\mathrm{d}\Gamma(\overline{B}^0 \to \pi^+ \ell \bar{\nu})}{\mathrm{d}q^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} \, |V_{ub}|^2 \, |f_+(q^2)|^2$$

  Tools: Lattice QCD, under control at large q^2 (small $|\vec{p}_\pi|$)
  Dispersion rel: constrain shape using few $f_+(q^2)$ values



- Many challenging open questions, active areas to date

Also related to $B \to X_s \ell^+ \ell^-$

- Complementary to $B \to X_s \gamma$, depends on:

$$O_7 = \overline{m}_b \, \bar{s} \sigma_{\mu\nu} e F^{\mu\nu} P_R b,$$

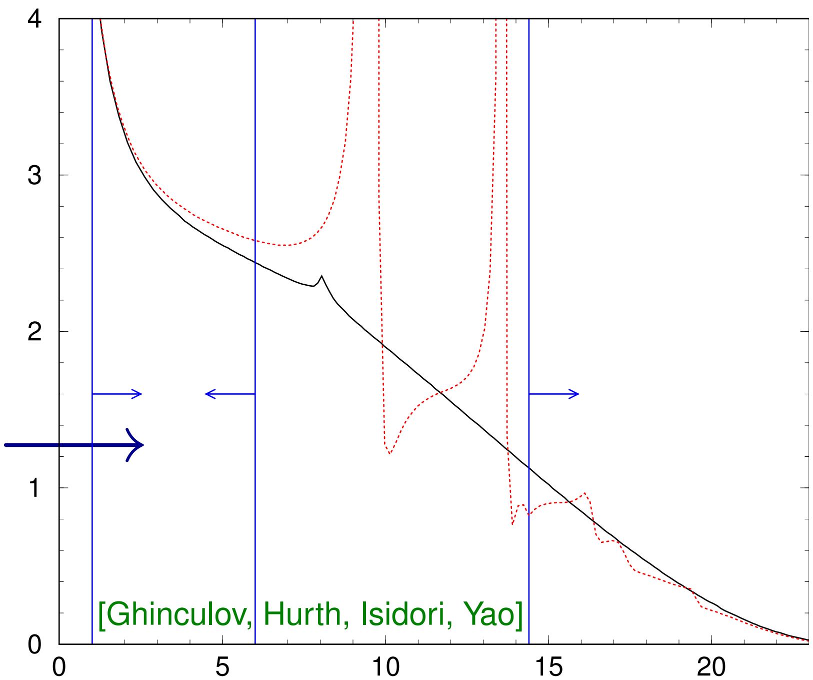
$$O_9 = e^2 (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell),$$

$$O_{10} = e^2 (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

Theory most precise for $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$

– NNLL perturbative calculations

– Nonperturbative corrections to q^2 spectrum



- In small q^2 region experiments require additional $m_{X_s} \lesssim 2\,\mathrm{GeV}$ cut to suppress $b \to c(\to s \ell^+ \nu) \ell^- \bar{\nu}$ $\Rightarrow$ nonperturbative effects [Ali & Hiller; Lee, ZL, Stewart, Tackmann]

- Theory same as for in inclusive $|V_{ub}|$ measurements (similar phase space cuts)

CP violation

The B factory era

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  A: 11; B: 15; C: 19; D: 23 (with different sensitivity to NP)

The B factory era

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  C: 19 (with different sensitivity to NP)

  ϵ_K, ϵ'_K,

  $S_{\eta' K}$, $S_{\psi K}$, $S_{f_0 K}$, $S_{K^+K^-K^0}$, $S_{\psi\pi^0}$, $S_{D^{*+}D^{*-}}$, $S_{D^{*+}D^-}$, $S_{\pi^+\pi^-}$

  $A_{\rho^0 K^+}$, $A_{\eta K^+}$, $A_{K^+\pi^-}$, $A_{\eta K^{*0}}$, $A_{\pi^+\pi^-}$, $A_{\rho^\pm\pi^\mp}$, $\Delta C_{\rho^\pm\pi^\mp}$, $a_{D^{*\pm}\pi^\mp}$, $A_{D_{\mathrm{CP}+}K^-}$

- Just because a measurement determines a CP violating quantity, it no longer automatically implies that it is interesting

  (E.g., if $S_{\eta' K}$ was still consistent with 0, it would be a many σ discovery of NP!)

- It doesn't matter if one measures a side or an angle — only experimental precision and theoretical cleanliness for interpretation for short distance physics do

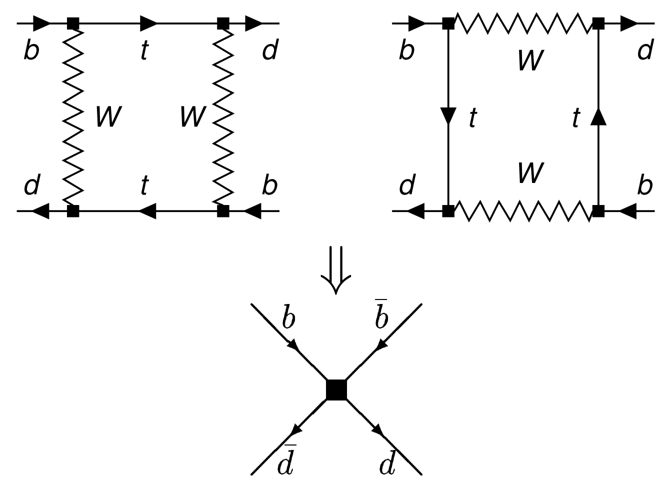
B^0–$\overline{B}^0$ mixing: matter – antimatter oscillation

- Quantum mechanical two-level system; flavor eigenstates: $|B^0\rangle = |\bar{b}d\rangle,\ |\overline{B}^0\rangle = |b\bar{d}\rangle$

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

  $M,\ \Gamma$: 2×2 Hermitian matrices

  Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$



$(\bar{b}_L\gamma_\nu d_L)(\bar{b}_L\gamma^\nu d_L)$

- CPV: mass eigenstates $\neq CP$ eigenstates

  $(|q/p| \neq 1 \ \Leftrightarrow\ \langle B_H|B_L\rangle \neq 0)$

- In SM: $q/p = e^{-2i\beta+(\xi_B+\xi_d-\xi_b)} + \mathcal{O}(10^{-3})$

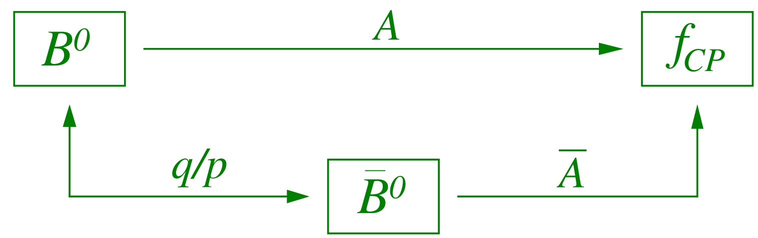
  $\Delta m = |V_{tb}V_{td}^*|^2\, f_B^2 B_B \times$ [known]

- For $B_{d,s}$: $|\Gamma_{12}| \ll |M_{12}| \ \Rightarrow\ \Delta m = 2|M_{12}|,\ \ \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12},\ \ \phi_{12} = \arg(-M_{12}/\Gamma_{12})$

- Sizable hadronic uncertainty in Δm and especially $|q/p|$, but not in $\arg(q/p)$

CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when B^0 and $\overline{B}^0$ decay to same final state



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle \qquad \lambda_{f_{CP}} = \frac{q}{p}\,\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

- Time dependent CP asymmetry:

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = \underbrace{\frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}}_{S_f} \sin(\Delta m\, t) - \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}_{C_f\ (-A_f)} \cos(\Delta m\, t)$$

- If amplitudes with one weak phase dominate a decay, hadronic physics drops out

- Measure a phase in the Lagrangian theoretically cleanly:

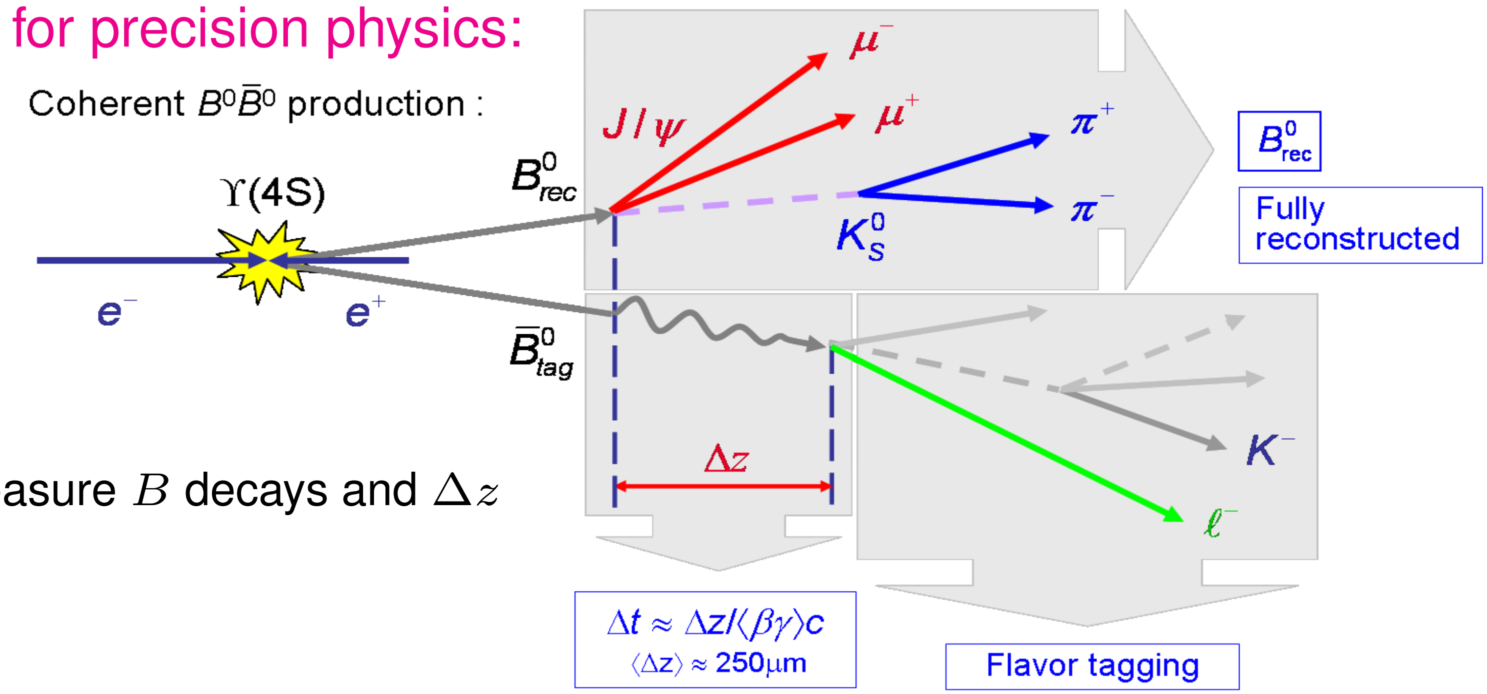
$$a_{f_{CP}} = \eta_{f_{CP}} \sin(\text{phase difference between decay paths}) \sin(\Delta m\, t)$$

Quantum entanglement in $\Upsilon(4S) \to B^0\overline{B}^0$

- $B^0\overline{B}^0$ pair created in a p-wave ($L = 1$) evolve coherently and undergo oscillations

  Two identical bosons cannot be in an antisymmetric state — if one B decays as a B^0 ($\overline{B}^0$), then at the same time the other B must be $\overline{B}^0$ (B^0)

- EPR effect used for precision physics:



Measure B decays and Δz

- First decay ends quantum correlation and tags the flavor of the other B at $t = t_1$

Some of the key CPV measurements

- β: $S_{\psi K_S} = -\sin[(B\text{-mix} = -2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)] = \sin 2\beta$

  World average: $\sin 2\beta = 0.681 \pm 0.025$ — 4% precision (theory uncertainty $< 1\%$)

- $S_{b\to s}$ "penguin" dominated modes: NP can enter in mixing (as $S_{\psi K}$), also in decay

  Earlier hints of deviations reduced: $S_{\psi K} - S_{\phi K_S} = 0.29 \pm 0.17$

- α: $S_{\pi^+\pi^-} = \sin[(B\text{-mix} = 2\beta) + (\overline{A}/A = 2\gamma + \ldots)] = \sin[2\alpha + \mathcal{O}(P/T)]$

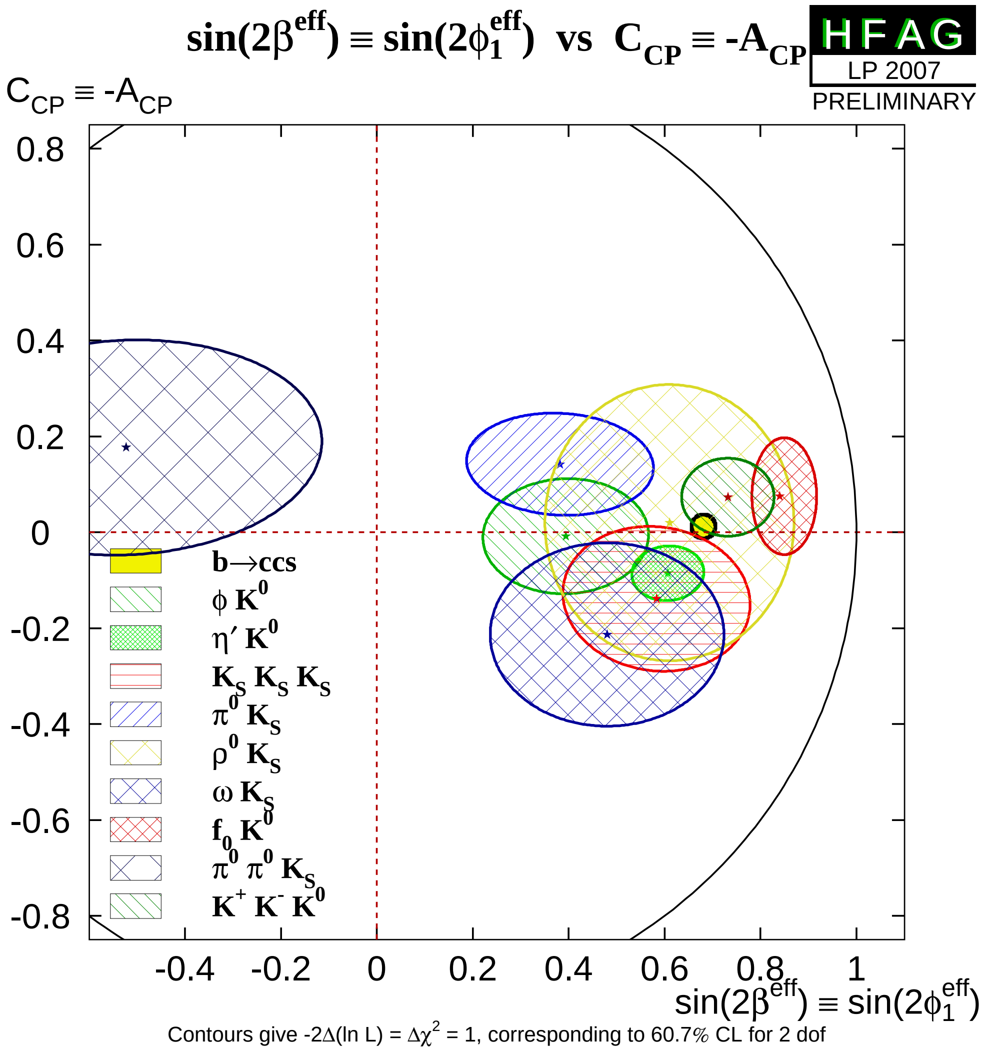
  CLEO 1997: $K\pi$ large, $\pi\pi$ small $\Rightarrow P_{\pi\pi}/T_{\pi\pi}$ large $\Rightarrow$ pursue all $\rho\rho$, $\rho\pi$, $\pi\pi$ modes

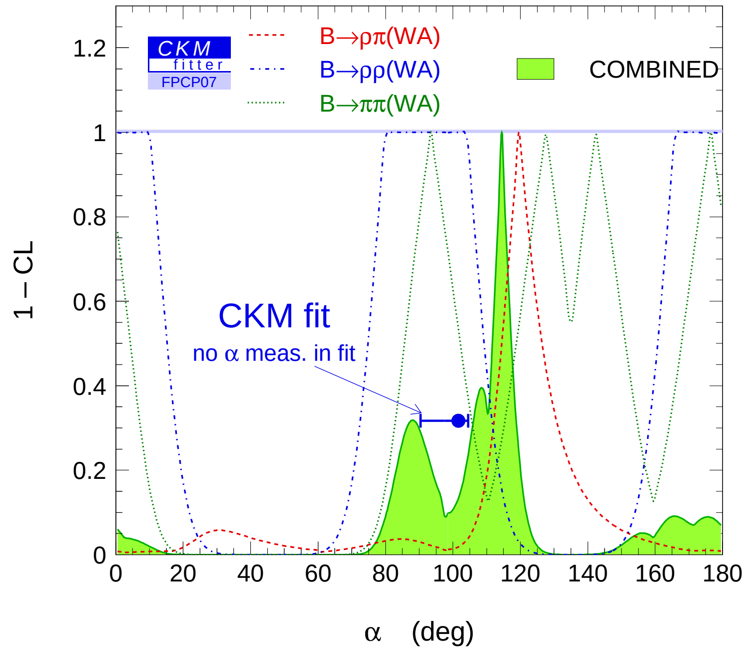
- γ: interference of tree level $b \to c\bar{u}s$ $(B^- \to D^0 K^-)$ and $b \to u\bar{c}s$ $(B^- \to \overline{D}^0 K^-)$

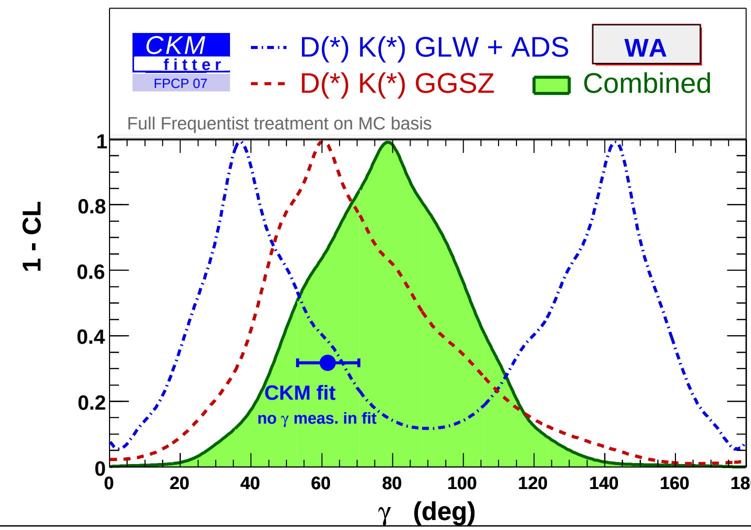
  Several difficult measurements ($D \to K_S\pi^+\pi^-$, D_{CP}, CF vs. DCS)

- Need a lot more data to approach irreducible theoretical limitations

Status of $\sin 2\beta_{\text{eff}}$, α, and γ





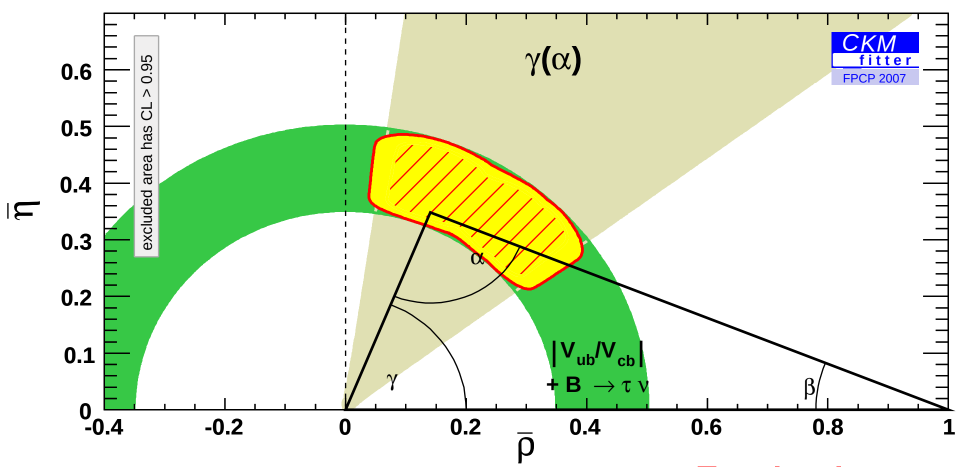


New physics in $B-\bar{B}$ mixing

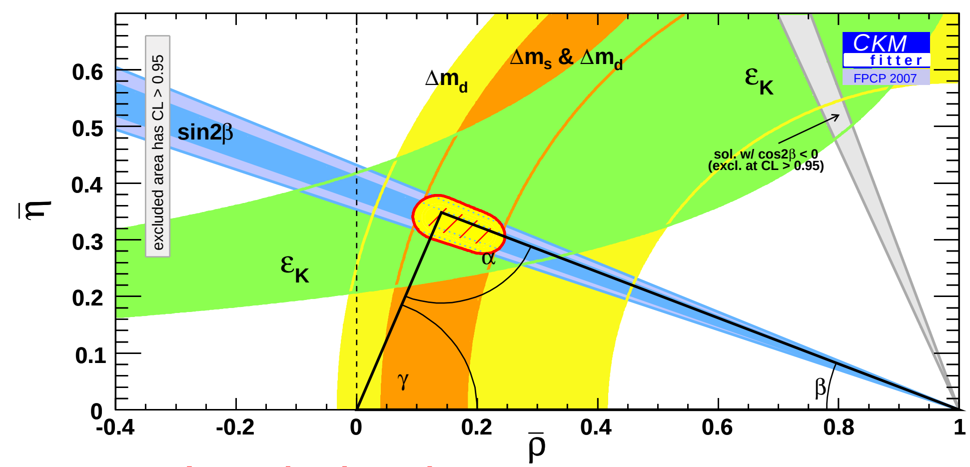
- Large class of models: (i) 3×3 CKM matrix is unitary
  (ii) Tree-level decays dominated by SM

Two NP parameters for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h\, e^{2i\sigma})$

- Tree-level CKM constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi-\beta-\alpha$)
- Observables sensitive to NP in mixing: $\Delta m_{d,s}$, $S_{\psi K}$, $S_{\rho\rho}$, $S_{B_s\to\psi\phi}$, $A_{\rm SL}^{d,s}$, $\Delta\Gamma_s^{CP}$



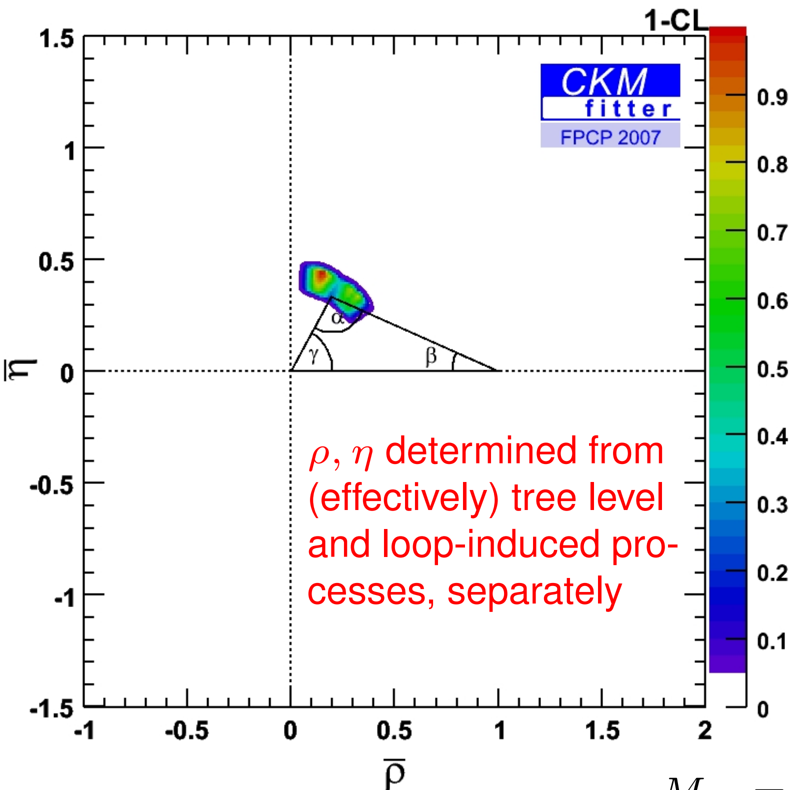
Tree-level

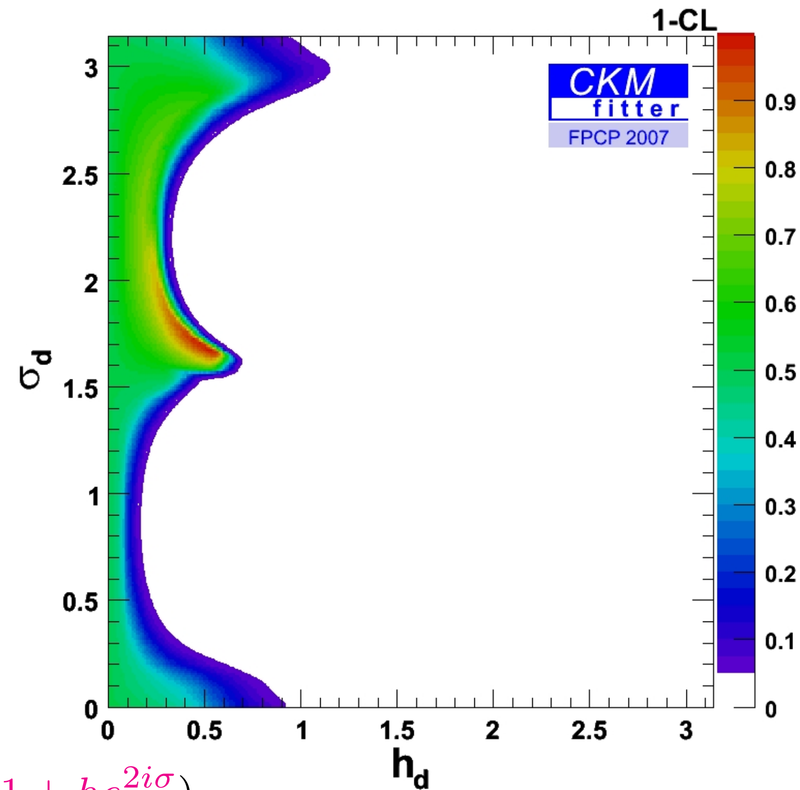


Loop-dominated

- Subsets of data give independent determinations, SM is impressively consistent

Constraints on NP in mixing





$$M_{12} = M_{12}^{\rm SM}\left(1 + h e^{2i\sigma}\right)$$

Only the SM-like region is allowed, even in the presence of NP in mixing

NP $\sim$ SM is still allowed; approaching NP $\ll$ SM unless $\sigma_d = 0$ (mod $\pi/2$)

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

B_s^0 and D^0 mixing

The D meson system

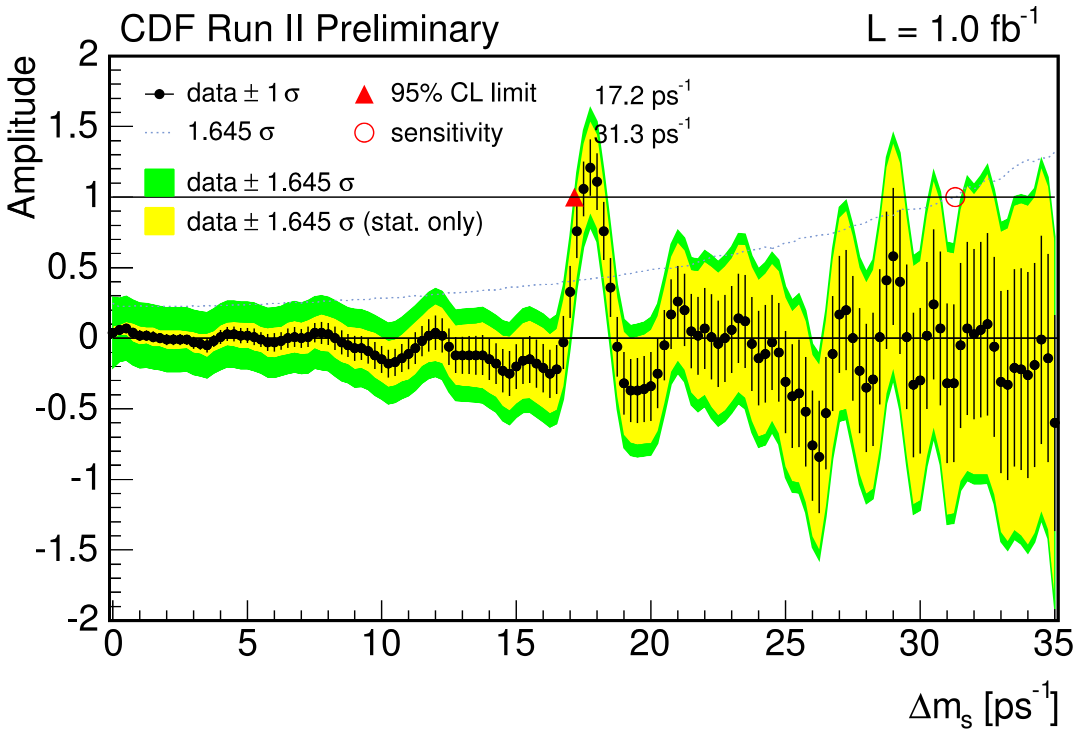
- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - Only meson mixing generated by down-type quarks (SUSY: up-type squarks)
  - SM suppression: $\Delta m_D,\, \Delta\Gamma_D \lesssim 10^{-2}\,\Gamma$, since doubly-Cabibbo-suppressed and vanish in flavor $SU(3)$ symmetry limit
  - First two generations dominate: CPV $\gg 10^{-3}$ would be unambiguously NP
  - 2007: signal for mixing at 4σ level; all measurements combined $> 5\sigma$

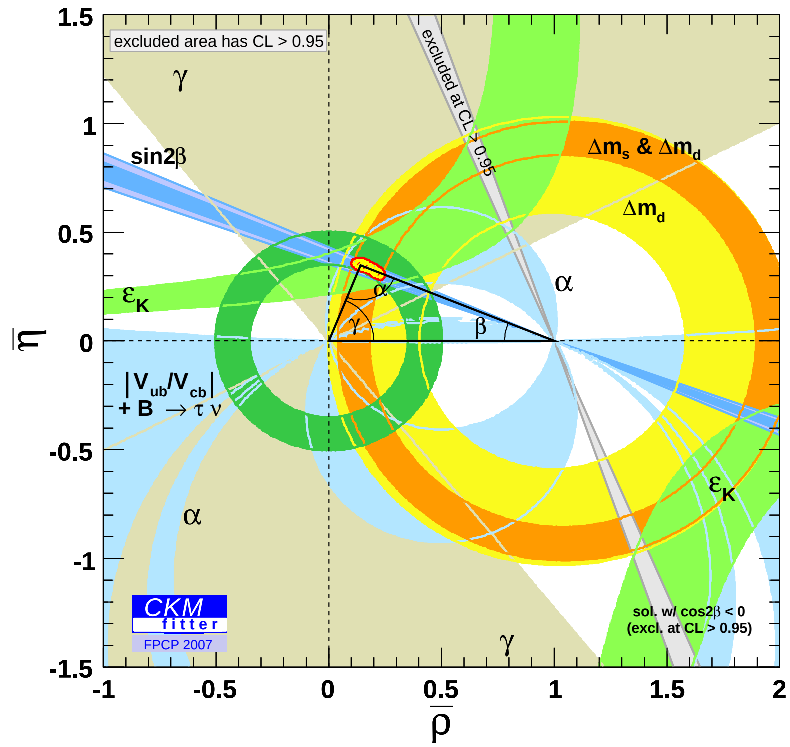
$$y_{CP} = \frac{\Gamma(CP\text{ even}) - \Gamma(CP\text{ odd})}{\Gamma(CP\text{ even}) + \Gamma(CP\text{ odd})} = (1.12 \pm 0.32)\%$$

[Babar, Belle, Cleo, Focus, E791]

- A wishlist: precise values of Δm and $\Delta\Gamma$? Will CPV be observed? Is $|q/p| \approx 1$?
- Particularly interesting for SUSY: Δm_D and $\Delta m_K \Rightarrow$ if first two squark doublets are within LHC reach, they must be quasi-degenerate (alignment alone not viable)

The news of 2006: Δm_{B_s} measured





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

[CDF, hep-ex/0609040]

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

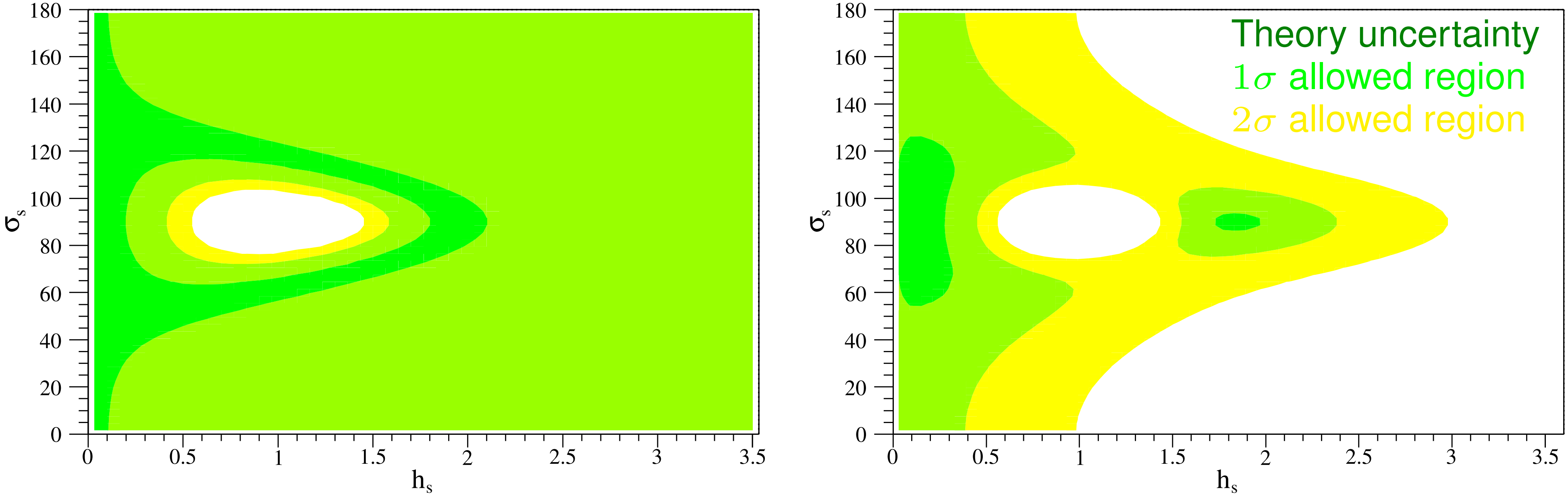
Largest uncertainty: $\xi = \dfrac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$

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

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]



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

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

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

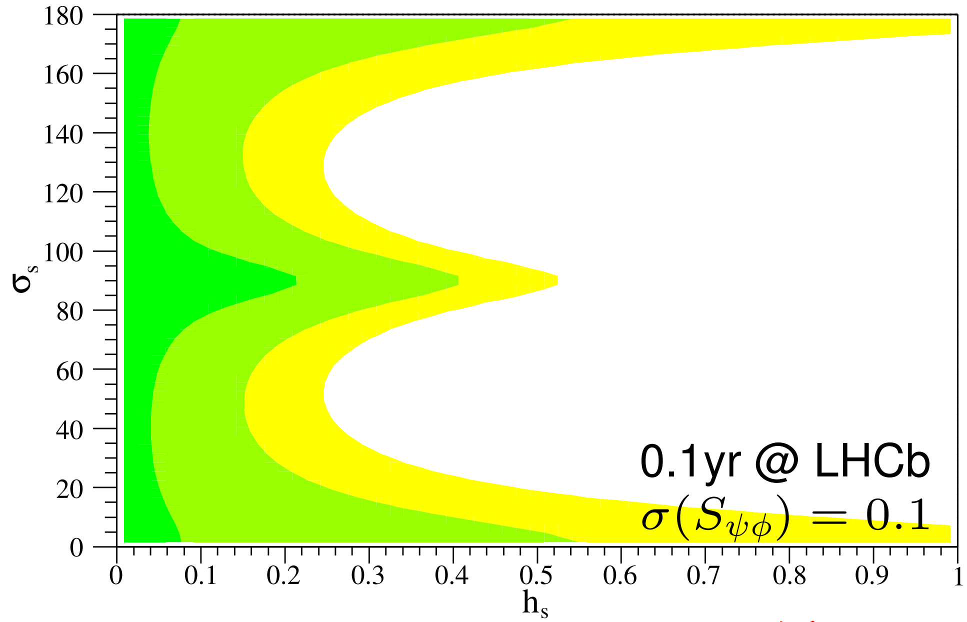
- $S_{\psi\phi}$ ($\sin 2\beta_s$ for CP-even) analog of $S_{\psi K}$
  CKM fit predicts: $\sin 2\beta_s = 0.0368^{+0.0017}_{-0.0018}$

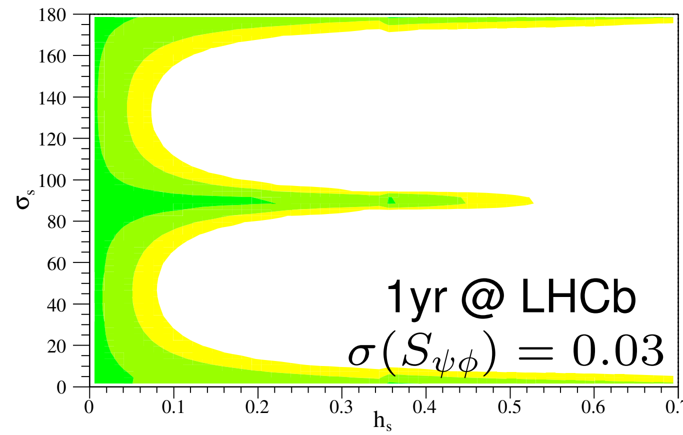
- 2000: Is $\sin 2\beta$ consistent with ϵ_K, $|V_{ub}|$
  Δm_B and other constraints?
  2009: Is $\sin 2\beta_s$ consistent with ...?

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

- With modest data sets, huge impact on our understanding; one of the most interesting early measurements

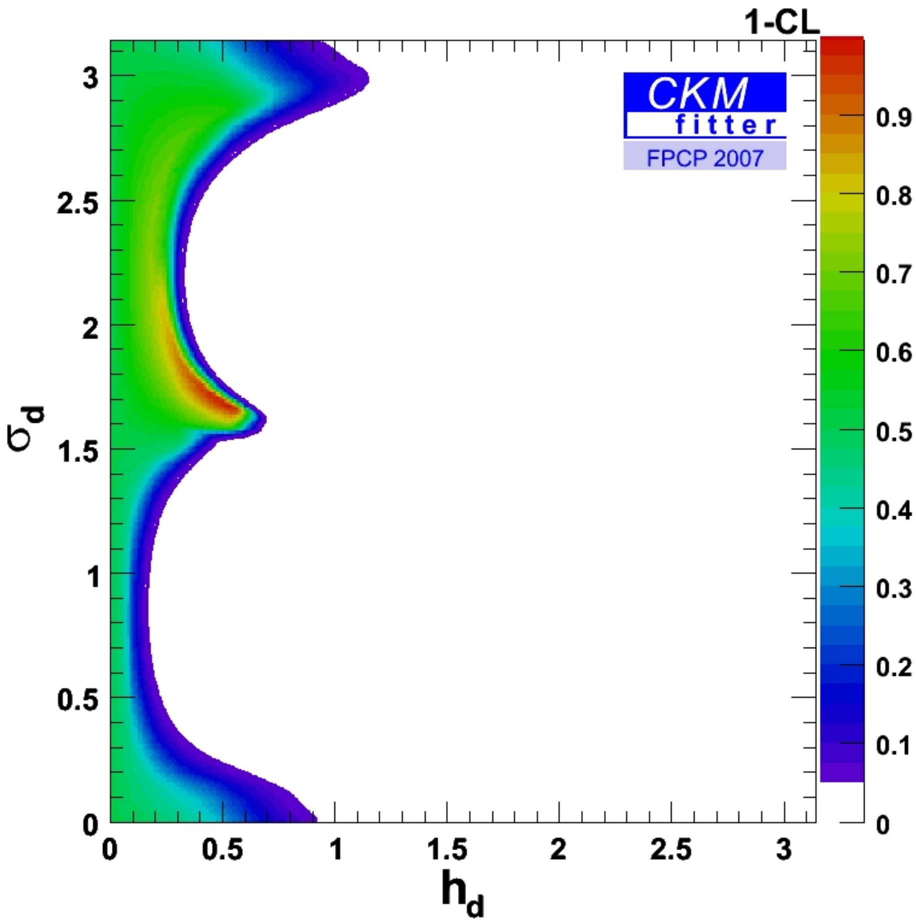
- Many important LHCb measurements

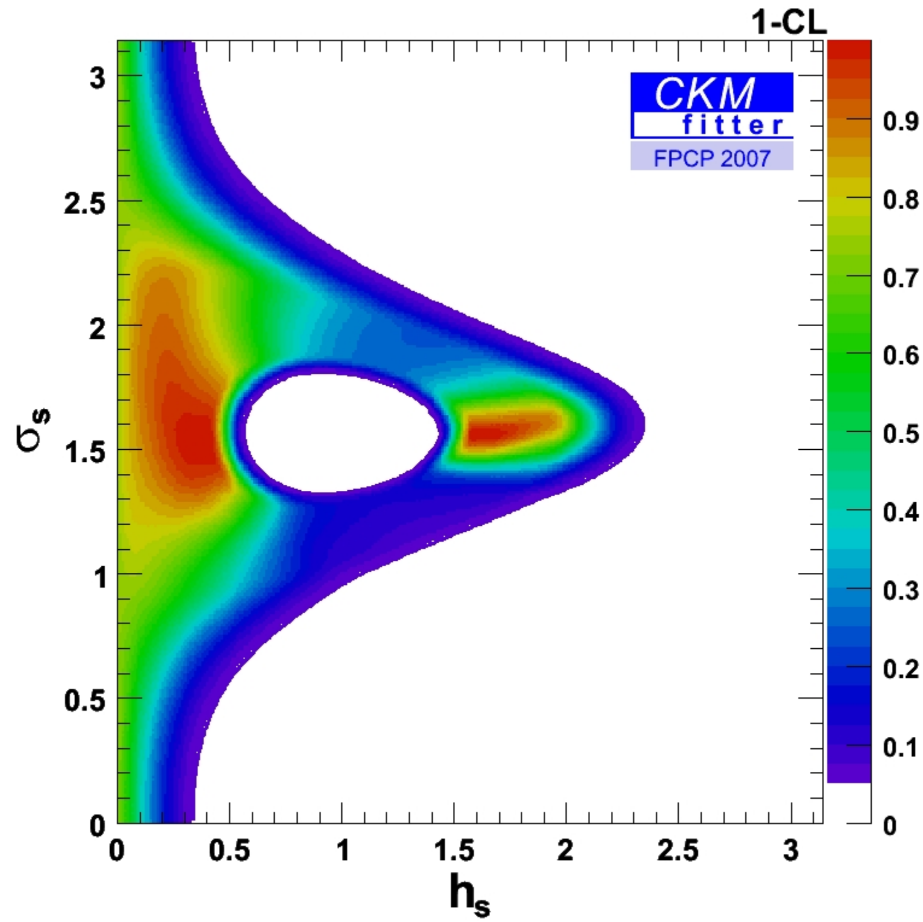




Notice scales!

New physics in $B_{d,s}$ mixings





- LHC(b) will probe NP in the B_s system at a level comparable to the B_d sector

Minimal flavor violation (MFV)

- How strongly can effects of NP at scale $\Lambda_{\rm NP}$ be (sensibly) suppressed?
- SM global flavor symmetry $U(3)_Q \times U(3)_u \times U(3)_d$ broken by nonzero Yukawa's

$$\mathcal{L}_Y = -Y_u^{ij}\, \overline{Q_{Li}^I}\, \widetilde{\phi}\, u_{Rj}^I - Y_d^{ij}\, \overline{Q_{Li}^I}\, \phi\, d_{Rj}^I \qquad \widetilde{\phi} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$$

- MFV: Assume Y's are the only source of flavor and CP violation (cannot demand all higher dimension operators to be flavor invariant and contain only SM fields)

[Chivukula & Georgi '87; Hall & Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02]

- CKM and GIM (m_q) suppressions similar to SM; allows EFT-like analyses

  Sizable corrections possible to some observables, even imposing MFV:
  $B \to X_s\gamma,\ B \to \tau\nu,\ B_s \to \mu^+\mu^-,\ \Delta m_{B_s},\ \Omega h^2,\ g-2$, precision electroweak

- In some scenarios high-p_T LHC data may rule out MFV or make it more plausible

Final comments

Shall we see new physics in flavor physics?

Do we just need to look with higher resolution?

A diamond field in Namibia

Summary

- The SM flavor sector has been tested with impressive & increasing precision
  KM phase is the dominant source of CP violation in flavor changing processes

- Measurements sensitive to scale $> \mathrm{TeV}$; sensitivity limited by statistics, not theory

- Deviations from SM in $B_{d,s}$ mixing, $b \to s$ and even $b \to d$ decays are constrained
  NP in $B\overline{B}$ mixing may still be comparable to the SM (sensitive to scales $\gg$ LHC)

- Tests of 3-2 generation transitions will approach precision of 3-1, approaching 2-1

- Synergy between theory and experiment and progress in both continue
  $\Rightarrow$ Learn more about electroweak physics and QCD — has been exciting and fun

Outlook

- The non-observation of NP at $E_{\rm exp} \sim m_B$ is a problem for NP at $\Lambda_{\rm NP} \sim \rm TeV$

  New physics could show up every time measurements improve

- If NP is seen: Study it in as many different operators as possible

  One / many sources of CPV? Only in CC interactions? NP couples mostly to up / down sector? 3rd / all generations? $\Delta(F) = 2$ or 1?

- If NP is not seen: Achieve what is theoretically possible

  Could teach us a lot whether or not NP is seen at LHC

- Flavor physics will provide important clues to model building in the LHC era

Backup slides

Neutral meson mixings

- Identities, neglecting CPV in mixing (not too important, surprisingly poorly known)

K: long-lived $=$ CP-odd $=$ heavy

D: long-lived $=$ CP-odd (3.5σ) $=$ light (2σ)

B_s: long-lived $=$ CP-odd (1.5σ) $=$ heavy in the SM

B_d: yet unknown, same as B_s in SM for $m_b \gg \Lambda_{\rm QCD}$

Before 2006, we only knew experimentally the kaon line above

- We have learned a lot about meson mixings — good consistency with SM

	$x = \Delta m/\Gamma$		$y = \Delta\Gamma/(2\Gamma)$		$A = 1 - \lvert q/p\rvert^2$	
	SM theory	data	SM theory	data	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	< 0.01	< 0.016	$\mathcal{O}(0.01)$	$y_{CP} = 0.011 \pm 0.003$	$< 10^{-4}$	$\mathcal{O}(1)$ bound only

SUSY contributions to $K^0 - \overline{K}^0$ mixing

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta \tilde m^2_{12}}{\tilde m^2}\right)^2 {\rm Re}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$$

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

- Classes of models to suppress each factors:

  (i) Heavy squarks: $\tilde m \gg 1\,{\rm TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde Q, \tilde D} \ll \tilde m^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetries)

- Similar formulae for Δm_B and Δm_{B_s}

  Constraint from ϵ_K: replace $10^4\,{\rm Re}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$ with $\sim 10^6\,{\rm Im}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$

- Has driven SUSY model building, all models incorporate some of the above

Testing the Standard Model

- All flavor changing processes depend only on a few parameters in the SM
  $\Rightarrow$ correlations between large number of s, c, b, t decays

- The SM flavor structure is very special — NP can violate each:
  – Single source of CP violation in CC interactions
  – Suppressions due to hierarchy of mixing angles
  – Suppression of FCNC loop processes

- Does the SM (i.e., integrating out virtual W, Z, and quarks in tree and loop diagrams) explain all flavor changing interactions?
  – Changes in correlations (B vs. K constraints, $S_{\psi K_S} \neq S_{\phi K_S}$, etc.)
  – Enhanced or suppressed CP violation (sizable $S_{B_s \to \psi\phi}$ or $A_{s\gamma}$, etc.)
  – Compare tree and loop processes — FCNC's at unexpected level

What's special about B's?

- Large variety of interesting processes:
  - Top quark loops neither GIM nor CKM suppressed
  - Large CP violating effects possible, some with clean interpretation
  - Some of the hadronic physics understood model independently $(m_b \gg \Lambda_{\rm QCD})$
- Experimentally feasible to study:
  - $\Upsilon(4S)$ resonance is clean source of B mesons
  - Long B meson lifetime
  - Timescale of oscillation and decay comparable: $\Delta m/\Gamma \simeq 0.77\, [= \mathcal{O}(1)]$ (and $\Delta\Gamma \ll \Gamma$)

Many interesting 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 μ)

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

Replacing $b \to s$ by $b \to d$ costs a factor ~ 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^*/ρ, and 5–10% K/π (model dept)

LHC: $B \to K^* \ell^+ \ell^-$ and $B_s \to \mu^+ \mu^-$

Inclusive modes impossible

Parameterization of NP in mixing

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

NP in mixing — 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 $\pi - \beta - \alpha$)

γ from $B_s^0 \to D_s^\pm K^\mp$

- Single weak phase in each $B_s, \overline{B}_s \to D_s^\pm K^\mp$ decay $\Rightarrow$ the 4 time dependent rates determine 2 amplitudes, a strong, and a weak phase (clean, although $|f\rangle \neq |f_{CP}\rangle$)

  Four amplitudes: $\overline{B}_s \stackrel{A_1}{\to} D_s^+ K^- \quad (b \to c\bar{u}s)\,, \qquad \overline{B}_s \stackrel{A_2}{\to} K^+ D_s^- \quad (b \to u\bar{c}s)$

  $$B_s \stackrel{A_1}{\to} D_s^- K^+ \quad (\bar{b} \to \bar{c}u\bar{s})\,, \qquad B_s \stackrel{A_2}{\to} K^- D_s^+ \quad (\bar{b} \to \bar{u}c\bar{s})$$

  $$\frac{\overline{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}} = \frac{A_1}{A_2} \left(\frac{V_{cb} V_{us}^*}{V_{ub}^* V_{cs}} \right), \qquad \frac{\overline{A}_{D_s^- K^+}}{A_{D_s^- K^+}} = \frac{A_2}{A_1} \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right)$$

  Magnitudes and relative strong phase of A_1 and A_2 drop out if four time dependent rates are measured $\Rightarrow$ no hadronic uncertainty:

  $$\lambda_{D_s^+ K^-}\, \lambda_{D_s^- K^+} = \left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right)^2 \left(\frac{V_{cb} V_{us}^*}{V_{ub}^* V_{cs}} \right) \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right) = e^{-2i(\gamma - 2\beta_s - \beta_K)}$$

- Similarly, $B_d \to D^{(*)\pm} \pi^\mp$ determines $\gamma + 2\beta$, since $\lambda_{D^+\pi^-}\, \lambda_{D^-\pi^+} = e^{-2i(\gamma+2\beta)}$

  ... ratio of amplitudes $\mathcal{O}(\lambda^2)$ $\Rightarrow$ small asymmetries (tag side interference)

CP violation in B_s mixing: $A^s_{\rm SL}$

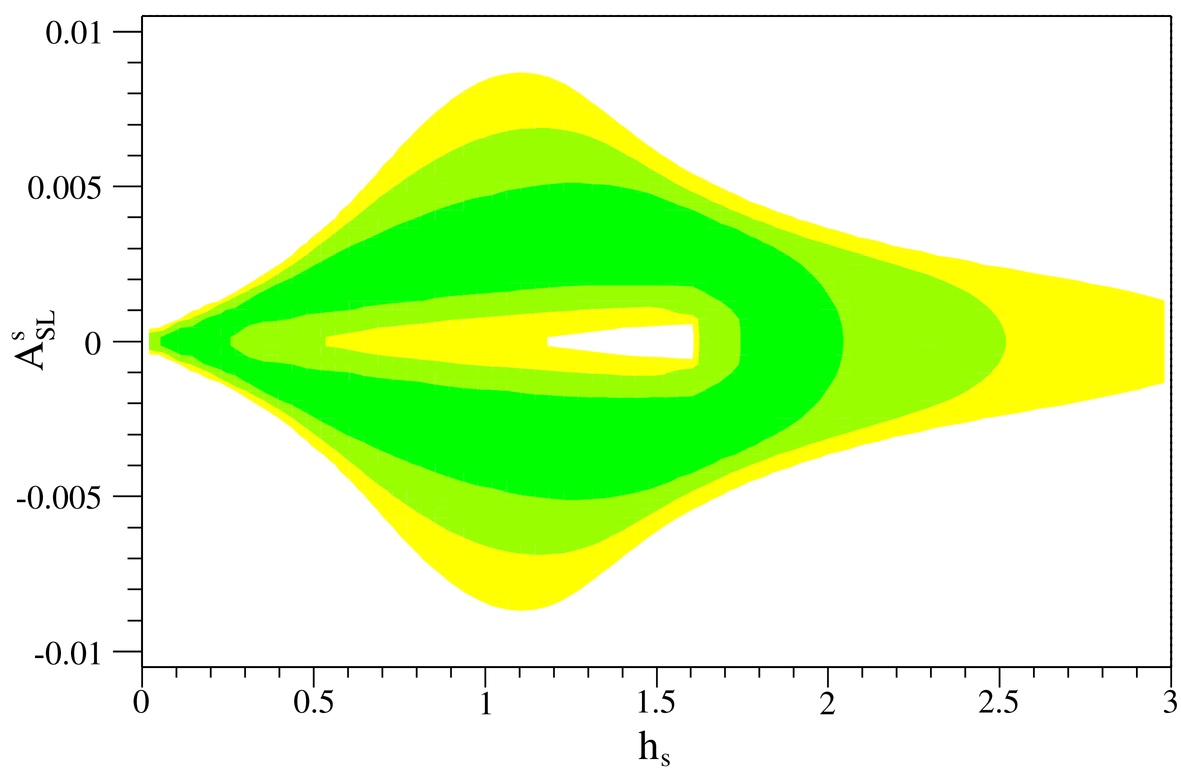
- Difference of $B \to \overline{B}$ vs. $\overline{B} \to B$ probability

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

– Can be $\mathcal{O}(10^3)$ times SM

– $|A^s_{\rm SL}| > |A^d_{\rm SL}|$ possible (contrary to SM)

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

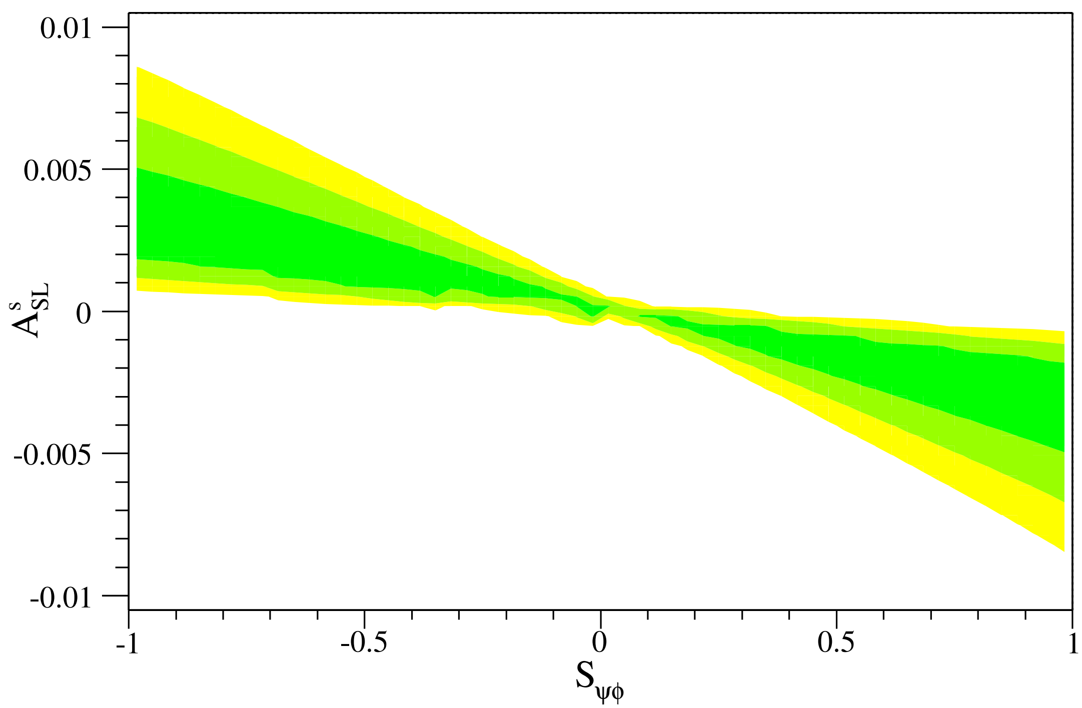


[see also: Buras *et al.*, hep-ph/0604057; Grossman, Nir, Raz, hep-ph/0605028]

Correlation between $S_{\psi\phi}$ and $A^s_{\rm SL}$

- $A^s_{\rm SL}$ and $S_{\psi\phi}$ are strongly correlated in $h_s, \sigma_s \gg \beta_s$ region [ZL, Papucci, Perez]

$$A^s_{\rm SL} = -\left|\frac{\Gamma^s_{12}}{M^s_{12}}\right|^{\rm SM} S_{\psi\phi} + \mathcal{O}\left(h_s^2,\, \frac{m_c^2}{m_b^2}\right)$$



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

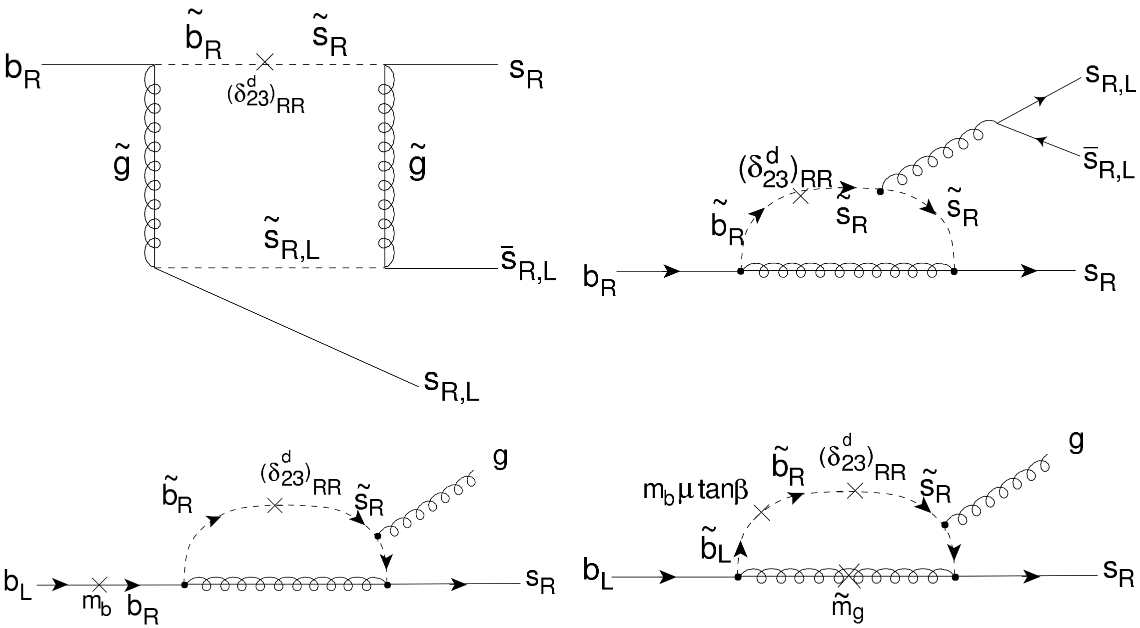
Some models to enhance Δm_s

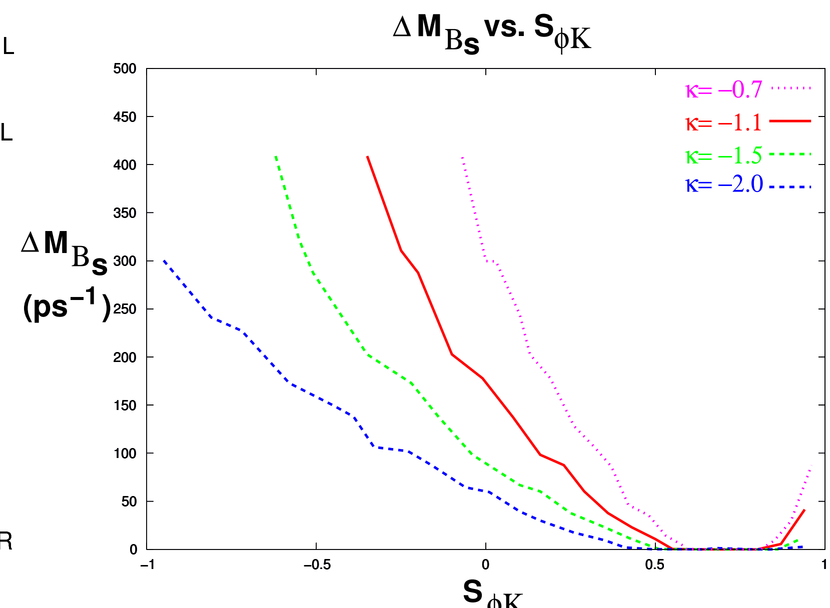
- SUSY GUTs: near-maximal $\nu_\mu - \nu_\tau$ mixing may imply large mixing between s_R and b_R, and between $\tilde{s}_R$ and $\tilde{b}_R$

  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





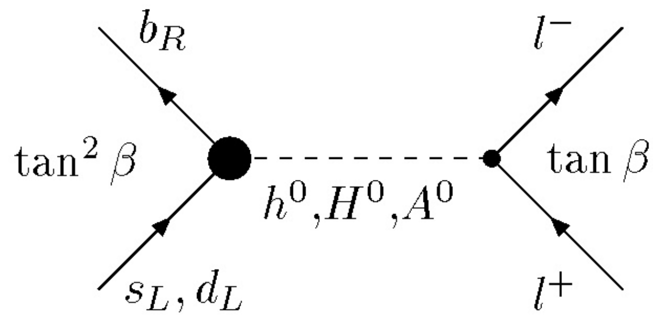
[Harnik, Larson, Murayama, Pierce, hep-ph/0212180]

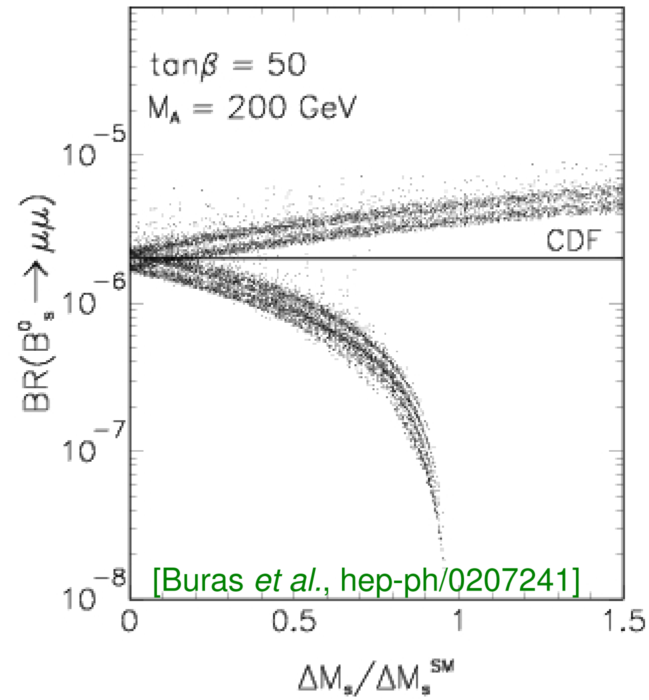
Some models to suppress Δm_s

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





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